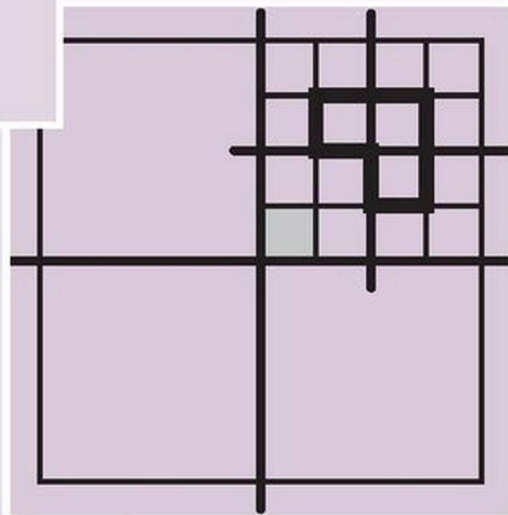
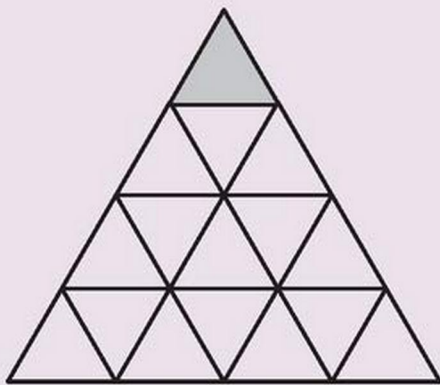
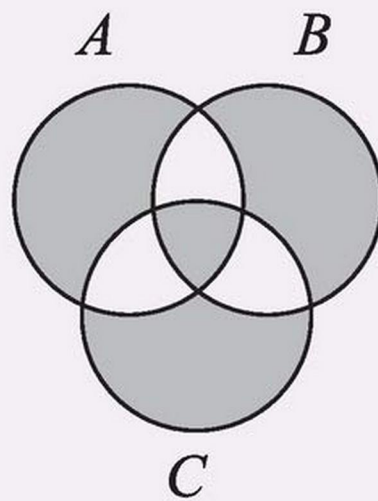
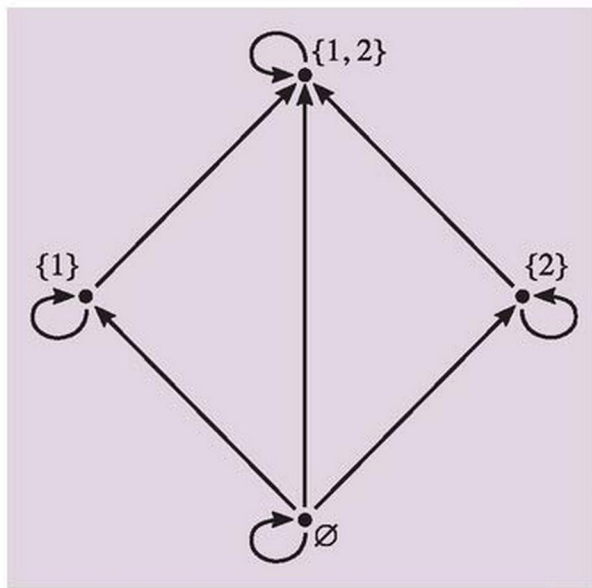


Third Edition

How to Prove It

A Structured Approach



Daniel J. Velleman

How To Prove It

HOW TO PROVE IT

A Structured Approach
Third Edition

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To Shelley

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Preface to the Third Edition

Students of mathematics and computer science often have trouble the first time they're asked to work seriously with mathematical proofs, because they don't know the "rules of the game." What is expected of you if you are asked to prove something? What distinguishes a correct proof from an incorrect one? This book is intended to help students learn the answers to these questions by spelling out the underlying principles involved in the construction of proofs.

Many students get their first exposure to mathematical proofs in a high school course on geometry. Unfortunately, students in high school geometry are usually taught to think of a proof as a numbered list of statements and reasons, a view of proofs that is too restrictive to be very useful. There is a parallel with computer science here that can be instructive. Early programming languages encouraged a similar restrictive view of computer programs as numbered lists of instructions. Now computer scientists have moved away from such languages and teach programming by using languages that encourage an approach called "structured programming." The discussion of proofs in this book is inspired by the belief that many of the considerations that have led computer scientists to embrace the structured approach to programming apply to proof writing as well. You might say that this book teaches "structured proving."

In structured programming, a computer program is constructed, not by listing instructions one after another, but by combining certain basic structures such as the if-else construct and do-while loop of the Java programming language. These structures are combined, not only by listing them one after another, but also by *nesting* one within another. For example, a program constructed by nesting an if-else construct within a do-while loop would look like this:

```

do
  if [condition]
    [List of instructions goes here.]
  else
    [Alternative list of instructions goes here.]
while [condition]

```

The indenting in this program outline is not absolutely necessary, but it is a convenient method often used in computer science to display the underlying structure of a program.

Mathematical proofs are also constructed by combining certain basic proof structures. For example, a proof of a statement of the form “if P then Q ” often uses what might be called the “suppose-until” structure: we *suppose* that P is true *until* we are able to reach the conclusion that Q is true, at which point we retract this supposition and conclude that the statement “if P then Q ” is true. Another example is the “for arbitrary x prove” structure: to prove a statement of the form “for all x , $P(x)$,” we *declare* x to be an arbitrary object and then *prove* $P(x)$. Once we reach the conclusion that $P(x)$ is true we retract the declaration of x as arbitrary and conclude that the statement “for all x , $P(x)$ ” is true. Furthermore, to prove more complex statements these structures are often combined, not only by listing one after another, but also by nesting one within another. For example, to prove a statement of the form “for all x , if $P(x)$ then $Q(x)$ ” we would probably nest a “suppose-until” structure within a “for arbitrary x prove” structure, getting a proof of this form:

```

Let  $x$  be arbitrary.
  Suppose  $P(x)$  is true.
    [Proof of  $Q(x)$  goes here.]
  Thus, if  $P(x)$  then  $Q(x)$  .
Thus, for all  $x$ , if  $P(x)$  then  $Q(x)$  .

```

As before, we have used indenting to make the underlying structure of the proof clear.

Of course, mathematicians don’t ordinarily write their proofs in this indented form. Our aim in this book is to teach students to write proofs in ordinary paragraphs, just as mathematicians do, and not in the indented form. Nevertheless, our approach is based on the belief that if students are to succeed at writing such proofs, they must understand the underlying structure that proofs have. They must learn, for example, that sentences like “Let x be arbitrary” and “Suppose P ” are not isolated steps in proofs, but are used to introduce the “for arbitrary x prove” and “suppose-until” proof structures. It is

not uncommon for beginning students to use these sentences inappropriately in other ways. Such mistakes are analogous to the programming error of using a “do” with no matching “while.”

Note that in our examples, the choice of proof structure is guided by the logical form of the statement being proven. For this reason, the book begins with elementary logic to familiarize students with the various forms that mathematical statements take. Chapter 1 discusses logical connectives, and quantifiers are introduced in Chapter 2. These chapters also present the basics of set theory, because it is an important subject that is used in the rest of the book (and throughout mathematics), and also because it serves to illustrate many of the points of logic discussed in these chapters.

Chapter 3 covers structured proving techniques in a systematic way, running through the various forms that mathematical statements can take and discussing the proof structures appropriate for each form. The examples of proofs in this chapter are for the most part chosen, not for their mathematical content, but for the proof structures they illustrate. This is especially true early in the chapter, when only a few proof techniques have been discussed, and as a result many of the proofs in this part of the chapter are rather trivial. As the chapter progresses, the proofs get more sophisticated and more interesting, mathematically.

Chapters 4 and 5, on relations and functions, serve two purposes. First, they provide subject matter on which students can practice the proof-writing techniques from Chapter 3. And second, they introduce students to some fundamental concepts used in all branches of mathematics.

Chapter 6 is devoted to a method of proof that is very important in both mathematics and computer science: mathematical induction. The presentation builds on the techniques from Chapter 3, which students should have mastered by this point in the book.

After completing Chapter 6, students should be ready to tackle more substantial mathematical topics. Two such topics are presented in Chapters 7 and 8. Chapter 7, new in this third edition, gives an introduction to number theory, and Chapter 8 discusses infinite cardinalities. These chapters give students more practice with mathematical proofs, and they also provide a glimpse of what more advanced mathematics is like.

Every section of every chapter ends with a list of exercises. Some exercises are marked with an asterisk; solutions or hints for these exercises are given in the appendix. Exercises marked with the symbol P_D can be done using Proof Designer software, which is available free on the internet.

The biggest changes in this third edition are the addition of a new chapter on number theory and also more than 150 additional exercises. The section

on reflexive, symmetric, and transitive closures of relations has been deleted from Chapter 4 (although these topics are now introduced in some exercises in Section 4.4); it has been replaced with a new section in Chapter 5 on closures of sets under functions. There are also numerous small changes throughout the text.

I would like to thank all those who sent me comments about earlier editions of this book. In particular, John Corcoran and Raymond Boute made several helpful suggestions. I am also grateful for advice from Jonathan Sands and several anonymous reviewers.

Introduction

What is mathematics? High school mathematics is concerned mostly with solving equations and computing answers to numerical questions. College mathematics deals with a wider variety of questions, involving not only numbers, but also sets, functions, and other mathematical objects. What ties them together is the use of *deductive reasoning* to find the answers to questions. When you solve an equation for x you are using the information given by the equation to *deduce* what the value of x must be. Similarly, when mathematicians solve other kinds of mathematical problems, they always justify their conclusions with deductive reasoning.

Deductive reasoning in mathematics is usually presented in the form of a *proof*. One of the main purposes of this book is to help you develop your mathematical reasoning ability in general, and in particular your ability to read and write proofs. In later chapters we'll study how proofs are constructed in detail, but first let's take a look at a few examples of proofs.

Don't worry if you have trouble understanding these proofs. They're just intended to give you a taste of what mathematical proofs are like. In some cases you may be able to follow many of the steps of the proof, but you may be puzzled about why the steps are combined in the way they are, or how anyone could have thought of the proof. If so, we ask you to be patient. Many of these questions will be answered later in this book, particularly in Chapter 3.

All of our examples of proofs in this introduction will involve prime numbers. Recall that an integer larger than 1 is said to be *prime* if it cannot be written as a product of two smaller positive integers. If it can be written as a product of two smaller positive integers, then it is *composite*. For example, 6 is a composite number, since $6 = 2 \cdot 3$, but 7 is a prime number.

Before we can give an example of a proof involving prime numbers, we need to find something to prove – some fact about prime numbers whose correctness can be verified with a proof. Sometimes you can find interesting

n	Is n prime?	$2^n - 1$	Is $2^n - 1$ prime?
2	yes	3	yes
3	yes	7	yes
4	no: $4 = 2 \cdot 2$	15	no: $15 = 3 \cdot 5$
5	yes	31	yes
6	no: $6 = 2 \cdot 3$	63	no: $63 = 7 \cdot 9$
7	yes	127	yes
8	no: $8 = 2 \cdot 4$	255	no: $255 = 15 \cdot 17$
9	no: $9 = 3 \cdot 3$	511	no: $511 = 7 \cdot 73$
10	no: $10 = 2 \cdot 5$	1023	no: $1023 = 31 \cdot 33$

Figure I.1.

patterns in mathematics just by trying out a calculation on a few numbers. For example, consider the table in Figure I.1. For each integer n from 2 to 10, the table shows whether or not both n and $2^n - 1$ are prime, and a surprising pattern emerges. It appears that $2^n - 1$ is prime in precisely those cases in which n is prime!

Will this pattern continue? It is tempting to guess that it will, but this is only a guess. Mathematicians call such guesses *conjectures*. Thus, we have the following two conjectures:

Conjecture 1. *Suppose n is an integer larger than 1 and n is prime. Then $2^n - 1$ is prime.*

Conjecture 2. *Suppose n is an integer larger than 1 and n is not prime. Then $2^n - 1$ is not prime.*

Unfortunately, if we continue the table in Figure I.1, we immediately find that Conjecture 1 is incorrect. It is easy to check that 11 is prime, but $2^{11} - 1 = 2047 = 23 \cdot 89$, so $2^{11} - 1$ is composite. Thus, 11 is a *counterexample* to Conjecture 1. The existence of even one counterexample establishes that the conjecture is incorrect, but it is interesting to note that in this case there are many counterexamples. If we continue checking numbers up to 30, we find two more counterexamples to Conjecture 1: both 23 and 29 are prime, but $2^{23} - 1 = 8,388,607 = 47 \cdot 178,481$ and $2^{29} - 1 = 536,870,911 = 2,089 \cdot 256,999$. However, no number up to 30 is a counterexample to Conjecture 2.

Do you think that Conjecture 2 is correct? Having found counterexamples to Conjecture 1, we know that this conjecture is incorrect, but our failure to find a counterexample to Conjecture 2 does not show that it is correct. Perhaps there are counterexamples, but the smallest one is larger than 30. Continuing to check examples might uncover a counterexample, or, if it doesn't, it might

increase our confidence in the conjecture. But we can never be sure that the conjecture is correct if we only check examples. No matter how many examples we check, there is always the possibility that the next one will be the first counterexample. The only way we can be sure that Conjecture 2 is correct is to *prove* it.

In fact, Conjecture 2 *is* correct. Here is a proof of the conjecture:

Proof of Conjecture 2. Since n is not prime, there are positive integers a and b such that $a < n$, $b < n$, and $n = ab$. Let $x = 2^b - 1$ and $y = 1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}$. Then

$$\begin{aligned} xy &= (2^b - 1) \cdot (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) \\ &= 2^b \cdot (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) - (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) \\ &= (2^b + 2^{2b} + 2^{3b} + \cdots + 2^{ab}) - (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) \\ &= 2^{ab} - 1 \\ &= 2^n - 1. \end{aligned}$$

Since $b < n$, we can conclude that $x = 2^b - 1 < 2^n - 1$. Also, since $ab = n > a$, it follows that $b > 1$. Therefore, $x = 2^b - 1 > 2^1 - 1 = 1$, so $y < xy = 2^n - 1$. Thus, we have shown that $2^n - 1$ can be written as the product of two positive integers x and y , both of which are smaller than $2^n - 1$, so $2^n - 1$ is not prime. \square

Now that the conjecture has been proven, we can call it a *theorem*. Don't worry if you find the proof somewhat mysterious. We'll return to it again at the end of Chapter 3 to analyze how it was constructed. For the moment, the most important point to understand is that if n is any integer larger than 1 that can be written as a product of two smaller positive integers a and b , then the proof gives a method (admittedly, a somewhat mysterious one) of writing $2^n - 1$ as a product of two smaller positive integers x and y . Thus, if n is not prime, then $2^n - 1$ must also not be prime. For example, suppose $n = 12$, so $2^n - 1 = 4095$. Since $12 = 3 \cdot 4$, we could take $a = 3$ and $b = 4$ in the proof. Then according to the formulas for x and y given in the proof, we would have $x = 2^b - 1 = 2^4 - 1 = 15$ and $y = 1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b} = 1 + 2^4 + 2^8 = 273$. And, just as the formulas in the proof predict, we have $xy = 15 \cdot 273 = 4095 = 2^n - 1$. Of course, there are other ways of factoring 12 into a product of two smaller integers, and these might lead to other ways of factoring 4095. For example, since $12 = 2 \cdot 6$, we could use the values $a = 2$ and $b = 6$. Try computing the corresponding values of x and y and make sure their product is 4095.

Although we already know that Conjecture 1 is incorrect, there are still interesting questions we can ask about it. If we continue checking prime numbers n to see if $2^n - 1$ is prime, will we continue to find counterexamples to the conjecture – examples for which $2^n - 1$ is not prime? Will we continue to find examples for which $2^n - 1$ is prime? If there were only finitely many prime numbers, then we might be able to investigate these questions by simply checking $2^n - 1$ for every prime number n . But in fact there are infinitely many prime numbers. Euclid (circa 300 BCE) gave a proof of this fact in Book IX of his *Elements*. His proof is one of the most famous in all of mathematics:¹

Theorem 3. *There are infinitely many prime numbers.*

Proof. Suppose there are only finitely many prime numbers. Let p_1, p_2, \dots, p_n be a list of all prime numbers. Let $m = p_1 p_2 \cdots p_n + 1$. Note that m is not divisible by p_1 , since dividing m by p_1 gives a quotient of $p_2 p_3 \cdots p_n$ and a remainder of 1. Similarly, m is not divisible by any of p_2, p_3, \dots, p_n .

We now use the fact that every integer larger than 1 is either prime or can be written as a product of two or more primes. (We'll see a proof of this fact in Chapter 6 – see Theorem 6.4.2.) Clearly m is larger than 1, so m is either prime or a product of primes. Suppose first that m is prime. Note that m is larger than all of the numbers in the list p_1, p_2, \dots, p_n , so we've found a prime number not in this list. But this contradicts our assumption that this was a list of *all* prime numbers.

Now suppose m is a product of primes. Let q be one of the primes in this product. Then m is divisible by q . But we've already seen that m is not divisible by any of the numbers in the list p_1, p_2, \dots, p_n , so once again we have a contradiction with the assumption that this list included all prime numbers.

Since the assumption that there are finitely many prime numbers has led to a contradiction, there must be infinitely many prime numbers. \square

Once again, you should not be concerned if some aspects of this proof seem mysterious. After you've read Chapter 3 you'll be better prepared to understand the proof in detail. We'll return to this proof then and analyze its structure.

We have seen that if n is not prime then $2^n - 1$ cannot be prime, but if n is prime then $2^n - 1$ can be either prime or composite. Because there are infinitely many prime numbers, there are infinitely many numbers of the form $2^n - 1$ that, based on what we know so far, *might* be prime. But how many of them *are* prime?

¹ Euclid phrased the theorem and proof somewhat differently. We have chosen to take a more modern approach in our presentation.

Prime numbers of the form $2^n - 1$ are called *Mersenne primes*, after Father Marin Mersenne (1588–1648), a French monk and scholar who studied these numbers. Although many Mersenne primes have been found, it is still not known if there are infinitely many of them. Many of the largest known prime numbers are Mersenne primes. As of this writing (February 2019), the largest known prime number is the Mersenne prime $2^{82,589,933} - 1$, a number with 24,862,048 digits.

Mersenne primes are related to perfect numbers, the subject of another famous unsolved problem of mathematics. A positive integer n is said to be *perfect* if n is equal to the sum of all positive integers smaller than n that divide n . (For any two integers m and n , we say that m *divides* n if n is divisible by m ; in other words, if there is an integer q such that $n = qm$.) For example, the only positive integers smaller than 6 that divide 6 are 1, 2, and 3, and $1 + 2 + 3 = 6$. Thus, 6 is a perfect number. The next smallest perfect number is 28. (You should check for yourself that 28 is perfect by finding all the positive integers smaller than 28 that divide 28 and adding them up.)

Euclid proved that if $2^n - 1$ is prime, then $2^{n-1}(2^n - 1)$ is perfect. Thus, every Mersenne prime gives rise to a perfect number. Furthermore, about 2000 years after Euclid's proof, the Swiss mathematician Leonhard Euler (1707–1783), the most prolific mathematician in history, proved that every even perfect number arises in this way. (For example, note that $6 = 2^1(2^2 - 1)$ and $28 = 2^2(2^3 - 1)$.) Because it is not known if there are infinitely many Mersenne primes, it is also not known if there are infinitely many even perfect numbers. It is also not known if there are any odd perfect numbers. For proofs of the theorems of Euclid and Euler, see exercises 18 and 19 in Section 7.4.

Although there are infinitely many prime numbers, the primes thin out as we look at larger and larger numbers. For example, there are 25 primes between 1 and 100, 16 primes between 1001 and 1100, and only six primes between 1,000,001 and 1,000,100. As our last introductory example of a proof, we show that there are long stretches of consecutive positive integers containing no primes at all. In this proof, we'll use the following terminology: for any positive integer n , the product of all integers from 1 to n is called *n factorial* and is denoted $n!$. Thus, $n! = 1 \cdot 2 \cdot 3 \cdots n$. As with our previous two proofs, we'll return to this proof at the end of Chapter 3 to analyze its structure.

Theorem 4. *For every positive integer n , there is a sequence of n consecutive positive integers containing no primes.*

Proof. Suppose n is a positive integer. Let $x = (n + 1)! + 2$. We will show that none of the numbers $x, x + 1, x + 2, \dots, x + (n - 1)$ is prime. Since this is a sequence of n consecutive positive integers, this will prove the theorem.

To see that x is not prime, note that

$$\begin{aligned} x &= 1 \cdot 2 \cdot 3 \cdot 4 \cdots (n+1) + 2 \\ &= 2 \cdot (1 \cdot 3 \cdot 4 \cdots (n+1) + 1). \end{aligned}$$

Thus, x can be written as a product of two smaller positive integers, so x is not prime.

Similarly, we have

$$\begin{aligned} x + 1 &= 1 \cdot 2 \cdot 3 \cdot 4 \cdots (n+1) + 3 \\ &= 3 \cdot (1 \cdot 2 \cdot 4 \cdots (n+1) + 1), \end{aligned}$$

so $x + 1$ is also not prime. In general, consider any number $x + i$, where $0 \leq i \leq n - 1$. Then we have

$$\begin{aligned} x + i &= 1 \cdot 2 \cdot 3 \cdot 4 \cdots (n+1) + (i+2) \\ &= (i+2) \cdot (1 \cdot 2 \cdot 3 \cdots (i+1) \cdot (i+3) \cdots (n+1) + 1), \end{aligned}$$

so $x + i$ is not prime. □

Theorem 4 shows that there are sometimes long stretches between one prime and the next prime. But primes also sometimes occur close together. Since 2 is the only even prime number, the only pair of consecutive integers that are both prime is 2 and 3. But there are lots of pairs of primes that differ by only two, for example, 5 and 7, 29 and 31, and 7949 and 7951. Such pairs of primes are called *twin primes*. It is not known whether there are infinitely many twin primes.

Recently, significant progress has been made on the twin primes question. In 2013, Yitang Zhang (1955–) proved that there is a positive integer $d \leq 70,000,000$ such that there are infinitely many pairs of prime numbers that differ by d . Work of many other mathematicians in 2013–14 narrowed down the possibilities for d to $d \leq 246$. Of course, if the statement holds with $d = 2$ then there are infinitely many twin primes.

Exercises

Note: Solutions or hints for exercises marked with an asterisk (*) are given in the appendix.

- *1. (a) Factor $2^{15} - 1 = 32,767$ into a product of two smaller positive integers.

- (b) Find an integer x such that $1 < x < 2^{32,767} - 1$ and $2^{32,767} - 1$ is divisible by x .
2. Make some conjectures about the values of n for which $3^n - 1$ is prime or the values of n for which $3^n - 2^n$ is prime. (You might start by making a table similar to Figure I.1.)
- *3. The proof of Theorem 3 gives a method for finding a prime number different from any in a given list of prime numbers.
- (a) Use this method to find a prime different from 2, 3, 5, and 7.
- (b) Use this method to find a prime different from 2, 5, and 11.
4. Find five consecutive integers that are not prime.
5. Use the table in Figure I.1 and the discussion on p. 5 to find two more perfect numbers.
6. The sequence 3, 5, 7 is a list of three prime numbers such that each pair of adjacent numbers in the list differ by two. Are there any more such “triplet primes”?
7. A pair of distinct positive integers (m, n) is called *amicable* if the sum of all positive integers smaller than n that divide n is m , and the sum of all positive integers smaller than m that divide m is n . Show that (220, 284) is amicable.

1

Sentential Logic

1.1. Deductive Reasoning and Logical Connectives

As we saw in the introduction, proofs play a central role in mathematics, and deductive reasoning is the foundation on which proofs are based. Therefore, we begin our study of mathematical reasoning and proofs by examining how deductive reasoning works.

Example 1.1.1. Here are three examples of deductive reasoning:

1. It will either rain or snow tomorrow.
It's too warm for snow.
Therefore, it will rain.
2. If today is Sunday, then I don't have to go to work today.
Today is Sunday.
Therefore, I don't have to go to work today.
3. I will go to work either tomorrow or today.
I'm going to stay home today.
Therefore, I will go to work tomorrow.

In each case, we have arrived at a *conclusion* from the assumption that some other statements, called *premises*, are true. For example, the premises in argument 3 are the statements "I will go to work either tomorrow or today" and "I'm going to stay home today." The conclusion is "I will go to work tomorrow," and it seems to be forced on us somehow by the premises.

But is this conclusion really correct? After all, isn't it possible that I'll stay home today, and then wake up sick tomorrow and end up staying home again? If that happened, the conclusion would turn out to be false. But notice that in that case the first premise, which said that I would go to work either tomorrow

or today, would be false as well! Although we have no guarantee that the conclusion is true, it can only be false if at least one of the premises is also false. *If* both premises are true, we can be sure that the conclusion is also true. This is the sense in which the conclusion is forced on us by the premises, and this is the standard we will use to judge the correctness of deductive reasoning. We will say that an argument is *valid* if the premises cannot all be true without the conclusion being true as well. All three of the arguments in our example are valid arguments.

Here's an example of an invalid deductive argument:

Either the butler is guilty or the maid is guilty.

Either the maid is guilty or the cook is guilty.

Therefore, either the butler is guilty or the cook is guilty.

The argument is invalid because the conclusion could be false even if both premises are true. For example, if the maid were guilty, but the butler and the cook were both innocent, then both premises would be true and the conclusion would be false.

We can learn something about what makes an argument valid by comparing the three arguments in Example 1.1.1. On the surface it might seem that arguments 2 and 3 have the most in common, because they're both about the same subject: attendance at work. But in terms of the reasoning used, arguments 1 and 3 are the most similar. They both introduce two possibilities in the first premise, rule out the second one with the second premise, and then conclude that the first possibility must be the case. In other words, both arguments have the form:

P or Q .

Not Q .

Therefore, P .

It is this form, and not the subject matter, that makes these arguments valid. You can see that argument 1 has this form by thinking of the letter P as standing for the statement "It will rain tomorrow," and Q as standing for "It will snow tomorrow." For argument 3, P would be "I will go to work tomorrow," and Q would be "I will go to work today."

Replacing certain statements in each argument with letters, as we have in stating the form of arguments 1 and 3, has two advantages. First, it keeps us from being distracted by aspects of the arguments that don't affect their validity. You don't need to know anything about weather forecasting or work habits to recognize that arguments 1 and 3 are valid. That's because both arguments have the form shown earlier, and you can tell that this argument

form is valid without even knowing what P and Q stand for. If you don't believe this, consider the following argument:

Either the framger widget is misfiring, or the wrompal mechanism is out of alignment.

I've checked the alignment of the wrompal mechanism, and it's fine.

Therefore, the framger widget is misfiring.

If a mechanic gave this explanation after examining your car, you might still be mystified about why the car won't start, but you'd have no trouble following his logic!

Perhaps more important, our analysis of the forms of arguments 1 and 3 makes clear what *is* important in determining their validity: the words *or* and *not*. In most deductive reasoning, and in particular in mathematical reasoning, the meanings of just a few words give us the key to understanding what makes a piece of reasoning valid or invalid. (Which are the important words in argument 2 in Example 1.1.1?) The first few chapters of this book are devoted to studying those words and how they are used in mathematical writing and reasoning.

In this chapter, we'll concentrate on words used to combine statements to form more complex statements. We'll continue to use letters to stand for statements, but only for unambiguous statements that are either true or false. Questions, exclamations, and vague statements will not be allowed. It will also be useful to use symbols, sometimes called *connective symbols*, to stand for some of the words used to combine statements. Here are our first three connective symbols and the words they stand for:

<u>Symbol</u>	<u>Meaning</u>
\vee	or
\wedge	and
\neg	not

Thus, if P and Q stand for two statements, then we'll write $P \vee Q$ to stand for the statement " P or Q ," $P \wedge Q$ for " P and Q ," and $\neg P$ for "not P " or " P is false." The statement $P \vee Q$ is sometimes called the *disjunction* of P and Q , $P \wedge Q$ is called the *conjunction* of P and Q , and $\neg P$ is called the *negation* of P .

Example 1.1.2. Analyze the logical forms of the following statements:

1. Either John went to the store, or we're out of eggs.
2. Joe is going to leave home and not come back.
3. Either Bill is at work and Jane isn't, or Jane is at work and Bill isn't.

Solutions

1. If we let P stand for the statement “John went to the store” and Q stand for “We’re out of eggs,” then this statement could be represented symbolically as $P \vee Q$.
2. If we let P stand for the statement “Joe is going to leave home” and Q stand for “Joe is not going to come back,” then we could represent this statement symbolically as $P \wedge Q$. But this analysis misses an important feature of the statement, because it doesn’t indicate that Q is a negative statement. We could get a better analysis by letting R stand for the statement “Joe is going to come back” and then writing the statement Q as $\neg R$. Plugging this into our first analysis of the original statement, we get the improved analysis $P \wedge \neg R$.
3. Let B stand for the statement “Bill is at work” and J for the statement “Jane is at work.” Then the first half of the statement, “Bill is at work and Jane isn’t,” can be represented as $B \wedge \neg J$. Similarly, the second half is $J \wedge \neg B$. To represent the entire statement, we must combine these two with *or*, forming their disjunction, so the solution is $(B \wedge \neg J) \vee (J \wedge \neg B)$.

Notice that in analyzing the third statement in the preceding example, we added parentheses when we formed the disjunction of $B \wedge \neg J$ and $J \wedge \neg B$ to indicate unambiguously which statements were being combined. This is like the use of parentheses in algebra, in which, for example, the product of $a + b$ and $a - b$ would be written $(a + b) \cdot (a - b)$, with the parentheses serving to indicate unambiguously which quantities are to be multiplied. As in algebra, it is convenient in logic to omit some parentheses to make our expressions shorter and easier to read. However, we must agree on some conventions about how to read such expressions so that they are still unambiguous. One convention is that the symbol \neg always applies only to the statement that comes immediately after it. For example, $\neg P \wedge Q$ means $(\neg P) \wedge Q$ rather than $\neg(P \wedge Q)$. We’ll see some other conventions about parentheses later.

Example 1.1.3. What English sentences are represented by the following expressions?

1. $(\neg S \wedge L) \vee S$, where S stands for “John is smart” and L stands for “John is lucky.”
2. $\neg S \wedge (L \vee S)$, where S and L have the same meanings as before.
3. $\neg(S \wedge L) \vee S$, with S and L still as before.

Solutions

1. Either John isn't smart and he is lucky, or he's smart.
2. John isn't smart, and either he's lucky or he's smart. Notice how the placement of the word *either* in English changes according to where the parentheses are.
3. Either John isn't both smart and lucky, or John is smart. The word *both* in English also helps distinguish the different possible positions of parentheses.

It is important to keep in mind that the symbols \wedge , \vee , and \neg don't really correspond to all uses of the words *and*, *or*, and *not* in English. For example, the symbol \wedge could not be used to represent the use of the word *and* in the sentence "John and Bill are friends," because in this sentence the word *and* is not being used to combine two statements. The symbols \wedge and \vee can only be used *between two statements*, to form their conjunction or disjunction, and the symbol \neg can only be used *before a statement*, to negate it. This means that certain strings of letters and symbols are simply meaningless. For example, $P \neg \wedge Q$, $P \wedge \vee Q$, and $P \neg Q$ are all "ungrammatical" expressions in the language of logic. "Grammatical" expressions, such as those in Examples 1.1.2 and 1.1.3, are sometimes called *well-formed formulas* or just *formulas*. Once again, it may be helpful to think of an analogy with algebra, in which the symbols $+$, $-$, $*$, and \div can be used *between two numbers*, as operators, and the symbol $-$ can also be used *before a number*, to negate it. These are the only ways that these symbols can be used in algebra, so expressions such as $x - \div y$ are meaningless.

Sometimes, words other than *and*, *or*, and *not* are used to express the meanings represented by \wedge , \vee , and \neg . For example, consider the first statement in Example 1.1.3. Although we gave the English translation "Either John isn't smart and he is lucky, or he's smart," an alternative way of conveying the same information would be to say "Either John isn't smart *but* he is lucky, or he's smart." Often, the word *but* is used in English to mean *and*, especially when there is some contrast or conflict between the statements being combined. For a more striking example, imagine a weather forecaster ending his forecast with the statement "Rain and snow are the only two possibilities for tomorrow's weather." This is just a roundabout way of saying that it will either rain or snow tomorrow. Thus, even though the forecaster has used the word *and*, the meaning expressed by his statement is a disjunction. The lesson of these examples is that to determine the logical form of a statement you must think about what the statement means, rather than just translating word by word into symbols.

Sometimes logical words are hidden within mathematical notation. For example, consider the statement $3 \leq \pi$. Although it appears to be a simple statement that contains no words of logic, if you read it out loud you will hear the word *or*. If we let P stand for the statement $3 < \pi$ and Q for the statement $3 = \pi$, then the statement $3 \leq \pi$ would be written $P \vee Q$. In this example the statements represented by the letters P and Q are so short that it hardly seems worthwhile to abbreviate them with single letters. In cases like this we will sometimes not bother to replace the statements with letters, so we might also write this statement as $(3 < \pi) \vee (3 = \pi)$.

For a slightly more complicated example, consider the statement $3 \leq \pi < 4$. This statement means $3 \leq \pi$ and $\pi < 4$, so once again a word of logic has been hidden in mathematical notation. Filling in the meaning that we just worked out for $3 \leq \pi$, we can write the whole statement as $[(3 < \pi) \vee (3 = \pi)] \wedge (\pi < 4)$. Knowing that the statement has this logical form might be important in understanding a piece of mathematical reasoning involving this statement.

Exercises

- *1. Analyze the logical forms of the following statements:
 - (a) We'll have either a reading assignment or homework problems, but we won't have both homework problems and a test.
 - (b) You won't go skiing, or you will and there won't be any snow.
 - (c) $\bar{7} \not\leq 2$.
2. Analyze the logical forms of the following statements:
 - (a) Either John and Bill are both telling the truth, or neither of them is.
 - (b) I'll have either fish or chicken, but I won't have both fish and mashed potatoes.
 - (c) 3 is a common divisor of 6, 9, and 15.
3. Analyze the logical forms of the following statements:
 - (a) Alice and Bob are not both in the room.
 - (b) Alice and Bob are both not in the room.
 - (c) Either Alice or Bob is not in the room.
 - (d) Neither Alice nor Bob is in the room.
4. Analyze the logical forms of the following statements:
 - (a) Either both Ralph and Ed are tall, or both of them are handsome.
 - (b) Both Ralph and Ed are either tall or handsome.
 - (c) Both Ralph and Ed are neither tall nor handsome.
 - (d) Neither Ralph nor Ed is both tall and handsome.

5. Which of the following expressions are well-formed formulas?
- $\neg(\neg P \vee \neg\neg R)$.
 - $\neg(P, Q, \wedge R)$.
 - $P \wedge \neg P$.
 - $(P \wedge Q)(P \vee R)$.
- *6. Let P stand for the statement “I will buy the pants” and S for the statement “I will buy the shirt.” What English sentences are represented by the following formulas?
- $\neg(P \wedge \neg S)$.
 - $\neg P \wedge \neg S$.
 - $\neg P \vee \neg S$.
7. Let S stand for the statement “Steve is happy” and G for “George is happy.” What English sentences are represented by the following formulas?
- $(S \vee G) \wedge (\neg S \vee \neg G)$.
 - $[S \vee (G \wedge \neg S)] \vee \neg G$.
 - $S \vee [G \wedge (\neg S \vee \neg G)]$.
8. Let T stand for the statement “Taxes will go up” and D for “The deficit will go up.” What English sentences are represented by the following formulas?
- $T \vee D$.
 - $\neg(T \wedge D) \wedge \neg(\neg T \wedge \neg D)$.
 - $(T \wedge \neg D) \vee (D \wedge \neg T)$.
9. Identify the premises and conclusions of the following deductive arguments and analyze their logical forms. Do you think the reasoning is valid? (Although you will have only your intuition to guide you in answering this last question, in the next section we will develop some techniques for determining the validity of arguments.)
- Jane and Pete won’t both win the math prize. Pete will win either the math prize or the chemistry prize. Jane will win the math prize. Therefore, Pete will win the chemistry prize.
 - The main course will be either beef or fish. The vegetable will be either peas or corn. We will not have both fish as a main course and corn as a vegetable. Therefore, we will not have both beef as a main course and peas as a vegetable.
 - Either John or Bill is telling the truth. Either Sam or Bill is lying. Therefore, either John is telling the truth or Sam is lying.
 - Either sales will go up and the boss will be happy, or expenses will go up and the boss won’t be happy. Therefore, sales and expenses will not both go up.

1.2. Truth Tables

We saw in Section 1.1 that an argument is valid if the premises cannot all be true without the conclusion being true as well. Thus, to understand how words such as *and*, *or*, and *not* affect the validity of arguments, we must see how they contribute to the truth or falsity of statements containing them.

When we evaluate the truth or falsity of a statement, we assign to it one of the labels *true* or *false*, and this label is called its *truth value*. It is clear how the word *and* contributes to the truth value of a statement containing it. A statement of the form $P \wedge Q$ can be true only if both P and Q are true; if either P or Q is false, then $P \wedge Q$ will be false too. Because we have assumed that P and Q both stand for statements that are either true or false, we can summarize all the possibilities with the table shown in Figure 1.1. This is called a *truth table* for the formula $P \wedge Q$. Each row in the truth table represents one of the four possible combinations of truth values for the statements P and Q . Although these four possibilities can appear in the table in any order, it is best to list them systematically so we can be sure that no possibilities have been skipped. The truth table for $\neg P$ is also quite easy to construct because for $\neg P$ to be true, P must be false. The table is shown in Figure 1.2.

P	Q	$P \wedge Q$
F	F	F
F	T	F
T	F	F
T	T	T

Figure 1.1.

P	$\neg P$
F	T
T	F

Figure 1.2.

The truth table for $P \vee Q$ is a little trickier. The first three lines should certainly be filled in as shown in Figure 1.3, but there may be some question about the last line. Should $P \vee Q$ be true or false in the case in which P and Q are both true? In other words, does $P \vee Q$ mean “ P or Q , or both” or does it mean “ P or Q but not both”? The first way of interpreting the word *or* is called the *inclusive or* (because it *includes* the possibility of both statements being true), and the second is called the *exclusive or*. In mathematics, *or* always means inclusive or, unless specified otherwise, so we will interpret \vee as inclusive or. We therefore complete the truth table for $P \vee Q$ as shown in Figure 1.4. See exercise 3 for more about the exclusive or.

Using the rules summarized in these truth tables, we can now work out truth tables for more complex formulas. All we have to do is work out the truth values of the component parts of a formula, starting with the individual letters and working up to more complex formulas a step at a time.

P	Q	$P \vee Q$
F	F	F
F	T	T
T	F	T
T	T	?

Figure 1.3.

P	Q	$P \vee Q$
F	F	F
F	T	T
T	F	T
T	T	T

Figure 1.4.

Example 1.2.1. Make a truth table for the formula $\neg(P \vee \neg Q)$.

Solution

P	Q	$\neg Q$	$P \vee \neg Q$	$\neg(P \vee \neg Q)$
F	F	T	T	F
F	T	F	F	T
T	F	T	T	F
T	T	F	T	F

The first two columns of this table list the four possible combinations of truth values of P and Q . The third column, listing truth values for the formula $\neg Q$, is found by simply negating the truth values for Q in the second column. The fourth column, for the formula $P \vee \neg Q$, is found by combining the truth values for P and $\neg Q$ listed in the first and third columns, according to the truth value rule for \vee summarized in Figure 1.4. According to this rule, $P \vee \neg Q$ will be false only if both P and $\neg Q$ are false. Looking in the first and third columns, we see that this happens only in row two of the table, so the fourth column contains an F in the second row and T's in all other rows. Finally, the truth values for the formula $\neg(P \vee \neg Q)$ are listed in the fifth column, which is found by negating the truth values in the fourth column. (Note that these columns had to be worked out in order, because each was used in computing the next.)

Example 1.2.2. Make a truth table for the formula $\neg(P \wedge Q) \vee \neg R$.

Solution

P	Q	R	$P \wedge Q$	$\neg(P \wedge Q)$	$\neg R$	$\neg(P \wedge Q) \vee \neg R$
F	F	F	F	T	T	T
F	F	T	F	T	F	T
F	T	F	F	T	T	T
F	T	T	F	T	F	T
T	F	F	F	T	T	T
T	F	T	F	T	F	T
T	T	F	T	F	T	T
T	T	T	T	F	F	F

Note that because this formula contains three letters, it takes eight lines to list all possible combinations of truth values for these letters. (If a formula contains n different letters, how many lines will its truth table have?)

Here's a way of making truth tables more compactly. Instead of using separate columns to list the truth values for the component parts of a formula, just list those truth values below the corresponding connective symbol in the original formula. This is illustrated in Figure 1.5, for the formula from Example 1.2.1. In the first step, we have listed the truth values for P and Q below these letters where they appear in the formula. In step two, the truth values for $\neg Q$ have been added under the \neg symbol for $\neg Q$. In the third step, we have combined the truth values for P and $\neg Q$ to get the truth values for $P \vee \neg Q$, which are listed under the \vee symbol. Finally, in the last step, these truth values are negated and listed under the initial \neg symbol. The truth values added in the last step give the truth value for the entire formula, so we will call the symbol under which they are listed (the first \neg symbol in this case) the *main connective* of the formula. Notice that the truth values listed under the main connective in this case agree with the values we found in Example 1.2.1.

Step 1				Step 2			
P	Q	$\neg(P \vee \neg Q)$		P	Q	$\neg(P \vee \neg Q)$	
F	F	F	F	F	F	F	TF
F	T	F	T	F	T	F	FT
T	F	T	F	T	F	T	TF
T	T	T	T	T	T	T	FT
Step 3				Step 4			
P	Q	$\neg(P \vee \neg Q)$		P	Q	$\neg(P \vee \neg Q)$	
F	F	F	T	F	F	F	F
F	T	F	F	F	T	T	F
T	F	T	T	T	F	F	T
T	T	T	T	T	T	F	T

Figure 1.5.

Now that we know how to make truth tables for complex formulas, we're ready to return to the analysis of the validity of arguments. Consider again our first example of a deductive argument:

- It will either rain or snow tomorrow.
- It's too warm for snow.
- Therefore, it will rain.

As we have seen, if we let P stand for the statement “It will rain tomorrow” and Q for the statement “It will snow tomorrow,” then we can represent the argument symbolically as follows:

$$\frac{P \vee Q \quad \neg Q}{\therefore P} \quad (\text{The symbol } \therefore \text{ means } \textit{therefore} .)$$

We can now see how truth tables can be used to verify the validity of this argument. Figure 1.6 shows a truth table for both premises and the conclusion of the argument. Recall that we decided to call an argument valid if the premises cannot all be true without the conclusion being true as well. Looking at Figure 1.6 we see that the only row of the table in which both premises come out true is row three, and in this row the conclusion is also true. Thus, the truth table confirms that if the premises are all true, the conclusion must also be true, so the argument is valid.

		Premises		Conclusion
P	Q	$P \vee Q$	$\neg Q$	P
F	F	F	T	F
F	T	T	F	F
T	F	T	T	T
T	T	T	F	T

Figure 1.6.

Example 1.2.3. Determine whether the following arguments are valid.

1. Either John isn't smart and he is lucky, or he's smart.
John is smart.
Therefore, John isn't lucky.
2. The butler and the cook are not both innocent.
Either the butler is lying or the cook is innocent.
Therefore, the butler is either lying or guilty.

Solutions

1. As in Example 1.1.3, we let S stand for the statement “John is smart” and L stand for “John is lucky.” Then the argument has the form:

$$\frac{(\neg S \wedge L) \vee S \quad S}{\therefore \neg L}$$

Now we make a truth table for both premises and the conclusion. (You should work out the intermediate steps in deriving column three of this table to confirm that it is correct.)

Premises			Conclusion	
S	L	$(\neg S \wedge L) \vee S$	S	$\neg L$
F	F	F	F	T
F	T	T	F	F
T	F	T	T	T
T	T	T	T	F

Both premises are true in lines three and four of this table. The conclusion is also true in line three, but it is false in line four. Thus, it is possible for both premises to be true and the conclusion false, so the argument is invalid. In fact, the table shows us exactly why the argument is invalid. The problem occurs in the fourth line of the table, in which S and L are both true – in other words, John is both smart and lucky. Thus, if John is both smart and lucky, then both premises will be true but the conclusion will be false, so it would be a mistake to infer that the conclusion must be true from the assumption that the premises are true.

2. Let B stand for the statement “The butler is innocent,” C for the statement “The cook is innocent,” and L for the statement “The butler is lying.” Then the argument has the form:

$$\frac{\neg(B \wedge C) \quad L \vee C}{\therefore L \vee \neg B}$$

Here is the truth table for the premises and conclusion:

Premises					Conclusion
B	C	L	$\neg(B \wedge C)$	$L \vee C$	$L \vee \neg B$
F	F	F	T	F	T
F	F	T	T	T	T
F	T	F	T	T	T
F	T	T	T	T	T
T	F	F	T	F	F
T	F	T	T	T	T
T	T	F	F	T	F
T	T	T	F	T	T

The premises are both true only in lines two, three, four, and six, and in each of these cases the conclusion is true as well. Therefore, the argument is valid.

If you expected the first argument in Example 1.2.3 to turn out to be valid, it's probably because the first premise confused you. It's a rather complicated statement, which we represented symbolically with the formula $(\neg S \wedge L) \vee S$. According to our truth table, this formula is false if S and L are both false, and true otherwise. But notice that this is exactly the same as the truth table for the simpler formula $L \vee S$! Because of this, we say that the formulas $(\neg S \wedge L) \vee S$ and $L \vee S$ are *equivalent*. Equivalent formulas always have the same truth value no matter what statements the letters in them stand for and no matter what the truth values of those statements are. The equivalence of the premise $(\neg S \wedge L) \vee S$ and the simpler formula $L \vee S$ may help you understand why the argument is invalid. Translating the formula $L \vee S$ back into English, we see that the first premise could have been stated more simply as "John is either lucky or smart (or both)." But from this premise and the second premise (that John is smart), it clearly doesn't follow that he's not lucky, because he might be both smart and lucky.

Example 1.2.4. Which of these formulas are equivalent?

$$\neg(P \wedge Q), \quad \neg P \wedge \neg Q, \quad \neg P \vee \neg Q.$$

Solution

Here's a truth table for all three statements. (You should check it yourself!)

P	Q	$\neg(P \wedge Q)$	$\neg P \wedge \neg Q$	$\neg P \vee \neg Q$
F	F	T	T	T
F	T	T	F	T
T	F	T	F	T
T	T	F	F	F

The third and fifth columns in this table are identical, but they are different from the fourth column. Therefore, the formulas $\neg(P \wedge Q)$ and $\neg P \vee \neg Q$ are equivalent, but neither is equivalent to the formula $\neg P \wedge \neg Q$. This should make sense if you think about what all the symbols mean. For example, suppose P stands for the statement "The Yankees won last night" and Q stands for "The Red Sox won last night." Then $\neg(P \wedge Q)$ would represent the statement "The Yankees and the Red Sox did not both win last night," and $\neg P \vee \neg Q$ would represent "Either the Yankees or the Red Sox lost last night"; these statements clearly convey the same information. On the other hand, $\neg P \wedge \neg Q$ would represent "The Yankees and the Red Sox both lost last night," which means something entirely different.

You can check for yourself by making a truth table that the formula $\neg P \wedge \neg Q$ from Example 1.2.4 is equivalent to the formula $\neg(P \vee Q)$. (To see that this equivalence makes sense, notice that the statements “Both the Yankees and the Red Sox lost last night” and “It is not the case that either the Yankees or the Red Sox won last night” mean the same thing.) This equivalence and the one discovered in Example 1.2.4 are called *De Morgan’s laws*. They are named for the British mathematician Augustus De Morgan (1806–1871).

In analyzing deductive arguments and the statements that occur in them, it is helpful to be familiar with a number of equivalences that come up often. Verify the equivalences in the following list yourself by making truth tables, and check that they make sense by translating the formulas into English, as we did in Example 1.2.4.

De Morgan’s laws

$$\begin{aligned}\neg(P \wedge Q) &\text{ is equivalent to } \neg P \vee \neg Q. \\ \neg(P \vee Q) &\text{ is equivalent to } \neg P \wedge \neg Q.\end{aligned}$$

Commutative laws

$$\begin{aligned}P \wedge Q &\text{ is equivalent to } Q \wedge P. \\ P \vee Q &\text{ is equivalent to } Q \vee P.\end{aligned}$$

Associative laws

$$\begin{aligned}P \wedge (Q \wedge R) &\text{ is equivalent to } (P \wedge Q) \wedge R. \\ P \vee (Q \vee R) &\text{ is equivalent to } (P \vee Q) \vee R.\end{aligned}$$

Idempotent laws

$$\begin{aligned}P \wedge P &\text{ is equivalent to } P. \\ P \vee P &\text{ is equivalent to } P.\end{aligned}$$

Distributive laws

$$\begin{aligned}P \wedge (Q \vee R) &\text{ is equivalent to } (P \wedge Q) \vee (P \wedge R). \\ P \vee (Q \wedge R) &\text{ is equivalent to } (P \vee Q) \wedge (P \vee R).\end{aligned}$$

Absorption laws

$$\begin{aligned}P \vee (P \wedge Q) &\text{ is equivalent to } P. \\ P \wedge (P \vee Q) &\text{ is equivalent to } P.\end{aligned}$$

Double Negation law

$$\neg\neg P \text{ is equivalent to } P.$$

Notice that because of the associative laws we can leave out parentheses in formulas of the forms $P \wedge Q \wedge R$ and $P \vee Q \vee R$ without worrying that the resulting formula will be ambiguous, because the two possible ways of filling in the parentheses lead to equivalent formulas.

Many of the equivalences in the list should remind you of similar rules involving $+$, \cdot , and $-$ in algebra. As in algebra, these rules can be applied to more complex formulas, and they can be combined to work out more complicated equivalences. Any of the letters in these equivalences can be replaced by more complicated formulas, and the resulting equivalence will still be true. For example, by replacing P in the double negation law with the formula $Q \vee \neg R$, you can see that $\neg\neg(Q \vee \neg R)$ is equivalent to $Q \vee \neg R$. Also, if two formulas are equivalent, you can always substitute one for the other in any expression and the results will be equivalent. For example, since $\neg\neg P$ is equivalent to P , if $\neg\neg P$ occurs in any formula, you can always replace it with P and the resulting formula will be equivalent to the original.

Example 1.2.5. Find simpler formulas equivalent to these formulas:

1. $\neg(P \vee \neg Q)$.
2. $\neg(Q \wedge \neg P) \vee P$.

Solutions

1. $\neg(P \vee \neg Q)$
 is equivalent to $\neg P \wedge \neg\neg Q$ (De Morgan's law),
 which is equivalent to $\neg P \wedge Q$ (double negation law).

You can check that this equivalence is right by making a truth table for $\neg P \wedge Q$ and seeing that it is the same as the truth table for $\neg(P \vee \neg Q)$ found in Example 1.2.1.

2. $\neg(Q \wedge \neg P) \vee P$
 is equivalent to $(\neg Q \vee \neg\neg P) \vee P$ (De Morgan's law),
 which is equivalent to $(\neg Q \vee P) \vee P$ (double negation law),
 which is equivalent to $\neg Q \vee (P \vee P)$ (associative law),
 which is equivalent to $\neg Q \vee P$ (idempotent law).

Some equivalences are based on the fact that certain formulas are either always true or always false. For example, you can verify by making a truth table that the formula $Q \wedge (P \vee \neg P)$ is equivalent to just Q . But even before you make the truth table, you can probably see why they are equivalent. In every line of the truth table, $P \vee \neg P$ will come out true, and therefore $Q \wedge (P \vee \neg P)$ will come out true when Q is also true, and false when Q is false. Formulas that are always true, such as $P \vee \neg P$, are called *tautologies*. Similarly, formulas that are always false are called *contradictions*. For example, $P \wedge \neg P$ is a contradiction.

Example 1.2.6. Are these formulas tautologies, contradictions, or neither?

$$P \vee (Q \vee \neg P), \quad P \wedge \neg(Q \vee \neg Q), \quad P \vee \neg(Q \vee \neg Q).$$

Solution

First we make a truth table for all three formulas.

P	Q	$P \vee (Q \vee \neg P)$	$P \wedge \neg(Q \vee \neg Q)$	$P \vee \neg(Q \vee \neg Q)$
F	F	T	F	F
F	T	T	F	F
T	F	T	F	T
T	T	T	F	T

From the truth table it is clear that the first formula is a tautology, the second a contradiction, and the third neither. In fact, since the last column is identical to the first, the third formula is equivalent to P .

We can now state a few more useful laws involving tautologies and contradictions. You should be able to convince yourself that all of these laws are correct by thinking about what the truth tables for the statements involved would look like.

Tautology laws

- $P \wedge$ (a tautology) is equivalent to P .
- $P \vee$ (a tautology) is a tautology.
- \neg (a tautology) is a contradiction.

Contradiction laws

- $P \wedge$ (a contradiction) is a contradiction.
- $P \vee$ (a contradiction) is equivalent to P .
- \neg (a contradiction) is a tautology.

Example 1.2.7. Find simpler formulas equivalent to these formulas:

1. $P \vee (Q \wedge \neg P)$.
2. $\neg(P \vee (Q \wedge \neg R)) \wedge Q$.

Solutions

1. $P \vee (Q \wedge \neg P)$
 is equivalent to $(P \vee Q) \wedge (P \vee \neg P)$ (distributive law),
 which is equivalent to $P \vee Q$ (tautology law).

The last step uses the fact that $P \vee \neg P$ is a tautology.

2. $\neg(P \vee (Q \wedge \neg R)) \wedge Q$
 is equivalent to $(\neg P \wedge \neg(Q \wedge \neg R)) \wedge Q$ (De Morgan's law),
 which is equivalent to $(\neg P \wedge (\neg Q \vee \neg\neg R)) \wedge Q$ (De Morgan's law),
 which is equivalent to $(\neg P \wedge (\neg Q \vee R)) \wedge Q$ (double negation law),
 which is equivalent to $\neg P \wedge ((\neg Q \vee R) \wedge Q)$ (associative law),
 which is equivalent to $\neg P \wedge (Q \wedge (\neg Q \vee R))$ (commutative law),
 which is equivalent to $\neg P \wedge ((Q \wedge \neg Q) \vee (Q \wedge R))$
 (distributive law),
 which is equivalent to $\neg P \wedge (Q \wedge R)$ (contradiction law).

The last step uses the fact that $Q \wedge \neg Q$ is a contradiction. Finally, by the associative law for \wedge we can remove the parentheses without making the formula ambiguous, so the original formula is equivalent to the formula $\neg P \wedge Q \wedge R$.

Exercises

- *1. Make truth tables for the following formulas:
 (a) $\neg P \vee Q$.
 (b) $(S \vee G) \wedge (\neg S \vee \neg G)$.
2. Make truth tables for the following formulas:
 (a) $\neg[P \wedge (Q \vee \neg P)]$.
 (b) $(P \vee Q) \wedge (\neg P \vee R)$.
3. In this exercise we will use the symbol $+$ to mean *exclusive or*. In other words, $P + Q$ means “ P or Q , but not both.”
 (a) Make a truth table for $P + Q$.
 (b) Find a formula using only the connectives \wedge , \vee , and \neg that is equivalent to $P + Q$. Justify your answer with a truth table.
4. Find a formula using only the connectives \wedge and \neg that is equivalent to $P \vee Q$. Justify your answer with a truth table.
- *5. Some mathematicians use the symbol \downarrow to mean *nor*. In other words, $P \downarrow Q$ means “neither P nor Q .”
 (a) Make a truth table for $P \downarrow Q$.
 (b) Find a formula using only the connectives \wedge , \vee , and \neg that is equivalent to $P \downarrow Q$.
 (c) Find formulas using only the connective \downarrow that are equivalent to $\neg P$, $P \vee Q$, and $P \wedge Q$.

6. Some mathematicians write $P \mid Q$ to mean “ P and Q are not both true.” (This connective is called *nand*, and is used in the study of circuits in computer science.)
- Make a truth table for $P \mid Q$.
 - Find a formula using only the connectives \wedge , \vee , and \neg that is equivalent to $P \mid Q$.
 - Find formulas using only the connective \mid that are equivalent to $\neg P$, $P \vee Q$, and $P \wedge Q$.
- *7. Use truth tables to determine whether or not the arguments in exercise 9 of Section 1.1 are valid.
8. Use truth tables to determine which of the following formulas are equivalent to each other:
- $(P \wedge Q) \vee (\neg P \wedge \neg Q)$.
 - $\neg P \vee Q$.
 - $(P \vee \neg Q) \wedge (Q \vee \neg P)$.
 - $\neg(P \vee Q)$.
 - $(Q \wedge P) \vee \neg P$.
- *9. Use truth tables to determine which of these statements are tautologies, which are contradictions, and which are neither:
- $(P \vee Q) \wedge (\neg P \vee \neg Q)$.
 - $(P \vee Q) \wedge (\neg P \wedge \neg Q)$.
 - $(P \vee Q) \vee (\neg P \vee \neg Q)$.
 - $[P \wedge (Q \vee \neg R)] \vee (\neg P \vee R)$.
10. Use truth tables to check these laws:
- The second De Morgan’s law. (The first was checked in the text.)
 - The distributive laws.
- *11. Use the laws stated in the text to find simpler formulas equivalent to these formulas. (See Examples 1.2.5 and 1.2.7.)
- $\neg(\neg P \wedge \neg Q)$.
 - $(P \wedge Q) \vee (P \wedge \neg Q)$.
 - $\neg(P \wedge \neg Q) \vee (\neg P \wedge Q)$.
12. Use the laws stated in the text to find simpler formulas equivalent to these formulas. (See Examples 1.2.5 and 1.2.7.)
- $\neg(\neg P \vee Q) \vee (P \wedge \neg R)$.
 - $\neg(\neg P \wedge Q) \vee (P \wedge \neg R)$.
 - $(P \wedge R) \vee [\neg R \wedge (P \vee Q)]$.
13. Use the first De Morgan’s law and the double negation law to derive the second De Morgan’s law.

- *14. Note that the associative laws say only that parentheses are unnecessary when combining *three* statements with \wedge or \vee . In fact, these laws can be used to justify leaving parentheses out when more than three statements are combined. Use associative laws to show that $[P \wedge (Q \wedge R)] \wedge S$ is equivalent to $(P \wedge Q) \wedge (R \wedge S)$.
15. How many lines will there be in the truth table for a statement containing n letters?
- *16. Find a formula involving the connectives \wedge , \vee , and \neg that has the following truth table:

P	Q	???
F	F	T
F	T	F
T	F	T
T	T	T

17. Find a formula involving the connectives \wedge , \vee , and \neg that has the following truth table:

P	Q	???
F	F	F
F	T	T
T	F	T
T	T	F

18. Suppose the conclusion of an argument is a tautology. What can you conclude about the validity of the argument? What if the conclusion is a contradiction? What if one of the premises is either a tautology or a contradiction?

1.3. Variables and Sets

In mathematical reasoning it is often necessary to make statements about objects that are represented by letters called *variables*. For example, if the variable x is used to stand for a number in some problem, we might be interested in the statement “ x is a prime number.” Although we may sometimes use a single letter, say P , to stand for this statement, at other times we will revise this notation slightly and write $P(x)$, to stress that this is a statement *about* x . The latter notation makes it easy to talk about assigning a value to x in the statement. For example, $P(7)$ would represent the statement “7 is a prime number;” and $P(a + b)$ would mean “ $a + b$ is a prime

number.” If a statement contains more than one variable, our abbreviation for the statement will include a list of all the variables involved. For example, we might represent the statement “ p is divisible by q ” by $D(p, q)$. In this case, $D(12, 4)$ would mean “12 is divisible by 4.”

Although you have probably seen variables used most often to stand for numbers, they can stand for anything at all. For example, we could let $M(x)$ stand for the statement “ x is a man,” and $W(x)$ for “ x is a woman.” In this case, we are using the variable x to stand for a person. A statement might even contain several variables that stand for different kinds of objects. For example, in the statement “ x has y children,” the variable x stands for a person, and y stands for a number.

Statements involving variables can be combined using connectives, just like statements without variables.

Example 1.3.1. Analyze the logical forms of the following statements:

1. x is a prime number, and either y or z is divisible by x .
2. x is a man and y is a woman and x likes y , but y doesn’t like x .

Solutions

1. We could let P stand for the statement “ x is a prime number,” D for “ y is divisible by x ,” and E for “ z is divisible by x .” The entire statement would then be represented by the formula $P \wedge (D \vee E)$. But this analysis, though not incorrect, fails to capture the relationship between the statements D and E . A better analysis would be to let $P(x)$ stand for “ x is a prime number” and $D(y, x)$ for “ y is divisible by x .” Then $D(z, x)$ would mean “ z is divisible by x ,” so the entire statement would be $P(x) \wedge (D(y, x) \vee D(z, x))$.
2. Let $M(x)$ stand for “ x is a man,” $W(y)$ for “ y is a woman,” and $L(x, y)$ for “ x likes y .” Then $L(y, x)$ would mean “ y likes x .” (Notice that the order of the variables after the L makes a difference!) The entire statement would then be represented by the formula $M(x) \wedge W(y) \wedge L(x, y) \wedge \neg L(y, x)$.

In the last section, we introduced the idea of assigning truth values to statements. This idea is unproblematic for statements that do not contain variables, since such statements are either true or false. But if a statement contains variables, we can no longer describe the statement as being simply true or false. Its truth value might depend on the values of the variables involved. For example, if $P(x)$ stands for the statement “ x is a prime number,” then $P(x)$ would be true if $x = 23$, but false if $x = 22$. To deal with this complication, we will define *truth sets* for statements containing variables.

Before giving this definition, though, it might be helpful to review some basic definitions from set theory.

A *set* is a collection of objects. The objects in the collection are called the *elements* of the set. The simplest way to specify a particular set is to list its elements between braces. For example, $\{3, 7, 14\}$ is the set whose elements are the three numbers 3, 7, and 14. We use the symbol \in to mean *is an element of*. For example, if we let A stand for the set $\{3, 7, 14\}$, then we could write $7 \in A$ to say that 7 is an element of A . To say that 11 is not an element of A , we write $11 \notin A$.

A set is completely determined once its elements have been specified. Thus, two sets that have exactly the same elements are always equal. Also, when a set is defined by listing its elements, all that matters is which objects are in the list of elements, not the order in which they are listed. An element can even appear more than once in the list. Thus, $\{3, 7, 14\}$, $\{14, 3, 7\}$, and $\{3, 7, 14, 7\}$ are three different names for the same set.

It may be impractical to define a set that contains a very large number of elements by listing all of its elements, and it would be impossible to give such a definition for a set that contains infinitely many elements. Often this problem can be overcome by listing a few elements with an ellipsis (...) after them, if it is clear how the list should be continued. For example, suppose we define a set B by saying that $B = \{2, 3, 5, 7, 11, 13, 17, \dots\}$. Once you recognize that the numbers listed in the definition of B are the prime numbers, then you know that, for example, $23 \in B$, even though it wasn't listed explicitly when we defined B . But this method requires recognition of the pattern in the list of numbers in the definition of B , and this requirement introduces an element of ambiguity and subjectivity into our notation that is best avoided in mathematical writing. It is therefore usually better to define such a set by spelling out the pattern that determines the elements of the set.

In this case we could be explicit by defining B as follows:

$$B = \{x \mid x \text{ is a prime number}\}.$$

This is read " B is equal to the set of all x such that x is a prime number," and it means that the elements of B are the values of x that make the statement " x is a prime number" come out true. You should think of the statement " x is a prime number" as an *elementhood test* for the set. Any value of x that makes this statement come out true passes the test and is an element of the set. Anything else fails the test and is not an element. Of course, in this case the values of x that make the statement true are precisely the prime numbers, so this definition says that B is the set whose elements are the prime numbers, exactly as before.

Example 1.3.2. Rewrite these set definitions using elementhood tests:

1. $E = \{2, 4, 6, 8, \dots\}$.
2. $P = \{\text{George Washington, John Adams, Thomas Jefferson, James Madison, } \dots\}$.

Solutions

Although there might be other ways of continuing these lists of elements, probably the most natural ones are given by the following definitions:

1. $E = \{n \mid n \text{ is a positive even integer}\}$.
2. $P = \{z \mid z \text{ was a president of the United States}\}$.

If a set has been defined using an elementhood test, then that test can be used to determine whether or not something is an element of the set. For example, consider the set $\{x \mid x^2 < 9\}$. If we want to know if 5 is an element of this set, we simply apply the elementhood test in the definition of the set – in other words, we check whether or not $5^2 < 9$. Since $5^2 = 25 > 9$, it fails the test, so $5 \notin \{x \mid x^2 < 9\}$. On the other hand, $(-2)^2 = 4 < 9$, so $-2 \in \{x \mid x^2 < 9\}$. The same reasoning would apply to any other number. For any number y , to determine whether or not $y \in \{x \mid x^2 < 9\}$, we just check whether or not $y^2 < 9$. In fact, we could think of the statement $y \in \{x \mid x^2 < 9\}$ as just a roundabout way of saying $y^2 < 9$.

Notice that because the statement $y \in \{x \mid x^2 < 9\}$ means the same thing as $y^2 < 9$, it is a statement about y , but not x ! To determine whether or not $y \in \{x \mid x^2 < 9\}$ you need to know what y is (so you can compare its square to 9), but not what x is. We say that in the statement $y \in \{x \mid x^2 < 9\}$, y is a *free* variable, whereas x is a *bound* variable (or a *dummy* variable). The free variables in a statement stand for objects that the statement says something about. Plugging in different values for a free variable affects the meaning of a statement and may change its truth value. The fact that you can plug in different values for a free variable means that it is free to stand for anything. Bound variables, on the other hand, are simply letters that are used as a convenience to help express an idea and should not be thought of as standing for any particular object. A bound variable can always be replaced by a new variable without changing the meaning of the statement, and often the statement can be rephrased so that the bound variables are eliminated altogether. For example, the statements $y \in \{x \mid x^2 < 9\}$ and $y \in \{w \mid w^2 < 9\}$ mean the same thing, because they both mean “ y is an element of the set of all numbers whose squares are less than 9.” In this last

statement, all bound variables have been eliminated, and the only variable that appears in the statement is the free variable y .

Note that x is a bound variable in the statement $y \in \{x \mid x^2 < 9\}$ even though it is a free variable in the statement $x^2 < 9$. This last statement is a statement about x that would be true for some values of x and false for others. It is only when this statement is used inside the elementhood test notation that x becomes a bound variable. We could say that the notation $\{x \mid . . .\}$ binds the variable x .

Everything we have said about the set $\{x \mid x^2 < 9\}$ would apply to any set defined by an elementhood test. In general, the statement $y \in \{x \mid P(x)\}$ means the same thing as $P(y)$, which is a statement about y but not x . Similarly, $y \notin \{x \mid P(x)\}$ means the same thing as $\neg P(y)$. Of course, the expression $\{x \mid P(x)\}$ is not a statement at all; it is a name for a set. As you learn more mathematical notation, it will become increasingly important to make sure you are careful to distinguish between expressions that are mathematical statements and expressions that are names for mathematical objects.

Example 1.3.3. What do these statements mean? What are the free variables in each statement?

1. $a + b \notin \{x \mid x \text{ is an even number}\}$.
2. $y \in \{x \mid x \text{ is divisible by } w\}$.
3. $2 \in \{w \mid 6 \notin \{x \mid x \text{ is divisible by } w\}\}$.

Solutions

1. This statement says that $a + b$ is not an element of the set of all even numbers, or in other words, $a + b$ is not an even number. Both a and b are free variables, but x is a bound variable. The statement will be true for some values of a and b and false for others.
2. This statement says that y is divisible by w . Both y and w are free variables, but x is a bound variable. The statement is true for some values of y and w and false for others.
3. This looks quite complicated, but if we go a step at a time, we can decipher it. First, note that the statement $6 \notin \{x \mid x \text{ is divisible by } w\}$, which appears inside the given statement, means the same thing as “6 is not divisible by w .” Substituting this into the given statement, we find that the original statement is equivalent to the simpler statement $2 \in \{w \mid 6 \text{ is not divisible by } w\}$. But this just means the same thing as “6 is not divisible by 2.” Thus, the statement has no free variables, and both x and w are bound variables.

Because there are no free variables, the truth value of the statement doesn't depend on the values of any variables. In fact, since 6 *is* divisible by 2, the statement is false.

Perhaps you have guessed by now how we can use set theory to help us understand truth values of statements containing free variables. As we have seen, a statement, say $P(x)$, containing a free variable x , may be true for some values of x and false for others. To distinguish the values of x that make $P(x)$ true from those that make it false, we could form the set of values of x for which $P(x)$ is true. We will call this set the *truth set* of $P(x)$.

Definition 1.3.4. The *truth set* of a statement $P(x)$ is the set of all values of x that make the statement $P(x)$ true. In other words, it is the set defined by using the statement $P(x)$ as an elementhood test: $\{x \mid P(x)\}$.

Note that we have defined truth sets only for statements containing *one* free variable. We will discuss truth sets for statements with more than one free variable in Chapter 4.

Example 1.3.5. What are the truth sets of the following statements?

1. Shakespeare wrote x .
2. n is an even prime number.

Solutions

1. $\{x \mid \text{Shakespeare wrote } x\} = \{\text{Hamlet, Macbeth, Twelfth Night, } \dots\}$.
2. $\{n \mid n \text{ is an even prime number}\}$. Because the only even prime number is 2, this is the set $\{2\}$. Note that 2 and $\{2\}$ are not the same thing! The first is a number, and the second is a set whose only element is a number. Thus, $2 \in \mathcal{Q}$, but $2 \notin \{2\}$.

Suppose A is the truth set of a statement $P(x)$. According to the definition of truth set, this means that $A = \{x \mid P(x)\}$. We've already seen that for any object y , the statement $y \in \{x \mid P(x)\}$ means the same thing as $P(y)$. Substituting in A for $\{x \mid P(x)\}$, it follows that $y \in A$ means the same thing as $P(y)$. Thus, we see that in general, if A is the truth set of $P(x)$, then to say that $y \in A$ means the same thing as saying $P(y)$.

When a statement contains free variables, it is often clear from context that these variables stand for objects of a particular kind. The set of all objects of this kind – in other words, the set of all possible values for the variables – is

called the *universe of discourse* for the statement, and we say that the variables *range over* this universe. For example, in most contexts the universe for the statement $x^2 < 9$ would be the set of all real numbers; the universe for the statement “ x is a man” might be the set of all people.

Certain sets come up often in mathematics as universes of discourse, and it is convenient to have fixed names for them. Here are a few of the most important ones:

$$\mathbb{R} = \{x \mid x \text{ is a real number}\}.$$

$$\mathbb{Q} = \{x \mid x \text{ is a rational number}\}.$$

(Recall that a *real* number is any number on the number line, and a *rational* number is a number that can be written as a fraction p/q , where p and q are integers.)

$$\mathbb{Z} = \{x \mid x \text{ is an integer}\} = \{\dots, -3, -2, -1, 0, 1, 2, 3, \dots\}.$$

$$\mathbb{N} = \{x \mid x \text{ is a natural number}\} = \{0, 1, 2, 3, \dots\}.$$

(Some books include 0 as a natural number and some don't. In this book, we consider 0 to be a natural number.)

The letters \mathbb{R} , \mathbb{Q} , and \mathbb{Z} can be followed by a superscript $+$ or $-$ to indicate that only positive or negative numbers are to be included in the set. For example, $\mathbb{R}^+ = \{x \mid x \text{ is a positive real number}\}$, and $\mathbb{Z}^- = \{x \mid x \text{ is a negative integer}\}$.

Although the universe of discourse can usually be determined from context, it is sometimes useful to identify it explicitly. Consider a statement $P(x)$ with a free variable x that ranges over a universe U . Although we have written the truth set of $P(x)$ as $\{x \mid P(x)\}$, if there were any possibility of confusion about what the universe was, we could specify it explicitly by writing $\{x \in U \mid P(x)\}$; this is read “the set of all x in U such that $P(x)$.” This notation indicates that only elements of U are to be considered for elementhood in this truth set, and among elements of U , only those that pass the elementhood test $P(x)$ will actually be in the truth set. For example, consider again the statement $x^2 < 9$. If the universe of discourse for this statement were the set of all real numbers, then its truth set would be $\{x \in \mathbb{R} \mid x^2 < 9\}$, or in other words, the set of all real numbers between -3 and 3 . But if the universe were the set of all integers, then the truth set would be $\{x \in \mathbb{Z} \mid x^2 < 9\} = \{-2, -1, 0, 1, 2\}$. Thus, for example, $1.58 \in \{x \in \mathbb{R} \mid x^2 < 9\}$ but $1.58 \notin \{x \in \mathbb{Z} \mid x^2 < 9\}$. Clearly, the choice of universe can sometimes make a difference!

Sometimes this explicit notation is used not to specify the universe of discourse but to restrict attention to just a part of the universe. For example, in the case of the statement $x^2 < 9$, we might want to consider the universe of discourse to be the set of all real numbers, but in the course of some reasoning involving this statement we might want to temporarily restrict our

attention to only positive real numbers. We might then be interested in the set $\{x \in \mathbb{R}^+ \mid x^2 < 9\}$. As before, this notation indicates that only positive real numbers will be considered for elementhood in this set, and among positive real numbers, only those whose square is less than 9 will be in the set. Thus, for a number to be an element of this set, it must pass two tests: it must be a positive real number, and its square must be less than 9. In other words, the statement $y \in \{x \in \mathbb{R}^+ \mid x^2 < 9\}$ means the same thing as $y \in \mathbb{R}^+ \wedge y^2 < 9$. In general, $y \in \{x \in A \mid P(x)\}$ means the same thing as $y \in A \wedge P(y)$.

When a new mathematical concept has been defined, mathematicians are usually interested in studying any possible extremes of this concept. For example, when we discussed truth tables, the extremes we studied were statements whose truth tables contained only T's (tautologies) or only F's (contradictions). For the concept of the truth set of a statement containing a free variable, the corresponding extremes would be the truth sets of statements that are always true or always false. Suppose $P(x)$ is a statement containing a free variable x that ranges over a universe U . It should be clear that if $P(x)$ comes out true for every value of x in U , then the truth set of $P(x)$ will be the whole universe U . For example, since the statement $x^2 \geq 0$ is true for every real number x , the truth set of this statement is $\{x \in \mathbb{R} \mid x^2 \geq 0\} = \mathbb{R}$. Of course, this is not unrelated to the concept of a tautology. For example, since $P \vee \neg P$ is a tautology, the statement $P(x) \vee \neg P(x)$ will be true for every $x \in U$, no matter what statement $P(x)$ stands for or what the universe U is, and therefore the truth set of the statement $P(x) \vee \neg P(x)$ will be U .

For a statement $P(x)$ that is false for every possible value of x , nothing in the universe can pass the elementhood test for the truth set of $P(x)$, and so this truth set must have no elements. The idea of a set with no elements may sound strange, but it arises naturally when we consider truth sets for statements that are always false. Because a set is completely determined once its elements have been specified, there is only one set that has no elements. It is called the *empty set*, or the *null set*, and is often denoted \emptyset . For example, $\{x \in \mathbb{Z} \mid x \equiv x\} = \emptyset$. Since the empty set has no elements, the statement $x \in \emptyset$ is an example of a statement that is always false, no matter what x is.

Another common notation for the empty set is based on the fact that any set can be named by listing its elements between braces. Since the empty set has no elements, we write nothing between the braces, like this: $\emptyset = \{\}$. Note that $\{\emptyset\}$ is not correct notation for the empty set. Just as we saw earlier that 2 and $\{2\}$ are not the same thing, \emptyset is not the same as $\{\emptyset\}$. The first is a set with no elements, whereas the second is a set with one element, that one element being \emptyset , the empty set.

Exercises

- *1. Analyze the logical forms of the following statements:
- (a) 3 is a common divisor of 6, 9, and 15. (Note: You did this in exercise 2 of Section 1.1, but you should be able to give a better answer now.)
 - (b) x is divisible by both 2 and 3 but not 4.
 - (c) x and y are natural numbers, and exactly one of them is prime.
2. Analyze the logical forms of the following statements:
- (a) x and y are men, and either x is taller than y or y is taller than x .
 - (b) Either x or y has brown eyes, and either x or y has red hair.
 - (c) Either x or y has both brown eyes and red hair.
- *3. Write definitions using elementhood tests for the following sets:
- (a) {Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune }.
 - (b) {Brown, Columbia, Cornell, Dartmouth, Harvard, Princeton, University of Pennsylvania, Yale }.
 - (c) {Alabama, Alaska, Arizona, . . . , Wisconsin, Wyoming }.
 - (d) {Alberta, British Columbia, Manitoba, New Brunswick, Newfoundland and Labrador, Northwest Territories, Nova Scotia, Nunavut, Ontario, Prince Edward Island, Quebec, Saskatchewan, Yukon }.
4. Write definitions using elementhood tests for the following sets:
- (a) {1, 4, 9, 16, 25, 36, 49, . . . }.
 - (b) {1, 2, 4, 8, 16, 32, 64, . . . }.
 - (c) {10, 11, 12, 13, 14, 15, 16, 17, 18, 19 }.
- *5. Simplify the following statements. Which variables are free and which are bound? If the statement has no free variables, say whether it is true or false.
- (a) $-3 \in \{x \in \mathbb{R} \mid 13 - 2x > 1\}$.
 - (b) $4 \in \{x \in \mathbb{R}^- \mid 13 - 2x > 1\}$.
 - (c) $5 \notin \{x \in \mathbb{R} \mid 13 - 2x > c\}$.
6. Simplify the following statements. Which variables are free and which are bound? If the statement has no free variables, say whether it is true or false.
- (a) $w \in \{x \in \mathbb{R} \mid 13 - 2x > c\}$.
 - (b) $4 \in \{x \in \mathbb{R} \mid 13 - 2x \in \{y \mid y \text{ is a prime number}\}\}$. (It might make this statement easier to read if we let $P = \{y \mid y \text{ is a prime number}\}$; using this notation, we could rewrite the statement as $4 \in \{x \in \mathbb{R} \mid 13 - 2x \in P\}$.)
 - (c) $4 \in \{x \in \{y \mid y \text{ is a prime number}\} \mid 13 - 2x > 1\}$. (Using the same notation as in part (b), we could write this as $4 \in \{x \in P \mid 13 - 2x > 1\}$.)

7. List the elements of the following sets:
- $\{x \in \mathbb{R} \mid 2x^2 + x - 1 = 0\}$.
 - $\{x \in \mathbb{R}^+ \mid 2x^2 + x - 1 = 0\}$.
 - $\{x \in \mathbb{Z} \mid 2x^2 + x - 1 = 0\}$.
 - $\{x \in \mathbb{N} \mid 2x^2 + x - 1 = 0\}$.
- *8. What are the truth sets of the following statements? List a few elements of the truth set if you can.
- Elizabeth Taylor was once married to x .
 - x is a logical connective studied in Section 1.1.
 - x is the author of this book.
9. What are the truth sets of the following statements? List a few elements of the truth set if you can.
- x is a real number and $x^2 - 4x + 3 = 0$.
 - x is a real number and $x^2 - 2x + 3 = 0$.
 - x is a real number and $5 \in \{y \in \mathbb{R} \mid x^2 + y^2 < 50\}$.

1.4. Operations on Sets

Suppose A is the truth set of a statement $P(x)$ and B is the truth set of $Q(x)$. What are the truth sets of the statements $P(x) \wedge Q(x)$, $P(x) \vee Q(x)$, and $\neg P(x)$? To answer these questions, we introduce some basic operations on sets.

Definition 1.4.1. The *intersection* of two sets A and B is the set $A \cap B$ defined as follows:

$$A \cap B = \{x \mid x \in A \text{ and } x \in B\}.$$

The *union* of A and B is the set $A \cup B$ defined as follows:

$$A \cup B = \{x \mid x \in A \text{ or } x \in B\}.$$

The *difference* of A and B is the set $A \setminus B$ defined as follows:

$$A \setminus B = \{x \mid x \in A \text{ and } x \notin B\}.$$

Remember that the statements that appear in these definitions are *elementhood tests*. Thus, for example, the definition of $A \cap B$ says that for an object to be an element of $A \cap B$, it must be an element of both A and B . In other words, $A \cap B$ is the set consisting of the elements that A and B have in common. Because the word *or* is always interpreted as *inclusive or* in mathematics,

anything that is an element of either A or B , or both, will be an element of $A \cup B$. Thus, we can think of $A \cup B$ as the set resulting from throwing all the elements of A and B together into one set. $A \setminus B$ is the set you would get if you started with the set A and removed from it any elements that were also in B .

Example 1.4.2. Suppose $A = \{1, 2, 3, 4, 5\}$ and $B = \{2, 4, 6, 8, 10\}$. List the elements of the following sets:

1. $A \cap B$.
2. $A \cup B$.
3. $A \setminus B$.
4. $(A \cup B) \setminus (A \cap B)$.
5. $(A \setminus B) \cup (B \setminus A)$.

Solutions

1. $A \cap B = \{2, 4\}$.
2. $A \cup B = \{1, 2, 3, 4, 5, 6, 8, 10\}$.
3. $A \setminus B = \{1, 3, 5\}$.
4. We have just computed $A \cup B$ and $A \cap B$ in solutions 1 and 2, so all we need to do is start with the set $A \cup B$ from solution 2 and remove from it any elements that are also in $A \cap B$. The answer is $(A \cup B) \setminus (A \cap B) = \{1, 3, 5, 6, 8, 10\}$.
5. We already have the elements of $A \setminus B$ listed in solution 3, and $B \setminus A = \{6, 8, 10\}$. Thus, their union is $(A \setminus B) \cup (B \setminus A) = \{1, 3, 5, 6, 8, 10\}$. Is it just a coincidence that this is the same as the answer to part 4?

Example 1.4.3. Suppose $A = \{x \mid x \text{ is a man}\}$ and $B = \{x \mid x \text{ has brown hair}\}$. What are $A \cap B$, $A \cup B$, and $A \setminus B$?

Solution

By definition, $A \cap B = \{x \mid x \in A \text{ and } x \in B\}$. As we saw in the last section, the definitions of A and B tell us that $x \in A$ means the same thing as “ x is a man,” and $x \in B$ means the same thing as “ x has brown hair.” Plugging this into the definition of $A \cap B$, we find that

$$A \cap B = \{x \mid x \text{ is a man and } x \text{ has brown hair}\}.$$

Similar reasoning shows that

$$A \cup B = \{x \mid \text{either } x \text{ is a man or } x \text{ has brown hair}\}$$

and

$$A \setminus B = \{x \mid x \text{ is a man and } x \text{ does not have brown hair}\}.$$

Sometimes it is helpful when working with operations on sets to draw pictures of the results of these operations. One way to do this is with diagrams like that in Figure 1.7. This is called a *Venn diagram*. The interior of the rectangle enclosing the diagram represents the universe of discourse U , and the interiors of the two circles represent the two sets A and B . Other sets formed by combining these sets would be represented by different regions in the diagram. For example, the shaded region in Figure 1.8 is the region common to the interiors of the circles representing A and B , and so it represents the set $A \cap B$. Figures 1.9 and 1.10 show the regions representing $A \cup B$ and $A \setminus B$, respectively.

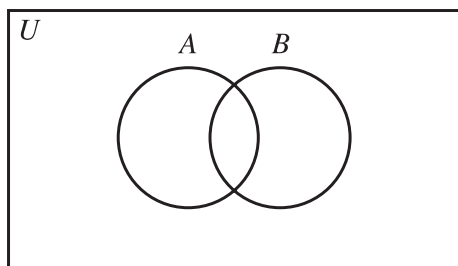


Figure 1.7.

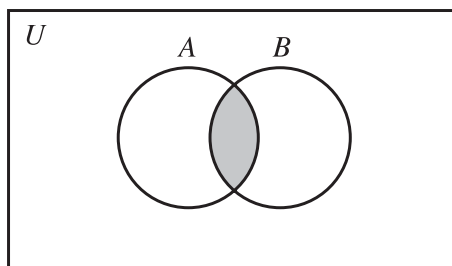


Figure 1.8. $A \cap B$.

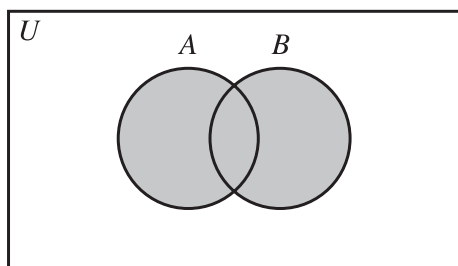


Figure 1.9. $A \cup B$.

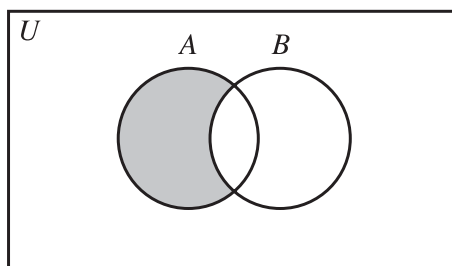


Figure 1.10. $A \setminus B$.

Here's an example of how Venn diagrams can help us understand operations on sets. In Example 1.4.2 the sets $(A \cup B) \setminus (A \cap B)$ and $(A \setminus B) \cup (B \setminus A)$ turned out to be equal, for a particular choice of A and B . You can see by making Venn diagrams for both sets that this was not a coincidence. You'll find that both Venn diagrams look like Figure 1.11. Thus, these sets will always be equal, no matter what the sets A and B are, because both sets will always be

the set of objects that are elements of either A or B but not both. This set is called the *symmetric difference* of A and B and is written $A \oplus B$. In other words, $A \oplus B = (A \setminus B) \cup (B \setminus A) = (A \cup B) \setminus (A \cap B)$. Later in this section we'll see another explanation of why these sets are always equal.

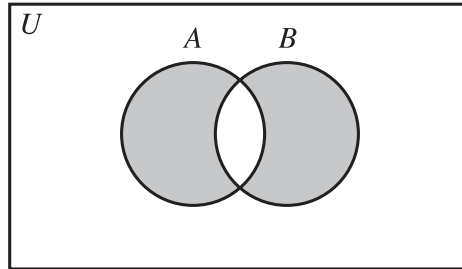


Figure 1.11. $(A \cup B) \setminus (A \cap B) = (A \setminus B) \cup (B \setminus A)$.

Let's return now to the question with which we began this section. If A is the truth set of a statement $P(x)$ and B is the truth set of $Q(x)$, then, as we saw in the last section, $x \in A$ means the same thing as $P(x)$ and $x \in B$ means the same thing as $Q(x)$. Thus, the truth set of $P(x) \wedge Q(x)$ is $\{x \mid P(x) \wedge Q(x)\} = \{x \mid x \in A \wedge x \in B\} = A \cap B$. This should make sense. It just says that the truth set of $P(x) \wedge Q(x)$ consists of those elements that the truth sets of $P(x)$ and $Q(x)$ have in common – in other words, the values of x that make both $P(x)$ and $Q(x)$ come out true. We have already seen an example of this. In Example 1.4.3 the sets A and B were the truth sets of the statements “ x is a man” and “ x has brown hair,” and $A \cap B$ turned out to be the truth set of “ x is a man and x has brown hair.”

Similar reasoning shows that the truth set of $P(x) \vee Q(x)$ is $A \cup B$. To find the truth set of $\neg P(x)$, we need to talk about the universe of discourse U . The truth set of $\neg P(x)$ will consist of those elements of the universe for which $P(x)$ is false, and we can find this set by starting with U and removing from it those elements for which $P(x)$ is true. Thus, the truth set of $\neg P(x)$ is $U \setminus A$.

These observations about truth sets illustrate the fact that the set theory operations \cap , \cup , and \setminus are related to the logical connectives \wedge , \vee , and \neg . This shouldn't be surprising, since after all the words *and*, *or*, and *not* appear in their definitions. (The word *not* doesn't appear explicitly, but it's there, hidden in the mathematical symbol \notin in the definition of the difference of two sets.) It is important to remember, though, that although the set theory operations and logical connectives are related, they are not interchangeable. The logical connectives can only be used to combine *statements*, whereas the set theory operations must be used to combine *sets*. For example, if A is the truth set of

$P(x)$ and B is the truth set of $Q(x)$, then we can say that $A \cap B$ is the truth set of $P(x) \wedge Q(x)$, but expressions such as $A \wedge B$ or $P(x) \cap Q(x)$ are completely meaningless and should never be used.

The relationship between set theory operations and logical connectives also becomes apparent when we analyze the logical forms of statements about intersections, unions, and differences of sets. For example, according to the definition of intersection, to say that $x \in A \cap B$ means that $x \in A \wedge x \in B$. Similarly, to say that $x \in A \cup B$ means that $x \in A \vee x \in B$, and $x \in A \setminus B$ means $x \in A \wedge x \notin B$, or in other words $x \in A \wedge \neg(x \in B)$. We can combine these rules when analyzing statements about more complex sets.

Example 1.4.4. Analyze the logical forms of the following statements:

1. $x \in A \cap (B \cup C)$.
2. $x \in A \setminus (B \cap C)$.
3. $x \in (A \cap B) \cup (A \cap C)$.

Solutions

1. $x \in A \cap (B \cup C)$
is equivalent to $x \in A \wedge x \in (B \cup C)$ (definition of \cap),
which is equivalent to $x \in A \wedge (x \in B \vee x \in C)$ (definition of \cup).
2. $x \in A \setminus (B \cap C)$
is equivalent to $x \in A \wedge \neg(x \in B \cap C)$ (definition of \setminus),
which is equivalent to $x \in A \wedge \neg(x \in B \wedge x \in C)$ (definition of \cap).
3. $x \in (A \cap B) \cup (A \cap C)$
is equivalent to $x \in (A \cap B) \vee x \in (A \cap C)$ (definition of \cup),
which is equivalent to $(x \in A \wedge x \in B) \vee (x \in A \wedge x \in C)$
(definition of \cap).

Look again at the solutions to parts 1 and 3 of Example 1.4.4. You should recognize that the statements we ended up with in these two parts are equivalent. (If you don't, look back at the distributive laws in Section 1.2.) This equivalence means that the statements $x \in A \cap (B \cup C)$ and $x \in (A \cap B) \cup (A \cap C)$ are equivalent. In other words, the objects that are elements of the set $A \cap (B \cup C)$ will be precisely the same as the objects that are elements of $(A \cap B) \cup (A \cap C)$, no matter what the sets A , B , and C are. But recall that sets with the same elements are equal, so it follows that for any sets A , B , and C , $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$. Another way to see this is with the Venn

diagram in Figure 1.12. Our earlier Venn diagrams had two circles, because in previous examples only two sets were being combined. This Venn diagram has three circles, which represent the three sets A , B , and C that are being combined in this case. Although it is possible to create Venn diagrams for more than three sets, it is rarely done, because it cannot be done with overlapping circles. For more on Venn diagrams for more than three sets, see exercise 12.

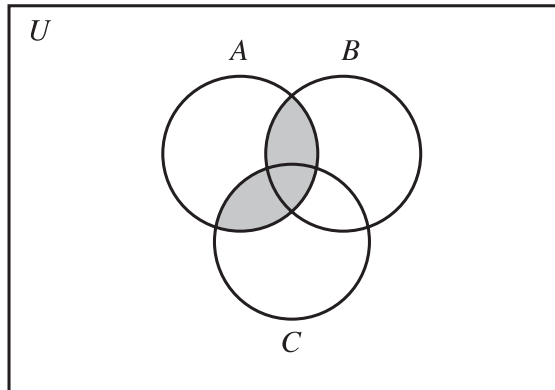


Figure 1.12. $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$.

Thus, we see that a distributive law for logical connectives has led to a distributive law for set theory operations. You might guess that because there were *two* distributive laws for the logical connectives, with \wedge and \vee playing opposite roles in the two laws, there might be two distributive laws for set theory operations too. The second distributive law for sets should say that for any sets A , B , and C , $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$. You can verify this for yourself by writing out the statements $x \in A \cup (B \cap C)$ and $x \in (A \cup B) \cap (A \cup C)$ using logical connectives and verifying that they are equivalent, using the second distributive law for the logical connectives \wedge and \vee . Another way to see it is to make a Venn diagram.

We can derive another set theory identity by finding a statement equivalent to the statement we ended up with in part 2 of Example 1.4.4:

$$x \in A \setminus (B \cap C)$$

is equivalent to $x \in A \wedge \neg(x \in B \wedge x \in C)$ (Example 1.4.4),

which is equivalent to $x \in A \wedge (x \notin B \vee x \notin C)$ (De Morgan's law),

which is equivalent to $(x \in A \wedge x \notin B) \vee (x \in A \wedge x \notin C)$ (distributive law),

which is equivalent to $(x \in A \setminus B) \vee (x \in A \setminus C)$ (definition of \setminus),

which is equivalent to $x \in (A \setminus B) \cup (A \setminus C)$ (definition of \cup).

Thus, we have shown that for any sets A , B , and C , we have $A \setminus (B \cap C) = (A \setminus B) \cup (A \setminus C)$. Once again, you can verify this with a Venn diagram as well.

Earlier we promised an alternative way to check the identity $(A \cup B) \setminus (A \cap B) = (A \setminus B) \cup (B \setminus A)$. You should see now how this can be done. First, we write out the logical forms of the statements $x \in (A \cup B) \setminus (A \cap B)$ and $x \in (A \setminus B) \cup (B \setminus A)$:

$$x \in (A \cup B) \setminus (A \cap B) \text{ means } (x \in A \vee x \in B) \wedge \neg(x \in A \wedge x \in B);$$

$$x \in (A \setminus B) \cup (B \setminus A) \text{ means } (x \in A \wedge x \notin B) \vee (x \in B \wedge x \notin A).$$

You can now check, using equivalences from Section 1.2, that these statements are equivalent. An alternative way to check the equivalence is with a truth table. To simplify the truth table, let's use P and Q as abbreviations for the statements $x \in A$ and $x \in B$. Then we must check that the formulas $(P \vee Q) \wedge \neg(P \wedge Q)$ and $(P \wedge \neg Q) \vee (Q \wedge \neg P)$ are equivalent. The truth table in Figure 1.13 shows this.

P	Q	$(P \vee Q) \wedge \neg(P \wedge Q)$	$(P \wedge \neg Q) \vee (Q \wedge \neg P)$
F	F	F	F
F	T	T	T
T	F	T	T
T	T	F	F

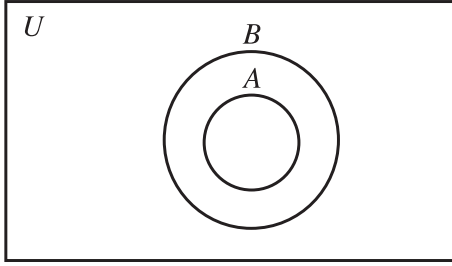
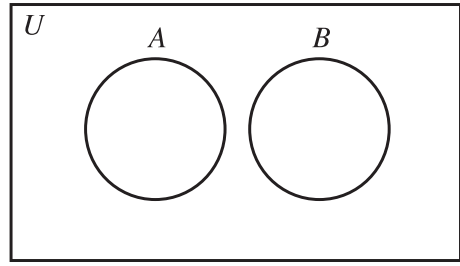
Figure 1.13.

Definition 1.4.5. Suppose A and B are sets. We will say that A is a *subset* of B if every element of A is also an element of B . We write $A \subseteq B$ to mean that A is a subset of B . A and B are said to be *disjoint* if they have no elements in common. Note that this is the same as saying that the set of elements they have in common is the empty set, or in other words $A \cap B = \emptyset$.

Example 1.4.6. Suppose $A = \{\text{red, green}\}$, $B = \{\text{red, yellow, green, purple}\}$, and $C = \{\text{blue, purple}\}$. Then the two elements of A , red and green, are both also in B , and therefore $A \subseteq B$. Also, $A \cap C = \emptyset$, so A and C are disjoint.

If we know that $A \subseteq B$, or that A and B are disjoint, then we might draw a Venn diagram for A and B differently to reflect this. Figures 1.14 and 1.15 illustrate this.

Just as we earlier derived identities showing that certain sets are always equal, it is also sometimes possible to show that certain sets are always

Figure 1.14. $A \subseteq B$.Figure 1.15. $A \cap B = \emptyset$.

disjoint, or that one set is always a subset of another. For example, you can see in a Venn diagram that the sets $A \cap B$ and $A \setminus B$ do not overlap, and therefore they will always be disjoint for any sets A and B . Another way to see this would be to write out what it means to say that $x \in (A \cap B) \cap (A \setminus B)$:

$$x \in (A \cap B) \cap (A \setminus B) \text{ means } (x \in A \wedge x \in B) \wedge (x \in A \wedge x \notin B),$$

$$\text{which is equivalent to } x \in A \wedge (x \in B \wedge x \notin B).$$

But this last statement is clearly a contradiction, so the statement $x \in (A \cap B) \cap (A \setminus B)$ will always be false, no matter what x is. In other words, nothing can be an element of $(A \cap B) \cap (A \setminus B)$, so it must be the case that $(A \cap B) \cap (A \setminus B) = \emptyset$. Therefore, $A \cap B$ and $A \setminus B$ are disjoint.

The next theorem gives another example of a general fact about set operations. The proof of this theorem illustrates that the principles of deductive reasoning we have been studying are actually used in mathematical proofs.

Theorem 1.4.7. *For any sets A and B , $(A \cup B) \setminus B \subseteq A$.*

Proof. We must show that if something is an element of $(A \cup B) \setminus B$, then it must also be an element of A , so suppose that $x \in (A \cup B) \setminus B$. This means that $x \in A \cup B$ and $x \notin B$, or in other words $x \in A \vee x \in B$ and $x \notin B$. But notice that these statements have the logical form $P \vee Q$ and $\neg Q$, and this is precisely the form of the premises of our very first example of a deductive argument in Section 1.1! As we saw in that example, from these premises we can conclude that $x \in A$ must be true. Thus, anything that is an element of $(A \cup B) \setminus B$ must also be an element of A , so $(A \cup B) \setminus B \subseteq A$. \square

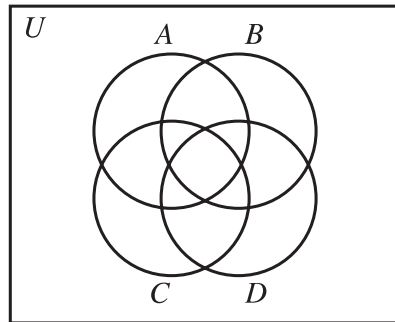
You might think that such a careful application of logical laws is not needed to understand why Theorem 1.4.7 is correct. The set $(A \cup B) \setminus B$ could be thought of as the result of starting with the set A , adding in the elements of B , and then removing them again. Common sense suggests that the result will

just be the original set A ; in other words, it appears that $(A \cup B) \setminus B = A$. However, as you are asked to show in exercise 10, this conclusion is incorrect. This illustrates that in mathematics, you must not allow imprecise reasoning to lead you to jump to conclusions. Applying laws of logic carefully, as we did in our proof of Theorem 1.4.7, may help you to avoid jumping to unwarranted conclusions.

Exercises

- *1. Let $A = \{1, 3, 12, 35\}$, $B = \{3, 7, 12, 20\}$, and $C = \{x \mid x \text{ is a prime number}\}$. List the elements of the following sets. Are any of the sets below disjoint from any of the others? Are any of the sets below subsets of any others?
 - (a) $A \cap B$.
 - (b) $(A \cup B) \setminus C$.
 - (c) $A \cup (B \setminus C)$.
2. Let $A = \{\text{United States, Germany, China, Australia}\}$, $B = \{\text{Germany, France, India, Brazil}\}$, and $C = \{x \mid x \text{ is a country in Europe}\}$. List the elements of the following sets. Are any of the sets below disjoint from any of the others? Are any of the sets below subsets of any others?
 - (a) $A \cup B$.
 - (b) $(A \cap B) \setminus C$.
 - (c) $(B \cap C) \setminus A$.
3. Verify that the Venn diagrams for $(A \cup B) \setminus (A \cap B)$ and $(A \setminus B) \cup (B \setminus A)$ both look like Figure 1.11, as stated in this section.
- *4. Use Venn diagrams to verify the following identities:
 - (a) $A \setminus (A \cap B) = A \setminus B$.
 - (b) $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$.
5. Verify the identities in exercise 4 by writing out (using logical symbols) what it means for an object x to be an element of each set and then using logical equivalences.
6. Use Venn diagrams to verify the following identities:
 - (a) $(A \cup B) \setminus C = (A \setminus C) \cup (B \setminus C)$.
 - (b) $A \cup (B \setminus C) = (A \cup B) \setminus (C \setminus A)$.
7. Verify the identities in exercise 6 by writing out (using logical symbols) what it means for an object x to be an element of each set and then using logical equivalences.
8. Use any method you wish to verify the following identities:

- (a) $(A \setminus B) \cap C = (A \cap C) \setminus B$.
- (b) $(A \cap B) \setminus B = \emptyset$.
- (c) $A \setminus (A \setminus B) = A \cap B$.
- *9. For each of the following sets, write out (using logical symbols) what it means for an object x to be an element of the set. Then determine which of these sets must be equal to each other by determining which statements are equivalent.
- (a) $(A \setminus B) \setminus C$.
- (b) $A \setminus (B \setminus C)$.
- (c) $(A \setminus B) \cup (A \cap C)$.
- (d) $(A \setminus B) \cap (A \setminus C)$.
- (e) $A \setminus (B \cup C)$.
10. It was shown in this section that for any sets A and B , $(A \cup B) \setminus B \subseteq A$.
- (a) Give an example of two sets A and B for which $(A \cup B) \setminus B \cong A$.
- (b) Show that for all sets A and B , $(A \cup B) \setminus B = A \setminus B$.
11. Suppose A and B are sets. Is it necessarily true that $(A \setminus B) \cup B = A$? If not, is one of these sets necessarily a subset of the other? Is $(A \setminus B) \cup B$ always equal to either $A \setminus B$ or $A \cup B$?
- *12. It is claimed in this section that you cannot make a Venn diagram for four sets using overlapping circles.
- (a) What's wrong with the following diagram? (Hint: Where's the set $(A \cap D) \setminus (B \cup C)$?)



- (b) Can you make a Venn diagram for four sets using shapes other than circles?
13. (a) Make Venn diagrams for the sets $(A \cup B) \setminus C$ and $A \cup (B \setminus C)$. What can you conclude about whether one of these sets is necessarily a subset of the other?
- (b) Give an example of sets A , B , and C for which $(A \cup B) \setminus C \cong A \cup (B \setminus C)$.

- *14. Use Venn diagrams to show that the associative law holds for symmetric difference; that is, for any sets A , B , and C , $A \oplus (B \oplus C) = (A \oplus B) \oplus C$.
15. Use any method you wish to verify the following identities:
- $(A \oplus B) \cup C = (A \cup C) \oplus (B \setminus C)$.
 - $(A \oplus B) \cap C = (A \cap C) \oplus (B \cap C)$.
 - $(A \oplus B) \setminus C = (A \setminus C) \oplus (B \setminus C)$.
16. Use any method you wish to verify the following identities:
- $(A \cup B) \oplus C = (A \oplus C) \oplus (B \setminus A)$.
 - $(A \cap B) \oplus C = (A \oplus C) \oplus (A \setminus B)$.
 - $(A \setminus B) \oplus C = (A \oplus C) \oplus (A \cap B)$.
17. Fill in the blanks to make true identities:
- $(A \oplus B) \cap C = (C \setminus A) \oplus \underline{\hspace{2cm}}$.
 - $C \setminus (A \oplus B) = (A \cap C) \oplus \underline{\hspace{2cm}}$.
 - $(B \setminus A) \oplus C = (A \oplus C) \oplus \underline{\hspace{2cm}}$.

1.5. The Conditional and Biconditional Connectives

It is time now to return to a question we left unanswered in Section 1.1. We have seen how the reasoning in the first and third arguments in Example 1.1.1 can be understood by analyzing the connectives \vee and \neg . But what about the reasoning in the second argument? Recall that the argument went like this:

If today is Sunday, then I don't have to go to work today.

Today is Sunday.

Therefore, I don't have to go to work today.

What makes this reasoning valid?

It appears that the crucial words here are *if* and *then*, which occur in the first premise. We therefore introduce a new logical connective, \rightarrow , and write $P \rightarrow Q$ to represent the statement "If P then Q ." This statement is sometimes called a *conditional* statement, with P as its *antecedent* and Q as its *consequent*. If we let P stand for the statement "Today is Sunday" and Q for the statement "I don't have to go to work today," then the logical form of the argument would be

$$\frac{P \rightarrow Q \quad P}{\therefore Q}$$

Our analysis of the new connective \rightarrow should lead to the conclusion that this argument is valid.

Example 1.5.1. Analyze the logical forms of the following statements:

1. If it's raining and I don't have my umbrella, then I'll get wet.
2. If Mary did her homework, then the teacher won't collect it, and if she didn't, then he'll ask her to do it on the board.

Solutions

1. Let R stand for the statement "It's raining," U for "I have my umbrella," and W for "I'll get wet." Then statement 1 would be represented by the formula $(R \wedge \neg U) \rightarrow W$.
2. Let H stand for "Mary did her homework," C for "The teacher will collect it," and B for "The teacher will ask Mary to do the homework on the board." Then the given statement means $(H \rightarrow \neg C) \wedge (\neg H \rightarrow B)$.

To analyze arguments containing the connective \rightarrow we must work out the truth table for the formula $P \rightarrow Q$. Because $P \rightarrow Q$ is supposed to mean that if P is true then Q is also true, we certainly want to say that if P is true and Q is false then $P \rightarrow Q$ is false. If P is true and Q is also true, then it seems reasonable to say that $P \rightarrow Q$ is true. This gives us the last two lines of the truth table in Figure 1.16. The remaining two lines of the truth table are harder to fill in, although probably most people would say that if P and Q are both false then $P \rightarrow Q$ should be considered true. Thus, we can sum up our conclusions so far with the table in Figure 1.16.

P	Q	$P \rightarrow Q$
F	F	T?
F	T	?
T	F	F
T	T	T

Figure 1.16.

To help us fill in the undetermined lines in this truth table, let's look at an example. Consider the statement "If $x > 2$ then $x^2 > 4$," which we could represent with the formula $P(x) \rightarrow Q(x)$, where $P(x)$ stands for the statement $x > 2$ and $Q(x)$ stands for $x^2 > 4$. Of course, the statements $P(x)$ and $Q(x)$ contain x as a free variable, and each will be true for some values of x and false for others. But surely, no matter what the value of x is, we

would say it is true that if $x > 2$ then $x^2 > 4$, so the conditional statement $P(x) \rightarrow Q(x)$ should be true. Thus, the truth table should be completed in such a way that no matter what value we plug in for x , this conditional statement comes out true.

For example, suppose $x = 3$. In this case $x > 2$ and $x^2 = 9 > 4$, so $P(x)$ and $Q(x)$ are both true. This corresponds to line four of the truth table in Figure 1.16, and we've already decided that the statement $P(x) \rightarrow Q(x)$ should come out true in this case. But now consider the case $x = 1$. Then $x < 2$ and $x^2 = 1 < 4$, so $P(x)$ and $Q(x)$ are both false, corresponding to line one in the truth table. We have tentatively placed a T in this line of the truth table, and now we see that this tentative choice must be right. If we put an F there, then the statement $P(x) \rightarrow Q(x)$ would come out false in the case $x = 1$, and we've already decided that it should be true for all values of x .

Finally, consider the case $x = -5$. Then $x < 2$, so $P(x)$ is false, but $x^2 = 25 > 4$, so $Q(x)$ is true. Thus, in this case we find ourselves in the second line of the truth table, and once again, if the conditional statement $P(x) \rightarrow Q(x)$ is to be true in this case, we must put a T in this line. So it appears that all the questionable lines in the truth table in Figure 1.16 must be filled in with T's, and the completed truth table for the connective \rightarrow must be as shown in Figure 1.17.

P	Q	$P \rightarrow Q$
F	F	T
F	T	T
T	F	F
T	T	T

Figure 1.17.

Of course, there are many other values of x that could be plugged into our statement “If $x > 2$ then $x^2 > 4$ ”; but if you try them, you’ll find that they all lead to line one, two, or four of the truth table, as our examples $x = 1, -5$, and 3 did. No value of x will lead to line three, because you could never have $x > 2$ but $x^2 \leq 4$. After all, that’s why we said that the statement “If $x > 2$ then $x^2 > 4$ ” was always true, no matter what x was! The point of saying that this conditional statement is always true is simply to say that you will never find a value of x such that $x > 2$ and $x^2 \leq 4$ – in other words, there is no value of x for which $P(x)$ is true but $Q(x)$ is false. Thus, it should make sense that in the truth table for $P \rightarrow Q$, the only line that is false is the line in which P is true and Q is false.

As the truth table in Figure 1.18 shows, the formula $\neg P \vee Q$ is also true in every case except when P is true and Q is false. Thus, if we accept the truth table in Figure 1.17 as the correct truth table for the formula $P \rightarrow Q$, then we will be forced to accept the conclusion that the formulas $P \rightarrow Q$ and $\neg P \vee Q$ are equivalent. Is this consistent with the way the words *if* and *then* are used in ordinary language? It may not seem to be at first, but, at least for some uses of the words *if* and *then*, it is.

P	Q	$\neg P \vee Q$
F	F	T
F	T	T
T	F	F
T	T	T

Figure 1.18.

For example, imagine a teacher saying to a class, in a threatening tone of voice, “You won’t neglect your homework, or you’ll fail the course.” Grammatically, this statement has the form $\neg P \vee Q$, where P is the statement “You will neglect your homework” and Q is “You’ll fail the course.” But what message is the teacher trying to convey with this statement? Clearly the intended message is “If you neglect your homework, then you’ll fail the course,” or in other words $P \rightarrow Q$. Thus, in this example, the formulas $\neg P \vee Q$ and $P \rightarrow Q$ seem to mean the same thing.

There is a similar idea at work in the first statement from Example 1.1.2, “Either John went to the store, or we’re out of eggs.” In Section 1.1 we represented this statement by the formula $P \vee Q$, with P standing for “John went to the store” and Q for “We’re out of eggs.” But someone who made this statement would probably be trying to express the idea that if John didn’t go to the store, then we’re out of eggs, or in other words $\neg P \rightarrow Q$. Thus, this example suggests that $\neg P \rightarrow Q$ means the same thing as $P \vee Q$. In fact, we can derive this equivalence from the previous one by substituting $\neg P$ for P . Because $P \rightarrow Q$ is equivalent to $\neg P \vee Q$, it follows that $\neg P \rightarrow Q$ is equivalent to $\neg(\neg P) \vee Q$, which is equivalent to $P \vee Q$ by the double negation law.

We can derive another useful equivalence as follows:

$$\begin{aligned} \neg P \vee Q &\text{ is equivalent to } \neg P \vee \neg\neg Q && \text{(double negation law),} \\ &\text{ which is equivalent to } \neg(P \wedge \neg Q) && \text{(De Morgan's law).} \end{aligned}$$

Thus, $P \rightarrow Q$ is also equivalent to $\neg(P \wedge \neg Q)$. In fact, this is precisely the conclusion we reached earlier when discussing the statement “If $x > 2$ then $x^2 > 4$.” We decided then that the reason this statement is true for every value of x is that there is no value of x for which $x > 2$ and $x^2 \leq 4$. In other words, the statement $P(x) \wedge \neg Q(x)$ is never true, where as before $P(x)$ stands for $x > 2$ and $Q(x)$ for $x^2 > 4$. But that’s the same as saying that the statement $\neg(P(x) \wedge \neg Q(x))$ is always true. Thus, to say that $P(x) \rightarrow Q(x)$ is always true means the same thing as saying that $\neg(P(x) \wedge \neg Q(x))$ is always true.

For another example of this equivalence, consider the statement “If it’s going to rain, then I’ll take my umbrella.” Of course, this statement has the form $P \rightarrow Q$, where P stands for the statement “It’s going to rain” and Q stands for “I’ll take my umbrella.” But we could also think of this statement as a declaration that I won’t be caught in the rain without my umbrella – in other words, $\neg(P \wedge \neg Q)$.

To summarize, so far we have discovered the following equivalences involving conditional statements:

Conditional laws

$P \rightarrow Q$ is equivalent to $\neg P \vee Q$.

$P \rightarrow Q$ is equivalent to $\neg(P \wedge \neg Q)$.

In case you’re still not convinced that the truth table in Figure 1.17 is right, we give one more reason. We know that, using this truth table, we can now analyze the validity of deductive arguments involving the words *if* and *then*. We’ll find, when we analyze a few simple arguments, that the truth table in Figure 1.17 leads to reasonable conclusions about the validity of these arguments. But if we were to make any changes in the truth table, we would end up with conclusions that are clearly incorrect. For example, let’s return to the argument form with which we started this section:

$$\frac{P \rightarrow Q \quad P}{\therefore Q}$$

We have already decided that this form of argument should be valid, and the truth table in Figure 1.19 confirms this. The premises are both true only in line four of the table, and in this line the conclusion is true as well.

You can also see from Figure 1.19 that both premises are needed to make this argument valid. But if we were to change the truth table for the conditional statement to make $P \rightarrow Q$ false in the first line of the table, then the second premise of this argument would no longer be needed. We would end up with

		Premises		Conclusion	
P	Q	$P \rightarrow Q$	P	Q	Q
F	F	T	F	F	F
F	T	T	F	T	T
T	F	F	T	F	F
T	T	T	T	T	T

Figure 1.19.

the conclusion that, just from the single premise $P \rightarrow Q$, we could infer that Q must be true, since in the two lines of the truth table in which the premise $P \rightarrow Q$ would still be true, lines two and four, the conclusion Q is true too. But this doesn't seem right. Just knowing that *if* P is true then Q is true, but not knowing that P *is* true, it doesn't seem reasonable that we should be able to conclude that Q is true. For example, suppose we know that the statement "If John didn't go to the store then we're out of eggs" is true. Unless we also know whether or not John has gone to the store, we can't reach any conclusion about whether or not we're out of eggs. Thus, changing the first line of the truth table for $P \rightarrow Q$ would lead to an incorrect conclusion about the validity of an argument.

Changing the second line of the truth table would also lead to unacceptable conclusions about the validity of arguments. To see this, consider the argument form:

$$\frac{P \rightarrow Q \quad Q}{\therefore P}$$

This should *not* be considered a valid form of reasoning. For example, consider the following argument, which has this form:

If Jones was convicted of murdering Smith, then he will go to jail.
Jones will go to jail.
Therefore, Jones was convicted of murdering Smith.

Even if the premises of this argument are true, the conclusion that Jones was convicted of murdering Smith doesn't follow. Maybe the reason he will go to jail is that he robbed a bank or cheated on his income tax. Thus, the conclusion of this argument could be false even if the premises were true, so the argument isn't valid.

The truth table analysis in Figure 1.20 agrees with this conclusion. In line two of the table, the conclusion P is false, but both premises are true, so the argument is invalid. But notice that if we were to change the truth table for

$P \rightarrow Q$ and make it false in line two, then the truth table analysis would say that the argument is valid. Thus, the analysis of this argument seems to support our decision to put a T in the second line of the truth table for $P \rightarrow Q$.

		Premises		Conclusion
P	Q	$P \rightarrow Q$	Q	P
F	F	T	F	F
F	T	T	T	F
T	F	F	F	T
T	T	T	T	T

Figure 1.20.

The last example shows that from the premises $P \rightarrow Q$ and Q it is incorrect to infer P . But it would certainly be correct to infer P from the premises $Q \rightarrow P$ and Q . This shows that the formulas $P \rightarrow Q$ and $Q \rightarrow P$ do *not* mean the same thing. You can check this by making a truth table for both and verifying that they are not equivalent. For example, a person might believe that, in general, the statement “If you are a convicted murderer then you are untrustworthy” is true, without believing that the statement “If you are untrustworthy then you are a convicted murderer” is generally true. The formula $Q \rightarrow P$ is called the *converse* of $P \rightarrow Q$. It is very important to make sure you never confuse a conditional statement with its converse.

The *contrapositive* of $P \rightarrow Q$ is the formula $\neg Q \rightarrow \neg P$, and it is equivalent to $P \rightarrow Q$. This may not be obvious at first, but you can verify it with a truth table. For example, the statements “If John cashed the check I wrote then my bank account is overdrawn” and “If my bank account isn’t overdrawn then John hasn’t cashed the check I wrote” are equivalent. I would be inclined to assert both in exactly the same circumstances – namely, if the check I wrote was for more money than I had in my account. The equivalence of conditional statements and their contrapositives is used often in mathematical reasoning. We add it to our list of important equivalences:

Contrapositive law

$$P \rightarrow Q \text{ is equivalent to } \neg Q \rightarrow \neg P.$$

Example 1.5.2. Which of the following statements are equivalent?

1. If it’s either raining or snowing, then the game has been canceled.
2. If the game hasn’t been canceled, then it’s not raining and it’s not snowing.
3. If the game has been canceled, then it’s either raining or snowing.

4. If it's raining then the game has been canceled, and if it's snowing then the game has been canceled.
5. If it's neither raining nor snowing, then the game hasn't been canceled.

Solution

We translate all of the statements into the notation of logic, using the following abbreviations: R stands for the statement "It's raining," S stands for "It's snowing," and C stands for "The game has been canceled."

1. $(R \vee S) \rightarrow C$.
2. $\neg C \rightarrow (\neg R \wedge \neg S)$. By one of De Morgan's laws, this is equivalent to $\neg C \rightarrow \neg(R \vee S)$. This is the contrapositive of statement 1, so they are equivalent.
3. $C \rightarrow (R \vee S)$. This is the converse of statement 1, which is *not* equivalent to it. You can verify this with a truth table, or just think about what the statements mean. Statement 1 says that rain or snow would result in cancellation of the game. Statement 3 says that these are the *only* circumstances in which the game will be canceled.
4. $(R \rightarrow C) \wedge (S \rightarrow C)$. This is also equivalent to statement 1, as the following reasoning shows:

$$\begin{aligned} &(R \rightarrow C) \wedge (S \rightarrow C) \\ &\quad \text{is equivalent to } (\neg R \vee C) \wedge (\neg S \vee C) \quad (\text{conditional law}), \\ &\quad \text{which is equivalent to } (\neg R \wedge \neg S) \vee C \quad (\text{distributive law}), \\ &\quad \text{which is equivalent to } \neg(R \vee S) \vee C \quad (\text{De Morgan's law}), \\ &\quad \text{which is equivalent to } (R \vee S) \rightarrow C \quad (\text{conditional law}). \end{aligned}$$

You should read statements 1 and 4 again and see if it makes sense to you that they're equivalent.

5. $\neg(R \vee S) \rightarrow \neg C$. This is the contrapositive of statement 3, so they are equivalent. It is not equivalent to statements 1, 2, and 4.

Statements that mean $P \rightarrow Q$ come up very often in mathematics, but sometimes they are not written in the form "If P then Q ." Here are a few other ways of expressing the idea $P \rightarrow Q$ that are used often in mathematics:

P implies Q .

Q , if P .

P only if Q .

P is a sufficient condition for Q .

Q is a necessary condition for P .

Some of these may require further explanation. The second expression, “ Q , if P ,” is just a slight rearrangement of the statement “If P then Q ,” so it should make sense that it means $P \rightarrow Q$. As an example of a statement of the form “ P only if Q ,” consider the sentence “You can run for president only if you are a citizen.” In this case, P is “You can run for president” and Q is “You are a citizen.” What the statement means is that if you’re not a citizen, then you can’t run for president, or in other words $\neg Q \rightarrow \neg P$. But by the contrapositive law, this is equivalent to $P \rightarrow Q$.

Think of “ P is a sufficient condition for Q ” as meaning “The truth of P suffices to guarantee the truth of Q ,” and it should make sense that this should be represented by $P \rightarrow Q$. Finally, “ Q is a necessary condition for P ” means that in order for P to be true, it is necessary for Q to be true also. This means that if Q isn’t true, then P can’t be true either, or in other words, $\neg Q \rightarrow \neg P$. Once again, by the contrapositive law we get $P \rightarrow Q$.

Example 1.5.3. Analyze the logical forms of the following statements:

1. If at least ten people are there, then the lecture will be given.
2. The lecture will be given only if at least ten people are there.
3. The lecture will be given if at least ten people are there.
4. Having at least ten people there is a sufficient condition for the lecture being given.
5. Having at least ten people there is a necessary condition for the lecture being given.

Solutions

Let T stand for the statement “At least ten people are there” and L for “The lecture will be given.”

1. $T \rightarrow L$.
2. $L \rightarrow T$. The given statement means that if there are not at least ten people there, then the lecture will not be given, or in other words $\neg T \rightarrow \neg L$. By the contrapositive law, this is equivalent to $L \rightarrow T$.
3. $T \rightarrow L$. This is just a rephrasing of statement 1.
4. $T \rightarrow L$. The statement says that having at least ten people there suffices to guarantee that the lecture will be given, and this means that if there are at least ten people there, then the lecture will be given.
5. $L \rightarrow T$. This statement means the same thing as statement 2: If there are not at least ten people there, then the lecture will not be given.

We have already seen that a conditional statement $P \rightarrow Q$ and its converse $Q \rightarrow P$ are not equivalent. Often in mathematics we want to say that both

$P \rightarrow Q$ and $Q \rightarrow P$ are true, and it is therefore convenient to introduce a new connective symbol, \leftrightarrow , to express this. You can think of $P \leftrightarrow Q$ as just an abbreviation for the formula $(P \rightarrow Q) \wedge (Q \rightarrow P)$. A statement of the form $P \leftrightarrow Q$ is called a *biconditional* statement, because it represents two conditional statements. By making a truth table for $(P \rightarrow Q) \wedge (Q \rightarrow P)$ you can verify that the truth table for $P \leftrightarrow Q$ is as shown in Figure 1.21. Note that, by the contrapositive law, $P \leftrightarrow Q$ is also equivalent to $(P \rightarrow Q) \wedge (\neg P \rightarrow \neg Q)$.

P	Q	$P \leftrightarrow Q$
F	F	T
F	T	F
T	F	F
T	T	T

Figure 1.21.

Because $Q \rightarrow P$ can be written “ P if Q ” and $P \rightarrow Q$ can be written “ P only if Q ,” $P \leftrightarrow Q$ means “ P if Q and P only if Q ,” and this is often written “ P if and only if Q .” The phrase *if and only if* occurs so often in mathematics that there is a common abbreviation for it, *iff*. Thus, $P \leftrightarrow Q$ is often written “ P iff Q .” Another statement that means $P \leftrightarrow Q$ is “ P is a necessary and sufficient condition for Q .”

Example 1.5.4. Analyze the logical forms of the following statements:

1. The game will be canceled iff it’s either raining or snowing.
2. Having at least ten people there is a necessary and sufficient condition for the lecture being given.
3. If John went to the store then we have some eggs, and if he didn’t then we don’t.

Solutions

1. Let C stand for “The game will be canceled,” R for “It’s raining,” and S for “It’s snowing.” Then the statement would be represented by the formula $C \leftrightarrow (R \vee S)$.
2. Let T stand for “There are at least ten people there” and L for “The lecture will be given.” Then the statement means $T \leftrightarrow L$.
3. Let S stand for “John went to the store” and E for “We have some eggs.” Then a literal translation of the given statement would be $(S \rightarrow E) \wedge (\neg S \rightarrow \neg E)$. This is equivalent to $S \leftrightarrow E$.

One of the reasons it's so easy to confuse a conditional statement with its converse is that in everyday speech we sometimes use a conditional statement when what we mean to convey is actually a biconditional. For example, you probably wouldn't say "The lecture will be given if at least ten people are there" unless it was also the case that if there were fewer than ten people, the lecture wouldn't be given. After all, why mention the number ten at all if it's not the minimum number of people required? Thus, the statement actually suggests that the lecture will be given *iff* there are at least ten people there. For another example, suppose a child is told by his parents, "If you don't eat your dinner, you won't get any dessert." The child certainly expects that if he *does* eat his dinner, he *will* get dessert, although that's not literally what his parents said. In other words, the child interprets the statement as meaning "Eating your dinner is a necessary *and sufficient* condition for getting dessert."

Such a blurring of the distinction between *if* and *iff* is never acceptable in mathematics. Mathematicians always use a phrase such as *iff* or *necessary and sufficient condition* when they want to express a biconditional statement. You should never interpret an if-then statement in mathematics as a biconditional statement, the way you might in everyday speech.

Exercises

- *1. Analyze the logical forms of the following statements:
 - (a) If this gas either has an unpleasant smell or is not explosive, then it isn't hydrogen.
 - (b) Having both a fever and a headache is a sufficient condition for George to go to the doctor.
 - (c) Both having a fever and having a headache are sufficient conditions for George to go to the doctor.
 - (d) If $x \neq 2$, then a necessary condition for x to be prime is that x be odd.
2. Analyze the logical forms of the following statements:
 - (a) Mary will sell her house only if she can get a good price and find a nice apartment.
 - (b) Having both a good credit history and an adequate down payment is a necessary condition for getting a mortgage.
 - (c) John will drop out of school, unless someone stops him. (Hint: First try to rephrase this using the words *if* and *then* instead of *unless*.)
 - (d) If x is divisible by either 4 or 6, then it isn't prime.
3. Analyze the logical form of the following statement:
 - (a) If it is raining, then it is windy and the sun is not shining.

Now analyze the following statements. Also, for each statement determine whether the statement is equivalent to either statement (a) or its converse.

- (b) It is windy and not sunny only if it is raining.
 - (c) Rain is a sufficient condition for wind with no sunshine.
 - (d) Rain is a necessary condition for wind with no sunshine.
 - (e) It's not raining, if either the sun is shining or it's not windy.
 - (f) Wind is a necessary condition for it to be rainy, and so is a lack of sunshine.
 - (g) Either it is windy only if it is raining, or it is not sunny only if it is raining.
- *4. Use truth tables to determine whether or not the following arguments are valid:
- (a) Either sales or expenses will go up. If sales go up, then the boss will be happy. If expenses go up, then the boss will be unhappy. Therefore, sales and expenses will not both go up.
 - (b) If the tax rate and the unemployment rate both go up, then there will be a recession. If the GDP goes up, then there will not be a recession. The GDP and taxes are both going up. Therefore, the unemployment rate is not going up.
 - (c) The warning light will come on if and only if the pressure is too high and the relief valve is clogged. The relief valve is not clogged. Therefore, the warning light will come on if and only if the pressure is too high.
5. Use truth tables to determine whether or not the following arguments are valid:
- (a) If Jones is convicted then he will go to prison. Jones will be convicted only if Smith testifies against him. Therefore, Jones won't go to prison unless Smith testifies against him.
 - (b) Either the Democrats or the Republicans will have a majority in the Senate, but not both. Having a Democratic majority is a necessary condition for the bill to pass. Therefore, if the Republicans have a majority in the Senate then the bill won't pass.
6. (a) Show that $P \leftrightarrow Q$ is equivalent to $(P \wedge Q) \vee (\neg P \wedge \neg Q)$.
- (b) Show that $(P \rightarrow Q) \vee (P \rightarrow R)$ is equivalent to $P \rightarrow (Q \vee R)$.
- *7. (a) Show that $(P \rightarrow R) \wedge (Q \rightarrow R)$ is equivalent to $(P \vee Q) \rightarrow R$.
- (b) Formulate and verify a similar equivalence involving $(P \rightarrow R) \vee (Q \rightarrow R)$.
8. (a) Show that $(P \rightarrow Q) \wedge (Q \rightarrow R)$ is equivalent to $(P \rightarrow R) \wedge [(P \leftrightarrow Q) \vee (R \leftrightarrow Q)]$.
- (b) Show that $(P \rightarrow Q) \vee (Q \rightarrow R)$ is a tautology.

- *9. Find a formula involving only the connectives \neg and \rightarrow that is equivalent to $P \wedge Q$.
- 10. Find a formula involving only the connectives \neg and \rightarrow that is equivalent to $P \leftrightarrow Q$.
- 11. (a) Show that $(P \vee Q) \leftrightarrow Q$ is equivalent to $P \rightarrow Q$.
(b) Show that $(P \wedge Q) \leftrightarrow Q$ is equivalent to $Q \rightarrow P$.
- 12. Which of the following formulas are equivalent?
 - (a) $P \rightarrow (Q \rightarrow R)$.
 - (b) $Q \rightarrow (P \rightarrow R)$.
 - (c) $(P \rightarrow Q) \wedge (P \rightarrow R)$.
 - (d) $(P \wedge Q) \rightarrow R$.
 - (e) $P \rightarrow (Q \wedge R)$.

2

Quantificational Logic

2.1. Quantifiers

We have seen that a statement $P(x)$ containing a free variable x may be true for some values of x and false for others. Sometimes we want to say something about *how many* values of x make $P(x)$ come out true. In particular, we often want to say either that $P(x)$ is true for *every* value of x or that it is true for *at least one* value of x . We therefore introduce two more symbols, called *quantifiers*, to help us express these ideas.

To say that $P(x)$ is true for every value of x in the universe of discourse U , we will write $\forall x P(x)$. This is read “For all x , $P(x)$.” Think of the upside down A as standing for the word *all*. The symbol \forall is called the *universal quantifier*, because the statement $\forall x P(x)$ says that $P(x)$ is *universally* true. As we discussed in Section 1.3, to say that $P(x)$ is true for every value of x in the universe means that the truth set of $P(x)$ will be the whole universe U . Thus, you could also think of the statement $\forall x P(x)$ as saying that the truth set of $P(x)$ is equal to U .

We write $\exists x P(x)$ to say that there is at least one value of x in the universe for which $P(x)$ is true. This is read “There exists an x such that $P(x)$.” The backward E comes from the word *exists* and is called the *existential quantifier*. Once again, you can interpret this statement as saying something about the truth set of $P(x)$. To say that $P(x)$ is true for at least one value of x means that there is at least one element in the truth set of $P(x)$, or in other words, the truth set is not equal to \emptyset .

For example, in Section 1.5 we discussed the statement “If $x > 2$ then $x^2 > 4$,” where x ranges over the set of all real numbers, and we claimed that this statement was true for all values of x . We can now write this claim symbolically as $\forall x(x > 2 \rightarrow x^2 > 4)$.

Example 2.1.1. What do the following formulas mean? Are they true or false?

1. $\forall x(x^2 \geq 0)$, where the universe of discourse is \mathbb{R} , the set of all real numbers.
2. $\exists x(x^2 - 2x + 3 = 0)$, with universe \mathbb{R} again.
3. $\exists x(M(x) \wedge B(x))$, where the universe of discourse is the set of all people, $M(x)$ stands for the statement “ x is a man,” and $B(x)$ means “ x has brown hair.”
4. $\forall x(M(x) \rightarrow B(x))$, with the same universe and the same meanings for $M(x)$ and $B(x)$.
5. $\forall xL(x, y)$, where the universe is the set of all people, and $L(x, y)$ means “ x likes y .”

Solutions

1. This means that for every real number x , $x^2 \geq 0$. This is true.
2. This means that there is at least one real number x that makes the equation $x^2 - 2x + 3 = 0$ come out true. In other words, the equation has at least one real solution. If you solve the equation, you’ll find that this statement is false; the equation has no real solutions. (Try either completing the square or using the quadratic formula.)
3. There is at least one person x such that x is a man and x has brown hair. In other words, there is at least one man who has brown hair. Of course, this is true.
4. For every person x , if x is a man then x has brown hair. In other words, all men have brown hair. If you’re not convinced that this is what the formula means, it might help to look back at the truth table for the conditional connective. According to this truth table, the statement $M(x) \rightarrow B(x)$ will be false only if $M(x)$ is true and $B(x)$ is false; that is, x is a man and x doesn’t have brown hair. Thus, to say that $M(x) \rightarrow B(x)$ is true for every person x means that this situation never occurs, or in other words, that there are no men who don’t have brown hair. But that’s exactly what it means to say that all men have brown hair. Of course, this statement is false.
5. For every person x , x likes y . In other words, everyone likes y . We can’t tell if this is true or false unless we know who y is.

Notice that in the fifth statement in this example, we needed to know who y was to determine if the statement was true or false, but not who x was. The statement says that everyone likes y , and this is a statement about y , but not x . This means that y is a free variable in this statement but x is a bound variable.

Similarly, although all the other statements contain the letter x , we didn't need to know the value of x to determine their truth values, so x is a bound variable in every case. In general, even if x is a free variable in some statement $P(x)$, it is a bound variable in the statements $\forall x P(x)$ and $\exists x P(x)$. For this reason, we say that the quantifiers *bind* a variable. As in Section 1.3, this means that a variable that is bound by a quantifier can always be replaced with a new variable without changing the meaning of the statement, and it is often possible to paraphrase the statement without mentioning the bound variable at all. For example, the statement $\forall x L(x, y)$ from Example 2.1.1 is equivalent to $\forall w L(w, y)$, because both mean the same thing as "Everyone likes y ." Words such as *everyone*, *someone*, *everything*, or *something* are often used to express the meanings of statements containing quantifiers. If you are translating an English statement into symbols, these words will often tip you off that a quantifier will be needed.

As with the symbol \neg , we follow the convention that the expressions $\forall x$ and $\exists x$ apply only to the statements that come immediately after them. For example, $\forall x P(x) \rightarrow Q(x)$ means $(\forall x P(x)) \rightarrow Q(x)$, not $\forall x (P(x) \rightarrow Q(x))$.

Example 2.1.2. Analyze the logical forms of the following statements.

1. Someone didn't do the homework.
2. Everything in that store is either overpriced or poorly made.
3. Nobody's perfect.
4. Susan likes everyone who dislikes Joe.
5. $A \subseteq B$.
6. $A \cap B \subseteq B \setminus C$.

Solutions

1. The word *someone* tips us off that we should use an existential quantifier. As a first step, we write $\exists x (x \text{ didn't do the homework})$. Now if we let $H(x)$ stand for the statement " x did the homework," then we can rewrite this as $\exists x \neg H(x)$.
2. Think of this statement as saying "If it's in that store, then it's either overpriced or poorly made (no matter what *it* is)." Thus, we start by writing $\forall x$ (if x is in that store then x is either overpriced or poorly made). To write the part in parentheses symbolically, we let $S(x)$ stand for " x is in that store," $O(x)$ for " x is overpriced," and $P(x)$ for " x is poorly made." Then our final answer is $\forall x [S(x) \rightarrow (O(x) \vee P(x))]$.

Note that, like statement 4 in Example 2.1.1, this statement has the form of a universal quantifier applied to a conditional statement. This form occurs quite often, and it is important to learn to recognize what it means

and when it should be used. We can check our answer to this problem as we did before, by using the truth table for the conditional connective. The only way that the statement $S(x) \rightarrow (O(x) \vee P(x))$ can be false is if x is in that store, but is neither overpriced nor poorly made. Thus, to say that the statement is true for all values of x means that this never happens, which is exactly what it means to say that everything in that store is either overpriced or poorly made.

3. This means $\neg(\text{somebody is perfect})$, or in other words $\neg\exists xP(x)$, where $P(x)$ stands for “ x is perfect.”
4. As in statement 2 in this example, we could think of this as meaning “If a person dislikes Joe then Susan likes that person (no matter who the person is).” Thus, we can start by rewriting the given statement as $\forall x(\text{if } x \text{ dislikes Joe then Susan likes } x)$. Let $L(x, y)$ stand for “ x likes y .” In statements that talk about specific elements of the universe of discourse it is sometimes convenient to introduce letters to stand for those specific elements. In this case we need to talk about Joe and Susan, so let’s let j stand for Joe and s for Susan. Thus, we can write $L(s, x)$ to mean “Susan likes x ,” and $\neg L(x, j)$ for “ x dislikes Joe.” Filling these in, we end up with the answer $\forall x(\neg L(x, j) \rightarrow L(s, x))$. Notice that, once again, we have a universal quantifier applied to a conditional statement. As before, you can check this answer using the truth table for the conditional connective.
5. According to Definition 1.4.5, to say that A is a subset of B means that everything in A is in B . If you’ve caught on to the pattern of how universal quantifiers and conditionals are combined, you should recognize that this would be written symbolically as $\forall x(x \in A \rightarrow x \in B)$.
6. As in the previous statement, we first write this as $\forall x(x \in A \cap B \rightarrow x \in B \setminus C)$. Now using the definitions of intersection and difference, we can expand this further to get $\forall x[(x \in A \wedge x \in B) \rightarrow (x \in B \wedge x \notin C)]$.

Although all of our examples so far have contained only one quantifier, there’s no reason why a statement can’t have more than one quantifier. For example, consider the statement “Some students are married.” The word *some* indicates that this statement should be written using an existential quantifier, so we can think of it as having the form $\exists x(x \text{ is a student and } x \text{ is married})$. Let $S(x)$ stand for “ x is a student.” We could similarly choose a letter to stand for “ x is married,” but perhaps a better analysis would be to recognize that to be married means to be married *to someone*. Thus, if we let $M(x, y)$ stand for “ x is married to y ,” then we can write “ x is married” as $\exists yM(x, y)$. We can therefore represent the entire statement by the formula $\exists x(S(x) \wedge \exists yM(x, y))$, a formula containing two existential quantifiers.

As another example, let's analyze the statement "All parents are married." We start by writing it as $\forall x(\text{if } x \text{ is a parent then } x \text{ is married})$. Parenthood, like marriage, is a relationship between two people; to be a parent means to be a parent of *someone*. Thus, it might be best to represent the statement " x is a parent" by the formula $\exists y P(x, y)$, where $P(x, y)$ means " x is a parent of y ." If we again represent " x is married" by the formula $\exists y M(x, y)$, then our analysis of the original statement will be $\forall x(\exists y P(x, y) \rightarrow \exists y M(x, y))$. Although this isn't wrong, the double use of the variable y could cause confusion. Perhaps a better solution would be to replace the formula $\exists y M(x, y)$ with the equivalent formula $\exists z M(x, z)$. (Recall that these are equivalent because a bound variable in any statement can be replaced by another without changing the meaning of the statement.) Our improved analysis of the statement would then be $\forall x(\exists y P(x, y) \rightarrow \exists z M(x, z))$.

A common mistake made by beginners is to leave out quantifiers. For example, you might be tempted to represent the statement "All parents are married" incorrectly by the formula $\forall x(P(x, y) \rightarrow M(x, z))$, leaving out $\exists y$ and $\exists z$. A good way to catch such mistakes is to pay attention to free and bound variables. In the incorrect formula, there are no quantifiers binding the variables y and z , so y and z are free variables. But the original statement, "All parents are married," is not a statement about y and z , so these variables should not be free in the answer. This is a tip-off that quantifiers on y and z are missing. Note that if we translate the incorrect formula $\forall x(P(x, y) \rightarrow M(x, z))$ back into English, we get a statement about y and z : "Everyone who is a parent of y is married to z ."

Example 2.1.3. Analyze the logical forms of the following statements.

1. Everybody in the dorm has a roommate he or she doesn't like.
2. Nobody likes a sore loser.
3. Anyone who has a friend who has the measles will have to be quarantined.
4. If anyone in the dorm has a friend who has the measles, then everyone in the dorm will have to be quarantined.
5. If $A \subseteq B$, then A and $C \setminus B$ are disjoint.

Solutions

1. This means $\forall x(\text{if } x \text{ lives in the dorm then } x \text{ has a roommate he or she doesn't like})$. To say that x has a roommate he or she doesn't like, we could write $\exists y(x \text{ and } y \text{ are roommates and } x \text{ doesn't like } y)$. If we let $R(x, y)$ stand for " x and y are roommates" and $L(x, y)$ for " x likes y ," then this becomes $\exists y(R(x, y) \wedge \neg L(x, y))$. Finally, if we let $D(x)$ mean " x lives in

the dorm,” then the complete analysis of the original statement would be $\forall x [D(x) \rightarrow \exists y (R(x, y) \wedge \neg L(x, y))]$.

2. This is tricky, because the phrase *a sore loser* doesn't refer to a *particular* sore loser, it refers to *all* sore losers. The statement means that all sore losers are disliked, or in other words $\forall x$ (if x is a sore loser then nobody likes x). To say nobody likes x we write \neg (somebody likes x), which means $\neg \exists y L(y, x)$, where $L(y, x)$ means “ y likes x .” If we let $S(x)$ mean “ x is a sore loser,” then the whole statement would be written $\forall x (S(x) \rightarrow \neg \exists y L(y, x))$.

3. You have probably realized by now that it is usually easiest to translate from English into symbols in several steps, translating only a little bit at a time. Here are the steps we might use to translate this statement:

- (i) $\forall x$ (if x has a friend who has the measles then x will have to be quarantined).
(ii) $\forall x [\exists y (y \text{ is a friend of } x \text{ and } y \text{ has the measles}) \rightarrow x \text{ will have to be quarantined}]$.

Now, letting $F(y, x)$ stand for “ y is a friend of x ,” $M(y)$ for “ y has the measles,” and $Q(x)$ for “ x will have to be quarantined,” we get:

- (iii) $\forall x [\exists y (F(y, x) \wedge M(y)) \rightarrow Q(x)]$.

4. The word *anyone* is difficult to interpret, because in different statements it means different things. In statement 3 it meant *everyone*, but in this statement it means *someone*. Here are the steps of our analysis:

- (i) (Someone in the dorm has a friend who has the measles) \rightarrow (everyone in the dorm will have to be quarantined).
(ii) $\exists x (x \text{ lives in the dorm and } x \text{ has a friend who has the measles}) \rightarrow \forall z (\text{if } z \text{ lives in the dorm then } z \text{ will have to be quarantined})$.

Using the same abbreviations as in the last statement and letting $D(x)$ stand for “ x lives in the dorm,” we end up with the following formula:

- (iii) $\exists x [D(x) \wedge \exists y (F(y, x) \wedge M(y))] \rightarrow \forall z (D(z) \rightarrow Q(z))$.

5. Clearly the answer will have the form of a conditional statement, $(A \subseteq B) \rightarrow (A \text{ and } C \setminus B \text{ are disjoint})$. We have already written $A \subseteq B$ symbolically in Example 2.1.2. To say that A and $C \setminus B$ are disjoint means that they have no elements in common, or in other words $\neg \exists x (x \in A \wedge x \in C \setminus B)$. Putting this all together, and filling in the definition of $C \setminus B$, we end up with $\forall x (x \in A \rightarrow x \in B) \rightarrow \neg \exists x (x \in A \wedge x \in C \wedge x \notin B)$.

When a statement contains more than one quantifier it is sometimes difficult to figure out what it means and whether it is true or false. It may be best in this case to think about the quantifiers one at a time, in order. For example, consider the statement $\forall x \exists y (x + y = 5)$, where the universe of discourse is the set of

all real numbers. Thinking first about just the first quantifier expression $\forall x$, we see that the statement means that for every real number x , the statement $\exists y(x + y = 5)$ is true. We can worry later about what $\exists y(x + y = 5)$ means; thinking about two quantifiers at once is too confusing.

If we want to figure out whether or not the statement $\exists y(x + y = 5)$ is true for every value of x , it might help to try out a few values of x . For example, suppose $x = 2$. Then we must determine whether or not the statement $\exists y(2 + y = 5)$ is true. Now it's time to think about the next quantifier, $\exists y$. This statement says that there is at least one value of y for which the equation $2 + y = 5$ holds. In other words, the equation $2 + y = 5$ has at least one solution. Of course, this is true, because the equation has the solution $y = 5 - 2 = 3$. Thus, the statement $\exists y(2 + y = 5)$ is true.

Let's try one more value of x . If $x = 7$, then we are interested in the statement $\exists y(7 + y = 5)$, which says that the equation $7 + y = 5$ has at least one solution. Once again, this is true, since the solution is $y = 5 - 7 = -2$. In fact, you have probably realized by now that no matter what value we plug in for x , the equation $x + y = 5$ will always have the solution $y = 5 - x$, so the statement $\exists y(x + y = 5)$ will be true. Thus, the original statement $\forall x \exists y(x + y = 5)$ is true.

On the other hand, the statement $\exists y \forall x(x + y = 5)$ means something entirely different. This statement means that there is at least one value of y for which the statement $\forall x(x + y = 5)$ is true. Can we find such a value of y ? Suppose, for example, we try $y = 4$. Then we must determine whether or not the statement $\forall x(x + 4 = 5)$ is true. This statement says that no matter what value we plug in for x , the equation $x + 4 = 5$ holds, and this is clearly false. In fact, no value of x other than $x = 1$ works in this equation. Thus, the statement $\forall x(x + 4 = 5)$ is false.

We have seen that when $y = 4$ the statement $\forall x(x + y = 5)$ is false, but maybe some other value of y will work. Remember, we are trying to determine whether or not there is *at least one* value of y that works. Let's try one more, say, $y = 9$. Then we must consider the statement $\forall x(x + 9 = 5)$, which says that no matter what x is, the equation $x + 9 = 5$ holds. Once again this is clearly false, since only $x = -4$ works in this equation. In fact, it should be clear by now that no matter what value we plug in for y , the equation $x + y = 5$ will be true for only one value of x , namely $x = 5 - y$, so the statement $\forall x(x + y = 5)$ will be false. Thus there are *no* values of y for which $\forall x(x + y = 5)$ is true, so the statement $\exists y \forall x(x + y = 5)$ is false.

Notice that we found that the statement $\forall x \exists y(x + y = 5)$ is true, but $\exists y \forall x(x + y = 5)$ is false. Apparently, the order of the quantifiers makes a difference! What is responsible for this difference? The first statement says

that for every real number x , there is a real number y such that $x + y = 5$. For example, when we tried $x = 2$ we found that $y = 3$ worked in the equation $x + y = 5$, and with $x = 7$, $y = -2$ worked. Note that for different values of x , we had to use different values of y to make the equation come out true. You might think of this statement as saying that for each real number x there is a *corresponding* real number y such that $x + y = 5$. On the other hand, when we were analyzing the statement $\exists y \forall x(x + y = 5)$ we found ourselves searching for a *single* value of y that made the equation $x + y = 5$ true for all values of x , and this turned out to be impossible. For each value of x there is a corresponding value of y that makes the equation true, but no single value of y works for every x .

For another example, consider the statement $\forall x \exists y L(x, y)$, where the universe of discourse is the set of all people and $L(x, y)$ means “ x likes y .” This statement says that for every person x , the statement $\exists y L(x, y)$ is true. Now $\exists y L(x, y)$ could be written as “ x likes someone,” so the original statement means that for every person x , x likes someone. In other words, everyone likes someone. On the other hand, $\exists y \forall x L(x, y)$ means that there is some person y such that $\forall x L(x, y)$ is true. As we saw in Example 2.1.1, $\forall x L(x, y)$ means “Everyone likes y ,” so $\exists y \forall x L(x, y)$ means that there is some person y such that everyone likes y . In other words, there is someone who is universally liked. These statements don’t mean the same thing. It might be the case that everyone likes someone, but no one is universally liked.

Example 2.1.4. What do the following statements mean? Are they true or false? The universe of discourse in each case is \mathbb{N} , the set of all natural numbers.

1. $\forall x \exists y(x < y)$.
2. $\exists y \forall x(x < y)$.
3. $\exists x \forall y(x < y)$.
4. $\forall y \exists x(x < y)$.
5. $\exists x \exists y(x < y)$.
6. $\forall x \forall y(x < y)$.

Solutions

1. This means that for every natural number x , the statement $\exists y(x < y)$ is true. In other words, for every natural number x , there is a natural number bigger than x . This is true. For example, $x + 1$ is always bigger than x .
2. This means that there is some natural number y such that the statement $\forall x(x < y)$ is true. In other words, there is some natural number y such

that all natural numbers are smaller than y . This is false. No matter what natural number y we pick, there will always be larger natural numbers.

3. This means that there is a natural number x such that the statement $\forall y(x < y)$ is true. You might be tempted to say that this statement will be true if $x = 0$, but this isn't right. Since 0 is the smallest natural number, the statement $0 < y$ is true for all values of y *except* $y = 0$, but if $y = 0$, then the statement $0 < y$ is false, and therefore $\forall y(0 < y)$ is false. Similar reasoning shows that for every value of x the statement $\forall y(x < y)$ is false, so $\exists x \forall y(x < y)$ is false.
4. This means that for every natural number y , there is a natural number smaller than y . This is true for every natural number y *except* $y = 0$, but there is no natural number smaller than 0. Therefore this statement is false.
5. This means that there is a natural number x such that $\exists y(x < y)$ is true. But as we saw in the first statement, this is actually true for *every* natural number x , so it is certainly true for at least one. Thus, $\exists x \exists y(x < y)$ is true.
6. This means that for every natural number x , the statement $\forall y(x < y)$ is true. But as we saw in the third statement, there isn't even *one* value of x for which this statement is true. Thus, $\forall x \forall y(x < y)$ is false.

Exercises

- *1. Analyze the logical forms of the following statements.
 - (a) Anyone who has forgiven at least one person is a saint.
 - (b) Nobody in the calculus class is smarter than everybody in the discrete math class.
 - (c) Everyone likes Mary, except Mary herself.
 - (d) Jane saw a police officer, and Roger saw one too.
 - (e) Jane saw a police officer, and Roger saw him too.
2. Analyze the logical forms of the following statements.
 - (a) Anyone who has bought a Rolls Royce with cash must have a rich uncle.
 - (b) If anyone in the dorm has the measles, then everyone who has a friend in the dorm will have to be quarantined.
 - (c) If nobody failed the test, then everybody who got an A will tutor someone who got a D.
 - (d) If anyone can do it, Jones can.
 - (e) If Jones can do it, anyone can.

3. Analyze the logical forms of the following statements. The universe of discourse is \mathbb{R} . What are the free variables in each statement?
- Every number that is larger than x is larger than y .
 - For every number a , the equation $ax^2 + 4x - 2 = 0$ has at least one solution iff $a \geq -2$.
 - All solutions of the inequality $x^3 - 3x < 3$ are smaller than 10.
 - If there is a number x such that $x^2 + 5x = w$ and there is a number y such that $4 - y^2 = w$, then w is strictly between -10 and 10 .
- *4. Translate the following statements into idiomatic English.
- $\forall x[(H(x) \wedge \neg \exists y M(x, y)) \rightarrow U(x)]$, where $H(x)$ means “ x is a man,” $M(x, y)$ means “ x is married to y ,” and $U(x)$ means “ x is unhappy.”
 - $\exists z(P(z, x) \wedge S(z, y) \wedge W(y))$, where $P(z, x)$ means “ z is a parent of x ,” $S(z, y)$ means “ z and y are siblings,” and $W(y)$ means “ y is a woman.”
5. Translate the following statements into idiomatic mathematical English.
- $\forall x[(P(x) \wedge \neg(x = 2)) \rightarrow O(x)]$, where $P(x)$ means “ x is a prime number” and $O(x)$ means “ x is odd.”
 - $\exists x[P(x) \wedge \forall y(P(y) \rightarrow y \leq x)]$, where $P(x)$ means “ x is a perfect number.”
6. Translate the following statements into idiomatic mathematical English. Are they true or false? The universe of discourse is \mathbb{R} .
- $\neg \exists x(x^2 + 2x + 3 = 0 \wedge x^2 + 2x - 3 = 0)$.
 - $\neg[\exists x(x^2 + 2x + 3 = 0) \wedge \exists x(x^2 + 2x - 3 = 0)]$.
 - $\neg \exists x(x^2 + 2x + 3 = 0) \wedge \neg \exists x(x^2 + 2x - 3 = 0)$.
7. Are these statements true or false? The universe of discourse is the set of all people, and $P(x, y)$ means “ x is a parent of y .”
- $\exists x \forall y P(x, y)$.
 - $\forall x \exists y P(x, y)$.
 - $\neg \exists x \exists y P(x, y)$.
 - $\exists x \neg \exists y P(x, y)$.
 - $\exists x \exists y \neg P(x, y)$.
- *8. Are these statements true or false? The universe of discourse is \mathbb{N} .
- $\forall x \exists y(2x - y = 0)$.
 - $\exists y \forall x(2x - y = 0)$.
 - $\forall x \exists y(x - 2y = 0)$.
 - $\forall x(x < 10 \rightarrow \forall y(y < x \rightarrow y < 9))$.
 - $\exists y \exists z(y + z = 100)$.
 - $\forall x \exists y(y > x \wedge \exists z(y + z = 100))$.
9. Same as exercise 8 but with \mathbb{R} as the universe of discourse.
10. Same as exercise 8 but with \mathbb{Z} as the universe of discourse.

2.2. Equivalences Involving Quantifiers

In our study of logical connectives in Chapter 1 we found it useful to examine equivalences between different formulas. In this section, we will see that there are also a number of important equivalences involving quantifiers.

For example, in Example 2.1.2 we represented the statement “Nobody’s perfect” by the formula $\neg\exists xP(x)$, where $P(x)$ meant “ x is perfect.” But another way to express the same idea would be to say that everyone fails to be perfect, or in other words $\forall x\neg P(x)$. This suggests that these two formulas are equivalent, and a little thought should show that they are. No matter what $P(x)$ stands for, the formula $\neg\exists xP(x)$ means that there’s no value of x in the universe of discourse for which $P(x)$ is true. But that’s the same as saying that for every value of x in the universe, $P(x)$ is false, or in other words $\forall x\neg P(x)$. Thus, $\neg\exists xP(x)$ is equivalent to $\forall x\neg P(x)$.

Similar reasoning shows that $\neg\forall xP(x)$ is equivalent to $\exists x\neg P(x)$. To say that $\neg\forall xP(x)$ means that it is not the case that for all values of x , $P(x)$ is true. That’s equivalent to saying there’s at least one value of x for which $P(x)$ is false, which is what it means to say $\exists x\neg P(x)$. For example, in Example 2.1.2 we translated “Someone didn’t do the homework” as $\exists x\neg H(x)$, where $H(x)$ stands for “ x did the homework.” An equivalent statement would be “Not everyone did the homework,” which would be represented by the formula $\neg\forall xH(x)$.

Thus, we have the following two laws involving negation and quantifiers:

Quantifier Negation laws

$\neg\exists xP(x)$ is equivalent to $\forall x\neg P(x)$.

$\neg\forall xP(x)$ is equivalent to $\exists x\neg P(x)$.

Combining these laws with De Morgan’s laws and other equivalences involving the logical connectives, we can often reexpress a negative statement as an equivalent, but easier to understand, positive statement. This will turn out to be an important skill when we begin to work with negative statements in proofs.

Example 2.2.1. Negate these statements and then reexpress the results as equivalent positive statements.

1. $A \subseteq B$.
2. Everyone has a relative he or she doesn’t like.

Solutions

1. We already know that $A \subseteq B$ means $\forall x(x \in A \rightarrow x \in B)$. To reexpress the negation of this statement as an equivalent positive statement, we reason as follows:

$$\neg \forall x(x \in A \rightarrow x \in B)$$

is equivalent to $\exists x \neg(x \in A \rightarrow x \in B)$ (quantifier negation law),

which is equivalent to $\exists x \neg(x \notin A \vee x \in B)$ (conditional law),

which is equivalent to $\exists x(x \in A \wedge x \notin B)$ (De Morgan's law).

Thus, $A \not\subseteq B$ means the same thing as $\exists x(x \in A \wedge x \notin B)$. If you think about this, it should make sense. To say that A is not a subset of B is the same as saying that there's something in A that is not in B .

2. First of all, let's write the original statement symbolically. You should be able to check that if we let $R(x, y)$ stand for “ x is related to y ” and $L(x, y)$ for “ x likes y ,” then the original statement would be written $\forall x \exists y(R(x, y) \wedge \neg L(x, y))$. Now we negate this and try to find a simpler, equivalent positive statement:

$$\neg \forall x \exists y(R(x, y) \wedge \neg L(x, y))$$

is equivalent to $\exists x \neg \exists y(R(x, y) \wedge \neg L(x, y))$

(quantifier negation law),

which is equivalent to $\exists x \forall y \neg(R(x, y) \wedge \neg L(x, y))$

(quantifier negation law),

which is equivalent to $\exists x \forall y(\neg R(x, y) \vee L(x, y))$

(De Morgan's law),

which is equivalent to $\exists x \forall y(R(x, y) \rightarrow L(x, y))$

(conditional law).

Let's translate this last formula back into colloquial English. Leaving aside the first quantifier for the moment, the formula $\forall y(R(x, y) \rightarrow L(x, y))$ means that for every person y , if x is related to y then x likes y . In other words, x likes all his or her relatives. Adding $\exists x$ to the beginning of this, we get the statement “There is someone who likes all his or her relatives.” You should take a minute to convince yourself that this really is equivalent to the negation of the original statement “Everyone has a relative he or she doesn't like.”

For another example of how the quantifier negation laws can help us understand statements, consider the statement “Everyone who Patricia likes, Sue doesn’t like.” If we let $L(x, y)$ stand for “ x likes y ,” and we let p stand for Patricia and s for Sue, then this statement would be represented by the formula $\forall x(L(p, x) \rightarrow \neg L(s, x))$. Now we can work out a formula equivalent to this one as follows:

$$\forall x(L(p, x) \rightarrow \neg L(s, x))$$

is equivalent to $\forall x(\neg L(p, x) \vee \neg L(s, x))$ (conditional law),

which is equivalent to $\forall x \neg(L(p, x) \wedge L(s, x))$ (De Morgan’s law),

which is equivalent to $\neg \exists x(L(p, x) \wedge L(s, x))$ (quantifier negation law).

Translating the last formula back into English, we get the statement “There’s no one who both Patricia and Sue like,” and this does mean the same thing as the statement we started with.

We saw in Section 2.1 that reversing the order of two quantifiers can sometimes change the meaning of a formula. However, if the quantifiers are the same type (both \forall or both \exists), it turns out the order can always be switched without affecting the meaning of the formula. For example, consider the statement “Someone has a teacher who is younger than he or she is.” To write this symbolically we first write $\exists x(x \text{ has a teacher who is younger than } x)$. Now to say “ x has a teacher who is younger than x ” we write $\exists y(T(y, x) \wedge P(y, x))$, where $T(y, x)$ means “ y is a teacher of x ” and $P(y, x)$ means “ y is younger than x .” Putting this all together, the original statement would be represented by the formula $\exists x \exists y(T(y, x) \wedge P(y, x))$.

Now what happens if we switch the quantifiers? In other words, what does the formula $\exists y \exists x(T(y, x) \wedge P(y, x))$ mean? You should be able to convince yourself that this formula says that there is a person y such that y is a teacher of someone who is older than y . In other words, someone has a student who is older than he or she is. But this would be true in exactly the same circumstances as the original statement, “Someone has a teacher who is younger than he or she is”! Both mean that there are people x and y such that y is a teacher of x and y is younger than x . In fact, this suggests that a good way of reading the pair of quantifiers $\exists y \exists x$ or $\exists x \exists y$ would be “there are objects x and y such that . . .”

Similarly, two universal quantifiers in a row can always be switched without changing the meaning of a formula, because $\forall x \forall y$ and $\forall y \forall x$ can both be thought of as meaning “for all objects x and y , . . .” For example, consider the formula $\forall x \forall y(L(x, y) \rightarrow A(x, y))$, where $L(x, y)$ means “ x likes y ” and $A(x, y)$ means “ x admires y .” You could think of this formula as saying “For

all people x and y , if x likes y then x admires y .” In other words, people always admire the people they like. The formula $\forall y \forall x (L(x, y) \rightarrow A(x, y))$ means exactly the same thing.

It is important to realize that when we say “there are objects x and y ” or “for all objects x and y ,” we are not ruling out the possibility that x and y are the same object. For example, the formula $\forall x \forall y (L(x, y) \rightarrow A(x, y))$ means not just that a person who likes another person always admires that other person, but also that people who like themselves also admire themselves. As another example, suppose we wanted to write a formula that means “ x is a bigamist.” (Of course, x will be a free variable in this formula.) You might think you could express this with the formula $\exists y \exists z (M(x, y) \wedge M(x, z))$, where $M(x, y)$ means “ x is married to y .” But to say that x is a bigamist you must say that there are two *different* people to whom x is married, and this formula doesn’t say that y and z are different. The right answer is $\exists y \exists z (M(x, y) \wedge M(x, z) \wedge y \neq z)$.

Example 2.2.2. Analyze the logical forms of the following statements.

1. All married couples have fights.
2. Everyone likes at least two people.
3. John likes exactly one person.

Solutions

1. $\forall x \forall y (M(x, y) \rightarrow F(x, y))$, where $M(x, y)$ means “ x and y are married to each other” and $F(x, y)$ means “ x and y fight with each other.”
2. $\forall x \exists y \exists z (L(x, y) \wedge L(x, z) \wedge y \neq z)$, where $L(x, y)$ stands for “ x likes y .” Note that the statement means that everyone likes at least two *different* people, so it would be incorrect to leave out the “ $y \neq z$ ” at the end.
3. Let $L(x, y)$ mean “ x likes y ,” and let j stand for John. We translate this statement into symbols gradually:
 - (i) $\exists x$ (John likes x and John doesn’t like anyone other than x).
 - (ii) $\exists x (L(j, x) \wedge \neg \exists y (\text{John likes } y \text{ and } y \neq x))$.
 - (iii) $\exists x (L(j, x) \wedge \neg \exists y (L(j, y) \wedge y \neq x))$.

Note that for the third statement in this example we could not have given the simpler answer $\exists x L(j, x)$, because this would mean that John likes *at least* one person, not *exactly one* person. The phrase *exactly one* occurs so often in mathematics that there is a special notation for it. We will write $\exists! x P(x)$ to represent the statement “There is exactly one value of x such that $P(x)$ is true.” It is sometimes also read “There is a unique x such that $P(x)$.” For

example, the third statement in Example 2.2.2 could be written symbolically as $\exists! xL(j, x)$. In fact, we could think of this as just an abbreviation for the formula given in Example 2.2.2 as the answer for statement 3. Similarly, in general we can think of $\exists! xP(x)$ as an abbreviation for the formula $\exists x(P(x) \wedge \neg \exists y(P(y) \wedge y \neq x))$.

Recall that when we were discussing set theory, we sometimes found it useful to write the truth set of $P(x)$ as $\{x \in U \mid P(x)\}$ rather than $\{x \mid P(x)\}$, to make sure it was clear what the universe of discourse was. Similarly, instead of writing $\forall xP(x)$ to indicate that $P(x)$ is true for every value of x in some universe U , we might write $\forall x \in U P(x)$. This is read “For all x in U , $P(x)$.” Similarly, we can write $\exists x \in U P(x)$ to say that there is at least one value of x in the universe U such that $P(x)$ is true. For example, the statement $\forall x(x \geq 0)$ would be false if the universe of discourse were the real numbers, but true if it were the natural numbers. We could avoid confusion when discussing this statement by writing either $\forall x \in \mathbb{R}(x \geq 0)$ or $\forall x \in \mathbb{N}(x \geq 0)$, to make it clear which we meant.

As before, we sometimes use this notation not to specify the universe of discourse but to restrict attention to a subset of the universe. For example, if our universe of discourse is the real numbers and we want to say that some real number x has a square root, we could write $\exists y(y^2 = x)$. To say that every positive real number has a square root, we would say $\forall x \in \mathbb{R}^+ \exists y(y^2 = x)$. We could say that every positive real number has a negative square root by writing $\forall x \in \mathbb{R}^+ \exists y \in \mathbb{R}^- (y^2 = x)$. In general, for any set A , the formula $\forall x \in A P(x)$ means that for every value of x in the set A , $P(x)$ is true, and $\exists x \in A P(x)$ means that there is at least one value of x in the set A such that $P(x)$ is true. The quantifiers in these formulas are sometimes called *bounded quantifiers*, because they place *bounds* on which values of x are to be considered. Occasionally we may use variations on this notation to place other kinds of restrictions on quantified variables. For example, the statement that every positive real number has a negative square root could also be written $\forall x > 0 \exists y < 0 (y^2 = x)$.

Formulas containing bounded quantifiers can also be thought of as abbreviations for more complicated formulas containing only normal, unbounded quantifiers. To say that $\exists x \in A P(x)$ means that there is some value of x that is in A and that also makes $P(x)$ come out true, and another way to write this would be $\exists x(x \in A \wedge P(x))$. Similarly, you should convince yourself that $\forall x \in A P(x)$ means the same thing as $\forall x(x \in A \rightarrow P(x))$. For example, the formula $\forall x \in \mathbb{R}^+ \exists y \in \mathbb{R}^- (y^2 = x)$ discussed earlier means the same thing as $\forall x(x \in \mathbb{R}^+ \rightarrow \exists y \in \mathbb{R}^- (y^2 = x))$, which in turn can be expanded as $\forall x(x \in \mathbb{R}^+ \rightarrow \exists y(y \in \mathbb{R}^- \wedge y^2 = x))$. By the definitions of \mathbb{R}^+ and \mathbb{R}^- ,

an equivalent way to say this would be $\forall x(x > 0 \rightarrow \exists y(y < 0 \wedge y^2 = x))$. You should make sure you are convinced that this formula, like the original formula, means that every positive real number has a negative square root. For another example, note that the statement $A \subseteq B$, which by definition means $\forall x(x \in A \rightarrow x \in B)$, could also be written as $\forall x \in A(x \in B)$.

It is interesting to note that the quantifier negation laws work for bounded quantifiers as well. In fact, we can derive these bounded quantifier negation laws from the original laws by thinking of the bounded quantifiers as abbreviations, as described earlier. For example,

$$\begin{aligned} \neg \forall x \in A P(x) & \\ & \text{is equivalent to } \neg \forall x(x \in A \rightarrow P(x)) \quad (\text{expanding abbreviation}), \\ & \text{which is equivalent to } \exists x \neg(x \in A \rightarrow P(x)) \quad (\text{quantifier negation law}), \\ & \text{which is equivalent to } \exists x \neg(x \notin A \vee P(x)) \quad (\text{conditional law}), \\ & \text{which is equivalent to } \exists x(x \in A \wedge \neg P(x)) \quad (\text{De Morgan's law}), \\ & \text{which is equivalent to } \exists x \in A \neg P(x) \quad (\text{abbreviation}). \end{aligned}$$

Thus, we have shown that $\neg \forall x \in A P(x)$ is equivalent to $\exists x \in A \neg P(x)$. You are asked in exercise 5 to prove the other bounded quantifier negation law, that $\neg \exists x \in A P(x)$ is equivalent to $\forall x \in A \neg P(x)$.

It should be clear that if $A = \emptyset$ then $\exists x \in A P(x)$ will be false no matter what the statement $P(x)$ is. There can be nothing in A that, when plugged in for x , makes $P(x)$ come out true, because there is nothing in A at all! It may not be so clear whether $\forall x \in A P(x)$ should be considered true or false, but we can find the answer using the quantifier negation laws:

$$\begin{aligned} \forall x \in A P(x) & \\ & \text{is equivalent to } \neg \neg \forall x \in A P(x) \quad (\text{double negation law}), \\ & \text{which is equivalent to } \neg \exists x \in A \neg P(x) \quad (\text{quantifier negation law}). \end{aligned}$$

Now if $A = \emptyset$ then this last formula will be true, no matter what the statement $P(x)$ is, because, as we have seen, $\exists x \in A \neg P(x)$ must be false. Thus, $\forall x \in A P(x)$ is always true if $A = \emptyset$. Mathematicians sometimes say that such a statement is *vacuously* true. Another way to see this is to rewrite the statement $\forall x \in A P(x)$ in the equivalent form $\forall x(x \in A \rightarrow P(x))$. Now according to the truth table for the conditional connective, the only way this can be false is if there is some value of x such that $x \in A$ is true but $P(x)$ is false. But there is no such value of x , simply because there isn't a value of x for which $x \in A$ is true.

As an application of this principle, we note that the empty set is a subset of every set. To see why, just rewrite the statement $A \subseteq B$ in the equivalent form $\forall x \in A (x \in B)$. Now if $A = \emptyset$ then, as we have just observed, this statement will be vacuously true. Thus, no matter what the set B is, $\emptyset \subseteq B$. Another example of a vacuously true statement is the statement “All unicorns are purple.” We could represent this by the formula $\forall x \in A P(x)$, where A is the set of all unicorns and $P(x)$ stands for “ x is purple.” Since there are no unicorns, A is the empty set, so the statement is vacuously true. (Notice that the statement “All unicorns are green” is also true – which does not contradict the fact that all unicorns are purple!)

Perhaps you have noticed by now that, although in Chapter 1 we were always able to check equivalences involving logical connectives by making truth tables, we have no such simple way of checking equivalences involving quantifiers. So far, we have justified our equivalences involving quantifiers by just looking at examples and using common sense. As the formulas we work with get more complicated, this method will become unreliable and difficult to use. Fortunately, in Chapter 3 we will develop better methods for reasoning about statements involving quantifiers. To get more practice in thinking about quantifiers, we will work out a few somewhat more complicated equivalences using common sense. If you’re not completely convinced that these equivalences are right, you’ll be able to check them more carefully when you get to Chapter 3.

Consider the statement “Everyone is bright-eyed and bushy-tailed.” If we let $E(x)$ mean “ x is bright-eyed” and $T(x)$ mean “ x is bushy-tailed,” then we could represent this statement by the formula $\forall x (E(x) \wedge T(x))$. Is this equivalent to the formula $\forall x E(x) \wedge \forall x T(x)$? This latter formula means “Everyone is bright-eyed, and also everyone is bushy-tailed,” and intuitively this means the same thing as the original statement. Thus, it appears that $\forall x (E(x) \wedge T(x))$ is equivalent to $\forall x E(x) \wedge \forall x T(x)$. In other words, we could say that the universal quantifier *distributes over* conjunction.

However, the corresponding distributive law doesn’t work for the existential quantifier. Consider the formulas $\exists x (E(x) \wedge T(x))$ and $\exists x E(x) \wedge \exists x T(x)$. The first means that there is someone who is both bright-eyed and bushy-tailed, and the second means that there is someone who is bright-eyed, and there is also someone who is bushy-tailed. These don’t mean the same thing at all. In the second statement the bright-eyed person and the bushy-tailed person don’t have to be the same, but in the first statement they do. Another way to see the difference between the two statements is to think about truth sets. Let A be the truth set of $E(x)$ and B the truth set of $T(x)$. In other words, A is the set of bright-eyed people, and B is the set of bushy-tailed people. Then the second

statement says that neither A nor B is the empty set, but the first says that $A \cap B$ is not the empty set, or in other words that A and B are not disjoint.

As an application of the distributive law for the universal quantifier and conjunction, suppose A and B are sets and consider the equation $A = B$. We know that two sets are equal when they have exactly the same elements. Thus, the equation $A = B$ means $\forall x(x \in A \leftrightarrow x \in B)$, which is equivalent to $\forall x[(x \in A \rightarrow x \in B) \wedge (x \in B \rightarrow x \in A)]$. Because the universal quantifier distributes over conjunction, this is equivalent to the formula $\forall x(x \in A \rightarrow x \in B) \wedge \forall x(x \in B \rightarrow x \in A)$, and by the definition of subset this means $A \subseteq B \wedge B \subseteq A$. Thus, we have shown that the equation $A = B$ is also equivalent to the formula $A \subseteq B \wedge B \subseteq A$.

We have now introduced seven basic logical symbols: the connectives \wedge , \vee , \neg , \rightarrow , and \leftrightarrow , and the quantifiers \forall and \exists . It is a remarkable fact that the structure of all mathematical statements can be understood using these symbols, and all mathematical reasoning can be analyzed in terms of the proper use of these symbols. To illustrate the power of the symbols we have introduced, we conclude this section by writing out a few more mathematical statements in logical notation.

Example 2.2.3. Analyze the logical forms of the following statements.

1. Statements about the natural numbers. The universe of discourse is \mathbb{N} .
 - (a) x is a perfect square.
 - (b) x is a multiple of y .
 - (c) x is prime.
 - (d) x is the smallest positive number that is a multiple of both y and z .
2. Statements about the real numbers. The universe of discourse is \mathbb{R} .
 - (a) The identity element for addition is 0.
 - (b) Every real number has an additive inverse.
 - (c) Negative numbers don't have square roots.
 - (d) Every positive number has exactly two square roots.

Solutions

1. (a) This means that x is the square of some natural number, or in other words $\exists y(x = y^2)$.
- (b) This means that x is equal to y times some natural number, or in other words $\exists z(x = yz)$.
- (c) This means that $x > 1$, and x cannot be written as a product of two smaller natural numbers. In symbols: $x > 1 \wedge \neg \exists y \exists z(x = yz \wedge y < x \wedge z < x)$.

- (d) We translate this in several steps:
- (i) x is positive and x is a multiple of both y and z and there is no smaller positive number that is a multiple of both y and z .
 - (ii) $x > 0 \wedge \exists a(x = ya) \wedge \exists b(x = zb) \wedge \neg \exists w(w > 0 \wedge w < x \wedge (w$ is a multiple of both y and $z))$.
 - (iii) $x > 0 \wedge \exists a(x = ya) \wedge \exists b(x = zb) \wedge \neg \exists w(w > 0 \wedge w < x \wedge \exists c(w = yc) \wedge \exists d(w = zd))$.
2. (a) $\forall x(x + 0 = x)$.
- (b) $\forall x \exists y(x + y = 0)$.
- (c) $\forall x(x < 0 \rightarrow \neg \exists y(y^2 = x))$.
- (d) We translate this gradually:
- (i) $\forall x(x > 0 \rightarrow x$ has exactly two square roots).
 - (ii) $\forall x(x > 0 \rightarrow \exists y \exists z(y$ and z are square roots of x and $y \neq z$ and nothing else is a square root of $x))$.
 - (iii) $\forall x(x > 0 \rightarrow \exists y \exists z(y^2 = x \wedge z^2 = x \wedge y \neq z \wedge \neg \exists w(w^2 = x \wedge w \neq y \wedge w \neq z)))$.

Exercises

- *1. Negate these statements and then reexpress the results as equivalent positive statements. (See Example 2.2.1.)
- (a) Everyone who is majoring in math has a friend who needs help with his or her homework.
 - (b) Everyone has a roommate who dislikes everyone.
 - (c) $A \cup B \subseteq C \setminus D$.
 - (d) $\exists x \forall y [y > x \rightarrow \exists z(z^2 + 5z = y)]$.
2. Negate these statements and then reexpress the results as equivalent positive statements. (See Example 2.2.1.)
- (a) There is someone in the freshman class who doesn't have a roommate.
 - (b) Everyone likes someone, but no one likes everyone.
 - (c) $\forall a \in A \exists b \in B(a \in C \leftrightarrow b \in C)$.
 - (d) $\forall y > 0 \exists x(ax^2 + bx + c = y)$.
3. Are these statements true or false? The universe of discourse is \mathbb{N} .
- (a) $\forall x(x < 7 \rightarrow \exists a \exists b \exists c(a^2 + b^2 + c^2 = x))$.
 - (b) $\exists! x(x^2 + 3 = 4x)$.
 - (c) $\exists! x(x^2 = 4x + 5)$.
 - (d) $\exists x \exists y(x^2 = 4x + 5 \wedge y^2 = 4y + 5)$.

- *4. Show that the second quantifier negation law, which says that $\neg\forall x P(x)$ is equivalent to $\exists x \neg P(x)$, can be derived from the first, which says that $\neg\exists x P(x)$ is equivalent to $\forall x \neg P(x)$. (Hint: Use the double negation law.)
5. Show that $\neg\exists x \in A P(x)$ is equivalent to $\forall x \in A \neg P(x)$.
- *6. Show that the existential quantifier distributes over disjunction. In other words, show that $\exists x(P(x) \vee Q(x))$ is equivalent to $\exists x P(x) \vee \exists x Q(x)$. (Hint: Use the fact, discussed in this section, that the universal quantifier distributes over conjunction.)
7. Show that $\exists x(P(x) \rightarrow Q(x))$ is equivalent to $\forall x P(x) \rightarrow \exists x Q(x)$.
- *8. Show that $(\forall x \in A P(x)) \wedge (\forall x \in B P(x))$ is equivalent to $\forall x \in (A \cup B) P(x)$. (Hint: Start by writing out the meanings of the bounded quantifiers in terms of unbounded quantifiers.)
9. Is $\forall x(P(x) \vee Q(x))$ equivalent to $\forall x P(x) \vee \forall x Q(x)$? Explain. (Hint: Try assigning meanings to $P(x)$ and $Q(x)$.)
10. (a) Show that $\exists x \in A P(x) \vee \exists x \in B P(x)$ is equivalent to $\exists x \in (A \cup B) P(x)$.
 (b) Is $\exists x \in A P(x) \wedge \exists x \in B P(x)$ equivalent to $\exists x \in (A \cap B) P(x)$? Explain.
- *11. Show that the statements $A \subseteq B$ and $A \setminus B = \emptyset$ are equivalent by writing each in logical symbols and then showing that the resulting formulas are equivalent.
12. Show that the statements $C \subseteq A \cup B$ and $C \setminus A \subseteq B$ are equivalent by writing each in logical symbols and then showing that the resulting formulas are equivalent.
13. (a) Show that the statements $A \subseteq B$ and $A \cup B = B$ are equivalent by writing each in logical symbols and then showing that the resulting formulas are equivalent. (Hint: You may find exercise 11 from Section 1.5 useful.)
 (b) Show that the statements $A \subseteq B$ and $A \cap B = A$ are equivalent.
- *14. Show that the statements $A \cap B = \emptyset$ and $A \setminus B = A$ are equivalent.
15. Let $T(x, y)$ mean “ x is a teacher of y .” What do the following statements mean? Under what circumstances would each one be true? Are any of them equivalent to each other?
- (a) $\exists! y T(x, y)$.
 (b) $\exists x \exists! y T(x, y)$.
 (c) $\exists! x \exists y T(x, y)$.
 (d) $\exists y \exists! x T(x, y)$.
 (e) $\exists! x \exists! y T(x, y)$.
 (f) $\exists x \exists y [T(x, y) \wedge \neg \exists u \exists v (T(u, v) \wedge (u \equiv x \vee v \equiv y))]$.

2.3. More Operations on Sets

Now that we know how to work with quantifiers, we are ready to discuss some more advanced topics in set theory.

So far, the only way we have to define sets, other than listing their elements one by one, is to use the elementhood test notation $\{x \mid P(x)\}$. Sometimes this notation is modified by allowing the x before the vertical line to be replaced with a more complex expression. For example, suppose we wanted to define S to be the set of all perfect squares. Perhaps the easiest way to describe this set is to say that it consists of all numbers of the form n^2 , where n is a natural number. This is written $S = \{n^2 \mid n \in \mathbb{N}\}$. Note that, using our solution for the first statement from Example 2.2.3, we could also define this set by writing $S = \{x \mid \exists n \in \mathbb{N}(x = n^2)\}$. Thus, $\{n^2 \mid n \in \mathbb{N}\} = \{x \mid \exists n \in \mathbb{N}(x = n^2)\}$ and therefore $x \in \{n^2 \mid n \in \mathbb{N}\}$ means the same thing as $\exists n \in \mathbb{N}(x = n^2)$.

Similar notation is often used if the elements of a set have been numbered. For example, suppose we wanted to form the set whose elements are the first 100 prime numbers. We might start by numbering the prime numbers, calling them p_1, p_2, p_3, \dots . In other words, $p_1 = 2, p_2 = 3, p_3 = 5$, and so on. Then the set we are looking for would be the set $P = \{p_1, p_2, p_3, \dots, p_{100}\}$. Another way of describing this set would be to say that it consists of all numbers p_i , for i an element of the set $I = \{1, 2, 3, \dots, 100\} = \{i \in \mathbb{N} \mid 1 \leq i \leq 100\}$. This could be written $P = \{p_i \mid i \in I\}$. Each element p_i in this set is identified by a number $i \in I$, called the *index* of the element. A set defined in this way is sometimes called an *indexed family*, and I is called the *index set*.

Although the indices for an indexed family are often numbers, they need not be. For example, suppose S is the set of all students at your school. If we wanted to form the set of all mothers of students, we might let m_s stand for the mother of s , for any student s . Then the set of all mothers of students could be written $M = \{m_s \mid s \in S\}$. This is an indexed family in which the index set is S , the set of all students. Each mother in the set is identified by naming the student who is her child. Note that we could also define this set using an elementhood test, by writing $M = \{m \mid m \text{ is the mother of some student}\} = \{m \mid \exists s \in S(m = m_s)\}$. In general, any indexed family $A = \{x_i \mid i \in I\}$ can also be defined as $A = \{x \mid \exists i \in I(x = x_i)\}$. It follows that the statement $x \in \{x_i \mid i \in I\}$ means the same thing as $\exists i \in I(x = x_i)$.

Example 2.3.1. Analyze the logical forms of the following statements by writing out the definitions of the set theory notation used.

1. $y \in \{\sqrt[3]{x} \mid x \in \mathbb{Q}\}$.
2. $\{x_i \mid i \in I\} \subseteq A$.
3. $\{n^2 \mid n \in \mathbb{N}\}$ and $\{n^3 \mid n \in \mathbb{N}\}$ are not disjoint.

Solutions

1. $\exists x \in \mathbb{Q}(y = \sqrt[3]{x})$.
2. By the definition of subset we must say that every element of $\{x_i \mid i \in I\}$ is also an element of A , so we could start by writing $\forall x(x \in \{x_i \mid i \in I\} \rightarrow x \in A)$. Filling in the meaning of $x \in \{x_i \mid i \in I\}$, which we worked out earlier, we would end up with $\forall x(\exists i \in I(x = x_i) \rightarrow x \in A)$. But since the elements of $\{x_i \mid i \in I\}$ are just the x_i 's, for all $i \in I$, perhaps an easier way of saying that every element of $\{x_i \mid i \in I\}$ is an element of A would be $\forall i \in I(x_i \in A)$. The two answers we have given are equivalent, but showing this would require the methods we will be studying in Chapter 3.
3. We must say that the two sets have a common element, so one solution is to start by writing $\exists x(x \in \{n^2 \mid n \in \mathbb{N}\} \wedge x \in \{n^3 \mid n \in \mathbb{N}\})$. However, as in the last statement, there is an easier way. An element common to the two sets would have to be the square of some natural number and also the cube of some (possibly different) natural number. Thus, we could say that there is such a common element by saying $\exists n \in \mathbb{N} \exists m \in \mathbb{N}(n^2 = m^3)$. Note that it would be wrong to write $\exists n \in \mathbb{N}(n^2 = n^3)$, because this wouldn't allow for the possibility of the two natural numbers being different. By the way, this statement is true, since $64 = 8^2 = 4^3$, so 64 is an element of both sets.

Anything at all can be an element of a set. Some interesting and useful ideas arise when we consider the possibility of a set having *other sets* as elements. For example, suppose $A = \{1, 2, 3\}$, $B = \{4\}$, and $C = \emptyset$. There is no reason why we couldn't form the set $\mathcal{F} = \{A, B, C\}$, whose elements are the three sets A , B , and C . Filling in the definitions of A , B , and C , we could write this in another way: $\mathcal{F} = \{\{1, 2, 3\}, \{4\}, \emptyset\}$. Note that $1 \in A$ and $A \in \mathcal{F}$ but $1 \notin \mathcal{F}$. \mathcal{F} has only three elements, and all three of them are sets, not numbers. Sets such as \mathcal{F} , whose elements are all sets, are sometimes called *families* of sets.

It is often convenient to define families of sets as indexed families. For example, suppose we again let S stand for the set of all students, and for each student s we let C_s be the set of courses that s has taken. Then the collection of all of these sets C_s would be an indexed family of sets $\mathcal{F} = \{C_s \mid s \in S\}$. Remember that the elements of this family are not courses but *sets* of courses.

If we let t stand for some particular student Tina, and if Tina has taken Calculus, English Composition, and American History, then $C_t = \{\text{Calculus, English Composition, American History}\}$ and $C_t \in \mathcal{F}$, but Calculus $\notin \mathcal{F}$.

An important example of a family of sets is given by the power set of a set.

Definition 2.3.2. Suppose A is a set. The *power set* of A , denoted $\mathcal{P}(A)$, is the set whose elements are all the subsets of A . In other words,

$$\mathcal{P}(A) = \{x \mid x \subseteq A\}.$$

For example, the set $A = \{7, 12\}$ has four subsets: \emptyset , $\{7\}$, $\{12\}$, and $\{7, 12\}$. Thus, $\mathcal{P}(A) = \{\emptyset, \{7\}, \{12\}, \{7, 12\}\}$. What about $\mathcal{P}(\emptyset)$? Although \emptyset has no elements, it does have one subset, namely \emptyset . Thus, $\mathcal{P}(\emptyset) = \{\emptyset\}$. Note that, as we saw in Section 1.3, $\{\emptyset\}$ is not the same as \emptyset .

Any time you are working with some subsets of a set X , it may be helpful to remember that all of these subsets of X are elements of $\mathcal{P}(X)$, by the definition of power set. For example, if we let C be the set of all courses offered at your school, then each of the sets C_s discussed earlier is a subset of C . Thus, for each student s , $C_s \in \mathcal{P}(C)$. This means that every element of the family $\mathcal{F} = \{C_s \mid s \in S\}$ is an element of $\mathcal{P}(C)$, so $\mathcal{F} \subseteq \mathcal{P}(C)$.

Example 2.3.3. Analyze the logical forms of the following statements.

1. $x \in \mathcal{P}(A)$.
2. $\mathcal{P}(A) \subseteq \mathcal{P}(B)$.
3. $B \in \{\mathcal{P}(A) \mid A \in \mathcal{F}\}$.
4. $x \in \mathcal{P}(A \cap B)$.
5. $x \in \mathcal{P}(A) \cap \mathcal{P}(B)$.

Solutions

1. By the definition of power set, the elements of $\mathcal{P}(A)$ are the subsets of A . Thus, to say that $x \in \mathcal{P}(A)$ means that $x \subseteq A$, which we already know can be written as $\forall y(y \in x \rightarrow y \in A)$.
2. By the definition of subset, this means $\forall x(x \in \mathcal{P}(A) \rightarrow x \in \mathcal{P}(B))$. Now, writing out $x \in \mathcal{P}(A)$ and $x \in \mathcal{P}(B)$ as before, we get $\forall x[\forall y(y \in x \rightarrow y \in A) \rightarrow \forall y(y \in x \rightarrow y \in B)]$.
3. As before, this means $\exists A \in \mathcal{F}(B = \mathcal{P}(A))$. Now, to say that $B = \mathcal{P}(A)$ means that the elements of B are precisely the subsets of A , or in other words $\forall x(x \in B \leftrightarrow x \subseteq A)$. Filling this in, and writing out the definition

of subset, we get our final answer, $\exists A \in \mathcal{F} \forall x(x \in B \leftrightarrow \forall y(y \in x \rightarrow y \in A))$.

4. As in the first statement, we start by writing this as $\forall y(y \in x \rightarrow y \in A \cap B)$. Now, filling in the definition of intersection, we get $\forall y(y \in x \rightarrow (y \in A \wedge y \in B))$.
5. By the definition of intersection, this means $(x \in \mathcal{P}(A)) \wedge (x \in \mathcal{P}(B))$. Now, writing out the definition of power set as before, we get $\forall y(y \in x \rightarrow y \in A) \wedge \forall y(y \in x \rightarrow y \in B)$.

Note that for statement 5 in this example we first wrote out the definition of intersection and then used the definition of power set, whereas in statement 4 we started by writing out the definition of power set and then used the definition of intersection. As you learn the definitions of more mathematical terms and symbols, it will become more important to be able to choose which definition to think about first when working out the meaning of a complex mathematical statement. A good rule of thumb is to always start with the “outermost” symbol. In statement 4 in Example 2.3.3, the intersection symbol occurred inside the power set notation, so we wrote out the definition of power set first. In statement 5, the power set notation occurred within both sides of the notation for the intersection of two sets, so we started with the definition of intersection. Similar considerations led us to use the definition of subset first, rather than power set, in statement 2.

It is interesting to note that our answers for statements 4 and 5 in Example 2.3.3 are equivalent. (You are asked to verify this in exercise 11.) As in Section 1.4, it follows that for any sets A and B , $\mathcal{P}(A \cap B) = \mathcal{P}(A) \cap \mathcal{P}(B)$. You are asked in exercise 12 to show that this equation is not true in general if we change \cap to \cup .

Consider once again the family of sets $\mathcal{F} = \{C_s \mid s \in S\}$, where S is the set of all students and for each student s , C_s is the set of all courses that s has taken. If we wanted to know which courses had been taken by all students, we would need to find those elements that all the sets in \mathcal{F} have in common. The set of all these common elements is called the intersection of the family \mathcal{F} and is written $\bigcap \mathcal{F}$. Similarly, the union of the family \mathcal{F} , written $\bigcup \mathcal{F}$, is the set resulting from throwing all the elements of all the sets in \mathcal{F} together into one set. In this case, $\bigcup \mathcal{F}$ would be the set of all courses that had been taken by any student.

Example 2.3.4. Let $\mathcal{F} = \{\{1, 2, 3, 4\}, \{2, 3, 4, 5\}, \{3, 4, 5, 6\}\}$. Find $\bigcap \mathcal{F}$ and $\bigcup \mathcal{F}$.

Solution

$$\bigcap \mathcal{F} = \{1, 2, 3, 4\} \cap \{2, 3, 4, 5\} \cap \{3, 4, 5, 6\} = \{3, 4\},$$

$$\bigcup \mathcal{F} = \{1, 2, 3, 4\} \cup \{2, 3, 4, 5\} \cup \{3, 4, 5, 6\} = \{1, 2, 3, 4, 5, 6\}.$$

Although these examples may make it clear what we mean by $\bigcap \mathcal{F}$ and $\bigcup \mathcal{F}$, we still have not given careful definitions for these sets. In general, if \mathcal{F} is any family of sets, then we want $\bigcap \mathcal{F}$ to contain the elements that all the sets in \mathcal{F} have in common. Thus, to be an element of $\bigcap \mathcal{F}$, an object will have to be an element of every set in \mathcal{F} . On the other hand, anything that is an element of any of the sets in \mathcal{F} should be in $\bigcup \mathcal{F}$, so to be in $\bigcup \mathcal{F}$ an object only needs to be an element of at least one set in \mathcal{F} . Thus, we are led to the following general definitions.

Definition 2.3.5. Suppose \mathcal{F} is a family of sets. Then the *intersection* and *union* of \mathcal{F} are the sets $\bigcap \mathcal{F}$ and $\bigcup \mathcal{F}$ defined as follows:

$$\bigcap \mathcal{F} = \{x \mid \forall A \in \mathcal{F} (x \in A)\} = \{x \mid \forall A (A \in \mathcal{F} \rightarrow x \in A)\}.$$

$$\bigcup \mathcal{F} = \{x \mid \exists A \in \mathcal{F} (x \in A)\} = \{x \mid \exists A (A \in \mathcal{F} \wedge x \in A)\}.$$

Some mathematicians consider $\bigcap \mathcal{F}$ to be undefined if $\mathcal{F} = \emptyset$. For an explanation of the reason for this, see exercise 15. We will use the notation $\bigcap \mathcal{F}$ only when $\mathcal{F} \neq \emptyset$.

Notice that if A and B are any two sets and $\mathcal{F} = \{A, B\}$, then $\bigcap \mathcal{F} = A \cap B$ and $\bigcup \mathcal{F} = A \cup B$. Thus, the definitions of intersection and union of a family of sets are actually generalizations of our old definitions of the intersection and union of two sets.

Example 2.3.6. Analyze the logical forms of the following statements.

1. $x \in \bigcap \mathcal{F}$.
2. $\bigcap \mathcal{F} \not\subseteq \bigcup \mathcal{G}$.
3. $x \in \mathcal{P}(\bigcup \mathcal{F})$.
4. $x \in \bigcup \{\mathcal{P}(A) \mid A \in \mathcal{F}\}$.

Solutions

1. By the definition of the intersection of a family of sets, this means $\forall A \in \mathcal{F} (x \in A)$, or equivalently, $\forall A (A \in \mathcal{F} \rightarrow x \in A)$.
2. As we saw in Example 2.2.1, to say that one set is not a subset of another means that there is something that is an element of the first but not the

- second. Thus, we start by writing $\exists x(x \in \bigcap \mathcal{F} \wedge x \notin \bigcup \mathcal{G})$. We have already written out what $x \in \bigcap \mathcal{F}$ means in solution 1. By the definition of the union of a family of sets, $x \in \bigcup \mathcal{G}$ means $\exists A \in \mathcal{G}(x \in A)$, so $x \notin \bigcup \mathcal{G}$ means $\neg \exists A \in \mathcal{G}(x \in A)$. By the quantifier negation laws, this is equivalent to $\forall A \in \mathcal{G}(x \notin A)$. Putting this all together, our answer is $\exists x[\forall A \in \mathcal{F}(x \in A) \wedge \forall A \in \mathcal{G}(x \notin A)]$.
3. Because the union symbol occurs within the power set notation, we start by writing out the definition of power set. As in Example 2.3.3, we get $x \subseteq \bigcup \mathcal{F}$, or in other words $\forall y(y \in x \rightarrow y \in \bigcup \mathcal{F})$. Now we use the definition of union to write out $y \in \bigcup \mathcal{F}$ as $\exists A \in \mathcal{F}(y \in A)$. The final answer is $\forall y(y \in x \rightarrow \exists A \in \mathcal{F}(y \in A))$.
 4. This time we start by writing out the definition of union. According to this definition, the statement means that x is an element of at least one of the sets $\mathcal{P}(A)$, for $A \in \mathcal{F}$. In other words, $\exists A \in \mathcal{F}(x \in \mathcal{P}(A))$. Inserting our analysis of the statement $x \in \mathcal{P}(A)$ from Example 2.3.3, we get $\exists A \in \mathcal{F} \forall y(y \in x \rightarrow y \in A)$.

Writing complex mathematical statements in logical symbols, as we did in the last example, may sometimes help you understand what the statements mean and whether they are true or false. For example, suppose that we once again let C_s be the set of all courses that have been taken by student s . Let M be the set of math majors and E the set of English majors, and let $\mathcal{F} = \{C_s \mid s \in M\}$ and $\mathcal{G} = \{C_s \mid s \in E\}$. With these definitions, what does statement 2 of Example 2.3.6 mean, and under what circumstances would it be true? According to our solution for this example, the statement means $\exists x[\forall A \in \mathcal{F}(x \in A) \wedge \forall A \in \mathcal{G}(x \notin A)]$, or in other words, there is something that is an element of each set in \mathcal{F} , and that fails to be an element of each set in \mathcal{G} . Taking into account the definitions of \mathcal{F} and \mathcal{G} that we are using, this means that there is some course that has been taken by all of the math majors but none of the English majors. If, for example, all of the math majors have taken Calculus but none of the English majors have, then the statement would be true.

As another example, suppose $\mathcal{F} = \{\{1, 2, 3\}, \{2, 3, 4\}, \{3, 4, 5\}\}$, and $x = \{4, 5, 6\}$. With these definitions, would statement 3 of Example 2.3.6 be true? You could determine this by finding $\mathcal{P}(\bigcup \mathcal{F})$ and then checking to see if x is an element of it, but this would take a very long time, because it turns out that $\mathcal{P}(\bigcup \mathcal{F})$ has 32 elements. It is easier to use the translation into logical symbols given in our solution for this example. According to that translation, the statement means $\forall y(y \in x \rightarrow \exists A \in \mathcal{F}(y \in A))$; in other words, every element of x is in at least one set in \mathcal{F} . Looking back at our definitions of \mathcal{F}

and x , it is not hard to see that this is false, because $6 \in x$, but 6 is not in any of the sets in \mathcal{F} .

An alternative notation is sometimes used for the union or intersection of an indexed family of sets. Suppose $\mathcal{F} = \{A_i \mid i \in I\}$, where each A_i is a set. Then $\bigcap \mathcal{F}$ would be the set of all elements common to all the A_i 's, for $i \in I$, and this can also be written as $\bigcap_{i \in I} A_i$. In other words,

$$\bigcap \mathcal{F} = \bigcap_{i \in I} A_i = \{x \mid \forall i \in I (x \in A_i)\}.$$

Similarly, an alternative notation for $\bigcup \mathcal{F}$ is $\bigcup_{i \in I} A_i$, so

$$\bigcup \mathcal{F} = \bigcup_{i \in I} A_i = \{x \mid \exists i \in I (x \in A_i)\}.$$

Returning to our example of courses taken by students, we could use this notation to write the set of courses taken by all students as $\bigcap_{s \in S} C_s$. You could think of this notation as denoting the result of running through all of the elements s in S , forming the set C_s for each of them, and then intersecting all of these sets.

Example 2.3.7. Let $I = \{1, 2, 3\}$, and for each $i \in I$ let $A_i = \{i, i + 1, i + 2, i + 3\}$. Find $\bigcap_{i \in I} A_i$ and $\bigcup_{i \in I} A_i$.

Solution

First we list the elements of the sets A_i , for $i \in I$:

$$A_1 = \{1, 2, 3, 4\}, \quad A_2 = \{2, 3, 4, 5\}, \quad A_3 = \{3, 4, 5, 6\}.$$

Then

$$\bigcap_{i \in I} A_i = A_1 \cap A_2 \cap A_3 = \{1, 2, 3, 4\} \cap \{2, 3, 4, 5\} \cap \{3, 4, 5, 6\} = \{3, 4\},$$

and similarly

$$\bigcup_{i \in I} A_i = \{1, 2, 3, 4\} \cup \{2, 3, 4, 5\} \cup \{3, 4, 5, 6\} = \{1, 2, 3, 4, 5, 6\}.$$

In fact, we can now see that the question asked in this example is exactly the same as the one in Example 2.3.4, but with different notation.

Example 2.3.8. For this example our universe of discourse will be the set S of all students. Let $L(x, y)$ stand for “ x likes y ” and $A(x, y)$ for “ x admires y .” For each student s , let L_s be the set of all students that s likes. In other

words $L_s = \{t \in S \mid L(s, t)\}$. Similarly, let $A_s = \{t \in S \mid A(s, t)\}$ = the set of all students that s admires. Describe the following sets.

1. $\bigcap_{s \in S} L_s$.
2. $\bigcup_{s \in S} L_s$.
3. $\bigcup_{s \in S} L_s \setminus \bigcup_{s \in S} A_s$.
4. $\bigcup_{s \in S} (L_s \setminus A_s)$.
5. $(\bigcap_{s \in S} L_s) \cap (\bigcap_{s \in S} A_s)$.
6. $\bigcap_{s \in S} (L_s \cap A_s)$.
7. $\bigcup_{b \in B} L_b$, where $B = \bigcap_{s \in S} A_s$.

Solutions

First of all, note that in general, $t \in L_s$ means the same thing as $L(s, t)$, and similarly $t \in A_s$ means $A(s, t)$.

1. $\bigcap_{s \in S} L_s = \{t \mid \forall s \in S (t \in L_s)\} = \{t \in S \mid \forall s \in S L(s, t)\}$ = the set of all students who are liked by all students.
2. $\bigcup_{s \in S} L_s = \{t \mid \exists s \in S (t \in L_s)\} = \{t \in S \mid \exists s \in S L(s, t)\}$ = the set of all students who are liked by at least one student.
3. As we saw in solution 2, $\bigcup_{s \in S} L_s$ = the set of all students who are liked by at least one student. Similarly, $\bigcup_{s \in S} A_s$ = the set of all students who are admired by at least one student. Thus $\bigcup_{s \in S} L_s \setminus \bigcup_{s \in S} A_s = \{t \mid t \in \bigcup_{s \in S} L_s \text{ and } t \notin \bigcup_{s \in S} A_s\}$ = the set of all students who are liked by at least one student, but are not admired by any students.
4. $\bigcup_{s \in S} (L_s \setminus A_s) = \{t \mid \exists s \in S (t \in L_s \setminus A_s)\} = \{t \in S \mid \exists s \in S (L(s, t) \wedge \neg A(s, t))\}$ = the set of all students t such that some student likes t , but doesn't admire t . Note that this is different from the set in part 3. For a student t to be in this set, there must be a student who likes t but doesn't admire t , but there could be other students who admire t . To be in the set in part 3, t must be admired by *nobody*.
5. $(\bigcap_{s \in S} L_s) \cap (\bigcap_{s \in S} A_s) = \{t \mid t \in \bigcap_{s \in S} L_s \text{ and } t \in \bigcap_{s \in S} A_s\} = \{t \mid \forall s \in S (t \in L_s) \wedge \forall s \in S (t \in A_s)\} = \{t \in S \mid \forall s \in S L(s, t) \wedge \forall s \in S A(s, t)\}$ = the set of all students who are liked by all students and also admired by all students.
6. $\bigcap_{s \in S} (L_s \cap A_s) = \{t \mid \forall s \in S (t \in L_s \cap A_s)\} = \{t \in S \mid \forall s \in S (L(s, t) \wedge A(s, t))\}$ = the set of all students who are both liked and admired by all students. This is the same as the set in part 5. In fact, you can use the distributive law for universal quantification and conjunction to show that the elementhood tests for the two sets are equivalent.

7. $\bigcup_{b \in B} L_b = \{t \mid \exists b \in B(t \in L_b)\} = \{t \in S \mid \exists b(b \in B \wedge L(b, t))\}$.
 But B was defined to be the set of all students who are admired by all students, so $b \in B$ means $b \in S \wedge \forall s \in S A(s, b)$. Inserting this, we get
 $\bigcup_{b \in B} L_b = \{t \in S \mid \exists b(b \in S \wedge \forall s \in S A(s, b) \wedge L(b, t))\} =$ the set of all students who are liked by some student who is admired by all students.

Exercises

- *1. Analyze the logical forms of the following statements. You may use the symbols $\in, \notin, =, \neq, \wedge, \vee, \rightarrow, \leftrightarrow, \forall$, and \exists in your answers, but not $\subseteq, \not\subseteq, \mathcal{P}, \cap, \cup, \setminus, \{, \}$, or \neg . (Thus, you must write out the definitions of some set theory notation, and you must use equivalences to get rid of any occurrences of \neg .)
- $\mathcal{F} \subseteq \mathcal{P}(A)$.
 - $A \subseteq \{2n + 1 \mid n \in \mathbb{N}\}$.
 - $\{n^2 + n + 1 \mid n \in \mathbb{N}\} \subseteq \{2n + 1 \mid n \in \mathbb{N}\}$.
 - $\mathcal{P}(\bigcup_{i \in I} A_i) \not\subseteq \bigcup_{i \in I} \mathcal{P}(A_i)$.
2. Analyze the logical forms of the following statements. You may use the symbols $\in, \notin, =, \neq, \wedge, \vee, \rightarrow, \leftrightarrow, \forall$, and \exists in your answers, but not $\subseteq, \not\subseteq, \mathcal{P}, \cap, \cup, \setminus, \{, \}$, or \neg . (Thus, you must write out the definitions of some set theory notation, and you must use equivalences to get rid of any occurrences of \neg .)
- $x \in \bigcup \mathcal{F} \setminus \bigcup \mathcal{G}$.
 - $\{x \in B \mid x \notin C\} \in \mathcal{P}(A)$.
 - $x \in \bigcap_{i \in I} (A_i \cup B_i)$.
 - $x \in (\bigcap_{i \in I} A_i) \cup (\bigcap_{i \in I} B_i)$.
3. We've seen that $\mathcal{P}(\emptyset) = \{\emptyset\}$, and $\{\emptyset\} \neq \emptyset$. What is $\mathcal{P}(\{\emptyset\})$?
- *4. Suppose $\mathcal{F} = \{\{\text{red, green, blue}\}, \{\text{orange, red, blue}\}, \{\text{purple, red, green, blue}\}\}$. Find $\bigcap \mathcal{F}$ and $\bigcup \mathcal{F}$.
5. Suppose $\mathcal{F} = \{\{3, 7, 12\}, \{5, 7, 16\}, \{5, 12, 23\}\}$. Find $\bigcap \mathcal{F}$ and $\bigcup \mathcal{F}$.
6. Let $I = \{2, 3, 4, 5\}$, and for each $i \in I$ let $A_i = \{i, i + 1, i - 1, 2i\}$.
- List the elements of all the sets A_i , for $i \in I$.
 - Find $\bigcap_{i \in I} A_i$ and $\bigcup_{i \in I} A_i$.
7. Let $P = \{\text{Johann Sebastian Bach, Napoleon Bonaparte, Johann Wolfgang von Goethe, David Hume, Wolfgang Amadeus Mozart, Isaac Newton, George Washington}\}$ and let $Y = \{1750, 1751, 1752, \dots, 1759\}$. For each $y \in Y$, let $A_y = \{p \in P \mid \text{the person } p \text{ was alive at some time during the year } y\}$. Find $\bigcup_{y \in Y} A_y$ and $\bigcap_{y \in Y} A_y$.

- *8. Let $I = \{2, 3\}$, and for each $i \in I$ let $A_i = \{i, 2i\}$ and $B_i = \{i, i + 1\}$.
- List the elements of the sets A_i and B_i for $i \in I$.
 - Find $\bigcap_{i \in I} (A_i \cup B_i)$ and $(\bigcap_{i \in I} A_i) \cup (\bigcap_{i \in I} B_i)$. Are they the same?
 - In parts (c) and (d) of exercise 2 you analyzed the statements $x \in \bigcap_{i \in I} (A_i \cup B_i)$ and $x \in (\bigcap_{i \in I} A_i) \cup (\bigcap_{i \in I} B_i)$. What can you conclude from your answer to part (b) about whether or not these statements are equivalent?
9. (a) Analyze the logical forms of the statements $x \in \bigcup_{i \in I} (A_i \setminus B_i)$, $x \in (\bigcup_{i \in I} A_i) \setminus (\bigcup_{i \in I} B_i)$, and $x \in (\bigcup_{i \in I} A_i) \setminus (\bigcap_{i \in I} B_i)$. Do you think that any of these statements are equivalent to each other?
- (b) Let I , A_i , and B_i be defined as in exercise 8. Find $\bigcup_{i \in I} (A_i \setminus B_i)$, $(\bigcup_{i \in I} A_i) \setminus (\bigcup_{i \in I} B_i)$, and $(\bigcup_{i \in I} A_i) \setminus (\bigcap_{i \in I} B_i)$. Now do you think any of the statements in part (a) are equivalent?
10. Give an example of an index set I and indexed families of sets $\{A_i \mid i \in I\}$ and $\{B_i \mid i \in I\}$ such that $\bigcup_{i \in I} (A_i \cap B_i) \neq (\bigcup_{i \in I} A_i) \cap (\bigcup_{i \in I} B_i)$.
11. Show that for any sets A and B , $\mathcal{P}(A \cap B) = \mathcal{P}(A) \cap \mathcal{P}(B)$, by showing that the statements $x \in \mathcal{P}(A \cap B)$ and $x \in \mathcal{P}(A) \cap \mathcal{P}(B)$ are equivalent. (See Example 2.3.3.)
- *12. Give examples of sets A and B for which $\mathcal{P}(A \cup B) \neq \mathcal{P}(A) \cup \mathcal{P}(B)$.
13. Verify the following identities by writing out (using logical symbols) what it means for an object x to be an element of each set and then using logical equivalences.
- $\bigcup_{i \in I} (A_i \cup B_i) = (\bigcup_{i \in I} A_i) \cup (\bigcup_{i \in I} B_i)$.
 - $(\bigcap \mathcal{F}) \cap (\bigcap \mathcal{G}) = \bigcap (\mathcal{F} \cup \mathcal{G})$.
 - $\bigcap_{i \in I} (A_i \setminus B_i) = (\bigcap_{i \in I} A_i) \setminus (\bigcup_{i \in I} B_i)$.
- *14. Sometimes each set in an indexed family of sets has *two* indices. For this problem, use the following definitions: $I = \{1, 2\}$, $J = \{3, 4\}$. For each $i \in I$ and $j \in J$, let $A_{i,j} = \{i, j, i + j\}$. Thus, for example, $A_{2,3} = \{2, 3, 5\}$.
- For each $j \in J$ let $B_j = \bigcup_{i \in I} A_{i,j} = A_{1,j} \cup A_{2,j}$. Find B_3 and B_4 .
 - Find $\bigcap_{j \in J} B_j$. (Note that, replacing B_j with its definition, we could say that $\bigcap_{j \in J} B_j = \bigcap_{j \in J} (\bigcup_{i \in I} A_{i,j})$.)
 - Find $\bigcup_{i \in I} (\bigcap_{j \in J} A_{i,j})$. (Hint: You may want to do this in two steps, corresponding to parts (a) and (b).) Are $\bigcap_{j \in J} (\bigcup_{i \in I} A_{i,j})$ and $\bigcup_{i \in I} (\bigcap_{j \in J} A_{i,j})$ equal?
 - Analyze the logical forms of the statements $x \in \bigcap_{j \in J} (\bigcup_{i \in I} A_{i,j})$ and $x \in \bigcup_{i \in I} (\bigcap_{j \in J} A_{i,j})$. Are they equivalent?
15. (a) Show that if $\mathcal{F} = \emptyset$, then the statement $x \in \bigcup \mathcal{F}$ will be false no matter what x is. It follows that $\bigcup \emptyset = \emptyset$.

- (b) Show that if $\mathcal{F} = \emptyset$, then the statement $x \in \bigcap \mathcal{F}$ will be true no matter what x is. In a context in which it is clear what the universe of discourse U is, we might therefore want to say that $\bigcap \emptyset = U$. However, this has the unfortunate consequence that the notation $\bigcap \emptyset$ will mean different things in different contexts. Furthermore, when working with sets whose elements are sets, mathematicians often do not use a universe of discourse at all. (For more on this, see the next exercise.) For these reasons, some mathematicians consider the notation $\bigcap \emptyset$ to be meaningless. We will avoid this problem in this book by using the notation $\bigcap \mathcal{F}$ only in contexts in which we can be sure that $\mathcal{F} \neq \emptyset$.
16. In Section 2.3 we saw that a set can have other sets as elements. When discussing sets whose elements are sets, it might seem most natural to consider the universe of discourse to be the set of all sets. However, as we will see in this problem, assuming that there is such a set leads to contradictions.
- Suppose U were the set of all sets. Note that in particular U is a set, so we would have $U \in U$. This is not yet a contradiction; although most sets are not elements of themselves, perhaps some sets are elements of themselves. But it suggests that the sets in the universe U could be split into two categories: the unusual sets that, like U itself, are elements of themselves, and the more typical sets that are not. Let R be the set of sets in the second category. In other words, $R = \{A \in U \mid A \notin A\}$. This means that for any set A in the universe U , A will be an element of R iff $A \notin A$. In other words, we have $\forall A \in U (A \in R \leftrightarrow A \notin A)$.
- (a) Show that applying this last fact to the set R itself (in other words, plugging in R for A) leads to a contradiction. This contradiction was discovered by Bertrand Russell (1872–1970) in 1901, and is known as *Russell's paradox*.
- (b) Think some more about the paradox in part (a). What do you think it tells us about sets?

3

Proofs

3.1. Proof Strategies

Mathematicians are skeptical people. They use many methods, including experimentation with examples, trial and error, and guesswork, to try to find answers to mathematical questions, but they are generally not convinced that an answer is correct unless they can prove it. You have probably seen some mathematical proofs before (there were some examples in the introduction), but you may not have any experience writing them yourself. In this chapter you'll learn more about how proofs are put together, so you can start writing your own proofs.

Proofs are a lot like jigsaw puzzles. There are no rules about how jigsaw puzzles must be solved. The only rule concerns the final product: all the pieces must fit together, and the picture must look right. The same holds for proofs.

Although there are no rules about how jigsaw puzzles must be solved, some techniques for solving them work better than others. For example, you'd never do a jigsaw puzzle by filling in every *other* piece, and then going back and filling in the holes! But you also don't do it by starting at the top and filling in the pieces in order until you reach the bottom. You probably fill in the border first, and then gradually put other chunks of the puzzle together and figure out where they go. Sometimes you try to put pieces in the wrong places, realize that they don't fit, and feel that you're not making any progress. And every once in a while you see, in a satisfying flash, how two big chunks fit together and feel that you've suddenly made a lot of progress. As the pieces of the puzzle fall into place, a picture emerges. You suddenly realize that the patch of blue you've been putting together is a lake, or part of the sky. But it's only when the puzzle is complete that you can see the whole picture.

Similar things could be said about the process of figuring out a proof. And I think one more similarity should be mentioned. When you finish a jigsaw

puzzle, you don't take it apart right away, do you? You probably leave it out for a day or two, so you can admire it. You should do the same thing with a proof. You figured out how to fit it together yourself, and once it's all done, isn't it pretty?

In this chapter we will discuss the proof-writing techniques that mathematicians use most often and explain how to use them to begin writing proofs yourself. Understanding these techniques may also help you read and understand proofs written by other people. Unfortunately, the techniques in this chapter do not give a step-by-step procedure for solving every proof problem. When trying to write a proof you may make a few false starts before finding the right way to proceed, and some proofs may require some cleverness or insight. With practice your proof-writing skills should improve, and you'll be able to tackle more and more challenging proofs.

Mathematicians usually state the answer to a mathematical question in the form of a *theorem* that says that if certain assumptions called the *hypotheses* of the theorem are true, then some conclusion must also be true. Often the hypotheses and conclusion contain free variables, and in this case it is understood that these variables can stand for any elements of the universe of discourse. An assignment of particular values to these variables is called an *instance* of the theorem, and in order for the theorem to be correct it must be the case that for every instance of the theorem that makes the hypotheses come out true, the conclusion is also true. If there is even one instance in which the hypotheses are true but the conclusion is false, then the theorem is incorrect. Such an instance is called a *counterexample* to the theorem.

Example 3.1.1. Consider the following theorem:

Theorem. *Suppose $x > 3$ and $y < 2$. Then $x^2 - 2y > 5$.*

This theorem is correct. (You are asked to prove it in exercise 15.) The hypotheses of the theorem are $x > 3$ and $y < 2$, and the conclusion is $x^2 - 2y > 5$. As an instance of the theorem, we could plug in 5 for x and 1 for y . Clearly with these values of the variables the hypotheses $x > 3$ and $y < 2$ are both true, so the theorem tells us that the conclusion $x^2 - 2y > 5$ must also be true. In fact, plugging in the values of x and y we find that $x^2 - 2y = 25 - 2 = 23$, and certainly $23 > 5$. Note that this calculation does not constitute a proof of the theorem. We have only checked one instance of the theorem, and a proof would have to show that *all* instances are correct.

If we drop the second hypothesis, then we get an incorrect theorem:

Incorrect Theorem. *Suppose $x > 3$. Then $x^2 - 2y > 5$.*

We can see that this theorem is incorrect by finding a counterexample. For example, suppose we let $x = 4$ and $y = 6$. Then the only remaining hypothesis, $x > 3$, is true, but $x^2 - 2y = 16 - 12 = 4$, so the conclusion $x^2 - 2y > 5$ is false.

If you find a counterexample to a theorem, then you can be sure that the theorem is incorrect, but the only way to know for sure that a theorem is correct is to prove it. A proof of a theorem is simply a deductive argument whose premises are the hypotheses of the theorem and whose conclusion is the conclusion of the theorem. Throughout the proof, we think of any free variables in the hypotheses and conclusion of the theorem as standing for some particular but unspecified elements of the universe of discourse. In other words, we imagine that we are reasoning about some instance of the theorem, but we don't actually choose a particular instance; the reasoning in the proof should apply to all instances. Of course the argument should be valid, so we can be sure that if the hypotheses of the theorem are true for any instance, then the conclusion will be true for that instance as well.

How you figure out and write up the proof of a theorem will depend mostly on the logical form of the conclusion. Often it will also depend on the logical forms of the hypotheses. The proof-writing techniques we will discuss in this chapter will tell you which proof strategies are most likely to work for various forms of hypotheses and conclusions.

Proof-writing techniques that are based on the logical forms of the hypotheses usually suggest ways of drawing inferences from the hypotheses. When you draw an inference from the hypotheses, you use the assumption that the hypotheses are true to justify the assertion that some other statement is also true. Once you have shown that a statement is true, you can use it later in the proof exactly as if it were a hypothesis. Perhaps the most important rule to keep in mind when drawing such inferences is this: *Never assert anything until you can justify it completely* using the hypotheses or using conclusions reached from them earlier in the proof. Your motto should be: "I shall make no assertion before its time." Following this rule will prevent you from using circular reasoning or jumping to conclusions and will guarantee that, if the hypotheses are true, then the conclusion must also be true. And this is the primary purpose of any proof: to provide a guarantee that the conclusion is true if the hypotheses are.

To make sure your assertions are adequately justified, you must be skeptical about every inference in your proof. If there is any doubt in your mind about whether the justification you have given for an assertion is adequate, then it isn't. After all, if your own reasoning doesn't even convince *you*, how can you expect it to convince anybody else?

Proof-writing techniques based on the logical form of the conclusion are often somewhat different from techniques based on the forms of the hypotheses. They usually suggest ways of transforming the problem into one that is equivalent but easier to solve. The idea of solving a problem by transforming it into an easier problem should be familiar to you. For example, adding the same number to both sides of an equation transforms the equation into an equivalent equation, and the resulting equation is sometimes easier to solve than the original one. Students who have studied calculus may be familiar with techniques of evaluating integrals, such as substitution or integration by parts, that can be used to transform a difficult integration problem into an easier one.

Proofs that are written using these transformation strategies often include steps in which you assume for the sake of argument that some statement is true without providing any justification for that assumption. It may seem at first that such reasoning would violate the rule that assertions must always be justified, but it doesn't, because *assuming* something is not the same as *asserting* it. To assert a statement is to claim that it is true, and such a claim is never acceptable in a proof unless it can be justified. However, the purpose of making an assumption in a proof is not to make a claim about what *is* true, but rather to enable you to find out what *would be* true if the assumption were correct. You must always keep in mind that any conclusion you reach that is based on an assumption might turn out to be false if the assumption is incorrect. Whenever you make a statement in a proof, it's important to be sure you know whether it's an assertion or an assumption.

Perhaps an example will help clarify this. Suppose that during the course of a proof you decide to assume that some statement, call it P , is true, and you use this assumption to conclude that another statement Q is true. It would be wrong to call this a proof that Q is true, because you can't be sure that your assumption about the truth of P was correct. All you can conclude at this point is that *if* P is true, then you can be sure that Q is true as well. In other words, you know that the statement $P \rightarrow Q$ is true. If the conclusion of the theorem being proven was Q , then the proof is incomplete at best. But if the conclusion was $P \rightarrow Q$, then the proof is complete. This brings us to our first proof strategy.

To prove a conclusion of the form $P \rightarrow Q$:

Assume P is true and then prove Q .

Here's another way of looking at what this proof technique means. Assuming that P is true amounts to the same thing as adding P to your list of hypotheses. Although P might not originally have been one of your

hypotheses, once you have assumed it, you can use it exactly the way you would use any other hypothesis. Proving Q means treating Q as your conclusion and forgetting about the original conclusion. So this technique says that if the conclusion of the theorem you are trying to prove has the form $P \rightarrow Q$, then you can *transform the problem* by adding P to your list of hypotheses and changing your conclusion from $P \rightarrow Q$ to Q . This gives you a new, perhaps easier proof problem to work on. If you can solve the new problem, then you will have shown that *if* P is true then Q is also true, thus solving the original problem of proving $P \rightarrow Q$. How you solve this new problem will now be guided by the logical form of the new conclusion Q (which might itself be a complex statement), and perhaps also by the logical form of the new hypothesis P .

Note that this technique doesn't tell you how to do the whole proof, it just gives you one step, leaving you with a new problem to solve in order to finish the proof. Proofs are usually not written all at once, but are created gradually by applying several proof techniques one after another. Often the use of these techniques will lead you to transform the problem several times. In discussing this process it will be helpful to have some way to keep track of the results of this sequence of transformations. We therefore introduce the following terminology. We will refer to the statements that are known or assumed to be true at some point in the course of figuring out a proof as *givens*, and the statement that remains to be proven at that point as the *goal*. When you are starting to figure out a proof, the givens will be just the hypotheses of the theorem you are proving, but they may later include other statements that have been inferred from the hypotheses or added as new assumptions as the result of some transformation of the problem. The goal will initially be the conclusion of the theorem, but it may be changed several times in the course of figuring out a proof.

To keep in mind that all of our proof strategies apply not only to the original proof problem but also to the results of any transformation of the problem, we will talk from now on only about givens and goals, rather than hypotheses and conclusions, when discussing proof-writing strategies. For example, the strategy stated earlier should really be called a strategy for proving a *goal* of the form $P \rightarrow Q$, rather than a conclusion of this form. Even if the conclusion of the theorem you are proving is not a conditional statement, if you transform the problem in such a way that a conditional statement becomes the goal, then you can apply this strategy as the next step in figuring out the proof.

Example 3.1.2. Suppose a and b are real numbers. Prove that if $0 < a < b$ then $a^2 < b^2$.

Scratch work

We are given as a hypothesis that a and b are real numbers. Our conclusion has the form $P \rightarrow Q$, where P is the statement $0 < a < b$ and Q is the statement $a^2 < b^2$. Thus we start with these statements as given and goal:

<i>Givens</i>	<i>Goal</i>
a and b are real numbers	$(0 < a < b) \rightarrow (a^2 < b^2)$

According to our proof technique we should assume that $0 < a < b$ and try to use this assumption to prove that $a^2 < b^2$. In other words, we transform the problem by adding $0 < a < b$ to the list of givens and making $a^2 < b^2$ our goal:

<i>Givens</i>	<i>Goal</i>
a and b are real numbers	$a^2 < b^2$
$0 < a < b$	

Comparing the inequalities $a < b$ and $a^2 < b^2$ suggests that multiplying both sides of the given inequality $a < b$ by either a or b might get us closer to our goal. Because we are given that a and b are positive, we won't need to reverse the direction of the inequality if we do this. Multiplying $a < b$ by a gives us $a^2 < ab$, and multiplying it by b gives us $ab < b^2$. Thus $a^2 < ab < b^2$, so $a^2 < b^2$.

Solution

Theorem. *Suppose a and b are real numbers. If $0 < a < b$ then $a^2 < b^2$.*

Proof. Suppose $0 < a < b$. Multiplying the inequality $a < b$ by the positive number a we can conclude that $a^2 < ab$, and similarly multiplying by b we get $ab < b^2$. Therefore $a^2 < ab < b^2$, so $a^2 < b^2$, as required. Thus, if $0 < a < b$ then $a^2 < b^2$. □

As you can see from the preceding example, there's a difference between the reasoning you use when you are figuring out a proof and the steps you write down when you write the final version of the proof. In particular, although we will often talk about givens and goals when trying to figure out a proof, the final write-up will generally not refer to them. Throughout this chapter, and sometimes in later chapters as well, we will precede our proofs with the scratch work used to figure out the proof, but this is just to help you understand how proofs are constructed. When mathematicians write proofs, they usually just write the steps needed to justify their conclusions with no explanation of

how they thought of them. Some of these steps will be sentences indicating that the problem has been transformed (usually according to some proof strategy based on the logical form of the goal); some steps will be assertions that are justified by inferences from the givens (often using some proof strategy based on the logical form of a given). However, there will usually be no explanation of how the mathematician thought of these transformations and inferences. For example, the proof in Example 3.1.2 starts with the sentence “Suppose $0 < a < b$,” indicating that the problem has been transformed according to our strategy, and then proceeds with a sequence of inferences leading to the conclusion that $a^2 < b^2$. No other explanations were necessary to justify the final conclusion, in the last sentence, that if $0 < a < b$ then $a^2 < b^2$.

Although this lack of explanation sometimes makes proofs hard to read, it serves the purpose of keeping two distinct objectives separate: *explaining your thought processes* and *justifying your conclusions*. The first is psychology; the second, mathematics. The primary purpose of a proof is to justify the claim that the conclusion follows from the hypotheses, and no explanation of your thought processes can substitute for adequate justification of this claim. Keeping any discussion of thought processes to a minimum in a proof helps to keep this distinction clear. Occasionally, in a very complicated proof, a mathematician may include some discussion of the strategy behind the proof to make the proof easier to read. Usually, however, it is up to readers to figure this out for themselves. Don’t worry if you don’t immediately understand the strategy behind a proof you are reading. Just try to follow the justifications of the steps, and the strategy will eventually become clear. If it doesn’t, a second reading of the proof might help.

To keep the distinction between the proof and the strategy behind the proof clear, in the future when we state a proof strategy we will often describe both the scratch work you might use to figure out the proof and the form that the final write-up of the proof should take. For example, here’s a restatement of the proof strategy we discussed earlier, in the form we will be using to present proof strategies from now on.

To prove a goal of the form $P \rightarrow Q$:

Assume P is true and then prove Q .

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
—	$P \rightarrow Q$
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
—	Q
—	
P	

Form of final proof:

Suppose P .

[Proof of Q goes here.]

Therefore $P \rightarrow Q$.

Note that the suggested form for the final proof tells you how the beginning and end of the proof will go, but more steps will have to be added in the middle. The givens and goal list under the heading “After using strategy” tells you what is known or can be assumed and what needs to be proven in order to fill in this gap in the proof. Many of our proof strategies will tell you how to write either the beginning or the end of your proof, leaving a gap to be filled in with further reasoning.

There is a second method that is sometimes used for proving goals of the form $P \rightarrow Q$. Because any conditional statement $P \rightarrow Q$ is equivalent to its contrapositive $\neg Q \rightarrow \neg P$, you can prove $P \rightarrow Q$ by proving $\neg Q \rightarrow \neg P$ instead, using the strategy discussed earlier. In other words:

To prove a goal of the form $P \rightarrow Q$:

Assume Q is false and prove that P is false.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
—	$P \rightarrow Q$
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
—	$\neg P$
—	
$\neg Q$	

Form of final proof:

Suppose Q is false.

[Proof of $\neg P$ goes here.]

Therefore $P \rightarrow Q$.

Example 3.1.3. Suppose $a, b,$ and c are real numbers and $a > b$. Prove that if $ac \leq bc$ then $c \leq 0$.

Scratch work

<i>Givens</i>	<i>Goal</i>
$a, b,$ and c are real numbers	$(ac \leq bc) \rightarrow (c \leq 0)$
$a > b$	

The contrapositive of the goal is $\neg(c \leq 0) \rightarrow \neg(ac \leq bc)$, or in other words $(c > 0) \rightarrow (ac > bc)$, so we can prove it by adding $c > 0$ to the list of givens and making $ac > bc$ our new goal:

<i>Givens</i>	<i>Goal</i>
$a, b,$ and c are real numbers	$ac > bc$
$a > b$	
$c > 0$	

We can also now write the first and last sentences of the proof. According to the strategy, the final proof should have this form:

Suppose $c > 0$.

[Proof of $ac > bc$ goes here.]

Therefore, if $ac \leq bc$ then $c \leq 0$.

Using the new given $c > 0$, we see that the goal $ac > bc$ follows immediately from the given $a > b$ by multiplying both sides by the positive number c . Inserting this step between the first and last sentences completes the proof.

Solution

Theorem. Suppose $a, b,$ and c are real numbers and $a > b$. If $ac \leq bc$ then $c \leq 0$.

Proof. We will prove the contrapositive. Suppose $c > 0$. Then we can multiply both sides of the given inequality $a > b$ by c and conclude that $ac > bc$. Therefore, if $ac \leq bc$ then $c \leq 0$. \square

Notice that, although we have used the symbols of logic freely in the scratch work, we have not used them in the final write-up of the proof. Although it would not be incorrect to use logical symbols in a proof, mathematicians usually try to avoid it. Using the notation and rules of logic can be very helpful when you are figuring out the strategy for a proof, but in the final write-up you should try to stick to ordinary English as much as possible.

You may be wondering how we knew in Example 3.1.3 that we should use the second method for proving a goal of the form $P \rightarrow Q$ rather than the first. The answer is simple: we tried both methods, and the second worked. When there is more than one strategy for proving a goal of a particular form, you may have to try a few different strategies before you hit on one that works. With practice, you will get better at guessing which strategy is most likely to work for a particular proof.

Notice that in each of the examples we have given, our strategy involved making changes in our givens and goal to try to make the problem easier. The beginning and end of the proof, which were supplied for us in the statement of the proof technique, serve to tell a reader of the proof that these changes have been made and how the solution to this revised problem solves the original problem. The rest of the proof contains the solution to this easier, revised problem.

Most of the other proof techniques in this chapter also suggest that you revise your givens and goal in some way. These revisions result in a new proof problem, and in every case the revisions have been designed so that a solution to the new problem, when combined with some beginning or ending sentences explaining these revisions, would also solve the original problem. This means that whenever you use one of these strategies you can write a sentence or two at the beginning or end of the proof and then forget about the original problem and work instead on the new problem, which will usually be easier. Often you will be able to figure out a proof by using the techniques in this chapter to revise your givens and goal repeatedly, making the remaining problem easier and easier until you reach a point at which it is completely obvious that the goal follows from the givens.

Exercises

- *1. Consider the following theorem. (This theorem was proven in the introduction.)

Theorem. *Suppose n is an integer larger than 1 and n is not prime. Then $2^n - 1$ is not prime.*

- (a) Identify the hypotheses and conclusion of the theorem. Are the hypotheses true when $n = 6$? What does the theorem tell you in this instance? Is it right?
 - (b) What can you conclude from the theorem in the case $n = 15$? Check directly that this conclusion is correct.
 - (c) What can you conclude from the theorem in the case $n = 11$?
2. Consider the following theorem. (The theorem is correct, but we will not ask you to prove it here.)

Theorem. Suppose that $b^2 > 4ac$. Then the quadratic equation $ax^2 + bx + c = 0$ has exactly two real solutions.

- (a) Identify the hypotheses and conclusion of the theorem.
 - (b) To give an instance of the theorem, you must specify values for a , b , and c , but not x . Why?
 - (c) What can you conclude from the theorem in the case $a = 2$, $b = -5$, $c = 3$? Check directly that this conclusion is correct.
 - (d) What can you conclude from the theorem in the case $a = 2$, $b = 4$, $c = 3$?
3. Consider the following incorrect theorem:

Incorrect Theorem. Suppose n is a natural number larger than 2, and n is not a prime number. Then $2n + 13$ is not a prime number.

What are the hypotheses and conclusion of this theorem? Show that the theorem is incorrect by finding a counterexample.

- *4. Complete the following alternative proof of the theorem in Example 3.1.2.

Proof. Suppose $0 < a < b$. Then $b - a > 0$.

[Fill in a proof of $b^2 - a^2 > 0$ here.]

Since $b^2 - a^2 > 0$, it follows that $a^2 < b^2$. Therefore if $0 < a < b$ then $a^2 < b^2$. □

5. Suppose a and b are real numbers. Prove that if $a < b < 0$ then $a^2 > b^2$.
 6. Suppose a and b are real numbers. Prove that if $0 < a < b$ then $1/b < 1/a$.
 7. Suppose that a is a real number. Prove that if $a^3 > a$ then $a^5 > a$. (Hint: One approach is to start by completing the following equation: $a^5 - a = (a^3 - a) \cdot \underline{\quad ? \quad}$.)
- *8. Suppose $A \setminus B \subseteq C \cap D$ and $x \in A$. Prove that if $x \notin D$ then $x \in B$.

9. Suppose $A \cap B \subseteq C \setminus D$. Prove that if $x \in A$, then if $x \in D$ then $x \notin B$.
- *10. Suppose a and b are real numbers. Prove that if $a < b$ then $(a + b)/2 < b$.
11. Suppose x is a real number and $x \neq 0$. Prove that if $(\sqrt[3]{x} + 5)/(x^2 + 6) = 1/x$ then $x \neq 8$.
- *12. Suppose a, b, c , and d are real numbers, $0 < a < b$, and $d > 0$. Prove that if $ac \geq bd$ then $c > d$.
13. Suppose x and y are real numbers, and $3x + 2y \leq 5$. Prove that if $x > 1$ then $y < 1$.
14. Suppose that x and y are real numbers. Prove that if $x^2 + y = -3$ and $2x - y = 2$ then $x = -1$.
- *15. Prove the first theorem in Example 3.1.1. (Hint: You might find it useful to apply the theorem from Example 3.1.2.)
16. Consider the following theorem.

Theorem. Suppose x is a real number and $x \neq 4$. If $(2x - 5)/(x - 4) = 3$ then $x = 7$.

- (a) What's wrong with the following proof of the theorem?

Proof. Suppose $x = 7$. Then $(2x - 5)/(x - 4) = (2(7) - 5)/(7 - 4) = 9/3 = 3$. Therefore if $(2x - 5)/(x - 4) = 3$ then $x = 7$. \square

- (b) Give a correct proof of the theorem.

17. Consider the following incorrect theorem:

Incorrect Theorem. Suppose that x and y are real numbers and $x \neq 3$. If $x^2y = 9y$ then $y = 0$.

- (a) What's wrong with the following proof of the theorem?

Proof. Suppose that $x^2y = 9y$. Then $(x^2 - 9)y = 0$. Since $x \neq 3$, $x^2 \neq 9$, so $x^2 - 9 \neq 0$. Therefore we can divide both sides of the equation $(x^2 - 9)y = 0$ by $x^2 - 9$, which leads to the conclusion that $y = 0$. Thus, if $x^2y = 9y$ then $y = 0$. \square

- (b) Show that the theorem is incorrect by finding a counterexample.

3.2. Proofs Involving Negations and Conditionals

We turn now to proofs in which the goal has the form $\neg P$. Usually it's easier to prove a positive statement than a negative statement, so it is often helpful to reexpress a goal of the form $\neg P$ before proving it. Instead of trying to prove

a goal that says what *shouldn't* be true, see if you can rephrase it as a goal that says what *should* be true. Fortunately, we have already studied several equivalences that will help with this reexpression. Thus, our first strategy for proving negated statements is:

To prove a goal of the form $\neg P$:

If possible, reexpress the goal in some other form and then use one of the proof strategies for this other goal form.

Example 3.2.1. Suppose $A \cap C \subseteq B$ and $a \in C$. Prove that $a \notin A \setminus B$.

Scratch work

<i>Givens</i>	<i>Goal</i>
$A \cap C \subseteq B$	$a \notin A \setminus B$
$a \in C$	

To prove the goal, we must show that it cannot be the case that $a \in A$ and $a \notin B$. Because this is a negative goal, we try to reexpress it as a positive statement:

$a \notin A \setminus B$ is equivalent to $\neg(a \in A \wedge a \notin B)$ (definition of $A \setminus B$),
 which is equivalent to $a \notin A \vee a \in B$ (De Morgan's law),
 which is equivalent to $a \in A \rightarrow a \in B$ (conditional law).

Rewriting the goal in this way gives us:

<i>Givens</i>	<i>Goal</i>
$A \cap C \subseteq B$	$a \in A \rightarrow a \in B$
$a \in C$	

We now prove the goal in this new form, using the first strategy from Section 3.1. Thus, we add $a \in A$ to our list of givens and make $a \in B$ our goal:

<i>Givens</i>	<i>Goal</i>
$A \cap C \subseteq B$	$a \in B$
$a \in C$	
$a \in A$	

The proof is now easy: from the givens $a \in A$ and $a \in C$ we can conclude that $a \in A \cap C$, and then, since $A \cap C \subseteq B$, it follows that $a \in B$.

Solution

Theorem. Suppose $A \cap C \subseteq B$ and $a \in C$. Then $a \notin A \setminus B$.

Proof. Suppose $a \in A$. Then since $a \in C$, $a \in A \cap C$. But then since $A \cap C \subseteq B$ it follows that $a \in B$. Thus, it cannot be the case that a is an element of A but not B , so $a \notin A \setminus B$. \square

Sometimes a goal of the form $\neg P$ cannot be reexpressed as a positive statement, and therefore this strategy cannot be used. In this case it is usually best to do a *proof by contradiction*. Start by assuming that P is true, and try to use this assumption to prove something that you know is false. Often this is done by proving a statement that contradicts one of the givens. Because you know that the statement you have proven is false, the assumption that P was true must have been incorrect. The only remaining possibility then is that P is false.

To prove a goal of the form $\neg P$:

Assume P is true and try to reach a contradiction. Once you have reached a contradiction, you can conclude that P must be false.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
—	$\neg P$
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
—	Contradiction
—	
P	

Form of final proof:

Suppose P is true.

[Proof of contradiction goes here.]

Thus, P is false.

Example 3.2.2. Prove that if $x^2 + y = 13$ and $y \equiv 4$ then $x \equiv 3$.

Scratch work

The goal is a conditional statement, so according to the first proof strategy in Section 3.1 we can treat the antecedent as given and make the consequent our new goal:

<i>Givens</i>	<i>Goal</i>
$x^2 + y = 13$	$x \neq 3$
$y \neq 4$	

This proof strategy also suggests what form the final proof should take. According to the strategy, the proof should look like this:

Suppose $x^2 + y = 13$ and $y \neq 4$.
 [Proof of $x \neq 3$ goes here.]
 Thus, if $x^2 + y = 13$ and $y \neq 4$ then $x \neq 3$.

In other words, the first and last sentences of the final proof have already been written, and the problem that remains to be solved is to fill in a proof of $x \neq 3$ between these two sentences. The givens–goal list summarizes what we know and what we have to prove in order to solve this problem.

The goal $x \neq 3$ means $\neg(x = 3)$, but because $x = 3$ has no logical connectives in it, none of the equivalences we know can be used to reexpress this goal in a positive form. We therefore try proof by contradiction and transform the problem as follows:

<i>Givens</i>	<i>Goal</i>
$x^2 + y = 13$	Contradiction
$y \neq 4$	
$x = 3$	

Once again, the proof strategy that suggested this transformation also tells us how to fill in a few more sentences of the final proof. As we indicated earlier, these sentences go between the first and last sentences of the proof, which were written before.

Suppose $x^2 + y = 13$ and $y \neq 4$.
 Suppose $x = 3$.
 [Proof of contradiction goes here.]
 Therefore $x \neq 3$.
 Thus, if $x^2 + y = 13$ and $y \neq 4$ then $x \neq 3$.

The indenting in this outline of the proof will not be part of the final proof. We have done it here to make the underlying structure of the proof clear. The first and last lines go together and indicate that we are proving a conditional

statement by assuming the antecedent and proving the consequent. Between these lines is a proof of the consequent, $x \cong 3$, which we have set off from the first and last lines by indenting it. This inner proof has the form of a proof by contradiction, as indicated by its first and last lines. Between these lines we still need to fill in a proof of a contradiction.

At this point we don't have a particular statement as our goal; any impossible conclusion will do. We must therefore look more closely at the givens to see if some of them contradict others. In this case, the first and third together imply that $y = 4$, which contradicts the second.

Solution

Theorem. *If $x^2 + y = 13$ and $y \cong 4$ then $x \cong 3$.*

Proof. Suppose $x^2 + y = 13$ and $y \cong 4$. Suppose $x \neq 3$. Substituting this into the equation $x^2 + y = 13$, we get $9 + y = 13$, so $y = 4$. But this contradicts the fact that $y \cong 4$. Therefore $x \cong 3$. Thus, if $x^2 + y = 13$ and $y \cong 4$ then $x \cong 3$. □

You may be wondering at this point why we were justified in concluding, when we reached a contradiction in the proof, that $x \cong 3$. After all, the second list of givens in our scratch work contained three givens. How could we be sure, when we reached a contradiction, that the culprit was the third given, $x = 3$? To answer this question, look back at the first givens and goal analysis for this example. According to that analysis, there were two givens, $x^2 + y = 13$ and $y \cong 4$, from which we had to deduce the goal $x \cong 3$. Those givens were introduced as assumptions in the first sentence of the proof. Our proof that $x \cong 3$ took place in a context in which those assumptions were in force, as indicated by the indenting in the outline of the proof in our scratch work. Thus, we only had to show that $x \cong 3$ *under the assumption that $x^2 + y = 13$ and $y \cong 4$* . When we reached a contradiction, we didn't need to figure out which of the three statements in the second list of givens was false. We were certainly justified in concluding that *if* neither of the first two was the culprit, then it had to be the third, and that was all that was required to finish the proof.

Proving a goal by contradiction has the advantage that it allows you to assume that your conclusion is false, providing you with another given to work with. But it has the disadvantage that it leaves you with a rather vague goal: produce a contradiction by proving something that you know is false. Because all the proof strategies we have discussed so far depend on analyzing the logical form of the goal, it appears that none of them will help you to

achieve the goal of producing a contradiction. In the preceding proof we were forced to look more closely at our givens to find a contradiction. In this case we did it by proving that $y = 4$, contradicting the given $y \neq 4$. This illustrates a pattern that occurs often in proofs by contradiction: if one of the givens has the form $\neg P$, then you can produce a contradiction by proving P . This is our first strategy based on the logical form of a *given*.

To use a given of the form $\neg P$:

If you're doing a proof by contradiction, try making P your goal. If you can prove P , then the proof will be complete, because P contradicts the given $\neg P$.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
$\neg P$	Contradiction
—	
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
$\neg P$	P
—	
—	

Form of final proof:

[Proof of P goes here.]

Since we already know $\neg P$, this is a contradiction.

Although we have recommended proof by contradiction for proving goals of the form $\neg P$, it can be used for any goal. Usually it's best to try the other strategies first if any of them apply; but if you're stuck, you can try proof by contradiction in any proof.

The next example illustrates this and also another important rule of proof writing: in many cases the logical form of a statement can be discovered by *writing out the definition* of some mathematical word or symbol that occurs in the statement. For this reason, knowing the precise statements of the definitions of all mathematical terms is extremely important when you're writing a proof.

Example 3.2.3. Suppose A , B , and C are sets, $A \setminus B \subseteq C$, and x is anything at all. Prove that if $x \in A \setminus C$ then $x \in B$.

Scratch work

We're given that $A \setminus B \subseteq C$, and our goal is $x \in A \setminus C \rightarrow x \in B$. Because the goal is a conditional statement, our first step is to transform the problem by adding $x \in A \setminus C$ as a second given and making $x \in B$ our goal:

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	$x \in B$
$x \in A \setminus C$	

The form of the final proof will therefore be as follows:

Suppose $x \in A \setminus C$.

[Proof of $x \in B$ goes here.]

Thus, if $x \in A \setminus C$ then $x \in B$.

The goal $x \in B$ contains no logical connectives, so none of the techniques we have studied so far apply, and it is not obvious why the goal follows from the givens. Lacking anything else to do, we try proof by contradiction:

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	Contradiction
$x \in A \setminus C$	
$x \notin B$	

As before, this transformation of the problem also enables us to fill in a few more sentences of the proof:

Suppose $x \in A \setminus C$.

Suppose $x \notin B$.

[Proof of contradiction goes here.]

Therefore $x \in B$.

Thus, if $x \in A \setminus C$ then $x \in B$.

Because we're doing a proof by contradiction and our last given is now a negated statement, we could try using our strategy for using givens of the form $\neg P$. Unfortunately, this strategy suggests making $x \in B$ our goal, which just gets us back to where we started. We must look at the other givens to try to find the contradiction.

In this case, writing out the definition of the second given is the key to the proof, since this definition also contains a negated statement. By definition,

$x \in A \setminus C$ means $x \in A$ and $x \notin C$. Replacing this given by its definition gives us:

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	Contradiction
$x \in A$	
$x \notin C$	
$x \notin B$	

Now the third given also has the form $\neg P$, where P is the statement $x \in C$, so we can apply the strategy for using givens of the form $\neg P$ and make $x \in C$ our goal. Showing that $x \in C$ would complete the proof because it would contradict the given $x \notin C$.

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	$x \in C$
$x \in A$	
$x \notin C$	
$x \notin B$	

Once again, we can add a little more to the proof we are gradually writing by filling in the fact that we plan to derive our contradiction by proving $x \in C$. We also add the definition of $x \in A \setminus C$ to the proof, inserting it in what seems like the most logical place, right after we stated that $x \in A \setminus C$:

Suppose $x \in A \setminus C$. This means that $x \in A$ and $x \notin C$.

Suppose $x \notin B$.

[Proof of $x \in C$ goes here.]

This contradicts the fact that $x \notin C$.

Therefore $x \in B$.

Thus, if $x \in A \setminus C$ then $x \in B$.

We have finally reached a point where the goal follows easily from the givens. From $x \in A$ and $x \notin B$ we conclude that $x \in A \setminus B$. Since $A \setminus B \subseteq C$ it follows that $x \in C$.

Solution

Theorem. Suppose $A, B,$ and C are sets, $A \setminus B \subseteq C,$ and x is anything at all. If $x \in A \setminus C$ then $x \in B$.

Proof. Suppose $x \in A \setminus C$. This means that $x \in A$ and $x \notin C$. Suppose $x \notin B$. Then $x \in A \setminus B$, so since $A \setminus B \subseteq C, x \in C$. But this contradicts the fact that $x \notin C$. Therefore $x \in B$. Thus, if $x \in A \setminus C$ then $x \in B$. □

The strategy we've recommended for using givens of the form $\neg P$ only applies if you are doing a proof by contradiction. For other kinds of proofs, the next strategy can be used. This strategy is based on the fact that givens of the form $\neg P$, like goals of this form, may be easier to work with if they are reexpressed as positive statements.

To use a given of the form $\neg P$:

If possible, reexpress this given in some other form.

We have discussed strategies for working with both givens and goals of the form $\neg P$, but only strategies for goals of the form $P \rightarrow Q$. We now fill this gap by giving two strategies for using givens of the form $P \rightarrow Q$. We said before that many strategies for using givens suggest ways of drawing inferences from the givens. Such strategies are called *rules of inference*. Both of our strategies for using givens of the form $P \rightarrow Q$ are examples of rules of inference.

To use a given of the form $P \rightarrow Q$:

If you are also given P , or if you can prove that P is true, then you can use this given to conclude that Q is true. Since it is equivalent to $\neg Q \rightarrow \neg P$, if you can prove that Q is false, you can use this given to conclude that P is false.

The first of these rules of inference says that if you know that both P and $P \rightarrow Q$ are true, you can conclude that Q must also be true. Logicians call this rule *modus ponens*. We saw this rule used in one of our first examples of valid deductive reasoning in Chapter 1, argument 2 in Example 1.1.1. The validity of this form of reasoning was verified using the truth table for the conditional connective in Section 1.5.

The second rule, called *modus tollens*, says that if you know that $P \rightarrow Q$ is true and Q is false, you can conclude that P must also be false. The validity of this rule can also be checked with truth tables, as you are asked to show in exercise 14. Usually you won't find a given of the form $P \rightarrow Q$ to be much use until you are able to prove either P or $\neg Q$. However, if you ever reach a point in your proof where you have determined that P is true, you should probably use this given immediately to conclude that Q is true. Similarly, if you ever establish $\neg Q$, immediately use this given to conclude $\neg P$.

Although most of our examples will involve specific mathematical statements, occasionally we will do examples of proofs containing letters standing for unspecified statements. Later in this chapter we will be able to use this

method to verify some of the equivalences from Chapter 2 that could only be justified on intuitive grounds before. Here's an example of this kind, illustrating the use of modus ponens and modus tollens.

Example 3.2.4. Suppose $P \rightarrow (Q \rightarrow R)$. Prove that $\neg R \rightarrow (P \rightarrow \neg Q)$.

Scratch work

This could actually be done with a truth table, as you are asked to show in exercise 15, but let's do it using the proof strategies we've been discussing. We start with the following situation:

<i>Givens</i>	<i>Goal</i>
$P \rightarrow (Q \rightarrow R)$	$\neg R \rightarrow (P \rightarrow \neg Q)$

Our only given is a conditional statement. By the rules of inference just discussed, if we knew P we could use modus ponens to conclude $Q \rightarrow R$, and if we knew $\neg(Q \rightarrow R)$ we could use modus tollens to conclude $\neg P$. Because we don't, at this point, know either of these, we can't yet do anything with this given. If either P or $\neg(Q \rightarrow R)$ ever gets added to the givens list, then we should consider using modus ponens or modus tollens. For now, we need to concentrate on the goal.

The goal is also a conditional statement, so we assume the antecedent and set the consequent as our new goal:

<i>Givens</i>	<i>Goal</i>
$P \rightarrow (Q \rightarrow R)$	$P \rightarrow \neg Q$
$\neg R$	

We can also now write a little bit of the proof:

Suppose $\neg R$.

[Proof of $P \rightarrow \neg Q$ goes here.]

Therefore $\neg R \rightarrow (P \rightarrow \neg Q)$.

We still can't do anything with the givens, but the goal is another conditional, so we use the same strategy again:

<i>Givens</i>	<i>Goal</i>
$P \rightarrow (Q \rightarrow R)$	$\neg Q$
$\neg R$	
P	

Now the proof looks like this:

Suppose $\neg R$.
 Suppose P .
 [Proof of $\neg Q$ goes here.]
 Therefore $P \rightarrow \neg Q$.
 Therefore $\neg R \rightarrow (P \rightarrow \neg Q)$.

We've been watching for our chance to use our first given by applying either modus ponens or modus tollens, and now we can do it. Since we know $P \rightarrow (Q \rightarrow R)$ and P , by modus ponens we can infer $Q \rightarrow R$. Any conclusion inferred from the givens can be added to the givens column:

<i>Givens</i>	<i>Goal</i>
$P \rightarrow (Q \rightarrow R)$	$\neg Q$
$\neg R$	
P	
$Q \rightarrow R$	

We also add one more line to the proof:

Suppose $\neg R$.
 Suppose P .
 Since P and $P \rightarrow (Q \rightarrow R)$, it follows that $Q \rightarrow R$.
 [Proof of $\neg Q$ goes here.]
 Therefore $P \rightarrow \neg Q$.
 Therefore $\neg R \rightarrow (P \rightarrow \neg Q)$.

Finally, our last step is to use modus tollens. We now know $Q \rightarrow R$ and $\neg R$, so by modus tollens we can conclude $\neg Q$. This is our goal, so the proof is done.

Solution

Theorem. Suppose $P \rightarrow (Q \rightarrow R)$. Then $\neg R \rightarrow (P \rightarrow \neg Q)$.

Proof. Suppose $\neg R$. Suppose P . Since P and $P \rightarrow (Q \rightarrow R)$, it follows that $Q \rightarrow R$. But then, since $\neg R$, we can conclude $\neg Q$. Thus, $P \rightarrow \neg Q$. Therefore $\neg R \rightarrow (P \rightarrow \neg Q)$. \square

Sometimes if you're stuck you can use rules of inference to work backward. For example, suppose one of your givens has the form $P \rightarrow Q$ and your goal is Q . If only you could prove P , you could use modus ponens to reach your goal. This suggests treating P as your goal instead of Q . If you can prove P ,

then you'll just have to add one more step to the proof to reach your original goal Q .

Example 3.2.5. Suppose that $A \subseteq B$, $a \in A$, and $a \notin B \setminus C$. Prove that $a \in C$.

Scratch work

<i>Givens</i>	<i>Goal</i>
$A \subseteq B$	$a \in C$
$a \in A$	
$a \notin B \setminus C$	

Our third given is a negative statement, so we begin by reexpressing it as an equivalent positive statement. According to the definition of the difference of two sets, this given means $\neg(a \in B \wedge a \notin C)$, and by one of De Morgan's laws, this is equivalent to $a \notin B \vee a \in C$. Because our goal is $a \in C$, it is probably more useful to rewrite this in the equivalent form $a \in B \rightarrow a \in C$:

<i>Givens</i>	<i>Goal</i>
$A \subseteq B$	$a \in C$
$a \in A$	
$a \in B \rightarrow a \in C$	

Now we can use our strategy for using givens of the form $P \rightarrow Q$. Our goal is $a \in C$, and we are given that $a \in B \rightarrow a \in C$. If we could prove that $a \in B$, then we could use modus ponens to reach our goal. So let's try treating $a \in B$ as our goal and see if that makes the problem easier:

<i>Givens</i>	<i>Goal</i>
$A \subseteq B$	$a \in B$
$a \in A$	
$a \in B \rightarrow a \in C$	

Now it is clear how to reach the goal. Since $a \in A$ and $A \subseteq B$, $a \in B$.

Solution

Theorem. Suppose that $A \subseteq B$, $a \in A$, and $a \notin B \setminus C$. Then $a \in C$.

Proof. Since $a \in A$ and $A \subseteq B$, we can conclude that $a \in B$. But $a \notin B \setminus C$, so it follows that $a \in C$. □

Exercises

- *1. This problem could be solved by using truth tables, but don't do it that way. Instead, use the methods for writing proofs discussed so far in this chapter. (See Example 3.2.4.)
- (a) Suppose $P \rightarrow Q$ and $Q \rightarrow R$ are both true. Prove that $P \rightarrow R$ is true.
- (b) Suppose $\neg R \rightarrow (P \rightarrow \neg Q)$ is true. Prove that $P \rightarrow (Q \rightarrow R)$ is true.
2. This problem could be solved by using truth tables, but don't do it that way. Instead, use the methods for writing proofs discussed so far in this chapter. (See Example 3.2.4.)
- (a) Suppose $P \rightarrow Q$ and $R \rightarrow \neg Q$ are both true. Prove that $P \rightarrow \neg R$ is true.
- (b) Suppose that P is true. Prove that $Q \rightarrow \neg(Q \rightarrow \neg P)$ is true.
3. Suppose $A \subseteq C$, and B and C are disjoint. Prove that if $x \in A$ then $x \notin B$.
4. Suppose that $A \setminus B$ is disjoint from C and $x \in A$. Prove that if $x \in C$ then $x \in B$.
- *5. Prove that it cannot be the case that $x \in A \setminus B$ and $x \in B \setminus C$.
- *6. Use the method of proof by contradiction to prove the theorem in Example 3.2.1.
7. Use the method of proof by contradiction to prove the theorem in Example 3.2.5.
8. Suppose that $y + x = 2y - x$, and x and y are not both zero. Prove that $y \equiv 0$.
- *9. Suppose that a and b are nonzero real numbers. Prove that if $a < 1/a < b < 1/b$ then $a < -1$.
10. Suppose that x and y are real numbers. Prove that if $x^2y = 2x + y$, then if $y \equiv 0$ then $x \equiv 0$.
11. Suppose that x and y are real numbers. Prove that if $x \equiv 0$, then if $y = (3x^2 + 2y)/(x^2 + 2)$ then $y = 3$.
- *12. Consider the following incorrect theorem:

Incorrect Theorem. Suppose x and y are real numbers and $x + y = 10$. Then $x \equiv 3$ and $y \equiv 8$.

- (a) What's wrong with the following proof of the theorem?

Proof. Suppose the conclusion of the theorem is false. Then $x = 3$ and $y = 8$. But then $x + y = 11$, which contradicts the given

information that $x + y = 10$. Therefore the conclusion must be true. \square

(b) Show that the theorem is incorrect by finding a counterexample.

13. Consider the following incorrect theorem:

Incorrect Theorem. *Suppose that $A \subseteq C$, $B \subseteq C$, and $x \in A$. Then $x \in B$.*

(a) What's wrong with the following proof of the theorem?

Proof. Suppose that $x \notin B$. Since $x \in A$ and $A \subseteq C$, $x \in C$. Since $x \notin B$ and $B \subseteq C$, $x \notin C$. But now we have proven both $x \in C$ and $x \notin C$, so we have reached a contradiction. Therefore $x \in B$. \square

(b) Show that the theorem is incorrect by finding a counterexample.

14. Use truth tables to show that modus tollens is a valid rule of inference.

*15. Use truth tables to check the correctness of the theorem in Example 3.2.4.

16. Use truth tables to check the correctness of the statements in exercise 1.

17. Use truth tables to check the correctness of the statements in exercise 2.

18. Can the proof in Example 3.2.2 be modified to prove that if $x^2 + y = 13$ and $x \equiv 3$ then $y \equiv 4$? Explain.

3.3. Proofs Involving Quantifiers

Look again at Example 3.2.3. In that example we said that x could be anything at all, and we proved the statement $x \in A \setminus C \rightarrow x \in B$. Because the reasoning we used would apply no matter what x was, our proof actually shows that $x \in A \setminus C \rightarrow x \in B$ is true for all values of x . In other words, we can conclude $\forall x(x \in A \setminus C \rightarrow x \in B)$.

This illustrates the easiest and most straightforward way of proving a goal of the form $\forall x P(x)$. If you can give a proof of the goal $P(x)$ that would work no matter what x was, then you can conclude that $\forall x P(x)$ must be true. To make sure that your proof would work for any value of x , it is important to start your proof with no assumptions about x . Mathematicians express this by saying that x must be *arbitrary*. In particular, you must not assume that x is equal to any other object already under discussion in the proof. Thus, if the letter x is already being used in the proof to stand for some particular object, then you cannot use it to stand for an arbitrary object. In this case you must choose a different variable that is not already being used in the proof, say y ,

and replace the goal $\forall x P(x)$ with the equivalent statement $\forall y P(y)$. Now you can proceed by letting y stand for an arbitrary object and proving $P(y)$.

To prove a goal of the form $\forall x P(x)$:

Let x stand for an arbitrary object and prove $P(x)$. The letter x must be a new variable in the proof. If x is already being used in the proof to stand for something, then you must choose an unused variable, say y , to stand for the arbitrary object, and prove $P(y)$.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
—	$\forall x P(x)$
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
—	$P(x)$
—	

Form of final proof:

Let x be arbitrary.

[Proof of $P(x)$ goes here.]

Since x was arbitrary, we can conclude that $\forall x P(x)$.

Example 3.3.1. Suppose A , B , and C are sets, and $A \setminus B \subseteq C$. Prove that $A \setminus C \subseteq B$.

Scratch work

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	$A \setminus C \subseteq B$

As usual, we look first at the logical form of the goal to plan our strategy. In this case we must write out the definition of \subseteq to determine the logical form of the goal.

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	$\forall x(x \in A \setminus C \rightarrow x \in B)$

Because the goal has the form $\forall x P(x)$, where $P(x)$ is the statement $x \in A \setminus C \rightarrow x \in B$, we will introduce a new variable x into the proof

to stand for an arbitrary object and then try to prove $x \in A \setminus C \rightarrow x \in B$. Note that x is a new variable in the proof. It appeared in the logical form of the goal as a bound variable, but remember that bound variables don't stand for anything in particular. We have not yet used x as a free variable in any statement, so it has not been used to stand for any particular object. To make sure x is arbitrary we must be careful not to add any assumptions about x to the givens column. However, we do change our goal:

<i>Givens</i>	<i>Goal</i>
$A \setminus B \subseteq C$	$x \in A \setminus C \rightarrow x \in B$

According to our strategy, the final proof should look like this:

Let x be arbitrary.

[Proof of $x \in A \setminus C \rightarrow x \in B$ goes here.]

Since x was arbitrary, we can conclude that $\forall x(x \in A \setminus C \rightarrow x \in B)$, so $A \setminus C \subseteq B$.

The problem is now exactly the same as in Example 3.2.3, so the rest of the solution is the same as well. In other words, we can simply insert the proof we wrote in Example 3.2.3 between the first and last sentences of the proof written here.

Solution

Theorem. Suppose A , B , and C are sets, and $A \setminus B \subseteq C$. Then $A \setminus C \subseteq B$.

Proof. Let x be arbitrary. Suppose $x \in A \setminus C$. This means that $x \in A$ and $x \notin C$. Suppose $x \notin B$. Then $x \in A \setminus B$, so since $A \setminus B \subseteq C$, $x \in C$. But this contradicts the fact that $x \notin C$. Therefore $x \in B$. Thus, if $x \in A \setminus C$ then $x \in B$. Since x was arbitrary, we can conclude that $\forall x(x \in A \setminus C \rightarrow x \in B)$, so $A \setminus C \subseteq B$. □

Notice that, although this proof shows that every element of $A \setminus C$ is also an element of B , it does not contain phrases such as “every element of $A \setminus C$ ” or “all elements of $A \setminus C$.” For most of the proof we simply reason about x , which is treated as a single, fixed element of $A \setminus C$. We pretend that x stands for some particular element of $A \setminus C$, being careful to make no assumptions about which element it stands for. It is only at the end of the proof that we observe that, because x was arbitrary, our conclusions about x would be true no matter what x was. This is the main advantage of using this strategy to prove a goal of the form $\forall x P(x)$. It enables you to prove a goal about *all* objects by reasoning about only *one* object, as long as that object is arbitrary. If you are proving a

goal of the form $\forall x P(x)$ and you find yourself saying a lot about “all x ’s” or “every x ,” you are probably making your proof unnecessarily complicated by not using this strategy.

As we saw in Chapter 2, statements of the form $\forall x(P(x) \rightarrow Q(x))$ are quite common in mathematics. It might be worthwhile, therefore, to consider how the strategies we’ve discussed can be combined to prove a goal of this form. Because the goal starts with $\forall x$, the first step is to let x be arbitrary and try to prove $P(x) \rightarrow Q(x)$. To prove this goal, you will probably want to assume that $P(x)$ is true and prove $Q(x)$. Thus, the proof will probably start like this: “Let x be arbitrary. Suppose $P(x)$.” It will then proceed with the steps needed to reach the goal $Q(x)$. Often in this type of proof the statement that x is arbitrary is left out, and the proof simply starts with “Suppose $P(x)$.” When a new variable x is introduced into a proof in this way, it is usually understood that x is arbitrary. In other words, no assumptions are being made about x other than the stated one that $P(x)$ is true.

An important example of this type of proof is a proof in which the goal has the form $\forall x \in A P(x)$. Recall that $\forall x \in A P(x)$ means the same thing as $\forall x(x \in A \rightarrow P(x))$, so according to our strategy the proof should start with “Suppose $x \in A$ ” and then proceed with the steps needed to conclude that $P(x)$ is true. Once again, it is understood that no assumptions are being made about x other than the stated assumption that $x \in A$, so x stands for an arbitrary element of A .

Mathematicians sometimes skip other steps in proofs, if knowledgeable readers could be expected to fill them in themselves. In particular, many of our proof strategies have suggested that the proof end with a sentence that sums up why the reasoning that has been given in the proof leads to the desired conclusion. In a proof in which several of these strategies have been combined, there might be several of these summing up sentences, one after another, at the end of the proof. Mathematicians often condense this summing up into one sentence, or even skip it entirely. When you are reading a proof written by someone else, you may find it helpful to fill in these skipped steps.

Example 3.3.2. Suppose A and B are sets. Prove that if $A \cap B = A$ then $A \subseteq B$.

Scratch work

Our goal is $A \cap B = A \rightarrow A \subseteq B$. Because the goal is a conditional statement, we add the antecedent to the givens list and make the consequent the goal. We will also write out the definition of \subseteq in the new goal to show what its logical form is.

<i>Givens</i>	<i>Goal</i>
$A \cap B = A$	$\forall x(x \in A \rightarrow x \in B)$

Now the goal has the form $\forall x(P(x) \rightarrow Q(x))$, where $P(x)$ is the statement $x \in A$ and $Q(x)$ is the statement $x \in B$. We therefore let x be arbitrary, assume $x \in A$, and prove $x \in B$:

<i>Givens</i>	<i>Goal</i>
$A \cap B = A$	$x \in B$
$x \in A$	

Combining the proof strategies we have used, we see that the final proof will have this form:

Suppose $A \cap B = A$.

Let x be arbitrary.

Suppose $x \in A$.

[Proof of $x \in B$ goes here.]

Therefore $x \in A \rightarrow x \in B$.

Since x was arbitrary, we can conclude that $\forall x(x \in A \rightarrow x \in B)$, so $A \subseteq B$.

Therefore, if $A \cap B = A$ then $A \subseteq B$.

As discussed earlier, when we write up the final proof we can skip the sentence “Let x be arbitrary,” and we can also skip some or all of the last three sentences.

We have now reached the point at which we can analyze the logical form of the goal no further. Fortunately, when we look at the givens, we discover that the goal follows easily. Since $x \in A$ and $A \cap B = A$, it follows that $x \in A \cap B$, so $x \in B$. (In this last step we are using the definition of \cap : $x \in A \cap B$ means $x \in A$ and $x \in B$.)

Solution

Theorem. Suppose A and B are sets. If $A \cap B = A$ then $A \subseteq B$.

Proof. Suppose $A \cap B = A$, and suppose $x \in A$. Then since $A \cap B = A$, $x \in A \cap B$, so $x \in B$. Since x was an arbitrary element of A , we can conclude that $A \subseteq B$. □

Proving a goal of the form $\exists x P(x)$ also involves introducing a new variable x into the proof and proving $P(x)$, but in this case x will not be arbitrary. Because you only need to prove that $P(x)$ is true for *at least one* x , it suffices to assign a particular value to x and prove $P(x)$ for this one value of x .

To prove a goal of the form $\exists x P(x)$:

Try to find a value of x for which you think $P(x)$ will be true. Then start your proof with “Let $x =$ (the value you decided on)” and proceed to prove $P(x)$ for this value of x . Once again, x should be a new variable. If the letter x is already being used in the proof for some other purpose, then you should choose an unused variable, say y , and rewrite the goal in the equivalent form $\exists y P(y)$. Now proceed as before by starting your proof with “Let $y =$ (the value you decided on)” and prove $P(y)$.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
—	$\exists x P(x)$
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
—	$P(x)$
—	
$x =$ (the value you decided on)	

Form of final proof:

Let $x =$ (the value you decided on).

[Proof of $P(x)$ goes here.]

Thus, $\exists x P(x)$.

Finding the right value to use for x may be difficult in some cases. One method that is sometimes helpful is to assume that $P(x)$ is true and then see if you can figure out what x must be, based on this assumption. If $P(x)$ is an equation involving x , this amounts to solving the equation for x . However, if this doesn't work, you may use any other method you please to try to find a value to use for x , including trial-and-error and guessing. The reason you have such freedom with this step is that *the reasoning you use to find a value for x will not appear in the final proof*. This is because of our rule that a proof should contain only the reasoning needed to justify the conclusion of the proof, not an explanation of how you thought of that reasoning. To justify the conclusion that $\exists x P(x)$ is true it is only necessary to verify that $P(x)$ comes out true when x is assigned some particular value. How you thought of that value is your own business, and not part of the justification of the conclusion.

Example 3.3.3. Prove that for every real number x , if $x > 0$ then there is a real number y such that $y(y + 1) = x$.

Scratch work

In symbols, our goal is $\forall x(x > 0 \rightarrow \exists y[y(y + 1) = x])$, where the variables x and y in this statement are understood to range over \mathbb{R} . We therefore start by letting x be an arbitrary real number, and we then assume that $x > 0$ and try to prove that $\exists y[y(y + 1) = x]$. Thus, we now have the following given and goal:

<i>Givens</i>	<i>Goal</i>
$x > 0$	$\exists y[y(y + 1) = x]$

Because our goal has the form $\exists yP(y)$, where $P(y)$ is the statement $y(y + 1) = x$, according to our strategy we should try to find a value of y for which $P(y)$ is true. In this case we can do it by solving the equation $y(y + 1) = x$ for y . It's a quadratic equation and can be solved using the quadratic formula:

$$y(y + 1) = x \quad \Leftrightarrow \quad y^2 + y - x = 0 \quad \Leftrightarrow \quad y = \frac{-1 \pm \sqrt{1 + 4x}}{2}.$$

Note that $\sqrt{1 + 4x}$ is defined, since we have $x > 0$ as a given. We have actually found two solutions for y , but to prove that $\exists y[y(y + 1) = x]$ we only need to exhibit one value of y that makes the equation $y(y + 1) = x$ true. Either of the two solutions could be used in the proof. We will use the solution $y = (-1 + \sqrt{1 + 4x})/2$.

The steps we've used to solve for y should not appear in the final proof. In the final proof we will simply say “Let $y = (-1 + \sqrt{1 + 4x})/2$ ” and then prove that $y(y + 1) = x$. In other words, the final proof will have this form:

Let x be an arbitrary real number.

Suppose $x > 0$.
 Let $y = (-1 + \sqrt{1 + 4x})/2$.

[Proof of $y(y + 1) = x$ goes here.]

Thus, $\exists y[y(y + 1) = x]$.

Therefore $x > 0 \rightarrow \exists y[y(y + 1) = x]$.

Since x was arbitrary, we can conclude that $\forall x(x > 0 \rightarrow \exists y[y(y + 1) = x])$.

To see what must be done to fill in the remaining gap in the proof, we add $y = (-1 + \sqrt{1 + 4x})/2$ to the givens list and make $y(y + 1) = x$ the goal:

<i>Givens</i>	<i>Goal</i>
$x > 0$ $y = (-1 + \sqrt{1 + 4x})/2$	$y(y + 1) = x$

We can now prove that the equation $y(y + 1) = x$ is true by simply substituting $(-1 + \sqrt{1 + 4x})/2$ for y and verifying that the resulting equation is true.

Solution

Theorem. For every real number x , if $x > 0$ then there is a real number y such that $y(y + 1) = x$.

Proof. Let x be an arbitrary real number, and suppose $x > 0$. Let

$$y = \frac{-1 + \sqrt{1 + 4x}}{2},$$

which is defined since $x > 0$. Then

$$\begin{aligned} y(y + 1) &= \left(\frac{-1 + \sqrt{1 + 4x}}{2} \right) \cdot \left(\frac{-1 + \sqrt{1 + 4x}}{2} + 1 \right) \\ &= \left(\frac{\sqrt{1 + 4x} - 1}{2} \right) \cdot \left(\frac{\sqrt{1 + 4x} + 1}{2} \right) \\ &= \frac{1 + 4x - 1}{4} = \frac{4x}{4} = x. \quad \square \end{aligned}$$

Sometimes when you're proving a goal of the form $\exists y Q(y)$ you won't be able to tell just by looking at the statement $Q(y)$ what value you should plug in for y . In this case you may want to look more closely at the givens to see if they suggest a value to use for y . In particular, a given of the form $\exists x P(x)$ may be helpful in this situation. This given says that an object with a certain property exists. It is probably a good idea to imagine that a particular object with this property has been chosen and to introduce a new variable, say x_0 , into the proof to stand for this object. Thus, for the rest of the proof you will be using x_0 to stand for some particular object, and you can assume that with x_0 standing for this object, $P(x_0)$ is true. In other words, you can add $P(x_0)$ to your givens list. This object x_0 , or something related to it, might turn out to be the right thing to plug in for y to make $Q(y)$ come out true.

To use a given of the form $\exists x P(x)$:

Introduce a new variable x_0 into the proof to stand for an object for which $P(x_0)$ is true. This means that you can now assume that $P(x_0)$ is true. Logicians call this rule of inference *existential instantiation*.

Note that using a given of the form $\exists x P(x)$ is very different from proving a goal of the form $\exists x P(x)$, because when using a given of the form $\exists x P(x)$, you don't get to choose a particular value to plug in for x . You can assume that x_0 stands for some object for which $P(x_0)$ is true, but you can't assume anything else about x_0 . On the other hand, a given of the form $\forall x P(x)$ says that $P(x)$ would be true *no matter what* value is assigned to x . You can therefore *choose any value you wish* to plug in for x and use this given to conclude that $P(x)$ is true.

To use a given of the form $\forall x P(x)$:

You can plug in any value, say a , for x and use this given to conclude that $P(a)$ is true. This rule is called *universal instantiation* .

Usually, if you have a given of the form $\exists x P(x)$, you should apply existential instantiation to it immediately. A good guideline is: if you know something exists, you should give it a name. On the other hand, you won't be able to apply universal instantiation to a given of the form $\forall x P(x)$ unless you have a particular value a to plug in for x , so you might want to wait until a likely choice for a pops up in the proof. For example, consider a given of the form $\forall x(P(x) \rightarrow Q(x))$. You can use this given to conclude that $P(a) \rightarrow Q(a)$ for any a , but according to our rule for using givens that are conditional statements, this conclusion probably won't be very useful unless you know either $P(a)$ or $\neg Q(a)$. You should probably wait until an object a appears in the proof for which you know either $P(a)$ or $\neg Q(a)$, and plug this a in for x when it appears.

We've already used this technique in some of our earlier proofs when dealing with givens of the form $A \subseteq B$. For instance, in Example 3.2.5 we used the givens $A \subseteq B$ and $a \in A$ to conclude that $a \in B$. The justification for this reasoning is that $A \subseteq B$ means $\forall x(x \in A \rightarrow x \in B)$, so by universal instantiation we can plug in a for x and conclude that $a \in A \rightarrow a \in B$. Since we also know $a \in A$, it follows by modus ponens that $a \in B$.

Example 3.3.4. Suppose \mathcal{F} and \mathcal{G} are families of sets and $\mathcal{F} \cap \mathcal{G} \equiv \emptyset$. Prove that $\bigcap \mathcal{F} \subseteq \bigcup \mathcal{G}$.

Scratch work

Our first step in analyzing the logical form of the goal is to write out the meaning of the subset symbol, which gives us the statement $\forall x(x \in \bigcap \mathcal{F} \rightarrow x \in \bigcup \mathcal{G})$. We could go further with this analysis by writing out the definitions of union and intersection, but the part of the analysis that we have already

done will be enough to allow us to decide how to get started on the proof. The definitions of union and intersection will be needed later in the proof, but we will wait until they are needed before filling them in. When analyzing the logical forms of givens and goals in order to figure out a proof, it is usually best to do only as much of the analysis as is needed to determine the next step of the proof. Going further with the logical analysis usually just introduces unnecessary complication, without providing any benefit.

Because the goal means $\forall x(x \in \bigcap \mathcal{F} \rightarrow x \in \bigcup \mathcal{G})$, we let x be arbitrary, assume $x \in \bigcap \mathcal{F}$, and try to prove $x \in \bigcup \mathcal{G}$.

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ \mathcal{F} \cap \mathcal{G} \neq \emptyset & x \in \bigcup \mathcal{G} \\ x \in \bigcap \mathcal{F} & \end{array}$$

The new goal means $\exists A \in \mathcal{G}(x \in A)$, so to prove it we should try to find a value that will “work” for A . Just looking at the goal doesn’t make it clear how to choose A , so we look more closely at the givens. We begin by writing them out in logical symbols:

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ \exists A(A \in \mathcal{F} \cap \mathcal{G}) & \exists A \in \mathcal{G}(x \in A) \\ \forall A \in \mathcal{F}(x \in A) & \end{array}$$

The second given starts with $\forall A$, so we may not be able to use this given until a likely value to plug in for A pops up during the course of the proof. In particular, we should keep in mind that if we ever come across an element of \mathcal{F} while trying to figure out the proof, we can plug it in for A in the second given and conclude that it contains x as an element. The first given, however, starts with $\exists A$, so we should use it immediately. It says that there is some object that is an element of $\mathcal{F} \cap \mathcal{G}$. By existential instantiation, we can introduce a name, say A_0 , for this object. Thus, we can treat $A_0 \in \mathcal{F} \cap \mathcal{G}$ as a given from now on. Because we now have a name, A_0 , for a particular element of $\mathcal{F} \cap \mathcal{G}$, it would be redundant to continue to discuss the given statement $\exists A(A \in \mathcal{F} \cap \mathcal{G})$, so we will drop it from our list of givens. Since our new given $A_0 \in \mathcal{F} \cap \mathcal{G}$ means $A_0 \in \mathcal{F}$ and $A_0 \in \mathcal{G}$, we now have the following situation:

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ A_0 \in \mathcal{F} & \exists A \in \mathcal{G}(x \in A) \\ A_0 \in \mathcal{G} & \\ \forall A \in \mathcal{F}(x \in A) & \end{array}$$

If you’ve been paying close attention, you should know what the next step should be. We decided before to keep our eyes open for any elements of \mathcal{F} that

might come up during the proof, because we might want to plug them in for A in the last given. An element of \mathcal{F} has come up: A_0 ! Plugging A_0 in for A in the last given, we can conclude that $x \in A_0$. Any conclusions can be treated in the future as givens, so you can add this statement to the givens column if you like.

Remember that we decided to look at the givens because we didn't know what value to assign to A in the goal. What we need is a value for A that is in \mathcal{G} and that will make the statement $x \in A$ come out true. Has this consideration of the givens suggested a value to use for A ? Yes! Use $A = A_0$.

Although we translated the given statements $x \in \bigcap \mathcal{F}$, $x \in \bigcup \mathcal{G}$, and $\mathcal{F} \cap \mathcal{G} \equiv \emptyset$ into logical symbols in order to figure out how to use them in the proof, these translations are not usually written out when the proof is written up in final form. In the final proof we just write these statements in their original form and leave it to the reader of the proof to work out their logical forms in order to follow our reasoning.

Solution

Theorem. Suppose \mathcal{F} and \mathcal{G} are families of sets, and $\mathcal{F} \cap \mathcal{G} \equiv \emptyset$. Then $\bigcap \mathcal{F} \subseteq \bigcup \mathcal{G}$.

Proof. Suppose $x \in \bigcap \mathcal{F}$. Since $\mathcal{F} \cap \mathcal{G} \equiv \emptyset$, we can let A_0 be an element of $\mathcal{F} \cap \mathcal{G}$. Thus, $A_0 \in \mathcal{F}$ and $A_0 \in \mathcal{G}$. Since $x \in \bigcap \mathcal{F}$ and $A_0 \in \mathcal{F}$, it follows that $x \in A_0$. But we also know that $A_0 \in \mathcal{G}$, so we can conclude that $x \in \bigcup \mathcal{G}$. \square

Proofs involving the quantifiers *for all* and *there exists* are often difficult for them.

That last sentence confused you, didn't it? You're probably wondering, "Who are *they*?" Readers of your proofs will experience the same sort of confusion if you use variables without explaining what they stand for. Beginning proof-writers are sometimes careless about this, and that's why proofs involving the quantifiers *for all* and *there exists* are often difficult for them. (It made more sense that time, didn't it?) When you use the strategies we've discussed in this section, you'll be introducing new variables into your proof, and when you do this, you must always be careful to make it clear to the reader what they stand for.

For example, if you were proving a goal of the form $\forall x \in A P(x)$, you would probably start by introducing a variable x to stand for an arbitrary element of A . Your reader won't know what x means, though, unless you begin your proof with "Let x be an arbitrary element of A ," or "Suppose $x \in A$." These sentences tell the reader that, from now on, he or she should think of x

as standing for some particular element of A , although which element it stands for is left unspecified. Of course, you must be clear in your own mind about what x means. In particular, because x is to be arbitrary, you must be careful not to assume anything about x other than the fact that $x \in A$. It might help to think of the value of x as being chosen by *someone else*; you have no control over which element of A they'll pick. Using a given of the form $\exists x P(x)$ is similar. This given tells you that you can introduce a new variable x_0 into the proof to stand for some object for which $P(x_0)$ is true, but you cannot assume anything else about x_0 . On the other hand, if you are *proving* $\exists x P(x)$, your proof will probably start "Let $x = \dots$." This time *you* get to choose the value of x , and you must tell the reader explicitly that you are choosing the value of x and what value you have chosen.

It's also important, when you're introducing a new variable x , to be sure you know what *kind* of object x stands for. Is it a number? a set? a function? a matrix? You'd better not write $a \in X$ unless X is a set, for example. If you aren't careful about this, you might end up writing nonsense. You also sometimes need to know what kind of object a variable stands for to figure out the logical form of a statement involving that variable. For example, $A = B$ means $\forall x(x \in A \leftrightarrow x \in B)$ if A and B are sets, but not if they're numbers.

The most important thing to keep in mind about introducing variables into a proof is simply the fact that variables must always be introduced before they are used. If you make a statement about x (i.e., a statement in which x occurs as a free variable) without first explaining what x stands for, a reader of your proof won't know what you're talking about – and there's a good chance that you won't know what you're talking about either!

Because proofs involving quantifiers may require more practice than the other proofs we have discussed so far, we end this section with two more examples.

Example 3.3.5. Suppose B is a set and \mathcal{F} is a family of sets. Prove that if $\bigcup \mathcal{F} \subseteq B$ then $\mathcal{F} \subseteq \mathcal{P}(B)$.

Scratch work

We assume $\bigcup \mathcal{F} \subseteq B$ and try to prove $\mathcal{F} \subseteq \mathcal{P}(B)$. Because this goal means $\forall x(x \in \mathcal{F} \rightarrow x \in \mathcal{P}(B))$, we let x be arbitrary, assume $x \in \mathcal{F}$, and set $x \in \mathcal{P}(B)$ as our goal. Recall that \mathcal{F} is a family of sets, so since $x \in \mathcal{F}$, x is a set. Thus, we now have the following givens and goal:

<i>Givens</i>	<i>Goal</i>
$\bigcup \mathcal{F} \subseteq B$	$x \in \mathcal{P}(B)$
$x \in \mathcal{F}$	

To figure out how to prove this goal, we must use the definition of power set. The statement $x \in \mathcal{P}(B)$ means $x \subseteq B$, or in other words $\forall y(y \in x \rightarrow y \in B)$. We must therefore introduce another arbitrary object into the proof. We let y be arbitrary, assume $y \in x$, and try to prove $y \in B$.

<i>Givens</i>	<i>Goal</i>
$\bigcup \mathcal{F} \subseteq B$	$y \in B$
$x \in \mathcal{F}$	
$y \in x$	

The goal can be analyzed no further, so we must look more closely at the givens. Our goal is $y \in B$, and the only given that even mentions B is the first. In fact, the first given would enable us to reach this goal, if only we knew that $y \in \bigcup \mathcal{F}$. This suggests that we might try treating $y \in \bigcup \mathcal{F}$ as our goal. If we can reach this goal, then we can just add one more step, applying the first given, and the proof will be done.

<i>Givens</i>	<i>Goal</i>
$\bigcup \mathcal{F} \subseteq B$	$y \in \bigcup \mathcal{F}$
$x \in \mathcal{F}$	
$y \in x$	

Once again, we have a goal whose logical form can be analyzed, so we use the form of the goal to guide our strategy. The goal means $\exists A \in \mathcal{F}(y \in A)$, so to prove it we must find a set A such that $A \in \mathcal{F}$ and $y \in A$. Looking at the givens, we see that x is such a set, so the proof is done.

Solution

Theorem. Suppose B is a set and \mathcal{F} is a family of sets. If $\bigcup \mathcal{F} \subseteq B$ then $\mathcal{F} \subseteq \mathcal{P}(B)$.

Proof. Suppose $\bigcup \mathcal{F} \subseteq B$. Let x be an arbitrary element of \mathcal{F} . Let y be an arbitrary element of x . Since $y \in x$ and $x \in \mathcal{F}$, by the definition of $\bigcup \mathcal{F}$, $y \in \bigcup \mathcal{F}$. But then since $\bigcup \mathcal{F} \subseteq B$, $y \in B$. Since y was an arbitrary element of x , we can conclude that $x \subseteq B$, so $x \in \mathcal{P}(B)$. But x was an arbitrary element of \mathcal{F} , so this shows that $\mathcal{F} \subseteq \mathcal{P}(B)$, as required. □

The Venn diagram in Figure 3.1 may help you see why the theorem in Example 3.3.5 is true, and you might find it useful to refer to the picture as you reread the proof. But notice that we didn't prove the theorem by simply explaining this picture; the proof was constructed by following the proof strategies we have discussed. There are many methods, such as drawing

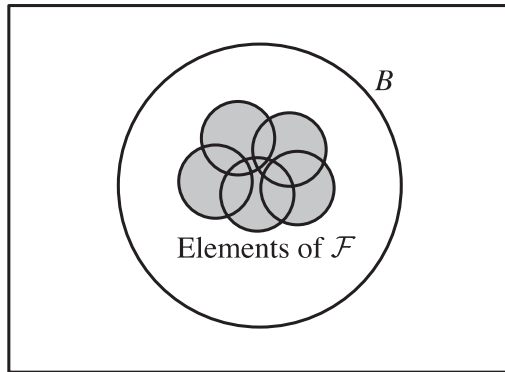


Figure 3.1. The small circles represent elements of \mathcal{F} , and the shaded region is $\bigcup \mathcal{F}$. The large circle represents B .

pictures or working out examples, that may help you achieve an understanding of why a theorem is true. But an explanation of this understanding is not a proof. To prove a theorem, you must follow the strategies in this chapter.

The proof in Example 3.3.5 is probably the most complex proof we've done so far. Read it again and make sure you understand its structure and the purpose of every sentence. Isn't it remarkable how much logical complexity has been packed into just a few lines?

It is not uncommon for a short proof to have such a rich logical structure. This efficiency of exposition is one of the most attractive features of proofs, but it also often makes them difficult to read. Although we've been concentrating so far on *writing* proofs, it is also important to learn how to *read* proofs written by other people. To give you some practice with this, we present our last proof in this section without the scratch work. See if you can follow the structure of the proof as you read it. We'll provide a commentary after the proof that should help you to understand it.

For this proof, we need the following definition:

Definition 3.3.6. For any integers x and y , we'll say that x *divides* y (or y is *divisible by* x) if $\exists k \in \mathbb{Z}(kx = y)$. We use the notation $x \mid y$ to mean " x divides y ," and $x \nmid y$ means " x does not divide y ."

For example, $4 \mid 20$, since $5 \cdot 4 = 20$, but $4 \nmid 21$.

Theorem 3.3.7. For all integers a , b , and c , if $a \mid b$ and $b \mid c$ then $a \mid c$.

Proof. Let a , b , and c be arbitrary integers and suppose $a \mid b$ and $b \mid c$. Since $a \mid b$, we can choose some integer m such that $ma = b$. Similarly, since $b \mid c$,

we can choose an integer n such that $nb = c$. Therefore $c = nb = nma$, so since nm is an integer, $a \mid c$. \square

Commentary. The theorem says $\forall a \in \mathbb{Z} \forall b \in \mathbb{Z} \forall c \in \mathbb{Z} (a \mid b \wedge b \mid c \rightarrow a \mid c)$, so the most natural way to proceed is to let a , b , and c be arbitrary integers, assume $a \mid b$ and $b \mid c$, and then prove $a \mid c$. The first sentence of the proof indicates that this strategy is being used, so the goal for the rest of the proof must be to prove that $a \mid c$. The fact that this is the goal for the rest of the proof is not explicitly stated. You are expected to figure this out for yourself by using your knowledge of proof strategies. You might even want to make a givens and goal list to help you keep track of what is known and what remains to be proven as you continue to read the proof. At this point in the proof, the list would look like this:

<i>Givens</i>	<i>Goal</i>
$a, b,$ and c are integers	$a \mid c$
$a \mid b$	
$b \mid c$	

Because the new goal means $\exists k \in \mathbb{Z} (ka = c)$, the proof will probably proceed by finding an integer k such that $ka = c$. As with many proofs of existential statements, the first step in finding such a k involves looking more closely at the givens. The next sentence of the proof uses the given $a \mid b$ to conclude that we can choose an integer m such that $ma = b$. The proof doesn't say what rule of inference justifies this. It is up to you to figure it out by working out the logical form of the given statement $a \mid b$, using the definition of *divides*. Because this given means $\exists k \in \mathbb{Z} (ka = b)$, you should recognize that the rule of inference being used is existential instantiation. Existential instantiation is also used in the next sentence of the proof to justify choosing an integer n such that $nb = c$. The equations $ma = b$ and $nb = c$ can now be added to the list of givens.

Some steps have also been skipped in the last sentence of the proof. We expected that the goal $a \mid c$ would be proven by finding an integer k such that $ka = c$. From the equation $c = nma$ and the fact that nm is an integer, it follows that $k = nm$ will work, but the proof doesn't explicitly say that this value of k is being used; in fact, the variable k does not appear at all in the proof. Of course, the variable k does not appear in the statement of the theorem either. A reader of the proof would expect us to prove that $a \mid c$ by finding an integer that, when multiplied by a , gives the value c , but based on reading the statement of the theorem, the reader would have no reason to expect this integer to be given the name k . Assigning this name to the integer nm would therefore not have made the proof easier to understand, so we didn't do it.

Exercises

Note: Exercises marked with the symbol P_D can be done with Proof Designer, which is computer software that is available free on the internet.

- *1. In exercise 7 of Section 2.2 you used logical equivalences to show that $\exists x(P(x) \rightarrow Q(x))$ is equivalent to $\forall x P(x) \rightarrow \exists x Q(x)$. Now use the methods of this section to prove that if $\exists x(P(x) \rightarrow Q(x))$ is true, then $\forall x P(x) \rightarrow \exists x Q(x)$ is true. (Note: The other direction of the equivalence is quite a bit harder to prove. See exercise 30 of Section 3.5.)
2. Prove that if A and $B \setminus C$ are disjoint, then $A \cap B \subseteq C$.
- *3. Prove that if $A \subseteq B \setminus C$ then A and C are disjoint.
- P_D 4. Suppose $A \subseteq \mathcal{P}(A)$. Prove that $\mathcal{P}(A) \subseteq \mathcal{P}(\mathcal{P}(A))$.
5. The hypothesis of the theorem proven in exercise 4 is $A \subseteq \mathcal{P}(A)$.
 - (a) Can you think of a set A for which this hypothesis is true?
 - (b) Can you think of another?
6. Suppose x is a real number.
 - (a) Prove that if $x \neq 1$ then there is a real number y such that $\frac{y+1}{y-2} = x$.
 - (b) Prove that if there is a real number y such that $\frac{y+1}{y-2} = x$, then $x \neq 1$.
- *7. Prove that for every real number x , if $x > 2$ then there is a real number y such that $y + 1/y = x$.
- P_D 8. Prove that if \mathcal{F} is a family of sets and $A \in \mathcal{F}$, then $A \subseteq \bigcup \mathcal{F}$.
- *9. Prove that if \mathcal{F} is a family of sets and $A \in \mathcal{F}$, then $\bigcap \mathcal{F} \subseteq A$.
10. Suppose that \mathcal{F} is a nonempty family of sets, B is a set, and $\forall A \in \mathcal{F}(B \subseteq A)$. Prove that $B \subseteq \bigcap \mathcal{F}$.
11. Suppose that \mathcal{F} is a family of sets. Prove that if $\emptyset \in \mathcal{F}$ then $\bigcap \mathcal{F} = \emptyset$.
- P_D *12. Suppose \mathcal{F} and \mathcal{G} are families of sets. Prove that if $\mathcal{F} \subseteq \mathcal{G}$ then $\bigcup \mathcal{F} \subseteq \bigcup \mathcal{G}$.
13. Suppose \mathcal{F} and \mathcal{G} are nonempty families of sets. Prove that if $\mathcal{F} \subseteq \mathcal{G}$ then $\bigcap \mathcal{G} \subseteq \bigcap \mathcal{F}$.
- *14. Suppose that $\{A_i \mid i \in I\}$ is an indexed family of sets. Prove that $\bigcup_{i \in I} \mathcal{P}(A_i) \subseteq \mathcal{P}(\bigcup_{i \in I} A_i)$. (Hint: First make sure you know what all the notation means!)
15. Suppose $\{A_i \mid i \in I\}$ is an indexed family of sets and $I \neq \emptyset$. Prove that $\bigcap_{i \in I} A_i \in \bigcap_{i \in I} \mathcal{P}(A_i)$.
- P_D 16. Prove the converse of the statement proven in Example 3.3.5. In other words, prove that if $\mathcal{F} \subseteq \mathcal{P}(B)$ then $\bigcup \mathcal{F} \subseteq B$.
- *17. Suppose \mathcal{F} and \mathcal{G} are nonempty families of sets, and every element of \mathcal{F} is a subset of every element of \mathcal{G} . Prove that $\bigcup \mathcal{F} \subseteq \bigcap \mathcal{G}$.

18. In this problem all variables range over \mathbb{Z} , the set of all integers.
- (a) Prove that if $a \mid b$ and $a \mid c$, then $a \mid (b + c)$.
 - (b) Prove that if $ac \mid bc$ and $c \neq 0$, then $a \mid b$.
19. (a) Prove that for all real numbers x and y there is a real number z such that $x + z = y - z$.
- (b) Would the statement in part (a) be correct if “real number” were changed to “integer”? Justify your answer.
- *20. Consider the following theorem:

Theorem. For every real number x , $x^2 \geq 0$.

What’s wrong with the following proof of the theorem?

Proof. Suppose not. Then for every real number x , $x^2 < 0$. In particular, plugging in $x = 3$ we would get $9 < 0$, which is clearly false. This contradiction shows that for every number x , $x^2 \geq 0$. \square

21. Consider the following incorrect theorem:

Incorrect Theorem. If $\forall x \in A(x \neq 0)$ and $A \subseteq B$ then $\forall x \in B(x \neq 0)$.

- (a) What’s wrong with the following proof of the theorem?

Proof. Suppose that $\forall x \in A(x \neq 0)$ and $A \subseteq B$. Let x be an arbitrary element of A . Since $\forall x \in A(x \neq 0)$, we can conclude that $x \neq 0$. Also, since $A \subseteq B$, $x \in B$. Since $x \in B$, $x \neq 0$, and x was arbitrary, we can conclude that $\forall x \in B(x \neq 0)$. \square

- (b) Find a counterexample to the theorem. In other words, find an example of sets A and B for which the hypotheses of the theorem are true but the conclusion is false.

- *22. Consider the following incorrect theorem:

Incorrect Theorem. $\exists x \in \mathbb{R} \forall y \in \mathbb{R}(xy^2 = y - x)$.

What’s wrong with the following proof of the theorem?

Proof. Let $x = y/(y^2 + 1)$. Then

$$y - x = y - \frac{y}{y^2 + 1} = \frac{y^3}{y^2 + 1} = \frac{y}{y^2 + 1} \cdot y^2 = xy^2. \quad \square$$

23. Consider the following incorrect theorem:

Incorrect Theorem. Suppose \mathcal{F} and \mathcal{G} are families of sets. If $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint, then so are \mathcal{F} and \mathcal{G} .

- (a) What's wrong with the following proof of the theorem?

Proof. Suppose $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint. Suppose \mathcal{F} and \mathcal{G} are not disjoint. Then we can choose some set A such that $A \in \mathcal{F}$ and $A \in \mathcal{G}$. Since $A \in \mathcal{F}$, by exercise 8, $A \subseteq \bigcup \mathcal{F}$, so every element of A is in $\bigcup \mathcal{F}$. Similarly, since $A \in \mathcal{G}$, every element of A is in $\bigcup \mathcal{G}$. But then every element of A is in both $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$, and this is impossible since $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint. Thus, we have reached a contradiction, so \mathcal{F} and \mathcal{G} must be disjoint. \square

- (b) Find a counterexample to the theorem.

24. Consider the following putative theorem:

Theorem? For all real numbers x and y , $x^2 + xy - 2y^2 = 0$.

- (a) What's wrong with the following proof of the theorem?

Proof. Let x and y be equal to some arbitrary real number r . Then

$$x^2 + xy - 2y^2 = r^2 + r \cdot r - 2r^2 = 0.$$

Since x and y were both arbitrary, this shows that for all real numbers x and y , $x^2 + xy - 2y^2 = 0$. \square

- (b) Is the theorem correct? Justify your answer with either a proof or a counterexample.

*25. Prove that for every real number x there is a real number y such that for every real number z , $yz = (x + z)^2 - (x^2 + z^2)$.

26. (a) Comparing the various rules for dealing with quantifiers in proofs, you should see a similarity between the rules for goals of the form $\forall x P(x)$ and givens of the form $\exists x P(x)$. What is this similarity? What about the rules for goals of the form $\exists x P(x)$ and givens of the form $\forall x P(x)$?

- (b) Can you think of a reason why these similarities might be expected? (Hint: Think about how proof by contradiction works when the goal starts with a quantifier.)

3.4. Proofs Involving Conjunctions and Biconditionals

The method for proving a goal of the form $P \wedge Q$ is very simple:

To prove a goal of the form $P \wedge Q$:

Prove P and Q separately.

In other words, a goal of the form $P \wedge Q$ is treated as two separate goals: P , and Q . The same is true of givens of the form $P \wedge Q$:

To use a given of the form $P \wedge Q$:

Treat this given as two separate givens: P , and Q .

We've already used these ideas, without mention, in some of our previous examples. For example, the definition of the given $x \in A \setminus C$ in Example 3.2.3 was $x \in A \wedge x \notin C$, but we treated it as two separate givens: $x \in A$, and $x \notin C$.

Example 3.4.1. Suppose $A \subseteq B$, and A and C are disjoint. Prove that $A \subseteq B \setminus C$.

Scratch work

<i>Givens</i>	<i>Goal</i>
$A \subseteq B$	$A \subseteq B \setminus C$
$A \cap C = \emptyset$	

Analyzing the logical form of the goal, we see that it has the form $\forall x(x \in A \rightarrow x \in B \setminus C)$, so we let x be arbitrary, assume $x \in A$, and try to prove that $x \in B \setminus C$. The new goal $x \in B \setminus C$ means $x \in B \wedge x \notin C$, so according to our strategy we should split this into two goals, $x \in B$ and $x \notin C$, and prove them separately.

<i>Givens</i>	<i>Goals</i>
$A \subseteq B$	$x \in B$
$A \cap C = \emptyset$	$x \notin C$
$x \in A$	

The final proof will have this form:

Let x be arbitrary.

Suppose $x \in A$.

[Proof of $x \in B$ goes here.]

[Proof of $x \notin C$ goes here.]

Thus, $x \in B \wedge x \notin C$, so $x \in B \setminus C$.

Therefore $x \in A \rightarrow x \in B \setminus C$.

Since x was arbitrary, $\forall x(x \in A \rightarrow x \in B \setminus C)$, so $A \subseteq B \setminus C$.

The first goal, $x \in B$, clearly follows from the fact that $x \in A$ and $A \subseteq B$. The second goal, $x \notin C$, follows from $x \in A$ and $A \cap C = \emptyset$. You can see

this by analyzing the logical form of the statement $A \cap C = \emptyset$. It is a negative statement, but it can be reexpressed as an equivalent positive statement:

$A \cap C = \emptyset$ is equivalent to $\neg \exists y (y \in A \wedge y \in C)$ (definitions of \cap and \emptyset),
 which is equivalent to $\forall y \neg (y \in A \wedge y \in C)$ (quantifier negation law),
 which is equivalent to $\forall y (y \notin A \vee y \notin C)$ (De Morgan's law),
 which is equivalent to $\forall y (y \in A \rightarrow y \notin C)$ (conditional law).

Plugging in x for y in this last statement, we see that $x \in A \rightarrow x \notin C$, and since we already know $x \in A$, we can conclude that $x \notin C$.

Solution

Theorem. Suppose $A \subseteq B$, and A and C are disjoint. Then $A \subseteq B \setminus C$.

Proof. Suppose $x \in A$. Since $A \subseteq B$, it follows that $x \in B$, and since A and C are disjoint, we must have $x \notin C$. Thus, $x \in B \setminus C$. Since x was an arbitrary element of A , we can conclude that $A \subseteq B \setminus C$. \square

Using our strategies for working with conjunctions, we can now work out the proper way to deal with statements of the form $P \leftrightarrow Q$ in proofs. Because $P \leftrightarrow Q$ is equivalent to $(P \rightarrow Q) \wedge (Q \rightarrow P)$, according to our strategies a given or goal of the form $P \leftrightarrow Q$ should be treated as two separate givens or goals: $P \rightarrow Q$, and $Q \rightarrow P$.

To prove a goal of the form $P \leftrightarrow Q$:

Prove $P \rightarrow Q$ and $Q \rightarrow P$ separately.

To use a given of the form $P \leftrightarrow Q$:

Treat this as two separate givens: $P \rightarrow Q$, and $Q \rightarrow P$.

This is illustrated in the next example, in which we use the following definitions.

Definition 3.4.2. An integer x is *even* if $\exists k \in \mathbb{Z} (x = 2k)$, and x is *odd* if $\exists k \in \mathbb{Z} (x = 2k + 1)$.

We also use the fact that every integer is either even or odd, but not both. For a proof of this fact, see exercise 16 in Section 6.1.

Example 3.4.3. Suppose x is an integer. Prove that x is even iff x^2 is even.

Scratch work

The goal is $(x \text{ is even}) \leftrightarrow (x^2 \text{ is even})$, so we prove the two goals $(x \text{ is even}) \rightarrow (x^2 \text{ is even})$ and $(x^2 \text{ is even}) \rightarrow (x \text{ is even})$ separately. For the first, we assume that x is even and prove that x^2 is even:

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ x \in \mathbb{Z} & x^2 \text{ is even} \\ x \text{ is even} & \end{array}$$

Writing out the definition of *even* in both the given and the goal will reveal their logical forms:

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ x \in \mathbb{Z} & \exists k \in \mathbb{Z}(x^2 = 2k) \\ \exists k \in \mathbb{Z}(x = 2k) & \end{array}$$

Because the second given starts with $\exists k$, we immediately use it and let k stand for some particular integer for which the statement $x = 2k$ is true. Thus, we have two new given statements: $k \in \mathbb{Z}$, and $x = 2k$.

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ x \in \mathbb{Z} & \exists k \in \mathbb{Z}(x^2 = 2k) \\ k \in \mathbb{Z} & \\ x = 2k & \end{array}$$

The goal starts with $\exists k$, but since k is already being used to stand for a particular number, we cannot assign a new value to k to prove the goal. We must therefore switch to a different letter, say j . One way to understand this is to think of rewriting the goal in the equivalent form $\exists j \in \mathbb{Z}(x^2 = 2j)$. To prove this goal we must come up with a value to plug in for j . It must be an integer, and it must satisfy the equation $x^2 = 2j$. Using the given equation $x = 2k$, we see that $x^2 = (2k)^2 = 4k^2 = 2(2k^2)$, so it looks like the right value to choose for j is $j = 2k^2$. Clearly $2k^2$ is an integer, so this choice for j will work to complete the proof of our first goal.

To prove the second goal $(x^2 \text{ is even}) \rightarrow (x \text{ is even})$, we'll prove the contrapositive $(x \text{ is not even}) \rightarrow (x^2 \text{ is not even})$ instead. Since any integer is either even or odd but not both, this is equivalent to the statement $(x \text{ is odd}) \rightarrow (x^2 \text{ is odd})$.

$$\begin{array}{ll} \textit{Givens} & \textit{Goal} \\ x \in \mathbb{Z} & x^2 \text{ is odd} \\ x \text{ is odd} & \end{array}$$

The steps are now quite similar to the first part of the proof. As before, we begin by writing out the definition of *odd* in both the second given and the

goal. This time, to avoid the conflict of variable names we ran into in the first part of the proof, we use different names for the bound variables in the two statements.

$$\begin{array}{ll} \text{Givens} & \text{Goal} \\ x \in \mathbb{Z} & \exists j \in \mathbb{Z}(x^2 = 2j + 1) \\ \exists k \in \mathbb{Z}(x = 2k + 1) & \end{array}$$

Next we use the second given and let k stand for a particular integer for which $x = 2k + 1$.

$$\begin{array}{ll} \text{Givens} & \text{Goal} \\ x \in \mathbb{Z} & \exists j \in \mathbb{Z}(x^2 = 2j + 1) \\ k \in \mathbb{Z} & \\ x = 2k + 1 & \end{array}$$

We must now find an integer j such that $x^2 = 2j + 1$. Plugging in $2k + 1$ for x we get $x^2 = (2k + 1)^2 = 4k^2 + 4k + 1 = 2(2k^2 + 2k) + 1$, so $j = 2k^2 + 2k$ looks like the right choice.

Before giving the final write-up of the proof, we should make a few explanatory remarks. The two conditional statements we've proven can be thought of as representing the two directions \rightarrow and \leftarrow of the biconditional symbol \leftrightarrow in the original goal. These two parts of the proof are sometimes labeled with the symbols \rightarrow and \leftarrow . In each part, we end up proving a statement that asserts the existence of a number with certain properties. We called this number j in the scratch work, but note that j was not mentioned explicitly in the statement of the problem. As in the proof of Theorem 3.3.7, we have chosen not to mention j explicitly in the final proof either.

Solution

Theorem. *Suppose x is an integer. Then x is even iff x^2 is even.*

Proof. (\rightarrow) Suppose x is even. Then for some integer k , $x = 2k$. Therefore, $x^2 = 4k^2 = 2(2k^2)$, so since $2k^2$ is an integer, x^2 is even. Thus, if x is even then x^2 is even.

(\leftarrow) Suppose x is odd. Then $x = 2k + 1$ for some integer k . Therefore, $x^2 = (2k + 1)^2 = 4k^2 + 4k + 1 = 2(2k^2 + 2k) + 1$, so since $2k^2 + 2k$ is an integer, x^2 is odd. Thus, if x^2 is even then x is even. \square

Using the proof techniques we've developed, we can now verify some of the equivalences that we were only able to justify on intuitive grounds in Chapter 2. As an example of this, let's prove that the formulas $\forall x \neg P(x)$ and

$\neg\exists xP(x)$ are equivalent. To say that these formulas are equivalent means that they will always have the same truth value. In other words, no matter what statement $P(x)$ stands for, the statement $\forall x\neg P(x) \leftrightarrow \neg\exists xP(x)$ will be true. We can prove this using our technique for proving biconditional statements.

Example 3.4.4. Prove that $\forall x\neg P(x) \leftrightarrow \neg\exists xP(x)$.

Scratch work

(\rightarrow) We must prove $\forall x\neg P(x) \rightarrow \neg\exists xP(x)$, so we assume $\forall x\neg P(x)$ and try to prove $\neg\exists xP(x)$. Our goal is now a negated statement, and reexpressing it would require the use of the very equivalence that we are trying to prove! We therefore fall back on our only other strategy for dealing with negative goals, proof by contradiction. We now have the following situation:

<i>Givens</i>	<i>Goal</i>
$\forall x\neg P(x)$	Contradiction
$\exists xP(x)$	

The second given starts with an existential quantifier, so we use it immediately and let x_0 stand for some object for which the statement $P(x_0)$ is true. But now plugging in x_0 for x in the first given we can conclude that $\neg P(x_0)$, which gives us the contradiction we need.

(\leftarrow) For this direction of the biconditional we should assume $\neg\exists xP(x)$ and try to prove $\forall x\neg P(x)$. Because this goal starts with a universal quantifier, we let x be arbitrary and try to prove $\neg P(x)$. Once again, we now have a negated goal that can't be reexpressed, so we use proof by contradiction:

<i>Givens</i>	<i>Goal</i>
$\neg\exists xP(x)$	Contradiction
$P(x)$	

Our first given is also a negated statement, and this suggests that we could get the contradiction we need by proving $\exists xP(x)$. We therefore set this as our goal.

<i>Givens</i>	<i>Goal</i>
$\neg\exists xP(x)$	$\exists xP(x)$
$P(x)$	

To keep from confusing the x that appears as a free variable in the second given (the arbitrary x introduced earlier in the proof) with the x that appears as a bound variable in the goal, you might want to rewrite the goal in the equivalent form $\exists yP(y)$. To prove this goal we have to find a value of y that

makes $P(y)$ come out true. But this is easy! Our second given, $P(x)$, tells us that our arbitrary x is the value we need.

Solution

Theorem. $\forall x \neg P(x) \leftrightarrow \neg \exists x P(x)$.

Proof. (\rightarrow) Suppose $\forall x \neg P(x)$, and suppose $\exists x P(x)$. Then we can choose some x_0 such that $P(x_0)$ is true. But since $\forall x \neg P(x)$, we can conclude that $\neg P(x_0)$, and this is a contradiction. Therefore $\forall x \neg P(x) \rightarrow \neg \exists x P(x)$.

(\leftarrow) Suppose $\neg \exists x P(x)$. Let x be arbitrary, and suppose $P(x)$. Since we have a specific x for which $P(x)$ is true, it follows that $\exists x P(x)$, which is a contradiction. Therefore, $\neg P(x)$. Since x was arbitrary, we can conclude that $\forall x \neg P(x)$, so $\neg \exists x P(x) \rightarrow \forall x \neg P(x)$. \square

Sometimes in a proof of a goal of the form $P \leftrightarrow Q$ the steps in the proof of $Q \rightarrow P$ are the same as the steps used to prove $P \rightarrow Q$, but in reverse order. In this case you may be able to simplify the proof by writing it as a string of equivalences, starting with P and ending with Q . For example, suppose you found that you could prove $P \rightarrow Q$ by first assuming P , then using P to infer some other statement R , and then using R to deduce Q ; and suppose that the same steps could be used, in reverse order, to prove that $Q \rightarrow P$. In other words, you could assume Q , use this assumption to conclude that R was true, and then use R to prove P . Since you would be asserting both $P \rightarrow R$ and $R \rightarrow P$, you could sum up these two steps by saying $P \leftrightarrow R$. Similarly, the other two steps of the proof tell you that $R \leftrightarrow Q$. These two statements imply the goal $P \leftrightarrow Q$. Mathematicians sometimes present this kind of proof by simply writing the string of equivalences

$$P \text{ iff } R \text{ iff } Q.$$

You can think of this as an abbreviation for “ P iff R and R iff Q (and therefore P iff Q).” This is illustrated in the next example.

Example 3.4.5. Suppose A , B , and C are sets. Prove that $A \cap (B \setminus C) = (A \cap B) \setminus C$.

Scratch work

As we saw in Chapter 2, the equation $A \cap (B \setminus C) = (A \cap B) \setminus C$ means $\forall x (x \in A \cap (B \setminus C) \leftrightarrow x \in (A \cap B) \setminus C)$, but it is also equivalent to the statement $[A \cap (B \setminus C) \subseteq (A \cap B) \setminus C] \wedge [(A \cap B) \setminus C \subseteq A \cap (B \setminus C)]$.

This suggests two approaches to the proof. We could let x be arbitrary and then prove $x \in A \cap (B \setminus C) \leftrightarrow x \in (A \cap B) \setminus C$, or we could prove the two statements $A \cap (B \setminus C) \subseteq (A \cap B) \setminus C$ and $(A \cap B) \setminus C \subseteq A \cap (B \setminus C)$. In fact, almost every proof that two sets are equal will involve one of these two approaches. In this case we will use the first approach, so once we have introduced our arbitrary x , we will have an iff goal.

For the (\rightarrow) half of the proof we assume $x \in A \cap (B \setminus C)$ and try to prove $x \in (A \cap B) \setminus C$:

<i>Givens</i>	<i>Goal</i>
$x \in A \cap (B \setminus C)$	$x \in (A \cap B) \setminus C$

To see the logical forms of the given and goal, we write out their definitions as follows:

$$x \in A \cap (B \setminus C) \text{ iff } x \in A \wedge x \in B \setminus C \text{ iff } x \in A \wedge x \in B \wedge x \notin C;$$

$$x \in (A \cap B) \setminus C \text{ iff } x \in A \cap B \wedge x \notin C \text{ iff } x \in A \wedge x \in B \wedge x \notin C.$$

At this point it is clear that the given implies the goal, since the last steps in both strings of equivalences turned out to be identical. In fact, it is also clear that the reasoning involved in the (\leftarrow) direction of the proof will be exactly the same, but with the given and goal columns reversed. Thus, we might try to shorten the proof by writing it as a string of equivalences, starting with $x \in A \cap (B \setminus C)$ and ending with $x \in (A \cap B) \setminus C$. In this case, if we start with $x \in A \cap (B \setminus C)$ and follow the first string of equivalences displayed above, we come to a statement that is the same as the last statement in the second string of equivalences. We can then continue by following the second string of equivalences *backward*, ending with $x \in (A \cap B) \setminus C$.

Solution

Theorem. Suppose A , B , and C are sets. Then $A \cap (B \setminus C) = (A \cap B) \setminus C$.

Proof. Let x be arbitrary. Then

$$\begin{aligned} x \in A \cap (B \setminus C) &\text{ iff } x \in A \wedge x \in B \setminus C \\ &\text{ iff } x \in A \wedge x \in B \wedge x \notin C \\ &\text{ iff } x \in (A \cap B) \wedge x \notin C \\ &\text{ iff } x \in (A \cap B) \setminus C. \end{aligned}$$

Thus, $\forall x (x \in A \cap (B \setminus C) \leftrightarrow x \in (A \cap B) \setminus C)$, so $A \cap (B \setminus C) = (A \cap B) \setminus C$.

□

The technique of figuring out a sequence of equivalences in one order and then writing it in the reverse order is used quite often in proofs. The order in which the steps should be written in the final proof is determined by our rule that an assertion should never be made until it can be justified. In particular, if you are trying to prove $P \leftrightarrow Q$, it is wrong to start your write-up of the proof with the unjustified statement $P \leftrightarrow Q$ and then work out the meanings of the two sides P and Q , showing that they are the same. You should instead start with equivalences you can justify and string them together to produce a justification of the goal $P \leftrightarrow Q$ before you assert this goal. A similar technique can sometimes be used to figure out proofs of equations, as the next example shows.

Example 3.4.6. Prove that for any real numbers a and b ,

$$(a + b)^2 - 4(a - b)^2 = (3b - a)(3a - b).$$

Scratch work

The goal has the form $\forall a \forall b((a + b)^2 - 4(a - b)^2 = (3b - a)(3a - b))$, so we start by letting a and b be arbitrary real numbers and try to prove the equation. Multiplying out both sides gives us:

$$\begin{aligned}(a + b)^2 - 4(a - b)^2 &= a^2 + 2ab + b^2 - 4(a^2 - 2ab + b^2) \\ &= -3a^2 + 10ab - 3b^2; \\ (3b - a)(3a - b) &= 9ab - 3a^2 - 3b^2 + ab = -3a^2 + 10ab - 3b^2.\end{aligned}$$

Clearly the two sides are equal. The simplest way to write the proof of this is to write a string of equalities starting with $(a + b)^2 - 4(a - b)^2$ and ending with $(3b - a)(3a - b)$. We can do this by copying down the first string of equalities displayed above, and then following it with the last line, written backward.

Solution

Theorem. For any real numbers a and b ,

$$(a + b)^2 - 4(a - b)^2 = (3b - a)(3a - b).$$

Proof. Let a and b be arbitrary real numbers. Then

$$\begin{aligned}(a + b)^2 - 4(a - b)^2 &= a^2 + 2ab + b^2 - 4(a^2 - 2ab + b^2) \\ &= -3a^2 + 10ab - 3b^2 \\ &= 9ab - 3a^2 - 3b^2 + ab = (3b - a)(3a - b). \quad \square\end{aligned}$$

We end this section by presenting another proof without preliminary scratch work, but with a commentary to help you read the proof.

Theorem 3.4.7. *For every integer n , $6 \mid n$ iff $2 \mid n$ and $3 \mid n$.*

Proof. Let n be an arbitrary integer.

(\rightarrow) Suppose $6 \mid n$. Then we can choose an integer k such that $6k = n$. Therefore $n = 6k = 2(3k)$, so $2 \mid n$, and similarly $n = 6k = 3(2k)$, so $3 \mid n$.

(\leftarrow) Suppose $2 \mid n$ and $3 \mid n$. Then we can choose integers j and k such that $n = 2j$ and $n = 3k$. Therefore $6(j - k) = 6j - 6k = 3(2j) - 2(3k) = 3n - 2n = n$, so $6 \mid n$. \square

Commentary. The statement to be proven is $\forall n \in \mathbb{Z}[6 \mid n \leftrightarrow ((2 \mid n) \wedge (3 \mid n))]$, and the most natural strategy for proving a goal of this form is to let n be arbitrary and then prove both directions of the biconditional separately. It should be clear that this is the strategy being used in the proof.

For the left-to-right direction of the biconditional, we assume $6 \mid n$ and then prove $2 \mid n$ and $3 \mid n$, treating this as two separate goals. The introduction of the integer k is justified by existential instantiation, since the assumption $6 \mid n$ means $\exists k \in \mathbb{Z}(6k = n)$. At this point in the proof we have the following givens and goals:

<i>Givens</i>	<i>Goals</i>
$n \in \mathbb{Z}$	$2 \mid n$
$k \in \mathbb{Z}$	$3 \mid n$
$6k = n$	

The first goal, $2 \mid n$, means $\exists j \in \mathbb{Z}(2j = n)$, so we must find an integer j such that $2j = n$. Although the proof doesn't say so explicitly, the equation $n = 2(3k)$, which is derived in the proof, suggests that the value being used for j is $j = 3k$. Clearly, $3k$ is an integer (another step skipped in the proof), so this choice for j works. The proof of $3 \mid n$ is similar.

For the right-to-left direction we assume $2 \mid n$ and $3 \mid n$ and prove $6 \mid n$. Once again, the introduction of j and k is justified by existential instantiation. No explanation is given for why we should compute $6(j - k)$, but a proof need not provide such explanations. The reason for the calculation should become clear when, surprisingly, it turns out that $6(j - k) = n$. Such surprises provide part of the pleasure of working with proofs. As in the first half of the proof, since $j - k$ is an integer, this shows that $6 \mid n$.

Exercises

- *1. Use the methods of this chapter to prove that $\forall x(P(x) \wedge Q(x))$ is equivalent to $\forall x P(x) \wedge \forall x Q(x)$.
- ^{P_D}2. Prove that if $A \subseteq B$ and $A \subseteq C$ then $A \subseteq B \cap C$.
- ^{P_D}3. Suppose $A \subseteq B$. Prove that for every set C , $C \setminus B \subseteq C \setminus A$.
- ^{P_D}*4. Prove that if $A \subseteq B$ and $A \not\subseteq C$ then $B \not\subseteq C$.
- ^{P_D}5. Prove that if $A \subseteq B \setminus C$ and $A \neq \emptyset$ then $B \not\subseteq C$.
6. Prove that for any sets A , B , and C , $A \setminus (B \cap C) = (A \setminus B) \cup (A \setminus C)$, by finding a string of equivalences starting with $x \in A \setminus (B \cap C)$ and ending with $x \in (A \setminus B) \cup (A \setminus C)$. (See Example 3.4.5.)
- ^{P_D}*7. Use the methods of this chapter to prove that for any sets A and B , $\mathcal{P}(A \cap B) = \mathcal{P}(A) \cap \mathcal{P}(B)$.
- ^{P_D}8. Prove that $A \subseteq B$ iff $\mathcal{P}(A) \subseteq \mathcal{P}(B)$.
- *9. Prove that if x and y are odd integers, then xy is odd.
10. Prove that if x and y are odd integers, then $x - y$ is even.
11. Prove that for every integer n , n^3 is even iff n is even.
12. Consider the following putative theorem:

Theorem? Suppose m is an even integer and n is an odd integer. Then $n^2 - m^2 = n + m$.

- (a) What's wrong with the following proof of the theorem?

Proof. Since m is even, we can choose some integer k such that $m = 2k$. Similarly, since n is odd we have $n = 2k + 1$. Therefore

$$\begin{aligned} n^2 - m^2 &= (2k + 1)^2 - (2k)^2 = 4k^2 + 4k + 1 - 4k^2 = 4k + 1 \\ &= (2k + 1) + (2k) = n + m. \quad \square \end{aligned}$$

- (b) Is the theorem correct? Justify your answer with either a proof or a counterexample.

- *13. Prove that $\forall x \in \mathbb{R}[\exists y \in \mathbb{R}(x + y = xy) \leftrightarrow x \neq 1]$.
14. Prove that $\exists z \in \mathbb{R} \forall x \in \mathbb{R}^+ [\exists y \in \mathbb{R}(y - x = y/x) \leftrightarrow x \neq z]$.
- ^{P_D}15. Suppose B is a set and \mathcal{F} is a family of sets. Prove that $\bigcup\{A \setminus B \mid A \in \mathcal{F}\} \subseteq \bigcup(\mathcal{F} \setminus \mathcal{P}(B))$.
- *16. Suppose \mathcal{F} and \mathcal{G} are nonempty families of sets and every element of \mathcal{F} is disjoint from some element of \mathcal{G} . Prove that $\bigcup \mathcal{F}$ and $\bigcap \mathcal{G}$ are disjoint.
- ^{P_D}17. Prove that for any set A , $A = \bigcup \mathcal{P}(A)$.
- ^{P_D}*18. Suppose \mathcal{F} and \mathcal{G} are families of sets.

- (a) Prove that $\bigcup(\mathcal{F} \cap \mathcal{G}) \subseteq (\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G})$.
 (b) What's wrong with the following proof that $(\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G}) \subseteq \bigcup(\mathcal{F} \cap \mathcal{G})$?

Proof. Suppose $x \in (\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G})$. This means that $x \in \bigcup \mathcal{F}$ and $x \in \bigcup \mathcal{G}$, so $\exists A \in \mathcal{F}(x \in A)$ and $\exists A \in \mathcal{G}(x \in A)$. Thus, we can choose a set A such that $A \in \mathcal{F}$, $A \in \mathcal{G}$, and $x \in A$. Since $A \in \mathcal{F}$ and $A \in \mathcal{G}$, $A \in \mathcal{F} \cap \mathcal{G}$. Therefore $\exists A \in \mathcal{F} \cap \mathcal{G}(x \in A)$, so $x \in \bigcup(\mathcal{F} \cap \mathcal{G})$. Since x was arbitrary, we can conclude that $(\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G}) \subseteq \bigcup(\mathcal{F} \cap \mathcal{G})$. \square

- (c) Find an example of families of sets \mathcal{F} and \mathcal{G} for which $\bigcup(\mathcal{F} \cap \mathcal{G}) \neq (\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G})$.

P_b19. Suppose \mathcal{F} and \mathcal{G} are families of sets. Prove that $(\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G}) \subseteq \bigcup(\mathcal{F} \cap \mathcal{G})$ iff $\forall A \in \mathcal{F} \forall B \in \mathcal{G}(A \cap B \subseteq \bigcup(\mathcal{F} \cap \mathcal{G}))$.

P_b20. Suppose \mathcal{F} and \mathcal{G} are families of sets. Prove that $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint iff for all $A \in \mathcal{F}$ and $B \in \mathcal{G}$, A and B are disjoint.

P_b21. Suppose \mathcal{F} and \mathcal{G} are families of sets.

- (a) Prove that $(\bigcup \mathcal{F}) \setminus (\bigcup \mathcal{G}) \subseteq \bigcup(\mathcal{F} \setminus \mathcal{G})$.
 (b) What's wrong with the following proof that $\bigcup(\mathcal{F} \setminus \mathcal{G}) \subseteq (\bigcup \mathcal{F}) \setminus (\bigcup \mathcal{G})$?

Proof. Suppose $x \in \bigcup(\mathcal{F} \setminus \mathcal{G})$. Then we can choose some $A \in \mathcal{F} \setminus \mathcal{G}$ such that $x \in A$. Since $A \in \mathcal{F} \setminus \mathcal{G}$, $A \in \mathcal{F}$ and $A \notin \mathcal{G}$. Since $x \in A$ and $A \in \mathcal{F}$, $x \in \bigcup \mathcal{F}$. Since $x \in A$ and $A \notin \mathcal{G}$, $x \notin \bigcup \mathcal{G}$. Therefore $x \in (\bigcup \mathcal{F}) \setminus (\bigcup \mathcal{G})$. \square

- (c) Prove that $\bigcup(\mathcal{F} \setminus \mathcal{G}) \subseteq (\bigcup \mathcal{F}) \setminus (\bigcup \mathcal{G})$ iff $\forall A \in (\mathcal{F} \setminus \mathcal{G}) \forall B \in \mathcal{G}(A \cap B = \emptyset)$.
 (d) Find an example of families of sets \mathcal{F} and \mathcal{G} for which $\bigcup(\mathcal{F} \setminus \mathcal{G}) \neq (\bigcup \mathcal{F}) \setminus (\bigcup \mathcal{G})$.

P_b*22. Suppose \mathcal{F} and \mathcal{G} are families of sets. Prove that if $\bigcup \mathcal{F} \not\subseteq \bigcup \mathcal{G}$, then there is some $A \in \mathcal{F}$ such that for all $B \in \mathcal{G}$, $A \not\subseteq B$.

23. Suppose B is a set, $\{A_i \mid i \in I\}$ is an indexed family of sets, and $I \neq \emptyset$.

- (a) What proof strategies are used in the following proof of the equation $B \cap (\bigcup_{i \in I} A_i) = \bigcup_{i \in I} (B \cap A_i)$?

Proof. Let x be arbitrary. Suppose $x \in B \cap (\bigcup_{i \in I} A_i)$. Then $x \in B$ and $x \in \bigcup_{i \in I} A_i$, so we can choose some $i_0 \in I$ such that $x \in A_{i_0}$. Since $x \in B$ and $x \in A_{i_0}$, $x \in B \cap A_{i_0}$. Therefore $x \in \bigcup_{i \in I} (B \cap A_i)$.

Now suppose $x \in \bigcup_{i \in I} (B \cap A_i)$. Then we can choose some $i_0 \in I$ such that $x \in B \cap A_{i_0}$. Therefore $x \in B$ and $x \in A_{i_0}$. Since $x \in A_{i_0}$, $x \in \bigcup_{i \in I} A_i$. Since $x \in B$ and $x \in \bigcup_{i \in I} A_i$, $x \in B \cap (\bigcup_{i \in I} A_i)$.

Since x was arbitrary, we have shown that $\forall x [x \in B \cap (\bigcup_{i \in I} A_i) \leftrightarrow x \in \bigcup_{i \in I} (B \cap A_i)]$, so $B \cap (\bigcup_{i \in I} A_i) = \bigcup_{i \in I} (B \cap A_i)$. \square

(b) Prove that $B \setminus (\bigcup_{i \in I} A_i) = \bigcap_{i \in I} (B \setminus A_i)$.

(c) Can you discover and prove a similar theorem about $B \setminus (\bigcap_{i \in I} A_i)$? (Hint: Try to guess the theorem, and then try to prove it. If you can't finish the proof, it might be because your guess was wrong. Change your guess and try again.)

*24. Suppose $\{A_i \mid i \in I\}$ and $\{B_i \mid i \in I\}$ are indexed families of sets and $I \neq \emptyset$.

(a) Prove that $\bigcup_{i \in I} (A_i \setminus B_i) \subseteq (\bigcup_{i \in I} A_i) \setminus (\bigcap_{i \in I} B_i)$.

(b) Find an example for which $\bigcup_{i \in I} (A_i \setminus B_i) \neq (\bigcup_{i \in I} A_i) \setminus (\bigcap_{i \in I} B_i)$.

25. Suppose $\{A_i \mid i \in I\}$ and $\{B_i \mid i \in I\}$ are indexed families of sets.

(a) Prove that $\bigcup_{i \in I} (A_i \cap B_i) \subseteq (\bigcup_{i \in I} A_i) \cap (\bigcup_{i \in I} B_i)$.

(b) Find an example for which $\bigcup_{i \in I} (A_i \cap B_i) \neq (\bigcup_{i \in I} A_i) \cap (\bigcup_{i \in I} B_i)$.

26. Prove that for all integers a and b there is an integer c such that $a \mid c$ and $b \mid c$.

27. (a) Prove that for every integer n , $15 \mid n$ iff $3 \mid n$ and $5 \mid n$.

(b) Prove that it is *not* true that for every integer n , $60 \mid n$ iff $6 \mid n$ and $10 \mid n$.

3.5. Proofs Involving Disjunctions

Suppose one of your givens in a proof has the form $P \vee Q$. This given tells you that either P or Q is true, but it doesn't tell you which. Thus, there are two possibilities that you must take into account. One way to do the proof would be to consider these two possibilities in turn. In other words, first assume that P is true and use this assumption to prove your goal. Then assume Q is true and give another proof that the goal is true. Although you don't know which of these assumptions is correct, the given $P \vee Q$ tells you that *one* of them must be correct. Whichever one it is, you have shown that it implies the goal. Thus, the goal must be true.

The two possibilities that are considered separately in this type of proof – the possibility that P is true and the possibility that Q is true – are called *cases*. The given $P \vee Q$ justifies the use of these two cases by guaranteeing that these cases cover all of the possibilities. Mathematicians say in this situation that the cases are *exhaustive*. Any proof can be broken into two or more cases at any time, as long as the cases are exhaustive.

To use a given of the form $P \vee Q$:

Break your proof into cases. For case 1, assume that P is true and use this assumption to prove the goal. For case 2, assume Q is true and give another proof of the goal.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
$P \vee Q$	—
—	

After using strategy:

Case 1:	<i>Givens</i>	<i>Goal</i>
	P	—
	—	
Case 2:	<i>Givens</i>	<i>Goal</i>
	Q	—
	—	

Form of final proof:

Case 1. P is true.

[Proof of goal goes here.]

Case 2. Q is true.

[Proof of goal goes here.]

Since we know $P \vee Q$, these cases cover all the possibilities. Therefore the goal must be true.

Example 3.5.1. Suppose that A , B , and C are sets. Prove that if $A \subseteq C$ and $B \subseteq C$ then $A \cup B \subseteq C$.

Scratch work

We assume $A \subseteq C$ and $B \subseteq C$ and prove $A \cup B \subseteq C$. Writing out the goal using logical symbols gives us the following givens and goal:

<i>Givens</i>	<i>Goal</i>
$A \subseteq C$	$\forall x(x \in A \cup B \rightarrow x \in C)$
$B \subseteq C$	

To prove the goal we let x be arbitrary, assume $x \in A \cup B$, and try to prove $x \in C$. Thus, we now have a new given $x \in A \cup B$, which we write as $x \in A \vee x \in B$, and our goal is now $x \in C$.

<i>Givens</i>	<i>Goal</i>
$A \subseteq C$	$x \in C$
$B \subseteq C$	
$x \in A \vee x \in B$	

Because the goal cannot be analyzed any further at this point, we look more closely at the givens. The first given will be useful if we ever come across an object that is an element of A , since it would allow us to conclude immediately that this object must also be an element of C . Similarly, the second given will be useful if we come across an element of B . Keeping in mind that we should watch for any elements of A or B that might come up, we move on to the third given. Because this given has the form $P \vee Q$, we try proof by cases. For the first case we assume $x \in A$, and for the second we assume $x \in B$. In the first case we therefore have the following givens and goal:

<i>Givens</i>	<i>Goal</i>
$A \subseteq C$	$x \in C$
$B \subseteq C$	
$x \in A$	

We've already decided that if we ever come across an element of A , we can use the first given to conclude that it is also an element of C . Since we now have $x \in A$ as a given, we can conclude that $x \in C$, which is our goal. The reasoning for the second case is quite similar, using the second given instead of the first.

Solution

Theorem. *Suppose that A , B , and C are sets. If $A \subseteq C$ and $B \subseteq C$ then $A \cup B \subseteq C$.*

Proof. Suppose $A \subseteq C$ and $B \subseteq C$, and let x be an arbitrary element of $A \cup B$. Then either $x \in A$ or $x \in B$.

Case 1. $x \in A$. Then since $A \subseteq C$, $x \in C$.

Case 2. $x \in B$. Then since $B \subseteq C$, $x \in C$.

Since we know that either $x \in A$ or $x \in B$, these cases cover all the possibilities, so we can conclude that $x \in C$. Since x was an arbitrary element of $A \cup B$, this means that $A \cup B \subseteq C$. \square

Note that the cases in this proof are not *exclusive*. In other words, it is possible for both $x \in A$ and $x \in B$ to be true, so some values of x might fall under both cases. There is nothing wrong with this. The cases in a proof

by cases must cover all possibilities, but there is no harm in covering some possibilities more than once. In other words, the cases must be exhaustive, but they need not be exclusive.

Proof by cases is sometimes also helpful if you are proving a goal of the form $P \vee Q$. If you can prove P in some cases and Q in others, then as long as your cases are exhaustive you can conclude that $P \vee Q$ is true. This method is particularly useful if one of the givens also has the form of a disjunction, because then you can use the cases suggested by this given.

To prove a goal of the form $P \vee Q$:

Break your proof into cases. In each case, either prove P or prove Q .

Example 3.5.2. Suppose that A , B , and C are sets. Prove that $A \setminus (B \setminus C) \subseteq (A \setminus B) \cup C$.

Scratch work

Because the goal is $\forall x(x \in A \setminus (B \setminus C) \rightarrow x \in (A \setminus B) \cup C)$, we let x be arbitrary, assume $x \in A \setminus (B \setminus C)$, and try to prove $x \in (A \setminus B) \cup C$. Writing these statements out in logical symbols gives us:

$$\begin{array}{ll} \text{Givens} & \text{Goal} \\ x \in A \wedge \neg(x \in B \wedge x \notin C) & (x \in A \wedge x \notin B) \vee x \in C \end{array}$$

We split the given into two separate givens, $x \in A$ and $\neg(x \in B \wedge x \notin C)$, and since the second is a negated statement we use one of De Morgan's laws to reexpress it as the positive statement $x \notin B \vee x \in C$.

$$\begin{array}{ll} \text{Givens} & \text{Goal} \\ x \in A & (x \in A \wedge x \notin B) \vee x \in C \\ x \notin B \vee x \in C & \end{array}$$

Now the second given and the goal are both disjunctions, so we'll try considering the two cases $x \notin B$ and $x \in C$ suggested by the second given. According to our strategy for proving goals of the form $P \vee Q$, if in each case we can either prove $x \in A \wedge x \notin B$ or prove $x \in C$, then the proof will be complete. For the first case we assume $x \notin B$.

$$\begin{array}{ll} \text{Givens} & \text{Goal} \\ x \in A & (x \in A \wedge x \notin B) \vee x \in C \\ x \notin B & \end{array}$$

In this case the goal is clearly true, because in fact we can conclude that $x \in A \wedge x \notin B$. For the second case we assume $x \in C$, and once again the goal is clearly true.

Solution

Theorem. Suppose that A , B , and C are sets. Then $A \setminus (B \setminus C) \subseteq (A \setminus B) \cup C$.

Proof. Suppose $x \in A \setminus (B \setminus C)$. Then $x \in A$ and $x \notin B \setminus C$. Since $x \notin B \setminus C$, it follows that either $x \notin B$ or $x \in C$. We will consider these cases separately.

Case 1. $x \notin B$. Then since $x \in A$, $x \in A \setminus B$, so $x \in (A \setminus B) \cup C$.

Case 2. $x \in C$. Then clearly $x \in (A \setminus B) \cup C$.

Since x was an arbitrary element of $A \setminus (B \setminus C)$, we can conclude that $A \setminus (B \setminus C) \subseteq (A \setminus B) \cup C$. \square

Sometimes you may find it useful to break a proof into cases even if the cases are not suggested by a given of the form $P \vee Q$. Any proof can be broken into cases at any time, as long as the cases exhaust all of the possibilities.

Example 3.5.3. Prove that for every integer x , the remainder when x^2 is divided by 4 is either 0 or 1.

Scratch work

We start by letting x be an arbitrary integer and then try to prove that the remainder when x^2 is divided by 4 is either 0 or 1.

Givens

$$x \in \mathbb{Z}$$

Goal

$$(x^2 \div 4 \text{ has remainder } 0) \vee (x^2 \div 4 \text{ has remainder } 1)$$

Because the goal is a disjunction, breaking the proof into cases seems like a likely approach, but there is no given that suggests what cases to use. However, trying out a few values for x suggests the right cases:

x	x^2	quotient of $x^2 \div 4$	remainder of $x^2 \div 4$
1	1	0	1
2	4	1	0
3	9	2	1
4	16	4	0
5	25	6	1
6	36	9	0

It appears that the remainder is 0 when x is even and 1 when x is odd. These are the cases we will use. Thus, for case 1 we assume x is even and try to prove that the remainder is 0, and for case 2 we assume x is odd and prove that the remainder is 1. Because every integer is either even or odd, these cases are exhaustive.

Filling in the definition of *even*, here are our givens and goal for case 1:

<i>Givens</i>	<i>Goal</i>
$x \in \mathbb{Z}$	$x^2 \div 4$ has remainder 0
$\exists k \in \mathbb{Z}(x = 2k)$	

We immediately use the second given and let k stand for some particular integer for which $x = 2k$. Then $x^2 = (2k)^2 = 4k^2$, so clearly when we divide x^2 by 4 the quotient is k^2 and the remainder is 0.

Case 2 is quite similar:

<i>Givens</i>	<i>Goal</i>
$x \in \mathbb{Z}$	$x^2 \div 4$ has remainder 1
$\exists k \in \mathbb{Z}(x = 2k + 1)$	

Once again we use the second given immediately and let k stand for an integer for which $x = 2k + 1$. Then $x^2 = (2k + 1)^2 = 4k^2 + 4k + 1 = 4(k^2 + k) + 1$, so when x^2 is divided by 4 the quotient is $k^2 + k$ and the remainder is 1.

Solution

Theorem. *For every integer x , the remainder when x^2 is divided by 4 is either 0 or 1.*

Proof. Suppose x is an integer. We consider two cases.

Case 1. x is even. Then $x = 2k$ for some integer k , so $x^2 = 4k^2$. Clearly the remainder when x^2 is divided by 4 is 0.

Case 2. x is odd. Then $x = 2k + 1$ for some integer k , so $x^2 = 4k^2 + 4k + 1 = 4(k^2 + k) + 1$. Clearly in this case the remainder when x^2 is divided by 4 is 1. □

Sometimes in a proof of a goal that has the form $P \vee Q$ it is hard to figure out how to break the proof into cases. Here's a way of doing it that is often helpful. Simply assume that P is true in case 1 and assume that it is false in case 2. Certainly P is either true or false, so these cases are exhaustive. In the first case you have assumed that P is true, so certainly the goal $P \vee Q$ is true. Thus, no further reasoning is needed in case 1. In the second case you have assumed that P is false, so the only way the goal $P \vee Q$ could be true is if Q is true. Thus, to complete this case you should try to prove Q .

To prove a goal of the form $P \vee Q$:

If P is true, then clearly the goal $P \vee Q$ is true, so you only need to worry about the case in which P is false. You can complete the proof in this case by proving that Q is true.

Scratch work

Before using strategy:

<i>Givens</i>	<i>Goal</i>
—	$P \vee Q$
—	

After using strategy:

<i>Givens</i>	<i>Goal</i>
—	Q
—	
$\neg P$	

Form of final proof:

If P is true, then of course $P \vee Q$ is true. Now suppose P is false.

[Proof of Q goes here.]

Thus, $P \vee Q$ is true.

Thus, this strategy for proving $P \vee Q$ suggests that you transform the problem by adding $\neg P$ as a new given and changing the goal to Q . It is interesting to note that this is exactly the same as the transformation you would use if you were proving the goal $\neg P \rightarrow Q$! This is not really surprising, because we already know that the statements $P \vee Q$ and $\neg P \rightarrow Q$ are equivalent. But we derived this equivalence before from the truth table for the conditional connective, and this truth table may have been hard to understand at first. Perhaps the reasoning we've given makes this equivalence, and therefore the truth table for the conditional connective, seem more natural.

Of course, the roles of P and Q could be reversed in using this strategy. Thus, you can also prove $P \vee Q$ by assuming that Q is false and proving P .

Example 3.5.4. Prove that for every real number x , if $x^2 \geq x$ then either $x \leq 0$ or $x \geq 1$.

Scratch work

Our goal is $\forall x(x^2 \geq x \rightarrow (x \leq 0 \vee x \geq 1))$, so to get started we let x be an arbitrary real number, assume $x^2 \geq x$, and set $x \leq 0 \vee x \geq 1$ as our goal:

<i>Givens</i>	<i>Goal</i>
$x^2 \geq x$	$x \leq 0 \vee x \geq 1$

According to our strategy, to prove this goal we can either assume $x > 0$ and prove $x \geq 1$ or assume $x < 1$ and prove $x \leq 0$. The assumption that x is positive seems more likely to be useful in reasoning about inequalities, so we take the first approach.

<i>Givens</i>	<i>Goal</i>
$x^2 \geq x$	$x \geq 1$
$x > 0$	

The proof is now easy. Since $x > 0$, we can divide the given inequality $x^2 \geq x$ by x to get the goal $x \geq 1$.

Solution

Theorem. For every real number x , if $x^2 \geq x$ then either $x \leq 0$ or $x \geq 1$.

Proof. Suppose $x^2 \geq x$. If $x \leq 0$, then of course $x \leq 0$ or $x \geq 1$. Now suppose $x > 0$. Then we can divide both sides of the inequality $x^2 \geq x$ by x to conclude that $x \geq 1$. Thus, either $x \leq 0$ or $x \geq 1$. □

The equivalence of $P \vee Q$ and $\neg P \rightarrow Q$ also suggests a rule of inference called *disjunctive syllogism* for using a given statement of the form $P \vee Q$:

To use a given of the form $P \vee Q$:

If you are also given $\neg P$, or you can prove that P is false, then you can use this given to conclude that Q is true. Similarly, if you are given $\neg Q$ or can prove that Q is false, then you can conclude that P is true.

In fact, this rule is the one we used in our first example of deductive reasoning in Chapter 1!

Once again, we end this section with a proof for you to read without the benefit of a preliminary scratch work analysis.

Theorem 3.5.5. Suppose m and n are integers. If mn is even, then either m is even or n is even.

Proof. Suppose mn is even. Then we can choose an integer k such that $mn = 2k$. If m is even then there is nothing more to prove, so suppose m is odd. Then $m = 2j + 1$ for some integer j . Substituting this into the equation $mn = 2k$, we get $(2j + 1)n = 2k$, so $2jn + n = 2k$, and therefore $n = 2k - 2jn = 2(k - jn)$. Since $k - jn$ is an integer, it follows that n is even. □

Commentary. The overall form of the proof is the following:

Suppose mn is even.

If m is even, then clearly either m is even or n is even. Now suppose m is not even. Then m is odd.

[Proof that n is even goes here.]

Therefore either m is even or n is even.

Therefore if mn is even then either m is even or n is even.

The assumptions that mn is even and m is odd lead, by existential instantiation, to the equations $mn = 2k$ and $m = 2j + 1$. Although the proof doesn't say so explicitly, you are expected to work out for yourself that in order to prove that n is even it suffices to find an integer c such that $n = 2c$. Straightforward algebra leads to the equation $n = 2(k - jn)$, so the choice $c = k - jn$ works.

Exercises

- P_D^* 1. Suppose A , B , and C are sets. Prove that $A \cap (B \cup C) \subseteq (A \cap B) \cup C$.
- P_D 2. Suppose A , B , and C are sets. Prove that $(A \cup B) \setminus C \subseteq A \cup (B \setminus C)$.
- P_D 3. Suppose A and B are sets. Prove that $A \setminus (A \setminus B) = A \cap B$.
- P_D 4. Suppose A , B , and C are sets. Prove that $A \setminus (B \setminus C) = (A \setminus B) \cup (A \cap C)$.
- P_D^* 5. Suppose $A \cap C \subseteq B \cap C$ and $A \cup C \subseteq B \cup C$. Prove that $A \subseteq B$.
- P_D 6. Recall from Section 1.4 that the symmetric difference of two sets A and B is the set $A \oplus B = (A \setminus B) \cup (B \setminus A) = (A \cup B) \setminus (A \cap B)$. Prove that if $A \oplus B \subseteq A$ then $B \subseteq A$.
- P_D 7. Suppose A , B , and C are sets. Prove that $A \cup C \subseteq B \cup C$ iff $A \setminus C \subseteq B \setminus C$.
- P_D^* 8. Prove that for any sets A and B , $\mathcal{P}(A) \cup \mathcal{P}(B) \subseteq \mathcal{P}(A \cup B)$.
- P_D 9. Prove that for any sets A and B , if $\mathcal{P}(A) \cup \mathcal{P}(B) = \mathcal{P}(A \cup B)$ then either $A \subseteq B$ or $B \subseteq A$.
10. Suppose x and y are real numbers and $x \neq 0$. Prove that $y + 1/x = 1 + y/x$ iff either $x = 1$ or $y = 1$.
11. Prove that for every real number x , if $|x - 3| > 3$ then $x^2 > 6x$. (Hint: According to the definition of $|x - 3|$, if $x - 3 \geq 0$ then $|x - 3| = x - 3$, and if $x - 3 < 0$ then $|x - 3| = 3 - x$. The easiest way to use this fact is to break your proof into cases. Assume that $x - 3 \geq 0$ in case 1, and $x - 3 < 0$ in case 2.)

- *12. Prove that for every real number x , $|2x - 6| > x$ iff $|x - 4| > 2$. (Hint: Read the hint for exercise 11.)
13. (a) Prove that for all real numbers a and b , $|a| \leq b$ iff $-b \leq a \leq b$.
 (b) Prove that for any real number x , $-|x| \leq x \leq |x|$. (Hint: Use part (a).)
 (c) Prove that for all real numbers x and y , $|x + y| \leq |x| + |y|$. (This is called the *triangle inequality*. One way to prove this is to combine parts (a) and (b), but you can also do it by considering a number of cases.)
 (d) Prove that for all real numbers x and y , $|x + y| \geq |x| - |y|$. (Hint: Start with the equation $|x| = |(x + y) + (-y)|$ and then apply the triangle inequality to the right-hand side.)
14. Prove that for every integer x , $x^2 + x$ is even.
15. Prove that for every integer x , the remainder when x^4 is divided by 8 is either 0 or 1.
- *16. Suppose \mathcal{F} and \mathcal{G} are nonempty families of sets.
 P_D (a) Prove that $\bigcup(\mathcal{F} \cup \mathcal{G}) = (\bigcup \mathcal{F}) \cup (\bigcup \mathcal{G})$.
 (b) Can you discover and prove a similar theorem about $\bigcap(\mathcal{F} \cup \mathcal{G})$?
17. Suppose \mathcal{F} is a nonempty family of sets and B is a set.
 P_D (a) Prove that $B \cup (\bigcup \mathcal{F}) = \bigcup(\mathcal{F} \cup \{B\})$.
 (b) Prove that $B \cup (\bigcap \mathcal{F}) = \bigcap_{A \in \mathcal{F}} (B \cup A)$.
 (c) Can you discover and prove similar theorems about $B \cap (\bigcup \mathcal{F})$ and $B \cap (\bigcap \mathcal{F})$?
18. Suppose \mathcal{F} , \mathcal{G} , and \mathcal{H} are nonempty families of sets and for every $A \in \mathcal{F}$ and every $B \in \mathcal{G}$, $A \cup B \in \mathcal{H}$. Prove that $\bigcap \mathcal{H} \subseteq (\bigcap \mathcal{F}) \cup (\bigcap \mathcal{G})$.
- P_D 19. Suppose A and B are sets. Prove that $\forall x(x \in A \supset B \leftrightarrow (x \in A \leftrightarrow x \notin B))$.
- P_D *20. Suppose A , B , and C are sets. Prove that $A \supset B$ and C are disjoint iff $A \cap C = B \cap C$.
- P_D 21. Suppose A , B , and C are sets. Prove that $A \supset B \subseteq C$ iff $A \cup C = B \cup C$.
- P_D 22. Suppose A , B , and C are sets. Prove that $C \subseteq A \supset B$ iff $C \subseteq A \cup B$ and $A \cap B \cap C = \emptyset$.
- P_D *23. Suppose A , B , and C are sets.
 (a) Prove that $A \setminus C \subseteq (A \setminus B) \cup (B \setminus C)$.
 (b) Prove that $A \supset C \subseteq (A \supset B) \cup (B \supset C)$.
- P_D *24. Suppose A , B , and C are sets.
 (a) Prove that $(A \cup B) \supset C \subseteq (A \supset C) \cup (B \supset C)$.
 (b) Find an example of sets A , B , and C such that $(A \cup B) \supset C \not\subseteq (A \supset C) \cup (B \supset C)$.
- P_D 25. Suppose A , B , and C are sets.
 (a) Prove that $(A \supset C) \cap (B \supset C) \subseteq (A \cap B) \supset C$.

- (b) Is it always true that $(A \cap B)^3 \subseteq (A^3 \cap B^3)$? Give either a proof or a counterexample.
- ^b26. Suppose A , B , and C are sets. Consider the sets $(A \setminus B)^3 \cap C$ and $(A^3 \cap C) \setminus (B^3 \cap C)$. Can you prove that either is a subset of the other? Justify your conclusions with either proofs or counterexamples.
- *27. Consider the following putative theorem.

Theorem? For every real number x , if $|x - 3| < 3$ then $0 < x < 6$.

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct?

Proof. Let x be an arbitrary real number, and suppose $|x - 3| < 3$. We consider two cases:

Case 1. $x - 3 \geq 0$. Then $|x - 3| = x - 3$. Plugging this into the assumption that $|x - 3| < 3$, we get $x - 3 < 3$, so clearly $x < 6$.

Case 2. $x - 3 < 0$. Then $|x - 3| = 3 - x$, so the assumption $|x - 3| < 3$ means that $3 - x < 3$. Therefore $3 < 3 + x$, so $0 < x$.

Since we have proven both $0 < x$ and $x < 6$, we can conclude that $0 < x < 6$. □

28. Consider the following putative theorem.

Theorem? For any sets A , B , and C , if $A \setminus B \subseteq C$ and $A \not\subseteq C$ then $A \cap B \cong \emptyset$.

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct?

Proof. Suppose $A \setminus B \subseteq C$ and $A \not\subseteq C$. Since $A \not\subseteq C$, we can choose some x such that $x \in A$ and $x \notin C$. Since $x \notin C$ and $A \setminus B \subseteq C$, $x \notin A \setminus B$. Therefore either $x \notin A$ or $x \in B$. But we already know that $x \in A$, so it follows that $x \in B$. Since $x \in A$ and $x \in B$, $x \in A \cap B$. Therefore $A \cap B \cong \emptyset$. □

- *29. Consider the following putative theorem.

Theorem? $\forall x \in \mathbb{R} \exists y \in \mathbb{R} (xy^2 \cong y - x)$.

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct?

Proof. Let x be an arbitrary real number.

Case 1. $x = 0$. Let $y = 1$. Then $xy^2 = 0$ and $y - x = 1 - 0 = 1$, so $xy^2 \neq y - x$.

Case 2. $x \neq 0$. Let $y = 0$. Then $xy^2 = 0$ and $y - x = -x \neq 0$, so $xy^2 \neq y - x$.

Since these cases are exhaustive, we have shown that $\exists y \in \mathbb{R}(xy^2 \neq y - x)$. Since x was arbitrary, this shows that $\forall x \in \mathbb{R} \exists y \in \mathbb{R}(xy^2 \neq y - x)$. \square

30. Prove that if $\forall x P(x) \rightarrow \exists x Q(x)$ then $\exists x(P(x) \rightarrow Q(x))$. (Hint: Remember that $P \rightarrow Q$ is equivalent to $\neg P \vee Q$.)

*31. Consider the following putative theorem.

Theorem? Suppose A , B , and C are sets and $A \subseteq B \cup C$. Then either $A \subseteq B$ or $A \subseteq C$.

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct?

Proof. Let x be an arbitrary element of A . Since $A \subseteq B \cup C$, it follows that either $x \in B$ or $x \in C$.

Case 1. $x \in B$. Since x was an arbitrary element of A , it follows that $\forall x \in A(x \in B)$, which means that $A \subseteq B$.

Case 2. $x \in C$. Similarly, since x was an arbitrary element of A , we can conclude that $A \subseteq C$.

Thus, either $A \subseteq B$ or $A \subseteq C$. \square

^P32. Suppose A , B , and C are sets and $A \subseteq B \cup C$. Prove that either $A \subseteq B$ or $A \cap C \neq \emptyset$.

33. Prove $\exists x(P(x) \rightarrow \forall y P(y))$. (Note: Assume the universe of discourse is not the empty set.)

3.6. Existence and Uniqueness Proofs

In this section we consider proofs in which the goal has the form $\exists! x P(x)$. Recall that this formula means “there is exactly one x such that $P(x)$,” and as we saw in Section 2.2, it can be thought of as an abbreviation for the formula $\exists x(P(x) \wedge \neg \exists y(P(y) \wedge y \neq x))$. According to the proof strategies discussed in previous sections, we could therefore prove this goal by finding a particular value of x for which we could prove both $P(x)$ and $\neg \exists y(P(y) \wedge y \neq x)$.

The last part of this proof would involve proving a negated statement, but we can reexpress it as an equivalent positive statement:

$$\neg \exists y (P(y) \wedge y \neq x)$$

is equivalent to $\forall y (\neg (P(y) \wedge y \neq x))$ (quantifier negation law),

which is equivalent to $\forall y (\neg P(y) \vee y = x)$ (De Morgan's law),

which is equivalent to $\forall y (P(y) \rightarrow y = x)$ (conditional law).

Thus, we see that $\exists! x P(x)$ could also be written as $\exists x (P(x) \wedge \forall y (P(y) \rightarrow y = x))$. In fact, as the next example shows, several other formulas are also equivalent to $\exists! x P(x)$, and they suggest other approaches to proving goals of this form.

Example 3.6.1. Prove that the following formulas are all equivalent:

1. $\exists x (P(x) \wedge \forall y (P(y) \rightarrow y = x))$.
2. $\exists x \forall y (P(y) \leftrightarrow y = x)$.
3. $\exists x P(x) \wedge \forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$.

Scratch work

If we prove directly that each of these statements is equivalent to each of the others, then we will have three biconditionals to prove: statement 1 iff statement 2, statement 1 iff statement 3, and statement 2 iff statement 3. If we prove each biconditional by the methods of Section 3.4, then each will involve two conditional proofs, so we will need a total of six conditional proofs. Fortunately, there is an easier way. We will prove that statement 1 implies statement 2, statement 2 implies statement 3, and statement 3 implies statement 1 – just three conditionals. Although we will not give a separate proof that statement 2 implies statement 1, it will follow from the fact that statement 2 implies statement 3 and statement 3 implies statement 1. Similarly, the other two conditionals follow from the three we will prove. Mathematicians almost always use some such shortcut when proving that several statements are all equivalent. Because we'll be proving three conditional statements, our proof will have three parts, which we will label $1 \rightarrow 2$, $2 \rightarrow 3$, and $3 \rightarrow 1$. We'll need to work out our strategy for the three parts separately.

$1 \rightarrow 2$. We assume statement 1 and prove statement 2. Because statement 1 starts with an existential quantifier, we choose a name, say x_0 , for some object for which both $P(x_0)$ and $\forall y (P(y) \rightarrow y = x_0)$ are true. Thus, we now have the following situation:

<i>Givens</i>	<i>Goal</i>
$P(x_0)$	$\exists x \forall y (P(y) \leftrightarrow y = x)$
$\forall y (P(y) \rightarrow y = x_0)$	

Our goal also starts with an existential quantifier, so to prove it we should try to find a value of x that makes the rest of the statement come out true. Of course, the obvious choice is $x = x_0$. Plugging in x_0 for x , we see that we must now prove $\forall y (P(y) \leftrightarrow y = x_0)$. We let y be arbitrary and prove both directions of the biconditional. The \rightarrow direction is clear by the second given. For the \leftarrow direction, suppose $y = x_0$. We also have $P(x_0)$ as a given, and plugging in y for x_0 in this given we get $P(y)$.

$2 \rightarrow 3$. Statement 2 is an existential statement, so we let x_0 be some object such that $\forall y (P(y) \leftrightarrow y = x_0)$. The goal, statement 3, is a conjunction, so we treat it as two separate goals.

<i>Givens</i>	<i>Goals</i>
$\forall y (P(y) \leftrightarrow y = x_0)$	$\exists x P(x)$
	$\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$

To prove the first goal we must choose a value for x , and of course the obvious value is $x = x_0$ again. Thus, we must prove $P(x_0)$. The natural way to use our only given is to plug in something for y ; and to prove the goal $P(x_0)$, the obvious thing to plug in is x_0 . This gives us $P(x_0) \leftrightarrow x_0 = x_0$. Of course, $x_0 = x_0$ is true, so by the \leftarrow direction of the biconditional, we get $P(x_0)$.

For the second goal, we let y and z be arbitrary, assume $P(y)$ and $P(z)$, and try to prove $y = z$.

<i>Givens</i>	<i>Goal</i>
$\forall y (P(y) \leftrightarrow y = x_0)$	$y = z$
$P(y)$	
$P(z)$	

Plugging in each of y and z in the first given we get $P(y) \leftrightarrow y = x_0$ and $P(z) \leftrightarrow z = x_0$. Since we've assumed $P(y)$ and $P(z)$, this time we use the \rightarrow directions of these biconditionals to conclude that $y = x_0$ and $z = x_0$. Our goal $y = z$ clearly follows.

$3 \rightarrow 1$. Because statement 3 is a conjunction, we treat it as two separate givens. The first is an existential statement, so we let x_0 stand for some object such that $P(x_0)$ is true. To prove statement 1 we again let $x = x_0$, so we have this situation:

<i>Givens</i>	<i>Goal</i>
$P(x_0)$	$P(x_0) \wedge \forall y (P(y) \rightarrow y = x_0)$
$\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$	

We already know the first half of the goal, so we only need to prove the second. For this we let y be arbitrary, assume $P(y)$, and make $y = x_0$ our goal.

<i>Givens</i>	<i>Goal</i>
$P(x_0)$	$y = x_0$
$\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$	
$P(y)$	

But now we know both $P(y)$ and $P(x_0)$, so the goal $y = x_0$ follows from the second given.

Solution

Theorem. *The following are equivalent:*

1. $\exists x (P(x) \wedge \forall y (P(y) \rightarrow y = x))$.
2. $\exists x \forall y (P(y) \leftrightarrow y = x)$.
3. $\exists x P(x) \wedge \forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$.

Proof. $1 \rightarrow 2$. By statement 1, we can let x_0 be some object such that $P(x_0)$ and $\forall y (P(y) \rightarrow y = x_0)$. To prove statement 2 we will show that $\forall y (P(y) \leftrightarrow y = x_0)$. Let y be arbitrary. We already know the \rightarrow direction of the biconditional. For the \leftarrow direction, suppose $y = x_0$. Then since we know $P(x_0)$, we can conclude $P(y)$.

$2 \rightarrow 3$. By statement 2, choose x_0 such that $\forall y (P(y) \leftrightarrow y = x_0)$. Then, in particular, $P(x_0) \leftrightarrow x_0 = x_0$, and since clearly $x_0 = x_0$, it follows that $P(x_0)$ is true. Thus, $\exists x P(x)$. To prove the second half of statement 3, let y and z be arbitrary and suppose $P(y)$ and $P(z)$. Then by our choice of x_0 (as something for which $\forall y (P(y) \leftrightarrow y = x_0)$ is true), it follows that $y = x_0$ and $z = x_0$, so $y = z$.

$3 \rightarrow 1$. By the first half of statement 3, let x_0 be some object such that $P(x_0)$. Statement 1 will follow if we can show that $\forall y (P(y) \rightarrow y = x_0)$, so suppose $P(y)$. Since we now have both $P(x_0)$ and $P(y)$, by the second half of statement 3 we can conclude that $y = x_0$, as required. \square

Because all three of the statements in the theorem are equivalent to $\exists! x P(x)$, we can prove a goal of this form by proving any of the three statements in the theorem. Probably the most common technique for proving a goal of the form $\exists! x P(x)$ is to prove statement 3 of the theorem.

To prove a goal of the form $\exists! x P(x)$:

Prove $\exists x P(x)$ and $\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$. The first of these goals shows that there exists an x such that $P(x)$ is true, and the second shows that it

is unique. The two parts of the proof are therefore sometimes labeled *existence* and *uniqueness*. Each part is proven using strategies discussed earlier.

Form of final proof:

Existence: [Proof of $\exists x P(x)$ goes here.]

Uniqueness: [Proof of $\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$ goes here.]

Example 3.6.2. Prove that there is a unique set A such that for every set B , $A \cup B = B$.

Scratch work

Our goal is $\exists! A P(A)$, where $P(A)$ is the statement $\forall B(A \cup B = B)$. According to our strategy, we can prove this by proving existence and uniqueness separately. For the existence half of the proof we must prove $\exists A P(A)$, so we try to find a value of A that makes $P(A)$ true. There is no formula for finding this set A , but if you think about what the statement $P(A)$ means, you should realize that the right choice is $A = \emptyset$. Plugging this value in for A , we see that to complete the existence half of the proof we must show that $\forall B(\emptyset \cup B = B)$. This is clearly true. (If you're not sure of this, work out the proof!)

For the uniqueness half of the proof we prove $\forall C \forall D ((P(C) \wedge P(D)) \rightarrow C = D)$. To do this, we let C and D be arbitrary, assume $P(C)$ and $P(D)$, and prove $C = D$. Writing out what the statements $P(C)$ and $P(D)$ mean, we have the following givens and goal:

<i>Givens</i>	<i>Goal</i>
$\forall B(C \cup B = B)$	$C = D$
$\forall B(D \cup B = B)$	

To use the givens, we should try to find something to plug in for B in each of them. There is a clever choice that makes the rest of the proof easy: we plug in D for B in the first given, and C for B in the second. This gives us $C \cup D = D$ and $D \cup C = C$. But clearly $C \cup D = D \cup C$. (If you don't see why, prove it!) The goal $C = D$ follows immediately.

Solution

Theorem. *There is a unique set A such that for every set B , $A \cup B = B$.*

Proof. Existence: Clearly $\forall B(\emptyset \cup B = B)$, so \emptyset has the required property.

Uniqueness: Suppose $\forall B(C \cup B = B)$ and $\forall B(D \cup B = B)$. Applying the first of these assumptions to D we see that $C \cup D = D$, and applying the second to C we get $D \cup C = C$. But clearly $C \cup D = D \cup C$, so $C = D$. \square

Sometimes a statement of the form $\exists! x P(x)$ is proven by proving statement 1 from Example 3.6.1. This leads to the following proof strategy.

To prove a goal of the form $\exists! x P(x)$:

Prove $\exists x(P(x) \wedge \forall y(P(y) \rightarrow y = x))$, using strategies from previous sections.

Example 3.6.3. Prove that for every real number x , if $x \neq 2$ then there is a unique real number y such that $2y/(y + 1) = x$.

Scratch work

Our goal is $\forall x(x \neq 2 \rightarrow \exists! y(2y/(y + 1) = x))$. We therefore let x be arbitrary, assume $x \neq 2$, and prove $\exists! y(2y/(y + 1) = x)$. According to the preceding strategy, we can prove this goal by proving the equivalent statement

$$\exists y \left(\frac{2y}{y + 1} = x \wedge \forall z \left(\frac{2z}{z + 1} = x \rightarrow z = y \right) \right).$$

We start by trying to find a value of y that will make the equation $2y/(y + 1) = x$ come out true. In other words, we solve this equation for y :

$$\frac{2y}{y + 1} = x \Rightarrow 2y = x(y + 1) \Rightarrow y(2 - x) = x \Rightarrow y = \frac{x}{2 - x}.$$

Note that we have $x \neq 2$ as a given, so the division by $2 - x$ in the last step makes sense. Of course, these steps will not appear in the proof. We simply let $y = x/(2 - x)$ and try to prove both $2y/(y + 1) = x$ and $\forall z(2z/(z + 1) = x \rightarrow z = y)$.

<i>Givens</i>	<i>Goals</i>
$x \neq 2$	$\frac{2y}{y + 1} = x$
$y = \frac{x}{2 - x}$	$\forall z \left(\frac{2z}{z + 1} = x \rightarrow z = y \right)$

The first goal is easy to verify by simply plugging in $x/(2 - x)$ for y . For the second, we let z be arbitrary, assume $2z/(z + 1) = x$, and prove $z = y$:

<i>Givens</i>	<i>Goal</i>
$x \neq 2$	$z = y$
$y = \frac{x}{2-x}$	
$\frac{2z}{z+1} = x$	

We can show that $z = y$ now by solving for z in the third given:

$$\frac{2z}{z+1} = x \Rightarrow 2z = x(z+1) \Rightarrow z(2-x) = x \Rightarrow z = \frac{x}{2-x} = y.$$

Note that the steps we used here are exactly the same as the steps we used earlier in solving for y . This is a common pattern in existence and uniqueness proofs. Although the scratch work for figuring out an existence proof should not appear in the proof, this scratch work, or reasoning similar to it, can sometimes be used to prove that the object shown to exist is unique.

Solution

Theorem. For every real number x , if $x \neq 2$ then there is a unique real number y such that $2y/(y+1) = x$.

Proof. Let x be an arbitrary real number, and suppose $x \neq 2$. Let $y = x/(2-x)$, which is defined since $x \neq 2$. Then

$$\frac{2y}{y+1} = \frac{2 \frac{x}{2-x}}{\frac{x}{2-x} + 1} = \frac{\frac{2x}{2-x}}{\frac{2}{2-x}} = \frac{2x}{2} = x.$$

To see that this solution is unique, suppose $2z/(z+1) = x$. Then $2z = x(z+1)$, so $z(2-x) = x$. Since $x \neq 2$ we can divide both sides by $2-x$ to get $z = x/(2-x) = y$. \square

The theorem in Example 3.6.1 can also be used to formulate strategies for using givens of the form $\exists! x P(x)$. Once again, statement 3 of the theorem is the one used most often.

To use a given of the form $\exists! x P(x)$:

Treat this as two given statements, $\exists x P(x)$ and $\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$. To use the first statement you should probably choose a name, say x_0 , to stand for some object such that $P(x_0)$ is true. The second tells you that if you ever come across two objects y and z such that $P(y)$ and $P(z)$ are both true, you can conclude that $y = z$.

Example 3.6.4. Suppose A , B , and C are sets, A and B are not disjoint, A and C are not disjoint, and A has exactly one element. Prove that B and C are not disjoint.

Scratch work

<i>Givens</i>	<i>Goal</i>
$A \cap B \neq \emptyset$	$B \cap C \neq \emptyset$
$A \cap C \neq \emptyset$	
$\exists! x(x \in A)$	

We treat the last given as two separate givens, as suggested by our strategy. Writing out the meanings of the other givens and the goal, we have the following situation:

<i>Givens</i>	<i>Goal</i>
$\exists x(x \in A \wedge x \in B)$	$\exists x(x \in B \wedge x \in C)$
$\exists x(x \in A \wedge x \in C)$	
$\exists x(x \in A)$	
$\forall y \forall z((y \in A \wedge z \in A) \rightarrow y = z)$	

To prove the goal, we must find something that is an element of both B and C . To do this, we turn to the givens. The first given tells us that we can choose a name, say b , for something such that $b \in A$ and $b \in B$. Similarly, by the second given we can let c be something such that $c \in A$ and $c \in C$. At this point the third given is redundant. We already know that there's something in A , because in fact we already know that $b \in A$ and $c \in A$. We may as well skip to the last given, which says that if we ever come across two objects that are elements of A , we can conclude that they are equal. But as we have just observed, we know that $b \in A$ and $c \in A$! We can therefore conclude that $b = c$. Since $b \in B$ and $b = c \in C$, we have found something that is an element of both B and C , as required to prove the goal.

Solution

Theorem. Suppose A , B , and C are sets, A and B are not disjoint, A and C are not disjoint, and A has exactly one element. Then B and C are not disjoint.

Proof. Since A and B are not disjoint, we can let b be something such that $b \in A$ and $b \in B$. Similarly, since A and C are not disjoint, there is some object c such that $c \in A$ and $c \in C$. Since A has only one element, we must have $b = c$. Thus $b = c \in B \cap C$ and therefore B and C are not disjoint. \square

Exercises

- *1. Prove that for every real number x there is a unique real number y such that $x^2y = x - y$.
2. Prove that there is a unique real number x such that for every real number y , $xy + x - 4 = 4y$.
3. Prove that for every real number x , if $x \neq 0$ and $x \neq 1$ then there is a unique real number y such that $y/x = y - x$.
- *4. Prove that for every real number x , if $x \neq 0$ then there is a unique real number y such that for every real number z , $zy = z/x$.
5. Recall that if \mathcal{F} is a family of sets, then $\bigcup \mathcal{F} = \{x \mid \exists A(A \in \mathcal{F} \wedge x \in A)\}$. Suppose we define a new set $\bigcup! \mathcal{F}$ by the formula $\bigcup! \mathcal{F} = \{x \mid \exists! A(A \in \mathcal{F} \wedge x \in A)\}$.
- (a) Prove that for any family of sets \mathcal{F} , $\bigcup! \mathcal{F} \subseteq \bigcup \mathcal{F}$.
- (b) A family of sets \mathcal{F} is said to be *pairwise disjoint* if every pair of distinct elements of \mathcal{F} are disjoint; that is, $\forall A \in \mathcal{F} \forall B \in \mathcal{F} (A \neq B \rightarrow A \cap B = \emptyset)$. Prove that for any family of sets \mathcal{F} , $\bigcup! \mathcal{F} = \bigcup \mathcal{F}$ iff \mathcal{F} is pairwise disjoint.
- ^{P_D}*6. Let U be any set.
- (a) Prove that there is a unique $A \in \mathcal{P}(U)$ such that for every $B \in \mathcal{P}(U)$, $A \cup B = B$.
- (b) Prove that there is a unique $A \in \mathcal{P}(U)$ such that for every $B \in \mathcal{P}(U)$, $A \cup B = A$.
- ^{P_D}7. Let U be any set.
- (a) Prove that there is a unique $A \in \mathcal{P}(U)$ such that for every $B \in \mathcal{P}(U)$, $A \cap B = B$.
- (b) Prove that there is a unique $A \in \mathcal{P}(U)$ such that for every $B \in \mathcal{P}(U)$, $A \cap B = A$.
- ^{P_D}8. Let U be any set.
- (a) Prove that for every $A \in \mathcal{P}(U)$ there is a unique $B \in \mathcal{P}(U)$ such that for every $C \in \mathcal{P}(U)$, $C \setminus A = C \cap B$.
- (b) Prove that for every $A \in \mathcal{P}(U)$ there is a unique $B \in \mathcal{P}(U)$ such that for every $C \in \mathcal{P}(U)$, $C \cap A = C \setminus B$.
- ^{P_D}9. Recall that you showed in exercise 14 of Section 1.4 that symmetric difference is associative; in other words, for all sets A , B , and C , $A \triangle (B \triangle C) = (A \triangle B) \triangle C$. You may also find it useful in this problem to note that symmetric difference is clearly commutative; in other words, for all sets A and B , $A \triangle B = B \triangle A$.

- (a) Prove that there is a unique identity element for symmetric difference. In other words, there is a unique set X such that for every set A , $A \oplus X = A$.
- (b) Prove that every set has a unique inverse for the operation of symmetric difference. In other words, for every set A there is a unique set B such that $A \oplus B = X$, where X is the identity element from part (a).
- (c) Prove that for any sets A and B there is a unique set C such that $A \oplus C = B$.
- (d) Prove that for every set A there is a unique set $B \subseteq A$ such that for every set $C \subseteq A$, $B \oplus C = A \setminus C$.
- ^P_D10. Suppose A is a set, and for every family of sets \mathcal{F} , if $\bigcup \mathcal{F} = A$ then $A \in \mathcal{F}$. Prove that A has exactly one element.
- ^P_D*11. Suppose \mathcal{F} is a family of sets that has the property that for every $\mathcal{G} \subseteq \mathcal{F}$, $\bigcup \mathcal{G} \in \mathcal{F}$. Prove that there is a unique set A such that $A \in \mathcal{F}$ and $\forall B \in \mathcal{F} (B \subseteq A)$.
12. (a) Suppose $P(x)$ is a statement with a free variable x . Find a formula, using the logical symbols we have studied, that means “there are exactly two values of x for which $P(x)$ is true.”
- (b) Based on your answer to part (a), design a proof strategy for proving a statement of the form “there are exactly two values of x for which $P(x)$ is true.”
- (c) Prove that there are exactly two solutions to the equation $x^3 = x^2$.
13. (a) Prove that there is a unique real number c such that there is a unique real number x such that $x^2 + 3x + c = 0$. (In other words, there is a unique real number c such that the equation $x^2 + 3x + c = 0$ has exactly one solution.)
- (b) Show that it is *not* the case that there is a unique real number x such that there is a unique real number c such that $x^2 + 3x + c = 0$. (Hint: You should be able to prove that for *every* real number x there is a unique real number c such that $x^2 + 3x + c = 0$.)

3.7. More Examples of Proofs

So far, most of our proofs have involved fairly straightforward applications of the proof techniques we’ve discussed. We end this chapter with a few examples of somewhat more difficult proofs. These proofs use the techniques of this chapter, but for various reasons they’re a little harder than most of our

earlier proofs. Some are simply longer, involving the application of more proof strategies. Some require clever choices of which strategies to use. In some cases it's clear what strategy to use, but some insight is required to see exactly how to use it. Our earlier examples, which were intended only to illustrate and clarify the proof techniques, may have made proof writing seem mechanical and dull. We hope that by studying these more difficult examples you will begin to see that mathematical reasoning can also be surprising and beautiful.

Some proof techniques are particularly difficult to apply. For example, when you're proving a goal of the form $\exists x P(x)$, the obvious way to proceed is to try to find a value of x that makes the statement $P(x)$ true, but sometimes it will not be obvious how to find that value of x . Using a given of the form $\forall x P(x)$ is similar. You'll probably want to plug in a particular value for x , but to complete the proof you may have to make a clever choice of what to plug in. Proofs that must be broken down into cases are also sometimes difficult to figure out. It is sometimes hard to know when to use cases and what cases to use.

We begin by looking again at the proofs from the introduction. Some aspects of these proofs probably seemed somewhat mysterious when you read them in the introduction. See if they make more sense to you now that you have a better understanding of how proofs are constructed. We will present each proof exactly as it appeared in the introduction and then follow it with a commentary discussing the proof techniques used.

Theorem 3.7.1. *Suppose n is an integer larger than 1 and n is not prime. Then $2^n - 1$ is not prime.*

Proof. Since n is not prime, there are positive integers a and b such that $a < n$, $b < n$, and $n = ab$. Let $x = 2^b - 1$ and $y = 1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}$. Then

$$\begin{aligned} xy &= (2^b - 1) \cdot (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) \\ &= 2^b \cdot (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) - (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) \\ &= (2^b + 2^{2b} + 2^{3b} + \cdots + 2^{ab}) - (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) \\ &= 2^{ab} - 1 \\ &= 2^n - 1. \end{aligned}$$

Since $b < n$, we can conclude that $x = 2^b - 1 < 2^n - 1$. Also, since $ab = n > a$, it follows that $b > 1$. Therefore, $x = 2^b - 1 > 2^1 - 1 = 1$, so $y < xy = 2^n - 1$. Thus, we have shown that $2^n - 1$ can be written as the product of two positive integers x and y , both of which are smaller than $2^n - 1$, so $2^n - 1$ is not prime. \square

Commentary. We are given that n is not prime, and we must prove that $2^n - 1$ is not prime. Both of these are negative statements, but fortunately it is easy to reexpress them as positive statements. To say that an integer larger than 1 is not prime means that it can be written as a product of two smaller positive integers. Thus, the hypothesis that n is not prime means $\exists a \in \mathbb{Z}^+ \exists b \in \mathbb{Z}^+ (ab = n \wedge a < n \wedge b < n)$, and what we must prove is that $2^n - 1$ is not prime, which means $\exists x \in \mathbb{Z}^+ \exists y \in \mathbb{Z}^+ (xy = 2^n - 1 \wedge x < 2^n - 1 \wedge y < 2^n - 1)$. In the second sentence of the proof we apply existential instantiation to the hypothesis that n is not prime, and the rest of the proof is devoted to exhibiting numbers x and y with the properties required to prove that $2^n - 1$ is not prime.

As usual in proofs of existential statements, the proof doesn't explain how the values of x and y were chosen, it simply demonstrates that these values work. After the values of x and y have been given, the goal remaining to be proven is $xy = 2^n - 1 \wedge x < 2^n - 1 \wedge y < 2^n - 1$. Of course, this is treated as three separate goals, which are proven one at a time. The proofs of these three goals involve only elementary algebra.

One of the attractive features of this proof is the calculation used to show that $xy = 2^n - 1$. The formulas for x and y are somewhat complicated, and at first their product looks even more complicated. It is a pleasant surprise when most of the terms in this product cancel and, as if by magic, the answer $2^n - 1$ appears. Of course, we can see with hindsight that it was this calculation that motivated the choice of x and y . There is, however, one aspect of this calculation that may bother you. The use of “ \dots ” in the formulas indicates that the proof depends on a pattern in the calculation that is not being spelled out. We'll give a more rigorous proof that $xy = 2^n - 1$ in Chapter 6, after we have introduced the method of proof by mathematical induction (see Theorem 6.5.2).

Theorem 3.7.2. *There are infinitely many prime numbers.*

Proof. Suppose there are only finitely many prime numbers. Let p_1, p_2, \dots, p_n be a list of all prime numbers. Let $m = p_1 p_2 \cdots p_n + 1$. Note that m is not divisible by p_1 , since dividing m by p_1 gives a quotient of $p_2 p_3 \cdots p_n$ and a remainder of 1. Similarly, m is not divisible by any of p_2, p_3, \dots, p_n .

We now use the fact that every integer larger than 1 is either prime or can be written as a product of primes. (We'll see a proof of this fact in Chapter 6 – see Theorem 6.4.2.) Clearly m is larger than 1, so m is either prime or a product of primes. Suppose first that m is prime. Note that m is larger than all of the numbers in the list p_1, p_2, \dots, p_n , so we've found a prime number not in this list. But this contradicts our assumption that this was a list of *all* prime numbers.

Now suppose m is a product of primes. Let q be one of the primes in this product. Then m is divisible by q . But we've already seen that m is not divisible by any of the numbers in the list p_1, p_2, \dots, p_n , so once again we have a contradiction with the assumption that this list included all prime numbers.

Since the assumption that there are finitely many prime numbers has led to a contradiction, there must be infinitely many prime numbers. \square

Commentary. Because *infinite* means *not finite*, the statement of the theorem might be considered to be a negative statement. It is therefore not surprising that the proof proceeds by contradiction. The assumption that there are finitely many primes means that there exists a natural number n such that there are n primes, and the statement that there are n primes means that there is a list of distinct numbers p_1, p_2, \dots, p_n such that every number in the list is prime, and there are no primes that are not in the list. Thus, the second sentence of the proof applies existential instantiation to introduce the numbers n and p_1, p_2, \dots, p_n into the proof. At this point in the proof we have the following situation:

<i>Givens</i>	<i>Goal</i>
p_1, p_2, \dots, p_n are all prime	Contradiction
$\neg \exists q (q \text{ is prime} \wedge q \notin \{p_1, p_2, \dots, p_n\})$	

The second given could be reexpressed as a positive statement, but since we are doing a proof by contradiction, another reasonable approach would be to try to reach a contradiction by proving that $\exists q (q \text{ is prime} \wedge q \notin \{p_1, p_2, \dots, p_n\})$. This is the strategy used in the proof. Thus, the goal for the rest of the proof is to show that there is a prime number not in the list p_1, p_2, \dots, p_n — an “unlisted prime.”

Because our goal is now an existential statement, it is not surprising that the next step in the proof is to introduce the new number m , without any explanation of how m was chosen. What *is* surprising is that m may or may not be the unlisted prime we are looking for. The problem is that m might not be prime. All we can be sure of is that m is either prime or a product of primes. Because this statement is a disjunction, it suggests proof by cases, and this is the method used in the rest of the proof. Although the cases are not explicitly labeled as cases in the proof, it is important to realize that the rest of the proof has the form of a proof by cases. In case 1 we assume that m is prime, and in case 2 we assume that it is a product of primes. In both cases we are able to produce an unlisted prime as required to complete the proof.

Our next proof uses factorial notation. Recall that for any positive integer n , n factorial is the number $n! = 1 \cdot 2 \cdot 3 \cdots n$.

Theorem 3.7.3. For every positive integer n , there is a sequence of n consecutive positive integers containing no primes.

Proof. Suppose n is a positive integer. Let $x = (n + 1)! + 2$. We will show that none of the numbers $x, x + 1, x + 2, \dots, x + (n - 1)$ is prime. Since this is a sequence of n consecutive positive integers, this will prove the theorem.

To see that x is not prime, note that

$$\begin{aligned} x &= 1 \cdot 2 \cdot 3 \cdot 4 \cdots (n + 1) + 2 \\ &= 2 \cdot (1 \cdot 3 \cdot 4 \cdots (n + 1) + 1). \end{aligned}$$

Thus, x can be written as a product of two smaller positive integers, so x is not prime.

Similarly, we have

$$\begin{aligned} x + 1 &= 1 \cdot 2 \cdot 3 \cdot 4 \cdots (n + 1) + 3 \\ &= 3 \cdot (1 \cdot 2 \cdot 4 \cdots (n + 1) + 1), \end{aligned}$$

so $x + 1$ is also not prime. In general, consider any number $x + i$, where $0 \leq i \leq n - 1$. Then we have

$$\begin{aligned} x + i &= 1 \cdot 2 \cdot 3 \cdot 4 \cdots (n + 1) + (i + 2) \\ &= (i + 2) \cdot (1 \cdot 2 \cdot 3 \cdots (i + 1) \cdot (i + 3) \cdots (n + 1) + 1), \end{aligned}$$

so $x + i$ is not prime. □

Commentary. A sequence of n consecutive positive integers is a sequence of the form $x, x + 1, x + 2, \dots, x + (n - 1)$, where x is a positive integer. Thus, the logical form of the statement to be proven is $\forall n > 0 \exists x > 0 \forall (0 \leq i \leq n - 1 \rightarrow x + i \text{ is not prime})$, where all variables range over the integers. The overall plan of the proof is exactly what one would expect for a proof of a statement of this form: we let $n > 0$ be arbitrary, specify a value for x , let i be arbitrary, and then assume that $0 \leq i \leq n - 1$ and prove that $x + i$ is not prime. As in the proof of Theorem 3.7.1, to prove that $x + i$ is not prime we show how to write it as a product of two smaller positive integers.

Before the demonstration that $x + i$ is not prime, where i is an arbitrary integer between 0 and $n - 1$, the proof includes verifications that x and $x + 1$ are not prime. These are completely unnecessary and are only included to make the proof easier to read.

Example 3.7.4. Prove that there is a unique real number m with the following two properties:

1. For every real number x , $x^2 + 2x + 3 \geq m$.
2. If y is any real number with the property that for every real number x , $x^2 + 2x + 3 \geq y$, then $m \geq y$.

Scratch work

It will be convenient to have a name for property 1. We will say that m is a *lower bound* for the expression $x^2 + 2x + 3$ if property 1 holds; that is, if for every real number x , $x^2 + 2x + 3 \geq m$. Property 2 then says that if y is any lower bound for $x^2 + 2x + 3$, then $m \geq y$. In other words, no lower bound can be larger than m , so m is the *greatest* lower bound. (We will have more to say about lower bounds and greatest lower bounds in Section 4.4 of Chapter 4.)

We will have to prove both existence and uniqueness of the number m . For the existence half of the proof, the hardest part is coming up with the right value for m . We can get a hint at how to choose m by completing the square:

$$x^2 + 2x + 3 = x^2 + 2x + 1 + 2 = (x + 1)^2 + 2.$$

Since $(x + 1)^2$ cannot be negative, for every real number x we will have $x^2 + 2x + 3 = (x + 1)^2 + 2 \geq 2$, so $m = 2$ will work in property 1 – in other words, 2 is a lower bound for $x^2 + 2x + 3$. Of course, any smaller number would also be a lower bound, but property 2 requires that m must be the greatest lower bound, so m can't be smaller than 2. Perhaps $m = 2$ is the right choice. Let's see if we can prove property 2 with this choice of m .

To prove that property 2 holds with $m = 2$, we must prove $\forall y[\forall x(x^2 + 2x + 3 \geq y) \rightarrow 2 \geq y]$. The obvious way to proceed is to let y be arbitrary, assume $\forall x(x^2 + 2x + 3 \geq y)$, and then prove $2 \geq y$, which gives us the following situation:

<i>Givens</i>	<i>Goal</i>
$\forall x(x^2 + 2x + 3 \geq y)$	$2 \geq y$

The natural way to use our given is to plug something in for x . Looking at the goal, we see that if only there were a value of x for which $x^2 + 2x + 3 = 2$, then plugging in this value of x in the given would lead directly to the goal. Solving the equation $x^2 + 2x + 3 = 2$, we find that setting $x = -1$ will complete the proof.

We still have to prove uniqueness of m . For this we should assume that m_1 and m_2 are two numbers that have properties 1 and 2, and then prove $m_1 = m_2$. This gives us the following givens and goal:

<i>Givens</i>	<i>Goal</i>
$\forall x(x^2 + 2x + 3 \geq m_1)$	$m_1 = m_2$
$\forall x(x^2 + 2x + 3 \geq m_2)$	
$\forall y[\forall x(x^2 + 2x + 3 \geq y) \rightarrow m_1 \geq y]$	
$\forall y[\forall x(x^2 + 2x + 3 \geq y) \rightarrow m_2 \geq y]$	

We should probably apply universal instantiation to one or more of the givens, but which ones, and what values should we plug in? The key observation is that the first two givens suggest that it would be useful to plug in m_1 or m_2 for y in the third and fourth givens. In fact we will set $y = m_2$ in the third given and $y = m_1$ in the fourth. (You might want to compare this to the strategy we used for the uniqueness proof in Example 3.6.2.) This gives us $m_1 \geq m_2$ and $m_2 \geq m_1$, and the goal $m_1 = m_2$ follows.

Solution

Theorem. *There is a unique real number m with the following two properties:*

1. *For every real number x , $x^2 + 2x + 3 \geq m$.*
2. *If y is any real number with the property that for every real number x , $x^2 + 2x + 3 \geq y$, then $m \geq y$.*

Proof. Existence: Let $m = 2$. To prove property 1, let x be an arbitrary real number. Then

$$x^2 + 2x + 3 = (x + 1)^2 + 2 \geq 2 = m,$$

as required. This shows that 2 is a lower bound for $x^2 + 2x + 3$.

For property 2, let y be an arbitrary number with the property that for every x , $x^2 + 2x + 3 \geq y$. In particular, setting $x = -1$ we find that

$$y \leq (-1)^2 + 2(-1) + 3 = 2 = m.$$

Since y was arbitrary, this proves property 2.

Uniqueness: Suppose m_1 and m_2 both have properties 1 and 2. In other words, m_1 and m_2 are both lower bounds for $x^2 + 2x + 3$, and also if y is any lower bound, then $m_1 \geq y$ and $m_2 \geq y$. Applying this last fact to both $y = m_1$ and $y = m_2$ we get $m_1 \geq m_2$ and $m_2 \geq m_1$, so $m_1 = m_2$. \square

For readers who are familiar with the definition of limits from calculus, we give one more example, showing how proofs involving limits can be worked out using the techniques in this chapter. Readers who are not familiar with this definition should skip this example.

Example 3.7.5. Show that

$$\lim_{x \rightarrow 3} \frac{2x^2 - 5x - 3}{x - 3} = 7.$$

Scratch work

According to the definition of limits, our goal means that for every positive number ϵ there is a positive number δ such that if x is any number such that $0 < |x - 3| < \delta$, then $|(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon$. Translating this into logical symbols, we have

$$\forall \epsilon > 0 \exists \delta > 0 \forall x \left(0 < |x - 3| < \delta \rightarrow \left| \frac{2x^2 - 5x - 3}{x - 3} - 7 \right| < \epsilon \right).$$

We therefore start by letting ϵ be an arbitrary positive number and then try to find a positive number δ for which we can prove

$$\forall x \left(0 < |x - 3| < \delta \rightarrow \left| \frac{2x^2 - 5x - 3}{x - 3} - 7 \right| < \epsilon \right).$$

The scratch work involved in finding δ will not appear in the proof, of course. In the final proof we'll just write "Let $\delta =$ (some positive number)" and then proceed to prove

$$\forall x \left(0 < |x - 3| < \delta \rightarrow \left| \frac{2x^2 - 5x - 3}{x - 3} - 7 \right| < \epsilon \right).$$

Before working out the value of δ , let's figure out what the rest of the proof will look like. Based on the form of the goal at this point, we should proceed by letting x be arbitrary, assuming $0 < |x - 3| < \delta$, and then proving $|(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon$. Thus, the entire proof will have the following form:

Let ϵ be an arbitrary positive number.

Let $\delta =$ (some positive number).

Let x be arbitrary.

Suppose $0 < |x - 3| < \delta$.

[Proof of $|(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon$ goes here.]

Therefore $0 < |x - 3| < \delta \rightarrow |(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon$.

Since x was arbitrary, we can conclude that $\forall x (0 < |x - 3| < \delta \rightarrow |(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon)$.

Therefore $\exists \delta > 0 \forall x (0 < |x - 3| < \delta \rightarrow |(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon)$.

Since ϵ was arbitrary, it follows that $\forall \epsilon > 0 \exists \delta > 0 \forall x (0 < |x - 3| < \delta \rightarrow |(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon)$.

Two steps remain to be worked out. We must decide what value to assign to δ , and we must fill in the proof of $|(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon$. We'll work on the second of these steps first, and in the course of working out this step it will become clear what value we should use for δ . The givens and goal for this second step are as follows:

<i>Givens</i>	<i>Goal</i>
$\epsilon > 0$	$\left \frac{2x^2 - 5x - 3}{x - 3} - 7 \right < \epsilon$
$\delta = (\text{some positive number})$	
$0 < x - 3 < \delta$	

First of all, note that we have $0 < |x - 3|$ as a given, so $x \neq 3$ and therefore the fraction $(2x^2 - 5x - 3)/(x - 3)$ is defined. Factoring the numerator, we find that

$$\begin{aligned} \left| \frac{2x^2 - 5x - 3}{x - 3} - 7 \right| &= \left| \frac{(2x + 1)(x - 3)}{x - 3} - 7 \right| \\ &= |2x + 1 - 7| = |2x - 6| = 2|x - 3|. \end{aligned}$$

Now we also have as a given that $|x - 3| < \delta$, so $2|x - 3| < 2\delta$. Combining this with the previous equation, we get $|(2x^2 - 5x - 3)/(x - 3) - 7| < 2\delta$, and our goal is $|(2x^2 - 5x - 3)/(x - 3) - 7| < \epsilon$. Thus, if we chose δ so that $2\delta = \epsilon$, we'd be done. In other words, we should let $\delta = \epsilon/2$. Note that since $\epsilon > 0$, this is a positive number, as required.

Solution

Theorem. $\lim_{x \rightarrow 3} \frac{2x^2 - 5x - 3}{x - 3} = 7.$

Proof. Suppose $\epsilon > 0$. Let $\delta = \epsilon/2$, which is also clearly positive. Let x be an arbitrary real number, and suppose that $0 < |x - 3| < \delta$. Then

$$\begin{aligned} \left| \frac{2x^2 - 5x - 3}{x - 3} - 7 \right| &= \left| \frac{(2x + 1)(x - 3)}{x - 3} - 7 \right| = |2x + 1 - 7| \\ &= |2x - 6| = 2|x - 3| < 2\delta = 2\left(\frac{\epsilon}{2}\right) = \epsilon. \quad \square \end{aligned}$$

Exercises

- ^P_D*1. Suppose \mathcal{F} is a family of sets. Prove that there is a unique set A that has the following two properties:
- (a) $\mathcal{F} \subseteq \mathcal{P}(A)$.

(b) $\forall B(\mathcal{F} \subseteq \mathcal{P}(B) \rightarrow A \subseteq B)$.

(Hint: First try an example. Let $\mathcal{F} = \{\{1, 2, 3\}, \{2, 3, 4\}, \{3, 4, 5\}\}$. Can you find the set A that has properties (a) and (b)?)

2. Prove that there is a unique positive real number m that has the following two properties:

(a) For every positive real number x , $\frac{x}{x+1} < m$.

(b) If y is any positive real number with the property that for every positive real number x , $\frac{x}{x+1} < y$, then $m \leq y$.

^Pb3. Suppose A and B are sets. What can you prove about $\mathcal{P}(A \setminus B) \setminus (\mathcal{P}(A) \setminus \mathcal{P}(B))$? (No, it's not equal to \emptyset . Try some examples and see what you get.)

^Pb4. Suppose that A , B , and C are sets. Prove that the following statements are equivalent:

(a) $(A \supseteq C) \cap (B \supseteq C) = \emptyset$.

(b) $A \cap B \subseteq C \subseteq A \cup B$. (Note: This is a shorthand way of saying that $A \cap B \subseteq C$ and $C \subseteq A \cup B$.)

(c) $A \supseteq C \subseteq A \supseteq B$.

*5. Suppose $\{A_i \mid i \in I\}$ is a family of sets. Prove that if $\mathcal{P}(\bigcup_{i \in I} A_i) \subseteq \bigcup_{i \in I} \mathcal{P}(A_i)$, then there is some $i \in I$ such that $\forall j \in I (A_j \subseteq A_i)$.

6. Suppose \mathcal{F} is a nonempty family of sets. Let $I = \bigcup \mathcal{F}$ and $J = \bigcap \mathcal{F}$. Suppose also that $J \neq \emptyset$, and notice that it follows that for every $X \in \mathcal{F}$, $X \neq \emptyset$, and also that $I \neq \emptyset$. Finally, suppose that $\{A_i \mid i \in I\}$ is an indexed family of sets.

(a) Prove that $\bigcup_{i \in I} A_i = \bigcup_{X \in \mathcal{F}} (\bigcup_{i \in X} A_i)$.

(b) Prove that $\bigcap_{i \in I} A_i = \bigcap_{X \in \mathcal{F}} (\bigcap_{i \in X} A_i)$.

(c) Prove that $\bigcup_{i \in J} A_i \subseteq \bigcap_{X \in \mathcal{F}} (\bigcup_{i \in X} A_i)$. Is it always the case that $\bigcup_{i \in J} A_i = \bigcap_{X \in \mathcal{F}} (\bigcup_{i \in X} A_i)$? Give either a proof or a counterexample to justify your answer.

(d) Discover and prove a theorem relating $\bigcap_{i \in J} A_i$ and $\bigcup_{X \in \mathcal{F}} (\bigcap_{i \in X} A_i)$.

7. Prove that $\lim_{x \rightarrow 2} \frac{3x^2 - 12}{x - 2} = 12$.

*8. Prove that if $\lim_{x \rightarrow c} f(x) = L$ and $L > 0$, then there is some number $\delta > 0$ such that for all x , if $0 < |x - c| < \delta$ then $f(x) > 0$.

9. Prove that if $\lim_{x \rightarrow c} f(x) = L$ then $\lim_{x \rightarrow c} 7f(x) = 7L$.

*10. Consider the following putative theorem.

Theorem? *There are irrational numbers a and b such that a^b is rational.*

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct? (Note: The proof uses the fact that $\sqrt{2}$ is irrational, which we'll prove in Chapter 6 – see Theorem 6.4.5.)

Proof. Either $\sqrt{\sqrt{2} \sqrt{2}}$ is rational or it's irrational.

Case 1. $\sqrt{\sqrt{2} \sqrt{2}}$ is rational. Let $a = b = \sqrt{2}$. Then a and b are irrational, and $a^b = \sqrt{2}^{\sqrt{2}}$, which we are assuming in this case is rational.

Case 2. $\sqrt{\sqrt{2} \sqrt{2}}$ is irrational. Let $a = \sqrt{\sqrt{2} \sqrt{2}}$ and $b = \sqrt{2}$. Then a is irrational by assumption, and we know that b is also irrational. Also,

$$a^b = \left(\sqrt{\sqrt{2} \sqrt{2}} \right)^{\sqrt{2}} = \sqrt{2}^{\left(\sqrt{2} \sqrt{2} \right)} = \left(\sqrt{2} \right)^2 = 2,$$

which is rational. □

4

Relations

4.1. Ordered Pairs and Cartesian Products

In Chapter 1 we discussed truth sets for statements containing a single free variable. In this chapter we extend this idea to include statements with more than one free variable.

For example, suppose $P(x, y)$ is a statement with two free variables x and y . We can't speak of this statement as being true or false until we have specified two values – one for x and one for y . Thus, if we want the truth set to identify which assignments of values to free variables make the statement come out true, then the truth set will have to contain not individual values, but pairs of values. We will specify a pair of values by writing the two values in parentheses separated by a comma. For example, let $D(x, y)$ mean “ x divides y .” Then $D(6, 18)$ is true, since $6 \mid 18$, so the pair of values $(6, 18)$ is an assignment of values to the variables x and y that makes the statement $D(x, y)$ come out true. Note that 18 does not divide 6, so the pair of values $(18, 6)$ makes the statement $D(x, y)$ false. We must therefore distinguish between the pairs $(18, 6)$ and $(6, 18)$. Because the order of the values in the pair makes a difference, we will refer to a pair (a, b) as an *ordered pair*, with *first coordinate* a and *second coordinate* b .

You have probably seen ordered pairs before when studying points in the xy -plane. The use of x and y coordinates to identify points in the plane works by assigning to each point in the plane an ordered pair, whose coordinates are the x and y coordinates of the point. The pairs must be ordered because, for example, the points $(2, 5)$ and $(5, 2)$ are different points in the plane. In this case the coordinates of the ordered pairs are real numbers, but ordered pairs can have anything at all as their coordinates. For example, suppose we let $C(x, y)$ stand for the statement “ x has y children.” In this statement the variable x ranges over the set of all people, and y ranges over the

set of all natural numbers. Thus, the only ordered pairs it makes sense to consider when discussing assignments of values to the variables x and y in this statement are pairs in which the first coordinate is a person and the second is a natural number. For example, the assignment (Prince Charles, 2) makes the statement $C(x, y)$ come out true, because Prince Charles does have two children, whereas the assignment (Angelina Jolie, 37) makes the statement false. Note that the assignment (2, Prince Charles) makes no sense, because it would lead to the nonsensical statement “2 has Prince Charles children.”

In general, if $P(x, y)$ is a statement in which x ranges over some set A and y ranges over a set B , then the only assignments of values to x and y that will make sense in $P(x, y)$ will be ordered pairs in which the first coordinate is an element of A and the second comes from B . We therefore make the following definition:

Definition 4.1.1. Suppose A and B are sets. Then the *Cartesian product* of A and B , denoted $A \times B$, is the set of all ordered pairs in which the first coordinate is an element of A and the second is an element of B . In other words,

$$A \times B = \{(a, b) \mid a \in A \text{ and } b \in B\}.$$

Example 4.1.2.

1. If $A = \{\text{red, green}\}$ and $B = \{2, 3, 5\}$ then

$$A \times B = \{(\text{red}, 2), (\text{red}, 3), (\text{red}, 5), (\text{green}, 2), (\text{green}, 3), (\text{green}, 5)\}.$$

2. If $P =$ the set of all people then

$$\begin{aligned} P \times \mathbb{N} &= \{(p, n) \mid p \text{ is a person and } n \text{ is a natural number}\} \\ &= \{(\text{Prince Charles}, 0), (\text{Prince Charles}, 1), (\text{Prince Charles}, 2), \dots, \\ &\quad (\text{Angelina Jolie}, 0), (\text{Angelina Jolie}, 1), \dots\}. \end{aligned}$$

These are the ordered pairs that make sense as assignments of values to the free variables x and y in the statement $C(x, y)$.

3. $\mathbb{R} \times \mathbb{R} = \{(x, y) \mid x \text{ and } y \text{ are real numbers}\}$. These are the coordinates of all the points in the plane. For obvious reasons, this set is sometimes written \mathbb{R}^2 .

The introduction of a new mathematical concept gives us an opportunity to practice our proof-writing techniques by proving some basic properties of the new concept. Here’s a theorem giving some basic properties of Cartesian products.

Theorem 4.1.3. *Suppose A , B , C , and D are sets.*

1. $A \times (B \cap C) = (A \times B) \cap (A \times C)$.
2. $A \times (B \cup C) = (A \times B) \cup (A \times C)$.
3. $(A \times B) \cap (C \times D) = (A \cap C) \times (B \cap D)$.
4. $(A \times B) \cup (C \times D) \subseteq (A \cup C) \times (B \cup D)$.
5. $A \times \emptyset = \emptyset \times A = \emptyset$.

Proof of 1. Let p be an arbitrary element of $A \times (B \cap C)$. Then by the definition of Cartesian product, p must be an ordered pair whose first coordinate is an element of A and second coordinate is an element of $B \cap C$. In other words, $p = (x, y)$ for some $x \in A$ and $y \in B \cap C$. Since $y \in B \cap C$, $y \in B$ and $y \in C$. Since $x \in A$ and $y \in B$, $p = (x, y) \in A \times B$, and similarly $p \in A \times C$. Thus, $p \in (A \times B) \cap (A \times C)$. Since p was an arbitrary element of $A \times (B \cap C)$, it follows that $A \times (B \cap C) \subseteq (A \times B) \cap (A \times C)$.

Now let p be an arbitrary element of $(A \times B) \cap (A \times C)$. Then $p \in A \times B$, so $p = (x, y)$ for some $x \in A$ and $y \in B$. Also, $(x, y) = p \in A \times C$, so $y \in C$. Since $y \in B$ and $y \in C$, $y \in B \cap C$. Thus, $p = (x, y) \in A \times (B \cap C)$. Since p was an arbitrary element of $(A \times B) \cap (A \times C)$ we can conclude that $(A \times B) \cap (A \times C) \subseteq A \times (B \cap C)$, so $A \times (B \cap C) = (A \times B) \cap (A \times C)$. \square

Commentary. Before continuing with the proofs of the other parts, we give a brief commentary on the proof just given. Statement 1 is an equation between two sets, so as we saw in Example 3.4.5, there are two natural approaches we could take to prove it. We could prove $\forall p [p \in A \times (B \cap C) \leftrightarrow p \in (A \times B) \cap (A \times C)]$ or we could prove both $A \times (B \cap C) \subseteq (A \times B) \cap (A \times C)$ and $(A \times B) \cap (A \times C) \subseteq A \times (B \cap C)$. In this proof, we have taken the second approach. The first paragraph gives the proof that $A \times (B \cap C) \subseteq (A \times B) \cap (A \times C)$, and the second gives the proof that $(A \times B) \cap (A \times C) \subseteq A \times (B \cap C)$.

In the first of these proofs we take the usual approach of letting p be an arbitrary element of $A \times (B \cap C)$ and then proving $p \in (A \times B) \cap (A \times C)$. Because $p \in A \times (B \cap C)$ means $\exists x \exists y (x \in A \wedge y \in B \cap C \wedge p = (x, y))$, we immediately introduce the variables x and y by existential instantiation. The rest of the proof involves simply working out the definitions of the set theory operations involved. The proof of the opposite inclusion in the second paragraph is similar.

Note that in both parts of this proof we introduced an arbitrary object p that turned out to be an ordered pair, and we were therefore able to say that $p = (x, y)$ for some objects x and y . In most proofs involving Cartesian products mathematicians suppress this step. If it is clear from the beginning

that an object will turn out to be an ordered pair, it is usually just called (x, y) from the outset. We will follow this practice in our proofs.

We leave the proofs of statements 2 and 3 as exercises (see exercise 5).

Proof of 4. Let (x, y) be an arbitrary element of $(A \times B) \cup (C \times D)$. Then either $(x, y) \in A \times B$ or $(x, y) \in C \times D$.

Case 1. $(x, y) \in A \times B$. Then $x \in A$ and $y \in B$, so clearly $x \in A \cup C$ and $y \in B \cup D$. Therefore $(x, y) \in (A \cup C) \times (B \cup D)$.

Case 2. $(x, y) \in C \times D$. A similar argument shows that $(x, y) \in (A \cup C) \times (B \cup D)$.

Since (x, y) was an arbitrary element of $(A \times B) \cup (C \times D)$, it follows that $(A \times B) \cup (C \times D) \subseteq (A \cup C) \times (B \cup D)$. \square

Proof of 5. Suppose $A \times \emptyset \equiv \emptyset$. Then $A \times \emptyset$ has at least one element, and by the definition of Cartesian product this element must be an ordered pair (x, y) for some $x \in A$ and $y \in \emptyset$. But this is impossible, because \emptyset has no elements. Thus, $A \times \emptyset = \emptyset$. The proof that $\emptyset \times A = \emptyset$ is similar. \square

Commentary. Statement 4 says that one set is a subset of another, and the proof follows the usual pattern for statements of this form: we start with an arbitrary element of the first set and then prove that it's an element of the second. It is clear that the arbitrary element of the first set must be an ordered pair, so we have written it as an ordered pair from the beginning.

Thus, for the rest of the proof we have $(x, y) \in (A \times B) \cup (C \times D)$ as a given, and the goal is to prove that $(x, y) \in (A \cup C) \times (B \cup D)$. The given means $(x, y) \in A \times B \vee (x, y) \in C \times D$, so proof by cases is an appropriate strategy. In each case it is easy to prove the goal.

Statement 5 means $A \times \emptyset = \emptyset \wedge \emptyset \times A = \emptyset$, so we treat this as two goals and prove $A \times \emptyset = \emptyset$ and $\emptyset \times A = \emptyset$ separately. To say that a set equals the empty set is actually a negative statement, although it may not look like it on the surface, because it means that the set does *not* have any elements. Thus, it is not surprising that the proof that $A \times \emptyset = \emptyset$ proceeds by contradiction. The assumption that $A \times \emptyset \equiv \emptyset$ means $\exists p(p \in A \times \emptyset)$, so our next step is to introduce a name for an element of $A \times \emptyset$. Once again, it is clear that the new object being introduced in the proof is an ordered pair, so we have written it as an ordered pair (x, y) from the beginning. Writing out the meaning of $(x, y) \in A \times \emptyset$ leads immediately to a contradiction.

The proof that $\emptyset \times A = \emptyset$ is similar, but simply *saying* this doesn't *prove* it. Thus, the claim in the proof that this part of the proof is similar is really an indication that the second half of the proof is being left as an exercise. You should work through the details of this proof in your head (or if necessary write them out on paper) to make sure that a proof similar to the proof in the first half will really work.

Because the order of the coordinates in an ordered pair matters, $A \times B$ and $B \times A$ mean different things. Does it ever happen that $A \times B = B \times A$? Well, one way this could happen is if $A = B$. Clearly if $A = B$ then $A \times B = A \times A = B \times A$. Are there any other possibilities?

Here's an incorrect proof that $A \times B = B \times A$ only if $A = B$: The first coordinates of the ordered pairs in $A \times B$ come from A , and the first coordinates of the ordered pairs in $B \times A$ come from B . But if $A \times B = B \times A$, then the first coordinates in these two sets must be the same, so $A = B$.

This is a good example of why it's important to stick to the rules of proof writing we've studied rather than allowing yourself to be convinced by any reasoning that looks plausible. The informal reasoning in the preceding paragraph is incorrect, and we can find the error by trying to reformulate this reasoning as a formal proof. Suppose $A \times B = B \times A$. To prove that $A = B$ we could let x be arbitrary and then try to prove $x \in A \rightarrow x \in B$ and $x \in B \rightarrow x \in A$. For the first of these we assume $x \in A$ and try to prove $x \in B$. Now the incorrect proof suggests that we should try to show that x is the first coordinate of some ordered pair in $A \times B$ and then use the fact that $A \times B = B \times A$. We could do this by trying to find some object $y \in B$ and then forming the ordered pair (x, y) . Then we would have $(x, y) \in A \times B$ and $A \times B = B \times A$, and it would follow that $(x, y) \in B \times A$ and therefore $x \in B$. But how can we find an object $y \in B$? We don't have any given information about B , other than the fact that $A \times B = B \times A$. In fact, B could be the empty set! This is the flaw in the proof. If $B = \emptyset$, then it will be impossible to choose $y \in B$, and the proof will fall apart. For similar reasons, the other half of the proof won't work if $A = \emptyset$.

Not only have we found the flaw in the proof, but we can now figure out what to do about it. We must take into account the possibility that A or B might be the empty set.

Theorem 4.1.4. *Suppose A and B are sets. Then $A \times B = B \times A$ iff either $A = \emptyset$, $B = \emptyset$, or $A = B$.*

Proof. (\rightarrow) Suppose $A \times B = B \times A$. If either $A = \emptyset$ or $B = \emptyset$, then there is nothing more to prove, so suppose $A \neq \emptyset$ and $B \neq \emptyset$. We will show that $A = B$. Let x be arbitrary, and suppose $x \in A$. Since $B \neq \emptyset$ we can choose some $y \in B$. Then $(x, y) \in A \times B = B \times A$, so $x \in B$.

Now suppose $x \in B$. Since $A \neq \emptyset$ we can choose some $z \in A$. Therefore $(x, z) \in B \times A = A \times B$, so $x \in A$. Thus $A = B$, as required.

(\leftarrow) Suppose either $A = \emptyset$, $B = \emptyset$, or $A = B$.

Case 1. $A = \emptyset$. Then $A \times B = \emptyset \times B = \emptyset = B \times \emptyset = B \times A$.

Case 2. $B = \emptyset$. Similar to case 1.

Case 3. $A = B$. Then $A \times B = A \times A = B \times A$. □

Commentary. Of course, the statement to be proven is an iff statement, so we prove both directions separately. For the \rightarrow direction, our goal is $A = \emptyset \vee B = \emptyset \vee A = B$, which could be written as $(A = \emptyset \vee B = \emptyset) \vee A = B$, so by one of our strategies for disjunctions from Chapter 3 we can assume $\neg(A = \emptyset \vee B = \emptyset)$ and prove $A = B$. Note that by one of De Morgan's laws, $\neg(A = \emptyset \vee B = \emptyset)$ is equivalent to $A \neq \emptyset \wedge B \neq \emptyset$, so we treat this as two assumptions, $A \neq \emptyset$ and $B \neq \emptyset$. Of course we could also have proceeded differently, for example by assuming $A \neq B$ and $B \neq \emptyset$ and then proving $A = \emptyset$. But recall from the commentary on part 5 of Theorem 4.1.3 that $A = \emptyset$ and $B = \emptyset$ are actually negative statements, so because it is generally better to work with positive than negative statements, we're better off negating both of them to get the assumptions $A \neq \emptyset$ and $B \neq \emptyset$ and then proving the positive statement $A = B$. The assumptions $A \neq \emptyset$ and $B \neq \emptyset$ are existential statements, so they are used in the proof to justify the introduction of y and z . The proof that $A = B$ proceeds in the obvious way, by introducing an arbitrary object x and then proving $x \in A \leftrightarrow x \in B$.

For the \leftarrow direction of the proof, we have $A = \emptyset \vee B = \emptyset \vee A = B$ as a given, so it is natural to use proof by cases. In each case, the goal is easy to prove.

This theorem is a better illustration of how mathematics is really done than most of the examples we've seen so far. Usually when you're trying to find the answer to a mathematical question you won't know in advance what the answer is going to be. You might be able to take a guess at the answer and you might have an idea for how the proof might go, but your guess might be wrong and your idea for the proof might be flawed. It is only by turning your idea into a formal proof, according to the rules in Chapter 3, that you can be sure your answer is right. Often in the course of trying to construct a formal proof you will discover a flaw in your reasoning, as we did earlier, and you may have to revise your ideas to overcome the flaw. The final theorem and proof are often the result of repeated mistakes and corrections. Of course, when mathematicians write up their theorems and proofs, they follow our rule that proofs are for justifying theorems, not for explaining thought processes, and so they don't describe all the mistakes they made. But just because mathematicians don't explain their mistakes in their proofs, you shouldn't be fooled into thinking they don't make any!

Now that we know how to use ordered pairs and Cartesian products to talk about assigning values to free variables, we're ready to define truth sets for statements containing two free variables.

Definition 4.1.5. Suppose $P(x, y)$ is a statement with two free variables in which x ranges over a set A and y ranges over another set B . Then $A \times B$ is the set of all assignments of values to x and y that make sense in the statement $P(x, y)$. The *truth set* of $P(x, y)$ is the subset of $A \times B$ consisting of those assignments that make the statement come out true. In other words, the truth set of $P(x, y)$ is the set $\{(a, b) \in A \times B \mid P(a, b)\}$.

Example 4.1.6. What are the truth sets of the following statements?

1. “ x has y children,” where x ranges over the set P of all people and y ranges over \mathbb{N} .
2. “ x is located in y ,” where x ranges over the set C of all cities and y ranges over the set N of all countries.
3. “ $y = 2x - 3$,” where x and y range over \mathbb{R} .

Solutions

1. $\{(p, n) \in P \times \mathbb{N} \mid \text{the person } p \text{ has } n \text{ children}\} = \{(\text{Prince Charles}, 2), \dots\}$.
2. $\{(c, n) \in C \times N \mid \text{the city } c \text{ is located in the country } n\} = \{(\text{New York, United States}), (\text{Tokyo, Japan}), (\text{Paris, France}), \dots\}$.
3. $\{(x, y) \in \mathbb{R} \times \mathbb{R} \mid y = 2x - 3\} = \{(0, -3), (1, -1), (2, 1), \dots\}$. You are probably already familiar with the fact that the ordered pairs in this set are the coordinates of points in the plane that lie along a certain straight line, called the *graph* of the equation $y = 2x - 3$. Thus, you can think of the graph of the equation as a picture of its truth set!

Many of the facts about truth sets for statements with one free variable that we discussed in Chapter 1 carry over to truth sets for statements with two free variables. For example, suppose T is the truth set of a statement $P(x, y)$, where x ranges over some set A and y ranges over B . Then for any $a \in A$ and $b \in B$ the statement $(a, b) \in T$ means the same thing as $P(a, b)$. Also, if $P(x, y)$ is true for every $x \in A$ and $y \in B$, then $T = A \times B$, and if $P(x, y)$ is false for every $x \in A$ and $y \in B$, then $T = \emptyset$. If S is the truth set of another statement $Q(x, y)$, then the truth set of the statement $P(x, y) \wedge Q(x, y)$ is $T \cap S$, and the truth set of $P(x, y) \vee Q(x, y)$ is $T \cup S$.

Although we’ll be concentrating on ordered pairs for the rest of this chapter, it is possible to work with ordered triples, ordered quadruples, and so on. These might be used to talk about truth sets for statements containing three or more free variables. For example, let $L(x, y, z)$ be the statement “ x has lived in y for z years,” where x ranges over the set P of all people, y ranges over the set C of all cities, and z ranges over \mathbb{N} . Then the assignments of values

to the free variables that make sense in this statement would be ordered triples (p, c, n) , where p is a person, c is a city, and n is a natural number. The set of all such ordered triples would be written $P \times C \times \mathbb{N}$, and the truth set of the statement $L(x, y, z)$ would be the set $\{(p, c, n) \in P \times C \times \mathbb{N} \mid \text{the person } p \text{ has lived in the city } c \text{ for } n \text{ years}\}$.

Exercises

- *1. What are the truth sets of the following statements? List a few elements of each truth set.
 - (a) “ x is a parent of y ,” where x and y both range over the set P of all people.
 - (b) “There is someone who lives in x and attends y ,” where x ranges over the set C of all cities and y ranges over the set U of all universities.
2. What are the truth sets of the following statements? List a few elements of each truth set.
 - (a) “ x lives in y ,” where x ranges over the set P of all people and y ranges over the set C of all cities.
 - (b) “The population of x is y ,” where x ranges over the set C of all cities and y ranges over \mathbb{N} .
3. The truth sets of the following statements are subsets of \mathbb{R}^2 . List a few elements of each truth set. Draw a picture showing all the points in the plane whose coordinates are in the truth set.
 - (a) $y = x^2 - x - 2$.
 - (b) $y < x$.
 - (c) Either $y = x^2 - x - 2$ or $y = 3x - 2$.
 - (d) $y < x$, and either $y = x^2 - x - 2$ or $y = 3x - 2$.
- *4. Let $A = \{1, 2, 3\}$, $B = \{1, 4\}$, $C = \{3, 4\}$, and $D = \{5\}$. Compute all the sets mentioned in Theorem 4.1.3 and verify that all parts of the theorem are true.
5. Prove parts 2 and 3 of Theorem 4.1.3.
- *6. What’s wrong with the following proof that for any sets A , B , C , and D , $(A \cup C) \times (B \cup D) \subseteq (A \times B) \cup (C \times D)$? (Note that this is the reverse of the inclusion in part 4 of Theorem 4.1.3.)

Proof. Suppose $(x, y) \in (A \cup C) \times (B \cup D)$. Then $x \in A \cup C$ and $y \in B \cup D$, so either $x \in A$ or $x \in C$, and either $y \in B$ or $y \in D$. We consider these cases separately.

Case 1. $x \in A$ and $y \in B$. Then $(x, y) \in A \times B$.

Case 2. $x \in C$ and $y \in D$. Then $(x, y) \in C \times D$.

Thus, either $(x, y) \in A \times B$ or $(x, y) \in C \times D$, so $(x, y) \in (A \times B) \cup (C \times D)$. \square

7. If A has m elements and B has n elements, how many elements does $A \times B$ have?
- ^{P_D*}8. Is it true that for any sets A, B , and C , $A \times (B \setminus C) = (A \times B) \setminus (A \times C)$? Give either a proof or a counterexample to justify your answer.
- ^{P_D}9. Prove that for any sets A, B , and C , $A \times (B^2 \setminus C) = (A \times B)^2 \setminus (A \times C)$.
- ^{P_D*}10. Prove that for any sets A, B, C , and D , $(A \setminus C) \times (B \setminus D) \subseteq (A \times B) \setminus (C \times D)$.
- ^{P_D}11. Prove that for any sets A, B, C , and D , $(A \times B) \setminus (C \times D) = [A \times (B \setminus D)] \cup [(A \setminus C) \times B]$.
- ^{P_D}12. Prove that for any sets A, B, C , and D , if $A \times B$ and $C \times D$ are disjoint, then either A and C are disjoint or B and D are disjoint.
13. Suppose $I \neq \emptyset$. Prove that for any indexed family of sets $\{A_i \mid i \in I\}$ and any set B , $(\bigcap_{i \in I} A_i) \times B = \bigcap_{i \in I} (A_i \times B)$. Where in the proof does the assumption that $I \neq \emptyset$ get used?
14. Suppose $\{A_i \mid i \in I\}$ and $\{B_i \mid i \in I\}$ are indexed families of sets.
- (a) Prove that $\bigcup_{i \in I} (A_i \times B_i) \subseteq (\bigcup_{i \in I} A_i) \times (\bigcup_{i \in I} B_i)$.
- (b) For each $(i, j) \in I \times I$ let $C_{(i,j)} = A_i \times B_j$, and let $P = I \times I$. Prove that $\bigcup_{p \in P} C_p = (\bigcup_{i \in I} A_i) \times (\bigcup_{i \in I} B_i)$.
- *15. This problem was suggested by Professor Alan Taylor of Union College, NY. Consider the following putative theorem.

Theorem? For any sets A, B, C , and D , if $A \times B \subseteq C \times D$ then $A \subseteq C$ and $B \subseteq D$.

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct?

Proof. Suppose $A \times B \subseteq C \times D$. Let a be an arbitrary element of A and let b be an arbitrary element of B . Then $(a, b) \in A \times B$, so since $A \times B \subseteq C \times D$, $(a, b) \in C \times D$. Therefore $a \in C$ and $b \in D$. Since a and b were arbitrary elements of A and B , respectively, this shows that $A \subseteq C$ and $B \subseteq D$. \square

4.2. Relations

Suppose $P(x, y)$ is a statement with two free variables x and y . Often such a statement can be thought of as expressing a *relationship* between x and y . The truth set of the statement $P(x, y)$ is a set of ordered pairs that records when this relationship holds. In fact, it is often useful to think of any set of ordered pairs in this way, as a record of when some relationship holds. This is the motivation behind the following definition.

Definition 4.2.1. Suppose A and B are sets. Then a set $R \subseteq A \times B$ is called a *relation from A to B* .

If x ranges over A and y ranges over B , then clearly the truth set of any statement $P(x, y)$ will be a relation from A to B . However, note that Definition 4.2.1 does not require that a set of ordered pairs be defined as the truth set of some statement for the set to be a relation. Although thinking about truth sets was the motivation for this definition, the definition says nothing explicitly about truth sets. According to the definition, *any* subset of $A \times B$ is to be called a relation from A to B .

Example 4.2.2. Here are some examples of relations from one set to another.

1. Let $A = \{1, 2, 3\}$, $B = \{3, 4, 5\}$, and $R = \{(1, 3), (1, 5), (3, 3)\}$. Then $R \subseteq A \times B$, so R is a relation from A to B .
2. Let $G = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x > y\}$. Then G is a relation from \mathbb{R} to \mathbb{R} .
3. Let $A = \{1, 2\}$ and $B = \mathcal{P}(A) = \{\emptyset, \{1\}, \{2\}, \{1, 2\}\}$. Let $E = \{(x, y) \in A \times B \mid x \in y\}$. Then E is a relation from A to B . In this case, $E = \{(1, \{1\}), (1, \{1, 2\}), (2, \{2\}), (2, \{1, 2\})\}$.

For the next three examples, let S be the set of all students at your school, R the set of all dorm rooms, P the set of all professors, and C the set of all courses.

4. Let $L = \{(s, r) \in S \times R \mid \text{the student } s \text{ lives in the dorm room } r\}$. Then L is a relation from S to R .
5. Let $E = \{(s, c) \in S \times C \mid \text{the student } s \text{ is enrolled in the course } c\}$. Then E is a relation from S to C .
6. Let $T = \{(c, p) \in C \times P \mid \text{the course } c \text{ is taught by the professor } p\}$. Then T is a relation from C to P .

So far we have concentrated mostly on developing your proof-writing skills. Another important skill in mathematics is the ability to understand and apply

new definitions. Here are the definitions for several new concepts involving relations. We'll soon give examples illustrating these concepts, but first see if you can understand the concepts based on their definitions.

Definition 4.2.3. Suppose R is a relation from A to B . Then the *domain* of R is the set

$$\text{Dom}(R) = \{a \in A \mid \exists b \in B((a, b) \in R)\}.$$

The *range* of R is the set

$$\text{Ran}(R) = \{b \in B \mid \exists a \in A((a, b) \in R)\}.$$

The *inverse* of R is the relation R^{-1} from B to A defined as follows:

$$R^{-1} = \{(b, a) \in B \times A \mid (a, b) \in R\}.$$

Finally, suppose R is a relation from A to B and S is a relation from B to C . Then the *composition* of S and R is the relation $S \circ R$ from A to C defined as follows:

$$S \circ R = \{(a, c) \in A \times C \mid \exists b \in B((a, b) \in R \text{ and } (b, c) \in S)\}.$$

Notice that we have assumed that the second coordinates of pairs in R and the first coordinates of pairs in S both come from the same set B , because that is the situation in which we will most often be interested in $S \circ R$. However, this restriction is not really necessary, as we ask you to show in exercise 15.

According to Definition 4.2.3, the domain of a relation from A to B is the set containing all the first coordinates of ordered pairs in the relation. This will in general be a subset of A , but it need not be all of A . For example, consider the relation L from part 4 of Example 4.2.2, which pairs up students with the dorm rooms in which they live. The domain of L would contain all students who appear as the first coordinate in some ordered pair in L – in other words, all students who live in some dorm room – but would not contain, for example, students who live in apartments off campus. Working it out more carefully from the definition as stated, we have

$$\begin{aligned} \text{Dom}(L) &= \{s \in S \mid \exists r \in R((s, r) \in L)\} \\ &= \{s \in S \mid \exists r \in R(\text{the student } s \text{ lives in the dorm room } r)\} \\ &= \{s \in S \mid \text{the student } s \text{ lives in some dorm room}\}. \end{aligned}$$

Similarly, the range of a relation is the set containing all the second coordinates of its ordered pairs. For example, the range of the relation L would be the

set of all dorm rooms in which some student lives. Any dorm rooms that are unoccupied would not be in the range of L .

The inverse of a relation contains exactly the same ordered pairs as the original relation, but with the order of the coordinates of each pair reversed. Thus, in the case of the relation L , if Joe Smith lives in room 213 Davis Hall, then $(\text{Joe Smith}, 213 \text{ Davis Hall}) \in L$ and $(213 \text{ Davis Hall}, \text{Joe Smith}) \in L^{-1}$. In general, for any student s and dorm room r , we would have $(r, s) \in L^{-1}$ iff $(s, r) \in L$. For another example, consider the relation G from part 2 of Example 4.2.2. It contains all ordered pairs of real numbers (x, y) in which x is greater than y . We might call it the “greater-than” relation. Its inverse is

$$\begin{aligned} G^{-1} &= \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid (y, x) \in G\} \\ &= \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid y > x\} \\ &= \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x < y\}. \end{aligned}$$

In other words, the inverse of the greater-than relation is the less-than relation!

The most difficult concept introduced in Definition 4.2.3 is the concept of the composition of two relations. For an example of this concept, consider the relations E and T from parts 5 and 6 of Example 4.2.2. Recall that E is a relation from the set S of all students to the set C of all courses, and T is a relation from C to the set P of all professors. According to Definition 4.2.3, the composition $T \circ E$ is the relation from S to P defined as follows:

$$\begin{aligned} T \circ E &= \{(s, p) \in S \times P \mid \exists c \in C((s, c) \in E \text{ and } (c, p) \in T)\} \\ &= \{(s, p) \in S \times P \mid \exists c \in C(\text{the student } s \text{ is enrolled in the course } c \\ &\quad \text{and the course } c \text{ is taught by the professor } p)\} \\ &= \{(s, p) \in S \times P \mid \text{the student } s \text{ is enrolled in some course taught} \\ &\quad \text{by the professor } p\}. \end{aligned}$$

Thus, if Joe Smith is enrolled in Biology 12 and Biology 12 is taught by Prof. Evans, then $(\text{Joe Smith}, \text{Biology 12}) \in E$ and $(\text{Biology 12}, \text{Prof. Evans}) \in T$, and therefore $(\text{Joe Smith}, \text{Prof. Evans}) \in T \circ E$. In general, if s is some particular student and p is a particular professor, then $(s, p) \in T \circ E$ iff there is some course c such that $(s, c) \in E$ and $(c, p) \in T$. This notation may seem backward at first. If $(s, c) \in E$ and $(c, p) \in T$, then you might be tempted to write $(s, p) \in E \circ T$, but according to our definition, the proper notation is $(s, p) \in T \circ E$. The reason we’ve chosen to write compositions of relations in this way will become clear in Chapter 5. For the moment, you’ll just have to be careful about this notational detail when working with compositions of relations.

Example 4.2.4. Let S , R , C , and P be the sets of students, dorm rooms, courses, and professors at your school, as before, and let L , E , and T be the relations defined in parts 4–6 of Example 4.2.2. Describe the following relations.

1. E^{-1} .
2. $E \circ L^{-1}$.
3. $E^{-1} \circ E$.
4. $E \circ E^{-1}$.
5. $T \circ (E \circ L^{-1})$.
6. $(T \circ E) \circ L^{-1}$.

Solutions

1. $E^{-1} = \{(c, s) \in C \times S \mid (s, c) \in E\} = \{(c, s) \in C \times S \mid \text{the student } s \text{ is enrolled in the course } c\}$. For example, if Joe Smith is enrolled in Biology 12, then $(\text{Joe Smith}, \text{Biology 12}) \in E$ and $(\text{Biology 12}, \text{Joe Smith}) \in E^{-1}$.
2. Because L^{-1} is a relation from R to S and E is a relation from S to C , $E \circ L^{-1}$ will be the relation from R to C defined as follows.

$$\begin{aligned} E \circ L^{-1} &= \{(r, c) \in R \times C \mid \exists s \in S((r, s) \in L^{-1} \text{ and } (s, c) \in E)\} \\ &= \{(r, c) \in R \times C \mid \exists s \in S((s, r) \in L \text{ and } (s, c) \in E)\} \\ &= \{(r, c) \in R \times C \mid \exists s \in S(\text{the student } s \text{ lives in the dorm room } r \text{ and is enrolled in the course } c)\} \\ &= \{(r, c) \in R \times C \mid \text{some student who lives in the room } r \text{ is enrolled in the course } c\}. \end{aligned}$$

Returning to our favorite student Joe Smith, who is enrolled in Biology 12 and lives in room 213 Davis Hall, we have $(213 \text{ Davis Hall}, \text{Joe Smith}) \in L^{-1}$ and $(\text{Joe Smith}, \text{Biology 12}) \in E$. According to the definition of composition, it follows that $(213 \text{ Davis Hall}, \text{Biology 12}) \in E \circ L^{-1}$.

3. Because E is a relation from S to C and E^{-1} is a relation from C to S , $E^{-1} \circ E$ is the relation from S to S defined as follows.

$$\begin{aligned} E^{-1} \circ E &= \{(s, t) \in S \times S \mid \exists c \in C((s, c) \in E \text{ and } (c, t) \in E^{-1})\} \\ &= \{(s, t) \in S \times S \mid \exists c \in C(\text{the student } s \text{ is enrolled in the course } c, \text{ and so is the student } t)\} \\ &= \{(s, t) \in S \times S \mid \text{there is some course that the students } s \text{ and } t \text{ are both enrolled in}\}. \end{aligned}$$

(Note that an arbitrary element of $S \times S$ is written (s, t) , not (s, s) , because we don't want to assume that the two coordinates are equal.)

4. This is not the same as the last example! Because E^{-1} is a relation from C to S and E is a relation from S to C , $E \circ E^{-1}$ is a relation from C to C . It is defined as follows.

$$\begin{aligned} E \circ E^{-1} &= \{(c, d) \in C \times C \mid \exists s \in S((c, s) \in E^{-1} \text{ and } (s, d) \in E)\} \\ &= \{(c, d) \in C \times C \mid \exists s \in S(\text{the student } s \text{ is enrolled in the} \\ &\quad \text{course } c, \text{ and he or she is also enrolled in the course } d)\} \\ &= \{(c, d) \in C \times C \mid \text{there is some student who is enrolled in} \\ &\quad \text{both of the courses } c \text{ and } d\}. \end{aligned}$$

5. We saw in part 2 that $E \circ L^{-1}$ is a relation from R to C , and T is a relation from C to P , so $T \circ (E \circ L^{-1})$ is the relation from R to P defined as follows.

$$\begin{aligned} T \circ (E \circ L^{-1}) &= \{(r, p) \in R \times P \mid \exists c \in C((r, c) \in E \circ L^{-1} \text{ and} \\ &\quad (c, p) \in T)\} \\ &= \{(r, p) \in R \times P \mid \exists c \in C(\text{some student who lives in the} \\ &\quad \text{room } r \text{ is enrolled in the course } c, \text{ and } c \text{ is taught by} \\ &\quad \text{the professor } p)\} \\ &= \{(r, p) \in R \times P \mid \text{some student who lives in the room } r \\ &\quad \text{is enrolled in some course taught by the professor } p\}. \end{aligned}$$

6. $(T \circ E) \circ L^{-1} = \{(r, p) \in R \times P \mid \exists s \in S((r, s) \in L^{-1} \text{ and} \\ (s, p) \in T \circ E)\} \\ = \{(r, p) \in R \times P \mid \exists s \in S(\text{the student } s \text{ lives in the} \\ \text{room } r, \text{ and is enrolled in some course taught by} \\ \text{the professor } p)\} \\ = \{(r, p) \in R \times P \mid \text{some student who lives in the room } r \\ \text{is enrolled in some course taught by the professor } p\}.$

Notice that our answers for parts 3 and 4 of Example 4.2.4 were different, so composition of relations is not commutative. However, our answers for parts 5 and 6 turned out to be the same. Is this a coincidence, or is it true in general that composition of relations is associative? Often, looking at examples of a new concept will suggest general rules that might apply to it. Although one counterexample is enough to show that a rule is incorrect, we should never accept a rule as correct without a proof. The next theorem summarizes some of the basic properties of the new concepts we have introduced.

Theorem 4.2.5. Suppose R is a relation from A to B , S is a relation from B to C , and T is a relation from C to D . Then:

1. $(R^{-1})^{-1} = R$.
2. $\text{Dom}(R^{-1}) = \text{Ran}(R)$.
3. $\text{Ran}(R^{-1}) = \text{Dom}(R)$.
4. $T \circ (S \circ R) = (T \circ S) \circ R$.
5. $(S \circ R)^{-1} = R^{-1} \circ S^{-1}$.

Proof. We will prove 1, 2, and half of 4, and leave the rest as exercises. (See exercise 7.)

1. First of all, note that R^{-1} is a relation from B to A , so $(R^{-1})^{-1}$ is a relation from A to B , just like R . To see that $(R^{-1})^{-1} = R$, let (a, b) be an arbitrary ordered pair in $A \times B$. Then

$$(a, b) \in (R^{-1})^{-1} \text{ iff } (b, a) \in R^{-1} \text{ iff } (a, b) \in R.$$

2. First note that $\text{Dom}(R^{-1})$ and $\text{Ran}(R)$ are both subsets of B . Now let b be an arbitrary element of B . Then

$$\begin{aligned} b \in \text{Dom}(R^{-1}) &\text{ iff } \exists a \in A((b, a) \in R^{-1}) \\ &\text{ iff } \exists a \in A((a, b) \in R) \text{ iff } b \in \text{Ran}(R). \end{aligned}$$

4. Clearly $T \circ (S \circ R)$ and $(T \circ S) \circ R$ are both relations from A to D . Let (a, d) be an arbitrary element of $A \times D$.

First, suppose $(a, d) \in T \circ (S \circ R)$. By the definition of composition, this means that we can choose some $c \in C$ such that $(a, c) \in S \circ R$ and $(c, d) \in T$. Since $(a, c) \in S \circ R$, we can again use the definition of composition and choose some $b \in B$ such that $(a, b) \in R$ and $(b, c) \in S$. Now since $(b, c) \in S$ and $(c, d) \in T$, we can conclude that $(b, d) \in T \circ S$. Similarly, since $(a, b) \in R$ and $(b, d) \in T \circ S$, it follows that $(a, d) \in (T \circ S) \circ R$.

Now suppose $(a, d) \in (T \circ S) \circ R$. A similar argument, which is left to the reader, shows that $(a, d) \in T \circ (S \circ R)$. Thus, $T \circ (S \circ R) = (T \circ S) \circ R$. \square

Commentary. Statement 1 means $\forall p(p \in (R^{-1})^{-1} \leftrightarrow p \in R)$, so the proof should proceed by introducing an arbitrary object p and then proving $p \in (R^{-1})^{-1} \leftrightarrow p \in R$. But because R and $(R^{-1})^{-1}$ are both relations from A to B , we could think of the universe over which p ranges as being $A \times B$, so p must be an ordered pair. Thus, in the preceding proof we've written it as an ordered pair (a, b) from the start. The proof of the biconditional statement $(a, b) \in (R^{-1})^{-1} \leftrightarrow (a, b) \in R$ uses the method, introduced in Example 3.4.5, of stringing together a sequence of equivalences.

The proofs of statements 2 and 4 are similar, except that the biconditional proof for statement 4 cannot easily be done by stringing together equivalences, so we prove the two directions separately. Only one direction was proven. The key to this proof is to recognize that the given $(a, d) \in T \circ (S \circ R)$ is an existential statement, since it means $\exists c \in C((a, c) \in S \circ R \text{ and } (c, d) \in T)$, so we should introduce a new variable c into the proof to stand for some element of C such that $(a, c) \in S \circ R$ and $(c, d) \in T$. Similarly, $(a, c) \in S \circ R$ is an existential statement, so it suggests introducing the variable b . Once these new variables have been introduced, it is easy to prove the goal $(a, d) \in (T \circ S) \circ R$.

Statement 5 of Theorem 4.2.5 perhaps deserves some comment. First of all, notice that the right-hand side of the equation is $R^{-1} \circ S^{-1}$, *not* $S^{-1} \circ R^{-1}$; the order of the relations has been reversed. You are asked to prove statement 5 in exercise 7, but it might be worthwhile to try an example first. We've already seen that, for the relations E and T from parts 5 and 6 of Example 4.2.2,

$$T \circ E = \{(s, p) \in S \times P \mid \text{the student } s \text{ is enrolled in some course} \\ \text{taught by the professor } p\}.$$

It follows that

$$(T \circ E)^{-1} = \{(p, s) \in P \times S \mid \text{the student } s \text{ is enrolled in some course} \\ \text{taught by the professor } p\}.$$

To compute $E^{-1} \circ T^{-1}$, first note that T^{-1} is a relation from P to C and E^{-1} is a relation from C to S , so $E^{-1} \circ T^{-1}$ is a relation from P to S . Now, applying the definition of composition, we get

$$\begin{aligned} E^{-1} \circ T^{-1} &= \{(p, s) \in P \times S \mid \exists c \in C((p, c) \in T^{-1} \text{ and } (c, s) \in E^{-1})\} \\ &= \{(p, s) \in P \times S \mid \exists c \in C((c, p) \in T \text{ and } (s, c) \in E)\} \\ &= \{(p, s) \in P \times S \mid \exists c \in C(\text{the course } c \text{ is taught by the} \\ &\quad \text{professor } p \text{ and the student } s \text{ is enrolled in the course } c)\} \\ &= \{(p, s) \in P \times S \mid \text{the student } s \text{ is enrolled in some course} \\ &\quad \text{taught by the professor } p\}. \end{aligned}$$

Thus, $(T \circ E)^{-1} = E^{-1} \circ T^{-1}$.

Exercises

*1. Find the domains and ranges of the following relations.

- $\{(p, q) \in P \times P \mid \text{the person } p \text{ is a parent of the person } q\}$, where P is the set of all living people.
- $\{(x, y) \in \mathbb{R}^2 \mid y > x^2\}$.

2. Find the domains and ranges of the following relations.
 - (a) $\{(p, q) \in P \times P \mid \text{the person } p \text{ is a brother of the person } q\}$,
where P is the set of all living people.
 - (b) $\{(x, y) \in \mathbb{R}^2 \mid y^2 = 1 - 2/(x^2 + 1)\}$.
3. Let L and E be the relations defined in parts 4 and 5 of Example 4.2.2. Describe the following relations:
 - (a) $L^{-1} \circ L$.
 - (b) $E \circ (L^{-1} \circ L)$.
4. Let E and T be the relations defined in parts 5 and 6 of Example 4.2.2. Also, as in that example, let C be the set of all courses at your school, and let $D = \{\text{Monday, Tuesday, Wednesday, Thursday, Friday}\}$. Let $M = \{(c, d) \in C \times D \mid \text{the course } c \text{ meets on the day } d\}$. Describe the following relations:
 - (a) $M \circ E$.
 - (b) $M \circ T^{-1}$.
- *5. Suppose that $A = \{1, 2, 3\}$, $B = \{4, 5, 6\}$, $R = \{(1, 4), (1, 5), (2, 5), (3, 6)\}$, and $S = \{(4, 5), (4, 6), (5, 4), (6, 6)\}$. Note that R is a relation from A to B and S is a relation from B to B . Find the following relations:
 - (a) $S \circ R$.
 - (b) $S \circ S^{-1}$.
6. Suppose that $A = \{1, 2, 3\}$, $B = \{4, 5\}$, $C = \{6, 7, 8\}$, $R = \{(1, 7), (3, 6), (3, 7)\}$, and $S = \{(4, 7), (4, 8), (5, 6)\}$. Note that R is a relation from A to C and S is a relation from B to C . Find the following relations:
 - (a) $S^{-1} \circ R$.
 - (b) $R^{-1} \circ S$.
7.
 - (a) Prove part 3 of Theorem 4.2.5 by imitating the proof of part 2 in the text.
 - (b) Give an alternative proof of part 3 of Theorem 4.2.5 by showing that it follows from parts 1 and 2.
 - (c) Complete the proof of part 4 of Theorem 4.2.5.
 - (d) Prove part 5 of Theorem 4.2.5.
- *8. Let $E = \{(p, q) \in P \times P \mid \text{the person } p \text{ is an enemy of the person } q\}$, and $F = \{(p, q) \in P \times P \mid \text{the person } p \text{ is a friend of the person } q\}$, where P is the set of all people. What does the saying “an enemy of one’s enemy is one’s friend” mean about the relations E and F ?
9. Suppose R is a relation from A to B and S is a relation from B to C .
 - (a) Prove that $\text{Dom}(S \circ R) \subseteq \text{Dom}(R)$.
 - (b) Prove that if $\text{Ran}(R) \subseteq \text{Dom}(S)$ then $\text{Dom}(S \circ R) = \text{Dom}(R)$.
 - (c) Formulate and prove similar theorems about $\text{Ran}(S \circ R)$.

10. Suppose R and S are relations from A to B . Must the following statements be true? Justify your answers with proofs or counterexamples.
- $R \subseteq \text{Dom}(R) \times \text{Ran}(R)$.
 - If $R \subseteq S$ then $R^{-1} \subseteq S^{-1}$.
 - $(R \cup S)^{-1} = R^{-1} \cup S^{-1}$.
- *11. Suppose R is a relation from A to B and S is a relation from B to C . Prove that $S \circ R = \emptyset$ iff $\text{Ran}(R)$ and $\text{Dom}(S)$ are disjoint.
- ^P_D12. Suppose R is a relation from A to B and S and T are relations from B to C .
- Prove that $(S \circ R) \setminus (T \circ R) \subseteq (S \setminus T) \circ R$.
 - What's wrong with the following proof that $(S \setminus T) \circ R \subseteq (S \circ R) \setminus (T \circ R)$?
- Proof.* Suppose $(a, c) \in (S \setminus T) \circ R$. Then we can choose some $b \in B$ such that $(a, b) \in R$ and $(b, c) \in S \setminus T$, so $(b, c) \in S$ and $(b, c) \notin T$. Since $(a, b) \in R$ and $(b, c) \in S$, $(a, c) \in S \circ R$. Similarly, since $(a, b) \in R$ and $(b, c) \notin T$, $(a, c) \notin T \circ R$. Therefore $(a, c) \in (S \circ R) \setminus (T \circ R)$. Since (a, c) was arbitrary, this shows that $(S \setminus T) \circ R \subseteq (S \circ R) \setminus (T \circ R)$. \square
- Must it be true that $(S \setminus T) \circ R \subseteq (S \circ R) \setminus (T \circ R)$? Justify your answer with either a proof or a counterexample.
13. Suppose R and S are relations from A to B and T is a relation from B to C . Must the following statements be true? Justify your answers with proofs or counterexamples.
- If R and S are disjoint, then so are R^{-1} and S^{-1} .
 - If R and S are disjoint, then so are $T \circ R$ and $T \circ S$.
 - If $T \circ R$ and $T \circ S$ are disjoint, then so are R and S .
- ^P_D14. Suppose R is a relation from A to B , and S and T are relations from B to C . Must the following statements be true? Justify your answers with proofs or counterexamples.
- If $S \subseteq T$ then $S \circ R \subseteq T \circ R$.
 - $(S \cap T) \circ R \subseteq (S \circ R) \cap (T \circ R)$.
 - $(S \cap T) \circ R = (S \circ R) \cap (T \circ R)$.
 - $(S \cup T) \circ R = (S \circ R) \cup (T \circ R)$.
15. Suppose R is a relation from A to B and S is a relation from C to D . Show that there is a set E such that R is a relation from A to E and S is a relation from E to D , and therefore the definition of $S \circ R$ in Definition 4.2.3 can be applied. Furthermore, the definition gives the same result no matter which such set E is used.

4.3. More About Relations

Although we have defined relations to be sets of ordered pairs, it is sometimes useful to be able to think about them in other ways. Often even a small change in notation can help us see things differently. One alternative notation that mathematicians sometimes use with relations is motivated by the fact that in mathematics we often express a relationship between two objects x and y by putting some symbol between them. For example, the notations $x = y$, $x < y$, $x \in y$, and $x \subseteq y$ express four important mathematical relationships between x and y . Imitating these notations, if R is a relation from A to B , $x \in A$, and $y \in B$, mathematicians sometimes write xRy to mean $(x, y) \in R$.

For example, if L is the relation defined in part 4 of Example 4.2.2, then for any student s and dorm room r , sLr means $(s, r) \in L$, or in other words, the student s lives in the dorm room r . Similarly, if E and T are the relations defined in parts 5 and 6 of Example 4.2.2, then sEc means that the student s is enrolled in the course c , and cTp means that the course c is taught by the professor p . The definition of composition of relations could have been stated by saying that if R is a relation from A to B and S is a relation from B to C , then $S \circ R = \{ (a, c) \in A \times C \mid \exists b \in B (aRb \text{ and } bSc) \}$.

Another way to think about relations is to draw pictures of them. Figure 4.1 shows a picture of the relation $R = \{(1, 3), (1, 5), (3, 3)\}$ from part 1 of Example 4.2.2. Recall that this was a relation from the set $A = \{1, 2, 3\}$ to the set $B = \{3, 4, 5\}$. In the figure, each of these sets is represented by an oval, with the elements of the set represented by dots inside the oval. Each ordered pair $(a, b) \in R$ is represented by an arrow from the dot representing a to the dot representing b . For example, there is an arrow from the dot inside A labeled 1 to the dot inside B labeled 5 because the ordered pair $(1, 5)$ is an element of R .

In general, any relation R from a set A to a set B can be represented by such a picture. The dots representing the elements of A and B in such a picture are called *vertices*, and the arrows representing the ordered pairs in R are called *edges*. It doesn't matter exactly how the vertices representing elements of A and B are arranged on the page; what's important is that the edges correspond precisely to the ordered pairs in R . Drawing these pictures may help you understand the concepts discussed in the last section. For example, you should be able to convince yourself that you could find the domain of R by locating those vertices in A that have edges pointing away from them. Similarly, the range of R would consist of those elements of B whose vertices have edges pointing toward them. For the relation R shown in Figure 4.1, we have $\text{Dom}(R) = \{1, 3\}$ and $\text{Ran}(R) = \{3, 5\}$. A picture of R^{-1} would look just like a picture of R but with the directions of all the arrows reversed.

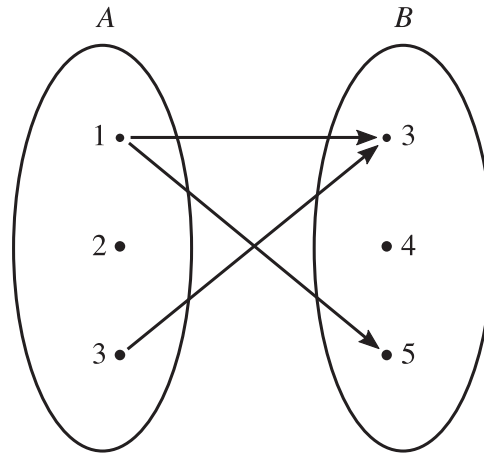


Figure 4.1.

Pictures illustrating the composition of two relations are a little harder to understand. For example, consider again the relations E and T from parts 5 and 6 of Example 4.2.2. Figure 4.2 shows what part of both relations might look like. (The complete picture might be quite large if there are many students, courses, and professors at your school.) We can see in this picture that, for example, Joe Smith is taking Biology 12 and Math 21, that Biology 12 is taught by Prof. Evans, and that Math 21 is taught by Prof. Andrews. Thus, applying the definition of composition, we can see that the pairs (Joe Smith, Prof. Evans) and (Joe Smith, Prof. Andrews) are both elements of the relation $T \circ E$.

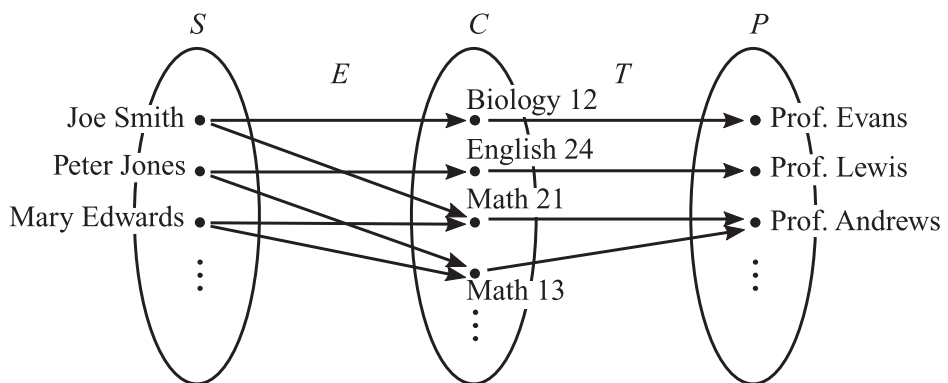


Figure 4.2.

To see more clearly how the composition $T \circ E$ is represented in this picture, first note that for any student s , course c , and professor p , there is an arrow

from s to c iff sEc , and there is an arrow from c to p iff cTp . Thus, according to the definition of composition,

$$\begin{aligned} T \circ E &= \{ (s, p) \in S \times P \mid \exists c \in C (sEc \text{ and } cTp) \} \\ &= \{ (s, p) \in S \times P \mid \exists c \in C (\text{in Figure 4.2, there is an arrow} \\ &\quad \text{from } s \text{ to } c \text{ and an arrow from } c \text{ to } p) \} \\ &= \{ (s, p) \in S \times P \mid \text{in Figure 4.2, you can get from } s \text{ to } p \text{ in} \\ &\quad \text{two steps by following the arrows} \}. \end{aligned}$$

For example, starting at the vertex labeled Mary Edwards, we can get to Prof. Andrews in two steps (going by way of either Math 21 or Math 13), so we can conclude that $(\text{Mary Edwards, Prof. Andrews}) \in T \circ E$.

In some situations we draw pictures of relations in a slightly different way. For example, if A is a set and $R \subseteq A \times A$, then according to Definition 4.2.1, R would be called a relation from A to A . Such a relation is also sometimes called a *relation on A* (or a *binary relation on A*). Relations of this type come up often in mathematics; in fact, we have already seen a few of them. For example, we described the relation G in part 2 of Example 4.2.2 as a relation from \mathbb{R} to \mathbb{R} , but in our new terminology we could call it a relation (or a binary relation) on \mathbb{R} . The relation $E^{-1} \circ E$ from Example 4.2.4 was a relation on the set S , and $E \circ E^{-1}$ was a relation on C .

Example 4.3.1. Here are some more examples of relations on sets.

1. Let $A = \{1, 2\}$ and $B = \mathcal{P}(A) = \{\emptyset, \{1\}, \{2\}, \{1, 2\}\}$ as in part 3 of Example 4.2.2. Let

$$\begin{aligned} S &= \{ (x, y) \in B \times B \mid x \subseteq y \} \\ &= \{ (\emptyset, \emptyset), (\emptyset, \{1\}), (\emptyset, \{2\}), (\emptyset, \{1, 2\}), (\{1\}, \{1\}), (\{1\}, \{1, 2\}), \\ &\quad (\{2\}, \{2\}), (\{2\}, \{1, 2\}), (\{1, 2\}, \{1, 2\}) \}. \end{aligned}$$

Then S is a relation on B .

2. Suppose A is a set. Let $i_A = \{ (x, y) \in A \times A \mid x = y \}$. Then i_A is a relation on A . (It is called the *identity relation* on A .) For example, if $A = \{1, 2, 3\}$, then $i_A = \{(1, 1), (2, 2), (3, 3)\}$. Note that i_A could also be defined by writing $i_A = \{(x, x) \mid x \in A\}$.
3. For each positive real number r , let $D_r = \{ (x, y) \in \mathbb{R} \times \mathbb{R} \mid x \text{ and } y \text{ differ by less than } r, \text{ or in other words } |x - y| < r \}$. Then D_r is a relation on \mathbb{R} .

Suppose R is a relation on a set A . If we used the method described earlier to draw a picture of R , then we would have to draw two copies of the set A

and then draw edges from one copy of A to the other to represent the ordered pairs in R . An easier way to draw the picture would be to draw just one copy of A and then connect the vertices representing the elements of A with edges to represent the ordered pairs in R . For example, Figure 4.3 shows a picture of the relation S from part 1 of Example 4.3.1. Pictures like the one in Figure 4.3 are called *directed graphs*.

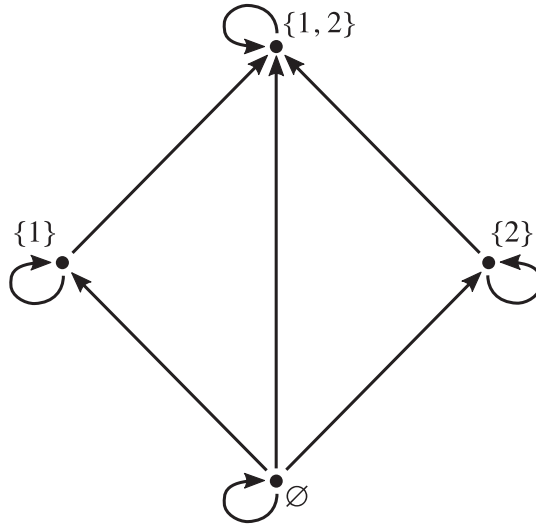


Figure 4.3.

Note that in this directed graph there is an edge from \emptyset to itself, because $(\emptyset, \emptyset) \in S$. Edges such as this one that go from a vertex to itself are called *loops*. In fact, in Figure 4.3 there is a loop at every vertex, because S has the property that $\forall x \in B((x, x) \in S)$. We describe this situation by saying that S is *reflexive*.

Definition 4.3.2. Suppose R is a relation on A .

1. R is said to be *reflexive on A* (or just *reflexive*, if A is clear from context) if $\forall x \in A(xRx)$, or in other words $\forall x \in A((x, x) \in R)$.
2. R is *symmetric* if $\forall x \in A \forall y \in A(xRy \rightarrow yRx)$.
3. R is *transitive* if $\forall x \in A \forall y \in A \forall z \in A((xRy \wedge yRz) \rightarrow xRz)$.

As we saw in Example 4.3.1, if R is reflexive on A , then the directed graph representing R will have loops at all vertices. If R is symmetric, then whenever there is an edge from x to y , there will also be an edge from y to x . If x and y are distinct, it follows that there will be two edges connecting x and y , one pointing in each direction. Thus, if R is symmetric, then all edges except loops

will come in such pairs. If R is transitive, then whenever there is an edge from x to y and y to z , there is also an edge from x to z .

Example 4.3.3. Is the relation G from part 2 of Example 4.2.2 reflexive? Is it symmetric? Transitive? Are the relations in Example 4.3.1 reflexive, symmetric, or transitive?

Solution

Recall that the relation G from Example 4.2.2 is a relation on \mathbb{R} and that for any real numbers x and y , xGy means $x > y$. Thus, to say that G is reflexive would mean that $\forall x \in \mathbb{R}(xGx)$, or in other words $\forall x \in \mathbb{R}(x > x)$, and this is clearly false. To say that G is symmetric would mean that $\forall x \in \mathbb{R} \forall y \in \mathbb{R}(x > y \rightarrow y > x)$, and this is also clearly false. Finally, to say that G is transitive would mean that $\forall x \in \mathbb{R} \forall y \in \mathbb{R} \forall z \in \mathbb{R}((x > y \wedge y > z) \rightarrow x > z)$, and this is true. Thus, G is transitive, but not reflexive or symmetric.

The analysis of the relations in Example 4.3.1 is similar. For the relation S in part 1 we use the fact that for any x and y in B , xSy means $x \subseteq y$. As we have already observed, S is reflexive, since $\forall x \in B(x \subseteq x)$, but it is not true that $\forall x \in B \forall y \in B(x \subseteq y \rightarrow y \subseteq x)$. For example, $\{1\} \subseteq \{1, 2\}$, but $\{1, 2\} \not\subseteq \{1\}$. You can see this in Figure 4.3 by noting that there is an edge from $\{1\}$ to $\{1, 2\}$ but not from $\{1, 2\}$ to $\{1\}$. Thus, S is not symmetric. S is transitive, because the statement $\forall x \in B \forall y \in B \forall z \in B((x \subseteq y \wedge y \subseteq z) \rightarrow x \subseteq z)$ is true.

For any set A the identity relation i_A will be reflexive, symmetric, and transitive, because the statements $\forall x \in A(x = x)$, $\forall x \in A \forall y \in A(x = y \rightarrow y = x)$, and $\forall x \in A \forall y \in A \forall z \in A((x = y \wedge y = z) \rightarrow x = z)$ are all clearly true. Finally, suppose r is a positive real number and consider the relation D_r . For any real number x , $|x - x| = 0 < r$, so $(x, x) \in D_r$. Thus, D_r is reflexive. Also, for any real numbers x and y , $|x - y| = |y - x|$, so if $|x - y| < r$ then $|y - x| < r$. Therefore, if $(x, y) \in D_r$ then $(y, x) \in D_r$, so D_r is symmetric. But D_r is not transitive. To see why, let x be any real number. Let $y = x + 2r/3$ and $z = y + 2r/3 = x + 4r/3$. Then $|x - y| = 2r/3 < r$ and $|y - z| = 2r/3 < r$, but $|x - z| = 4r/3 > r$. Thus, $(x, y) \in D_r$ and $(y, z) \in D_r$, but $(x, z) \notin D_r$.

Perhaps you've already guessed that the properties of relations defined in Definition 4.3.2 are related to the operations defined in Definition 4.2.3. To say that a relation R is symmetric involves reversing the roles of two variables in a way that may remind you of the definition of R^{-1} . The definition of

transitivity of a relation involves stringing together two ordered pairs, just as the definition of composition of relations does. The following theorem spells these connections out more carefully.

Theorem 4.3.4. *Suppose R is a relation on a set A .*

1. R is reflexive iff $i_A \subseteq R$, where as before i_A is the identity relation on A .
2. R is symmetric iff $R = R^{-1}$.
3. R is transitive iff $R \circ R \subseteq R$.

Proof. We will prove 2 and leave the proofs of 1 and 3 as exercises (see exercises 7 and 8).

2. (\rightarrow) Suppose R is symmetric. Let (x, y) be an arbitrary element of R . Then xRy , so since R is symmetric, yRx . Thus, $(y, x) \in R$, so by the definition of R^{-1} , $(x, y) \in R^{-1}$. Since (x, y) was arbitrary, it follows that $R \subseteq R^{-1}$.

Now suppose $(x, y) \in R^{-1}$. Then $(y, x) \in R$, so since R is symmetric, $(x, y) \in R$. Thus, $R^{-1} \subseteq R$, so $R = R^{-1}$.

(\leftarrow) Suppose $R = R^{-1}$, and let x and y be arbitrary elements of A . Suppose xRy . Then $(x, y) \in R$, so since $R = R^{-1}$, $(x, y) \in R^{-1}$. By the definition of R^{-1} this means $(y, x) \in R$, so yRx . Thus, $\forall x \in A \forall y \in A (xRy \rightarrow yRx)$, so R is symmetric. \square

Commentary. This proof is fairly straightforward. The statement to be proven is an iff statement, so we prove both directions separately. In the \rightarrow half we must prove that $R = R^{-1}$, and this is done by proving both $R \subseteq R^{-1}$ and $R^{-1} \subseteq R$. Each of these goals is proven by taking an arbitrary element of the first set and showing that it is in the second set. In the \leftarrow half we must prove that R is symmetric, which means $\forall x \in A \forall y \in A (xRy \rightarrow yRx)$. We use the obvious strategy of letting x and y be arbitrary elements of A , assuming xRy , and proving yRx .

Exercises

- *1. Let $L = \{a, b, c, d, e\}$ and $W = \{\text{bad, bed, cab}\}$. Let $R = \{(l, w) \in L \times W \mid \text{the letter } l \text{ occurs in the word } w\}$. Draw a diagram (like the one in Figure 4.1) of R .
2. Let $A = \{\text{cat, dog, bird, rat}\}$, and let $R = \{(x, y) \in A \times A \mid \text{there is at least one letter that occurs in both of the words } x \text{ and } y\}$. Draw

a directed graph (like the one in Figure 4.3) for the relation R . Is R reflexive? Symmetric? Transitive?

- *3. Let $A = \{1, 2, 3, 4\}$. Draw a directed graph for i_A , the identity relation on A .
- 4. List the ordered pairs in the relations represented by the directed graphs in Figure 4.4. Determine whether each relation is reflexive, symmetric, or transitive.

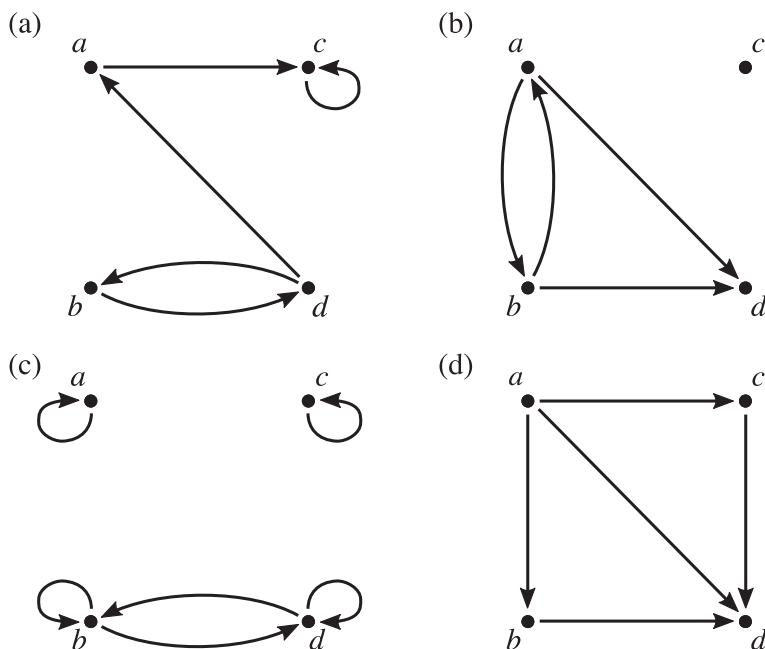


Figure 4.4.

- *5. Figure 4.5 shows two relations R and S . Find $S \circ R$.
- 6. Suppose r and s are two positive real numbers. Let D_r and D_s be defined as in part 3 of Example 4.3.1. What is $D_r \circ D_s$? Justify your answer with a proof. (Hint: In your proof, you may find it helpful to use the triangle inequality; see exercise 13(c) of Section 3.5.)
- *7. Prove part 1 of Theorem 4.3.4.
- 8. Prove part 3 of Theorem 4.3.4.
- 9. Suppose A and B are sets.
 - (a) Show that for every relation R from A to B , $R \circ i_A = R$.
 - (b) Show that for every relation R from A to B , $i_B \circ R = R$.
- *10. Suppose S is a relation on A . Let $D = \text{Dom}(S)$ and $R = \text{Ran}(S)$. Prove that $i_D \subseteq S^{-1} \circ S$ and $i_R \subseteq S \circ S^{-1}$.
- 11. Suppose R is a relation on A . Prove that if R is reflexive then $R \subseteq R \circ R$.

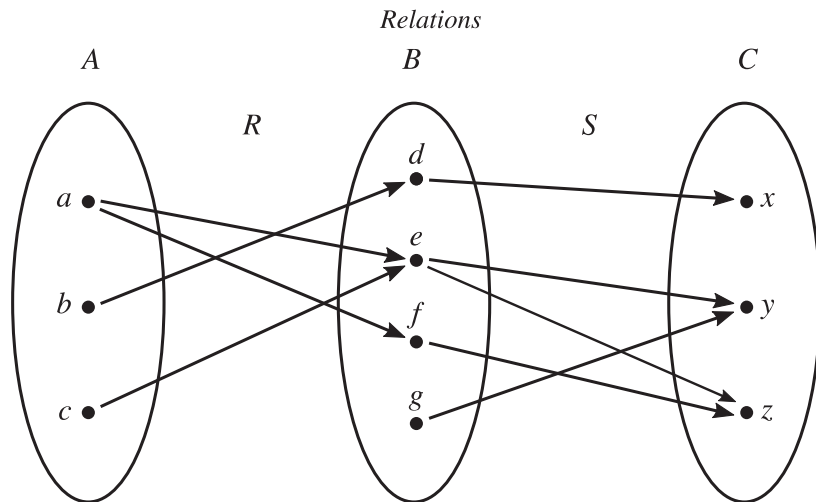


Figure 4.5.

12. Suppose R is a relation on A .
 - (a) Prove that if R is reflexive, then so is R^{-1} .
 - (b) Prove that if R is symmetric, then so is R^{-1} .
 - (c) Prove that if R is transitive, then so is R^{-1} .
- *13. Suppose R_1 and R_2 are relations on A . For each part, give either a proof or a counterexample to justify your answer.
 - (a) If R_1 and R_2 are reflexive, must $R_1 \cup R_2$ be reflexive?
 - (b) If R_1 and R_2 are symmetric, must $R_1 \cup R_2$ be symmetric?
 - (c) If R_1 and R_2 are transitive, must $R_1 \cup R_2$ be transitive?
14. Suppose R_1 and R_2 are relations on A . For each part, give either a proof or a counterexample to justify your answer.
 - (a) If R_1 and R_2 are reflexive, must $R_1 \cap R_2$ be reflexive?
 - (b) If R_1 and R_2 are symmetric, must $R_1 \cap R_2$ be symmetric?
 - (c) If R_1 and R_2 are transitive, must $R_1 \cap R_2$ be transitive?
15. Suppose R_1 and R_2 are relations on A . For each part, give either a proof or a counterexample to justify your answer.
 - (a) If R_1 and R_2 are reflexive, must $R_1 \setminus R_2$ be reflexive?
 - (b) If R_1 and R_2 are symmetric, must $R_1 \setminus R_2$ be symmetric?
 - (c) If R_1 and R_2 are transitive, must $R_1 \setminus R_2$ be transitive?
16. Suppose R and S are reflexive relations on A . Prove that $R \circ S$ is reflexive.
- *17. Suppose R and S are symmetric relations on A . Prove that $R \circ S$ is symmetric iff $R \circ S = S \circ R$.
18. Suppose R and S are transitive relations on A . Prove that if $S \circ R \subseteq R \circ S$ then $R \circ S$ is transitive.
19. Consider the following putative theorem.

Theorem? Suppose R is a relation on A , and define a relation S on $\mathcal{P}(A)$ as follows:

$$S = \{ (X, Y) \in \mathcal{P}(A) \times \mathcal{P}(A) \mid \exists x \in X \exists y \in Y (xRy) \}.$$

If R is transitive, then so is S .

(a) What's wrong with the following proof of the theorem?

Proof. Suppose R is transitive. Suppose $(X, Y) \in S$ and $(Y, Z) \in S$. Then by the definition of S , xRy and yRz , where $x \in X$, $y \in Y$, and $z \in Z$. Since xRy , yRz , and R is transitive, xRz . But then since $x \in X$ and $z \in Z$, it follows from the definition of S that $(X, Z) \in S$. Thus, S is transitive. \square

(b) Is the theorem correct? Justify your answer with either a proof or a counterexample.

*20. Suppose R is a relation on A . Let $B = \{ X \in \mathcal{P}(A) \mid X \neq \emptyset \}$, and define a relation S on B as follows:

$$S = \{ (X, Y) \in B \times B \mid \forall x \in X \forall y \in Y (xRy) \}.$$

Prove that if R is transitive, then so is S . Why did the empty set have to be excluded from the set B to make this proof work?

21. Suppose R is a relation on A , and define a relation S on $\mathcal{P}(A)$ as follows:

$$S = \{ (X, Y) \in \mathcal{P}(A) \times \mathcal{P}(A) \mid \forall x \in X \exists y \in Y (xRy) \}.$$

For each part, give either a proof or a counterexample to justify your answer.

(a) If R is reflexive, must S be reflexive?

(b) If R is symmetric, must S be symmetric?

(c) if R is transitive, must S be transitive?

22. Consider the following putative theorem:

Theorem? Suppose R is a relation on A . If R is symmetric and transitive, then R is reflexive.

Is the following proof correct? If so, what proof strategies does it use? If not, can it be fixed? Is the theorem correct?

Proof. Let x be an arbitrary element of A . Let y be any element of A such that xRy . Since R is symmetric, it follows that yRx . But then by transitivity, since xRy and yRx we can conclude that xRx . Since x was arbitrary, we have shown that $\forall x \in A (xRx)$, so R is reflexive. \square

- *23. This problem was suggested by Professor William Zwicker of Union College, NY. Suppose A is a set, and $\mathcal{F} \subseteq \mathcal{P}(A)$. Let $R = \{(a, b) \in A \times A \mid \text{for every } X \subseteq A \setminus \{a, b\}, \text{ if } X \cup \{a\} \in \mathcal{F} \text{ then } X \cup \{b\} \in \mathcal{F}\}$. Show that R is transitive.
24. Let $R = \{(m, n) \in \mathbb{N} \times \mathbb{N} \mid |m - n| \leq 1\}$, which is a relation on \mathbb{N} . Note that $R \subseteq \mathbb{Z} \times \mathbb{Z}$, so R is also a relation on \mathbb{Z} . This exercise will illustrate why, in part 1 of Definition 4.3.2, we defined the phrase “ R is reflexive on A ,” rather than simply “ R is reflexive.”
- (a) Is R reflexive on \mathbb{N} ?
- (b) Is R reflexive on \mathbb{Z} ?

4.4. Ordering Relations

Consider the relation $L = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \leq y\}$. You should be able to check for yourself that it is reflexive and transitive, but not symmetric. It fails to be symmetric in a rather extreme way because there are many pairs (x, y) such that xLy is true but yLx is false. In fact, the only way xLy and yLx can both be true is if $x \leq y$ and $y \leq x$, and thus $x = y$. We therefore say that L is *antisymmetric*. Here is the general definition.

Definition 4.4.1. Suppose R is a relation on a set A . Then R is said to be *antisymmetric* if $\forall x \in A \forall y \in A ((xRy \wedge yRx) \rightarrow x = y)$.

We have already seen a relation with many of the same properties as L . Look again at the relation S defined in part 1 of Example 4.3.1. Recall that in that example we let $A = \{1, 2\}$, $B = \mathcal{P}(A)$, and $S = \{(x, y) \in B \times B \mid x \subseteq y\}$. Thus, if x and y are elements of B , then xSy means $x \subseteq y$. We checked in the last section that S is reflexive and transitive, but not symmetric. In fact, S is also antisymmetric, because for any sets x and y , if $x \subseteq y$ and $y \subseteq x$ then $x = y$. You may find it useful to look back at Figure 4.3 in the last section, which shows the directed graph representing S .

Intuitively, L and S are both relations that have something to do with comparing the sizes of two objects. Each of the statements $x \leq y$ and $x \subseteq y$ can be thought of as saying that, in some sense, y is “at least as large as” x . You might say that each of these statements specifies what *order* x and y come in. This motivates the following definition.

Definition 4.4.2. Suppose R is a relation on a set A . Then R is called a *partial order* on A (or just a *partial order* if A is clear from context) if it is reflexive,

transitive, and antisymmetric. It is called a *total order on A* (or just a *total order*) if it is a partial order, and in addition it has the following property:

$$\forall x \in A \forall y \in A (xRy \vee yRx) .$$

The relations L and S just considered are both partial orders. S is not a total order, because it is not true that $\forall x \in B \forall y \in B (x \subseteq y \vee y \subseteq x)$. For example, if we let $x = \{1\}$ and $y = \{2\}$, then $x \not\subseteq y$ and $y \not\subseteq x$. Thus, although we can think of the relation S as indicating a sense in which one element of B might be at least as large as another, it does not give us a way of comparing *every* pair of elements of B . For some pairs, such as $\{1\}$ and $\{2\}$, S doesn't pick out either one as being at least as large as the other. This is the sense in which the ordering is *partial*. On the other hand, L is a total order, because if x and y are any two real numbers, then either $x \leq y$ or $y \leq x$. Thus, L does give us a way of comparing *any* two real numbers.

Example 4.4.3. Which of the following relations are partial orders? Which are total orders?

1. Let A be any set, and let $B = \mathcal{P}(A)$ and $S = \{(x, y) \in B \times B \mid x \subseteq y\}$.
2. Let $A = \{1, 2\}$ and $B = \mathcal{P}(A)$ as before. Let

$$\begin{aligned} R &= \{(x, y) \in B \times B \mid y \text{ has at least as many elements as } x\} \\ &= \{(\emptyset, \emptyset), (\emptyset, \{1\}), (\emptyset, \{2\}), (\emptyset, \{1, 2\}), (\{1\}, \{1\}), (\{1\}, \{2\}), \\ &\quad (\{1\}, \{1, 2\}), (\{2\}, \{1\}), (\{2\}, \{2\}), (\{2\}, \{1, 2\}), (\{1, 2\}, \{1, 2\})\}. \end{aligned}$$

3. $D = \{(x, y) \in \mathbb{Z}^+ \times \mathbb{Z}^+ \mid x \text{ divides } y\}$.
4. $G = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \geq y\}$.

Solutions

1. This is just a generalization of one of the examples discussed earlier, and it is easy to check that it is a partial order. As long as A has at least two elements, it will not be a total order. To see why, just note that if a and b are distinct elements of A , then $\{a\}$ and $\{b\}$ are elements of B for which $\{a\} \not\subseteq \{b\}$ and $\{b\} \not\subseteq \{a\}$.
2. Note that $(\{1\}, \{2\}) \in R$ and $(\{2\}, \{1\}) \in R$, but of course $\{1\} \not\subseteq \{2\}$. Thus, R is not antisymmetric, so it is not a partial order. Although R was defined by picking out pairs (x, y) in which y is, in a certain sense, at least as large as x , it does not satisfy the definition of partial order. This example shows that our description of partial orders as relations that indicate a sense in which one object is at least as large as another should not be taken too

seriously. This was the *motivation* for the definition of partial order, but it is not the definition itself.

3. Clearly every positive integer is divisible by itself, so D is reflexive. Also, as we showed in Theorem 3.3.7, if $x \mid y$ and $y \mid z$ then $x \mid z$. Thus, if $(x, y) \in D$ and $(y, z) \in D$ then $(x, z) \in D$, so D is transitive. Finally, suppose $(x, y) \in D$ and $(y, x) \in D$. Then $x \mid y$ and $y \mid x$, and because x and y are positive it follows that $x \leq y$ and $y \leq x$, so $x = y$. Thus, D is antisymmetric, so it is a partial order. It is easy to find examples illustrating that D is not a total order. For example, $(3, 5) \notin D$ and $(5, 3) \notin D$.

Perhaps you were surprised to discover that D is a partial order. It doesn't seem to involve comparing the sizes of things, like the other partial orders we've seen. But we have shown that it does share with these other relations the important properties of reflexivity, transitivity, and antisymmetry. In fact, this is one of the reasons for formulating definitions such as Definition 4.4.2. They help us to see similarities between things that, on the surface, might not seem similar at all.

4. You should be able to check for yourself that G is a total order. Notice that in this case it seems more reasonable to think of xGy as meaning that y is as least as *small* as x rather than at least as *large*. The definition of partial order, though motivated by thinking about orderings that go in one direction, actually applies to orderings in either direction. In fact, this example might lead you to conjecture that if R is a partial order on A , then so is R^{-1} . You are asked to prove this conjecture in exercise 13.

So far we have always used letters as the names for our relations, but sometimes mathematicians represent relations with symbols rather than letters. For example, in part 4 of Example 4.4.3 we used the letter G as the name for a relation. But in that example, for all real numbers x and y , xGy meant the same thing as $x \geq y$. This suggests that we didn't really need to introduce the letter G ; we could simply have treated the symbol \geq as the name for the relation. Using this notation, we could say that \geq is a total order on \mathbb{R} .

Here's another example of a partial order. Let A be the set of all words in English, and let $R = \{(x, y) \in A \times A \mid \text{all the letters in the word } x \text{ appear, consecutively and in the right order, in the word } y\}$. For example, (can, cannot), (tar, start), and (ball, ball) are all elements of R , but (can, anchor) and (can, carnival) are not. You should be able to check that R is reflexive, transitive, and antisymmetric, so R is a partial order. Now consider the set $B = \{\text{me, men, tame, mental}\} \subseteq A$. Clearly many ordered pairs of words in B are in the relation R , but note in particular that the ordered pairs (me, me), (me, men), (me, tame), and (me, mental) are all in R . If we think of xRy as

meaning that y is in some sense at least as large as x , then we could say that the word *me* is the *smallest* element of B , in the sense that it is smaller than everything else in the set.

Not every set of words will have an element that is smallest in this sense. For example, consider the set $C = \{a, me, men, tame, mental\} \subseteq A$. Each of the words *men*, *tame*, and *mental* is larger than at least one other word in the set, but neither *a* nor *me* is larger than anything else in the set. We'll call *a* and *me* *minimal* elements of C . But note that neither *a* nor *me* is the smallest element of C in the sense described in the last paragraph, because neither is smaller than the other. The set C has two minimal elements but no smallest element.

These examples might raise a number of questions in your mind about smallest and minimal elements. The set C has two minimal elements, but B has only one smallest element. Can a set ever have more than one smallest element? Until we have settled this question, we should only talk about an object being *a* smallest element of a set, rather than *the* smallest element. If a set has only one minimal element, must it be a smallest element? Can a set have a smallest element and a minimal element that are different? Would the answers to these questions be different if we restricted our attention to *total* orders rather than all partial orders? Before we try to answer any of these questions, we should state the definitions of the terms *smallest* and *minimal* more carefully.

Definition 4.4.4. Suppose R is a partial order on a set A , $B \subseteq A$, and $b \in B$. Then b is called an R -*smallest* element of B (or just a *smallest* element if R is clear from the context) if $\forall x \in B(bRx)$. It is called an R -*minimal* element (or just a *minimal* element) if $\neg \exists x \in B(xRb \wedge x \neq b)$.

Example 4.4.5.

1. Let $L = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \leq y\}$, as before. Let $B = \{x \in \mathbb{R} \mid x \geq 7\}$. Does B have any L -smallest or L -minimal elements? What about the set $C = \{x \in \mathbb{R} \mid x > 7\}$? As mentioned earlier, we could do without the letter L here and ask for \leq -smallest or \leq -minimal elements of B and C .
2. Let D be the divisibility relation defined in part 3 of Example 4.4.3. Let $B = \{3, 4, 5, 6, 7, 8, 9\}$. Does B have any D -smallest or D -minimal elements?
3. Let $S = \{(X, Y) \in \mathcal{P}(\mathbb{N}) \times \mathcal{P}(\mathbb{N}) \mid X \subseteq Y\}$, which is a partial order on the set $\mathcal{P}(\mathbb{N})$. Let $F = \{X \in \mathcal{P}(\mathbb{N}) \mid 2 \in X \text{ and } 3 \in X\}$. Note that the elements of F are not natural numbers, but *sets* of natural numbers.

For example, $\{1, 2, 3\}$ and $\{n \in \mathbb{N} \mid n \text{ is prime}\}$ are both elements of \mathcal{F} . Does \mathcal{F} have any S -smallest or S -minimal elements? What about the set $\mathcal{G} = \{X \in \mathcal{P}(\mathbb{N}) \mid \text{either } 2 \in X \text{ or } 3 \in X\}$?

Solutions

1. Clearly $7 \leq x$ for every $x \in B$, so $\forall x \in B (7Lx)$ and therefore 7 is a smallest element of B . It is also a minimal element, since nothing in B is smaller than 7, so $\neg \exists x \in B (xL7 \wedge x \neq 7)$. There are no other smallest or minimal elements. Note that 7 is *not* a smallest or minimal element of C , since $7 \notin C$. According to Definition 4.4.4, a smallest or minimal element of a set must actually be an element of the set. In fact, C has no smallest or minimal elements.
2. First of all, note that 6 and 9 are not minimal because both are divisible by 3, and 8 is not minimal because it is divisible by 4. All the other elements of B are minimal elements, but none is a smallest element.
3. The set $\{2, 3\}$ is a smallest element of \mathcal{F} , since 2 and 3 are elements of every set in \mathcal{F} , and therefore $\forall X \in \mathcal{F} (\{2, 3\} \subseteq X)$. It is also a minimal element, since no other element of \mathcal{F} is a subset of it, and there are no other smallest or minimal elements. The set \mathcal{G} has two minimal elements, $\{2\}$ and $\{3\}$. Every other set in \mathcal{G} must contain one of these two as a subset, so no other set can be minimal. Neither set is smallest, since neither is a subset of the other.

We are now ready to answer some of the questions we raised before Definition 4.4.4.

Theorem 4.4.6. *Suppose R is a partial order on a set A , and $B \subseteq A$.*

1. *If B has a smallest element, then this smallest element is unique. Thus, we can speak of **the** smallest element of B rather than **a** smallest element.*
2. *Suppose b is the smallest element of B . Then b is also a minimal element of B , and it is the only minimal element.*
3. *If R is a total order and b is a minimal element of B , then b is the smallest element of B .*

Scratch work

These proofs are somewhat harder than earlier ones in this chapter, so we do some scratch work before the proofs.

1. Of course, we start by assuming that B has a smallest element, and because this is an existential statement, we immediately introduce a name, say b , for a smallest element of B . We must prove that b is the only smallest element. As we saw in Section 3.6, this can be written $\forall c(c \text{ is a smallest element of } B \rightarrow b = c)$, so our next step should be to let c be arbitrary, assume it is also a smallest element, and prove $b = c$.

At this point, we don't know much about b and c . We know they're both elements of B , but we don't even know what kinds of objects are in B – whether they're numbers, or sets, or some other type of object – so this doesn't help us much in deciding how to prove that $b = c$. The only other fact we know about b and c is that they are both smallest elements of B , which means $\forall x \in B(bRx)$ and $\forall x \in B(cRx)$. The most promising way to use these statements is to plug something in for x in each statement. What we plug in should be an element of B , and we only know of two elements of B at this point, b and c . Plugging in both of them in both statements, we get bRb , bRc , cRb , and cRc . Of course, we already knew bRb and cRc , since R is reflexive. But when you see that bRc and cRb , you should think of antisymmetry. Since R is a partial order, it is antisymmetric, so from bRc and cRb it follows that $b = c$.

2. Our first goal is to prove that b is a minimal element of B , which means $\neg \exists x \in B(xRb \wedge x \neq b)$. Because this is a negative statement, it might help to reexpress it as an equivalent positive statement:

$$\begin{aligned} \neg \exists x \in B(xRb \wedge x \neq b) &\text{ iff } \forall x \in B \neg (xRb \wedge x \neq b) \\ &\text{ iff } \forall x \in B (\neg xRb \vee x = b) \\ &\text{ iff } \forall x \in B (xRb \rightarrow x = b). \end{aligned}$$

Thus, to prove that b is minimal we could let x be an arbitrary element of B , assume that xRb , and prove $x = b$.

Once again, it's a good idea to take stock of what we know at this point about b and x . We know xRb , and we know that b is the smallest element of B , which means $\forall x \in B(bRx)$. If we apply this last fact to our arbitrary x , then as in part 1 we can use antisymmetry to complete the proof.

We still must prove that b is the only minimal element, and as in part 1 this means $\forall c(c \text{ is a minimal element of } B \rightarrow b = c)$. So we let c be arbitrary and assume that c is a minimal element of B , and we must prove that $b = c$. The assumption that c is a minimal element of B means that $c \in B$ and $\neg \exists x \in B(xRc \wedge x \neq c)$, but as before, we can reexpress this last statement in the equivalent positive form $\forall x \in B(xRc \rightarrow x = c)$. To use this statement we should plug in something for x , and because our goal is

to show that $b = c$, plugging in b for x seems like a good idea. This gives us $bRc \rightarrow b = c$, so if only we could show bRc , we could complete the proof by using modus ponens to conclude that $b = c$. But we know b is the smallest element of B , so of course bRc is true.

3. Of course, we start by assuming that R is a total order and b is a minimal element of B . We must prove that b is the smallest element of B , which means $\forall x \in B(bRx)$, so we let x be an arbitrary element of B and try to prove bRx .

We know from examples we've looked at that minimal elements in *partial* orders are not always smallest elements, so the assumption that R is a *total* order must be crucial. The assumption that R is total means $\forall x \in A \forall y \in A(xRy \vee yRx)$, so to use it we should plug in something for x and y . The only likely candidates for what to plug in are b and our arbitrary object x , and plugging these in we get $xRb \vee bRx$. Our goal is bRx , so this certainly looks like progress. If only we could rule out the possibility that xRb , we'd be done. So let's see if we can prove $\neg xRb$.

Because this is a negative statement, we try proof by contradiction. Suppose xRb . What given statement can we contradict? The only given we haven't used yet is the fact that b is minimal, and since this is a negative statement, it is the natural place to look for a contradiction. To contradict the fact that b is minimal, we should try to show that $\exists x \in B(xRb \wedge x \neq b)$. But we've already assumed xRb , so if we could show $x \neq b$ we'd be done.

You should try proving $x \neq b$ at this point. You won't get anywhere. The fact is, we started out by letting x be an arbitrary element of B , and this means that it could be any element of B , including b . We then assumed that xRb , but since R is reflexive, this still doesn't rule out the possibility that $x = b$. There really isn't any hope of proving $x \neq b$. We seem to be stuck.

Let's review our overall plan for the proof. We needed to show $\forall x \in B(bRx)$, so we let x be an arbitrary element of B , and we're trying to show bRx . We've now run into problems because of the possibility that $x = b$. But if our ultimate goal is to prove bRx , then the possibility that $x = b$ really isn't a problem after all. Since R is reflexive, if $x = b$ then of course bRx will be true!

Now, how should we structure the final write-up of the proof? It appears that our reasoning to establish bRx will have to be different depending on whether or not $x = b$. This suggests *proof by cases*. In case 1 we assume that $x = b$, and use the fact that R is reflexive to complete the proof. In case 2 we assume that $x \neq b$, and then we can use our original line of attack, starting with the fact that R is total.

Proof.

1. Suppose b is a smallest element of B , and suppose c is also a smallest element of B . Since b is a smallest element, $\forall x \in B(bRx)$, so in particular bRc . Similarly, since c is a smallest element, cRb . But now since R is a partial order, it must be antisymmetric, so from bRc and cRb we can conclude $b = c$.
2. Let x be an arbitrary element of B and suppose that xRb . Since b is the smallest element of B , we must have bRx , and now by antisymmetry it follows that $x = b$. Thus, there can be no $x \in B$ such that xRb and $x \not\equiv b$, so b is a minimal element.

To see that it is the only one, suppose c is also a minimal element. Since b is the smallest element of B , bRc . But then since c is minimal we must have $b = c$. Thus b is the only minimal element of B .

3. Suppose R is a total order and b is a minimal element of B . Let x be an arbitrary element of B . If $x = b$, then since R is reflexive, bRx . Now suppose $x \not\equiv b$. Since R is a total order, we know that either xRb or bRx . But xRb can't be true, since by combining xRb with our assumption that $x \not\equiv b$ we could conclude that b is not minimal, thereby contradicting our assumption that it is minimal. Thus, bRx must be true. Since x was arbitrary, we can conclude that $\forall x \in B(bRx)$, so b is the smallest element of B . \square

When comparing subsets of some set A , mathematicians often use the partial order $S = \{(X, Y) \in \mathcal{P}(A) \times \mathcal{P}(A) \mid X \subseteq Y\}$, although this is not always made explicit. Recall that if $\mathcal{F} \subseteq \mathcal{P}(A)$ and $X \in \mathcal{F}$, then according to Definition 4.4.4, X is the S -smallest element of \mathcal{F} iff $\forall Y \in \mathcal{F}(X \subseteq Y)$. In other words, to say that an element of \mathcal{F} is the smallest element means that it is a subset of every element of \mathcal{F} . Similarly, mathematicians sometimes talk of a set being the smallest one with a certain property. Generally this means that the set has the property in question, and furthermore it is a subset of every set that has the property. For example, we might describe our conclusion in part 3 of Example 4.4.5 by saying that $\{2, 3\}$ is the smallest set $X \subseteq \mathbb{N}$ with the property that $2 \in X$ and $3 \in X$. We will see more examples of this idea in later chapters.

Example 4.4.7.

1. Find the smallest set of real numbers X such that $5 \in X$ and for all real numbers x and y , if $x \in X$ and $x < y$ then $y \in X$.
2. Find the smallest set of real numbers X such that $X \not\equiv \emptyset$ and for all real numbers x and y , if $x \in X$ and $x < y$ then $y \in X$.

Solutions

- Another way to phrase the question would be to say that we are looking for the smallest element of the family of sets $\mathcal{F} = \{X \subseteq \mathbb{R} \mid 5 \in X \text{ and } \forall x \forall y((x \in X \wedge x < y) \rightarrow y \in X)\}$, where it is understood that *smallest* means smallest with respect to the subset partial order. Now for any set $X \in \mathcal{F}$ we know that $5 \in X$, and we know that $\forall x \forall y((x \in X \wedge x < y) \rightarrow y \in X)$. In particular, since $5 \in X$ we can say that $\forall y(5 < y \rightarrow y \in X)$. Thus, if we let $A = \{y \in \mathbb{R} \mid 5 \leq y\}$, then we can conclude that $\forall X \in \mathcal{F}(A \subseteq X)$. But it is easy to see that $A \in \mathcal{F}$, so A is the smallest element of \mathcal{F} .
- We must find the smallest element of the family of sets $\mathcal{F} = \{X \subseteq \mathbb{R} \mid X \neq \emptyset \text{ and } \forall x \forall y((x \in X \wedge x < y) \rightarrow y \in X)\}$. The set $A = \{y \in \mathbb{R} \mid 5 \leq y\}$ from part 1 is an element of \mathcal{F} , but it is not the smallest element, or even a minimal element, because the set $A^3 = \{y \in \mathbb{R} \mid 6 \leq y\}$ is smaller – in other words, $A^3 \subseteq A$ and $A^3 \neq A$. But A^3 is also not the smallest element, since $A^{33} = \{y \in \mathbb{R} \mid 7 \leq y\}$ is still smaller. In fact, this family has no smallest, or even minimal, element. You're asked to verify this in exercise 12. This example shows that we must be careful when talking about the smallest set with some property. There may be no such smallest set!

You have probably already guessed how to define maximal and largest elements in partially ordered sets. Suppose R is a partial order on A , $B \subseteq A$, and $b \in B$. We say that b is the *largest* element of B if $\forall x \in B(xRb)$, and it is a *maximal* element of B if $\neg \exists x \in B(bRx \wedge b \neq x)$. Of course, these definitions are quite similar to the ones in Definition 4.4.4. You are asked in exercise 14 to work out some of the connections among these ideas. Another useful related idea is the concept of an upper or lower bound for a set.

Definition 4.4.8. Suppose R is a partial order on A , $B \subseteq A$, and $a \in A$. Then a is called a *lower bound* for B if $\forall x \in B(aRx)$. Similarly, it is an *upper bound* for B if $\forall x \in B(xRa)$.

Note that a lower bound for B need not be an element of B . This is the only difference between lower bounds and smallest elements. A smallest element of B is just a lower bound that is also an element of B . For example, in part 1 of Example 4.4.5, we concluded that 7 was not a smallest element of the set $C = \{x \in \mathbb{R} \mid x > 7\}$ because $7 \notin C$. But 7 is a lower bound for C . In fact, so is every real number smaller than 7, but not any number larger than 7. Thus, the set of all lower bounds of C is the set $\{x \in \mathbb{R} \mid x \leq 7\}$, and 7 is its largest element. We say that 7 is the *greatest lower bound* of the set C .

Definition 4.4.9. Suppose R is a partial order on A and $B \subseteq A$. Let U be the set of all upper bounds for B , and let L be the set of all lower bounds. If U has a smallest element, then this smallest element is called the *least upper bound* of B . If L has a largest element, then this largest element is called the *greatest lower bound* of B . The phrases *least upper bound* and *greatest lower bound* are sometimes abbreviated *l.u.b.* and *g.l.b.*

Example 4.4.10.

1. Let $L = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \leq y\}$, a total order on \mathbb{R} . Let $B = \{1/n \mid n \in \mathbb{Z}^+\} = \{1, 1/2, 1/3, 1/4, 1/5, \dots\} \subseteq \mathbb{R}$. Does B have any upper or lower bounds? Does it have a least upper bound or greatest lower bound?
2. Let A be the set of all English words, and let R be the partial order on A described after Example 4.4.3. Let $B = \{\text{hold, up}\}$. Does B have any upper or lower bounds? Does it have a least upper bound or a greatest lower bound?

Solutions

1. Clearly the largest element of B is 1. It is also an upper bound for B , as is any number larger than 1. By definition, an upper bound for B must be at least as large as every element of B , so in particular it must be at least as large as 1. Thus, no number smaller than 1 is an upper bound for B , so the set of upper bounds for B is $\{x \in \mathbb{R} \mid x \geq 1\}$. Clearly the smallest element of this set is 1, so 1 is the l.u.b. of B .

Clearly 0 is a lower bound for B , as is any negative number. On the other hand, suppose a is a positive number. Then for a large enough integer n we will have $1/n < a$. (You should convince yourself that any integer n larger than $1/a$ would do.) Thus, it is not the case that $\forall x \in B(a \leq x)$, and therefore a is not a lower bound for B . So the set of all lower bounds for B is $\{x \in \mathbb{R} \mid x \leq 0\}$, and the g.l.b. of B is 0.

2. Clearly *holdup* and *uphold* are upper bounds for B . In fact, no shorter word could be an upper bound, so they are both minimal elements of the set of all upper bounds. According to part 2 of Theorem 4.4.6, a set that has more than one minimal element can have no smallest element, so the set of all upper bounds for B does not have a smallest element, and therefore B doesn't have a least upper bound.

The words *hold* and *up* have no letters in common, so B has no lower bounds.

Notice that in part 1 of Example 4.4.10, the largest element of B also turned out to be its least upper bound. You might wonder whether largest elements are

always least upper bounds and whether smallest elements are always greatest lower bounds. You are asked to prove that they are in exercise 20. Another interesting fact about this example is that, although B did not have a smallest element, it did have a greatest lower bound. This was not a coincidence. It is an important fact about the real numbers that *every* nonempty set of real numbers that has a lower bound has a greatest lower bound and, similarly, every nonempty set of real numbers that has an upper bound has a least upper bound. The proof of this fact is beyond the scope of this book, but it is important to realize that it is a special fact about the real numbers; it does not apply to all partial orders or even to all total orders. For example, the set B in the second part of Example 4.4.10 had upper bounds but no least upper bound.

We end this section by looking once again at how these new concepts apply to the subset partial order on $\mathcal{P}(A)$, for any set A . It turns out that in this partial order, least upper bounds and greatest lower bounds are our old friends unions and intersections.

Theorem 4.4.11. *Suppose A is a set, $\mathcal{F} \subseteq \mathcal{P}(A)$, and $\mathcal{F} \neq \emptyset$. Then the least upper bound of \mathcal{F} (in the subset partial order) is $\bigcup \mathcal{F}$ and the greatest lower bound of \mathcal{F} is $\bigcap \mathcal{F}$.*

Proof. See exercise 23. □

Exercises

- *1. In each case, say whether or not R is a partial order on A . If so, is it a total order?
- (a) $A = \{a, b, c\}$, $R = \{(a, a), (b, a), (b, b), (b, c), (c, c)\}$.
 - (b) $A = \mathbb{R}$, $R = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid |x| \leq |y|\}$.
 - (c) $A = \mathbb{R}$, $R = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid |x| < |y| \text{ or } x = y\}$.
2. In each case, say whether or not R is a partial order on A . If so, is it a total order?
- (a) $A =$ the set of all words of English, $R = \{(x, y) \in A \times A \mid \text{the word } y \text{ occurs at least as late in alphabetical order as the word } x\}$.
 - (b) $A =$ the set of all words of English, $R = \{(x, y) \in A \times A \mid \text{the first letter of the word } y \text{ occurs at least as late in the alphabet as the first letter of the word } x\}$.

- (c) $A =$ the set of all countries in the world, $R = \{(x, y) \in A \times A \mid \text{the population of the country } y \text{ is at least as large as the population of the country } x\}$.
3. In each case find all minimal and maximal elements of B . Also find, if they exist, the largest and smallest elements of B , and the least upper bound and greatest lower bound of B .
- (a) $R =$ the relation shown in the directed graph in Figure 4.6, $B = \{2, 3, 4\}$.

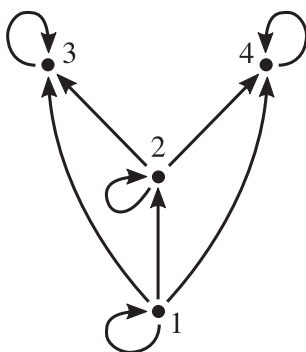


Figure 4.6.

- (b) $R = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \leq y\}$, $B = \{x \in \mathbb{R} \mid 1 \leq x < 2\}$.
- (c) $R = \{(x, y) \in \mathcal{P}(\mathbb{N}) \times \mathcal{P}(\mathbb{N}) \mid x \subseteq y\}$, $B = \{x \in \mathcal{P}(\mathbb{N}) \mid x \text{ has at most 5 elements}\}$.
- *4. Suppose R is a relation on A . You might think that R could not be both antisymmetric and symmetric, but this isn't true. Prove that R is both antisymmetric and symmetric iff $R \subseteq i_A$.
5. Suppose R is a partial order on A and $B \subseteq A$. Prove that $R \cap (B \times B)$ is a partial order on B .
6. Suppose R_1 and R_2 are partial orders on A . For each part, give either a proof or a counterexample to justify your answer.
- (a) Must $R_1 \cap R_2$ be a partial order on A ?
- (b) Must $R_1 \cup R_2$ be a partial order on A ?
7. Suppose R_1 is a partial order on A_1 , R_2 is a partial order on A_2 , and $A_1 \cap A_2 = \emptyset$.
- (a) Prove that $R_1 \cup R_2$ is a partial order on $A_1 \cup A_2$.
- (b) Prove that $R_1 \cup R_2 \cup (A_1 \times A_2)$ is a partial order on $A_1 \cup A_2$.
- (c) Suppose that R_1 and R_2 are total orders. Are the partial orders in parts (a) and (b) also total orders?

- *8. Suppose R is a partial order on A and S is a partial order on B . Define a relation T on $A \times B$ as follows: $T = \{((a, b), (a^3, b^3)) \in (A \times B) \times (A \times B) \mid aRa^3 \text{ and } bSb^3\}$. Show that T is a partial order on $A \times B$. If both R and S are total orders, will T also be a total order?
9. Suppose R is a partial order on A and S is a partial order on B . Define a relation L on $A \times B$ as follows: $L = \{((a, b), (a^3, b^3)) \in (A \times B) \times (A \times B) \mid aRa^3, \text{ and if } a = a^3 \text{ then } bSb^3\}$. Show that L is a partial order on $A \times B$. If both R and S are total orders, will L also be a total order?
10. Suppose R is a partial order on A . For each $x \in A$, let $P_x = \{a \in A \mid aRx\}$. Prove that $\forall x \in A \forall y \in A (xRy \leftrightarrow P_x \subseteq P_y)$.
- *11. Let D be the divisibility relation defined in part 3 of Example 4.4.3. Let $B = \{x \in \mathbb{Z} \mid x > 1\}$. Does B have any minimal elements? If so, what are they? Does B have a smallest element? If so, what is it?
12. Show that, as was stated in part 2 of Example 4.4.7, $\{X \subseteq \mathbb{R} \mid X \neq \emptyset \text{ and } \forall x \forall y ((x \in X \wedge x < y) \rightarrow y \in X)\}$ has no minimal element.
13. Suppose R is a partial order on A . Prove that R^{-1} is also a partial order on A . If R is a total order, will R^{-1} also be a total order?
- *14. Suppose R is a partial order on A , $B \subseteq A$, and $b \in B$. Exercise 13 shows that R^{-1} is also a partial order on A .
- (a) Prove that b is the R -largest element of B iff it is the R^{-1} -smallest element of B .
- (b) Prove that b is an R -maximal element of B iff it is an R^{-1} -minimal element of B .
15. Suppose R_1 and R_2 are partial orders on A , $R_1 \subseteq R_2$, $B \subseteq A$, and $b \in B$.
- (a) Prove that if b is the R_1 -smallest element of B , then it is also the R_2 -smallest element of B .
- (b) Prove that if b is an R_2 -minimal element of B , then it is also an R_1 -minimal element of B .
16. Suppose R is a partial order on A , $B \subseteq A$, and $b \in B$. Prove that if b is the largest element of B , then b is also a maximal element of B , and it's the only maximal element.
- *17. If a subset of a partially ordered set has exactly one minimal element, must that element be a smallest element? Give either a proof or a counterexample to justify your answer.
18. Suppose R is a partial order on A , $B_1 \subseteq A$, $B_2 \subseteq A$, $\forall x \in B_1 \exists y \in B_2 (xRy)$, and $\forall x \in B_2 \exists y \in B_1 (xRy)$.
- (a) Prove that for all $x \in A$, x is an upper bound of B_1 iff x is an upper bound of B_2 .

- (b) Prove that if B_1 and B_2 are disjoint then neither of them has a maximal element.

19. Consider the following putative theorem.

Theorem? *Suppose R is a total order on A and $B \subseteq A$. Then every element of B is either the smallest element of B or the largest element of B .*

- (a) What's wrong with the following proof of the theorem?

Proof. Suppose $b \in B$. Let x be an arbitrary element of B . Since R is a total order, either bRx or xRb .

Case 1. bRx . Since x was arbitrary, we can conclude that $\forall x \in B(bRx)$, so b is the smallest element of R .

Case 2. xRb . Since x was arbitrary, we can conclude that $\forall x \in B(xRb)$, so b is the largest element of R .

Thus, b is either the smallest element of B or the largest element of B . Since b was arbitrary, every element of B is either its smallest element or its largest element. \square

- (b) Is the theorem correct? Justify your answer with either a proof or a counterexample.

20. Suppose R is a partial order on A , $B \subseteq A$, and $b \in B$.

- (a) Prove that if b is the smallest element of B , then it is also the greatest lower bound of B .
- (b) Prove that if b is the largest element of B , then it is also the least upper bound of B .

*21. Suppose R is a partial order on A and $B \subseteq A$. Let U be the set of all upper bounds for B .

- (a) Prove that U is *closed upward*; that is, prove that if $x \in U$ and xRy , then $y \in U$.
- (b) Prove that every element of B is a lower bound for U .
- (c) Prove that if x is the greatest lower bound of U , then x is the least upper bound of B .

22. Suppose that R is a partial order on A , $B_1 \subseteq A$, $B_2 \subseteq A$, x_1 is the least upper bound of B_1 , and x_2 is the least upper bound of B_2 . Prove that if $B_1 \subseteq B_2$ then x_1Rx_2 .

23. Prove Theorem 4.4.11.

*24. Suppose R is a relation on A . Let $S = R \cup R^{-1}$.

- (a) Show that S is a symmetric relation on A and $R \subseteq S$.
- (b) Show that if T is a symmetric relation on A and $R \subseteq T$ then $S \subseteq T$.

Note that this exercise shows that S is the smallest element of the set $\mathcal{F} = \{T \subseteq A \times A \mid R \subseteq T \text{ and } T \text{ is symmetric}\}$; in other words, it is the smallest symmetric relation on A that contains R as a subset. The relation S is called the *symmetric closure* of R .

25. Suppose that R is a relation on A . Let $\mathcal{F} = \{T \subseteq A \times A \mid R \subseteq T \text{ and } T \text{ is transitive}\}$.
- Show that $\mathcal{F} \neq \emptyset$.
 - Show that $\bigcap \mathcal{F}$ is a transitive relation on A and $R \subseteq \bigcap \mathcal{F}$.
 - Show that $\bigcap \mathcal{F}$ is the smallest transitive relation on A that contains R as a subset. The relation $\bigcap \mathcal{F}$ is called the *transitive closure* of R .
26. Suppose R_1 and R_2 are relations on A and $R_1 \subseteq R_2$.
- Let S_1 and S_2 be the symmetric closures of R_1 and R_2 , respectively. Prove that $S_1 \subseteq S_2$. (See exercise 24 for the definition of symmetric closure.)
 - Let T_1 and T_2 be the transitive closures of R_1 and R_2 , respectively. Prove that $T_1 \subseteq T_2$. (See exercise 25 for the definition of transitive closure.)
- *27. Suppose R_1 and R_2 are relations on A , and let $R = R_1 \cup R_2$.
- Let S_1 , S_2 , and S be the symmetric closures of R_1 , R_2 , and R , respectively. Prove that $S_1 \cup S_2 = S$. (See exercise 24 for the definition of symmetric closure.)
 - Let T_1 , T_2 , and T be the transitive closures of R_1 , R_2 , and R , respectively. Prove that $T_1 \cup T_2 \subseteq T$, and give an example to show that it may happen that $T_1 \cup T_2 \neq T$. (See exercise 25 for the definition of transitive closure.)
28. Suppose A is a set.
- Prove that if A has at least two elements then there is no largest antisymmetric relation on A . In other words, there is no relation R on A such that R is antisymmetric, and for every antisymmetric relation S on A , $S \subseteq R$.
 - Suppose R is a total order on A . Prove that R is a maximal antisymmetric relation on A . In other words, there is no antisymmetric relation S on A such that $R \subseteq S$ and $R \neq S$.
29. Suppose R is a relation on A . We say that R is *irreflexive* if $\forall x \in A (x, x) \notin R$. R is called a *strict partial order* on A if it is irreflexive and transitive. It is called a *strict total order* if it is a strict partial order and in addition $\forall x \in A \forall y \in A (xRy \vee yRx \vee x = y)$. (Note that the terminology here is somewhat misleading, because a strict partial order isn't a special kind of partial order. It's not a partial order at all, since it's not reflexive!)

- (a) Let $L = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x < y\}$. Show that L is a strict total order on \mathbb{R} .
- (b) Show that if R is a partial order on A , then $R \setminus i_A$ is a strict partial order on A , and if R is a total order on A , then $R \setminus i_A$ is a strict total order on A .
- (c) Show that if R is a strict partial order on A , then $R \cup i_A$ is a partial order on A , and if R is a strict total order on A , then $R \cup i_A$ is a total order on A .
30. Suppose R is a relation on A , and let T be the transitive closure of R . Prove that if R is symmetric, then so is T . (Hint: Assume that R is symmetric. Prove that $R \subseteq T^{-1}$ and T^{-1} is transitive. What can you conclude about T and T^{-1} ? See exercise 25 for the definition of transitive closure.)

4.5. Equivalence Relations

We saw in Example 4.3.3 that the identity relation i_A on any set A is always reflexive, symmetric, and transitive. Relations with this combination of properties come up often in mathematics, and they have some important properties that we will investigate in this section. These relations are called *equivalence relations*.

Definition 4.5.1. Suppose R is a relation on a set A . Then R is called an *equivalence relation on A* (or just an *equivalence relation* if A is clear from context) if it is reflexive, symmetric, and transitive.

As we observed earlier, the identity relation i_A on a set A is an equivalence relation. For another example, let T be the set of all triangles, and let C be the relation of congruence of triangles. In other words, $C = \{(s, t) \in T \times T \mid \text{the triangle } s \text{ is congruent to the triangle } t\}$. (Recall that a triangle is congruent to another if it can be moved without distorting it so that it coincides with the other.) Clearly every triangle is congruent to itself, so C is reflexive. Also, if triangle s is congruent to triangle t , then t is congruent to s , so C is symmetric; and if r is congruent to s and s is congruent to t , then r is congruent to t , so C is transitive. Thus, C is an equivalence relation on T .

As another example, let P be the set of all people, and let $B = \{(p, q) \in P \times P \mid \text{the person } p \text{ has the same birthday as the person } q\}$. (By “same birthday” we mean same month and day, but not necessarily the same year.)

Everyone has the same birthday as himself or herself, so B is reflexive. If p has the same birthday as q , then q has the same birthday as p , so B is symmetric. And if p has the same birthday as q and q has the same birthday as r , then p has the same birthday as r , so B is transitive. Therefore B is an equivalence relation.

It may be instructive to look at the relation B more closely. We can think of this relation as splitting the set P of all people into 366 categories, one for each possible birthday. (Remember, some people were born on February 29!) An ordered pair of people will be an element of B if the people come from the same category, but will not be an element of B if the people come from different categories. We could think of these categories as forming a family of subsets of P , which we could write as an indexed family as follows. First of all, let D be the set of all possible birthdays. In other words, $D = \{\text{Jan. 1, Jan. 2, Jan. 3, } \dots, \text{Dec. 30, Dec. 31}\}$. Now for each $d \in D$, let $P_d = \{p \in P \mid \text{the person } p \text{ was born on the day } d\}$. Then the family $\mathcal{F} = \{P_d \mid d \in D\}$ is an indexed family of subsets of P . The elements of \mathcal{F} are called *equivalence classes* for the relation B , and every person is an element of exactly one of these equivalence classes. The relation B consists of those pairs $(p, q) \in P \times P$ such that the people p and q are in the same equivalence class. In other words,

$$\begin{aligned} B &= \{(p, q) \in P \times P \mid \exists d \in D(p \in P_d \text{ and } q \in P_d)\} \\ &= \{(p, q) \in P \times P \mid \exists d \in D((p, q) \in P_d \times P_d)\} \\ &= \bigcup_{d \in D} (P_d \times P_d). \end{aligned}$$

We will call the family \mathcal{F} a *partition* of P because it breaks the set P into disjoint pieces. It turns out that every equivalence relation on a set A determines a partition of A , whose elements are the equivalence classes for the equivalence relation. But before we can work out the details of why this is true, we must define the terms *partition* and *equivalence class* more carefully.

Definition 4.5.2. Suppose A is a set and $\mathcal{F} \subseteq \mathcal{P}(A)$. We will say that \mathcal{F} is *pairwise disjoint* if every pair of distinct elements of \mathcal{F} are disjoint, or in other words $\forall X \in \mathcal{F} \forall Y \in \mathcal{F} (X \neq Y \rightarrow X \cap Y = \emptyset)$. (This concept was discussed in exercise 5 of Section 3.6.) \mathcal{F} is called a *partition* of A if it has the following properties:

1. $\bigcup \mathcal{F} = A$.
2. \mathcal{F} is pairwise disjoint.
3. $\forall X \in \mathcal{F} (X \neq \emptyset)$.

For example, suppose $A = \{1, 2, 3, 4\}$ and $\mathcal{F} = \{\{2\}, \{1, 3\}, \{4\}\}$. Then $\bigcup \mathcal{F} = \{2\} \cup \{1, 3\} \cup \{4\} = \{1, 2, 3, 4\} = A$, so \mathcal{F} satisfies the first clause in the definition of partition. Also, no two sets in \mathcal{F} have any elements in common, so \mathcal{F} is pairwise disjoint, and clearly all the sets in \mathcal{F} are nonempty. Thus, \mathcal{F} is a partition of A . On the other hand, the family $\mathcal{G} = \{\{1, 2\}, \{1, 3\}, \{4\}\}$ is not pairwise disjoint, because $\{1, 2\} \cap \{1, 3\} = \{1\} \neq \emptyset$, so it is not a partition of A . The family $\mathcal{H} = \{\emptyset, \{2\}, \{1, 3\}, \{4\}\}$ is also not a partition of A , because it fails on the third requirement in the definition.

Definition 4.5.3. Suppose R is an equivalence relation on a set A , and $x \in A$. Then the *equivalence class of x with respect to R* is the set

$$[x]_R = \{y \in A \mid yRx\}.$$

If R is clear from context, then we just write $[x]$ instead of $[x]_R$. The set of all equivalence classes of elements of A is called *A modulo R* , and is denoted A/R . Thus,

$$A/R = \{[x]_R \mid x \in A\} = \{X \subseteq A \mid \exists x \in A (X = [x]_R)\}.$$

In the case of the same-birthday relation B , if p is any person, then according to Definition 4.5.3,

$$\begin{aligned} [p]_B &= \{q \in P \mid qBp\} \\ &= \{q \in P \mid \text{the person } q \text{ has the same birthday as the person } p\}. \end{aligned}$$

For example, if John was born on August 10, then

$$\begin{aligned} [\text{John}]_B &= \{q \in P \mid \text{the person } q \text{ has the same birthday as John}\} \\ &= \{q \in P \mid \text{the person } q \text{ was born on August 10}\}. \end{aligned}$$

In the notation we introduced earlier, this is just the set P_d , for $d = \text{August 10}$. In fact, it should be clear now that for any person p , if we let d be p 's birthday, then $[p]_B = P_d$. This is in agreement with our earlier statement that the sets P_d are the equivalence classes for the equivalence relation B . According to Definition 4.5.3, the set of all of these equivalence classes is called *P modulo B* :

$$P/B = \{[p]_B \mid p \in P\} = \{P_d \mid d \in D\}.$$

You are asked to give a more careful proof of this equation in exercise 6. As we observed before, this family is a partition of P .

Let's consider one more example. Let S be the relation on \mathbb{R} defined as follows:

$$S = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x - y \in \mathbb{Z}\}.$$

For example, $(5.73, 2.73) \in S$ and $(-1.27, 2.73) \in S$, since $5.73 - 2.73 = 3 \in \mathbb{Z}$ and $-1.27 - 2.73 = -4 \in \mathbb{Z}$, but $(1.27, 2.73) \notin S$, since $1.27 - 2.73 = -1.46 \notin \mathbb{Z}$. Clearly for any $x \in \mathbb{R}$, $x - x = 0 \in \mathbb{Z}$, so $(x, x) \in S$, and therefore S is reflexive. To see that S is symmetric, suppose $(x, y) \in S$. By the definition of S , this means that $x - y \in \mathbb{Z}$. But then $y - x = -(x - y) \in \mathbb{Z}$ too, since the negative of any integer is also an integer, so $(y, x) \in S$. Because (x, y) was an arbitrary element of S , this shows that S is symmetric. Finally, to see that S is transitive, suppose that $(x, y) \in S$ and $(y, z) \in S$. Then $x - y \in \mathbb{Z}$ and $y - z \in \mathbb{Z}$. Because the sum of any two integers is an integer, it follows that $x - z = (x - y) + (y - z) \in \mathbb{Z}$, so $(x, z) \in S$, as required. Thus, S is an equivalence relation on \mathbb{R} .

What do the equivalence classes for this equivalence relation look like? We have already observed that $(5.73, 2.73) \in S$ and $(-1.27, 2.73) \in S$, so $5.73 \in [2.73]$ and $-1.27 \in [2.73]$. In fact, it is not hard to see what the other elements of this equivalence class will be:

$$[2.73] = \{ \dots, -1.27, -0.27, 0.73, 1.73, 2.73, 3.73, 4.73, 5.73, \dots \}.$$

In other words, the equivalence class contains all positive real numbers of the form “ $_.73$ ” and all negative real numbers of the form “ $-_.27$.” In general, for any real number x , the equivalence class of x will contain all real numbers that differ from x by an integer amount:

$$[x] = \{ \dots, x - 3, x - 2, x - 1, x, x + 1, x + 2, x + 3, \dots \}.$$

Here are a few facts about these equivalence classes that you might try to prove to yourself. As you can see in the last equation, x is always an element of $[x]$. If we choose any number $x \in [2.73]$, then $[x]$ will be exactly the same as $[2.73]$. For example, taking $x = 4.73$ we find that

$$[4.73] = \{ \dots, -1.27, -0.27, 0.73, 1.73, 2.73, 3.73, 4.73, 5.73, \dots \} = [2.73].$$

Thus, $[4.73]$ and $[2.73]$ are just two different names for the same set. But if we choose $x \notin [2.73]$, then $[x]$ will be different from $[2.73]$. For example,

$$[1.3] = \{ \dots, -1.7, -0.7, 0.3, 1.3, 2.3, 3.3, 4.3, \dots \}.$$

In fact, you can see from these equations that $[1.3]$ and $[2.73]$ have no elements in common. In other words, $[1.3]$ is actually *disjoint* from $[2.73]$. In general, for any two real numbers x and y , the equivalence classes $[x]$ and $[y]$ are

either identical or disjoint. Each equivalence class has many different names, but different equivalence classes are disjoint. Because $[x]$ always contains x as an element, every equivalence class is nonempty, and every real number x is in exactly one equivalence class, namely $[x]$. In other words, the set of all of the equivalence classes, \mathbb{R}/S , is a partition of \mathbb{R} . This is another illustration of the fact that the equivalence classes determined by an equivalence relation always form a partition.

Theorem 4.5.4. *Suppose R is an equivalence relation on a set A . Then A/R is a partition of A .*

The proof of Theorem 4.5.4 will be easier to understand if we first prove a few facts about equivalence classes. Facts that are proven primarily for the purpose of using them to prove a theorem are usually called *lemmas*.

Lemma 4.5.5. *Suppose R is an equivalence relation on A . Then:*

1. *For every $x \in A$, $x \in [x]$.*
2. *For every $x \in A$ and $y \in A$, $y \in [x]$ iff $[y] = [x]$.*

Proof.

1. Let $x \in A$ be arbitrary. Since R is reflexive, xRx . Therefore, by the definition of equivalence class, $x \in [x]$.
2. (\rightarrow) Suppose $y \in [x]$. Then by the definition of equivalence class, yRx . Now suppose $z \in [y]$. Then zRy . Since zRy and yRx , by transitivity of R we can conclude that zRx , so $z \in [x]$. Since z was arbitrary, this shows that $[y] \subseteq [x]$.

Now suppose $z \in [x]$, so zRx . We already know yRx , and since R is symmetric we can conclude that xRy . Applying transitivity to zRx and xRy , we can conclude that zRy , so $z \in [y]$. Therefore $[x] \subseteq [y]$, so $[x] = [y]$.

(\leftarrow) Suppose $[y] = [x]$. By part 1 we know that $y \in [y]$, so since $[y] = [x]$, it follows that $y \in [x]$. \square

Commentary.

1. According to the definition of equivalence classes, $x \in [x]$ means xRx . This is what leads us to apply the fact that R is reflexive.
2. Of course, the iff form of the goal leads us to prove both directions separately. For the \rightarrow direction, the goal is $[y] = [x]$, and, since $[y]$ and $[x]$ are sets, we can prove this by proving $[y] \subseteq [x]$ and $[x] \subseteq [y]$. We prove

each of these statements by the usual method of taking an arbitrary element of one set and proving that it is in the other. Throughout the proof we use the definition of equivalence classes repeatedly, as we did in the proof of statement 1.

Proof of Theorem 4.5.4 . To prove that A/R is a partition of A , we must prove the three properties in Definition 4.5.2. For the first, we must show that $\bigcup_{(A/R)} = A$, or in other words that $\bigcup_{x \in A} [x] = A$. Now every equivalence class in A/R is a subset of A , so it should be clear that their union is also a subset of A . Thus, $\bigcup_{(A/R)} \subseteq A$, so all we need to show to finish the proof is that $A \subseteq \bigcup_{(A/R)}$. To prove this, suppose $x \in A$. Then by Lemma 4.5.5, $x \in [x]$, and of course $[x] \in A/R$, so $x \in \bigcup_{(A/R)}$. Thus, $\bigcup_{(A/R)} = A$.

To see that A/R is pairwise disjoint, suppose that X and Y are two elements of A/R , and $X \cap Y \neq \emptyset$. By definition of A/R , X and Y are equivalence classes, so we must have $X = [x]$ and $Y = [y]$ for some $x, y \in A$. Since $X \cap Y \neq \emptyset$, we can choose some z such that $z \in X \cap Y = [x] \cap [y]$. Now by Lemma 4.5.5, since $z \in [x]$ and $z \in [y]$, it follows that $[x] = [z] = [y]$. Thus, $X = Y$. This shows that if $X \neq Y$ then $X \cap Y = \emptyset$, so A/R is pairwise disjoint.

Finally, for the last clause of the definition of partition, suppose $X \in A/R$. As before, this means that $X = [x]$ for some $x \in A$. Now by Lemma 4.5.5, $x \in [x] = X$, so $X \neq \emptyset$, as required. \square

Commentary. We have given an intuitive reason why $\bigcup_{(A/R)} \subseteq A$, but if you're not sure why this is correct, you should write out a formal proof. (You might also want to look at exercise 16 in Section 3.3.) The proof that $A \subseteq \bigcup_{(A/R)}$ is straightforward.

The definition of pairwise disjoint suggests that to prove that A/R is pairwise disjoint we should let X and Y be arbitrary elements of A/R and then prove $X \neq Y \rightarrow X \cap Y = \emptyset$. Recall that the statement that a set is empty is really a negative statement, so both the antecedent and the consequent of this conditional are negative. This suggests that it will probably be easier to prove the contrapositive, so we assume $X \cap Y \neq \emptyset$ and prove $X = Y$. The givens $X \in A/R$, $Y \in A/R$, and $X \cap Y \neq \emptyset$ are all existential statements, so we use them to introduce the variables x , y , and z . Lemma 4.5.5 now takes care of the proof that $X = Y$ as well as the proof of the final clause in the definition of partition.

Theorem 4.5.4 shows that if R is an equivalence relation on A then A/R is a partition of A . In fact, it turns out that *every* partition of A arises in this way.

Theorem 4.5.6. *Suppose A is a set and \mathcal{F} is a partition of A . Then there is an equivalence relation R on A such that $A/R = \mathcal{F}$.*

Before proving this theorem, it might be worthwhile to discuss the strategy for the proof briefly. Because the conclusion of the theorem is an existential statement, we should try to find an equivalence relation R such that $A/R = \mathcal{F}$. Clearly for different choices of \mathcal{F} we will need to choose R differently, so the definition of R should depend on \mathcal{F} in some way. Looking back at the same-birthday example at the start of this section may help you see how to proceed. Recall that in that example the equivalence relation B consisted of all pairs of people (p, q) such that p and q were in the same set in the partition $\{P_d \mid d \in D\}$. In fact, we found that we could also express this by saying that $B = \bigcup_{d \in D} (P_d \times P_d)$. This suggests that in the proof of Theorem 4.5.6 we should let R be the set of all pairs $(x, y) \in A \times A$ such that x and y are in the same set in the partition \mathcal{F} . An alternative way to write this would be $R = \bigcup_{X \in \mathcal{F}} (X \times X)$.

For example, consider again the example of a partition given after Definition 4.5.2. In that example we had $A = \{1, 2, 3, 4\}$ and $\mathcal{F} = \{\{2\}, \{1, 3\}, \{4\}\}$. Now let's define a relation R on A as suggested in the last paragraph. This gives us:

$$\begin{aligned} R &= \bigcup_{X \in \mathcal{F}} (X \times X) \\ &= (\{2\} \times \{2\}) \cup (\{1, 3\} \times \{1, 3\}) \cup (\{4\} \times \{4\}) \\ &= \{(2, 2)\} \cup \{(1, 1), (1, 3), (3, 1), (3, 3)\} \cup \{(4, 4)\} \\ &= \{(2, 2), (1, 1), (1, 3), (3, 1), (3, 3), (4, 4)\}. \end{aligned}$$

The directed graph for this relation is shown in Figure 4.7. We will let you check that R is an equivalence relation and that the equivalence classes are

$$[2] = \{2\}, \quad [1] = [3] = \{1, 3\}, \quad [4] = \{4\}.$$

Thus, the set of all equivalence classes is $A/R = \{\{2\}, \{1, 3\}, \{4\}\}$, which is precisely the same as the partition \mathcal{F} we started with.

Of course, the reasoning that led us to the formula $R = \bigcup_{X \in \mathcal{F}} (X \times X)$ will not be part of the proof of Theorem 4.5.6. When we write the proof, we can simply define R in this way and then verify that it is an equivalence relation on A and that $A/R = \mathcal{F}$. It may make the proof easier to follow if we once again prove some lemmas first.

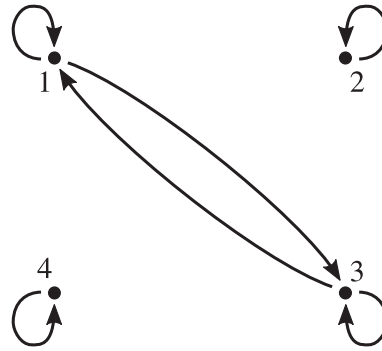


Figure 4.7.

Lemma 4.5.7. Suppose A is a set and \mathcal{F} is a partition of A . Let $R = \bigcup_{X \in \mathcal{F}} (X \times X)$. Then R is an equivalence relation on A . We will call R the equivalence relation determined by \mathcal{F} .

Proof. We'll prove that R is reflexive and leave the rest for you to do in exercise 8. Let x be an arbitrary element of A . Since \mathcal{F} is a partition of A , $\bigcup \mathcal{F} = A$, so $x \in \bigcup \mathcal{F}$. Thus, we can choose some $X \in \mathcal{F}$ such that $x \in X$. But then $(x, x) \in X \times X$, so $(x, x) \in \bigcup_{X \in \mathcal{F}} (X \times X) = R$. Therefore, R is reflexive. \square

Commentary. After letting x be an arbitrary element of A , we must prove $(x, x) \in R$. Because $R = \bigcup_{X \in \mathcal{F}} (X \times X)$, this means we must prove $\exists X \in \mathcal{F} ((x, x) \in X \times X)$, or in other words $\exists X \in \mathcal{F} (x \in X)$. But this just means $x \in \bigcup \mathcal{F}$, so this suggests using the first clause in the definition of partition, which says that $\bigcup \mathcal{F} = A$.

Lemma 4.5.8. Suppose A is a set and \mathcal{F} is a partition of A . Let R be the equivalence relation determined by \mathcal{F} . Suppose $X \in \mathcal{F}$ and $x \in X$. Then $[x]_R = X$.

Proof. Suppose $y \in [x]_R$. Then $(y, x) \in R$, so by the definition of R there must be some $Y \in \mathcal{F}$ such that $(y, x) \in Y \times Y$, and therefore $y \in Y$ and $x \in Y$. Since $x \in X$ and $x \in Y$, $X \cap Y \neq \emptyset$, and since \mathcal{F} is pairwise disjoint it follows that $X = Y$. Thus, since $y \in Y$, $y \in X$. Since y was an arbitrary element of $[x]_R$, we can conclude that $[x]_R \subseteq X$.

Now suppose $y \in X$. Then $(y, x) \in X \times X$, so $(y, x) \in R$ and therefore $y \in [x]_R$. Thus $X \subseteq [x]_R$, so $[x]_R = X$. \square

Commentary. To prove $[x]_R = X$ we prove $[x]_R \subseteq X$ and $X \subseteq [x]_R$. For the first we start with an arbitrary $y \in [x]_R$ and prove $y \in X$. Writing out the definition of $[x]_R$ we get $(y, x) \in R$, and since R was defined to be $\bigcup_{Y \in \mathcal{F}} (Y \times Y)$, this means $\exists Y \in \mathcal{F} ((y, x) \in Y \times Y)$. Of course, since this is an existential statement we immediately introduce the new variable Y by existential instantiation. Since this gives us $y \in Y$ and our goal is $y \in X$, it is not surprising that the proof is completed by proving $Y = X$.

The proof that $X \subseteq [x]_R$ also uses the definitions of $[x]_R$ and R , but is more straightforward.

Proof of Theorem 4.5.6 . Let $R = \bigcup_{X \in \mathcal{F}} (X \times X)$. We have already seen that R is an equivalence relation, so we need only check that $A/R = \mathcal{F}$. To see this, suppose $X \in A/R$. This means that $X = [x]$ for some $x \in A$. Since \mathcal{F} is a partition, we know that $\bigcup \mathcal{F} = A$, so $x \in \bigcup \mathcal{F}$, and therefore we can choose some $Y \in \mathcal{F}$ such that $x \in Y$. But then by Lemma 4.6.8, $[x] = Y$. Thus $X = Y \in \mathcal{F}$, so $A/R \subseteq \mathcal{F}$.

Now suppose $X \in \mathcal{F}$. Then since \mathcal{F} is a partition, $X \neq \emptyset$, so we can choose some $x \in X$. Therefore by Lemma 4.6.8, $X = [x] \in A/R$, so $\mathcal{F} \subseteq A/R$. Thus, $A/R = \mathcal{F}$. \square

Commentary. We prove that $A/R = \mathcal{F}$ by proving that $A/R \subseteq \mathcal{F}$ and $\mathcal{F} \subseteq A/R$. For the first, we take an arbitrary $X \in A/R$ and prove that $X \in \mathcal{F}$. Because $X \in A/R$ means $\exists x \in A (X = [x])$, we immediately introduce the new variable x to stand for an element of A such that $X = [x]$. The proof that $X \in \mathcal{F}$ now proceeds by the slightly roundabout route of finding a set $Y \in \mathcal{F}$ such that $X = Y$. This is motivated by Lemma 4.5.8, which suggests a way of showing that an element of \mathcal{F} is equal to $[x] = X$. The proof that $\mathcal{F} \subseteq A/R$ also relies on Lemma 4.5.8.

We have seen how an equivalence relation R on a set A can be used to define a partition A/R of A and also how a partition \mathcal{F} of A can be used to define an equivalence relation $\bigcup_{X \in \mathcal{F}} (X \times X)$ on A . The proof of Theorem 4.5.6 demonstrates an interesting relationship between these operations. If you start with a partition \mathcal{F} of A , use \mathcal{F} to define the equivalence relation $R = \bigcup_{X \in \mathcal{F}} (X \times X)$, and then use R to define a partition A/R , then you end up back where you started. In other words, the final partition A/R is the same as the original partition \mathcal{F} . You might wonder if the same idea would work in the other order. In other words, suppose you start with an equivalence relation R on A , use R to define a partition $\mathcal{F} = A/R$, and then use \mathcal{F} to define an equivalence relation $S = \bigcup_{X \in \mathcal{F}} (X \times X)$. Would the final equivalence relation S be the same as the original equivalence relation R ? You are asked in exercise 10 to show that the answer is yes.

We end this section by considering a few more examples of equivalence relations. A very useful family of equivalence relations is given by the next definition.

Definition 4.5.9. Suppose m is a positive integer. For any integers x and y , we will say that x is *congruent to y modulo m* if $\exists k \in \mathbb{Z}(x - y = km)$. In other words, x is congruent to y modulo m iff $m \mid (x - y)$. We will use the notation $x \equiv y \pmod{m}$ to mean that x is congruent to y modulo m .

For example, $12 \equiv 27 \pmod{5}$, since $12 - 27 = -15 = (-3) \cdot 5$. Now for any positive integer m we can consider the relation $\{(x, y) \in \mathbb{Z} \times \mathbb{Z} \mid x \equiv y \pmod{m}\}$. As we mentioned in the last section, mathematicians sometimes use symbols rather than letters as names of relations. In this case, motivated by the notation in Definition 4.5.9, we will use the symbol \equiv_m as our name for this relation. Thus, for any integers x and y , $x \equiv_m y$ means the same thing as $x \equiv y \pmod{m}$. It turns out that this relation is another example of an equivalence relation.

Theorem 4.5.10. For every positive integer m , \equiv_m is an equivalence relation on \mathbb{Z} .

Proof. We will check transitivity for \equiv_m and let you check reflexivity and symmetry in exercise 11. To see that \equiv_m is transitive, suppose that $x \equiv_m y$ and $y \equiv_m z$. This means that $x \equiv y \pmod{m}$ and $y \equiv z \pmod{m}$, or in other words $m \mid (x - y)$ and $m \mid (y - z)$. Therefore, by exercise 18(a) in Section 3.3, $m \mid [(x - y) + (y - z)]$. But $(x - y) + (y - z) = x - z$, so it follows that $m \mid (x - z)$, and therefore $x \equiv_m z$. \square

We will have more to say about these equivalence relations later in this book, especially in Chapter 7.

Equivalence relations often come up when we want to group together elements of a set that have something in common. For example, if you've studied vectors in a previous math course or perhaps in a physics course, then you may have been told that vectors can be thought of as arrows. But you were probably also told that different arrows that point in the same direction and have the same length must be thought of as representing the same vector. Here's a more lucid explanation of the relationship between vectors and arrows. Let A be the set of all arrows, and let $R = \{(x, y) \in A \times A \mid \text{the arrows } x \text{ and } y \text{ point in the same direction and have the same length}\}$. We will let you check for yourself that R is an equivalence relation on A . Each equivalence class consists of arrows that all have the same length and point in the same

direction. We can now think of vectors as being represented, not by arrows, but by equivalence classes of arrows.

Students who are familiar with computer programming may be interested in our next example. Suppose we let P be the set of all computer programs, and for any computer programs p and q we say that p and q are *equivalent* if they always produce the same output when given the same input. Let $R = \{(p, q) \in P \times P \mid \text{the programs } p \text{ and } q \text{ are equivalent}\}$. It is not hard to check that R is an equivalence relation on P . The equivalence classes group together programs that produce the same output when given the same input.

Exercises

- *1. Find all partitions of the set $A = \{1, 2, 3\}$.
2. Find all equivalence relations on the set $A = \{1, 2, 3\}$.
- *3. Let $W =$ the set of all words in the English language. Which of the following relations on W are equivalence relations? For those that are equivalence relations, what are the equivalence classes?
 - (a) $R = \{(x, y) \in W \times W \mid \text{the words } x \text{ and } y \text{ start with the same letter}\}$.
 - (b) $S = \{(x, y) \in W \times W \mid \text{the words } x \text{ and } y \text{ have at least one letter in common}\}$.
 - (c) $T = \{(x, y) \in W \times W \mid \text{the words } x \text{ and } y \text{ have the same number of letters}\}$.
4. Which of the following relations on \mathbb{R} are equivalence relations? For those that are equivalence relations, what are the equivalence classes?
 - (a) $R = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x - y \in \mathbb{N}\}$.
 - (b) $S = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x - y \in \mathbb{Q}\}$.
 - (c) $T = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid \exists n \in \mathbb{Z}(y = x \cdot 10^n)\}$.
5. Let L be the set of all nonvertical lines in the plane. Which of the following relations on L are equivalence relations? For those that are equivalence relations, what are the equivalence classes?
 - (a) $R = \{(k, l) \in L \times L \mid \text{the lines } k \text{ and } l \text{ have the same slope}\}$.
 - (b) $S = \{(k, l) \in L \times L \mid \text{the lines } k \text{ and } l \text{ are perpendicular}\}$.
 - (c) $T = \{(k, l) \in L \times L \mid k \cap x = l \cap x \text{ and } k \cap y = l \cap y\}$, where x and y are the x -axis and the y -axis. (We are treating lines as sets of points here.)
- *6. In the discussion of the same-birthday equivalence relation B following Definition 4.5.3, we claimed that $P/B = \{P_d \mid d \in D\}$. Give a

careful proof of this claim. You will find when you work out the proof that there is an assumption you must make about people's birthdays (a very reasonable assumption) to make the proof work. What is this assumption?

7. Let T be the set of all triangles, and let $S = \{(s, t) \in T \times T \mid \text{the triangles } s \text{ and } t \text{ are similar}\}$. (Recall that two triangles are similar if the angles of one triangle are equal to corresponding angles of the other.) Verify that S is an equivalence relation.
8. Complete the proof of Lemma 4.5.7.
9. Suppose R and S are equivalence relations on A and $A/R = A/S$. Prove that $R = S$.
- *10. Suppose R is an equivalence relation on A . Let $\mathcal{F} = A/R$, and let S be the equivalence relation determined by \mathcal{F} . In other words, $S = \bigcup_{X \in \mathcal{F}} (X \times X)$. Prove that $S = R$.
11. Let \equiv_m be the "congruence modulo m " relation defined in the text, for a positive integer m .
 - (a) Complete the proof of Theorem 4.5.10 by showing that \equiv_m is reflexive and symmetric.
 - (b) Find all the equivalence classes for \equiv_2 and \equiv_3 . How many equivalence classes are there in each case? In general how many equivalence classes do you think there are for \equiv_m ?
12. Prove that for every integer n , either $n^2 \equiv 0 \pmod{4}$ or $n^2 \equiv 1 \pmod{4}$.
- *13. Suppose m is a positive integer. Prove that for all integers a, a^3, b , and b^3 , if $a^3 \equiv a \pmod{m}$ and $b^3 \equiv b \pmod{m}$ then $a^3 + b^3 \equiv a + b \pmod{m}$ and $a^3 b^3 \equiv ab \pmod{m}$.
14. Suppose that R is an equivalence relation on A and $B \subseteq A$. Let $S = R \cap (B \times B)$.
 - (a) Prove that S is an equivalence relation on B .
 - (b) Prove that for all $x \in B$, $[x]_S = [x]_R \cap B$.
15. Suppose $B \subseteq A$, and define a relation R on $\mathcal{P}(A)$ as follows:

$$R = \{(X, Y) \in \mathcal{P}(A) \times \mathcal{P}(A) \mid X^2 \ Y \subseteq B\}.$$
 - (a) Prove that R is an equivalence relation on $\mathcal{P}(A)$.
 - (b) Prove that for every $X \in \mathcal{P}(A)$ there is exactly one $Y \in [X]_R$ such that $Y \cap B = \emptyset$.
- *16. Suppose \mathcal{F} is a partition of A , \mathcal{G} is a partition of B , and A and B are disjoint. Prove that $\mathcal{F} \cup \mathcal{G}$ is a partition of $A \cup B$.
17. Suppose R is an equivalence relation on A , S is an equivalence relation on B , and A and B are disjoint.

(a) Prove that $R \cup S$ is an equivalence relation on $A \cup B$.

(b) Prove that for all $x \in A$, $[x]_{R \cup S} = [x]_R$, and for all $y \in B$, $[y]_{R \cup S} = [y]_S$.

(c) Prove that $(A \cup B)/(R \cup S) = (A/R) \cup (B/S)$.

18. Suppose \mathcal{F} and \mathcal{G} are partitions of a set A . We define a new family of sets $\mathcal{F} \cdot \mathcal{G}$ as follows:

$$\mathcal{F} \cdot \mathcal{G} = \{Z \in \mathcal{P}(A) \mid Z \neq \emptyset \text{ and } \exists X \in \mathcal{F} \exists Y \in \mathcal{G} (Z = X \cap Y)\}.$$

Prove that $\mathcal{F} \cdot \mathcal{G}$ is a partition of A .

19. Let $\mathcal{F} = \{\mathbb{R}^-, \mathbb{R}^+, \{0\}\}$ and $\mathcal{G} = \{\mathbb{Z}, \mathbb{R} \setminus \mathbb{Z}\}$, and note that both \mathcal{F} and \mathcal{G} are partitions of \mathbb{R} . List the elements of $\mathcal{F} \cdot \mathcal{G}$. (See exercise 18 for the meaning of the notation used here.)
- *20. Suppose R and S are equivalence relations on a set A . Let $T = R \cap S$.
- (a) Prove that T is an equivalence relation on A .
- (b) Prove that for all $x \in A$, $[x]_T = [x]_R \cap [x]_S$.
- (c) Prove that $A/T = (A/R) \cdot (A/S)$. (See exercise 18 for the meaning of the notation used here.)
21. Suppose \mathcal{F} is a partition of A and \mathcal{G} is a partition of B . We define a new family of sets $\mathcal{F} \otimes \mathcal{G}$ as follows:

$$\mathcal{F} \otimes \mathcal{G} = \{Z \in \mathcal{P}(A \times B) \mid \exists X \in \mathcal{F} \exists Y \in \mathcal{G} (Z = X \times Y)\}.$$

Prove that $\mathcal{F} \otimes \mathcal{G}$ is a partition of $A \times B$.

- *22. Let $\mathcal{F} = \{\mathbb{R}^-, \mathbb{R}^+, \{0\}\}$, which is a partition of \mathbb{R} . List the elements of $\mathcal{F} \otimes \mathcal{F}$, and describe them geometrically as subsets of the xy -plane. (See exercise 21 for the meaning of the notation used here.)
23. Suppose R is an equivalence relation on A and S is an equivalence relation on B . Define a relation T on $A \times B$ as follows:

$$T = \{((a, b), (a^3, b^3)) \in (A \times B) \times (A \times B) \mid aRa^3 \text{ and } bSb^3\}.$$

(a) Prove that T is an equivalence relation on $A \times B$.

(b) Prove that if $a \in A$ and $b \in B$ then $[(a, b)]_T = [a]_R \times [b]_S$.

(c) Prove that $(A \times B)/T = (A/R) \otimes (B/S)$. (See exercise 21 for the meaning of the notation used here.)

- *24. Suppose R and S are relations on a set A , and S is an equivalence relation. We will say that R is *compatible* with S if for all x, y, x^3 , and y^3 in A , if xSx^3 and ySy^3 then xRy iff x^3Ry^3 .
- (a) Prove that if R is compatible with S , then there is a unique relation T on A/S such that for all x and y in A , $[x]_S T [y]_S$ iff xRy .
- (b) Suppose T is a relation on A/S and for all x and y in A , $[x]_S T [y]_S$ iff xRy . Prove that R is compatible with S .

25. Suppose R is a relation on A and R is reflexive and transitive. (Such a relation is called a *preorder* on A .) Let $S = R \cap R^{-1}$.
- Prove that S is an equivalence relation on A .
 - Prove that there is a unique relation T on A/S such that for all x and y in A , $[x]_S T [y]_S$ iff $x R y$. (Hint: Use exercise 24.)
 - Prove that T is a partial order on A/S , where T is the relation from part (b).
26. Let $I = \{1, 2, \dots, 100\}$, $A = \mathcal{P}(I)$, and $R = \{(X, Y) \in A \times A \mid Y \text{ has at least as many elements as } X\}$.
- Prove that R is a preorder on A . (See exercise 25 for the definition of *preorder*.)
 - Let S and T be defined as in exercise 25. Describe the elements of A/S and the partial order T . How many elements does A/S have? Is T a total order?
27. Suppose A is a set. If \mathcal{F} and \mathcal{G} are partitions of A , then we'll say that \mathcal{F} *refines* \mathcal{G} if $\forall X \in \mathcal{F} \exists Y \in \mathcal{G} (X \subseteq Y)$. Let P be the set of all partitions of A , and let $R = \{(\mathcal{F}, \mathcal{G}) \in P \times P \mid \mathcal{F} \text{ refines } \mathcal{G}\}$.
- Prove that R is a partial order on P .
 - Suppose that S and T are equivalence relations on A . Let $\mathcal{F} = A/S$ and $\mathcal{G} = A/T$. Prove that $S \subseteq T$ iff \mathcal{F} refines \mathcal{G} .
 - Suppose \mathcal{F} and \mathcal{G} are partitions of A . Prove that $\mathcal{F} \cdot \mathcal{G}$ is the greatest lower bound of the set $\{\mathcal{F}, \mathcal{G}\}$ in the partial order R . (See exercise 18 for the meaning of the notation used here.)

5

Functions

5.1. Functions

Suppose P is the set of all people, and let $H = \{(p, n) \in P \times \mathbb{N} \mid \text{the person } p \text{ has } n \text{ children}\}$. Then H is a relation from P to \mathbb{N} , and it has the following important property. For every $p \in P$, there is *exactly one* $n \in \mathbb{N}$ such that $(p, n) \in H$. Mathematicians express this by saying that H is a *function* from P to \mathbb{N} .

Definition 5.1.1. Suppose F is a relation from A to B . Then F is called a *function from A to B* if for every $a \in A$ there is exactly one $b \in B$ such that $(a, b) \in F$. In other words, to say that F is a function from A to B means:

$$\forall a \in A \exists! b \in B ((a, b) \in F).$$

To indicate that F is a function from A to B , we will write $F : A \rightarrow B$.

Example 5.1.2.

1. Let $A = \{1, 2, 3\}$, $B = \{4, 5, 6\}$, and $F = \{(1, 5), (2, 4), (3, 5)\}$. Is F a function from A to B ?
2. Let $A = \{1, 2, 3\}$, $B = \{4, 5, 6\}$, and $G = \{(1, 5), (2, 4), (1, 6)\}$. Is G a function from A to B ?
3. Let C be the set of all cities and N the set of all countries, and let $L = \{(c, n) \in C \times N \mid \text{the city } c \text{ is in the country } n\}$. Is L a function from C to N ?
4. Let P be the set of all people, and let $C = \{(p, q) \in P \times P \mid \text{the person } p \text{ is a parent of the person } q\}$. Is C a function from P to P ?
5. Let P be the set of all people, and let $D = \{(p, x) \in P \times \mathcal{P}(P) \mid x = \text{the set of all children of } p\}$. Is D a function from P to $\mathcal{P}(P)$?

6. Let A be any set. Recall that $i_A = \{(a, a) \mid a \in A\}$ is called the identity relation on A . Is it a function from A to A ?
7. Let $f = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid y = x^2\}$. Is f a function from \mathbb{R} to \mathbb{R} ?

Solutions

1. Yes. Note that 1 is paired with 5 in the relation F , but it is not paired with any other element of B . Similarly, 2 is paired only with 4, and 3 with 5. In other words, each element of A appears as the first coordinate of exactly one ordered pair in F . Therefore F is a function from A to B . Note that the definition of function does *not* require that each element of B be paired with exactly one element of A . Thus, it doesn't matter that 5 occurs as the second coordinate of two different pairs in F and that 6 doesn't occur in any ordered pairs at all.
2. No. G fails to be a function from A to B for two reasons. First of all, 3 isn't paired with any element of B in the relation G , which violates the requirement that every element of A must be paired with some element of B . Second, 1 is paired with two different elements of B , 5 and 6, which violates the requirement that each element of A be paired with *only one* element of B .
3. If we make the reasonable assumption that every city is in exactly one country, then L is a function from C to N .
4. Because some people have no children and some people have more than one child, C is not a function from P to P .
5. Yes, D is a function from P to $\mathcal{P}(P)$. Each person p is paired with exactly one set $x \subseteq P$, namely the set of all children of p . Note that in the relation D , a person p is paired with the set consisting of all of p 's children, *not* with the children themselves. Even if p does not have exactly one child, it is still true that there is exactly one set that contains precisely the children of p and nothing else.
6. Yes. Each $a \in A$ is paired in the relation i_A with exactly one element of A , namely a itself. In other words, $(a, a) \in i_A$, but for every $a^\pm \neq a$, $(a, a^\pm) \notin i_A$. Thus, we can call i_A the *identity function* on A .
7. Yes. For each real number x there is exactly one value of y , namely $y = x^2$, such that $(x, y) \in f$.

Suppose $f : A \rightarrow B$. If $a \in A$, then we know that there is exactly one $b \in B$ such that $(a, b) \in f$. This unique b is called "the value of f at a ," or "the image of a under f ," or "the result of applying f to a ," or just " f of a ," and it is written $f(a)$. In other words, for every $a \in A$ and $b \in B$, $b = f(a)$

iff $(a, b) \in f$. For example, for the function $F = \{(1, 5), (2, 4), (3, 5)\}$ in part 1 of Example 5.1.2, we could say that $F(1) = 5$, since $(1, 5) \in F$. Similarly, $F(2) = 4$ and $F(3) = 5$. If L is the function in part 3 and c is any city, then $L(c)$ would be the unique country n such that $(c, n) \in L$. In other words, $L(c) =$ the country in which c is located. For example, $L(\text{Paris}) = \text{France}$. For the function D in part 5, we could say that for any person p , $D(p) =$ the set of all children of p . If A is any set and $a \in A$, then $(a, a) \in i_A$, so $i_A(a) = a$. And if f is the function in part 7, then for every real number x , $f(x) = x^2$.

A function f from a set A to another set B is often specified by giving a rule that can be used to determine $f(a)$ for any $a \in A$. For example, if A is the set of all people and $B = \mathbb{R}^+$, then we could define a function f from A to B by the rule that for every $a \in A$, $f(a) = a$'s height in inches. Although this definition doesn't say explicitly which ordered pairs are elements of f , we can determine this by using our rule that for all $a \in A$ and $b \in B$, $(a, b) \in f$ iff $b = f(a)$. Thus,

$$\begin{aligned} f &= \{(a, b) \in A \times B \mid b = f(a)\} \\ &= \{(a, b) \in A \times B \mid b = a\text{'s height in inches}\}. \end{aligned}$$

For example, if Joe Smith is 68 inches tall, then $(\text{Joe Smith}, 68) \in f$ and $f(\text{Joe Smith}) = 68$.

It is often useful to think of a function f from A to B as representing a rule that associates, with each $a \in A$, some corresponding object $b = f(a) \in B$. However, it is important to remember that although a function can be defined by giving such a rule, it need not be defined in this way. Any subset of $A \times B$ that satisfies the requirements given in Definition 5.1.1 is a function from A to B .

Example 5.1.3. Here are some more examples of functions defined by rules.

1. Suppose every student is assigned an academic advisor who is a professor. Let S be the set of students and P the set of professors. Then we can define a function f from S to P by the rule that for every student s , $f(s) =$ the advisor of s . In other words,

$$\begin{aligned} f &= \{(s, p) \in S \times P \mid p = f(s)\} \\ &= \{(s, p) \in S \times P \mid \text{the professor } p \text{ is the academic advisor of} \\ &\quad \text{the student } s\}. \end{aligned}$$

2. We can define a function g from \mathbb{Z} to \mathbb{R} by the rule that for every $x \in \mathbb{Z}$, $g(x) = 2x + 3$. Then

$$\begin{aligned}
 g &= \{ (x, y) \in \mathbb{Z} \times \mathbb{R} \mid y = g(x) \} \\
 &= \{ (x, y) \in \mathbb{Z} \times \mathbb{R} \mid y = 2x + 3 \} \\
 &= \{ \dots, (-2, -1), (-1, 1), (0, 3), (1, 5), (2, 7), \dots \}.
 \end{aligned}$$

3. Let h be the function from \mathbb{R} to \mathbb{R} defined by the rule that for every $x \in \mathbb{R}$, $h(x) = 2x + 3$. Note that the formula for $h(x)$ is the same as the formula for $g(x)$ in part 2. However, h and g are *not* the same function. You can see this by noting that, for example, $(\pi, 2\pi + 3) \in h$ but $(\pi, 2\pi + 3) \notin g$, since $\pi \notin \mathbb{Z}$. (For more on the relationship between g and h , see exercise 7(c).)

Notice that when a function f from A to B is specified by giving a rule for finding $f(a)$, the rule must determine the value of $f(a)$ for *every* $a \in A$. Sometimes when mathematicians are stating such a rule they don't say explicitly that the rule applies to all $a \in A$. For example, a mathematician might say "let f be the function from \mathbb{R} to \mathbb{R} defined by the formula $f(x) = x^2 + 7$." It is understood in this case that the equation $f(x) = x^2 + 7$ applies to all $x \in \mathbb{R}$ even though it hasn't been said explicitly. This means that you can plug in any real number for x in this equation, and the resulting equation will be true. For example, you can conclude that $f(3) = 3^2 + 7 = 16$. Similarly, if w is a real number, then you can write $f(w) = w^2 + 7$, or even $f(2w - 3) = (2w - 3)^2 + 7 = 4w^2 - 12w + 16$.

Because a function f from A to B is completely determined by the rule for finding $f(a)$, two functions that are defined by equivalent rules must be equal. More precisely, we have the following theorem:

Theorem 5.1.4. *Suppose f and g are functions from A to B . If $\forall a \in A (f(a) = g(a))$, then $f = g$.*

Proof. Suppose $\forall a \in A (f(a) = g(a))$, and let (a, b) be an arbitrary element of f . Then $b = f(a)$. But by our assumption $f(a) = g(a)$, so $b = g(a)$ and therefore $(a, b) \in g$. Thus, $f \subseteq g$. A similar argument shows $g \subseteq f$, so $f = g$. \square

Commentary. Because f and g are sets, we prove $f = g$ by proving $f \subseteq g$ and $g \subseteq f$. Each of these goals is proven by showing that an arbitrary element of one set must be an element of the other. Note that, now that we have proven Theorem 5.1.4, we have another method for proving that two functions f and g from a set A to another set B are equal. In the future, to prove $f = g$ we will usually prove $\forall a \in A (f(a) = g(a))$ and then apply Theorem 5.1.4.

Because functions are just relations of a special kind, the concepts introduced in Chapter 4 for relations can be applied to functions as well. For example, suppose $f : A \rightarrow B$. Then f is a relation from A to B , so it makes sense to talk about the domain of f , which is a subset of A , and the range of f , which is a subset of B . According to the definition of function, every element of A must appear as the first coordinate of some (in fact, exactly one) ordered pair in f , so the domain of f must actually be all of A . But the range of f need not be all of B . The elements of the range of f will be the second coordinates of all the ordered pairs in f , and the second coordinate of an ordered pair in f is what we have called the image of its first coordinate. Thus, the range of f could also be described as the set of all images of elements of A under f :

$$\text{Ran}(f) = \{ f(a) \mid a \in A \}.$$

For example, for the function f defined in part 1 of Example 5.1.3, $\text{Ran}(f) = \{ f(s) \mid s \in S \} =$ the set of all advisors of students.

We can draw diagrams of functions in exactly the same way we drew diagrams for relations in Chapter 4. If $f : A \rightarrow B$, then as before, every ordered pair $(a, b) \in f$ would be represented in the diagram by an edge connecting a to b . By the definition of function, every $a \in A$ occurs as the first coordinate of exactly one ordered pair in f , and the second coordinate of this ordered pair is $f(a)$. Thus, for every $a \in A$ there will be exactly one edge coming from a , and it will connect a to $f(a)$. For example, Figure 5.1 shows what the diagram for the function L defined in part 3 of Example 5.1.2 would look like.

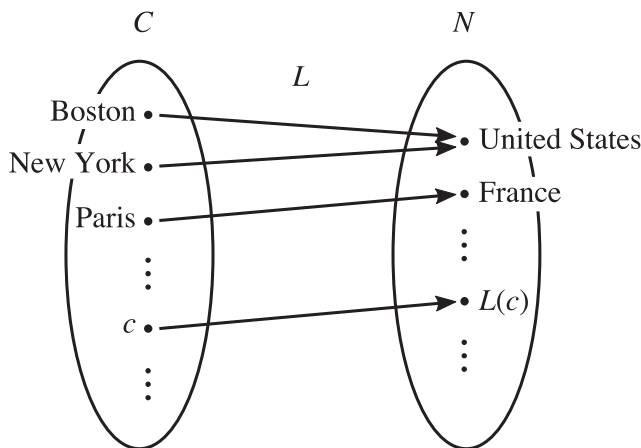


Figure 5.1.

The definition of composition of relations can also be applied to functions. If $f : A \rightarrow B$ and $g : B \rightarrow C$, then f is a relation from A to B and g is a relation from B to C , so $g \circ f$ will be a relation from A to C . In fact, it turns out that $g \circ f$ is a function from A to C , as the next theorem shows.

Theorem 5.1.5. *Suppose $f : A \rightarrow B$ and $g : B \rightarrow C$. Then $g \circ f : A \rightarrow C$, and for any $a \in A$, the value of $g \circ f$ at a is given by the formula $(g \circ f)(a) = g(f(a))$.*

Scratch work

Before proving this theorem, it might be helpful to discuss the scratch work for the proof. According to the definition of function, to show that $g \circ f : A \rightarrow C$ we must prove that $\forall a \in A \exists! c \in C((a, c) \in g \circ f)$, so we will start out by letting a be an arbitrary element of A and then try to prove that $\exists! c \in C((a, c) \in g \circ f)$. As we saw in Section 3.6, we can prove this statement by proving existence and uniqueness separately. To prove existence, we should try to find a $c \in C$ such that $(a, c) \in g \circ f$. For uniqueness, we should assume that $(a, c_1) \in g \circ f$ and $(a, c_2) \in g \circ f$, and then try to prove that $c_1 = c_2$.

Proof. Let a be an arbitrary element of A . We must show that there is a unique $c \in C$ such that $(a, c) \in g \circ f$.

Existence: Let $b = f(a) \in B$. Let $c = g(b) \in C$. Then $(a, b) \in f$ and $(b, c) \in g$, so by the definition of composition of relations, $(a, c) \in g \circ f$. Thus, $\exists c \in C((a, c) \in g \circ f)$.

Uniqueness: Suppose $(a, c_1) \in g \circ f$ and $(a, c_2) \in g \circ f$. Then by the definition of composition, we can choose $b_1 \in B$ such that $(a, b_1) \in f$ and $(b_1, c_1) \in g$, and we can also choose $b_2 \in B$ such that $(a, b_2) \in f$ and $(b_2, c_2) \in g$. Since f is a function, there can be only one $b \in B$ such that $(a, b) \in f$. Thus, since (a, b_1) and (a, b_2) are both elements of f , it follows that $b_1 = b_2$. But now applying the same reasoning to g , since $(b_1, c_1) \in g$ and $(b_1, c_2) = (b_2, c_2) \in g$, it follows that $c_1 = c_2$, as required.

This completes the proof that $g \circ f$ is a function from A to C . Finally, to derive the formula for $(g \circ f)(a)$, note that we showed in the existence half of the proof that for any $a \in A$, if we let $b = f(a)$ and $c = g(b)$, then $(a, c) \in g \circ f$. Thus,

$$(g \circ f)(a) = c = g(b) = g(f(a)). \quad \square$$

When we first introduced the idea of the composition of two relations in Chapter 4, we pointed out that the notation was somewhat peculiar and promised to explain the reason for the notation in this chapter. We can

now provide this explanation. The reason for the notation we've used for composition of relations is that it leads to the convenient formula $(g \circ f)(x) = g(f(x))$ derived in Theorem 5.1.5. Note that because functions are just relations of a special kind, everything we have proven about composition of relations applies to composition of functions. In particular, by Theorem 4.2.5, we know that composition of functions is associative.

Example 5.1.6. Here are some examples of compositions of functions.

- Let C and N be the sets of all cities and countries, respectively, and let $L : C \rightarrow N$ be the function defined in part 3 of Example 5.1.2. Thus, for every city c , $L(c) =$ the country in which c is located. Let B be the set of all buildings located in cities, and define $F : B \rightarrow C$ by the formula $F(b) =$ the city in which the building b is located. Then $L \circ F : B \rightarrow N$. For example, $F(\text{Eiffel Tower}) = \text{Paris}$, so according to the formula derived in Theorem 5.1.5,

$$\begin{aligned} (L \circ F)(\text{Eiffel Tower}) &= L(F(\text{Eiffel Tower})) \\ &= L(\text{Paris}) = \text{France}. \end{aligned}$$

In general for every building $b \in B$,

$$\begin{aligned} (L \circ F)(b) &= L(F(b)) = L(\text{the city in which } b \text{ is located}) \\ &= \text{the country in which } b \text{ is located}. \end{aligned}$$

A diagram of this function is shown in Figure 5.2.

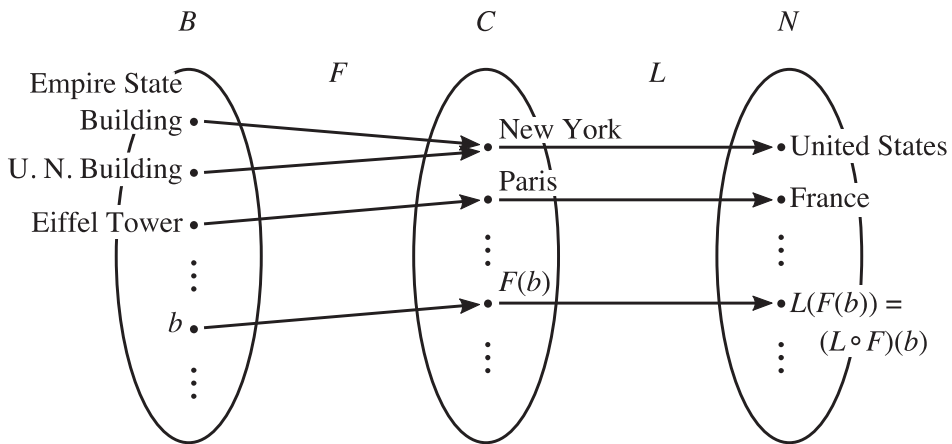


Figure 5.2.

2. Let $g : \mathbb{Z} \rightarrow \mathbb{R}$ be the function from part 2 of Example 5.1.3, which was defined by the formula $g(x) = 2x + 3$. Let $f : \mathbb{Z} \rightarrow \mathbb{Z}$ be defined by the formula $f(n) = n^2 - 3n + 1$. Then $g \circ f : \mathbb{Z} \rightarrow \mathbb{R}$. For example, $f(2) = 2^2 - 3 \cdot 2 + 1 = -1$, so $(g \circ f)(2) = g(f(2)) = g(-1) = 1$. In general for every $n \in \mathbb{Z}$,

$$\begin{aligned}(g \circ f)(n) &= g(f(n)) = g(n^2 - 3n + 1) = 2(n^2 - 3n + 1) + 3 \\ &= 2n^2 - 6n + 5.\end{aligned}$$

Exercises

- *1. (a) Let $A = \{1, 2, 3\}$, $B = \{4\}$, and $f = \{(1, 4), (2, 4), (3, 4)\}$. Is f a function from A to B ?
- (b) Let $A = \{1\}$, $B = \{2, 3, 4\}$, and $f = \{(1, 2), (1, 3), (1, 4)\}$. Is f a function from A to B ?
- (c) Let C be the set of all cars registered in your state, and let S be the set of all finite sequences of letters and digits. Let $L = \{(c, s) \in C \times S \mid \text{the license plate number of the car } c \text{ is } s\}$. Is L a function from C to S ?
2. (a) Let f be the relation represented by the graph in Figure 5.3. Is f a function from A to B ?

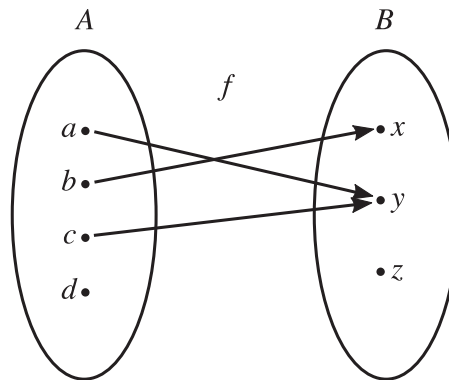


Figure 5.3.

- (b) Let W be the set of all words of English, and let A be the set of all letters of the alphabet. Let $f = \{(w, a) \in W \times A \mid \text{the letter } a \text{ occurs in the word } w\}$, and let $g = \{(w, a) \in W \times A \mid \text{the letter } a \text{ is the first letter of the word } w\}$. Is f a function from W to A ? How about g ?

- (c) John, Mary, Susan, and Fred go out to dinner and sit at a round table. Let $P = \{\text{John, Mary, Susan, Fred}\}$, and let $R = \{(p, q) \in P \times P \mid \text{the person } p \text{ is sitting immediately to the right of the person } q\}$. Is R a function from P to P ?
- *3. (a) Let $A = \{a, b, c\}$, $B = \{a, b\}$, and $f = \{(a, b), (b, b), (c, a)\}$. Then $f : A \rightarrow B$. What are $f(a)$, $f(b)$, and $f(c)$?
- (b) Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be the function defined by the formula $f(x) = x^2 - 2x$. What is $f(2)$?
- (c) Let $f = \{(x, n) \in \mathbb{R} \times \mathbb{Z} \mid n \leq x < n + 1\}$. Then $f : \mathbb{R} \rightarrow \mathbb{Z}$. What is $f(\pi)$? What is $f(-\pi)$?
4. (a) Let N be the set of all countries and C the set of all cities. Let $H : N \rightarrow C$ be the function defined by the rule that for every country n , $H(n) =$ the capital of the country n . What is $H(\text{Italy})$?
- (b) Let $A = \{1, 2, 3\}$ and $B = \mathcal{P}(A)$. Let $F : B \rightarrow B$ be the function defined by the formula $F(X) = A \setminus X$. What is $F(\{1, 3\})$?
- (c) Let $f : \mathbb{R} \rightarrow \mathbb{R} \times \mathbb{R}$ be the function defined by the formula $f(x) = (x + 1, x - 1)$. What is $f(2)$?
- *5. Let L be the function defined in part 3 of Example 5.1.2 and let H be the function defined in exercise 4(a). Describe $L \circ H$ and $H \circ L$.
6. Let f and g be functions from \mathbb{R} to \mathbb{R} defined by the following formulas:

$$f(x) = \frac{1}{x^2 + 2}, \quad g(x) = 2x - 1.$$

Find formulas for $(f \circ g)(x)$ and $(g \circ f)(x)$.

- *7. Suppose $f : A \rightarrow B$ and $C \subseteq A$. The set $f \cap (C \times B)$, which is a relation from C to B , is called the *restriction* of f to C , and is sometimes denoted $f \upharpoonright C$. In other words,

$$f \upharpoonright C = f \cap (C \times B).$$

- (a) Prove that $f \upharpoonright C$ is a function from C to B and that for all $c \in C$, $f(c) = (f \upharpoonright C)(c)$.
- (b) Suppose $g : C \rightarrow B$. Prove that $g = f \upharpoonright C$ iff $g \subseteq f$.
- (c) Let g and h be the functions defined in parts 2 and 3 of Example 5.1.3. Show that $g = h \upharpoonright \mathbb{Z}$.
8. Suppose $f : A \rightarrow B$ and $g \subseteq f$. Prove that there is a set $A^\pm \subseteq A$ such that $g : A^\pm \rightarrow B$.
9. Suppose $f : A \rightarrow B$, $B \cong \emptyset$, and $A \subseteq A^\pm$. Prove that there is a function $g : A^\pm \rightarrow B$ such that $f \subseteq g$.
- *10. Suppose that f and g are functions from A to B and $f \cong g$. Show that $f^3 \circ g$ is not a function.

11. Suppose A is a set. Show that i_A is the only relation on A that is both an equivalence relation on A and also a function from A to A .
12. Suppose $f : A \rightarrow C$ and $g : B \rightarrow C$.
- (a) Prove that if A and B are disjoint, then $f \cup g : A \cup B \rightarrow C$.
- (b) Prove that $f \cup g : A \cup B \rightarrow C$ iff $f \upharpoonright (A \cap B) = g \upharpoonright (A \cap B)$. (See exercise 7 for the meaning of the notation used here.)
- *13. Suppose R is a relation from A to B , S is a relation from B to C , $\text{Ran}(R) = \text{Dom}(S) = B$, and $S \circ R : A \rightarrow C$.
- (a) Prove that $S : B \rightarrow C$.
- (b) Give an example to show that it need not be the case that $R : A \rightarrow B$.
14. Suppose $f : A \rightarrow B$ and S is a relation on B . Define a relation R on A as follows:

$$R = \{ (x, y) \in A \times A \mid (f(x), f(y)) \in S \}.$$

- (a) Prove that if S is reflexive, then so is R .
- (b) Prove that if S is symmetric, then so is R .
- (c) Prove that if S is transitive, then so is R .
- *15. Suppose $f : A \rightarrow B$ and R is a relation on A . Define a relation S on B as follows:

$$S = \{ (x, y) \in B \times B \mid \exists u \in A \exists v \in A (f(u) = x \wedge f(v) = y \wedge (u, v) \in R) \}.$$

Justify your answers to the following questions with either proofs or counterexamples.

- (a) If R is reflexive, must it be the case that S is reflexive?
- (b) If R is symmetric, must it be the case that S is symmetric?
- (c) If R is transitive, must it be the case that S is transitive?
16. Suppose A and B are sets, and let $\mathcal{F} = \{ f \mid f : A \rightarrow B \}$. Also, suppose R is a relation on B , and define a relation S on \mathcal{F} as follows:

$$S = \{ (f, g) \in \mathcal{F} \times \mathcal{F} \mid \forall x \in A ((f(x), g(x)) \in R) \}.$$

Justify your answers to the following questions with either proofs or counterexamples.

- (a) If R is reflexive, must it be the case that S is reflexive?
- (b) If R is symmetric, must it be the case that S is symmetric?
- (c) If R is transitive, must it be the case that S is transitive?
17. Suppose A is a nonempty set and $f : A \rightarrow A$.
- (a) Suppose there is some $a \in A$ such that $\forall x \in A (f(x) = a)$. (In this case, f is called a *constant* function.) Prove that for all $g : A \rightarrow A$, $f \circ g = f$.

- (b) Suppose that for all $g : A \rightarrow A$, $f \circ g = f$. Prove that f is a constant function. (Hint: What happens if g is a constant function?)
18. Let $\mathcal{F} = \{f \mid f : \mathbb{R} \rightarrow \mathbb{R}\}$. Let $R = \{(f, g) \in \mathcal{F} \times \mathcal{F} \mid \exists a \in \mathbb{R} \forall x > a (f(x) = g(x))\}$.
- (a) Let $f : \mathbb{R} \rightarrow \mathbb{R}$ and $g : \mathbb{R} \rightarrow \mathbb{R}$ be the functions defined by the formulas $f(x) = |x|$ and $g(x) = x$. Show that $(f, g) \in R$.
- (b) Prove that R is an equivalence relation.
- *19. Let $\mathcal{F} = \{f \mid f : \mathbb{Z}^+ \rightarrow \mathbb{R}\}$. For $g \in \mathcal{F}$, we define the set $O(g)$ as follows:

$$O(g) = \{f \in \mathcal{F} \mid \exists a \in \mathbb{Z}^+ \exists c \in \mathbb{R}^+ \forall x > a (|f(x)| \leq c|g(x)|)\}.$$

(If $f \in O(g)$, then mathematicians say that “ f is big-oh of g .”)

- (a) Let $f : \mathbb{Z}^+ \rightarrow \mathbb{R}$ and $g : \mathbb{Z}^+ \rightarrow \mathbb{R}$ be defined by the formulas $f(x) = 7x + 3$ and $g(x) = x^2$. Prove that $f \in O(g)$, but $g \notin O(f)$.
- (b) Let $S = \{(f, g) \in \mathcal{F} \times \mathcal{F} \mid f \in O(g)\}$. Prove that S is a preorder, but not a partial order. (See exercise 25 of Section 4.5 for the definition of *preorder*.)
- (c) Suppose $f_1 \in O(g)$ and $f_2 \in O(g)$, and s and t are real numbers. Define a function $f : \mathbb{Z}^+ \rightarrow \mathbb{R}$ by the formula $f(x) = sf_1(x) + tf_2(x)$. Prove that $f \in O(g)$. (Hint: You may find the triangle inequality helpful. See exercise 13(c) of Section 3.5.)
20. (a) Suppose $g : A \rightarrow B$ and let $R = \{(x, y) \in A \times A \mid g(x) = g(y)\}$. Show that R is an equivalence relation on A .
- (b) Suppose R is an equivalence relation on A and let $g : A \rightarrow A/R$ be the function defined by the formula $g(x) = [x]_R$. Show that $R = \{(x, y) \in A \times A \mid g(x) = g(y)\}$.
- *21. Suppose $f : A \rightarrow B$ and R is an equivalence relation on A . We will say that f is *compatible* with R if $\forall x \in A \forall y \in A (xRy \rightarrow f(x) = f(y))$. (You might want to compare this exercise to exercise 24 of Section 4.5.)
- (a) Suppose f is compatible with R . Prove that there is a unique function $h : A/R \rightarrow B$ such that for all $x \in A$, $h([x]_R) = f(x)$.
- (b) Suppose $h : A/R \rightarrow B$ and for all $x \in A$, $h([x]_R) = f(x)$. Prove that f is compatible with R .
22. Let $R = \{(x, y) \in \mathbb{N} \times \mathbb{N} \mid x \equiv y \pmod{5}\}$. Note that by Theorem 4.5.10 and exercise 14 in Section 4.5, R is an equivalence relation on \mathbb{N} .
- (a) Show that there is a unique function $h : \mathbb{N}/R \rightarrow \mathbb{N}/R$ such that for every natural number x , $h([x]_R) = [x^2]_R$. (Hint: Use exercise 21.)
- (b) Show that there is no function $h : \mathbb{N}/R \rightarrow \mathbb{N}/R$ such that for every natural number x , $h([x]_R) = [2^x]_R$.

5.2. One-to-One and Onto

In the last section we saw that the composition of two functions is again a function. What about inverses of functions? If $f : A \rightarrow B$, then f is a relation from A to B , so f^{-1} is a relation from B to A . Is it a function from B to A ? We'll answer this question in the next section. As we will see, the answer hinges on the following two properties of functions.

Definition 5.2.1. Suppose $f : A \rightarrow B$. We will say that f is *one-to-one* if

$$\neg \exists a_1 \in A \exists a_2 \in A (f(a_1) = f(a_2) \wedge a_1 \neq a_2).$$

We say that f *maps onto* B (or just *is onto* if B is clear from context) if

$$\forall b \in B \exists a \in A (f(a) = b).$$

One-to-one functions are sometimes also called *injections*, and onto functions are sometimes called *surjections*.

Note that our definition of one-to-one starts with the negation symbol \neg . In other words, to say that f is one-to-one means that a certain situation does *not* occur. The situation that must not occur is that there are two different elements of the domain of f , a_1 and a_2 , such that $f(a_1) = f(a_2)$. This situation is illustrated in Figure 5.4(a). Thus, the function in Figure 5.4(a) is not one-to-one. Figure 5.4(b) shows a function that is one-to-one.

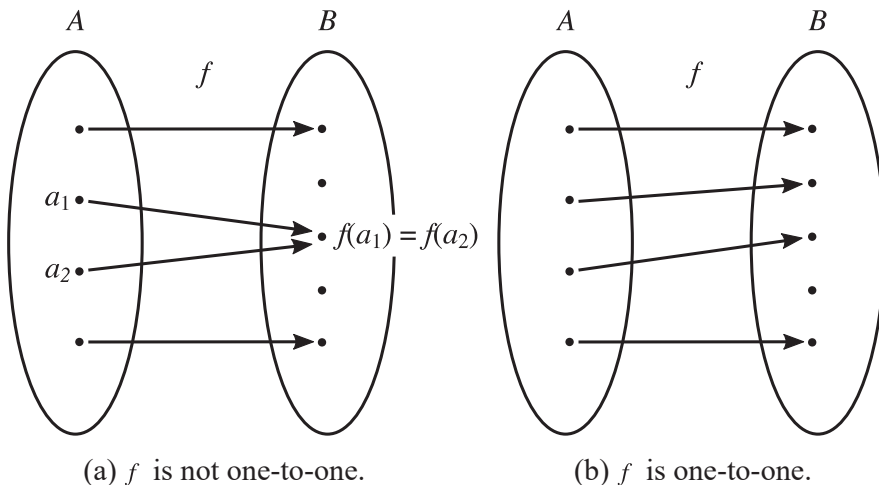


Figure 5.4.

If $f : A \rightarrow B$, then to say that f is onto means that every element of B is the image under f of some element of A . In other words, in the diagram of f , every element of B has an edge pointing to it. Neither of the functions in Figure 5.4 is onto, because in both cases there are elements of B without edges pointing to them. Figure 5.5 shows two functions that are onto.

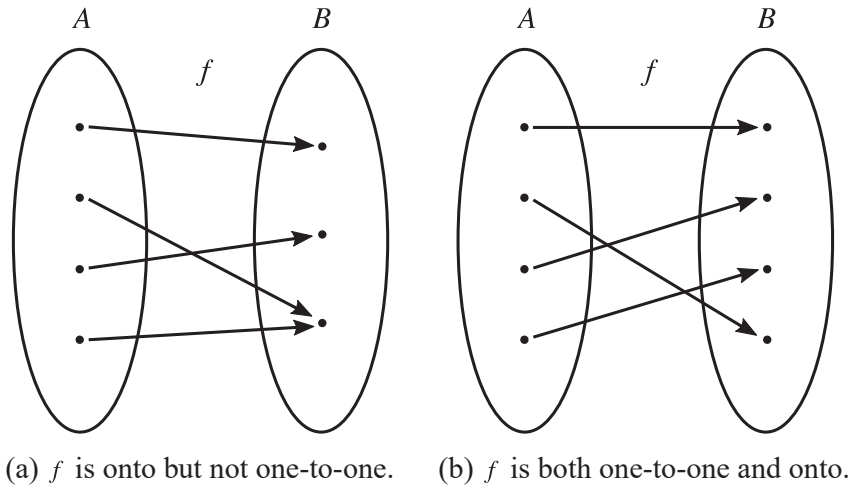


Figure 5.5.

Example 5.2.2. Are the following functions one-to-one? Are they onto?

1. The function F from part 1 of Example 5.1.2.
2. The function L from part 3 of Example 5.1.2.
3. The identity function i_A , for any set A .
4. The function g from part 2 of Example 5.1.3.
5. The function h from part 3 of Example 5.1.3.

Solutions

1. F is not one-to-one because $F(1) = 5 = F(3)$. It is also not onto, because $6 \in B$ but there is no $a \in A$ such that $F(a) = 6$.
2. L is not one-to-one because there are many pairs of different cities c_1 and c_2 for which $L(c_1) = L(c_2)$. For example, $L(\text{Chicago}) = \text{United States} = L(\text{Seattle})$. To say that L is onto means that $\forall n \in N \exists c \in C (L(c) = n)$, or in other words, for every country n there is a city c such that the city c is located in the country n . This is probably true, since it is unlikely that there is a country that contains no cities at all. Thus, L is probably onto.

3. To decide whether i_A is one-to-one we must determine whether there are two elements a_1 and a_2 of A such that $i_A(a_1) = i_A(a_2)$ and $a_1 \neq a_2$. But as we saw in Section 5.1, for every $a \in A$, $i_A(a) = a$, so $i_A(a_1) = i_A(a_2)$ means $a_1 = a_2$. Thus, there cannot be elements a_1 and a_2 of A such that $i_A(a_1) = i_A(a_2)$ and $a_1 \neq a_2$, so i_A is one-to-one.

To say that i_A is onto means that for every $a \in A$, $a = i_A(b)$ for some $b \in A$. This is clearly true because, in fact, $a = i_A(a)$. Thus i_A is also onto.

4. As in solution 3, to decide whether g is one-to-one, we must determine whether there are integers n_1 and n_2 such that $g(n_1) = g(n_2)$ and $n_1 \neq n_2$. According to the definition of g , we have

$$\begin{aligned} g(n_1) = g(n_2) &\text{ iff } 2n_1 + 3 = 2n_2 + 3 \\ &\text{ iff } 2n_1 = 2n_2 \\ &\text{ iff } n_1 = n_2. \end{aligned}$$

Thus there can be no integers n_1 and n_2 for which $g(n_1) = g(n_2)$ and $n_1 \neq n_2$. In other words, g is one-to-one. However, g is not onto because, for example, there is no integer n for which $g(n) = 0$. To see why, suppose n is an integer and $g(n) = 0$. Then by the definition of g we have $2n + 3 = 0$, so $n = -3/2$. But this contradicts the fact that n is an integer. Note that the domain of g is \mathbb{Z} , so for g to be onto it must be the case that for every real number y there is an integer n such that $g(n) = y$. Since we have seen that there is no integer n such that $g(n) = 0$, we can conclude that g is not onto.

5. This function is both one-to-one and onto. The verification that h is one-to-one is very similar to the verification in solution 4 that g is one-to-one, and it is left to the reader. To see that h is onto, we must show that $\forall y \in \mathbb{R} \exists x \in \mathbb{R} (h(x) = y)$. Here is a brief proof of this statement. Let y be an arbitrary real number. Let $x = (y - 3)/2$. Then $g(x) = 2x + 3 = 2 \cdot ((y - 3)/2) + 3 = y - 3 + 3 = y$. Thus, $\forall y \in \mathbb{R} \exists x \in \mathbb{R} (h(x) = y)$, so h is onto.

Although the definition of one-to-one is easiest to understand when it is stated as a negative statement, as in Definition 5.2.1, we know from Chapter 3 that the definition will be easier to use in proofs if we reexpress it as an equivalent positive statement. The following theorem shows how to do this. It also gives a useful equivalence for the definition of onto.

Theorem 5.2.3. Suppose $f : A \rightarrow B$.

1. f is one-to-one iff $\forall a_1 \in A \forall a_2 \in A (f(a_1) = f(a_2) \rightarrow a_1 = a_2)$.
2. f is onto iff $\text{Ran}(f) = B$.

Proof.

1. We use the rules from Chapters 1 and 2 for reexpressing negative statements as positive ones.

$$\begin{aligned} f \text{ is one-to-one} &\text{ iff } \neg \exists a_1 \in A \exists a_2 \in A (f(a_1) = f(a_2) \wedge a_1 \neq a_2) \\ &\text{ iff } \forall a_1 \in A \forall a_2 \in A \neg (f(a_1) = f(a_2) \wedge a_1 \neq a_2) \\ &\text{ iff } \forall a_1 \in A \forall a_2 \in A (f(a_1) \neq f(a_2) \vee a_1 = a_2) \\ &\text{ iff } \forall a_1 \in A \forall a_2 \in A (f(a_1) = f(a_2) \rightarrow a_1 = a_2). \end{aligned}$$

2. First we relate the definition of onto to the definition of range.

$$\begin{aligned} f \text{ is onto} &\text{ iff } \forall b \in B \exists a \in A (f(a) = b) \\ &\text{ iff } \forall b \in B \exists a \in A ((a, b) \in f) \\ &\text{ iff } \forall b \in B (b \in \text{Ran}(f)) \\ &\text{ iff } B \subseteq \text{Ran}(f). \end{aligned}$$

Now we are ready to prove part 2 of the theorem.

(\rightarrow) Suppose f is onto. By the equivalence just derived we have $B \subseteq \text{Ran}(f)$, and by the definition of range we have $\text{Ran}(f) \subseteq B$. Thus, it follows that $\text{Ran}(f) = B$.

(\leftarrow) Suppose $\text{Ran}(f) = B$. Then certainly $B \subseteq \text{Ran}(f)$, so by the equivalence, f is onto. \square

Commentary. It is often most efficient to write the proof of an iff statement as a string of equivalences, if this can be done. In the case of statement 1 this is easy, using rules of logic. For statement 2 this strategy doesn't quite work, but it does give us an equivalence that turns out to be useful in the proof.

Example 5.2.4. Let $A = \mathbb{R} \setminus \{-1\}$, and define $f : A \rightarrow \mathbb{R}$ by the formula

$$f(a) = \frac{2a}{a+1}.$$

Prove that f is one-to-one but not onto.

Scratch work

By part 1 of Theorem 5.2.3, we can prove that f is one-to-one by proving the equivalent statement $\forall a_1 \in A \forall a_2 \in A (f(a_1) = f(a_2) \rightarrow a_1 = a_2)$. Thus, we let a_1 and a_2 be arbitrary elements of A , assume $f(a_1) = f(a_2)$, and then prove $a_1 = a_2$. This is the strategy that is almost always used when proving that a function is one-to-one. The remaining details of the proof involve only simple algebra and are given later.

To show that f is not onto we must prove $\neg \forall x \in \mathbb{R} \exists a \in A (f(a) = x)$. Reexpressing this as a positive statement, we see that we must prove $\exists x \in \mathbb{R} \forall a \in A (f(a) \neq x)$, so we should try to find a particular real number x such that $\forall a \in A (f(a) \neq x)$. Unfortunately, it is not at all clear what value we should use for x . We'll use a somewhat unusual procedure to overcome this difficulty. Instead of trying to prove that f is not onto, let's try to prove that it *is* onto! Of course, we're expecting that this proof won't work, but maybe seeing *why* it won't work will help us figure out what value of x to use in the proof that f is *not* onto.

To prove that f is onto we would have to prove $\forall x \in \mathbb{R} \exists a \in A (f(a) = x)$, so we should let x be an arbitrary real number and try to find some $a \in A$ such that $f(a) = x$. Filling in the definition of f , we see that we must find $a \in A$ such that

$$\frac{2a}{a+1} = x.$$

To find this value of a , we simply solve the equation for a :

$$\frac{2a}{a+1} = x \quad \Rightarrow \quad 2a = ax + x \quad \Rightarrow \quad a(2-x) = x \quad \Rightarrow \quad a = \frac{x}{2-x}.$$

Aha! The last step in this derivation wouldn't work if $x = 2$, because then we would be dividing by 0. This is the only value of x that seems to cause trouble when we try to find a value of a for which $f(a) = x$. Perhaps $x = 2$ is the value to use in the proof that f is *not* onto.

Let's return now to the proof that f is not onto. If we let $x = 2$, then to complete the proof we must show that $\forall a \in A (f(a) \neq 2)$. We'll do this by letting a be an arbitrary element of A , assuming $f(a) = 2$, and then trying to derive a contradiction. The remaining details of the proof are not hard.

Solution

Proof. To see that f is one-to-one, let a_1 and a_2 be arbitrary elements of A and assume that $f(a_1) = f(a_2)$. Applying the definition of f , it follows that $2a_1/(a_1+1) = 2a_2/(a_2+1)$. Thus, $2a_1(a_2+1) = 2a_2(a_1+1)$. Multiplying out both sides gives us $2a_1a_2 + 2a_1 = 2a_1a_2 + 2a_2$, so $2a_1 = 2a_2$ and therefore $a_1 = a_2$.

To show that f is not onto we will prove that $\forall a \in A (f(a) \neq 2)$. Suppose $a \in A$ and $f(a) = 2$. Applying the definition of f , we get $2a/(a+1) = 2$. Thus, $2a = 2a + 2$, which is clearly impossible. Thus, $2 \notin \text{Ran}(f)$, so $\text{Ran}(f) \neq \mathbb{R}$ and therefore f is not onto. \square

As we saw in the preceding example, when proving that a function f is one-to-one it is usually easiest to prove the equivalent statement $\forall a_1 \in A \forall a_2 \in A (f(a_1) = f(a_2) \rightarrow a_1 = a_2)$ given in part 1 of Theorem 5.2.3. Of course, this is just an example of the fact that it is generally easier to prove a positive statement than a negative one. This equivalence is also often used in proofs in which we are *given* that a function is one-to-one, as you will see in the proof of part 1 of the following theorem.

Theorem 5.2.5. *Suppose $f : A \rightarrow B$ and $g : B \rightarrow C$. As we saw in Theorem 5.1.5, it follows that $g \circ f : A \rightarrow C$.*

1. *If f and g are both one-to-one, then so is $g \circ f$.*
2. *If f and g are both onto, then so is $g \circ f$.*

Proof.

1. Suppose f and g are both one-to-one. Let a_1 and a_2 be arbitrary elements of A and suppose that $(g \circ f)(a_1) = (g \circ f)(a_2)$. By Theorem 5.1.5 this means that $g(f(a_1)) = g(f(a_2))$. Since g is one-to-one it follows that $f(a_1) = f(a_2)$, and similarly since f is one-to-one we can then conclude that $a_1 = a_2$. Thus, $g \circ f$ is one-to-one.
2. Suppose f and g are both onto, and let c be an arbitrary element of C . Since g is onto, we can find some $b \in B$ such that $g(b) = c$. Similarly, since f is onto, there is some $a \in A$ such that $f(a) = b$. Then $(g \circ f)(a) = g(f(a)) = g(b) = c$. Thus, $g \circ f$ is onto. \square

Commentary.

1. As in Example 5.2.4, we prove that $g \circ f$ is one-to-one by proving that $\forall a_1 \in A \forall a_2 \in A ((g \circ f)(a_1) = (g \circ f)(a_2) \rightarrow a_1 = a_2)$. Thus, we let a_1 and a_2 be arbitrary elements of A , assume that $(g \circ f)(a_1) = (g \circ f)(a_2)$, which means $g(f(a_1)) = g(f(a_2))$, and then prove that $a_1 = a_2$. The next sentence of the proof says that the assumption that g is one-to-one is being used, but it might not be clear *how* it is being used. To understand this step, let's write out what it means to say that g is one-to-one. As we observed before, rather than using the original definition, which is a negative statement, we are probably better off using the equivalent positive statement $\forall b_1 \in B \forall b_2 \in B (g(b_1) = g(b_2) \rightarrow b_1 = b_2)$. The natural way to use a given of this form is to plug something in for b_1 and b_2 . Plugging in $f(a_1)$ and $f(a_2)$, we get $g(f(a_1)) = g(f(a_2)) \rightarrow f(a_1) = f(a_2)$, and since we know $g(f(a_1)) = g(f(a_2))$, it follows by modus ponens that $f(a_1) = f(a_2)$. None of this was explained in the proof; readers of the

proof are expected to work it out for themselves. Make sure you understand how, using similar reasoning, you can get from $f(a_1) = f(a_2)$ to $a_1 = a_2$ by applying the fact that f is one-to-one.

2. After the assumption that f and g are both onto, the form of the rest of the proof is entirely guided by the logical form of the goal of proving that $g \circ f$ is onto. Because this means $\forall c \in C \exists a \in A((g \circ f)(a) = c)$, we let c be an arbitrary element of C and then find some $a \in A$ for which we can prove $(g \circ f)(a) = c$.

Functions that are both one-to-one and onto are particularly important in mathematics. Such functions are sometimes called *one-to-one correspondences* or *bijections*. Figure 5.5(b) shows an example of a one-to-one correspondence. Notice that in this figure both A and B have four elements. In fact, you should be able to convince yourself that if there is a one-to-one correspondence between two finite sets, then the sets must have the same number of elements. This is one of the reasons why one-to-one correspondences are so important. We will discuss one-to-one correspondences between infinite sets in Chapter 8.

Here's another example of a one-to-one correspondence. Suppose A is the set of all members of the audience at a sold-out concert and S is the set of all seats in the concert hall. Let $f : A \rightarrow S$ be the function defined by the rule

$$f(a) = \text{the seat in which } a \text{ is sitting.}$$

Because different people would not be sitting in the same seat, f is one-to-one. Because the concert is sold out, every seat is taken, so f is onto. Thus, f is a one-to-one correspondence. Even without counting people or seats, we can tell that the number of people in the audience must be the same as the number of seats in the concert hall.

Exercises

1. Which of the functions in exercise 1 of Section 5.1 are one-to-one? Which are onto?
- *2. Which of the functions in exercise 2 of Section 5.1 are one-to-one? Which are onto?
3. Which of the functions in exercise 3 of Section 5.1 are one-to-one? Which are onto?
4. Which of the functions in exercise 4 of Section 5.1 are one-to-one? Which are onto?

*5. Let $A = \mathbb{R} \setminus \{1\}$, and let $f : A \rightarrow A$ be defined as follows:

$$f(x) = \frac{x+1}{x-1}.$$

- (a) Show that f is one-to-one and onto.
 (b) Show that $f \circ f = i_A$.
6. Suppose a and b are real numbers and $a \neq 0$. Define $f : \mathbb{R} \rightarrow \mathbb{R}$ by the formula $f(x) = ax + b$. Show that f is one-to-one and onto.
7. Define $f : \mathbb{R}^+ \rightarrow \mathbb{R}$ by the formula $f(x) = 1/x - x$.
 (a) Show that f is one-to-one. (Hint: You may find it useful to prove first that if $0 < a < b$ then $f(a) > f(b)$.)
 (b) Show that f is onto.
 (c) Define $g : \mathbb{R}^+ \rightarrow \mathbb{R}$ by the formula $g(x) = 1/x + x$. Is g one-to-one? Is it onto?
8. Let $A = \mathcal{P}(\mathbb{R})$. Define $f : \mathbb{R} \rightarrow A$ by the formula $f(x) = \{y \in \mathbb{R} \mid y^2 < x\}$.
 (a) Find $f(2)$.
 (b) Is f one-to-one? Is it onto?
- *9. Let $A = \mathcal{P}(\mathbb{R})$ and $B = \mathcal{P}(A)$. Define $f : B \rightarrow A$ by the formula $f(\mathcal{F}) = \bigcup \mathcal{F}$.
 (a) Find $f(\{\{1, 2\}, \{3, 4\}\})$.
 (b) Is f one-to-one? Is it onto?
10. Suppose $f : A \rightarrow B$ and $g : B \rightarrow C$.
 (a) Prove that if $g \circ f$ is onto then g is onto.
 (b) Prove that if $g \circ f$ is one-to-one then f is one-to-one.
11. Suppose $f : A \rightarrow B$ and $g : B \rightarrow C$.
 (a) Prove that if f is onto and g is not one-to-one, then $g \circ f$ is not one-to-one.
 (b) Prove that if f is not onto and g is one-to-one, then $g \circ f$ is not onto.
12. Suppose $f : A \rightarrow B$. Define a function $g : B \rightarrow \mathcal{P}(A)$ by the formula $g(b) = \{a \in A \mid f(a) = b\}$. Prove that if f is onto then g is one-to-one. What if f is not onto?
- *13. Suppose $f : A \rightarrow B$ and $C \subseteq A$. In exercise 7 of Section 5.1 we defined $f \upharpoonright C$ (the restriction of f to C), and you showed that $f \upharpoonright C : C \rightarrow B$.
 (a) Prove that if f is one-to-one, then so is $f \upharpoonright C$.
 (b) Prove that if $f \upharpoonright C$ is onto, then so is f .
 (c) Give examples to show that the converses of parts (a) and (b) are not always true.
14. Suppose $f : A \rightarrow B$, and there is some $b \in B$ such that $\forall x \in A (f(x) = b)$. (Thus, f is a *constant* function.)

- (a) Prove that if A has more than one element then f is not one-to-one.
 (b) Prove that if B has more than one element then f is not onto.
15. Suppose $f : A \rightarrow C, g : B \rightarrow C$, and A and B are disjoint. In exercise 12(a) of Section 5.1 you proved that $f \cup g : A \cup B \rightarrow C$. Now suppose that f and g are both one-to-one. Prove that $f \cup g$ is one-to-one iff $\text{Ran}(f)$ and $\text{Ran}(g)$ are disjoint.
16. Suppose R is a relation from A to B , S is a relation from B to C , $\text{Ran}(R) = \text{Dom}(S) = B$, and $S \circ R : A \rightarrow C$. In exercise 13(a) of Section 5.1 you proved that $S : B \rightarrow C$. Now prove that if S is one-to-one then $R : A \rightarrow B$.
- *17. Suppose $f : A \rightarrow B$ and R is a relation on A . As in exercise 15 of Section 5.1, define a relation S on B as follows:

$$S = \{ (x, y) \in B \times B \mid \exists u \in A \exists v \in A (f(u) = x \wedge f(v) = y \wedge (u, v) \in R) \}.$$

- (a) Prove that if R is reflexive and f is onto then S is reflexive.
 (b) Prove that if R is transitive and f is one-to-one then S is transitive.
18. Suppose R is an equivalence relation on A , and let $g : A \rightarrow A/R$ be defined by the formula $g(x) = [x]_R$, as in exercise 20(b) in Section 5.1.
 (a) Show that g is onto.
 (b) Show that g is one-to-one iff $R = i_A$.
19. Suppose $f : A \rightarrow B$, R is an equivalence relation on A , and f is compatible with R . (See exercise 21 of Section 5.1 for the definition of *compatible*.) In exercise 21(a) of Section 5.1 you proved that there is a unique function $h : A/R \rightarrow B$ such that for all $x \in A, h([x]_R) = f(x)$. Now prove that h is one-to-one iff $\forall x \in A \forall y \in A (f(x) = f(y) \rightarrow xRy)$.
- *20. Suppose A, B , and C are sets and $f : A \rightarrow B$.
 (a) Prove that if f is onto, $g : B \rightarrow C, h : B \rightarrow C$, and $g \circ f = h \circ f$, then $g = h$.
 (b) Suppose that C has at least two elements, and for all functions g and h from B to C , if $g \circ f = h \circ f$ then $g = h$. Prove that f is onto.
21. Suppose A, B , and C are sets and $f : B \rightarrow C$.
 (a) Prove that if f is one-to-one, $g : A \rightarrow B, h : A \rightarrow B$, and $f \circ g = f \circ h$, then $g = h$.
 (b) Suppose that $A \cong \emptyset$, and for all functions g and h from A to B , if $f \circ g = f \circ h$ then $g = h$. Prove that f is one-to-one.
22. Let $\mathcal{F} = \{f \mid f : \mathbb{R} \rightarrow \mathbb{R}\}$, and define a relation R on \mathcal{F} as follows:

$$R = \{ (f, g) \in \mathcal{F} \times \mathcal{F} \mid \exists h \in \mathcal{F} (f = h \circ g) \}.$$

- (a) Let $f, g,$ and h be the functions from \mathbb{R} to \mathbb{R} defined by the formulas $f(x) = x^2 + 1, g(x) = x^3 + 1,$ and $h(x) = x^4 + 1.$ Prove that $hRf,$ but it is not the case that $gRf.$
- (b) Prove that R is a preorder. (See exercise 25 of Section 4.5 for the definition of *preorder*.)
- (c) Prove that for all $f \in \mathcal{F}, f Ri_{\mathbb{R}}.$
- (d) Prove that for all $f \in \mathcal{F}, i_{\mathbb{R}}Rf$ iff f is one-to-one. (Hint for right-to-left direction: Suppose f is one-to-one. Let $A = \text{Ran}(f),$ and let $h = f^{-1} \cup ((\mathbb{R} \setminus A) \times \{0\}).$ Now prove that $h : \mathbb{R} \rightarrow \mathbb{R}$ and $i_{\mathbb{R}} = h \circ f.$)
- (e) Suppose that $g \in \mathcal{F}$ is a constant function; in other words, there is some real number c such that $\forall x \in \mathbb{R}(g(x) = c).$ Prove that for all $f \in \mathcal{F}, gRf.$ (Hint: See exercise 17 of Section 5.1.)
- (f) Suppose that $g \in \mathcal{F}$ is a constant function. Prove that for all $f \in \mathcal{F}, fRg$ iff f is a constant function.
- (g) As in exercise 25 of Section 4.5, if we let $S = R \cap R^{-1},$ then S is an equivalence relation on $\mathcal{F}.$ Also, there is a unique relation T on \mathcal{F}/S such that for all f and g in $\mathcal{F}, [f]_S T [g]_S$ iff $fRg,$ and T is a partial order on $\mathcal{F}/S.$ Prove that the set of all one-to-one functions from \mathbb{R} to \mathbb{R} is the largest element of \mathcal{F}/S in the partial order $T,$ and the set of all constant functions from \mathbb{R} to \mathbb{R} is the smallest element.
23. Let $f : \mathbb{N} \rightarrow \mathbb{N}$ be defined by the formula $f(n) = n.$ Note that we could also say that $f : \mathbb{N} \rightarrow \mathbb{Z}.$ This exercise will illustrate why, in Definition 5.2.1, we defined the phrase “ f maps onto $B,$ ” rather than simply “ f is onto.”
- (a) Does f map onto $\mathbb{N}?$
- (b) Does f map onto $\mathbb{Z}?$

5.3. Inverses of Functions

We are now ready to return to the question of whether the inverse of a function from A to B is always a function from B to $A.$ Consider again the function F from part 1 of Example 5.1.2. Recall that in that example we had $A = \{1, 2, 3\}, B = \{4, 5, 6\},$ and $F = \{(1, 5), (2, 4), (3, 5)\}.$ As we saw in Example 5.1.2, F is a function from A to $B.$ According to the definition of the inverse of a relation, $F^{-1} = \{(5, 1), (4, 2), (5, 3)\},$ which is clearly a relation from B to $A.$ But F^{-1} fails to be a function from B to A for two reasons. First of all, $6 \in B,$ but 6 isn't paired with any element of A in the relation $F^{-1}.$ Second, 5

is paired with two different elements of A , 1 and 3. Thus, this example shows that the inverse of a function from A to B is not always a function from B to A .

You may have noticed that the reasons why F^{-1} isn't a function from B to A are related to the reasons why F is neither one-to-one nor onto, which were discussed in part 1 of Example 5.2.2. This suggests the following theorem.

Theorem 5.3.1. *Suppose $f : A \rightarrow B$. If f is one-to-one and onto, then $f^{-1} : B \rightarrow A$.*

Proof. Suppose f is one-to-one and onto, and let b be an arbitrary element of B . To show that f^{-1} is a function from B to A , we must prove that $\exists! a \in A((b, a) \in f^{-1})$, so we prove existence and uniqueness separately.

Existence: Since f is onto, there is some $a \in A$ such that $f(a) = b$. Thus, $(a, b) \in f$, so $(b, a) \in f^{-1}$.

Uniqueness: Suppose $(b, a_1) \in f^{-1}$ and $(b, a_2) \in f^{-1}$ for some $a_1, a_2 \in A$. Then $(a_1, b) \in f$ and $(a_2, b) \in f$, so $f(a_1) = b = f(a_2)$. Since f is one-to-one, it follows that $a_1 = a_2$. \square

Commentary. The form of the proof is guided by the logical form of the statement that $f^{-1} : B \rightarrow A$. Because this means $\forall b \in B \exists! a \in A((b, a) \in f^{-1})$, we let b be an arbitrary element of B and then prove existence and uniqueness for the required $a \in A$ separately. Note that the assumption that f is onto is the key to the existence half of the proof, and the assumption that f is one-to-one is the key to the uniqueness half.

Suppose f is any function from a set A to a set B . Theorem 5.3.1 says that a sufficient condition for f^{-1} to be a function from B to A is that f be one-to-one and onto. Is it also a necessary condition? In other words, is the converse of Theorem 5.3.1 true? (If you don't remember what the words *sufficient*, *necessary*, and *converse* mean, you should review Section 1.5!) We will show in Theorem 5.3.4 that the answer to this question is yes. In other words, if f^{-1} is a function from B to A , then f must be one-to-one and onto.

If $f^{-1} : B \rightarrow A$ then, by the definition of function, for every $b \in B$ there is exactly one $a \in A$ such that $(b, a) \in f^{-1}$, and

$$\begin{aligned} f^{-1}(b) &= \text{the unique } a \in A \text{ such that } (b, a) \in f^{-1} \\ &= \text{the unique } a \in A \text{ such that } (a, b) \in f \\ &= \text{the unique } a \in A \text{ such that } f(a) = b. \end{aligned}$$

This gives another useful way to think about f^{-1} . If f^{-1} is a function from B to A , then it is the function that assigns, to each $b \in B$, the unique $a \in A$

such that $f(a) = b$. The assumption in Theorem 5.3.1 that f is one-to-one and onto guarantees that there is exactly one such a .

As an example, consider again the function f that assigns, to each person in the audience at a sold-out concert, the seat in which that person is sitting. As we saw at the end of the last section, f is a one-to-one, onto function from the set A of all members of the audience to the set S of all seats in the concert hall. Thus, f^{-1} must be a function from S to A , and for each $s \in S$,

$$\begin{aligned} f^{-1}(s) &= \text{the unique } a \in A \text{ such that } f(a) = s \\ &= \text{the unique person } a \text{ such that the seat in which } a \text{ is sitting is } s \\ &= \text{the person who is sitting in the seat } s. \end{aligned}$$

In other words, the function f assigns to each person the seat in which that person is sitting, and the function f^{-1} assigns to each seat the person sitting in that seat.

Because $f : A \rightarrow S$ and $f^{-1} : S \rightarrow A$, it follows by Theorem 5.1.5 that $f^{-1} \circ f : A \rightarrow A$ and $f \circ f^{-1} : S \rightarrow S$. What are these functions? To figure out what the first function is, let's let a be an arbitrary element of A and compute $(f^{-1} \circ f)(a)$.

$$\begin{aligned} (f^{-1} \circ f)(a) &= f^{-1}(f(a)) \\ &= f^{-1}(\text{the seat in which } a \text{ is sitting}) \\ &= \text{the person sitting in the seat in which } a \text{ is sitting} \\ &= a. \end{aligned}$$

But recall that for every $a \in A$, $i_A(a) = a$. Thus, we have shown that $\forall a \in A ((f^{-1} \circ f)(a) = i_A(a))$, so by Theorem 5.1.4, $f^{-1} \circ f = i_A$. Similarly, you should be able to check that $f \circ f^{-1} = i_S$.

When mathematicians find an unusual phenomenon like this in an example, they always wonder whether it's just a coincidence or if it's part of a more general pattern. In other words, can we prove a theorem that says that what happened in this example will happen in other examples too? In this case, it turns out that we can.

Theorem 5.3.2. *Suppose f is a function from A to B , and suppose that f^{-1} is a function from B to A . Then $f^{-1} \circ f = i_A$ and $f \circ f^{-1} = i_B$.*

Proof. Let a be an arbitrary element of A . Let $b = f(a) \in B$. Then $(a, b) \in f$, so $(b, a) \in f^{-1}$ and therefore $f^{-1}(b) = a$. Thus,

$$(f^{-1} \circ f)(a) = f^{-1}(f(a)) = f^{-1}(b) = a = i_A(a).$$

Since a was arbitrary, we have shown that $\forall a \in A((f^{-1} \circ f)(a) = i_A(a))$, so $f^{-1} \circ f = i_A$. The proof of the second half of the theorem is similar and is left as an exercise (see exercise 8). \square

Commentary. To prove that two functions are equal, we usually apply Theorem 5.1.4. Thus, since $f^{-1} \circ f$ and i_A are both functions from A to A , to prove that they are equal we prove that $\forall a \in A((f^{-1} \circ f)(a) = i_A(a))$.

Theorem 5.3.2 says that if $f : A \rightarrow B$ and $f^{-1} : B \rightarrow A$, then each function undoes the effect of the other. For any $a \in A$, applying the function f gives us $f(a) \in B$. According to Theorem 5.3.2, $f^{-1}(f(a)) = (f^{-1} \circ f)(a) = i_A(a) = a$. Thus, applying f^{-1} to $f(a)$ undoes the effect of applying f , giving us back the original element a . Similarly, for any $b \in B$, applying f^{-1} we get $f^{-1}(b) \in A$, and we can undo the effect of applying f^{-1} by applying f , since $f(f^{-1}(b)) = b$.

For example, let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = 2x$. You should be able to check that f is one-to-one and onto, so $f^{-1} : \mathbb{R} \rightarrow \mathbb{R}$, and for any $x \in \mathbb{R}$,

$$f^{-1}(x) = \text{the unique } y \text{ such that } f(y) = x.$$

Because $f^{-1}(x)$ is the unique solution for y in the equation $f(y) = x$, we can find a formula for $f^{-1}(x)$ by solving this equation for y . Filling in the definition of f in the equation gives us $2y = x$, so $y = x/2$. Thus, for every $x \in \mathbb{R}$, $f^{-1}(x) = x/2$. Notice that applying f to any number doubles the number and applying f^{-1} halves the number, and each of these operations undoes the effect of the other. In other words, if you double a number and then halve the result, you get back the number you started with. Similarly, halving any number and then doubling the result gives you back the original number.

Are there other circumstances in which the composition of two functions is equal to the identity function? Investigation of this question leads to the following theorem.

Theorem 5.3.3. *Suppose $f : A \rightarrow B$.*

1. *If there is a function $g : B \rightarrow A$ such that $g \circ f = i_A$ then f is one-to-one.*
2. *If there is a function $g : B \rightarrow A$ such that $f \circ g = i_B$ then f is onto.*

Proof.

1. Suppose $g : B \rightarrow A$ and $g \circ f = i_A$. Let a_1 and a_2 be arbitrary elements of A , and suppose that $f(a_1) = f(a_2)$. Applying g to both sides of this

equation we get $g(f(a_1)) = g(f(a_2))$. But $g(f(a_1)) = (g \circ f)(a_1) = i_A(a_1) = a_1$, and similarly, $g(f(a_2)) = a_2$. Thus, we can conclude that $a_1 = a_2$, and therefore f is one-to-one.

2. See exercise 9. □

Commentary. The assumption that there is a $g : B \rightarrow A$ such that $g \circ f = i_A$ is an existential statement, so we immediately imagine that a particular function g has been chosen. The proof that f is one-to-one follows the usual pattern for such proofs, based on Theorem 5.2.3.

We have come full circle. In Theorem 5.3.1 we found that if f is a one-to-one, onto function from A to B , then f^{-1} is a function from B to A . From this conclusion it follows, as we showed in Theorem 5.3.2, that the composition of f with its inverse must be the identity function. And in Theorem 5.3.3 we found that when the composition of two functions is the identity function, we are led back to the properties one-to-one and onto! Thus, combining Theorems 5.3.1–5.3.3, we get the following theorem.

Theorem 5.3.4. *Suppose $f : A \rightarrow B$. Then the following statements are equivalent.*

1. f is one-to-one and onto.
2. $f^{-1} : B \rightarrow A$.
3. There is a function $g : B \rightarrow A$ such that $g \circ f = i_A$ and $f \circ g = i_B$.

Proof. $1 \rightarrow 2$. This is precisely what Theorem 5.3.1 says.

$2 \rightarrow 3$. Suppose $f^{-1} : B \rightarrow A$. Let $g = f^{-1}$ and apply Theorem 5.3.2.

$3 \rightarrow 1$. Apply Theorem 5.3.3. □

Commentary. As we saw in Section 3.6, the easiest way to prove that several statements are equivalent is to prove a circle of implications. In this case we have proven the circle $1 \rightarrow 2 \rightarrow 3 \rightarrow 1$. Note that the proofs of these implications are quite sketchy. You should make sure you know how to fill in all the details.

For example, let f and g be functions from \mathbb{R} to \mathbb{R} defined by the following formulas:

$$f(x) = \frac{x+7}{5}, \quad g(x) = 5x - 7.$$

Then for any real number x ,

$$(g \circ f)(x) = g(f(x)) = g\left(\frac{x+7}{5}\right) = 5 \cdot \frac{x+7}{5} - 7 = x + 7 - 7 = x.$$

Thus, $g \circ f = i_{\mathbb{R}}$. A similar computation shows that $f \circ g = i_{\mathbb{R}}$. Thus, it follows from Theorem 5.3.4 that f must be one-to-one and onto, and f^{-1} must also be a function from \mathbb{R} to \mathbb{R} . What is f^{-1} ? Of course, a logical guess would be that $f^{-1} = g$, but this doesn't actually follow from the theorems we've proven. You could check it directly by solving for $f^{-1}(x)$, using the fact that $f^{-1}(x)$ must be the unique solution for y in the equation $f(y) = x$. However, there is no need to check. The next theorem shows that f^{-1} must be equal to g .

Theorem 5.3.5. *Suppose $f : A \rightarrow B$, $g : B \rightarrow A$, $g \circ f = i_A$, and $f \circ g = i_B$. Then $g = f^{-1}$.*

Proof. By Theorem 5.3.4, $f^{-1} : B \rightarrow A$. Therefore, by Theorem 5.3.2, $f^{-1} \circ f = i_A$. Thus,

$$\begin{aligned} g &= i_A \circ g && \text{(exercise 9 of Section 4.3)} \\ &= (f^{-1} \circ f) \circ g \\ &= f^{-1} \circ (f \circ g) && \text{(Theorem 4.2.5)} \\ &= f^{-1} \circ i_B \\ &= f^{-1} && \text{(exercise 9 of Section 4.3).} \quad \square \end{aligned}$$

Commentary. This proof gets the desired conclusion quickly by clever use of previous theorems and exercises. For a more direct but somewhat longer proof, see exercise 10.

Example 5.3.6. In each part, determine whether or not f is one-to-one and onto. If it is, find f^{-1} .

- Let $A = \mathbb{R} \setminus \{0\}$ and $B = \mathbb{R} \setminus \{2\}$, and define $f : A \rightarrow B$ by the formula

$$f(x) = \frac{1}{x} + 2.$$

(Note that for all $x \in A$, $1/x$ is defined and nonzero, so $f(x) \neq 2$ and therefore $f(x) \in B$.)

- Let $A = \mathbb{R}$ and $B = \{x \in \mathbb{R} \mid x \geq 0\}$, and define $f : A \rightarrow B$ by the formula

$$f(x) = x^2.$$

Solutions

- You can check directly that f is one-to-one and onto, but we won't bother to check. Instead, we'll simply try to find a function $g : B \rightarrow A$ such that

$g \circ f = i_A$ and $f \circ g = i_B$. We know by Theorems 5.3.4 and 5.3.5 that if we find such a g , then we can conclude that f is one-to-one and onto and $g = f^{-1}$.

Because we're hoping to have $g = f^{-1}$, we know that for any $x \in B = \mathbb{R} \setminus \{2\}$, $g(x)$ must be the unique $y \in A$ such that $f(y) = x$. Thus, to find a formula for $g(x)$, we solve for y in the equation $f(y) = x$. Filling in the definition of f , we see that the equation we must solve is

$$\frac{1}{y} + 2 = x.$$

Solving this equation we get

$$\frac{1}{y} + 2 = x \quad \Rightarrow \quad \frac{1}{y} = x - 2 \quad \Rightarrow \quad y = \frac{1}{x - 2}.$$

Thus, we define $g : B \rightarrow A$ by the formula

$$g(x) = \frac{1}{x - 2}.$$

(Note that for all $x \in B$, $x \neq 2$, so $1/(x - 2)$ is defined and nonzero, and therefore $g(x) \in A$.) Let's check that g has the required properties. For any $x \in A$, we have

$$g(f(x)) = g\left(\frac{1}{x} + 2\right) = \frac{1}{1/x + 2 - 2} = \frac{1}{1/x} = x.$$

Thus, $g \circ f = i_A$. Similarly, for any $x \in B$,

$$f(g(x)) = f\left(\frac{1}{x - 2}\right) = \frac{1}{1/(x - 2)} + 2 = x - 2 + 2 = x,$$

so $f \circ g = i_B$. Therefore, as we observed earlier, f must be one-to-one and onto, and $g = f^{-1}$.

2. Imitating the solution to part 1, let's try to find a function $g : B \rightarrow A$ such that $g \circ f = i_A$ and $f \circ g = i_B$. Because applying f to a number squares the number and we want g to undo the effect of f , a reasonable guess would be to let $g(x) = \sqrt{x}$. Let's see if this works.

For any $x \in B$ we have

$$f(g(x)) = f(\sqrt{x}) = (\sqrt{x})^2 = x,$$

so $f \circ g = i_B$. But for $x \in A$ we have

$$g(f(x)) = g(x^2) = \sqrt{x^2},$$

and this is *not* always equal to x . For example, $g(f(-3)) = \sqrt{(-3)^2} = \sqrt{9} = 3 \neq -3$. Thus, $g \circ f \neq i_A$. This example illustrates that you must

check both $f \circ g = i_B$ and $g \circ f = i_A$. It is possible for one to work but not the other.

What went wrong? We know that if f^{-1} is a function from B to A , then for any $x \in B$, $f^{-1}(x)$ must be the unique solution for y in the equation $f(y) = x$. Applying the definition of f gives us $y^2 = x$, so $y = \sqrt{x}$. Thus, there is not a *unique* solution for y in the equation $f(y) = x$; there are two solutions. For example, when $x = 9$ we get $y = \pm 3$. In other words, $f(3) = f(-3) = 9$. But this means that f is not one-to-one! Thus, f^{-1} is not a function from B to A .

Functions that undo each other come up often in mathematics. For example, if you are familiar with logarithms, then you will recognize the formulas $10^{\log x} = x$ and $\log 10^x = x$. (We are using base-10 logarithms here.) We can rephrase these formulas in the language of this section by defining functions $f : \mathbb{R} \rightarrow \mathbb{R}^+$ and $g : \mathbb{R}^+ \rightarrow \mathbb{R}$ as follows:

$$f(x) = 10^x, \quad g(x) = \log x.$$

Then for any $x \in \mathbb{R}$ we have $g(f(x)) = \log 10^x = x$, and for any $x \in \mathbb{R}^+$, $f(g(x)) = 10^{\log x} = x$. Thus, $g \circ f = i_{\mathbb{R}}$ and $f \circ g = i_{\mathbb{R}^+}$, so $g = f^{-1}$. In other words, the logarithm function is the inverse of the “raise 10 to the power” function.

We saw another example of functions that undo each other in Section 4.5. Suppose A is any set, let \mathcal{E} be the set of all equivalence relations on A , and let \mathcal{P} be the set of all partitions of A . Define a function $f : \mathcal{E} \rightarrow \mathcal{P}$ by the formula $f(R) = A/R$, and define another function $g : \mathcal{P} \rightarrow \mathcal{E}$ by the formula

$$\begin{aligned} g(\mathcal{F}) &= \text{the equivalence relation determined by } \mathcal{F} \\ &= \bigcup_{X \in \mathcal{F}} (X \times X). \end{aligned}$$

You should verify that the proof of Theorem 4.5.6 shows that $f \circ g = i_{\mathcal{P}}$, and exercise 10 in Section 4.5 shows that $g \circ f = i_{\mathcal{E}}$. Thus, f is one-to-one and onto, and $g = f^{-1}$. One interesting consequence of this is that if A has a finite number of elements, then we can say that the number of equivalence relations on A is exactly the same as the number of partitions of A , even though we don't know what this number is.

Exercises

- *1. Let R be the function defined in exercise 2(c) of Section 5.1. In exercise 2 of Section 5.2, you showed that R is one-to-one and onto, so $R^{-1} : P \rightarrow P$. If $p \in P$, what is $R^{-1}(p)$?
2. Let F be the function defined in exercise 4(b) of Section 5.1. In exercise 4 of Section 5.2, you showed that F is one-to-one and onto, so $F^{-1} : B \rightarrow B$. If $X \in B$, what is $F^{-1}(X)$?
- *3. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula

$$f(x) = \frac{2x + 5}{3}.$$

Show that f is one-to-one and onto, and find a formula for $f^{-1}(x)$. (You may want to imitate the method used in the example after Theorem 5.3.2, or in Example 5.3.6.)

4. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = 2x^3 - 3$. Show that f is one-to-one and onto, and find a formula for $f^{-1}(x)$.
- *5. Let $f : \mathbb{R} \rightarrow \mathbb{R}^+$ be defined by the formula $f(x) = 10^{2-x}$. Show that f is one-to-one and onto, and find a formula for $f^{-1}(x)$.
6. Let $A = \mathbb{R} \setminus \{2\}$, and let f be the function with domain A defined by the formula

$$f(x) = \frac{3x}{x - 2}.$$

- (a) Show that f is a one-to-one, onto function from A to B for some set $B \subseteq \mathbb{R}$. What is the set B ?
- (b) Find a formula for $f^{-1}(x)$.
7. In the example after Theorem 5.3.4, we had $f(x) = (x + 7)/5$ and found that $f^{-1}(x) = 5x - 7$. Let f_1 and f_2 be functions from \mathbb{R} to \mathbb{R} defined by the formulas

$$f_1(x) = x + 7, \quad f_2(x) = \frac{x}{5}.$$

- (a) Show that $f = f_2 \circ f_1$.
- (b) According to part 5 of Theorem 4.2.5, $f^{-1} = (f_2 \circ f_1)^{-1} = f_1^{-1} \circ f_2^{-1}$. Verify that this is true by computing $f_1^{-1} \circ f_2^{-1}$ directly.
8. (a) Prove the second half of Theorem 5.3.2 by imitating the proof of the first half.
- (b) Give an alternative proof of the second half of Theorem 5.3.2 by applying the first half to f^{-1} .
- *9. Prove part 2 of Theorem 5.3.3.

10. Use the following strategy to give an alternative proof of Theorem 5.3.5: Let (b, a) be an arbitrary element of $B \times A$. Assume $(b, a) \in g$ and prove $(b, a) \in f^{-1}$. Then assume $(b, a) \in f^{-1}$ and prove $(b, a) \in g$.
- *11. Suppose $f : A \rightarrow B$ and $g : B \rightarrow A$.
- Prove that if f is one-to-one and $f \circ g = i_B$, then $g = f^{-1}$.
 - Prove that if f is onto and $g \circ f = i_A$, then $g = f^{-1}$.
 - Prove that if $f \circ g = i_B$ but $g \circ f \neq i_A$, then f is onto but not one-to-one, and g is one-to-one but not onto.
12. Suppose $f : A \rightarrow B$ and f is one-to-one. Prove that there is some set $B^\pm \subseteq B$ such that $f^{-1} : B^\pm \rightarrow A$.
13. Suppose $f : A \rightarrow B$ and f is onto. Let $R = \{(x, y) \in A \times A \mid f(x) = f(y)\}$. By exercise 20(a) of Section 5.1, R is an equivalence relation on A .
- Prove that there is a function $h : A/R \rightarrow B$ such that for all $x \in A$, $h([x]_R) = f(x)$. (Hint: See exercise 21 of Section 5.1.)
 - Prove that h is one-to-one and onto. (Hint: See exercise 19 of Section 5.2.)
 - It follows from part (b) that $h^{-1} : B \rightarrow A/R$. Prove that for all $b \in B$, $h^{-1}(b) = \{x \in A \mid f(x) = b\}$.
 - Suppose $g : B \rightarrow A$. Prove that $f \circ g = i_B$ iff $\forall b \in B (g(b) \in h^{-1}(b))$.
- *14. Suppose $f : A \rightarrow B$, $g : B \rightarrow A$, and $f \circ g = i_B$. Let $A^\pm = \text{Ran}(g) \subseteq A$.
- Prove that for all $x \in A^\pm$, $(g \circ f)(x) = x$.
 - Prove that $f \upharpoonright A^\pm$ is a one-to-one, onto function from A^\pm to B and $g = (f \upharpoonright A^\pm)^{-1}$. (See exercise 7 of Section 5.1 for the meaning of the notation used here.)
15. Let $B = \{x \in \mathbb{R} \mid x \geq 0\}$. Let $f : \mathbb{R} \rightarrow B$ and $g : B \rightarrow \mathbb{R}$ be defined by the formulas $f(x) = x^2$ and $g(x) = \sqrt{x}$. As we saw in part 2 of Example 5.3.6, $g \neq f^{-1}$. Show that $g = (f \upharpoonright B)^{-1}$. (Hint: See exercise 14.)
- *16. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = 4x - x^2$. Let $B = \text{Ran}(f)$.
- Find B .
 - Find a set $A \subseteq \mathbb{R}$ such that $f \upharpoonright A$ is a one-to-one, onto function from A to B , and find a formula for $(f \upharpoonright A)^{-1}(x)$. (Hint: See exercise 14.)
17. Suppose A is a set, and let $\mathcal{F} = \{f \mid f : A \rightarrow A\}$ and $\mathcal{P} = \{f \in \mathcal{F} \mid f \text{ is one-to-one and onto}\}$. Define a relation R on \mathcal{F} as follows:

$$R = \{(f, g) \in \mathcal{F} \times \mathcal{F} \mid \exists h \in \mathcal{P}(f = h^{-1} \circ g \circ h)\}.$$

- (a) Prove that R is an equivalence relation.
- (b) Prove that if $f R g$ then $(f \circ f)R(g \circ g)$.
- (c) For any $f \in \mathcal{F}$ and $a \in A$, if $f(a) = a$ then we say that a is a *fixed point* of f . Prove that if f has a fixed point and $f R g$, then g also has a fixed point.
- *18. Suppose $f : A \rightarrow C$, $g : B \rightarrow C$, and g is one-to-one and onto. Prove that there is a function $h : A \rightarrow B$ such that $g \circ h = f$.

5.4. Closures

Often in mathematics we work with a function from a set to itself. In that situation, the following concept can be useful.

Definition 5.4.1. Suppose $f : A \rightarrow A$ and $C \subseteq A$. We will say that C is *closed under f* if $\forall x \in C (f(x) \in C)$.

Example 5.4.2.

- Let $A = \{a, b, c, d\}$ and $f = \{(a, c), (b, b), (c, d), (d, c)\}$. Then $f : A \rightarrow A$. Let $C_1 = \{a, c, d\}$ and $C_2 = \{a, b\}$. Is C_1 closed under f ? Is C_2 ?
- Let $f : \mathbb{R} \rightarrow \mathbb{R}$ and $g : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formulas $f(x) = x + 1$ and $g(x) = x - 1$. Is \mathbb{N} closed under f ? Is it closed under g ?
- Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = x^2$. Let $C_1 = \{x \in \mathbb{R} \mid 0 < x < 1\}$ and $C_2 = \{x \in \mathbb{R} \mid 0 < x < 2\}$. Is C_1 closed under f ? Is C_2 ?

Solutions

- The set C_1 is closed under f , because $f(a) = f(d) = c \in C_1$ and $f(c) = d \in C_1$. However, C_2 is not closed under f , because $a \in C_2$ but $f(a) = c \notin C_2$.
- For every natural number n , $n + 1$ is also a natural number, so \mathbb{N} is closed under f . However, \mathbb{N} is not closed under g , because $0 \in \mathbb{N}$ but $g(0) = -1 \notin \mathbb{N}$.
- For every real number x , if $0 < x < 1$ then $0 < x^2 < 1$ (see Example 3.1.2), so C_1 is closed under f . But $1.5 \in C_2$ and $f(1.5) = 1.5^2 = 2.25 \notin C_2$, so C_2 is not closed under f .

We saw in part 2 of Example 5.4.2 that \mathbb{N} is not closed under the function $g : \mathbb{R} \rightarrow \mathbb{R}$ defined by the formula $g(x) = x - 1$. Suppose we wanted to

add elements to \mathbb{N} to get a set that is closed under g . Since $0 \in \mathbb{N}$, we'd need to add $g(0) = -1$. But if -1 were added to the set, then it would also have to contain $g(-1) = -2$, and if we threw in -2 then we'd also have to add $g(-2) = -3$. Continuing in this way, it should be clear that we'd have to add all of the negative integers to \mathbb{N} , giving us the set of all integers, \mathbb{Z} . But notice that \mathbb{Z} is closed under g , because for every integer n , $n - 1$ is also an integer. So we have succeeded in our task of enlarging \mathbb{N} to get a set closed under g .

When we enlarged \mathbb{N} to \mathbb{Z} , the numbers we added – the negative integers – were numbers that *had* to be added if we wanted the resulting set to be closed under g . It follows that \mathbb{Z} is the smallest set containing \mathbb{N} that is closed under g . We are using the word *smallest* here in exactly the way we defined it in Section 4.4. If we let $\mathcal{F} = \{C \subseteq \mathbb{R} \mid \mathbb{N} \subseteq C \text{ and } C \text{ is closed under } g\}$, then \mathbb{Z} is the smallest element of \mathcal{F} , where as usual it is understood that we mean smallest in the sense of the subset partial order. In other words, \mathbb{Z} is an element of \mathcal{F} , and it's a subset of every element of \mathcal{F} . We will say that \mathbb{Z} is the *closure* of \mathbb{N} under g .

Definition 5.4.3. Suppose $f : A \rightarrow A$ and $B \subseteq A$. Then the *closure* of B under f is the smallest set $C \subseteq A$ such that $B \subseteq C$ and C is closed under f , if there is such a smallest set. In other words, a set $C \subseteq A$ is the closure of B under f if it has the following properties:

1. $B \subseteq C$.
2. C is closed under f .
3. For every set $D \subseteq A$, if $B \subseteq D$ and D is closed under f then $C \subseteq D$.

According to Theorem 4.4.6, if a set has a smallest element, then it can have only one smallest element. Thus, if a set B has a closure under a function f , then this closure must be unique, so it makes sense to call it *the* closure rather than *a* closure. However, as we saw in Example 4.4.7, some families of sets don't have smallest elements, so it is not immediately clear if sets always have closures under functions. In fact they do, as we will show in our proof of Theorem 5.4.5 below. But first let's look at a few more examples of closures.

Example 5.4.4.

1. In part 1 of Example 5.4.2, the set $C_2 = \{a, b\}$ was not closed under f . What is the closure of C_2 under f ?
2. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = x + 1$, and let $B = \{0\}$. What is the closure of B under f ?

Solutions

1. Since $a \in C_2$, to get a set closed under f we will need to add in $f(a) = c$. But then we'll also have to add $f(c) = d$, giving us the entire set $A = \{a, b, c, d\}$. Clearly A is closed under f , so the closure of C_2 under f is A .
2. Since $0 \in B$, the closure of B under f will have to contain $f(0) = 1$. But then it must also contain $f(1) = 2$, $f(2) = 3$, $f(3) = 4$, and in fact all positive integers. Adding all the positive integers to B gives us the set \mathbb{N} , which we already know from part 2 of Example 5.4.2 is closed under f . Thus the closure of $\{0\}$ under f is \mathbb{N} .

Here's an example that illustrates the usefulness of the concepts we have been discussing. Let P be a set of people, and suppose that each person in the set P has a best friend who is also in P . Then we can define a function $f : P \rightarrow P$ by let $f(p) = p$'s best friend. Suppose that whenever someone in the set P hears a piece of gossip, he or she tells it to his or her best friend (but no one else). Now consider any set $C \subseteq P$, and suppose that C is closed under f . Then for any person $p \in C$, p 's best friend is also in C . Thus, if any person in C hears a piece of gossip, the only person he or she will tell the gossip to is also in C . No one in C will ever transmit gossip to a person who is not in C . Thus, if we tell some people in C a bit of gossip, it may spread to other people in C , but it will never leave C . If you want to track the spread of gossip in this population, you should be interested in recognizing which subsets of P are closed under f .

Suppose we tell a piece of gossip to all of the people in some set $B \subseteq P$. How will the gossip spread? The people in B will tell their best friends, and then they will tell their best friends, who will tell their best friends, and so on. Based on our previous examples, you might guess that the set H of people who eventually hear the gossip will be the closure of B under f . Let's see if we can give a careful proof that H has the three properties listed in Definition 5.4.3.

Clearly $B \subseteq H$, since the people in B hear the gossip right at the start of the process. This confirms property 1 of Definition 5.4.3. If p is any element of H , then p eventually hears the gossip. But as soon as p hears the gossip, he or she will tell $f(p)$, so $f(p) \in H$ as well. Thus H is closed under f , as required by property 2 of the definition. Finally, suppose $B \subseteq C \subseteq P$ and C is closed under f . Then as we observed earlier, any gossip that is told to the people in B may spread to others in C , but it will never leave C . Thus, everyone who ever hears the gossip must belong to C , which means that $H \subseteq C$. This confirms property 3, so H is indeed the closure of B under f .

We turn now to the proof that closures always exist. Suppose $f : A \rightarrow A$ and $B \subseteq A$. One way to try to prove the existence of the closure of B under f is to add to B those elements that must be added to make it closed under f , as we did in earlier examples, and then prove that the result is closed under f . Although this can be done, a careful treatment of the details of this proof would require the method of mathematical induction, which we have not yet discussed. We will present this proof in Section 6.5, after we've discussed mathematical induction. But there is another approach to the proof that uses only ideas that we have already studied. We know that the closure of B under f , if it exists, must be the smallest element of the family $\mathcal{F} = \{C \subseteq A \mid B \subseteq C \text{ and } C \text{ is closed under } f\}$. According to exercise 20 of Section 4.4, the smallest element of a set is also always the greatest lower bound of the set, and by Theorem 4.4.11, the g.l.b. of any nonempty family of sets \mathcal{F} is $\bigcap \mathcal{F}$. This is the motivation for our next proof.

Theorem 5.4.5. *Suppose that $f : A \rightarrow A$ and $B \subseteq A$. Then B has a closure under f .*

Proof. Let $\mathcal{F} = \{C \subseteq A \mid B \subseteq C \text{ and } C \text{ is closed under } f\}$. You should be able to check that $A \in \mathcal{F}$, and therefore $\mathcal{F} \neq \emptyset$. Thus, we can let $C = \bigcap \mathcal{F}$, and by exercise 9 of Section 3.3, $C \subseteq A$. We will show that C is the closure of B under f by proving the three properties in Definition 5.4.3.

To prove the first property, suppose $x \in B$. Let D be an arbitrary element of \mathcal{F} . Then by the definition of \mathcal{F} , $B \subseteq D$, so $x \in D$. Since D was arbitrary, this shows that $\forall D \in \mathcal{F} (x \in D)$, so $x \in \bigcap \mathcal{F} = C$. Thus, $B \subseteq C$.

Next, suppose $x \in C$ and again let D be an arbitrary element of \mathcal{F} . Then since $x \in C = \bigcap \mathcal{F}$, $x \in D$. But since $D \in \mathcal{F}$, D is closed under f , so $f(x) \in D$. Since D was arbitrary, we can conclude that $\forall D \in \mathcal{F} (f(x) \in D)$, so $f(x) \in \bigcap \mathcal{F} = C$. Thus, we have shown that C is closed under f , which is the second property in Definition 5.4.3.

Finally, to prove the third property, suppose $B \subseteq D \subseteq A$ and D is closed under f . Then $D \in \mathcal{F}$, and applying exercise 9 of Section 3.3 again we can conclude that $C = \bigcap \mathcal{F} \subseteq D$. \square

Commentary. Our goal is $\exists C (C \text{ is the closure of } B \text{ under } f)$, so we should begin by defining C . However, the definition $C = \bigcap \mathcal{F}$ doesn't make sense unless we know $\mathcal{F} \neq \emptyset$, so we must prove this first. Because $\mathcal{F} \neq \emptyset$ means $\exists D (D \in \mathcal{F})$, we prove it by giving an example of an element of \mathcal{F} . The example is A , so we must prove $A \in \mathcal{F}$. The statement in the proof that "you should be able to check" that $A \in \mathcal{F}$ really does mean that you should do

the checking. According to the definition of \mathcal{F} , to say that $A \in \mathcal{F}$ means that $A \subseteq A$, $B \subseteq A$, and A is closed under f . You should make sure you see why all three of these statements are true.

Having defined C and verified that $C \subseteq A$, we must prove that C has the three properties in the definition of the closure of B under f . To prove the first statement, $B \subseteq C$, we let x be an arbitrary element of B and prove $x \in C$. Since $C = \bigcap \mathcal{F}$, the goal $x \in C$ means $\forall D \in \mathcal{F}(x \in D)$, so to prove it we let D be an arbitrary element of \mathcal{F} and prove $x \in D$. To prove that C is closed under f , we assume that $x \in C$ and prove $f(x) \in C$. Once again, by the definition of C this goal means $\forall D \in \mathcal{F}(f(x) \in D)$, so we let D be an arbitrary element of \mathcal{F} and prove $f(x) \in D$. Finally, to prove the third goal we assume that $D \subseteq A$, $B \subseteq D$, and D is closed under f and prove $C \subseteq D$. Fortunately, an exercise from an earlier section takes care of this proof.

Closed sets and closures also come up in the study of functions of more than one variable. If $f : A \times A \rightarrow A$, then f is called a *function of two variables*. An element of the domain of f would be an ordered pair (x, y) , where $x, y \in A$. The result of applying f to this pair should be written $f((x, y))$, but it is customary to leave out one pair of parentheses and just write $f(x, y)$.

Definition 5.4.6. Suppose $f : A \times A \rightarrow A$ and $C \subseteq A$. We will say that C is *closed under f* if $\forall x \in C \forall y \in C(f(x, y) \in C)$.

Example 5.4.7.

1. Let $f : \mathbb{R}^+ \times \mathbb{R}^+ \rightarrow \mathbb{R}^+$ and $g : \mathbb{R}^+ \times \mathbb{R}^+ \rightarrow \mathbb{R}^+$ be defined by the formulas $f(x, y) = x/y$ and $g(x, y) = x^y$. Is \mathbb{Q}^+ closed under f ? Is it closed under g ?
2. Let $f : \mathcal{P}(\mathbb{N}) \times \mathcal{P}(\mathbb{N}) \rightarrow \mathcal{P}(\mathbb{N})$ and $g : \mathcal{P}(\mathbb{N}) \times \mathcal{P}(\mathbb{N}) \rightarrow \mathcal{P}(\mathbb{N})$ be defined by the formulas $f(X, Y) = X \cup Y$ and $g(X, Y) = X \cap Y$. Let $\mathcal{I} = \{X \in \mathcal{P}(\mathbb{N}) \mid X \text{ is infinite}\}$. Is \mathcal{I} closed under f ? Is it closed under g ?

Solutions

1. If $x, y \in \mathbb{Q}^+$, then there are positive integers p, q, r , and s such that $x = p/q$ and $y = r/s$. Therefore

$$f(x, y) = \frac{x}{y} = \frac{p/q}{r/s} = \frac{p}{q} \cdot \frac{s}{r} = \frac{ps}{qr} \in \mathbb{Q}^+.$$

This shows that \mathbb{Q}^+ is closed under f . However, 2 and $1/2$ are elements of \mathbb{Q}^+ and $g(2, 1/2) = 2^{1/2} = \sqrt{2} \notin \mathbb{Q}^+$ (see Theorem 6.4.5), so \mathbb{Q}^+ is not closed under g .

2. If X and Y are infinite sets of natural numbers, then $f(X, Y) = X \cup Y$ is also infinite, so \mathcal{I} is closed under f . On the other hand, let E be the set of even natural numbers and let P be the set of prime numbers. Then E and P are both infinite, but $g(E, P) = E \cap P = \{2\}$, which is finite. Therefore \mathcal{I} is not closed under g .

As before, we can define the closure of a set under a function of two variables to be the smallest closed set containing it, and we can prove that such closures always exist.

Definition 5.4.8. Suppose $f : A \times A \rightarrow A$ and $B \subseteq A$. Then the *closure of B under f* is the smallest set $C \subseteq A$ such that $B \subseteq C$ and C is closed under f , if there is such a smallest set. In other words, a set $C \subseteq A$ is the closure of B under f if it has the following properties:

1. $B \subseteq C$.
2. C is closed under f .
3. For every set $D \subseteq A$, if $B \subseteq D$ and D is closed under f then $C \subseteq D$.

Theorem 5.4.9. Suppose that $f : A \times A \rightarrow A$ and $B \subseteq A$. Then B has a closure under f .

Proof. See exercise 11. □

A function from $A \times A$ to A could be thought of as an operation that can be applied to a pair of objects $(x, y) \in A \times A$ to produce another element of A . Often in mathematics an operation to be performed on a pair of mathematical objects (x, y) is represented by a symbol that we write between x and y . For example, if x and y are real numbers then $x + y$ denotes another number, and if x and y are sets then $x \cup y$ is another set. Imitating this notation, when mathematicians define a function from $A \times A$ to A they sometimes represent it with a symbol rather than a letter, and they write the result of applying the function to a pair (x, y) by putting the symbol between x and y , rather than by putting a letter before (x, y) . When a function from $A \times A$ to A is written in this way, it is usually called a *binary operation on A* .

For example, in part 2 of Example 5.4.7 we defined $g : \mathcal{P}(\mathbb{N}) \times \mathcal{P}(\mathbb{N}) \rightarrow \mathcal{P}(\mathbb{N})$ by the formula $g(X, Y) = X \cap Y$. Instead of introducing the name g for this function, we could have talked about \cap as a binary operation on $\mathcal{P}(\mathbb{N})$. We showed in the example that the set \mathcal{I} of all infinite subsets of \mathbb{N} is not closed under g . Another way to say this is that \mathcal{I} is not closed under the binary operation \cap . What is the closure of \mathcal{I} under \cap ? For the answer, see exercise 16.

Here's another example. We could define a binary operation $*$ on \mathbb{Z} by saying that for any integers x and y , $x * y = x^2 - y^2$. Is the set $\{0, 1\}$ closed under the binary operation $*$? The answer is no, because $0 * 1 = 0^2 - 1^2 = -1 \notin \{0, 1\}$. Thus, the closure of $\{0, 1\}$ under $*$ must include -1 . But as you can easily check, $\{-1, 0, 1\}$ is closed under $*$. Therefore the closure of $\{0, 1\}$ under $*$ is $\{-1, 0, 1\}$.

Exercises

- *1. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = (x + 1)/2$. Are the following sets closed under f ?
 - (a) \mathbb{Z} .
 - (b) \mathbb{Q} .
 - (c) $\{x \in \mathbb{R} \mid 0 \leq x < 4\}$.
 - (d) $\{x \in \mathbb{R} \mid 2 \leq x < 4\}$.
2. Let $f : \mathcal{P}(\mathbb{N}) \rightarrow \mathcal{P}(\mathbb{N})$ be defined by the formula $f(X) = X \cup \{17\}$. Are the following sets closed under f ?
 - (a) $\{X \subseteq \mathbb{N} \mid X \text{ is infinite}\}$.
 - (b) $\{X \subseteq \mathbb{N} \mid X \text{ is finite}\}$.
 - (c) $\{X \subseteq \mathbb{N} \mid X \text{ has at most 100 elements}\}$.
 - (d) $\{X \subseteq \mathbb{N} \mid 16 \in X\}$.
- *3. Let $f : \mathbb{Z} \rightarrow \mathbb{Z}$ be defined by the formula $f(n) = n^2 - n$. Find the closure of $\{-1, 1\}$ under f .
4. For any set A , the set of all relations on A is $\mathcal{P}(A \times A)$. Let $f : \mathcal{P}(A \times A) \rightarrow \mathcal{P}(A \times A)$ be defined by the formula $f(R) = R^{-1}$. Is the set of reflexive relations on A closed under f ? What about the set of symmetric relations and the set of transitive relations? (Hint: See exercise 12 of Section 4.3.)
5. Suppose $f : A \rightarrow A$. Is \emptyset closed under f ?
6. Suppose $f : A \rightarrow A$.
 - (a) Prove that if $\text{Ran}(f) \subseteq C \subseteq A$ then C is closed under f .
 - (b) Prove that for every set $B \subseteq A$, the closure of B under f is a subset of $B \cup \text{Ran}(f)$.
- *7. Suppose $f : A \rightarrow A$ and f is one-to-one and onto. Then by Theorem 5.3.1, $f^{-1} : A \rightarrow A$. Prove that if $C \subseteq A$ and C is closed under f , then $A \setminus C$ is closed under f^{-1} .
8. Suppose $f : A \rightarrow A$ and $C \subseteq A$. Prove that C is closed under f iff the closure of C under f is C .

- *9. Suppose $f : A \rightarrow A$ and C_1 and C_2 are subsets of A that are closed under f .
- Prove that $C_1 \cup C_2$ is closed under f .
 - Must $C_1 \cap C_2$ be closed under f ? Justify your answer.
 - Must $C_1 \setminus C_2$ be closed under f ? Justify your answer.
10. Suppose $f : A \rightarrow A$, $B_1 \subseteq A$, and $B_2 \subseteq A$. Let C_1 be the closure of B_1 under f , and let C_2 be the closure of B_2 .
- Prove that if $B_1 \subseteq B_2$ then $C_1 \subseteq C_2$.
 - Prove that the closure of $B_1 \cup B_2$ under f is $C_1 \cup C_2$.
 - Must the closure of $B_1 \cap B_2$ be $C_1 \cap C_2$? Justify your answer.
 - Must the closure of $B_1 \setminus B_2$ be $C_1 \setminus C_2$? Justify your answer.
11. Prove Theorem 5.4.9.
- *12. If \mathcal{F} is a set of functions from A to A and $C \subseteq A$, then we will say that C is *closed under \mathcal{F}* if $\forall f \in \mathcal{F} \forall x \in C (f(x) \in C)$. In other words, C is closed under \mathcal{F} iff for all $f \in \mathcal{F}$, C is closed under f . If $B \subseteq A$, then the *closure* of B under \mathcal{F} is the smallest set $C \subseteq A$ such that $B \subseteq C$ and C is closed under \mathcal{F} . (You are asked to prove in the next exercise that the closure always exists.)
- Let f and g be the functions from \mathbb{R} to \mathbb{R} defined by the formulas $f(x) = x + 1$ and $g(x) = x - 1$. Find the closure of $\{0\}$ under $\{f, g\}$.
 - For each natural number n , let $f_n : \mathcal{P}(\mathbb{N}) \rightarrow \mathcal{P}(\mathbb{N})$ be defined by the formula $f_n(X) = X \cup \{n\}$, and let $\mathcal{F} = \{f_n \mid n \in \mathbb{N}\}$. Find the closure of $\{\emptyset\}$ under \mathcal{F} .
13. Suppose \mathcal{F} is a set of functions from A to A and $B \subseteq A$. See the previous exercise for the definition of the closure of B under \mathcal{F} .
- Prove that B has a closure under \mathcal{F} .
For each $f \in \mathcal{F}$, let C_f be the closure of B under f , and let C be the closure of B under \mathcal{F} .
 - Prove that $\bigcup_{f \in \mathcal{F}} C_f \subseteq C$.
 - Must $\bigcup_{f \in \mathcal{F}} C_f$ be closed under \mathcal{F} ? Justify your answer with either a proof or a counterexample.
 - Must $\bigcup_{f \in \mathcal{F}} C_f = C$? Justify your answer with either a proof or a counterexample.
- *14. Let $f : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x, y) = x - y$. What is the closure of \mathbb{N} under f ?
15. Let $f : \mathbb{R}^+ \times \mathbb{R}^+ \rightarrow \mathbb{R}^+$ be defined by the formula $f(x, y) = x/y$. What is the closure of \mathbb{Z}^+ under f ?
16. As in part 2 of Example 5.4.7, let $\mathcal{I} = \{X \in \mathcal{P}(\mathbb{N}) \mid X \text{ is infinite}\}$.
- Prove that for every set $X \subseteq \mathbb{N}$ there are sets $Y, Z \in \mathcal{I}$ such that $Y \cap Z = X$.

- (b) What is the closure of \mathcal{I} under the binary operation \cap ?
- *17. Let $\mathcal{F} = \{f \mid f : \mathbb{R} \rightarrow \mathbb{R}\}$. Then for any $f, g \in \mathcal{F}$, $f \circ g \in \mathcal{F}$, so \circ is a binary operation on \mathcal{F} . Are the following sets closed under \circ ?
- $\{f \in \mathcal{F} \mid f \text{ is one-to-one}\}$. (Hint: See Theorem 5.2.5.)
 - $\{f \in \mathcal{F} \mid f \text{ is onto}\}$.
 - $\{f \in \mathcal{F} \mid f \text{ is strictly increasing}\}$. (A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is *strictly increasing* if $\forall x \in \mathbb{R} \forall y \in \mathbb{R} (x < y \rightarrow f(x) < f(y))$.)
 - $\{f \in \mathcal{F} \mid f \text{ is strictly decreasing}\}$. (A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is *strictly decreasing* if $\forall x \in \mathbb{R} \forall y \in \mathbb{R} (x < y \rightarrow f(x) > f(y))$.)
18. Let $\mathcal{F} = \{f \mid f : \mathbb{R} \rightarrow \mathbb{R}\}$. If $f, g \in \mathcal{F}$, then we define the function $f + g : \mathbb{R} \rightarrow \mathbb{R}$ by the formula $(f + g)(x) = f(x) + g(x)$. Note that $+$ is a binary operation on \mathcal{F} . Are the following sets closed under $+$?
- $\{f \in \mathcal{F} \mid f \text{ is one-to-one}\}$.
 - $\{f \in \mathcal{F} \mid f \text{ is onto}\}$.
 - $\{f \in \mathcal{F} \mid f \text{ is strictly increasing}\}$. (See the previous exercise for the definition of strictly increasing.)
 - $\{f \in \mathcal{F} \mid f \text{ is strictly decreasing}\}$. (See the previous exercise for the definition of strictly decreasing.)
19. For any set A , the set of all relations on A is $\mathcal{P}(A \times A)$, and \circ is a binary operation on $\mathcal{P}(A \times A)$. Is the set of reflexive relations on A closed under \circ ? What about the set of symmetric relations and the set of transitive relations?
- *20. Division is not a binary operation on \mathbb{R} , because you can't divide by 0. But we can fix this problem. We begin by adding a new element to \mathbb{R} . We will call the new element "NaN" (for "Not a Number"). Let $\overline{\mathbb{R}} = \mathbb{R} \cup \{\text{NaN}\}$, and define $f : \overline{\mathbb{R}} \times \overline{\mathbb{R}} \rightarrow \overline{\mathbb{R}}$ as follows:

$$f(x, y) = \begin{cases} x/y, & \text{if } x, y \in \mathbb{R} \text{ and } y \neq 0, \\ \text{NaN}, & \text{otherwise.} \end{cases}$$

This notation means that if $x, y \in \mathbb{R}$ and $y \neq 0$ then $f(x, y) = x/y$, and otherwise $f(x, y) = \text{NaN}$. Thus, for example, $f(3, 7) = 3/7$, $f(3, 0) = \text{NaN}$, and $f(\text{NaN}, 7) = \text{NaN}$. Which of the following sets are closed under f ?

- \mathbb{R} .
- \mathbb{R}^+ .
- \mathbb{R}^- .
- \mathbb{Q} .
- $\mathbb{Q} \cup \{\text{NaN}\}$.

21. If \mathcal{F} is a set of functions from $A \times A$ to A and $C \subseteq A$, then we will say that C is *closed under \mathcal{F}* if $\forall f \in \mathcal{F} \forall x \in C \forall y \in C (f(x, y) \in C)$. In other words, C is closed under \mathcal{F} iff for all $f \in \mathcal{F}$, C is closed under f . If $B \subseteq A$, then the *closure* of B under \mathcal{F} is the smallest set $C \subseteq A$ such that $B \subseteq C$ and C is closed under \mathcal{F} , if there is such a smallest set. (Compare these definitions to the definitions in exercise 12.)
- (a) Prove that the closure of B under \mathcal{F} exists.
- (b) Let $f : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ and $g : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formulas $f(x, y) = x + y$ and $g(x, y) = \sqrt{xy}$. Prove that the closure of $\mathbb{Q} \cup \{\sqrt{2}\}$ under $\{f, g\}$ is the set $\{a + b\sqrt{2} \mid a, b \in \mathbb{Q}\}$. (This set is called \mathbb{Q} with $\sqrt{2}$ adjoined, and is denoted $\mathbb{Q}(\sqrt{2})$.)
- (c) With f and g defined as in part (b), what is the closure of $\mathbb{Q} \cup \{\sqrt[3]{2}\}$ under $\{f, g\}$?

5.5. Images and Inverse Images: A Research Project

Suppose $f : A \rightarrow B$. We have already seen that we can think of f as matching each element of A with exactly one element of B . In this section we will see that f can also be thought of as matching *subsets* of A with subsets of B and vice-versa.

Definition 5.5.1. Suppose $f : A \rightarrow B$ and $X \subseteq A$. Then the *image* of X under f is the set $f(X)$ defined as follows:

$$\begin{aligned} f(X) &= \{f(x) \mid x \in X\} \\ &= \{b \in B \mid \exists x \in X (f(x) = b)\}. \end{aligned}$$

(Note that the image of the whole domain A under f is $\{f(a) \mid a \in A\}$, and as we saw in Section 5.1 this is the same as the range of f .)

If $Y \subseteq B$, then the *inverse image* of Y under f is the set $f^{-1}(Y)$ defined as follows:

$$f^{-1}(Y) = \{a \in A \mid f(a) \in Y\}.$$

Note that the function f in Definition 5.5.1 may fail to be one-to-one or onto, and as a result f^{-1} may not be a function from B to A , and for $y \in B$, the notation " $f^{-1}(y)$ " may be meaningless. However, even in this case Definition 5.5.1 still assigns a meaning to the notation " $f^{-1}(Y)$ " for $Y \subseteq B$. If you find this surprising, look again at the definition of $f^{-1}(Y)$, and notice that it does

not treat f^{-1} as a function. The definition refers only to the results of applying f to elements of A , not the results of applying f^{-1} to elements of B .

For example, let L be the function defined in part 3 of Example 5.1.2, which assigns to each city the country in which that city is located. As in Example 5.1.2, let C be the set of all cities and N the set of all countries. If B is the set of all cities with population at least one million, then B is a subset of C , and the image of B under L would be the set

$$\begin{aligned} L(B) &= \{L(b) \mid b \in B\} \\ &= \{n \in N \mid \exists b \in B(L(b) = n)\} \\ &= \{n \in N \mid \text{there is some city with population at least} \\ &\quad \text{one million that is located in the country } n\}. \end{aligned}$$

Thus, $L(B)$ is the set of all countries that contain a city with population at least one million. Now let A be the subset of N consisting of all countries in Africa. Then the inverse image of A under L is the set

$$\begin{aligned} L^{-1}(A) &= \{c \in C \mid L(c) \in A\} \\ &= \{c \in C \mid \text{the country in which } c \text{ is located is in Africa}\}. \end{aligned}$$

Thus, $L^{-1}(A)$ is the set of all cities in African countries.

Let's do one more example. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = x^2$, and let $X = \{x \in \mathbb{R} \mid 0 \leq x < 2\}$. Then

$$f(X) = \{f(x) \mid x \in X\} = \{x^2 \mid 0 \leq x < 2\}.$$

Thus, $f(X)$ is the set of all squares of real numbers between 0 and 2 (including 0 but not 2). A moment's reflection should convince you that this set is $\{x \in \mathbb{R} \mid 0 \leq x < 4\}$. Now let's let $Y = \{x \in \mathbb{R} \mid 0 \leq x < 4\}$ and compute $f^{-1}(Y)$. According to the definition of inverse image,

$$\begin{aligned} f^{-1}(Y) &= \{x \in \mathbb{R} \mid f(x) \in Y\} \\ &= \{x \in \mathbb{R} \mid 0 \leq f(x) < 4\} \\ &= \{x \in \mathbb{R} \mid 0 \leq x^2 < 4\} \\ &= \{x \in \mathbb{R} \mid -2 < x < 2\}. \end{aligned}$$

By now you have had enough experience writing proofs that you should be ready to put your proof-writing skills to work in answering mathematical questions. Thus, most of this section will be devoted to a research project in which you will discover for yourself the answers to basic mathematical questions about images and inverse images. To get you started, we'll work out the answer to the first question.

Suppose $f : A \rightarrow B$, and W and X are subsets of A . A natural question you might ask is whether or not $f(W \cap X)$ must be the same as $f(W) \cap f(X)$. It seems plausible that the answer is yes, so let's see if we can prove it. Thus, our goal will be to prove that $f(W \cap X) = f(W) \cap f(X)$. Because this is an equation between two sets, we proceed by taking an arbitrary element of each set and trying to prove that it is an element of the other.

Suppose first that y is an arbitrary element of $f(W \cap X)$. By the definition of $f(W \cap X)$, this means that $y = f(x)$ for some $x \in W \cap X$. Since $x \in W \cap X$, it follows that $x \in W$ and $x \in X$. But now we have $y = f(x)$ and $x \in W$, so we can conclude that $y \in f(W)$. Similarly, since $y = f(x)$ and $x \in X$, it follows that $y \in f(X)$. Thus, $y \in f(W) \cap f(X)$. This completes the first half of the proof.

Now suppose that $y \in f(W) \cap f(X)$. Then $y \in f(W)$, so there is some $w \in W$ such that $f(w) = y$, and also $y \in f(X)$, so there is some $x \in X$ such that $y = f(x)$. If only we knew that w and x were equal, we could conclude that $w = x \in W \cap X$, so $y = f(x) \in f(W \cap X)$. But the best we can do is to say that $f(w) = y = f(x)$. This should remind you of the definition of one-to-one. If we knew that f was one-to-one, we could conclude from the fact that $f(w) = f(x)$ that $w = x$, and the proof would be done. But without this information we seem to be stuck.

Let's summarize what we've discovered. First of all, the first half of the proof worked fine, so we can certainly say that in general $f(W \cap X) \subseteq f(W) \cap f(X)$. The second half worked *if* we knew that f was one-to-one, so we can also say that if f is one-to-one, then $f(W \cap X) = f(W) \cap f(X)$. But what if f isn't one-to-one? There might be some way of fixing up the proof to show that the equation $f(W \cap X) = f(W) \cap f(X)$ is still true even if f isn't one-to-one. But by now you have probably come to suspect that perhaps $f(W \cap X)$ and $f(W) \cap f(X)$ are not always equal, so maybe we should devote some time to trying to show that the proposed theorem is incorrect. In other words, let's see if we can find a counterexample – an example of a function f and sets W and X for which $f(W \cap X) \not\subseteq f(W) \cap f(X)$.

Fortunately, we can do better than just trying examples at random. Of course, we know we'd better use a function that isn't one-to-one, but by examining our attempt at a proof, we can tell more than that. The attempted proof that $f(W \cap X) = f(W) \cap f(X)$ ran into trouble only when W and X contained elements w and x such that $w \neq x$ but $f(w) = f(x)$, so we should choose an example in which this happens. In other words, not only should we make sure f isn't one-to-one, we should also make sure W and X contain elements that *show* that f isn't one-to-one.

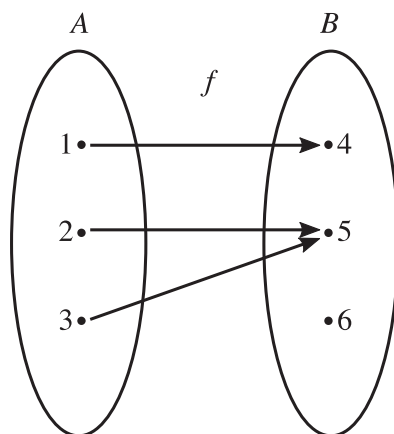


Figure 5.6.

The graph in Figure 5.6 shows a simple function that isn't one-to-one. Writing it as a set of ordered pairs, we could say $f = \{(1, 4), (2, 5), (3, 5)\}$ and $f : A \rightarrow B$, where $A = \{1, 2, 3\}$ and $B = \{4, 5, 6\}$. The two elements of A that show that f is not one-to-one are 2 and 3, so these should be elements of W and X , respectively. Why not just try letting $W = \{2\}$ and $X = \{3\}$? With these choices we get $f(W) = \{f(2)\} = \{5\}$ and $f(X) = \{f(3)\} = \{5\}$, so $f(W) \cap f(X) = \{5\} \cap \{5\} = \{5\}$. But $f(W \cap X) = f(\emptyset) = \emptyset$, so $f(W \cap X) \neq f(W) \cap f(X)$. (If you're not sure why $f(\emptyset) = \emptyset$, work it out using Definition 5.5.1!) If you want to see an example in which $W \cap X \neq \emptyset$, try $W = \{1, 2\}$ and $X = \{1, 3\}$.

This example shows that it would be incorrect to state a theorem saying that $f(W \cap X)$ and $f(W) \cap f(X)$ are always equal. But our proof shows that the following theorem is correct:

Theorem 5.5.2. *Suppose $f : A \rightarrow B$, and W and X are subsets of A . Then $f(W \cap X) \subseteq f(W) \cap f(X)$. Furthermore, if f is one-to-one, then $f(W \cap X) = f(W) \cap f(X)$.*

Now, here are some questions for you to try to answer. In each case, try to figure out as much as you can. Justify your answers with proofs and counterexamples.

1. Suppose $f : A \rightarrow B$ and W and X are subsets of A .
 - (a) Will it always be true that $f(W \cup X) = f(W) \cup f(X)$?
 - (b) Will it always be true that $f(W \setminus X) = f(W) \setminus f(X)$?
 - (c) Will it always be true that $W \subseteq X \leftrightarrow f(W) \subseteq f(X)$?

2. Suppose $f : A \rightarrow B$ and Y and Z are subsets of B .
 - (a) Will it always be true that $f^{-1}(Y \cap Z) = f^{-1}(Y) \cap f^{-1}(Z)$?
 - (b) Will it always be true that $f^{-1}(Y \cup Z) = f^{-1}(Y) \cup f^{-1}(Z)$?
 - (c) Will it always be true that $f^{-1}(Y \setminus Z) = f^{-1}(Y) \setminus f^{-1}(Z)$?
 - (d) Will it always be true that $Y \subseteq Z \leftrightarrow f^{-1}(Y) \subseteq f^{-1}(Z)$?
3. Suppose $f : A \rightarrow B$ and $X \subseteq A$. Will it always be true that $f^{-1}(f(X)) = X$?
4. Suppose $f : A \rightarrow B$ and $Y \subseteq B$. Will it always be true that $f(f^{-1}(Y)) = Y$?
5. Suppose $f : A \rightarrow A$ and $C \subseteq A$. Prove that the following statements are equivalent:
 - (a) C is closed under f .
 - (b) $f(C) \subseteq C$.
 - (c) $C \subseteq f^{-1}(C)$.
6. Suppose $f : A \rightarrow B$ and $g : B \rightarrow C$. Can you prove any interesting theorems about images and inverse images of sets under $g \circ f$?

Note: An observant reader may have noticed an ambiguity in our notation for images and inverse images. If $f : A \rightarrow B$ and $Y \subseteq B$, then we have used the notation $f^{-1}(Y)$ to stand for the inverse image of Y under f . But if f is one-to-one and onto, then, as we saw in Section 5.3, f^{-1} is a function from B to A . Thus, $f^{-1}(Y)$ could also be interpreted as the image of Y under the function f^{-1} . Fortunately, this ambiguity is harmless, as the next problem shows.

7. Suppose $f : A \rightarrow B$, f is one-to-one and onto, and $Y \subseteq B$. Show that the inverse image of Y under f and the image of Y under f^{-1} are equal. (Hint: First write out the definitions of the two sets carefully!)

6

Mathematical Induction

6.1. Proof by Mathematical Induction

In Chapter 3 we studied proof techniques that could be used in reasoning about any mathematical topic. In this chapter we'll discuss one more proof technique, called *mathematical induction*, that is designed for proving statements about what is perhaps the most fundamental of all mathematical structures, the natural numbers. Recall that the set of all natural numbers is $\mathbb{N} = \{0, 1, 2, 3, \dots\}$.

Suppose you want to prove that every natural number has some property P . In other words, you want to show that $0, 1, 2, \dots$ all have the property P . Of course, there are infinitely many numbers in this list, so you can't check one-by-one that they all have property P . The key idea behind mathematical induction is that to list all the natural numbers all you have to do is start with 0 and repeatedly add 1. Thus, you can show that every natural number has the property P by showing that 0 has property P , and that whenever you add 1 to a number that has property P , the resulting number also has property P . This would guarantee that, as you go through the list of all natural numbers, starting with 0 and repeatedly adding 1, every number you encounter must have property P . In other words, all natural numbers have property P . Here, then, is how the method of mathematical induction works.

To prove a goal of the form $\forall n \in \mathbb{N} P(n)$:

First prove $P(0)$, and then prove $\forall n \in \mathbb{N} (P(n) \rightarrow P(n+1))$. The first of these proofs is sometimes called the *base case* and the second the *induction step*.

Form of final proof:

Base case: [Proof of $P(0)$ goes here.]

Induction step: [Proof of $\forall n \in \mathbb{N} (P(n) \rightarrow P(n+1))$ goes here.]

We'll say more about the justification of the method of mathematical induction later, but first let's look at an example of a proof that uses mathematical induction. The following list of calculations suggests a surprising pattern:

$$\begin{aligned}2^0 &= 1 = 2^1 - 1 \\2^0 + 2^1 &= 1 + 2 = 3 = 2^2 - 1 \\2^0 + 2^1 + 2^2 &= 1 + 2 + 4 = 7 = 2^3 - 1 \\2^0 + 2^1 + 2^2 + 2^3 &= 1 + 2 + 4 + 8 = 15 = 2^4 - 1\end{aligned}$$

The general pattern appears to be:

$$2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1.$$

Will this pattern hold for all values of n ? Let's see if we can prove it.

Example 6.1.1. Prove that for every natural number n , $2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$.

Scratch work

Our goal is to prove the statement $\forall n \in \mathbb{N} P(n)$, where $P(n)$ is the statement $2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$. According to our strategy, we can do this by proving two other statements, $P(0)$ and $\forall n \in \mathbb{N}(P(n) \rightarrow P(n+1))$.

Plugging in 0 for n , we see that $P(0)$ is simply the statement $2^0 = 2^1 - 1$, the first statement in our list of calculations. The proof of this is easy – just do the arithmetic to verify that both sides are equal to 1. Often the base case of an induction proof is very easy, and the only hard work in figuring out the proof is in carrying out the induction step.

For the induction step, we must prove $\forall n \in \mathbb{N}(P(n) \rightarrow P(n+1))$. Of course, all of the proof techniques discussed in Chapter 3 can be used in mathematical induction proofs, so we can do this by letting n be an arbitrary natural number, assuming that $P(n)$ is true, and then proving that $P(n+1)$ is true. In other words, we'll let n be an arbitrary natural number, assume that $2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$, and then prove that $2^0 + 2^1 + \cdots + 2^{n+1} = 2^{n+2} - 1$. This gives us the following givens and goal:

<i>Givens</i>	<i>Goal</i>
$n \in \mathbb{N}$	$2^0 + 2^1 + \cdots + 2^{n+1} = 2^{n+2} - 1$
$2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$	

Clearly the second given is similar to the goal. Is there some way to start with the second given and derive the goal using algebraic steps? The key to the

proof is to recognize that the left side of the equation in the goal is exactly the same as the left side of the second given, but with the extra term 2^{n+1} added on. So let's try adding 2^{n+1} to both sides of the second given. This gives us

$$(2^0 + 2^1 + \cdots + 2^n) + 2^{n+1} = (2^{n+1} - 1) + 2^{n+1},$$

or in other words,

$$2^0 + 2^1 + \cdots + 2^{n+1} = 2 \cdot 2^{n+1} - 1 = 2^{n+2} - 1.$$

This is the goal, so we are done!

Solution

Theorem. For every natural number n , $2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$.

Proof. We use mathematical induction.

Base case: Setting $n = 0$, we get $2^0 = 1 = 2^1 - 1$ as required.

Induction step: Let n be an arbitrary natural number and suppose that $2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$. Then

$$\begin{aligned} 2^0 + 2^1 + \cdots + 2^{n+1} &= (2^0 + 2^1 + \cdots + 2^n) + 2^{n+1} \\ &= (2^{n+1} - 1) + 2^{n+1} \\ &= 2 \cdot 2^{n+1} - 1 \\ &= 2^{n+2} - 1. \end{aligned} \quad \square$$

Does the proof in Example 6.1.1 convince you that the equation $2^0 + 2^1 + \cdots + 2^n = 2^{n+1} - 1$, which we called $P(n)$ in our scratch work, is true for all natural numbers n ? Well, certainly $P(0)$ is true, since we checked that explicitly in the base case of the proof. In the induction step we showed that $\forall n \in \mathbb{N}(P(n) \rightarrow P(n+1))$, so we know that for every natural number n , $P(n) \rightarrow P(n+1)$. For example, plugging in $n = 0$ we can conclude that $P(0) \rightarrow P(1)$. But now we know that both $P(0)$ and $P(0) \rightarrow P(1)$ are true, so applying modus ponens we can conclude that $P(1)$ is true too. Similarly, plugging in $n = 1$ in the induction step we get $P(1) \rightarrow P(2)$, so applying modus ponens to the statements $P(1)$ and $P(1) \rightarrow P(2)$ we can conclude that $P(2)$ is true. Setting $n = 2$ in the induction step we get $P(2) \rightarrow P(3)$, so by modus ponens, $P(3)$ is true. Continuing in this way, you should be able to see that by repeatedly applying the induction step you can show that $P(n)$ must be true for every natural number n . In other words, the proof really does show that $\forall n \in \mathbb{N} P(n)$.

As we saw in the last example, the hardest part of a proof by mathematical induction is usually the induction step, in which you must prove the statement $\forall n \in \mathbb{N}(P(n) \rightarrow P(n+1))$. It is usually best to do this by letting n be an arbitrary natural number, assuming $P(n)$ is true, and then proving that $P(n+1)$ is true. The assumption that $P(n)$ is true is sometimes called the *inductive hypothesis*, and the key to the proof is usually to work out some relationship between the inductive hypothesis $P(n)$ and the goal $P(n+1)$.

Here's another example of a proof by mathematical induction.

Example 6.1.2. Prove that $\forall n \in \mathbb{N}(3 \mid (n^3 - n))$.

Scratch work

As usual, the base case is easy to check. The details are given in the following proof. For the induction step, we let n be an arbitrary natural number and assume that $3 \mid (n^3 - n)$, and we must prove that $3 \mid ((n+1)^3 - (n+1))$. Filling in the definition of *divides*, we can sum up our situation as follows:

<i>Givens</i>	<i>Goal</i>
$n \in \mathbb{N}$	$\exists j \in \mathbb{Z}(3j = (n+1)^3 - (n+1))$
$\exists k \in \mathbb{Z}(3k = n^3 - n)$	

The second given is the inductive hypothesis, and we need to figure out how it can be used to establish the goal.

According to our techniques for dealing with existential quantifiers in proofs, the best thing to do first is to use the second given and let k stand for a particular integer such that $3k = n^3 - n$. To complete the proof we'll need to find an integer j (which will probably be related to k in some way) such that $3j = (n+1)^3 - (n+1)$. We expand the right side of this equation, looking for some way to relate it to the given equation $3k = n^3 - n$:

$$\begin{aligned}
 (n+1)^3 - (n+1) &= n^3 + 3n^2 + 3n + 1 - n - 1 \\
 &= (n^3 - n) + 3n^2 + 3n \\
 &= 3k + 3n^2 + 3n \\
 &= 3(k + n^2 + n).
 \end{aligned}$$

It should now be clear that we can complete the proof by letting $j = k + n^2 + n$. As in similar earlier proofs, we don't bother to mention j in the proof.

Solution

Theorem. For every natural number n , $3 \mid (n^3 - n)$.

Proof. We use mathematical induction.

Base case: If $n = 0$, then $n^3 - n = 0 = 3 \cdot 0$, so $3 \mid (n^3 - n)$.

Induction step: Let n be an arbitrary natural number and suppose $3 \mid (n^3 - n)$. Then we can choose an integer k such that $3k = n^3 - n$. Thus,

$$\begin{aligned}(n + 1)^3 - (n + 1) &= n^3 + 3n^2 + 3n + 1 - n - 1 \\ &= (n^3 - n) + 3n^2 + 3n \\ &= 3k + 3n^2 + 3n \\ &= 3(k + n^2 + n).\end{aligned}$$

Therefore $3 \mid ((n + 1)^3 - (n + 1))$, as required. \square

Once you understand why mathematical induction works, you should be able to understand proofs that involve small variations on the method of induction. The next example illustrates such a variation. In this example we'll try to figure out which is larger, n^2 or 2^n . Let's try out a few values of n :

n	n^2	2^n	Which is larger?
0	0	1	2^n
1	1	2	2^n
2	4	4	tie
3	9	8	n^2
4	16	16	tie
5	25	32	2^n
6	36	64	2^n

It's a close race at first, but starting with $n = 5$, it looks like 2^n is taking a decisive lead over n^2 . Can we prove that it will stay ahead for larger values of n ?

Example 6.1.3. Prove that $\forall n \geq 5 (2^n > n^2)$.

Scratch work

We are only interested in proving the inequality $2^n > n^2$ for $n \geq 5$. Thus, it would make no sense to use $n = 0$ in the base case of our induction proof. We'll take $n = 5$ as the base case for our induction rather than $n = 0$. Once we've checked that the inequality holds when $n = 5$, the induction step will show that the inequality must continue to hold if, starting with $n = 5$, we repeatedly add 1 to n . Thus, it must also hold for $n = 6, 7, 8, \dots$. In other words, we'll be able to conclude that the inequality holds for all $n \geq 5$.

The base case $n = 5$ has already been checked in the table. For the induction step, we let $n \geq 5$ be arbitrary, assume $2^n > n^2$, and try to prove that $2^{n+1} > (n+1)^2$. How can we relate the inductive hypothesis to the goal? Perhaps the simplest relationship involves the left sides of the two inequalities: $2^{n+1} = 2 \cdot 2^n$. Thus, multiplying both sides of the inductive hypothesis $2^n > n^2$ by 2, we can conclude that $2^{n+1} > 2n^2$. Now compare this inequality to the goal, $2^{n+1} > (n+1)^2$. If we could prove that $2n^2 \geq (n+1)^2$, then the goal would follow easily. So let's forget about the original goal and see if we can prove that $2n^2 \geq (n+1)^2$.

Multiplying out the right side of the new goal we see that we must prove that $2n^2 \geq n^2 + 2n + 1$, or in other words $n^2 \geq 2n + 1$. This isn't hard to prove: Since we've assumed that $n \geq 5$, it follows that $n^2 \geq 5n = 2n + 3n > 2n + 1$.

Solution

Theorem. For every natural number $n \geq 5$, $2^n > n^2$.

Proof. By mathematical induction.

Base case: When $n = 5$ we have $2^n = 32 > 25 = n^2$.

Induction step: Let $n \geq 5$ be arbitrary, and suppose that $2^n > n^2$. Then

$$\begin{aligned}
 2^{n+1} &= 2 \cdot 2^n \\
 &> 2n^2 && \text{(inductive hypothesis)} \\
 &= n^2 + n^2 \\
 &\geq n^2 + 5n && \text{(since } n \geq 5\text{)} \\
 &= n^2 + 2n + 3n \\
 &> n^2 + 2n + 1 = (n+1)^2. && \square
 \end{aligned}$$

Exercises

- *1. Prove that for all $n \in \mathbb{N}$, $0 + 1 + 2 + \cdots + n = n(n+1)/2$.
2. Prove that for all $n \in \mathbb{N}$, $0^2 + 1^2 + 2^2 + \cdots + n^2 = n(n+1)(2n+1)/6$.
- *3. Prove that for all $n \in \mathbb{N}$, $0^3 + 1^3 + 2^3 + \cdots + n^3 = [n(n+1)/2]^2$.
4. Find a formula for $1 + 3 + 5 + \cdots + (2n-1)$, for $n \geq 1$, and prove that your formula is correct. (Hint: First try some particular values of n and look for a pattern.)
5. Prove that for all $n \in \mathbb{N}$, $0 \cdot 1 + 1 \cdot 2 + 2 \cdot 3 + \cdots + n(n+1) = n(n+1)(n+2)/3$.

6. Find a formula for $0 \cdot 1 \cdot 2 + 1 \cdot 2 \cdot 3 + 2 \cdot 3 \cdot 4 + \cdots + n(n+1)(n+2)$, for $n \in \mathbb{N}$, and prove that your formula is correct. (Hint: Compare this exercise to exercises 1 and 5, and try to guess the formula.)
- *7. Find a formula for $3^0 + 3^1 + 3^2 + \cdots + 3^n$, for $n \geq 0$, and prove that your formula is correct. (Hint: Try to guess the formula, basing your guess on Example 6.1.1. Then try out some values of n and adjust your guess if necessary.)
8. Prove that for all $n \geq 1$,
- $$1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \cdots + \frac{1}{2n-1} - \frac{1}{2n} = \frac{1}{n+1} + \frac{1}{n+2} + \frac{1}{n+3} + \cdots + \frac{1}{2n}.$$
9. (a) Prove that for all $n \in \mathbb{N}$, $2 \mid (n^2 + n)$.
 (b) Prove that for all $n \in \mathbb{N}$, $6 \mid (n^3 - n)$.
- *10. Prove that for all $n \in \mathbb{N}$, $64 \mid (9^n - 8n - 1)$.
11. Prove that for all $n \in \mathbb{N}$, $9 \mid (4^n + 6n - 1)$.
- *12. (a) Prove that for all $n \in \mathbb{N}$, $7^n - 5^n$ is even.
 (b) Prove that for all $n \in \mathbb{N}$, $24 \mid (2 \cdot 7^n - 3 \cdot 5^n + 1)$.
13. Prove that for all integers a and b and all $n \in \mathbb{N}$, $(a - b) \mid (a^n - b^n)$. (Hint: Let a and b be arbitrary integers and then prove by induction that $\forall n \in \mathbb{N} [(a - b) \mid (a^n - b^n)]$. For the induction step, you must relate $a^{n+1} - b^{n+1}$ to $a^n - b^n$. You might find it useful to start by completing the following equation: $a^{n+1} - b^{n+1} = a(a^n - b^n) + \underline{\quad}$.)
14. Prove that for all integers a and b and all $n \in \mathbb{N}$, $(a + b) \mid (a^{2n+1} + b^{2n+1})$.
- *15. Prove that for all $n \geq 10$, $2^n > n^3$.
16. (a) Prove that for all $n \in \mathbb{N}$, either n is even or n is odd, but not both.
 (b) Prove that, as claimed in Section 3.4, every integer is either even or odd, but not both. (Hint: To prove that a negative integer n is even or odd, but not both, apply part (a) to $-n$.)
17. Prove that for all $n \geq 1$, $2 \cdot 2^1 + 3 \cdot 2^2 + 4 \cdot 2^3 + \cdots + (n+1)2^n = n2^{n+1}$.
18. (a) What's wrong with the following proof that for every $n \in \mathbb{N}$, $1 \cdot 3^0 + 3 \cdot 3^1 + 5 \cdot 3^2 + \cdots + (2n+1)3^n = n3^{n+1}$?

Proof. We use mathematical induction. Let n be an arbitrary natural number, and suppose $1 \cdot 3^0 + 3 \cdot 3^1 + 5 \cdot 3^2 + \cdots + (2n+1)3^n = n3^{n+1}$.

Then

$$\begin{aligned} 1 \cdot 3^0 + 3 \cdot 3^1 + 5 \cdot 3^2 + \cdots + (2n + 1)3^n + (2n + 3)3^{n+1} \\ &= n3^{n+1} + (2n + 3)3^{n+1} \\ &= (3n + 3)3^{n+1} \\ &= (n + 1)3^{n+2}, \end{aligned}$$

as required. \square

(b) Find a formula for $1 \cdot 3^0 + 3 \cdot 3^1 + 5 \cdot 3^2 + \cdots + (2n + 1)3^n$, and prove that your formula is correct.

19. Suppose a is a real number and $a < 0$. Prove that for all $n \in \mathbb{N}$, if n is even then $a^n > 0$, and if n is odd then $a^n < 0$.

*20. Suppose a and b are real numbers and $0 < a < b$.

(a) Prove that for all $n \geq 1$, $0 < a^n < b^n$. (Notice that this generalizes Example 3.1.2.)

(b) Prove that for all $n \geq 2$, $0 < \sqrt[n]{a} < \sqrt[n]{b}$.

(c) Prove that for all $n \geq 1$, $ab^n + ba^n < a^{n+1} + b^{n+1}$.

(d) Prove that for all $n \geq 2$,

$$\left(\frac{a+b}{2}\right)^n < \frac{a^n + b^n}{2}.$$

6.2. More Examples

We introduced mathematical induction in the last section as a method for proving that all natural numbers have some property. However, the applications of mathematical induction extend far beyond the study of the natural numbers. In this section we'll look at some examples of proofs by mathematical induction that illustrate the wide range of uses of induction.

Example 6.2.1. Suppose R is a partial order on a set A . Prove that every finite, nonempty set $B \subseteq A$ has an R -minimal element.

Scratch work

You might think at first that mathematical induction is not appropriate for this proof, because the goal doesn't seem to have the form $\forall n \in \mathbb{N} P(n)$. In fact, the goal doesn't explicitly mention natural numbers at all! But we can see that natural numbers enter into the problem when we recognize that to say that B is finite and nonempty means that it has n elements, for some $n \in \mathbb{N}$, $n \geq 1$.

(We'll give a more careful definition of the number of elements in a finite set in Chapter 8. For the moment, an intuitive understanding of this concept will suffice.) Thus, the goal means $\forall n \geq 1 \forall B \subseteq A (B \text{ has } n \text{ elements} \rightarrow B \text{ has a minimal element})$. We can now use induction to prove this statement.

In the base case we will have $n = 1$, so we must prove that if B has one element, then it has a minimal element. It is easy to check that in this case the one element of B must be minimal.

For the induction step we let $n \geq 1$ be arbitrary, assume that $\forall B \subseteq A (B \text{ has } n \text{ elements} \rightarrow B \text{ has a minimal element})$, and try to prove that $\forall B \subseteq A (B \text{ has } n + 1 \text{ elements} \rightarrow B \text{ has a minimal element})$. Guided by the form of the goal, we let B be an arbitrary subset of A , assume that B has $n + 1$ elements, and try to prove that B has a minimal element.

How can we use the inductive hypothesis to reach our goal? The inductive hypothesis tells us that if we had a subset of A with n elements, then it would have a minimal element. To apply it, we need to find a subset of A with n elements. Our arbitrary set B is a subset of A , and we have assumed that it has $n + 1$ elements. Thus, a simple way to produce a subset of A with n elements would be to remove one element from B . It is not clear where this reasoning will lead, but it seems to be the simplest way to make use of the inductive hypothesis. Let's give it a try.

Let b be any element of B , and let $B^\pm = B \setminus \{b\}$. Then B^\pm is a subset of A with n elements, so by the inductive hypothesis, B^\pm has a minimal element. This is an existential statement, so we immediately introduce a new variable, say c , to stand for a minimal element of B^\pm .

Our goal is to prove that B has a minimal element, which is also an existential statement, so we should try to come up with a minimal element of B . We only know about two elements of B at this point, b and c , so we should probably try to prove that one of these is a minimal element of B . Which one? Well, it may depend on whether one of them is smaller than the other according to the partial order R . This suggests that we may need to use proof by cases. In our proof we use the cases bRc and $\neg bRc$. In the first case we prove that b is a minimal element of B , and in the second case we prove that c is a minimal element of B . Note that to say that something is a minimal element of B is a negative statement, so in both cases we use proof by contradiction.

Solution

Theorem. *Suppose R is a partial order on a set A . Then every finite, nonempty set $B \subseteq A$ has an R -minimal element.*

Proof. We will show by induction that for every natural number $n \geq 1$, every subset of A with n elements has a minimal element.

Base case: $n = 1$. Suppose $B \subseteq A$ and B has one element. Then $B = \{b\}$ for some $b \in A$. Clearly $\neg \exists x \in B(x \not\approx b)$, so certainly $\neg \exists x \in B(xRb \wedge x \not\approx b)$. Thus, b is minimal.

Induction step: Suppose $n \geq 1$, and suppose that every subset of A with n elements has a minimal element. Now let B be an arbitrary subset of A with $n + 1$ elements. Let b be any element of B , and let $B^\pm = B \setminus \{b\}$, a subset of A with n elements. By the inductive hypothesis, we can choose a minimal element $c \in B^\pm$.

Case 1. bRc . We claim that b is a minimal element of B . To see why, suppose it isn't. Then we can choose some $x \in B$ such that xRb and $x \not\approx b$. Since $x \not\approx b$, $x \in B^\pm$. Also, since xRb and bRc , by transitivity of R it follows that xRc . Thus, since c is a minimal element of B^\pm , we must have $x = c$. But then since xRb we have cRb , and we also know bRc , so by antisymmetry of R it follows that $b = c$. This is clearly impossible, since $c \in B^\pm = B \setminus \{b\}$. Thus, b must be a minimal element of B .

Case 2. $\neg bRc$. We claim in this case that c is a minimal element of B . To see why, suppose it isn't. Then we can choose some $x \in B$ such that xRc and $x \not\approx c$. Since c is a minimal element of B^\pm , we can't have $x \in B^\pm$, so the only other possibility is $x = b$. But then since xRc we must have bRc , which contradicts our assumption that $\neg bRc$. Thus, c is a minimal element of B . \square

Note that an infinite subset of a partially ordered set need not have a minimal element, as we saw in part 1 of Example 4.4.5. Thus, the assumption that B is finite was needed in our last theorem. This theorem can be used to prove another interesting fact about partial orders, again using mathematical induction:

Example 6.2.2. Suppose A is a finite set and R is a partial order on A . Prove that R can be extended to a total order on A . In other words, prove that there is a total order T on A such that $R \subseteq T$.

Scratch work

We'll only outline the proof, leaving many details as exercises. The idea is to prove by induction that $\forall n \in \mathbb{N} \forall A \forall R [(A \text{ has } n \text{ elements and } R \text{ is a partial order on } A) \rightarrow \exists T (T \text{ is a total order on } A \text{ and } R \subseteq T)]$. The induction step is similar to the induction step of the last example. If R is a partial order on a set A with $n + 1$ elements, then we remove one element, call it a , from A , and

apply the inductive hypothesis to the remaining set $A^{\pm} = A \setminus \{a\}$. This will give us a total order T^{\pm} on A^{\pm} , and to complete the proof we must somehow turn this into a total order T on A such that $R \subseteq T$. The relation T^{\pm} already tells us how to compare any two elements of A^{\pm} , but it doesn't tell us how to compare a to the elements of A^{\pm} . This is what we must decide in order to define T , and the main difficulty in this step of the proof is that we must make this decision in such a way that we end up with $R \subseteq T$. Our resolution of this difficulty in the following proof involves choosing a carefully in the first place. We choose a to be an R -minimal element of A , and then when we define T , we make a smaller in the T ordering than every element of A^{\pm} . We use the theorem in the last example, with $B = A$, to guarantee that A has an R -minimal element.

Solution

Theorem. *Suppose A is a finite set and R is a partial order on A . Then there is a total order T on A such that $R \subseteq T$.*

Proof. We will show by induction on n that every partial order on a set with n elements can be extended to a total order. Clearly this suffices to prove the theorem.

Base case: $n = 0$. Suppose R is a partial order on A and A has 0 elements. Then clearly $A = R = \emptyset$. It is easy to check that \emptyset is a total order on A (all required properties hold vacuously), so we are done.

Induction step: Let n be an arbitrary natural number, and suppose that every partial order on a set with n elements can be extended to a total order. Now suppose that A has $n + 1$ elements and R is a partial order on A . By the theorem in the last example, there must be some $a \in A$ such that a is an R -minimal element of A . Let $A^{\pm} = A \setminus \{a\}$ and let $R^{\pm} = R \cap (A^{\pm} \times A^{\pm})$. You are asked to show in exercise 1 that R^{\pm} is a partial order on A^{\pm} . By the inductive hypothesis, we can let T^{\pm} be a total order on A^{\pm} such that $R^{\pm} \subseteq T^{\pm}$. Now let $T = T^{\pm} \cup (\{a\} \times A)$. You are also asked to show in exercise 1 that T is a total order on A and $R \subseteq T$, as required. \square

The theorem in the last example can be extended to apply to partial orders on infinite sets. For a step in this direction, see exercise 19 in Section 8.1.

Example 6.2.3. Prove that for all $n \geq 3$, if n distinct points on a circle are connected in consecutive order with straight lines, then the interior angles of the resulting polygon add up to $(n - 2)180^\circ$.

Solution

Figure 6.1 shows an example with $n = 4$. We won't give the scratch work separately for this proof.

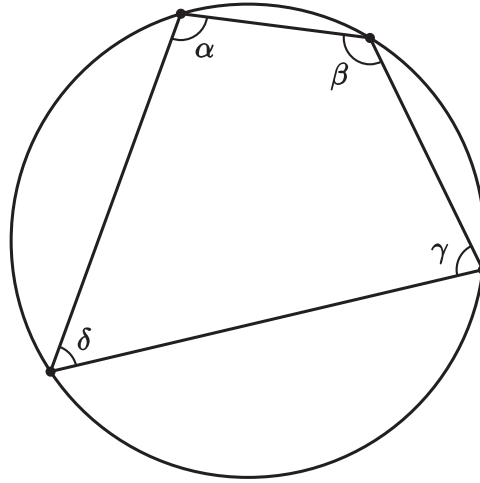


Figure 6.1. $\alpha + \beta + \gamma + \delta = (4 - 2)180^\circ = 360^\circ$.

Theorem. For all $n \geq 3$, if n distinct points on a circle are connected in consecutive order with straight lines, then the interior angles of the resulting polygon add up to $(n - 2)180^\circ$.

Proof. We use induction on n .

Base case: Suppose $n = 3$. Then the polygon is a triangle, and it is well known that the interior angles of a triangle add up to 180° .

Induction step: Let n be an arbitrary natural number, $n \geq 3$, and assume the statement is true for n . Now consider the polygon P formed by connecting some $n + 1$ distinct points A_1, A_2, \dots, A_{n+1} on a circle. If we skip the last point A_{n+1} , then we get a polygon P^\pm with only n vertices, and by the inductive hypothesis the interior angles of this polygon add up to $(n - 2)180^\circ$. But now as you can see in Figure 6.2, the sum of the interior angles of P is equal to the sum of the interior angles of P^\pm plus the sum of the interior angles of the triangle $A_1 A_n A_{n+1}$. Since the sum of the interior angles of the triangle is 180° , we can conclude that the sum of the interior angles of P is

$$(n - 2)180^\circ + 180^\circ = ((n + 1) - 2)180^\circ,$$

as required. □

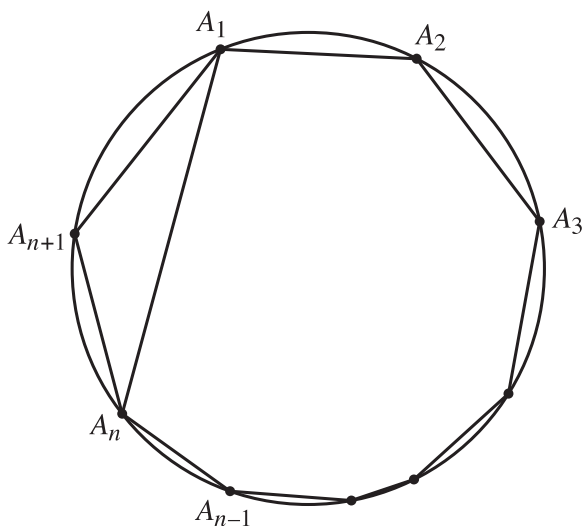

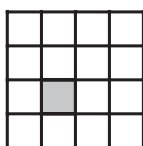


Figure 6.2.

Example 6.2.4. Prove that for any positive integer n , a $2^n \times 2^n$ square grid with any one square removed can be covered with L-shaped tiles that look like this: .

Scratch work

Figure 6.3 shows an example for the case $n = 2$. In this case $2^n = 4$, so we have a 4×4 grid, and the square that has been removed is shaded. The heavy lines show how the remaining squares can be covered with five L-shaped tiles.



(a) 4×4 grid with one square removed.



(b) Grid covered with L-shaped tiles.

Figure 6.3.

We'll use induction in our proof, and because we're only interested in positive n , the base case will be $n = 1$. In this case we have a 2×2 grid with one square removed, and this can clearly be covered with one L-shaped tile. (Draw a picture!)

For the induction step, we let n be an arbitrary positive integer and assume that a $2^n \times 2^n$ grid with any one square removed can be covered with L-shaped

tiles. Now suppose we have a $2^{n+1} \times 2^{n+1}$ grid with one square removed. To use our inductive hypothesis we must somehow relate this to the $2^n \times 2^n$ grid. Since $2^{n+1} = 2^n \cdot 2$, the $2^{n+1} \times 2^{n+1}$ grid is twice as wide and twice as high as the $2^n \times 2^n$ grid. In other words, by dividing the $2^{n+1} \times 2^{n+1}$ grid in half both horizontally and vertically, we can split it into four $2^n \times 2^n$ “subgrids.” This is illustrated in Figure 6.4. The one square that has been removed will be in one of the four subgrids; in Figure 6.4, it is in the upper right.

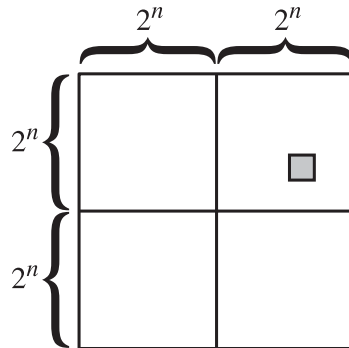


Figure 6.4.

The inductive hypothesis tells us that it is possible to cover the upper right subgrid in Figure 6.4 with L-shaped tiles. But what about the other three subgrids? It turns out that there is a clever way of placing one tile on the grid so that the inductive hypothesis can then be used to show that the remaining subgrids can be covered. See if you can figure it out before reading the answer in the following proof.

Solution

Theorem. For any positive integer n , a $2^n \times 2^n$ square grid with any one square removed can be covered with L-shaped tiles.

Proof. We use induction on n .

Base case: Suppose $n = 1$. Then the grid is a 2×2 grid with one square removed, which can clearly be covered with one L-shaped tile.

Induction step: Let n be an arbitrary positive integer, and suppose that a $2^n \times 2^n$ grid with any one square removed can be covered with L-shaped tiles. Now consider a $2^{n+1} \times 2^{n+1}$ grid with one square removed. Cut the grid in half both vertically and horizontally, splitting it into four $2^n \times 2^n$ subgrids. The one square that has been removed comes from one of these subgrids, so by the inductive hypothesis the rest of this subgrid can be covered with L-

shaped tiles. To cover the other three subgrids, first place one L-shaped tile in the center so that it covers one square from each of the three remaining subgrids, as illustrated in Figure 6.5. The area remaining to be covered now contains every square except one in each of the subgrids, so by applying the inductive hypothesis to each subgrid we can see that this area can be covered with tiles. \square

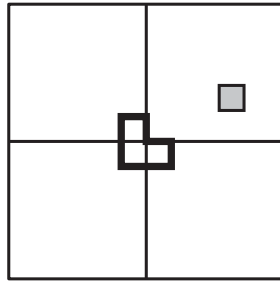


Figure 6.5.

It is interesting to note that this proof can actually be used to figure out how to place tiles on a particular grid. For example, consider the 8×8 grid with one square removed shown in Figure 6.6.

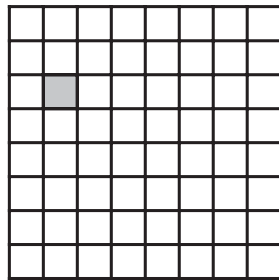


Figure 6.6.

According to the preceding proof, the first step in covering this grid with tiles is to split it into four 4×4 subgrids and place one tile in the center, covering one square from each subgrid except the upper left. This is illustrated in Figure 6.7. The area remaining to be covered now consists of four 4×4 subgrids with one square removed from each of them.

How do we cover the remaining 4×4 subgrids? By the same method, of course! For example, let's cover the subgrid in the upper right of Figure 6.7. We need to cover every square of this subgrid except the lower left corner, which has already been covered. We start by cutting it into four 2×2 subgrids

and put one tile in the middle, as in Figure 6.8. The area remaining to be covered now consists of four 2×2 subgrids with one square removed from each. Each of these can be covered with one tile, thus completing the upper right subgrid of Figure 6.7.

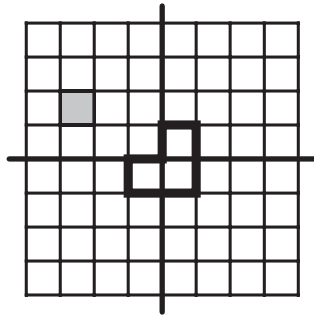


Figure 6.7.

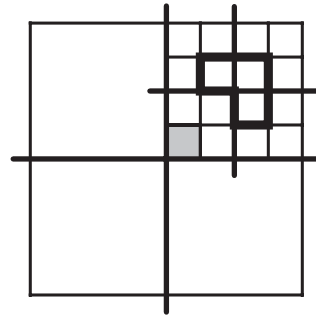


Figure 6.8.

The remaining three quarters of Figure 6.7 are completed by a similar procedure. The final solution is shown in Figure 6.9.

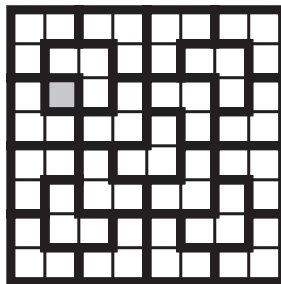


Figure 6.9.

The method we used in solving this problem is an example of a *recursive* procedure. We solved the problem for an 8×8 grid by splitting it into four 4×4 grid problems. To solve each of these, we split it into four 2×2 problems, each of which was easy to solve. If we had started with a larger grid, we might have had to repeat the splitting many times before reaching easy 2×2 problems. Recursion and its relationship to mathematical induction are the subject of our next section.

Exercises

- *1. Complete the proof in Example 6.2.2 by doing the following proofs. (We use the same notation here as in the example.)
- Prove that R^\pm is a partial order on A^\pm .
 - Prove that T is a total order on A and $R \subseteq T$.
2. Suppose R is a partial order on a set A , $B \subseteq A$, and B is finite. Prove that there is a partial order T on A such that $R \subseteq T$ and $\forall x \in B \forall y \in A(xTy \vee yTx)$. Note that, in particular, if A is finite we can let $B = A$, and the conclusion then means that T is a total order on A . Thus, this gives an alternative approach to the proof of the theorem in Example 6.2.2. (Hint: Use induction on the number of elements in B . For the induction step, assume the conclusion holds for any set $B \subseteq A$ with n elements, and suppose B is a subset of A with $n + 1$ elements. Let b be any element of B and let $B^\pm = B \setminus \{b\}$, a subset of A with n elements. By the inductive hypothesis, let T^\pm be a partial order on A such that $R \subseteq T^\pm$ and $\forall x \in B^\pm \forall y \in A(xT^\pm y \vee yT^\pm x)$. Now let $A_1 = \{x \in A \mid (x, b) \in T^\pm\}$ and $A_2 = A \setminus A_1$, and let $T = T^\pm \cup (A_1 \times A_2)$. Prove that T has all the required properties.)
3. Suppose R is a total order on a set A . Prove that every finite, nonempty set $B \subseteq A$ has an R -smallest element and an R -largest element.
- *4. (a) Suppose R is a relation on A , and $\forall x \in A \forall y \in A(xRy \vee yRx)$. (Note that this implies that R is reflexive.) Prove that for every finite, nonempty set $B \subseteq A$ there is some $x \in B$ such that $\forall y \in B((x, y) \in R \circ R)$. (Hint: Imitate Example 6.2.1.)
- Consider a tournament in which each contestant plays every other contestant exactly once, and one of them wins. We'll say that a contestant x is *excellent* if, for every other contestant y , either x beats y or there is a third contestant z such that x beats z and z beats y . Prove that there is at least one excellent contestant.
5. For each $n \in \mathbb{N}$, let $F_n = 2^{(2^n)} + 1$. (These numbers are called the *Fermat numbers*, after the French mathematician Pierre de Fermat (1601–1665). Fermat showed that F_0, F_1, F_2, F_3 , and F_4 are prime, and conjectured that all of the Fermat numbers are prime. However, over 100 years later Euler showed that F_5 is not prime. It is not known if there is any $n > 4$ for which F_n is prime.)
- Prove that for all $n \geq 1$, $F_n = (F_0 \cdot F_1 \cdot F_2 \cdots F_{n-1}) + 2$.
6. Prove that if $n \geq 1$ and a_1, a_2, \dots, a_n are any real numbers, then $|a_1 + a_2 + \cdots + a_n| \leq |a_1| + |a_2| + \cdots + |a_n|$. (Note that this generalizes the triangle inequality; see exercise 13(c) of Section 3.5.)

7. (a) Prove that if a and b are positive real numbers, then $a/b + b/a \geq 2$. (Hint: Start with the fact that $(a - b)^2 \geq 0$.)
- (b) Suppose that a , b , and c are real numbers and $0 < a \leq b \leq c$. Prove that $b/c + c/a - b/a \geq 1$. (Hint: Start with the fact that $(c - a)(c - b) \geq 0$.)
- (c) Prove that if $n \geq 2$ and a_1, a_2, \dots, a_n are real numbers such that $0 < a_1 \leq a_2 \leq \dots \leq a_n$, then $a_1/a_2 + a_2/a_3 + \dots + a_{n-1}/a_n + a_n/a_1 \geq n$.
- *8. If $n \geq 2$ and a_1, a_2, \dots, a_n is a list of positive real numbers, then the number $(a_1 + a_2 + \dots + a_n)/n$ is called the *arithmetic mean* of the numbers a_1, a_2, \dots, a_n , and the number $\sqrt[n]{a_1 a_2 \dots a_n}$ is called their *geometric mean*. In this exercise you will prove the *arithmetic mean–geometric mean inequality*, which says that the arithmetic mean is always at least as large as the geometric mean.

- (a) Prove that the arithmetic mean–geometric mean inequality holds for lists of numbers of length 2. In other words, prove that for all positive real numbers a and b , $(a + b)/2 \geq \sqrt{ab}$.
- (b) Prove that the arithmetic mean–geometric mean inequality holds for any list of numbers whose length is a power of 2. In other words, prove that for all $n \geq 1$, if a_1, a_2, \dots, a_{2^n} is a list of positive real numbers, then

$$\frac{a_1 + a_2 + \dots + a_{2^n}}{2^n} \geq \sqrt[2^n]{a_1 a_2 \dots a_{2^n}}.$$

- (c) Suppose that $n_0 \geq 2$ and the arithmetic mean–geometric mean inequality fails for some list of length n_0 . In other words, there are positive real numbers a_1, a_2, \dots, a_{n_0} such that

$$\frac{a_1 + a_2 + \dots + a_{n_0}}{n_0} < \sqrt[n_0]{a_1 a_2 \dots a_{n_0}}.$$

Prove that for all $n \geq n_0$, the arithmetic mean–geometric mean inequality fails for some list of length n .

- (d) Prove that the arithmetic mean–geometric mean inequality always holds.
9. Prove that if $n \geq 2$ and a_1, a_2, \dots, a_n is a list of positive real numbers, then

$$\frac{n}{\frac{1}{a_1} + \frac{1}{a_2} + \dots + \frac{1}{a_n}} \leq \sqrt[n]{a_1 a_2 \dots a_n}.$$

(Hint: Apply exercise 8. The number on the left side of the inequality above is called the *harmonic mean* of the numbers a_1, a_2, \dots, a_n .)

- *10. (a) Prove that if a_1, a_2, b_1 , and b_2 are real numbers, with $a_1 \leq a_2$ and $b_1 \leq b_2$, then $a_1 b_2 + a_2 b_1 \leq a_1 b_1 + a_2 b_2$.

- (b) Suppose that n is a positive integer, a_1, a_2, \dots, a_n and b_1, b_2, \dots, b_n are real numbers, $a_1 \leq a_2 \leq \dots \leq a_n$, $b_1 \leq b_2 \leq \dots \leq b_n$, and f is a one-to-one, onto function from $\{1, 2, \dots, n\}$ to $\{1, 2, \dots, n\}$. Prove that $a_1 b_{f(1)} + a_2 b_{f(2)} + \dots + a_n b_{f(n)} \leq a_1 b_1 + a_2 b_2 + \dots + a_n b_n$. (This fact is known as the *rearrangement inequality*.)
- *11. Prove that for every set A , if A has n elements then $\mathcal{P}(A)$ has 2^n elements.
12. If A is a set, let $\mathcal{P}_2(A)$ be the set of all subsets of A that have exactly two elements. Prove that for every set A , if A has n elements then $\mathcal{P}_2(A)$ has $n(n-1)/2$ elements. (Hint: See the solution for exercise 11.)
13. Suppose n is a positive integer. An equilateral triangle is cut into 4^n congruent equilateral triangles by equally spaced line segments parallel to the sides of the triangle, and one corner is removed. (Figure 6.10 shows an example in the case $n = 2$.) Show that the remaining area can be covered by trapezoidal tiles like this: $\triangleleft \triangle$.

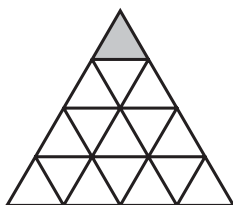


Figure 6.10.

- *14. Let n be a positive integer. Suppose n chords are drawn in a circle in such a way that each chord intersects every other, but no three intersect at one point. Prove that the chords cut the circle into $(n^2 + n + 2)/2$ regions. (Figure 6.11 shows an example in the case $n = 4$. Note that there are $(4^2 + 4 + 2)/2 = 11$ regions in this figure.)

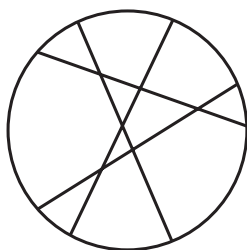


Figure 6.11.

15. Let n be a positive integer, and suppose that n chords are drawn in a circle in any way, cutting the circle into a number a regions. Prove that the regions can be colored with two colors in such a way that

adjacent regions (that is, regions that share an edge) are different colors. (Figure 6.12 shows an example in the case $n = 4$.)

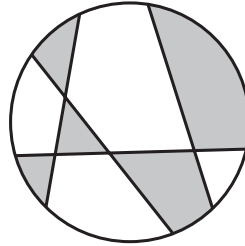


Figure 6.12.

16. Prove that for every finite set A and every function $f : A \rightarrow A$, if f is one-to-one then f is onto. (Hint: Use induction on the number of elements in A . For the induction step, assume the conclusion holds for any set A with n elements, and suppose that A has $n + 1$ elements and $f : A \rightarrow A$. Suppose f is one-to-one but not onto. Then there is some $a \in A$ such that $a \notin \text{Ran}(f)$. Let $A^\pm = A \setminus \{a\}$ and $f^\pm = f \cap (A^\pm \times A^\pm)$. Show that $f^\pm : A^\pm \rightarrow A^\pm$, f^\pm is one-to-one, and f^\pm is not onto, which contradicts the inductive hypothesis.)
17. What's wrong with the following proof that if $A \subseteq \mathbb{N}$ and $0 \in A$ then $A = \mathbb{N}$?

Proof. We will prove by induction that $\forall n \in \mathbb{N} (n \in A)$.

Base case: If $n = 0$, then $n \in A$ by assumption.

Induction step: Let $n \in \mathbb{N}$ be arbitrary, and suppose that $n \in A$. Since n was arbitrary, it follows that every natural number is an element of A , and therefore in particular $n + 1 \in A$. \square

18. Suppose $f : \mathbb{R} \rightarrow \mathbb{R}$. What's wrong with the following proof that for every finite, nonempty set $A \subseteq \mathbb{R}$ there is a real number c such that $\forall x \in A (f(x) = c)$?

Proof. We will prove by induction that for every $n \geq 1$, if A is any subset of \mathbb{R} with n elements then $\exists c \in \mathbb{R} \forall x \in A (f(x) = c)$.

Base case: $n = 1$. Suppose $A \subseteq \mathbb{R}$ and A has one element. Then $A = \{a\}$, for some $a \in \mathbb{R}$. Let $c = f(a)$. Then clearly $\forall x \in A (f(x) = c)$.

Induction step: Suppose $n \geq 1$, and for all $A \subseteq \mathbb{R}$, if A has n elements then $\exists c \in \mathbb{R} \forall x \in A (f(x) = c)$. Now suppose $A \subseteq \mathbb{R}$ and A has $n + 1$ elements. Let a_1 be any element of A , and let $A_1 = A \setminus \{a_1\}$. Then A_1 has n elements, so by the inductive hypothesis there is some $c_1 \in \mathbb{R}$ such that $\forall x \in A_1 (f(x) = c_1)$. If we can show that $f(a_1) = c_1$ then we will be done, since then it will follow that $\forall x \in A (f(x) = c_1)$.

Let a_2 be an element of A that is different from a_1 , and let $A_2 = A \setminus \{a_2\}$. Applying the inductive hypothesis again, we can choose a number $c_2 \in \mathbb{R}$ such that $\forall x \in A_2 (f(x) = c_2)$. Notice that since $a_1 \neq a_2$, $a_1 \in A_2$, so $f(a_1) = c_2$. Now let a_3 be an element of A that is different from both a_1 and a_2 . Then $a_3 \in A_1$ and $a_3 \in A_2$, so $f(a_3) = c_1$ and $f(a_3) = c_2$. Therefore $c_1 = c_2$, so $f(a_1) = c_1$, as required. \square

6.3. Recursion

In Chapter 3 we learned to prove statements of the form $\forall n P(n)$ by letting n be arbitrary and proving $P(n)$. In this chapter we've learned another method for proving such statements, when n ranges over the natural numbers: prove $P(0)$, and then prove that for any natural number n , if $P(n)$ is true then so is $P(n + 1)$. Once we have proven these statements, we can run through all the natural numbers in order and see that P must be true of all of them.

We can use a similar idea to introduce a new way of defining functions. In Chapter 5, we usually defined a function f by saying how to compute $f(n)$ for any n in the domain of f . If the domain of f is the set of all natural numbers, an alternative method to define f would be to say what $f(0)$ is and then, for any natural number n , say how we could compute $f(n + 1)$ if we already knew the value of $f(n)$. Such a definition would enable us to run through all the natural numbers in order computing the image of each one under f .

For example, we might use the following equations to define a function f with domain \mathbb{N} :

$$f(0) = 1;$$

$$\text{for every } n \in \mathbb{N}, f(n + 1) = (n + 1) \cdot f(n).$$

The second equation tells us how to compute $f(n + 1)$, but only if we already know the value of $f(n)$. Thus, although we cannot use this equation to tell us directly what the image of any number is under f , we *can* use it to run through all the natural numbers in order and compute their images.

We start with $f(0)$, which we know from the first equation is equal to 1. Plugging in $n = 0$ in the second equation, we see that $f(1) = 1 \cdot f(0) = 1 \cdot 1 = 1$, so we've determined the value of $f(1)$. But now that we know that $f(1) = 1$, we can use the second equation again to compute $f(2)$. Plugging in $n = 1$ in the second equation, we find that $f(2) = 2 \cdot f(1) = 2 \cdot 1 = 2$. Similarly, setting $n = 2$ in the second equation we get $f(3) = 3 \cdot f(2) = 3 \cdot 2 = 6$. Continuing in this way we can compute $f(n)$ for any natural number n . Thus, the two equations really do give us a rule that determines a unique value

$f(n)$ for each natural number n , so they define a function f with domain \mathbb{N} . Definitions of this kind are called *recursive* definitions.

Sometimes we'll work backwards when using a recursive definition to evaluate a function. For example, suppose we want to compute $f(6)$, where f is the function just defined. According to the second equation in the definition of f , $f(6) = 6 \cdot f(5)$, so to complete the calculation we must compute $f(5)$. Using the second equation again, we find that $f(5) = 5 \cdot f(4)$, so we must compute $f(4)$. Continuing in this way leads to the following calculation:

$$\begin{aligned} f(6) &= 6 \cdot f(5) \\ &= 6 \cdot 5 \cdot f(4) \\ &= 6 \cdot 5 \cdot 4 \cdot f(3) \\ &= 6 \cdot 5 \cdot 4 \cdot 3 \cdot f(2) \\ &= 6 \cdot 5 \cdot 4 \cdot 3 \cdot 2 \cdot f(1) \\ &= 6 \cdot 5 \cdot 4 \cdot 3 \cdot 2 \cdot 1 \cdot f(0) \\ &= 6 \cdot 5 \cdot 4 \cdot 3 \cdot 2 \cdot 1 \cdot 1 \\ &= 720. \end{aligned}$$

Perhaps now you recognize the function f . For any positive integer n , $f(n) = n \cdot (n-1) \cdot (n-2) \cdots 1$, and $f(0) = 1$. The number $f(n)$ is called *n factorial*, and is denoted $n!$. (Recall that we used this notation in our proof of Theorem 3.7.3.) For example, $6! = 720$. Often, if a function can be written as a formula with an ellipsis (...) in it, then the use of the ellipsis can be avoided by giving a recursive definition for the function. Such a definition is usually easier to work with.

Many familiar functions are most easily defined using recursive definitions. For example, for any number a , we could define a^n with the following recursive definition:

$$\begin{aligned} a^0 &= 1; \\ \text{for every } n \in \mathbb{N}, a^{n+1} &= a^n \cdot a. \end{aligned}$$

Using this definition, we would compute a^4 like this:

$$\begin{aligned} a^4 &= a^3 \cdot a \\ &= a^2 \cdot a \cdot a \\ &= a^1 \cdot a \cdot a \cdot a \\ &= a^0 \cdot a \cdot a \cdot a \cdot a \\ &= 1 \cdot a \cdot a \cdot a \cdot a. \end{aligned}$$

For another example, consider the sum $2^0 + 2^1 + 2^2 + \cdots + 2^n$, which appeared in the first example of this chapter. The ellipsis suggests that we might be able to use a recursive definition. If we let $f(n) = 2^0 + 2^1 + 2^2 + \cdots + 2^n$, then notice that for every $n \in \mathbb{N}$, $f(n+1) = 2^0 + 2^1 + 2^2 + \cdots + 2^n + 2^{n+1} = f(n) + 2^{n+1}$. Thus, we could define f recursively as follows:

$$f(0) = 2^0 = 1;$$

$$\text{for every } n \in \mathbb{N}, f(n+1) = f(n) + 2^{n+1}.$$

As a check that this definition is right, let's try it out in the case $n = 3$:

$$\begin{aligned} f(3) &= f(2) + 2^3 \\ &= f(1) + 2^2 + 2^3 \\ &= f(0) + 2^1 + 2^2 + 2^3 \\ &= 2^0 + 2^1 + 2^2 + 2^3 \\ &= 15. \end{aligned}$$

Sums such as the one in the last example come up often enough that there is a special notation for them. If a_0, a_1, \dots, a_n is a list of numbers, then the sum of these numbers is written $\sum_{i=0}^n a_i$. This is read "the sum as i goes from 0 to n of a_i ." For example, we can use this notation to write the sum in the last example:

$$\sum_{i=0}^n 2^i = 2^0 + 2^1 + 2^2 + \cdots + 2^n.$$

More generally, if $n \geq m$, then

$$\sum_{i=m}^n a_i = a_m + a_{m+1} + a_{m+2} + \cdots + a_n.$$

For example,

$$\sum_{i=3}^6 i^2 = 3^2 + 4^2 + 5^2 + 6^2 = 9 + 16 + 25 + 36 = 86.$$

The letter i in these formulas is a bound variable and therefore can be replaced by a new variable without changing the meaning of the formula.

Now let's try giving a recursive definition for this notation. We let m be an arbitrary integer, and then proceed by recursion on n . Just as the base case for an induction proof need not be $n = 0$, the base for a recursive definition can

also be a number other than 0. In this case we are only interested in $n \geq m$, so we take $n = m$ as the base for our recursion:

$$\sum_{i=m}^m a_i = a_m;$$

$$\text{for every } n \geq m, \sum_{i=m}^{n+1} a_i = \sum_{i=m}^n a_i + a_{n+1}.$$

Trying this definition out on the previous example, we get

$$\begin{aligned} \sum_{i=3}^6 i^2 &= \sum_{i=3}^5 i^2 + 6^2 \\ &= \sum_{i=3}^4 i^2 + 5^2 + 6^2 \\ &= \sum_{i=3}^3 i^2 + 4^2 + 5^2 + 6^2 \\ &= 3^2 + 4^2 + 5^2 + 6^2, \end{aligned}$$

just as we wanted.

Clearly induction and recursion are closely related, so it shouldn't be surprising that if a concept has been defined by recursion, then proofs involving this concept are often best done by induction. For example, in Section 6.1 we saw some proofs by induction that involved summations and exponentiation, and now we have seen that summations and exponentiation can be defined recursively. Because the factorial function can also be defined recursively, proofs involving factorials also often use induction.

Example 6.3.1. Prove that for every $n \geq 4$, $n! > 2^n$.

Scratch work

Because the problem involves factorial and exponentiation, both of which are defined recursively, induction seems like a good method to use. The base case will be $n = 4$, and it is just a matter of simple arithmetic to check that the inequality is true in this case. For the induction step, our inductive hypothesis will be $n! > 2^n$, and we must prove that $(n + 1)! > 2^{n+1}$. Of course, the way to relate the inductive hypothesis to the goal is to use the recursive definitions of factorial and exponentiation, which tell us that $(n + 1)! = (n + 1) \cdot n!$

and $2^{n+1} = 2^n \cdot 2$. Once these equations are plugged in, the rest is fairly straightforward.

Solution

Theorem. For every $n \geq 4$, $n! > 2^n$.

Proof. By mathematical induction.

Base case: When $n = 4$ we have $n! = 24 > 16 = 2^n$.

Induction step: Let $n \geq 4$ be arbitrary and suppose that $n! > 2^n$. Then

$$\begin{aligned} (n + 1)! &= (n + 1) \cdot n! \\ &> (n + 1) \cdot 2^n && \text{(inductive hypothesis)} \\ &> 2 \cdot 2^n = 2^{n+1}. \end{aligned} \quad \square$$

Example 6.3.2. Prove that for every real number a and all natural numbers m and n , $a^{m+n} = a^m \cdot a^n$.

Scratch work

There are three universal quantifiers here, and we'll treat the first two differently from the third. We let a and m be arbitrary and then use mathematical induction to prove that $\forall n \in \mathbb{N}(a^{m+n} = a^m \cdot a^n)$. The key algebraic fact in the induction step will be the formula $a^{n+1} = a^n \cdot a$ from the recursive definition of exponentiation.

Solution

Theorem. For every real number a and all natural numbers m and n , $a^{m+n} = a^m \cdot a^n$.

Proof. Let a be an arbitrary real number and m an arbitrary natural number. We now proceed by induction on n .

Base case: When $n = 0$, we have $a^{m+n} = a^{m+0} = a^m = a^m \cdot 1 = a^m \cdot a^0 = a^m \cdot a^n$.

Induction step. Suppose $a^{m+n} = a^m \cdot a^n$. Then

$$\begin{aligned} a^{m+(n+1)} &= a^{(m+n)+1} \\ &= a^{m+n} \cdot a && \text{(definition of exponentiation)} \\ &= a^m \cdot a^n \cdot a && \text{(inductive hypothesis)} \\ &= a^m \cdot a^{n+1} && \text{(definition of exponentiation)}. \end{aligned} \quad \square$$

Example 6.3.3. A sequence of numbers a_0, a_1, a_2, \dots is defined recursively as follows:

$$\begin{aligned} a_0 &= 0; \\ \text{for every } n \in \mathbb{N}, a_{n+1} &= 2a_n + 1. \end{aligned}$$

Find a formula for a_n and prove that your formula is correct.

Scratch work

It's probably a good idea to start out by computing the first few terms in the sequence. We already know $a_0 = 0$, so plugging in $n = 0$ in the second equation we get $a_1 = 2a_0 + 1 = 0 + 1 = 1$. Thus, plugging in $n = 1$, we get $a_2 = 2a_1 + 1 = 2 + 1 = 3$. Continuing in this way we get the following table of values:

n	0	1	2	3	4	5	6	\dots
a_n	0	1	3	7	15	31	63	\dots

Aha! The numbers we're getting are one less than the powers of 2. It looks like the formula is probably $a_n = 2^n - 1$, but we can't be sure this is right unless we prove it. Fortunately, it is fairly easy to prove the formula by induction.

Solution

Theorem. *If the sequence a_0, a_1, a_2, \dots is defined by the recursive definition given earlier, then for every natural number n , $a_n = 2^n - 1$.*

Proof. By induction.

Base case: $a_0 = 0 = 2^0 - 1$.

Induction step: Suppose $a_n = 2^n - 1$. Then

$$\begin{aligned} a_{n+1} &= 2a_n + 1 && \text{(definition of } a_{n+1}) \\ &= 2(2^n - 1) + 1 && \text{(inductive hypothesis)} \\ &= 2^{n+1} - 2 + 1 = 2^{n+1} - 1. \end{aligned}$$

□

We end this section with a rather unusual example. We'll prove that for every real number $x > -1$ and every natural number n , $(1 + x)^n > nx$. A natural way to proceed would be to let $x > -1$ be arbitrary, and then use induction on n . In the induction step we assume that $(1 + x)^n > nx$, and then try to prove that $(1 + x)^{n+1} > (n + 1)x$. Because we've assumed $x > -1$,

we have $1 + x > 0$, so we can multiply both sides of the inductive hypothesis $(1 + x)^n > nx$ by $1 + x$ to get

$$\begin{aligned} (1 + x)^{n+1} &= (1 + x)(1 + x)^n \\ &> (1 + x)nx \\ &= nx + nx^2. \end{aligned}$$

But the conclusion we need for the induction step is $(1 + x)^{n+1} > (n + 1)x$, and it's not clear how to get this conclusion from the inequality we've derived.

Our solution to this difficulty will be to replace our original problem with a problem that appears to be harder but is actually easier. Instead of proving the inequality $(1 + x)^n > nx$ directly, we'll prove $(1 + x)^n \geq 1 + nx$, and then observe that since $1 + nx > nx$, it follows immediately that $(1 + x)^n > nx$. You might think that if we had difficulty proving $(1 + x)^n > nx$, we'll surely have more difficulty proving the stronger statement $(1 + x)^n \geq 1 + nx$. But it turns out that the approach we tried unsuccessfully on the original problem works perfectly on the new problem!

Theorem 6.3.4. For every $x > -1$ and every natural number n , $(1 + x)^n > nx$.

Proof. Let $x > -1$ be arbitrary. We will prove by induction that for every natural number n , $(1 + x)^n \geq 1 + nx$, from which it clearly follows that $(1 + x)^n > nx$.

Base case: If $n = 0$, then $(1 + x)^n = (1 + x)^0 = 1 = 1 + 0 = 1 + nx$.

Induction step: Suppose $(1 + x)^n \geq 1 + nx$. Then

$$\begin{aligned} (1 + x)^{n+1} &= (1 + x)(1 + x)^n \\ &\geq (1 + x)(1 + nx) && \text{(inductive hypothesis)} \\ &= 1 + x + nx + nx^2 \\ &\geq 1 + (n + 1)x && \text{(since } nx^2 \geq 0\text{)}. \quad \square \end{aligned}$$

Exercises

- *1. Find a formula for $\sum_{i=1}^n \frac{1}{i(i+1)}$ and prove that your formula is correct.
- 2. Prove that for all $n \geq 1$,

$$\sum_{i=1}^n \frac{1}{i(i+1)(i+2)} = \frac{n^2 + 3n}{4(n+1)(n+2)}.$$

3. Prove that for all $n \geq 2$,

$$\sum_{i=2}^n \frac{1}{(i-1)(i+1)} = \frac{3n^2 - n - 2}{4n(n+1)}.$$

4. Prove that for all $n \in \mathbb{N}$,

$$\sum_{i=0}^n (2i+1)^2 = \frac{(n+1)(2n+1)(2n+3)}{3}.$$

5. Suppose r is a real number and $r \neq 1$. Prove that for all $n \in \mathbb{N}$,

$$\sum_{i=0}^n r^i = \frac{r^{n+1} - 1}{r - 1}.$$

(Note that this exercise generalizes Example 6.1.1 and exercise 7 of Section 6.1.)

- *6. Prove that for all $n \geq 1$,

$$\sum_{i=1}^n \frac{1}{i^2} \leq 2 - \frac{1}{n}.$$

7. (a) Suppose $a_0, a_1, a_2, \dots, a_n$ and $b_0, b_1, b_2, \dots, b_n$ are two sequences of real numbers. Prove that

$$\sum_{i=0}^n (a_i + b_i) = \sum_{i=0}^n a_i + \sum_{i=0}^n b_i.$$

- (b) Suppose c is a real number and a_0, a_1, \dots, a_n is a sequence of real numbers. Prove that

$$c \cdot \sum_{i=0}^n a_i = \sum_{i=0}^n (c \cdot a_i).$$

- *8. The *harmonic numbers* are the numbers H_n for $n \geq 1$ defined by the formula

$$H_n = \sum_{i=1}^n \frac{1}{i}.$$

- (a) Prove that for all natural numbers n and m , if $n \geq m \geq 1$ then $H_n - H_m \geq (n-m)/n$. (Hint: Let m be an arbitrary natural number with $m \geq 1$ and then proceed by induction on n , with $n = m$ as the base case of the induction.)
- (b) Prove that for all $n \geq 0$, $H_{2^n} \geq 1 + n/2$.

(c) (For those who have studied calculus.) Show that $\lim_{n \rightarrow \infty} H_n = \infty$, so $\sum_{i=1}^{\infty} (1/i)$ diverges.

9. Let H_n be defined as in exercise 8. Prove that for all $n \geq 2$,

$$\sum_{k=1}^{n-1} H_k = nH_n - n.$$

10. Find a formula for $\sum_{i=1}^n (i \cdot (i!))$ and prove that your formula is correct.

11. Find a formula for $\sum_{i=0}^n (i/(i+1)!)$ and prove that your formula is correct.

*12. (a) Prove that for all $n \in \mathbb{N}$, $2^n > n$.

(b) Prove that for all $n \geq 9$, $n! \geq (2^n)^2$.

(c) Prove that for all $n \in \mathbb{N}$, $n! \leq 2^{(n^2)}$.

13. Suppose k is a positive integer.

(a) Prove that for all $n \in \mathbb{N}$, $(k^2 + n)! \geq k^{2n}$.

(b) Prove that for all $n \geq 2k^2$, $n! \geq k^n$. (Hint: Use induction, and for the base case use part (a). Note that in the language of exercise 19 of Section 5.1, this shows that if $f(n) = k^n$ and $g(n) = n!$, then $f \in O(g)$.)

14. Prove that for every real number a and all natural numbers m and n , $(a^m)^n = a^{mn}$.

*15. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = 0;$$

$$\text{for every } n \in \mathbb{N}, a_{n+1} = 2a_n + n.$$

Prove that for all $n \in \mathbb{N}$, $a_n = 2^n - n - 1$.

16. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = 2;$$

$$\text{for every } n \in \mathbb{N}, a_{n+1} = (a_n)^2.$$

Find a formula for a_n and prove that your formula is correct.

17. A sequence a_1, a_2, a_3, \dots is defined recursively as follows:

$$a_1 = 1;$$

$$\text{for every } n \geq 1, a_{n+1} = \frac{a_n}{a_n + 1}.$$

Find a formula for a_n and prove that your formula is correct.

*18. For $n \geq k \geq 0$, the quantity $\binom{n}{k}$ is defined as follows:

$$\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!}.$$

- (a) Prove that for all $n \in \mathbb{N}$, $\binom{n}{0} = \binom{n}{n} = 1$.
- (b) Prove that for all natural numbers n and k , if $n \geq k > 0$ then $\binom{n+1}{k} = \binom{n}{k} + \binom{n}{k-1}$.
- (c) If A is a set and $k \in \mathbb{N}$, let $\mathcal{P}_k(A)$ be the set of all subsets of A that have k elements. Prove that if A has n elements and $n \geq k \geq 0$, then $\mathcal{P}_k(A)$ has $\binom{n}{k}$ elements. (Hint: Prove by induction that $\forall n \in \mathbb{N} \forall A [A \text{ is a set with } n \text{ elements} \rightarrow \forall k (n \geq k \geq 0 \rightarrow \mathcal{P}_k(A) \text{ has } \binom{n}{k} \text{ elements})$]. Imitate exercises 11 and 12 of Section 6.2. In fact, this exercise generalizes exercise 12 of Section 6.2. This exercise shows that $\binom{n}{k}$ is the number of ways of choosing k elements out of a set of size n , so it is sometimes called *n choose k*.)
- (d) Prove that for all real numbers x and y and every natural number n ,

$$(x + y)^n = \sum_{k=0}^n \binom{n}{k} x^{n-k} y^k.$$

(This is called the *binomial theorem*, so the numbers $\binom{n}{k}$ are sometimes called *binomial coefficients*.)

Note: Parts (a) and (b) show that we can compute the numbers $\binom{n}{k}$ conveniently by using a triangular array as in Figure 6.13. This array is called *Pascal's triangle*, after the French mathematician Blaise Pascal (1623–1662). Each row of the triangle corresponds to a particular value of n , and it lists the values of $\binom{n}{k}$ for all k from 0 to n . Part (a) shows that the first and last numbers in every row are 1. Part (b) shows that every other number is the sum of the two numbers above it. For example, the lines in Figure 6.13 illustrate that $\binom{3}{2} = 3$ is the sum of $\binom{2}{1} = 2$ and $\binom{2}{2} = 1$.

$$\begin{array}{rcccc}
 n = 0: & & & & 1 \\
 n = 1: & & & 1 & 1 \\
 n = 2: & & 1 & 2 & 1 \\
 n = 3: & & 1 & 3 & 3 & 1 \\
 n = 4: & & 1 & 4 & 6 & 4 & 1 \\
 & & & & \vdots & &
 \end{array}$$

Figure 6.13. Pascal's triangle.

19. For the meaning of the notation used in this exercise, see exercise 18.
- (a) Prove that for all $n \in \mathbb{N}$, $\sum_{k=0}^n \binom{n}{k} = 2^n$. (Hint: You can do this by induction using parts (a) and (b) of exercise 18, or you can combine

part (c) of exercise 18 with exercise 11 of Section 6.2, or you can plug something in for x and y in part (d) of exercise 18.)

(b) Prove that for all $n \geq 1$, $\sum_{k=0}^n (-1)^k \binom{n}{k} = 0$.

*20. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = 0;$$

$$\text{for every } n \in \mathbb{N}, a_{n+1} = (a_n)^2 + \frac{1}{4}.$$

Prove that for all $n \geq 1$, $0 < a_n < 1$.

21. In this problem we will define, for each natural number n , a function $f_n : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$. The sequence of functions f_0, f_1, f_2, \dots is defined recursively as follows:

$$\text{for every } x \in \mathbb{Z}^+, f_0(x) = x;$$

$$\text{for every } n \in \mathbb{N} \text{ and every } x \in \mathbb{Z}^+, f_{n+1}(x) = 2^{f_n(x)}.$$

(a) The first equation in this recursive definition gives a formula for $f_0(x)$, namely $f_0(x) = x$. Find formulas for $f_1(x)$, $f_2(x)$, and $f_3(x)$.

(b) Prove that for all natural numbers n and all positive integers x and y , if $x < y$ then $f_n(x) < f_n(y)$.

(c) Prove that for all natural numbers m and n and all positive integers x , if $m < n$ then $f_m(x) < f_n(x)$.

(d) Prove that for every natural number n , $f_n \in O(f_{n+1})$ but $f_{n+1} \notin O(f_n)$. (See exercise 19 in Section 5.1 for the meaning of the notation used here.)

Now define $g : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$ by the formula $g(x) = f_x(x)$.

(e) Compute $g(1)$, $g(2)$, and $g(3)$. (Do not try to compute $g(4)$; the answer would be a number with more than 6×10^{19727} digits.)

(f) Prove that for every natural number n , $f_n \in O(g)$ but $g \notin O(f_n)$.

22. Explain the paradox in the proof of Theorem 6.3.4, in which we made the proof easier by changing the goal to a statement that looked like it would be harder to prove.

6.4. Strong Induction

In the induction step of a proof by mathematical induction, we prove that a natural number has some property based on the assumption that the previous number has the same property. In some cases this assumption isn't strong enough to make the proof work, and we need to assume that *all* smaller natural

numbers have the property. This is the idea behind a variant of mathematical induction sometimes called *strong induction* :

To prove a goal of the form $\forall n \in \mathbb{N} P(n)$:

Prove that $\forall n [(\forall k < n P(k)) \rightarrow P(n)]$, where both n and k range over the natural numbers in this statement. Of course, the most direct way to prove this is to let n be an arbitrary natural number, assume that $\forall k < n P(k)$, and then prove $P(n)$.

Note that no base case is necessary in a proof by strong induction. All that is needed is a modified form of the induction step in which we prove that if every natural number smaller than n has the property P , then n has the property P . In a proof by strong induction, we refer to the assumption that every natural number smaller than n has the property P as the *inductive hypothesis* .

To see why strong induction works, it might help if we first review briefly why ordinary induction works. Recall that a proof by ordinary induction enables us to go through all the natural numbers in order and see that each of them has some property P . The base case gets the process started, and the induction step shows that the process can always be continued from one number to the next. But note that in this process, by the time we check that some natural number n has the property P , we've already checked that *all smaller numbers* have the property. In other words, we already know that $\forall k < n P(k)$. The idea behind strong induction is that we should be allowed to use this information in our proof of $P(n)$.

Let's work out the details of this idea more carefully. Suppose that we have followed the strong induction proof strategy, and we've proven the statement $\forall n [(\forall k < n P(k)) \rightarrow P(n)]$. Then, plugging in 0 for n , we can conclude that $(\forall k < 0 P(k)) \rightarrow P(0)$. But because there are no natural numbers smaller than 0, the statement $\forall k < 0 P(k)$ is vacuously true. Therefore, by modus ponens, $P(0)$ is true. (This explains why the base case doesn't have to be checked separately in a proof by strong induction; the base case $P(0)$ actually follows from the modified form of the induction step used in strong induction.) Similarly, plugging in 1 for n we can conclude that $(\forall k < 1 P(k)) \rightarrow P(1)$. The only natural number smaller than 1 is 0, and we've just shown that $P(0)$ is true, so the statement $\forall k < 1 P(k)$ is true. Therefore, by modus ponens, $P(1)$ is also true. Now plug in 2 for n to get the statement $(\forall k < 2 P(k)) \rightarrow P(2)$. Since $P(0)$ and $P(1)$ are both true, the statement $\forall k < 2 P(k)$ is true, and therefore by modus ponens, $P(2)$ is true. Continuing in this way we can show that $P(n)$ is true for every natural number n , as required. For an alternative justification of the method of strong induction, see exercise 1.

As our first example of the method of strong induction, we prove an important fact of number theory known as the *division algorithm*.¹

Theorem 6.4.1. (Division algorithm) *For all natural numbers n and m , if $m > 0$ then there are natural numbers q and r such that $n = qm + r$ and $r < m$. (The numbers q and r are called the quotient and remainder when n is divided by m .)*

Scratch work

We let m be an arbitrary positive integer and then use strong induction to prove that $\forall n \exists q \exists r (n = qm + r \wedge r < m)$. According to the description of strong induction, this means that we should let n be an arbitrary natural number, assume that $\forall k < n \exists q \exists r (k = qm + r \wedge r < m)$, and prove that $\exists q \exists r (n = qm + r \wedge r < m)$.

Our goal is an existential statement, so we should try to come up with values of q and r with the required properties. If $n < m$ then this is easy because we can just let $q = 0$ and $r = n$. But if $n \geq m$, then this won't work, since we must have $r < m$, so we must do something different in this case. As usual in induction proofs, we look to the inductive hypothesis. The inductive hypothesis starts with $\forall k < n$, so to apply it we should plug in some natural number smaller than n for k , but what should we plug in? The reference to division in the statement of the theorem provides a hint. If we think of division as repeated subtraction, then dividing n by m involves subtracting m from n repeatedly. The first step in this process would be to compute $n - m$, which is a natural number smaller than n . Perhaps we should plug in $n - m$ for k . It's not entirely clear where this will lead, but it's worth a try. In fact, as you'll see in the proof, once we take this step the desired conclusion follows almost immediately.

Notice that we are using the fact that a quotient and remainder exist for some natural number smaller than n to prove that they exist for n , but this smaller number is not $n - 1$, it's $n - m$. This is why we're using strong induction rather than ordinary induction for this proof.

Proof. We let m be an arbitrary positive integer and then proceed by strong induction on n .

Suppose n is a natural number, and for every $k < n$ there are natural numbers q and r such that $k = qm + r$ and $r < m$.

¹ The terminology here is somewhat unfortunate, since what we are calling the division algorithm is actually a theorem and not an algorithm. Nevertheless, this terminology is common.

Case 1. $n < m$. Let $q = 0$ and $r = n$. Then clearly $n = qm + r$ and $r < m$.

Case 2. $n \geq m$. Let $k = n - m < n$ and note that since $n \geq m$, k is a natural number. By the inductive hypothesis we can choose q^\pm and r^\pm such that $k = q^\pm m + r^\pm$ and $r^\pm < m$. Then $n - m = q^\pm m + r^\pm$, so $n = q^\pm m + r^\pm + m = (q^\pm + 1)m + r^\pm$. Thus, if we let $q = q^\pm + 1$ and $r = r^\pm$, then we have $n = qm + r$ and $r < m$, as required. \square

The division algorithm can also be extended to negative integers n , and it can be shown that for every m and n the quotient and remainder q and r are unique. For more on this, see exercise 14.

Our next example is another important theorem of number theory. We used this theorem in our proof in the introduction that there are infinitely many primes. We will have more to say about this theorem in Chapter 7.

Theorem 6.4.2. *Every integer $n > 1$ is either prime or a product of two or more primes.*

Scratch work

We write the goal in the form $\forall n \in \mathbb{N}[n > 1 \rightarrow (n \text{ is prime } \vee n \text{ is a product of primes})]$ and then use strong induction. Thus, our inductive hypothesis is $\forall k < n[k > 1 \rightarrow (k \text{ is prime } \vee k \text{ is a product of primes})]$, and we must prove that $n > 1 \rightarrow (n \text{ is prime } \vee n \text{ is a product of primes})$. Of course, we start by assuming $n > 1$, and according to our strategies for proving disjunctions, a good way to complete the proof would be to assume that n is not prime and prove that it must be a product of primes. Because the assumption that n is not prime means $\exists a \exists b(n = ab \wedge a < n \wedge b < n)$, we immediately use existential instantiation to introduce the new variables a and b into the proof. Applying the inductive hypothesis to a and b now leads to the desired conclusion.

Proof. We use strong induction. Suppose $n > 1$, and suppose that for every integer k , if $1 < k < n$ then k is either prime or a product of primes. Of course, if n is prime then there is nothing to prove, so suppose n is not prime. Then we can choose positive integers a and b such that $n = ab$, $a < n$, and $b < n$. Note that since $a < n = ab$, it follows that $b > 1$, and similarly we must have $a > 1$. Thus, by the inductive hypothesis, each of a and b is either prime or a product of primes. But then since $n = ab$, n is a product of primes. \square

The method of recursion studied in the last section also has a strong form. As an example of this, consider the following definition of a sequence of numbers, called the *Fibonacci numbers*. These numbers were first studied by

the Italian mathematician Leonardo of Pisa (circa 1170–circa 1250), who is better known by the nickname Fibonacci.

$$F_0 = 0;$$

$$F_1 = 1;$$

$$\text{for every } n \geq 2, F_n = F_{n-2} + F_{n-1}.$$

For example, plugging in $n = 2$ in the last equation we find that $F_2 = F_0 + F_1 = 0 + 1 = 1$. Similarly, $F_3 = F_1 + F_2 = 1 + 1 = 2$ and $F_4 = F_2 + F_3 = 1 + 2 = 3$. Continuing in this way leads to the following values:

n	0	1	2	3	4	5	6	7	8	...
F_n	0	1	1	2	3	5	8	13	21	...

Note that, starting with F_2 , each Fibonacci number is computed using, not just the previous number in the sequence, but also the one before that. This is the sense in which the recursion is strong. It shouldn't be surprising, therefore, that proofs involving the Fibonacci numbers often require strong induction rather than ordinary induction.

To illustrate this we'll prove the following remarkable formula for the Fibonacci numbers:

$$F_n = \frac{\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n}{\sqrt{5}}.$$

It is hard at first to believe that this formula is right. After all, the Fibonacci numbers are integers, and it is not at all clear that this formula will give an integer value. And what do the Fibonacci numbers have to do with $\sqrt{5}$? Nevertheless, a proof by strong induction shows that the formula is correct. (To see how this formula could be derived, see exercise 9.)

Theorem 6.4.3. *If F_n is the n th Fibonacci number, then*

$$F_n = \frac{\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n}{\sqrt{5}}.$$

Scratch work

Because F_0 and F_1 are defined separately from F_n for $n \geq 2$, we check the formula for these cases separately. For $n \geq 2$, the definition of F_n suggests that we should use the assumption that the formula is correct for F_{n-2} and F_{n-1} to prove that it is correct for F_n . Because we need to know that the formula works for *two* previous cases, we must use strong induction rather

than ordinary induction. The rest of the proof is straightforward, although the algebra gets a little messy.

Proof. We use strong induction. Let n be an arbitrary natural number, and suppose that for all $k < n$,

$$F_k = \frac{\left(\frac{1+\sqrt{5}}{2}\right)^k - \left(\frac{1-\sqrt{5}}{2}\right)^k}{\sqrt{5}}.$$

Case 1. $n = 0$. Then

$$\begin{aligned} \frac{\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n}{\sqrt{5}} &= \frac{\left(\frac{1+\sqrt{5}}{2}\right)^0 - \left(\frac{1-\sqrt{5}}{2}\right)^0}{\sqrt{5}} \\ &= \frac{1-1}{\sqrt{5}} = 0 = F_0. \end{aligned}$$

Case 2. $n = 1$. Then

$$\begin{aligned} \frac{\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n}{\sqrt{5}} &= \frac{\left(\frac{1+\sqrt{5}}{2}\right)^1 - \left(\frac{1-\sqrt{5}}{2}\right)^1}{\sqrt{5}} \\ &= \frac{\sqrt{5}}{\sqrt{5}} = 1 = F_1. \end{aligned}$$

Case 3. $n \geq 2$. Then applying the inductive hypothesis to $n - 2$ and $n - 1$, we get

$$\begin{aligned} F_n &= F_{n-2} + F_{n-1} \\ &= \frac{\left(\frac{1+\sqrt{5}}{2}\right)^{n-2} - \left(\frac{1-\sqrt{5}}{2}\right)^{n-2}}{\sqrt{5}} + \frac{\left(\frac{1+\sqrt{5}}{2}\right)^{n-1} - \left(\frac{1-\sqrt{5}}{2}\right)^{n-1}}{\sqrt{5}} \\ &= \frac{\left[\left(\frac{1+\sqrt{5}}{2}\right)^{n-2} + \left(\frac{1+\sqrt{5}}{2}\right)^{n-1}\right] - \left[\left(\frac{1-\sqrt{5}}{2}\right)^{n-2} + \left(\frac{1-\sqrt{5}}{2}\right)^{n-1}\right]}{\sqrt{5}} \\ &= \frac{\left(\frac{1+\sqrt{5}}{2}\right)^{n-2} \left[1 + \frac{1+\sqrt{5}}{2}\right] - \left(\frac{1-\sqrt{5}}{2}\right)^{n-2} \left[1 + \frac{1-\sqrt{5}}{2}\right]}{\sqrt{5}}. \end{aligned}$$

Now note that

$$\left(\frac{1+\sqrt{5}}{2}\right)^2 = \frac{1+2\sqrt{5}+5}{4} = \frac{6+2\sqrt{5}}{4} = \frac{3+\sqrt{5}}{2} = 1 + \frac{1+\sqrt{5}}{2},$$

and similarly

$$\left(\frac{1-\sqrt{5}}{2}\right)^2 = 1 + \frac{1-\sqrt{5}}{2}.$$

Substituting into the formula for F_n , we get

$$\begin{aligned} F_n &= \frac{\left(\frac{1+\sqrt{5}}{2}\right)^{n-2} \left(\frac{1+\sqrt{5}}{2}\right)^2 - \left(\frac{1-\sqrt{5}}{2}\right)^{n-2} \left(\frac{1-\sqrt{5}}{2}\right)^2}{\sqrt{5}} \\ &= \frac{\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n}{\sqrt{5}}. \quad \square \end{aligned}$$

Notice that in the proof of Theorem 6.4.3 we had to treat the cases $n = 0$ and $n = 1$ separately. The role that these cases play in the proof is similar to the role played by the base case in a proof by ordinary mathematical induction. Although we have said that proofs by strong induction don't need base cases, it is not uncommon to find some initial cases treated separately in such proofs.

An important property of the natural numbers that is related to mathematical induction is the fact that every nonempty set of natural numbers has a smallest element. This is sometimes called the *well-ordering principle*, and we can prove it using strong induction.

Theorem 6.4.4. (Well-ordering principle) *Every nonempty set of natural numbers has a smallest element.*

Scratch work

Our goal is $\forall S \subseteq \mathbb{N} (S \neq \emptyset \rightarrow S \text{ has a smallest element})$. After letting S be an arbitrary subset of \mathbb{N} , we'll prove the contrapositive of the conditional statement. In other words, we will assume that S has no smallest element and prove that $S = \emptyset$. The way induction comes into it is that, for a set $S \subseteq \mathbb{N}$, to say that $S = \emptyset$ is the same as saying that $\forall n \in \mathbb{N} (n \notin S)$. We'll prove this last statement by strong induction.

Proof. Suppose $S \subseteq \mathbb{N}$, and S does not have a smallest element. We will prove that $\forall n \in \mathbb{N} (n \notin S)$, so $S = \emptyset$. Thus, if $S \neq \emptyset$ then S must have a smallest element.

To prove that $\forall n \in \mathbb{N} (n \notin S)$, we use strong induction. Suppose that $n \in \mathbb{N}$ and $\forall k < n (k \notin S)$. Clearly if $n \in S$ then n would be the smallest element of S , and this would contradict the assumption that S has no smallest element. Therefore $n \notin S$. \square

Sometimes, proofs that could be done by induction are written instead as applications of the well-ordering principle. As an example of the use of the well-ordering principle in a proof, we present a proof that $\sqrt{2}$ is irrational. See exercise 2 for an alternative approach to this proof using strong induction.

Theorem 6.4.5. $\sqrt{2}$ is irrational.

Scratch work

Because *irrational* means “not rational,” our goal is a negative statement, so proof by contradiction is a logical method to use. Thus, we assume $\sqrt{2}$ is rational and try to reach a contradiction. The assumption that $\sqrt{2}$ is rational means that there exist integers p and q such that $p/q = \sqrt{2}$, and since $\sqrt{2}$ is positive, we may as well restrict our attention to positive p and q . Because this is an existential statement, our next step should probably be to let p and q stand for positive integers such that $p/q = \sqrt{2}$. As you will see in the proof, simple algebraic manipulations with the equation $p/q = \sqrt{2}$ do not lead to any obvious contradictions, but they do lead to the conclusion that p and q must both be even. Thus, in the fraction p/q we can cancel a 2 from both numerator and denominator, getting a new fraction with smaller numerator and denominator that is equal to $\sqrt{2}$.

How can we derive a contradiction from this conclusion? The key idea is to note that our reasoning would apply to *any* fraction that is equal to $\sqrt{2}$. Thus, in any such fraction we can cancel a factor of 2 from numerator and denominator, and therefore there can be no smallest possible numerator or denominator for such a fraction. But this would violate the well-ordering principle! Thus, we have our contradiction.

This idea is spelled out more carefully in the following proof, in which we’ve applied the well-ordering principle to the set of all possible denominators of fractions equal to $\sqrt{2}$. We have chosen to put this application of the well-ordering principle at the beginning of the proof, because this seems to give the shortest and most direct proof. Readers of the proof might be puzzled at first about why we’re using the well-ordering principle (unless they’ve read this *scratch work!*), but after the algebraic manipulations with the equation $p/q = \sqrt{2}$ are completed, the contradiction appears almost immediately. This is a good example of how a clever, carefully planned step early in a proof can lead to a wonderful punch line at the end of the proof.

Proof. Suppose that $\sqrt{2}$ is rational. This means that $\exists q \in \mathbb{Z}^+ \exists p \in \mathbb{Z}^+ (p/q = \sqrt{2})$, so the set $S = \{q \in \mathbb{Z}^+ \mid \exists p \in \mathbb{Z}^+ (p/q = \sqrt{2})\}$ is nonempty. By the well-ordering principle we can let q be the smallest element of S . Since $q \in S$, we can choose some $p \in \mathbb{Z}^+$ such that $p/q = \sqrt{2}$. Therefore $p^2/q^2 = 2$, so $p^2 = 2q^2$ and therefore p^2 is even. We now apply the theorem from Example 3.4.3, which says that for any integer x , x is even iff x^2 is even. Since p^2 is even, p must be even, so we can choose some $\bar{p} \in \mathbb{Z}^+$ such that $p = 2\bar{p}$. Therefore $p^2 = 4\bar{p}^2$, and substituting this into the equation $p^2 = 2q^2$ we get

$4\bar{p}^2 = 2q^2$, so $2\bar{p}^2 = q^2$ and therefore q^2 is even. Appealing to Example 3.4.3 again, this means q must be even, so we can choose some $\bar{q} \in \mathbb{Z}^+$ such that $q = 2\bar{q}$. But then $\bar{2} = p/q = (2\bar{p})/(2\bar{q}) = \bar{p}/\bar{q}$, so $\bar{q} \in S$. Clearly $\bar{q} < q$, so this contradicts the fact that q was chosen to be the *smallest* element of S . Therefore $\bar{2}$ is irrational. \square

Exercises

- *1. This exercise gives an alternative way to justify the method of strong induction. All variables in this exercise range over \mathbb{N} . Suppose $P(n)$ is a statement about a natural number n , and suppose that, following the strong induction strategy, we have proven that $\forall n[(\forall k < n P(k)) \rightarrow P(n)]$. Let $Q(n)$ be the statement $\forall k < n P(k)$.
 - (a) Prove $\forall n Q(n) \leftrightarrow \forall n P(n)$ without using induction.
 - (b) Prove $\forall n Q(n)$ by *ordinary* induction. Thus, by part (a), $\forall n P(n)$ is true.
2. Rewrite the proof of Theorem 6.4.5 as a proof by strong induction that $\forall q \in \mathbb{N}[q > 0 \rightarrow \neg \exists p \in \mathbb{Z}^+ (p/q = \bar{2})]$.
3. In this exercise you will give another proof that $\bar{2}$ is irrational. Suppose $\bar{2}$ is rational. As in the proof of Theorem 6.4.5, let $S = \{q \in \mathbb{Z}^+ \mid \exists p \in \mathbb{Z}^+ (p/q = \bar{2})\} \neq \emptyset$, let q be the smallest element of S , and let p be a positive integer such that $p/q = \bar{2}$. Now get a contradiction by showing that $p - q \in S$ and $p - q < q$.
- *4. (a) Prove that $\sqrt{6}$ is irrational.
 (b) Prove that $\bar{2} + \bar{3}$ is irrational.
5. The Martian monetary system uses colored beads instead of coins. A blue bead is worth 3 Martian credits, and a red bead is worth 7 Martian credits. Thus, three blue beads are worth 9 credits, and a blue and red bead together are worth 10 credits, but no combination of blue and red beads is worth 11 credits. Prove that for all $n \geq 12$, there is some combination of blue and red beads that is worth n credits.
6. Suppose that x is a real number, $x \neq 0$, and $x + 1/x$ is an integer. Prove that for all $n \geq 1$, $x^n + 1/x^n$ is an integer.
- *7. Let F_n be the n th Fibonacci number. All variables in this exercise range over \mathbb{N} .
 - (a) Prove that for all n , $\sum_{i=0}^n F_i = F_{n+2} - 1$.
 - (b) Prove that for all n , $\sum_{i=0}^n (F_i)^2 = F_n F_{n+1}$.
 - (c) Prove that for all n , $\sum_{i=0}^n F_{2i+1} = F_{2n+2}$.
 - (d) Find a formula for $\sum_{i=0}^n F_{2i}$ and prove that your formula is correct.

8. Let F_n be the n th Fibonacci number. All variables in this exercise range over \mathbb{N} .
- (a) Prove that for all $m \geq 1$ and all n , $F_{m+n} = F_{m-1}F_n + F_mF_{n+1}$.
- (b) Prove that for all $m \geq 1$ and all $n \geq 1$, $F_{m+n} = F_{m+1}F_{n+1} - F_{m-1}F_{n-1}$.
- (c) Prove that for all n , $(F_n)^2 + (F_{n+1})^2 = F_{2n+1}$ and $(F_{n+2})^2 - (F_n)^2 = F_{2n+2}$.
- (d) Prove that for all m and n , if $m \mid n$ then $F_m \mid F_n$.
- (e) See exercise 18 in Section 6.3 for the meaning of the notation used in this exercise. Prove that for all $n \geq 1$,

$$\begin{aligned} F_{2n-1} &= \binom{2n-2}{0} + \binom{2n-3}{1} + \binom{2n-4}{2} + \cdots + \binom{n-1}{n-1} \\ &= \sum_{i=0}^{n-1} \binom{2n-i-2}{i} \end{aligned}$$

and

$$\begin{aligned} F_{2n} &= \binom{2n-1}{0} + \binom{2n-2}{1} + \binom{2n-3}{2} + \cdots + \binom{n}{n-1} \\ &= \sum_{i=0}^{n-1} \binom{2n-i-1}{i}. \end{aligned}$$

- *9. A sequence of numbers a_0, a_1, a_2, \dots is called a *generalized Fibonacci sequence*, or a *Gibonacci sequence* for short, if for every $n \geq 2$, $a_n = a_{n-2} + a_{n-1}$. Thus, a Gibonacci sequence satisfies the same *recurrence relation* as the Fibonacci numbers, but it may start out differently.
- (a) Suppose c is a real number and $\forall n \in \mathbb{N} (a_n = c^n)$. Prove that a_0, a_1, a_2, \dots is a Gibonacci sequence iff either $c = (1 + \sqrt{5})/2$ or $c = (1 - \sqrt{5})/2$.
- (b) Suppose s and t are real numbers, and for all $n \in \mathbb{N}$,

$$a_n = s \left(\frac{1 + \sqrt{5}}{2} \right)^n + t \left(\frac{1 - \sqrt{5}}{2} \right)^n.$$

Prove that a_0, a_1, a_2, \dots is a Gibonacci sequence.

- (c) Suppose a_0, a_1, a_2, \dots is a Gibonacci sequence. Prove that there are real numbers s and t such that for all $n \in \mathbb{N}$,

$$a_n = s \left(\frac{1 + \sqrt{5}}{2} \right)^n + t \left(\frac{1 - \sqrt{5}}{2} \right)^n.$$

(Hint: First show that there are real numbers s and t such that the formula above is correct for a_0 and a_1 . Then show that with this choice of s and t , the formula is correct for all n .)

10. The *Lucas numbers* (named for the French mathematician Edouard Lucas (1842–1891)) are the numbers L_0, L_1, L_2, \dots defined as follows:

$$L_0 = 2;$$

$$L_1 = 1;$$

$$\text{for every } n \geq 2, L_n = L_{n-2} + L_{n-1}.$$

Find a formula for L_n and prove that your formula is correct. (Hint: Apply exercise 9.)

- *11. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = -1;$$

$$a_1 = 0;$$

$$\text{for every } n \geq 2, a_n = 5a_{n-1} - 6a_{n-2}.$$

Find a formula for a_n and prove that your formula is correct. (Hint: Imitate exercise 9.)

12. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = 0;$$

$$a_1 = 1;$$

$$a_2 = 1;$$

$$\text{for every } n \geq 3, a_n = \frac{1}{2}a_{n-3} + \frac{3}{2}a_{n-2} + \frac{1}{2}a_{n-1}.$$

Prove that for all $n \in \mathbb{N}$, $a_n = F_n$, the n th Fibonacci number.

13. For each positive integer n , let $A_n = \{1, 2, \dots, n\}$, and let $P_n = \{X \in \mathcal{P}(A_n) \mid X \text{ does not contain two consecutive integers}\}$. For example, $P_3 = \{\emptyset, \{1\}, \{2\}, \{3\}, \{1, 3\}\}$; P_3 does not contain the sets $\{1, 2\}$, $\{2, 3\}$, and $\{1, 2, 3\}$ because each contains at least one pair of consecutive integers. Prove that for every n , the number of elements in P_n is F_{n+2} , the $(n + 2)$ th Fibonacci number. (For example, the number of elements in P_3 is $5 = F_5$. Hint: Which elements of P_n contain n ? Which don't? The answers to both questions are related to the elements of P_m , for certain $m < n$.)
14. Suppose n and m are integers and $m > 0$.
- (a) Prove that there are integers q and r such that $n = qm + r$ and $0 \leq r < m$. (Hint: If $n \geq 0$, then this follows from Theorem 6.4.1. If $n < 0$, then start by applying Theorem 6.4.1 to $-n$ and m . Another possibility is to apply Theorem 6.4.1 to $-n - 1$ and m .)

- (b) Prove that the integers q and r in part (a) are unique. In other words, show that if q^\pm and r^\pm are integers such that $n = q^\pm m + r^\pm$ and $0 \leq r^\pm < m$, then $q = q^\pm$ and $r = r^\pm$.
- (c) Prove that for every integer n , exactly one of the following statements is true: $n \equiv 0 \pmod{3}$, $n \equiv 1 \pmod{3}$, $n \equiv 2 \pmod{3}$. (Recall that this notation was introduced in Definition 4.5.9.)
- *15. Suppose k is a positive integer. Prove that there is some positive integer a such that for all $n > a$, $2^n \geq n^k$. (In the language of exercise 19 of Section 5.1, this implies that if $f(n) = n^k$ and $g(n) = 2^n$ then $f \in O(g)$. Hint: By the division algorithm, for any natural number n there are natural numbers q and r such that $n = qk + r$ and $0 \leq r < k$. Therefore $2^n \geq 2^{qk} = (2^q)^k$. To choose a , figure out how large q has to be to guarantee that $2^q \geq n$. You may find Example 6.1.3 useful.)
16. (a) Suppose k is a positive integer, a_1, a_2, \dots, a_k are real numbers, and f_1, f_2, \dots, f_k , and g are all functions from \mathbb{Z}^+ to \mathbb{R} . Also, suppose that f_1, f_2, \dots, f_k are all elements of $O(g)$. (See exercise 19 of Section 5.1 for the meaning of the notation used here.) Define $f : \mathbb{Z}^+ \rightarrow \mathbb{R}$ by the formula $f(n) = a_1 f_1(n) + a_2 f_2(n) + \dots + a_k f_k(n)$. Prove that $f \in O(g)$. (Hint: Use induction on k , and exercise 19(c) of Section 5.1.)
- (b) Let $g : \mathbb{Z}^+ \rightarrow \mathbb{R}$ be defined by the formula $g(n) = 2^n$. Suppose $a_0, a_1, a_2, \dots, a_k$ are real numbers, and define $f : \mathbb{Z}^+ \rightarrow \mathbb{R}$ by the formula $f(n) = a_0 + a_1 n + a_2 n^2 + \dots + a_k n^k$. (Such a function is called a *polynomial*.) Prove that $f \in O(g)$. (Hint: Use exercise 15 and part (a).)
17. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = 1;$$

$$\text{for every } n \in \mathbb{N}, a_{n+1} = 1 + \sum_{i=0}^n a_i.$$

Find a formula for a_n and prove that your formula is correct.

- *18. A sequence a_0, a_1, a_2, \dots is defined recursively as follows:

$$a_0 = 1;$$

$$\text{for every } n \in \mathbb{N}, a_{n+1} = 1 + \frac{1}{a_n}.$$

Find a formula for a_n and prove that your formula is correct. (Hint: These numbers are related to the Fibonacci numbers.)

19. In this problem, you will prove that there are no positive integers a , b , c , and d such that

$$a^2 + 2b^2 = c^2 \quad \text{and} \quad 2a^2 + b^2 = d^2. \quad (*)$$

- (a) Prove that for all integers m and n , if $3 \mid (m^2 + n^2)$ then $3 \mid m$ and $3 \mid n$. (Hint: By exercise 14(c), either $m \equiv 0 \pmod{3}$ or $m \equiv 1 \pmod{3}$ or $m \equiv 2 \pmod{3}$, and also either $n \equiv 0 \pmod{3}$ or $n \equiv 1 \pmod{3}$ or $n \equiv 2 \pmod{3}$. This gives nine possibilities. Determine which of these possibilities are compatible with the assumption that $3 \mid (m^2 + n^2)$.)

Now suppose there are positive integers satisfying (*). Let

$$S = \{d \in \mathbb{Z}^+ \mid \exists a \in \mathbb{Z}^+ \exists b \in \mathbb{Z}^+ \exists c \in \mathbb{Z}^+ (a^2 + 2b^2 = c^2 \wedge 2a^2 + b^2 = d^2)\}.$$

Then $S \neq \emptyset$, so by the well-ordering principle we can let d be the smallest element of S . Let a , b , and c be positive integers satisfying (*).

- (b) Prove that $3 \mid c$ and $3 \mid d$. (Hint: Add the two equations in (*) and then apply part (a).)
- (c) Prove that $3 \mid a$ and $3 \mid b$. (Hint: Add the two equations in (*) and then apply part (b).)
- (d) Show that there is an element of S that is smaller than d , which contradicts our choice of d . (Hint: Combine parts (b) and (c).)
20. The number $(1 + \sqrt{5})/2$ that appears in the formula for the Fibonacci numbers in Theorem 6.4.3 is called the *golden ratio*. It is usually denoted φ , and it comes up in numerous contexts in mathematics, art, and the natural world. In this exercise you will investigate a few of the mathematical contexts in which φ arises.
- (a) In Figure 6.14, $AEFD$ is a square. Show that if the ratio of the length of the longer side of rectangle $BCFE$ to its shorter side is the same as the ratio of the length of the longer side of rectangle $ABCD$ to its shorter side, then that ratio is φ .
- (b) Show that $\cos(36^\circ) = \varphi/2$. (Hint: Let $x = \cos(36^\circ)$. First show that $\cos(108^\circ) = -\cos(72^\circ)$. Then use trigonometric identities to express $\cos(108^\circ)$ and $\cos(72^\circ)$ in terms of x . Substitute into the equation $\cos(108^\circ) = -\cos(72^\circ)$ to get an equation involving x and then solve the equation.)
- (c) In Figure 6.15, $ABCDE$ is a regular pentagon with side length 1. Show that the length of the diagonal AC is φ . (Hint: First find the angles in triangle ABC ; you may find Example 6.2.3 helpful for this. Then use part (b).)

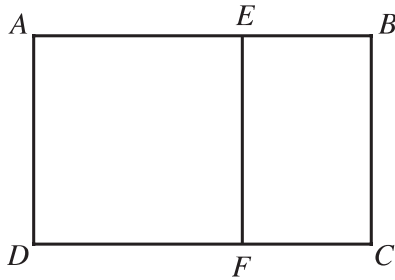


Figure 6.14.

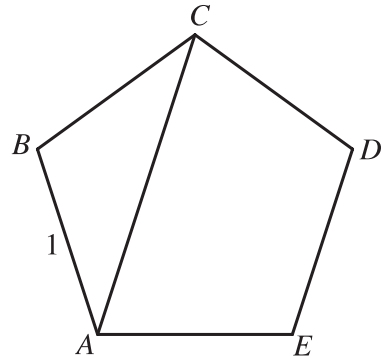


Figure 6.15.

*21. The commutative law for multiplication says that for any numbers a and b , $ab = ba$. The associative law says that for any numbers a , b , and c , $(ab)c = a(bc)$. In this problem you will show that, although these laws are stated for products of two or three numbers, they can be used to justify reordering and regrouping the terms in a product of any list of numbers in any way.

- (a) Use the commutative and associative laws to show that for any numbers a , b , c , and d , $(ab)(cd) = c((ad)b)$.
- (b) Let us say that the *left-grouped product* of a list of numbers a_1, a_2, \dots, a_n is the product in which the terms are grouped as follows:

$$(\cdots(((a_1 a_2) a_3) a_4) \cdots a_{n-1}) a_n.$$

More precisely, we can define the left-grouped product recursively as follows: For a list consisting of a single number a_1 , the left-grouped product is a_1 . If the left-grouped product of a_1, a_2, \dots, a_n is p , then the left-grouped product of $a_1, a_2, \dots, a_n, a_{n+1}$ is pa_{n+1} . Use the associative law to show that any product of a list of numbers a_1, a_2, \dots, a_n (with the terms in that order, but with parentheses inserted to group the terms in any way) is equal to the left-grouped product.

- (c) Use the commutative and associative laws to show that any two products of the numbers a_1, a_2, \dots, a_n , with the terms in any order and grouped in any way, are equal.

6.5. Closures Again

In Section 5.4 we promised to use mathematical induction to give an alternative treatment of closures of sets under functions. In this section we fulfill this promise.

Recall that if $f : A \rightarrow A$ and $B \subseteq A$, then the closure of B under f is the smallest set $C \subseteq A$ such that $B \subseteq C$ and C is closed under f . In this section we'll find this set C by starting with B and then adding only those elements of A that *must* be added if we want to end up with a set that is closed under f . We begin with a sketchy description of how we'll do this, motivated by the examples in Section 5.4. Then we'll use recursion and induction to make this sketchy idea precise and prove that it works.

As we saw in the examples in Section 5.4, if we want to find a set $C \subseteq A$ such that $B \subseteq C$ and C is closed under f , then for every $x \in B$, we must have $f(x) \in C$. In other words, $\{f(x) \mid x \in B\} \subseteq C$. Recall from Section 5.5 that $\{f(x) \mid x \in B\}$ is called the image of B under f , and is denoted $f(B)$. So we will need to have $f(B) \subseteq C$. But then similar reasoning implies that the image of $f(B)$ under f must also be a subset of C ; in other words, $f(f(B)) \subseteq C$.

Continuing in this way leads to a sequence of sets that must be contained in C : B , $f(B)$, $f(f(B))$, and so on. We will prove that putting these sets together by taking their union will give us the closure of B under f . In other words, if we let $B_0 = B$, $B_1 = f(B)$, $B_2 = f(f(B))$, \dots , then the closure of B under f is $B_0 \cup B_1 \cup B_2 \cup \dots$. The use of ellipses in our description of this process suggests that to make it precise, we should use induction and recursion. This is what we do in the statement and proof of our next theorem.

Theorem 6.5.1. *Suppose $f : A \rightarrow A$ and $B \subseteq A$. Let the sets B_0, B_1, B_2, \dots be defined recursively as follows:*

$$\begin{aligned} B_0 &= B; \\ \text{for all } n \in \mathbb{N}, B_{n+1} &= f(B_n). \end{aligned}$$

Then the closure of B under f is the set $\bigcup_{n \in \mathbb{N}} B_n$.

Proof. Let $C = \bigcup_{n \in \mathbb{N}} B_n$. Since $f : A \rightarrow A$, it is not hard to see that each set B_n is a subset of A , and therefore $C \subseteq A$. According to the definition of closure, we must check that $B \subseteq C$, C is closed under f , and for every set $D \subseteq A$, if $B \subseteq D$ and D is closed under f then $C \subseteq D$.

The first of these holds because $B = B_0 \subseteq \bigcup_{n \in \mathbb{N}} B_n = C$. For the second, suppose that $x \in C$. Then by the definition of C , we can choose some $m \in \mathbb{N}$ such that $x \in B_m$. But then $f(x) \in f(B_m) = B_{m+1}$, so $f(x) \in \bigcup_{n \in \mathbb{N}} B_n = C$. Since x was an arbitrary element of C , this shows that C is closed under f .

Finally, suppose that $B \subseteq D \subseteq A$ and D is closed under f . We must show that $C \subseteq D$, and by the definition of C it suffices to show that $\forall n \in \mathbb{N} (B_n \subseteq D)$. We prove this by induction on n .

The base case holds because we have $B_0 = B \subseteq D$ by assumption. For the induction step, suppose that $n \in \mathbb{N}$ and $B_n \subseteq D$. Now suppose $x \in B_{n+1}$. By the definition of B_{n+1} this means $x \in f(B_n)$, so there is some $b \in B_n$ such that $x = f(b)$. But by the inductive hypothesis, $B_n \subseteq D$, so $b \in D$, and since D is closed under f it follows that $x = f(b) \in D$. Since x was an arbitrary element of B_{n+1} , this shows that $B_{n+1} \subseteq D$. \square

Commentary. Because the proof must refer to the set $\bigcup_{n \in \mathbb{N}} B_n$ often, it is convenient to give this set the name C right at the beginning of the proof. The proof claims that it is not hard to see that for every $n \in \mathbb{N}$, $B_n \subseteq A$, and therefore $C \subseteq A$. As usual, if you don't see why this is true you should work out the details of the proof yourself. (You might try proving $\forall n \in \mathbb{N}(B_n \subseteq A)$ by mathematical induction.) The definition of closure then tells us that we must prove three statements: $B \subseteq C$, C is closed under f , and for all $D \subseteq A$, if $B \subseteq D$ and D is closed under f then $C \subseteq D$. Of course, we prove them one at a time.

The proof of the first of these statements, $B \subseteq C$, is also not worked out in detail. If you have trouble following it, see exercise 8 in Section 3.3. The second statement we must prove says that C is closed under f , and the proof is based on the definition of closed: we let x be arbitrary, assume $x \in C$, and prove that $f(x) \in C$. According to the definition of C , the statement $x \in C$ means $\exists n \in \mathbb{N}(x \in B_n)$, so we immediately introduce the variable m to stand for a natural number such that $x \in B_m$. The goal $f(x) \in C$ is also an existential statement, so to prove it we must find a natural number k such that $f(x) \in B_k$. The proof shows that $k = m + 1$ works.

Finally, to prove the third statement we use the natural strategy of letting D be an arbitrary set, assuming $B \subseteq D \subseteq A$ and D is closed under f , and then proving that $C \subseteq D$. Once again, if you don't see why the conclusion $C \subseteq D$ follows from $\forall n \in \mathbb{N}(B_n \subseteq D)$, as claimed in the proof, you should work out the details of the proof yourself. This last statement is proven by induction, as you might expect based on the recursive nature of the definition of B_n . For the induction step, we let n be an arbitrary natural number, assume that $B_n \subseteq D$, and prove that $B_{n+1} \subseteq D$. To prove that $B_{n+1} \subseteq D$ we take an arbitrary element of B_{n+1} and prove that it must be an element of D . Writing out the recursive definition of B_{n+1} gives us a way to use the inductive hypothesis, which, as usual, is the key to completing the induction step.

We end this chapter by returning once again to one of the proofs in the introduction. Recall that in our first proof in the introduction we used the formula

$$(2^b - 1) \cdot (1 + 2^b + 2^{2b} + \cdots + 2^{(a-1)b}) = 2^{ab} - 1.$$

We discussed this proof again in Section 3.7 and promised to give a more careful proof of this formula after we had discussed mathematical induction. We are ready now to give this more careful proof. Of course, we can also state the formula more precisely now, using summation notation.

Theorem 6.5.2. For all positive integers a and b ,

$$(2^b - 1) \cdot \sum_{k=0}^{a-1} 2^{kb} = 2^{ab} - 1.$$

Proof. We let b be an arbitrary positive integer and then proceed by induction on a .

Base case: When $a = 1$ we have

$$\begin{aligned} (2^b - 1) \cdot \sum_{k=0}^{a-1} 2^{kb} &= (2^b - 1) \cdot \sum_{k=0}^0 2^{kb} \\ &= (2^b - 1) \cdot 1 \\ &= 2^{ab} - 1. \end{aligned}$$

Induction step: Suppose $a \geq 1$ and $(2^b - 1) \cdot \sum_{k=0}^{a-1} 2^{kb} = 2^{ab} - 1$. Then

$$\begin{aligned} (2^b - 1) \cdot \sum_{k=0}^a 2^{kb} &= (2^b - 1) \cdot \left(\sum_{k=0}^{a-1} 2^{kb} + 2^{ab} \right) \\ &= (2^b - 1) \cdot \sum_{k=0}^{a-1} 2^{kb} + 2^b \cdot 2^{ab} - 2^{ab} \\ &= 2^{ab} - 1 + 2^{b+ab} - 2^{ab} \quad (\text{inductive hypothesis}) \\ &= 2^{(a+1)b} - 1. \quad \square \end{aligned}$$

Exercises

- *1. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = x + 1$, and let $B = \{0\}$. We saw in part 2 of Example 5.4.4 that the closure of B under f is \mathbb{N} . What are the sets B_0, B_1, B_2, \dots defined in Theorem 6.5.1?
2. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x) = x - 1$, and let $B = \mathbb{N}$. We saw after Example 5.4.2 that the closure of B under f is \mathbb{Z} . What are the sets B_0, B_1, B_2, \dots defined in Theorem 6.5.1?

3. Suppose \mathcal{F} is a set of functions from A to A and $B \subseteq A$. In exercise 12 of Section 5.4 we defined the closure of B under \mathcal{F} to be the smallest set $C \subseteq A$ such that $B \subseteq C$ and for every $f \in \mathcal{F}$, C is closed under f . Let the sets B_0, B_1, B_2, \dots be defined recursively as follows:

$$B_0 = B;$$

$$\text{for all } n \in \mathbb{N}, B_{n+1} = \bigcup_{f \in \mathcal{F}} f(B_n).$$

Prove that $\bigcup_{n \in \mathbb{N}} B_n$ is the closure of B under \mathcal{F} .

- *4. For each natural number n , let $f_n : \mathcal{P}(\mathbb{N}) \rightarrow \mathcal{P}(\mathbb{N})$ be defined by the formula $f_n(X) = X \cup \{n\}$, and let $\mathcal{F} = \{f_n \mid n \in \mathbb{N}\}$. Let $B = \{\emptyset\}$. In part (b) of exercise 12 in Section 5.4 you showed that the closure of B under \mathcal{F} is the set of all finite subsets of \mathbb{N} . What are the sets B_0, B_1, B_2, \dots defined in exercise 3?
- *5. Let $f : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{N}$ be defined by the formula $f(x, y) = xy$. Let P be the set of all prime numbers. What is the closure of P under f ?
6. Consider the following incorrect theorem:

Incorrect Theorem. Suppose $f : A \times A \rightarrow A$ and $B \subseteq A$. Let the sets B_0, B_1, B_2, \dots be defined recursively as follows:

$$B_0 = B;$$

$$\text{for all } n \in \mathbb{N}, B_{n+1} = f(B_n \times B_n).$$

Then the closure of B under f is the set $\bigcup_{n \in \mathbb{N}} B_n$.

What's wrong with the following proof of the theorem?

Proof. Let $C = \bigcup_{n \in \mathbb{N}} B_n$. It is not hard to see that each set B_n is a subset of A , so $C \subseteq A$, and $B = B_0 \subseteq C$.

To see that C is closed under f , suppose $x, y \in C$. Then by the definition of C , there is some $m \in \mathbb{N}$ such that $x, y \in B_m$. Therefore $f(x, y) \in f(B_m \times B_m) = B_{m+1}$, so $f(x, y) \in \bigcup_{n \in \mathbb{N}} B_n = C$.

Finally, suppose $B \subseteq D \subseteq A$ and D is closed under f . To prove that $C \subseteq D$, it will suffice to prove that $\forall n \in \mathbb{N} (B_n \subseteq D)$. We prove this by induction. The base case holds because $B_0 = B \subseteq D$ by assumption. For the induction step, suppose $B_n \subseteq D$ and let $x \in B_{n+1}$ be arbitrary. By the definition of B_{n+1} this means that $x = f(a, b)$ for some $a, b \in B_n$. By the inductive hypothesis, $B_n \subseteq D$, so $a, b \in D$, and since D is closed under f , it follows that $x = f(a, b) \in D$. Therefore $B_{n+1} \subseteq D$. \square

- *7. Let $f : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ be defined by the formula $f(x, y) = xy$, and let $B = \{x \in \mathbb{R} \mid -2 \leq x \leq 0\}$. In this problem you will show that f and B are a counterexample to the incorrect theorem in exercise 6.
- What are the sets B_0, B_1, B_2, \dots defined in the incorrect theorem?
 - Show that $\bigcup_{n \in \mathbb{N}} B_n$ is not the closure of B under f . Which of the three properties in the definition of closure (Definition 5.4.8) does not hold?
 - What is the closure of B under f ?
8. Suppose $f : A \times A \rightarrow A$ and $B \subseteq A$. Let the sets B_0, B_1, B_2, \dots be defined recursively as follows:

$$B_0 = B;$$

$$\text{for all } n \in \mathbb{N}, B_{n+1} = B_n \cup f(B_n \times B_n).$$

- Prove that for all natural numbers m and n , if $m \leq n$ then $B_m \subseteq B_n$. (Hint: Let m be arbitrary and then use induction on n .)
 - Prove that $\bigcup_{n \in \mathbb{N}} B_n$ is the closure of B under f .
9. Suppose $f : A \rightarrow A$ and f is a constant function; in other words, there is some $c \in A$ such that for all $x \in A$, $f(x) = c$. Suppose $B \subseteq A$. What are the sets B_0, B_1, B_2, \dots defined in Theorem 6.5.1? What is the closure of B under f ?
- *10. There is another proof in the introduction that could be written more rigorously using induction. Recall that in the proof of Theorem 4 in the introduction we used the fact that if n is a positive integer, $x = (n + 1)! + 2$, and $0 \leq i \leq n - 1$, then $(i + 2) \mid (x + i)$. Use induction to prove this. (We used this fact to show that $x + i$ is not prime.)

The remaining exercises in this section will use the following definition. Suppose $R \subseteq A \times A$. Let R^1, R^2, R^3, \dots be defined recursively as follows:

$$R^1 = R;$$

$$\text{for all } n \in \mathbb{Z}^+, R^{n+1} = R^n \circ R.$$

Clearly for every positive integer n , R^n is a relation on A .

- Suppose $R \subseteq A \times A$. Prove that for all positive integers m and n , $R^{m+n} = R^m \circ R^n$.
- Suppose $f : A \rightarrow A$.
 - Prove that for every positive integer n , $f^n : A \rightarrow A$.
 - Suppose $B \subseteq A$, and let the sets B_0, B_1, B_2, \dots be defined as in Theorem 6.5.1. Prove that for every positive integer n , $f^n(B) = B_n$.

13. Suppose $f : A \rightarrow A$ and $a \in A$. We say that a is a *periodic point* for f if there is some positive integer n such that $f^n(a) = a$.
- Show that if a is a periodic point for f then the closure of $\{a\}$ under f is a finite set.
 - Suppose the closure of $\{a\}$ under f is a finite set. Must a be a periodic point for f ?
- *14. Suppose $R \subseteq A \times A$ and let $T = \bigcup_{n \in \mathbb{Z}^+} R^n$. Prove that T is the transitive closure of R . (See exercise 25 of Section 4.4 for the definition of transitive closure.)
15. Suppose R and S are relations on A and $R \subseteq S$. Prove that for every positive integer n , $R^n \subseteq S^n$.
- *16. Suppose R and S are relations on A and n is a positive integer.
- What is the relationship between $R^n \cap S^n$ and $(R \cap S)^n$? Justify your conclusions with proofs or counterexamples.
 - What is the relationship between $R^n \cup S^n$ and $(R \cup S)^n$? Justify your conclusions with proofs or counterexamples.
17. Suppose R is a relation on A and T is the transitive closure of R . If $(a, b) \in T$, then by exercise 14 there is some positive integer n such that $(a, b) \in R^n$, and therefore by the well-ordering principle (Theorem 6.4.4), there must be a smallest such n . We define the *distance* from a to b to be the smallest positive integer n such that $(a, b) \in R^n$, and we write $d(a, b)$ to denote this distance.
- Suppose that $(a, b) \in T$ and $(b, c) \in T$ (and therefore $(a, c) \in T$, since T is transitive). Prove that $d(a, c) \leq d(a, b) + d(b, c)$.
 - Suppose $(a, c) \in T$ and $0 < m < d(a, c)$. Prove that there is some $b \in A$ such that $d(a, b) = m$ and $d(b, c) = d(a, c) - m$.
- *18. Suppose R is a relation on A . For each positive integer n , let $J_n = \{0, 1, 2, \dots, n\}$. If $a \in A$ and $b \in A$, we will say that a function $f : J_n \rightarrow A$ is an *R -path from a to b of length n* if $f(0) = a$, $f(n) = b$, and for all $i < n$, $(f(i), f(i+1)) \in R$.
- Prove that for all $n \in \mathbb{Z}^+$, $R^n = \{(a, b) \in A \times A \mid \text{there is an } R\text{-path from } a \text{ to } b \text{ of length } n\}$.
 - Prove that the transitive closure of R is $\{(a, b) \in A \times A \mid \text{there is an } R\text{-path from } a \text{ to } b \text{ (of any length)}\}$.
19. Suppose R is a relation on A . In this problem we find a relationship between distance, as defined in exercise 17, and R -paths, which were discussed in exercise 18.
- Suppose $d(a, b) = n$ and $a \not\cong b$. Prove that if f is an R -path from a to b of length n , then f is one-to-one.

- (b) Suppose $d(a, a) = n$. Prove that if f is an R -path from a to a of length n , then $\forall i < n \forall j < n (f(i) = f(j) \rightarrow i = j)$. (In other words, f is one-to-one, except for the fact that $f(0) = f(n) = a$.)
20. Suppose R is a relation on A , T is the transitive closure of R , and A has m elements. Prove that

$$T = R \cup R^2 \cup \cdots \cup R^m = \bigcup \{R^n \mid 1 \leq n \leq m\}.$$

(Hint: Use exercise 19.)

7

Number Theory

7.1. Greatest Common Divisors

In this chapter we will give an introduction to number theory: the study of the positive integers $1, 2, 3, \dots$. It may seem that these numbers are so easy to understand that investigating them will not lead to any interesting discoveries. But we will see in this chapter that simple questions about the positive integers can be surprisingly difficult to resolve, and the answers sometimes reveal subtle and unexpected patterns. Of course, the only way to be sure of the answers to our questions will be to give proofs, using the methods we have developed in earlier chapters of this book. By now, you should be fairly proficient at reading and writing proofs, so we'll give less discussion of the strategy behind proofs and leave more proofs as exercises.

We begin with a concept that is fundamental to all of number theory, the *greatest common divisor* of a pair of positive integers.

Definition 7.1.1. Suppose a is a positive integer. The *divisors* of a are the positive integers that divide a . We will denote the set of divisors of a by $D(a)$. Thus,

$$D(a) = \{d \in \mathbb{Z}^+ \mid d \text{ divides } a\} = \{d \in \mathbb{Z}^+ \mid \exists k \in \mathbb{Z}(a = kd)\}.$$

If a and b are two positive integers, then $D(a) \cap D(b)$ is the set of positive integers that divide both a and b – the *common divisors* of a and b . The largest element of this set is called the *greatest common divisor* of a and b , and is denoted $\gcd(a, b)$.

For example, $D(18) = \{1, 2, 3, 6, 9, 18\}$ and $D(12) = \{1, 2, 3, 4, 6, 12\}$, so the set of common divisors of 18 and 12 is $D(18) \cap D(12) = \{1, 2, 3, 6\}$. The largest of these common divisors is 6, so $\gcd(18, 12) = 6$.

Notice that 1 and a are always elements of $D(a)$, and $D(a)$ is a finite set, since $D(a) \subseteq \{1, 2, \dots, a\}$. Thus, for any two positive integers a and b , $D(a) \cap D(b)$ is a finite set that is nonempty (since it contains 1), so it has a largest element (see exercise 3 in Section 6.2). In other words, $\gcd(a, b)$ is always defined.

Given two positive integers a and b , how can we compute $\gcd(a, b)$? One possibility is to start by listing all elements of $D(a)$ and $D(b)$, as we did when we computed $\gcd(18, 12)$. But if a and b are large then this may be impractical. Fortunately, there is a better way.

Since $D(a) \cap D(b) = D(b) \cap D(a)$, $\gcd(a, b) = \gcd(b, a)$. In other words, in our notation for the greatest common divisor of two positive integers, it doesn't matter which integer we list first. We will often find it convenient to list the larger integer first; in particular, when computing $\gcd(a, b)$, we will assume that $a \geq b$.

One helpful observation is that if $b \mid a$ then $\gcd(a, b) = b$. This is because b is the largest element of $D(b)$. If $b \mid a$ then b is also an element of $D(a)$, so it must be the largest element of $D(a) \cap D(b)$. This suggests that to compute $\gcd(a, b)$, where $a \geq b$, we could start by dividing a by b . According to the division algorithm (Theorem 6.4.1), if we divide a by b we will find natural numbers q and r (the quotient and remainder) such that $a = qb + r$ and $r < b$. If $r = 0$, then $a = qb$, so $b \mid a$ and therefore $\gcd(a, b) = b$.

But what if $r > 0$? How can we compute $\gcd(a, b)$ in that case? We claim that in that case, $D(a) \cap D(b) = D(b) \cap D(r)$. Let's prove this fact. Suppose first that $d \in D(a) \cap D(b)$. Then $d \mid a$ and $d \mid b$, so there are integers j and k such that $a = jd$ and $b = kd$. But then from the equation $a = qb + r$ we get $r = a - qb = jd - qkd = (j - qk)d$, so $d \mid r$. Therefore $d \in D(r)$, and since we also have $d \in D(b)$, $d \in D(b) \cap D(r)$. A similar argument shows that if $d \in D(b) \cap D(r)$ then $d \in D(a) \cap D(b)$, so $D(a) \cap D(b) = D(b) \cap D(r)$. By the definition of greatest common divisor, it follows that $\gcd(a, b) = \gcd(b, r)$.

Let's summarize what we've learned with a theorem.

Theorem 7.1.2. *Suppose a and b are positive integers with $a \geq b$. Let r be the remainder when we divide a by b . If $r = 0$ then $\gcd(a, b) = b$, and if $r > 0$ then $\gcd(a, b) = \gcd(b, r)$.*

Now, if $r > 0$, does this theorem help us to compute $\gcd(a, b)$? One reason to think it might is that $b \leq a$ and $r < b$, so it is probably easier to compute $\gcd(b, r)$ than $\gcd(a, b)$. Thus, the theorem allows us to replace our original problem of computing $\gcd(a, b)$ with the potentially easier problem of computing $\gcd(b, r)$.

This should remind you of our study of recursion in Chapter 6. A recursive definition of a function f with domain \mathbb{Z}^+ gives us a method of finding $f(n)$ by using the values of $f(k)$ for $k < n$. By using this method repeatedly, we are able to compute $f(n)$ for any n . Perhaps if we apply our division method repeatedly we will be able to compute $\gcd(a, b)$.

Before working out this idea in general, let's try it out in an example. Suppose we want to find $\gcd(672, 161)$. We begin by dividing $a = 672$ by $b = 161$, which gives us a quotient $q = 4$ and remainder $r = 28$:

$$672 = 4 \cdot 161 + 28.$$

By Theorem 7.1.2, we conclude that $\gcd(672, 161) = \gcd(a, b) = \gcd(b, r) = \gcd(161, 28)$. So let's try to compute $\gcd(161, 28)$, which seems like an easier problem.

How do we solve this problem? By the same method, of course! We start by dividing 161 by 28, to get a quotient of 5 and remainder of 21:

$$161 = 5 \cdot 28 + 21.$$

Applying Theorem 7.1.2 again, we see that $\gcd(161, 28) = \gcd(28, 21)$. To compute $\gcd(28, 21)$ we divide 28 by 21:

$$28 = 1 \cdot 21 + 7.$$

Thus $\gcd(28, 21) = \gcd(21, 7)$. But $21 = 3 \cdot 7 + 0$, so $7 \mid 21$ and therefore $\gcd(21, 7) = 7$. We conclude that this is the answer to our original problem: $\gcd(672, 161) = 7$.

We can summarize our calculations with the following list of equations:

$$672 = 4 \cdot 161 + 28,$$

$$161 = 5 \cdot 28 + 21,$$

$$28 = 1 \cdot 21 + 7,$$

$$21 = 3 \cdot 7 + 0.$$

These calculations produce a decreasing list of natural numbers: 672, 161, 28, 21, 7, 0. The first two numbers are our original positive integers a and b , and after that every number is the remainder when dividing the previous number into the one before that. The greatest common divisors of all adjacent pairs of positive integers in the list are the same. The calculation ended when we got a remainder of 0, and the last nonzero number in the list is $7 = \gcd(21, 7) = \gcd(672, 161)$.

Now let's generalize. Suppose we want to find $\gcd(a, b)$, where a and b are positive integers and $a \geq b$. We define a sequence of natural numbers

r_0, r_1, r_2, \dots recursively as follows. To start off the sequence, we let $r_0 = a$ and $r_1 = b$; notice that $r_0 \geq r_1$. Then we let q_2 and r_2 be the quotient and remainder when we divide r_0 by r_1 :

$$r_0 = q_2 \cdot r_1 + r_2, \quad 0 \leq r_2 < r_1.$$

If $r_2 \neq 0$, then we divide r_1 by r_2 to get a quotient q_3 and remainder r_3 . In general, having computed r_0, r_1, \dots, r_n , if $r_n \neq 0$ then we divide r_{n-1} by r_n to produce a quotient and remainder of q_{n+1} and r_{n+1} :

$$r_{n-1} = q_{n+1} \cdot r_n + r_{n+1}, \quad 0 \leq r_{n+1} < r_n.$$

The calculation stops when we reach a remainder of 0.

Are we sure that we will eventually have a remainder of 0? Well, if we don't, then the sequence of divisions will go on forever, and we will end up with an infinite sequence of positive integers r_0, r_1, r_2, \dots with $r_0 \geq r_1 > r_2 > \dots$. This is impossible, since $\{r_0, r_1, r_2, \dots\}$ would be a nonempty set of natural numbers with no smallest element, contradicting the well-ordering principle (Theorem 6.4.4). Thus, we must eventually have a remainder of 0.

Suppose m is the largest index for which $r_m \neq 0$. Then $r_{m+1} = 0$, and there are m divisions, which can be summarized as follows:

$$\begin{aligned} r_0 &= q_2 \cdot r_1 + r_2, \\ r_1 &= q_3 \cdot r_2 + r_3, \\ &\vdots \\ r_{m-1} &= q_{m+1} \cdot r_m + 0. \end{aligned}$$

Applying Theorem 7.1.2 to each division, we conclude that

$$\gcd(a, b) = \gcd(r_0, r_1) = \gcd(r_1, r_2) = \dots = \gcd(r_{m-1}, r_m) = r_m.$$

Thus, $\gcd(a, b)$ is the last nonzero value in the sequence r_0, r_1, r_2, \dots .

This method of computing the greatest common divisor of two positive integers is called the *Euclidean algorithm*. It is named for Euclid, who described it in Book VII of his *Elements*.

Example 7.1.3. Find the greatest common divisor of 444 and 1392.

Solution

We apply the Euclidean algorithm with $a = 1392$ and $b = 444$. The calculations are shown in Figure 7.1. Each equation in the column "Division" shows the division calculation that leads to the quotient and remainder in

the next row. Since the last nonzero remainder is 12, we conclude that $\gcd(1392, 444) = 12$.

n	q_n	r_n	Division
0		1392	
1		444	$1392 = 3 \cdot 444 + 60$
2	3	60	$444 = 7 \cdot 60 + 24$
3	7	24	$60 = 2 \cdot 24 + 12$
4	2	12	$24 = 2 \cdot 12 + 0$
5	2	0	

Figure 7.1. Calculation of $\gcd(1392, 444)$ by Euclidean algorithm.

The inputs to the Euclidean algorithm in the last example were $a = 1392$ and $b = 444$. It is instructive to see how the remainders we computed are related to these inputs. Rearranging the first equation in the “Division” column in Figure 7.1, we see that

$$r_2 = 60 = 1392 - 3 \cdot 444 = a - 3b.$$

Similarly, from the next equation we get

$$r_3 = 24 = 444 - 7 \cdot 60 = b - 7r_2 = b - 7(a - 3b) = -7a + 22b,$$

and the third equation gives us

$$r_4 = 12 = 60 - 2 \cdot 24 = r_2 - 2r_3 = (a - 3b) - 2(-7a + 22b) = 15a - 47b.$$

We see that each remainder can be written in the form $sa + tb$, for some integers s and t . We say that each remainder is a *linear combination* of a and b . But the last nonzero remainder is the greatest common divisor of a and b , so we conclude that $\gcd(a, b)$ is a linear combination of a and b : $\gcd(a, b) = r_4 = 15a - 47b$. Working out this reasoning in general proves our next theorem.

Theorem 7.1.4. *For all positive integers a and b there are integers s and t such that $\gcd(a, b) = sa + tb$.*

Proof. As usual, we may assume $a \geq b$; if not, we can simply reverse the values of a and b . Let r_0, r_1, \dots, r_{m+1} be the sequence of numbers produced by the Euclidean algorithm, where $r_m \neq 0$ and $r_{m+1} = 0$. We claim that for

every natural number $n \leq m$, r_n is a linear combination of a and b . In other words, for every natural number n , if $n \leq m$ then there are integers s_n and t_n such that $r_n = s_n a + t_n b$. We prove this statement by strong induction.

Suppose n is a natural number and $n \leq m$, and suppose also that for all $k < n$, r_k is a linear combination of a and b . We now consider three cases.

Case 1: $n = 0$. Then $r_n = r_0 = a = s_0 a + t_0 b$, where $s_0 = 1$ and $t_0 = 0$.

Case 2: $n = 1$. Then $r_n = r_1 = b = s_1 a + t_1 b$, where $s_1 = 0$ and $t_1 = 1$.

Case 3: $n \geq 2$. Then r_n is the remainder when r_{n-2} is divided by r_{n-1} :

$$r_{n-2} = q_n \cdot r_{n-1} + r_n.$$

By the inductive hypothesis, there are integers s_{n-1} , s_{n-2} , t_{n-1} , and t_{n-2} such that

$$r_{n-1} = s_{n-1} a + t_{n-1} b, \quad r_{n-2} = s_{n-2} a + t_{n-2} b.$$

Therefore

$$\begin{aligned} r_n &= r_{n-2} - q_n \cdot r_{n-1} = (s_{n-2} a + t_{n-2} b) - q_n (s_{n-1} a + t_{n-1} b) \\ &= (s_{n-2} - q_n s_{n-1}) a + (t_{n-2} - q_n t_{n-1}) b, \end{aligned}$$

so $r_n = s_n a + t_n b$, where $s_n = s_{n-2} - q_n s_{n-1}$ and $t_n = t_{n-2} - q_n t_{n-1}$.

This completes the inductive proof that for every $n \leq m$, r_n is a linear combination of a and b . Applying this statement in the case $n = m$, we conclude that $\gcd(a, b) = r_m$ is a linear combination of a and b . \square

For an alternative proof of Theorem 7.1.4, see exercise 4. One advantage of the proof we have given is that it provides us with a method to find integers s and t such that $\gcd(a, b) = sa + tb$. While carrying out the Euclidean algorithm, we can compute numbers s_n and t_n recursively by using the formulas:

$$\begin{aligned} s_0 &= 1, & t_0 &= 0, \\ s_1 &= 0, & t_1 &= 1, \\ \text{for } n \geq 2, & s_n &= s_{n-2} - q_n s_{n-1}, & t_n &= t_{n-2} - q_n t_{n-1}. \end{aligned}$$

If m is the largest index for which $r_m \neq 0$, then $\gcd(a, b) = r_m = s_m a + t_m b$. The version of the Euclidean algorithm in which we keep track of these extra numbers s_n and t_n is called the *extended Euclidean algorithm*.

Example 7.1.5. Use the extended Euclidean algorithm to find $\gcd(574, 168)$ and express it as a linear combination of 574 and 168.

Solution

The calculations are shown in Figure 7.2. We conclude that $\gcd(574, 168) = 14 = 5 \cdot 574 - 17 \cdot 168$.

n	q_n	r_n		s_n	t_n	Division
0		574		1	0	
1		168		0	1	$574 = 3 \cdot 168 + 70$
2	3	70	$1 - 3 \cdot 0 =$	1	$0 - 3 \cdot 1 =$	$168 = 2 \cdot 70 + 28$
3	2	28	$0 - 2 \cdot 1 =$	-2	$1 - 2 \cdot (-3) =$	$70 = 2 \cdot 28 + 14$
4	2	14	$1 - 2 \cdot (-2) =$	5	$-3 - 2 \cdot 7 =$	$28 = 2 \cdot 14 + 0$
5	2	0				

Figure 7.2. Calculation of $\gcd(574, 168)$ by extended Euclidean algorithm.

As an immediate consequence of Theorem 7.1.4, we have the following surprising fact.

Theorem 7.1.6. *For all positive integers a , b , and d , if $d \mid a$ and $d \mid b$ then $d \mid \gcd(a, b)$.*

Proof. Let a, b , and d be arbitrary positive integers and suppose that $d \mid a$ and $d \mid b$. Then there are integers j and k such that $a = jd$ and $b = kd$. Now by Theorem 7.1.4 let s and t be integers such that $\gcd(a, b) = sa + tb$. Then

$$\gcd(a, b) = sa + tb = sjd + tkd = (sj + tk)d,$$

so $d \mid \gcd(a, b)$. □

Recall from part 3 of Example 4.4.3 that the divisibility relation is a partial order on \mathbb{Z}^+ . We could interpret Theorem 7.1.6 as saying that $\gcd(a, b)$ is the largest element of $D(a) \cap D(b)$ not only with respect to the usual ordering of the positive integers, but also with respect to the divisibility partial order.

Exercises

1. Let $a = 57$ and $b = 36$.
 - (a) Find $D(a)$, $D(b)$, and $D(a) \cap D(b)$.
 - (b) Use the Euclidean algorithm to find $\gcd(a, b)$.
- *2. Find $\gcd(a, b)$, and express it as a linear combination of a and b .

- (a) $a = 775, b = 682$.
- (b) $a = 562, b = 243$.
3. Find $\gcd(a, b)$, and express it as a linear combination of a and b .
- (a) $a = 2790, b = 1206$.
- (b) $a = 191, b = 156$.
4. Complete the following alternative proof of Theorem 7.1.4. Suppose a and b are positive integers. Let $L = \{n \in \mathbb{Z}^+ \mid \exists s \in \mathbb{Z} \exists t \in \mathbb{Z} (n = sa + tb)\}$. Show that L has a smallest element. Let d be the smallest element of L . Now show that $d = \gcd(a, b)$. (Hint: Show that when you divide either a or b by d , the remainder cannot be positive.)
- *5. Suppose a and b are positive integers, and let $d = \gcd(a, b)$. Show that for every integer n , n is a linear combination of a and b iff $d \mid n$.
6. Prove that for all positive integers a, b , and c , $\gcd(a, b) = \gcd(a + bc, b)$.
- *7. Suppose that a, a^2, b , and b^2 are positive integers.
- (a) If $a \leq a^2$ and $b \leq b^2$, must it be the case that $\gcd(a, b) \leq \gcd(a^2, b^2)$? Justify your answer with either a proof or a counterexample.
- (b) If $a \mid a^2$ and $b \mid b^2$, must it be the case that $\gcd(a, b) \mid \gcd(a^2, b^2)$? Justify your answer with either a proof or a counterexample.
8. Prove that for every positive integer a , $\gcd(5a + 2, 13a + 5) = 1$.
- *9. Prove that for all positive integers a and b , $\gcd(2^a - 1, 2^b - 1) = 2^{\gcd(a, b)} - 1$.
10. Prove that for all positive integers a, b , and n , $\gcd(na, nb) = n \gcd(a, b)$.
11. Suppose a, b , and c are positive integers.
- (a) Prove that $D(\gcd(a, b)) = D(a) \cap D(b)$.
- (b) Prove that $\gcd(\gcd(a, b), c)$ is the largest element of $D(a) \cap D(b) \cap D(c)$.
- *12. (a) Use the Euclidean algorithm to find $\gcd(55, 34)$. Do you recognize the numbers in the sequence r_0, r_1, \dots ? (Hint: Look back at Section 6.4.) How many division steps are there?
- (b) Suppose $n \geq 2$. What is $\gcd(F_{n+1}, F_n)$? How many division steps are there when using the Euclidean algorithm to find $\gcd(F_{n+1}, F_n)$? (F_n is the n th Fibonacci number.)
13. Suppose a and b are positive integers with $a \geq b$. Let r_0, r_1, \dots, r_{m+1} be the sequence of numbers produced when using the Euclidean algorithm to compute $\gcd(a, b)$, where $r_m \neq 0$ and $r_{m+1} = 0$. Note that this means that the algorithm required m divisions.
- (a) Prove that $\forall k \in \mathbb{N} (k < m \rightarrow r_{m-k} \geq F_{k+2})$, where F_{k+2} is the $(k + 2)$ th Fibonacci number.

(b) Let $\varphi = (1 + \sqrt{5})/2$. (φ is the golden ratio; see exercise 20 in Section 6.4.) Prove that for every positive integer k , $F_k > \varphi^k / \sqrt{5} - 1$. (Hint: Use Theorem 6.4.3.)

(c) Show that

$$m < \frac{\log(b+1)}{\log \varphi} + \frac{\log 5}{2 \log \varphi} - 1.$$

(You can use either base-10 logarithms or natural logarithms in this formula.)

(d) Show that if b has at most 100 digits, then the number of divisions when using the Euclidean algorithm to compute $\gcd(a, b)$ will be at most 479.

14. (a) Prove the following alternative version of the division algorithm: For any positive integers a and b , there are natural numbers q and r such that $r \leq b/2$ and either $a = qb + r$ or $a = qb - r$.

(b) Suppose that a, b , and r are positive integers, q is a natural number, and either $a = qb + r$ or $a = qb - r$. Prove that $\gcd(a, b) = \gcd(b, r)$.

(c) Suppose a and b are positive integers with $a \geq b$. Define a sequence r_0, r_1, \dots recursively as follows: $r_0 = a, r_1 = b$, and for all $n \geq 1$, if $r_n \neq 0$ then we use part (a) to find natural numbers q_{n+1} and r_{n+1} such that $r_{n+1} \leq r_n/2$ and either $r_{n-1} = q_{n+1}r_n + r_{n+1}$ or $r_{n-1} = q_{n+1}r_n - r_{n+1}$. Prove that there is some m such that $r_m \neq 0$ and $r_{m+1} = 0$, and $\gcd(a, b) = r_m$. This gives us a new method of computing greatest common divisors; it is called the *least absolute remainder Euclidean algorithm*.

(d) Compute $\gcd(1515, 555)$ by both the Euclidean algorithm and the least absolute remainder Euclidean algorithm. Which takes fewer steps?

7.2. Prime Factorization

In Section 6.4 we saw that every integer $n > 1$ is either prime or can be written as a product of prime numbers; we say that n has a *prime factorization*. In this section we will show that this prime factorization is in a certain sense unique. One important tool in this investigation will be greatest common divisors. In particular, we will be interested in pairs of positive integers whose greatest common divisor has the smallest possible value, 1.

Definition 7.2.1. If a and b are positive integers and $\gcd(a, b) = 1$, then we say that a and b are *relatively prime*.

Equivalently, we can say that a and b are relatively prime if their only common divisor is 1. For example, $D(50) = \{1, 2, 5, 10, 25, 50\}$ and $D(63) = \{1, 3, 7, 9, 21, 63\}$, so $D(50) \cap D(63) = \{1\}$. Therefore $\gcd(50, 63) = 1$, so 50 and 63 are relatively prime.

One reason relatively prime integers are important is given by our next theorem. The key to the proof of the theorem is the use of existential instantiation to introduce names for integers that we know exist.

Theorem 7.2.2. For all positive integers a, b , and c , if $c \mid ab$ and $\gcd(a, c) = 1$ then $c \mid b$.

Proof. Suppose $c \mid ab$ and $\gcd(a, c) = 1$. Then there is some integer j such that $ab = jc$, and by Theorem 7.1.4, there are integers s and t such that $sa + tc = 1$. Therefore

$$b = b \cdot 1 = b \cdot (sa + tc) = sab + tbc = sjc + tbc = (sj + tb)c,$$

so $c \mid b$. □

Notice that if p is a prime number then $D(p) = \{1, p\}$. Thus, for any positive integer a , the only possible values of $\gcd(a, p)$ are 1 and p . If $p \mid a$ then $\gcd(a, p) = p$, and if not, then the only common divisor of a and p is 1 and therefore a and p are relatively prime. Combining this observation with Theorem 7.2.2, we get the following important fact about prime divisors.

Theorem 7.2.3. For all positive integers a, b , and p , if p is prime and $p \mid ab$ then either $p \mid a$ or $p \mid b$.

Proof. Suppose p is prime and $p \mid ab$. As we observed earlier, if $p \nmid a$ then a and p are relatively prime, and therefore by Theorem 7.2.2, $p \mid b$. Thus, either $p \mid a$ or $p \mid b$. □

Commentary. Notice that to prove the disjunction $(p \mid a) \vee (p \mid b)$, we used the strategy of assuming $p \nmid a$ and then proving $p \mid b$.

Using mathematical induction, we can extend this theorem to the case of a prime number dividing a product of a list of positive integers.

Theorem 7.2.4. Suppose p is a prime number and a_1, a_2, \dots, a_k are positive integers. If $p \mid (a_1 a_2 \cdots a_k)$, then for some $i \in \{1, 2, \dots, k\}$, $p \mid a_i$.

Proof. We prove this theorem by induction on k . In other words, we will use induction to prove the following statement: for every $k \geq 1$, if p divides the product of any list of k positive integers, then it divides one of the integers in the list.

Our base case is $k = 1$, and in that case the statement is clearly true: if $p \mid a_1$, then there is some $i \in \{1\}$ such that $p \mid a_i$, namely, $i = 1$.

Now suppose the statement holds for any list of k positive integers, and let a_1, a_2, \dots, a_{k+1} be a list of positive integers such that $p \mid (a_1 a_2 \cdots a_k a_{k+1})$. Since $a_1 a_2 \cdots a_k a_{k+1} = (a_1 a_2 \cdots a_k) a_{k+1}$, by Theorem 7.2.3 either $p \mid (a_1 a_2 \cdots a_k)$ or $p \mid a_{k+1}$. In the first case, by the inductive hypothesis we have $p \mid a_i$ for some $i \in \{1, 2, \dots, k\}$, and in the second we have $p \mid a_i$ where $i = k + 1$. \square

We are now ready to address the issue of the uniqueness of prime factorizations. Consider, for example, the problem of writing 12 as a product of prime numbers. There are actually three different ways to write 12 as a product of prime numbers: $12 = 2 \cdot 2 \cdot 3 = 2 \cdot 3 \cdot 2 = 3 \cdot 2 \cdot 2$. But of course in all three cases we are multiplying the same three prime numbers, just in a different order. To avoid counting these as three different prime factorizations of 12, we will only consider factorizations in which the primes are listed from smallest to largest. There is only one prime factorization of 12 that meets this additional requirement: $12 = 2 \cdot 2 \cdot 3$.

More generally, we will be interested in expressions of the form $p_1 p_2 \cdots p_k$, where p_1, p_2, \dots, p_k are prime numbers and $p_1 \leq p_2 \leq \cdots \leq p_k$. We will say that such an expression is the product of a *nondecreasing list of prime numbers*. We will show that every integer larger than 1 can be written as the product of a nondecreasing list of prime numbers in a unique way.

Recall that, to show that an object with some property is unique, we show that any two objects with the property would have to be equal. Thus, the key to proving the uniqueness of prime factorizations will be the following fact.

Theorem 7.2.5. *Suppose that p_1, p_2, \dots, p_k and q_1, q_2, \dots, q_m are prime numbers, $p_1 \leq p_2 \leq \cdots \leq p_k$, $q_1 \leq q_2 \leq \cdots \leq q_m$, and $p_1 p_2 \cdots p_k = q_1 q_2 \cdots q_m$. Then $k = m$ and for all $i \in \{1, \dots, k\}$, $p_i = q_i$.*

Proof. The proof will be by induction on k . In other words, we use induction to prove that for all $k \geq 1$, if the product of some nondecreasing list of k prime numbers is equal to the product of another nondecreasing list of prime numbers, then the two lists must be the same.

When $k = 1$, we have $p_1 = q_1 q_2 \cdots q_m$. If $m > 1$ then this contradicts the fact that p_1 is prime. Therefore $m = 1$ and $p_1 = q_1$.

For the induction step, suppose the statement is true for products of nondecreasing lists of k prime numbers, and suppose that p_1, p_2, \dots, p_{k+1} and q_1, q_2, \dots, q_m are prime numbers, $p_1 \leq p_2 \leq \dots \leq p_{k+1}$, $q_1 \leq q_2 \leq \dots \leq q_m$, and $p_1 p_2 \cdots p_{k+1} = q_1 q_2 \cdots q_m$. Notice that if $m = 1$ then this equation says $p_1 p_2 \cdots p_{k+1} = q_1$, and as in the base case this contradicts the fact that q_1 is prime, so $m > 1$.

Clearly $p_{k+1} \mid (p_1 p_2 \cdots p_{k+1})$, so $p_{k+1} \mid (q_1 q_2 \cdots q_m)$, and by Theorem 7.2.4 it follows that $p_{k+1} \mid q_i$ for some i . Therefore $p_{k+1} \leq q_i \leq q_m$. A similar argument shows that $q_m \mid p_j$ for some j , so $q_m \leq p_j \leq p_{k+1}$. We conclude that $p_{k+1} = q_m$. Canceling these factors from the equation $p_1 p_2 \cdots p_{k+1} = q_1 q_2 \cdots q_m$ gives us $p_1 p_2 \cdots p_k = q_1 q_2 \cdots q_{m-1}$, and now the inductive hypothesis tells us that the remaining factors on both sides of the equation are the same, as required. \square

We now have in place everything we need to establish the existence and uniqueness of prime factorizations. This theorem is so important it is known as the fundamental theorem of arithmetic.

Theorem 7.2.6. (Fundamental theorem of arithmetic) *For every integer $n > 1$ there are unique prime numbers p_1, p_2, \dots, p_k such that $p_1 \leq p_2 \leq \dots \leq p_k$ and $n = p_1 p_2 \cdots p_k$.*

Proof. By Theorem 6.4.2, every integer greater than 1 is either prime or a product of primes. Listing the primes from smallest to largest gives us the required nondecreasing prime factorization. Uniqueness of the factorization follows from Theorem 7.2.5. \square

If we write the product of the list of prime numbers p_1, p_2, \dots, p_k in the form $1 \cdot p_1 p_2 \cdots p_k$, then it is natural to introduce the convention that the product of the empty list is 1. With this convention we can extend the fundamental theorem of arithmetic to say that every positive integer has a unique prime factorization, where the factorization of the number 1 is the product of the empty list of prime numbers.

Example 7.2.7. Find the prime factorizations of the following integers:

$$275, \quad 276, \quad 277.$$

Solution

The most straightforward way to find the prime factorization of a positive integer is to search for its smallest prime divisor, factor it out, and repeat until

all factors are prime. This gives the following results. (Note that 277 is prime, so the factoring process for 277 stops immediately.)

$$275 = 5 \cdot 55 = 5 \cdot 5 \cdot 11,$$

$$276 = 2 \cdot 138 = 2 \cdot 2 \cdot 69 = 2 \cdot 2 \cdot 3 \cdot 23,$$

$$277 = 277.$$

When there are repeated primes in the prime factorization of an integer, we often use exponent notation to write the prime factorization. For example, the factorizations of 275 and 276 in the last example could be written in the form $275 = 5^2 \cdot 11$ and $276 = 2^2 \cdot 3 \cdot 23$. More generally, we can write the prime factorization of a positive integer n in the form $n = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$, where p_1, p_2, \dots, p_k are prime numbers, $p_1 < p_2 < \cdots < p_k$, and e_1, e_2, \dots, e_k are positive integers. Again, by the fundamental theorem of arithmetic, this representation of n is unique.

The fundamental theorem of arithmetic can provide insight into a number of concepts of number theory. For example, suppose n and d are positive integers and $d \mid n$. Then there is some positive integer c such that $cd = n$. Now let the prime factorizations of c and d be $c = p_1 p_2 \cdots p_k$ and $d = q_1 q_2 \cdots q_m$. Then $n = cd = p_1 p_2 \cdots p_k q_1 q_2 \cdots q_m$. If we rearrange the primes in this product into nondecreasing order, then this must be the unique prime factorization of n . Therefore d must be the product of some subcollection of the primes in the prime factorization of n . Notice that we are including here the possibility that the subcollection is the empty subcollection (so that $d = 1$ and $c = n$) or that it includes all of the primes in the factorization of n (so that $d = n$ and $c = 1$).

Rephrasing this conclusion using exponent notation, suppose the prime factorization of n is $n = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$. Then the divisors of n are precisely the numbers of the form $p_1^{f_1} p_2^{f_2} \cdots p_k^{f_k}$, where for all $i \in \{1, 2, \dots, k\}$, $0 \leq f_i \leq e_i$. For example, we saw in Example 7.2.7 that the prime factorization of 276 is $276 = 2^2 \cdot 3 \cdot 23$. Therefore

$$\begin{aligned} D(276) &= \{1, 2, 2^2, 3, 2 \cdot 3, 2^2 \cdot 3, 23, 2 \cdot 23, 2^2 \cdot 23, 3 \cdot 23, 2 \cdot 3 \cdot 23, 2^2 \cdot 3 \cdot 23\} \\ &= \{1, 2, 4, 3, 6, 12, 23, 46, 92, 69, 138, 276\}. \end{aligned}$$

Prime factorization can also help us understand greatest common divisors. Suppose a and b are positive integers. Let p_1, p_2, \dots, p_k be a list of all primes that occur in the prime factorization of either a or b . Then we can write a and b in the form

$$a = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}, \quad b = p_1^{f_1} p_2^{f_2} \cdots p_k^{f_k},$$

where some of the exponents e_i and f_i might be 0, since some primes might occur in only one of the factorizations. By the discussion of divisibility and prime factorization in the previous paragraph, the common divisors of a and b are all numbers of the form $p_1^{g_1} p_2^{g_2} \cdots p_k^{g_k}$, where for every $i \in \{1, \dots, k\}$, $g_i \leq e_i$ and $g_i \leq f_i$. The greatest common divisor can be found by letting each g_i have the largest possible value, which is $\min(e_i, f_i)$ = the minimum of e_i and f_i . In other words,

$$\gcd(a, b) = p_1^{\min(e_1, f_1)} p_2^{\min(e_2, f_2)} \cdots p_k^{\min(e_k, f_k)}.$$

For example, in Example 7.1.3 we used the Euclidean algorithm to find that $\gcd(1392, 444) = 12$. We could instead have factored 1392 and 444 into primes:

$$\begin{aligned} 1392 &= 2^4 \cdot 3 \cdot 29 = 2^4 \cdot 3^1 \cdot 29^1 \cdot 37^0, \\ 444 &= 2^2 \cdot 3 \cdot 37 = 2^2 \cdot 3^1 \cdot 29^0 \cdot 37^1. \end{aligned}$$

These factorizations give us another way to find the greatest common divisor of 1392 and 444:

$$\begin{aligned} \gcd(1392, 444) &= 2^{\min(4,2)} \cdot 3^{\min(1,1)} \cdot 29^{\min(1,0)} \cdot 37^{\min(0,1)} \\ &= 2^2 \cdot 3^1 \cdot 29^0 \cdot 37^0 = 12. \end{aligned}$$

Usually the Euclidean algorithm is a more efficient way to find the greatest common divisor of two positive integers than prime factorization. But if you happen to know the prime factorizations of two positive integers, then you can compute their greatest common divisor very easily.

Another concept that is elucidated by prime factorization is least common multiples. For any positive integers a and b , the *least common multiple* of a and b , denoted $\text{lcm}(a, b)$, is the smallest positive integer m such that $a \mid m$ and $b \mid m$. Least common multiples come up when we are adding fractions: to add two fractions with denominators a and b , we start by rewriting them with the common denominator $\text{lcm}(a, b)$.

Suppose that, as before,

$$a = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}, \quad b = p_1^{f_1} p_2^{f_2} \cdots p_k^{f_k}.$$

For each $i \in \{1, \dots, k\}$, any common multiple of a and b must include a factor $p_i^{g_i}$ in its prime factorization, where $g_i \geq e_i$ and $g_i \geq f_i$. The smallest possible value of g_i is the maximum of e_i and f_i , which we will denote $\max(e_i, f_i)$, so

$$\text{lcm}(a, b) = p_1^{\max(e_1, f_1)} p_2^{\max(e_2, f_2)} \cdots p_k^{\max(e_k, f_k)}.$$

It is not hard to show that for any numbers e and f , $\min(e, f) + \max(e, f) = e + f$ (see exercise 4), so

$$\begin{aligned}
\gcd(a, b) \cdot \text{lcm}(a, b) &= \left(p_1^{\min(e_1, f_1)} \cdots p_k^{\min(e_k, f_k)} \right) \cdot \left(p_1^{\max(e_1, f_1)} \cdots p_k^{\max(e_k, f_k)} \right) \\
&= p_1^{\min(e_1, f_1) + \max(e_1, f_1)} \cdots p_k^{\min(e_k, f_k) + \max(e_k, f_k)} \\
&= p_1^{e_1 + f_1} \cdots p_k^{e_k + f_k} \\
&= \left(p_1^{e_1} \cdots p_k^{e_k} \right) \cdot \left(p_1^{f_1} \cdots p_k^{f_k} \right) = ab.
\end{aligned}$$

This gives us another way to compute $\text{lcm}(a, b)$:

$$\text{lcm}(a, b) = \frac{ab}{\gcd(a, b)}.$$

For an alternative proof of this formula, see exercise 8.

For example, we now have two ways to compute $\text{lcm}(1392, 444)$:

$$\begin{aligned}
\text{lcm}(1392, 444) &= 2^{\max(4,2)} \cdot 3^{\max(1,1)} \cdot 29^{\max(1,0)} \cdot 37^{\max(0,1)} \\
&= 2^4 \cdot 3^1 \cdot 29^1 \cdot 37^1 = 51504,
\end{aligned}$$

and

$$\text{lcm}(1392, 444) = \frac{1392 \cdot 444}{\gcd(1392, 444)} = \frac{618048}{12} = 51504.$$

This shows that if we want to add two fractions with denominators 1392 and 444, we should use the common denominator 51504.

Example 7.2.8. Find the least common multiple of 1386 and 1029.

Solution

We begin by using the Euclidean algorithm to find $\gcd(1386, 1029)$. The calculations in Figure 7.3 show that $\gcd(1386, 1029) = 21$. Therefore

$$\text{lcm}(1386, 1029) = \frac{1386 \cdot 1029}{\gcd(1386, 1029)} = \frac{1386 \cdot 1029}{21} = 67914.$$

n	q_n	r_n	Division
0		1386	
1		1029	$1386 = 1 \cdot 1029 + 357$
2	1	357	$1029 = 2 \cdot 357 + 315$
3	2	315	$357 = 1 \cdot 315 + 42$
4	1	42	$315 = 7 \cdot 42 + 21$
5	7	21	$42 = 2 \cdot 21 + 0$
6	2	0	

Figure 7.3. Calculation of $\gcd(1386, 1029)$ by Euclidean algorithm.

Alternatively, we could use prime factorizations: $1386 = 2 \cdot 3^2 \cdot 7 \cdot 11$ and $1029 = 3 \cdot 7^3$, so $\text{lcm}(1386, 1029) = 2 \cdot 3^2 \cdot 7^3 \cdot 11 = 67914$.

Exercises

1. Find the prime factorizations of the following positive integers: 650, 756, 1067.
- *2. Find $\text{lcm}(1495, 650)$.
3. Find $\text{lcm}(1953, 868)$.
4. Prove that for any numbers e and f , $\min(e, f) + \max(e, f) = e + f$.
- *5. Suppose a and b are positive integers. Prove that a and b are relatively prime iff their prime factorizations have no primes in common.
6. Suppose a and b are positive integers. Prove that a and b are relatively prime iff there are integers s and t such that $sa + tb = 1$.
7. Suppose a, b, a^2 , and b^2 are positive integers, a and b are relatively prime, $a^2 \mid a$, and $b^2 \mid b$. Prove that a^2 and b^2 are relatively prime.
- *8. Suppose a and b are positive integers. In this exercise you will give an alternative proof of the formula $\text{lcm}(a, b) = ab / \text{gcd}(a, b)$. Let $m = \text{lcm}(a, b)$.
 - (a) Prove that $ab / \text{gcd}(a, b)$ is an integer and that $a \mid (ab / \text{gcd}(a, b))$ and $b \mid (ab / \text{gcd}(a, b))$. Use this to conclude that $m \leq ab / \text{gcd}(a, b)$. Let q and r be the quotient and remainder when ab is divided by m . Thus, $ab = qm + r$ and $0 \leq r < m$.
 - (b) Prove that $r = 0$.
 - (c) By part (b), $ab = qm$. Prove that $q \mid a$ and $q \mid b$.
 - (d) Use part (c) to conclude that $m \geq ab / \text{gcd}(a, b)$. Together with part (a), this shows that $m = ab / \text{gcd}(a, b)$.
9. Suppose a and b are positive integers, and let $d = \text{gcd}(a, b)$. Then $d \mid a$ and $d \mid b$, so there are positive integers j and k such that $a = jd$ and $b = kd$. Prove that j and k are relatively prime.
10. Prove that for all positive integers a, b , and d , if $d \mid ab$ then there are positive integers d_1 and d_2 such that $d = d_1 d_2$, $d_1 \mid a$, and $d_2 \mid b$.
- *11. Prove that for all positive integers a, b , and m , if $a \mid m$ and $b \mid m$ then $\text{lcm}(a, b) \mid m$.
12. Suppose a, b , and c are positive integers. Let m be the smallest positive integer such that $a \mid m$, $b \mid m$, and $c \mid m$. Prove that $m = \text{lcm}(\text{lcm}(a, b), c)$.
- *13. Prove that for all positive integers a and b , if $a^2 \mid b^2$ then $a \mid b$.

14. (a) Find all prime numbers p such that $5p + 9 \in \{n^2 \mid n \in \mathbb{N}\}$.
 (b) Find all prime numbers p such that $15p + 4 \in \{n^2 \mid n \in \mathbb{N}\}$.
 (c) Find all prime numbers p such that $5p + 8 \in \{n^3 \mid n \in \mathbb{N}\}$.
15. Let $H = \{4n + 1 \mid n \in \mathbb{N}\} = \{1, 5, 9, 13, \dots\}$. The elements of H are called *Hilbert numbers* (named for David Hilbert (1862–1943)). A Hilbert number that is larger than 1 and cannot be written as a product of two smaller Hilbert numbers is called a *Hilbert prime*. For example, 9 is a Hilbert prime. (Of course, 9 is not a prime, since $9 = 3 \cdot 3$, but $3 \notin H$.)
- (a) Show that H is closed under multiplication; that is, $\forall x \in H \forall y \in H(xy \in H)$.
- (b) Show that every Hilbert number that is larger than 1 is either a Hilbert prime or a product of two or more Hilbert primes.
- (c) Show that 441 is a Hilbert number that can be written as a product of a nondecreasing list of Hilbert primes in two different ways. Thus, Hilbert prime factorization is not unique.
- *16. Suppose a and b are positive integers. Prove that there are relatively prime positive integers c and d such that $c \mid a$, $d \mid b$, and $cd = \text{lcm}(a, b)$.
17. Suppose a , b , and c are positive integers.
- (a) Prove that $\text{gcd}(a, bc) \mid (\text{gcd}(a, b) \cdot \text{gcd}(a, c))$.
- (b) Prove that $\text{lcm}(\text{gcd}(a, b), \text{gcd}(a, c)) \mid \text{gcd}(a, bc)$. (Hint: Use exercise 11.)
- (c) Suppose that b and c are relatively prime. Prove that $\text{gcd}(a, bc) = \text{gcd}(a, b) \cdot \text{gcd}(a, c)$.
18. Recall from exercise 5 in Section 6.2 that the numbers $F_n = 2^{(2^n)} + 1$ are called Fermat numbers. Fermat showed that F_n is prime for $0 \leq n \leq 4$, and Euler showed that F_5 is not prime. It is not known if there is any $n > 4$ for which F_n is prime. In this exercise you will see one reason why one might be interested in prime numbers of this form. Show that if m is a positive integer and $2^m + 1$ is prime, then m is a power of 2. (Hint: If m is not a power of 2, then m has an odd prime number p in its prime factorization. Thus there is a positive integer r such that $m = pr$. Now apply exercise 14 in Section 6.1 to conclude that $(2^r + 1) \mid (2^m + 1)$.)
- *19. Suppose x is a positive rational number.
- (a) Prove that there are positive integers a and b such that $x = a/b$ and $\text{gcd}(a, b) = 1$.
- (b) Suppose a, b, c , and d are positive integers, $x = a/b = c/d$, and $\text{gcd}(a, b) = \text{gcd}(c, d) = 1$. Prove that $a = c$ and $b = d$.

- (c) Prove that there are prime numbers p_1, p_2, \dots, p_k and nonzero integers e_1, e_2, \dots, e_k such that $p_1 < p_2 < \dots < p_k$ and

$$x = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}.$$

Note that some of the exponents e_i may be negative.

- (d) Prove that the representation of x in part (c) is unique. In other words, if p_1, p_2, \dots, p_k and q_1, q_2, \dots, q_m are prime numbers, e_1, e_2, \dots, e_k and f_1, f_2, \dots, f_m are nonzero integers, $p_1 < p_2 < \dots < p_k$, $q_1 < q_2 < \dots < q_m$, and

$$x = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k} = q_1^{f_1} q_2^{f_2} \cdots q_m^{f_m},$$

then $k = m$ and for all $i \in \{1, 2, \dots, k\}$, $p_i = q_i$ and $e_i = f_i$.

20. Complete the following proof that $\sqrt{2}$ is irrational: Suppose $a/b = \sqrt{2}$, where a and b are positive integers. Then $a^2 = 2b^2$. Now derive a contradiction by considering the exponent of 2 in the prime factorizations of a and b .

7.3. Modular Arithmetic

Suppose m is a positive integer. Recall from Definition 4.5.9 that for any integers a and b , we say that a is congruent to b modulo m if $m \mid (a - b)$. We write $a \equiv b \pmod{m}$, or more briefly $a \equiv_m b$, to indicate that a is congruent to b modulo m . We saw in Theorem 4.5.10 that \equiv_m is an equivalence relation on \mathbb{Z} . For any integer a , let $[a]_m$ be the equivalence class of a with respect to the equivalence relation \equiv_m . The set of all of these equivalence classes is denoted \mathbb{Z}/\equiv_m . Thus,

$$[a]_m = \{b \in \mathbb{Z} \mid b \equiv a \pmod{m}\}, \quad \mathbb{Z}/\equiv_m = \{[a]_m \mid a \in \mathbb{Z}\}.$$

As we know from Theorem 4.5.4, \mathbb{Z}/\equiv_m is a partition of \mathbb{Z} .

For example, in the case $m = 3$ we have

$$\begin{aligned} [0]_3 &= \{b \in \mathbb{Z} \mid b \equiv 0 \pmod{3}\} = \{0, 3, 6, 9, \dots, -3, -6, -9, \dots\}, \\ [1]_3 &= \{b \in \mathbb{Z} \mid b \equiv 1 \pmod{3}\} = \{1, 4, 7, 10, \dots, -2, -5, -8, \dots\}, \\ [2]_3 &= \{b \in \mathbb{Z} \mid b \equiv 2 \pmod{3}\} = \{2, 5, 8, 11, \dots, -1, -4, -7, \dots\}. \end{aligned}$$

Notice that every integer is an element of exactly one of these equivalence classes. It follows that every integer is congruent modulo 3 to exactly one of the numbers 0, 1, and 2. This is an instance of the following general theorem.

Theorem 7.3.1. *Suppose m is a positive integer. Then for every integer a , there is exactly one integer r such that $0 \leq r < m$ and $a \equiv r \pmod{m}$.*

Proof. Let a be an arbitrary integer. Let q and r be the quotient and remainder when a is divided by m (see exercise 14 in Section 6.4). This means that $a = qm + r$ and $0 \leq r < m$. Then $a - r = qm$, so $m \mid (a - r)$, and therefore $a \equiv r \pmod{m}$. This proves the existence of the required integer r .

To prove uniqueness, suppose r_1 and r_2 are integers such that $0 \leq r_1 < m$, $0 \leq r_2 < m$, $a \equiv r_1 \pmod{m}$, and $a \equiv r_2 \pmod{m}$. Then by the symmetry and transitivity of the equivalence relation \equiv_m , $r_1 \equiv r_2 \pmod{m}$, so there is some integer d such that $r_1 - r_2 = dm$. But from $0 \leq r_1 < m$ and $0 \leq r_2 < m$ we see that $-m < r_1 - r_2 < m$. Thus $-m < dm < m$, which implies that $-1 < d < 1$. The only integer strictly between -1 and 1 is 0 , so $d = 0$ and therefore $r_1 - r_2 = dm = 0$. In other words, $r_1 = r_2$. \square

Commentary. Of course, the existence and uniqueness of the number r are proven separately, and the proof of uniqueness uses the usual strategy of assuming that r_1 and r_2 are two integers with the required properties and then proving $r_1 = r_2$.

Theorem 7.3.1 says that every integer is congruent modulo m to exactly one element of the set $\{0, 1, \dots, m-1\}$. We say that this set is a *complete residue system modulo m* .

Note that by Lemma 4.5.5,

$$a \equiv r \pmod{m} \quad \text{iff} \quad a \in [r]_m \quad \text{iff} \quad [a]_m = [r]_m.$$

Thus, Theorem 7.3.1 shows that every equivalence class in \mathbb{Z}/\equiv_m is equal to exactly one of the equivalence classes in the list $[0]_m, [1]_m, \dots, [m-1]_m$. Thus, these m equivalence classes are distinct, and $\mathbb{Z}/\equiv_m = \{[0]_m, [1]_m, \dots, [m-1]_m\}$.

Consider any two equivalence classes X and Y in \mathbb{Z}/\equiv_m . Something surprising happens if we add or multiply elements of X and Y . It turns out that all sums of the form $x + y$, where $x \in X$ and $y \in Y$, belong to the same equivalence class, and also all products xy belong to the same equivalence class. In other words, we have the following theorem.

Theorem 7.3.2. *Suppose m is a positive integer and X and Y are elements of \mathbb{Z}/\equiv_m . Then:*

1. *There is a unique $S \in \mathbb{Z}/\equiv_m$ such that $\forall x \in X \forall y \in Y (x + y \in S)$.*
2. *There is a unique $P \in \mathbb{Z}/\equiv_m$ such that $\forall x \in X \forall y \in Y (xy \in P)$.*

We will prove this theorem shortly, but first we use it to introduce two binary operations on \mathbb{Z}/\equiv_m .

Definition 7.3.3. Suppose X and Y are elements of \mathbb{Z}/\equiv_m . Then we define the sum and product of X and Y , denoted $X + Y$ and $X \cdot Y$, as follows:

$$X + Y = \text{the unique } S \in \mathbb{Z}/\equiv_m \text{ such that } \forall x \in X \forall y \in Y (x + y \in S),$$

$$X \cdot Y = \text{the unique } P \in \mathbb{Z}/\equiv_m \text{ such that } \forall x \in X \forall y \in Y (xy \in P).$$

The key to our proof of Theorem 7.3.2 will be the following lemma.

Lemma 7.3.4. Suppose m is a positive integer. Then for all integers $a, a^2, b,$ and b^2 , if $a^2 \equiv a \pmod{m}$ and $b^2 \equiv b \pmod{m}$ then $a^2 + b^2 \equiv a + b \pmod{m}$ and $a^2 b^2 \equiv ab \pmod{m}$.

Proof. Suppose $a^2 \equiv a \pmod{m}$ and $b^2 \equiv b \pmod{m}$. Then $m \mid (a^2 - a)$ and $m \mid (b^2 - b)$, so we can choose integers c and d such that $a^2 - a = cm$ and $b^2 - b = dm$, or in other words $a^2 = a + cm$ and $b^2 = b + dm$. Therefore

$$(a^2 + b^2) - (a + b) = (a + cm + b + dm) - (a + b) = cm + dm = (c + d)m,$$

so $m \mid ((a^2 + b^2) - (a + b))$, which means $a^2 + a \equiv b^2 + b \pmod{m}$. Similarly,

$$a^2 b^2 - ab = (a + cm)(b + dm) - ab = adm + bcm + cdm^2 = (ad + bc + cdm)m,$$

so $m \mid (a^2 b^2 - ab)$, and therefore $a^2 b^2 \equiv ab \pmod{m}$. □

Proof of Theorem 7.3.2. Since X and Y are elements of \mathbb{Z}/\equiv_m , we can let a and b be integers such that $X = [a]_m$ and $Y = [b]_m$. To prove part 1 of the theorem, let $S = [a + b]_m$. Now let $x \in X$ and $y \in Y$ be arbitrary. Then $x \in [a]_m$ and $y \in [b]_m$, so $x \equiv a \pmod{m}$ and $y \equiv b \pmod{m}$. By Lemma 7.3.4 it follows that $x + y \equiv a + b \pmod{m}$, so $x + y \in [a + b]_m = S$. Since x and y were arbitrary, we conclude that $\forall x \in X \forall y \in Y (x + y \in S)$.

To prove that S is unique, suppose S^2 is another equivalence class such that $\forall x \in X \forall y \in Y (x + y \in S^2)$. Since $a \in X$ and $b \in Y$, $a + b \in S$ and $a + b \in S^2$. Therefore S and S^2 are not disjoint, and since \mathbb{Z}/\equiv_m is pairwise disjoint, this implies that $S = S^2$.

The proof of part 2 is similar, using $P = [ab]_m$; see exercise 2. □

The proof of Theorem 7.3.2 shows that if $X = [a]_m$ and $Y = [b]_m$, then the sum of X and Y is the equivalence class $S = [a + b]_m$ and the product is $P = [ab]_m$. Thus, we have the following theorem.

Theorem 7.3.5. For any positive integer m and any integers a and b ,

$$[a]_m + [b]_m = [a + b]_m \quad \text{and} \quad [a]_m \cdot [b]_m = [ab]_m.$$

Let's try out these ideas. Consider the case $m = 5$. We know that every element of \mathbb{Z}/\equiv_5 is equal to either $[0]_5$, $[1]_5$, $[2]_5$, $[3]_5$, or $[4]_5$, and we will often choose to write equivalence classes in one of these forms. For example, $[2]_5 + [4]_5 = [6]_5$, but also $6 \equiv 1 \pmod{5}$, so $[6]_5 = [1]_5$. Thus, we can say that $[2]_5 + [4]_5 = [1]_5$. Similarly, $[2]_5 \cdot [4]_5 = [8]_5 = [3]_5$. Figure 7.4 shows the complete addition and multiplication tables for \mathbb{Z}/\equiv_5 .

$+$	$[0]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[4]_5$	\cdot	$[0]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[4]_5$
$[0]_5$	$[0]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[4]_5$	$[0]_5$	$[0]_5$	$[0]_5$	$[0]_5$	$[0]_5$	$[0]_5$
$[1]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[4]_5$	$[0]_5$	$[1]_5$	$[0]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[4]_5$
$[2]_5$	$[2]_5$	$[3]_5$	$[4]_5$	$[0]_5$	$[1]_5$	$[2]_5$	$[0]_5$	$[2]_5$	$[4]_5$	$[1]_5$	$[3]_5$
$[3]_5$	$[3]_5$	$[4]_5$	$[0]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[0]_5$	$[3]_5$	$[1]_5$	$[4]_5$	$[2]_5$
$[4]_5$	$[4]_5$	$[0]_5$	$[1]_5$	$[2]_5$	$[3]_5$	$[4]_5$	$[0]_5$	$[4]_5$	$[3]_5$	$[2]_5$	$[1]_5$

Figure 7.4. Addition and multiplication tables for \mathbb{Z}/\equiv_5 .

How do addition and multiplication in \mathbb{Z}/\equiv_m compare to addition and multiplication in \mathbb{Z} ? Many properties of addition and multiplication in \mathbb{Z} carry over easily to \mathbb{Z}/\equiv_m .

Theorem 7.3.6. Suppose m is a positive integer. Then for all equivalence classes X , Y , and Z in \mathbb{Z}/\equiv_m :

1. $X + Y = Y + X$. (Addition is commutative.)
2. $(X + Y) + Z = X + (Y + Z)$. (Addition is associative.)
3. $X + [0]_m = X$. ($[0]_m$ is an identity element for addition.)
4. There is some $X^{-1} \in \mathbb{Z}/\equiv_m$ such that $X + X^{-1} = [0]_m$. (X has an additive inverse.)
5. $X \cdot Y = Y \cdot X$. (Multiplication is commutative.)
6. $(X \cdot Y) \cdot Z = X \cdot (Y \cdot Z)$. (Multiplication is associative.)
7. $X \cdot [1]_m = X$. ($[1]_m$ is an identity element for multiplication.)
8. $X \cdot [0]_m = [0]_m$.
9. $X \cdot (Y + Z) = (X \cdot Y) + (X \cdot Z)$. (Multiplication distributes over addition.)

Proof. Since $X, Y, Z \in \mathbb{Z}/\equiv_m$, there are integers a, b , and c such that $X = [a]_m$, $Y = [b]_m$, and $Z = [c]_m$. For part 1, we use the commutativity of addition in \mathbb{Z} :

$$X + Y = [a]_m + [b]_m = [a + b]_m = [b + a]_m = [b]_m + [a]_m = Y + X.$$

The proof of 2 is similar. To prove part 3, we compute

$$x + [0]_m = [a]_m + [0]_m = [a + 0]_m = [a]_m = x.$$

For part 4, let $x^2 = [-a]_m$. Then

$$x + x^2 = [a]_m + [-a]_m = [a + (-a)]_m = [0]_m.$$

The proofs of the remaining parts are similar (see exercise 3). □

You are asked to show in exercise 4 that the identity elements and inverses in Theorem 7.3.6 are unique. Thus, in part 3 of the theorem we can say that $[0]_m$ is not just *an* identity element for addition, but *the* identity element, and similarly $[1]_m$ is *the* identity element for multiplication. In part 4, we can say that x^2 is *the* additive inverse of x ; we will denote the additive inverse of x by $-x$. For example, according to the addition table for \mathbb{Z}/\equiv_5 in Figure 7.4, $[4]_5 + [1]_5 = [0]_5$, so $-[4]_5 = [1]_5$.

What about multiplicative inverses? If $x \in \mathbb{Z}/\equiv_m$, $x^2 \in \mathbb{Z}/\equiv_m$, and $x \cdot x^2 = [1]_m$, then we say that x^2 is a multiplicative inverse of x . For example, according to the multiplication table for \mathbb{Z}/\equiv_5 in Figure 7.4, $[3]_5 \cdot [2]_5 = [1]_5$, so $[2]_5$ is a multiplicative inverse of $[3]_5$. In fact, in \mathbb{Z}/\equiv_5 , every element except $[0]_5$ has a multiplicative inverse. Multiplicative inverses, when they exist, are also unique (see exercise 4), so we can say that $[2]_5$ is *the* multiplicative inverse of $[3]_5$. In general, if $x \in \mathbb{Z}/\equiv_m$, then the multiplicative inverse of x , if it exists, is denoted x^{-1} . Thus $[3]_5^{-1} = [2]_5$.

A little experimentation reveals that multiplicative inverses often don't exist. For example, we leave it for you to check that in \mathbb{Z}/\equiv_6 , only $[1]_6$ and $[5]_6$ have multiplicative inverses (see exercise 1). When does an equivalence class have a multiplicative inverse? The answer is given by our next theorem.

Theorem 7.3.7. *Suppose that a and m are positive integers. Then $[a]_m$ has a multiplicative inverse iff m and a are relatively prime.*

Proof. Suppose first that $[a]_m$ has a multiplicative inverse; say $[a]_m^{-1} = [a^2]_m$. Then $[a]_m \cdot [a^2]_m = [aa^2]_m = [1]_m$, and therefore $aa^2 \equiv 1 \pmod{m}$. This means that $m \mid (aa^2 - 1)$, so we can choose some integer c such that $aa^2 - 1 = cm$, or equivalently $-cm + a^2a = 1$. Thus 1 is a linear combination of m and a , and by exercise 6 in the last section it follows that m and a are relatively prime.

For the other direction, assume that m and a are relatively prime. Then by Theorem 7.1.4 there are positive integers s and t such that $sm + ta = 1$. Therefore $ta - 1 = -sm$, so $ta \equiv 1 \pmod{m}$. We conclude that $[a]_m \cdot [t]_m = [ta]_m = [1]_m$, so $[t]_m$ is the multiplicative inverse of $[a]_m$. □

Commentary. Notice that the conclusion of the theorem is a biconditional statement, and the proof uses the usual strategy of proving both directions of the biconditional separately.

The proof of Theorem 7.3.7 shows that for any positive integers m and a , we can use the extended Euclidean algorithm to find $[a]_m^{-1}$. If the algorithm shows that $\gcd(m, a) \neq 1$ then $[a]_m^{-1}$ doesn't exist, and if we find that $\gcd(m, a) = 1 = sm + ta$ then $[a]_m^{-1} = [t]_m$.

Example 7.3.8. Find, if possible, the multiplicative inverses of $[34]_{847}$ and $[35]_{847}$ in $\mathbb{Z}/\cong 847$.

Solution

Figure 7.5 shows the calculation of $\gcd(847, 34)$ by the extended Euclidean algorithm. We conclude that $\gcd(847, 34) = 1 = 11 \cdot 847 - 274 \cdot 34$, and therefore $[34]_{847}^{-1} = [-274]_{847} = [573]_{847}$. As you can easily check, $34 \cdot 573 = 19482 \equiv 1 \pmod{847}$, so $[34]_{847} \cdot [573]_{847} = [19482]_{847} = [1]_{847}$.

We leave it to you to compute that $\gcd(847, 35) = 7$. Therefore $[35]_{847}$ does not have a multiplicative inverse.

n	q_n	r_n	s_n	t_n	Division
0		847	1	0	
1		34	0	1	$847 = 24 \cdot 34 + 31$
2	24	31	1	-24	$34 = 1 \cdot 31 + 3$
3	1	3	-1	25	$31 = 10 \cdot 3 + 1$
4	10	1	11	-274	$3 = 3 \cdot 1 + 0$
5	3	0			

Figure 7.5. Calculation of $\gcd(847, 34)$ by extended Euclidean algorithm.

Example 7.3.9. A class has 25 students. For Easter, the teacher bought several cartons of eggs, each containing a dozen eggs, and then distributed the eggs among the students for them to decorate. After giving an equal number of eggs to each student, she had 7 eggs left over. What is the smallest number of cartons of eggs she could have bought?

Solution

Let x be the number of cartons of eggs the teacher bought. Then she had $12x$ eggs, and setting aside the 7 left over at the end, the remaining eggs

were divided evenly among 25 students. Therefore $25 \mid (12x - 7)$, so $12x \equiv 7 \pmod{25}$. We must find the smallest positive integer x satisfying this congruence.

If we were solving the equation $12x = 7$ for a real number x , we would know what to do. If $12x = 7$, then by multiplying both sides of the equation by $1/12$ we conclude that $x = 7/12$. In fact, this reasoning can be reversed: if $x = 7/12$, then multiplying by 12 we get $12x = 7$. Thus, the equations $12x = 7$ and $x = 7/12$ are equivalent, which means that $x = 7/12$ is the unique solution to the equation $12x = 7$.

Unfortunately, we are working with the congruence $12x \equiv 7 \pmod{25}$, which is not an equation. But we can turn it into an equation by working with equivalence classes. Our congruence is equivalent to the equation $[12]_{25} \cdot [x]_{25} = [7]_{25}$, and we can solve this equation by imitating our solution to the equation $12x = 7$. We begin by finding the multiplicative inverse of $[12]_{25}$. Applying the extended Euclidean algorithm, we find that $\gcd(25, 12) = 1 = 1 \cdot 25 - 2 \cdot 12$, so $[12]_{25}^{-1} = [-2]_{25} = [23]_{25}$.

To solve the equation $[12]_{25} \cdot [x]_{25} = [7]_{25}$, we multiply both sides by $[12]_{25}^{-1} = [23]_{25}$. We spell out all the steps in detail, to make it clear how the properties in Theorem 7.3.6 are being used:

$$\begin{aligned} [12]_{25} \cdot [x]_{25} &= [7]_{25}, \\ [12]_{25}^{-1} \cdot ([12]_{25} \cdot [x]_{25}) &= [12]_{25}^{-1} \cdot [7]_{25}, \\ ([12]_{25}^{-1} \cdot [12]_{25}) \cdot [x]_{25} &= [23]_{25} \cdot [7]_{25}, \\ [1]_{25} \cdot [x]_{25} &= [161]_{25} = [11]_{25}, \\ [x]_{25} &= [11]_{25}. \end{aligned}$$

As before, these steps can be reversed: multiplying both sides of the equation $[x]_{25} = [11]_{25}$ by $[12]_{25}$ gives us $[12]_{25} \cdot [x]_{25} = [7]_{25}$. Therefore

$$12x \equiv 7 \pmod{25} \text{ iff } [12]_{25} \cdot [x]_{25} = [7]_{25} \text{ iff } [x]_{25} = [11]_{25} \text{ iff } x \in [11]_{25}.$$

In other words, the solutions to the congruence $12x \equiv 7 \pmod{25}$ are precisely the elements of the equivalence class $[11]_{25}$, and the smallest positive solution is $x = 11$. If the teacher bought 11 cartons of eggs, then she had 132 eggs, and after giving 5 to each student she had 7 left over.

We were lucky in this example that 25 and 12 were relatively prime, so that $[12]_{25}$ had a multiplicative inverse. This multiplicative inverse played a crucial role in our solution of the congruence $12x \equiv 7 \pmod{25}$. How can we solve a congruence $ax \equiv b \pmod{m}$ if m and a are not relatively prime? We won't analyze such congruences in detail, but we'll give a couple of examples

illustrating how such congruences can be solved by using the following two theorems.

Theorem 7.3.10. *Suppose m and a are positive integers, and let $d = \gcd(m, a)$. Then for every integer b , if $d \nmid b$ then there is no integer x such that $ax \equiv b \pmod{m}$.*

Proof. See exercise 7. □

Theorem 7.3.11. *Suppose n and m are positive integers. Then for all integers a and b ,*

$$na \equiv nb \pmod{nm} \quad \text{iff} \quad a \equiv b \pmod{m}.$$

Proof. See exercise 8. □

Example 7.3.12. Solve the following congruences:

$$77x \equiv 120 \pmod{374}, \quad 77x \equiv 121 \pmod{374}.$$

Solution

We begin by computing that $\gcd(374, 77) = 11$. Since $11 \nmid 120$, Theorem 7.3.10 tells us that the first congruence, $77x \equiv 120 \pmod{374}$, has no solutions. To solve the second congruence, we first write it as $11 \cdot 7x \equiv 11 \cdot 11 \pmod{11 \cdot 34}$ and then observe that by Theorem 7.3.11, this is equivalent to $7x \equiv 11 \pmod{34}$. To solve this congruence, we compute that $\gcd(34, 7) = 1 = -1 \cdot 34 + 5 \cdot 7$, so $[7]_{34}^{-1} = [5]_{34}$. Therefore

$$\begin{aligned} 7x \equiv 11 \pmod{34} &\text{ iff } [7]_{34} \cdot [x]_{34} = [11]_{34} \\ &\text{ iff } [x]_{34} = [7]_{34}^{-1} \cdot [11]_{34} = [5]_{34} \cdot [11]_{34} = [55]_{34} = [21]_{34} \\ &\text{ iff } x \in [21]_{34}. \end{aligned}$$

Thus the solutions to the second congruence are the elements of $[21]_{34}$.

Exercises

1. Make addition and multiplication tables for \mathbb{Z}/\equiv_6 .
2. Complete the proof of Theorem 7.3.2.
3. Prove parts 5–9 of Theorem 7.3.6.
- *4. Suppose m is a positive integer.

- (a) Suppose Z_1 and Z_2 are both additive identity elements for \mathbb{Z}/\equiv_m ; in other words, for all $X \in \mathbb{Z}/\equiv_m$, $X + Z_1 = X$ and $X + Z_2 = X$. Prove that $Z_1 = Z_2$. This shows that the additive identity element in \mathbb{Z}/\equiv_m is unique. (Hint: Compute $Z_1 + Z_2$ in two different ways.)
- (b) Suppose $X \in \mathbb{Z}/\equiv_m$ and X_1^2 and X_2^2 are both additive inverses for X ; in other words, $X + X_1^2 = X + X_2^2 = [0]_m$. Prove that $X_1^2 = X_2^2$. This shows that the additive inverse of X is unique. (Hint: Compute $X_1^2 + X + X_2^2$ in two different ways.)
- (c) Prove that the multiplicative identity element in \mathbb{Z}/\equiv_m is unique.
- (d) Prove that if an equivalence class $X \in \mathbb{Z}/\equiv_m$ has a multiplicative inverse, then this inverse is unique.
5. Show that if p is a prime number then every element of \mathbb{Z}/\equiv_p except $[0]_p$ has a multiplicative inverse.
6. If $ab \equiv 0 \pmod{m}$, is it necessarily true that either $a \equiv 0 \pmod{m}$ or $b \equiv 0 \pmod{m}$? Justify your answer with either a proof or a counterexample.
7. Prove Theorem 7.3.10.
- *8. Prove Theorem 7.3.11.
9. A class has 26 students. The teacher bought some packages of file cards, each of which contained 20 file cards. When he passed the cards out to the students, he discovered that he needed to add 2 additional cards from his desk to be able to give each student the same number of cards. If each student got between 10 and 20 cards, how many packages did he buy?
- *10. Solve the following congruences.
- (a) $40x \equiv 8 \pmod{237}$.
- (b) $40x \equiv 8 \pmod{236}$.
11. Solve the following congruences.
- (a) $31x \equiv 24 \pmod{384}$.
- (b) $32x \equiv 24 \pmod{384}$.
12. In this exercise you will solve the following problem: Suppose a chair without arms costs \$35 and a chair with arms costs \$50. If Alice spent \$720 on chairs, how many of each kind of chair did she buy?
- (a) Show that if x is the number of chairs without arms that she bought, then $35x \equiv 20 \pmod{50}$.
- (b) Solve the congruence in part (a).
- (c) Not every solution to the congruence in part (a) leads to a possible answer to the problem. Which ones do? (Note: There is more than one possible answer to the problem.)
- *13. Suppose m and n are relatively prime positive integers. Prove that for all integers a and b , $a \equiv b \pmod{m}$ iff $na \equiv nb \pmod{m}$.

14. Suppose that m_1 and m_2 are positive integers. Prove that for all integers a and b , if $a \equiv b \pmod{m_1}$ and $a \equiv b \pmod{m_2}$ then $a \equiv b \pmod{\text{lcm}(m_1, m_2)}$. (Hint: Use exercise 11 in Section 7.2.)
- *15. Prove that for all positive integers m , a , and b , if $a \equiv b \pmod{m}$ then $\gcd(m, a) = \gcd(m, b)$.
16. Suppose $a \equiv b \pmod{m}$. Prove that for every natural number n , $a^n \equiv b^n \pmod{m}$.

In exercises 17–19, we use the following notation. If $d_0, d_1, \dots, d_k \in \{0, 1, \dots, 9\}$, then $(d_k \cdots d_1 d_0)_{10}$ is the number whose representation in decimal notation is $d_k \cdots d_1 d_0$. In other words,

$$(d_k \cdots d_1 d_0)_{10} = d_0 + 10d_1 + \cdots + 10^k d_k.$$

- *17. Suppose $n = (d_k \cdots d_1 d_0)_{10}$.
- Show that $n \equiv (d_0 + d_1 + \cdots + d_k) \pmod{3}$.
 - Show that $3 \mid n$ iff $3 \mid (d_0 + d_1 + \cdots + d_k)$. (This gives a convenient way to test a natural number for divisibility by 3: add up the digits and check if the digit sum is divisible by 3.)
18. Suppose $n = (d_k \cdots d_1 d_0)_{10}$.
- Show that $n \equiv (d_0 - d_1 + d_2 - d_3 + \cdots + (-1)^k d_k) \pmod{11}$.
 - Show that $11 \mid n$ iff $11 \mid (d_0 - d_1 + \cdots + (-1)^k d_k)$.
 - Is 535172 divisible by 11?
- *19. Define a function f with domain $\{n \in \mathbb{Z} \mid n \geq 10\}$ as follows: if $n = (d_k \cdots d_1 d_0)_{10}$ then $f(n) = (d_k \cdots d_1)_{10} + 5d_0$. For example, $f(1743) = 174 + 5 \cdot 3 = 189$.
- Show that for all $n \geq 10$, $f(n) \equiv 5n \pmod{7}$ and $n \equiv 3f(n) \pmod{7}$.
 - Show that for all $n \geq 10$, $7 \mid n$ iff $7 \mid f(n)$. (This gives a convenient way to test a large integer n for divisibility by 7: repeatedly apply f until you get a number whose divisibility by 7 is easy to determine.)
 - Is 627334 divisible by 7?
20. (a) Find an example of positive integers m , a , a^2 , b , and b^2 such that $a^2 \equiv a \pmod{m}$ and $b^2 \equiv b \pmod{m}$ but $(a^2)^{b^2} \not\equiv a^b \pmod{m}$.
- (b) Show that it is impossible to define an exponentiation operation on equivalence classes in such a way that for all positive integers m , a , and b , $([a]_m)^{[b]_m} = [a^b]_m$.
21. Suppose m is a positive integer. Define $f : \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}/\equiv_m$ by the formula $f(a, b) = [a + b]_m$, and define $h : (\mathbb{Z}/\equiv_m) \times (\mathbb{Z}/\equiv_m) \rightarrow \mathbb{Z}/\equiv_m$ by the formula $h(X, Y) = X + Y$. You might want to compare this exercise to exercise 21 in Section 5.1.

- (a) Show that for all integers $x_1, x_2, y_1,$ and $y_2,$ if $x_1 \equiv_m y_1$ and $x_2 \equiv_m y_2$ then $f(x_1, x_2) = f(y_1, y_2)$. (Extending the terminology of exercise 21 in Section 5.1, we could say that f is compatible with \equiv_m .)
- (b) Show that for all integers x_1 and $x_2,$ $h([x_1]_m, [x_2]_m) = f(x_1, x_2)$.

7.4. Euler's Theorem

In the last section, we saw that some elements of \mathbb{Z}/\equiv_m have multiplicative inverses and some don't. In this section, we focus on the ones that do. We let $(\mathbb{Z}/\equiv_m)^*$ denote the set of elements of \mathbb{Z}/\equiv_m that have multiplicative inverses. In other words,

$$(\mathbb{Z}/\equiv_m)^* = \{X \in \mathbb{Z}/\equiv_m \mid \text{for some } X^{-1} \in \mathbb{Z}/\equiv_m, X \cdot X^{-1} = [1]_m\}.$$

The number of elements of $(\mathbb{Z}/\equiv_m)^*$ is denoted $\varphi(m)$. The function φ is called *Euler's phi function*, or *Euler's totient function*; it was introduced by Euler in 1763. For every positive integer $m,$ $(\mathbb{Z}/\equiv_m)^* \subseteq \mathbb{Z}/\equiv_m$ and \mathbb{Z}/\equiv_m has m elements, so $\varphi(m) \leq m$. And $[1]_m \cdot [1]_m = [1]_m,$ so $[1]_m \in (\mathbb{Z}/\equiv_m)^*$ and therefore $\varphi(m) \geq 1$. For example,

$$(\mathbb{Z}/\equiv_{10})^* = \{[1]_{10}, [3]_{10}, [7]_{10}, [9]_{10}\},$$

so $\varphi(10) = 4$.

For our purposes, the most important properties of $(\mathbb{Z}/\equiv_m)^*$ are that it is closed under inverses and multiplication. That is:

Theorem 7.4.1. *Suppose m is a positive integer.*

1. For every X in $(\mathbb{Z}/\equiv_m)^*, X^{-1} \in (\mathbb{Z}/\equiv_m)^*.$
2. For every X and Y in $(\mathbb{Z}/\equiv_m)^*, X \cdot Y \in (\mathbb{Z}/\equiv_m)^*.$

Proof.

1. Suppose $X \in (\mathbb{Z}/\equiv_m)^*.$ Then X has a multiplicative inverse $X^{-1},$ and $X \cdot X^{-1} = [1]_m.$ But this equation also tells us that X is the multiplicative inverse of $X^{-1};$ in other words, $(X^{-1})^{-1} = X.$ Therefore $X^{-1} \in (\mathbb{Z}/\equiv_m)^*.$
2. Suppose $X \in (\mathbb{Z}/\equiv_m)^*$ and $Y \in (\mathbb{Z}/\equiv_m)^*.$ Then X and Y have multiplicative inverses X^{-1} and $Y^{-1}.$ Therefore

$$(X \cdot Y) \cdot (X^{-1} \cdot Y^{-1}) = (X \cdot X^{-1}) \cdot (Y \cdot Y^{-1}) = [1]_m \cdot [1]_m = [1]_m.$$

This means that $X^{-1} \cdot Y^{-1}$ is the multiplicative inverse of $X \cdot Y,$ so $(X \cdot Y)^{-1} = X^{-1} \cdot Y^{-1}$ and $X \cdot Y \in (\mathbb{Z}/\equiv_m)^*.$ \square

Suppose $X \in (\mathbb{Z}/\equiv_m)^*$. By Theorem 7.4.1, for every $Y \in (\mathbb{Z}/\equiv_m)^*$, $X \cdot Y \in (\mathbb{Z}/\equiv_m)^*$, so we can define a function $f_X : (\mathbb{Z}/\equiv_m)^* \rightarrow (\mathbb{Z}/\equiv_m)^*$ by the formula $f_X(Y) = X \cdot Y$. Let's investigate the properties of this function.

We claim first that f_X is one-to-one. To see why, suppose $Y_1 \in (\mathbb{Z}/\equiv_m)^*$, $Y_2 \in (\mathbb{Z}/\equiv_m)^*$, and $f_X(Y_1) = f_X(Y_2)$. Then $X \cdot Y_1 = X \cdot Y_2$, and therefore

$$Y_1 = [1]_m \cdot Y_1 = X^{-1} \cdot X \cdot Y_1 = X^{-1} \cdot X \cdot Y_2 = [1]_m \cdot Y_2 = Y_2.$$

This proves that f_X is one-to-one. Next, we claim that f_X is onto. To prove this, suppose $Y \in (\mathbb{Z}/\equiv_m)^*$. Then since $(\mathbb{Z}/\equiv_m)^*$ is closed under inverses and multiplication, $X^{-1} \cdot Y \in (\mathbb{Z}/\equiv_m)^*$, and

$$f_X(X^{-1} \cdot Y) = X \cdot X^{-1} \cdot Y = [1]_m \cdot Y = Y.$$

Thus, f_X is onto.

For example, consider the case $m = 10$, and let $X = [3]_{10}$. Applying f_X to the four elements of $(\mathbb{Z}/\equiv_{10})^*$ gives the values shown in Figure 7.6. Notice that, since f_X is one-to-one and onto, each of the four elements of $(\mathbb{Z}/\equiv_{10})^*$ appears exactly once in the column under $f_X(Y)$; each element appears at least once because f_X is onto, and it appears only once because f_X is one-to-one. Thus, the entries in the second column of Figure 7.6 are exactly the same as the entries in the first column, but listed in a different order.

Y	$f_X(Y)$
$[1]_{10}$	$[3]_{10} \cdot [1]_{10} = [3]_{10}$
$[3]_{10}$	$[3]_{10} \cdot [3]_{10} = [9]_{10}$
$[7]_{10}$	$[3]_{10} \cdot [7]_{10} = [1]_{10}$
$[9]_{10}$	$[3]_{10} \cdot [9]_{10} = [7]_{10}$

Figure 7.6. Values of f_X when $X = [3]_{10}$.

More generally, suppose m is a positive integer and $X \in (\mathbb{Z}/\equiv_m)^*$. By the definition of Euler's phi function, there are $\varphi(m)$ elements in $(\mathbb{Z}/\equiv_m)^*$. Let $Y_1, Y_2, \dots, Y_{\varphi(m)}$ be a list of these elements. Then since f_X is one-to-one and onto, each of these elements occurs exactly once in the list $f_X(Y_1), f_X(Y_2), \dots, f_X(Y_{\varphi(m)})$. In other words, the two lists $Y_1, Y_2, \dots, Y_{\varphi(m)}$ and $f_X(Y_1), f_X(Y_2), \dots, f_X(Y_{\varphi(m)})$ contain exactly the same entries, but listed in different orders – just like the two columns in Figure 7.6. It follows, by the commutative and associative laws for multiplication, that if we multiply all of

the entries in each of the two lists, the products will be the same (see exercise 21 in Section 6.4):

$$\begin{aligned} Y_1 \cdot Y_2 \cdots Y_{\varphi(m)} &= f_X(Y_1) \cdot f_X(Y_2) \cdots f_X(Y_{\varphi(m)}) \\ &= (X \cdot Y_1) \cdot (X \cdot Y_2) \cdots (X \cdot Y_{\varphi(m)}) \\ &= X^{\varphi(m)} \cdot (Y_1 \cdot Y_2 \cdots Y_{\varphi(m)}), \end{aligned}$$

where of course by $X^{\varphi(m)}$ we mean X multiplied by itself $\varphi(m)$ times. To simplify this equation, let $Z = Y_1 \cdot Y_2 \cdots Y_{\varphi(m)}$. Then the equation says $Z = X^{\varphi(m)} \cdot Z$. Since $(\mathbb{Z}/\equiv_m)^*$ is closed under multiplication, $Z \in (\mathbb{Z}/\equiv_m)^*$, so it has an inverse. Multiplying both sides of the equation $Z = X^{\varphi(m)} \cdot Z$ by Z^{-1} , we get

$$[1]_m = Z \cdot Z^{-1} = X^{\varphi(m)} \cdot Z \cdot Z^{-1} = X^{\varphi(m)} \cdot [1]_m = X^{\varphi(m)}.$$

Thus, we have proven the following theorem.

Theorem 7.4.2. *Suppose m is a positive integer and $X \in (\mathbb{Z}/\equiv_m)^*$. Then $X^{\varphi(m)} = [1]_m$.*

To understand the significance of this theorem, it may help to rephrase it in terms of numbers.

Theorem 7.4.3. (Euler's theorem) *Suppose m is a positive integer. Then for every positive integer a , if $\gcd(m, a) = 1$ then $a^{\varphi(m)} \equiv 1 \pmod{m}$.*

Proof. Suppose a is a positive integer and $\gcd(m, a) = 1$. Then by Theorem 7.3.7, $[a]_m \in (\mathbb{Z}/\equiv_m)^*$, so by Theorem 7.4.2, $[a]_m^{\varphi(m)} = [1]_m$, where $[a]_m^{\varphi(m)}$ denotes $[a]_m$ multiplied by itself $\varphi(m)$ times. But

$$[a]_m^{\varphi(m)} = \underbrace{[a]_m \cdot [a]_m \cdots [a]_m}_{\varphi(m) \text{ terms}} = \underbrace{[a \cdot a \cdots a]_m}_{\varphi(m) \text{ terms}} = [a^{\varphi(m)}]_m.$$

(For a more careful proof of this equation, see exercise 5.) Thus, $[a^{\varphi(m)}]_m = [a]_m^{\varphi(m)} = [1]_m$, and therefore $a^{\varphi(m)} \equiv 1 \pmod{m}$. \square

For example, 10 and 7 are relatively prime, so according to Euler's theorem, $7^{\varphi(10)}$ should be congruent to 1 modulo 10. To check this, we compute

$$7^{\varphi(10)} = 7^4 = 2401 \equiv 1 \pmod{10}.$$

To apply Euler's theorem, we need to be able to compute $\varphi(m)$. Of course, we can check all the elements of \mathbb{Z}/\equiv_m one-by-one and count how many have multiplicative inverses, as we did in the case $m = 10$, but for large m this will

be impractical. We devote the rest of this section to finding a more efficient way to compute $\varphi(m)$.

We begin by rephrasing the definition of $\varphi(m)$. We know that $\{0, 1, \dots, m-1\}$ is a complete residue system modulo m , but since $0 \equiv m \pmod{m}$, we can also say that $\{1, 2, \dots, m\}$ is a complete residue system. Thus, $\mathbb{Z}/\equiv_m = \{[1]_m, [2]_m, \dots, [m-1]_m, [m]_m\} = \{[a]_m \mid 1 \leq a \leq m\}$, where each element of \mathbb{Z}/\equiv_m appears exactly once in this list of elements. To identify which of these elements are in $(\mathbb{Z}/\equiv_m)^*$, we use Theorem 7.3.7, which tells us that for any positive integer a , $[a]_m$ has a multiplicative inverse iff m and a are relatively prime. Thus,

$$(\mathbb{Z}/\equiv_m)^* = \{[a]_m \mid 1 \leq a \leq m \text{ and } \gcd(m, a) = 1\}.$$

This gives us another way to understand Euler's phi function:

$$\varphi(m) = \text{the number of elements in the set } \{a \mid 1 \leq a \leq m \text{ and } \gcd(m, a) = 1\}.$$

Using this characterization of the phi function, it is easy to compute $\varphi(p)$ when p is prime: If $1 \leq a \leq p-1$ then $p \nmid a$, and therefore $\gcd(p, a) = 1$, but $\gcd(p, p) = p > 1$. Therefore

$$\{a \mid 1 \leq a \leq p \text{ and } \gcd(p, a) = 1\} = \{1, 2, \dots, p-1\},$$

so $\varphi(p) = p-1$. In fact, it is almost as easy to compute $\varphi(p^k)$ for any positive integer k . If a is a positive integer and $p \mid a$ then $\gcd(p^k, a) \geq p > 1$, but if $p \nmid a$ then the only common divisor of p^k and a is 1, so $\gcd(p^k, a) = 1$. Thus the elements of the set $\{a \mid 1 \leq a \leq p^k\}$ that are *not* relatively prime to p^k are precisely the ones that are divisible by p , and those elements are $p, 2p, 3p, \dots, p^k = p^{k-1}p$. In other words,

$$\{a \mid 1 \leq a \leq p^k \text{ and } \gcd(p^k, a) = 1\} = \{1, 2, \dots, p^k\} \setminus \{p, 2p, \dots, p^{k-1}p\},$$

and the number of elements in this set is $p^k - p^{k-1} = p^{k-1}(p-1)$. Thus $\varphi(p^k) = p^{k-1}(p-1)$.

To compute $\varphi(m)$ for other values of m , we use the following theorem, which we will prove later in this section.

Theorem 7.4.4. *Suppose m and n are relatively prime positive integers. Then*
 $\varphi(mn) = \varphi(m) \cdot \varphi(n)$.

A function f from the positive integers to the real numbers is called a *multiplicative function* if it has the property that for all relatively prime positive integers m and n , $f(mn) = f(m) \cdot f(n)$. Thus, Theorem 7.4.4 says that Euler's phi function is a multiplicative function. A number of other

important functions in number theory are also multiplicative, but φ is the only one we will study in this book. (For two more examples, see exercises 16 and 17.)

Theorem 7.4.4 allows us to use the prime factorization of any positive integer m to find $\varphi(m)$. Suppose the prime factorization of m is $m = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$, where p_1, p_2, \dots, p_k are prime numbers and $p_1 < p_2 < \cdots < p_k$. Then $p_1^{e_1}$ and $p_2^{e_2} \cdots p_k^{e_k}$ are relatively prime, because they have no prime factors in common (see exercise 5 in Section 7.2), so $\varphi(m) = \varphi(p_1^{e_1}) \cdot \varphi(p_2^{e_2} \cdots p_k^{e_k})$. Repeating this reasoning we conclude that

$$\begin{aligned} \varphi(m) &= \varphi(p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}) = \varphi(p_1^{e_1}) \cdot \varphi(p_2^{e_2}) \cdots \varphi(p_k^{e_k}) \\ &= p_1^{e_1-1}(p_1-1) \cdot p_2^{e_2-1}(p_2-1) \cdots p_k^{e_k-1}(p_k-1). \end{aligned}$$

For example, $600 = 2^3 \cdot 3 \cdot 5^2$, so

$$\varphi(600) = \varphi(2^3 \cdot 3 \cdot 5^2) = 2^2(2-1) \cdot 3^0(3-1) \cdot 5^1(5-1) = 160.$$

That was a lot easier than explicitly listing the 160 elements of $(\mathbb{Z}/\equiv_{600})^*$!

Our proof of Theorem 7.4.4 will depend on three lemmas.

Lemma 7.4.5. *Suppose m and n are relatively prime positive integers. Then for all integers a and b , $a \equiv b \pmod{mn}$ iff $a \equiv b \pmod{m}$ and $a \equiv b \pmod{n}$.*

Proof. See exercise 6. □

Lemma 7.4.6. *For all positive integers a , b , and c , $\gcd(ab, c) = 1$ iff $\gcd(a, c) = 1$ and $\gcd(b, c) = 1$.*

Proof. See exercise 7. □

Lemma 7.4.7. *Suppose m and n are relatively prime positive integers. Then for all integers a and b , there is some integer r such that $1 \leq r \leq mn$, $r \equiv a \pmod{m}$, and $r \equiv b \pmod{n}$.*

Proof. Let a and b be arbitrary integers. Since m and n are relatively prime, there are integers s and t such that $sm + tn = 1$. Therefore $tn - 1 = -sm$ and $sm - 1 = -tn$.

Let $x = tna + smb$. Then

$$x - a = (tn - 1)a + smb = -sma + smb = sm(b - a),$$

so $m \mid (x - a)$, and therefore $x \equiv a \pmod{m}$. Similarly,

$$x - b = tna + (sm - 1)b = tna - tnb = tn(a - b),$$

so $n \mid (x - b)$ and $x \equiv b \pmod{n}$.

Since $\{1, 2, \dots, mn\}$ is a complete residue system modulo mn , we can find some integer r such that $r \equiv x \pmod{mn}$ and $1 \leq r \leq mn$. By Lemma 7.4.5, $r \equiv x \pmod{m}$ and $r \equiv x \pmod{n}$, and by the transitivity of \equiv_m and \equiv_n it follows that $r \equiv a \pmod{m}$ and $r \equiv b \pmod{n}$. \square

Commentary. After the introduction of the arbitrary integers a and b , the goal is an existential statement. As is common in proofs of existential statements, the proof introduces a number x without providing any motivation for the choice of x . The number x turns out to have most of the properties we want, but perhaps not all of them, since it might not be between 1 and mn . We therefore need an extra step to come up with the number r that has all of the required properties.

We will need one more idea for our proof of Theorem 7.4.4. Suppose A is a set with p elements and B is a set with q elements; say $A = \{a_1, a_2, \dots, a_p\}$ and $B = \{b_1, b_2, \dots, b_q\}$. Then $A \times B$ has pq elements. To see why, imagine arranging the elements of $A \times B$ in a table, with the ordered pair (a_i, b_j) in row i , column j of the table. Since the table will have p rows and q columns, $A \times B$ must have pq elements. For a more careful proof of this fact, see exercise 22 in Section 8.1.

We are now ready to prove that φ is a multiplicative function.

Proof of Theorem 7.4.4. Let $R = \{a \mid 1 \leq a \leq mn \text{ and } \gcd(mn, a) = 1\}$. By Lemma 7.4.6, if $a \in R$ then $\gcd(m, a) = 1$ and $\gcd(n, a) = 1$, so $[a]_m \in (\mathbb{Z}/\equiv_m)^*$ and $[a]_n \in (\mathbb{Z}/\equiv_n)^*$. Thus we can define a function $f : R \rightarrow (\mathbb{Z}/\equiv_m)^* \times (\mathbb{Z}/\equiv_n)^*$ by the formula $f(a) = ([a]_m, [a]_n)$. Our plan is to show that f is one-to-one and onto, which implies that the sets R and $(\mathbb{Z}/\equiv_m)^* \times (\mathbb{Z}/\equiv_n)^*$ have the same number of elements. But R has $\varphi(mn)$ elements and $(\mathbb{Z}/\equiv_m)^* \times (\mathbb{Z}/\equiv_n)^*$ has $\varphi(m) \cdot \varphi(n)$ elements, so this will establish that $\varphi(mn) = \varphi(m) \cdot \varphi(n)$.

To show that f is one-to-one, suppose $a_1 \in R$, $a_2 \in R$, and $f(a_1) = f(a_2)$. This means that $([a_1]_m, [a_1]_n) = ([a_2]_m, [a_2]_n)$, so $[a_1]_m = [a_2]_m$ and $[a_1]_n = [a_2]_n$, and therefore $a_1 \equiv a_2 \pmod{m}$ and $a_1 \equiv a_2 \pmod{n}$. By Lemma 7.4.5 it follows that $a_1 \equiv a_2 \pmod{mn}$. But since $\{a \mid 1 \leq a \leq mn\}$ is a complete residue system modulo mn , no two distinct elements of R are congruent modulo mn , so $a_1 = a_2$. This completes the proof that f is one-to-one.

Finally, to show that f is onto, let $([a]_m, [b]_n)$ be an arbitrary element of $(\mathbb{Z}/\equiv_m)^* \times (\mathbb{Z}/\equiv_n)^*$. By Lemma 7.4.7, there is some integer r such that $1 \leq r \leq mn$, $r \equiv a \pmod{m}$, and $r \equiv b \pmod{n}$. Therefore $[r]_m = [a]_m \in (\mathbb{Z}/\equiv_m)^*$ and $[r]_n = [b]_n \in (\mathbb{Z}/\equiv_n)^*$, so by Theorem 7.3.7, $\gcd(m, r) = \gcd(n, r) = 1$. Applying Lemma 7.4.6, we conclude that $\gcd(mn, r) = 1$. Therefore $r \in R$ and $f(r) = ([r]_m, [r]_n) = ([a]_m, [b]_n)$, which shows that f is onto. \square

Exercises

1. List the elements of $(\mathbb{Z}/\equiv_{20})^*$.
- *2. Find $\varphi(m)$:
 - (a) $m = 539$.
 - (b) $m = 540$.
 - (c) $m = 541$.
3. Check these instances of Euler's theorem by computing $a^{\varphi(m)}$ and verifying that $a^{\varphi(m)} \equiv 1 \pmod{m}$.
 - (a) $m = 18, a = 5$.
 - (b) $m = 19, a = 2$.
 - (c) $m = 20, a = 3$.
4. Check these instances of Lemma 7.4.7 by finding an integer r such that $1 \leq r \leq mn$, $r \equiv a \pmod{m}$, and $r \equiv b \pmod{n}$.
 - (a) $m = 5, n = 8, a = 4, b = 1$.
 - (b) $m = 7, n = 10, a = 6, b = 4$.
5. Suppose m and a are positive integers. Use mathematical induction to prove that for every positive integer n , $[a]_m^n = [a^n]_m$.
- *6. Prove Lemma 7.4.5.
7. Prove Lemma 7.4.6.
- *8. Show that if we drop the hypothesis that m and n are relatively prime from Lemma 7.4.5, then one direction of the "iff" statement is correct and one is not. Justify your answer by giving a proof for one direction and a counterexample for the other.
9. If we drop the hypothesis that m and n are relatively prime from Lemma 7.4.7, is the lemma still correct? Justify your answer by giving either a proof or a counterexample.
- *10. Prove Fermat's little theorem, which says that if p is a prime number, then for every positive integer a , $a^p \equiv a \pmod{p}$.

11. Prove that if m and a are relatively prime positive integers, then $[a]_m^{-1} = [a^{\varphi(m)^{-1}}]_m$.
12. Prove that for all positive integers m, a, p , and q , if m and a are relatively prime and $p \equiv q \pmod{\varphi(m)}$ then $a^p \equiv a^q \pmod{m}$.
- *13. Prove that if a, b_1, b_2, \dots, b_k are positive integers and $\gcd(a, b_1) = \gcd(a, b_2) = \dots = \gcd(a, b_k) = 1$, then $\gcd(a, b_1 b_2 \cdots b_k) = 1$.
14. Suppose that m_1, m_2, \dots, m_k are positive integers that are pairwise relatively prime; i.e., for all $i, j \in \{1, 2, \dots, k\}$, if $i \neq j$ then $\gcd(m_i, m_j) = 1$. Let $M = m_1 m_2 \cdots m_k$. Prove that for all integers a and b , $a \equiv b \pmod{M}$ iff for every $i \in \{1, 2, \dots, k\}$, $a \equiv b \pmod{m_i}$.
- *15. In this exercise you will prove the Chinese remainder theorem. (The theorem was first stated by the Chinese mathematician Sun Zi in the third century.)
- (a) Suppose that m_1, m_2, \dots, m_k are positive integers that are pairwise relatively prime; i.e., for all $i, j \in \{1, 2, \dots, k\}$, if $i \neq j$ then $\gcd(m_i, m_j) = 1$. Let $M = m_1 m_2 \cdots m_k$. Prove that for all integers a_1, a_2, \dots, a_k there is an integer r such that $1 \leq r \leq M$ and for all $i \in \{1, 2, \dots, k\}$, $r \equiv a_i \pmod{m_i}$. (Hint: Use induction on k . In the induction step, use Lemma 7.4.7. You will also find exercises 13 and 14 helpful.)
- (b) Prove that the integer r in part (a) is unique.
16. For each positive integer n , let $\tau(n) =$ the number of elements of $D(n)$. For example, $D(6) = \{1, 2, 3, 6\}$, so $\tau(6) = 4$. In this exercise you will prove that τ is a multiplicative function. Suppose m and n are relatively prime positive integers.
- (a) Prove that if $a \in D(m)$ and $b \in D(n)$ then $ab \in D(mn)$.
- (b) By part (a), we can define a function $f : D(m) \times D(n) \rightarrow D(mn)$ by the formula $f(a, b) = ab$. Prove that f is one-to-one and onto.
- (c) Prove that $\tau(mn) = \tau(m) \cdot \tau(n)$, which shows that τ is multiplicative.
- *17. For each positive integer n , let $\sigma(n) =$ the sum of all elements of $D(n)$. For example, $D(6) = \{1, 2, 3, 6\}$, so $\sigma(6) = 1 + 2 + 3 + 6 = 12$. Prove that σ is a multiplicative function. (Hint: Use the function f from part (b) of exercise 16.)
18. In this exercise you will prove Euclid's theorem on perfect numbers. Recall that a positive integer n is called perfect if n is equal to the sum of all divisors of n that are smaller than n . Equivalently, n is perfect if $\sigma(n) = 2n$, where σ is the function defined in exercise 17. Prove that if p is a positive integer and $2^p - 1$ is prime, then $2^{p-1}(2^p - 1)$ is perfect. (Hint: You will find exercise 17 and Example 6.1.1 useful.)

19. In this exercise you will prove Euler's theorem on perfect numbers. Suppose n is an even perfect number. (As in exercise 18, to say that n is perfect means that $\sigma(n) = 2n$, where σ is the function defined in exercise 17.)
- Prove that there are positive integers k and m such that $n = 2^k m$ and m is odd.
 - Prove that $2^{k+1}m = (2^{k+1} - 1)\sigma(m)$.
 - Prove that $2^{k+1} \mid \sigma(m)$. Thus there is a positive integer d such that $\sigma(m) = 2^{k+1}d$.
 - Prove that $m = (2^{k+1} - 1)d$.
 - Prove that $d = 1$. (Hint: Suppose $d > 1$. Then 1, d , and m are distinct divisors of m , so $\sigma(m) \geq 1 + d + m$. Derive a contradiction.)
 - Let $p = k + 1$. Then by parts (a), (d), and (e), $n = 2^{p-1}(2^p - 1)$. Prove that $2^p - 1$ is prime. Thus n is a perfect number of the form considered in exercise 18.

7.5. Public-Key Cryptography

Suppose you want to make a purchase online. You go to the merchant's website and place your order. Then the website asks you to enter your credit card number. You type the number on your computer, and your computer must transmit the number over the internet to the merchant's computer.

Internet communications generally pass through several computers on their way from the sender to the recipient. As a result, there is a possibility that someone with access to one of those intermediary computers could be eavesdropping when your computer sends your credit card number to the merchant. To keep such an eavesdropper from stealing your credit card number, your computer scrambles, or *encrypts* the number before sending it. The merchant's computer then unscrambles, or *decrypts* the number and charges your credit card.

For example, suppose your credit card number is the 16-digit sequence $m = m_1 m_2 \cdots m_{16}$. Each m_i is one of the digits 0, 1, 2, ..., 9, but we will think of it as representing the equivalence class $[m_i]_{10} \in \mathbb{Z}/\equiv_{10}$. If your computer and the merchant's computer could agree on a random sequence of digits $k = k_1 k_2 \cdots k_{16}$, then they could proceed as follows, doing all calculations in \mathbb{Z}/\equiv_{10} . Your computer could replace the i th digit m_i of your credit card number with the digit c_i such that $[c_i]_{10} = [m_i]_{10} + [k_i]_{10}$. Your computer would send the 16-digit sequence $c = c_1 c_2 \cdots c_{16}$ to the merchant's computer,

which would then recover the original sequence m by using the formula $[m_i]_{10} = [c_i]_{10} + (-[k_i]_{10})$. The sequence k is the *key* that your computer uses to encrypt the credit card number and the merchant's computer uses to decrypt it. An eavesdropper who didn't know the key k would be unable to decrypt the encrypted message c and learn your credit card number m .

But how can your computer and the merchant's computer agree on the key k ? If one computer chooses the key and sends it to the other, then an eavesdropper could learn the key and then decrypt the encrypted message. Sending the key securely is just as hard as sending the credit card number, so we don't seem to have made any progress.

The problem with this scheme is that it uses *symmetric cryptography*, in which the same key is used for both encryption and decryption. The solution to the problem is to use *public-key cryptography*, in which the encryption and decryption keys are different. The merchant's computer creates two keys, one for encryption and one for decryption. It sends the encryption key to your computer. Your computer uses the encryption key to encrypt your credit card number and then sends the encrypted number to the merchant's computer, which uses the decryption key to recover the credit card number. An eavesdropper could learn the encryption key, so this key is regarded as a *public key*. But this doesn't help the eavesdropper, because decryption requires the decryption key, and this key is never transmitted and remains secret.

It may seem surprising that it is possible to have different keys for encryption and decryption, but it can be done. In this section we discuss one well-known public-key encryption system called RSA. It is named for Ron Rivest (1947–), Adi Shamir (1952–), and Leonard Adleman (1945–), who developed the system in 1977. A similar system was developed in 1973 by Clifford Cocks (1950–), a mathematician working for the British intelligence agency, but it was classified and not revealed until 1997. As we will see, the RSA system is based on Euler's theorem.

We have introduced the idea of public-key cryptography in the context of internet purchases, but it can be used any time one person wants to send a message to another while preventing an eavesdropper from reading the message. Suppose Alice wants to send a message securely to Bob. To use the RSA public-key system, they would proceed as follows. First Bob chooses two distinct prime numbers p and q . He computes $n = pq$ and $\varphi(n) = (p - 1)(q - 1)$. Next, he chooses a positive integer e such that e and $\varphi(n)$ are relatively prime and $e < \varphi(n)$. By Theorem 7.3.7, $[e]_{\varphi(n)}$ has a multiplicative inverse in $\mathbb{Z}/\equiv_{\varphi(n)}$, which can be computed by the extended Euclidean algorithm. Thus, Bob can compute a positive integer d such that $d < \varphi(n)$ and $[e]_{\varphi(n)} \cdot [d]_{\varphi(n)} = [1]_{\varphi(n)}$, which means that

$ed \equiv 1 \pmod{\varphi(n)}$. Bob sends the pair of numbers (n, e) to Alice; this is the encryption key that Alice will use to encrypt her message. He keeps the numbers p , q , and d secret; he will use d to decrypt Alice's message.

We will assume that the message Alice wants to send is a natural number $m < n$. Of course, her message might actually be a piece of text, not a number, but a piece of text can be encoded as a natural number. If the text is long, it might be necessary to encode it as a sequence of natural numbers, each of which is less than n , and then each of these natural numbers would have to be encrypted separately. But to keep the discussion simple, we will assume that Alice's message is a single natural number $m < n$.

As before, we think of the message m as representing an equivalence class $[m]_n \in \mathbb{Z}/\equiv_n$, and Alice and Bob will do all of their calculations using arithmetic in \mathbb{Z}/\equiv_n . To encrypt her message, Alice computes $[m]_n^e$; in other words, she computes the unique natural number $c < n$ such that $[m]_n^e = [c]_n$. The number c is the encrypted message, which she sends to Bob.

To decrypt the message, Bob computes $[c]_n^d$. What makes the RSA system work is the surprising fact that $[c]_n^d = [m]_n$, as we will prove below. Thus, by computing $[c]_n^d$, Bob can recover the original message m . Notice that encryption and decryption both involve exponentiation, but the encryption exponent e and the decryption exponent d are different. Thus, it doesn't matter if an eavesdropper learns e ; as long as Bob keeps d secret, the eavesdropper will not know what exponent to use to decrypt the encrypted message.

To show that RSA works we need to prove the following theorem.

Theorem 7.5.1. *Suppose p and q are distinct primes, $n = pq$, e and d are positive integers such that $ed \equiv 1 \pmod{\varphi(n)}$, and m and c are natural numbers such that $[m]_n^e = [c]_n$. Then $[c]_n^d = [m]_n$.*

Proof. If $e = d = 1$ then $[m]_n = [c]_n$ and the conclusion clearly holds. If not, then $ed > 1$, so since $ed \equiv 1 \pmod{\varphi(n)}$, there is some positive integer k such that $ed - 1 = k\varphi(n)$, and therefore $ed = k\varphi(n) + 1 = k(p-1)(q-1) + 1$. And since $[m]_n^e = [c]_n$, we have $m^e \equiv c \pmod{n}$, so $n \mid (m^e - c)$.

Although we ultimately want to draw a conclusion about arithmetic in \mathbb{Z}/\equiv_n , we will find it useful to do some calculations in \mathbb{Z}/\equiv_p and \mathbb{Z}/\equiv_q first. Since $p \mid n$ and $n \mid (m^e - c)$, by the transitivity of the divisibility relation, $p \mid (m^e - c)$. Therefore $m^e \equiv c \pmod{p}$, or equivalently $[m]_p^e = [c]_p$.

Note that the usual exponent rules work for exponentiation in \mathbb{Z}/\equiv_p . Specifically, for any $X \in \mathbb{Z}/\equiv_p$ and any positive integers a and b we have

$$X^a \cdot X^b = \underbrace{X \cdots X}_a \text{ terms} \cdot \underbrace{X \cdots X}_b \text{ terms} = \underbrace{X \cdots X}_{a+b} \text{ terms} = X^{a+b}$$

and

$$(X^a)^b = \underbrace{X \cdots X \cdot X \cdots X \cdots X \cdots X}_{b \text{ groups of terms}} = \underbrace{X \cdots X}_{ab \text{ terms}} = X^{ab}.$$

(For more careful proofs of these equations, see exercise 8.) Applying these rules, we see that

$$[c]_p^d = ([m]_p^e)^d = [m]_p^{ed} = [m]_p^{k(p-1)(q-1)+1} = ([m]_p^{p-1})^{k(q-1)} \cdot [m]_p.$$

We claim now that $[c]_p^d = [m]_p$. To prove this, we consider two cases.

Case 1. $p \nmid m$. Then p and m are relatively prime, so by Euler's theorem, $[m]_p^{p-1} = [1]_p$. Therefore

$$[c]_p^d = ([m]_p^{p-1})^{k(q-1)} \cdot [m]_p = [1]_p^{k(q-1)} \cdot [m]_p = [1]_p \cdot [m]_p = [m]_p.$$

Case 2. $p \mid m$. Then $[m]_p = [0]_p$, so

$$[c]_p^d = [m]_p^{ed} = [0]_p^{ed} = [0]_p = [m]_p.$$

In both cases we have reached the desired conclusion that $[c]_p^d = [m]_p$. Therefore $c^d \equiv m \pmod{p}$. Similar reasoning shows that $c^d \equiv m \pmod{q}$, and since $pq = n$, it follows by Lemma 7.4.5 that $c^d \equiv m \pmod{n}$. In other words, $[c]_n^d = [m]_n$, which is what we wanted to prove. \square

Let's try this out in a simple example. Suppose Bob chooses the primes $p = 3$ and $q = 11$, so $n = pq = 33$ and $\varphi(n) = (p-1)(q-1) = 20$. He also chooses $e = 7$, and he then computes $[e]_{\varphi(n)}^{-1} = [7]_{20}^{-1} = [3]_{20}$, so $d = 3$. (As a check on Bob's work, note that $[7]_{20} \cdot [3]_{20} = [21]_{20} = [1]_{20}$.) Bob sends the numbers $n = 33$ and $e = 7$ to Alice.

Suppose Alice wants to send the message $m = 5$ to Bob. She computes

$$[m]_n^e = [5]_{33}^7 = [78125]_{33} = [14]_{33},$$

so her encrypted message is $c = 14$. She sends this number to Bob. To decrypt the message, Bob computes

$$[c]_n^d = [14]_{33}^3 = [2744]_{33} = [5]_{33}.$$

Thus, Bob successfully recovers the original message $m = 5$.

Are Alice and Bob's communications secure? Suppose an eavesdropper intercepts both Bob's message to Alice and Alice's message to Bob, thus learning the numbers $n = 33$, $e = 7$, and $c = 14$. By factoring $n = 33 = 3 \cdot 11$, the eavesdropper could learn that $p = 3$ and $q = 11$ (or vice-versa), and therefore $\varphi(n) = (p-1)(q-1) = 20$. But then the eavesdropper could

compute, just as Bob did, that $[e]_{\varphi(n)}^{-1} = [7]_{20}^{-1} = [3]_{20}$, thus learning the decryption exponent $d = 3$. The eavesdropper can now decrypt Alice's message just the way Bob did. The communications are not secure!

What has gone wrong? The problem is that in this simple example we have used small numbers. The eavesdropper's first step was to factor $n = 33$, which is a product of two prime numbers. A small number n can be factored easily by simply dividing n by all smaller prime numbers until a prime factor is found, but if n is large then this procedure will take too long to be practical. Factoring numbers that are products of two large prime numbers is especially hard. As of 2019, the largest such number that has ever been factored is a product of two 116-digit primes. It was factored in 2009 after two years of computation by many hundreds of computers working together on the problem, using the equivalent of almost 2000 years of computing by a single computer. Factoring a product of primes significantly larger than this would not be feasible with current computing technology. Today most people who use RSA choose prime numbers that are several hundreds of digits long. If an eavesdropper learns the numbers n and e , then in principle he has enough information to find the decryption exponent d , but the only known way to do it is to factor n . The security of RSA depends on the fact that, in practice, the numbers used are so large that factoring n is not feasible.

But wait! What about the computations that Alice and Bob have to do with these extremely large numbers? Will they also be computationally infeasible? If so, then the system will be useless. Fortunately, there are efficient ways to do the computations required of Alice and Bob. While a detailed discussion of how these computations are performed is beyond the scope of this book, we can briefly comment on the main points.

The most difficult computations Alice and Bob have to do are:

- Bob must find two large prime numbers p and q .
- Bob must find $[e]_{\varphi(n)}^{-1}$.
- Alice must compute $[m]_n^e$, and Bob must compute $[c]_n^d$.

To find the primes p and q , Bob can simply choose suitably large numbers at random and test them to see if they are prime until he finds two primes. The problem of testing a large number to see if it is prime has been studied extensively. In 2019, using the best known methods, a computer can determine whether or not a 1000-digit number is prime in a few minutes. But this is not fast enough to be convenient for RSA, since Bob may have to test hundreds of numbers for primality before he finds a prime. So most implementations of RSA use *probabilistic primality tests*. These tests take a fraction of a second, but they are not guaranteed to be accurate; in particular, if a number is not

prime, there is a chance that the test will fail to detect this and report that the number is prime. But by repeating the test several times, the probability of an error can be made as small as desired. For more on probabilistic primality testing, see exercises 10–14.

We already know a method that Bob can use to compute $[e]_{\varphi(n)}^{-1}$: the extended Euclidean algorithm. This algorithm is very fast, even with very large numbers. For more on this, see exercise 13 in Section 7.1.

Finally, to encrypt and decrypt messages, Alice and Bob must raise elements of \mathbb{Z}/\equiv_n to high powers. Suppose $X \in \mathbb{Z}/\equiv_n$ and a is a positive integer. The most straightforward way to compute X^a is to multiply X by itself a times, but this will not be feasible if a is large. There is a better way using recursion. If $a = 1$, then of course $X^a = X$. For larger values of a , we use the following formulas:

$$\begin{aligned} X^{2k} &= X^k \cdot X^k; \\ X^{2k+1} &= X^k \cdot X^k \cdot X. \end{aligned}$$

Example 7.5.2. Find $[347]_{582}^{172}$.

Solution

Let $X = [347]_{582} \in \mathbb{Z}/\equiv_{582}$; we must find X^{172} . Since 172 is even, we start with

$$X^{172} = X^{2 \cdot 86} = X^{86} \cdot X^{86}.$$

If we can find X^{86} , then we'll just have to multiply it by itself to find X^{172} . To find X^{86} , we use the same method:

$$X^{86} = X^{2 \cdot 43} = X^{43} \cdot X^{43}.$$

Now we need to find X^{43} , and since 43 is odd, we use the formula

$$X^{43} = X^{2 \cdot 21 + 1} = X^{21} \cdot X^{21} \cdot X.$$

Continuing in this way, we get the following list of formulas:

$$\begin{aligned} X^{172} &= X^{86} \cdot X^{86}, \\ X^{86} &= X^{43} \cdot X^{43}, \\ X^{43} &= X^{21} \cdot X^{21} \cdot X, \\ X^{21} &= X^{10} \cdot X^{10} \cdot X, \\ X^{10} &= X^5 \cdot X^5, \\ X^5 &= X^2 \cdot X^2 \cdot X, \end{aligned}$$

$$X^2 = X^1 \cdot X^1 = X \cdot X.$$

We can now work through this list in reverse order and evaluate each formula:

$$X^2 = X \cdot X = [347]_{582} \cdot [347]_{582} = [120409]_{582} = [517]_{582},$$

$$X^5 = X^2 \cdot X^2 \cdot X = [517]_{582} \cdot [517]_{582} \cdot [347]_{582} = [92749283]_{582} = [17]_{582},$$

$$X^{10} = X^5 \cdot X^5 = [17]_{582} \cdot [17]_{582} = [289]_{582},$$

$$X^{21} = X^{10} \cdot X^{10} \cdot X = [289]_{582} \cdot [289]_{582} \cdot [347]_{582} = [28981787]_{582} = [515]_{582},$$

$$X^{43} = X^{21} \cdot X^{21} \cdot X = [515]_{582} \cdot [515]_{582} \cdot [347]_{582} = [92033075]_{582} = [251]_{582},$$

$$X^{86} = X^{43} \cdot X^{43} = [251]_{582} \cdot [251]_{582} = [63001]_{582} = [145]_{582},$$

$$X^{172} = X^{86} \cdot X^{86} = [145]_{582} \cdot [145]_{582} = [21025]_{582} = [73]_{582}.$$

We conclude that $[347]_{582}^{172} = [73]_{582}$. If you count, you will find that we only performed 10 multiplications – much less than the 171 that would be required if we simply multiplied 172 X s. For more on the number of multiplications required to compute X^a in general, see exercise 9.

We end this section with one more example of the use of RSA. This time we will use numbers that are large enough to force us to use efficient methods of calculation, although they are still not as large as would be used in a real application of RSA.

Example 7.5.3. Suppose Bob chooses the prime numbers $p = 48611$ and $q = 37813$. He computes $n = pq = 1838127743$ and $\varphi(n) = (p - 1)(q - 1) = 1838041320$. He then chooses the encryption exponent $e = 184270657$.

1. Find the decryption exponent d .
2. Suppose Alice wants to send the message $m = 357249732$. Find the encrypted message c , and verify that Bob can decrypt it.

Solutions

1. To compute d , Bob uses the extended Euclidean algorithm to find $[e]_{\varphi(n)}^{-1} = [184270657]_{1838041320}^{-1}$. The steps are shown in Figure 7.7. Bob concludes that $d = 88235833$.

As a check, Bob can compute that

$$ed - 1 = 16259274917852280 = 8845979\varphi(n),$$

so $ed \equiv 1 \pmod{\varphi(n)}$.

n	q_n	r_n	s_n	t_n
0		1838041320	1	0
1		184270657	0	1
2	9	179605407	1	-9
3	1	4665250	-1	10
4	38	2325907	39	-389
5	2	13436	-79	788
6	173	1479	13706	-136713
7	9	125	-123433	1231205
8	11	104	1371469	-13679968
9	1	21	-1494902	14911173
10	4	20	7351077	-73324660
11	1	1	-8845979	88235833
12	20	0		

Figure 7.7. Computing the decryption exponent d .

2. Let $X = [m]_n = [357249732]_{1838127743}$. To encrypt her message, Alice must compute $X^e = X^{184270657}$. The steps are shown in Figure 7.8; of course, Alice plans her calculations by starting at the end of this table, but performs the calculations from the beginning. She sends the encrypted message $c = 1357673396$.

k	X^k	k	X^k
2	$[413387288]_n$	44987	$[418397817]_n$
5	$[1105456936]_n$	89975	$[1597035021]_n$
10	$[1522283045]_n$	179951	$[1491451285]_n$
21	$[1773257888]_n$	359903	$[954701208]_n$
43	$[638596171]_n$	719807	$[1817497177]_n$
87	$[664005337]_n$	1439614	$[1774588706]_n$
175	$[661296271]_n$	2879229	$[1061291500]_n$
351	$[993223048]_n$	5758458	$[21397340]_n$
702	$[1294276724]_n$	11516916	$[1624593674]_n$
1405	$[1088781967]_n$	23033832	$[1474914774]_n$
2811	$[1010306117]_n$	46067664	$[1189097151]_n$
5623	$[1064784897]_n$	92135328	$[46825442]_n$
11246	$[1739950485]_n$	184270657	$[1357673396]_n$
22493	$[799178524]_n$		

Figure 7.8. Computing the encrypted message c .

To decrypt the message, Bob lets $Y = [c]_n$ and computes $Y^d = Y^{88235833}$, as shown in Figure 7.9. As expected, he gets $m = 357249732$.

k	Y^k	k	Y^k
2	$[42593275]_n$	21541	$[120530669]_n$
5	$[1698473378]_n$	43083	$[189879402]_n$
10	$[1210371791]_n$	86167	$[781925623]_n$
21	$[1085519751]_n$	172335	$[1276315424]_n$
42	$[1335983514]_n$	344671	$[1511938429]_n$
84	$[1212154100]_n$	689342	$[1116941725]_n$
168	$[638363154]_n$	1378684	$[748516067]_n$
336	$[1695419879]_n$	2757369	$[590443992]_n$
673	$[250463254]_n$	5514739	$[1169450853]_n$
1346	$[1092090842]_n$	11029479	$[83459512]_n$
2692	$[149835148]_n$	22058958	$[643822280]_n$
5385	$[1009240318]_n$	44117916	$[1032113647]_n$
10770	$[1219871219]_n$	88235833	$[357249732]_n$

Figure 7.9. Decrypting the message.

Exercises

1. Suppose Bob chooses $p = 5$, $q = 11$, and $e = 7$.
 - (a) Find n , $\varphi(n)$, and d .
 - (b) Suppose Alice wants to send the message $m = 9$. Find the encrypted message c , and verify that Bob can decrypt it.
- *2. Suppose Bob chooses $p = 71$, $q = 83$, and $e = 1369$.
 - (a) Find n , $\varphi(n)$, and d .
 - (b) Suppose Alice wants to send the message $m = 1001$. Find the encrypted message c , and verify that Bob can decrypt it.
3. Suppose Bob chooses $p = 71$ and $q = 83$. Why would $e = 1368$ be a bad choice?
4. Suppose Bob chooses $p = 17389$, $q = 14947$, and $e = 35824631$.
 - (a) Find n , $\varphi(n)$, and d .
 - (b) Suppose Alice wants to send the message $m = 123456789$. Find the encrypted message c , and verify that Bob can decrypt it.
- *5. You are eavesdropping on Alice and Bob. You intercept the message $(n, e) = (493, 129)$ sent to Alice by Bob, and then the message $c = 149$ sent to Bob by Alice.

- (a) Factor n .
- (b) Find the decryption exponent d .
- (c) Decrypt the message.
6. Suppose Alice and Bob are using RSA. As usual, Bob has generated the numbers n , e , and d , and he has sent n and e to Alice but kept d secret. Alice has a message m that represents a contract that she wants Bob to sign. The contract is not secret – she is glad to send it to Bob without encrypting it. But she wants Bob to send back a *digital signature* for the contract. Like an ordinary signature, it should be a message that someone else could not forge, so that Alice knows that Bob, and not some impostor, has written the signature, and Bob cannot deny at a later date that he signed the contract. To create his signature, Bob computes the unique integer s such that $0 \leq s < n$ and $[m]_n^d = [s]_n$, and he sends s to Alice.
- (a) Show that $[s]_n^e = [m]_n$, and if s^2 is any integer such that $0 \leq s^2 < n$ and $s^2 \equiv s$, then $[s^2]_n^e \equiv [m]_n$. Thus, Alice can authenticate the signature by computing $[s]_n^e$ and verifying that it is equal to $[m]_n$.
- (b) Why can't an impostor forge Bob's signature?
- *7. In this exercise we will see why it is important for p and q to be prime. Suppose Bob chooses $p = 9$, $q = 35$, and $e = 95$, not noticing that 9 and 35 are not prime. He computes $n = pq = 315$, and he sends $(n, e) = (315, 95)$ to Alice.
- (a) Suppose Alice wants to send the message $m = 123$. What encrypted message c will she send?
- (b) Bob computes $\varphi = (p - 1)(q - 1) = 272$; he thinks this is $\varphi(n)$, but he's wrong. To find the decryption exponent d , he then computes $[e]_\varphi^{-1} = [d]_\varphi$. What value of d does he get?
- (c) Using the decryption exponent d from part (b), what does Bob get when he tries to decrypt Alice's message?
- (d) What is the correct value of $\varphi(n)$? What decryption exponent d would Bob have gotten if he had used the correct value for $\varphi(n)$ and computed $[e]_{\varphi(n)}^{-1} = [d]_{\varphi(n)}$? Using this decryption exponent, what would Bob have gotten when he tried to decrypt Alice's message?
8. Suppose m is a positive integer and $X \in \mathbb{Z}/\equiv_m$.
- (a) Give a recursive definition of X^a , for positive integers a .
- (b) Use mathematical induction to prove that for all positive integers a and b , $X^a \cdot X^b = X^{a+b}$.
- (c) Use mathematical induction to prove that for all positive integers a and b , $(X^a)^b = X^{ab}$.

- *9. Suppose $X \in \mathbb{Z}_n/\equiv_n$. Prove that for every positive integer a , the recursive method of computing X^a that is illustrated in Example 7.5.2 uses at most $2 \log_2 a$ multiplications.

Exercises 10–14 are concerned with probabilistic primality testing. In these problems, we are looking for a computational test that can be performed on a positive integer n so that if n is prime then n passes the test, and if n is not prime then it fails the test. We will find that there are some tests that work in many cases, but not all cases.

10. According to Euler's theorem, if n is prime and $2 \leq a \leq n - 1$, then $a^{n-1} \equiv 1 \pmod{n}$. This suggests the following primality test: To test whether or not an integer $n > 2$ is prime, choose a random number $a \in \{2, 3, \dots, n - 1\}$ and check whether or not $a^{n-1} \equiv 1 \pmod{n}$. If so, then n passes the test, and if not, then it fails. This test is called the *Fermat primality test*, because the instance of Euler's theorem on which it is based is closely related to Fermat's little theorem; see exercise 10 in Section 7.4. If n is prime, then by Euler's theorem, it is guaranteed to pass the test. Unfortunately, composite numbers sometimes pass the test as well. If $2 \leq a \leq n - 1$ and $a^{n-1} \equiv 1 \pmod{n}$, but n is not prime, then we say that n is a *Fermat pseudoprime to the base a* ; it passes the Fermat primality test using the base a , even though it is not prime. If $2 \leq a \leq n - 1$ and $a^{n-1} \not\equiv 1 \pmod{n}$ then we say that a is a *Fermat witness* for n . If there is a Fermat witness for n then, by Euler's theorem, n is not prime.
- (a) Show that 15 is a Fermat pseudoprime to the base 4, but 3 is a Fermat witness for 15.
- (b) Show that if n is a Fermat pseudoprime to the base a , then n and a are relatively prime.
11. Recall from exercise 5 in Section 6.2 that the numbers $F_n = 2^{(2^n)} + 1$ are called Fermat numbers. Fermat showed that F_n is prime for $0 \leq n \leq 4$, and Euler showed that F_5 is not prime. It is not known if there is any $n > 4$ for which F_n is prime. In this exercise you will show that for every natural number n , $2^{F_n-1} \equiv 1 \pmod{F_n}$. Thus, if F_n is not prime, then in the terminology of exercise 10, it is a Fermat pseudoprime to the base 2. In other words, the Fermat primality test with $a = 2$ will not be useful for testing whether F_n is prime.
- (a) Show that $2^{(2^n)} \equiv -1 \pmod{F_n}$.
- (b) Show that $2^{(2^{n+1})} \equiv 1 \pmod{F_n}$.
- (c) Show that $2^{n+1} \mid (F_n - 1)$. (Hint: Use exercise 12(a) in Section 6.3.)

(d) Show that $2^{F_n-1} \equiv 1 \pmod{F_n}$. (Hint: Use parts (b) and (c) and exercise 16 in Section 7.3.)

*12. Suppose n is an integer larger than 2 and let $R = \{2, 3, \dots, n-1\}$. Let

$$R_1 = \{a \in R \mid a^{n-1} \equiv 1 \pmod{n}\},$$

$$R_2 = R \setminus R_1 = \{a \in R \mid a^{n-1} \not\equiv 1 \pmod{n}\}.$$

Suppose $a \in R_2$ and $\gcd(n, a) = 1$. Then a is a Fermat witness for n , so n is not prime. (See exercise 10 for the meanings of the terms used in this exercise.)

(a) Show that for every $x \in R_1$ there is a unique $y \in R_2$ such that $ax \equiv y \pmod{n}$.

(b) By part (a), we can define a function $f : R_1 \rightarrow R_2$ by the formula

$$f(x) = \text{the unique } y \in R_2 \text{ such that } ax \equiv y \pmod{n}.$$

Show that f is one-to-one.

(c) Use part (b) to conclude that at least half of the elements of R are Fermat witnesses for n . (This shows that, with probability at least $1/2$, n will fail the Fermat primality test. By repeating the test with different choices for a , the probability of an incorrect result can be made as small as desired.)

13. Exercise 12 shows that if there is at least one Fermat witness for n that is relatively prime to n , then the Fermat primality test has a good chance of detecting that n is not prime. Unfortunately, there are composite numbers n for which no such witness exists. An integer $n > 2$ is called a *Carmichael number* if it is not prime, but it is a Fermat pseudoprime to the base a for every integer $a \in \{2, 3, \dots, n-1\}$ such that a and n are relatively prime. They are named for Robert Daniel Carmichael (1879–1967), who first studied them. If n is a Carmichael number, then although n is not prime, the Fermat primality test is unlikely to detect this fact. In 1994, W. R. Alford (1937–2003), Andrew Granville (1962–), and Carl Pomerance (1944–) proved that there are infinitely many Carmichael numbers. In this problem you will show that 561 is a Carmichael number. (In fact, it is the smallest Carmichael number.) We leave it to you to verify that $561 = 3 \cdot 11 \cdot 17$, so 561 is not prime. Suppose $2 \leq a \leq n-1$ and $\gcd(561, a) = 1$.

(a) Show that $a^{560} \equiv 1 \pmod{3}$.

(b) Show that $a^{560} \equiv 1 \pmod{11}$.

(c) Show that $a^{560} \equiv 1 \pmod{17}$.

(d) Show that $a^{560} \equiv 1 \pmod{561}$. (Hint: Use exercise 14 in Section 7.4.)

14. In this exercise you will work out some of the mathematical basis for the Miller-Rabin test, a commonly used probabilistic primality test. It is named for Gary L. Miller (1946–) and Michael O. Rabin (1931–). Suppose n is an odd integer and $n > 1$.

(a) Prove that there are positive integers s and d such that $n - 1 = 2^s d$ and d is odd.

(b) Prove that if n is prime and b is a positive integer such that $b^2 \equiv 1 \pmod{n}$, then either $b \equiv 1 \pmod{n}$ or $b \equiv -1 \pmod{n}$.

Let s and d be as in part (a). If $2 \leq a \leq n - 1$, $a^d \not\equiv 1 \pmod{n}$, and for all natural numbers $i < s$, $a^{2^i d} \not\equiv -1 \pmod{n}$, then a is called a *Miller-Rabin witness* for n .

(c) Prove that if there is a Miller-Rabin witness for n then n is not prime. (Hint: Suppose a is a Miller-Rabin witness for n and n is prime. Then by Euler's theorem, $a^{2^s d} = a^{n-1} \equiv 1 \pmod{n}$. Therefore we can let k be the smallest natural number such that $a^{2^k d} \equiv 1 \pmod{n}$. Now use part (b) to get a contradiction.)

The Miller-Rabin test works as follows: To test whether or not an odd integer $n > 1$ is prime, choose a random number $a \in \{2, 3, \dots, n - 1\}$ and check whether or not a is a Miller-Rabin witness for n . If it is, then n fails the test. If it is not, then n passes the test. By part (c), if n is prime then there are no Miller-Rabin witnesses, so n is guaranteed to pass the test. It can be proven that if n is not prime then at least $3/4$ of the numbers $a \in \{2, 3, \dots, n - 1\}$ are Miller-Rabin witnesses for n , so n will fail the test with probability at least $3/4$. As in exercise 12, the probability of an incorrect result can be made as small as desired by repeating the test with different choices of a .

(d) Show that 13 is not a Miller-Rabin witness for 85, but 14 is.

8

Infinite Sets

8.1. Equinumerous Sets

In this chapter, we'll discuss a method of comparing the sizes of infinite sets. Surprisingly, we'll find that, in a sense, infinity comes in different sizes!

For finite sets, we determine the size of a set by counting. What does it mean to count the number of elements in a set? When you count the elements in a set A , you point to the elements of A in turn while saying the words *one*, *two*, and so forth. We could think of this process as defining a function f from the set $\{1, 2, \dots, n\}$ to A , for some natural number n . For each $i \in \{1, 2, \dots, n\}$, we let $f(i)$ be the element of A you're pointing to when you say " i ." Because every element of A gets pointed to exactly once, the function f is one-to-one and onto. Thus, counting the elements of A is simply a method of establishing a one-to-one correspondence between the set $\{1, 2, \dots, n\}$ and A , for some natural number n . One-to-one correspondence is the key idea behind measuring the sizes of sets, and sets of the form $\{1, 2, \dots, n\}$ are the standards against which we measure the sizes of finite sets. This suggests the following definition.

Definition 8.1.1. Suppose A and B are sets. We'll say that A is *equinumerous* with B if there is a function $f : A \rightarrow B$ that is one-to-one and onto. We'll write $A \sim B$ to indicate that A is equinumerous with B . For each natural number n , let $I_n = \{i \in \mathbb{Z}^+ \mid i \leq n\}$. A set A is called *finite* if there is a natural number n such that $I_n \sim A$. Otherwise, A is *infinite*.

You are asked in exercise 6 to show that if A is finite, then there is *exactly one* n such that $I_n \sim A$. Thus, it makes sense to define the *number of elements* of a finite set A to be the unique n such that $I_n \sim A$. This number is also sometimes called the *cardinality* of A , and it is denoted $|A|$. Note that according to this definition, \emptyset is finite and $|\emptyset| = 0$.

The definition of equinumerous can also be applied to infinite sets, with results that are sometimes surprising. For example, you might think that \mathbb{Z}^+ could not be equinumerous with \mathbb{Z} because \mathbb{Z} includes not only all the positive integers, but also all the negative integers and zero. But consider the function $f : \mathbb{Z}^+ \rightarrow \mathbb{Z}$ defined as follows:

$$f(n) = \begin{cases} n/2, & \text{if } n \text{ is even,} \\ (1-n)/2, & \text{if } n \text{ is odd.} \end{cases}$$

This notation means that for every positive integer n , if n is even then $f(n) = n/2$ and if n is odd then $f(n) = (1-n)/2$. The table of values for f in Figure 8.1 reveals a pattern that suggests that f might be one-to-one and onto.

n	1	2	3	4	5	6	7	\dots
$f(n)$	0	1	-1	2	-2	3	-3	\dots

Figure 8.1.

To check this more carefully, first note that for every positive integer n , if n is even then $f(n) = n/2 > 0$, and if n is odd then $f(n) = (1-n)/2 \leq 0$. Now suppose n_1 and n_2 are positive integers and $f(n_1) = f(n_2)$. If $f(n_1) = f(n_2) > 0$ then n_1 and n_2 must both be even, so the equation $f(n_1) = f(n_2)$ means $n_1/2 = n_2/2$, and therefore $n_1 = n_2$. Similarly, if $f(n_1) = f(n_2) \leq 0$ then n_1 and n_2 are both odd, so we get $(1-n_1)/2 = (1-n_2)/2$, and once again it follows that $n_1 = n_2$. Thus, f is one-to-one.

To see that f is onto, let m be an arbitrary integer. If $m > 0$ then let $n = 2m$, an even positive integer, and if $m \leq 0$ then let $n = 1 - 2m$, an odd positive integer. In both cases it is easy to verify that $f(n) = m$. Thus, f is onto as well as one-to-one, so according to Definition 8.1.1, $\mathbb{Z}^+ \sim \mathbb{Z}$.

Note that the function f had to be chosen very carefully. There are many other functions from \mathbb{Z}^+ to \mathbb{Z} that are one-to-one but not onto, onto but not one-to-one, or neither one-to-one nor onto, but this does not contradict our claim that $\mathbb{Z}^+ \sim \mathbb{Z}$. According to Definition 8.1.1, to show that $\mathbb{Z}^+ \sim \mathbb{Z}$ we need only show that there is at least one function from \mathbb{Z}^+ to \mathbb{Z} that is both one-to-one and onto, and of course to prove this it suffices to give an example of such a function.

Perhaps an even more surprising example is that $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z}^+$. To show this we must come up with a one-to-one, onto function $f : \mathbb{Z}^+ \times \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$. An element of the domain of this function would be an ordered pair (i, j) , where i and j are positive integers. Exercise 12 asks you to show that the

following formula defines a function from $\mathbb{Z}^+ \times \mathbb{Z}^+$ to \mathbb{Z}^+ that is one-to-one and onto:

$$f(i, j) = \frac{(i + j - 2)(i + j - 1)}{2} + i.$$

Once again, the table of values in Figure 8.2 may help you understand this example.

	j				
$f(i, j)$	1	2	3	4	5
1	1	2	4	7	11
2	3	5	8	12	
i 3	6	9	13		
4	10	14		⋮	
5	15				

Figure 8.2.

Theorem 8.1.2. *Suppose $A \sim B$ and $C \sim D$. Then:*

1. $A \times C \sim B \times D$.
2. If A and C are disjoint and B and D are disjoint, then $A \cup C \sim B \cup D$.

Proof. Since $A \sim B$ and $C \sim D$, we can choose functions $f : A \rightarrow B$ and $g : C \rightarrow D$ that are one-to-one and onto.

1. Define $h : A \times C \rightarrow B \times D$ by the formula

$$h(a, c) = (f(a), g(c)).$$

To see that h is one-to-one, suppose $h(a_1, c_1) = h(a_2, c_2)$. This means that $(f(a_1), g(c_1)) = (f(a_2), g(c_2))$, so $f(a_1) = f(a_2)$ and $g(c_1) = g(c_2)$. Since f and g are both one-to-one, it follows that $a_1 = a_2$ and $c_1 = c_2$, so $(a_1, c_1) = (a_2, c_2)$.

To see that h is onto, suppose $(b, d) \in B \times D$. Then since f and g are both onto, we can choose $a \in A$ and $c \in C$ such that $f(a) = b$ and $g(c) = d$. Therefore $h(a, c) = (f(a), g(c)) = (b, d)$, as required. Thus h is one-to-one and onto, so $A \times C \sim B \times D$.

2. Suppose A and C are disjoint and B and D are disjoint. You are asked in exercise 14 to show that $f \cup g$ is a one-to-one, onto function from $A \cup C$ to $B \cup D$, so $A \cup C \sim B \cup D$. □

It is not hard to show that \sim is reflexive, symmetric, and transitive. In other words, we have the following theorem:

Theorem 8.1.3. For any sets A , B , and C :

1. $A \sim A$.
2. If $A \sim B$ then $B \sim A$.
3. If $A \sim B$ and $B \sim C$ then $A \sim C$.

Proof.

1. The identity function i_A is a one-to-one, onto function from A to A .
2. Suppose $A \sim B$. Then we can choose some function $f : A \rightarrow B$ that is one-to-one and onto. By Theorem 5.3.4, f^{-1} is a function from B to A . But now note that $(f^{-1})^{-1} = f$, which is a function from A to B , so by Theorem 5.3.4 again, f^{-1} is also one-to-one and onto. Therefore $B \sim A$.
3. Suppose $A \sim B$ and $B \sim C$. Then we can choose one-to-one, onto functions $f : A \rightarrow B$ and $g : B \rightarrow C$. By Theorem 5.2.5, $g \circ f : A \rightarrow C$ is one-to-one and onto, so $A \sim C$. \square

Theorems 8.1.2 and 8.1.3 are often helpful in showing that sets are equinumerous. For example, we showed earlier that $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z}^+$ and $\mathbb{Z}^+ \sim \mathbb{Z}$, so by part 3 of Theorem 8.1.3 it follows that $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z}$. Part 2 tells us that we need not distinguish between the statements “ A is equinumerous with B ” and “ B is equinumerous with A ,” because they are equivalent. For example, we already know that $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z}^+$, so we can also write $\mathbb{Z}^+ \sim \mathbb{Z}^+ \times \mathbb{Z}^+$. By part 1 of Theorem 8.1.2, $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z} \times \mathbb{Z}$, so we also have $\mathbb{Z}^+ \sim \mathbb{Z} \times \mathbb{Z}$.

We have now found three sets, \mathbb{Z} , $\mathbb{Z}^+ \times \mathbb{Z}^+$, and $\mathbb{Z} \times \mathbb{Z}$, that are equinumerous with \mathbb{Z}^+ . Such sets are especially important and have a special name.

Definition 8.1.4. A set A is called *denumerable* if $\mathbb{Z}^+ \sim A$. It is called *countable* if it is either finite or denumerable. Otherwise, it is *uncountable*.

You might think of the countable sets as those sets whose elements can be *counted* by pointing to all of them, one by one, while naming positive integers in order. If the counting process ends at some point, then the set is finite; and if it never ends, then the set is denumerable. The following theorem gives two more ways of thinking about countable sets.

Theorem 8.1.5. Suppose A is a set. The following statements are equivalent:

1. A is countable.
2. Either $A = \emptyset$ or there is a function $f : \mathbb{Z}^+ \rightarrow A$ that is onto.
3. There is a function $f : A \rightarrow \mathbb{Z}^+$ that is one-to-one.

Proof. 1 \rightarrow 2. Suppose A is countable. If A is denumerable, then there is a function $f : \mathbb{Z}^+ \rightarrow A$ that is one-to-one and onto, so clearly statement 2 is true. Now suppose A is finite. If $A = \emptyset$ then there is nothing more to prove, so suppose $A \neq \emptyset$. Then we can choose some element $a_0 \in A$. Let $g : I_n \rightarrow A$ be a one-to-one, onto function, where n is the number of elements of A . Now define $f : \mathbb{Z}^+ \rightarrow A$ as follows:

$$f(i) = \begin{cases} g(i), & \text{if } i \leq n, \\ a_0, & \text{if } i > n. \end{cases}$$

It is easy to check now that f is onto, as required.

2 \rightarrow 3. Suppose that either $A = \emptyset$ or there is an onto function from \mathbb{Z}^+ to A . We consider these two possibilities in turn. If $A = \emptyset$, then the empty set is a one-to-one function from A to \mathbb{Z}^+ . Now suppose $g : \mathbb{Z}^+ \rightarrow A$, and g is onto. Then for each $a \in A$, the set $\{n \in \mathbb{Z}^+ \mid g(n) = a\}$ is not empty, so by the well-ordering principle it must have a smallest element. Thus, we can define a function $f : A \rightarrow \mathbb{Z}^+$ by the formula

$$f(a) = \text{the smallest } n \in \mathbb{Z}^+ \text{ such that } g(n) = a.$$

Note that for each $a \in A$, $g(f(a)) = a$, so $g \circ f = i_A$. But then by Theorem 5.3.3, it follows that f is one-to-one, as required.

3 \rightarrow 1. Suppose $g : A \rightarrow \mathbb{Z}^+$ and g is one-to-one. Let $B = \text{Ran}(g) \subseteq \mathbb{Z}^+$. Then g maps onto B . This means that if we think of g as a function from A to B , then it is one-to-one and onto, so $A \sim B$. Thus, it suffices to show that B is countable, since by Theorem 8.1.3 it follows from this that A is also countable.

Suppose B is not finite. We must show that B is denumerable, which we can do by defining a one-to-one, onto function $f : \mathbb{Z}^+ \rightarrow B$. The idea behind the definition is simply to let $f(n)$ be the n th element of B , for each $n \in \mathbb{Z}^+$. (Recall that $B \subseteq \mathbb{Z}^+$, so we can use the ordering of the positive integers to make sense of the idea of the n th element of B .) For a more careful definition of f and the proof that f is one-to-one and onto, see exercise 15. \square

If A is countable and $A \neq \emptyset$, then by Theorem 8.1.5 there is a function $f : \mathbb{Z}^+ \rightarrow A$ that is onto. If, for every $n \in \mathbb{Z}^+$, we let $a_n = f(n)$, then the fact that f is onto means that every element of A appears at least once in the list a_1, a_2, a_3, \dots . In other words, $A = \{a_1, a_2, a_3, \dots\}$. Countability of a set A is often used in this way to enable us to write the elements of A in a list, indexed by the positive integers. In fact, you might want to think of countability for nonempty sets as meaning *listability*. Of course, if A is denumerable, then the function f can be taken to be one-to-one, which means that each element of A will appear only once in the list a_1, a_2, a_3, \dots . For an example of an application

of countability in which the elements of a countable set are written in a list, see exercise 19.

Theorem 8.1.5 is also sometimes useful for proving that a set is denumerable, as the proof of our next theorem shows.

Theorem 8.1.6. \mathbb{Q} is denumerable.

Proof. Let $f : \mathbb{Z} \times \mathbb{Z}^+ \rightarrow \mathbb{Q}$ be defined as follows:

$$f(p, q) = p/q.$$

Clearly f is onto, since by definition all rational numbers can be written as fractions, but note that f is not one-to-one. For example, $f(1, 2) = f(2, 4) = 1/2$. Since $\mathbb{Z}^+ \sim \mathbb{Z}$, by Theorem 8.1.2 we have $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z} \times \mathbb{Z}^+$, and since we already know that $\mathbb{Z}^+ \times \mathbb{Z}^+$ is denumerable, it follows that $\mathbb{Z} \times \mathbb{Z}^+$ is also denumerable. Thus, we can choose a one-to-one, onto function $g : \mathbb{Z}^+ \rightarrow \mathbb{Z} \times \mathbb{Z}^+$. By Theorem 5.2.5, $f \circ g : \mathbb{Z}^+ \rightarrow \mathbb{Q}$ is onto, so by Theorem 8.1.5, \mathbb{Q} is countable. Clearly \mathbb{Q} is not finite, so it must be denumerable. \square

Although our focus in this chapter is on infinite sets, the methods in this section can be used to prove theorems that are useful for computing the cardinalities of finite sets. We end this section with one example of such a theorem, and give several other examples in the exercises (see exercises 20–30).

Theorem 8.1.7. Suppose A and B are disjoint finite sets. Then $A \cup B$ is finite, and $|A \cup B| = |A| + |B|$.

Proof. Let $n = |A|$ and $m = |B|$. Then $A \sim I_n$ and $B \sim I_m$. Notice that if $x \in I_m$ then $1 \leq x \leq m$, and therefore $n + 1 \leq x + n \leq n + m$, so $x + n \in I_{n+m} \setminus I_n$. Thus we can define a function $f : I_m \rightarrow I_{n+m} \setminus I_n$ by the formula $f(x) = x + n$. It is easy to check that f is one-to-one and onto, so $I_m \sim I_{n+m} \setminus I_n$. Since $B \sim I_m$, it follows that $B \sim I_{n+m} \setminus I_n$. Applying part 2 of Theorem 8.1.2, we can conclude that $A \cup B \sim I_n \cup (I_{n+m} \setminus I_n) = I_{n+m}$. Therefore $A \cup B$ is finite, and $|A \cup B| = n + m = |A| + |B|$. \square

Exercises

*1. Show that the following sets are denumerable.

- (a) \mathbb{N} .
- (b) The set of all even integers.

2. Show that the following sets are denumerable:

(a) $\mathbb{Q} \times \mathbb{Q}$.

(b) $\mathbb{Q}(\sqrt{2})$. (See exercise 21(b) of Section 5.4 for the meaning of the notation used here.)

3. In this problem we'll use the following notation for intervals of real numbers. If a and b are real numbers and $a < b$, then

$$[a, b] = \{x \in \mathbb{R} \mid a \leq x \leq b\},$$

$$(a, b) = \{x \in \mathbb{R} \mid a < x < b\},$$

$$[a, b) = \{x \in \mathbb{R} \mid a < x \leq b\},$$

$$[a, b) = \{x \in \mathbb{R} \mid a \leq x < b\}.$$

(a) Show that $[0, 1] \sim [0, 2]$.

(b) Show that $(-\pi/2, \pi/2) \sim \mathbb{R}$. (Hint: Use a trigonometric function.)

(c) Show that $(0, 1) \sim \mathbb{R}$.

(d) Show that $(0, 1] \sim (0, 1)$.

*4. Justify your answer to each question with either a proof or a counterexample.

(a) Suppose $A \sim B$ and $A \times C \sim B \times D$. Must it be the case that $C \sim D$?

(b) Suppose $A \sim B$, A and C are disjoint, B and D are disjoint, and $A \cup C \sim B \cup D$. Must it be the case that $C \sim D$?

5. Prove that if $A \sim B$ then $\mathcal{P}(A) \sim \mathcal{P}(B)$.

*6. (a) Prove that for all natural numbers n and m , if $I_n \sim I_m$ then $n = m$. (Hint: Use induction on n .)

(b) Prove that if A is finite, then there is exactly one natural number n such that $I_n \sim A$.

7. Suppose A and B are sets and A is finite. Prove that $A \sim B$ iff B is also finite and $|A| = |B|$.

*8. (a) Prove that if $n \in \mathbb{N}$ and $A \subseteq I_n$, then A is finite and $|A| \leq n$. Furthermore, if $A \cong I_n$, then $|A| < n$.

(b) Prove that if A is finite and $B \subseteq A$, then B is also finite, and $|B| \leq |A|$. Furthermore, if $B \cong A$, then $|B| < |A|$.

9. Suppose $B \subseteq A$, $B \cong A$, and $B \sim A$. Prove that A is infinite.

*10. Prove that if $n \in \mathbb{N}$, $f : I_n \rightarrow B$, and f is onto, then B is finite and $|B| \leq n$.

11. Suppose A and B are finite sets and $f : A \rightarrow B$.

(a) Prove that if $|A| < |B|$ then f is not onto.

(b) Prove that if $|A| > |B|$ then f is not one-to-one. (This is sometimes called the *pigeonhole principle*, because it means that if n items are

put into m pigeonholes, where $n > m$, then some pigeonhole must contain more than one item.)

(c) Prove that if $|A| = |B|$ then f is one-to-one iff f is onto.

*12. Show that the function $f : \mathbb{Z}^+ \times \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$ defined by the formula

$$f(i, j) = \frac{(i + j - 2)(i + j - 1)}{2} + i$$

is one-to-one and onto.

13. In this exercise you will give another proof that $\mathbb{Z}^+ \times \mathbb{Z}^+ \sim \mathbb{Z}^+$. Let $f : \mathbb{Z}^+ \times \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$ be defined by the formula

$$f(m, n) = 2^{m-1}(2n - 1).$$

Prove that f is one-to-one and onto.

14. Complete the proof of part 2 of Theorem 8.1.2 by showing that if $f : A \rightarrow B$ and $g : C \rightarrow D$ are one-to-one, onto functions, A and C are disjoint, and B and D are disjoint, then $f \cup g$ is a one-to-one, onto function from $A \cup C$ to $B \cup D$.

*15. In this exercise you will complete the proof of $3 \rightarrow 1$ of Theorem 8.1.5. Suppose $B \subseteq \mathbb{Z}^+$ and B is infinite. We now define a function $f : \mathbb{Z}^+ \rightarrow B$ by recursion as follows:

For all $n \in \mathbb{Z}^+$,

$$f(n) = \text{the smallest element of } B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < n\}.$$

Of course, the definition is recursive because the specification of $f(n)$ refers to $f(m)$ for all $m < n$.

(a) Suppose $n \in \mathbb{Z}^+$. The definition of $f(n)$ only makes sense if we can be sure that $B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < n\} \neq \emptyset$, in which case the well-ordering principle guarantees that it has a smallest element.

Prove that $B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < n\} \neq \emptyset$. (Hint: See exercises 8 and 10.)

(b) Prove that for all $n \in \mathbb{Z}^+$, $f(n) \geq n$.

(c) Prove that f is one-to-one and onto.

16. In this exercise you will give an alternative proof of Theorem 8.1.6.

(a) Find a function $f : \mathbb{Z}^+ \rightarrow \mathbb{Z} \setminus \{0\}$ that is one-to-one and onto.

(b) Let $g : \mathbb{Z}^+ \rightarrow \mathbb{Q}^+$ be defined as follows. Suppose $n \in \mathbb{Z}^+$ and the prime factorization of n is $n = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$, where p_1, p_2, \dots, p_k are prime numbers, $p_1 < p_2 < \cdots < p_k$, and e_1, e_2, \dots, e_k are positive integers. Then we let

$$g(n) = g(p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}) = p_1^{f(a)} p_2^{f(b)} \cdots p_k^{f(c)},$$

where f is the function from part (a). (As in Section 7.2, we consider the empty product to be 1, so that $g(1) = 1$.) Prove that g is one-to-one and onto. (Hint: You will find exercise 19 in Section 7.2 useful.)

- (c) Use g to define a one-to-one, onto function $h : \mathbb{Z} \rightarrow \mathbb{Q}$, and conclude that \mathbb{Q} is denumerable.
- *17. Prove that if $B \subseteq A$ and A is countable, then B is countable.
18. Prove that if $B \subseteq A$, A is infinite, and B is finite, then $A \setminus B$ is infinite.
- *19. Suppose A is denumerable and R is a partial order on A . Prove that R can be extended to a total order on A . In other words, prove that there is a total order T on A such that $R \subseteq T$. Note that we proved a similar theorem for finite A in Example 6.2.2. (Hint: Since A is denumerable, we can write the elements of A in a list: $A = \{a_1, a_2, a_3, \dots\}$. Now, using exercise 2 of Section 6.2, recursively define partial orders R_n , for $n \in \mathbb{N}$, so that $R = R_0 \subseteq R_1 \subseteq R_2 \subseteq \dots$ and $\forall i \in I_n \forall j \in \mathbb{Z}^+ ((a_i, a_j) \in R_n \vee (a_j, a_i) \in R_n)$. Let $T = \bigcup_{n \in \mathbb{N}} R_n$.)
20. Suppose A is finite and $B \subseteq A$. By exercise 8, B and $A \setminus B$ are both finite. Prove that $|A \setminus B| = |A| - |B|$. (In particular, if $a \in A$ then $|A \setminus \{a\}| = |A| - 1$. We used this fact in several proofs in Chapter 6; for example, we used it in Examples 6.2.1 and 6.2.2.)
21. Suppose n is a positive integer and for each $i \in I_n$, A_i is a finite set. Also, assume that $\forall i \in I_n \forall j \in I_n (i \neq j \rightarrow A_i \cap A_j = \emptyset)$. Prove that $\bigcup_{i \in I_n} A_i$ is finite and $|\bigcup_{i \in I_n} A_i| = \sum_{i=1}^n |A_i|$.
- *22. (a) Prove that if A and B are finite sets, then $A \times B$ is finite and $|A \times B| = |A| \cdot |B|$. (Hint: Use induction on $|B|$. In other words, prove the following statement by induction: $\forall n \in \mathbb{N} \forall A \forall B$ (if A and B are finite and $|B| = n$, then $A \times B$ is finite and $|A \times B| = |A| \cdot n$). You may find Theorem 4.1.3 useful.)
- (b) A meal at Alice's Restaurant consists of an entree and a dessert. The entree can be either steak, chicken, pork chops, shrimp, or spaghetti, and dessert can be either ice cream, cake, or pie. How many different meals can you order at Alice's Restaurant?
23. For any sets A and B , the set of all functions from A to B is denoted ${}^A B$.
- (a) Prove that if $A \sim B$ and $C \sim D$ then ${}^A C \sim {}^B D$.
- (b) Prove that if A , B , and C are sets and $A \cap B = \emptyset$, then ${}^{A \cup B} C \sim {}^A C \times {}^B C$.
- (c) Prove that if A and B are finite sets, then ${}^A B$ is finite and $|{}^A B| = |B|^{|A|}$. (Hint: Use induction on $|A|$.)
- (d) A professor has 20 students in his class, and he has to assign a grade of either A, B, C, D, or F to each student. In how many ways can the grades be assigned?

- *24. Suppose $|A| = n$, and let $F = \{f \mid f \text{ is a one-to-one, onto function from } I_n \text{ to } A\}$.
- Prove that F is finite, and $|F| = n!$. (Hint: Use induction on n .)
 - Let $L = \{R \mid R \text{ is a total order on } A\}$. Prove that $F \sim L$, and therefore $|L| = n!$.
 - Five people are to sit in a row of five seats. In how many ways can they be seated?
25. Suppose A is a finite set and R is an equivalence relation on A . Suppose also that there is some positive integer n such that $\forall x \in A (|[x]_R| = n)$. Prove that A/R is finite and $|A/R| = |A|/n$. (Hint: Use exercise 21.)
26. (a) Suppose that A and B are finite sets. Prove that $A \cup B$ is finite, and $|A \cup B| = |A| + |B| - |A \cap B|$.
- (b) Suppose that A , B , and C are finite sets. Prove that $A \cup B \cup C$ is finite, and
- $$|A \cup B \cup C| = |A| + |B| + |C| - |A \cap B| - |A \cap C| - |B \cap C| + |A \cap B \cap C|.$$

- *27. In this problem you will prove the *inclusion-exclusion principle*, which generalizes the formulas in exercise 26. Suppose A_1, A_2, \dots, A_n are finite sets. Let $P = \mathcal{P}(I_n) \setminus \{\emptyset\}$, and for each $S \in P$ let $A_S = \bigcap_{i \in S} A_i$. Prove that $\bigcup_{i \in I_n} A_i$ is finite and

$$\left| \bigcup_{i \in I_n} A_i \right| = \sum_{S \in P} (-1)^{|S|+1} |A_S|.$$

(The notation on the right-hand side of this equation denotes the result of running through all sets $S \in P$, computing the number $(-1)^{|S|+1} |A_S|$ for each S , and then adding these numbers. Hint: Use induction on n .)

28. Prove that if A and B are finite sets and $|A| = |B|$, then $|A \times B|$ is even.
29. Each customer in a certain bank has a PIN number, which is a sequence of four digits. Show that if the bank has more than 10,000 customers, then some two customers must have the same PIN number. (Hint: See exercise 11.)
30. Alice opened her grade report and exclaimed, "I can't believe Prof. Jones flunked me in Probability." "You were in that course?" said Bob. "That's funny, I was in it too, and I don't remember ever seeing you there." "Well," admitted Alice sheepishly, "I guess I did skip class a lot." "Yeah, me too" said Bob. Prove that either Alice or Bob missed at least half of the classes.

8.2. Countable and Uncountable Sets

Often when we perform some set-theoretic operation with countable sets, the result is again a countable set.

Theorem 8.2.1. *Suppose A and B are countable sets. Then:*

1. $A \times B$ is countable.
2. $A \cup B$ is countable.

Proof. Since A and B are countable, by Theorem 8.1.5 we can choose one-to-one functions $f : A \rightarrow \mathbb{Z}^+$ and $g : B \rightarrow \mathbb{Z}^+$.

1. Define $h : A \times B \rightarrow \mathbb{Z}^+ \times \mathbb{Z}^+$ by the formula

$$h(a, b) = (f(a), g(b)) .$$

As in the proof of part 1 of Theorem 8.1.2, it is not hard to show that h is one-to-one. Since $\mathbb{Z}^+ \times \mathbb{Z}^+$ is denumerable, we can let $j : \mathbb{Z}^+ \times \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$ be a one-to-one, onto function. Then by Theorem 5.2.5, $j \circ h : A \times B \rightarrow \mathbb{Z}^+$ is one-to-one, so by Theorem 8.1.5, $A \times B$ is countable.

2. Define $h : A \cup B \rightarrow \mathbb{Z}$ as follows:

$$h(x) = \begin{cases} f(x), & \text{if } x \in A, \\ -g(x), & \text{if } x \notin A. \end{cases}$$

We claim now that h is one-to-one. To see why, suppose that $h(x_1) = h(x_2)$, for some x_1 and x_2 in $A \cup B$. If $h(x_1) = h(x_2) > 0$, then according to the definition of h , we must have $x_1 \in A$, $x_2 \in A$, and $f(x_1) = h(x_1) = h(x_2) = f(x_2)$. But then since f is one-to-one, $x_1 = x_2$. Similarly, if $h(x_1) = h(x_2) \leq 0$, then we must have $g(x_1) = -h(x_1) = -h(x_2) = g(x_2)$, and then since g is one-to-one, $x_1 = x_2$. Thus, h is one-to-one.

Since \mathbb{Z} is denumerable, we can let $j : \mathbb{Z} \rightarrow \mathbb{Z}^+$ be a one-to-one, onto function. As in part 1, we then find that $j \circ h : A \cup B \rightarrow \mathbb{Z}^+$ is one-to-one, so $A \cup B$ is countable. \square

As our next theorem shows, part 2 of Theorem 8.2.1 can be extended to unions of more than two sets.

Theorem 8.2.2. *The union of countably many countable sets is countable. In other words, if \mathcal{F} is a family of sets, \mathcal{F} is countable, and also every element of \mathcal{F} is countable, then $\bigcup \mathcal{F}$ is countable.*

Proof. We will assume first that $\emptyset \notin \mathcal{F}$. At the end of the proof we will discuss the case $\emptyset \in \mathcal{F}$.

If $\mathcal{F} = \emptyset$, then of course $\bigcup \mathcal{F} = \emptyset$, which is countable. Now suppose $\mathcal{F} \neq \emptyset$. Then, as described after the proof of Theorem 8.1.5, since \mathcal{F} is countable and nonempty we can write the elements of \mathcal{F} in a list, indexed by the positive integers. In other words, we can say that $\mathcal{F} = \{A_1, A_2, A_3, \dots\}$. Similarly, every element of \mathcal{F} is countable and nonempty (since $\emptyset \notin \mathcal{F}$), so for each positive integer i the elements of A_i can be written in a list. Thus we can write

$$\begin{aligned} A_1 &= \{a_1^1, a_2^1, a_3^1, \dots\}, \\ A_2 &= \{a_1^2, a_2^2, a_3^2, \dots\}, \end{aligned}$$

and, in general,

$$A_i = \{a_1^i, a_2^i, a_3^i, \dots\}.$$

Note that, by the definition of union, $\bigcup \mathcal{F} = \{a_j^i \mid i \in \mathbb{Z}^+, j \in \mathbb{Z}^+\}$.

Now define a function $f : \mathbb{Z}^+ \times \mathbb{Z}^+ \rightarrow \bigcup \mathcal{F}$ by the formula

$$f(i, j) = a_j^i.$$

Clearly f is onto. Since $\mathbb{Z}^+ \times \mathbb{Z}^+$ is denumerable, we can let $g : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+ \times \mathbb{Z}^+$ be a one-to-one, onto function. Then $f \circ g : \mathbb{Z}^+ \rightarrow \bigcup \mathcal{F}$ is onto, so $\bigcup \mathcal{F}$ is countable.

Finally, suppose $\emptyset \in \mathcal{F}$. Let $\mathcal{F}^3 = \mathcal{F} \setminus \{\emptyset\}$. Then \mathcal{F}^3 is also a countable family of countable sets and $\emptyset \notin \mathcal{F}^3$, so by the earlier reasoning, $\bigcup \mathcal{F}^3$ is countable. But clearly $\bigcup \mathcal{F} = \bigcup \mathcal{F}^3$, so $\bigcup \mathcal{F}$ is countable too. \square

Another operation that preserves countability is the formation of finite sequences. Suppose A is a set and a_1, a_2, \dots, a_n is a list of elements of A . We might specify the terms in this list with a function $f : I_n \rightarrow A$, where for each i , $f(i) = a_i =$ the i th term in the list. Such a function is called a *finite sequence* of elements of A .

Definition 8.2.3. Suppose A is a set. A function $f : I_n \rightarrow A$, where n is a natural number, is called a *finite sequence* of elements of A , and n is called the *length* of the sequence.

Theorem 8.2.4. Suppose A is a countable set. Then the set of all finite sequences of elements of A is also countable.

Proof. For each $n \in \mathbb{N}$, let S_n be the set of all sequences of length n of elements of A . We first show that for every $n \in \mathbb{N}$, S_n is countable. We proceed by induction on n .

In the base case we assume $n = 0$. Note that $I_0 = \emptyset$, so a sequence of length 0 is a function $f : \emptyset \rightarrow A$, and the only such function is \emptyset . Thus, $S_0 = \{\emptyset\}$, which is clearly a countable set.

For the induction step, suppose n is a natural number and S_n is countable. We must show that S_{n+1} is countable. Consider the function $F : S_n \times A \rightarrow S_{n+1}$ defined as follows:

$$F(f, a) = f \cup \{(n + 1, a)\}.$$

In other words, for any sequence $f \in S_n$ and any element $a \in A$, $F(f, a)$ is the sequence you get by starting with f , which is a sequence of length n , and then tacking on a as term number $n + 1$. You are asked in exercise 2 to verify that F is one-to-one and onto. Thus, $S_n \times A \sim S_{n+1}$. But S_n and A are both countable, so by Theorem 8.2.1, $S_n \times A$ is countable, and therefore S_{n+1} is countable.

This completes the inductive proof that for every $n \in \mathbb{N}$, S_n is countable. Finally, note that the set of all finite sequences of elements of A is $\bigcup_{n \in \mathbb{N}} S_n$, and this is countable by Theorem 8.2.2. \square

As an example of the use of Theorem 8.2.4, you should be able to show that the set of all grammatical sentences of English is a denumerable set. (See exercise 17.)

By now you may be wondering if perhaps *all* sets are countable! Is there any set-theoretic operation that can be used to produce uncountable sets? We'll see in our next theorem that the answer is yes, the power set operation. This fact was discovered by the German mathematician Georg Cantor (1845–1918) by means of a famous and ingenious proof. In fact, it was Cantor who first conceived of the idea of comparing the sizes of infinite sets. Cantor's proof is somewhat harder than the previous proofs in this chapter, so we'll discuss the strategy behind the proof before presenting the proof itself.

Theorem 8.2.5. (Cantor's theorem) $\mathcal{P}(\mathbb{Z}^+)$ is uncountable.

Scratch work

The proof is based on statement 2 of Theorem 8.1.5. We'll show that there is no function $f : \mathbb{Z}^+ \rightarrow \mathcal{P}(\mathbb{Z}^+)$ that is onto. Clearly $\mathcal{P}(\mathbb{Z}^+) \neq \emptyset$, so by Theorem 8.1.5 this shows that $\mathcal{P}(\mathbb{Z}^+)$ is not countable.

Our strategy will be to let $f : \mathbb{Z}^+ \rightarrow \mathcal{P}(\mathbb{Z}^+)$ be an arbitrary function and prove that f is not onto. Reexpressing this negative goal as a positive statement, we must show that $\exists D [D \in \mathcal{P}(\mathbb{Z}^+) \wedge \forall n \in \mathbb{Z}^+ (D \not\equiv f(n))]$. This suggests that we should try to find a particular set D for which we can prove

both $D \in \mathcal{P}(\mathbb{Z}^+)$ and $\forall n \in \mathbb{Z}^+ (D \not\equiv f(n))$. This is the most difficult step in figuring out the proof. There is a set D that makes the proof work, but it will take some cleverness to come up with it.

We want to make sure that $D \in \mathcal{P}(\mathbb{Z}^+)$, or in other words $D \subseteq \mathbb{Z}^+$, so we know that we need only consider positive integers when deciding what the elements of D should be. But this still leaves us infinitely many decisions to make: for each positive integer n , we must decide whether or not we want n to be an element of D . We also need to make sure that $\forall n \in \mathbb{Z}^+ (D \not\equiv f(n))$. This imposes infinitely many restrictions on our choice of D : for each positive integer n , we must make sure that $D \not\equiv f(n)$. Why not make each of our infinitely many decisions in such a way that it guarantees that the corresponding restriction is satisfied? In other words, for each positive integer n , we'll make our decision about whether or not n is an element of D in such a way that it will guarantee that $D \not\equiv f(n)$. This isn't hard to do. We can let n be an element of D if $n \notin f(n)$, and leave n out of D if $n \in f(n)$. This will guarantee that $D \not\equiv f(n)$, because one of these sets will contain n as an element and the other won't. This suggests that we should let $D = \{n \in \mathbb{Z}^+ \mid n \notin f(n)\}$.

Figure 8.3 may help you understand the definition of the set D . For each $m \in \mathbb{Z}^+$, $f(m)$ is a subset of \mathbb{Z}^+ , and it can be specified by saying, for each positive integer n , whether or not $n \in f(m)$. The answers to these questions can be arranged in a table as shown in Figure 8.3. Each row of the table gives the answers needed to specify the set $f(m)$ for a particular value of m . The set D can also be specified with a row of yesses and noes, as shown at the bottom of Figure 8.3. For each $n \in \mathbb{Z}^+$ we've decided to determine whether or not $n \in D$ by asking whether or not $n \in f(n)$, and the answers to these questions are the ones surrounded by boxes in Figure 8.3. Because $n \in D$ iff $n \notin f(n)$, the row of yesses and noes that specifies D can be found by reading the boxed answers along the diagonal of Figure 8.3 and reversing all the answers. This is guaranteed to be different from every row of the table in Figure 8.3, because for each $n \in \mathbb{Z}^+$ it differs from row n in the n th position.

If you found this reasoning difficult to follow, don't worry about it. Remember, the reasoning used in choosing the set D won't be part of the proof anyway! After you finish reading the proof, you can go back and try reading the last two paragraphs again.

It should be clear that the set D we have chosen is a subset of \mathbb{Z}^+ , so $D \in \mathcal{P}(\mathbb{Z}^+)$. Our other goal is to prove that $\forall n \in \mathbb{Z}^+ (D \not\equiv f(n))$, so we let n be an arbitrary positive integer and prove $D \not\equiv f(n)$. Now recall that we chose D carefully so that we would be able to prove $D \not\equiv f(n)$, and the reasoning behind this choice hinged on whether or not $n \in f(n)$. Perhaps

	n					
Is $n \in f(m)$?	1	2	3	4	5	
1	yes	no	no	yes	yes	
2	yes	yes	no	no	yes	
m 3	no	no	no	yes	no	...
4	yes	yes	no	yes	no	
5	no	yes	yes	no	no	
			\vdots			
Is $n \in D$?	no	no	yes	no	yes	...

Figure 8.3.

the easiest way to write the proof is to consider the two cases $n \in f(n)$ and $n \notin f(n)$ separately. In each case, applying the definition of D easily leads to the conclusion that $D \neq f(n)$.

Proof. Suppose $f : \mathbb{Z}^+ \rightarrow \mathcal{P}(\mathbb{Z}^+)$. We will show that f cannot be onto by finding a set $D \in \mathcal{P}(\mathbb{Z}^+)$ such that $D \notin \text{Ran}(f)$. Let $D = \{n \in \mathbb{Z}^+ \mid n \notin f(n)\}$. Clearly $D \subseteq \mathbb{Z}^+$, so $D \in \mathcal{P}(\mathbb{Z}^+)$. Now let n be an arbitrary positive integer. We consider two cases.

Case 1. $n \in f(n)$. Since $D = \{n \in \mathbb{Z}^+ \mid n \notin f(n)\}$, we can conclude that $n \notin D$. But then since $n \in f(n)$ and $n \notin D$, it follows that $D \neq f(n)$.

Case 2. $n \notin f(n)$. Then by the definition of D , $n \in D$. Since $n \in D$ and $n \notin f(n)$, $D \neq f(n)$.

Since these cases are exhaustive, this shows that $\forall n \in \mathbb{Z}^+ (D \neq f(n))$, so $D \notin \text{Ran}(f)$. Since f was arbitrary, this shows that there is no onto function $f : \mathbb{Z}^+ \rightarrow \mathcal{P}(\mathbb{Z}^+)$. Clearly $\mathcal{P}(\mathbb{Z}^+) \neq \emptyset$, so by Theorem 8.1.5, $\mathcal{P}(\mathbb{Z}^+)$ is uncountable. \square

The method used in the proof of Theorem 8.2.5 is called *diagonalization* because of the diagonal arrangement of the boxed answers in Figure 8.3. Diagonalization is a powerful technique that can be used to prove many theorems, including our next theorem. However, rather than doing another diagonalization argument, we'll simply apply Theorem 8.2.5 to prove the next theorem.

Theorem 8.2.6. \mathbb{R} is uncountable.

Proof. We will define a function $f : \mathcal{P}(\mathbb{Z}^+) \rightarrow \mathbb{R}$ and show that f is one-to-one. If \mathbb{R} were countable, then there would be a one-to-one function $g : \mathbb{R} \rightarrow \mathbb{Z}^+$. But then $g \circ f$ would be a one-to-one function from $\mathcal{P}(\mathbb{Z}^+)$ to

\mathbb{Z}^+ and therefore $\mathcal{P}(\mathbb{Z}^+)$ would be countable, contradicting Cantor's theorem. Thus, this will show that \mathbb{R} is uncountable.

To define f , suppose $A \in \mathcal{P}(\mathbb{Z}^+)$. Then $f(A)$ will be a real number between 0 and 1 that we will specify by giving its decimal expansion. For each positive integer n , the n th digit of $f(A)$ will be the number d_n defined as follows:

$$d_n = \begin{cases} 3, & \text{if } n \notin A, \\ 7, & \text{if } n \in A. \end{cases}$$

In other words, in decimal notation we have $f(A) = 0.d_1d_2d_3\dots$. For example, if E is the set of all positive even integers, then $f(E) = 0.37373737\dots$. If P is the set of all prime numbers, then $f(P) = 0.37737373337\dots$.

To see that f is one-to-one, suppose that $A \in \mathcal{P}(\mathbb{Z}^+)$, $B \in \mathcal{P}(\mathbb{Z}^+)$, and $A \not\equiv B$. Then there is some $n \in \mathbb{Z}^+$ such that either $n \in A$ and $n \notin B$, or $n \in B$ and $n \notin A$. But then $f(A)$ and $f(B)$ cannot be equal, since their decimal expansions differ in the n th digit.¹ Thus, f is one-to-one. \square

Exercises

- *1. (a) Prove that the set of all irrational numbers, $\mathbb{R} \setminus \mathbb{Q}$, is uncountable.
(b) Prove that $\mathbb{R} \setminus \mathbb{Q} \sim \mathbb{R}$.
2. Let $F : S_n \times A \rightarrow S_{n+1}$ be the function defined in the proof of Theorem 8.2.4. Show that F is one-to-one and onto.
3. In this exercise you will give an alternative proof of Theorem 8.2.4. Suppose A is a countable set, and let S be the set of all finite sequences of elements of A . Since A is countable, there is a one-to-one function $g : A \rightarrow \mathbb{Z}^+$. For each positive integer n , let p_n be the n th prime number; thus, $p_1 = 2$, $p_2 = 3$, and so on. Define $F : S \rightarrow \mathbb{Z}^+$ as follows: Suppose $f \in S$ and the length of f is n . Then

$$F(f) = p_1^{g(f(1))} p_2^{g(f(2))} \dots p_n^{g(f(n))}.$$

Show that F is one-to-one, and therefore S is countable.

4. Let $P = \{X \in \mathcal{P}(\mathbb{Z}^+) \mid X \text{ is finite}\}$. Prove that P is denumerable.

¹ We should really be a bit more careful here. It is actually possible for two different decimal expansions to represent the same number. For example, in a calculus class you may have learned the surprising fact that $0.999\dots = 1.000\dots$. However, this only happens with decimal expansions that end with either an infinite sequence of 9s or an infinite sequence of 0s. For decimal expansions made up of 3s and 7s, different decimal expansions always represent different numbers.

- *5. Prove the following more general form of Cantor's theorem: For any set A , $A \approx \mathcal{P}(A)$. (Hint: Imitate the proof of Theorem 8.2.5.)
6. For the meaning of the notation used in this exercise, see exercise 23 of Section 8.1.
- (a) Prove that for any sets A , B , and C , $A^{(B \times C)} \sim A^B \times A^C$.
- (b) Prove that for any sets A , B , and C , $(A \times B)^C \sim A^{(B^C)}$.
- (c) Prove that for any set A , $\mathcal{P}(A) \sim A^{\{\text{yes, no}\}}$. (Note that if A is finite and $|A| = n$ then, by exercise 23(c) of Section 8.1, it follows that $|\mathcal{P}(A)| = |\{\text{yes, no}\}|^{|A|} = 2^n$. Of course, you already proved this, by a different method, in exercise 11 of Section 6.2.)
- (d) Prove that $\mathbb{Z}^+ \mathcal{P}(\mathbb{Z}^+) \sim \mathcal{P}(\mathbb{Z}^+)$.
7. Suppose A is denumerable. Prove that there is a partition P of A such that P is denumerable and for every $X \in P$, X is denumerable.
- *8. Prove that if A and B are disjoint sets, then $\mathcal{P}(A \cup B) \sim \mathcal{P}(A) \times \mathcal{P}(B)$.
9. (a) Suppose $A_1 \subseteq A_2 \subseteq A_3 \subseteq \cdots$ and $\bigcup_{n \in \mathbb{Z}^+} A_n = \mathbb{R}$. Prove that for every uncountable set $B \subseteq \mathbb{R}$ there is some positive integer n such that $B \cap A_n$ is uncountable.
- (b) Suppose $A_1 \subseteq A_2 \subseteq A_3 \subseteq \cdots$ and $\bigcup_{n \in \mathbb{Z}^+} A_n = \mathbb{Z}^+$. Suppose also that for every infinite set $B \subseteq \mathbb{Z}^+$ there is some positive integer n such that $B \cap A_n$ is infinite. Prove that for some n , $A_n = \mathbb{Z}^+$.
- *10. Suppose $A \subseteq \mathbb{R}^+$, $b \in \mathbb{R}^+$, and for every list a_1, a_2, \dots, a_k of finitely many distinct elements of A , $a_1 + a_2 + \cdots + a_k \leq b$. Prove that A is countable. (Hint: For each positive integer n , let $A_n = \{x \in A \mid x \geq 1/n\}$. What can you say about the number of elements in A_n ?)
11. Suppose E is an equivalence relation on \mathbb{R} and for all real numbers x and y , $[x]_E \sim [y]_E$. Prove that either \mathbb{R}/E is uncountable or for every $x \in \mathbb{R}$, $[x]_E$ is uncountable.
12. A real number x is called *algebraic* if there is a positive integer n and integers a_0, a_1, \dots, a_n such that $a_0 + a_1x + a_2x^2 + \cdots + a_nx^n = 0$ and $a_n \neq 0$. Let A be the set of all algebraic numbers.
- (a) Prove that $\mathbb{Q} \subseteq A$.
- (b) Prove that $\sqrt{2} \in A$.
- (c) Prove that A is countable. Note: You may use the fact that if n is a positive integer, a_0, a_1, \dots, a_n are integers, and $a_n \neq 0$, then $\{x \in \mathbb{R} \mid a_0 + a_1x + a_2x^2 + \cdots + a_nx^n = 0\}$ is finite.
- *13. Suppose $\mathcal{F} \subseteq \{f \mid f : \mathbb{Z}^+ \rightarrow \mathbb{R}\}$ and \mathcal{F} is countable. Prove that there is a function $g : \mathbb{Z}^+ \rightarrow \mathbb{R}$ such that $\mathcal{F} \subseteq O(g)$. (See exercise 19 of Section 5.1 for the meaning of the notation used here.)
14. Suppose $\mathcal{F} \subseteq \mathcal{P}(\mathbb{Z}^+)$ and \mathcal{F} is pairwise disjoint. Prove that \mathcal{F} is countable.

- *15. If A and B are infinite sets, we say that A and B are *almost disjoint* if $A \cap B$ is finite. If \mathcal{F} is a family of infinite sets, then we say that \mathcal{F} is *pairwise almost disjoint* if for all A and B in \mathcal{F} , if $A \neq B$ then A and B are almost disjoint. In this exercise you will prove that there is some $\mathcal{F} \subseteq \mathcal{P}(\mathbb{Z}^+)$ such that all elements of \mathcal{F} are infinite, \mathcal{F} is pairwise almost disjoint, and \mathcal{F} is uncountable. (Contrast this with the previous exercise.)

Let $P = \{X \in \mathcal{P}(\mathbb{Z}^+) \mid X \text{ is finite}\}$ and $Q = \{X \in \mathcal{P}(\mathbb{Z}^+) \mid X \text{ is infinite}\}$. By exercise 4, P is denumerable, so we can choose a one-to-one, onto function $g : P \rightarrow \mathbb{Z}^+$.

(a) Prove that Q is uncountable.

For each $A \in Q$, let $S_A = \{A \cap I_n \mid n \in \mathbb{Z}^+\}$. For example, if A is the set of all prime numbers, then $S_A = \{\emptyset, \{2\}, \{2, 3\}, \{2, 3, 5\}, \dots\}$. (We might describe S_A as the set of all initial segments of A .)

(b) Prove that if $A \in Q$ then $S_A \subseteq P$ and S_A is infinite.

(c) Prove that if $A, B \in Q$ and $A \neq B$ then $S_A \cap S_B$ is finite.

(d) Let $\mathcal{F} = \{g(S_A) \mid A \in Q\}$. Prove that $\mathcal{F} \subseteq \mathcal{P}(\mathbb{Z}^+)$, every element of \mathcal{F} is infinite, \mathcal{F} is pairwise almost disjoint, and \mathcal{F} is uncountable.

16. Prove that there is a function $f : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+$ such that for all positive integers a, b , and c there is some positive integer n such that $f(an + b) = c$.
17. Prove that the set of all grammatical sentences of English is denumerable. (Hint: Every grammatical sentence of English is a finite sequence of English words. First show that the set of all grammatical sentences is countable, and then show that it is infinite.)
18. Some real numbers can be defined by a phrase in the English language. For example, the phrase “the ratio of the circumference of a circle to its diameter” defines the number π .
- (a) Prove that the set of numbers that can be defined by an English phrase is denumerable. (Hint: See exercise 17.)
- (b) Prove that there are real numbers that cannot be defined by English phrases.

8.3. The Cantor-Schröder-Bernstein Theorem

Suppose A and B are sets and f is a one-to-one function from A to B . Then f shows that $A \sim \text{Ran}(f) \subseteq B$, so it is natural to think of B as being *at least as large as* A . This suggests the following notation:

Definition 8.3.1. If A and B are sets, then we will say that B *dominates* A , and write $A \lesssim B$, if there is a function $f : A \rightarrow B$ that is one-to-one. If $A \lesssim B$ and $A \approx B$, then we say that B *strictly dominates* A , and write $A < B$.

For example, in the proof of Theorem 8.2.6 we gave a one-to-one function $f : \mathcal{P}(\mathbb{Z}^+) \rightarrow \mathbb{R}$, so $\mathcal{P}(\mathbb{Z}^+) \lesssim \mathbb{R}$. Of course, for any sets A and B , if $A \sim B$ then also $A \lesssim B$. It should also be clear that if $A \subseteq B$ then $A \lesssim B$. For example, $\mathbb{Z}^+ \lesssim \mathbb{R}$. In fact, by Theorem 8.2.6 we also know that $\mathbb{Z}^+ \approx \mathbb{R}$ so we can say that $\mathbb{Z}^+ < \mathbb{R}$.

You might think that \lesssim would be a partial order, but it turns out that it isn't. You're asked in exercise 1 to check that \lesssim is reflexive and transitive, but it is not antisymmetric. (In the terminology of exercise 25 of Section 4.5, \lesssim is a preorder.) For example, $\mathbb{Z}^+ \sim \mathbb{Q}$, so $\mathbb{Z}^+ \lesssim \mathbb{Q}$ and $\mathbb{Q} \lesssim \mathbb{Z}^+$, but of course $\mathbb{Z}^+ \not\equiv \mathbb{Q}$. But this suggests an interesting question: If $A \lesssim B$ and $B \lesssim A$, then A and B might not be equal, but must they be equinumerous?

The answer, it turns out, is yes, as we'll prove in our next theorem. Several mathematicians' names are usually associated with this theorem. Cantor was the first person to state the theorem, and he gave a partial proof. Later, Ernst Schröder (1841–1902) and Felix Bernstein (1878–1956) discovered proofs independently.

Theorem 8.3.2. (Cantor-Schröder-Bernstein theorem) *Suppose A and B are sets. If $A \lesssim B$ and $B \lesssim A$, then $A \sim B$.*

Scratch work

We start by assuming that $A \lesssim B$ and $B \lesssim A$, which means that we can choose one-to-one functions $f : A \rightarrow B$ and $g : B \rightarrow A$. To prove that $A \sim B$ we need to find a one-to-one, onto function $h : A \rightarrow B$.

At this point, we don't know much about A and B . The only tools we have to help us match up the elements of A and B are the functions f and g . If f is onto, then of course we can let $h = f$; and if g is onto, then we can let $h = g^{-1}$. But it may turn out that neither f nor g is onto. How can we come up with the required function h in this case?

Our solution will be to combine parts of f and g^{-1} to get h . To do this, we'll split A into two pieces X and Y , and B into two pieces W and Z , in such a way that X and W can be matched up by f , and Y and Z can be matched up by g . More precisely, we'll have $W = f(X) = \{f(x) \mid x \in X\}$ and $Y = g(Z) = \{g(z) \mid z \in Z\}$. The situation is illustrated in Figure 8.4. Once we have this, we'll be able to define h by letting $h(a) = f(a)$ for $a \in X$, and $h(a) = g^{-1}(a)$ for $a \in Y$.

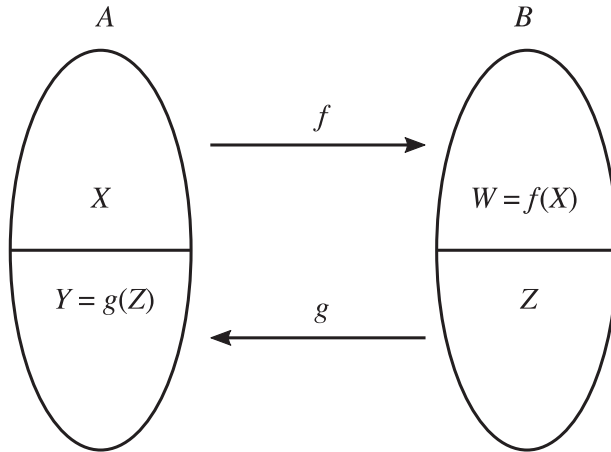


Figure 8.4.

How can we choose the sets X , Y , W , and Z ? First of all, note that every element of Y must be in $\text{Ran}(g)$, so any element of A that is not in $\text{Ran}(g)$ must be in X . In other words, if we let $A_1 = A \setminus \text{Ran}(g)$, then we must have $A_1 \subseteq X$. But now consider any $a \in A_1$. We know that we must have $a \in X$, and therefore $f(a) \in W$. But now note that since g is one-to-one, $g(f(a))$ will be different from $g(z)$ for every $z \in Z$, and therefore $g(f(a)) \notin g(Z) = Y$. Thus, we must have $g(f(a)) \in X$. Since a was an arbitrary element of A_1 , this shows that if we let $A_2 = g(f(A_1)) = \{g(f(a)) \mid a \in A_1\}$, then we must have $A_2 \subseteq X$. Similarly, if we let $A_3 = g(f(A_2))$, then it will turn out that we must have $A_3 \subseteq X$. Continuing in this way we can define sets A_n for every positive integer n , and for every n we must have $A_n \subseteq X$. As you will see, letting $X = \bigcup_{n \in \mathbb{Z}^+} A_n$ works. In the following proof, we actually do not mention the sets W and Z .

Proof. Suppose $A \lesssim B$ and $B \lesssim A$. Then we can choose one-to-one functions $f : A \rightarrow B$ and $g : B \rightarrow A$. Let $R = \text{Ran}(g) \subseteq A$. Then g maps onto R , so by Theorem 5.3.4, $g^{-1} : R \rightarrow B$.

We now define a sequence of sets A_1, A_2, A_3, \dots by recursion as follows:

$$A_1 = A \setminus R;$$

$$\text{for every } n \in \mathbb{Z}^+, A_{n+1} = g(f(A_n)) = \{g(f(a)) \mid a \in A_n\}.$$

Let $X = \bigcup_{n \in \mathbb{Z}^+} A_n$ and $Y = A \setminus X$. Of course, every element of A is in either X or Y , but not both. Now define $h : A \rightarrow B$ as follows:

$$h(a) = \begin{cases} f(a), & \text{if } a \in X, \\ g^{-1}(a), & \text{if } a \in Y. \end{cases}$$

Note that for every $a \in A$, if $a \notin R$ then $a \in A_1 \subseteq X$. Thus, if $a \in Y$ then $a \in R$, so $g^{-1}(a)$ is defined. Therefore this definition makes sense.

We will show that h is one-to-one and onto, which will establish that $A \sim B$. To see that h is one-to-one, suppose $a_1 \in A$, $a_2 \in A$, and $h(a_1) = h(a_2)$.

Case 1. $a_1 \in X$. Suppose $a_2 \in Y$. Then according to the definition of h , $h(a_1) = f(a_1)$ and $h(a_2) = g^{-1}(a_2)$. Thus, the equation $h(a_1) = h(a_2)$ means $f(a_1) = g^{-1}(a_2)$, so $g(f(a_1)) = g(g^{-1}(a_2)) = a_2$. Since $a_1 \in X = \bigcup_{n \in \mathbb{Z}^+} A_n$, we can choose some $n \in \mathbb{Z}^+$ such that $a_1 \in A_n$. But then $a_2 = g(f(a_1)) \in g(f(A_n)) = A_{n+1}$, so $a_2 \in X$, contradicting our assumption that $a_2 \in Y$.

Thus, $a_2 \notin Y$, so $a_2 \in X$. This means that $h(a_2) = f(a_2)$, so from the equation $h(a_1) = h(a_2)$ we get $f(a_1) = f(a_2)$. But f is one-to-one, so it follows that $a_1 = a_2$.

Case 2. $a_1 \in Y$. As in case 1, if $a_2 \in X$, then we can derive a contradiction, so we must have $a_2 \in Y$. Thus, the equation $h(a_1) = h(a_2)$ means $g^{-1}(a_1) = g^{-1}(a_2)$. Therefore, $a_1 = g(g^{-1}(a_1)) = g(g^{-1}(a_2)) = a_2$.

In both cases we have $a_1 = a_2$, so h is one-to-one.

To see that h is onto, suppose $b \in B$. Then $g(b) \in A$, so either $g(b) \in X$ or $g(b) \in Y$.

Case 1. $g(b) \in X$. Choose n such that $g(b) \in A_n$. Note that $g(b) \in \text{Ran}(g) = R$ and $A_1 = A \setminus R$, so $g(b) \notin A_1$. Thus, $n > 1$, so $A_n = g(f(A_{n-1}))$, and therefore we can choose some $a \in A_{n-1}$ such that $g(f(a)) = g(b)$. But then since g is one-to-one, $f(a) = b$. Since $a \in A_{n-1}$, $a \in X$, so $h(a) = f(a) = b$. Thus, $b \in \text{Ran}(h)$.

Case 2. $g(b) \in Y$. Then $h(g(b)) = g^{-1}(g(b)) = b$, so $b \in \text{Ran}(h)$.

In both cases we have $b \in \text{Ran}(h)$, so h is onto. \square

The Cantor-Schröder-Bernstein theorem is often useful for showing that sets are equinumerous. For example, in exercise 3 of Section 8.1 you were asked to show that $(0, 1] \sim (0, 1)$, where

$$(0, 1] = \{x \in \mathbb{R} \mid 0 < x \leq 1\}$$

and

$$(0, 1) = \{x \in \mathbb{R} \mid 0 < x < 1\}.$$

It is surprisingly difficult to find a one-to-one correspondence between these two sets, but it is easy to show that they are equinumerous using the Cantor-Schröder-Bernstein theorem. Of course, $(0, 1) \subseteq (0, 1]$, so clearly $(0, 1) \lesssim (0, 1]$. For the other direction, define $f : (0, 1] \rightarrow (0, 1)$ by the formula $f(x) = x/2$. It is easy to check that this function is one-to-one (although it is

not onto), so $(0, 1] \lesssim (0, 1)$. Thus, by the Cantor-Schröder-Bernstein theorem, $(0, 1] \sim (0, 1)$. For more on this example see exercise 9.

Our next theorem gives a more surprising consequence of the Cantor-Schröder-Bernstein theorem.

Theorem 8.3.3. $\mathbb{R} \sim \mathcal{P}(\mathbb{Z}^+)$.

It is quite difficult to prove Theorem 8.3.3 directly by giving an example of a one-to-one, onto function from \mathbb{R} to $\mathcal{P}(\mathbb{Z}^+)$. In our proof we'll use the Cantor-Schröder-Bernstein theorem and the following lemma.

Lemma 8.3.4. *Suppose x and y are real numbers and $x < y$. Then there is a rational number q such that $x < q < y$.*

Proof. Let k be a positive integer larger than $1/(y - x)$. Then $1/k < y - x$. We will show that there is a fraction with denominator k that is between x and y .

Let m and n be integers such that $m < x < n$, and let $S = \{j \in \mathbb{N} \mid m + j/k > x\}$. Note that $m + k(n - m)/k = n > x$, and therefore $k(n - m) \in S$. Thus $S \neq \emptyset$, so by the well-ordering principle it has a smallest element. Let j be the smallest element of S . Note also that $m + 0/k = m < x$, so $0 \notin S$, and therefore $j > 0$. Thus, $j - 1$ is a natural number, but since j is the smallest element of S , $j - 1 \notin S$. It follows that $m + (j - 1)/k \leq x$.

Let $q = m + j/k$. Clearly q is a rational number, and since $j \in S$, $q = m + j/k > x$. Also, combining the observations that $m + (j - 1)/k \leq x$ and $1/k < y - x$, we have

$$q = m + \frac{j}{k} = m + \frac{j - 1}{k} + \frac{1}{k} < x + (y - x) = y.$$

Thus, we have $x < q < y$, as required. \square

Proof of Theorem 8.3.3. As we noted earlier, we already know that $\mathcal{P}(\mathbb{Z}^+) \lesssim \mathbb{R}$. Now consider the function $f : \mathbb{R} \rightarrow \mathcal{P}(\mathbb{Q})$ defined as follows:

$$f(x) = \{q \in \mathbb{Q} \mid q < x\}.$$

We claim that f is one-to-one. To see why, suppose $x \in \mathbb{R}$, $y \in \mathbb{R}$, and $x \neq y$. Then either $x < y$ or $y < x$. Suppose first that $x < y$. By Lemma 8.3.4, we can choose a rational number q such that $x < q < y$. But then $q \in f(y)$ and $q \notin f(x)$, so $f(x) \neq f(y)$. A similar argument shows that if $y < x$ then $f(x) \neq f(y)$, so f is one-to-one.

Since f is one-to-one, we have shown that $\mathbb{R} \lesssim \mathcal{P}(\mathbb{Q})$. But we also know that $\mathbb{Q} \sim \mathbb{Z}^+$, so by exercise 5 in Section 8.1 it follows that $\mathcal{P}(\mathbb{Q}) \sim \mathcal{P}(\mathbb{Z}^+)$.

Thus, $\mathbb{R} \lesssim \mathcal{P}(\mathbb{Q}) \lesssim \mathcal{P}(\mathbb{Z}^+)$, so by transitivity of \lesssim (see exercise 1) we have $\mathbb{R} \lesssim \mathcal{P}(\mathbb{Z}^+)$. Combining this with the fact that $\mathcal{P}(\mathbb{Z}^+) \lesssim \mathbb{R}$ and applying the Cantor-Schröder-Bernstein theorem, we conclude that $\mathbb{R} \sim \mathcal{P}(\mathbb{Z}^+)$. \square

We said at the beginning of this chapter that we would show that infinity comes in different sizes. We now see that, so far, we have found only two sizes of infinity. One size is represented by the denumerable sets, which are all equinumerous with each other. The only examples of nondenumerable infinite sets we have given so far are $\mathcal{P}(\mathbb{Z}^+)$ and \mathbb{R} , which we now know are equinumerous. In fact, there are many more sizes of infinity. For example, $\mathcal{P}(\mathbb{R})$ is an infinite set that is neither denumerable nor equinumerous with \mathbb{R} . Thus, it represents a third size of infinity. For more on this see exercise 8.

Because $\mathbb{Z}^+ < \mathbb{R}$, it is natural to think of the set of real numbers as *larger* than the set of positive integers. In 1878, Cantor asked whether there was a size of infinity between these two sizes. More precisely, is there a set X such that $\mathbb{Z}^+ < X < \mathbb{R}$? Cantor conjectured that the answer was no, but he was unable to prove it. His conjecture is known as the *continuum hypothesis*. At the Second International Congress of Mathematicians in 1900, David Hilbert (1862–1943) gave a famous lecture in which he listed what he believed to be the most important unsolved mathematical problems of the time, and the proof or disproof of the continuum hypothesis was number one on his list.

The status of the continuum hypothesis was “resolved” in a remarkable way by the work of Kurt Gödel (1906–1978) in 1939 and Paul Cohen (1934–2007) in 1963. The resolution turns out to require even more careful analyses than we have given in this book of both the notion of proof and the basic assumptions underlying set theory. Once such analyses have been given, it is possible to prove theorems about what can be proven and what cannot be proven. What Gödel and Cohen proved was that, using the methods of mathematical proof and set-theoretic assumptions accepted by most mathematicians today, it is impossible to prove the continuum hypothesis, and it is also impossible to disprove it!

Exercises

- *1. Prove that \lesssim is reflexive and transitive. In other words:
 - (a) For every set A , $A \lesssim A$.
 - (b) For all sets A , B , and C , if $A \lesssim B$ and $B \lesssim C$ then $A \lesssim C$.
2. Prove that $<$ is irreflexive and transitive. In other words:
 - (a) For every set A , $A \not< A$.
 - (b) For all sets A , B , and C , if $A < B$ and $B < C$ then $A < C$.

3. Suppose $A \subseteq B \subseteq C$ and $A \sim C$. Prove that $B \sim C$.
4. Suppose $A \lesssim B$ and $C \lesssim D$.
 - (a) Prove that $A \times C \lesssim B \times D$.
 - (b) Prove that if A and C are disjoint and B and D are disjoint, then $A \cup C \lesssim B \cup D$.
 - (c) Prove that $\mathcal{P}(A) \lesssim \mathcal{P}(B)$.
- *5. For the meaning of the notation used in this exercise, see exercise 23 of Section 8.1. Suppose $A \lesssim B$ and $C \lesssim D$.
 - (a) Prove that if $A \neq \emptyset$ then ${}^A C \lesssim {}^B D$.
 - (b) Is the assumption that $A \neq \emptyset$ needed in part (a)?
6. (a) Prove that if $A \lesssim B$ and B is finite, then A is finite and $|A| \leq |B|$.
 (b) Prove that if $A < B$ and B is finite, then A is finite and $|A| < |B|$.
7. Prove that for every set A , $A < \mathcal{P}(A)$. (Hint: See exercise 5 of Section 8.2. Note that in particular, if A is finite and $|A| = n$ then, as you showed in exercise 11 of Section 6.2, and again in exercise 6(c) of Section 8.2, $|\mathcal{P}(A)| = 2^n$. It follows, by exercise 6(b), that $2^n > n$. Of course, you already proved this, by a different method, in exercise 12(a) of Section 6.3.)
- *8. Let $A_1 = \mathbb{Z}^+$, and for all $n \in \mathbb{Z}^+$ let $A_{n+1} = \mathcal{P}(A_n)$.
 - (a) Prove that for all $n \in \mathbb{Z}^+$ and $m \in \mathbb{Z}^+$, if $n < m$ then $A_n < A_m$.
 - (b) The sets A_n , for $n \in \mathbb{Z}^+$, represent infinitely many sizes of infinity. Are there any more sizes of infinity? In other words, can you think of an infinite set that is not equinumerous with A_n for any $n \in \mathbb{Z}^+$?
9. The proof of the Cantor-Schröder-Bernstein theorem gives a method for constructing a one-to-one and onto function $h : A \rightarrow B$ from one-to-one functions $f : A \rightarrow B$ and $g : B \rightarrow A$. Use this method to find a one-to-one, onto function $h : (0, 1] \rightarrow (0, 1)$. Start with the functions $f : (0, 1] \rightarrow (0, 1)$ and $g : (0, 1) \rightarrow (0, 1]$ given by the formulas:

$$f(x) = \frac{x}{2}, \quad g(x) = x.$$

- *10. Let $\mathcal{E} = \{R \mid R \text{ is an equivalence relation on } \mathbb{Z}^+\}$.
 - (a) Prove that $\mathcal{E} \lesssim \mathcal{P}(\mathbb{Z}^+)$.
 - (b) Let $A = \mathbb{Z}^+ \setminus \{1, 2\}$ and let \mathcal{P} be the set of all partitions of \mathbb{Z}^+ . Define $f : \mathcal{P}(A) \rightarrow \mathcal{P}$ by the formula $f(X) = \{X \cup \{1\}, (A \setminus X) \cup \{2\}\}$. Prove that f is one-to-one.
 - (c) Prove that $\mathcal{E} \sim \mathcal{P}(\mathbb{Z}^+)$.
11. Let $\mathcal{T} = \{R \mid R \text{ is a total order on } \mathbb{Z}^+\}$. Prove that $\mathcal{T} \sim \mathcal{P}(\mathbb{Z}^+)$. (Hint: Imitate the solution to exercise 10.)

12. (a) Prove that if A has at least two elements and $A \times A \sim A$ then $\mathcal{P}(A) \times \mathcal{P}(A) \sim \mathcal{P}(A)$.
- (b) Prove that $\mathbb{R} \times \mathbb{R} \sim \mathbb{R}$.
13. An *interval* is a set $I \subseteq \mathbb{R}$ with the property that for all real numbers x , y , and z , if $x \in I$, $z \in I$, and $x < y < z$, then $y \in I$. An interval is *nondegenerate* if it contains at least two different real numbers. Suppose \mathcal{F} is a set of nondegenerate intervals and \mathcal{F} is pairwise disjoint. Prove that \mathcal{F} is countable. (Hint: By Lemma 8.3.4, every nondegenerate interval contains a rational number.)
- *14. For the meaning of the notation used in this exercise, see exercise 23 of Section 8.1.
- (a) Prove that ${}^{\mathbb{R}}\mathbb{R} \sim \mathcal{P}(\mathbb{R})$.
- (b) Prove that ${}^{\mathbb{Q}}\mathbb{R} \sim \mathbb{R}$.
- (c) (For readers who have studied calculus.) Let $\mathcal{C} = \{f \in {}^{\mathbb{R}}\mathbb{R} \mid f \text{ is continuous}\}$. Prove that $\mathcal{C} \sim \mathbb{R}$. (Hint: Show that if f and g are continuous functions and $\forall x \in \mathbb{Q}(f(x) = g(x))$, then $f = g$.)

Appendix

Solutions to Selected Exercises

Introduction

1. (a) One possible answer is $32,767 = 31 \cdot 1057$.
 (b) One possible answer is $x = 2^{31} - 1 = 2,147,483,647$.
3. (a) The method yields the prime number 211.
 (b) The method yields two primes, 3 and 37.

Chapter 1

Section 1.1

1. (a) $(R \vee H) \wedge \neg(H \wedge T)$, where R stands for the statement “We’ll have a reading assignment,” H stands for “We’ll have homework problems,” and T stands for “We’ll have a test.”
 (b) $\neg G \vee (G \wedge \neg S)$, where G stands for “You’ll go skiing,” and S stands for “There will be snow.”
 (c) $\neg[(\bar{7} < 2) \vee (\bar{7} = 2)]$.
6. (a) I won’t buy the pants without the shirt.
 (b) I won’t buy the pants and I won’t buy the shirt.
 (c) Either I won’t buy the pants or I won’t buy the shirt.

Section 1.2

1. (a)

P	Q	$\neg P \vee Q$
F	F	T
F	T	T
T	F	F
T	T	T

(b)

S	G	$(S \vee G) \wedge (\neg S \vee \neg G)$
F	F	F
F	T	T
T	F	T
T	T	F

5. (a)

P	Q	$P \downarrow Q$
F	F	T
F	T	F
T	F	F
T	T	F

(b) $\neg(P \vee Q)$.(c) $\neg P$ is equivalent to $P \downarrow P$, $P \vee Q$ is equivalent to $(P \downarrow Q) \downarrow (P \downarrow Q)$, and $P \wedge Q$ is equivalent to $(P \downarrow P) \downarrow (Q \downarrow Q)$.

7. (a) and (c) are valid; (b) and (d) are invalid.

9. (a) is neither a contradiction nor a tautology; (b) is a contradiction; (c) and (d) are tautologies.

11. (a) $P \vee Q$.(b) P .(c) $\neg P \vee Q$.14. We use the associative law for \wedge twice:

$$[P \wedge (Q \wedge R)] \wedge S \text{ is equivalent to } [(P \wedge Q) \wedge R] \wedge S$$

$$\text{which is equivalent to } (P \wedge Q) \wedge (R \wedge S).$$

16. $P \vee \neg Q$.

Section 1.3

1. (a) $D(6) \wedge D(9) \wedge D(15)$, where $D(x)$ means “ x is divisible by 3.”
- (b) $D(x, 2) \wedge D(x, 3) \wedge \neg D(x, 4)$, where $D(x, y)$ means “ x is divisible by y .”
- (c) $N(x) \wedge N(y) \wedge [(P(x) \wedge \neg P(y)) \vee (P(y) \wedge \neg P(x))]$, where $N(x)$ means “ x is a natural number” and $P(x)$ means “ x is prime.”
3. (a) $\{x \mid x \text{ is a planet}\}$.
- (b) $\{x \mid x \text{ is an Ivy League school}\}$.
- (c) $\{x \mid x \text{ is a state in the United States}\}$.
- (d) $\{x \mid x \text{ is a province or territory in Canada}\}$.
5. (a) $(-3 \in \mathbb{R}) \wedge (13 - 2(-3) > 1)$. Bound variables: x ; no free variables. This statement is true.
- (b) $(4 \in \mathbb{R}) \wedge (4 < 0) \wedge (13 - 2(4) > 1)$. Bound variables: x ; no free variables. This statement is false.

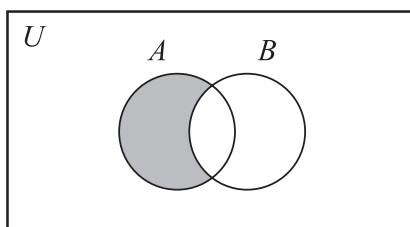
- (c) $\neg[(5 \in \mathbb{R}) \wedge (13 - 2(5) > c)]$. Bound variables: x ; free variables: c .
8. (a) $\{x \mid \text{Elizabeth Taylor was once married to } x\} = \{\text{Conrad Hilton Jr., Michael Wilding, Michael Todd, Eddie Fisher, Richard Burton, John Warner, Larry Fortensky}\}$.
- (b) $\{x \mid x \text{ is a logical connective studied in Section 1.1}\} = \{\wedge, \vee, \neg\}$.
- (c) $\{x \mid x \text{ is the author of this book}\} = \{\text{Daniel J. Velleman}\}$.

Section 1.4

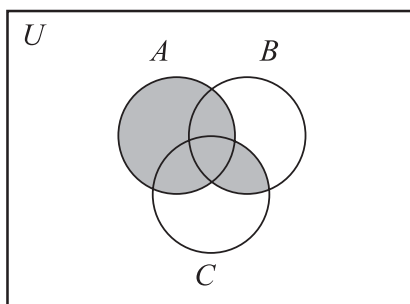
1. (a) $\{3, 12\}$.
- (b) $\{1, 12, 20, 35\}$.
- (c) $\{1, 3, 12, 20, 35\}$.

The sets in parts (a) and (b) are both subsets of the set in part (c).

4. (a) Both Venn diagrams look like this:

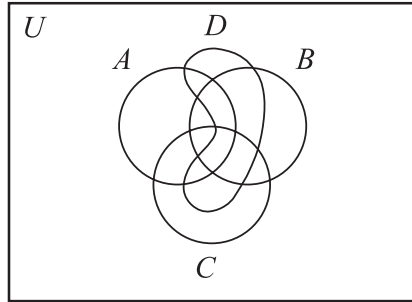


- (b) Both Venn diagrams look like this:

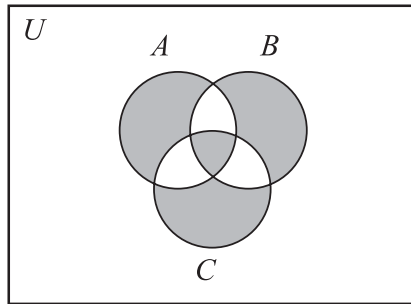


9. Sets (a), (d), and (e) are equal, and sets (b) and (c) are equal.
12. (a) There is no region corresponding to the set $(A \cap D) \setminus (B \cup C)$, but this set could have elements.

(b) Here is one possibility:



14. The Venn diagrams for both sets look like this:



Section 1.5

1. (a) $(S \vee \neg E) \rightarrow \neg H$, where S stands for "This gas has an unpleasant smell," E stands for "This gas is explosive," and H stands for "This gas is hydrogen."
 - (b) $(F \wedge H) \rightarrow D$, where F stands for "George has a fever," H stands for "George has a headache," and D stands for "George will go to the doctor."
 - (c) $(F \rightarrow D) \wedge (H \rightarrow D)$, where the letters have the same meanings as in part (b).
 - (d) $(x \equiv 2) \rightarrow (P(x) \rightarrow O(x))$, where $P(x)$ stands for " x is prime" and $O(x)$ stands for " x is odd."
4. (a) and (b) are valid, but (c) is invalid.
 7. (a) Either make a truth table, or reason as follows:

$$(P \rightarrow R) \wedge (Q \rightarrow R) \text{ is equivalent to } (\neg P \vee R) \wedge (\neg Q \vee R)$$

$$\text{which is equivalent to } (\neg P \wedge \neg Q) \vee R$$

$$\text{which is equivalent to } \neg(P \vee Q) \vee R$$

$$\text{which is equivalent to } (P \vee Q) \rightarrow R$$

$$(b) (P \rightarrow R) \vee (Q \rightarrow R) \text{ is equivalent to } (P \wedge Q) \rightarrow R.$$

$$9. \neg(P \rightarrow \neg Q).$$

Chapter 2

Section 2.1

1. (a) $\forall x[\exists y F(x, y) \rightarrow S(x)]$, where $F(x, y)$ stands for “ x has forgiven y ,” and $S(x)$ stands for “ x is a saint.”
 - (b) $\neg\exists x[C(x) \wedge \forall y(D(y) \rightarrow S(x, y))]$, where $C(x)$ stands for “ x is in the calculus class,” $D(y)$ stands for “ y is in the discrete math class,” and $S(x, y)$ stands for “ x is smarter than y .”
 - (c) $\forall x(\neg(x = m) \rightarrow L(x, m))$, where $L(x, y)$ stands for “ x likes y ,” and m stands for Mary.
 - (d) $\exists x(P(x) \wedge S(j, x)) \wedge \exists y(P(y) \wedge S(r, y))$, where $P(x)$ stands for “ x is a police officer,” $S(x, y)$ stands for “ x saw y ,” j stands for Jane, and r stands for Roger.
 - (e) $\exists x(P(x) \wedge S(j, x) \wedge S(r, x))$, where the letters have the same meanings as in part (d).
4. (a) All unmarried men are unhappy.
 - (b) y is a sister of one of x 's parents; i.e., y is x 's blood aunt.
8. (a), (d), and (e) are true; (b), (c), and (f) are false.

Section 2.2

1. (a) $\exists x[M(x) \wedge \forall y(F(x, y) \rightarrow \neg H(y))]$, where $M(x)$ stands for “ x is majoring in math,” $F(x, y)$ stands for “ x and y are friends,” and $H(y)$ stands for “ y needs help with his or her homework.” In English: There is a math major all of whose friends don't need help with their homework.
 - (b) $\exists x \forall y(R(x, y) \rightarrow \exists z L(y, z))$, where $R(x, y)$ stands for “ x and y are roommates” and $L(y, z)$ stands for “ y likes z .” In English: There is someone all of whose roommates like at least one person.
 - (c) $\exists x[(x \in A \vee x \in B) \wedge (x \notin C \vee x \in D)]$.
 - (d) $\forall x \exists y[y > x \wedge \forall z(z^2 + 5z \equiv y)]$.
4. Hint: Begin by replacing $P(x)$ with $\neg P(x)$ in the first quantifier negation law, to get the fact that $\neg\exists x\neg P(x)$ is equivalent to $\forall x\neg\neg P(x)$.
 6. Hint: Begin by showing that $\exists x(P(x) \vee Q(x))$ is equivalent to $\neg\forall x\neg(P(x) \vee Q(x))$.

8. $(\forall x \in A P(x)) \wedge (\forall x \in B P(x))$
 is equivalent to $\forall x(x \in A \rightarrow P(x)) \wedge \forall x(x \in B \rightarrow P(x))$
 which is equivalent to $\forall x[(x \in A \rightarrow P(x)) \wedge (x \in B \rightarrow P(x))]$
 which is equivalent to $\forall x[(x \notin A \vee P(x)) \wedge (x \notin B \vee P(x))]$
 which is equivalent to $\forall x[(x \notin A \wedge x \notin B) \vee P(x)]$
 which is equivalent to $\forall x[\neg(x \in A \vee x \in B) \vee P(x)]$
 which is equivalent to $\forall x[x \notin (A \cup B) \vee P(x)]$
 which is equivalent to $\forall x[x \in (A \cup B) \rightarrow P(x)]$
 which is equivalent to $\forall x \in (A \cup B) P(x)$.
11. $A \setminus B = \emptyset$ is equivalent to $\neg \exists x(x \in A \wedge x \notin B)$
 which is equivalent to $\forall x \neg(x \in A \wedge x \notin B)$
 which is equivalent to $\forall x(x \notin A \vee x \in B)$
 which is equivalent to $\forall x(x \in A \rightarrow x \in B)$
 which is equivalent to $A \subseteq B$.
14. $A \cap B = \emptyset$ is equivalent to $\neg \exists x(x \in A \wedge x \in B)$
 which is equivalent to $\forall x \neg(x \in A \wedge x \in B)$
 which is equivalent to $\forall x(x \notin A \vee x \notin B)$
 which is equivalent to $\forall x(x \in A \rightarrow x \notin B)$
 which is equivalent to $\forall x((x \notin B \wedge x \in A) \leftrightarrow x \in A)$
 (by Section 1.5 exercise 11(b))
 which is equivalent to $\forall x(x \in A \setminus B \leftrightarrow x \in A)$
 which is equivalent to $A \setminus B = A$.

Section 2.3

1. (a) $\forall x(x \in \mathcal{F} \rightarrow \forall y(y \in x \rightarrow y \in A))$.
 (b) $\forall x(x \in A \rightarrow \exists n \in \mathbb{N}(x = 2n + 1))$.
 (c) $\forall n \in \mathbb{N} \exists m \in \mathbb{N}(n^2 + n + 1 = 2m + 1)$.
 (d) $\exists x(\forall y(y \in x \rightarrow \exists i \in I(y \in A_i)) \wedge \forall i \in I \exists y(y \in x \wedge y \notin A_i))$.
4. $\bigcap \mathcal{F} = \{\text{red, blue}\}$ and $\bigcup \mathcal{F} = \{\text{red, green, blue, orange, purple}\}$.
8. (a) $A_2 = \{2, 4\}$, $A_3 = \{3, 6\}$, $B_2 = \{2, 3\}$, $B_3 = \{3, 4\}$.
 (b) $\bigcap_{i \in I} (A_i \cup B_i) = \{3, 4\}$ and $(\bigcap_{i \in I} A_i) \cup (\bigcap_{i \in I} B_i) = \{3\}$.
 (c) They are not equivalent.
12. One example is $A = \{1, 2\}$ and $B = \{2, 3\}$.
14. (a) $B_3 = \{1, 2, 3, 4, 5\}$ and $B_4 = \{1, 2, 4, 5, 6\}$.
 (b) $\bigcap_{j \in J} B_j = \{1, 2, 4, 5\}$.
 (c) $\bigcup_{i \in I} (\bigcap_{j \in J} A_{i,j}) = \{1, 2, 4\}$. This is not equal to the set in part (b).
 (d) $x \in \bigcap_{j \in J} (\bigcup_{i \in I} A_{i,j})$ means $\forall j \in J \exists i \in I(x \in A_{i,j})$ and $x \in \bigcup_{i \in I} (\bigcap_{j \in J} A_{i,j})$ means $\exists i \in I \forall j \in J(x \in A_{i,j})$. They are not equivalent.

Chapter 3

Section 3.1

1. (a) Hypotheses: n is an integer larger than 1 and n is not prime.
Conclusion: $2^n - 1$ is not prime. The hypotheses are true when $n = 6$, so the theorem tells us that $2^6 - 1$ is not prime. This is correct, since $2^6 - 1 = 63 = 9 \cdot 7$.
- (b) We can conclude that 32767 is not prime. This is correct, since $32767 = 151 \cdot 217$.
- (c) The theorem tells us nothing; 11 is prime, so the hypotheses are not satisfied.
4. Suppose $0 < a < b$. Then $b - a > 0$. Multiplying both sides by the positive number $b + a$, we get $(b + a) \cdot (b - a) > (b + a) \cdot 0$, or in other words $b^2 - a^2 > 0$. Since $b^2 - a^2 > 0$, it follows that $a^2 < b^2$. Therefore if $0 < a < b$ then $a^2 < b^2$.
8. We will prove the contrapositive. Suppose $x \notin B$. Then since $x \in A$, it follows that $x \in A \setminus B$. But we also know that $A \setminus B \subseteq C \cap D$, so we can conclude that $x \in C \cap D$, and therefore $x \in D$. Thus, if $x \notin D$ then $x \in B$.
10. Hint: Add b to both sides of the inequality $a < b$.
12. We will prove the contrapositive. Suppose $c \leq d$. Multiplying both sides of this inequality by the positive number a , we get $ac \leq ad$. Also, multiplying both sides of the given inequality $a < b$ by the positive number d gives us $ad < bd$. Combining $ac \leq ad$ and $ad < bd$, we can conclude that $ac < bd$. Thus, if $ac \geq bd$ then $c > d$.
15. Since $x > 3 > 0$, by the theorem in Example 3.2.1, $x^2 > 9$. Also, multiplying both sides of the given inequality $y < 2$ by -2 (and reversing the direction of the inequality, since -2 is negative) we get $-2y > -4$. Finally, adding the inequalities $x^2 > 9$ and $-2y > -4$ gives us $x^2 - 2y > 5$.

Section 3.2

1. (a) Suppose P . Since $P \rightarrow Q$, it follows that Q . But then, since $Q \rightarrow R$, we can conclude R . Thus, $P \rightarrow R$.
- (b) Suppose P . To prove that $Q \rightarrow R$, we will prove the contrapositive, so suppose $\neg R$. Since $\neg R \rightarrow (P \rightarrow \neg Q)$, it follows that $P \rightarrow \neg Q$, and since we know P , we can conclude $\neg Q$. Thus, $Q \rightarrow R$, so $P \rightarrow (Q \rightarrow R)$.
5. Suppose $x \in A \setminus B$ and $x \in B \setminus C$. Since $x \in A \setminus B$, $x \in A$ and $x \notin B$, and since $x \in B \setminus C$, $x \in B$ and $x \notin C$. But now we have $x \in B$ and $x \notin B$,

which is a contradiction. Therefore it cannot be the case that $x \in A \setminus B$ and $x \in B \setminus C$.

6. Suppose $a \in A \setminus B$. This means that $a \in A$ and $a \notin B$. Since $a \in A$ and $a \in C$, $a \in A \cap C$. But then since $A \cap C \subseteq B$, it follows that $a \in B$, and this contradicts the fact that $a \notin B$. Thus, $a \notin A \setminus B$.
9. Hint: Assume $a < 1/a < b < 1/b$. Now prove that $a < 1$, then use this fact to prove that $a < 0$, and then use this fact to prove that $a < -1$.
12. (a) The sentence "Then $x = 3$ and $y = 8$ " is incorrect. (Why?)
(b) One counterexample is $x = 3, y = 7$.

15.	P	Q	R	$P \rightarrow (Q \rightarrow R)$	$\neg R \rightarrow (P \rightarrow \neg Q)$
	F	F	F	T	T
	F	F	T	T	T
	F	T	F	T	T
	F	T	T	T	T
	T	F	F	T	T
	T	F	T	T	T
	T	T	F	F	F
	T	T	T	T	T

Section 3.3

1. Suppose $\exists x(P(x) \rightarrow Q(x))$. Then we can choose some x_0 such that $P(x_0) \rightarrow Q(x_0)$. Now suppose that $\forall x P(x)$. Then in particular, $P(x_0)$, and since $P(x_0) \rightarrow Q(x_0)$, it follows that $Q(x_0)$. Since we have found a particular value of x for which $Q(x)$ holds, we can conclude that $\exists x Q(x)$. Thus $\forall x P(x) \rightarrow \exists x Q(x)$.
3. Suppose that $A \subseteq B \setminus C$, but A and C are not disjoint. Then we can choose some x such that $x \in A$ and $x \in C$. Since $x \in A$ and $A \subseteq B \setminus C$, it follows that $x \in B \setminus C$, which means that $x \in B$ and $x \notin C$. But now we have both $x \in C$ and $x \notin C$, which is a contradiction. Thus, if $A \subseteq B \setminus C$ then A and C are disjoint.
7. Suppose $x > 2$. Let $y = (x + \sqrt{x^2 - 4})/2$, which is defined since $x^2 - 4 > 0$. Then

$$y + \frac{1}{y} = \frac{x + \sqrt{x^2 - 4}}{2} + \frac{\sqrt{2}}{x + \sqrt{x^2 - 4}} = \frac{2x^2 + 2\sqrt{x^2 - 4}}{2(x + \sqrt{x^2 - 4})} = x.$$
9. Suppose \mathcal{F} is a family of sets and $A \in \mathcal{F}$. Suppose $x \in \bigcap \mathcal{F}$. Then by the definition of $\bigcap \mathcal{F}$, since $x \in \bigcap \mathcal{F}$ and $A \in \mathcal{F}$, $x \in A$. But x was an arbitrary element of $\bigcap \mathcal{F}$, so it follows that $\bigcap \mathcal{F} \subseteq A$.
12. Hint: Assume $\mathcal{F} \subseteq \mathcal{G}$ and let x be an arbitrary element of $\bigcup \mathcal{F}$. You must prove that $x \in \bigcup \mathcal{G}$, which means $\exists A \in \mathcal{G}(x \in A)$, so you should try

to find some $A \in \mathcal{G}$ such that $x \in A$. To do this, write out the givens in logical notation. You will find that one of them is a universal statement, and one is existential. Apply existential instantiation to the existential one.

14. Suppose $x \in \bigcup_{i \in I} \mathcal{P}(A_i)$. Then we can choose some $i \in I$ such that $x \in \mathcal{P}(A_i)$, or in other words $x \subseteq A_i$. Now let a be an arbitrary element of x . Then $a \in A_i$, and therefore $a \in \bigcup_{i \in I} A_i$. Since a was an arbitrary element of x , it follows that $x \subseteq \bigcup_{i \in I} A_i$, which means that $x \in \mathcal{P}(\bigcup_{i \in I} A_i)$. Thus $\bigcup_{i \in I} \mathcal{P}(A_i) \subseteq \mathcal{P}(\bigcup_{i \in I} A_i)$.
17. Hint: The last hypothesis means $\forall A \in \mathcal{F} \forall B \in \mathcal{G} (A \subseteq B)$, so if in the course of the proof you ever come across sets $A \in \mathcal{F}$ and $B \in \mathcal{G}$, you can conclude that $A \subseteq B$. Start the proof by letting x be arbitrary and assuming $x \in \bigcup \mathcal{F}$, and prove that $x \in \bigcap \mathcal{G}$. To see where to go from there, write these statements in logical symbols.
20. The sentence “Then for every real number x , $x^2 < 0$ ” is incorrect. (Why?)
22. Based on the logical form of the statement to be proven, the proof should have this outline:

Let $x = \dots$

Let y be an arbitrary real number.

[Proof of $xy^2 = y - x$ goes here.]

Since y was arbitrary, $\forall y \in \mathbb{R} (xy^2 = y - x)$.

Thus, $\exists x \in \mathbb{R} \forall y \in \mathbb{R} (xy^2 = y - x)$.

This outline makes it clear that y should be introduced into the proof *after* x . Therefore, x cannot be defined in terms of y , because y will not yet have been introduced into the proof when x is being defined. But in the given proof, x is defined in terms of y in the first sentence. (The mistake has been disguised by the fact that the sentence “Let y be an arbitrary real number” has been left out of the proof. If you try to add this sentence to the proof, you will find that there is nowhere it could be added that would lead to a correct proof of the incorrect theorem.)

25. Here is the beginning of the proof: Let x be an arbitrary real number. Let $y = 2x$. Now let z be an arbitrary real number. Then . . .

Section 3.4

1. (\rightarrow) Suppose $\forall x (P(x) \wedge Q(x))$. Let y be arbitrary. Then since $\forall x (P(x) \wedge Q(x))$, $P(y) \wedge Q(y)$, and so in particular $P(y)$. Since y was arbitrary, this shows that $\forall x P(x)$. A similar argument proves $\forall x Q(x)$: for arbitrary y , $P(y) \wedge Q(y)$, and therefore $Q(y)$. Thus, $\forall x P(x) \wedge \forall x Q(x)$.

(\leftarrow) Suppose $\forall x P(x) \wedge \forall x Q(x)$. Let y be arbitrary. Then since $\forall x P(x)$, $P(y)$, and similarly since $\forall x Q(x)$, $Q(y)$. Thus, $P(y) \wedge Q(y)$, and since y was arbitrary, it follows that $\forall x (P(x) \wedge Q(x))$.

4. Suppose that $A \subseteq B$ and $A \not\subseteq C$. Since $A \not\subseteq C$, we can choose some $a \in A$ such that $a \notin C$. Since $a \in A$ and $A \subseteq B$, $a \in B$. Since $a \in B$ and $a \notin C$, $B \not\subseteq C$.
7. Let A and B be arbitrary sets. Let x be arbitrary, and suppose that $x \in \mathcal{P}(A \cap B)$. Then $x \subseteq A \cap B$. Now let y be an arbitrary element of x . Then since $x \subseteq A \cap B$, $y \in A \cap B$, and therefore $y \in A$. Since y was arbitrary, this shows that $x \subseteq A$, so $x \in \mathcal{P}(A)$. A similar argument shows that $x \subseteq B$, and therefore $x \in \mathcal{P}(B)$. Thus, $x \in \mathcal{P}(A) \cap \mathcal{P}(B)$.
Now suppose that $x \in \mathcal{P}(A) \cap \mathcal{P}(B)$. Then $x \in \mathcal{P}(A)$ and $x \in \mathcal{P}(B)$, so $x \subseteq A$ and $x \subseteq B$. Suppose that $y \in x$. Then since $x \subseteq A$ and $x \subseteq B$, $y \in A$ and $y \in B$, so $y \in A \cap B$. Thus, $x \subseteq A \cap B$, so $x \in \mathcal{P}(A \cap B)$.
9. Suppose that x and y are odd. Then we can choose integers j and k such that $x = 2j + 1$ and $y = 2k + 1$. Therefore $xy = (2j + 1)(2k + 1) = 4jk + 2j + 2k + 1 = 2(2jk + j + k) + 1$. Since $2jk + j + k$ is an integer, it follows that xy is odd.
13. Hint: Let $x \in \mathbb{R}$ be arbitrary, and prove both directions of the biconditional separately. For the " \rightarrow " direction, use existential instantiation and proof by contradiction. For the " \leftarrow " direction, assume that $x \neq 1$ and then solve the equation $x + y = xy$ for y in order to decide what value to choose for y .
16. Suppose that $\bigcup \mathcal{F}$ and $\bigcap \mathcal{G}$ are not disjoint. Then we can choose some x such that $x \in \bigcup \mathcal{F}$ and $x \in \bigcap \mathcal{G}$. Since $x \in \bigcup \mathcal{F}$, we can choose some $A \in \mathcal{F}$ such that $x \in A$. Since we are given that every element of \mathcal{F} is disjoint from some element of \mathcal{G} , there must be some $B \in \mathcal{G}$ such that $A \cap B = \emptyset$. Since $x \in A$, it follows that $x \notin B$. But we also have $x \in \bigcap \mathcal{G}$ and $B \in \mathcal{G}$, from which it follows that $x \in B$, which is a contradiction. Thus, $\bigcup \mathcal{F}$ and $\bigcap \mathcal{G}$ must be disjoint.
18. (a) Suppose $x \in \bigcup (\mathcal{F} \cap \mathcal{G})$. Then we can choose some $A \in \mathcal{F} \cap \mathcal{G}$ such that $x \in A$. Since $A \in \mathcal{F} \cap \mathcal{G}$, $A \in \mathcal{F}$ and $A \in \mathcal{G}$. Since $x \in A$ and $A \in \mathcal{F}$, $x \in \bigcup \mathcal{F}$, and similarly since $x \in A$ and $A \in \mathcal{G}$, $x \in \bigcup \mathcal{G}$. Therefore, $x \in (\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G})$. Since x was arbitrary, this shows that $\bigcup (\mathcal{F} \cap \mathcal{G}) \subseteq (\bigcup \mathcal{F}) \cap (\bigcup \mathcal{G})$.
(b) The sentence "Thus, we can choose a set A such that $A \in \mathcal{F}$, $A \in \mathcal{G}$, and $x \in A$ " is incorrect. (Why?)
(c) One example is $\mathcal{F} = \{\{1\}, \{2\}\}$, $\mathcal{G} = \{\{1\}, \{1, 2\}\}$.
22. Suppose that $\bigcup \mathcal{F} \not\subseteq \bigcup \mathcal{G}$. Then there is some $x \in \bigcup \mathcal{F}$ such that $x \notin \bigcup \mathcal{G}$. Since $x \in \bigcup \mathcal{F}$, we can choose some $A \in \mathcal{F}$ such that $x \in A$. Now

let $B \in \mathcal{G}$ be arbitrary. If $A \subseteq B$, then since $x \in A$, $x \in B$. But then since $x \in B$ and $B \in \mathcal{G}$, $x \in \bigcup \mathcal{G}$, which we already know is false. Therefore $A \not\subseteq B$. Since B was arbitrary, this shows that for all $B \in \mathcal{G}$, $A \not\subseteq B$. Thus, we have shown that there is some $A \in \mathcal{F}$ such that for all $B \in \mathcal{G}$, $A \not\subseteq B$.

24. (a) Suppose $x \in \bigcup_{i \in I} (A_i \setminus B_i)$. Then we can choose some $i \in I$ such that $x \in A_i \setminus B_i$, which means $x \in A_i$ and $x \notin B_i$. Since $x \in A_i$, $x \in \bigcup_{i \in I} A_i$, and since $x \notin B_i$, $x \notin \bigcap_{i \in I} B_i$. Thus, $x \in (\bigcup_{i \in I} A_i) \setminus (\bigcap_{i \in I} B_i)$.
- (b) One example is $I = \{1, 2\}$, $A_1 = B_1 = \{1\}$, $A_2 = B_2 = \{2\}$.

Section 3.5

1. Suppose $x \in A \cap (B \cup C)$. Then $x \in A$, and either $x \in B$ or $x \in C$.
- Case 1. $x \in B$. Then since $x \in A$, $x \in A \cap B$, so $x \in (A \cap B) \cup C$.
- Case 2. $x \in C$. Then clearly $x \in (A \cap B) \cup C$.
- Since x was arbitrary, we can conclude that $A \cap (B \cup C) \subseteq (A \cap B) \cup C$.
5. Suppose $x \in A$. We now consider two cases:
- Case 1. $x \in C$. Then $x \in A \cap C$, so since $A \cap C \subseteq B \cap C$, $x \in B \cap C$, and therefore $x \in B$.
- Case 2. $x \notin C$. Since $x \in A$, $x \in A \cup C$, so since $A \cup C \subseteq B \cup C$, $x \in B \cup C$. But $x \notin C$, so we must have $x \in B$.
- Thus, $x \in B$, and since x was arbitrary, $A \subseteq B$.
8. Hint: Assume $x \in \mathcal{P}(A) \cup \mathcal{P}(B)$, which means that either $x \in \mathcal{P}(A)$ or $x \in \mathcal{P}(B)$. Treat these as two separate cases. In case 1, assume $x \in \mathcal{P}(A)$, which means $x \subseteq A$, and prove $x \in \mathcal{P}(A \cup B)$, which means $x \subseteq A \cup B$. Case 2 is similar.
12. Let x be an arbitrary real number.
- (\leftarrow) Suppose $|x - 4| > 2$.
- Case 1. $x - 4 \geq 0$. Then $|x - 4| = x - 4$, so we have $x - 4 > 2$, and therefore $x > 6$. Adding x to both sides gives us $2x > 6 + x$, so $2x - 6 > x$. Since $x > 6$, this implies that $2x - 6$ is positive, so $|2x - 6| = 2x - 6 > x$.
- Case 2. $x - 4 < 0$. Then $|x - 4| = 4 - x$, so we have $4 - x > 2$, and therefore $x < 2$. Therefore $3x < 6$, and subtracting $2x$ from both sides we get $x < 6 - 2x$. Also, from $x < 2$ we get $2x < 4$, so $2x - 6 < -2$. Therefore $2x - 6$ is negative, so $|2x - 6| = 6 - 2x > x$.
- (\rightarrow) Hint: Imitate the " \leftarrow " direction, using the cases $2x - 6 \geq 0$ and $2x - 6 < 0$.

16. (a) Suppose $x \in \bigcup(\mathcal{F} \cup \mathcal{G})$. Then we can choose some $A \in \mathcal{F} \cup \mathcal{G}$ such that $x \in A$. Since $A \in \mathcal{F} \cup \mathcal{G}$, either $A \in \mathcal{F}$ or $A \in \mathcal{G}$.
- Case 1. $A \in \mathcal{F}$. Since $x \in A$ and $A \in \mathcal{F}$, $x \in \bigcup \mathcal{F}$, so $x \in (\bigcup \mathcal{F}) \cup (\bigcup \mathcal{G})$.
- Case 2. $A \in \mathcal{G}$. Since $x \in A$ and $A \in \mathcal{G}$, $x \in \bigcup \mathcal{G}$, so $x \in (\bigcup \mathcal{F}) \cup (\bigcup \mathcal{G})$.
- Thus, $x \in (\bigcup \mathcal{F}) \cup (\bigcup \mathcal{G})$.
- Now suppose that $x \in (\bigcup \mathcal{F}) \cup (\bigcup \mathcal{G})$. Then either $x \in \bigcup \mathcal{F}$ or $x \in \bigcup \mathcal{G}$.
- Case 1. $x \in \bigcup \mathcal{F}$. Then we can choose some $A \in \mathcal{F}$ such that $x \in A$. Since $A \in \mathcal{F}$, $A \in \mathcal{F} \cup \mathcal{G}$, so since $x \in A$, it follows that $x \in \bigcup(\mathcal{F} \cup \mathcal{G})$.
- Case 2. $x \in \bigcup \mathcal{G}$. A similar argument shows that $x \in \bigcup(\mathcal{F} \cup \mathcal{G})$.
- Thus, $x \in \bigcup(\mathcal{F} \cup \mathcal{G})$.
- (b) The theorem is: $\bigcap(\mathcal{F} \cup \mathcal{G}) = (\bigcap \mathcal{F}) \cap (\bigcap \mathcal{G})$.
20. (\rightarrow) Suppose that $A \cap B = \emptyset$ and C are disjoint. Let x be an arbitrary element of $A \cap C$. Then $x \in A$ and $x \in C$. If $x \notin B$, then since $x \in A$, $x \in A \setminus B$, and therefore $x \in A \cap B$. But also $x \in C$, so this contradicts our assumption that $A \cap B = \emptyset$ and C are disjoint. Therefore $x \in B$. Since we also know $x \in C$, we have $x \in B \cap C$. Since x was an arbitrary element of $A \cap C$, this shows that $A \cap C \subseteq B \cap C$. A similar argument shows that $B \cap C \subseteq A \cap C$.
- (\leftarrow) Suppose that $A \cap C = B \cap C$. Suppose that $A \cap B = \emptyset$ and C are not disjoint. Then we can choose some x such that $x \in A \cap B$ and $x \in C$. Since $x \in A \cap B$, either $x \in A \setminus B$ or $x \in B \setminus A$.
- Case 1. $x \in A \setminus B$. Then $x \in A$ and $x \notin B$. Since we also know $x \in C$, we can conclude that $x \in A \cap C$ but $x \notin B \cap C$. This contradicts the fact that $A \cap C = B \cap C$.
- Case 2. $x \in B \setminus A$. Similarly, this leads to a contradiction.
- Thus we can conclude that $A \cap B = \emptyset$ and C are disjoint.
23. (a) Hint: Suppose $x \in A \setminus C$, and then break the proof into cases, depending on whether or not $x \in B$.
- (b) Hint: Apply part (a).
24. (a) Suppose $x \in (A \cup B) \setminus C$. Then either $x \in (A \cup B) \setminus C$ or $x \in C \setminus (A \cup B)$.
- Case 1. $x \in (A \cup B) \setminus C$. Then either $x \in A$ or $x \in B$, and $x \notin C$. We now break case 1 into two subcases, depending on whether $x \in A$ or $x \in B$:
- Case 1a. $x \in A$. Then $x \in A \setminus C$, so $x \in A \setminus C$, so $x \in (A \setminus C) \cup (B \setminus C)$.

Case 1b. $x \in B$. Similarly, $x \in B^2 \setminus C$, so $x \in (A^2 \setminus C) \cup (B^2 \setminus C)$.

Case 2. $x \in C \setminus (A \cup B)$. Then $x \in C$, $x \notin A$, and $x \notin B$. It follows that $x \in A^2 \setminus C$ and $x \in B^2 \setminus C$, so certainly $x \in (A^2 \setminus C) \cup (B^2 \setminus C)$.

(b) Here is one example: $A = \{1\}$, $B = \{2\}$, $C = \{1, 2\}$.

27. The proof is incorrect, because it only establishes that either $0 < x$ or $x < 6$, but what must be proven is that $0 < x$ and $x < 6$. However, it can be fixed.
29. The proof is correct.
31. Hint: Here is a counterexample to the theorem: $A = \{1, 2\}$, $B = \{1\}$, $C = \{2\}$.

Section 3.6

1. Let x be an arbitrary real number. Let $y = x/(x^2 + 1)$. Then

$$x^2 - y = x^2 - \frac{x}{x^2 + 1} = \frac{x^3 + x}{x^2 + 1} - \frac{x}{x^2 + 1} = \frac{x^3}{x^2 + 1} = x^2 \cdot \frac{x}{x^2 + 1} = x^2 y.$$

To see that y is unique, suppose that $x^2 z = x - z$. Then $z(x^2 + 1) = x$, and since $x^2 + 1 \neq 0$, we can divide both sides by $x^2 + 1$ to conclude that $z = x/(x^2 + 1) = y$.

4. Suppose $x \neq 0$. Let $y = 1/x$. Now let z be an arbitrary real number. Then $zy = z(1/x) = z/x$, as required.

To see that y is unique, suppose that y^3 is a number with the property that $\forall z \in \mathbb{R} (zy^3 = z/x)$. Then in particular, taking $z = 1$, we have $y^3 = 1/x$, so $y^3 = y$.

6. (a) Let $A = \emptyset \in \mathcal{P}(U)$. Then clearly for any $B \in \mathcal{P}(U)$, $A \cup B = \emptyset \cup B = B$.

To see that A is unique, suppose that $A^3 \in \mathcal{P}(U)$ and for all $B \in \mathcal{P}(U)$, $A^3 \cup B = B$. Then in particular, taking $B = \emptyset$, we can conclude that $A^3 \cup \emptyset = \emptyset$. But clearly $A^3 \cup \emptyset = A^3$, so we have $A^3 = \emptyset = A$.

(b) Hint: Let $A = U$.

11. Existence: We are given that for every $\mathcal{G} \subseteq \mathcal{F}$, $\bigcup \mathcal{G} \in \mathcal{F}$, so in particular, since $\mathcal{F} \subseteq \mathcal{F}$, $\bigcup \mathcal{F} \in \mathcal{F}$. Let $A = \bigcup \mathcal{F}$. Now suppose $B \in \mathcal{F}$. Then by exercise 8 of Section 3.3, $B \subseteq \bigcup \mathcal{F} = A$, as required.

Uniqueness: Suppose that $A_1 \in \mathcal{F}$, $A_2 \in \mathcal{F}$, $\forall B \in \mathcal{F} (B \subseteq A_1)$, and $\forall B \in \mathcal{F} (B \subseteq A_2)$. Applying this last fact with $B = A_1$ we can conclude that $A_1 \subseteq A_2$, and similarly the previous fact implies that $A_2 \subseteq A_1$. Thus $A_1 = A_2$.

Section 3.7

1. Hint: Comparing (b) to exercise 16 of Section 3.3 may give you an idea of what to use for A .
5. Suppose $\mathcal{P}(\bigcup_{i \in I} A_i) \subseteq \bigcup_{i \in I} \mathcal{P}(A_i)$. It is clear that $\bigcup_{i \in I} A_i \subseteq \bigcup_{i \in I} A_i$, so $\bigcup_{i \in I} A_i \in \mathcal{P}(\bigcup_{i \in I} A_i)$ and therefore $\bigcup_{i \in I} A_i \in \bigcup_{i \in I} \mathcal{P}(A_i)$. By the definition of the union of a family, this means that there is some $i \in I$ such that $\bigcup_{i \in I} A_i \subseteq A_i$. Now let $j \in I$ be arbitrary. Then by exercise 8 in Section 3.3, $A_j \subseteq \bigcup_{i \in I} A_i$, so $A_j \subseteq A_i$.
8. Suppose that $\lim_{x \rightarrow c} f(x) = L > 0$. Let $\epsilon = L$. Then by the definition of limit, we can choose some $\delta > 0$ such that for all x , if $0 < |x - c| < \delta$ then $|f(x) - L| < \epsilon = L$. Now let x be an arbitrary real number and suppose $0 < |x - c| < \delta$. Then $|f(x) - L| < L$, so $-L < f(x) - L < L$ and therefore $0 < f(x) < 2L$. Therefore, for every real number x , if $0 < |x - c| < \delta$ then $f(x) > 0$.
10. The proof is correct.

Chapter 4

Section 4.1

1. (a) $\{(x, y) \in P \times P \mid x \text{ is a parent of } y\} = \{(\text{Bill Clinton, Chelsea Clinton}), (\text{Goldie Hawn, Kate Hudson}), \dots\}$.
- (b) $\{(x, y) \in C \times U \mid \text{there is someone who lives in } x \text{ and attends } y\}$. If you are a university student, then let x be the city you live in, and let y be the university you attend; (x, y) will then be an element of this truth set.
4. $A \times (B \cap C) = (A \times B) \cap (A \times C) = \{(1, 4), (2, 4), (3, 4)\}$,
 $A \times (B \cup C) = (A \times B) \cup (A \times C) = \{(1, 1), (2, 1), (3, 1), (1, 3), (2, 3), (3, 3), (1, 4), (2, 4), (3, 4)\}$,
 $(A \times B) \cap (C \times D) = (A \cap C) \times (B \cap D) = \emptyset$,
 $(A \times B) \cup (C \times D) = \{(1, 1), (2, 1), (3, 1), (1, 4), (2, 4), (3, 4), (3, 5), (4, 5)\}$,
 $(A \cup C) \times (B \cup D) = \{(1, 1), (2, 1), (3, 1), (4, 1), (1, 4), (2, 4), (3, 4), (4, 4), (1, 5), (2, 5), (3, 5), (4, 5)\}$.
6. The cases are not exhaustive.
8. Yes, it is true.
10. Suppose $(x, y) \in (A \setminus C) \times (B \setminus D)$. Then $x \in A \setminus C$ and $y \in B \setminus D$, which means $x \in A$, $x \notin C$, $y \in B$, and $y \notin D$. Since $x \in A$ and $y \in B$, $(x, y) \in A \times B$. And since $x \notin C$, $(x, y) \notin C \times D$. Therefore $(x, y) \in (A \times B) \setminus (C \times D)$.

15. The theorem is incorrect. Counterexample: $A = \{1\}$, $B = C = D = \emptyset$. Notice that $A \not\subseteq C$. Where is the mistake in the proof that $A \subseteq C$?

Section 4.2

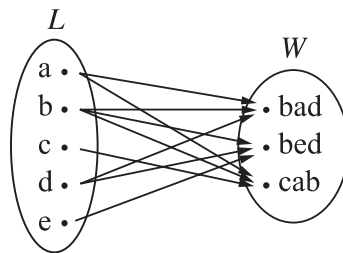
1. (a) Domain = $\{p \in P \mid p \text{ has a living child}\}$; Range = $\{p \in P \mid p \text{ has a living parent}\}$.
 (b) Domain = \mathbb{R} ; Range = \mathbb{R}^+ .
5. (a) $\{(1, 4), (1, 5), (1, 6), (2, 4), (3, 6)\}$.
 (b) $\{(4, 4), (5, 5), (5, 6), (6, 5), (6, 6)\}$.
8. $E \circ E \subseteq F$.
11. We prove the contrapositives of both directions.

(\rightarrow) Suppose $\text{Ran}(R)$ and $\text{Dom}(S)$ are not disjoint. Then we can choose some $b \in \text{Ran}(R) \cap \text{Dom}(S)$. Since $b \in \text{Ran}(R)$, we can choose some $a \in A$ such that $(a, b) \in R$. Similarly, since $b \in \text{Dom}(S)$, we can choose some $c \in C$ such that $(b, c) \in S$. But then $(a, c) \in S \circ R$, so $S \circ R \neq \emptyset$.

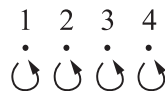
(\leftarrow) Suppose $S \circ R \neq \emptyset$. Then we can choose some $(a, c) \in S \circ R$. By the definition of $S \circ R$, this means that we can choose some $b \in B$ such that $(a, b) \in R$ and $(b, c) \in S$. But then $b \in \text{Ran}(R)$ and $b \in \text{Dom}(S)$, so $\text{Ran}(R)$ and $\text{Dom}(S)$ are not disjoint.

Section 4.3

1.



3.



5. $S \circ R = \{(a, y), (a, z), (b, x), (c, y), (c, z)\}$.
7. (\rightarrow) Suppose R is reflexive. Let (x, y) be an arbitrary element of i_A . Then by the definition of i_A , $x = y \in A$. Since R is reflexive, $(x, y) = (x, x) \in R$. Since (x, y) was arbitrary, this shows that $i_A \subseteq R$.

- (\leftarrow) Suppose $i_A \subseteq R$. Let $x \in A$ be arbitrary. Then $(x, x) \in i_A$, so since $i_A \subseteq R$, $(x, x) \in R$. Since x was arbitrary, this shows that R is reflexive.
10. Suppose $(x, y) \in i_D$. Then $x = y \in D = \text{Dom}(S)$, so there is some $z \in A$ such that $(x, z) \in S$. Therefore $(z, x) \in S^{-1}$, so $(x, y) = (x, x) \in S^{-1} \circ S$. Thus, $i_D \subseteq S^{-1} \circ S$. The proof of the other statement is similar.
13. (a) Yes. To prove it, suppose R_1 and R_2 are reflexive, and suppose $a \in A$. Since R_1 is reflexive, $(a, a) \in R_1$, so $(a, a) \in R_1 \cup R_2$.
- (b) Yes. To prove it, suppose R_1 and R_2 are symmetric, and suppose $(x, y) \in R_1 \cup R_2$. Then either $(x, y) \in R_1$ or $(x, y) \in R_2$. If $(x, y) \in R_1$ then since R_1 is symmetric, $(y, x) \in R_1$, so $(y, x) \in R_1 \cup R_2$. Similar reasoning shows that if $(x, y) \in R_2$ then $(y, x) \in R_1 \cup R_2$.
- (c) No. Counterexample: $A = \{1, 2, 3\}$, $R_1 = \{(1, 2)\}$, $R_2 = \{(2, 3)\}$.
17. First note that by part 2 of Theorem 4.3.4, since R and S are symmetric, $R = R^{-1}$ and $S = S^{-1}$. Therefore

$$\begin{aligned} R \circ S \text{ is symmetric iff } R \circ S &= (R \circ S)^{-1} && \text{(Theorem 4.3.4, part 2)} \\ &\text{iff } R \circ S = S^{-1} \circ R^{-1} && \text{(Theorem 4.2.5, part 5)} \\ &\text{iff } R \circ S = S \circ R. \end{aligned}$$

20. Suppose R is transitive, and suppose $(X, Y) \in S$ and $(Y, Z) \in S$. To prove that $(X, Z) \in S$ we must show that $\forall x \in X \forall z \in Z (xRz)$, so let $x \in X$ and $z \in Z$ be arbitrary. Since $Y \in B$, $Y \neq \emptyset$, so we can choose $y \in Y$. Since $(X, Y) \in S$ and $(Y, Z) \in S$, by the definition of S we have xRy and yRz . But then since R is transitive, xRz , as required. The empty set had to be excluded from B so that we could come up with $y \in Y$ in this proof. (Can you find a counterexample if the empty set is not excluded?)
23. Hint: Suppose aRb and bRc . To prove aRc , suppose that $X \subseteq A \setminus \{a, c\}$ and $X \cup \{a\} \in \mathcal{F}$; you must prove that $X \cup \{c\} \in \mathcal{F}$. To do this, you may find it helpful to consider two cases: $b \notin X$ or $b \in X$. In the second of these cases, try working with the sets $X^3 = (X \cup \{a\}) \setminus \{b\}$ and $X^{33} = (X \cup \{c\}) \setminus \{b\}$.

Section 4.4

1. (a) Partial order, but not total order.
- (b) Not a partial order.
- (c) Partial order, but not total order.
4. (\rightarrow) Suppose that R is both antisymmetric and symmetric. Suppose that $(x, y) \in R$. Then since R is symmetric, $(y, x) \in R$, and since R is

antisymmetric, it follows that $x = y$. Therefore $(x, y) \in i_A$. Since (x, y) was arbitrary, this shows that $R \subseteq i_A$.

(\leftarrow) Suppose that $R \subseteq i_A$. Suppose $(x, y) \in R$. Then $(x, y) \in i_A$, so $x = y$, and therefore $(y, x) = (x, y) \in R$. This shows that R is symmetric. To see that R is antisymmetric, suppose that $(x, y) \in R$ and $(y, x) \in R$. Then $(x, y) \in i_A$, so $x = y$.

8. To see that T is reflexive, consider an arbitrary $(a, b) \in A \times B$. Since R and S are both reflexive, we have aRa and bSb . By the definition of T , it follows that $(a, b)T(a, b)$. To see that T is antisymmetric, suppose that $(a, b)T(a^3, b^3)$ and $(a^3, b^3)T(a, b)$. Then aRa^3 and a^3Ra , so since R is antisymmetric, $a = a^3$. Similarly, bSb^3 and b^3Sb , so since S is antisymmetric, we also have $b = b^3$. Thus $(a, b) = (a^3, b^3)$, as required. Finally, to see that T is transitive, suppose that $(a, b)T(a^3, b^3)$ and $(a^3, b^3)T(a^{33}, b^{33})$. Then aRa^3 and a^3Ra^{33} , so since R is transitive, aRa^{33} . Similarly, bSb^3 and b^3Sb^{33} , so bSb^{33} , and therefore $(a, b)T(a^{33}, b^{33})$.

Even if both R and S are total orders, T need not be a total order.

11. The minimal elements of B are the prime numbers. B has no smallest element.

14. (a) b is the R -largest element of B

iff $b \in B$ and $\forall x \in B(xRb)$

iff $b \in B$ and $\forall x \in B(bR^{-1}x)$

iff b is the R^{-1} -smallest element of B .

- (b) b is an R -maximal element of B

iff $b \in B$ and $\neg \exists x \in B(bRx \wedge b \neq x)$

iff $b \in B$ and $\neg \exists x \in B(xR^{-1}b \wedge x \neq b)$

iff b is an R^{-1} -minimal element of B .

17. No. Let $A = \mathbb{R} \times \mathbb{R}$, and let $R = \{((x, y), (x^3, y^3)) \in A \times A \mid x \leq x^3 \text{ and } y \leq y^3\}$. (You might want to compare this to exercise 8.) Let $B = \{(0, 0)\} \cup (\{1\} \times \mathbb{R})$. We will leave it to you to check that R is a partial order on A , and that $(0, 0)$ is the only minimal element of B , but it is not a smallest element.

21. (a) Suppose that $x \in U$ and xRy . To prove that $y \in U$, we must show that y is an upper bound for B , so suppose that $b \in B$. Since $x \in U$, x is an upper bound for B , so bRx . But we also have xRy , so by the transitivity of R we can conclude that bRy . Since b was arbitrary, this shows that y is an upper bound for B .
- (b) Suppose $b \in B$. To prove that b is a lower bound for U , let x be an arbitrary element of U . Then by the definition of U , x is an upper bound for B , so bRx . Since x was arbitrary, this shows that b is a lower bound for U .

- (c) Hint: Suppose x is the greatest lower bound of U . First use part (b) to show that x is an upper bound for B , and therefore $x \in U$. Then use the fact that x is a lower bound for U to show that x is the smallest element of U – in other words, it is the least upper bound of B .
24. (a) Suppose $(x, y) \in S$. Then either $(x, y) \in R$ or $(x, y) \in R^{-1}$. If $(x, y) \in R$, then $(y, x) \in R^{-1}$, so $(y, x) \in S$. If $(x, y) \in R^{-1}$, then $(y, x) \in R$, so $(y, x) \in S$. Therefore S is symmetric. Since $S = R \cup R^{-1}$, it is clear that $R \subseteq S$.
- (b) Suppose T is a symmetric relation on A and $R \subseteq T$. To show that $S \subseteq T$, let (x, y) be an arbitrary element of S . Then either $(x, y) \in R$ or $(x, y) \in R^{-1}$. If $(x, y) \in R$, then since $R \subseteq T$, $(x, y) \in T$. If $(x, y) \in R^{-1}$, then $(y, x) \in R$, so since $R \subseteq T$, $(y, x) \in T$. But T is symmetric, so it follows that $(x, y) \in T$.
27. (a) First, note that $R_1 \subseteq R$ and $R_2 \subseteq R$. It follows, by exercise 26, that $S_1 \subseteq S$ and $S_2 \subseteq S$, so $S_1 \cup S_2 \subseteq S$. For the other direction, note that $R = R_1 \cup R_2 \subseteq S_1 \cup S_2$, and by exercise 13(b) of Section 4.3, $S_1 \cup S_2$ is symmetric. Therefore, by exercise 24(b), $S \subseteq S_1 \cup S_2$.
- (b) Imitating the first half of the proof in part (a), we can use exercise 26 to show that $T_1 \cup T_2 \subseteq T$. However, the answer to exercise 13(c) of Section 4.3 was no, so we can't imitate the second half of the proof. In fact, the example given in the solution to exercise 13(c) works as an example for which $T_1 \cup T_2 \not\equiv T$.

Section 4.5

1. Here is a list of all partitions:

$$\begin{aligned} & \{\{1, 2, 3\}\} \\ & \{\{1, 2\}, \{3\}\} \\ & \{\{1, 3\}, \{2\}\} \\ & \{\{2, 3\}, \{1\}\} \\ & \{\{1\}, \{2\}, \{3\}\} \end{aligned}$$

3. (a) R is an equivalence relation. There are 26 equivalence classes – one for each letter of the alphabet. The equivalence classes are: the set of all words that start with a , the set of all words that start with b , ..., the set of all words that start with z .
- (b) S is not an equivalence relation, because it is not transitive.
- (c) T is an equivalence relation. The equivalence classes are: the set of all one-letter words, the set of all two-letter words, and so on. For every positive integer n , if there is at least one English word of length n , then the set of all words of length n is an equivalence class.

6. The assumption that is needed is that for every date d , someone was born on the date d . What would go wrong if, say, just by chance, no one was born on April 23? Where in the proof is this assumption used?
10. Since S is the equivalence relation determined by \mathcal{F} , the proof of Theorem 4.5.6 shows that $A/S = \mathcal{F} = A/R$. The desired conclusion now follows from exercise 9.
13. See Lemma 7.3.4.
16. By exercise 16(a) of Section 3.5, $\bigcup(\mathcal{F} \cup \mathcal{G}) = (\bigcup \mathcal{F}) \cup (\bigcup \mathcal{G}) = A \cup B$. To see that $\mathcal{F} \cup \mathcal{G}$ is pairwise disjoint, suppose that $X \in \mathcal{F} \cup \mathcal{G}$, $Y \in \mathcal{F} \cup \mathcal{G}$, and $X \cap Y \neq \emptyset$. If $X \in \mathcal{F}$ and $Y \in \mathcal{G}$ then $X \subseteq A$ and $Y \subseteq B$, and since A and B are disjoint it follows that X and Y are disjoint, which is a contradiction. Thus it cannot be the case that $X \in \mathcal{F}$ and $Y \in \mathcal{G}$, and a similar argument can be used to rule out the possibility that $X \in \mathcal{G}$ and $Y \in \mathcal{F}$. Thus, X and Y are either both elements of \mathcal{F} or both elements of \mathcal{G} . If they are both in \mathcal{F} , then since \mathcal{F} is pairwise disjoint, $X = Y$. A similar argument applies if they are both in \mathcal{G} . Finally, we have $\forall X \in \mathcal{F}(X \neq \emptyset)$ and $\forall X \in \mathcal{G}(X \neq \emptyset)$, and it follows by exercise 8 of Section 2.2 that $\forall X \in \mathcal{F} \cup \mathcal{G}(X \neq \emptyset)$.
20. (a) Here is the proof of transitivity: Suppose $(x, y) \in T$ and $(y, z) \in T$. Then since $T = R \cap S$, $(x, y) \in R$ and $(y, z) \in R$, so since R is transitive, $(x, z) \in R$. Similarly, $(x, z) \in S$, so $(x, z) \in R \cap S = T$.
- (b) Suppose $x \in A$. Then for all $y \in A$,
- $$y \in [x]_T \text{ iff } (y, x) \in T \text{ iff } (y, x) \in R \wedge (y, x) \in S$$
- $$\text{iff } y \in [x]_R \wedge y \in [x]_S \text{ iff } y \in [x]_R \cap [x]_S.$$
- (c) Suppose $X \in A/T$. Then since A/T is a partition, $X \neq \emptyset$. Also, for some $x \in A$, $X = [x]_T = [x]_R \cap [x]_S$, so since $[x]_R \in A/R$ and $[x]_S \in A/S$, $X \in (A/R) \cdot (A/S)$.
- Now suppose $X \in (A/R) \cdot (A/S)$. Then for some y and z in A , $X = [y]_R \cap [z]_S$. Also, $X \neq \emptyset$, so we can choose some $x \in X$. Therefore $x \in [y]_R$ and $x \in [z]_S$, and by part 2 of Lemma 4.5.5 it follows that $[x]_R = [y]_R$ and $[x]_S = [z]_S$. Therefore $X = [x]_R \cap [x]_S = [x]_T \in A/T$.
22. $\mathcal{F} \otimes \mathcal{F} = \{\mathbb{R}^+ \times \mathbb{R}^+, \mathbb{R}^- \times \mathbb{R}^+, \mathbb{R}^- \times \mathbb{R}^-, \mathbb{R}^+ \times \mathbb{R}^-, \mathbb{R}^+ \times \{0\}, \mathbb{R}^- \times \{0\}, \{0\} \times \mathbb{R}^+, \{0\} \times \mathbb{R}^-, \{(0, 0)\}\}$. In geometric terms these are the four quadrants of the plane, the positive and negative x -axes, the positive and negative y -axes, and the origin.
24. (a) Hint: Let $T = \{(X, Y) \in A/S \times A/S \mid \exists x \in X \exists y \in Y(xRy)\}$.
- (b) Suppose $x, y, x^3, y^3 \in A$, xSx^3 , and ySy^3 . Then $[x]_S = [x^3]_S$ and $[y]_S = [y^3]_S$, so xRy iff $[x]_S T [y]_S$ iff $[x^3]_S T [y^3]_S$ iff $x^3 R y^3$.

Chapter 5

Section 5.1

1. (a) Yes.
(b) No.
(c) Yes.
3. (a) $f(a) = b, f(b) = b, f(c) = a$.
(b) $f(2) = 0$.
(c) $f(\pi) = 3$ and $f(-\pi) = -4$.
5. $L \circ H : N \rightarrow N$, and for every $n \in N$, $(L \circ H)(n) = n$. Thus, $L \circ H = i_N$.
 $H \circ L : C \rightarrow C$, and for every $c \in C$, $(H \circ L)(c) =$ the capital of the country in which c is located.
7. (a) Suppose that $c \in C$. We must prove that there is a unique $b \in B$ such that $(c, b) \in f \upharpoonright C$.

Existence: Let $b = f(c) \in B$. Then $(c, b) \in f$ and $(c, b) \in C \times B$, and therefore $(c, b) \in f \cap (C \times B) = f \upharpoonright C$.

Uniqueness: Suppose that $(c, b_1) \in f \upharpoonright C$ and $(c, b_2) \in f \upharpoonright C$. Then $(c, b_1) \in f$ and $(c, b_2) \in f$, so since f is a function, $b_1 = b_2$.

This proves that $f \upharpoonright C$ is a function from C to B . Finally, to derive the formula for $(f \upharpoonright C)(c)$, suppose that $c \in C$, and let $b = f(c)$. We showed in the existence half of the proof that $(c, b) \in f \upharpoonright C$. It follows that

$$f(c) = b = (f \upharpoonright C)(c).$$

- (b) (\rightarrow) Suppose $g = f \upharpoonright C$. Then $g = f \cap (C \times B)$, so clearly $g \subseteq f$.
(\leftarrow) Suppose $g \subseteq f$. Suppose $c \in C$, and let $b = g(c)$. Then $(c, b) \in g$, so $(c, b) \in f$, and therefore $f(c) = b$. But then by part (a), $(f \upharpoonright C)(c) = f(c) = b = g(c)$. Since c was arbitrary, it follows by Theorem 5.1.4 that $g = f \upharpoonright C$.
- (c) $h \upharpoonright \mathbb{Z} = h \cap (\mathbb{Z} \times \mathbb{R}) = \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid y = 2x + 3\} \cap (\mathbb{Z} \times \mathbb{R}) = \{(x, y) \in \mathbb{Z} \times \mathbb{R} \mid y = 2x + 3\} = g$.
10. Since $f \equiv g$, by Theorem 5.1.4 we can choose some $a \in A$ such that $f(a) \equiv g(a)$. Therefore $(a, f(a)) \in f$ and $(a, f(a)) \notin g$, so by the definition of symmetric difference, $(a, f(a)) \in f \oplus g$, and similarly $(a, g(a)) \in f \oplus g$. Since $f(a) \equiv g(a)$, it follows that $f \oplus g$ is not a function.
13. (a) Suppose $b \in B$. Since $\text{Dom}(S) = B$, we know that there is some $c \in C$ such that $(b, c) \in S$. To see that it is unique, suppose that $c^3 \in C$ and $(b, c^3) \in S$. Since $\text{Ran}(R) = B$, we can choose some $a \in A$ such

that $(a, b) \in R$. But then $(a, c) \in S \circ R$ and $(a, c^3) \in S \circ R$, and since $S \circ R$ is a function, it follows that $c = c^3$.

- (b) $A = \{1\}$, $B = \{2, 3\}$, $C = \{4\}$, $R = \{(1, 2), (1, 3)\}$, $S = \{(2, 4), (3, 4)\}$.
15. (a) No. Example: $A = \{1\}$, $B = \{2, 3\}$, $f = \{(1, 2)\}$, $R = \{(1, 1)\}$.
- (b) Yes. Suppose R is symmetric. Suppose $(x, y) \in S$. Then we can choose some u and v in A such that $f(u) = x$, $f(v) = y$, and $(u, v) \in R$. Since R is symmetric, $(v, u) \in R$, and therefore $(y, x) \in S$.
- (c) No. Example: $A = \{1, 2, 3, 4\}$, $B = \{5, 6, 7\}$, $f = \{(1, 5), (2, 6), (3, 6), (4, 7)\}$, $R = \{(1, 2), (3, 4)\}$.
19. (a) Let $a = 3$ and $c = 8$. Then for any $x > a = 3$,

$$|f(x)| = |7x + 3| = 7x + 3 < 7x + x = 8x < 8x^2 = c|g(x)|.$$

This shows that $f \in O(g)$.

Now suppose that $g \in O(f)$. Then we can choose $a \in \mathbb{Z}^+$ and $c \in \mathbb{R}^+$ such that $\forall x > a(|g(x)| \leq c|f(x)|)$, or in other words, $\forall x > a(x^2 \leq c(7x + 3))$. Let x be any positive integer larger than both a and $10c$. Multiplying both sides of the inequality $x > 10c$ by x , we can conclude that $x^2 > 10cx$. But since $x > a$, we also have $x^2 \leq c(7x + 3) \leq c(7x + 3x) = 10cx$, so we have reached a contradiction. Therefore $g \notin O(f)$.

- (b) Clearly for any function $f \in \mathcal{F}$ we have $\forall x \in \mathbb{Z}^+ (|f(x)| \leq 1 \cdot |f(x)|)$, so $f \in O(f)$, and therefore $(f, f) \in S$. Thus, S is reflexive. To see that it is also transitive, suppose $(f, g) \in S$ and $(g, h) \in S$. Then there are positive integers a_1 and a_2 and positive real numbers c_1 and c_2 such that $\forall x > a_1 (|f(x)| \leq c_1|g(x)|)$ and $\forall x > a_2 (|g(x)| \leq c_2|h(x)|)$. Let a be the maximum of a_1 and a_2 , and let $c = c_1c_2$. Then for all $x > a$,

$$|f(x)| \leq c_1|g(x)| \leq c_1c_2|h(x)| = c|h(x)|.$$

Thus, $(f, h) \in S$, so S is transitive. Finally, to see that S is not a partial order, we show that it is not antisymmetric. Let f and g be the functions from $\mathbb{Z}^+ \rightarrow \mathbb{R}$ defined by the formulas $f(x) = x$ and $g(x) = 2x$. Then for all $x \in \mathbb{Z}^+$, $|f(x)| \leq |g(x)|$ and $|g(x)| \leq 2|f(x)|$, so $f \in O(g)$ and also $g \in O(f)$. Therefore $(f, g) \in S$ and $(g, f) \in S$, but $f \not\equiv g$.

- (c) Since $f_1 \in O(g)$, we can choose $a_1 \in \mathbb{Z}^+$ and $c_1 \in \mathbb{R}^+$ such that $\forall x > a_1 (|f_1(x)| \leq c_1|g(x)|)$. Similarly, since $f_2 \in O(g)$ we can choose $a_2 \in \mathbb{Z}^+$ and $c_2 \in \mathbb{R}^+$ such that $\forall x > a_2 (|f_2(x)| \leq c_2|g(x)|)$. Let a be the maximum of a_1 and a_2 , and let $c = |s|c_1 + |t|c_2 + 1$. (We

have added 1 here just to make sure that c is positive, as required in the definition of O .) Then for all $x > a$,

$$\begin{aligned} |f(x)| &= |sf_1(x) + tf_2(x)| \leq |s| |f_1(x)| + |t| |f_2(x)| \\ &\leq |s|c_1|g(x)| + |t|c_2|g(x)| = (|s|c_1 + |t|c_2)|g(x)| \leq c|g(x)|. \end{aligned}$$

Therefore $f \in O(g)$.

21. (a) Hint: Let $h = \{(X, y) \in A/R \times B \mid \exists x \in X(f(x) = y)\}$.
 (b) Hint: Use the fact that for all x and y in A , if xRy then $[x]_R = [y]_R$.

Section 5.2

2. (a) f is not a function.
 (b) f is not a function. g is a function that is onto, but not one-to-one.
 (c) R is one-to-one and onto.
 5. (a) Suppose that $x_1 \in A$, $x_2 \in A$, and $f(x_1) = f(x_2)$. Then we can perform the following algebraic steps:

$$\begin{aligned} \frac{x_1 + 1}{x_1 - 1} &= \frac{x_2 + 1}{x_2 - 1}, \\ (x_1 + 1)(x_2 - 1) &= (x_2 + 1)(x_1 - 1), \\ x_1x_2 - x_1 + x_2 - 1 &= x_1x_2 - x_2 + x_1 - 1, \\ 2x_2 &= 2x_1, \\ x_2 &= x_1. \end{aligned}$$

This shows that f is one-to-one.

To show that f is onto, suppose that $y \in A$. Let

$$x = \frac{y + 1}{y - 1}.$$

Notice that this is defined, since $y \neq 1$, and also clearly $x \neq 1$, so $x \in A$. Then

$$f(x) = \frac{x + 1}{x - 1} = \frac{\frac{y+1}{y-1} + 1}{\frac{y+1}{y-1} - 1} = \frac{\frac{2y}{y-1}}{\frac{2}{y-1}} = y.$$

- (b) For any $x \in A$,

$$(f \circ f)(x) = \frac{\frac{x+1}{x-1} + 1}{\frac{x+1}{x-1} - 1} = \frac{\frac{2x}{x-1}}{\frac{2}{x-1}} = x = i_A(x).$$

9. (a) $\{1, 2, 3, 4\}$.
 (b) f is onto, but not one-to-one.

13. (a) Suppose that f is one-to-one. Suppose that $c_1 \in C$, $c_2 \in C$, and $(f \upharpoonright C)(c_1) = (f \upharpoonright C)(c_2)$. By exercise 7(a) of Section 5.1, it follows that $f(c_1) = f(c_2)$, so since f is one-to-one, $c_1 = c_2$.
- (b) Suppose that $f \upharpoonright C$ is onto. Suppose $b \in B$. Then since $f \upharpoonright C$ is onto, we can choose some $c \in C$ such that $(f \upharpoonright C)(c) = b$. But then $c \in A$, and by exercise 7(a) of Section 5.1, $f(c) = b$.
- (c) Let $A = B = \mathbb{R}$ and $C = \mathbb{R}^+$. For (a), use $f(x) = |x|$, and for (b), use $f(x) = x$.
17. (a) Suppose R is reflexive and f is onto. Let $x \in B$ be arbitrary. Since f is onto, we can choose some $u \in A$ such that $f(u) = x$. Since R is reflexive, $(u, u) \in R$. Therefore $(x, x) \in S$.
- (b) Suppose R is transitive and f is one-to-one. Suppose that $(x, y) \in S$ and $(y, z) \in S$. Since $(x, y) \in S$, we can choose some u and v in A such that $f(u) = x$, $f(v) = y$, and $(u, v) \in R$. Similarly, since $(y, z) \in S$ we can choose p and q in A such that $f(p) = y$, $f(q) = z$, and $(p, q) \in R$. Since $f(v) = y = f(p)$ and f is one-to-one, $v = p$. Therefore $(v, q) = (p, q) \in R$. Since we also have $(u, v) \in R$, by the transitivity of R it follows that $(u, q) \in R$, so $(x, z) \in S$.
20. (a) Let $b \in B$ be arbitrary. Since f is onto, we can choose some $a \in A$ such that $f(a) = b$. Therefore $g(b) = (g \circ f)(a) = (h \circ f)(a) = h(b)$. Since b was arbitrary, this shows that $\forall b \in B(g(b) = h(b))$, so $g = h$.
- (b) Let c_1 and c_2 be two distinct elements of C . Suppose $b \in B$. Let g and h be functions from B to C such that $\forall x \in B(g(x) = c_1)$, $\forall x \in B \setminus \{b\}(h(x) = c_1)$, and $h(b) = c_2$. (Formally, $g = B \times \{c_1\}$ and $h = [(B \setminus \{b\}) \times \{c_1\}] \cup \{(b, c_2)\}$.) Then $g \neq h$, so by assumption $g \circ f \neq h \circ f$, and therefore we can choose some $a \in A$ such that $g(f(a)) \neq h(f(a))$. But by the way g and h were defined, the only $x \in B$ for which $g(x) \neq h(x)$ is $x = b$, so it follows that $f(a) = b$. Since b was arbitrary, this shows that f is onto.

Section 5.3

1. $R^{-1}(p) =$ the person sitting immediately to the right of p .
3. Let $g(x) = (3x - 5)/2$. Then for any $x \in \mathbb{R}$,

$$f(g(x)) = \frac{2(3x - 5)/2 + 5}{3} = \frac{3x - 5 + 5}{3} = \frac{3x}{3} = x$$

and

$$g(f(x)) = \frac{3(2x + 5)/3 - 5}{2} = \frac{2x + 5 - 5}{2} = \frac{2x}{2} = x.$$

Therefore $f \circ g = i_{\mathbb{R}}$ and $g \circ f = i_{\mathbb{R}}$, and by Theorems 5.3.4 and 5.3.5 it follows that f is one-to-one and onto and $f^{-1} = g$.

5. $f^{-1}(x) = 2 - \log x$.
9. Suppose that $f : A \rightarrow B$, $g : B \rightarrow A$, and $f \circ g = i_B$. Let b be an arbitrary element of B . Let $a = g(b) \in A$. Then $f(a) = f(g(b)) = (f \circ g)(b) = i_B(b) = b$. Since b was arbitrary, this shows that f is onto.
11. (a) Suppose that f is one-to-one and $f \circ g = i_B$. By part 2 of Theorem 5.3.3, f is also onto, so $f^{-1} : B \rightarrow A$ and $f^{-1} \circ f = i_A$. This gives us enough information to imitate the reasoning in the proof of Theorem 5.3.5:

$$g = i_A \circ g = (f^{-1} \circ f) \circ g = f^{-1} \circ (f \circ g) = f^{-1} \circ i_B = f^{-1}.$$

- (b) Hint: Imitate the solution to part (a).
- (c) Hint: Use parts (a) and (b), together with Theorem 5.3.3.
14. (a) Suppose $x \in A^3 = \text{Ran}(g)$. Then we can choose some $b \in B$ such that $g(b) = x$. Therefore $(g \circ f)(x) = g(f(g(b))) = g((f \circ g)(b)) = g(i_B(b)) = g(b) = x$.
- (b) By the given information, $(f \upharpoonright A^3) \circ g = i_B$, and by part (a), $g \circ (f \upharpoonright A^3) = i_{A^3}$. Therefore by Theorem 5.3.4, $f \upharpoonright A^3$ is a one-to-one, onto function from A^3 to B , and by Theorem 5.3.5, $g = (f \upharpoonright A^3)^{-1}$.
16. Hint: Suppose $x \in \mathbb{R}$. To determine whether or not $x \in \text{Ran}(f)$, you must see if you can find a real number y such that $f(y) = x$. In other words, you must try to solve the equation $4y - y^2 = x$ for y in terms of x . Notice that this is similar to the method we used in part 1 of Example 5.3.6. However, in this case you will find that for some values of x there is no solution for y , and for some values of x there is more than one solution for y .
18. Since g is one-to-one and onto, $g^{-1} : C \rightarrow B$. Let $h = g^{-1} \circ f$. Then $h : A \rightarrow B$ and

$$\begin{aligned} g \circ h &= g \circ (g^{-1} \circ f) \\ &= (g \circ g^{-1}) \circ f && \text{(Theorem 4.2.5)} \\ &= i_C \circ f && \text{(Theorem 5.3.2)} \\ &= f && \text{(exercise 9 of Section 4.3).} \end{aligned}$$

Section 5.4

1. (a) No.
- (b) Yes.
- (c) Yes.
- (d) No.

3. $\{-1, 0, 1, 2\}$.
7. Suppose $C \subseteq A$ and C is closed under f . Suppose $x \in A \setminus C$, so $x \in A$ and $x \notin C$. Then $f^{-1}(x) \in A$. Suppose $f^{-1}(x) \in C$. Then since C is closed under f , $x = f(f^{-1}(x)) \in C$, which is a contradiction. Therefore $f^{-1}(x) \notin C$, so $f^{-1}(x) \in A \setminus C$. Since x was an arbitrary element of $A \setminus C$, this shows that $A \setminus C$ is closed under f^{-1} .
9. (a) Suppose $x \in C_1 \cup C_2$. Then either $x \in C_1$ or $x \in C_2$.
- Case 1. $x \in C_1$. Then since C_1 is closed under f , $f(x) \in C_1$, so $f(x) \in C_1 \cup C_2$.
- Case 2. $x \in C_2$. Then since C_2 is closed under f , $f(x) \in C_2$, so $f(x) \in C_1 \cup C_2$.
- Therefore $f(x) \in C_1 \cup C_2$. Since x was arbitrary, we can conclude that $C_1 \cup C_2$ is closed under f .
- (b) Yes. Proof: Suppose $x \in C_1 \cap C_2$. Then $x \in C_1$ and $x \in C_2$. Since $x \in C_1$ and C_1 is closed under f , $f(x) \in C_1$. Similarly, $f(x) \in C_2$. Therefore $f(x) \in C_1 \cap C_2$, so since x was arbitrary, $C_1 \cap C_2$ is closed under f .
- (c) No. Here is a counterexample: $A = \{1, 2\}$, $f = \{(1, 2), (2, 2)\}$, $C_1 = \{1, 2\}$, $C_2 = \{2\}$.
12. (a) \mathbb{Z} .
- (b) $\{X \subseteq \mathbb{N} \mid X \text{ is finite}\}$.
14. \mathbb{Z} .
17. (a) Yes.
- (b) Yes.
- (c) Yes.
- (d) No. (The composition of two strictly decreasing functions is strictly increasing.)
20. (b) and (e) are closed under f .

Chapter 6

Section 6.1

1. Base case: When $n = 0$, both sides of the equation are 0.

Induction step: Suppose that $n \in \mathbb{N}$ and $0 + 1 + 2 + \cdots + n = n(n + 1)/2$.

Then

$$\begin{aligned}
0 + 1 + 2 + \cdots + (n + 1) &= (0 + 1 + 2 + \cdots + n) + (n + 1) \\
&= \frac{n(n + 1)}{2} + (n + 1) \\
&= (n + 1) \left(\frac{n}{2} + 1 \right) = \frac{(n + 1)(n + 2)}{2},
\end{aligned}$$

as required.

3. Base case: When $n = 0$, both sides of the equation are 0.

Induction step: Suppose $n \in \mathbb{N}$ and $0^3 + 1^3 + 2^3 + \cdots + n^3 = [n(n + 1)/2]^2$. Then

$$\begin{aligned}
0^3 + 1^3 + 2^3 + \cdots + (n + 1)^3 &= \left(0^3 + 1^3 + 2^3 + \cdots + n^3 \right) + (n + 1)^3 \\
&= \left[\frac{n(n + 1)}{2} \right]^2 + (n + 1)^3 \\
&= (n + 1)^2 \left[\frac{n^2}{4} + n + 1 \right] \\
&= (n + 1)^2 \cdot \frac{n^2 + 4n + 4}{4} \\
&= \left[\frac{(n + 1)(n + 2)}{2} \right]^2.
\end{aligned}$$

7. Hint: The formula is $(3^{n+1} - 1)/2$.
10. Base case: When $n = 0$, $9^n - 8n - 1 = 0 = 64 \cdot 0$, so $64 \mid (9^n - 8n - 1)$.

Induction step: Suppose that $n \in \mathbb{N}$ and $64 \mid (9^n - 8n - 1)$. Then there is some integer k such that $9^n - 8n - 1 = 64k$. Therefore

$$\begin{aligned}
9^{n+1} - 8(n + 1) - 1 &= 9^{n+1} - 8n - 9 \\
&= 9^{n+1} - 72n - 9 + 64n \\
&= 9(9^n - 8n - 1) + 64n \\
&= 9(64k) + 64n \\
&= 64(9k + n),
\end{aligned}$$

so $64 \mid (9^{n+1} - 8(n + 1) - 1)$.

12. (a) Base case: When $n = 0$, $7^n - 5^n = 0 = 2 \cdot 0$, so $7^n - 5^n$ is even.

Induction step: Suppose $n \in \mathbb{N}$ and $7^n - 5^n$ is even. Then there is some integer k such that $7^n - 5^n = 2k$. Therefore

$$\begin{aligned}
7^{n+1} - 5^{n+1} &= 7 \cdot 7^n - 5 \cdot 5^n = 2 \cdot 7^n + 5 \cdot (7^n - 5^n) \\
&= 2 \cdot 7^n + 5 \cdot 2k = 2(7^n + 5k),
\end{aligned}$$

so $7^{n+1} - 5^{n+1}$ is even.

(b) For the induction step, you might find it useful to complete the following equation: $2 \cdot 7^{n+1} - 3 \cdot 5^{n+1} + 1 = 2 \cdot 7^n - 3 \cdot 5^n + 1 + \underline{\quad}$.

15. Base case: When $n = 10$, $2^n = 1024 > 1000 = n^3$.

Induction step: Suppose $n \geq 10$ and $2^n > n^3$. Then

$$\begin{aligned}
 2^{n+1} &= 2 \cdot 2^n \\
 &> 2n^3 && \text{(inductive hypothesis)} \\
 &= n^3 + n^3 \\
 &\geq n^3 + 10n^2 && \text{(since } n \geq 10\text{)} \\
 &= n^3 + 3n^2 + 7n^2 \\
 &\geq n^3 + 3n^2 + 70n && \text{(since } n \geq 10\text{)} \\
 &= n^3 + 3n^2 + 3n + 67n \\
 &> n^3 + 3n^2 + 3n + 1 = (n + 1)^3.
 \end{aligned}$$

20. (a) Base case: When $n = 1$, the statement to be proven is $0 < a < b$, which was given.

Induction step: Suppose that $n \geq 1$ and $0 < a^n < b^n$. Multiplying this inequality by the positive number a we get $0 < a^{n+1} < ab^n$, and multiplying the inequality $a < b$ by the positive number b^n gives us $ab^n < b^{n+1}$. Combining these inequalities, we can conclude that $0 < a^{n+1} < b^{n+1}$.

- (b) Hint: First note that $\sqrt[n]{a}$ and $\sqrt[n]{b}$ are both positive. (For n odd, this follows from exercise 19. For n even, each of $\sqrt[n]{a}$ and $\sqrt[n]{b}$ has two n th roots, one positive and one negative, but $\sqrt[n]{a}$ and $\sqrt[n]{b}$ are by definition the positive roots.) Now use proof by contradiction, and apply part (a).
- (c) Hint: The inequality to be proven can be rearranged to read $a^{n+1} - ab^n - ba^n + b^{n+1} > 0$. Now factor the left side of this inequality.
- (d) Hint: Use mathematical induction. For the base case, use the $n = 1$ case of part (c). For the induction step, multiply both sides of the inductive hypothesis by $(a + b)/2$ and then apply part (c).

Section 6.2

1. (a) We must prove that R^3 is reflexive (on A^3), transitive, and antisymmetric. For the first, suppose $x \in A^3$. Since R is reflexive (on A) and $x \in A$, $(x, x) \in R$, so $(x, x) \in R \cap (A^3 \times A^3) = R^3$. This shows that R^3 is reflexive.

Next, suppose that $(x, y) \in R^3$ and $(y, z) \in R^3$. Then $(x, y) \in R$, $(y, z) \in R$, and $x, y, z \in A^3$. Since R is transitive, $(x, z) \in R$, so $(x, z) \in R \cap (A^3 \times A^3) = R^3$. Therefore R^3 is transitive.

Finally, suppose that $(x, y) \in R^3$ and $(y, x) \in R^3$. Then $(x, y) \in R$ and $(y, x) \in R$, so since R is antisymmetric, $x = y$. Thus R^3 is antisymmetric.

- (b) To see that T is reflexive, suppose $x \in A$. If $x = a$, then $(x, x) = (a, a) \in \{a\} \times A \subseteq T$. If $x \neq a$, then $x \in A^3$, so since R^3 is reflexive, $(x, x) \in R^3 \subseteq T^3 \subseteq T$.

For transitivity, suppose that $(x, y) \in T$ and $(y, z) \in T$. If $x = a$ then $(x, z) = (a, z) \in \{a\} \times A \subseteq T$. Now suppose $x \neq a$. Then $(x, y) \notin \{a\} \times A$, so since $(x, y) \in T = T^3 \cup (\{a\} \times A)$ we must have $(x, y) \in T^3$. But $T^3 \subseteq A^3 \times A^3$, so $y \in A^3$ and therefore $y \neq a$. Similar reasoning now shows that $(y, z) \in T^3$. Since T^3 is transitive, it follows that $(x, z) \in T^3 \subseteq T$.

To show that T is antisymmetric, suppose $(x, y) \in T$ and $(y, x) \in T$. If $x = a$ then $(y, x) \notin T^3$, so $(y, x) \in \{a\} \times A$ and therefore $y = a = x$. Similarly, if $y = a$ then $x = y$. Now suppose $x \neq a$ and $y \neq a$. Then as in the proof of transitivity it follows that $(x, y) \in T^3$ and $(y, x) \in T^3$, so by antisymmetry of T^3 , $x = y$.

We now know that T is a partial order. To see that it is total, suppose $x \in A$ and $y \in A$. If $x = a$ then $(x, y) \in \{a\} \times A \subseteq T$. Similarly, if $y = a$ then $(y, x) \in T$. Now suppose $x \neq a$ and $y \neq a$. Then $x \in A^3$ and $y \in A^3$, so since T^3 is a total order, either $(x, y) \in T^3 \subseteq T$ or $(y, x) \in T^3 \subseteq T$.

Finally, to see that $R \subseteq T$, suppose that $(x, y) \in R$. If $x = a$ then $(x, y) \in \{a\} \times A \subseteq T$. Now suppose $x \neq a$. If $y = a$ then the fact that $(x, y) \in R$ would contradict the R -minimality of a . Therefore $y \neq a$. But then $(x, y) \in R \cap (A^3 \times A^3) = R^3 \subseteq T^3 \subseteq T$.

4. (a) We will prove the statement: $\forall n \geq 1 \forall B \subseteq A [B \text{ has } n \text{ elements} \rightarrow \exists x \in B \forall y \in B ((x, y) \in R \circ R)]$. We proceed by induction on n .

Base case: Suppose $n = 1$. If $B \subseteq A$ and B has one element, then for some $x \in B$, $B = \{x\}$. Since R is reflexive, $(x, x) \in R$, and therefore $(x, x) \in R \circ R$. But x is the only element in B , so $\forall y \in B ((x, y) \in R \circ R)$, as required.

Induction step: Suppose that $n \geq 1$ and for every $B \subseteq A$, if B has n elements then $\exists x \in B \forall y \in B ((x, y) \in R \circ R)$. Now suppose that $B \subseteq A$ and B has $n + 1$ elements. Choose some $b \in B$, and let $B^3 = B \setminus \{b\}$. Then $B^3 \subseteq A$ and B^3 has n elements, so by the inductive hypothesis there is some $x \in B^3$ such that $\forall y \in B^3 ((x, y) \in R \circ R)$. We now consider two cases.

Case 1: $(x, b) \in R \circ R$. Then $\forall y \in B ((x, y) \in R \circ R)$, so we are done.

Case 2: $(x, b) \notin R \circ R$. In this case, we will prove that $\forall y \in B((b, y) \in R \circ R)$. To do this, let $y \in B$ be arbitrary. If $y = b$, then since R is reflexive, $(b, b) \in R$, and therefore $(b, y) = (b, b) \in R \circ R$. Now suppose $y \neq b$. Then $y \in B^3$, so by the choice of x we know that $(x, y) \in R \circ R$. This means that for some $z \in A$, $(x, z) \in R$ and $(z, y) \in R$. We have $(x, z) \in R$, so if $(z, b) \in R$ then $(x, b) \in R \circ R$, contrary to the assumption for this case. Therefore $(z, b) \notin R$, so by the hypothesis on R , $(b, z) \in R$. But then since $(b, z) \in R$ and $(z, y) \in R$, we have $(b, y) \in R \circ R$, as required.

(b) Hint: Let $A = B =$ the set of contestants and let $R = \{(x, y) \in A \times A \mid x \text{ beats } y\} \cup i_A$. Now apply part (a).

8. (a) Let $m = (a + b)/2$, the arithmetic mean of a and b , and let $d = (a - b)/2$. Then it is easy to check that $m + d = a$ and $m - d = b$, so

$$\sqrt{\frac{ab}{ab}} = \sqrt{(m + d)(m - d)} = \sqrt{m^2 - d^2} \leq \sqrt{m^2} = m = \frac{a + b}{2}.$$

(b) We use induction on n .

Base case: $n = 1$. This case is taken care of by part (a).

Induction step: Suppose $n \geq 1$, and the arithmetic mean–geometric mean inequality holds for lists of length 2^n . Now let $a_1, a_2, \dots, a_{2^{n+1}}$ be a list of 2^{n+1} positive real numbers. Let

$$m_1 = \frac{a_1 + a_2 + \cdots + a_{2^n}}{2^n}, \quad m_2 = \frac{a_{2^{n+1}} + a_{2^{n+2}} + \cdots + a_{2^{2n+1}}}{2^n}.$$

Notice that $a_1 + a_2 + \cdots + a_{2^n} = m_1 2^n$, and similarly $a_{2^{n+1}} + a_{2^{n+2}} + \cdots + a_{2^{2n+1}} = m_2 2^n$. Also, by the inductive hypothesis, we know that $m_1 \geq \sqrt[2^n]{a_1 a_2 \cdots a_{2^n}}$ and $m_2 \geq \sqrt[2^n]{a_{2^{n+1}} a_{2^{n+2}} \cdots a_{2^{2n+1}}}$. Therefore

$$\begin{aligned} \frac{a_1 + a_2 + \cdots + a_{2^{n+1}}}{2^{n+1}} &= \frac{m_1 2^n + m_2 2^n}{2^{n+1}} = \frac{m_1 + m_2}{2} \geq \sqrt{\frac{m_1 m_2}{m_1 m_2}} \\ &\geq \sqrt{\sqrt[2^n]{a_1 a_2 \cdots a_{2^n}} \sqrt[2^n]{a_{2^{n+1}} a_{2^{n+2}} \cdots a_{2^{2n+1}}}} \\ &= \sqrt[2^{n+1}]{a_1 a_2 \cdots a_{2^{n+1}}}. \end{aligned}$$

(c) We use induction on n .

Base case: If $n = n_0$, then by assumption the arithmetic mean–geometric mean inequality fails for some list of length n .

Induction step: Suppose $n \geq n_0$, and there are positive real numbers a_1, a_2, \dots, a_n such that

$$\frac{a_1 + a_2 + \cdots + a_n}{n} < \sqrt[n]{a_1 a_2 \cdots a_n}.$$

Let $m = \sqrt[n]{(a_1 + a_2 + \cdots + a_n)/n}$, and let $a_{n+1} = m$. Then we have $m < \sqrt[n]{a_1 a_2 \cdots a_n}$, so $m^n < a_1 a_2 \cdots a_n$. Multiplying both sides of this inequality by m gives us $m^{n+1} < a_1 a_2 \cdots a_n m = a_1 a_2 \cdots a_{n+1}$, so $m < \sqrt[n+1]{a_1 a_2 \cdots a_{n+1}}$. But notice that we also have $mn = a_1 + a_2 + \cdots + a_n$, so

$$\frac{a_1 + \cdots + a_{n+1}}{n+1} = \frac{mn + m}{n+1} = \frac{m(n+1)}{n+1} = m < \sqrt[n+1]{a_1 a_2 \cdots a_{n+1}}.$$

Thus, we have a list of length $n+1$ for which the arithmetic mean–geometric mean inequality fails.

- (d) Suppose that the arithmetic mean–geometric mean inequality fails for some list of positive real numbers. Let n_0 be the length of this list, and choose an integer $n \geq 1$ such that $n_0 \leq 2^n$. (In fact, we could just let $n = n_0$, as you will show in exercise 12(a) in Section 6.3.) Then by part (b), the arithmetic mean–geometric mean inequality holds for all lists of length 2^n , but by part (c), it must fail for some list of length 2^n . This is a contradiction, so the inequality must always hold.
10. (a) Hint: Show that $(a_1 b_1 + a_2 b_2) - (a_1 b_2 + a_2 b_1) \geq 0$.
- (b) Use induction on n . For the induction step, assume the result holds for sequences of length n , and suppose $a_1 \leq a_2 \leq \cdots \leq a_n \leq a_{n+1}$, $b_1 \leq b_2 \leq \cdots \leq b_n \leq b_{n+1}$, and f is a one-to-one, onto function from $\{1, 2, \dots, n+1\}$ to itself. Now consider two cases. For case 1, assume that $f(n+1) = n+1$, and use the inductive hypothesis to complete the proof. For case 2, assume that $f(n+1) < n+1$. Find a one-to-one, onto function g from $\{1, 2, \dots, n+1\}$ to itself such that g is almost the same as f but $g(n+1) = n+1$, and show that

$$\begin{aligned} a_1 b_{f(1)} + \cdots + a_{n+1} b_{f(n+1)} &\leq a_1 b_{g(1)} + \cdots + a_{n+1} b_{g(n+1)} \\ &\leq a_1 b_1 + \cdots + a_{n+1} b_{n+1}. \end{aligned}$$

11. We proceed by induction on n .

Base case: $n = 0$. If A has 0 elements, then $A = \emptyset$, so $\mathcal{P}(A) = \{\emptyset\}$, which has $1 = 2^0$ elements.

Induction step: Suppose that for every set A with n elements, $\mathcal{P}(A)$ has 2^n elements. Now suppose that A has $n+1$ elements. Let a be any element of A , and let $A^3 = A \setminus \{a\}$. Then A^3 has n elements, so by the inductive hypothesis $\mathcal{P}(A^3)$ has 2^n elements. There are two kinds of subsets of A : those that contain a as an element, and those that don't. The subsets that don't contain a are just the subsets of A^3 , and there are 2^n of these. Those that do contain a are the sets of the form $X \cup \{a\}$, where $X \in \mathcal{P}(A^3)$, and

there are also 2^n of these, since there are 2^n possible choices for X . Thus the total number of elements of $\mathcal{P}(A)$ is $2^n + 2^n = 2^{n+1}$.

14. Base case: $n = 1$. One chord cuts the circle into two regions, and $(n^2 + n + 2)/2 = 2$.

Induction step: Suppose that when n chords are drawn, the circle is cut into $(n^2 + n + 2)/2$ regions. When another chord is drawn, it will intersect each of the first n chords exactly once. Therefore it will pass through $n + 1$ regions, cutting each of those regions in two. (Each time it crosses one of the first n chords, it passes from one region to another.) Therefore the number of regions after the next chord is drawn is

$$\frac{n^2 + n + 2}{2} + (n + 1) = \frac{n^2 + 3n + 4}{2} = \frac{(n + 1)^2 + (n + 1) + 2}{2},$$

as required.

Section 6.3

1. Hint: The formula is

$$\sum_{i=1}^n \frac{1}{i(i+1)} = \frac{n}{n+1}.$$

6. Base case: $n = 1$. Then

$$\sum_{i=1}^n \frac{1}{i^2} = 1 \leq 1 = 2 - \frac{1}{n}.$$

Induction step: Suppose that

$$\sum_{i=1}^n \frac{1}{i^2} \leq 2 - \frac{1}{n}.$$

Then

$$\begin{aligned} \sum_{i=1}^{n+1} \frac{1}{i^2} &= \sum_{i=1}^n \frac{1}{i^2} + \frac{1}{(n+1)^2} \leq 2 - \frac{1}{n} + \frac{1}{(n+1)^2} \\ &= 2 - \frac{n^2 + n + 1}{n(n+1)^2} < 2 - \frac{n^2 + n}{n(n+1)^2} = 2 - \frac{1}{n+1}. \end{aligned}$$

8. (a) We let m be arbitrary and then prove by induction that for all $n \geq m$,

$$H_n - H_m \geq (n - m)/n.$$

$$\text{Base case: } n = m. \text{ Then } H_n - H_m = 0 \geq 0 = (n - m)/n.$$

Induction step: Suppose that $n \geq m$ and $H_n - H_m \geq (n - m)/n$.
Then

$$\begin{aligned} H_{n+1} - H_m &= H_n + \frac{1}{n+1} - H_m \geq \frac{n-m}{n} + \frac{1}{n+1} \\ &\geq \frac{n-m}{n+1} + \frac{1}{n+1} = \frac{n+1-m}{n+1}. \end{aligned}$$

(b) Base case: If $n = 0$ then $H_{2^n} = H_1 = 1 \geq 1 + n/2$.

Induction step: Suppose $n \geq 0$ and $H_{2^n} \geq 1 + n/2$. By part (a),

$$H_{2^{n+1}} - H_{2^n} \geq \frac{2^{n+1} - 2^n}{2^{n+1}} = \frac{1}{2}.$$

Therefore

$$H_{2^{n+1}} \geq H_{2^n} + \frac{1}{2} \geq 1 + \frac{n}{2} + \frac{1}{2} = 1 + \frac{n+1}{2}.$$

(c) Since $\lim_{n \rightarrow \infty} (1 + n/2) = \infty$, by part (b) $\lim_{n \rightarrow \infty} H_{2^n} = \infty$. Clearly the H_n 's form an increasing sequence, so $\lim_{n \rightarrow \infty} H_n = \infty$.

12. (a) Hint: Try proving that $2^n \geq n + 1$, from which the desired conclusion follows.

(b) Base case: $n = 9$. Then $n! = 362880 \geq 262144 = (2^n)^2$.

Induction step: Suppose that $n \geq 9$ and $n! \geq (2^n)^2$. Then

$$\begin{aligned} (n+1)! &= (n+1) \cdot n! \geq (n+1) \cdot (2^n)^2 \geq 10 \cdot 2^{2n} \geq 2^2 \cdot 2^{2n} \\ &= 2^{2n+2} = (2^{n+1})^2. \end{aligned}$$

(c) Base case: $n = 0$. Then $n! = 1 \leq 1 = 2^{(n^2)}$.

Induction step: Suppose that $n! \leq 2^{(n^2)}$. Then

$$\begin{aligned} 2^{((n+1)^2)} &= 2^{n^2+2n+1} = 2^{(n^2)} \cdot 2^{2n+1} \geq 2^{(n^2)} \cdot 2^{n+1} \\ &> n! \cdot (n+1) \quad (\text{by inductive hypothesis and part (a)}) \\ &= (n+1)!. \end{aligned}$$

15. Base case: $n = 0$. Then $a_n = a_0 = 0 = 2^0 - 0 - 1 = 2^n - n - 1$.

Induction step: Suppose that $n \in \mathbb{N}$ and $a_n = 2^n - n - 1$. Then

$$\begin{aligned} a_{n+1} &= 2a_n + n = 2(2^n - n - 1) + n \\ &= 2^{n+1} - 2n - 2 + n = 2^{n+1} - n - 2 = 2^{n+1} - (n+1) - 1. \end{aligned}$$

18. (a) $\binom{n}{0} = n!/(0!n!) = 1$ and $\binom{n}{n} = n!/(n!0!) = 1$.

$$\begin{aligned} \text{(b)} \quad \binom{n}{k} + \binom{n}{k-1} &= \frac{n!}{k!(n-k)!} + \frac{n!}{(k-1)!(n-k+1)!} \\ &= \frac{n!(n-k+1)}{k!(n-k+1)!} + \frac{n!k}{k!(n-k+1)!} \\ &= \frac{n!(n+1)}{k!(n+1-k)!} = \binom{n+1}{k}. \end{aligned}$$

(c) We follow the hint.

Base case: $n = 0$. Suppose A is a set with 0 elements. Then $A = \emptyset$, the only value of k we have to worry about is $k = 0$, $\mathcal{P}_0(A) = \{\emptyset\}$, which has 1 element, and $\binom{0}{0} = 1$.

Induction step: Suppose the desired conclusion holds for sets with n elements, and A is a set with $n + 1$ elements. Let a be an element of A , and let $A^3 = A \setminus \{a\}$, which is a set with n elements. Now suppose $0 \leq k \leq n + 1$. We consider three cases.

Case 1: $k = 0$. Then $\mathcal{P}_k(A) = \{\emptyset\}$, which has 1 element, and $\binom{n+1}{k} = 1$.

Case 2: $k = n + 1$. Then $\mathcal{P}_k(A) = \{A\}$, which has 1 element, and $\binom{n+1}{k} = 1$.

Case 3. $0 < k \leq n$. There are two kinds of k -element subsets of A : those that contain a as an element, and those that don't. The k -element subsets that don't contain a are just the k -element subsets of A^3 , and by the inductive hypothesis there are $\binom{n}{k}$ of these. Those that do contain a are the sets of the form $X \cup \{a\}$, where $X \in \mathcal{P}_{k-1}(A^3)$, and by the inductive hypothesis there are $\binom{n}{k-1}$ of these, since this is the number of possibilities for X . Therefore by part (b), the total number of k -element subsets of A is

$$\binom{n}{k} + \binom{n}{k-1} = \binom{n+1}{k}.$$

(d) We let x and y be arbitrary and then prove the equation by induction on n .

Base case: $n = 0$. Then both sides of the equation are equal to 1.

Induction step: We will make use of parts (a) and (b). Suppose that

$$(x + y)^n = \sum_{k=0}^n \binom{n}{k} x^{n-k} y^k.$$

Then

$$\begin{aligned} (x + y)^{n+1} &= (x + y)(x + y)^n \\ &= (x + y) \sum_{k=0}^n \binom{n}{k} x^{n-k} y^k \quad (\text{inductive hypothesis}) \\ &= (x + y) \left[\binom{n}{0} x^n + \binom{n}{1} x^{n-1} y + \binom{n}{2} x^{n-2} y^2 \right. \\ &\quad \left. + \cdots + \binom{n}{n} y^n \right] \end{aligned}$$

$$\begin{aligned}
&= \binom{n}{0}x^{n+1} + \binom{n}{0}x^ny + \binom{n}{1}x^ny + \binom{n}{1}x^{n-1}y^2 \\
&\quad + \cdots + \binom{n}{n}xy^n + \binom{n}{n}y^{n+1} \\
&= x^{n+1} + \left[\binom{n}{0} + \binom{n}{1} \right] x^ny + \left[\binom{n}{1} + \binom{n}{2} \right] x^{n-1}y^2 \\
&\quad + \cdots + \left[\binom{n}{n-1} + \binom{n}{n} \right] xy^n + y^{n+1} \\
&= \binom{n+1}{0}x^{n+1} + \binom{n+1}{1}x^ny + \binom{n+1}{2}x^{n-1}y^2 \\
&\quad + \cdots + \binom{n+1}{n}xy^n + \binom{n+1}{n+1}y^{n+1} \\
&= \sum_{k=0}^{n+1} \binom{n+1}{k} x^{n+1-k} y^k.
\end{aligned}$$

20. Hint: Surprisingly, it is easier to prove that for all $n \geq 1$, $0 < a_n < 1/2$.

Section 6.4

1. (a) (\rightarrow) Suppose that $\forall n Q(n)$. Let n be arbitrary. Then $Q(n+1)$ is true, which means $\forall k < n+1 P(k)$. In particular, since $n < n+1$, $P(n)$ is true. Since n was arbitrary, this shows that $\forall n P(n)$.

(\leftarrow) Suppose that $\forall n P(n)$. Then for any n , it is clearly true that $\forall k < n P(k)$, which means that $Q(n)$ is true.

(b) Base case: $n = 0$. Then $Q(n)$ is the statement $\forall k < 0 P(k)$, which is vacuously true.

Induction step: Suppose $Q(n)$ is true. This means that $\forall k < n P(k)$ is true, so by assumption, it follows that $P(n)$ is true. Therefore $\forall k < n+1 P(k)$ is true, which means that $Q(n+1)$ is true.

4. (a) Suppose $\sqrt{6}$ is rational. Let $S = \{q \in \mathbb{Z}^+ \mid \exists p \in \mathbb{Z}^+ (p/q = \sqrt{6})\}$. Then $S \neq \emptyset$, so we can let q be the smallest element of S , and we can choose a positive integer p such that $p/q = \sqrt{6}$. Therefore $p^2 = 6q^2$, so p^2 is even, and hence p is even. This means that $p = 2\bar{p}$, for some integer \bar{p} . Thus $4\bar{p}^2 = 6q^2$, so $2\bar{p}^2 = 3q^2$ and therefore $3q^2$ is even. It is easy to check that if q is odd then $3q^2$ is odd, so q must be even, which means that $q = 2\bar{q}$ for some integer \bar{q} . But then $\sqrt{6} = \bar{p}/\bar{q}$ and $\bar{q} < q$, contradicting the fact that q is the smallest element of S .

(b) Suppose that $\sqrt{2} + \sqrt{3} = p/q$. Squaring both sides gives us $5 + 2\sqrt{6} = p^2/q^2$, so $\sqrt{6} = (p^2 - 5q^2)/(2q^2)$, which contradicts part (a).

7. (a) We use ordinary induction on n .

Base case: $n = 0$. Both sides of the equation are equal to 0.

Induction step: Suppose that $\sum_{i=0}^n F_i = F_{n+2} - 1$. Then

$$\sum_{i=0}^{n+1} F_i = \sum_{i=0}^n F_i + F_{n+1} = (F_{n+2} - 1) + F_{n+1} = F_{n+3} - 1.$$

(b) We use ordinary induction on n .

Base case: $n = 0$. Both sides of the equation are equal to 0.

Induction step. Suppose that $\sum_{i=0}^n (F_i)^2 = F_n F_{n+1}$. Then

$$\begin{aligned} \sum_{i=0}^{n+1} (F_i)^2 &= \sum_{i=0}^n (F_i)^2 + (F_{n+1})^2 = F_n F_{n+1} + (F_{n+1})^2 \\ &= F_{n+1}(F_n + F_{n+1}) = F_{n+1} F_{n+2}. \end{aligned}$$

(c) We use ordinary induction on n .

Base case: $n = 0$. Both sides of the equation are equal to 1.

Induction step: Suppose that $\sum_{i=0}^n F_{2i+1} = F_{2n+2}$. Then

$$\begin{aligned} \sum_{i=0}^{n+1} F_{2i+1} &= \sum_{i=0}^n F_{2i+1} + F_{2n+3} = F_{2n+2} + F_{2n+3} \\ &= F_{2n+4} = F_{2(n+1)+2}. \end{aligned}$$

(d) The formula is $\sum_{i=0}^n F_{2i} = F_{2n+1} - 1$.

9. (a) (\rightarrow) Suppose a_0, a_1, a_2, \dots is a Gibonacci sequence. Then in particular $a_2 = a_0 + a_1$, which means $c^2 = 1 + c$. Solving this quadratic equation by the quadratic formula leads to the conclusion $c = (1 + \sqrt{5})/2$.

(\leftarrow) Suppose either $c = (1 + \sqrt{5})/2$ or $c = (1 - \sqrt{5})/2$. Then $c^2 = 1 + c$, and therefore for every $n \geq 2$, $a_n = c^n = c^{n-2} c^2 = c^{n-2}(1 + c) = c^{n-2} + c^{n-1} = a_{n-2} + a_{n-1}$.

(b) It will be convenient to introduce the notation $c_1 = (1 + \sqrt{5})/2$ and $c_2 = (1 - \sqrt{5})/2$. Then for any $n \geq 2$, $a_n = s c_1^n + t c_2^n = s c_1^{n-2} c_1^2 + t c_2^{n-2} c_2^2 = s c_1^{n-2}(1 + c_1) + t c_2^{n-2}(1 + c_2) = (s c_1^{n-2} + t c_2^{n-2}) + (s c_1^{n-1} + t c_2^{n-1}) = a_{n-2} + a_{n-1}$.

(c) Hint: Let $s = (5a_0 + (2a_1 - a_0)\sqrt{5})/10$ and $t = (5a_0 - (2a_1 - a_0)\sqrt{5})/10$.

11. Hint: The formula is $a_n = 2 \cdot 3^n - 3 \cdot 2^n$.

15. Let a be the larger of $5k$ and $k(k + 1)$. Now suppose $n > a$, and by the division algorithm choose q and r such that $n = qk + r$ and $0 \leq r < k$. Note that if $q \leq 4$ then $n = qk + r \leq 4k + r < 5k \leq a$, which is a contradiction. Therefore $q > 4$, so $q \geq 5$, and by Example 6.1.3 it follows that $2^q \geq q^2$. Similar reasoning shows that $q \geq k + 1$, so

$q^2 \geq q(k+1) = qk + q > qk + k > qk + r = n$. Therefore $2^n \geq 2^{qk} = (2^q)^k \geq (q^2)^k \geq n^k$.

18. Hint: The formula is $a_n = F_{n+2}/F_{n+1}$.

21. (a) For any numbers a, b, c , and d ,

$$\begin{aligned} (ab)(cd) &= (cd)(ab) && \text{(commutative law)} \\ &= c(d(ab)) && \text{(associative law)} \\ &= c((da)b) && \text{(associative law)} \\ &= c((ad)b) && \text{(commutative law)}. \end{aligned}$$

(b) To simplify notation, we will assume that any product is the left-grouped product unless parentheses are used to indicate otherwise. We use strong induction on n . Assume the statement is true for products of fewer than n terms, and consider any product of a_1, a_2, \dots, a_n . If $n = 1$, then the only product is the left-grouped product, so there is nothing to prove. Now suppose $n > 1$. Then our product has the form pq , where p is a product of a_1, \dots, a_{k-1} and q is a product of a_k, \dots, a_n for some k with $2 \leq k \leq n$. By the inductive hypothesis, $p = a_1 \cdots a_{k-1}$ and $q = a_k \cdots a_n$ (where by our convention, these two products are left-grouped). Thus, it will suffice to prove $(a_1 \cdots a_{k-1})(a_k \cdots a_n) = a_1 \cdots a_n$. If $k = n$, then the left-hand side of this equation is already left-grouped, so there is nothing to prove. If $k < n$, then

$$\begin{aligned} (a_1 \cdots a_{k-1})(a_k \cdots a_n) &= (a_1 \cdots a_{k-1})((a_k \cdots a_{n-1})a_n) && \text{(definition of left-grouped)} \\ &= ((a_1 \cdots a_{k-1})(a_k \cdots a_{n-1}))a_n && \text{(associative law)} \\ &= (a_1 \cdots a_{n-1})a_n && \text{(inductive hypothesis)} \\ &= a_1 \cdots a_n && \text{(definition of left-grouped)}. \end{aligned}$$

(c) By part (b), we may assume that the two products are left-grouped. Thus, we must prove that if b_1, b_2, \dots, b_n is some reordering of a_1, a_2, \dots, a_n , then $a_1 \cdots a_n = b_1 \cdots b_n$, where as in part (b) we assume products are left-grouped unless parentheses indicate otherwise. We use induction on n . If $n = 1$ then the products are clearly equal because $b_1 = a_1$. Now suppose the statement is true for products of length n , and suppose that b_1, \dots, b_{n+1} is a reordering of a_1, \dots, a_{n+1} . Then b_{n+1} is one of a_1, \dots, a_{n+1} . If $b_{n+1} = a_{n+1}$ then

$$\begin{aligned} b_1 \cdots b_{n+1} &= (b_1 \cdots b_n)a_{n+1} && \text{(definition of left-grouped)} \\ &= (a_1 \cdots a_n)a_{n+1} && \text{(inductive hypothesis)} \\ &= a_1 \cdots a_{n+1} && \text{(definition of left-grouped)}. \end{aligned}$$

Now suppose $b_{n+1} = a_k$ for some $k \leq n$. We will write $a_1 \cdots \widehat{a_k} \cdots a_n$ for the (left-grouped) product of the numbers a_1, \dots, a_n with the factor a_k left out. Then

$$\begin{aligned}
 b_1 \cdots b_{n+1} &= (b_1 \cdots b_n) a_k && \text{(definition of left-grouped)} \\
 &= (a_1 \cdots \widehat{a_k} \cdots a_n) a_k && \text{(inductive hypothesis)} \\
 &= ((a_1 \cdots \widehat{a_k} \cdots a_n) a_{n+1}) a_k && \text{(definition of left-grouped)} \\
 &= (a_1 \cdots \widehat{a_k} \cdots a_n) (a_{n+1} a_k) && \text{(associative law)} \\
 &= (a_1 \cdots \widehat{a_k} \cdots a_n) (a_k a_{n+1}) && \text{(commutative law)} \\
 &= ((a_1 \cdots \widehat{a_k} \cdots a_n) a_k) a_{n+1} && \text{(associative law)} \\
 &= (a_1 \cdots a_n) a_{n+1} && \text{(inductive hypothesis)} \\
 &= a_1 \cdots a_{n+1} && \text{(definition of left-grouped).}
 \end{aligned}$$

Section 6.5

1. $B_n = \{n\}$.
4. $B_0 = \{\emptyset\}$, $B_1 = \{X \in \mathcal{P}(\mathbb{N}) \mid X \text{ has exactly one element}\}$, $B_2 = \{X \in \mathcal{P}(\mathbb{N}) \mid X \text{ has either one or two elements}\}$, \dots . In general, for every positive integer n , $B_n = \{X \in \mathcal{P}(\mathbb{N}) \mid X \neq \emptyset \text{ and } X \text{ has at most } n \text{ elements}\}$.
5. $\{n \in \mathbb{Z} \mid n \geq 2\}$.
7. (a) $B_0 = \{x \in \mathbb{R} \mid -2 \leq x \leq 0\}$, $B_1 = \{x \in \mathbb{R} \mid 0 \leq x \leq 4\}$, $B_2 = \{x \in \mathbb{R} \mid 0 \leq x \leq 16\}$, \dots . In general, for every positive integer n , $B_n = \{x \in \mathbb{R} \mid 0 \leq x \leq 2^{(2^n)}\}$.
- (b) $\bigcup_{n \in \mathbb{N}} B_n = \{x \in \mathbb{R} \mid x \geq -2\}$. Therefore $-1, 3 \in \bigcup_{n \in \mathbb{N}} B_n$ but $f(-1, 3) = -3 \notin \bigcup_{n \in \mathbb{N}} B_n$, so $\bigcup_{n \in \mathbb{N}} B_n$ is not closed under f . In other words, property 2 in Definition 5.4.8 does not hold.
- (c) \mathbb{R} .
10. We use induction on n .

Base case: $n = 1$. Then $x = 2! + 2 = 4$. The only value of i we have to worry about is $i = 0$, and for this value of i we have $i + 2 = 2$ and $x + i = 4$. Since $2 \mid 4$, we have $(i + 2) \mid (x + i)$, as required.

Induction step: Suppose that n is a positive integer, and for every integer i , if $0 \leq i \leq n - 1$ then $(i + 2) \mid ((n + 1)! + 2 + i)$. Now let $x = (n + 2)! + 2$, and suppose that $0 \leq i \leq n$. If $i = n$ then we have

$$x + i = (n + 2)! + 2 + i = (i + 2)! + (i + 2) = (i + 2)((i + 1)! + 1),$$

so $(i + 2) \mid (x + i)$. Now suppose $0 \leq i \leq n - 1$. By the inductive hypothesis, we know that $(i + 2) \mid ((n + 1)! + 2 + i)$, so we can choose some integer k such that $(n + 1)! + 2 + i = k(i + 2)$, and therefore $(n + 1)! = (k - 1)(i + 2)$. Therefore

$$\begin{aligned}x + i &= (n + 2)! + 2 + i = (n + 2)(n + 1)! + (i + 2) \\ &= (n + 2)(k - 1)(i + 2) + (i + 2) = (i + 2)((n + 2)(k - 1) + 1),\end{aligned}$$

so $(i + 2) \mid (x + i)$.

14. Clearly T is a relation on A and $R = R^1 \subseteq T$. To see that T is transitive, suppose $(x, y) \in T$ and $(y, z) \in T$. Then by the definition of T , we can choose positive integers n and m such that $(x, y) \in R^n$ and $(y, z) \in R^m$. Thus by exercise 11, $(x, z) \in R^m \circ R^n = R^{m+n}$, so $(x, z) \in \bigcup_{n \in \mathbb{Z}^+} R^n = T$. Therefore T is transitive.

Finally, suppose $R \subseteq S \subseteq A \times A$ and S is transitive. We must show that $T \subseteq S$, and clearly by the definition of T it suffices to show that $\forall n \in \mathbb{Z}^+ (R^n \subseteq S)$. We prove this by induction on n . We have assumed $R \subseteq S$, so when $n = 1$ we have $R^n = R^1 = R \subseteq S$. For the induction step, suppose n is a positive integer and $R^n \subseteq S$. Now suppose $(x, y) \in R^{n+1}$. Then by the definition of R^{n+1} we can choose some $z \in A$ such that $(x, z) \in R$ and $(z, y) \in R^n$. By assumption $R \subseteq S$, and by the inductive hypothesis $R^n \subseteq S$. Therefore $(x, z) \in S$ and $(z, y) \in S$, so since S is transitive, $(x, y) \in S$. Since (x, y) was an arbitrary element of R^{n+1} , this shows that $R^{n+1} \subseteq S$.

16. (a) $R \cap S \subseteq R$ and $R \cap S \subseteq S$. Therefore by exercise 15, for every positive integer n , $(R \cap S)^n \subseteq R^n$ and $(R \cap S)^n \subseteq S^n$, so $(R \cap S)^n \subseteq R^n \cap S^n$. However, the two need not be equal. For example, if $A = \{1, 2, 3, 4\}$, $R = \{(1, 2), (2, 4)\}$, and $S = \{(1, 3), (3, 4)\}$, then $(R \cap S)^2 = \emptyset$ but $R^2 \cap S^2 = \{(1, 4)\}$.
- (b) $R^n \cup S^n \subseteq (R \cup S)^n$, but they need not be equal. (You should be able to prove the first statement, and find a counterexample to justify the second.)
18. (a) We use induction.

Base case: $n = 1$. Suppose $(a, b) \in R^1 = R$. Let $f = \{(0, a), (1, b)\}$. Then f is an R -path from a to b of length 1. For the other direction, suppose f is an R -path from a to b of length 1. By the definition of R -path, this means that $f(0) = a$, $f(1) = b$, and $(f(0), f(1)) \in R$. Therefore $(a, b) \in R = R^1$.

Induction step: Suppose n is a positive integer and $R^n = \{(a, b) \in A \times A \mid \text{there is an } R\text{-path from } a \text{ to } b \text{ of length } n\}$. Now suppose $(a, b) \in R^{n+1} = R^1 \circ R^n$ by exercise 11. Then there is some c such that $(a, c) \in R^n$ and $(c, b) \in R$. By the inductive hypothesis, there is an R -path f from a to c of length n . Then $f \cup \{(n+1, b)\}$ is an R -path from a to b of length $n+1$. For the other direction, suppose f is an R -path from a to b of length $n+1$. Let $c = f(n)$. Then

$f \setminus \{(n+1, b)\}$ is an R -path from a to c of length n , so by the inductive hypothesis $(a, c) \in R^n$. But also $(c, b) = (f(n), f(n+1)) \in R$, so $(a, b) \in R^1 \circ R^n = R^{n+1}$.

(b) This follows from part (a) and exercise 14.

Chapter 7

Section 7.1

2. (a) $\gcd(775, 682) = 31 = -7 \cdot 775 + 8 \cdot 682$.

(b) $\gcd(562, 243) = 1 = 16 \cdot 562 - 37 \cdot 243$.

5. Let n be an arbitrary integer.

(\rightarrow) Suppose n is a linear combination of a and b . Then there are integers s and t such that $n = sa + tb$. Since $d = \gcd(a, b)$, $d \mid a$ and $d \mid b$, so there are integers j and k such that $a = jd$ and $b = kd$. Therefore $n = sa + tb = sjd + tkd = (sj + tk)d$, so $d \mid n$.

(\leftarrow) Suppose $d \mid n$. Then there is some integer k such that $n = kd$. By Theorem 7.1.4, there are integers s and t such that $d = sa + tb$. Therefore $n = kd = k(sa + tb) = ksa + ktb$, so n is a linear combination of a and b .

7. (a) No. Counterexample: $a = b = 2$, $a^3 = 3$, $b^3 = 4$.

(b) Yes. Suppose $a \mid a^3$ and $b \mid b^3$. Let $d = \gcd(a, b)$. Then $d \mid a$ and $d \mid b$. Since $d \mid a$ and $a \mid a^3$, by Theorem 3.3.7, $d \mid a^3$. Similarly, $d \mid b^3$. Therefore, by Theorem 7.1.6, $d \mid \gcd(a^3, b^3)$.

9. We use strong induction on the maximum of a and b . In other words, we prove the following statement by strong induction:

$$\forall k \in \mathbb{Z}^+ [\forall a \in \mathbb{Z}^+ \forall b \in \mathbb{Z}^+ (\max(a, b) = k \rightarrow \gcd(2^a - 1, 2^b - 1) = 2^{\gcd(a, b)} - 1)],$$

where $\max(a, b)$ denotes the maximum of a and b .

Let $k \in \mathbb{Z}^+$ be arbitrary and assume that for every positive integer $k^3 < k$,

$$\forall a \in \mathbb{Z}^+ \forall b \in \mathbb{Z}^+ (\max(a, b) = k^3 \rightarrow \gcd(2^a - 1, 2^b - 1) = 2^{\gcd(a, b)} - 1).$$

Now let a and b be arbitrary positive integers and assume that $\max(a, b) = k$. We may assume that $a \geq b$, since otherwise we can swap the values of a and b . We consider two cases.

Case 1. $a = b$. Then

$$\begin{aligned} \gcd(2^a - 1, 2^b - 1) &= \gcd(2^a - 1, 2^a - 1) = 2^a - 1 = 2^{\gcd(a, a)} - 1 \\ &= 2^{\gcd(a, b)} - 1. \end{aligned}$$

Case 2. $a > b$. Let $c = a - b > 0$, so that $a = c + b$. Let $k^3 = \max(c, b)$. Since $b < a$ and $c < a$, $k^3 < a = \max(a, b) = k$. Therefore

$$\begin{aligned} \gcd(2^a - 1, 2^b - 1) &= \gcd(2^c - 1 + 2^a - 2^c, 2^b - 1) \\ &= \gcd(2^c - 1 + 2^c(2^b - 1), 2^b - 1) \\ &= \gcd(2^c - 1, 2^b - 1) \quad (\text{exercise 6}) \\ &= 2^{\gcd(c, b)} - 1 \quad (\text{inductive hypothesis}) \\ &= 2^{\gcd(c+b, b)} - 1 \quad (\text{exercise 6}) \\ &= 2^{\gcd(a, b)} - 1. \end{aligned}$$

12. (a) $\gcd(55, 34) = 1$. The numbers r_i are the Fibonacci numbers. There are 8 divisions.
 (b) $\gcd(F_{n+1}, F_n) = 1$. There are $n - 1$ division steps.

Section 7.2

2. 14950.

5. Suppose some prime number p appears in the prime factorizations of both a and b . Then $p \mid a$ and $p \mid b$, so $\gcd(a, b) \geq p > 1$, and therefore a and b are not relatively prime.

Now suppose a and b are not relatively prime. Let $d = \gcd(a, b) > 1$. Let p be any prime number in the prime factorization of d . Then since $d \mid a$ and $d \mid b$, p must occur in the prime factorizations of both a and b .

8. Let $d = \gcd(a, b)$ and $x = ab / \gcd(a, b) = ab/d$.

(a) Since $d = \gcd(a, b)$, $d \mid b$, so there is some integer k such that $b = kd$. Therefore $x = akd/d = ak$, so x is an integer and $a \mid x$. A similar argument shows that $b \mid x$, so x is a common multiple of a and b . Since m is the least common multiple, $m \leq x$.

(b) Suppose $r > 0$. Since $a \mid m$, there is some integer t such that $m = ta$. Therefore $r = ab - qm = ab - qta = (b - qt)a$, so $a \mid r$. Similarly, $b \mid r$. But $r < m$, so this contradicts the definition of m as the least positive integer that is divisible by both a and b . Therefore $r = 0$.

(c) With t defined as in part (b), $ab = qm = qta$. Dividing both sides by a , we get $b = qt$, so $q \mid b$. The proof that $q \mid a$ is similar.

(d) Since $q \mid a$ and $q \mid b$, $q \leq \gcd(a, b)$. Therefore $ab = qm \leq \gcd(a, b)m$, so $m \geq ab / \gcd(a, b)$.

11. Hint: One approach is to let q and r be the quotient and remainder when m is divided by $\text{lcm}(a, b)$, and prove that $r = 0$.

13. Let the prime factorization of b be $b = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$. Then the factorization of b^2 is $b^2 = p_1^{2e_1} p_2^{2e_2} \cdots p_k^{2e_k}$. Since $a^2 \mid b^2$, every prime factor of a must be one of p_1, p_2, \dots, p_k , so $a = p_1^{f_1} p_2^{f_2} \cdots p_k^{f_k}$ for some

natural numbers f_1, f_2, \dots, f_k . Therefore $a^2 = p_1^{2f_1} p_2^{2f_2} \dots p_k^{2f_k}$. Since $a^2 \mid b^2$, for every i we must have $2f_i \leq 2e_i$, and therefore $f_i \leq e_i$. Thus $a \mid b$.

16. Let p_1, p_2, \dots, p_k be a list of all primes that occur in the prime factorization of either a or b , so that

$$a = p_1^{e_1} p_2^{e_2} \dots p_k^{e_k}, \quad b = p_1^{f_1} p_2^{f_2} \dots p_k^{f_k}$$

for some natural numbers e_1, e_2, \dots, e_k and f_1, f_2, \dots, f_k . For $i = 1, 2, \dots, k$, let

$$g_i = \begin{cases} e_i, & \text{if } e_i \geq f_i, \\ 0, & \text{if } e_i < f_i, \end{cases} \quad h_i = \begin{cases} 0, & \text{if } e_i \geq f_i, \\ f_i, & \text{if } e_i < f_i. \end{cases}$$

Let

$$c = p_1^{g_1} p_2^{g_2} \dots p_k^{g_k}, \quad d = p_1^{h_1} p_2^{h_2} \dots p_k^{h_k}.$$

Then for all i , $g_i \leq e_i$ and $h_i \leq f_i$, and therefore $c \mid a$ and $d \mid b$. Also, c and d have no prime factors in common, so by exercise 5, c and d are relatively prime. Finally,

$$cd = p_1^{g_1+h_1} \dots p_k^{g_k+h_k} = p_1^{\max(e_1, f_1)} \dots p_k^{\max(e_k, f_k)} = \text{lcm}(a, b).$$

19. (a) Since x is a positive rational number, there are positive integers m and n such that $x = m/n$. Let $d = \text{gcd}(m, n)$. By exercise 9, we can let a and b be positive integers such that $m = da$, $n = db$, and $\text{gcd}(a, b) = 1$. Then

$$x = \frac{m}{n} = \frac{da}{db} = \frac{a}{b}.$$

- (b) Since $a/b = c/d$, $ad = bc$. Therefore $a \mid bc$. Since $\text{gcd}(a, b) = 1$, by Theorem 7.2.2, $a \mid c$. A similar argument shows $c \mid a$, so $a = c$. Therefore $ad = bc = ba$, and dividing both sides by a we conclude that $b = d$.
- (c) By part (a), we have $x = a/b$, where a and b are relatively prime positive integers. Let the prime factorizations of a and b be

$$a = r_1^{g_1} r_2^{g_2} \dots r_j^{g_j}, \quad b = s_1^{h_1} s_2^{h_2} \dots s_l^{h_l}.$$

Note that by exercise 5, these factorizations have no primes in common. Then

$$x = \frac{r_1^{g_1} r_2^{g_2} \dots r_j^{g_j}}{s_1^{h_1} s_2^{h_2} \dots s_l^{h_l}} = r_1^{g_1} r_2^{g_2} \dots r_j^{g_j} s_1^{-h_1} s_2^{-h_2} \dots s_l^{-h_l}.$$

Rearranging the primes $r_1, \dots, r_j, s_1, \dots, s_l$ into increasing order gives the required product $p_1^{e_1} \cdots p_k^{e_k}$.

- (d) We begin by reversing the steps of part (c). Let r_1, r_2, \dots, r_j be those primes in the product $p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$ whose exponents are positive, listed in increasing order, and s_1, s_2, \dots, s_l those whose exponents are negative. Rewriting each prime raised to a negative power as the prime to a positive power in the denominator, we get

$$x = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k} = \frac{r_1^{g_1} r_2^{g_2} \cdots r_j^{g_j}}{s_1^{h_1} s_2^{h_2} \cdots s_l^{h_l}},$$

where all the exponents g_i and h_i are positive integers. The numerator and denominator have no prime factors in common, so they are relatively prime. Similarly, the product $q_1^{f_1} q_2^{f_2} \cdots q_m^{f_m}$ can be rewritten as a fraction with all exponents positive:

$$x = q_1^{f_1} q_2^{f_2} \cdots q_m^{f_m} = \frac{v_1^{y_1} v_2^{y_2} \cdots v_t^{y_t}}{w_1^{z_1} w_2^{z_2} \cdots w_u^{z_u}}.$$

By part (b), $r_1^{g_1} \cdots r_j^{g_j} = v_1^{y_1} \cdots v_t^{y_t}$ and $s_1^{h_1} \cdots s_l^{h_l} = w_1^{z_1} \cdots w_u^{z_u}$. By the uniqueness of prime factorizations, $j = t$ and for all $i \in \{1, \dots, j\}$, $r_i = v_i$ and $g_i = y_i$, and also $l = u$ and for all $i \in \{1, \dots, l\}$, $s_i = w_i$ and $h_i = z_i$. Rewriting the primes in the denominator as primes raised to negative powers, we find that the original two products $p_1^{e_1} \cdots p_k^{e_k}$ and $q_1^{f_1} \cdots q_m^{f_m}$ are the same.

Section 7.3

4. (a) Since Z_1 is an additive identity element, $Z_1 + Z_2 = Z_2$. And since Z_2 is an additive identity element, $Z_1 + Z_2 = Z_1$. Therefore $Z_1 = Z_1 + Z_2 = Z_2$.
- (b) Since X_1^3 is an additive inverse for X , $X_1^3 + X + X_2^3 = [0]_m + X_2^3 = X_2^3$. Similarly, since X_2^3 is an additive inverse for X , $X_1^3 + X + X_2^3 = X_1^3 + [0]_m = X_1^3$. Therefore $X_1^3 = X_2^3$.
- (c) Suppose O_1 and O_2 are multiplicative identity elements. Then $O_1 = O_1 \cdot O_2 = O_2$.
- (d) Suppose X_1^3 and X_2^3 are multiplicative inverses of X . Then $X_1^3 = X_1^3 \cdot [1]_m = X_1^3 \cdot X \cdot X_2^3 = [1]_m \cdot X_2^3 = X_2^3$.
8. Let a and b be arbitrary integers. Then

$$\begin{aligned} na \equiv nb \pmod{nm} & \quad \text{iff} \quad \exists k \in \mathbb{Z}(nb - na = knm) \\ & \quad \text{iff} \quad \exists k \in \mathbb{Z}(b - a = km) \quad \text{iff} \quad a \equiv b \pmod{m}. \end{aligned}$$

10. (a) $x \in [95]_{237}$.
 (b) $x \in [12]_{59}$.
13. Let a and b be arbitrary integers. Suppose first that $a \equiv b \pmod{m}$. Then $[a]_m = [b]_m$, so $[na]_m = [n]_m \cdot [a]_m = [n]_m \cdot [b]_m = [nb]_m$, and therefore $na \equiv nb \pmod{m}$.
- Now suppose that $na \equiv nb \pmod{m}$, so $[n]_m \cdot [a]_m = [na]_m = [nb]_m = [n]_m \cdot [b]_m$. Since m and n are relatively prime, $[n]_m$ has a multiplicative inverse. Multiplying both sides of the equation $[n]_m \cdot [a]_m = [n]_m \cdot [b]_m$ by $[n]_m^{-1}$, we get $[a]_m = [b]_m$, so $a \equiv b \pmod{m}$.
15. Hint: Prove that if $a \equiv b \pmod{m}$ then $D(m) \cap D(a) = D(m) \cap D(b)$.
17. (a) First note that $10 \equiv 1 \pmod{3}$, so $[10]_3 = [1]_3$. Therefore $[10^2]_3 = [10]_3 \cdot [10]_3 = [1]_3 \cdot [1]_3 = [1]_3$, $[10^3]_3 = [10^2]_3 \cdot [10]_3 = [1]_3 \cdot [1]_3 = [1]_3$, and, in general, for every $i \in \mathbb{N}$, $[10^i]_3 = [1]_3$. (A more careful proof could be done by induction.) Thus

$$\begin{aligned} [n]_3 &= [d_0 + 10d_1 + \cdots + 10^k d_k]_3 \\ &= [d_0]_3 + [10]_3 \cdot [d_1]_3 + \cdots + [10^k]_3 \cdot [d_k]_3 \\ &= [d_0]_3 + [1]_3 \cdot [d_1]_3 + \cdots + [1]_3 \cdot [d_k]_3 \\ &= [d_0 + d_1 + \cdots + d_k]_3. \end{aligned}$$

In other words, $n \equiv (d_0 + d_1 + \cdots + d_k) \pmod{3}$.

- (b) $3 \mid n$ iff $[n]_3 = [0]_3$ iff $[d_0 + \cdots + d_k]_3 = [0]_3$ iff $3 \mid (d_0 + \cdots + d_k)$.
19. (a) Suppose $n \geq 10$. First note that
- $$10f(n) = (d_k \cdots d_1 0)_{10} + 50d_0 = (d_k \cdots d_1 d_0)_{10} + 49d_0 = n + 49d_0.$$
- Therefore $3f(n) - n = 49d_0 - 7f(n) = 7(7d_0 - f(n))$, so $n \equiv 3f(n) \pmod{7}$, or equivalently $[n]_7 = [3]_7 \cdot [f(n)]_7$. Since $[3]_7^{-1} = [5]_7$, it follows that $[f(n)]_7 = [5]_7 \cdot [n]_7$, so $f(n) \equiv 5n \pmod{7}$.
- (b) Suppose $n \geq 10$. If $7 \mid n$ then $[n]_7 = [0]_7$, so $[f(n)]_7 = [5n]_7 = [5]_7 \cdot [0]_7 = [0]_7$, and therefore $7 \mid f(n)$. Similarly, if $7 \mid f(n)$ then $[f(n)]_7 = [0]_7$, so $[n]_7 = [3f(n)]_7 = [3]_7 \cdot [0]_7 = [0]_7$ and $7 \mid n$.
- (c) $f(627334) = 62733 + 5 \cdot 4 = 62753$; $f(62753) = 6275 + 5 \cdot 3 = 6290$; $f(6290) = 629 + 5 \cdot 0 = 629$; $f(629) = 62 + 5 \cdot 9 = 107$; $f(107) = 10 + 5 \cdot 7 = 45$; $f(45) = 4 + 5 \cdot 5 = 29$. Since $7 \nmid 29$, $7 \nmid 627334$.

Section 7.4

2. (a) $\varphi(539) = 420$.
 (b) $\varphi(540) = 144$.
 (c) $\varphi(541) = 540$.

6. Suppose $a \equiv b \pmod{mn}$. Then $mn \mid (b - a)$, so for some integer k , $b - a = kmn$. Therefore $m \mid (b - a)$ and $n \mid (b - a)$, so $a \equiv b \pmod{m}$ and $a \equiv b \pmod{n}$.

Now suppose $a \equiv b \pmod{m}$ and $a \equiv b \pmod{n}$. Since $a \equiv b \pmod{n}$, $n \mid (b - a)$, so there is some integer j such that $b - a = jn$. Since $a \equiv b \pmod{m}$, $m \mid (b - a)$, so $m \mid jn$. But $\gcd(m, n) = 1$, so by Theorem 7.2.2 it follows that $m \mid j$. Let k be an integer such that $j = km$. Then $b - a = jn = kmn$. Therefore $mn \mid (b - a)$, so $a \equiv b \pmod{mn}$.

8. The first half of the solution to exercise 6 does not use the hypothesis that m and n are relatively prime, so the left-to-right direction of the “iff” statement is correct even if this hypothesis is dropped. Here is a counterexample for the other direction: $a = 0$, $b = 12$, $m = 4$, $n = 6$.
10. Suppose p is prime and a is a positive integer. We consider two cases.

Case 1. $p \nmid a$. Then p and a are relatively prime, so by Theorem 7.4.2, $[a]_p^{p-1} = [1]_p$. Therefore $[a^p]_p = [a]_p^{p-1} \cdot [a]_p = [1]_p \cdot [a]_p = [a]_p$, so $a^p \equiv a \pmod{p}$.

Case 2. $p \mid a$. Then $[a]_p = [0]_p$, so $[a^p]_p = [0]_p^p = [0]_p = [a]_p$ and therefore $a^p \equiv a \pmod{p}$.

13. Hint: Use Lemma 7.4.6 and induction on k .
15. (a) We proceed by induction on k .

Base case: When $k = 1$, the statement to be proven is that for every positive integer m_1 and every integer a_1 , there is an integer r such that $1 \leq r \leq m_1$ and $r \equiv a_1 \pmod{m_1}$. This is true because $\{1, 2, \dots, m_1\}$ is a complete residue system modulo m_1 .

Induction step: Suppose that the statement holds for lists of k pairwise relatively prime positive integers, and let m_1, m_2, \dots, m_{k+1} be a list of $k + 1$ pairwise relatively prime positive integers. Let $M^3 = m_1 m_2 \cdots m_k$ and $M = m_1 m_2 \cdots m_{k+1} = M^3 m_{k+1}$. Let a_1, a_2, \dots, a_{k+1} be arbitrary integers. By the inductive hypothesis, there is an integer r^3 such that for all $i \in \{1, 2, \dots, k\}$, $r^3 \equiv a_i \pmod{m_i}$. By exercise 13, $\gcd(M^3, m_{k+1}) = 1$, so by Lemma 7.4.7 there is some integer r such that $1 \leq r \leq M$, $r \equiv r^3 \pmod{M^3}$, and $r \equiv a_{k+1} \pmod{m_{k+1}}$. By exercise 14, for every $i \in \{1, 2, \dots, k\}$, $r \equiv r^3 \pmod{m_i}$, and therefore $r \equiv a_i \pmod{m_i}$.

- (b) Suppose that $1 \leq r_1, r_2 \leq M$ and for all $i \in \{1, 2, \dots, k\}$, $r_1 \equiv a_i \pmod{m_i}$ and $r_2 \equiv a_i \pmod{m_i}$. Then for all $i \in \{1, 2, \dots, k\}$, $r_1 \equiv r_2 \pmod{m_i}$, so by exercise 14, $r_1 \equiv r_2 \pmod{M}$. Therefore $r_1 = r_2$.

17. Suppose m and n are relatively prime. Let the elements of $D(m)$ be a_1, a_2, \dots, a_s , and let the elements of $D(n)$ be b_1, b_2, \dots, b_t . Then $\sigma(m) =$

$a_1 + a_2 + \cdots + a_s$ and $\sigma(n) = b_1 + b_2 + \cdots + b_t$. Using the function f from part (b) of exercise 16, we see that the elements of $D(mn)$ are all products of the form $a_i b_j$, where $1 \leq i \leq s$ and $1 \leq j \leq t$. Thus we can arrange the elements of $D(mn)$ in a table with s rows and t columns, where the entry in row i , column j of the table is $a_i b_j$; every element of $D(mn)$ appears exactly once in this table. To compute $\sigma(mn)$, we must add up all entries in this table. We will do this by first adding up each row of the table, and then adding these row sums.

For $1 \leq i \leq s$, let r_i be the sum of row i of the table. Then

$$r_i = a_i b_1 + a_i b_2 + \cdots + a_i b_t = a_i (b_1 + b_2 + \cdots + b_t) = a_i \sigma(n).$$

Therefore

$$\begin{aligned} \sigma(mn) &= r_1 + r_2 + \cdots + r_s = a_1 \sigma(n) + a_2 \sigma(n) + \cdots + a_s \sigma(n) \\ &= (a_1 + a_2 + \cdots + a_s) \sigma(n) = \sigma(m) \sigma(n). \end{aligned}$$

Section 7.5

2. (a) $n = 5893$, $\varphi(n) = 5740$, $d = 2109$.
(b) $c = 3421$.
5. (a) $n = 17 \cdot 29$.
(b) $d = 257$.
(c) $m = 183$.
7. (a) $c = 72$.
(b) $d = 63$.
(c) 288.
- (d) $\varphi(n) = 144$, $d = 47, 18$.
9. We use strong induction. Suppose that a is a positive integer, and for every positive integer $k < a$, the computation of X^k uses at most $2 \log_2 k$ multiplications.

Case 1. $a = 1$. Then $X^a = X^1 = X$, so no multiplications are needed, and $2 \log_2 a = 2 \log_2 1 = 0$.

Case 2. a is even. Then $a = 2k$ for some positive integer $k < a$, and to compute X^a we use the formula $X^a = X^k \cdot X^k$. Let m be the number of multiplications used to compute X^k . By the inductive hypothesis, $m \leq 2 \log_2 k$. To compute X^a we use one additional multiplication (to multiply X^k by itself), so the number of multiplications is

$$m + 1 \leq 2 \log_2 k + 1 < 2(\log_2 k + 1) = 2 \log_2(2k) = 2 \log_2 a.$$

Case 3. $a > 1$ and a is odd. Then $a = 2k + 1$ for some positive integer $k < a$, and to compute X^a we use the formula $X^a = X^k \cdot X^k \cdot X$. As

in case 2, if we let m be the number of multiplications used to compute X^k then we have $m \leq 2 \log_2 k$. To compute X^a we use two additional multiplications, so the number of multiplications is

$$m + 2 \leq 2 \log_2 k + 2 = 2(\log_2 k + 1) = 2 \log_2(2k) < 2 \log_2(2k + 1) = 2 \log_2 a.$$

12. Since $a \in R_2$, $[a]_n^{n-1} \equiv [1]_n$. And since $\gcd(n, a) = 1$, $[a]_n$ has a multiplicative inverse.
- (a) Suppose $x \in R_1$. Then $2 \leq x \leq n - 1$ and $[x]_n^{n-1} = [1]_n$. Since $\{0, 1, \dots, n - 1\}$ is a complete residue system modulo n , there is a unique y such that $0 \leq y \leq n - 1$ and $ax \equiv y \pmod{n}$, so $[a]_n \cdot [x]_n = [y]_n$. We must prove that $y \in R_2$. If $y = 0$ then $[x]_n = [a]_n^{-1} \cdot [y]_n = [a]_n^{-1} \cdot [0]_n = [0]_n$, which contradicts the fact that $2 \leq x \leq n - 1$. Therefore $1 \leq y \leq n - 1$. And $[y]_n^{n-1} = [a]_n^{n-1} \cdot [x]_n^{n-1} = [a]_n^{n-1} \cdot [1]_n = [a]_n^{n-1} \equiv [1]_n$. Therefore $y^{n-1} \equiv 1 \pmod{n}$. It follows that $y \equiv 1$, so $2 \leq y \leq n - 1$.
- (b) Suppose $f(x_1) = f(x_2) = y$. Then $[a]_n \cdot [x_1]_n = [y]_n = [a]_n \cdot [x_2]_n$, so $[x_1]_n = [a]_n^{-1} \cdot [y]_n = [x_2]_n$, and therefore $x_1 = x_2$.
- (c) By part (b), R_1 has the same number of elements as $\text{Ran}(f)$. Since $\text{Ran}(f) \subseteq R_2$, R_2 has at least as many elements as R_1 . So at least half the elements of R are in R_2 .

Chapter 8

Section 8.1

1. (a) Define $f : \mathbb{Z}^+ \rightarrow \mathbb{N}$ by the formula $f(n) = n - 1$. It is easy to check that f is one-to-one and onto.
- (b) Let $E = \{n \in \mathbb{Z} \mid n \text{ is even}\}$, and define $f : \mathbb{Z} \rightarrow E$ by the formula $f(n) = 2n$. It is easy to check that f is one-to-one and onto, so $\mathbb{Z} \sim E$. But we already know that $\mathbb{Z}^+ \sim \mathbb{Z}$, so by Theorem 8.1.3, $\mathbb{Z}^+ \sim E$, and therefore E is denumerable.
4. (a) No. Counterexample: Let $A = B = C = \mathbb{Z}^+$ and $D = \{1\}$.
- (b) No. Counterexample: Let $A = B = \mathbb{N}$, $C = \mathbb{Z}^-$, and $D = \emptyset$.
6. (a) We prove that $\forall n \in \mathbb{N} \forall m \in \mathbb{N} (I_n \sim I_m \rightarrow n = m)$ by induction on n .

Base case: $n = 0$. Suppose that $m \in \mathbb{N}$ and there is a one-to-one, onto function $f : I_n \rightarrow I_m$. Since $n = 0$, $I_n = \emptyset$. But then since f is onto, we must also have $I_m = \emptyset$, so $m = 0 = n$.

Induction step: Suppose that $n \in \mathbb{N}$, and for all $m \in \mathbb{N}$, if $I_n \sim I_m$ then $n = m$. Now suppose that $m \in \mathbb{N}$ and $I_{n+1} \sim I_m$. Let $f : I_{n+1} \rightarrow I_m$ be a one-to-one, onto function. Let $k = f(n+1)$, and notice that $1 \leq k \leq m$, so m is positive. Using the fact that f is onto, choose some $j \leq n+1$ such that $f(j) = m$.

We now define $g : I_n \rightarrow I_{m-1}$ as follows:

$$g(i) = \begin{cases} f(i), & \text{if } i \neq j, \\ k, & \text{if } i = j. \end{cases}$$

We leave it to the reader to verify that g is one-to-one and onto. By the inductive hypothesis, it follows that $n = m - 1$, so $n + 1 = m$.

(b) Suppose A is finite. Then by the definition of “finite,” we know that there is at least one $n \in \mathbb{N}$ such that $I_n \sim A$. To see that it is unique, suppose that n and m are natural numbers, $I_n \sim A$, and $I_m \sim A$. Then by Theorem 8.1.3, $I_n \sim I_m$, so by part (a), $n = m$.

8. (a) We use induction on n .

Base case: $n = 0$. Suppose $A \subseteq I_n = \emptyset$. Then $A = \emptyset$, so $|A| = 0$.

Induction step: Suppose that $n \in \mathbb{N}$, and for all $A \subseteq I_n$, A is finite, $|A| \leq n$, and if $A \cong I_n$ then $|A| < n$. Now suppose that $A \subseteq I_{n+1}$. If $A = I_{n+1}$ then clearly $A \sim I_{n+1}$, so A is finite and $|A| = n + 1$. Now suppose that $A \cong I_{n+1}$. If $n + 1 \notin A$, then $A \subseteq I_n$, so by the inductive hypothesis, A is finite and $|A| \leq n$. If $n + 1 \in A$, then there must be some $k \in I_n$ such that $k \notin A$. Let $A^3 = (A \cup \{k\}) \setminus \{n + 1\}$. Then by matching up k with $n + 1$ it is not hard to show that $A^3 \sim A$. Also, $A^3 \subseteq I_n$, so by the inductive hypothesis, A^3 is finite and $|A^3| \leq n$. Therefore by exercise 7, A is finite and $|A| \leq n$.

(b) Suppose A is finite and $B \subseteq A$. Let $n = |A|$, and let $f : A \rightarrow I_n$ be one-to-one and onto. Then $f(B) \subseteq I_n$, so by part (a), $f(B)$ is finite, $|f(B)| \leq n$, and if $B \cong A$ then $f(B) \cong I_n$, so $|f(B)| < n$. Since $B \sim f(B)$, the desired conclusion follows.

10. Hint: Define $g : B \rightarrow I_n$ by the formula

$$g(x) = \text{the smallest } i \in I_n \text{ such that } f(i) = x,$$

and show that g is one-to-one.

12. Notice first that either $i + j - 2$ or $i + j - 1$ is even, so $f(i, j)$ is a positive integer, and therefore f is a function from $\mathbb{Z}^+ \times \mathbb{Z}^+$ to \mathbb{Z}^+ , as claimed. It will be helpful to verify two facts about the function f . Both of the facts below can be checked by straightforward algebra:

(a) For all $j \in \mathbb{Z}^+$, $f(1, j + 1) - f(1, j) = j$.

(b) For all $i \in \mathbb{Z}^+$ and $j \in \mathbb{Z}^+$, $f(1, i+j-1) \leq f(i, j) < f(1, i+j)$. It follows that $i+j$ is the smallest $k \in \mathbb{Z}^+$ such that $f(i, j) < f(1, k)$.

To see that f is one-to-one, suppose that $f(i_1, j_1) = f(i_2, j_2)$. Then by fact (b) above,

$$\begin{aligned} i_1 + j_1 &= \text{the smallest } k \in \mathbb{Z}^+ \text{ such that } f(i_1, j_1) < f(1, k) \\ &= \text{the smallest } k \in \mathbb{Z}^+ \text{ such that } f(i_2, j_2) < f(1, k) \\ &= i_2 + j_2. \end{aligned}$$

Using the definition of f , it follows that

$$\begin{aligned} i_1 &= f(i_1, j_1) - \frac{(i_1 + j_1 - 2)(i_1 + j_1 - 1)}{2} \\ &= f(i_2, j_2) - \frac{(i_2 + j_2 - 2)(i_2 + j_2 - 1)}{2} \\ &= i_2. \end{aligned}$$

But then since $i_1 = i_2$ and $i_1 + j_1 = i_2 + j_2$, we must also have $j_1 = j_2$, so $(i_1, j_1) = (i_2, j_2)$. This shows that f is one-to-one.

To see that f is onto, suppose $n \in \mathbb{Z}^+$. It is easy to verify that $f(1, n+1) > n$, so we can let k be the smallest positive integer such that $f(1, k) > n$. Notice that $f(1, 1) = 1 \leq n$, so $k \geq 2$. Since k is smallest, $f(1, k-1) \leq n$, and therefore by fact (a),

$$0 \leq n - f(1, k-1) < f(1, k) - f(1, k-1) = k-1.$$

Adding 1 to all terms, we get

$$1 \leq n - f(1, k-1) + 1 < k.$$

Thus, if we let $i = n - f(1, k-1) + 1$ then $1 \leq i < k$. Let $j = k - i$, and notice that $i \in \mathbb{Z}^+$ and $j \in \mathbb{Z}^+$. With this choice for i and j we have

$$\begin{aligned} f(i, j) &= \frac{(i+j-2)(i+j-1)}{2} + i \\ &= \frac{(k-2)(k-1)}{2} + n - f(1, k-1) + 1 \\ &= \frac{(k-2)(k-1)}{2} + n - \left[\frac{(k-2)(k-1)}{2} + 1 \right] + 1 = n. \end{aligned}$$

15. (a) If $B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < n\} = \emptyset$ then $B \subseteq \{f(m) \mid m \in \mathbb{Z}^+, m < n\}$, so by exercises 8 and 10, B is finite. But we assumed that B was infinite, so this is impossible.

- (b) We use strong induction. Suppose that $\forall m < n, f(m) \geq m$. Now suppose that $f(n) < n$. Let $m = f(n)$. Then by the inductive hypothesis, $f(m) \geq m$. Also, by the definition of $f(n), m = f(n) \in B \setminus \{f(k) \mid k \in \mathbb{Z}^+, k < n\} \subseteq B \setminus \{f(k) \mid k \in \mathbb{Z}^+, k < m\}$. But since $f(m)$ is the *smallest* element of this last set, it follows that $f(m) \leq m$. Since we have $f(m) \geq m$ and $f(m) \leq m$, we can conclude that $f(m) = m$. But then $m \notin B \setminus \{f(k) \mid k \in \mathbb{Z}^+, k < n\}$, so we have a contradiction.
- (c) Suppose that $i \in \mathbb{Z}^+, j \in \mathbb{Z}^+$, and $i \not\equiv j$. Then either $i < j$ or $j < i$. Suppose first that $i < j$. Then according to the definition of $f(j), f(j) \in B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < j\}$, and clearly $f(i) \in \{f(m) \mid m \in \mathbb{Z}^+, m < j\}$. It follows that $f(i) \equiv f(j)$. A similar argument shows that if $j < i$ then $f(i) \equiv f(j)$. This shows that f is one-to-one.

To see that f is onto, suppose that $n \in B$. By part (b), $f(n+1) \geq n+1 > n$. But according to the definition of $f, f(n+1)$ is the smallest element of $B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < n+1\}$. It follows that $n \notin B \setminus \{f(m) \mid m \in \mathbb{Z}^+, m < n+1\}$. But $n \in B$, so it must be the case that also $n \in \{f(m) \mid m \in \mathbb{Z}^+, m < n+1\}$. In other words, for some positive integer $m < n+1, f(m) = n$.

17. Suppose $B \subseteq A$ and A is countable. Then by Theorem 8.1.5, there is a one-to-one function $f : A \rightarrow \mathbb{Z}^+$. By exercise 13 of Section 5.2, $f \upharpoonright B$ is a one-to-one function from B to \mathbb{Z}^+ , so B is countable. (See exercise 7 of Section 5.1 for the definition of the notation used here.)
19. Following the hint, we recursively define partial orders R_n , for $n \in \mathbb{N}$, so that $R = R_0 \subseteq R_1 \subseteq R_2 \subseteq \cdots$ and

$$\forall i \in I_n \forall j \in \mathbb{Z}^+ ((a_i, a_j) \in R_n \vee (a_j, a_i) \in R_n). \quad (*)$$

Let $R_0 = R$. Given R_n , to define R_{n+1} we apply exercise 2 of Section 6.2, with $B = \{a_i \mid i \in I_{n+1}\}$. Finally, let $T = \bigcup_{n \in \mathbb{N}} R_n$. Clearly T is reflexive, because every R_n is. To see that T is transitive, suppose that $(a, b) \in T$ and $(b, c) \in T$. Then for some natural numbers m and n , $(a, b) \in R_m$ and $(b, c) \in R_n$. If $m \leq n$ then $R_m \subseteq R_n$, and therefore $(a, b) \in R_n$ and $(b, c) \in R_n$. Since R_n is transitive, it follows that $(a, c) \in R_n \subseteq T$. A similar argument shows that if $n < m$ then $(a, c) \in T$, so T is transitive. The proof that T is antisymmetric is similar. Finally, to see that T is a total order, suppose $x \in A$ and $y \in A$. Since we have numbered the elements of A , we know that for some positive integers m and $n, x = a_m$ and $y = a_n$. But then by (*) we know that either (a_m, a_n) or (a_n, a_m) is an element of R_n , and therefore also an element of T .

22. (a) We follow the hint.

Base case: $n = 0$. Suppose A and B are finite sets and $|B| = 0$. Then $B = \emptyset$, so $A \times B = \emptyset$ and $|A \times B| = 0 = |A| \cdot 0$.

Induction step: Let n be an arbitrary natural number, and suppose that for all finite sets A and B , if $|B| = n$ then $A \times B$ is finite and $|A \times B| = |A| \cdot n$. Now suppose A and B are finite sets and $|B| = n + 1$. Choose an element $b \in B$, and let $B^3 = B \setminus \{b\}$, a set with n elements. Then $A \times B = A \times (B^3 \cup \{b\}) = (A \times B^3) \cup (A \times \{b\})$, and since $b \notin B^3$, $A \times B^3$ and $A \times \{b\}$ are disjoint. By the inductive hypothesis, $A \times B^3$ is finite and $|A \times B^3| = |A| \cdot n$. Also, it is not hard to see that $A \sim A \times \{b\}$ – just match up each $x \in A$ with $(x, b) \in A \times \{b\}$ – so $A \times \{b\}$ is finite and $|A \times \{b\}| = |A|$. By Theorem 8.1.7, it follows that $A \times B$ is finite and $|A \times B| = |A \times B^3| + |A \times \{b\}| = |A| \cdot n + |A| = |A| \cdot (n + 1)$.

(b) To order a meal, you name an element of $A \times B$, where $A = \{\text{steak, chicken, pork chops, shrimp, spaghetti}\}$ and $B = \{\text{ice cream, cake, pie}\}$. So the number of meals is $|A \times B| = |A| \cdot |B| = 5 \cdot 3 = 15$.

24. (a) Base case: $n = 0$. If $|A| = 0$ then $A = \emptyset$, so $F = \{\emptyset\}$, and $|F| = 1 = 0!$.

Induction step: Suppose n is a natural number, and the desired conclusion holds for n . Now let A be a set with $n + 1$ elements, and let $F = \{f \mid f \text{ is a one-to-one, onto function from } I_{n+1} \text{ to } A\}$. Let $g : I_{n+1} \rightarrow A$ be a one-to-one, onto function. For each $i \in I_{n+1}$, let $A_i = A \setminus \{g(i)\}$, a set with n elements, and let $F_i = \{f \mid f \text{ is a one-to-one, onto function from } I_n \text{ to } A_i\}$. By the inductive hypothesis, F_i is finite and $|F_i| = n!$. Now let $F_i^3 = \{f \in F \mid f(n+1) = g(i)\}$. Define a function $h : F_i \rightarrow F_i^3$ by the formula $h(f) = f \cup \{(n+1, g(i))\}$. It is not hard to check that h is one-to-one and onto, so F_i^3 is finite and $|F_i^3| = |F_i| = n!$. Finally, notice that $F = \bigcup_{i \in I_{n+1}} F_i^3$ and $\forall i \in I_{n+1} \forall j \in I_{n+1} (i \neq j \rightarrow F_i^3 \cap F_j^3 = \emptyset)$. It follows, by exercise 21, that F is finite and $|F| = \sum_{i=1}^{n+1} |F_i^3| = (n+1) \cdot n! = (n+1)!$.

(b) Hint: Define $h : F \rightarrow L$ by the formula $h(f) = \{(a, b) \in A \times A \mid f^{-1}(a) \leq f^{-1}(b)\}$. (You should check that this set is a total order on A .) To see that h is one-to-one, suppose that $f \in F$, $g \in F$, and $f \neq g$. Let i be the smallest element of I_n for which $f(i) \neq g(i)$. Now show that $(f(i), g(i)) \in h(f)$ but $(f(i), g(i)) \notin h(g)$, so $h(f) \neq h(g)$. To see that h is onto, suppose R is a total order on A . Define $g : A \rightarrow I_n$ by the formula $g(a) = |\{x \in A \mid xRa\}|$. Show that $\forall a \in A \forall b \in A (aRb \leftrightarrow g(a) \leq g(b))$, and use this fact to show that $g^{-1} \in F$ and $h(g^{-1}) = R$.

(c) $5! = 120$.

27. Base case: $n = 1$. Then $I_n = \{1\}$, $P = \{\{1\}\}$, and $A_{\{1\}} = A_1$. Therefore $|\bigcup_{i \in I_n} A_i| = |A_1|$ and $\sum_{S \in P} (-1)^{|S|+1} |A_S| = (-1)^2 |A_{\{1\}}| = |A_1|$.

Induction step: Suppose the inclusion-exclusion principle holds for n sets, and suppose A_1, A_2, \dots, A_{n+1} are finite sets. Let $P_n = \mathcal{P}(I_n) \setminus \{\emptyset\}$ and $P_{n+1} = \mathcal{P}(I_{n+1}) \setminus \{\emptyset\}$. By exercise 26(a), exercise 23(a) of Section 3.4, and the inductive hypothesis,

$$\begin{aligned} \left| \bigcup_{i \in I_{n+1}} A_i \right| &= \left| \left(\bigcup_{i \in I_n} A_i \right) \cup A_{n+1} \right| \\ &= \left| \bigcup_{i \in I_n} A_i \right| + |A_{n+1}| - \left| \left(\bigcup_{i \in I_n} A_i \right) \cap A_{n+1} \right| \\ &= \sum_{S \in P_n} (-1)^{|S|+1} |A_S| + |A_{n+1}| - \left| \bigcup_{i \in I_n} (A_i \cap A_{n+1}) \right|. \end{aligned}$$

Now notice that for every $S \in P_n$,

$$\bigcap_{i \in S} (A_i \cap A_{n+1}) = \left(\bigcap_{i \in S} A_i \right) \cap A_{n+1} = A_{S \cup \{n+1\}}.$$

Therefore, by another application of the inductive hypothesis,

$$\left| \bigcup_{i \in I_n} (A_i \cap A_{n+1}) \right| = \sum_{S \in P_n} (-1)^{|S|+1} |A_{S \cup \{n+1\}}|.$$

Thus

$$\begin{aligned} \left| \bigcup_{i \in I_{n+1}} A_i \right| &= \sum_{S \in P_n} (-1)^{|S|+1} |A_S| + |A_{n+1}| - \sum_{S \in P_n} (-1)^{|S|+1} |A_{S \cup \{n+1\}}| \\ &= \sum_{S \in P_n} (-1)^{|S|+1} |A_S| + (-1)^2 |A_{\{n+1\}}| \\ &\quad + \sum_{S \in P_n} (-1)^{|S \cup \{n+1\}|+1} |A_{S \cup \{n+1\}}|. \end{aligned}$$

Finally, notice that there are three kinds of elements of P_{n+1} : those that are elements of P_n , the set $\{n+1\}$, and sets of the form $S \cup \{n+1\}$, where $S \in P_n$. It follows that the last formula above is just $\sum_{S \in P_{n+1}} (-1)^{|S|+1} |A_S|$, as required.

Section 8.2

- (a) By Theorem 8.1.6, \mathbb{Q} is countable. If $\mathbb{R} \setminus \mathbb{Q}$ were countable then, by Theorem 8.2.1, $\mathbb{Q} \cup (\mathbb{R} \setminus \mathbb{Q}) = \mathbb{R}$ would be countable, contradicting Theorem 8.2.6. Thus, $\mathbb{R} \setminus \mathbb{Q}$ must be uncountable.

- (b) Let $A = \{ \sqrt[3]{2} + \frac{1}{n} \mid n \in \mathbb{Z}^+ \}$. It is not hard to see that A and \mathbb{Q} are disjoint, since $\sqrt[3]{2}$ is irrational, and A is denumerable. Now apply Theorems 8.1.6 and 8.2.1 to conclude that $A \cup \mathbb{Q}$ is denumerable, and therefore $A \cup \mathbb{Q} \sim A$. Finally, observe that $\mathbb{R} = (\mathbb{R} \setminus (A \cup \mathbb{Q})) \cup (A \cup \mathbb{Q})$ and $\mathbb{R} \setminus \mathbb{Q} = (\mathbb{R} \setminus (A \cup \mathbb{Q})) \cup A$, and apply part 2 of Theorem 8.1.2.
5. Suppose that $A \sim \mathcal{P}(A)$. Then there is a function $f : A \rightarrow \mathcal{P}(A)$ that is one-to-one and onto. Let $X = \{a \in A \mid a \notin f(a)\} \in \mathcal{P}(A)$. Since f is onto, there must be some $a \in A$ such that $f(a) = X$. But then according to the definition of X , $a \in X$ iff $a \notin f(a)$, so $X \neq f(a)$, which is a contradiction.
8. Hint: Define $f : \mathcal{P}(A) \times \mathcal{P}(B) \rightarrow \mathcal{P}(A \cup B)$ by the formula $f(X, Y) = X \cup Y$, and prove that f is one-to-one and onto.
10. For each positive integer n , let $A_n = \{x \in A \mid x \geq 1/n\}$. Clearly $\bigcup_{n \in \mathbb{Z}^+} A_n \subseteq A$. Now suppose $x \in A$. Then $x \in \mathbb{R}^+$, so $x > 0$. Let n be a positive integer large enough that $n \geq 1/x$. Then $x \geq 1/n$, so $x \in A_n$. We conclude that $A \subseteq \bigcup_{n \in \mathbb{Z}^+} A_n$, and therefore $\bigcup_{n \in \mathbb{Z}^+} A_n = A$.
Suppose a_1, a_2, \dots, a_k are distinct elements of A_n . Then
- $$b \geq a_1 + a_2 + \dots + a_k \geq \frac{1}{n} + \frac{1}{n} + \dots + \frac{1}{n} = \frac{k}{n},$$
- so $k \leq bn$. Therefore A_n is finite, and in fact $|A_n| \leq bn$. By Theorem 8.2.2, it follows that $A = \bigcup_{n \in \mathbb{Z}^+} A_n$ is countable.
13. Hint: First note that if $\mathcal{F} = \emptyset$ then g can be any function. If $\mathcal{F} \neq \emptyset$, then since \mathcal{F} is countable, we can write its elements in a list: $\mathcal{F} = \{f_1, f_2, \dots\}$. Now define $g : \mathbb{Z}^+ \rightarrow \mathbb{R}$ by the formula $g(n) = \max\{|f_1(n)|, |f_2(n)|, \dots, |f_n(n)|\}$.
15. (a) If Q is countable, then by part 2 of Theorem 8.2.1, $P \cup Q$ is countable. But $P \cup Q = \mathcal{P}(\mathbb{Z}^+)$, which is uncountable by Cantor's theorem. Therefore Q is uncountable.
- (b) Suppose $A \in Q$. For every $n \in \mathbb{Z}^+$, $A \cap I_n \subseteq I_n$, so by exercise 8(a) in Section 8.1, $A \cap I_n$ is finite. Therefore $S_A \subseteq P$. Now suppose S_A is finite. Then there is some positive integer n such that $S_A = \{A \cap I_1, A \cap I_2, \dots, A \cap I_n\}$. We claim now that $A \subseteq I_n$; this will complete the proof, because it implies that A is finite, contradicting our assumption that $A \in Q$. To prove this claim, suppose that $m \in A$. Then $A \cap I_m \in S_A$, so there is some $k \leq n$ such that $A \cap I_m = A \cap I_k \subseteq I_k \subseteq I_n$. But $m \in A \cap I_m$, so we conclude that $m \in I_n$, as required.
- (c) Suppose $A \in Q$, $B \in Q$, and $A \neq B$. Then there is some positive integer n such that either $n \in A$ and $n \notin B$ or $n \in B$ and $n \notin A$. We will assume $n \in A$ and $n \notin B$; the proof for the other case is similar.

We claim now that $S_A \cap S_B \subseteq \{A \cap I_1, A \cap I_2, \dots, A \cap I_{n-1}\}$; this will complete the proof, because it implies that $S_A \cap S_B$ is finite. To prove the claim, suppose that $X \in S_A \cap S_B$. Then there are positive integers n_A and n_B such that $X = A \cap I_{n_A}$ and $X = B \cap I_{n_B}$. If $n_A \geq n$ then

$$n \in A \cap I_{n_A} = X = B \cap I_{n_B} \subseteq B,$$

which is a contradiction. Therefore $n_A < n$, so $X = A \cap I_{n_A} \in \{A \cap I_1, \dots, A \cap I_{n-1}\}$, as required.

- (d) If $A \in Q$ then $S_A \subseteq P$, so since $g : P \rightarrow \mathbb{Z}^+$, $g(S_A) \subseteq \mathbb{Z}^+$. Also, since S_A is infinite and g is one-to-one, $g(S_A)$ is also infinite. This proves that $\mathcal{F} \subseteq \mathcal{P}(\mathbb{Z}^+)$ and every element of \mathcal{F} is infinite. To see that \mathcal{F} is pairwise almost disjoint, suppose $X, Y \in \mathcal{F}$ and $X \# Y$. Then there are sets $A, B \in Q$ such that $X = g(S_A)$ and $Y = g(S_B)$. Since $X \# Y$, $A \# B$, so by part (c), $S_A \cap S_B$ is finite, and therefore $g(S_A \cap S_B)$ is finite. By Theorem 5.5.2, $g(S_A \cap S_B) = g(S_A) \cap g(S_B) = X \cap Y$, so X and Y are almost disjoint. Finally, define $h : Q \rightarrow \mathcal{F}$ by the formula $h(A) = g(S_A)$. It is easy to check that h is one-to-one and onto, so $\mathcal{F} \sim Q$ and therefore, by part (a), \mathcal{F} is uncountable.

Section 8.3

1. (a) The function $i_A : A \rightarrow A$ is one-to-one.
- (b) Suppose $A \lesssim B$ and $B \lesssim C$. Then there are one-to-one functions $f : A \rightarrow B$ and $g : B \rightarrow C$. By part 1 of Theorem 5.2.5, $g \circ f : A \rightarrow C$ is one-to-one, so $A \lesssim C$.
5. Let $g : A \rightarrow B$ and $h : C \rightarrow D$ be one-to-one functions.
 - (a) Since $A \# \emptyset$, we can choose some $a_0 \in A$. Notice that $g^{-1} : \text{Ran}(g) \rightarrow A$. Define $j : B \rightarrow A$ as follows:

$$j(b) = \begin{cases} g^{-1}(b), & \text{if } b \in \text{Ran}(g), \\ a_0, & \text{otherwise.} \end{cases}$$

We let you verify that j is onto.

Now define $F : {}^A C \rightarrow {}^B D$ by the formula $F(f) = h \circ f \circ j$. To see that F is one-to-one, suppose that $f_1 \in {}^A C$, $f_2 \in {}^A C$, and $F(f_1) = F(f_2)$, which means $h \circ f_1 \circ j = h \circ f_2 \circ j$. Let $a \in A$ be arbitrary. Since j is onto, there is some $b \in B$ such that $j(b) = a$. Therefore $h(f_1(a)) = (h \circ f_1 \circ j)(b) = (h \circ f_2 \circ j)(b) = h(f_2(a))$, and since h is one-to-one, it follows that $f_1(a) = f_2(a)$. Since a was arbitrary, this shows that $f_1 = f_2$.

- (b) Yes. (You should be able to justify this answer with a counterexample.)

8. (a) Let n be arbitrary, and then proceed by induction on m . The base case is $m = n + 1$, and it is taken care of by exercise 7. For the induction step, apply exercise 2(b).
- (b) $\bigcup_{n \in \mathbb{Z}^+} A_n$ is an infinite set that is not equinumerous with A_n for any $n \in \mathbb{Z}^+$. In fact, for every positive integer n , $A_n < \bigcup_{n \in \mathbb{Z}^+} A_n$. Can you find even larger infinite sets?
10. (a) Note that $\mathcal{E} \subseteq \mathcal{P}(\mathbb{Z}^+ \times \mathbb{Z}^+)$. It follows, using exercise 5 of Section 8.1, that $\mathcal{E} \lesssim \mathcal{P}(\mathbb{Z}^+ \times \mathbb{Z}^+) \sim \mathcal{P}(\mathbb{Z}^+)$.
- (b) Suppose $f(X) = f(Y)$. Then $X \cup \{1\} \in f(X) = f(Y) = \{Y \cup \{1\}, (A \setminus Y) \cup \{2\}\}$, so either $X \cup \{1\} = Y \cup \{1\}$ or $X \cup \{1\} = (A \setminus Y) \cup \{2\}$. But clearly $2 \notin X \cup \{1\}$, so the second possibility can be ruled out. Therefore $X \cup \{1\} = Y \cup \{1\}$. Since neither X nor Y contains 1, it follows that $X = Y$.
- (c) Clearly A is denumerable, and we showed at the end of Section 5.3 that $\mathcal{P} \sim \mathcal{E}$. It follows that $\mathcal{P}(\mathbb{Z}^+) \sim \mathcal{P}(A) \lesssim \mathcal{P} \sim \mathcal{E}$. Combining this with part (a) and applying the Cantor-Schröder-Bernstein theorem gives the desired conclusion.
14. (a) According to the definition of function, ${}^{\mathbb{R}}\mathbb{R} \subseteq \mathcal{P}(\mathbb{R} \times \mathbb{R})$, and therefore by exercise 12(b) and exercise 5 of Section 8.1, ${}^{\mathbb{R}}\mathbb{R} \lesssim \mathcal{P}(\mathbb{R} \times \mathbb{R}) \sim \mathcal{P}(\mathbb{R})$.
- Clearly $\{\text{yes, no}\} \lesssim \mathbb{R}$, so by exercise 6(c) of Section 8.2 and exercise 5, $\mathcal{P}(\mathbb{R}) \sim {}^{\mathbb{R}}\{\text{yes, no}\} \lesssim {}^{\mathbb{R}}\mathbb{R}$. Since we have both ${}^{\mathbb{R}}\mathbb{R} \lesssim \mathcal{P}(\mathbb{R})$ and $\mathcal{P}(\mathbb{R}) \lesssim {}^{\mathbb{R}}\mathbb{R}$, by the Cantor-Schröder-Bernstein theorem, ${}^{\mathbb{R}}\mathbb{R} \sim \mathcal{P}(\mathbb{R})$.
- (b) By Theorems 8.1.6 and 8.3.3, exercise 23(a) of Section 8.1, and exercise 6(d) of Section 8.2, ${}^{\mathbb{Q}}\mathbb{R} \sim {}^{\mathbb{Z}^+}\mathcal{P}(\mathbb{Z}^+) \sim \mathcal{P}(\mathbb{Z}^+) \sim \mathbb{R}$.
- (c) Define $F : \mathcal{C} \rightarrow {}^{\mathbb{Q}}\mathbb{R}$ by the formula $F(f) = f \upharpoonright \mathbb{Q}$. (See exercise 7 of Section 5.1 for the meaning of the notation used here.) Suppose $f \in \mathcal{C}$, $g \in \mathcal{C}$, and $F(f) = F(g)$. Then $f \upharpoonright \mathbb{Q} = g \upharpoonright \mathbb{Q}$, which means that for all $x \in \mathbb{Q}$, $f(x) = g(x)$. Now let x be an arbitrary real number. Use Lemma 8.3.4 to construct a sequence x_1, x_2, \dots of rational numbers such that $\lim_{n \rightarrow \infty} x_n = x$. Then since f and g are continuous, $f(x) = \lim_{n \rightarrow \infty} f(x_n) = \lim_{n \rightarrow \infty} g(x_n) = g(x)$. Since x was arbitrary, this shows that $f = g$. Therefore F is one-to-one, so $\mathcal{C} \lesssim {}^{\mathbb{Q}}\mathbb{R}$. Combining this with part (b), we can conclude that $\mathcal{C} \lesssim \mathbb{R}$.

Now define $G : \mathbb{R} \rightarrow \mathcal{C}$ by the formula $G(x) = \mathbb{R} \times \{x\}$. In other words, $G(x)$ is the constant function whose value at every real number is x . Clearly G is one-to-one, so $\mathbb{R} \lesssim \mathcal{C}$. By the Cantor-Schröder-Bernstein theorem, it follows that $\mathcal{C} \sim \mathbb{R}$.

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Summary of Proof Techniques

To prove a goal of the form:

1. $\neg P$:
 - (a) Reexpress as a positive statement.
 - (b) Use proof by contradiction; that is, assume that P is true and try to reach a contradiction.
2. $P \rightarrow Q$:
 - (a) Assume P is true and prove Q .
 - (b) Prove the contrapositive; that is, assume that Q is false and prove that P is false.
3. $P \wedge Q$:

Prove P and Q separately. In other words, treat this as two separate goals: P , and Q .
4. $P \vee Q$:
 - (a) Assume P is false and prove Q , or assume Q is false and prove P .
 - (b) Use proof by cases. In each case, either prove P or prove Q .
5. $P \leftrightarrow Q$:

Prove $P \rightarrow Q$ and $Q \rightarrow P$, using the methods listed under part 2.
6. $\forall x P(x)$:

Let x stand for an arbitrary object, and prove $P(x)$. (If the letter x already stands for something in the proof, you will have to use a different letter for the arbitrary object.)
7. $\exists x P(x)$:

Find a value of x that makes $P(x)$ true. Prove $P(x)$ for this value of x .
8. $\exists! x P(x)$:
 - (a) Prove $\exists x P(x)$ (existence) and $\forall y \forall z ((P(y) \wedge P(z)) \rightarrow y = z)$ (uniqueness).
 - (b) Prove the equivalent statement $\exists x (P(x) \wedge \forall y (P(y) \rightarrow y = x))$.

9. $\forall n \in \mathbb{N} P(n)$:
- (a) Mathematical induction: Prove $P(0)$ (base case) and $\forall n \in \mathbb{N}(P(n) \rightarrow P(n+1))$ (induction step).
 - (b) Strong induction: Prove $\forall n \in \mathbb{N}[(\forall k < n P(k)) \rightarrow P(n)]$.

To use a given of the form:

1. $\neg P$:
 - (a) Reexpress as a positive statement.
 - (b) In a proof by contradiction, you can reach a contradiction by proving P .
2. $P \rightarrow Q$:
 - (a) If you are also given P , or you can prove that P is true, then you can conclude that Q is true.
 - (b) Use the contrapositive: If you are given or can prove that Q is false, then you can conclude that P is false.
3. $P \wedge Q$:
Treat this as two givens: P , and Q .
4. $P \vee Q$:
 - (a) Use proof by cases. In case 1 assume that P is true, and in case 2 assume that Q is true.
 - (b) If you are also given that P is false, or you can prove that P is false, then you can conclude that Q is true. Similarly, if you know that Q is false then you can conclude that P is true.
5. $P \leftrightarrow Q$:
Treat this as two givens: $P \rightarrow Q$, and $Q \rightarrow P$.
6. $\forall x P(x)$:
You can plug in any value, say a , for x , and conclude that $P(a)$ is true.
7. $\exists x P(x)$:
Introduce a new variable, say x_0 , into the proof, to stand for a particular object for which $P(x_0)$ is true.
8. $\exists! x P(x)$:
Introduce a new variable, say x_0 , into the proof, to stand for a particular object for which $P(x_0)$ is true. You may also assume that $\forall y(P(y) \rightarrow y = x_0)$.

Techniques that can be used in any proof:

1. Proof by contradiction: Assume the goal is false and derive a contradiction.
2. Proof by cases: Consider several cases that are *exhaustive*, that is, that include all the possibilities. Prove the goal in each case.

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