

The Limits of Logic

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Preface

There is nothing careless in the attitude of the exemplary person toward what is said.

Confucius (551?–479? BCE), *Analects*

The Big Picture

Between roughly 1870 and 1940 a group of people studying philosophy and mathematics—as well as fields that hadn’t yet emerged as disciplines with their own names and course catalogues, like linguistics and computer science—made some of the most important and beautiful discoveries in the history of human inquiry. Through these remarkable discoveries, finite beings began to understand the limits on finite beings in new ways: limits on what can be counted, described, calculated, or proved. Even more remarkably, we began to precisely understand what is *beyond* those limits: we now can give precise, well-understood, and rigorously demonstrated general principles and specific examples of the infinite and uncountable, the indescribable, the uncomputable, and the unprovable.

Here are some of the highlights. These are facts which we will be examining in detail throughout this text.

The Uncountable. There are infinities of different sizes. (Indeed, infinitely many different sizes!) (This is called “Cantor’s Theorem.”)

The Inexpressible. For any precise language, there are properties that it cannot precisely express. These include the property of being a true sentence in that language. (This is called “Tarski’s Theorem.”)

The Undecidable. There are questions that cannot be answered in general by any systematic method. These “undecidable” questions include the question of which general systematic methods will eventually succeed. (This is called

“Turing’s Theorem”.) They also include the question of which arguments are logically valid. (This is called “Church’s Theorem.”)

The Unprovable. For any reasonable logical system, there are facts that can be formally described, but cannot be formally proved. (This is called “Gödel’s First Incompleteness Theorem.”) Thus there can be no elegant “theory of everything”: no reasonably simple, consistent principles can settle the answer to every question. Furthermore, among the facts that a logical theory cannot prove is the fact that its own theorizing is logically consistent. (This is called “Gödel’s Second Incompleteness Theorem.”)

Later on we will state each of these facts more exactly, and we will work through detailed arguments for each one of them. We’ll work up to this slowly, starting by developing some basic skills and concepts for reasoning carefully about the relationship between language and the world. But let’s start with a more informal look.

The arguments for each of these facts rely on the same basic idea. The starting place is the *Liar Paradox*. Let L be the following sentence:

This sentence is not true.

Apparently, what L says is just that L is not true. So presumably, if L is true, then what L says is so—that is, L is not true. And presumably, if L is *not* true, then what L says is *not* so—that is, L is true. But that means we have a contradiction either way. This is very puzzling.

People have known about this puzzle since the ancient Greeks. For a long time it was widely thought of as just a brain-teaser—not especially important. Maybe there is something wrong with expressions like this sentence, but you might reasonably think that the responsible policy is just to avoid using self-referential sentences like L for official purposes, and move on to other more serious questions. But it turns out that this policy is not as easy to carry out as it seems—in a sense, self-reference is inevitable. And taking this old puzzle seriously turns out to lead us to some very important discoveries.

Here is another trick—a variation on the Liar Paradox. The word red applies to red things.

For any thing x , the word red applies to x if and only if x is red.

Similarly, the word short applies to short things. In general:

For any thing x , the word short applies to x if and only if x is short.

Some of the things that **short** applies to are short *words*. For example, the word **red** is short. So the word **short** applies to **red**. The word **short** is also short, so **short** applies to **short**. So we can say that **short** is *self-applying*. In contrast, **long** is not a long word, so **long** is *non-self-applying*.

Now let's look at how things go for *this* new word we have introduced: **non-self-applying**.

The word **non-self-applying** applies to **long**

The word **non-self-applying** does not apply to **short**

Just like with **red** and **short**, we'd like to say in general,

For any thing x , the word **non-self-applying** applies to x if and only if x is non-self-applying.

In other words:

For any thing x , the word **non-self-applying** applies to x if and only if x does not apply to x .

This principle about **non-self-applying** seems very reasonable. But it leads to disaster! What happens if we plug in the word **non-self-applying** itself? Then we get:

non-self-applying applies to **non-self-applying** if and only if
non-self-applying does not apply to **non-self-applying**.

And this is logically contradictory. If **non-self-applying** *does* self-apply, then it doesn't, and if **non-self-applying** *does not* self-apply, then it does!

In this version of the puzzle we never used self-referential words like **this sentence**. Instead of self-reference, we used *self-application*. We fed a word to itself, and this landed us in serious trouble.

Feeding something to itself like this is the devious trick behind all of the main facts we are going to study. For example, Cantor showed that if infinite sets were all the same size, then in a sense you could “feed a set to itself” and arrive at a contradiction. Roughly, you get to inexpressible properties by feeding *descriptions* to themselves, you get to undecidable questions by feeding *programs* to themselves, and you get to unprovable statements by feeding *proofs* to themselves. (This trick is sometimes called “diagonalization,” for reasons we will talk about in Section 1.5.)

Let's look at how this idea works for Gödel's Theorem about unprovability. Waving our hands a little, we can sketch an argument for a simplified version of this theorem.

Suppose that we have some logical theory which is both reasonably powerful and also reasonably simple. We can show that either this theory *does* prove something false, or else it *doesn't* prove something true.

The description `shorter than 100 symbols` is itself shorter than 100 symbols. In a reasonably powerful logical theory, we should also be able to *prove* this statement.

`"shorter than 100 symbols"` is shorter than 100 symbols

Call this statement the *self-application* of the description `shorter than 100 symbols`. So to put it another way, the description `shorter than 100 symbols` *has a provable self-application*. In contrast, the following statement is false:

`"does not contain a vowel"` does not contain a vowel

So if our theory doesn't prove false things, then we *can't* prove that statement. In other words, the description `does not contain a vowel` *has an unprovable self-application*.

Now, it turns out that in any logical theory which is both reasonably powerful and reasonably simple, we can write down *this* description, too:

`has an unprovable self-application`

Let's call this description *H*. The self-application of *H* is the statement

`"has an unprovable self-application"` has an unprovable self-application

Let's call this statement *G*. This is another equivalent way of restating *G*:

`The self-application of H is not provable`

But we just said that *G* *is* the self-application of *H*! So in fact, what we just said is equivalent to

`G is not provable`

To sum up, the statement *G* is *equivalent* to the statement `G is not provable`. And furthermore, if we're careful, we can *prove* this equivalence in the logical theory we started out with. Notice that *G* is very similar to the Liar sentence *L*, except that now we are talking about what is provable instead of what is true.

Finally, we ask, can we prove *G* in our logical theory? If we can, then using the equivalence, we can also prove `G is not provable`—which means we can prove something false. But also, if we *can't* prove *G*, then `G is not provable` is *true*. Since this statement is equivalent to *G*, that means that *G* is also true—which means

we *can't* prove something *true*. So either there is a false statement that we can prove, or else there is a true statement that we *can't* prove.

This very brief overview of Gödel's Theorem leaves a lot out, and it might seem mysterious and suspicious at this point. To do everything properly, without so much hand-waving, we'll have to start by carefully investigating what sets, numbers, descriptions, programs, and proofs are like. This will take quite a bit of work. (We'll get to the official version of this theorem in Section 8.5) But there is a big reward. We finite beings can use these tools to explore the infinite world: to count, describe, calculate, and reason. If we understand how these tools work—using precise language and careful reasoning to learn *about* language and reasoning themselves—then we can also understand their limits, and what is beyond them.

About This Text

Here are three ways in which I have aimed to make this text distinctive.

Philosophical

While I hope that students in other neighboring fields (like linguistics, computer science, and mathematics) will also find it helpful, this book is primarily aimed at people who are interested in philosophy, particularly advanced undergraduates and beginning graduate students. The results in this course—the Theorems named after Cantor, Tarski, Turing, Church, and Gödel—are not just bits of abstract mathematics: they are *philosophical* discoveries. Of course, they are also central to other disciplines besides philosophy. And they are especially rigorous and well-established, and they require some technical skills to understand. But it would be a shame if we philosophers lose track of this part of our intellectual heritage for these reasons. Forgetting about discoveries like these leads people to sad thoughts like “philosophy makes no progress.”

What's more, these discoveries are not just part of the philosophy of *mathematics*. These Theorems are central facts in the philosophy of language and epistemology. They also have important connections to metaphysics, philosophy of mind, decision theory, and many other topics. But the historical presentation of these ideas, which most texts faithfully transcribe, unfortunately obscures some of this. You might come away from many courses thinking that (for example) Gödel's First Incompleteness Theorem is a parochial brainteaser about “formal theories of arithmetic”—a taste for which not that many of us acquire.

In this text, what takes center stage is not arithmetic but *language*. Languages used

by finite beings (whether natural or artificial) typically consist of expressions that are straightforwardly represented as finite strings of discrete symbols, like the letters of the alphabet. Thus, rather than theories of arithmetic, we will think a lot about theories of these *strings*. (Of course, we will still occasionally need to reason about numbers, so they are not entirely absent.) This shift in focus will make some of our results look unfamiliar to those who are already initiated. (For example, theories of arithmetic take a back seat to the *minimal theory of strings* S.) But the shift from theorems about numbers to theorems about strings is usually pretty straightforward, technically, and the string-centered approach is conceptually simpler. We can almost entirely dispense with one conceptual hurdle from the historical approach: the technique of Gödel-numbering. (This is still discussed in Section 6.11, since while it is dispensable, of course it is still *interesting* that theories of strings can be interpreted in a simple theory of arithmetic.)

I have also departed from historical presentations in other ways. In the 1930’s three different equivalent definitions of *computability* were proposed: Gödel’s general recursive functions, Church’s untyped lambda-calculus, and Turing’s machines. Those who are familiar with this history might be surprised to find that this text does not include any of these three topics. Nowadays the idea of a universal formal system for representing algorithms is very familiar—not under any of these three guises, but rather under the guise of a *programming language*. So in this text we will study an elementary fragment of a modern programming language. (We use Python, because it has especially tidy syntax, but pretty much any modern language has an equivalent fragment.) Besides using more widely familiar concepts, another nice pedagogical advantage of this approach is that we can use the very same techniques to study the semantics of first-order logic and the semantics of programs. This makes the parallels between first-order *definable* sets and effectively *decidable* sets more straightforward. (Of course, this model of computation is also equivalent to Gödel, Church, and Turing’s versions, so there is no real change in the content of the theorems we prove.)

This text does not itself provide much detailed discussion of the philosophical questions that arise from these results, though I attempt to gesture at interesting connections along the way. But I don’t think it’s as if the Theorems and their proofs are a hard kernel of “mathematics” surrounded by a fuzzy penumbra of “philosophy.” The Theorems and their proofs *are* philosophical theses and arguments, themselves—theses and arguments displaying a distinctive degree of precision, distinctively intricate reasoning, and displaying all of their premises with a distinctive degree of clarity. But these are virtues to which we can aspire with all philosophical argumentation. (It should go without saying: not the *only* such virtues!)

Accessible

This book presupposes that its readers have taken one previous course in formal logic which goes as far as first-order predicate logic—ideally one that at least mentioned models and assignment functions, but this much isn’t absolutely essential. It does not presuppose *any* experience with mathematics, or mathematical logic. In particular, this text is not meant to presuppose any experience with reading or writing rigorous arguments (“informal proofs”). Rather, this text aims to teach those skills, alongside the technical and philosophical content.

Because of this, we start things off at a slow, gentle pace, building up technical tools from their foundations, introducing each new assumption as it arises. For students with a bit more technical experience, it may be reasonable to skim over the first three chapters pretty quickly. (But make sure not to skip Section 1.5, which introduces one of the key ideas!)

I have also chosen not to use the Greek alphabet (which involves an unnecessary extra deciphering step for students without the benefit of a classical education), and I have stated things in words rather than just symbols as much as seems practical. (I take the latter to be good practice even for experts.)

Skills-based

As far as I know, there is only one way for humans to learn this kind of material: by doing it. When it comes to a technical argument, just reading it or hearing it explained isn’t usually enough to really understand it at more than a superficial level. You have to work it out yourself. You have to see how each step follows from the previous; you have to get a feel for which parts of a proof are important, and which are routine. You have to develop useful intuitions that give you a sense of which results are going to work out in the end. False proofs should smell fishy. An argument that seems like just a mass of details, one after another, is an argument that you don’t fully understand yet.

Logic is often taught as a mass of details, one after another. (I’ve certainly been guilty of teaching it this way—there are a lot of details, after all.) Our hope is to get past that, to understand the important and beautiful parts. But we can’t do this (at least, not very well) by just ignoring the details—rather, we have to get good enough at dealing with details that they become automatic and recede into the background. The way to do this is practice.

This text is intended to provide lots of practice, by providing lots of exercises. In the end, the exercises add up to proofs of the central Theorems (Cantor, Tarski,

Church, Turing, Gödel). Generally, whenever I provide a proof myself, it's for one of two reasons: either (a) to provide examples of an important style of reasoning for what comes later, or (b) to save students from especially tedious or fiddly bits of the argument. I've tried to teach all of the main ideas through exercises, to allow students to learn things by doing them, rather than just being told.

When I teach this course, I use two different teaching modes. The first is a standard instructor-led lecture, which I use mainly to present new concepts, work through definitions, and do example exercises. The second mode is student-led, in which students present their own solutions to exercises, discuss any questions that come up about them, and collectively fix any problems. (I've found the logistics work best if students sign up online for specific exercises before class. For a somewhat larger class, you can give points just for volunteering, and choose which volunteer actually presents by lottery or some other system. For a very large class, you'll probably need to try something else.) I roughly alternate sessions between the two modes: in a course that meets twice a week, we'll have one "lecture day" and one "problem day." (I take over a bit more of the time at the points in the course that have a lot of new concepts: especially Chapter 1, Chapter 2, and Chapter 7.)

Be warned, this format takes a lot of class time. If you want to cover the material more quickly, in order to get to some more advanced topics, you could present more of the exercise solutions as part of a traditional lecture.

The starred sections can be skipped without losing the main thread. Some of them go into background issues in more detail, and others are more advanced topics.

Acknowledgments

This text has been a long time in the making, and I have benefited from a lot of help from a lot people. Thanks are due to all of the students at USC on whom I inflicted early drafts of this text. The first draft, which consisted of my teaching notes for PHIL 450 in the Fall of 2014, was particularly rough going, and I am very grateful for those students' patience.

I also owe special thanks to Cian Dorr, who "alpha tested" this text with his class at NYU when it was still in a pretty rough form, in the Spring of 2017. He wrote me many long emails that semester full of detailed ideas for improving things, many of which I have incorporated.

Strategies for Proving Things

Art¹ does not make Reason, but Reason makes Art;
and therefore as much as Reason is above Art, so
much is a natural rational discourse to be preferred
before an artificial ...

Margaret Cavendish, *The Blazing World* (1668)

One of the central skills this text is meant to help you learn is showing that certain statements are true, by giving very careful arguments from clearly specified premises, at a very high standard of precision.² The way we do this is with *informal proofs*. Here “informal” contrasts with the *formalized* proofs that we will discuss later in the class (and which you might have practiced in previous logic classes). We are writing our arguments in clear English, rather than in an artificial language like predicate logic, and we are using any kind of clear reasoning that shows that our conclusions follow from our premises, rather than restricting ourselves to mechanical rules of the sort that a simple computer program could check. But “informal” doesn’t mean sloppy, and it doesn’t mean that just anything goes. You may never have had to write out rigorous proofs before, and that’s fine: this text does not assume that you already have these skills. You’ll learn them.

Sometimes students don’t know how to get started on an exercise. The techniques presented in this chapter give you a way to get started. These are all pretty “low-level” techniques. With practice, they will become automatic, and when that happens you’ll be able to give more of your attention to the really interesting parts of the proofs, instead of the basic details of “every” statements and “if” statements, and what to suppose and what you have to show. Once you get good at it, prov-

¹That is, artificial formal methods.

²This chapter is inspired by a series of blog posts by Tim Gowers: <https://gowers.wordpress.com/category/cambridge-teaching/basic-logic/>

ing things can be like making music—but we have to start by practicing scales and arpeggios.

You don’t need to read all the way through this chapter before you start on Chapter 1. I recommend instead that you keep this chapter close at hand when you are working on the exercises. If you don’t know how to get started on an exercise, or if you feel like you’re stuck, look here for some ideas about what you might want to do next.

If you look at an exercise and feel like you have no idea how to do it, don’t fear! You don’t need to be able to see your way all the way from the beginning to the end, in some single flash of inspiration. Start by just trying to take one step at a time. Try to break up your problem into pieces that are just a little bit simpler. Keep doing that, and a lot of times that will take you all the way to the solution.

0.1 Give yourself room

It might be tempting to try to start writing down your proof from the beginning, and keep going until you reach the end. That doesn’t usually work. The activity of **discovering** a proof and the activity of **presenting** or **explaining** a proof to others are very different. You’re going to do both things, so to keep things clear you’re going to need (at least) two pieces of paper: a *discovery* page, and a *presentation* page. Once you have discovered the whole proof, using the techniques we’ll discuss, then you can write it down neatly from beginning to end. (See the section “Putting it together”, Section 0.6 below.)

0.2 Keep track of your goals

When you are working on a proof, you need to keep track of the answers to **the two most important questions**.

1. What am I trying to show?
2. What relevant things do I already know?

When you start working on your proof, start by writing down the answers to these questions. First write down “*Show*”, and the statement of what you are trying to prove. Then write down “*Suppose*” (or “*Assume*” or “*Given*” or “*Know*”) and the statements of the things that you already know.

You shouldn’t always try to write down *everything* you know. You can’t always tell in advance what’s going to be relevant, and you can always add something else to your list later when you think of it. But you should at least write down the things

that are given to you in the statement of the exercise itself. You should also make sure to look carefully at the other definitions, lemmas, theorems, and exercises that come immediately before the exercise you’re working on, especially those that use similar words or notation.

When you write these down, you should pay attention to the *logical structure* of each statement. Is it an “if … then …” statement? A “for all …” statement? A “there exists …” statement? There are different strategies to use for each of these kinds of statement, so it’s important to figure out what kind you are dealing with.

As you go, your goals will change. (See the examples below.) You’ll need to keep your notes organized so that you can easily tell what the answer is to the two key questions at your current stage of progress: What am I trying to show? What relevant things do I know?

0.3 Proving an “every” statement

Suppose this is your goal:

Show Every set is a subset of itself.

This is an “every” statement. We can rewrite it another way that makes its structure more explicit:

Show For every set A , A is a subset of A .

In this explicit form, an “every” statement has four parts.

1. “For every”. This tells us what kind of statement we are dealing with—a *universal* statement, which says that *all* of a certain kind of thing have a certain property.
2. The *kind of thing* we are talking about: “set”. (This is called the *restrictor*.)
3. The letter A ; this is a *variable*. It doesn’t matter very much which letter we use, but we’ll want to choose a letter that isn’t too confusing. There are conventions to use certain letters for certain kinds of things: for example, for *sets* we’ll normally use the capital letters A , B , C , or X , Y , Z . I’ll follow these conventions in the examples, but you haven’t learned them yet, so for now just use whatever letter you think makes sense. We also want to avoid

using a letter that we’re already using for some other purpose. If we need to, we can add decorations to distinguish different variables from each other, like A' , B_2 , or \hat{X} .

4. The *property* we are showing that every set has—“ A is a subset of A ”. (This is called the *matrix clause*.)

In English—even in the relatively regimented English of technical writing—“every” statements can come in a lot of forms. It’s important to be able to recognize them, and to break them up into these four pieces. Here are some more examples (with brackets around the *restrictor* and the *matrix*).

0.3.1 Example

- (a) All ravens are black.

For every [raven] x , [x is black].

- (b) Any consistent set of sentences has a model.

For every [consistent set of sentences] X , [X has a model].

- (c) If f is a function from A to B , then the range of f is a subset of B .

For every [function from A to B] f , [the range of f is a subset of B].

- (d) Every closed term contains at least one constant.

For every [closed term] a , [a contains at least one constant].

- (e) Every set is smaller than its power set.

For every [set] A , [A is smaller than A ’s power set].

- (f) No set is as large as its own power set.

For every [set] A , [A is not as large as A ’s power set].

The examples and exercises in this chapter use concepts that come from later parts in the text—such as “range” or “closed term”. You aren’t expected to know what any of these words *mean* at this point. You can apply these low-level techniques just by looking at the *form* of the statements, without worrying about what a function is, or a range, or a subset, or a term, and so on. (To practice proof techniques, we need *some* subject matter to talk about, but we haven’t actually introduced any subject matter yet, at this point in the text!)

Now suppose we are trying to show an “every” statement, and we have identified its logical structure.

For every [set] A , [A is a subset of A].

Now here is our strategy:

<i>Suppose</i>	A is a set
<i>Show</i>	A is a subset of A

That is, we’ll add “ A is a set” to our list of things we are *supposing*, and we’ll write down “*Show* A is a subset of A .” This doesn’t solve the problem yet—but it *simplifies* the problem. Our problem asked us to prove something complex, with some logical structure. We have now broken down our goal into something *less* complex.

When we apply this strategy, it’s important to be careful with our choice of variables. One way we can make mistakes is if we have already been using the letter A for some other purpose that’s different from showing this “for all” statement; then there is a risk of mixing up the two different uses of “ A .”

Here’s how this strategy works for our other example sentences.

0.3.2 Example

- (a) All ravens are black.

<i>Suppose</i>	x is a raven
<i>Show</i>	x is black

- (b) Any consistent set of sentences has a model.

<i>Suppose</i>	X is a consistent set of sentences
<i>Show</i>	X has a model

- (c) If f is a function from A to B , then the range of f is a subset of B .

<i>Suppose</i>	f is a function from A to B
<i>Show</i>	The range of f is a subset of B

- (d) Every closed term contains at least one constant.

<i>Suppose</i>	a is a closed term
<i>Show</i>	a contains at least one constant

- (e) Every set is smaller than its power set.

<i>Suppose</i>	A is a set
<i>Show</i>	A is smaller than A 's power set

- (f) No set is as large as its own power set.

<i>Suppose</i>	A is a set
<i>Show</i>	A is not as large as A 's power set

0.3.3 Exercise

Identify the logical structure of each of the following “every” statements, and use this structure to write down the new “suppose” and “show” statements you would need to prove it.

- (a) Every one-to-one correspondence is an onto function.
- (b) Every set which is at least as large as the set of numbers is infinite.
- (c) A set of sentences is logically consistent iff it has a model.
- (d) For any sets A and B , if $A \subseteq B$ and $B \subseteq A$, then $A = B$.
- (e) If A is any non-empty set, there is a one-to-one function A to B or there is an onto function from B to A .
- (f) No theory is simple, strong, consistent and complete.

0.4 Unpacking definitions

Suppose we have this goal:

<i>Show</i>	A is a subset of A .
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This involves a technical term “subset”, which has an official definition. We can look it up in the relevant part of the textbook:

Definition 1.1.2. If A and B are sets, then A is a **subset** of B iff every element of A is an element of B . This is also written $A \subseteq B$ for short. We say A is a **proper subset** of B iff A is a subset of B , but not the same set as B .

We can use this definition to “unpack” the statement “ A is a subset of A ”, transforming it into this:

Show Every element of A is an element of A .

The same trick applies to technical *notation* which is expressed in symbols rather than words. The notation

$$A \subseteq A$$

is defined to be a shorthand for “ A is a subset of A ”. So we can use the same definition to unpack this in exactly the same way, as “Every element of A is an element of A .”

Notice that the particular *letters* that we used as variables in the definition don’t matter. They are placeholders. Think of the A and B in the definition of “subset” as holes, where we can plug in any sets we want. In this case, we have plugged the same set A into *both* spots in the definition—both the “ A ” and the “ B ” slots from the definition of “ A is a subset of B ” get plugged up with A .

0.4.1 Example

We can use Definition 1.1.2 to unpack the following statements.

- (a) X is a proper subset of Y

Every element of X is an element of Y , and X and Y are not the same set.

- (b) $B \subseteq A$

Every element of B is an element of A .

(Pay attention to the order!)

0.4.2 Example

Here are some examples of how to unpack these definitions in different statements.

- (a) There is a one-to-one function from A to its power set.

There is a function f from A to the power set of A such that, for each $a, a' \in A$, if $fa = fa'$, then $a = a'$.

- (b) No set has the same number of elements as its power set.

There is no set X such that there is a one-to-one correspondence between X and the power set of X .

(Notice that in order to unpack the definition, we introduced a *variable* X for the set we are talking about. The letter X was arbitrary. We could have used A or B or A' or something else if we wanted to. We just want to be clear, and make sure that our choice doesn't conflict with other variables we are already using in the context of our proof.)

- (c) The sentence $\forall x(x = x)$ is a logical truth.

The sentence $\forall x(x = x)$ is true in every structure.

- (d) Every logical truth is a logical consequence of the empty set.

For every sentence A which is true in every structure, A is a logical consequence of the empty set.

0.4.3 Exercise

Unpack the definitions from above in the following statements.

- (a) C is a logical truth.
- (b) g is a one-to-one function from B to A .
- (c) \mathbb{N} (the set of all natural numbers) is not a subset of the empty set.
- (d) The successor function suc (which is a function from \mathbb{N} to \mathbb{N}) is one-to-one.
- (e) The empty set is a proper subset of its power set.
- (f) Every logical truth is consistent.
- (g) There are one-to-one functions from A to B and from B to A .

(All of the examples we've discussed here are examples of what are called *explicit* definitions. Later on we'll encounter a different, trickier kind of definition, called a *recursive* definition.)

It can be tempting to try to unpack definitions as your very first line of attack on a problem. But usually this isn't a good idea. Notice that unlike most of our strategies,

unpacking definitions turns *simple* statements into *more complicated* statements. That means that if you do it right away, you make your problem more complicated. Usually you want to wait to unpack definitions until *after* you’ve already applied all the other strategies you can (like the “proving an ‘every’ statement” technique). Sometimes you won’t have to unpack a definition at all to finish a problem. In those cases, your solution will be easier to discover and easier to understand if you keep the definition “packed in.”

A definition is like a suitcase. You can pack a lot of information into a definition, and then carry it around your proof in a small tidy container. The right time to unpack your suitcase is when you’ve arrived at the place where you’re going to use what’s inside it.

0.5 Proving an “if” statement

Suppose we have this goal:

Show If A is a subset of B , and B is a subset of C ,
then A is a subset of C .

The first thing to do is to identify its structure. In this case, we recognize that this is an “if … then …” statement. Other than the “if” and “then”, it has two parts:

If [A is a subset of B , and B is a subset of C], then [A is a subset of C].

We can think of the first piece,

A is a subset of B , and B is a subset of C

as the “input” for the “if … then …” statement, and we can think of the second piece

A is a subset of C

as its “output.” What we want to show is that we can get *from* the input *to* the output. (These two pieces are called the *antecedent* and the *consequent*.) So here is our strategy:

<i>Suppose</i>	A is a subset of B , and B is a subset of C
<i>Show</i>	A is a subset of C .

That is, we can write down the first part in our list of things we are supposing, and write down “ A is a subset of C ” as our new “to show”.

While we’re at it, we can split up the “and” statement. So we’ll add *two* assumptions:

<i>Suppose</i>	A is a subset of B
	B is a subset of C
<i>Show</i>	A is a subset of C

Now that we have new things to suppose, and a new thing to show, we can go on and apply more strategies to try to finish the proof. (“Unpacking definitions” is a good one to go for next.)

0.5.1 Example

Identify the “if … then …” structure of the following statements, and use this to write down the new “suppose” and “show” statements that you would use to prove them.

- (a) If $A \subseteq B$ and $B \subseteq A$, then $A = B$.

<i>Suppose</i>	$A \subseteq B$
	$B \subseteq A$
<i>Show</i>	$A = B$

- (b) If there is an onto function from A to B , then there is a one-to-one function from B to A .

<i>Suppose</i>	There is an onto function from A to B
<i>Show</i>	There is a one-to-one function from B to A

- (c) If there is a one-to-one function from A to B , then there is an onto function from B to A , unless A is empty.

<i>Suppose</i>	There is a one-to-one function from A to B
	A is not empty
<i>Show</i>	There is an onto function from B to A

- (d) If $X \models A$ and $Y, A \models B$ then $X, Y \models B$

<i>Suppose</i>	$X \models A$
	$Y, A \models B$
<i>Show</i>	$X, Y \models B$

(Notice that you don't even need to know what this notation means in order to identify the logical *structure*.)

0.5.2 Exercise

Identify the “if … then …” structure of the following statements, and use this to write down the new “suppose” and “show” statements that you would use to prove them.

- (a) If A is no larger than B and B is no larger than C , then A is no larger than C .
- (b) If $m \leq n$, then either $m = n$, or $\text{suc } m \leq n$.
- (c) If $\{A, B\}$ is consistent, then $\neg B$ is not a logical consequence of A .
- (d) If T is sufficiently strong, axiomatizable, and consistent, then T is incomplete.

0.6 Putting it together

0.6.1 Example

Suppose we are doing this exercise:

Prove that every set is a subset of itself

We start by writing down our goal.

<i>Show</i>	Every set is a subset of itself
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We don't have any relevant facts to write down as “given” for this problem, but we will want to make sure to keep the definition of “subset” handy.

Our first step is to identify the structure of this statement. It looks like an “every” statement. Let's rewrite it so its logical structure is very clear.

Show For every set A , A is a subset of A

Now we can break this up, given us a new goal:

<i>Suppose</i>	A is a set
<i>Show</i>	A is a subset of A

How can we solve this simpler problem? Our “given” and our “show” don’t look like they have any more complex logical structure at this point, so it looks like it’s time to unpack the definition of “subset.”

<i>Suppose</i>	A is a set
<i>Show</i>	Every element of A is an element of A .

But now the thing we have to show is completely obvious. (You could break it down even further with the “every” strategy: *assume* a is an element of A , and then *show* a is an element of A —which is trivial. But there is no need to go this far in breaking it down.) So we’re done! That is, we’re done *discovering the structure* of our informal proof. The last step is to put together all of our pieces in the right order, to make the proof understandable to other people. Here is how this might go:

Let A be a set. It is obvious that every element of A is an element of A .

This means that A is a subset of A . So every set is a subset of itself.

This paragraph looks pretty different from the fragments that we wrote down on the way to finding it. Instead of a bunch of “givens” and “shows”, we have put the whole thing together in logical order, from beginning to end. The *order of discovery* is different from the *order of justification*. In the order of discovery, we wrote down whatever was going to be helpful for us at the time for our next stage of simplification. But in the order of justification, we want to write things down step-by-step, so that each part of the proof comes immediately *after* what it relies on for justification.

Roughly, the steps we took to *find* this proof correspond to the final structure of the *presented* proof, not from beginning to end, but rather from the outside in. We can represent the logical structure of our informal proof like this:

Let A be a set.
 [It is obvious that]

every element of A is an element of A . [This means that]
 A is a subset of A .
 So every set is a subset of itself.

The “highest” or “outermost” level of logical structure is the thing we were originally trying to prove:

So every set is a subset of itself.

The next level in corresponds to the first strategy we used to prove this, the “prove an “every” statement” strategy.

Let A be a set. ... A is a subset of A .

The next level in corresponds to the next strategy we used, unpacking the definition of “subset”

... every element of A is an element of A . This means that ...

And the final, deepest level corresponds to the last part of our process of discovery, where we noticed that the only thing thing we had left to show was obvious.

It is obvious that ...

Here’s the basic idea. After you have found the logical structure of your proof, by breaking things down until your “Show” statement very obviously follows from your “Suppose” statements, you need to retrace your steps. It’s helpful to start from the end, looking at the last statement of your proof—the main thing you are trying to show. Then ask “what strategy did I use to get to this point?” That tells you what should go *before* that step in your polished presentation of the proof. Keep doing this until the answer is “nothing—it was obvious”. This will give you the *order* in which you need to write things down.

As for the actual words you write down, there is no mechanical recipe. The goal is to communicate the steps of you proof in a way which is elegant, concise, accurate, and easy to understand. Getting there takes practice and a sense of style.

Let’s look at another example.

0.6.2 Example

We have this goal:

Show For any sets A , B , and C , if $A \subseteq B$ and $B \subseteq C$,
 then $A \subseteq C$.

First we observe that this is an “every” statement. We can think of it as being built up out of three different nested “every” statements (“For every set A , for every set B , for every set C , …”). But it’s simpler to just handle all three of them at once.

<i>Suppose</i>	A is a set B is a set C is a set
----------------	--

<i>Show</i>	If $A \subseteq B$ and $B \subseteq C$, then $A \subseteq C$
-------------	---

Next we notice that we have an “if … then …” statement that we can break down. We’ll keep our old “suppose” statements and add some new ones.

<i>Suppose</i>	A is a set B is a set C is a set $A \subseteq B$ $B \subseteq C$
----------------	--

<i>Show</i>	$A \subseteq C$
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This looks about as simple as we can get without unpacking definitions. So let’s do that now. We’ll unpack the definition of \subseteq three times.

<i>Suppose</i>	A is a set B is a set C is a set Every element of A is an element of B Every element of B is an element of C
----------------	--

<i>Show</i>	Every element of A is an element of C
-------------	---

At this point we could declare it obvious enough that what we want to show follows from what we are supposing, and be done. But for the practice, let’s go ahead and break this proof down into even more basic steps this time. Again, we have an “every” statement to show. We can restate it, introducing a new variable:

For every [element of A] a , [a is an element of C].

So we can break it down again:

<i>Suppose</i>	A is a set
	B is a set
	C is a set
	Every element of A is an element of B
	Every element of B is an element of C
	a is an element of A

<i>Show</i>	a is an element of C
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And now it's clear how to finish. We know a is an element of A . One of our assumptions tells us that this implies a is an element of B . Then another assumption tells us that *this* implies a is an element of C .

Now let's put this all together, and write up our informal proof.

Let A , B , and C be sets, and suppose that $A \subseteq B$ and $B \subseteq C$. Let a be any element of A . Then since every element of A is an element of B , a is an element of B . And since every element of B is an element of C , a is an element of C . This shows that every element of A is an element of C . That is, $A \subseteq C$.

Once again, we can find the “order of discovery” here by looking at the proof from the outside in, more or less. At the outermost level, we find the traces of the “prove an ‘every’ ” strategy and the “prove an ‘if’ ” strategy that we began with.

Let A , B , and C be sets, and suppose that $A \subseteq B$ and $B \subseteq C$
 $A \subseteq C$.

Looking a little bit further back from the end, we see a definition unpacked:

... every element of A is an element of C . That is ...

A bit further in yet, we have our second “every” strategy:

Let a be any element of A a is an element of C . This shows that
 ...

And at the middle of the proof we have our other two unpackings of the definition, and our final observation about how they are related.

Then since every element of A is an element of B , a is an element of B . And since every element of B is an element of C , a is an element of C .

0.7 Using existence statements

Say we are trying to prove this:

If there is a one-to-one function from A to B , and there is a one-to-one function from B to C , then there is a one-to-one function from A to C .

We can start by splitting up the “if” statement:

<i>Suppose</i>	There is a one-to-one function from A to B
	There is a one-to-one function from B to C
<i>Show</i>	There is a one-to-one function from A to C

We have written down three “there is” statements. These are called *existential generalizations*, and each of them says that there is at least one of some kind of thing. (Even though we use the singular expression “a one-to-one function,” we do not mean to imply that there can’t be more than one function like this.)

So we know that *there is* a one-to-one function from A to B , but we don’t know what specific function this is. How we can use this information? The first thing we should do is *give it a name*. This gives us something more specific to hang onto in our reasoning. We can replace our two suppositions with new, more specific-looking suppositions:

<i>Suppose</i>	f is a one-to-one function from A to B
	g is a one-to-one function from B to C
<i>Show</i>	There is a one-to-one function from A to C

We have introduced two new variables, f and g as “names” for functions that we are supposing to exist.

Just like when we are proving “for every” statements, we have to be careful with our choice of variables. It’s important that we aren’t already using the letters f or g as names for some other things in this proof—otherwise we could get different uses of “ f ” mixed up, which would lead to mistakes. Beyond that, you can use whatever

variable you want, but again there are certain conventions which help us keep track of what kind of thing you are talking about. For example: f, g, h for functions, A, B, C or X, Y, Z for sets, lower-case a for an element of the set A , and so on.

(Note that we did *not* introduce a new variable for the “there is” statement we are trying to *show*. That actually wouldn’t help at all.)

This helps, because now we can use things we know about one-to-one functions to draw conclusions about the “specific” functions f and g .

Like “for every” statements, “there is” statements can take a lot of different shapes, even in the relatively regimented English of technical writing.

0.7.1 Example

Write down the “suppose” statements you would use to prove things from the following existential statements.

- (a) There is a one-to-one correspondence between A and B .

Suppose f is a one-to-one correspondence between A and B

- (b) There is a proof of A .

Suppose P is a proof of A

- (c) X has a model.

Suppose S is a model of X

- (d) Some subset of X is inconsistent.

*Suppose Y is a subset of X
 Y is inconsistent*

- (e) X has a finite subset that entails A .

Suppose Y is a finite subset of X

Y entails A

- (f) Not every model of X satisfies A .

<i>Suppose</i>	S is a model of X
	S does not satisfy A

0.7.2 Exercise

Write down the “suppose” statements you would use to prove things from the following existential statements.

- (a) There is an onto function from PA to A .
- (b) X is the extension of some formula.
- (c) T has a countable model.
- (d) Not every subset of A is empty.
- (e) Some program decides the set of logical truths.
- (f) There is at least one odd prime.

0.8 Proving existence statements

The main way to show that a certain kind of thing exists is to give an example. Suppose we want to show that some set has at least two elements.

Show Some set has at least two elements

We could do this by coming up with some example of a set, and showing that *that specific* set has at least two elements. So we can rewrite the goal like this:

Show _____ has at least two elements

Before we can do this, we have to figure out how to fill in the blank. For example, we might do it like this:

Show The power set of the empty set has at least two elements

The trick is to fill in the blank in a way that gives us a “Show” statement that we can actually show. If put in the wrong thing, we can end up at a dead end. Then we just have to backtrack and try filling in the blank some different way.

Filling in the blank to prove an existence statement is very often the trickiest part of a proof. There is no mechanical rule for this. Sometimes it is easy to find the right thing, but sometimes it requires creativity and insight. For example, here is one of the theorems we will prove in Chapter 8:

Any consistent theory has a model.

We can break this down like this:

Suppose	T is a consistent theory
Show	There is a model of T

Then we can rewrite our goal again:

Suppose	T is a consistent theory
Show	_____ is a model of T

The hard part of this proof is figuring out how to fill in the blank. In fact, precisely describing a model that we can use to fill in the blank ends up taking about ten pages!

0.8.1 Example

Prove that there is no greatest number.

Proof

We can rewrite this in a more transparent logical form.

Show	For any number n , some number is greater than n .
------	--

Using the “for every” trick:

Suppose	n is a number.
Show	Some number is greater than n.

Our goal now is to prove an existence statement. So we have a blank to fill in.

Suppose n is a number.
Show _____ is greater than n .

Now we need to come up with some way of filling in the blank. What is some number that we know is greater than n ? Of course, the number will depend on what n is, but that's fine. Here we can use something that we happen to know: for any number n , $n + 1$ is greater than n . (We haven't officially proved much of anything about numbers yet, so we'll just cheat here and bring in a fact from later.)

Now we can put this all together:

Let n be any number. We know that $n + 1$ is greater than n . So for any number n , some number is greater than n . In other words, there is no greatest number. □

0.9 “And” statements

Say we have this goal:

Show that any set is a proper subset of its power set.

Suppose A is a set
Show _____ A is a proper subset of the power set of A .

Now we unpack the definition of “proper subset”

Suppose A is a set
Show _____ A is a subset of the power set of A ,
and A is not the same set as the power set of A .

Our goal is an “and” statement. This means we really have *two* goals. Let's split them up.

Suppose A is a set.
Show _____ A is a subset of the power set of A .

Suppose A is a set.
Show A is not the same set as the power set of A .

What was one big problem is now two smaller problems, which we can tackle one at a time. In each of these subproblems, we can use any of the assumptions we had for the original problem.

In general, if you have to prove an “and” statement, you really have to prove two different things. Split your problem up into two pieces, and take them one by one.

0.10 “Iff” statements

The word “iff” is an abbreviation for “if and only if”. For example:

Suppose A is a set of sentences.
Show A is inconsistent iff
 A logically implies a contradiction.

We can rewrite this:

Suppose A is a set of sentences.
Show If A is inconsistent, then
 A logically implies a contradiction,
 and if A logically implies a contradiction,
 then A is inconsistent.

So proving an “iff” statement amounts to proving an “and” statement. We can break it up into two subproblems.

Suppose A is a set of sentences.
Show If A is inconsistent, then
 A logically implies a contradiction.

Suppose A is a set of sentences.
Show If A logically implies a contradiction,

then A is inconsistent.

0.11 “Or” statements

Start with an example:

<i>Suppose</i>	A is a finite set.
<i>Show</i>	Either A is empty, or there is an onto function from \mathbb{N} to A .

How do we tackle proving this “or” statement? One useful strategy is to think of it like an “if” statement: *if* A is *not* empty, then there is an onto function from \mathbb{N} to A . Then we can use our usual “if” trick.

<i>Suppose</i>	A is a finite set.
	A is not empty.
<i>Show</i>	There is an onto function from \mathbb{N} to A .

Since “or” statements are symmetrical, we could just as well try to do this the other way around, if it seems easier.

<i>Suppose</i>	A is a finite set.
	There is no onto function from \mathbb{N} to A .
<i>Show</i>	A is empty.

That gives us a way of approaching “or” statements in our “Show” section. What if we have an “or” statement in the “Suppose” section?

<i>Suppose</i>	n is prime number or $n = 1$
<i>Show</i>	n does not have three factors.

Our main tool for handling this kind of problem is called *proof by cases*. It’s similar to proving an “and”: this time, instead of splitting up our “Show”, we split up our “Suppose”. We have two subproblems to work on.

<i>Suppose</i>	n is prime number
<i>Show</i>	n does not have three factors.

<i>Suppose</i>	$n = 1$
<i>Show</i>	n does not have three factors.

0.12 Proof by contradiction

All of the other techniques we have discussed so far in this chapter applied to very specific contexts, where you are supposing or showing something with a specific logical structure. But you can use proof by contradiction to prove anything at all. The idea is pretty straightforward: if you want to prove something, assume the opposite and show that a contradiction follows. For example, say we have this goal:

<i>Suppose</i>	T is a consistent theory.
<i>Show</i>	T is not representable in T .

Then we can transform it into two goals:

<i>Suppose</i>	T is a consistent theory
	T is representable in T
<i>Show</i>	_____

<i>Suppose</i>	T is a consistent theory
	T is representable in T
<i>Show</i>	It is not the case that _____

We have to put the same statement in each of the two blanks. Using our extra assumption, we have to prove something, and also prove the opposite. Then we can conclude that the extra assumption must have been false.

We can fill in the blank with any statement at all. Sometimes it will be obvious what to put there, but a lot of times it won't be. This means that using proof by contradiction is not totally mechanical, the way many of these rules are: it involves insight and creativity.

One good clue for when proof by contradiction is the right tool is when what you’re trying to show is a “not” statement, like in the example above. When you take the opposite of “ T is not representable in T ”, the “not” disappears and you end up with a simpler “Suppose” statement, “ T is representable in T ”. But you can use proof by contradiction even if there isn’t any explicit “not” around already. For example:

<i>Suppose</i>	A is a set
<i>Show</i>	A is either finite or infinite.

You can use proof by contradiction to transform this into two goals:

<i>Suppose</i>	A is a set
	A is neither finite nor infinite
<i>Show</i>	_____

<i>Suppose</i>	A is a set
	A is neither finite nor infinite
<i>Show</i>	Not: _____

(You can simplify these two goals further by rewriting “ A is neither finite nor infinite” as “ A is not finite and A is not infinite”.)

Because you can apply proof by contradiction to any goal at all, it can be tempting to use it all the time. But proof by contradiction is a sledgehammer. It is powerful, but it can make a big mess pretty fast if you use it in the wrong place. It can turn specific, concrete goals that you can work with mechanically into blanks that you might need to fill in with anything at all, which can make it harder to find proofs. Overusing proof by contradiction can also make proofs harder to follow, if you can prove the same thing more directly. So I generally recommend using proof by contradiction sparingly, just when it is the right tool for the job.

0.13 Thinking big and thinking small

The strategies we have discussed so far are just a start. There are lots more strategies that we’ll introduce as we go. But this should be enough to get going on the exercises. This text will provide many more examples and lots more practice.

All of the strategies we've talked about in this chapter are very "small scale". You can use the logical structure of the individual statements that you are using in your proof to break your problem down, step by step. With enough practice, all of these small scale moves will become automatic for you. If you have learned to drive, think about the first time you sat behind the wheel: you had to think carefully about every move of your feet and hands, every stop, every turn. But if you are an experienced driver, then those skills become so automatic that you might not even notice you are doing them—you might get all the way across town "on autopilot".

Once you get good at these small scale logical moves, what comes next? That's the fun part. Instead of focusing on getting out of your parking space and when to change lanes, you can focus on where you are going and think about strategies for how to get there.

As you are learning, you'll need to move back and forth between two different ways of thinking. When you are "thinking small", you are thinking about the basic moves you need to use to get from one logical statement to another. When you are "thinking big", you are developing your intuitions and conceptual understanding for how the things you are learning about really work—the things we have been ignoring in this chapter, about what it means for a theory to be logically consistent, or what infinite structures are like. One of the key skills you will develop is fluidly moving back and forth between these two perspectives.

Chapter 1

Sets and Functions

All things are woven together, and they make a sacred pattern ... For there is one universe made out of all things ...

Marcus Aurelius (121–180 CE), *Meditations* VII.9

Sometimes we reason about particular things one at a time; but it's often useful to reason about a whole collection of things taken together, all at once. We don't just look at what individual physical particles are like, but what the universe of *all* such particles is like; not just what individual sentences are like, but what a whole *language* is like. So it's generally useful to have a theory of such “totalities”—a theory of *sets*, and of how sets can be related to one another.

Our first job is to get familiar with some basic techniques for working with sets. These techniques are grounded in certain basic assumptions, or “axioms,” about what sets there are and what they are like. We'll practice using these axioms to carefully show other simple facts about sets.¹

1.1 Sets

A **set** is a collection of **elements**.

¹These “axioms” don't make up a standard *axiomatization* of set theory. First, they are redundant: with a bit of trickery, some of the axioms—like the “Axiom of Pairs”—can be derived from other axioms and definitions. Second, they are not complete enough for some purposes. You can find some further details about how these axioms are related to one another, and what has been left out, in Section 1.6. But these issues don't really matter for the main purposes of this course.

1.1.1 Notation

Typically we'll use capital letters as labels for sets, and lowercase letters as labels for their elements. The notation $a \in A$ means that a is an element of A . Sometimes we'll describe a set by listing all of its elements. For example, the set

$$\{\text{Silver Lake, Echo Park}\}$$

has two members, both of which are neighborhoods in Los Angeles. The set

$$\{0, 1 + 1, 2 + 3, 3 - 1\}$$

has three members (even though the list we've written out has four terms in it)—because $1 + 1$ and $3 - 1$ are the very same thing, the number two. (A set doesn't contain anything “more than once”.) In general, it's good to remember that just because we're using two different *labels*, it doesn't follow that they are labels for two different *things*.

In general, if we say

$$A = \{a_1, a_2, \dots, a_n\}$$

then this means that a_1, a_2, \dots, a_n are all of the elements of A . Every one of those things is an element of A , and nothing else besides those things is an element of A .

(We'll also introduce a different “curly bracket” notation for sets in a moment.)

1.1.2 Definition

If A and B are sets, then A is a **subset** of B iff every element of A is an element of B . This is also written $A \subseteq B$ for short. We say A is a **proper subset** of B iff A is a subset of B , but not the same set as B .

(If the abbreviation “iff” is unfamiliar to you, read Section 0.10.)

1.1.3 Example

- (a) For any set A , A is a subset of A . (That is, $A \subseteq A$. We say \subseteq is **reflexive**.)
- (b) For any sets A , B , and C , if A is a subset of B , and B is a subset of C , then A is a subset of C . (That is, if $A \subseteq B$ and $B \subseteq C$ then $A \subseteq C$. We say \subseteq is **transitive**.)

Proof

- (a) Let A be a set. We want to show that $A \subseteq A$, which means that every element of A is an element of A . This is obvious: that is, for any $a \in A$, obviously $a \in A$. So we're done.

- (b) Let A , B , and C be sets, and suppose that $A \subseteq B$ and $B \subseteq C$. We want to show that $A \subseteq C$. So suppose that a is any element of A ; we want to show that $a \in C$. Since $A \subseteq B$, and we are supposing $a \in A$, it follows that $a \in B$. Then, since $B \subseteq C$, it follows that $a \in C$. So every element of A is an element of C , which means that $A \subseteq C$. \square

To know what a set is, you just have to know what elements it has. No two *different* sets have the very same elements.

1.1.4 Technique (Proving sets are equal)

Say we have a set A and a set B , and we want to know whether they are the *same* set. (Remember—just because we are using different *labels*, it doesn't follow that they are labels for different *things*.) We can do this in two steps.

1. Show that every element of A is an element of B . That is, we come up with a subproof which begins “Let a be any element of A ”, and which ends “Therefore, a is an element of B ”.
2. Show that every element of B is an element of A . That is, we come up with a subproof which begins “Let b be any element of B ”, and which ends “Therefore, b is an element of A ”.

1.1.5 Example

If A and B are sets, then their **intersection** is a set $A \cap B$ whose elements are the things which are elements of *both* A and B . That is, to be explicit:

For any object x , $x \in A \cap B$ iff $x \in A$ and $x \in B$.

A **union** of A and B is a set $A \cup B$ whose elements are the things which are elements of either one of the sets A or B (or maybe both). That is, to be explicit:

For any object x , $x \in A \cup B$ iff $x \in A$ or $x \in B$.

Show the following fact:

$$A \cap (A \cup B) = A$$

Proof

In order to show that the set $A \cap (A \cup B)$ is the same set as A , we need to show two things:

1. Every element of $A \cap (A \cup B)$ is an element of A .

Let a be any element of $A \cap (A \cup B)$. By the definition of intersection, this means that a is an element of A and a is an element of $A \cup B$. So obviously

$a \in A$, and we're done.

2. Every element of A is an element of $A \cap (A \cup B)$.

Let a be any element of A . To show that $a \in A \cap (A \cup B)$, we need to show that $a \in A$ and $a \in A \cup B$. The first part ($a \in A$) we already know. For the second part ($a \in A \cup B$), we need to show that $a \in A$ or $a \in B$, by the definition of union. But since $a \in A$, that means the first case holds, and we're done. \square

1.1.6 Exercise

Using the definitions from Example 1.1.5, show the following facts:

- (a) If $A \subseteq B$, then $A \cup B = B$.
- (b) If $A \cup B = B$, then $A \subseteq B$.
- (c) For any set C , $C \subseteq A$ and $C \subseteq B$ iff $C \subseteq A \cap B$.

The reason that Technique 1.1.4 works is the following fundamental general principle about sets—which we call an *axiom*, because it is one of our basic assumptions.

1.1.7 Axiom of Extensionality

If A is a subset of B and B is a subset of A , then A and B are the very same set. That is, $A = B$.

In other words, if A and B have the exact same elements—that is, every element of A is an element of B , and also every element of B is an element of A —then A and B are exactly the same set. Again, what this axiom tells us, practically, is that if A and B are sets, and we want to show that $A = B$, then we should first show that $A \subseteq B$, and next show that $B \subseteq A$.

The proof of Example 1.1.5 implicitly relies on the Axiom of Extensionality. So does any proof that uses Technique 1.1.4 to prove sets are equal.

1.1.8 Example

Suppose A is the set $\{1, 2, 3, 4, 5\}$. It's often useful to “separate out” some of the elements of this set into another set—such as the set containing just the *odd* elements of A , which is $\{1, 3, 5\}$. We can label this set

$$\{a \in A \mid a \text{ is an odd number}\}$$

Similarly,

$$\{a \in A \mid a \text{ is prime}\} = \{2, 3, 5\}$$

And the set

$$\{a \in A \mid a \text{ is greater than } 10\}$$

is the *empty* set, since no elements of A are greater than 10.

1.1.9 Example

For any sets A and B , there is a **set difference** of A and B , containing just those elements of A which are not in B . This is denoted $A - B$. The existence of this set follows from Separation. The difference of A and B is the set

$$\{a \in A \mid a \text{ is not an element of } B\}$$

Or more briefly:

$$A - B = \{a \in A \mid a \notin B\}$$

1.1.10 Technique (Defining a Subset)

Suppose we have a set A , and we want to come up with an example of a subset of A . We can do this using our special curly brace notation. We can write down:

$$\text{Let } B = \{a \in A \mid \text{_____}\}.$$

Then we fill in the blank with some property. This should be a property that the elements of the subset we want have in common, and which no other elements of A have. Once we have written this down, we know that the elements of B are exactly the things which are elements of A that have the special property we wrote in the blank. That is, we know that every element of B is an element of A that has the special property. We also know that any element of A that has the special property is an element of B .

Again, the reason this technique works is because of another general principle about sets.

1.1.11 Axiom of Separation

Let F be any property. For any set A , there is a set B such that, for any thing a : a is an element of B iff a is an element of A that has the property F . The special notation we use for this is

$$B = \{a \in A \mid F(a)\}$$

where $F(a)$ is a statement that says that a has the property F .

There is something tricky about the Axiom of Separation. I have stated it in terms of *properties*. But this raises lots of philosophical questions. What are properties?

Are there any such things? What are they like? This also raises technical questions: what exactly counts as a legitimate application of the Axiom of Separation?

There are standard ways of stating the Axiom of Separation that either avoid or answer these philosophical questions. (There is more than one way to do it, and occasionally they give subtly different answers to the question of “what counts.”) But these alternative ways of making the Axiom of Separation more precise rely on concepts and tools that come much later in this text. For practical purposes, we can go ahead and use this intuitive version for now, with our intuitive sense of “properties”, and postpone the difficulties until we’re better equipped to handle them. Still, we can look ahead a bit to at least understand the general idea.

One way of restating the Axiom of Separation is as an *axiom schema* (which we will discuss in Section 5.4). Instead of a single axiom, what we really have are infinitely many different axioms: every single way of replacing $F(a)$ with some precise statement about a gives you a different axiom. One of these axioms says:

For any set A , there is a set B such that, for any thing a : a is an element of B iff a is an element of A and $\underline{a \text{ is a non-empty set}}$.

Another axiom says:

For any set A , there is a set B such that, for any thing a : a is an element of B iff a is an element of A and $\underline{a \text{ is an odd number}}$.

And so on. Every way of filling in the blank gives you another axiom. These are called *instances* of the Axiom Schema of Separation. But to make this idea totally precise, we would need to be more precise about what counts as an *instance*. What things can you write down in the blank and get a legitimate axiom? You can get paradoxes if you’re not careful about this. To state the rules carefully, we’ll need a theory of “things you can write down”—that is, a theory of *linguistic expressions*. We’ll be working on that soon (particularly in Section 2.4, Section 3.2, and Chapter 5).

A second way of restating the Axiom of Separation uses what’s called *second-order logic* (Chapter 9). Second-order logic lets us “generalize in predicate position.” Putting it roughly, instead of just saying “anything”, we can also say “anyhow.” For any way for a thing to be, there is a subset of A that includes just the elements of A that are that way.

But we are getting way ahead of ourselves. For now, while we should note that there are philosophical and technical subtleties here, we should be able to get by using our intuitive understanding of properties. When we define a subset, we can fill in the blank with any description of an element that seems clear and precise enough.

1.1.12 Example

Here are some more examples of using separation notation to define subsets. Let $C = \{\text{Los Angeles}, \text{San Diego}, \text{San Jose}\}$.

$$\begin{aligned}A_1 &= \{c \in C \mid c \text{ is in Southern California}\} \\A_2 &= \{c \in C \mid c \text{ is not San Diego}\} \\A_3 &= \{c \in C \mid \text{the population of } c \text{ is less than 100}\}\end{aligned}$$

We can also describe the same sets by explicitly listing their elements.

$$\begin{aligned}A_1 &= \{\text{Los Angeles}, \text{San Diego}\} \\A_2 &= \{\text{Los Angeles}, \text{San Jose}\} \\A_3 &= \{\} \quad (\text{the empty set})\end{aligned}$$

1.1.13 Exercise

Let U be a set, and let A and B be subsets of U . Write down the definitions of “union” and “intersection” (Example 1.1.5) using “separation notation” as in Technique 1.1.10. This shows that *there is* a set which is a union of A and B , and there is a set which is an intersection of A and B .

Here’s another basic principle about sets.

1.1.14 Empty Set Axiom

There is a set with no elements. This is called the **empty set**. It is labeled \emptyset or $\{\}$.

(In fact, we could equivalently have used the simpler axiom that *there is a set*. Then we could use Separation to conclude that there is a set with no elements: the set $\{a \in A \mid a \neq a\}$.)

1.1.15 Example

There is a *unique* set with no elements. (This justifies us in calling it “*the* empty set” rather than “*an* empty set”.)

Proof

What we need to show is that if A and A' are *both* empty sets—that is, if A and A' each have no elements—then $A = A'$. We show this in two steps.

1. Every element of A is an element of A' .

This is true because A has no elements! A counterexample would have to be an element of A which is *not* an element of A' , and clearly there are no such

things.

2. Every element of A' is an element of A .

This works just the same way, this time because A' has no elements.

So $A = A'$ (by Extensionality). □

1.1.16 Technique (Existence and Uniqueness)

When we need to show that there is *exactly one* F , or (in other words) that *there is a unique* F , it's usually helpful to break this up into two steps.

1. **Existence.** We show that there is *at least one* F .
2. **Uniqueness.** We show that there is *at most one* F .

The Uniqueness part means that for any x and y which are both F 's, x and y are the very same thing. So to prove there is at most one F , this is a good strategy. *Suppose* that x is F and y is F ; then *show* that $x = y$.

1.2 Functions

Every building in Los Angeles has an address: a certain sequence of numbers and letters that labels that building, like ~~3709 Trousdale Parkway~~. To keep track of the relationship between buildings and addresses, we can consider an **address function**, which we'll call "address". For each building b , address b is its address. Functions are useful throughout logic, because we are often interested in relationships like this one: for example, the relationship between things in the world and the words that we use to label them.

Here's another example: for every number, there is another number which immediately follows it. Zero is followed by one, one by two, and so on. We can represent this relationship between numbers using a function, which is called the **successor function**, and which we'll call suc for short. For each number n , there is a number $\text{suc } n$ which is one more than n .

In general, suppose that A and B are sets. A **function from A to B** assigns an element of B to each element of A . For every element $a \in A$, there is some element of B which is the result of **applying f to a** . This is labeled $f a$. So for every $a \in A$, $f a \in B$.

(Some people write function application with lots of extra parentheses, always writing $f(a)$ rather than $f a$. But I won't do that unless things would be unclear otherwise.)

wise.)

1.2.1 Notation

The notation $f : A \rightarrow B$ means that f is a function from A to B . We call A the **domain** of f , and B the **codomain** of f .

For example, the domain of the address function is the set of Los Angeles buildings, and its codomain is the set of all strings of symbols. The domain and the codomain of the successor function `suc` are both the set of natural numbers $\{0, 1, 2, \dots\}$.

(Sometimes functions are defined to be certain special sets—for instance, as sets of ordered pairs—see Section 1.6 for some discussion. But we won’t bother with that for now. We’ll just treat functions as another basic kind of thing alongside sets. Another thing to be aware of is that some people think of a function as something that can have *more than one* codomain, while we’ll talk about a thing that has both some particular domain and some particular codomain. Terminology among mathematicians is split on this point. We’ll come back to this below.)

We should distinguish the codomain from another thing. Not every string of symbols is the address of some building: there is no building in Los Angeles with the address `00000 Main Stresjkkj`. So there are elements of the codomain of the address function—which I said was the set of all strings of symbols—which are not actually “hit” by the function. We say that the string `00000 Main Stresjkkj` is not in the *range* of the address function.

1.2.2 Definition

The **range** of a function $f : A \rightarrow B$ is the set of elements of B that are assigned by f to some element of A . That is,

$$\text{range } f = \{b \in B \mid \text{for some } a \in A, fa = b\}$$

(What is the range of the successor function?)

We have three different ways of coming up with functions: the *list* method, the *rule* method, and the *relation* method.

1.2.3 Example

Let A be the set $\{1, 2, 3\}$ and let B be the set of cities in California. Then we can define a function $f : A \rightarrow B$ by specifying the value of f for each element of A .

For instance, we could say

$$f(1) = \text{Los Angeles}$$

$$f(2) = \text{San Diego}$$

$$f(3) = \text{San Jose}$$

This definition of f uses the *list* method.

We can also use some handy alternative notation for this kind of function definition:

$$[\quad 1 \mapsto \text{Los Angeles}, \quad 2 \mapsto \text{San Diego}, \quad 3 \mapsto \text{San Jose} \quad]$$

You can read this notation as saying “the function that takes 1 to Los Angeles, 2 to San Diego, and 3 to San Jose.”

1.2.4 Technique (Defining a function using an explicit list of values)

If a set A is finite, we can define a function $f : A \rightarrow B$ by listing out its values one by one.

1.2.5 Example

Another way we could define a function $g : A \rightarrow B$ is using a *rule*:

$$g(n) = \text{the } n\text{th largest city in California (in 2015)} \quad \text{for every } n \in \{1, 2, 3\}$$

1.2.6 Technique (Defining a function using a rule)

This is the most common way of coming up with a function $f : A \rightarrow B$: we precisely describe what “output” value f should have for each “input” value a in A . For example, we can define the function from numbers to numbers that takes each number to the number which is six more than it:

$$fn = n + 6 \quad \text{for each number } n$$

In general, to come up with a function from A to B , first choose a name, like “ f ” (though we would might want to use something more descriptive, like “address” or “suc” or “greatest-prime-divisor”). Then write down

$$f(a) = \underline{\hspace{2cm}} \quad \text{for every } a \in A$$

Fill in the blank with a description of an element of B , where this description can depend on a . For example “ $a + 6$ ”, “ a ’s great-grandfather”, or “the first letter of a ” are all fine descriptions (though which of them make sense will depend on what kind of thing a is—that is, for instance, whether the elements of A include numbers, people, or words).

The third way to come up with a function is the trickiest. Instead of giving an explicit *rule* for what the value fa should be, we can describe a general *relationship* that each input should have to its output. Here are some examples.

- Every building in Los Angeles has an address: that is, for every building b in Los Angeles, there is a string of symbols which is an address for b . So there is a *function*, address, from buildings in Los Angeles to strings of symbols such that, for each building b , address b is an address for b .
- Every number has a successor: that is, for every number n , there is some number that comes immediately after n . So there is a *function*, suc, from numbers to numbers such that, for each n , suc n comes immediately after n .
- For every number n , there is some number which is two more than n . So there is a function f from numbers to numbers such that, for every number n , fn is two more than n .
- For every building b in Los Angeles, there is a person within one mile of b . So there is a function g from buildings to people such that, for each building b , gb is a person within one mile of b .
- For every non-empty set of numbers A , there is some number n which is an element of A . So there is a function h from non-empty sets of numbers to numbers such that, for each non-empty set of numbers A , $hA \in A$.

Notice that the first three examples, each “input” in the domain stands in the relationship to *just one* object in the codomain. A building only has one address, and a number only has one successor, and likewise a number has only one number which is two more than it. But the last two examples aren’t like that. In the last two examples, we didn’t *uniquely* describe the output of the function for each input. But we did describe what relationship the output should stand in to the input, and that is enough.

1.2.7 Technique (Coming up with a function using a relation)

Say we want to come up with a function from A to B . We can do this by describing a relationship that should hold between the inputs and outputs of the function. First, choose a name for the function, like f . Then write down this:

For each $a \in A$ and $b \in B$, if $fa = b$, then _____.

Fill in the blank with some relationship that should hold between a and b . You’re not quite done: in order to conclude that there is a function like this, you first need to *show* this:

For each $a \in A$, there is some $b \in B$ such that _____.

Here you fill in the blank with the same relation that you wrote down in the first blank. Once you have shown this, then you're good to go: you can conclude that *there is a function* that satisfies the relation you wrote down.

Notice that there's another way of writing down the key property of your function f , which is a little more concise. Instead of saying

For each $a \in A$ and $b \in B$, if $fa = b$, then $F(a, b)$.

(where $F(a, b)$ is the relationship between a and b that you want) you could write this equivalent thing instead:

For each $a \in A$, $F(a, fa)$

This is just another more concise way of saying that the relation F holds between each input a and its corresponding output fa . To justify this, what you need to prove first is

For each $a \in A$, there is some $b \in B$ such that $F(a, b)$.

(Of course, what you actually write down depends on which relation F stands for.)

The “rule” method for defining a function is really just a more specific version of the “relation” method. If we define the function f using a rule

$f(a) = \text{_____}$ for each $a \in A$

Then we can think of this as defining f using a *relation*, like this:

For each each $a \in A$ and $b \in B$, if $f(a) = b$ then $b = \text{_____}$.

Here we fill in the blank with the very same description that we used for our rule.

Furthermore, the “list” method for defining functions is really just a more specific version of the “rule” method. For example, we can think of our function

[1 \mapsto Los Angeles, 2 \mapsto San Diego, 3 \mapsto San Jose]

as defined by the three-part rule

$$f(n) = \begin{cases} \text{Los Angeles} & \text{if } n = 1 \\ \text{San Diego} & \text{if } n = 2 \\ \text{San Jose} & \text{if } n = 3 \end{cases}$$

So in fact, all three of these techniques for coming up with functions are versions of the “relation” method, and they are all based on the same fundamental principle. We can state the basic general principle like this.

1.2.8 Axiom of Choice

Let F be a relation. Let A and B be sets. If for every $a \in A$ there is some $b \in B$ such that $F(a, b)$, then there is a function $f : A \rightarrow B$ such that for every $a \in A$, $F(a, fa)$.

This principle is also tricky in the same way as the Axiom of Separation. I stated it in terms of a *relation F*. But again, it would be hard work to give a theory of relations, in addition to our theory of sets and functions. Again, one way to make this principle precise is to think of it as an axiom *schema*: we get a different axiom for each way of replacing $F(a, b)$ with a precise description of a relationship between a and b . To make this fully precise, we would have to spell out the rules for what statements about a and b you are allowed to “plug in” for $F(a, b)$. We can do that using ideas that come later in the text. But in practice, we can get by with common sense.

As it happens, Choice is more controversial than the rest of standard set theory, for a couple of reasons. First, Choice has some very surprising consequences when it comes to infinite sets. One famous example is the Banach-Tarski Theorem: you can use Choice to prove that a unit sphere can be divided into four pieces that can be rigidly rearranged to form *two* unit spheres, each exactly like the original. Second (and relatedly), unlike the other standard axioms of set theory, Choice is *non-constructive*. Choice tells us that there are functions that we have no way of describing uniquely. This challenges the philosophical idea that mathematical objects are things that we mentally “construct” in some sense.

These controversies are entirely about the kind of applications of Choice where we know that for every a there is *at least one* b such that $F(a, b)$, but we *don't* know that for every a there is *exactly one* b such that $F(a, b)$. For most of what we do in this text, we could get by with a restricted “Axiom of Function Existence,” which only applies in the “exactly one” case. But a few things in this text really do rely on the full power of “at least one” Choice. In this text, I don’t bother to carefully distinguish the things that rely on full-fledged Choice from the things that don’t.

Now let’s turn to another basic technique for working with functions.

1.2.9 Example

Recall the functions f and g from Example 1.2.3, which take the numbers in $\{1, 2, 3\}$ to cities in California. As it happens, though we used different definitions,

f and g are the very same function. The largest city in California is Los Angeles, the second largest is San Diego, and the third largest is San Jose. The functions f and g have the same “output” for every “input.” Furthermore, there is no more to a function than what “output” it has for each “input”—it doesn’t matter how this relationship is *described*. So f and g are the same function.

1.2.10 Technique (Proving Functions are Equal)

Say f and g are functions from A to B , and we want to show that $f = g$ —that is, we want to show that f and g are the same function. (Again, remember that just because we are using two different *names* for the function, that doesn’t mean f and g are different *functions*!) To show this, we need to show that f and g have the same “output” for each possible “input”. The proof usually goes like this:

Let a be any element of A . [Fill in reasoning.] So $fa = ga$. Therefore,
 $f = g$.

Here is a simple example.

1.2.11 Example

Let $\mathbb{1}$ be a set with exactly one element. Prove that for any set A , there is exactly one function from A to $\mathbb{1}$.

Proof

Showing that *there is exactly one* of something has two parts (Technique 1.1.16).

Existence. Let x be the single element of the set $\mathbb{1}$. For any set A , there is a function $f : A \rightarrow \mathbb{1}$ defined by the rule $fa = x$ for each $a \in A$.

Uniqueness. Consider any functions $f : A \rightarrow \mathbb{1}$ and $g : A \rightarrow \mathbb{1}$. We will show that $f = g$. To show this, let $a \in A$. Then since $fa \in \mathbb{1}$, and $ga \in \mathbb{1}$, and $\mathbb{1}$ contains only one element, we know $fa = ga$. Since this holds for every $a \in A$, this proves that $f = g$. \square

Once again, the reason this strategy works is because of a fundamental general principle about functions—another axiom.

1.2.12 Axiom of Function Extensionality

For any functions $f : A \rightarrow B$ and $g : A \rightarrow B$, if $fa = ga$ for every $a \in A$, then $f = g$.

Extensionality and Choice work together to tell us what functions are like. Choice guarantees that there are *enough* functions, and Extensionality guarantees that there are *not too many* functions.

1.2.13 Exercise

Suppose $\mathbb{2}$ is a set with exactly two elements, which we'll call True and False. We can think of functions to $\mathbb{2}$ as “tests”, which say True for things that pass the test and False for the rest.

If X is a subset of A , we can define a function from A to $\mathbb{2}$ which we call the **characteristic function** of X , or $\text{char } X : A \rightarrow \mathbb{2}$ for short. Intuitively, this is the function that says whether something is an element of X . For every $a \in A$,

$$(\text{char } X)a = \begin{cases} \text{True} & \text{if } a \in X \\ \text{False} & \text{otherwise} \end{cases}$$

We can also go the other way around. If $f : A \rightarrow \mathbb{2}$ is a function, we can define a subset of A that includes just the things that pass the f -test. This is called the **kernel** of f , or $\ker f$.

$$\ker f = \{a \in A \mid fa = \text{True}\}$$

- (a) Show that for any set $X \subseteq A$,

$$\ker(\text{char } X) = X$$

- (b) Show that for any function $f : A \rightarrow \mathbb{2}$,

$$\text{char}(\ker f) = f$$

Here's a special feature of the address function: no two buildings have exactly the same address. (Maybe this isn't quite true, since there can be more than one building on the same lot. But let's ignore this complication.) In other words, for any two different buildings b and b' , address b and address b' are two different strings. Or to put that the other way around, for any buildings b and b' , if address $b =$ address b' , then $b = b'$. A function like this is called *one-to-one*: it never takes two or more inputs to one output.

On the other hand, as we noted earlier, there are many different strings of symbols which are not addresses of any building at all, like `alfkj/404.html`. We say that this function is not *onto*: its range does not completely “cover” the set of strings of

symbols.

1.2.14 Definition

- (a) A function $f : A \rightarrow B$ is **one-to-one** (or *injective*) iff for each $a, a' \in A$, if $fa = fa'$ then $a = a'$.
- (b) A function $f : A \rightarrow B$ is **onto** (or *surjective*) iff for each $b \in B$ there is some $a \in A$ such that $fa = b$.
- (c) A function $f : A \rightarrow B$ is a **one-to-one correspondence** (or *bijection*) iff it is both one-to-one and onto.

Here's another way of putting this. The elements of the *domain* of a function are its "possible inputs," and the elements of the *codomain* of a function are its "possible outputs." Each possible input results in some possible output. For a *one-to-one* function, each possible output is the result of *at most one* possible input. For an *onto* function, each possible output is the result of *at least one* possible input. Thus, for a *one-to-one correspondence*, each possible output is the result of *exactly one* possible input.

1.2.15 Exercise

Give an example (other than the address function) of a function which is ...

- (a) One-to-one but not onto.
- (b) Onto but not one-to-one.
- (c) One-to-one and onto.

1.2.16 Exercise

- (a) For any function $f : A \rightarrow B$, f is onto iff the range of f is B .
- (b) For any sets A and B , there is a one-to-one function $f : A \rightarrow B$ iff there is a one-to-one correspondence from A to some subset of B .

1.2.17 Example

If $f : A \rightarrow B$ and $g : B \rightarrow C$ are each one-to-one, then there is a one-to-one function from A to C .

Proof

Let $f : A \rightarrow B$ and $g : B \rightarrow C$ be one-to-one functions. We can use these

functions to define a function $h : A \rightarrow C$, like this:

$$h(a) = g(fa) \quad \text{for every } a \in A$$

Intuitively, we are chaining the two functions together: first apply f , then apply g . We need to check that the resulting function h is one-to-one. Let $a, a' \in A$, and suppose that $ha = ha'$. That is,

$$g(fa) = g(fa')$$

Since g is one-to-one, this tells us that

$$fa = fa'$$

Then since f is one-to-one, this tells us that

$$a = a'$$

This shows that for any a and a' in A , if $ha = ha'$, then $a = a'$, which means that h is one-to-one. \square

1.2.18 Exercise

- (a) If $f : A \rightarrow B$ and $g : B \rightarrow C$ are each onto, then there is an onto function from A to C .
- (b) If $f : A \rightarrow B$ and $g : B \rightarrow C$ are each one-to-one correspondences, then there is a one-to-one correspondence from A to C .

1.2.19 Exercise

If B is a non-empty subset of C , and there is an onto function from A to C , then there is an onto function from A to B .

1.2.20 Definition

Let $f : A \rightarrow B$ and $g : B \rightarrow A$ be functions. We say g and f are **inverses** iff we have both

$$\begin{aligned} g(f(a)) &= a && \text{for every } a \in A \\ f(g(b)) &= b && \text{for every } b \in B \end{aligned}$$

That is, the two functions f and g undo each other.

1.2.21 Proposition

Every one-to-one correspondence has an inverse.

Proof

Suppose $f : A \rightarrow B$ is a one-to-one correspondence. That is, f is one-to-one and onto. Since f is onto, we know

For each $b \in B$, there is some $a \in A$ such that $fa = b$.

Then by Choice, that means there is a *function* $g : B \rightarrow A$ such that,

$$f(gb) = b \quad \text{for every } b \in B$$

That tells us half of what we need to prove that g is an inverse of f . For the other half, suppose $a \in A$. Then, by the way we chose g , we have

$$f(g(fa)) = fa$$

Since f is one-to-one, this implies that $g(fa) = a$. So g is an inverse of f . \square

1.2.22 Exercise

Every function that has an inverse is a one-to-one correspondence. That is, if $f : A \rightarrow B$ has an inverse $g : B \rightarrow A$, then f is a one-to-one correspondence.

The previous two facts, taken together, tell us that a function is a one-to-one correspondence *if and only if* it has an inverse. That means that, from now on, you can think of “function with an inverse” as if it was an alternative *definition* of “one-to-one correspondence,” right there alongside the official definition “function which is one-to-one and onto.” When you are doing any exercise involving one-to-one correspondences, you can unpack that in either of these two equivalent ways. You should go straight to whichever version makes the exercise easier to solve.

1.2.23 Exercise

For any sets A and B , if there is a one-to-one correspondence from A to B , then there is also a one-to-one correspondence from B to A .

1.3 Ordered Pairs

Sometimes we want to work with functions with more than one input (or more than one output). For example, addition takes *two* numbers m and n and spits out a single number $m + n$. One way to approach this would be to work out a whole separate theory of “multiple-input functions” in addition to the “single-input functions”—but that would end up repeating lots of work. A nicer way to do it is to think of a

function that takes *two* numbers as its input as really being a function that takes one thing, a *pair* of numbers, as its input. That is, addition is a function from pairs of numbers to numbers.

An *ordered pair* (a, b) is something whose *first element* is a , and whose *second element* is b . Unlike a set, the elements of a pair are *ordered* (as the name suggests). The ordered pair $(1, 2)$ is different from the ordered pair $(2, 1)$. In contrast, the *set* $\{1, 2\}$ is the very same thing as the set $\{2, 1\}$, because they have the same elements.

1.3.1 Axiom of Pairs

For any sets A and B , there is a set $A \times B$ whose elements are called **ordered pairs**. Each ordered pair in $A \times B$ has a **first element**, which is an element of A , and a **second element**, which is an element of B . For any $a \in A$ and $b \in B$, there is exactly one ordered pair whose first element is a , and whose second element is b . This pair is labeled (a, b) .

1.3.2 Exercise

Let \emptyset , $\mathbb{1}$, and $\mathbb{2}$ be sets with 0, 1, and 2 elements, respectively. How many elements do the following sets have? Explain your answers.

- (a) $\mathbb{1} \times \mathbb{2}$
- (b) $\mathbb{2} \times \emptyset$
- (c) $(\mathbb{2} \times \mathbb{2}) \times \mathbb{2}$

1.3.3 Exercise

Show that for any sets A and B , there is a one-to-one correspondence between $A \times B$ and $B \times A$.

1.3.4 Exercise

For any set A , the **diagonal** of $A \times A$ is the set of all ordered pairs of the form (a, a) . That is, it's the set

$$\{(a_1, a_2) \in A \times A \mid a_1 = a_2\}$$

Show that for any set A , there is a one-to-one correspondence between A and the diagonal of $A \times A$.

1.3.5 Exercise

For any sets A , B , and C , there is a one-to-one correspondence between $A \times B \times C$ and $A \times (B \times C)$.

1.3.6 Exercise

For any function $f : A \rightarrow B$, there is a set of ordered pairs in $A \times B$ called the **graph** of f : this is the set of pairs

$$\{(a, b) \mid f a = b\}$$

Suppose that X is a subset of $A \times B$. Say that X is **functional** iff, for each $a \in A$, there is exactly one $b \in B$ such that (a, b) is in X . Show that X is functional iff X is the graph of some function from A to B .

1.4 Higher-Order Sets and Functions

Sets and functions become more powerful when we start to consider sets of *sets*, and sets of functions, and functions whose inputs and outputs are themselves sets or functions. These are “higher-order” sets and functions. Let’s start with a simple example.

1.4.1 Axiom of Power Sets

For any set A there is set of all subsets of A . This is called the **power set** of A , or PA for short. In other words, for every B ,

$$B \in PA \quad \text{iff} \quad B \subseteq A$$

1.4.2 Example

The power set of $\{0, 1\}$ is the four-membered set

$$\{\{\}, \{0\}, \{1\}, \{0, 1\}\}$$

1.4.3 Exercise

(a) For any set A , there is a one-to-one function from A to PA .

(b) For any non-empty set A , there is an onto function from PA to A .

Similarly, it is often useful to consider *sets of functions*.

1.4.4 Axiom of Functions

For any sets A and B , there is a set containing every function from A to B . This set

is labeled B^A , or $A \rightarrow B$.

1.4.5 Exercise

For each function $f : A \rightarrow B$, the *range* of f is a subset of B : the set of elements of B which are equal to fa for some $a \in A$ (Definition 1.2.2). In other words, for each function $f \in B^A$, there is a set

$$\text{range } f \in PB$$

So this defines a higher-order *function*

$$\text{range} : B^A \rightarrow PB$$

Is the range function one-to-one? Is it onto? Justify your answers.

1.4.6 Exercise

Suppose A and B are sets. If A is not empty, then there is a one-to-one function from B to B^A .

1.4.7 Exercise

In Exercise 1.2.13 we defined the *characteristic function* for a subset $X \subseteq A$ to be a certain function $\text{char } X : A \rightarrow 2$. So this defines a higher-order function:

$$\text{char} : PA \rightarrow 2^A$$

Show that this function is a one-to-one correspondence.

1.4.8 Example

For any set A , there is a one-to-one correspondence from A^2 (the set of functions from a two-element set to A) to $A \times A$ (the set of ordered pairs of elements of A).

Proof

Let's call the two elements of 2 "1" and "2". The rough idea is that being given a value for 1 and a value for 2 amounts to the same thing as being given two values, in order, which amounts to the same as being given an ordered pair of values.

First we will define a function from A^2 to $A \times A$, and then we will show that it is one-to-one and onto. We can define a function f as follows:

$$fh = (h1, h2) \quad \text{for each function } h : 2 \rightarrow A$$

To show that f is one-to-one, suppose that h and h' are each functions from $\mathbb{2}$ to A , and $fh = fh'$. That is, $(h1, h2) = (h'1, h'2)$. That means that these ordered pairs have the same first element and the same second element, so $h1 = h'1$ and $h2 = h'2$. Since 1 and 2 are the only elements of $\mathbb{2}$, this shows that h and h' have the same output for every input. So by Function Extensionality, $h = h'$. So f is one-to-one.

To show that f is onto, suppose that (a, a') is any element of $A \times A$. We want to show that there is some element h in $A^{\mathbb{2}}$ such that $fh = (a, a')$. And there is: we can let

$$h = [1 \mapsto a, \quad 2 \mapsto a']$$

Then $fh = (h1, h2) = (a, a')$, which is what we wanted. \square

1.4.9 Exercise

Let $\mathbb{1}$ be a set with exactly one element. For any set A , there is a one-to-one correspondence from A to $A^{\mathbb{1}}$.

1.4.10 Exercise

Let A , B , and C be any sets. There is a one-to-one correspondence between $C^{A \times B}$ (the set of two-place functions from $A \times B$ to C) and $(C^B)^A$ (the set of *higher-order* functions from A to functions from B to C).

(Applying this one-to-one correspondence is called “currying” a function, or sometimes “Schönfinkelizing” it, after the two people who independently discovered it, Curry and Schönfinkel.)

1.5 The Uncollectable

It is very useful to collect together some things into a single thing—a set. This move from *many things* to a *single set* is very natural, and you might think that it just amounts to an entirely innocent redescription. What difference could there be between there being some people, and there being a *set* of people?

But things are not so straightforward. Not every way of picking out *some things* picks out a *set*. Some things cannot be “gathered together” in a single set. This is weird! It might not be feasible to bring some things into the same *room*, because there are too many of them or they are too big or too far apart. But putting some elements into a set isn’t like putting them in a room. For example, there is a set

containing the Moon, the Eiffel Tower, every finite string of letters which does not appear in any book in the Library of Congress, and the number seven. If there are sets as gerrymandered and arbitrary as this, it is hard to imagine what could possibly prevent some things from all going together in a set. We are faced with a very puzzling and counterintuitive result.

The proof that some things don't form a set is very short, but it uses a clever trick. As we have discussed, sets can be elements of “higher-order” sets. Can a set be an element of *itself*? We have not said anything about this one way or the other. Normally this is ruled out by an extra axiom, called the Axiom of Foundation, which says (in part) that set membership can never go around in a circle. We won't need the Axiom of Foundation for the purposes of this text. But the clever trick uses the idea of trying to “feed a set to itself.”

1.5.1 Exercise (Russell's Paradox)

Call a set X a **self-member** iff X is an element of X . Call X a **non-self-member** iff X is not a self-member. Show that there is no set that contains all and only the non-self-members.

(Note that the Axiom of Foundation would imply that *all* sets are non-self-members. But we don't have to use this axiom to do this problem.)

1.5.2 Exercise

- (a) There is no set of all sets.
- (b) There is no *universal set* containing everything there is.

These limits on set-formation are the reason why we stated the Axiom of Separation in the careful way that we did. The Axiom of Separation lets us *cut down* a set using some description of its elements. For example, if we start with a set of all the numbers, then we can cut it down to a set of all the odd numbers. But Separation doesn't let us *build up* a set from some arbitrary description. For example, we can't write down

$$\{x \mid x \notin x\}$$

and expect this to pick out a set—in fact, there is no such set, because of Russell's Paradox. Instead, if we start with a set A , we *can* write down

$$\{x \in A \mid x \notin x\}$$

By Separation, this will give us a set—the set of all elements of A which are not self-members. There is nothing paradoxical about this set. (In fact, assuming the

Axiom of Foundation, which implies there are no self-members, this will just be the same set A that we started with.)

Russell's paradox kind of feels like a party trick. But it is really important, for two different reasons. First, it is foundationally important: the surprising fact that not just any things form a set, and in particular that there is no universal set, is crucial to understanding how set theory works at all. It makes a big technical difference to how we state our basic axioms, and a big philosophical difference to how we think about what sets are. Second, the devious trick we used in Russell's paradox is important—feeding sets to themselves in order to get a contradiction. This *self-application* trick (which is often called “diagonalization”) will be used over and over again in this text: it shows up along the way to almost all of the central theorems in this course, about what is uncountable, inexpressible, undecidable, and unprovable. So it's worth going slowly to make sure we really understand what is going on here. While we're at it, we can also work out a more general lesson.

Let's consider an analogous puzzle (Russell [1918] 2009, 101). A certain small English community in 1918 consists only of clean-shaven men (a Cambridge college, say). One of these clean-shaven men is a barber. Someone tells us:

The barber shaves all the men in the community who do not shave themselves, and only them.

But this can't be true! Does the barber shave himself? If so, then he shaves someone who shaves himself, which contradicts what we are told. If not, then he fails to shave someone who does not shave himself, which again contradicts what we are told. So this situation is impossible (and not just because of the implausibility of Oxbridge social structure): *nobody* shaves just those people who do not shave themselves.

This was just the same reasoning as Russell's paradox, except instead of considering the relation “ x is a an element of y ”, we considered the relation “ x is shaved by y . ” Looking at it this way makes it clear that nothing depends on *which* relation we were talking about—there is a lesson here which is not specifically about either elements or shaving.

We can also redescribe things in terms of *functions*, instead of relations. Let A be the set of men in that community, and let f be the function that takes each person a to the set of people that a shaves. (It's fine if f takes some people to the empty set.) Call this “the shaving function.” The shaving function is a function $f : A \rightarrow PA$, such that, for any people a_1 and a_2 in A ,

$$a_2 \in fa_1 \quad \text{iff} \quad a_1 \text{ shaves } a_2$$

Now we can restate the lesson of the “barber paradox” in terms of the shaving function. What it told us is that there is a certain set of men X (namely, the set of men who do not shave themselves) such that nobody shaves just the men in X . Anybody who did that would be like the paradoxical barber, who shaves himself if and only if he doesn’t shave himself, which is impossible. In short, there is no $a \in A$ such that $fa = X$. This is not a contradiction: what it tells us is simply that the set X is not in the *range* of the shaving function f . So what we have proved is that the shaving function is *not onto*.

Again, this lesson has nothing special to do with *shaving*. Our reasoning applies equally well to *any* set A , and *any* function $f : A \rightarrow PA$. This general fact turns out to be very important.

1.5.3 Exercise (Cantor’s Theorem)

For any set A , there is no onto function from A to PA .

Hint. Use the same reasoning as the barber paradox to show that for any function $f : A \rightarrow PA$, there is a set $X \subseteq A$ which is not in the range of f .

Notice that we can also use Cantor’s Theorem to give an alternative proof that there is no set of all sets. Suppose there were a set S that contained every set. Then in particular every *subset* of S would also be in S . That means we would have $PS \subseteq S$. But then we could define an onto function from S to PS : for example, we could take each $X \in PS$ to itself, and if there are any sets left over we could take them to the empty set.² This would contradict Cantor’s Theorem.

In a moment we’ll come back to why Cantor’s Theorem matters. First, though, let’s look at the proof idea—the self-application trick—from a couple other perspectives.

Here is a way of picturing the self-application trick that gives it the name “diagonalization.” Take a simple example where the elements of the set A are just Al, Bea, and Cece. Then consider any function f from elements of A to subsets of A . Here is an example of a function like this:

$$\begin{aligned} \text{Al} &\mapsto \{ \quad \text{Al}, \quad \text{Bea} \quad \} \\ \text{Bea} &\mapsto \{ \quad \quad \quad \quad \quad \} \\ \text{Cece} &\mapsto \{ \quad \text{Al}, \quad \quad \text{Cece} \quad \} \end{aligned}$$

(The unusual spacing is just to keep the same elements visually lined up for each set.) To show that f is not onto, we need a rule for finding a subset of A which is

²The sets that are “left over” would be “impure” sets containing elements that are not themselves sets.

not in the range of f . This rule should work not just for this example, but for any choice of a set A and a function $f : A \rightarrow PA$.

We can represent this function in a slightly different way. As we showed in Exercise 1.2.13, we can describe a subset $X \subseteq A$ by answering a series of True-or-False questions: for each element of A , we just need to know whether or not it is in X . So we can draw a picture of this particular function f by listing the answers to these questions:

	Al	Bea	Cece
Al \mapsto	True	True	False
Bea \mapsto	False	False	False
Cece \mapsto	True	False	True

As before, the rows of this diagram correspond to the “inputs” to the function f , which are just the elements $a \in A$. The list of Trues and Falses in row a correspond to the “output” set fa , represented by its characteristic function. Row Al, column Cece says False, because Cece is not an element of $f(Al)$. Row Cece, column Al says True, because Al is an element of $f(Cece)$. In general, at any row a_1 and column a_2 , the table says True if $a_2 \in fa_1$, and it says False if $a_2 \notin fa_1$. (Make sure you see why this table matches the definition of f given above.)

We are trying to come up with a recipe that, given any table like this, gives us a set X that is not represented by any row of the table. To do that, it’s enough to guarantee that for each row, X disagrees with the table for at least one True-or-False question in that row. That is, for each row a_1 , there is some element $a_2 \in A$ such that either a_2 is in fa_1 but not in X , or else a_2 is in X but not in fa_1 .

Here’s a trick that accomplishes this: we can work our way down the *diagonal* of the table: row Al, column Al; row Bea, column Bea; row Cece, column Cece. If we make sure that our set X doesn’t match any of these, then X is different from every row of the table in at least one place. That is, we can make sure that X disagrees with the Al-row about Al, and disagrees with the Bea-row about Bea, and disagrees with the Cece-row about Cece. Since the diagonal says “True, False, True”, we just want to flip this and say “False, True, False”. That is, we can let X be the set which does not contain Al, which does contain Bea, and which does not contain Cece—that is, in this case it’s the set $\{Bea\}$.

In general, the diagonal of this table tells us, for each $a \in A$, whether a is an element of fa . The trick is to consider the set that “flips” the diagonal, by including a iff a is *not* an element of fa . This brings us back to the very same Russell-style set we considered before: the set $\{a \in A \mid a \notin fa\}$, the set of elements which are not among the things “shaved by” themselves.

Here's one more perspective on Russell and Cantor's arguments, which connects them to an idea we will explore more deeply later (Section 6.7). The *Liar Paradox* is about the sentence

This sentence is not true.

Call this sentence L . Since apparently what L says is just that L is not true, it seems that

(*) L is true iff L is not true

Is L true? If so, then by (*) L is not true, which is a contradiction. Alternatively, if L is not true, then by (*) L is true, so again we have a contradiction. Since we have a contradiction either way, we have a paradox.

Russell's Paradox and Cantor's Theorem have the same structure as a variant of the Liar Paradox, called *Grelling's Paradox*. Unlike the original Liar, this variant does not depend on a self-referential sentence. Adjectives, like `short`, `interesting`, or `simple`, are words that can be truly applied to some things but not others. (Let's ignore the problems of vagueness for now, and pretend that all of these adjectives are perfectly precise.) The *extension* of an adjective is the set of things that it truly applies to. So if A is the set of adjectives and D is some set of things, then the *extension function* for D is a function $f : A \rightarrow PD$ that takes each adjective $a \in A$ to the set of things in D that a truly applies to.

Words are themselves among the things that adjectives can apply to: for instance, `red` is a short word, so the adjective `short` applies to `red`. Furthermore, `short` is a short word, so `short` applies to itself; `long` is not a long word, so `long` does not apply to itself. Some adjectives self-apply, and others don't. Now consider *the set of all adjectives which do not self-apply*. Is there any adjective which has this set as its extension? Suppose there were such an adjective: in particular, suppose that the adjective `non-self-applying` applies just to those adjectives which do not self-apply. For all adjectives a :

`non-self-applying` applies to a iff a does not apply to a

Does `non-self-applying` self-apply? If so, then it applies to some adjective which self-applies—namely `non-self-applying` itself—contradicting the assumption. If not, then it fails to apply to some adjective which does not self-apply—again, `non-self-applying` itself—again contradicting the assumption.

(This reasoning is just like the “barber paradox”; but unlike the “barber paradox”, this case seems genuinely paradoxical, like the Liar: after all, `non-self-applying` is an expression we can understand, that applies to some adjectives, like `short` and

not others, like `long`. So what else could its extension be, if not the set of adjectives which do not self-apply? This is a hard philosophical problem.)

Let f be the extension function for A , which takes each adjective in A to the set of adjectives that a truly applies to. So the set of adjectives that do not self-apply is the set

$$X = \{a \in A \mid a \notin fa\}$$

The reasoning we just went through shows that there is no adjective a such that $fa = X$. Once again, f is not onto. Not every set of things is the extension of some adjective. This is a simple version of a kind of reasoning that will be very important later on when we consider limits on what can be expressed in language and what can be proved.

Another reason that Cantor's Theorem is important is that it underlies a very useful technique called "counting arguments." We will return to this in more detail in Chapter 4, but for now let's look at a few examples of the basic idea. Intuitively, Cantor's Theorem can tell us when two sets are mismatched in a way that prevents one set from "covering" or "representing" all of another.

1.5.4 Example (Undefinable Sets)

Let S be a set of *strings of symbols*. Let L be a set of *descriptions*, and suppose that each description is a string. (That is, $L \subseteq S$.) Suppose that for any pair of a description $d \in L$ and a string $s \in S$, either d is *true of* s or else it is not. A set of strings X is *definable* iff there is some description $d \in L$ such that d is true of each string $s \in X$ and d is not true of any string $s \notin X$. Otherwise, X is *undefinable*. Show that there exists at least one undefinable set of strings.

Proof

The basic idea is that if every set was definable, then there would be an onto function from strings to sets of strings. Consider the function that takes each description $d \in L$ to the set of strings that d is true of. That is, for each description $d \in L$, let

$$f(d) = \{s \in S \mid d \text{ is true of } s\}$$

Suppose for contradiction there are no undefinable sets of strings: that is, every set of strings is definable. This means that $f : L \rightarrow PS$ is onto. But L is a subset of S , so PL is a subset of PS . So Exercise 1.2.19 tells us that there is an onto function from L to PL . This contradicts Cantor's Theorem. \square

1.5.5 Exercise (Undecidable Sets)

Let S be a set of *strings*. Let P be a set of *programs*. Each program is a string in S . (That is, $P \subseteq S$.)

We can *run* a program with any given *input* string, and the program may or may not *succeed* (for example, by eventually printing out the result **True**). So we have a two-place relation *program A succeeds with input string s*.

Say a set of strings X is *decidable* iff there is some program A that succeeds for all and only the strings in X . If there is no program A like this, then X is *undecidable*.

Show that there is at least one undecidable set of strings.

Hint. Consider the function that takes each program A to the set of all strings s that A succeeds with.

1.5.6 Exercise (Kaplan's Paradox)

Let P be a set of *propositions*, and let W be a set of *possible worlds*. We'll consider two relations between propositions and possible worlds. First, a proposition can be *true at* a possible world. Second, a proposition p can be the only proposition that anyone believes at w ; in this case we say that w *singles out* p .

We'll make two assumptions about these relations. First, for any set X of possible worlds, there is some proposition p_X which is true at each possible world in X , and which is not true at any possible world which is not in X . Second, no world singles out more than one proposition.

Given these assumptions, show that there is at least one proposition which is not singled out by any possible world. In other words, some proposition cannot possibly be uniquely believed.

Hint. Consider the function that takes each world w that singles out some proposition p to the set of worlds at which p is true.

1.6 Simplifications of Set Theory*

We have introduced many different principles about sets as “axioms”. But these principles are not all *independent* of one another. In fact, we can prove some of these principles from others. This allows us to reduce the number of assumptions that our reasoning relies on.

A closely related point is that we have treated several different kinds of objects as “*sui generis*”: sets, ordered pairs, and functions were each introduced separately, and each as a kind of thing to be understood on its own terms. But in fact, there are ways of “constructing” some of these things from others. This allows us to simplify our abstract *ontology*.

One tricky point is that there is more than one way to do this—and the different ways of doing it provide us *different* pictures of our primitive ontology and basic assumptions. So if we are taking seriously the question of which of these kinds of objects (sets, or functions, or pairs) are *fundamental*, and which of these principles about them are really fundamental *axioms*, then we have many different choices available. It isn’t obvious how we would choose between them.

There is one choice of axioms which at least has the weight of historical tradition behind it. This axiomatization is called “Zermelo-Fraenkel Set Theory with Choice”, or **ZFC**, after two of its main discoverers (Ernst Zermelo and Abraham Fraenkel) and one of its main distinctive axioms (the Axiom of Choice). I’ll briefly sketch here how this goes and how it can be used to derive the other axioms I’ve mentioned in this chapter. (For now, though, I’ll be setting aside the distinctive issues arising for *infinite* sets. We’ll discuss this in the next chapter.) This way of presenting set theory is so common that it is what many people mean by “set theory” or “standard set theory”.³

ZFC uses only one primitive kind of object, which is a *set*, and the basic relation of being an *element* of a set.

(One tricky point worth noticing is that ZFC is standardly written in a way that presupposes that *everything* is a set. For instance, the standard way of writing the Axiom of Extensionality says “For any x and y , if x and y have exactly the same elements, then $x = y$. ” But suppose that I am not a set, and so I have no elements. Then this version of the Axiom of Extensionality implies that I am identical to the empty set, since we both have exactly the same elements—none at all. The same would go for you, or Jupiter, or anything else that has no elements. There is a standard way of fixing this up, and it is called **ZFCU**, where the U stands for “urelements”: things which are not sets, but are elements of sets.⁴ I won’t be fussy about the distinction, and in this section I’ll keep calling this theory “ZFC”, even though that isn’t quite historically accurate.)

³For a much more detailed introduction to standard set theory with lots of philosophical discussion of its motivations, I recommend Potter (2004).

⁴I suppose the U probably really stands for the German word *Urelemente*, which means “primordial elements,” from which the English word is borrowed.

ZFC has five axioms that we have already discussed, one we will discuss in the next chapter (the Axiom of Infinity) and three additional axioms that we won't need to use in this course. Here are four of the five familiar axioms.

Empty Set Axiom. There is a set with no elements.

Axiom of Extensionality. For any sets A and B , if every element of A is an element of B , and every element of B is an element of A , then A and B are the very same set.

Axiom of Power Sets. For any set A , there is a set of all subsets of A .

Axiom of Separation. For any set A , there is a set whose elements are just those elements a of A such that $F(a)$.

As we noted in Section 1.1, one way of understanding this more precisely is as an *axiom schema*: $F(a)$ can be replaced with any precise description of a . A different way of doing it uses *second-order quantification*. It turns out that there are not just important philosophical differences, but also important *mathematical* differences between these two different approaches; see Chapter 10.

Here is the fifth familiar axiom:

Axiom of Choice. Let A and B be sets. Suppose that for each element $a \in A$, there is some element $b \in B$ such that $F(a, b)$. Then there is a function $f : A \rightarrow B$ such that, for each $a \in A$, $F(a, f a)$.⁵

But there is something important to notice about the last one here, the Axiom of Choice. This is an axiom about *functions*. But functions are not a basic concept in ZFC. So in order to make sense of the Axiom of Choice, we have to say what “function $f : A \rightarrow B$ ” means (as well as “ $f a$ ”). The standard way to do this uses the idea from Exercise 1.3.6: every function can be represented by a *graph*, which is a functional set of ordered pairs. In ZFC, we simply define the word “function” to mean “functional set of ordered pairs.” In other words, ZFC uses this definition:

1.6.1 Definition

A **function** from A to B is a set of ordered pairs $f \subseteq A \times B$ such that for each $a \in A$ there is exactly one $b \in B$ such that $(a, b) \in f$. For $a \in A$, we let $f a$ stand for the unique $b \in B$ such that $(a, b) \in f$.

This pushes the problem back a bit. But note also that *ordered pair* is not a basic concept in ZFC. So we also have to say what “ $A \times B$ ” and “ (a, b) ” are supposed to

⁵I have also written the Axiom of Choice schematically: $F(a, b)$ can be replaced by any precise description of a and b . But in fact in this case it is possible, and more standard, to rewrite the axiom schema as a single axiom, by talking about sets of ordered pairs instead of relations.

mean in this definition. The standard way to do this uses a clever trick. We can use unordered *sets* to represent ordered pairs. Of course, we can't just represent (a, b) with the set $\{a, b\}$. If we did that, then (a, b) and (b, a) would be represented by the very same set, which isn't what we want. Here's the trick: we can instead represent the ordered pair (a, b) with the set $X = \{\{a\}, \{a, b\}\}$. The two elements of the pair, a and b , are guaranteed to play different “roles” within X (unless $a = b$). The set X has just one element Y that is itself a set with only one element; the unique element of Y is the first element of the pair, a . If X has an element Z which has two elements, then just one element of Z is different from a , and this is the second element of the pair, b . But X might not have any element with two elements: in this case, X represents the pair (a, a) .

1.6.2 Definition

For any a and b , let the **ordered pair** (a, b) be the set $\{\{a\}, \{a, b\}\}$. If X is an ordered pair and a and b are objects, we call a the **first element** of X iff $\{a\} \in X$, and we call b the **second element** of X iff $\{a, b\} \in X$, where a is the first element of X .

The reasoning above shows that each “ordered pair”, understood in this sneaky way, does indeed have a unique “first element”, and a unique “second element”, understood this way. In other words, for any ordered pairs (a, b) and (a', b') , if $(a, b) = (a', b')$, then $a = a'$ and $b = b'$. We can also use other axioms to prove that for any sets A and B , there really is a set containing all ordered pairs (a, b) such that $a \in A$ and $b \in B$.

So we can define ordered pairs to be certain sets, and we can define functions to be certain sets of ordered pairs. That lets us make sense of what the Axiom of Choice means, even though it talks about functions, from a foundation of nothing but sets. But we also had some other important axioms about ordered pairs and functions: the Axiom of Pairs and the Axiom of Functions, which say that there *exist* certain sets of ordered pairs and sets of functions. We could write these down directly as axioms in ZFC now, but this isn't how it's usually done. Instead, they are each *theorems*, which we can prove from different axioms.

These other axioms are ones that we don't really need in this text, so I have not discussed them. These guarantee that there are “wide enough” and “deep enough” sets. First, you can take any *set* of sets $\{A, B, C, \dots\}$, and put all of the elements of A together with all of the elements of B and all of the elements of C , and so on, and stick them together into a single set. This is the *union* of the sets A, B, C, \dots .

Axiom of Union. For any set X , there is a set that we call $\bigcup X$ (the *union* of X),

such that, for any a , $a \in \bigcup X$ iff there is some $A \in X$ such that $a \in A$.

Second, if you have a set, you can replace all of its elements one by one with other things and get another set.

Axiom of Replacement. Let A be a set, and suppose that for each element $a \in A$, there is exactly one b such that $F(a, b)$. Then there is a set B such that, for any b , $b \in B$ iff for some $a \in A$, $F(a, b)$.

(Like Separation and Choice, Replacement can also be understood either as an axiom schema or else as a second-order axiom.)

Using the tricky definitions of pairs and functions, we don't have to take the Axiom of Pairs, the Axiom of Functions, or Function Extensionality as extra *axioms*. We can prove these facts as *theorems*.

1.6.3 Example

The axioms listed above imply the Axiom of Pairs: for any sets A and B , there is a set $A \times B$ containing all of the ordered pairs of elements of A and B .

Proof

First, we can show that there is a set $\{A, B\}$. (We haven't even shown this yet!) We can show this using Replacement. We do know that there is a set with two elements, namely the power set of the empty set, which is $\{\emptyset, \{\emptyset\}\}$. Call this $\mathbb{2}$. For each element $a \in \mathbb{2}$, there is exactly one b with this property: either $a = \emptyset$ and $b = A$, or else $a = \{\emptyset\}$ and $b = B$. So the Axiom of Replacement implies that there is a set containing just A and B .

Second, there is a *union* of A and B , applying the Axiom of Union to $\{A, B\}$. That is, there is a set $A \cup B$ such that $x \in A \cup B$ iff $x \in A$ or $x \in B$.

Third, notice that any ordered pair of an element of A and an element of B is by definition a set of the form $\{\{a\}, \{a, b\}\}$ for $a \in A$ and $b \in B$. Each element of this set is a subset of $A \cup B$. So each ordered pair is a subset of the power set of $A \cup B$. Using the Axiom of Power Sets and the Axiom of Separation, there is a set

$$A \times B = \{x \in P(A \cup B) \mid x \text{ is an ordered pair of some } a \in A \text{ and } b \in B\}$$

Every ordered pair of an element of A and an element of B is in $A \times B$. □

1.6.4 Exercise

Use the axioms and definitions in this section to prove the Axiom of Functions

and the Axiom of Function Extensionality.

There is something nice and economical about the approach of ZFC. By using the right definitions, we have cut down how many undefined primitive *concepts* we are taking for granted—instead of sets and functions and ordered pairs, we just have sets. And we have also cut down on how many unproved basic *assumptions* we are taking for granted.

But this approach also raises some hard philosophical questions. Is this really what a function *is*—a set of ordered pairs? If so, why think that a function $f : A \rightarrow B$ is a subset of $A \times B$, rather than a subset of $B \times A$? And similarly, is an ordered pair really just a set? If so, why think it’s the set we described above, rather than some other set that could do the same job? These definitions look *arbitrary*.⁶

These are philosophically important questions: we’d like to understand the nature of abstract objects, what things like functions and ordered pairs really are. But they aren’t *technically* important questions. For the purposes of proving the theorems that come later, all we really care about is whether there is *something or other* that plays the role of functions, and something or other that plays the role of pairs. What we care about is whether there is *some* way of understanding “function” (and “ $f a$ ”) such that principles like Function Extensionality, the Axiom of Functions, and the Axiom of Choice come out true. The ZFC definitions are good enough for this. It doesn’t really matter for the theorems if there is *more than one* way of understanding these principles that makes them come out true.

This kind of issue will come up over and over. What are numbers really? What are sequences, or strings, or sentences, or programs, or proofs? It’s not clear how to answer these questions. But very often, for our purposes it’s enough to find *something or other* that has the right structural features to play the *role* of numbers, sequences, strings, and so on.

I have left out two other standard axioms of ZFC. One of them is something we don’t need in this text, but I should mention it for completeness. This axiom says that sets have a nice hierarchical structure: if you take elements of elements of elements ... you always eventually reach a bottom level of things without any more elements (which are either the empty set or urelements). It is a bit tricky to figure out how to state this precisely without appealing to *finite numbers*, which is something we haven’t discussed yet. But there turns out to be a nice elegant way of capturing this idea (given the other axioms).

Axiom of Foundation. For any non-empty set A , there is some element $a \in A$

⁶Benacerraf (1965) develops this idea to argue against the standard ZFC definitions.

such that a and A have no elements in common.

The final axiom of ZFC is something we definitely *will* need in this class, and we will discuss it in detail in Chapter 2: the Axiom of Infinity.

1.7 Review

Key Techniques

- You can show that A and B are **the same set** in two steps:
 1. Show that every element of A is an element of B .
 2. Show that every element of B is an element of A .
- You can show that $f : A \rightarrow B$ and $g : A \rightarrow B$ are **the same function** by showing that $fa = ga$ for every element $a \in A$.
- You can **come up with a subset** of a set A by precisely stating a property of elements of A . By **Separation**, there is a subset $B \subseteq A$ whose elements are all and only the elements of A that have that property.
- You can **come up with a function** from A to B by precisely describing a relation between elements of A and elements of B such that each element of A stands in that relation to at least one element of B .
- Cantor's Theorem (Exercise 1.5.3) is proved using the **self-application trick** (which is also called **diagonalization**). If there was an onto function $f : PA \rightarrow A$, then you could use this to "apply" sets to themselves (by checking whether $f(X) \in X$). But then if you consider the set of all sets that do not "apply" to themselves in this sense, you can derive a contradiction.

Key Concepts and Facts

- If A and B are **sets**, A is a **subset** of B ($A \subseteq B$) iff every **element** of A is an element of B .
- If f is a **function** from a set A to a set B (written $f : A \rightarrow B$) then f maps each element a in A to some element fa in B .
- An **ordered pair** is something with a **first element** and a **second element**. For each $a \in A$ and $b \in B$, there is exactly one ordered pair in the set of ordered pairs $A \times B$ whose first element is a and whose second element is b . This ordered pair is labeled (a, b) .

- A function $f : A \rightarrow B$ is **one-to-one** iff f maps *at most one* element of A to each element of B .
- A function $f : A \rightarrow B$ is **onto** iff f maps *at least one* element of A to each element of B .
- A function is a **one-to-one correspondence** iff it is both one-to-one and onto.
- The **power set** of A (called PA for short) is the set of all subsets of A .
- The **function set** B^A is the set of all functions from A to B .
- For any set A , there is a one-to-one correspondence between PA and 2^A . That is, we can put *subsets* of A in one-to-one correspondence with True-or-False “test functions” on A .
- **Russell’s Paradox.** Some things don’t form a set at all. In particular, there is no “universal set” containing every set.
- **Cantor’s Theorem.** There is no onto function from a set A to its set of subsets PA .

Chapter 2

The Infinite

In this chapter we'll explore some important infinite sets—especially the set of *numbers* and the set of *strings*. Infinite sets have some striking and counterintuitive properties. This can be delightful, if you have the taste for it, but you might worry that they are too far removed from practical experience to be important, and you might suspect that lessons we draw from infinity for our ordinary language and reasoning are insecure. Many philosophers and mathematicians have shared these worries and suspicions. But the infinite is very close to home.

We speak a language with finitely many words, and each sentence combines just finitely many of them. But it is possible to combine these words in ways no one else ever has in all of human history—and this will always be possible. Here's a simple example:

```
I like logic.  
I know someone who likes logic.  
I know someone who knows someone who likes logic.  
I know someone who knows someone who knows someone who likes logic.
```

We can go on this way indefinitely. It's not as if there is some finite stopping point, beyond which one would lapse into unintelligibility. So there are infinitely many such sentences. Each sentence in English is a finite thing. But *all* the English sentences taken together form an infinite set. It's plausible that we'll only ever get around to writing down some small finite subset of this vast variety, since it's plausible that humanity (or at least written English) will only exist for a finite amount of time. But to understand the structure of our language and thought in general, as a whole, we will need to confront the infinite.

Infinity shows up everywhere in logic. Our standard logical languages are like English: though each sentence is made up of finitely many symbols, there are infinitely many different sentences that allow us to express infinitely many different ideas. There are likewise infinitely many different formal proofs, infinitely many different counterexamples to invalid arguments, infinitely many different systematic procedures for answering questions, and so on.

In this chapter we will get acquainted with some basic tools for working with infinity, which we will use over and over again in the following chapters.

2.1 Numbers and Induction

Now it is the same thing to say this once and to keep saying it forever.

Zeno (c. 490 – c. 430 BCE) as reported by Simplicius
(c. 490 – c. 560 CE), *On Aristotle's Physics*

We begin with the simplest and most familiar infinite set.

The **natural numbers** are the finite counting numbers, starting from zero: 0, 1, 2, ... and so on. (In this text, by “number” I will always mean “natural number.”) We’ll use the symbol \mathbb{N} as a label for the set of all natural numbers. Let’s start with some basic observations.

The numbers have a starting place: **zero**. (Starting from zero instead of one turns out to be convenient in lots of ways. But it does introduce some potential confusion, since this means the first number is zero, the second is one, the third is two, and so on. This can be a source of “off-by-one bugs,” so be careful.)

Every number is immediately followed by another bigger number. This is called its **successor**. The successor of n is $n + 1$. But as it turns out, the notion of a successor is conceptually more basic than the notion of addition, so it will be helpful to give it its own special notation: we’ll write $\text{suc } n$ for the successor of the number n . (Some people use the notation n' or S_n instead.) In fact, the notion of successor is even conceptually more basic than the notion of *one*. We can define one as the successor of zero. (So defining $\text{suc } n$ as $n + 1$ would be circular.)

For every number n , $\text{suc } n$ is a number. This means we have a function $\text{suc} : \mathbb{N} \rightarrow \mathbb{N}$. This is called the **successor function**.

2.1.1 Definition

The number one is the successor of zero, two is the successor of one; three is the

successor of two; and so on.

$$\begin{aligned} 1 &= \text{suc } 0 \\ 2 &= \text{suc } 1 = \text{suc suc } 0 \\ 3 &= \text{suc } 2 = \text{suc suc suc } 0 \\ &\vdots \end{aligned}$$

By taking successors over and over again, we eventually reach every number. We also never double back on the same numbers over again: taking successors gives us a new, bigger number every time. Every number can be reached in just one way by starting from zero and taking successors. This means that if we keep going from one number to the next, we are never going to end up at a number we've already seen before. The successor function doesn't have any "loops"—it just goes on and on to ever-bigger numbers. You can't ever take a successor-step and end up back at zero. You also can't ever take a successor-step and end up at a number which was *already* a successor of some earlier number. We can sum up this "no looping" condition as follows:

2.1.2 Injective Property

- (a) Zero is not a successor of any number;
- (b) No two numbers have the same successor.

We can put this another way using the terminology of functions:

- (a) Zero is not in the range of the successor function;
- (b) The successor function is one-to-one.

Here is a concise way of representing the structure of numbers: they are generated by the following two rules.

$$\frac{0 \text{ is a number}}{n \text{ is a number}} \qquad \frac{n \text{ is a number}}{\text{suc } n \text{ is a number}}$$

Here's how to read this notation. Each rule says: if we have everything above the line, then we can also get the conclusion below the line. The zero rule has nothing above the line, because we can conclude that zero is a number without relying on any further assumptions. The successor rule says that, for any n , if n is a number, then $\text{suc } n$ is also a number. Every number can be reached in exactly one way by repeatedly applying these rules. (In the case of numbers, this notation doesn't really make things any clearer than what we've already said. But when we consider more

complicated structures later on, this notation for “formation rules” will become more useful.)

Every number can eventually be reached by starting with zero, and repeatedly taking successors. This is the basic idea behind a fundamental technique—one of the basic tools we will use over and over again—which is called **proof by induction**. Let’s start with an example.

(Note that this mathematical use of the word “induction” is different from the traditional philosophical meaning of “induction”, which is a way of gaining empirical knowledge by generalizing from past observations. The kind of induction we’re talking about here—“mathematical induction”—is really a kind of *deduction*.)

2.1.3 Example

No number is its own successor. That is, there is no number n such that $\text{suc } n = n$.

What we want to show is that every number n has a certain property: namely, the property that $\text{suc } n \neq n$. Let’s call a number *nice* iff it has this property: that is, a nice number is a number which is not its own successor. We want to show that every number is nice.

How can we prove this? It would be nice if we could do it in steps, by proving each of the following things:

- 0 is nice
- 1 is nice
- 2 is nice
- \vdots

The trouble is that this would require a proof with infinitely many steps, which we have no hope of finishing before the semester ends. But let’s go ahead and try.

For the first step, we show that *zero* is nice: that is, $\text{suc } 0 \neq 0$. This is guaranteed by the Injective Property, which says that zero is not the successor of any number—including zero itself.

Next we show that one is nice: that is, $\text{suc } 1 \neq 1$. Remember that one is defined to be the successor of zero: so what we want to show is that $\text{suc}(\text{suc } 0) \neq \text{suc } 0$. We just proved that $\text{suc } 0 \neq 0$, so this follows from the fact that suc is one-to-one: $\text{suc } 0$ and 0 are different numbers, so their successors are also different.

Next we show that two is nice: that is, $\text{suc } 2 \neq 2$. Two is defined to be the successor of one, so what we want to show is that $\text{suc}(\text{suc } 1) \neq \text{suc } 1$. We just proved that

$\text{suc } 1 \neq 1$, so again this follows from the fact that suc is one-to-one.

But now we notice a pattern: the proof that two is nice worked exactly the same way as the proof that one is nice. And we could keep going in the same way: the fact $\text{suc } 2 \neq 2$ also implies that $\text{suc } 3 \neq 3$, and this then implies that $\text{suc } 4 \neq 4$, and so on. In other words, it looks like we can use the same pattern of reasoning to show each of the following things:

$$\begin{aligned} &\text{if } 0 \text{ is nice then } \text{suc } 0 \text{ is nice} \\ &\text{if } 1 \text{ is nice then } \text{suc } 1 \text{ is nice} \\ &\text{if } 2 \text{ is nice then } \text{suc } 2 \text{ is nice} \\ &\vdots \end{aligned}$$

Furthermore, we can prove each of these things in the very same way. So what we can do is write down a *general* argument that covers all of these cases at once. That is, instead of proving these conditionals one by one, we can prove the following *general* fact:

For every number n , if n is nice, then $\text{suc } n$ is nice.

Here is the proof. Let n be a number, and suppose that n is nice: that is, $\text{suc } n \neq n$. We want to show that $\text{suc } n$ is nice. That is, we want to show:

$$\text{suc}(\text{suc } n) \neq \text{suc } n$$

The Injective Property says that the successor function is one-to-one. So our assumption that $\text{suc } n$ and n are different numbers implies that they also have different successors. This is exactly what we wanted to show: $\text{suc } n$ is nice.

To sum up, we showed two things.

1. 0 is nice.
2. For every number n , if n is nice, then $\text{suc } n$ is nice.

Together, these two steps guarantee that *every* number is nice. Why does this follow? Well, in the first step, we showed that zero is nice.

$$0 \text{ is nice}$$

Then the second step tells us in particular:

$$\text{If } 0 \text{ is nice, then } 1 \text{ is nice}$$

Thus

$$1 \text{ is nice}$$

The second step *also* tells us:

If 1 is nice, then 2 is nice

Thus

2 is nice

And the second step *also* tells us:

If 2 is nice, then 3 is nice.

Thus

3 is nice

And obviously we can keep going, using the same two steps to show that 4 is nice, and 5 is nice, and so on. By taking successors over and over, eventually we reach every number. So by applying our second step, “if n is nice, then $\text{suc } n$ is nice”, over and over again to larger and larger numbers n , eventually we can show that *any* given number is nice. So every number is nice.

That is the key idea of proof by induction. In order to prove *infinitely* many things, it is enough to prove just two things. The first thing is called the *base case*: 0 is nice. The second thing is called the *inductive step*: every nice number is followed by another nice number.

Now that we’ve figured it out, let’s write out the proof in a more concise, official way, which shows the standard structure of a proof by induction.

Proof

Call a number n *nice* iff $\text{suc } n \neq n$. We will prove by induction that every number is nice.

Base case. By the Injective Property, 0 is not a successor, so $\text{suc } 0 \neq 0$. That is, 0 is nice.

Inductive Step. We will show that for any number n , if n is nice then $\text{suc } n$ is nice. Let n be any number, and suppose n is nice: that is, $\text{suc } n \neq n$. By the Injective Property, the successor function is one-to-one, so this implies $\text{suc}(\text{suc } n) \neq \text{suc } n$. This means that $\text{suc } n$ nice. \square

Let’s do another example.

2.1.4 Example

Every number is either zero or a successor. That is, for any number n , either $n = 0$ or else there is some number m such that $n = \text{suc } m$.

Proof

We'll prove this by induction as well. We want to show that every number n has a certain property: the property of either being zero, or else being the successor of some number. For short, let's say a number n is *good* iff either $n = 0$ or else there is some number m such that $n = \text{suc } m$. We want to show that every number is good. Again, we can do this in two steps.

For the *base case*, we'll show that zero is good. That is, either $0 = 0$ or else 0 is a successor. Obviously the first case is true.

For the *inductive step*, we'll show that goodness is inherited by successors: for any number n , if n is good, then the successor of n is also good. That is, we assume that n is either zero or a successor, and we want to show that $\text{suc } n$ is either zero or a successor. Again, this is obvious, because obviously $\text{suc } n$ is the successor of some number (namely n). \square

Like before, the two parts of this proof together guarantee that every number is good. The base case tells us that zero is good. The inductive step tells us that, if zero is good, so is one. The inductive step also tells us that if one is good, so is two. And it tells us that if two is good, so is three. And going on this way, eventually we can reach any number, and show that it is good. So every number is good.

2.1.5 Technique (Proof by Induction)

We use proof by induction when we are trying to show that every number has a certain property. To do a proof by induction, start by clearly identifying the property.

We want to show that for every number n , _____.

Fill in the blank with some statement about n .

Once you've identified the key property, a proof by induction has two parts. The first step is to show that zero has the property. This step is called the **base case**. It is usually the easiest part of the proof. (But not always!)

The second step is to prove a certain universal conditional statement. You want to show, for every number n , if n has the property, then the successor of n also has the property. This is called the **inductive step**. Usually the inductive step will begin like this, where you fill in the blanks with the property you are trying to prove every number has:

For the inductive step, let n be any number, and suppose that n is _____. We want to show that $\text{suc } n$ is also _____.

Once you've done both steps, you're done. For in fact, every number is either zero, or else the successor of zero, or the successor of the successor of zero, or So by chaining together the conditional you proved in the inductive step some number of times, eventually you prove that every number has the property you wanted.

Until you get used to proof by induction, it can feel a little magical. In particular, the inductive step might seem like cheating. You are *assuming* that something has the property that you are trying to prove *everything* has. But this is okay! Of course it would be useless to prove “for any n , if n is nice, then n is nice”. That would amount to a pointlessly circular argument. But that's not what you do in a proof by induction: instead, you prove “for any n , if n is nice, then n 's successor is nice”. Proving this makes a real advance—an advance of exactly one step. The key insight involved in proof by induction is that the journey to *any* finite number at all is nothing more than many journeys of a single step, one after another.

We'll have lots more examples and opportunities for practice as we go. But first we'll need to introduce another concept, in the next section.

In fact, the validity of proof by induction is often taken to be part of the *definition* of the natural numbers.¹ The intuitive idea of the natural numbers is that every number can be reached by starting with zero and taking successors some *finite number of times*. This would obviously be circular as a definition of “finite number”. But we can make this idea precise and non-circular using the idea of induction. The key idea of proof by induction is that, for any property, if zero has it, and it is always inherited by successors, then *every* number has the property. There aren't any *infinite* natural numbers which are never reached by the process of repeatedly taking successors.

So this is another way of putting the important fact about the natural numbers. Like the Axiom of Separation and the Axiom of Choice from Chapter 1, we can state this as a generalization about all properties.

2.1.6 Inductive Property of Numbers

Let F be any property. Suppose that

- (a) 0 is F
- (b) For each number n , if n is F , then the successor of n is F also.

Then every number is F .

¹TODO. Historical note: Dedekind, Peano, Frege

What this says is just that proof by induction *works*. Part (a) says that the base case holds for the property of being F , and part (b) is the inductive step. The Inductive Property says that if (a) and (b) both hold, then (“by induction”) every number has the property.

If we want to avoid talking about properties here, we can say the same thing in terms of sets instead.

2.1.7 Inductive Property of Numbers (Set Version)

Let X be any set. Suppose that

- (a) 0 is in X
- (b) For each number n in X , the successor of n is also in X .

Then every number is in X .

This says, in particular, induction works for the property of being an element of the set X . (The two versions of the axiom are equivalent because being in the set of numbers that are F is equivalent to being a number which is F .) Part (a) says that the base case holds for the property of being an element of X ; part (b) says that the inductive step also holds for this property. The Inductive Property says that if (a) and (b) both hold, then (“by induction”) every number has this property.

We can put these ideas together to say exactly what we are assuming about what the natural numbers are like. These assumptions are called the **Peano Axioms**.²

2.1.8 Axiom of Numbers

There is a set \mathbb{N} , the set of all (**natural numbers**). There is an element of \mathbb{N} called **zero**, and a **successor** function $\text{suc} : \mathbb{N} \rightarrow \mathbb{N}$. These have the following two properties.

- (a) **Injective Property.**
 - (i) Zero is not in the range of the successor function. That is, zero is not a successor of any number.
 - (ii) The successor function is one-to-one. That is, no two numbers have the same successor.

²There is really more than one collection of assumptions that is sometimes called “the Peano Axioms”. An important thing about this way of putting the axioms is that they talk about *properties* or *sets*. In Section 5.4 we’ll encounter some other principles that are also called “the Peano Axioms,” but which don’t say anything about sets. There are some important differences between the different versions, which are discussed in Chapter 9.

(b) **Inductive Property.** Let X be any set. Suppose

- (i) $0 \in X$;
- (ii) For each $n \in X$, the successor of n is also in X .

Then X contains every number.

2.1.9 Exercise

In this exercise we'll explore the way that the Injective Property and Inductive Property each help pin down the structure of the numbers. Let A be a set, let z be an element of A , and let s be a function from A to A . We'll say A , z , and s have the *Injective Property* iff z is not in the range of s , and s is one-to-one. We'll say A , z , and s have the *Inductive Property* iff, for any set X , if (a) $z \in X$ and (b) for every element $a \in A$ which is in X , sa is also in X , then X includes every element of A .

- (a) Give an example of A , z , and s that have neither the Inductive Property nor the Injective Property.
- (b) Give an example of A , z , and s that have the Inductive Property, but not the Injective Property.
- (c) Give an example of A , z , and s that have the Injective Property, but not the Inductive Property.

2.2 Recursive Definitions

‘Can you do Addition?’ the White Queen asked.
 ‘What’s one and one?’
 ‘I don’t know,’ said Alice. ‘I lost count.’
 ‘She can’t do Addition,’ the Red Queen interrupted.

Lewis Carroll, *Through the Looking Glass* (1871)

Another fundamental technique we'll use when working with infinite sets such as numbers and strings is *recursive definition*. This is very closely related to inductive proof. A recursive definition is a way of defining an infinite set or relation, or a function with an infinite domain.

There are many different kinds of recursive definitions. We'll start with an example of a recursively defined *property*.

2.2.1 Definition

We can define **even number** recursively, using the following rules.

$$\frac{0 \text{ is even}}{\text{suc suc } n \text{ is even}} \qquad \frac{n \text{ is even}}{\text{suc suc } n \text{ is even}}$$

Intuitively, what this definition means is that a number is even if and only if we eventually reach that number by applying these two rules finitely many times. The set of even numbers include

$$\begin{aligned} & 0 \\ & \text{suc suc } 0 \\ & \text{suc suc suc suc } 0 \\ & \text{suc suc suc suc suc suc } 0 \\ & \vdots \end{aligned}$$

and so on. Or in more familiar notation: 0, 2, 4, 6, ...

The recursive definition of *even* tells us that we can use certain kinds of reasoning in our proofs. First, we can use the rules that we wrote down as part of the definition. At any point in our proofs, for any number n , we can write down “ n is even,” and justify this step “by Definition 2.2.1.” And similarly, at any point in our proofs where we have *already* shown “ n is even” we can then also infer “ $\text{suc suc } n$ is even” as well, with the justification “by Definition 2.2.1.” For example, we know this:

2.2.2 Example

4 is even.

Let’s spell this out very explicitly.

Proof

By the first part of Definition 2.2.1, 0 is even. By the second part of Definition 2.2.1, it follows that $\text{suc suc } 0$ is even. By the second part of Definition 2.2.1 again, it then follows that $\text{suc suc suc suc } 0$ is even, and this is equal to 4 by definition. \square

Here is another example. Instead of defining a *property* like evenness, we can recursively define a *relation*.

2.2.3 Definition

The relation **m is less than or equal to n** , abbreviated $m \leq n$, is defined recursively by the following rules (for any numbers m and n):

$$\frac{n \leq n}{m \leq \text{suc } n} \quad \frac{m \leq n}{m \leq \text{suc } n}$$

Again, intuitively what this definition means is that for any numbers m and n , we have $m \leq n$ if and only if, by repeatedly applying these two rules finitely many times, we can eventually reach the conclusion that $m \leq n$. So, for example, the definition tells us:

$$\begin{aligned} 0 &\leq 0 \\ 0 &\leq \text{suc } 0 = 1 \\ 0 &\leq \text{suc } 1 = 2 \\ &\vdots \end{aligned}$$

Similarly:

$$\begin{aligned} 3 &\leq 3 \\ 3 &\leq \text{suc } 3 = 4 \\ 3 &\leq \text{suc } 4 = 5 \\ &\vdots \end{aligned}$$

And so on, for infinitely many different pairs of numbers.

As with the recursive definition of *even*, this recursive definition of *less than or equal* lets us use certain kinds of reasoning in our proofs. At any point in our proofs, for any number n , we can write down $n \leq n$. And at any point in our proofs where we have already shown $m \leq n$, we can infer $m \leq n + 1$. For example, we know this:

2.2.4 Example

For each number n , $n \leq n$. (That is, the *less than or equal* relation is *reflexive*.)

Proof

By the first rule in Definition 2.2.3. □

2.2.5 Example

For each number n , $n \leq \text{suc suc } n$.

Proof

Let n be any number. By Definition 2.2.3, we have

$$\begin{aligned} n &\leq n \\ \text{so } n &\leq \text{suc } n \\ \text{so } n &\leq \text{suc suc } n \end{aligned}$$
□

But recursive definitions also give us something more interesting: a new kind of *proof by induction*. Again, let's start with an example.

2.2.6 Example

For any numbers m and n such that $m \leq n$, either $m = n$ or $\text{suc } m \leq n$.

Proof

Say that a pair of numbers (m, n) is *nice* iff

either $m = n$ or $m + 1 \leq n$.

We are trying to show that every pair of numbers (m, n) such that $m \leq n$ is nice. We can prove this by *induction on the recursive definition* of \leq , Definition 2.2.3. Like inductive proofs on numbers, this inductive proof has two parts, one for each part of the recursive definition.

1. The first rule in the definition of \leq says that each pair (n, n) is a \leq -pair. So the first part of our inductive proof is to show that for each number n , the pair (n, n) is nice.

This is clear, because $n = n$, which satisfies the first disjunct of the “either ... or ...” statement.

1. The second rule in the definition of \leq says that, for any pair of numbers (m, n) , if $m \leq n$, then $\text{suc } m \leq \text{suc } n$. Accordingly, the second part of our inductive proof is to show that for any numbers m and n , if (m, n) is nice, then $(\text{suc } m, \text{suc } n)$ is also nice.

To show this, we *suppose*:

either $m = n$ or $\text{suc } m \leq n$

We will then *show*:

either $m = \text{suc } n$ or $\text{suc } m \leq \text{suc } n$

There are two cases.

First, suppose $m = n$. Then $\text{suc } m = \text{suc } n$, and so $\text{suc } m \leq \text{suc } n$ by the first rule in Definition 2.2.3.

Second, suppose $\text{suc } m \leq n$. Then $\text{suc } m \leq \text{suc } n$ by the second rule in Definition 2.2.3.

In either case, the pair $(m, \text{suc } n)$ is nice. This completes the inductive proof. \square

In this proof, we tried to show that whenever $m \leq n$, the pair (m, n) is nice. We did this by showing that each of the rules in the recursive definition of \leq preserve niceness. Again, intuitively, whenever $m \leq n$, we can reach the conclusion that (m, n) is nice by chaining together the two parts of this proof some finite number of times.

2.2.7 Exercise

Prove by induction that for all numbers m, n, k , if $m \leq n$ and $n \leq k$, then $m \leq k$. (That is, the *less than or equal* relation is *transitive*.)

Hint. This is a bit tricky, because there are several different ways of restating this claim in order to prove it by induction. The proof goes most straightforwardly if you structure it like this: let m be any number, and then show by induction on \leq that every pair of numbers (n, k) such that $n \leq k$ has this property:

If $m \leq n$, then $m \leq k$.

Like other kinds of induction and recursion, recursively defined properties and relations can seem like magic. How is it that saying “by definition” lets us just start pulling statements like “ $5 \leq 5$ ” or “if n is even then $n + 2$ is even” out of the air?

The set of even numbers E is supposed to have certain properties. First, it’s supposed to have certain *closure* properties, given by the rules we wrote down.

- (i) $0 \in E$
- (ii) For each number $n \in E$, also $\text{suc suc } n \in E$.

For short, let’s say that any set with these two properties is **E-closed**.

That isn’t enough, though. For example, the set of *all* numbers is also E-closed. So is the set of all numbers except 1 and 3. (Check this!)

Besides the *closure* properties, the set of even numbers is supposed to have a certain *inductive property*. Like the inductive property of numbers, the inductive property of *even* numbers tells us that proofs by induction on the definition of *even* really works. That is, abstractly:

For any property F , if

- (i) 0 is F , and
- (ii) for every number n , if n is F then $\text{suc suc } n$ is also F , then every even number is F .

Alternatively, we can write down that inductive property in terms of sets:

Let X be any set of numbers. If

- (i) $0 \in X$, and
- (ii) for each number $n \in X$, also $\text{suc suc } n \in X$,

then every even number is in X .

Using our definition of “E-closed”, and letting E be the set of even numbers, we can restate the inductive property even more concisely:

For any set X , if X is E-closed, then $E \subseteq X$.

So the set of even numbers is supposed to have both the *closure* property and the *inductive* property. We can put those two properties together in the following pithy characterization of the set of even numbers:

E is the *smallest E-closed set*.

Here is another way of saying this:

2.2.8 Exercise

For any number n , n is even iff n is an element of *every* E-closed set.

Hint. For the left-to-right direction, use induction on the recursive definition of *even*.

This gives us an alternative way to define the set of even numbers—not *recursively*, but *explicitly*—in a way that guarantees that this set has the properties that were encoded in the *recursive* definition. We can say:

A number n is **even** iff n is an element of every E-closed set.

And then we can straightforwardly check that *this* alternative definition of “even” guarantees that the even numbers have the properties we wanted for the recursive definition: the set of even numbers is *closed*, and it has the right inductive property. (Check this!)

In short, it is possible to eliminate the recursive definition of *even*, and replace it with an *explicit* definition. But since we know we *can* do this, now we don’t have to! We know that if we write down the recursive definition of *even*, then there really is a set that has the properties that the definition requires, for which all of the appropriate proof rules really work.

We can do the same thing for the recursive definition of *less than or equal*, \leq . This time, for a set X of *ordered pairs* of numbers, let’s say that X is **\leq -closed** iff

- (i) For any number n , $(n, n) \in X$, and
- (ii) For any pair of numbers (m, n) , if $(m, n) \in X$, then $(m, \text{suc } n) \in X$ as well.

Then we can replace the recursive definition of \leq with this *explicit* definition:

For any numbers m and n , $m \leq n$ iff (m, n) is an element of every \leq -closed set.

Again, we can check that this guarantees that all of the proof rules corresponding to the recursive definition of \leq really work.

All of this is done more carefully and generally in Section 2.3.

2.2.9 Technique (Recursively defining a property or relation)

We can recursively define a property F by writing down certain “derivation rules,” like this:

$$\frac{x_1 \text{ is } F \quad \dots \quad x_n \text{ is } F}{\text{_____ is } F}$$

where the blank is filled in with some description of another thing, which can depend on x_1, \dots, x_n . Note that we can have $n = 0$, in which case there is nothing written above the line.

Once we have written down this definition, we can use any of these rules we wrote down anywhere we want in our proofs.

We can also use the following kind of proof by induction. Suppose that we want to prove that *every* F is *nice*. (Here *nice* is a placeholder for some other property.) We can do this by doing one step for each rule in our definition. Each step looks like this:

Suppose that x_1 is nice, ..., and x_n is nice. *Show* that _____ is nice.

Fill in the blank with the same description that appeared in the definition. Again, notice that we can have $n = 0$, with nothing written above the line, and this means that we just don’t suppose anything for that step. (It is a “base case”.)

We can do the same thing for *relations*, just by thinking of a relation as a property of ordered pairs (or more generally, ordered triples, 4-tuples, etc.).

We can also generalize the reasoning that shows that this kind of definition really works—there really *is* a property for which all of these different rules are valid. The

proof is not very hard, but it is very abstract. So we won't do that here; you can find it in Section 2.3.

Besides properties and relations, we can also recursively define *functions*. Again, let's start with an example.

The **doubling** function takes each number n to the number $2 \cdot n$. That way of describing it assumes we already know how to multiply—but we haven't officially said what multiplication is. But we can define doubling in a different way that doesn't depend on already understanding multiplication—using a recursive definition. We do this in two steps. The two steps are exactly analogous to the two steps in an inductive proof.

2.2.10 Definition

First (for the *base case*) we say what the doubling function does to zero. This is easy: the double of zero is zero.

$$\text{double } 0 = 0$$

Second (for the *recursive step*) we let n be an arbitrary number, and we *suppose* that we already know how to double n . *Given* this assumption, we say how to double $\text{suc } n$. That is, we suppose that we know $\text{double } n$, and we say what $\text{double}(\text{suc } n)$ should be in terms of that. For this, we can use the fact that $2 \cdot (n + 1) = 2 \cdot n + 1 + 1$. (Though of course we haven't officially defined multiplication or addition yet.) So this is a reasonable rule to use:

$$\text{double}(\text{suc } n) = \text{suc suc double } n$$

Once we've done both of these steps, this is enough to settle what the doubling function does to every number. For example, let's calculate $\text{double } 3$ using these rules. We know $3 = \text{suc } 2$, and $2 = \text{suc } 1$, and $1 = \text{suc } 0$. So we can work it out like

this:

$$\begin{aligned}
 \text{double } 0 &= 0 \\
 \text{double } 1 &= \text{double}(\text{suc } 0) \\
 &= \text{suc suc}(\text{double } 0) \\
 &= \text{suc suc } 0 \\
 \text{double } 2 &= \text{double}(\text{suc } 1) \\
 &= \text{suc suc double } 1 \\
 &= \text{suc suc suc suc } 0 \\
 \text{double } 3 &= \text{double}(\text{suc } 2) \\
 &= \text{suc suc double } 2 \\
 &= \text{suc suc suc suc suc } 0 \\
 &= 6
 \end{aligned}$$

We have successfully calculated that twice 3 is 6! And it's clear that we can keep going this way, using the result for 3 to get the result for 4, and using the result for 4 to get the result for 5, and so on. By applying the recursive rule over and over again, we eventually reach a value for any number. (But it will take longer and longer to get results for bigger and bigger numbers.) What makes this work is the basic fact about numbers: we can reach every number in exactly one way, by starting from zero, and repeatedly taking successors.

As we have already seen, recursive definitions and inductive proofs very often work hand in hand. Often we use recursion to *define* a function, and then we use induction to *prove* that it does what it's supposed to do.

2.2.11 Example

For every number n , $\text{double } n$ is even.

Proof

We prove this by induction on numbers.

Base case. By definition, $\text{double } 0 = 0$, which is even.

Inductive step. Let n be any number, and suppose for the inductive hypothesis that $\text{double } n$ is even. We want to show that $\text{double}(\text{suc } n)$ is also even. By definition,

$$\text{double}(\text{suc } n) = \text{suc suc}(\text{double } n)$$

Since $\text{double } n$ is even (by the inductive hypothesis), the definition of *even* tells us that $\text{suc suc}(\text{double } n)$ is also even. So we are done. \square

Now that we have several different kinds of inductive proofs around, an important part of problem solving is to decide which kind (if any) is appropriate for our goal.

2.2.12 Example

For every even number n , there is some number k such that double $k = n$.

Proof

This time we will use induction on the definition of *even*.

1. First we need to show that there is some number k such that double $k = 0$. This is clear, since 0 has this property.
2. Next, let n be any even number, and assume for the inductive hypothesis that there is some number k such that double $k = n$. We need to show that there is some number k' such that double $k' = \text{suc suc } n$ (corresponding to the second part of the definition of *even\$). In fact, we can let $k' = \text{suc } k$. Then, using the definition of the doubling function:

$$\text{double}(\text{suc } k) = \text{suc suc}(\text{double } k) = \text{suc suc } n$$

□

Here's another example of a recursively defined function.

2.2.13 Definition

Let k be a number. We can recursively define the function that *adds* k to any number. For any number n , we can write the result of this function as $k + n$. For the base case:

$$k + 0 = k$$

For the recursive step, we suppose we already know the result of $k + n$, and we then define the next step, which is the result of adding k to $\text{suc } n$.

$$k + (\text{suc } n) = \text{suc}(k + n)$$

In this way we can recursively define addition for any two numbers, in terms of the successor function and zero.

We can use the definition of addition to prove something that we've been taking for granted: the successor function is the same thing as adding one.

2.2.14 Example

For any number n , $\text{suc } n = n + 1$.

Proof

Remember that $1 = \text{suc } 0$. So:

$$\begin{aligned} n + 1 &= n + \text{suc } 0 && \text{by the definition of 1} \\ &= \text{suc}(n + 0) && \text{by the recursive step of the definition of +} \\ &= \text{suc } n && \text{by the base case of the definition of +} \end{aligned}$$

□

So from now on, we can go ahead and use either the notation $\text{suc } n$ or the notation $n + 1$ equally well: they both mean the same thing. For example, this is an equivalent way of rewriting the recursive definition of addition:

$$\begin{aligned} k + 0 &= k \\ k + (n + 1) &= (k + n) + 1 \end{aligned}$$

2.2.15 Exercise

Use the definition of addition to explicitly show the following:

- (a) $1 + 1 = 2$.
- (b) $k + 2 = \text{suc suc } k$, for any number k .

(Remember that 1 is defined to be $\text{suc } 0$ and 2 is defined to be $\text{suc } 1 = \text{suc suc } 0$.)

Let's look at some more examples of using inductive proofs to show things about addition.

2.2.16 Example

Prove by induction on numbers that $0 + n = n$ for every number n .

(Note that this *doesn't* just follow directly from the first clause of the recursive definition of $+$: that definition tells us about $n + 0$, not $0 + n$, and we haven't shown yet that those are the same thing. Don't worry—we'll show this very soon.)

Proof

We want to show that every number n has the property that $0 + n = n$. The *base case* of the proof is to show that 0 has this property: that is, $0 + 0 = 0$. This follows immediately from the first clause of the recursive definition of addition.

For the *inductive step*, we want to show that the property is inherited by successors. For this, we'll let n be an arbitrary number, we'll suppose that n has the property, and we'll need show that $\text{suc } n$ has the property as well. That is, for an arbitrary

number n , we'll *suppose* that $0 + n = n$, and try to *show* that $0 + \text{suc } n = \text{suc } n$. We can show this using the recursive step of the definition of addition.

$$0 + \text{suc } n = \text{suc}(0 + n) = \text{suc } n$$

(The first equation uses the recursive step of the recursive definition. The second equation uses the *inductive hypothesis*, that $0 + n = n$.) \square

2.2.17 Example

Prove that $1 + n = n + 1$ for every number n .

Proof

We'll prove this by induction. For the base case, we need to show that $1 + 0 = 0 + 1$. In fact, by the definition of addition, we know $1 + 0 = 1$. And by the previous exercise, we know $1 = 0 + 1$. So the base case is done.

For the inductive step, we *suppose* that $1 + n = n + 1$. (This is the *inductive hypothesis*.) Then we want to *show* that $1 + \text{suc } n = (\text{suc } n) + 1$.

$$\begin{aligned} 1 + \text{suc } n &= \text{suc}(1 + n) \quad \text{by the definition of addition} \\ &= \text{suc}(n + 1) \quad \text{by the inductive hypothesis} \\ &= \text{suc suc } n \end{aligned}$$

The last step uses the fact we showed earlier, that taking the successor of a number is the same as adding one to it: so we know that $\text{suc}(\text{suc } n) = (\text{suc } n) + 1$. That finishes the proof. \square

2.2.18 Example

Addition is **associative**: $(k + m) + n = k + (m + n)$ for any numbers k, m, n .

Proof

We'll show by induction that every number n has the property that, for any numbers k and m , $(k + m) + n = k + (m + n)$.

For the base case:

$$(k + m) + 0 = k + m = k + (m + 0)$$

This applies the base case of the inductive definition of addition twice.

For the inductive step, *suppose* $(k + m) + n = k + (m + n)$. We want to *show* that

$$(k + m) + \text{suc } n = k + (m + \text{suc } n).$$

$$\begin{aligned} (k + m) + \text{suc } n &= \text{suc}((k + m) + n) && \text{definition of } + \\ &= \text{suc}(k + (m + n)) && \text{inductive hypothesis} \\ &= k + \text{suc}(m + n) && \text{definition of } + \\ &= k + (m + \text{suc } n) && \text{definition of } + \end{aligned}$$

□

Note a common structural feature of these proofs. In each example, the base case of the *proof* uses the base case of the recursive *definition* of addition. Similarly, in each example the inductive step of the proof uses the recursive step of the definition of addition. This is usually how this kind of proof goes.

With a bit of practice, this kind of inductive proof should end up basically feeling like routine symbol-juggling. Conceptually, the most important part is how to *set up* a proof by induction. Figure out what you need to show, in order to do a proof by induction: identify what property you want to prove every number has (“for every number n , n is nice”), and carefully spell out the base case (“0 is nice”) and the inductive step (“if n is nice, then $\text{suc } n$ is nice”). The details of how you end up *showing* that each of these statements is true are not especially significant for these exercises, though it’s worth working through them to get the feel of it.

2.2.19 Exercise

Prove by induction that for any numbers k and n , $\text{suc } k + n = \text{suc}(k + n)$.

2.2.20 Exercise

Prove by induction that addition is **commutative**: $k + n = n + k$, for any numbers k and n .

(*Hint.* Use Exercise 2.2.19.)

2.2.21 Exercise

Prove that, for any number n ,

$$\text{double } n = n + n$$

2.2.22 Exercise

Prove that for any numbers m and k ,

$$m \leq m + k$$

(Use the recursive definition of \leq , Definition 2.2.3.)

2.2.23 Exercise

Prove that for any numbers m and n , if $m \leq n$, then there exists a number k such that $n = m + k$.

2.2.24 Definition

We can also recursively define *multiplication* of numbers. For any number m , we can define $m \cdot n$ recursively as follows:

$$\begin{aligned}m \cdot 0 &= 0 \\m \cdot \text{suc } n &= m \cdot n + m\end{aligned}$$

For example, let's work out $3 \cdot 2$.

$$\begin{aligned}3 \cdot 0 &= 0 \\3 \cdot 1 &= 3 \cdot \text{suc } 0 \\&= (3 \cdot 0) + 3 \\&= 0 + 3 \\&= 3 \\3 \cdot 2 &= 3 \cdot \text{suc } 1 \\&= (3 \cdot 1) + 3 \\&= 3 + 3\end{aligned}$$

No surprises there.

2.2.25 Example

For any number n , $1 \cdot n = n$. (Again, notice that this isn't the same as the definition, because we haven't shown that $m \cdot n$ and $n \cdot m$ are the same thing.)

Proof

We will prove this by induction.

Base case. By definition, $1 \cdot 0 = 0$.

Inductive step. For the inductive hypothesis, we assume that $1 \cdot n = n$. We will show that $1 \cdot \text{suc } n = \text{suc } n$. In fact, by the definition of multiplication,

$$\begin{aligned}1 \cdot \text{suc } n &= 1 \cdot n + 1 && \text{by the definition of } \cdot \\&= n + 1 && \text{by the inductive hypothesis} \\&= \text{suc } n && \text{by a fact we proved earlier}\end{aligned}$$

□

2.2.26 Exercise

Using the definitions of the doubling function and multiplication to show that, for any number $n \in \mathbb{N}$, $\text{double } n = 2 \cdot n$.

2.2.27 Exercise

Show that for any numbers k and n ,

$$k \cdot \text{double } n = \text{double}(k \cdot n)$$

Now that we've seen a bunch of examples, let's describe the technique of recursively defining a function a bit more abstractly.

2.2.28 Technique (defining a function recursively)

Let's say you are trying to come up with a function whose *domain* is the set of all natural numbers: you have some other set A , and you want to come up with some function $f : \mathbb{N} \rightarrow A$. (You should fill in A with whatever the codomain of your function should be, and you should replace the letter f with some suitable name for the function you are defining, like `double` or whatever.) You can do this in two steps.

- (a) Choose a *starting place*: figure out which value the function should have at zero. Write down:

$$f0 = \underline{\hspace{2cm}}$$

Fill in the blank with some description of an element of your set A .

- (b) Choose a *step rule*: figure out a general rule for how the value of your function for a number $n + 1$ should *depend* on its value for the previous number n . Again, you'll be filling in the blank:

$$f(n + 1) = \underline{\hspace{2cm}}$$

(or alternatively, $f(\text{suc } n) = \underline{\hspace{2cm}}$, if you prefer to keep this notation). This time, though, you don't just have to describe an element of A out of nowhere. The thing you write down in the blank can use " fn ". When you describe the value of f for $n + 1$, you get to assume that you already know fn , the value of f for the previous number n .

Once you've finished both steps, you're done. You will have successfully described what the function f should do guaranteed that there is one (and only one!) function

2.2.29 Exercise

- (a) Write down a recursive definition for the *exponentiation* function that takes each number n to 2^n . (For example, $2^0 = 1$, $2^1 = 2$, $2^2 = 4$, $2^3 = 8$, ...) Feel free to use the doubling, addition, or multiplication functions that have already been defined.
- (b) Use your definition, together with the definitions of addition and multiplication (and properties of addition and multiplication we have already proven), to show that for any number n ,

$$2^{\text{double } n} = 2^n \cdot 2^n$$

Once again, there is a bit of magic going on with recursive definitions of functions. How do we get to pull statements like $k + \text{suc } n = \text{suc}(k + n)$ out of the air “by definition”? In Section 2.3 we’ll redescribe this general technique more precisely, and we’ll *prove* that it really works: if you do both of these two steps, you will have correctly described one and only one function. The basic idea is the same as for recursively defined properties and relations: it is possible to replace *recursive* definitions with *explicit* definitions that have all the right properties. First, instead of defining a function like double, we can recursively define a *relation*—call it the *doubling* relation.

$$\frac{}{0 \text{ doubles } 0} \qquad \frac{m \text{ doubles } n}{\text{suc suc } m \text{ doubles suc } n}$$

Notice how the two clauses of this definition correspond to the two parts of the original recursive definition of the doubling function:

$$\begin{aligned} \text{double } 0 &= 0 \\ \text{double } n &= \text{suc suc double } n \end{aligned}$$

The main difference is that we have rewritten this in a way that doesn’t assume doubling is a *function*. We also know that we can replace this recursive definition of the doubling relation with an explicit definition in terms of closed sets.

The only thing left to do is to show that this relation is *functional*: for every number n , there is *exactly one* number m that doubles n . We can show this by induction. (Check this!) Once we have shown that doubling is a functional relation, we know that there is a *function* that takes each number to the unique number that doubles it.

Saying all this in general is, once again, pretty abstract, so we’ll put it in the “starred” Section 2.3. The point is that the magic of recursive definitions can be eliminated,

in principle, and replaced with more ordinary ways of defining properties, relations, and functions. But since we know that we *can* eliminate recursive definitions, we also don't *have to*. Nor should we—because recursive definitions are incredibly useful throughout logic.

2.3 The Recursion Theorem*

In this section we'll say what is going on with recursive definitions more generally and more precisely, and then back the method up by proving that recursive definitions work the way they are supposed to. This section is logically prior to Section 2.2. There we *assumed* that recursive definition is legitimate, and used it. Here we will *prove* it, providing justification for the claims we made before. So in this section we shouldn't rely on any of the things we proved in Section 2.2. We'll only be using the Axiom of Numbers.

First we'll talk about recursive definitions for properties and relations, and then we'll move on to recursively defined functions.

Let's start by looking more abstractly at how recursive definitions of properties work. Officially, we can do this in terms of recursively defining a *set*, such as the set of even numbers, or the set of pairs (m, n) such that $m \leq n$. In Section 2.2 we talked about *rules*. We can redescribe these rules in terms of *functions*. Consider the recursive definition of *even* again:

$$\frac{}{0 \text{ is even}} \quad \frac{n \text{ is even}}{n + 2 \text{ is even}}$$

The first rule says that 0 is even. The second rule says that the *function* $n \mapsto n + 2$ *preserves* evenness. Similarly, consider our recursive definition of *less than or equal*.

$$\frac{}{n \leq n} \quad \frac{m \leq n}{m \leq n + 1}$$

The first rule says that each pair (n, n) stands in the \leq relation, and second rule says that the *function* $(m, n) \mapsto (m, n + 1)$ *preserves* the \leq relation.

Let's generalize. (This is where things get a bit abstract.) Say an *operation* on a set A is either an element of A , or a function from A to A , or a two-place function from $A \times A$ to A , or a three-place function from $A \times A \times A$ to A , or If we count an

element of A as a *zero*-place function, then we can say in general that an operation is an n -place function from $A \times \dots \times A$ to A , for some n or other.

Suppose F is a set of operations on some set A . These operations correspond to the different rules of a recursive definition of a subset $X \subseteq A$. For each n -place operation $f \in F$, we can write down a rule:

$$\frac{x_1 \in X \quad \dots \quad x_n \in X}{f(x_1, \dots, x_n) \in X}$$

If the set X is *recursively* defined by these rules, then, first, we should be able to use each of the rules in our proofs, and second, we should be able to do proof by induction on these rules. We can state this carefully as follows.

2.3.1 Definition

Let F be a set of operations on some set A .

- A subset $X \subseteq A$ is **F -closed** iff for each n -place function $f \in F$, and for any elements $x_1, \dots, x_n \in X$, we also have $f(x_1, \dots, x_n) \in X$.
- A subset $X \subseteq A$ has the **F -inductive property** iff for any F -closed set Y , $X \subseteq Y$.
- A subset $X \subseteq A$ is **F -recursive** iff X is both F -closed and F -inductive.

In short, the F -recursive set is the *smallest* F -closed set. So to prove that recursive definitions work, we just have to show that whenever we write down a recursive definition of this kind, we have really described a unique set. This is the sort of fact which is difficult to *state* correctly, in the abstract, but once we have stated it, it really isn't very hard to prove.

2.3.2 Exercise

For any set of operations F on a set A , there is exactly one F -recursive set.

Hint. Put in this form, the inductive property basically tells us exactly what need to do: let

$$X = \{x \in A \mid x \text{ is in every } F\text{-closed set}\}$$

Check that X really is F -recursive.

Before we move on, here is a cool way of thinking about things. If F is a set of operations on A and X is a subset of A , we can let

$$F(X) = \{f(x_1, \dots, x_n) \mid f \in F \text{ is an } n\text{-place operation and } x_1, \dots, x_n \in X\}$$

This is the result of applying all the F -operations to things in X every way we can. For X to be F -closed just means $F(X) \subseteq X$. We can also check that if X is F -recursive, then $X \subseteq F(X)$.

2.3.3 Exercise

- (a) For any sets $X \subseteq Y$, $F(X) \subseteq F(Y)$.
- (b) If X is F -closed, then $F(F(X)) \subseteq F(X)$.
- (c) If X is F -recursive, then $X \subseteq F(X)$.
- (d) Therefore, if X is F -recursive,

$$F(X) = X$$

In other words, the set X is a *fixed point* of the F -operations. Applying those operations to X take you right back to the same set we started with. In particular, because of the inductive property, X is the *least fixed point* of F : it is a subset of every fixed point. This idea of a fixed point comes up in several important places in this text (see Section 6.7, Section 7.5), and as we have already glimpsed here, it is intimately connected to recursion and self-reference.

Now for recursively defined *functions*. As an example, recall the recursive definition we gave for the doubling function.

$$\begin{aligned} \text{double } 0 &= 0 \\ \text{double}(\text{suc } n) &= \text{suc suc}(\text{double } n) \quad \text{for each number } n \end{aligned}$$

This definition has two parts. The first part is a starting place: the value of $\text{double } 0$. The second part is a “step” rule, which tells us how to get from the value of $\text{double } n$ to the value of $\text{double}(\text{suc } n)$. We can represent the shape of this definition more abstractly like this:

$$\begin{aligned} \text{double } 0 &= z \\ \text{double}(\text{suc } n) &= s(\text{double } n) \quad \text{for each number } n \end{aligned}$$

The starting place is z , which in this case is the number 0. The step rule is given by the function s , which in this case is the function that takes each number m to $\text{suc suc } m$. In general, the element $z \in A$ and the function $s : A \rightarrow A$ correspond to what we write down in the two blanks when we use Technique 2.2.28 to recursively define a function.

The key fact about the natural numbers is that this always works. Given a starting point z , and a step rule s , there is always *exactly one* function on the natural numbers that they describe. We can put this a bit more precisely.

2.3.4 The Recursion Theorem

Let A be a set, let z be an element of A , and let $s : A \rightarrow A$ be a function. Then there is a unique function $f : \mathbb{N} \rightarrow A$ with these two properties:

$$\begin{aligned} f0 &= z \\ f(\text{suc } n) &= s(fn) \quad \text{for each number } n \end{aligned}$$

Call these the Recursive Properties.

In the rest of this section we'll prove the Recursion Theorem. We have already justified recursively defined *relations*, and induction using such definitions—so we can use this technique in our proof. In particular, to get to the recursively defined function f , we'll start by defining a closely related relation. For a number n and an element $a \in A$, we define n selects a recursively as follow:

$$\frac{}{0 \text{ selects } z} \qquad \frac{n \text{ selects } a}{\text{suc } n \text{ selects } sa}$$

What we still need to check is that this recursively defined *relation* picks out a *function*. In the terms from Exercise 1.3.6, we will check that the set of pairs (n, a) such that n selects a is *functional*: this means that each number selects exactly one value. Once we have done this, we can check that the corresponding function has the Recursive Properties.

2.3.5 Exercise

Prove each of the following by induction on the definition of “selects.”

- (a) If 0 selects a , then $a = z$
- (b) If $\text{suc } n$ selects a , then there is some $b \in A$ such that n selects b and $sb = a$.

Hint. You can restate (a) as “for every pair (n, a) such that n selects a , if $n = 0$, then $a = z$.” You can restate (b) in a similar way. These inductive proofs are kind of trivial, which makes them look a little weird. They use the Injective Property.

2.3.6 Exercise

- (a) For each number $n \in \mathbb{N}$, there is at least one $a \in A$ such that n selects a .
- (b) For each number $n \in \mathbb{N}$, there is at most one $a \in A$ such that n selects a .

Thus we can use this relation to pick out a (unique) function: there is exactly one function $f : \mathbb{N} \rightarrow A$ such that

$$fn = a \quad \text{iff} \quad n \text{ selects } a \quad \text{for every } n \in \mathbb{N} \text{ and } a \in A$$

2.3.7 Exercise

- (a) For any function $f : \mathbb{N} \rightarrow A$, f has the Recursive Properties iff f satisfies Section 2.3.
- (b) Explain how this completes the proof of the Recursion Theorem ((2.3.4)).

Hint for part (a). Here is another equivalent way of stating the Recursive Properties.

- (i) For each $a \in A$, $f0 = a$ iff $a = z$.
- (ii) For each $a \in A$, $f(\text{suc } n) = a$ iff $a = s(fn)$.

2.4 Sequences and Strings

The elements of a *set* don't come in any special "order". But sometimes order matters. The sentences `dog bites man` and `man bites dog` say different things, but they both are made up from the very same set of symbols. The order of words and letters matter.

Just like we did with numbers and sets, it will be useful to give a careful and precise description of the structure of *finite sequences*. This will equip us with tools for proving things about *all* ways of arranging certain things in a sequence, and for defining functions on the set of all such sequences.

So far we have learned basic techniques for reasoning about *sets* and *numbers*. *Finite sequences* bring together both of these kinds of reasoning. Like a set, a sequence is a kind of collection, putting some things together. Like numbers, finite sequences can be reasoned about using induction and recursion.

Sequences have a starting place—the *empty sequence*, which has length zero, containing no elements at all. We'll use the notation $()$ for the empty sequence. (Including the empty sequence is handy for similar reasons as counting *zero* as a number, or the *empty set* as a set.) And there is a rule for building up longer sequences from shorter ones, by adding on a single element. We can build up any finite sequence at all by starting with the empty sequence, and adding on elements one at a time. For example, we can extend the length-two sequence (Los Angeles, San Diego) by adding San Jose to form the length-three sequences (Los Angeles, San Diego, San Jose).

We'll use the comma for the "append" operation that adds an element to a sequence. This is being a little bit notationally tricky, so let's pay attention to what's happening. If we have a sequence s and a new element a , then (s, a) will be the extended

sequence. That means that if we are going to be all official, the sequence

(Los Angeles, San Diego, San Jose)

should really be written

(((), Los Angeles), San Diego), San Jose)

We start with the empty sequence, and append elements one at a time. But this is ugly and unwieldy. In general, we'll hide parentheses that could be filled in from context: for example, if we want to append two elements a and b to a sequence s , instead of writing $((s, a), b)$, we can simplify this as (s, a, b) . Second, if we are joining something to the empty sequence, we'll usually make both the $()$ and the first comma invisible. For example, for a length one sequence, instead of writing $(((), a)$, we can just write (a) . Putting both of these shorthands together, the ugly notation

(((), Los Angeles), San Diego), San Jose)

gets simplified to

(Los Angeles, San Diego, San Jose)

which looks much nicer. But we can always “unpack” these shorthands if it helps make our reasoning clearer. (This notation does raise some potential ambiguity when we consider sequences whose elements are also sequences, but this generally does not cause trouble in practice.)

(If you want to, you can suppose that this is also what's going on with the *ordered pairs* we have already seen, so there's no notational ambiguity: the ordered pair (Al, Bea) is the same thing as the length-two sequence that we could more officially write as $(((), \text{Al}), \text{Bea})$. But you don't have to think this—for our technical purposes, we don't have to answer this metaphysical question about what an ordered pair really *is*. We just need to know that a pair has a first component and a second component, somehow or other, and we don't have to ask what kind of abstract glue holds them together.)

We can build up any sequence this way, starting with the empty sequence and adding one element at a time.

$(\text{Al}, \text{Bea}, \text{Cece}) = ((((), \text{Al}), \text{Bea}), \text{Cece})$

Furthermore, this is the *only* way to produce this sequence by adding elements one at a time. It isn't as if you could put together some other things in some other order and end up with the very same sequence. In general, every finite sequence can be

reached in *exactly one way* by starting with the empty sequence and adding things one by one.

We can summarize this fact using “formation rule” notation, similar to what we did for numbers. Let A be any set. We’ll use the notation A^* for the set of all finite sequences of elements of A . There are two ways of building up these sequences, which can be described with the following rules:

$$\frac{}{() \text{ is a sequence in } A^*} \quad \frac{s \text{ is a sequence in } A^* \quad a \text{ is an element of } A}{(s, a) \text{ is a sequence in } A^*}$$

Every sequence of elements of A can be produced in exactly one way using these two rules.

This means that, just like with numbers, we can do *proofs by induction* for sequences. If we want to prove that *every sequence* of elements of A has a certain property, it’s enough to show two things. (a) The empty sequence has the property. (b) The property is inherited whenever we add a single element to a sequence. We will look at examples of this in a moment.

Inductive proofs are one important thing that sequences have in common with numbers. Another thing they have in common is *recursive definitions*. In Section 2.2 we showed how to give a recursive definition for a function whose domain is the set of numbers. This works for sequences, too. Every sequence of elements of A can be reached in exactly one way, by starting with the empty sequence and adding elements one by one. So we can define an “output” of a function f for *every* sequence of elements of A in two steps.

1. We say what the output is for the empty sequence, $f()$.
2. We assume that we already have the output for a shorter sequence s , and then we use this value $f s$ to define the value of f for a sequence which is just one element longer, $f(a, s)$ for any element $a \in A$.

Here’s an example.

2.4.1 Definition

Let A be any set. Let’s recursively define the *length* of a sequence of elements of A . This is a function $\text{length} : A^* \rightarrow \mathbb{N}$ that takes each sequence to a number. The definition has two parts. For the *base case*, we define the length of the empty sequence:

$$\text{length}() = 0$$

For the *recursive step*, we suppose that we already know the length of a sequence s , and we use this to define the length of the sequence that results from adding one element to s . That is, supposing we know $\text{length } s$, we want to define $\text{length}(s, a)$. This is easy: it should be just one more than the length of s .

$$\text{length}(s, a) = \text{suc}(\text{length } s) \quad \text{for every } a \in A$$

A length n sequence is also called an **n -tuple**. We use the notation A^n for the set of all length n sequences of elements of A .

Here's another example. The "comma" operation lets us add one element to a sequence. But another thing we sometimes want to do is add a bunch of elements at once, sticking two long sequences together end to end. If s and t are both sequences, we'll call the result of sticking them together this way $s \oplus t$. We can give an official definition of this operation using recursion. This is closely analogous to the definition of addition for numbers, so it might be helpful to compare the parts of this definition side-by-side with Definition 2.2.13.

2.4.2 Definition

Let A be any set. For any sequence $s \in A^*$, we define the function that takes a sequence $t \in A^*$ to a sequence $s \oplus t$ recursively, as follows.

For the base case, we say how to join the empty sequence to s . This is easy:

$$s \oplus () = s$$

For the recursive step, we suppose that we already know how to join s to t , and then use this to define the result of joining s to the longer sequence (t, a) . The idea is that we can do this by first joining s to t , and then finally putting in the element a as well.

$$s \oplus (t, a) = (s \oplus t, a)$$

2.4.3 Example

Show explicitly using the definition:

$$(1, 2, 3) \oplus (4, 5) = (1, 2, 3, 4, 5)$$

Proof

Remember that the notation $(4, 5)$ is shorthand for

$$((((), 4), 5)$$

Using the the definition of \oplus ,

$$\begin{aligned}(1, 2, 3) \oplus (((), 4), 5) &= ((1, 2, 3) \oplus ((), 4), 5) \\ &= (((1, 2, 3) \oplus (), 4), 5) \\ &= (((1, 2, 3), 4), 5)\end{aligned}$$

And when we simplify the comma notation, this is $(1, 2, 3, 4, 5)$. \square

Just like with numbers, recursive definitions and inductive proofs for sequences work hand in hand.

2.4.4 Example

For any sequences s and t in A^* ,

$$\text{length}(s \oplus t) = \text{length } t + \text{length } s$$

Proof

Let s be any sequence in A^* . We'll use induction to prove that every sequence $t \in A^*$ has the property ?? 2.4.4.

Base case. For the empty sequence, by definition, $s \oplus () = s$. So:

$$\begin{aligned}\text{length}(s \oplus ()) &= \text{length } s && \text{by the definition of } \oplus \\ &= \text{length } s + 0 && \text{by the definition of } + \\ &= \text{length } s + \text{length}() && \text{by the definition of length}\end{aligned}$$

Inductive step. Suppose that $t \in A^*$ has the property (?? 2.4.4). (This assumption is the *inductive hypothesis*.) We want to show that, for any element $a \in A$, the sequence (t, a) also has the property (?? 2.4.4).

$$\begin{aligned}\text{length}(s \oplus (t, a)) &= \text{length}(s \oplus t, a) && \text{by the definition of } \oplus \\ &= \text{suc}(\text{length}(s \oplus t)) && \text{by the definition of length} \\ &= \text{suc}(\text{length } s + \text{length } t) && \text{by the inductive hypothesis} \\ &= \text{length } s + \text{suc}(\text{length } t) && \text{by the definition of } + \\ &= \text{length } s + \text{length}(t, a) && \text{by the definition of length} \quad \square\end{aligned}$$

2.4.5 Exercise

Let A be a set with at least two elements.

- (a) Is joining sequences commutative? That is, does

$$s \oplus t = t \oplus s$$

for all sequences $s, t \in A^*$? If so, give a proof by induction; otherwise, give a counterexample.

- (b) Is joining sequences associative? That is, does

$$s \oplus (t \oplus u) = (s \oplus t) \oplus u$$

for all sequences $s, t, u \in A^*$? If so, give a proof by induction; otherwise, give a counterexample.

Hint. It might be helpful to look back at Example 2.2.18.

2.4.6 Definition

For any sequence s of elements of A , we can recursively define the **set of elements** in s as follows.

$$\begin{aligned} \text{elem}() &= \emptyset \\ \text{elem}(s, a) &= \text{elem } s \cup \{a\} \end{aligned}$$

This recursively defines a function

$$\text{elem} : A^* \rightarrow PA$$

2.4.7 Exercise

Use the definition to show explicitly, step by step:

$$\text{elem}(1, 2, 3) = \{1, 2, 3\}$$

2.4.8 Exercise

For any set A , and any sequences s and t of elements of A ,

$$\text{elem}(s \oplus t) = \text{elem } s \cup \text{elem } t$$

Let's summarize the two main things we have learned to do with sequences in this section.

2.4.9 Technique (proof by induction for sequences)

Suppose you have some set A , and you want to show:

For every sequence s of elements of A , s is nice.

Here “ s is nice” is a placeholder for any statement about s . You can do this in two steps.

1. *Base case.* Show that the *empty* sequence is nice.
2. *Inductive step.* Show that for any sequence $s \in A^*$, and any element $a \in A$, *if* s is nice, *then* the longer sequence (s, a) is also nice.

Then you’re done: this is enough to show that *every* sequence of elements of A is nice.

2.4.10 Technique (recursively defining a function on sequences)

Suppose you want to come up with a function whose *domain* is the set A^* of all sequences of elements of A . That is, for some set B , you’re trying to come up with a function $f : A^* \rightarrow B$. You can do this in two steps.

1. Choose a value of f for the empty sequence. That is, you’ll write down

$$f() = \underline{\hspace{2cm}}$$

Fill in the blank with some description of an element of B .

2. Choose a rule for getting a value of f for a sequence *using* the value of f for a shorter sequence. That is, you’ll write down

$$\text{For any sequence } s \text{ and element } a \in A, f(s, a) = \underline{\hspace{2cm}}$$

Fill in the blank with another description of an element of B , where this description is allowed to use $f(s)$ (as well as a).

Once you have done these two things, you have precisely described one (and only one!) function from A^* to B .

The set of numbers and the set of sequences of elements of a set are both *inductive structures*. Inductive structures play a starring role throughout logic, and in this text we’ll encounter many others. (For example, terms, formulas, formal proofs, and programs.) For this reason, *proofs by induction* and *recursive definitions* are two very important fundamental skills in logic.

There is one particularly important kind of sequence. This text consists of symbols written down in order to form words and sentences, as well as special logical notation. When we express ideas, we almost always do it by stringing together symbols

in some order (whether they are written, spoken, signed, or otherwise). So the theory of *finite sequences of symbols*—or **strings**—is centrally important for studying language, philosophy, and logic.

Strings bridge between the finite and the infinite. There are only finitely many symbols which can be typed using a standard keyboard. But by typing these symbols in different orders, in sequences of different lengths, they can be used to represent infinitely many different ideas—all the books ever written, and infinitely many merely possible books besides.

We will use strings to represent language—including words, sentences, logical formulas, programs, and proofs. It will be helpful to fix in advance a standard alphabet for this purpose. We could get by with the twenty-six English letters and a few punctuation marks—or if we wanted to be very austere, we could get away with just dots and dashes like in Morse code, or zeros and ones or some other very simple alphabet. But let's be a little more extravagant.

Since 1991, the Unicode Consortium has standardized a very large “alphabet”, called the Unicode Character Set, which includes all the symbols used in most human writing systems. This includes not just letters, punctuation marks, and spaces, but also many technical symbols like \forall , \rightarrow , and \oplus , and even emoji. Unicode is nowadays a worldwide standard, especially for representing text on the Internet, which of course is written in many different natural and artificial languages. (This text is also written using Unicode.) Our **standard alphabet** will consist of the entire Unicode 8.0 Character Set. This is a set of about 120,000 different symbols—including all of the symbols used in this text. (But in practice we will use fewer than a hundred symbols or so, so if you want you can use a significantly smaller alphabet without changing anything.) We will use the notation \mathbb{A} for the standard alphabet, the set of basic symbols. A **symbol** is any element of the standard alphabet. A **string** is a finite sequence of symbols. We will use the notation \mathbb{S} for the set of all strings (which we could also call \mathbb{A}^*).

(In what follows we often won't bother to distinguish the *symbol* a from the *length-one string* (a) . Officially, nothing we have said commits us to a view about whether these are the same thing or two different things. But from now on, we'll treat them as the same thing, for convenience.)

We'll be talking about strings of symbols a lot. In this written medium, we also *use* strings of symbols in order to talk—strings of symbols that represent English words, as well as technical notation. For instance, this paragraph begins with the string of symbols `We'll be talking about strings`, and so on. It will be important to be distinguish these two activities, which are standardly called *use* and *mention*: that

is, *using* strings of symbols to say things, and *mentioning* strings of symbols to talk about the symbols themselves. So it will be helpful to have some special notation.

2.4.11 Notation

We use the notation ABC to refer to the three-letter string consisting of A followed by B followed by C .

Instead of using the join symbol \oplus , we can just write two strings next to each other, so st is the same as $s \oplus t$. Likewise, As is the same as $\text{A} \oplus s$, and ABCsDEF is the same as $\text{ABC} \oplus s \oplus \text{DEF}$. This is convenient when we are building up complicated strings out of shorter ones. (This is similar to the convention in algebra of writing xy for multiplication, instead of $x \cdot y$ or $x \times y$.)

2.4.12 Exercise

Let $s = \text{tu}$. Which of these strings are the same?

- (a) stu
- (b) $\text{s} \oplus \text{tu}$
- (c) $s \oplus \text{tu}$
- (d) $\text{s} \otimes \text{tu}$
- (e) stu
- (f) $\text{s} \oplus s$
- (g) ss
- (h) $\text{t} \oplus \text{u} \oplus \text{t} \oplus \text{u}$
- (i) $s \otimes \text{tu}$
- (j) $\text{s} \oplus \otimes \text{tu}$

2.4.13 Exercise

When you log into a website, to protect your privacy your password usually isn't shown directly on your screen: instead, a string of dots with the same length as your password is displayed. Instead of the string `password`, you'll see the string `••••••••`. For each string s , let $\text{dots } s$ be the string of dots with the same length as s .

- (a) Write out a recursive definition of the `dots` function.
- (b) Use your definition to show

$$\text{length}(\text{dots } s) = \text{length } s$$

(c) Use your definition to show

$$\text{elem}(\text{dots } s) = \{\bullet\}$$

(d) Use your definition to show

$$\text{dots}(s \oplus t) = \text{dots } s \oplus \text{dots } t$$

(e) Show that

$$\text{length } s = \text{length } t \quad \text{iff} \quad \text{dots } s = \text{dots } t$$

2.5 Official Principles for Sequences*

Just like we did with numbers, we can describe the inductive structure of sequences more officially using an *axiom*, which is closely analogous to the Axiom of Numbers. This new axiom is a little more complicated, though, because the adding-one-element operation $(,)$ is a little more complicated than the successor function. Likewise, we can more precisely state, and more carefully justify, the technique of recursively defining a function on strings with a *theorem*—a Recursion Theorem for Sequences, which is closely analogous to the Recursion Theorem for numbers. The idea is basically the same as with numbers, but again it's a little bit more complicated. I'll state both of these explicitly here for completeness. But for this course, the more important thing to have a handle on is the practical *skills* of inductive proofs and recursive definitions—not the official statements we will give for the Axiom of Sequences or the Recursion Theorem for Sequences. The Axiom of Sequences is just a way of precisely spelling out the main intuitive idea:

Every sequence can be reached in exactly one way by starting from the empty sequence and adding elements one by one.

Similarly, the Recursion Theorem for Sequences is just a way of precisely spelling out the intuitive idea that we can define a function on all sequences using a “starting place” and a “step rule.”

2.5.1 Axiom of Sequences

Let A be a set. There is a set of **finite sequences** A^* , an **empty sequence** $()$ which is an element of A^* , and an “**append**” function $(,)$ that takes each sequence $s \in A^*$ and each element $a \in A$ to a sequence (s, a) , which have the following properties.

(a) **Injective Property.**

- (i) The empty sequence $()$ is not in the range of the append function $(,)$. That is, there is no sequence $s \in A^*$ and element $a \in A$ such that $(s, a) = ()$.
- (ii) The append function $(,)$ is one-to-one. That is, for any sequences s and s' in A^* , and any elements a and a' in A , if $(s, a) = (s', a')$ then $s = s'$ and $a = a'$.

(b) **Inductive Property.** Let X be a set. Suppose

- (i) the empty string $()$ is in X , and
- (ii) for each sequence $s \in X$ and element $a \in A$ and, (s, a) is also in X .

Then X includes every sequence in A^* : that is, $A^* \subseteq X$.

2.5.2 The Recursion Theorem for Sequences

Let A and B be any sets. For any element $e \in B$ and any function $c : B \times A \rightarrow B$, there is a unique function $f : \mathbb{S} \rightarrow B$ with the following two *Recursive Properties*:

$$\begin{aligned} f() &= e \\ f(s, a) &= c(f(s), a) \quad \text{for each element } a \in A \text{ and sequence } s \in A^* \end{aligned}$$

Proof Sketch

We can use the same idea we used for numbers. First, we can use the recursive properties to recursively define a *relation* between strings and values (using Exercise 2.3.2). Second, we can show that this relation is *functional*, and thus that it picks out a function. Finally, we can check that this function has the recursive properties.

For a sequence s and an element $b \in B$, we define s **selects** b recursively by the following two rules:

$$\frac{}{\emptyset \text{ selects } e} \qquad \frac{s \text{ selects } b \quad a \in A}{(s, a) \text{ selects } c(b, a)}$$

As in the proof of the Recursion Theorem for Numbers, we can prove the following things.

1. (a) If \emptyset selects b , then $b = e$.
- (b) If (s, a) selects b , then there is some b' such that s selects b' and $b = c(b', a)$.

2. Any function f has the Recursive Properties iff, for each sequence s and $b \in B$,

$$fs = b \quad \text{iff} \quad s \text{ selects } b$$

Finally we can prove (by induction on sequences)

3. Each sequence selects exactly one value.

This implies that there really is exactly one function f with the Recursive Properties. \square

As we'll see later, induction and recursion make sense not just for numbers and strings, but also for formulas, proofs, and many other kinds of things which are important for logic. Each of these inductive structures has both an Inductive Property and a corresponding Recursion Theorem.

2.6 Properties of Numbers and Strings

At this point, we have stated the Axiom of Numbers and the Axiom of Sequences: these describe the fundamental structure of finite numbers and finite sequences, using the Injective Property and Inductive Property for each of them. We've also given recursive definitions for a few important operations on these structures: especially addition (+), multiplication (\cdot), concatenation (\oplus), and length. In this section we'll summarize some other important facts about how these operations on numbers and sequences work, which follow from the axioms and definitions we have already given. Working through all the proofs of the facts in this section would provide good extra exercises for getting practice. Even though I've marked them as "Exercises," though, they won't be assigned as homework and I won't go over them in class—that would just take us too much time, and we want to move on to more interesting things. Still, it's important to know not only that the facts listed here about numbers and strings are *true*, but also that we *can prove* all of these facts from our basic axioms and definitions—even though we won't actually bother to do this.

It will be helpful to refer back to these facts later on.

2.6.1 Exercise (Cancellation Property for Addition)

For any numbers n , k , and k' , if $n + k = n + k'$, then $k = k'$.

Hint. Prove that every number n has the property:

For any $k, k' \in \mathbb{N}$, if $n + k = n + k'$, then $k = k'$.

We defined $m \leq n$ recursively, in Section 2.2, and proved that this relation was reflexive and transitive. Here are some more related facts.

2.6.2 Exercise

For any numbers m and n , $m \leq n$ iff there is some number $k \in \mathbb{N}$ such that $m + k = n$.

Hint. For the left-to-right direction, use induction on the definition of \leq . For the right-to-left direction, use induction on k .

2.6.3 Exercise

If $n \leq 0$ then $n = 0$.

Hint. We can restate this: for any pair (n, k) such that $n \leq k$, if $k = 0$, then $n = 0$.

2.6.4 Exercise

If $m \leq n$ and $n \leq m$, then $m = n$. (In other words, \leq is **anti-symmetric**.)

2.6.5 Definition

We say m is (strictly) **less than** n (abbreviated $m < n$) iff $m \leq n$ and $m \neq n$.

2.6.6 Exercise

There is no natural number $n < 0$.

2.6.7 Exercise

$m \leq n$ iff $m < \text{suc } n$, for any numbers m and n .

2.6.8 Exercise

For any numbers m and n , either $m \leq n$ or $n \leq m$. (In other words, \leq is **complete**.)

A relation which is reflexive, transitive, and anti-symmetric is called a **partial order**.

A partial order which is also complete is called a **total order**. So we have shown that the natural numbers are totally ordered.

2.6.9 Exercise

- If $m \leq \text{suc } n$, then either $m \leq n$ or $m = \text{suc } n$.
- If $m < \text{suc } n$, then either $m < n$ or $m = n$.

2.6.10 Exercise (The Least Number Property)

Any non-empty set of numbers X has a least element: that is, there is some $m \in X$ such that $m \leq n$ for every $n \in X$. (Another name for this property is that \leq is a **well-ordering**.)

Hint. Suppose X has no least element, and prove by induction that, for every number n , the set $\{k \in X \mid k < n\}$ is empty.

2.6.11 Exercise

Let X be any set of numbers. Show that X has *at most one* least element: that is, there is at most one $m \in X$ such that, for every number $n \in X$, $m \leq n$.

Let's collect together some of the useful basic facts we've established. Some of these are definitions, and others were proved as examples or in exercises. This particular collection of facts will be useful to refer back to later.

2.6.12 The Minimal Theory of Arithmetic

The following properties hold for all numbers m, n, k :

1. 0 is not a successor.
2. No two numbers have the same successor.
3. $n + 0 = n$.
4. $m + \text{suc } n = \text{suc}(m + n)$
5. $n \cdot 0 = 0$
6. $m \cdot \text{suc } n = (m \cdot n) + m$
7. n is not less than 0
8. $m \leq n$ iff $m < \text{suc } n$
9. $m \leq n$ or $n \leq m$

We can do some similar things for sequences. Since the most important kind of sequences in what follows are strings, we will focus on them.

2.6.13 Definition

For strings s and t , we say s is an **initial substring** of t (abbreviated $s \leq t$) iff there is some string $u \in \mathbb{S}$ such that $s \oplus u = t$. We say s is a **proper initial substring** of t (abbreviated $s < t$) iff $s \leq t$ and $s \neq t$.

2.6.14 Exercise

$s \leq t$ iff either s is empty, or for some symbol a , $s = a \oplus s'$, $t = a \oplus t'$, and $s' \leq t'$.

2.6.15 Exercise

If $s \leq t$ then $\text{length } s \leq \text{length } t$.

2.6.16 Exercise (Cancellation Property for Strings)

If $s \oplus t = s' \oplus t$, then $s = s'$. Likewise, if $s \oplus t = s \oplus t'$, then $t = t'$.

2.6.17 Exercise

If $s \leq t$ and $s' \leq t$, then either $s \leq s'$ or $s' \leq s$.

2.6.18 Exercise (The Shortest String Property)

Let X be any non-empty set of strings. Then X has a minimal-length element: that is, there is some $s \in X$ such that every string in X is at least as long as s .

The Shortest String Property underlies an alternative induction technique for reasoning about strings, which is usually called *strong induction*. Say we want to prove that every string is nice. We can do it like this. Let s be any string, and show the following:

If every string which is strictly *shorter* than s is nice, then s is also nice.

It then follows that every string is nice. The reason this follows, is because otherwise the set X of non-nice strings would be non-empty, in which case it would have a minimal-length element. But that would mean that s is a non-nice string such that every string *shorter* than s is nice—and what the “strong induction” proof shows is precisely that there is no such string. Strong induction on strings is a bit more flexible than ordinary (“primitive”) induction on strings, so it is occasionally handy.

2.6.19 The Minimal Theory of Strings

Let s and t be strings, and let a and b be strings each of which consists of a single symbol.

1. $a \oplus s \neq ()$
2. If $a \oplus s = a \oplus t$, then $s = t$.
3. If a and b are distinct symbols, then $a \oplus s \neq b \oplus t$.
4. $() \oplus s = s$
5. $a \oplus (s \oplus t) = (a \oplus s) \oplus t$

6. $a = a \oplus ()$
7. The empty string $()$ is no longer than s .
8. s is no longer than $()$ iff $s = ()$.
9. $a \oplus s$ is no longer than $b \oplus t$ iff s is no longer than t .
10. Either s is no longer than t , or t is no longer than s (or perhaps both).
11. Either $s = ()$, or else there is some single-symbol string a and string t such that $s = a \oplus t$.

2.7 Review

Key Techniques

- You can use **induction** to prove that every number has a certain property. (Technique 2.1.5)
- You can use a **recursive definition** to come up with a function whose domain is the set of all numbers. (Technique 2.2.28)
- You can use **induction on sequences** to prove that every sequence of elements from a certain set has a certain property. (Technique 2.4.9)
- You can use **recursion on sequences** to come up with a function whose domain is the set of all sequences. (Technique 2.4.10)

Key Concepts and Facts

- The **Injective Property of numbers** intuitively says that every number can be reached in *at most one way* by starting from zero and taking successors.
- The **Inductive Property of numbers** intuitively says that every number can be reached in *at least one way* by starting from zero and taking successors.
- The **Recursion Theorem** intuitively says that recursive definitions work. If you give a value for zero, and a “step function” to go from the value for n to the value for $n + 1$, then this pins down exactly one function which is defined for every number.
- Together, the Injective Property and Inductive Property for numbers tell us everything we need to know about the structure of numbers: we can use these basic properties to prove familiar facts about how operations like addition and multiplication work.

- The **Injective Property of Sequences** intuitively says that every sequence can be reached in *at most one way* by starting from the empty sequence and adding elements one at a time.
- The **Inductive Property of Sequences** intuitively says that every string can be reached in *at least one way* by starting from the empty sequence and adding symbols one at a time.
- The **Recursion Theorem for Sequences** intuitively says that recursive definitions on sequences work. If you give a value for the empty sequence, and a rule for going from the value for a sequence s to a value for any string (s, a) which is one element longer, then this pins down exactly one function which is defined for every sequence.
- The Injective Property and Inductive Property for sequences tells us everything we need to know about the structure of sequences: we can use these basic properties to prove facts about operations like joining sequences together work.
- Sequences of symbols are especially important, and they are called **strings**. We have to be careful to distinguish when we are **using** a string of symbols to say something about the world, and when we are **mentioning** a string to say something about the string itself. We have some special notation to help with this, like this: **We have some special notation.** (Notation 2.4.11)

Chapter 3

Terms

Philosophy is written in this grand book—I mean the Universe—which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the symbols in which it is written.

Galileo Galilei, *The Assayer* (1623)

3.1 Signatures and Structures

We have talked about the set of natural numbers, and we have talked about various special features they have: the starting place zero, the “next-number” successor function, operations like addition and multiplication, relations like \leq . In the course of doing this, we also introduced notation: the symbols `0`, `suc`, `+`, `*`, and `s`, among others. Now we will take a step back, and study what we were doing when we did that, when we used *strings* to refer to *things*. As we go on through this text we will take many steps like this, building up a richer and richer theory of more and more of what we have been saying and doing—making claims, defining new terms, and proving things. But here we start small, with a crude sketch of some basic relationships between the kind of language we use, and the world that it is intended to describe.

We have the number zero, and we have the string `0`. It is always important to remember that these are two different things, which should not be confused with each other. But of course there is an important relationship between them: we use the

string `0` as a *name* for the number zero. Similarly, `suc` is a name for the successor function `suc`, `+` is a name for the addition function, and so on. When we put together a bunch of these strings, we get a very simple kind of language, which we call a **signature**. When we specify what each of these strings is supposed to mean, we get something that we call a **structure**.

A language has words for different kinds of things, such as an individual object like zero, a function like `suc`, or a relation like \leq . A signature spells out the basic words of a language, and what type of thing each word is supposed to stand for. These “types” will constrain what ways of putting words together make grammatical sense. But grammar will wait until Section 3.2.

The **signature of the language of arithmetic** has five basic “words” in it, with the obvious types: `0` is a name for an individual thing, `suc` is a name for a one-place function, `+` and `·` are names for two-place functions, and `\leq` is the name for a two-place relation. The standard *structure* that corresponds to this consists of the set of all natural numbers \mathbb{N} together with a function that tells the story about how each of these names works: the symbol `0` is mapped to the number zero, `suc` is mapped to the successor function, and so on. This “word-world” function is called the *extension* function.

The strings that we use as names for functions are ordinarily called “function symbols”—despite the fact that they don’t have to consist of a single symbol from the alphabet. For instance, it’s fine to use the length-three string `suc` as a function symbol. (So this is a slightly different meaning of “symbol” from when we say “a string is a sequence of symbols”.) But we shouldn’t be totally loosey-goosey: it would make things a complete mess if we used, say, `) \wedge (x`, as the notation for one of our basic function symbols. So we’d better not allow strings like this. Call a string that does not contain any parentheses or commas a **token** (more on this in Section 3.3; in Section 5.1 we will impose some extra constraints on tokens).¹

¹ A restriction that may not be so obviously restrictive is that all of our names, function symbols, and predicates are *strings*. As we will see in Section 4.2, this puts some restrictions on how “big” a language can be. In other contexts sometimes it’s nice to be less restrictive, and use things other than strings as the “signs” in signatures and structures. For instance, it can occasionally be nice to think about a “Lagadonian language” in which each object serves as a name for *itself*. But for the purposes of this text it makes sense to be more restrictive: we are focusing on logical languages that can be written down as strings of symbols—like the languages that humans use.

The term “Lagadonian language” comes from Lewis (1986). It is inspired by *Gulliver’s Travels*: the professors in the “school of languages” in the city of Lagado proposed the following scheme:

An expedient was therefore offered, “that since words are only names for things, it would be more convenient for all men to carry about them such things as were necessary to express a particular business they are to discourse on.” … [M]any of the most learned and wise adhere to the new scheme of expressing themselves by things; which

3.1.1 Definition

A **signature** L consists of four components. First, there are three disjoint sets of tokens:

1. The set of **names** of L
2. The set of **function symbols** of L
3. The set of **predicates** of L

The fourth component is a function that takes each function symbol or predicate to a non-zero natural number, which is called its **adicity**—its number of arguments. For example, if the adicity of a predicate is two, we call it a *two-place predicate*.

3.1.2 Example

The **signature of the language of arithmetic** has one basic name $\textcolor{green}{0}$, one one-place function symbol $\textcolor{brown}{suc}$, two two-place function symbols $\textcolor{orange}{+}$ and $\textcolor{brown}{\cdot}$, and one two-place predicate $\textcolor{brown}{\leq}$. We also call this signature $L_{\mathbb{N}}$.

The next important question is how to interpret all these symbols. The things we use to represent possible interpretations of a signature are called *structures*.

3.1.3 Definition

Let L be a signature. A **structure** S with signature L (for short, an **L -structure**) consists of the following two components.

1. A non-empty set D_S called the **domain** of S .
2. An **extension function**, written $[\cdot]_S$, which takes each basic symbol of L to an appropriate kind of thing.
 - a. The extension of each *name* c in L is an element of the domain of S , which we write $[c]_S$.

has only this inconvenience attending it, that if a man's business be very great, and of various kinds, he must be obliged, in proportion, to carry a greater bundle of things upon his back, unless he can afford one or two strong servants to attend him. I have often beheld two of those sages almost sinking under the weight of their packs, like pedlars among us, who, when they met in the street, would lay down their loads, open their sacks, and hold conversation for an hour together; then put up their implements, help each other to resume their burdens, and take their leave.

But for short conversations, a man may carry implements in his pockets, and under his arms, enough to supply him; and in his house, he cannot be at a loss. Therefore the room where company meet who practise this art, is full of all things, ready at hand, requisite to furnish matter for this kind of artificial converse. [TODO CITE]

- b. The extension of each n -place function symbol f in L is an n -place function $D_S^n \rightarrow D_S$, which takes any n -tuple of elements of the domain of S to an element of the domain of S . We call this function $[f]_S$.
- c. The extension of each n -place predicate symbol F is a subset of D_S^n , that is, a set of n -tuples of elements of the domain of S , which we call $[F]_S$.

Another name for a structure is a **model**. This term is a bit old-fashioned, but we still use it in certain contexts.

3.1.4 Definition

The **standard model of arithmetic**, which we also just call \mathbb{N} , is specified as follows:

1. The domain $D_{\mathbb{N}}$ is the set of natural numbers \mathbb{N} .
2. The extension of the name 0 is the number zero.
3. The extension of the function symbol suc is the successor function.
4. The extension of the function symbol $+$ is the addition function.
5. The extension of the function symbol \cdot is the multiplication function.
6. The extension of the relation symbol \leq is the set of pairs (m, n) such that m is less than or equal to n .

We can restate this more concisely:

$$\begin{aligned} D_{\mathbb{N}} &= \mathbb{N} \\ [0]_{\mathbb{N}} &= 0 \\ [suc]_{\mathbb{N}} &= suc \\ [+]_{\mathbb{N}}(m, n) &= m + n \quad \text{for each } m, n \in \mathbb{N} \\ [\cdot]_{\mathbb{N}}(m, n) &= m \cdot n \quad \text{for each } m, n \in \mathbb{N} \\ [\leq]_{\mathbb{N}} &= \{(m, n) \in \mathbb{N} \times \mathbb{N} \mid m \leq n\} \end{aligned}$$

We standardly use the symbols 0 , $+$, and so on to talk about numbers. But we could also interpret them in other ways. There are *non-standard* structures that have the same signature as the standard model of arithmetic, but which assign its words very different “meanings”. Here’s a simple example:

3.1.5 Example

There is a structure S with the signature $(\text{0}, \text{suc}, +)$ given as follows:

1. The domain of S consists of all of the buildings in Los Angeles.
2. The extension of 0 in S is the Natural History Museum of Los Angeles County.
3. The extension of suc in S is the function that takes each building to the nearest building directly east of it. (This will map buildings at the eastern edge of LA all the way around the world to the West Side again.)
4. The extension of $+$ in S is the function that takes two buildings to whichever one of them contains the most dinosaur skeletons (or the building farthest east in the case of a tie).

The main point of the language of arithmetic is to talk about the *standard* number structure \mathbb{N} . But non-standard structures are also important. As we will see later on (especially in Section 5.3), one way of investigating how much we have managed to say about an *intended* structure is to look at what *unintended* interpretations are still compatible with what we have said so far.

We use language to talk about things like numbers, buildings, or people. But we can also use language to talk about *language*—as we have been doing in this chapter. Talking about language is also something we want to talk about! So it will be useful to introduce another little formal language. This is a little sketch of the way we *use* strings of symbols to talk *about* strings of symbols—a language about languages.

3.1.6 Definition

The **signature of the language of strings**, abbreviated $L_{\mathbb{S}}$, has a two-place function symbol o , a two-place predicate s (which we will use for the no-longer-than relation), a name "" (which will represent the empty string), and a name for the singleton string for each symbol in the standard alphabet \mathbb{A} . We'll use quotation marks for these symbol-names. The name for the singleton string A will be $"A"$, the name for B will be $"B"$, and so on. There are a few exceptions to this pattern.

- It would be confusing and potentially ambiguous to use $"""$ as the name for the quotation mark $"$. So we'll use quo , instead.
- To guarantee unique parses (Section 3.3), it's convenient to stick to names that don't include any commas or parentheses. But that means we can't use $", "$ as a name for the comma $,$. Instead, we'll use com for the comma, lpa for $($ and rpa for $)$, instead of the more obvious $", "$, $"($, and $")"$.

- In Section 4.1, Chapter 7, and Chapter 8 it will sometimes be convenient to use *multi-line* strings, particularly to write down programs and proofs. For this purpose, we have a symbol in our alphabet that represents the start of a new line—called newline. This symbol is difficult to write down on its own. Our name for the newline symbol in the language of strings is `new`.

In general, we will use the notation c_a for the name in $L_{\mathbb{S}}$ for the symbol $a \in \mathbb{A}$. For example, $c_{\text{A}} = \text{"A"}$, and $c_{\text{.}} = \text{quo}$.

(Why the weird abbreviations for these names? It turns out that making all of the names for single symbols the *same length* is a useful hack later on, in Section 6.4.)

(The language of arithmetic $L_{\mathbb{N}}$ and the language of strings $L_{\mathbb{S}}$ both have *finite* signatures. That is, each of these signatures has only finitely many names, function symbols, and predicates. In general, a signature doesn't have to be finite, but the ones we will be focusing on in this text are.)

3.1.7 Definition

The **standard string structure** \mathbb{S} is a structure whose signature is $L_{\mathbb{S}}$ (Definition 3.1.6).

- Its domain is the set of all strings (which we also called \mathbb{S}). The extension of the name `""` is the empty string.
- For each symbol a in the standard alphabet \mathbb{A} , its corresponding name c_a has as its extension the singleton string of just a . (For example, the extension of the name `"A"` is the singleton string `A`, and the extension of the name `quo` is the singleton string `.`.)
- The extension of the function symbol `⊕` is the function \oplus that joins two strings together.
- The extension of the predicate `≤` is the set of pairs of strings (s, t) such that $\text{length } s \leq \text{length } t$.

More briefly:

$$\begin{aligned} D_{\mathbb{S}} &= \mathbb{S} \\ [\oplus]_{\mathbb{S}}(s, t) &= s \oplus t \quad \text{for each } s, t \in \mathbb{S} \\ [\leq]_{\mathbb{S}} &= \{(s, t) \mid \text{length } s \leq \text{length } t\} \\ ["]_{\mathbb{S}} &= () \quad (\text{that is, the empty string}) [c_a]_{\mathbb{S}} = (a) \quad \text{for every } a \in \mathbb{A} \end{aligned}$$

Here c_a is the name for the symbol a in L_S . (For example, $["A"]_S = A$, and $["quo"]_S = "$.)

We need to be careful about use and mention. The word `Obama` is a different thing from the former president Obama, and the string `0` is a different thing from the number 0. The same goes for words in the language of *strings*, but now we need to be extra careful, because strings are not only the things we are using as names, but also the things that these names *stand for*. For example, `"A"` and `A` are both strings, but they are not the *same* string. The string `"A"` is a name in the name of strings. The string `A` is not a name in that language, though—it is the string that `"A"` is a name for. Even when we are naming parts of language—indeed, even when we are naming names!—it is important to keep track of the difference between names and what is named.

3.1.8 Exercise

Let L be the signature that includes one name `bar`, and one one-place function symbol `foo`. Give an example of an L -structure with an infinite domain, and an example of an L -structure with a finite domain. What is the smallest domain an L -structure can have?

3.2 Syntax and Semantics

“Were the Lord of Wey to turn the administration of his state over to you, what would be your first priority?” asked Zilu.
“Without question it would be to ensure that names are used properly”, replied the Master.

Confucius (551?–479? BCE), *Analects*

A *signature* is a very simple kind of language. It is basically just a “bag of words”, without any glue that holds different words together. We’ll now take a step to a slightly more complicated language. We can put basic symbols together to build up complex expressions—this is called *syntax*. And there are rules for how these complex expressions can also stand for things in the world—this is called *semantics*.

A signature gives us some basic symbols for picking out features of interest. Take the standard model of arithmetic $\mathbb{N}(0, \text{suc}, +, \cdot, \leq)$ as an example: we have a label for zero, and a label for the successor function. But once we have these, we can put them together to pick out other numbers as well. We know that the number

one is $\text{suc } 0$, so we can use the expression $\text{suc } 0$ to pick it out. Similarly, we can use $\text{suc suc } 0$ to stand for the number two, and so on. Here $\text{suc } 0$ is a *complex term*, built out of two basic expressions suc and 0 . The things we get by putting these symbols together like this are called **numerals**: they are *names* or *labels* for numbers. The numerals are these expressions:

$0, \quad \text{suc } 0, \quad \text{suc suc } 0, \quad \text{suc suc suc } 0, \quad \dots$

We can also describe a number in other ways: for example, the number two isn't just $\text{suc suc } 0$, but it's also $(\text{suc } 0) + (\text{suc } 0)$ (that is, $1 + 1$). We also have $+$ in the language of arithmetic, so we can also build up the expression $(\text{suc } 0) + (\text{suc } 0)$ as an alternative way to refer to the number two. In general we can build up arbitrarily complicated terms by putting these names and function symbols together in different ways.

(*Predicates* do not ever appear in terms. We will set them aside for a while, and bring them back in Chapter 5.)

Hopefully that gets across the intuitive idea of what a term for a certain signature is. The next thing we'll do is give a more precise description of terms.

In the language of arithmetic, one term is $\text{suc suc } 0 + (\text{suc } 0 + \text{suc } 0)$. We can visualize its structure as in (Fig. 3.1). This has the form of a **labeled tree**, where each node of the tree is labeled with some symbol in the language of arithmetic. The key idea here is that every term can be represented by a syntax tree like this, and in exactly one way.

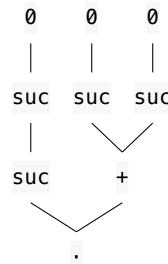
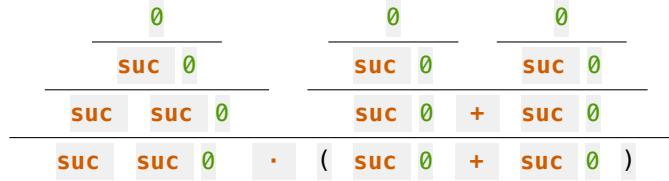


Figure 3.1: The syntactic structure of a term, as a labeled tree.

Another way of representing the same structure is with a **syntax derivation**, which shows how each stage is built up using one of the basic symbols.



We can think of a derivation as a complex argument, consisting of statements of the form “*a* is a term”, where each step of the argument follows from some basic *formation rule* for building up terms.

We can define the terms in the language of arithmetic *recursively*. These are the rules for putting together terms in the language of arithmetic.

$$\begin{array}{c}
 \text{---} \\
 0 \text{ is a term}
 \end{array}
 \qquad
 \begin{array}{c}
 t \text{ is a term} \\
 \text{---} \\
 \text{suc } t \text{ is a term}
 \end{array}$$

$$\begin{array}{c}
 t_1 \text{ is a term} \quad t_2 \text{ is a term} \\
 \text{---} \\
 (t_1 + t_2) \text{ is a term}
 \end{array}
 \qquad
 \begin{array}{c}
 t_1 \text{ is a term} \quad t_2 \text{ is a term} \\
 \text{---} \\
 (t_1 \cdot t_2) \text{ is a term}
 \end{array}$$

Just as in Section 2.2, each rule means that, given the facts written above the line, we can derive the fact written below the line.

Let’s state this idea more abstractly, not just for the language of arithmetic, but for an *arbitrary* signature. Before we do this, though, we should talk about some notational issues. In practice, we write down function symbols in several different styles. Some function symbols, like $+$ and \cdot , look best in between the two things they apply to (“infix” notation). Other function symbols, like **suc** or **f**, look best in front of them (“prefix” notation). In practice, we use both notations, depending on which one is more convenient. But when we give an official definition of the syntax of a formal language, it’s a nuisance to keep track of two different ways of writing things down, and this would add annoying and useless complications to our proofs. So we won’t do that. Instead, we’ll make one official choice. Because it happens to be a little less cumbersome in general, our official choice will be “prefix” notation: we’ll write two-place function terms like **f(x, y)**, rather than like **(x f y)**. *Officially*, we’ll apply this convention to all function terms, even $+$ and \cdot and \otimes . So when we’re being totally official, the terms of the language of arithmetic will look like $+(0, 0)$, rather than $(0 + 0)$. But we will almost never bother being totally official. In practice, we can freely write our terms whichever way is most convenient, trusting

that this won't lead to confusion. (It isn't as if there is some *other* term that you might plausibly mean by $(\text{0} + \text{0})$.)

There are similar issues that come up with parentheses and spaces. Again, our official definition of terms is going to commit us to one particular choice of where to put parentheses and spaces. Our official choices are mainly driven by the goal of keeping things simple in the general case. But in practice, things often look better and are clearer to human readers if we leave out parentheses that are officially called for (as long as this doesn't make things ambiguous), and put in extra spaces. Computer programs might make a fuss over this, but since we're all humans it shouldn't make too much trouble.

That means that often when we write down a term—for example, as $\text{suc } 0 + 0$ —*officially* we are really talking about a different, closely related string—in this case, $+ (\text{suc}(\text{0}), \text{0})$. In practice, this shouldn't really be a big deal. (There will be other notational issues like this that come up from time to time.)

3.2.1 Definition

Let L be a signature. The L -terms are defined recursively by the following rules:

$$\frac{c \text{ is a name in } L}{c \text{ is an } L\text{-term}}$$

$$\frac{f \text{ is an } n\text{-place function symbol in } L \quad t_1 \text{ is an } L\text{-term} \quad \dots \quad t_n \text{ is an } L\text{-term}}{f(t_1, \dots, t_n) \text{ is an } L\text{-term}}$$

To be totally explicit: if we have an n -place function symbol and n terms, then we can form a new term by putting together first f , then an open parenthesis $($, then all of the terms, one after another, separated by commas $,$, and finally a closing parenthesis $)$.

We will also use the notation \mathbb{T}_L for the set of all L -terms. We leave off the L subscript when it is clear in context.

Let's pause here on a philosophical question. Our definition says that terms are certain strings. But is that really what terms are? This is similar to some questions that came up earlier: whether sequences are really functions from numbers, whether functions are really sets of ordered pairs, or whether ordered pairs are really certain sets. There are some reasons to think that the answer is no. After all, we had to make some arbitrary notational choices in order to decide *which* string

was the term $(0 + 0)$ (that is, officially, $+ (0, 0)$). The *nature* of the term—which basic symbols are put together in what syntactic structure—doesn’t seem tied to one notation or another. We could have used $(+ 0 0)$ or any other unambiguous notational system to write down the same term. But it will make things harder for us down the road if we are always distinguishing between a term and its (somewhat arbitrary) string representation in a certain system of notation. So we will proceed as if the philosophical myth were true, that terms (and syntactic structures more generally) just *are* strings.

The important thing about terms is not the notational details of how specific symbols are put together. The important thing is more structural: each term can be put together out of names and function symbols, in just one way. An important thing for us to check is that our official system of notation really does have this structural feature—so these strings can at least play the *role* of terms.

As with numbers and strings, the important structural features of terms can be spelled out in two parts: an *Inductive Property* and an *Injective Property*. Intuitively, the Inductive Property says that we can reach every term using these rules in *at least one way*, and the Injective Property says that we can reach every term using these rules in *at most one way*. Let’s take a closer look at each of these properties.

The Inductive Property for Terms follows directly from our recursive definition (which is underlined by Exercise 2.3.2). This definition tells us that each of our syntactic rules for forming terms takes you to an L -term, and it also tells us that every L -term can be reached somehow or other by applying these rules. Practically speaking, what this gives us is a new kind of inductive proof: induction on syntactic structure. This is an extremely important tool in logic.

3.2.2 Technique (Induction on Terms)

Suppose that we want to show that every term is *nice*. We can do this in three steps.

1. Let c be any name. *Show* that c is nice.
2. Let f be any n -place function symbol, and let t_1, \dots, t_n be terms. *Suppose* that each of the terms t_1, \dots, t_n is nice. (This is the *inductive hypothesis*.) Then *show* that the term $f(t_1, \dots, t_n)$ is also nice.

3.2.3 Example

For any signature L , every L -term contains at least one name as a substring.

Proof

The proof is by induction on the structure of terms. There are two parts to this proof.

1. Let c be a name (in L). Then it's obvious that c is a substring of itself.
2. Let f be an n -place function symbol (in L), and let t_1, \dots, t_n be terms. Suppose, for the inductive hypothesis, that t_1 contains a name, t_2 contains a name, and so on up to t_n . Then clearly $f(t_1, \dots, t_n)$ also contains whatever names appear in t_1 , since it has t_1 as a substring. \square

3.2.4 Example

Say a string is **balanced** iff it includes the same number of left parentheses (as right parentheses). Prove by induction that for any signature L , every L -term is balanced.

Proof

Again our strategy is induction on L -terms.

1. Let c be a name. Then c is a *token*, which requires that it is a string that does not contain any parentheses. So the number of left parentheses and the number of right parentheses are both zero.
2. Let f be an n -place function symbol, and let t_1, \dots, t_n be terms. For the inductive hypothesis, we suppose that t_i is balanced for each $i \in \{1, \dots, n\}$. For each i , let p_i be the number of left parentheses in t_i , which is equal to the number of right parentheses in t_i . Then the total number of left parentheses in $f(t_1, \dots, t_n)$ is $1 + p_1 + \dots + p_n$. Similarly, the total number of right parentheses is $p_1 + \dots + p_n + 1$. These numbers are equal, so $f(t_1, \dots, t_n)$ is balanced.

That completes the inductive proof. \square

After the Inductive Property, the second important thing about terms is that they are not syntactically ambiguous. For example, you can't have one term which is *both* a name and *also* of the form $f(t)$ for some function symbol f and term t . So something we need to check, to make sure that our official definition of terms really has the right structural features, is that the formation rules are unambiguous. Each term should only be reached in *one way* using these rules. That means that terms also have an Injective Property, analogous to the Injective Properties for numbers and strings. This fact seems kind of obvious when you look at the definition: we've

inserted parentheses and commas between things, so you should always be able to find those “delimiters” and use them to break up a term into parts in just one way. But precisely stating this fact and officially proving it is surprisingly fiddly. The Injective Property for Terms is spelled out and proved in Section 3.3. (This fact also goes by other names, including the Parsing Theorem and the Unique Readability Theorem.)

Because terms have both an inductive property and an injective property, this also gives us an important new kind of *recursive definition*. Say we want to define a function that assigns a value to every term. In order to define the value of the function for a certain term, we can assume that we have already defined the function for each of its *subterms*.

3.2.5 Example

Here’s an example of a recursively defined function: the **complexity** function, which assigns a number to each term. The idea is that the complexity of a term is its total number of names and function symbols. (This is *not* the same as its *length* as a string.) Here are some examples of some terms in the language of arithmetic with their complexities.

$$\begin{aligned} \textcolor{brown}{0} &\mapsto 1 \\ \textcolor{brown}{\mathbf{suc}} \textcolor{brown}{0} &\mapsto 2 \\ \textcolor{brown}{\mathbf{suc}} \textcolor{brown}{0} + \textcolor{brown}{0} &\mapsto 4 \\ \textcolor{brown}{\mathbf{suc}} \textcolor{brown}{0} \cdot (\textcolor{brown}{\mathbf{suc}} \textcolor{brown}{0} + \textcolor{brown}{0}) &\mapsto 7 \end{aligned}$$

Here is the recursive definition:

1. For each name c in L ,

$$\text{complex } c = 1$$

2. For each n -place function symbol f in L , and any terms t_1, \dots, t_n ,

$$\text{complex}(f(t_1, \dots, t_n)) = 1 + \text{complex } t_1 + \dots + \text{complex } t_n$$

As usual, recursive definitions work hand in hand with inductive proofs.

3.2.6 Example

For any term t ,

$$\text{complex } t \leq \text{length } t$$

Proof

We will prove this by induction on the structure of terms.

- Let c be any name. Then

$$\text{complex } c = 1 \leq \text{length } c$$

since the name c is required to be a non-empty string.

- Let f be an n -place function symbol, and let t_1, \dots, t_n be any terms. Suppose for the inductive hypothesis that for each $i \in \{1, \dots, n\}$,

$$\text{complex } t_i \leq \text{length } t_i$$

Then by definition,

$$\begin{aligned} \text{complex}(f(t_1, \dots, t_n)) &= 1 + \text{complex } t_1 + \dots + \text{complex } t_n \\ &\leq 1 + \text{length } t_1 + \dots + \text{length } t_n \end{aligned}$$

using the inductive hypothesis. We can calculate the length of $f(t_1, \dots, t_n)$ by adding up the lengths of each of its pieces, including the two parentheses and the $n - 1$ commas.

$$\text{length}(f(t_1, \dots, t_n)) = n + 1 + \text{length } f + \text{length } t_1 + \dots + \text{length } t_n$$

This is clearly greater than the sum of the lengths of t_1, \dots, t_n plus one. So

$$\text{complex}(f(t_1, \dots, t_n)) \leq \text{length}(f(t_1, \dots, t_n))$$

□

3.2.7 Technique (Recursively defining a function on terms)

Suppose we want to come up with a function r whose domain is the set of all L -terms. We can do this in two steps.

- Fill in the blank:

For each name c in L , $r(c) = \underline{\hspace{2cm}}$

- Fill in the blank:

For each n -place function symbol f in L and any L -terms t_1, \dots, t_n ,

$r(f(t_1, \dots, t_n)) = \underline{\hspace{2cm}}$

This time, the description you write down can make reference to any or all of the values $r(t_1), \dots, r(t_n)$.

3.2.8 Exercise

Let L be a signature with one name `bar` and one two-place function symbol `foo`. Consider the recursively defined function g :

$$\begin{aligned} g(\text{bar}) &= 2 \\ g(\text{foo}(t_1, t_2)) &= g(t_1) + g(t_2) \quad \text{for any } L\text{-terms } t_1 \text{ and } t_2 \end{aligned}$$

Prove by induction that $g(t)$ is even for every L -term t .

3.2.9 Notation

We'll be working with a lot of sequences, so it will be useful to have some slightly cleaner notation for working with them. We'll use the notation \bar{x} to stand for a sequence (x_1, \dots, x_n) . (Similarly, \bar{t} is the sequence (t_1, \dots, t_n) , etc.) We'll also abuse notation a bit and write $f(\bar{t})$ as a shorthand for $f(t_1, \dots, t_n)$ —leaving the comma separators implicit. So, for example, we can rewrite the last line of the solution to Example 3.2.6 more simply like this:

$$\text{complex}(f(\bar{t})) \leq \text{length}(f(\bar{t}))$$

Another convenient shorthand will be to write down the *rule* for generating the elements of a sequence, instead of writing out all of the elements one by one. We'll use the notation (\dots, x_i, \dots) for the sequence (x_1, \dots, x_n) . (Here i is an “iterator variable”.) We can write (\dots, i, \dots) for the sequence $(1, 2, \dots, n)$, or $(\dots, 2i, \dots)$ for the sequence $(2, 4, \dots, 2n)$. We rely on context to tell us what n should be.

Here's another important example of a recursively defined function on terms. In many ways, this is the most important example: it spells out how terms can be meaningful. Terms stand for objects in structures. For example, in the standard number structure, the term `suc 0 + 0` stands for the number 1. The same term can also stand for other things in other structures. What a term stands for depends on how we interpret its basic symbols. For example, in the structure from Example 3.1.5 which has Los Angeles buildings in its domain, the term `suc 0 + 0` stands for the Natural History Museum.

If we have an L -structure S , then we can map each L -term to the object in S which it is supposed to stand for. In general, each term **denotes** some object in S . Remember that a structure S provides some important information. For each name, S gives us an extension $[c]_S$, which is a certain object in the domain of S . For each function symbol f , S gives us an extension $[f]_S$, which is a certain function from sequences of objects in the domain to other objects in the domain. We will use these extensions

for the primitive symbols to build up the denotations of complex terms. The idea is that we start from the extensions of names, and then put things together by applying the extension of each function symbol in the term step by step.

3.2.10 Definition

Let L be a signature, and let S be an L -structure. The **denotation** of an L -term is defined recursively as follows.

1. Each name c denotes $[c]_S$.
2. Let f be an n -place function symbol, let \bar{t} be an n -tuple of terms, and let \bar{d} be an n -tuple of elements of the domain D_S . Suppose that t_i denotes d_i , for each $i \in \{1, \dots, n\}$. Then the term $f(\bar{t})$ denotes the object $[f]_S(\bar{d})$. This is the result of applying the function which is the extension of f in S to the n -tuple (d_1, \dots, d_n) .

The denotation of a term t in a structure S is written $\llbracket t \rrbracket_S$. Using this notation, we can rewrite the recursive definition more concisely.

$$\begin{aligned} \llbracket c \rrbracket_S &= [c]_S && \text{for each name } c \text{ in } L \\ \llbracket f(\bar{t}) \rrbracket_S &= [f]_S(\dots, \llbracket t_i \rrbracket_S, \dots) && \text{for each } n\text{-place function symbol } f \text{ in } L \\ &&& \text{and any } n\text{-tuple of } L\text{-terms } \bar{t} \end{aligned}$$

We can also write $\llbracket \cdot \rrbracket_S$ for the denotation *function*, which takes each term to its denotation in S . (The dot shows where to write the function's argument.)

We'll often leave off the S subscripts from the denotation function to keep our notation tidier, when it's clear in context which structure we're talking about.

3.2.11 Example

Use the definition of the denotation function to show that the term $\text{suc suc } 0 + \text{suc } 0$ denotes the number three, in the standard model of arithmetic \mathbb{N} . That is,

$$\llbracket \text{suc suc } 0 + \text{suc } 0 \rrbracket_{\mathbb{N}} = 3$$

(In our totally official notation, this term would be written

```
+ (suc (suc (0)), suc (0))
```

But you don't have to bother with this, unless you really want to.)

Proof

$$\begin{aligned}
 & [[\mathbf{suc} \ \mathbf{suc} 0 + \mathbf{suc} 0]] \\
 & = [[\mathbf{suc} \ \mathbf{suc} 0]] + [[\mathbf{suc} 0]] \quad \text{by the clause for the function symbol } + \\
 & = \mathbf{suc} [[\mathbf{suc} 0]] + \mathbf{suc} [[0]] \quad \text{by the } \mathbf{suc} \text{ clause (twice)} \\
 & = \mathbf{suc} \mathbf{suc} [[0]] + \mathbf{suc} [[0]] \quad \text{by the } \mathbf{suc} \text{ clause again} \\
 & = \mathbf{suc} \mathbf{suc} 0 + \mathbf{suc} 0 \quad \text{by the clause for the name } 0 \\
 & = 2 + 1 = 3
 \end{aligned}$$

□

3.2.12 Exercise

Use the definition of the denotation function in the standard string structure \mathbb{S} to show the following:

- (a) The term $(\cdots \oplus "A") \oplus "B"$ denotes the string AB in \mathbb{S} . That is,

$$[[(\cdots \oplus "A") \oplus "B"]]_{\mathbb{S}} = AB$$

- (b) For any term t , the term $t \oplus \cdots$ has the same denotation in \mathbb{S} as t . That is,

$$[[t \oplus \cdots]]_{\mathbb{S}} = [[t]]_{\mathbb{S}}$$

3.2.13 Definition

For each number, there is a corresponding term in the language of arithmetic, which is called its **numeral**. The numeral for the number zero is the term 0 , the numeral for the number one is the term $\mathbf{suc} 0$, the numeral for the number two is the term $\mathbf{suc} \mathbf{suc} 0$, and so on. For a number n , we'll call its numeral $\langle n \rangle$. We can make the definition of numerals explicit using a recursive definition—that is, a recursive definition on *numbers*.

$$\begin{aligned}
 \langle 0 \rangle &= 0 \\
 \langle \mathbf{suc} n \rangle &= \mathbf{suc} \langle n \rangle \quad \text{for every } n \in \mathbb{N}
 \end{aligned}$$

Use and mention can be a little confusing here, so I'll spell it out. Notice that the 0 on the left side of the definition is the *number* zero, while the 0 on the right side is a name in the language of arithmetic. Similarly the \mathbf{suc} on the left side is a function on numbers, while the \mathbf{suc} on the right side is a one-place function symbol in the language of arithmetic.

3.2.14 Exercise

- (a) Prove by induction that for any number n , the numeral $\langle n \rangle$ denotes the number n , in the standard model of arithmetic. In short:

$$\llbracket \langle n \rangle \rrbracket_{\mathbb{N}} = n \quad \text{for every } n \in \mathbb{N}$$

Hint. What kind of induction should you use?

- (b) No two numbers have the same numeral. That is, for any numbers m and n , if $\langle m \rangle = \langle n \rangle$, then $m = n$. In other words, the numeral function is one-to-one.

Hint. Look back at how you proved that every function that has an inverse is one-to-one, as one step of Exercise 1.2.22.

In our official language of arithmetic, we have adopted a very simple “unary” notation for numbers. There are other ways of writing numbers down which are more familiar, such as *decimal notation*:

$$\begin{aligned} 0 &\mapsto 0 \\ 1 &\mapsto 1 \\ 2 &\mapsto 2 \\ &\vdots \\ 10 &\mapsto 10 \\ 11 &\mapsto 11 \\ &\vdots \end{aligned}$$

But while this notation is familiar, actually writing down the official rules for this system of notation is quite a bit trickier than our simple system. Other notational systems, like Roman numerals, are even more complicated. For our official purposes, it’s helpful to keep things as simple as we can.

3.2.15 Definition

We’ll call an L -structure **explicit** iff every element of its domain is denoted by some L -term.

Exercise 3.2.14 showed that the standard model of arithmetic \mathbb{N} is an explicit structure.

3.2.16 Exercise

- (a) Give an example of a structure which is not explicit.
- (b) Show that the string structure \mathbb{S} is explicit, by recursively defining a function that takes each string $s \in \mathbb{S}$ to some term $\langle s \rangle$ in the standard language of strings such that $\llbracket \langle s \rangle \rrbracket_{\mathbb{S}} = s$ (as in Exercise 3.2.14).

3.3 Parsing Terms*



Figure 3.2: Randall Munroe, *xkcd*. <https://xkcd.com/327/>

At this point we have worked through some examples of inductive proofs and recursive definitions for terms. These practical tools are the most important thing to understand about terms. But it's also worthwhile to understand the foundations on which these tools based.

The crucial property of terms is that every term can be built up from basic names and function symbols in exactly one way. As with numbers and strings, we can split that property up into two properties. The **Inductive Property** says that every term can be built up in *at least one way* using these rules. The **Injective Property** says that no term can be built up in two different ways using these rules. In this section, first we'll state these properties more carefully. Next, we'll see how they can be proved.

The idea of the Inductive Property for terms is very similar to our official Inductive Properties for numbers and strings. It is a version of the kind of inductive property for recursively defined sets in Section 2.2. There are certain rules for building up terms: the rules for names and function symbols. The idea of the Inductive Property is that every term can be reached in at least one way using these rules. This means that any set that includes everything you eventually reach by applying these rules includes every term.

Say you have a set X , and you want to prove by induction that every term is in X . You would have to show two things:

1. Every name is in X .
2. For any n -place function symbol f and any $t_1, t_2, \dots, t_n \in X$, we also have $f(\bar{t})$ in X .

Call a set like this **L -closed**. What it means to say that proof by induction works is that, if X has these three properties, then X contains every term.

(In fact, this is an application of the definition of “ F -closed” in Definition 2.3.1 to certain operations for joining together strings.)

3.3.1 Inductive Property for Terms

Let L be a signature. For any L -closed set X , we have $\mathbb{T}_L \subseteq X$.

This fact immediately follows from the recursive definition of terms, using Exercise 2.3.2.

The Inductive Property means that every term can be formed in *at least* one way using the formation rules for names and function symbols. The other thing to check is that each term can be formed in *at most* one way from these rules: that is, no two different formation rules ever give the same result. This amounts to the fact that our system of notation does not have any syntactic ambiguity. (It is also called the *Unique Readability Theorem*, or the *Parsing Theorem*.) This is rather complicated to state.

3.3.2 Injective Property for Terms

Let L be a signature.

- (a) c and $f(\bar{t})$ are distinct from one another, for any name c , n -place function symbol f , and n -tuple of terms \bar{t} .
- (b) For any n -place function symbol f and n -tuple of terms \bar{t} , and any m -place function symbol g and m -tuple of terms \bar{u} , if $f(\bar{t})$ is the same as $g(\bar{u})$, then $n = m$, $f = g$, and $\bar{t} = \bar{u}$.

Like the Injective Properties for numbers and sequences, we can state this more elegantly in terms of functions. If L is a signature, let L_0 be its set of names, and for each $n > 0$ let L_n be the set of n -place function symbols. (We can think of names as “zero-place function symbols”.) Let \mathbb{T}_L be the set of all L -terms. We will drop the L subscript when it is clear in context. Consider these “term-constructing”

functions:

- $\text{con}_0 : L_0 \rightarrow \mathbb{T}$ takes each name to itself;
- $\text{con}_n : L_n \times \mathbb{T}^n \rightarrow \mathbb{T}$ takes each pair of an n -place function symbol f and an n -tuple of terms \bar{t} to the term $f(\bar{t})$;

Then we can more succinctly restate the Injective Property like this:

Each of the term-forming functions $\text{con}_0, \text{con}_1, \text{con}_2, \dots$ is one-to-one, and their ranges have no elements in common.

We can go a bit further, making this even more elegant and abstract, by combining all three of these term-builders into one big function. First, let

$$L(\mathbb{T}) = L_0 \cup (L_1 \times \mathbb{T}^1) \cup (L_2 \times \mathbb{T}^2) \cup \dots$$

This is the set of basic *term-constructors*—all of the different ingredients we can use to build a term: this can be a name, a one-place function symbol and one term, or a two-place function symbol and two terms, and so on. When we define the term-constructing function $\text{con} : L(\mathbb{T}) \rightarrow \mathbb{T}$ such that

$$\begin{aligned}\text{con}(c) &= \text{con}_0(c) = c && \text{for } c \in L_0 \\ \text{con}(f, \bar{t}) &= \text{con}_n(f, \bar{t}) = f(\bar{t}) && \text{for } f \in L_n \text{ and } \bar{t} \in \mathbb{T}^n\end{aligned}$$

Then this is an even more concise way to state the Injective Property:

The term-building function $\text{con} : L(\mathbb{T}) \rightarrow \mathbb{T}$ is one-to-one.

3.3.3 Exercise

Show that the function $\text{con} : L(\mathbb{T}) \rightarrow \mathbb{T}$ is onto.

Hint. The induction argument is almost *too* straightforward.

Before we work on proving the Injective Property, remember that there are rules for what strings are allowed to be used as names or function symbols. If you chose something perverse like **suc**(x) or ,(as one of your basic names, you really could get ambiguities. (This is the idea behind many computer viruses, which deliberately try to trick programs into accepting “control” code as ordinary input data.) To avoid this, we say that you aren’t allowed to use any parentheses or commas in your names or function symbols.

3.3.4 Definition

- A symbol is a **delimiter** iff it is one of , , (, or).
- A string is a **token** iff it is non-empty and does not contain any delimiters.

Here is a basic fact to get us started. Consider the term $\text{suc}(+(0,0))$ (written in official “prefix” notation). In order to break this down, the first thing we need to notice is that it starts with the function symbol **suc**. This is the initial *token* of the string. It’s important that each string has a *unique* initial token. That is, if we take a token and stick a *delimited* string onto the end of it, we can always figure out what the original token was.

Let’s recall some basic facts about strings (TODO CROSS-REF):

3.3.5 Proposition

For any strings $s, t, t' \in \mathbb{S}$:

- (a) s is an **initial substring** of t iff $s \oplus s' = t$ for some string $s' \in \mathbb{S}$. If s is an initial substring of t , and t is an initial substring of s , then $s = t$.
- (b) **Cancellation.** If $s \oplus t = s \oplus t'$, then $t = t'$.
- (c) **Strong Inductive Property (The Shortest String Property).** Let X be a set of strings. Suppose that, for every string $s \in \mathbb{S}$, if every string shorter than s is in X , then $s \in X$ as well. It follows that every string is in X .

3.3.6 Definition

A string s is a **delimited initial substring** of a string t iff either $s = t$, or else for some delimiter d , $s \oplus (d)$ is an initial substring of t . If s is also a token, then we call s the **initial token** of t .

3.3.7 Lemma

Every string has at most one initial token.

Proof

Suppose that for some tokens c and c' and delimited strings s and s' , $c \oplus s = c' \oplus s'$. If s is empty, then $c \oplus s = c$, so c' is an initial substring of c . Otherwise, s begins with a delimiter, and c' does not contain any delimiters. So in this case too, c' is an initial substring of c .

By parallel reasoning, c must also be an initial substring of c' . So $c = c'$. \square

This means that if we have a term, we can figure out what *kind* of term it is, by identifying its initial token, and whether this is a name or a function symbol.

3.3.8 Exercise

- (a) Prove that con_0 is one-to-one.

- (b) Prove that the ranges of $\text{con}_0, \text{con}_1, \text{con}_2, \dots$ have no elements in common.
- (c) Prove more generally that if $\text{con}_m(f, \bar{t})$ and $\text{con}_n(g, \bar{u})$ are both delimited initial substrings of s , then $m = n$ and $f = g$.

That's a good start, but we're not quite done. The last thing we need to show is that each of the functions con_n is one-to-one (for $n > 0$). To do this, we need to take a term $f(t_1, \dots, t_n)$ and work out its component parts. But we can't just look for the first comma and declare everything in front of that to be the first argument of the function symbol. The terms t_i might include commas themselves. So in order to break up this term we need to figure out which commas are the "right" ones, which go along with the outermost function symbol. To do that, we need to figure out how much of the string after the first parenthesis goes with t_1 , and then how much goes with t_2 , and so on.

3.3.9 Lemma

For each string s , there is at most one $x \in L(\mathbb{T})$ such that $\text{con}(x)$ is a delimited initial substring of s .

Proof

Call a string with this property *parseable*. We will use the Shortest String Property prove that every string is parseable.

Suppose that every string shorter than s is parseable, let $x, x' \in L(\mathbb{T})$, and suppose that $\text{con}(x)$ and $\text{con}(x')$ are both delimited initial substrings of s .

There are two cases to consider for x .

1. Suppose that $x = c$ for some name c . Then c is the initial token of s . There are also two cases for x' .
 - (a) If x' is also a name c' , then c' is also the initial token of s , so we must have $c = c'$ by Lemma 3.3.7.
 - (b) Otherwise, x' is (f, \bar{t}) for some function symbol f . Then we would also have f as the initial token of s , which would imply $c = f$ (by Lemma 3.3.7 again). But in a signature the set of names L_0 has no elements in common with the set of function symbols L_n , so this can't happen.
2. Otherwise $x = (f, \bar{t})$ for some $f \in L_n$ and $\bar{t} \in \mathbb{T}^n$. Again we have two cases for x' .
 - (a) x' can't be a name, by the same reasoning as case 1(b).

- (b) So $x' = (g, \bar{u})$ for some $g \in L_m$ and $\bar{u} \in \mathbb{T}^m$. In this case, again, f and g are both the initial token of s , so $f = g$. So the adicity $m = n$ as well. Now we just need to show that $\bar{t} = \bar{u}$. We will prove this by (strong) induction.

Let $k \in \{1, \dots, n\}$, and suppose for the inductive hypothesis that $t_i = u_i$ for each $i < k$. We know that $f(\bar{t})$ and $g(\bar{u})$ are both initial substrings of s , which implies that there are strings s' and s'' such that

$$\begin{aligned}s &= f(t_1, \dots, t_{k-1}, t_k, s') \\ s &= g(u_1, \dots, u_{k-1}, u_k, s'')\end{aligned}$$

Furthermore, the part of the first string up to t_k is identical to the part of the second string up to u_k . So by the Cancellation Property,

$$t_k \oplus \dots \oplus s' = u_k \oplus \dots \oplus s''$$

Furthermore, since con is onto this implies that there are $y, z \in L(\mathbb{T})$ such that

$$t_k = \text{con } y \quad u_k = \text{con } z$$

This means that $\text{con } x$ and $\text{con } y$ are both delimited initial substrings of a string that is shorter than s . But the “outer” inductive hypothesis tells us that this implies that $x = y$. So $t_k = u_k$.

By induction, $t_k = u_k$ for every $k \in \{1, \dots, n\}$. Thus $f = g$ and $\bar{t} = \bar{u}$, which completes the proof.

Thus every string is parseable. □

3.3.10 Exercise

Use Lemma 3.3.9 to finish the proof of the Injective Property for terms.

Here is one more thing to notice about what we have done. For each constant c , we have a certain term—namely, c itself. And for each function symbol f , we have a way of mapping each sequence of terms $\bar{t} \in \mathbb{T}^n$ to another term, $f(\bar{t})$. That is, each constant c has a corresponding element of \mathbb{T} , and each function symbol f has a corresponding function from \mathbb{T}^n to \mathbb{T} . What we have described here is a *structure*.

3.3.11 Definition

For a signature L , the **term structure** is the following L -structure, which we also call \mathbb{T}_L . (We leave off the L subscript when it is clear in context). The domain of

\mathbb{T}_L is the set of all L -terms. The extensions in \mathbb{T}_L correspond to the various ways of constructing terms:

$$\begin{aligned}[c]_{\mathbb{T}} &= \text{con } c & = c & \quad \text{for each } c \in L_0 \\ [f]_{\mathbb{T}}(\bar{t}) &= \text{con}(f, \bar{t}) & = f(\bar{t}) & \quad \text{for each } f \in L_n, \bar{t} \in \mathbb{T}^n\end{aligned}$$

As we will see in the next section, term structures are particularly special L -structures.

3.4 Recursion for Terms*

In Section 3.2 we saw some examples of functions which are defined recursively using the syntactic structure of terms, like the complexity function and the denotation function. This is analogous to recursive definitions for numbers and sequences. Just like those kinds of recursive definition, recursive definitions for terms are based on a general Recursion Theorem. Intuitively, what this theorem says is just that *recursive definitions work*: that is, if you write down a recursive definition, you will have successfully described one and only one function defined for every term. This theorem a bit tricky to state in general, because the structure of terms is a bit more complicated than the structure of numbers. But it works very similarly. In fact, we will go on to show that recursion and induction for terms is a *generalization* of other kinds of induction and recursion, including for numbers and terms.

Say we are writing down a recursive definition of a function from terms to a set A . First, write down some value for each name. Abstractly, we can represent this part of the definition as a function s_0 from L_0 (the set of names in L) to A . Second, we write down some “recursive step” rule s_n that takes each n -place function symbol f , together with a value for each of its n arguments, and gives us an element of A . Abstractly, we can represent this as another function, this time $s_n : L_n \times A^n \rightarrow A$. We take an n -place function symbol and an n -tuple of values in A , and then get a new value in A .

This is now looking a lot like the way we formulated the Injective Property for Terms. There, we considered the *term-constructing* functions

$$\begin{aligned}\text{con}_0 &: L_0 \rightarrow \mathbb{T} \\ \text{con}_n &: L_n \times \mathbb{T}^n \rightarrow \mathbb{T}\end{aligned}$$

A recursive definition on terms specifies a rule corresponding to each way of con-

structing a term. These are represented by functions:

$$\begin{aligned}s_0 &: L_0 \rightarrow A \\ s_n &: L_n \times A^n \rightarrow A\end{aligned}$$

What does it mean for rules like these to recursively define a function r ? We want s_0 to give us the values of f for names:

$$r(c) = s_0(c) \quad \text{for every } c \in L_0$$

And, given a function symbol f and the values $r(t_1), \dots, r(t_n)$, we want the “recursive step function” s_n to give us the value for $\text{con}(f, \bar{t}) = f(\bar{t})$:

$$r(f(\bar{t})) = s_n(f, (\dots, r(t_i), \dots)) \quad \text{for every } f \in L_n, \bar{t} \in \mathbb{T}^n$$

So this is what the Recursion Theorem for Terms says.

3.4.1 The Recursion Theorem for Terms

Let \mathbb{T} be the set of L -terms, and let A be any set. For any “step” functions

$$\begin{aligned}s_0 &: L_0 \rightarrow A \\ s_n &: L_n \times A^n \rightarrow A\end{aligned}$$

there is exactly one “recursive” function $r : \mathbb{T} \rightarrow A$ such that

$$\begin{aligned}r(\text{con } c) &= s_0(c) && \text{for each } c \in L_0 \\ r(\text{con}(f, \bar{t})) &= s_n(f, (\dots, r(t_i), \dots)) && \text{for each } f \in L_n, \bar{t} \in \mathbb{T}^n\end{aligned}$$

Here is an alternative way of thinking about this. We already saw that the term-constructor functions make the set of terms into a *structure* \mathbb{T}_L . Things go the same way with the “step” functions. Each s_0 associates each constant with an element of A , and s_n associates each function symbol with an n -place function from A to itself. So the step functions in a recursive definition turn the set A into a structure, too.

There is also a nice way of describing the recursively-defined relationship between these two structures.

3.4.2 Definition

Let L be a signature without predicates, and let S and T be L -structures. A **homomorphism** from S to T is a function $h : D_S \rightarrow D_T$ from the domain of S to the domain of T , such that

$$\begin{aligned}h[c]_S &= [c]_T && \text{for each } c \in L_0 \\ h([f]_S(\bar{d})) &= [f]_T(\dots, h\bar{d}, \dots) && \text{for each } f \in L_n, \bar{d} \in D_S^n\end{aligned}$$

We also use the notation $h : S \rightarrow T$ to indicate that h is a homomorphism from S to T .

A homomorphism is a kind of “structure-preserving map”.

We can use these ideas to restate the Recursion Theorem for Terms much more elegantly.

3.4.3 The Recursion Theorem for Terms (Structure Version)

Let \mathbb{T}_L be the L -term structure. For any L -structure S , there is exactly one homomorphism $r : \mathbb{T}_L \rightarrow S$.

3.4.4 Exercise

Check for yourself that the two formulations of the Recursion Theorem for Terms are really equivalent.

There is a nice word for this feature of \mathbb{T}_L from the language of category theory: \mathbb{T}_L is a *universal L-structure*. In a sense, it is the “most general” L -structure.

Of course, *anything* can be restated very concisely if you just introduce complicated enough definitions. The point of restating the Recursion Theorem this way is that it uses notational tricks to hide away the messy details of constructing and parsing *terms*, and puts out in the open the basic structure that makes the function r *recursive*. For in fact, all recursively defined functions—including those on numbers and strings—can be understood this way.

Take numbers. Numbers are build up using a zero element and a successor function. So the “signature” of the inductive structure for numbers has one name and one one-place function. Let L be this signature $(\text{0}, \text{suc})$, and let \mathbb{N}_L be the natural number structure with signature L , where these each get their intended interpretation ($[\text{0}]_{\mathbb{N}} = 0$ and $[\text{suc}]_{\mathbb{N}} = \text{suc}$). A recursive definition of a function on numbers tells you what to do with zero, and it tells you a rule for going from the value for one number to the value for its successor. So a recursive definition also gives us a structure with the same signature $(\text{0}, \text{suc})$. The extension of 0 is the starting value for the function, and the extension of suc is the rule that takes you from the value for one number to the value for its successor.

Then we can restate the Recursion Theorem for Numbers:

3.4.5 The Recursion Theorem for Numbers (Structure Version)

Let L be the signature $(\text{0}, \text{suc})$, and let \mathbb{N} be the standard natural number L -structure.

For any L -structure S , there is exactly one homomorphism $\mathbb{N} \rightarrow S$.

3.4.6 Exercise

Check that this is equivalent to the original Recursion Theorem for Numbers as stated in Section 2.2.

The same goes for sequences. Let A be any set. The set of sequences A^* is built up from the empty sequence and appending single elements. Accordingly, let L be a signature which has a name `empty` for the empty sequence, and which has a one-place function symbol for the “append a ” function $s \mapsto (s, a)$, for each element $a \in A$. (If A is a big set, this signature has a lot of function symbols.)² Then there is an obvious way of turning A^* into an L -structure. Furthermore, any recursive definition of a function from sequences to a set B effectively gives us a way to turn B into an L -structure, as well. We interpret `empty` as the value assigned to the empty sequence, and we interpret the “append a ” function symbol as the corresponding rule in the recursive definition. So, once again, we can rewrite the Recursion Theorem for Sequences:

3.4.7 The Recursion Theorem for Sequences (Structure Version)

Let L be the signature with one name `empty`, and one function symbol f_a for each $a \in A$. Let A^* be the structure whose domain is the set of sequences of elements of A , where

$$\begin{aligned} [\text{empty}]_{A^*} &= () \\ [f_a]_{A^*}(s) &= (s, a) \quad \text{for each } a \in A \text{ and } s \in A^* \end{aligned}$$

For any L -structure S , there is a unique homomorphism $r : A^* \rightarrow S$.

We can also restate the Inductive and Injective Properties in a general way, in terms of structures.

3.4.8 Definition

Let L be a signature, and let S be an L -structure.

- (a) Call a set $X \subseteq D_S$ **L -closed** iff

²This is one place where it would be useful to relax our definition of “signature” to allow things other than strings to serve as function symbols—for instance, the elements of A themselves. Since officially we haven’t allowed this, to be precise, the version of the Recursion Theorem for Sequences stated here only works for sets A where it is possible to assign a unique string token to each element of A . As we will see in Section 4.1, this is the same as requiring that A is a *countable* set. But that is plenty for the purposes of this text.

- (i) $[c]_S \in X$, and
- (ii) for each $f \in L_n$ and $\bar{d} \in X^n$, we also have $[f]_S(\bar{d}) \in X$.

The structure S is **inductive** iff every L -closed set X contains every element of the domain of S .

- (b) For any set X , let $L(X)$ be the set³

$$L_0 \cup L_1 \times X^1 \cup L_2 \times X^2 \cup \dots$$

Define the function $\text{con}_S : L(D_S) \rightarrow D_S$ such that

$$\begin{aligned}\text{con}_S c &= [c]_S && \text{for each } c \in L_0 \\ \text{con}_S(f, \bar{d}) &= [f]_S(\bar{d}) && \text{for each } f \in L_n \text{ and } \bar{d} \in D_S^n\end{aligned}$$

The structure S is **injective** iff con_S is a one-to-one function.

Notice how this generalizes the Inductive and Injective Properties for terms.

3.4.9 The General Recursion Theorem

Let S be an inductive and injective L -structure. Then for any L -structure T , there is exactly one homomorphism $r : S \rightarrow T$.

The proof of this general Recursion Theorem is structurally exactly parallel to the proof of the Recursion Theorem for Numbers (2.3.4). It is just more abstract. We will break it up into steps.

First we can recursively define a *relation* between the domains of S and T . Then we will prove that it is a functional relation, and then that its corresponding function is a homomorphism.

$$\overline{[c]_S \text{ selects } [c]_T} \text{ for each } c \in L_0$$

$$\overline{\frac{a_1 \text{ selects } b_1 \quad \dots \quad a_n \text{ selects } b_n}{[f]_S(\bar{a}) \text{ selects } [f]_T(\bar{b})}} \text{ for each } f \in L_n, \bar{a} \in D_S^n, \bar{b} \in D_T^n$$

³You might remember from algebra that a *polynomial* is a function of the form

$$f(x) = a_0 + a_1 \cdot x^1 + a_2 \cdot x^2 + \dots + a_n \cdot x^n$$

for some numbers a_0, \dots, a_n . By analogy, this operation that takes each set X to a set $L(X)$ is called a *polynomial functor*. (We can think of a union of two disjoint sets as “adding” the two sets together.)

For short, we will also say that a sequence $\bar{a} \in D_S^n$ **selects** the sequence $\bar{b} \in D_T^n$ iff a_i selects b_i for each i .

3.4.10 Exercise

Let $h : D_S \rightarrow D_T$ be a function. Suppose that for every $a \in D_S$, $h(a)$ is the unique $b \in D_T$ such that a selects b . Show that h is a homomorphism.

3.4.11 Exercise

Let $h : S \rightarrow T$ be a homomorphism. Show that for every $a \in D_S$, a selects $h(a)$.

Hint. Use the inductive property of S .

Next we will prove that the recursive definition of “selects” can also be run backwards, in a sense. This is straightforward, as long as we can keep all the pieces straight.

3.4.12 Lemma

For any $a \in D_S, b \in D_T$ such that a selects b ,

- (a) For any $c \in L_0$, if $a = [c]_S$, then $b = [c]_T$, and
- (b) For any $f \in L_n$ and $\bar{a} \in D_S^n$, if $a = [f]_S(\bar{a})$, then there are $\bar{b} \in D_T^n$ such that $b = [f]_T(\bar{b})$ and \bar{a} selects \bar{b} .

Proof

We prove this by induction on the definition of “selects”. There are two parts to the proof.

1. First, we show that $[c]_S$ and $[c]_T$ have this property.

Part (a) is clear: by the injective property, if $[c]_S = [c']_S$, then $c = c'$, and so $[c]_T = [c']_T$ as well.

Part (b) also follows from the injective property, since this implies that there is no $f \in L_n$ and $\bar{a} \in D_S^n$ such that $[c]_S = [f]_S(\bar{a})$.

2. Second, let $f \in L_n$, $\bar{a} \in D_S^n$, and $\bar{b} \in D_T^n$, and suppose that \bar{a} selects \bar{b} . We will show that $[f]_S(\bar{a})$ and $[f]_T(\bar{b})$ have the property.

For part (a), the injective property implies that there is no $c \in L_0$ such that $[f]_S(\bar{a}) = [c]_S$. So this part holds vacuously.

For part (b), the injective property implies that if $[f]_S(\bar{a}) = [f']_S(\bar{a}')$, then

$f = f'$ and $\bar{a} = \bar{a}'$. So $[f]_T(\bar{b}) = [f']_S(\bar{b})$, as well, and \bar{a} selects \bar{b} .

(We do not need to use the inductive hypothesis.) \square

3.4.13 Lemma

For every $a \in D_S$ there is exactly one $b \in D_T$ such that a selects b .

Proof

We can prove this using the inductive property of S . We need to show that the extension of each constant has this property, and the extension of each function symbol preserves the property.

1. Let $c \in L_0$. Then by definition $[c]_S$ selects $[c]_T$. Furthermore, by the first part, if $[c]_S$ selects any $b \in D_T$, then $b = [c]_T$. So $[c]_S$ selects exactly one value.
2. Let $f \in L_n$, let $\bar{a} \in D_S^n$, and suppose for the inductive hypothesis that each element of \bar{a} selects exactly one value. In other words, there is exactly one $\bar{b} \in D_T^n$ such that \bar{a} selects \bar{b} .

Again by definition, $[f]_S(\bar{a})$ selects $[f]_S(\bar{b})$. Furthermore, for any $b \in D_T$, if $[f]_S(\bar{a})$ selects b , then there is some $\bar{b}' \in D_T^n$ such that \bar{a} selects \bar{b}' and $b = [f]_S(\bar{b}')$. By the uniqueness assumption in the inductive hypothesis, we must have $\bar{b} = \bar{b}'$. So $[f]_S(\bar{b})$ is the unique value selected by $[f]_S(\bar{a})$. \square

This much proves that there is a unique *function* $r : D_S \rightarrow D_T$ such that, for every $a \in D_S$, a selects $r(a)$.

3.4.14 Exercise

Put the pieces together to complete the proof of the General Recursion Theorem.

We can also go in the other direction, from the *recursive* property to the inductive and injective properties.

3.4.15 Exercise

Let S be an L -structure, and suppose that for every L -structure T there is exactly one homomorphism $r : S \rightarrow T$.

- (a) S is injective.
- (b) S is inductive.

[TODO. Give some hints for this one.]

3.5 Variables

So far our term language is pretty limited. We can use it to label particular objects in a structure—and that’s it. In this section we’ll extend our language to make it more flexible, so we can also build up complex expressions that stand for *functions*, going beyond just the basic function symbols. The key idea is to use symbols which don’t have a *fixed* interpretation. They’re called *variables*, because their denotations can vary within a single structure.

In the language of arithmetic, we can use $\text{suc } 0 + \text{suc suc } 0$ to label the number three; and we can use $+$ to label the addition function, or suc to label the successor function. But how about the “add two” function?

$$[\quad 0 \mapsto 2, \quad 1 \mapsto 3, \quad 2 \mapsto 4, \quad \dots \quad]$$

Or how about the doubling function?

$$[\quad 0 \mapsto 0, \quad 1 \mapsto 2, \quad 2 \mapsto 4, \quad \dots \quad]$$

We can represent these functions using a language with variables. For instance, the “add two” function can be represented by the term $\text{suc suc } x$. (“For each x , take the successor of the successor of x .”) Similarly, the doubling function can be represented by the term $x \cdot \text{suc suc } 0$. (“For each x , multiply x by 2.” Of course, these aren’t the only options. We could also use $x + \text{suc suc } 0$ for the “add two” function, or $x + x$ for the doubling function.)

The free variable x works just like a name for some object, except we haven’t chosen in advance which object it is supposed to stand for. It is an “arbitrary name”. Introducing names like this is a move we often make in our informal proofs. We can say things like

Let n be any number.

Before we said this, the symbol n may not have meant anything at all. After we say it, though, we can use n as a term in just the same way we use other terms that stand for numbers; just as we could write $3 + 2$, and we can also write $3 + n$. We have effectively added n as a new word in our language.

We can do the same thing with our formal language. We can add a variable like x to a signature alongside whatever other names we already have in our language—say, the language of arithmetic. Applying the usual syntax rules to this expanded

language, we get new terms like $x + \text{suc suc } 0$ that weren't in the original language.⁴

Now it makes sense to divide up a signature's set of *names* into two categories: *constants*—the original names—and *variables*—the new ones. Semantically, we will hold the extensions of constants fixed, while letting the extensions of variables vary. But the difference between constants and variables is all about what we *do* with them, rather than how their syntax and semantics work.

3.5.1 Definition

Suppose that L is a signature, and suppose x is a variable which does not already appear as a name in L . (We will generally keep this restriction implicit.) Let $L(x)$ be the **expanded signature** which has x as a new name alongside the other symbols in L .

If t is an $L(x)$ -term, we also call t an *L -term of one variable*. We'll often use the notation $t(x)$ to indicate that t is an $L(x)$ -term. We'll also write $\mathbb{T}_L(x)$ an alternative for $\mathbb{T}_{L(x)}$, the set of all $L(x)$ -terms.

For example, if $L_{\mathbb{N}}$ is the language of arithmetic, then $L_{\mathbb{N}}(y)$ is the signature whose set of names includes both 0 and y , and which has exactly the same function symbols and predicates as the language of arithmetic (**suc**, **+**, **·**, and **\leq**).

(If you're watching very closely, you'll notice that in Definition 3.5.1 I wrote x rather than \underline{x} . That's because this definition doesn't just work for the specific variable \underline{x} , but also for any other variable, like y , z''' , or `awesome_variable`. I used x as a *metalinguage* variable which ranges over arbitrary *object language* variables, such as \underline{x} , \underline{y} , or \underline{z} . If that seems confusing—it is a little bit, but don't worry too much and you'll get the hang of it.)

Here's a basic fact which is straightforward to prove by induction.

3.5.2 Example

For any signature L and variable x , each L -term is also an $L(x)$ -term. (In short, $\mathbb{T}_L \subseteq \mathbb{T}_{L(x)}$.)

Proof

By induction on L -terms.

⁴There are a variety of different ways of handling the semantics of variables which you'll find in different textbooks. We'll use *expanded structures* in this book, but an alternative is to use what's called a *variable assignment* alongside the structure, or just a sequence of objects. The differences between these approaches do not run very deep.

1. Let c be any name in L . Then c is also a name in $L(x)$, and thus an $L(x)$ -term.
2. Let f be an n -place function symbol in L , and let \bar{t} be any n -tuple of L -terms. For the inductive hypothesis, we suppose that t_1, \dots, t_n are each $L(x)$ -terms. Then $f(\bar{t})$ is also an $L(x)$ -term by the definition of terms (Definition 3.2.1).

That's all we have to show. \square

3.5.3 Example

A variable is like a hole in a term. One useful thing to do is plug the hole up with another term. Here are some examples of what happens when we plug the term $0 + 0$ into the x -spot in various terms:

$$\begin{array}{ll} \text{suc suc } x & \mapsto \quad \text{suc suc } (0 + 0) \\ x + \text{suc } x & \mapsto \quad (0 + 0) + \text{suc } (0 + 0) \\ 0 + \text{suc } 0 & \mapsto \quad 0 + \text{suc } 0 \end{array}$$

We'll now give a precise definition of the “plugging in” operation. Once again, this definition is recursive. The intuitive idea is that whenever we meet a function term like $f(t_1, t_2)$, we just apply the substitution to each of its inner terms, until eventually we reach the constants and variables. At this point, if it's the variable we want, then we replace it; otherwise we leave it alone.

3.5.4 Definition

Let L be a signature, and let x be a variable (not occurring in L). Let a be an L -term. For any $L(x)$ -term $t(x)$, we recursively define the **substitution instance** $t(a)$ as follows.

1. For the variable x , the substitution instance $x(a)$ is just a .
2. For each L -name c , the substitution instance $c(a)$ is just c .
3. Let f be an n -place function symbol, let $(\dots, t_i(x), \dots)$ be a sequence of $L(x)$ -terms, and let $u(x)$ be the term $f(\dots, t_i(x), \dots)$. Then

$$u(a) = f(\dots, t_i(a), \dots)$$

That is, first we replace each occurrence of x with a in $t_1(x)$ to get $t_1(a)$, and then in $t_2(x)$, and so on up to $t_n(x)$, and finally we construct a new function term from the results (with appropriate punctuation).

In Section 3.2 we defined the *denotation* of a term in a structure: the object that the term stands for in that structure. Our next job is to extend this definition to

apply to terms with variables. But this time it's a little trickier. If we are finding the denotation of the term $\text{suc } x$, what should the variable x stand for? A variable doesn't pick out any one thing once and for all. So we won't define a "once and for all" denotation of a term that contains variables. Instead, we can interpret a term *with respect to a choice of values for its variables*. Once we choose a value for a variable, terms using that variable get a denotation just like any other terms.

For example, consider the term $\text{suc } x$, which is a term in the language $L_{\mathbb{N}}(x)$, the language of arithmetic with the variable x added to it. This term doesn't have any denotation at all in the standard model of arithmetic \mathbb{N} , because \mathbb{N} doesn't assign any denotation to the variable x . But we can *expand* this structure in lots of different ways, by choosing a value for x . In the expanded structure $\mathbb{N}[x \mapsto 2]$, the variable x denotes the number 2, and so the term $\text{suc } x$ denotes the number 3. In a different expanded structure $\mathbb{N}[x \mapsto 6]$, the term $\text{suc } x$ denotes the number 7. Similarly,

$$\llbracket \text{suc } x \cdot x \rrbracket_{\mathbb{N}[x \mapsto 4]} = (4 + 1) \cdot 4 = 20$$

3.5.5 Definition

Let L be a signature and let S be an L -structure, and let x be a variable (not in L). Let d be any element of the domain of S . Then we define the **expansion** $S[x \mapsto d]$ to be the $L(x)$ -structure that is exactly like S , except that the variable x is assigned d as its extension. To be explicit:

$$\begin{aligned} D_{S[x \mapsto d]} &= D_S \\ [x]_{S[x \mapsto d]} &= d \\ [c]_{S[x \mapsto d]} &= [c]_S \quad \text{for each } L\text{-name } c \\ [f]_{S[x \mapsto d]} &= [f]_S \quad \text{for each } L\text{-function symbol } f \\ [F]_{S[x \mapsto d]} &= [F]_S \quad \text{for each } L\text{-predicate } F \end{aligned}$$

If it is clear from context which variable we are talking about, we can write $S(d)$ rather than $S[x \mapsto d]$.

This notation can get pretty cumbersome, so we'll also introduce a nicer alternative.

3.5.6 Definition

Let L be a signature and let S be an L -structure, let x be a variable, let $t(x)$ be an $L(x)$ -term. The **extension** of $t(x)$ in S , written $\llbracket t(x) \rrbracket_S$, is the function that takes each object $d \in D_S$ to the denotation of $t(x)$ with respect to d . That is,

$$\llbracket t(x) \rrbracket_S(d) = \quad \text{for every } d \in D_S$$

For an object $d \in D_S$, we call $\llbracket t(x) \rrbracket_S(d)$ the **denotation of $t(x)$ in S with respect to d** .

(As before, we may leave out the S subscripts when it is clear in context what structure we are talking about.)

For example, the extension of **suc suc** x in the standard model of arithmetic \mathbb{N} is the “add two” function.

We can also use this notation to rewrite the definition of the denotation function for terms with variables a bit more cleanly.

3.5.7 Exercise

Let L be a signature, let x be a variable, let S be an L -structure, and let $d \in D_S$. Use the definitions to check:

$$(a) \llbracket x \rrbracket_S(d) = d.$$

$$(b) \text{ For each } L\text{-name } c,$$

$$\llbracket c \rrbracket_S(d) = [c]_S$$

$$(c) \text{ For each } n\text{-place } L\text{-function symbol } f \text{ and terms } t_1(x), \dots, t_n(x),$$

$$\llbracket f(\dots, t_i(x), \dots) \rrbracket_S(d) = [f]_S(\dots, \llbracket t_i(x) \rrbracket_S(d), \dots)$$

3.5.8 Example

Show step by step that the denotation of the term $x \oplus "D"$ with respect to the string ABC in \mathbb{S} is the string ABCD.

Proof

$$\begin{aligned} \llbracket (x \oplus "D") \rrbracket_{\mathbb{S}}(\text{ABC}) &= \llbracket x \rrbracket_{\mathbb{S}}(\text{ABC}) \oplus \llbracket "D" \rrbracket_{\mathbb{S}}(\text{ABC}) && \text{since } [\oplus]_{\mathbb{S}} \text{ is } \oplus \\ &= \llbracket x \rrbracket_{\mathbb{S}}(\text{ABC}) \oplus \text{D} && \text{since } ["D"]_{\mathbb{S}} = \text{D} \\ &= \text{ABC} \oplus \text{D} \\ &= \text{ABCD} \end{aligned}$$

□

3.5.9 Exercise

Show step by step that, with respect to the number 3 in \mathbb{N} , the term $x \cdot x$ denotes

the number 9.

We have discussed two different ways of “plugging something into” a term $t(x)$. It is important to keep them straight.

- First, we defined a *syntactic* operation. If we have a *term* a , we can plug this into the term $t(x)$, and this produces another term $t(a)$. This operation is all about gluing together certain strings.
- Second, we defined a *semantic* operation. If we have an *object* d in the domain of a structure, then we can evaluate the denotation of $t(x)$ with respect to d , and this produces another *object* $\llbracket t \rrbracket d$ in the domain. Or to put this another way, we can plug the object d into the *function* that the term $t(x)$ stands for.

Substitution relates bits of language to other bits of language, while *denotation* relates bits of language to things “out in the world.” But while it is very important not to confuse these two ideas with each other, they are closely related, in the following important way.

3.5.10 Exercise (Substitution Lemma)

Let L be a signature, let S be an L -structure, let $t(x)$ be an $L(x)$ -term, and let a be an L -term. Suppose a denotes d in S . Prove by induction that the denotation of $t(x)$ with respect to d in S is the same as the denotation of $t(a)$ in S . In short:

$$\llbracket t(x) \rrbracket_S (\llbracket a \rrbracket_S) = \llbracket t(a) \rrbracket_S$$

What does this mean? Say we have terms $t(x)$ and a , and we want to stick them together and figure out what this stands for in a structure. There are two different ways of doing this. We could start by figuring out what object a stands for, and figure out what function $t(x)$ stands for, and then plug that object into this function. Or we could start by plugging the *term* a into $t(x)$, and figure out directly what the resulting term $t(a)$ stands for. What Exercise 3.5.10 tells us is that we get exactly the same result either way. This is a foundational fact that tells us that all of our definitions are playing nicely together.

Using just our primitive symbols like 0 , suc , $+$, or \otimes , we could describe a basic object (zero), and a few basic functions. In Section 3.2, we discussed how we could put symbols together to describe lots more *objects*. Now that we have variables, we can also describe lots more *functions*. For example, we can define the “add two” function using the term $\text{suc suc } x$, and we can define the “take the third power” function using the term $(x \cdot x) \cdot x$. In general, say D is the domain of

a structure, and f is any function from D to D . We can “describe” or “express” or “define” f whenever we can find a term of one variable $t(x)$ that has f as its *extension*.

3.5.11 Definition

Let D be the domain of an L -structure S , and suppose $f : D \rightarrow D$ is a function. We say f is **simply definable** (in S) iff there is some L -term of one variable whose extension is f . That is, there is some term $t(x)$ such that, for every element of the domain $d \in D_S$,

$$\llbracket t \rrbracket_S(d) = f(d)$$

The word “simply” in this definition is there to signal that this is just our *preliminary* definition of “definable”. We’ll give another definition later on, in Section 6.1, when we have introduced more expressive languages. This will allow us to define even more functions.

3.5.12 Exercise

Show that the doubling function is simply definable in the standard model of arithmetic.

3.5.13 Exercise

Let $a \in \mathbb{A}$ be any symbol in the standard alphabet. Show that the function that takes each string s to (s, a) (the result of appending the single symbol a to s) is simply definable in the string structure \mathbb{S} .

So far we have just been considering adding a single variable to a language. We can add more variables just by adding one variable at a time. The extension of a term $t(x, y)$ of two variables will be a two-place function, and to get the denotation of $t(x, y)$ we will need to supply a pair of objects (d_1, d_2) from the domain. Otherwise things go basically the exact same way.

3.5.14 Definition

Let L be a signature and let x and y be variables.

- (a) The notation $L(x, y)$ means the same thing as the **expanded signature** $L(x)(y)$. First we add the variable x to the signature L , and then we add the variable y to the *expanded* signature $L(x)$. The notation $t(x, y)$ indicates that t is an $L(x, y)$ -term.
- (b) The **extension** of a term $t(x, y)$, written $\llbracket t(x, y) \rrbracket_S$, is the function such that,

for each pair $(d_1, d_2) \in D_S^2$,

$$\llbracket t(x, y) \rrbracket_S(d_1, d_2) = \llbracket t(x, y) \rrbracket_{S[x_1 \mapsto d_1][x_2 \mapsto d_2]}$$

We also call $\llbracket t(x, y) \rrbracket_S(d_1, d_2)$ the **denotation of $t(x, y)$ in S with respect to (d_1, d_2)** .

- (c) For an $L(x, y)$ -term $t(x, y)$ and L -terms a and b , the **substitution instance** $t(a, b)$ is defined to be the result of substituting a and b in one at a time.

(To be totally explicit: since $t(x, y)$ is a $L(x)(y)$ -term, and b is an $L(x)$ -term (by Example 3.5.2), we can apply the usual definition of substitution (Definition 3.5.4) to the signature $L(x)$ and the variable y , to get an $L(x)$ -term $t(x, b)$. Then we can use Definition 3.5.4 again to substitute the L -term a into $t(x, b)$. The result is what we call $t(a, b)$.)

3.5.15 Example

For any numbers m and n in \mathbb{N} , the denotation of the term $\text{suc } x \cdot y$ of two variables (x, y) , with respect to (m, n) in the standard model of arithmetic, is $(m + 1) \cdot n$.

Proof

$$\begin{aligned} & \llbracket \text{suc } x \cdot y \rrbracket_{\mathbb{N}}(m, n) \\ &= \llbracket \text{suc } x \rrbracket_{\mathbb{N}}(m, n) \cdot \llbracket y \rrbracket_{\mathbb{N}}(m, n) \\ &= \text{suc} \llbracket x \rrbracket_{\mathbb{N}}(m, n) \cdot \llbracket y \rrbracket_{\mathbb{N}}(m, n) \\ &= \text{suc } m \cdot n = (m + 1) \cdot n \end{aligned}$$

The step to the last line is using the fact that x was assigned the value m and y was assigned the value n in the expanded structure $\mathbb{N}[x \mapsto m][y \mapsto n]$. (We get the relevant variables and their order from context, since we know we are evaluating an $L_{\mathbb{N}}(x, yV)$ -term.) \square

Similarly, the extension of the $L_{\mathbb{S}}(x, y)$ -term $x \oplus " " \oplus y$ in the standard string structure \mathbb{S} is the function that takes a pair of strings and returns the result of putting a space between them. For example,

$$\llbracket x \oplus " " \oplus y \rrbracket_S(\text{the}, \text{cat}) = \text{the cat}$$

Or in other words, $x \oplus " " \oplus y$, in \mathbb{S} , with respect to (the, cat) , denotes the cat .

All of this generalizes straightforwardly for any number of variables. Let's go ahead and spell it all out.

3.5.16 Definition

Let L be a signature and let \bar{x} be a sequence of n variables.

- (a) $L(\bar{x})$ means the same thing as the **expanded signature** $L(x_1)\dots(x_n)$, expanding the signature one variable at a time. The notation $t(\bar{x})$ indicates that t is an $L(\bar{x})$ -term.
- (b) The **extension** of a term $t(\bar{x})$ is the function, written $\llbracket t(\bar{x}) \rrbracket_S$, such that for each n -tuple $\bar{d} \in D_S^n$,

$$\llbracket t(\bar{x}) \rrbracket_S(\bar{d}) = \llbracket t(\bar{x}) \rrbracket_{S[x_1 \mapsto d_1]\dots[x_n \mapsto d_n]}$$

where we have also expanded the structure S one variable and value at a time. We also call the object $\llbracket t(\bar{x}) \rrbracket_S(\bar{d})$ the **denotation** of $t(\bar{x})$ in S with respect to \bar{d} .

- (c) For an $L(\bar{x})$ -term $t(\bar{x})$ and a sequence of L -terms \bar{a} the **substitution instance** $t(\bar{a})$ is understood by applying Definition 3.5.4 to each variable, one at a time.

A more general version of the Substitution Lemma follows from these definitions.

3.5.17 Proposition (General Substitution Lemma)

Let L be a signature, let S be an L -structure, let \bar{x} be a sequence of variables, let $t(\bar{x})$ be an $L(\bar{x})$ -term, and let \bar{a} be a sequence of L -terms.

$$\llbracket t(\bar{x}) \rrbracket_S(\dots, \llbracket a_i \rrbracket_S, \dots) = \llbracket t(\bar{a}) \rrbracket_S$$

If the general statement of the Substitution Lemma is confusing, it may be helpful to check what this says for a term with just two variables.

Let $t(x_1, x_2)$ be a term of two variables, and let a_1 and a_2 be two terms.

Let S be any structure. Then

$$\llbracket t \rrbracket_S(\llbracket a_1 \rrbracket_S, \llbracket a_2 \rrbracket_S) = \llbracket t(a_1, a_2) \rrbracket_S$$

That is, if a_1 denotes d_1 and a_2 denotes d_2 , then $t(a_1, a_2)$ denotes the same thing that $t(x_1, x_2)$ denotes with respect to (d_1, d_2) .

Proof

We can prove this by induction on the *sequence of variables*, using the one-variable Substitution Lemma that we have already proved (Exercise 3.5.10).

1. For the empty sequence, we have the limiting case where $t(\bar{x})$ is simply a term t . Then the two sides are trivially the same.

2. Let \bar{x} be a sequence of variables. For the inductive hypothesis, we suppose that for any $L(\bar{x})$ -term $u(\bar{x})$ and any sequence of terms \bar{a} ,

$$\llbracket u(\bar{x}) \rrbracket_S (\dots, \llbracket a_i \rrbracket_S, \dots) = \llbracket u(\bar{a}) \rrbracket_S$$

We wish to show that this still holds when we add an additional variable y . Accordingly, let $t(\bar{x}, y)$ be any $L(\bar{x}, y)$ -term, and let (\bar{a}, b) be a sequence of terms.

$$\begin{aligned} & \llbracket t(\bar{x}, y) \rrbracket_S (\dots, \llbracket a_i \rrbracket_S, \dots, \llbracket b \rrbracket_S) \\ &= \llbracket t(\bar{x}, b) \rrbracket_S (\dots, \llbracket a_i \rrbracket_S, \dots) \quad \text{Substitution Lemma} \\ &= \llbracket t(\bar{a}, b) \rrbracket_S \quad \text{inductive hypothesis} \end{aligned}$$

To apply the Substitution Lemma, we are using the fact that $L(\bar{x}, y)$ is the same thing as adding just one variable y to the signature $L(\bar{x})$. To apply the inductive hypothesis, we are using the fact that $t(\bar{a}, b)$ is an $L(\bar{x})$ -term—the extra variable y is gone, because we replaced it with b . \square

3.5.18 Definition

Let S be an L -structure. An n -place function $f : D_S^n \rightarrow D_S$ is **simply definable in S** iff there is some $L(\bar{x})$ -term $t(\bar{x})$ whose extension is f . That is, for any sequence of objects $\bar{d} \in D_S^n$,

$$\llbracket t \rrbracket_S (\bar{d}) = f(\bar{d})$$

3.5.19 Exercise

Let $f : \mathbb{S}^2 \rightarrow \mathbb{S}$ be the two-place function that takes a pair of strings s and t to the result of joining together three copies of s , separated by copies of t . For example,

$$f(\text{foo}, \text{bar}) = \text{foobarfoobarfoo}$$

Show that this function f is simply definable in \mathbb{S} . (Explicitly work through the definition of the denotation function to prove this.)

3.6 Review

Key Techniques

- We can use **structures** to represent the relationship between simple languages and the world.

- You can prove that every term has a certain property by **induction on terms**. (Technique 3.2.2)
- You can **recursively define** a function whose domain is the set of all terms. (Technique 3.2.7)

Key Concepts and Facts

- A **structure** consists of a set of objects called its **domain**, together with **extensions** for names, variables, and function symbols. (Definition 3.1.3)
- **Terms** are built up recursively out of names and function symbols. (Definition 3.2.1)
- A signature can be **expanded** by adding a new “arbitrary” name, which we call a **variable**. Structures can also be expanded by assigning a value to the variable. The expansion of L is called $L(x)$, and the expansion of S is called $S[x \mapsto d]$. Once we do this, the syntax and semantics for terms with variables works just the same as before.
- You can plug a term into another term using **substitution**. (Definition 3.5.4)
- In any structure, each term **denotes** an object, with respect to some sequence of objects in the domain which are “input” values for its variables. (Definition 3.2.10)
- We can use terms to represent functions. The **extension** of a term $t(x)$ in a structure is the function that takes each object d to the denotation of $t(x)$ with respect to d . (Definition 3.5.6)
- These ideas (substitution, denotation, and extension) are closely related: for any $L(x)$ -term $t(x)$, any L -term a , and any L -structure S ,

$$\llbracket t \rrbracket_S \llbracket a \rrbracket_S = \llbracket t(a) \rrbracket_S$$

(Exercise 3.5.10)

Chapter 4

The Uncountable

Unity added to infinity adds nothing to it, any more than does one foot added to infinite length. The finite is annihilated in presence of the infinite, and becomes pure nothingness. So does our mind before God ...

Blaise Pascal, *Pensées* (1670)

People have been mystified by the infinite every since they first noticed it in antiquity—for example, that there are infinitely many numbers, and (perhaps) infinitely many different positions in space or time. In the quotation above, Pascal is playing up the mystery (for theological purposes) but he is pointing to something genuinely weird. Consider an infinite ray, extending from a point A in one direction, forever. Next consider another point B which is one foot from A along this ray.



Figure 4.1: An infinite ray

Suppose we just delete the part of the ray between A and B . What are we left with? It's another infinite ray starting from B —a ray which looks exactly like the ray we began with. In particular, it is the *same size* as the ray we began with—*infinite*.¹

¹This puzzle is inspired by one of Zeno's paradoxes—though it is hard to tell from the surviving fragments what exactly Zeno's original puzzle was. In his commentary, Simplicius quotes (or paraphrases) Zeno: “But if when it is subtracted, the other thing is no smaller, nor is it increased

But if the ray from A and the ray from B are the same, then the difference between them—the foot from A to B —seems to make no difference at all. A finite distance seems to become “pure nothingness”!

But while we may be mystified, this doesn’t mean we can make no further progress. This puzzle is not a stopping place, but a starting place. The puzzle points us to an essential feature of infinity. If something is infinitely large, then it is *the same size as one of its parts*. (Since that part is also infinite, it is then also the same size as one of *its* parts—we can delete the next mile after B , and the next mile after that, and so on, and at every step we are left with another infinite ray just like the first. So in fact, something infinite is the same size as *infinitely many* different parts.)

We can make the idea of the “size” of a set more precise using one-to-one correspondences (which we introduced in Section 1.2). If we can pair off the elements of two sets, so that neither of them has any extra elements left over, then this gives us a precise sense in which the two sets are the same “size”, or have the *same number of elements*. Then this is the basic observation: an infinite set can be put in *one-to-one correspondence* with one of its proper subsets.

Once we see this, though, this raises many questions. What sets can be put in one-to-one correspondence? As we’ll see in Section 4.2, it’s lots more than you might initially think. For example, you might think it’s obvious that there are *more* numbers than there are even numbers, and that there are more *pairs* of numbers than there are numbers. But these thoughts are wrong.

You might also be tempted by the opposite thought, that all infinite sets are the *same* size. But as it turns out, just as finite sets come in many different sizes, there are also infinite sets which have different sizes. In fact, there are infinitely many different sizes of infinite sets. This chain of ever-vaster infinities is very beautiful, but it also turns out to be a surprisingly practical tool. Just as it’s helpful to use individual numbers as a measuring stick against finite sets—we call this *counting*, and we’ve done it since prehistory—the set of *all* natural numbers is a useful measuring stick for infinite sets. The set of natural numbers is the smallest kind of infinity.

These beautiful facts follow pretty straightforwardly from Cantor’s Theorem (Exercise 1.5.3), which was proved using the “self-application” (or “diagonalization”) trick.

when it is added, clearly the thing being added or subtracted is nothing.” (sec. 139.9) TODO CITE
The paradox of addition is developed much more explicitly as an argument against the infinite by the Arab philosopher al-Kindī (c. 801–866 CE). McGinnis (2007) gives a nice overview of these historical debates. The Indian mathematician Bhāskara (c. 1114–1185) took a similar idea in the opposite direction, developing a calculus of infinite quantities that included rules like $1 + \infty = \infty$.

4.1 Counting

Galileo wrote, “It is wrong to speak of infinite quantities as being the one greater or less than or equal to the other.”² The history of philosophy, science, and mathematics is full of warnings like this—cautions which, as Georg Cantor wrote in 1883³, are

intended to contain the flight of mathematical speculation and conceptualization within its true limits, where it runs no danger of falling into the abyss of the “transcendent,” the place where supposedly, as is said in order to inspire fear and wholesome terror, “all is possible.”

But in fact, infinity is not a conceptual “abyss” about which it is impossible to even think clearly. One key discovery (made precise by Cantor) is that there really *is* a reasonable way of making size comparisons between infinite sets. We really can speak of infinite quantities as *greater* or *less* or *equal* in a way that makes perfect sense. There are some ways in which our intuitions (guided by our experience with finite sets) might lead us astray—so we so have to be careful. But “wholesome terror” would be overreacting!

Consider this function (from Example 1.2.3)

$$[\quad 1 \mapsto \text{Los Angeles}, \quad 2 \mapsto \text{San Diego}, \quad 3 \mapsto \text{San Jose} \quad]$$

This function is a one-to-one correspondence between the sets

$$\begin{aligned} A &= \{1, 2, 3\} \\ B &= \{\text{Los Angeles, San Diego, San Jose}\} \end{aligned}$$

It pairs off each element of A with exactly one element of B , with no elements left over. This is possible because A and B are both three-element sets. They are two different sets with the same number of elements—they are the same *size*.

We can generalize this idea. In general, if A and B are any sets, then if there is a *one-to-one correspondence* between A and B , this pairs off each element of A with exactly one element of B , with no elements left over. We can line up the elements of A with the elements of B , and neither set sticks out past the other. This gives us a reasonable sense in which A and B have the *same size*, or the *same number of elements*. In fact, we will use this as a definition.

²1638, *Two New Sciences* CITE

³CITE “Foundations of a General Theory of Manifolds”

4.1.1 Definition

If A and B are sets, A and B have the **same number of elements** iff there is a one-to-one correspondence between A and B . This is abbreviated $A \sim B$.

4.1.2 Example

- (a) Exercise 1.3.3 showed that there is a one-to-one correspondence between $A \times B$ and $B \times A$. That is,

$$A \times B \sim B \times A$$

- (b) Exercise 1.3.5 showed that there is a one-to-one correspondence between $(A \times B) \times C$, and $A \times (B \times C)$. That is,

$$(A \times B) \times C \sim A \times (B \times C)$$

- (c) Exercise 1.3.4 showed that there is a one-to-one correspondence between any set A and the diagonal of $A \times A$. That is,

$$A \sim \{(a_1, a_2) \in A \times A \mid a_1 = a_2\}$$

- (d) Exercise 1.4.7 showed that there is a one-to-one correspondence between the subsets of a set A and the functions from A to a two-element set. That is,

$$P A \sim 2^A$$

- (e) Example 1.4.8 showed that for any set A ,

$$A^2 \sim A \times A$$

- (f) Exercise 1.4.9 showed that for any set A ,

$$A^1 \sim A$$

- (g) Exercise 1.4.10 showed that for any sets A , B , and C ,

$$C^{A \times B} \sim (C^A)^B$$

Notice that our definition of “same number” doesn’t actually say anything about *numbers*. You can think of *has-the-same-number-of-elements-as* if it was just one word, which describes a certain relationship between sets. In particular, this notion of “same number of elements” even makes sense when we apply it to *infinite*

sets, which don't have any finite number of elements. For example, the facts in the previous example are not restricted just to finite sets. For example, the infinite set of functions \mathbb{N}^2 has-the-same-number-of-elements-as the infinite set of pairs of numbers $\mathbb{N} \times \mathbb{N}$.

But we have to be careful: there are some ways in which this can be counterintuitive.

4.1.3 Exercise (Hilbert's hotel)

There is a one-to-one correspondence between \mathbb{N} (the set of all numbers) and its proper subset $\mathbb{N} - \{0\}$. That is, \mathbb{N} has the same number of elements as $\mathbb{N} - \{0\}$.

Imagine that there is an infinite hotel, with one room for each natural number. Every room has one person in it. What Exercise 4.1.3 shows is that it is still possible to accommodate another person, without kicking anybody out or doubling up. We can use the one-to-one correspondence in Exercise 4.1.3 to rearrange people within the hotel, giving each person a new room, in a way that leaves room 0 unoccupied for a new guest. An infinite hotel can be full, but still have room for more people.

In fact, this is the defining feature of infinite sets.

4.1.4 Definition

A set A is **infinite** iff there is a one-to-one correspondence from A to some proper subset of A . That is, A is infinite iff there is some proper subset $B \subsetneq A$ such that $A \sim B$. Otherwise, A is **finite**.

So Exercise 4.1.3 shows that, in this official sense, there are infinitely many numbers.

Here is another way of putting this definition.

4.1.5 Proposition

A is infinite iff there is a function $f : A \rightarrow A$ which is one-to-one, but not onto.

Proof

Suppose that A is infinite: that is, for some proper subset $B \subsetneq A$, there is a one-to-one correspondence $f : A \rightarrow B$. In that case, f is a one-to-one function, and the range of f is not the same as A , so there is a function from A to A which is one-to-one but not onto.

For the other direction, suppose that $f : A \rightarrow A$ is one-to-one and not onto. Then, by Exercise 1.2.16, there is a one-to-one correspondence between A and the range of f , which by assumption is a proper subset of A . So A is infinite. \square

4.1.6 Exercise

The set \mathbb{S} of all strings is infinite.

4.2 Countable Sets

Our abstract definition of “same number of elements” using functions is especially useful when it comes to infinite sets. In this case, our intuitions about counting, and about which sets are the “same size” or “different sizes,” are not very reliable. We need these precise abstract tools to make progress.

Let’s start by focusing on \mathbb{N} , the set of numbers. In Section 4.1 we discussed one counterintuitive feature of this set: it has the same number of elements as one of its proper subsets. If we have infinitely many people in hotel rooms numbered $0, 1, 2, 3, \dots$, then we can shift each of them down to the next room. This puts them in the rooms $1, 2, 3, 4, \dots$, leaving room 0 unoccupied.

We can go much further than this. Suppose Hilbert’s hotel is full, and then *infinitely* many guests arrive. Can we accommodate them? That is, can we rearrange the guests in rooms $0, 1, 2, 3, \dots$ in such a way as to leave *infinitely* many rooms unoccupied? Yes, we can.

4.2.1 Exercise

The set of even numbers $\{0, 2, 4, \dots\}$ has the same number of elements as \mathbb{N} . That is, if E is the set of even numbers, then $E \sim \mathbb{N}$.

This shows that we can move the guests in Hilbert’s hotel into just the rooms $0, 2, 4, 6, \dots$, without kicking anyone out, or doubling people up in the same room, leaving all of the odd-numbered rooms unoccupied. This is counterintuitive. The set of even numbers E leaves out infinitely many numbers. It’s very intuitive to think that this means there aren’t as many even numbers as natural numbers: that is, that $E < \mathbb{N}$. This intuitive thought is wrong!

Very similarly, one can show that the set of all odd numbers is in one-to-one correspondence with \mathbb{N} . So in fact, the set of all numbers \mathbb{N} is a union of two sets, each of which has the same number of elements as \mathbb{N} . We can take two “copies” of \mathbb{N} (the even numbers and the odd numbers) and stick them together, and we end up with a set which is the same size as we started with.

This raises an interesting question: of the many different infinite sets out there, which of them are the same size as the set of numbers? Are there just as many

strings as numbers, or is one of these infinite sets bigger than the other? What about the set of all *sets* of numbers? What about sets of strings?

4.2.2 Definition

A set is **countably infinite** iff it has the same number of elements as the set of numbers—that is, $A \sim \mathbb{N}$.

A set is **countable** iff it is either countably infinite or else finite.

When we count things, we point at each one of them and say a number. If the set is finite, then we can count all of them using just finitely many numbers. That is, if A is a finite set, then there is a one-to-one correspondence between A and the numbers $0, 1, 2, \dots, n$, for some number n . If A is an infinite set, then this process can never stop. But suppose we don't have to stop—we just keep counting forever. Then we might succeed in “counting” A in the sense of assigning every element of A a unique number. We might put A in one-to-one correspondence with *all* the numbers. A countable set is one that can be counted in this way using either some or all of the counting numbers. (We haven't actually *proved* this about finite sets, though—see Section 4.4 for further details.) Many important sets can be “infinitely counted” this way—but as we will see, not all of them!

Another useful way to think about a countably infinite set is as one that can be *listed* in an infinite sequence. Putting things into an ordered sequence basically amounts to the same thing as assigning each of them a number—its position in the sequence. This works for infinite sequences, too. For example, consider this infinite sequence:

$$\text{A, B, C, A, B, C, \dots}$$

To represent this sequence, we just need to specify which letter appears at each place in the sequence: at position 0 we have A, at 1, B, at 2, C, and so on. So we can represent this sequence with the function

$$[0 \mapsto \text{A}, \quad 1 \mapsto \text{B}, \quad 2 \mapsto \text{C}, 4 \mapsto \text{A}, \quad 5 \mapsto \text{B}, \quad 6 \mapsto \text{C}, \quad \dots \quad]$$

4.2.3 Definition

For any set A , an **infinite sequence** of elements of A is a function from \mathbb{N} to A . So $A^{\mathbb{N}}$ is the set of all infinite sequences in A .

(Really, there can also be infinite sequences that are even *longer* than this sort of sequence. A more precise name for this particular kind of infinite sequence is an **omega-sequence**, or ω -sequence.)

So another way of putting Definition 4.2.2 is that a countably infinite set is one whose elements can be listed in an infinite sequence (or else the empty set).

Let's look at another important example. How does the set of *strings* compare in size to the set of numbers? Is it countable? We could try to list the strings one by one like this:

```
A
AA
AAA
AAAA
⋮
```

But this is not encouraging—putting the strings in this order, we'll never reach any string that includes the letter **B**. But remember, just because we can find some infinite list that *doesn't* include every string, that doesn't mean there isn't some other way of listing strings that *does* include them all. In fact, we can use this trick. First list all the length-zero strings (the empty string). Then list all the length-one strings, in alphabetical order. Then list all the length-two strings, in alphabetical order. And so on. For any number n , there are only finitely many length- n strings. So eventually, going on this way, we will reach every string.

If we imagine that the alphabet just includes the symbols **A**, **B**, and **C**, this sequence of strings will look like this:

```
(),
A, B, C,
AA, AB, AC, BA, BB, BC, CA, CB, CC,
AAA, AAB, AAC, ABA, ABB, ABC, ...
```

This should be enough to get across the main idea, showing that it is possible to list all of the strings in one infinite list. For most purposes, we don't need to bother with making this proof completely official.

4.2.4 Proposition

The set of strings \mathbb{S} is countably infinite. That is $\mathbb{S} \sim \mathbb{N}$.

To make the proof of this fact more precise, we can explicitly define the functions this infinite sequence corresponds to—a function from numbers to strings, and an-

other function from strings to numbers which is its inverse.

$$\begin{array}{llllll} 0 \mapsto (), & 1 \mapsto A, & 2 \mapsto B, & 3 \mapsto C, & 4 \mapsto AA, & \dots \\ () \mapsto 0, & A \mapsto 1, & B \mapsto 2, & C \mapsto 3, & AA \mapsto 4, & \dots \end{array}$$

Writing out this correspondence carefully and checking it is kind of fiddly and involves a bit of basic number theory; the details are given in Section 4.3.

These details aren't very important for our current purposes—but the basic idea is important. Each string can be assigned a unique numerical *code*. There are two functions

$$\text{code} : \mathbb{S} \rightarrow \mathbb{N}$$

$$\text{decode} : \mathbb{N} \rightarrow \mathbb{S}$$

which are inverses to each other. This is the underlying idea of how computers represent data. When text is stored on a computer, it is represented as a sequence of bits—zeros and ones. Essentially, text is thus represented by a very large number. Representing strings with numbers is called “arithmetization.” This makes it possible to talk about properties of strings obliquely, in the language of numbers, by talking about arithmetical properties of their numerical codes. (This idea will come up again in Section 6.11. Numerical codes for strings are also called *Gödel numbers*.)

Here is another useful perspective on countable sets.

4.2.5 Definition

Let A and B be sets. We say that B has at least as many elements as A , abbreviated $B \gtrsim A$ (or $A \lesssim B$), iff A has the same number of elements as some subset of B .

4.2.6 Exercise

For any sets A and B , $A \lesssim B$ iff there is some one-to-one function from A to B .

An important foundational fact is that the set of natural numbers \mathbb{N} is at least as big as any countable set, and there is no infinite set *smaller* than \mathbb{N} . It follows that being *countable* is the same thing as *having no more elements than there are natural numbers*. To prove this, we'll start by using a different notion that is closely related to finiteness.

4.2.7 Definition

A set of numbers $X \subseteq \mathbb{N}$ is **bounded** iff there is some number $n \in \mathbb{N}$ such that $x \leq n$ for every $x \in X$.

4.2.8 Proposition

For any unbounded set of numbers $X \subseteq \mathbb{N}$, $X \sim \mathbb{N}$.

Proof sketch

Here is the intuitive idea for how to show this. If X is an unbounded set of numbers, then X has a least element, and a second-least element, and a third-least element, and so on. This defines a one-to-one correspondence between X and the set of all numbers. That basic idea will do for now; making this argument totally precise is a bit tricky, so we'll put the details in Section 4.4.

TODO. Illustration

□

Completing the proof then turns on a basic fact about finite sets that may seem obvious, but which is actually kind of tricky to prove using our official definitions. We'll take this for granted here; Section 4.4 takes you through a careful proof.

4.2.9 Proposition

A set is finite iff it has the same number of elements as some bounded set of numbers. That is, for any set A , A is finite iff there is some bounded set $X \subseteq \mathbb{N}$ such that $A \sim X$.

4.2.10 Exercise

Using Proposition 4.2.9 and Proposition 4.2.8, show that for any set A , A is countable iff $A \lesssim \mathbb{N}$.

Now we can use the one-to-one correspondence between numbers and strings to put this a different way.

4.2.11 Exercise

A set A is countable iff there is a one-to-one function from A to \mathbb{S} .

This way of thinking about what it means to be countable is particularly important in logic: a countable set is a set whose elements can be *written down* in some system of notation or other. If A is countable, we can assign each element of A a unique string as its label. So the countable sets include all the sets that can be “named” in any language whose expressions can be written down as a finite sequence of symbols. In general, we'll call a one-to-one function from A to \mathbb{S} a **string representation** for A , or a **labeling** for A .

This tells us, in particular, that all of the *languages* we discussed in Chapter 3 are

countable. The terms in the language of arithmetic are strings of symbols. So are the terms in the language of strings, and any other language we might discuss in this class.

4.2.12 Proposition

For any signature L , the set of L -terms is countable.⁴

For another example, we already know that there are one-to-one functions from numbers to strings. This follows from the fact that there are infinitely many strings. But another way to get here is from the fact that there is a *labeling* function, which represents each number with a unique string. The system we have used in our official language of arithmetic is the simple “unary” notation (Definition 3.2.13):

$$\begin{aligned} 0 &\mapsto \textcolor{green}{0} \\ 1 &\mapsto \textcolor{orange}{suc } \textcolor{green}{0} \\ 2 &\mapsto \textcolor{orange}{suc } \textcolor{orange}{suc } \textcolor{green}{0} \\ &\vdots \\ n &\mapsto \langle n \rangle \end{aligned}$$

Exercise 3.2.14 told us that this representation is unique: the function that takes each number to its numeral is one-to-one.

Many things can be written down as strings—even things that might initially appear to be more complicated than strings. Consider *ordered pairs* of strings. This set is also countable. One way to show this would be to come up with a way of arranging all these pairs in an infinite list. But a different approach is to think about how we can *write down* an ordered pair of strings, as a single string.

One tempting way to do this would be to write down the two strings side by side. For example, we could try to represent the pair (ABC, DE) with the single string $ABCDE$. But this won’t quite work: this representation loses track of where one string ends and the other begins. We’ll need to mark the boundary between them. Another thing to try is to put a *delimiting* symbol in between them, like a comma. But this also won’t quite work. Consider the string $A, , C$. This would be ambiguous between two different pairs of strings: $(A, , B)$ and $(A, , B)$.

Here’s a trick to avoid this problem. Instead of just joining up the strings, we can join up *labels* for the two strings. In Exercise 3.2.16, we showed that for each string,

⁴This is relying on our stipulation that all of the basic names and function symbols in a signature are *strings*. For abstract signatures where we do not require this, we would need to add the additional requirement that L is a *countable* signature.

we can choose a *term* in the language of strings that denotes it. For example, for the string ABC, we might choose the label

```
( "A" ⊕ ("B" ⊕ ("C" ⊕ "")))
```

We call this the **quotation** of ABC. We will also sometimes use shorthand like "ABC" for the spelled-out quotation label ("A" ⊕ ("B" ⊕ ("C" ⊕ ""))), which is a term in the language of strings.

Arbitrary strings might be annoying to stick together, but these *labels* for the strings are guaranteed to be nice expressions in a well-behaved language. In particular, we have engineered this language so that it does not use every symbol in the alphabet, and so that terms have unique parses.

Now we can represent a pair of strings by sticking their quotations together. For neatness, we can put a *newline* symbol in between them—this symbol is guaranteed not to appear in any term in the language of strings, so we can't get any ambiguities this way.⁵ For example, we can represent the ordered pair of strings (AB, C) with the two-line string

```
"A" ⊕ "B" ⊕ ""  
"C" ⊕ ""
```

This even works for strings that have newlines in them! For example, consider this two-line string:

```
AB  
C
```

The *label* for this string is

```
"A" ⊕ "B" ⊕ new ⊕ "C" ⊕ ""
```

Notice that this label is a single-line string: this is because the newline isn't represented by something that includes newline, but rather by the constant *new*. Now say we want to represent the ordered pair whose first element is this two-line string, and whose second element is D. This pair is unambiguously represented by

⁵Remember that in our official notation, this label for the string ABC is really
 $\oplus("A", \oplus("B", \oplus("C", "")))$

This has commas in it. If we also used commas for pairs, we wouldn't actually get any ambiguities (because of the Parsing Theorem!), but it would make decoding pairs a little more complicated—particularly when we get a bit fancier in Section 6.3.

```
"A" ⊕ "B" ⊕ new ⊕ "C" ⊕ ""
"D" ⊕ ""
```

This is just a two-line string, rather than blowing up into an ambiguous three-line string like

```
AB
C
D
```

When we represent strings using their labels, it is easy to recover the original strings. We just have to split up the lines, and then figure out which string each line represents.

(To be clear, there is nothing magical about the newline symbol, and this trick does not essentially rely on “multiline strings.” The newline symbol just happens to be a convenient symbol that we weren’t already using for other purposes, which makes for pretty formatting. The convenient thing about the newline symbol is that its *name* in the language of strings, `new`, does not include that same symbol. But we could have done this with any symbol, just by choosing an appropriate name for it.)

4.2.13 Proposition

The set of ordered pairs of strings $\mathbb{S} \times \mathbb{S}$ is countable.

Proof

Let $\langle \cdot \rangle$ be a label function as in Exercise 3.2.16, which assigns each string s a term that denotes s in the standard string structure. We can define a string representation function for $\mathbb{S} \times \mathbb{S}$. In general, if $\langle s \rangle$ and $\langle t \rangle$ are the labels for the strings s and t , then we can represent the ordered pair of strings (s, t) with

$$\text{rep}(s, t) = \langle s \rangle \oplus \text{newline} \oplus \langle t \rangle \quad \text{for each pair of strings } (s, t) \in \mathbb{S} \times \mathbb{S}$$

This function rep is one-to-one, so $\mathbb{S} \times \mathbb{S}$ is countable. (Checking this involves another little parsing fact: since each string in the range of rep contains exactly one newline symbol, there is only one way of breaking it up into two lines. See Section 4.3.) \square

Since we can write down an ordered pair of strings as a single string, it follows that we can also write down ordered pairs of anything that can be *represented* by strings. For example, we can write down pairs of numbers. One obvious way to do this would be with strings like $(3, 1)$. This would work, and since numerals don’t include commas it would be unambiguous. But another way to do it is using

the fact we have just proved: each number can be written as a string, and we have a general strategy for representing pairs of strings. This trick works for *anything* that has a string representation.

4.2.14 Exercise

If A and B are each countable sets, then $A \times B$ is countable.

In particular, this tells us that the set of ordered pairs of numbers $\mathbb{N} \times \mathbb{N}$ is countable. It's worth pausing to think about this fact, because it's rather striking. How would you put all of the ordered pairs of numbers into a single infinite list? You might try to start listing the ordered pairs like this:

$$(0, 0), (0, 1), (0, 2), \dots$$

But this will never get you to any of the pairs

$$(1, 0), (1, 1), (1, 2), \dots$$

or

$$(2, 0), (2, 1), (2, 2), \dots$$

and so on. Each of these lists of numbers looks just like a copy of the numbers. So $\mathbb{N} \times \mathbb{N}$ looks like infinitely many copies of \mathbb{N} put together. The fact that $\mathbb{N} \times \mathbb{N}$ is countable tells us that we can squish all of these infinitely many copies of \mathbb{N} into just one copy of \mathbb{N} . Not only can Hilbert's hotel accommodate some extra guests, and not only can it accommodate infinitely many extra guests, but in fact it can hold *infinitely many Hilbert's hotels* full of guests. This might seem pretty weird. How could you flatten out this two-dimensional grid of numbers in a single one-dimensional list? It can be done. One way, suggested by the proofs we have just given, is to first write out each pair of numbers as a string, and then list those strings in order from shortest to longest, with ties broken alphabetically. An alternative way of doing this is suggested by Fig. 4.2.

We can straightforwardly generalize the idea of Proposition 4.2.13: we can use exactly the same trick to write down any *finite sequence* of strings.

4.2.15 Exercise

- (a) Explain why the set of all finite sequences of strings is countable, by describing a string representation function. (You don't have to rigorously prove that this function is one-to-one.)

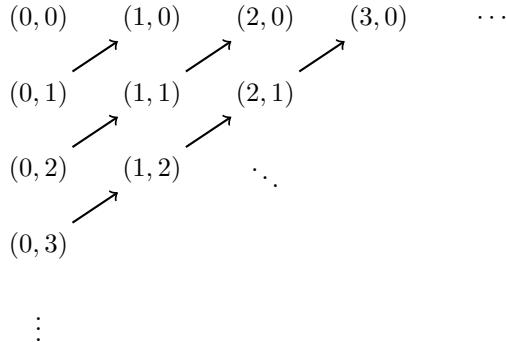


Figure 4.2: A way of listing ordered pairs

- (b) For any countable set A , the set A^* of all finite sequences of elements of A is also countable.

4.3 Coding and Parsing Details*

In this section we'll fill in some of the details we glossed over in the previous section.

First, we'll discuss the details of the correspondence between numbers and strings, in order to show that the set of strings is countable. What we need to do is define a numerical *code* for each string, and then show that we can convert back and forth between strings and their codes. That is, we will define a *coding* function from strings to numbers, and we can prove that this function is one-to-one by also defining a *decoding* function. The key thing to check is that if you decode a code for a string, you get the original string back. (Numerical codes for strings are also sometimes called *Gödel numbers*.)

The details of the coding involve a little bit of basic arithmetic. In particular, we will use the fact that it is possible to *divide* one number by another, with a remainder.

4.3.1 Exercise (Division Lemma)

Let $n > 0$. For any number m , there are unique numbers q and r such that $r < n$ and $m = n \cdot q + r$. The number q is the *quotient*, and the number r is the *remainder*.

4.3.2 Proposition

The set of strings \mathbb{S} is countably infinite. That is $\mathbb{S} \sim \mathbb{N}$.

Proof

We will start by choosing a standard way of ordering the symbols in the alphabet \mathbb{A} —an alphabetical order for individual symbols. This amounts to choosing a number for each symbol, which means we have a function $d : \mathbb{A} \rightarrow \{0, 1, \dots, N - 1\}$, where N is the number of symbols in \mathbb{A} (which is a finite set).

Next we will recursively define a function $f : \mathbb{S} \rightarrow \mathbb{N}$, which says what position in the infinite list each string gets. We can do it like this:

$$\begin{aligned} f() &= 0 \\ f(s, a) &= N \cdot f(s) + d(a) + 1 \quad \text{for each string } s \text{ and symbol } a \end{aligned}$$

Now we just need to prove that f is one-to-one. We can do this by also defining an *inverse* function for f . This will be a “decoder” function $g : \mathbb{N} \rightarrow \mathbb{S}$ that takes each number to the string that it encodes.

We’ll define the function g recursively.⁶ For the base case, clearly $g(0)$ should be the empty string. For the recursive part, we’ll need a bit of simple arithmetic. The Division Lemma (Exercise 4.3.1) tells us that we can *divide* the number $n - 1$ by the number N (which is not zero), with some remainder. That is, there is a number q (the *quotient*) and a number r (the *remainder*) such that

$$n - 1 = N \cdot q + r$$

and $r < N$. Furthermore, these numbers q and r are unique. The quotient q is guaranteed to be smaller than n . (Since $N \geq 1$ and $r \geq 0$, it follows that $N \cdot q + r \geq q$, and this is equal to $n - 1$.) That means we can assume we already know how to decode q for our recursive definition. So we can let

$$g(n) = d^{-1}(r) \oplus g(q)$$

where $d^{-1} : \{0, \dots, n - 1\} \rightarrow \mathbb{A}$ is the inverse function of \mathbb{A} : that is, $d^{-1}(r)$ is the r th symbol in the alphabet.

Now we have to prove that $g(f(s)) = s$ for each string s , by induction on strings. For the base case, it is clear from the definitions that $g(f()) = g(0) = ()$. For the inductive step, let s be any string, let a be any symbol, and suppose that $g(f(s)) = s$. Then

$$f(a \oplus s) = N \cdot f(s) + d(a) + 1$$

⁶The alert reader will notice that this definition uses *strong* recursion on numbers. **TODO. Explain.**

If we divide $N \cdot f(s) + d(a)$, by N , the (unique) quotient and remainder are $f(s)$ and $d(a)$. So by the definition of g , we have

$$g(f(a \oplus s)) = g(N \cdot f(s) + d(a) + 1) = d^{-1}(d(a)) \oplus g(f(s))$$

Furthermore, $d^{-1}(d(a)) = a$ and by the inductive hypothesis $g(f(s)) = s$. So this simplifies to $a \oplus s$, as we intended.

That much shows that \mathbb{S} is countable. We have already shown that \mathbb{S} is infinite, and thus \mathbb{S} is countably infinite. \square

The next thing we'll do is show that the string representation for *pairs of numbers* that we discussed in Section 4.2 is unique. This will also introduce some of the basic machinery we will use for more complicated string representations and parsing facts in Section 3.3 and Section 6.3.

One further detail is to check some facts we took for granted about breaking strings into lines.

4.3.3 Exercise

There is a function $\text{line} : \mathbb{S} \rightarrow \mathbb{S} \times \mathbb{S}$ such that for each pair of strings s and t such that s does not contain any newlines, and t either is empty or begins with a newline,

$$\text{line}(s \oplus t) = (s, t)$$

Hint. Compare Lemma 3.3.7 for “tokenizing” strings.

4.3.4 Exercise

There is a function $\text{lines} : \mathbb{S} \rightarrow \mathbb{S}^*$ such that, for any strings t_1, \dots, t_n which do not contain any newline symbols,

$$\text{lines}(t_1 \oplus \text{newline} \oplus \dots \oplus \text{newline } t_n) = (t_1, \dots, t_n)$$

4.4 Finite Sets*

In Section 4.2, we relied on a basic fact about finite sets, which we have not yet proved (Proposition 4.2.9). Recall this definition:

4.4.1 Definition

A set of numbers $X \subseteq \mathbb{N}$ is **bounded** iff there is some number $n \in \mathbb{N}$ such that $x \leq n$ for every $x \in X$.

4.4.2 Proposition

For any set A , A is finite iff A has the same number of elements as some bounded set of numbers: that is, there is some bounded set $X \subseteq \mathbb{N}$ such that $A \sim X$.

Let's start with something more basic. The finite set $\{\text{Silver Lake}, \text{Echo Park}\}$ doesn't just have *finitely many* elements; it has *two* elements. We can count them. What this looks like is we point to Silver Lake and say "one," and then we point to Echo Park and say "two." When we do this, we are demonstrating that there is a one-to-one correspondence between $\{\text{Silver Lake}, \text{Echo Park}\}$ and the set of *numbers* $\{1, 2\}$. Since our counting numbers start from zero, though, for official purposes it's a little more convenient to do things in terms of a correspondence with the set $\{0, 1\}$.

4.4.3 Definition

A set A **has n elements** iff A has the same number of elements as the set of numbers less than n : that is,

$$A \sim \{k \in \mathbb{N} \mid k < n\}$$

In Section 4.1, we defined an *infinite* set as one that has the "Hilbert's Hotel" property: an infinite set is the same size as one of its proper subsets. Putting that the other way around, a *finite* set was defined to be one that *doesn't* have the "Hilbert's Hotel" property. But now we want to show something else: a finite set is one that *has some finite number of elements*.

4.4.4 Exercise

For each number n , the set of numbers

$$\{k \in \mathbb{N} \mid k < n\}$$

is finite.

Hint. This is kind of tricky! Use induction. Use the fact that $k < n + 1$ iff either $k < n$ or $k = n$. So if there were a "Hilbert's hotel" function f for the numbers less than $n + 1$, this could also be used to build a "Hilbert's hotel" function g for the numbers less than n . The key trick is to say what $g(k)$ should be in the case where $f(k) = n + 1$.

4.4.5 Exercise

For any sets A and B such that $A \sim B$, if A is infinite then B is infinite.

4.4.6 Exercise

For any set A and number $n \in \mathbb{N}$, if A has n elements, then A is finite.

4.4.7 Exercise

Any set that has an infinite subset is infinite.

Hint. If $A \subseteq B$ and you have a “Hilbert’s hotel” function from A to A , you can extend this function to define a “Hilbert’s hotel” function from B to B .

4.4.8 Exercise

For any set A , if $\mathbb{N} \lesssim A$, then A is infinite.

Recall that Proposition 4.2.8 said that for any unbounded set of numbers $X \subseteq \mathbb{N}$, we have $X \sim \mathbb{N}$. In Section 4.2 we gave the basic idea of the proof: we can define a one-to-one correspondence between X and \mathbb{N} by mapping the number zero to the smallest element of X , one to the next smallest, two to the next smallest after that, and so on. Let’s make that argument more precise now.

Proof of ?? 4.2.8

Let X be an unbounded set of numbers. We will start by recursively defining a function $f : \mathbb{N} \rightarrow X^*$, which intuitively will take each number to the sequence of the n smallest elements of X . Then we will use that function to officially define our one-to-one correspondence between X and the set of all numbers.

For the base case, let $f0 = ()$, the empty sequence.

For the recursive step, let n be any number, and suppose that fn is some finite sequence of elements of X . Then, since X is unbounded, there must be some number in X which is strictly greater than every element of fn : otherwise, some element of fn would be an upper bound for X . (This is intuitively clear, but we could argue for it rigorously using a proof by induction on sequences.) The Least Number Property implies that, since the set of elements of $X - \text{elem } fn$ is not empty, it has a *smallest* element. That is, there is some number $x \in X$ which is the *next* number in X after all of the elements of the sequence fn : call this number x . We will let $f(n + 1)$ be the extended sequence x, fn , adding x on to the sequence.

Now, for every number n , let gn be the first element in the non-empty sequence $f(n + 1)$. We will check that g is a one-to-one correspondence between \mathbb{N} and X .

First, g is one-to-one. In fact, it is clear from the definitions that for any number n , $g(n) < g(n+1)$. This implies (by induction) that for any numbers $k < n$, $g(k) < g(n)$, and so in particular $g(k)$ and $g(n)$ are distinct.

Second, g is onto. Another inductive argument shows that for each number $n \in \mathbb{N}$, there is some number m such that every element of X less than n is an element of the sequence $f m$. (*Exercise*: check this. For the inductive step, consider separately the cases where $n + 1 \in X$ or $n + 1 \notin X$.) Furthermore, it is clear from the definitions that if x is in $f m$, then there is some number $k \leq m$ such that $x = gk$. It follows that every element of X is in the range of g . \square

4.4.9 Exercise

Use the facts above to complete the proof of Proposition 4.4.2: a set is finite iff it has the same number of elements as some bounded set of numbers.

The things we have shown in this section give us three different perspectives on infinite sets, which are all equivalent to one another.

4.4.10 Exercise

For any set A , the following are equivalent:

- (a) A is infinite: there is a one-to-one correspondence between A and a proper subset of A ;
- (b) There is no number n such that A has n elements.
- (c) $\mathbb{N} \lesssim A$: there is a one-to-one function from \mathbb{N} to A .

We also now have a nice way of thinking about countably infinite sets. A set is *countable* iff it has *no more* elements than the natural numbers; it is *infinite* iff it has *at least as many* elements as the natural numbers; and it is *countably infinite* iff it has *exactly as many* elements as the natural numbers. In short, for any set A :

- A is *countable* iff $A \lesssim \mathbb{N}$;
- A is *infinite* iff $\mathbb{N} \lesssim A$;
- A is *countably infinite* iff $A \sim \mathbb{N}$.

4.5 Uncountable Sets

So far we have considered how it is possible to compare the sizes of infinite sets, using one-to-one correspondences. We have also considered a bunch of *countably infinite* sets, which all have the same number of elements as there are counting numbers. These include the set of numbers \mathbb{N} itself (obviously), any infinite subset of \mathbb{N} , as well as the set of strings \mathbb{S} , the set of pairs of numbers $\mathbb{N} \times \mathbb{N}$, and the set of finite sequences of strings \mathbb{S}^* . We can also use similar methods to show many

other sets are countable: for example, $\mathbb{S} \cup \mathbb{N}$, $\mathbb{S} \times (\mathbb{N}^* \times \mathbb{S})$, the set of finite sets of strings, the set of pairs of a number and a finite set of numbers, etc. As we said, any set of things that can be *written down*, in principle, using finite strings of symbols, is a countable set.

So you might wonder, does this include *all* of the infinite sets? Are all infinite sets the same size? We know that there aren't any infinite sets that are *smaller* than the set of numbers. But are there infinite sets which are *bigger*?

4.5.1 Definition

For any sets A and B , we say B has (**strictly**) **more elements than** A , abbreviated $A < B$, iff $A \lesssim B$ and $A \not\sim B$: that is, B has at least as many elements as A , but not the same number of elements.

We have to be careful about this definition. Here are two other things which you might think were right in general, based on your experience with *finite* sets. You might be tempted to think that \mathbb{N} , the numbers starting from zero, has strictly more elements than $\mathbb{N} - \{0\}$, the numbers starting from one. But that's not right—in the sense of “number” we are talking about right now, these two sets have the *same* number of elements. As “Hilbert’s hotel” shows, there is a one-to-one correspondence between them. More generally, you might be tempted by this thought:

- **Wrong.** If there is a one-to-one correspondence between A and a proper subset of B , then $A < B$.
- **Wrong.** If there is a function from A to B which is one-to-one but *not* onto, then $A < B$.

Both of these claims are true if A and B happen to be finite sets, but they aren't true in general. Your intuitions probably need some retraining when it comes to counting the elements of infinite sets.

If you can easily come up with a function from A to B that is one-to-one, but not onto, then it's very tempting to conclude that $A < B$. But infinite sets don't work that way! Finding a way of mapping A into B with some stuff left over does tell you that $A \lesssim B$ —that B has *at least* as many elements as A —but it could still turn out that there is some *other* way of mapping A into B which *doesn't* leave anything left over, in which case they would be the same size after all. To show that $A < B$, you have to prove that *no* function from A to B is a one-to-one correspondence.

Now back to our question: are there bigger infinities? In fact, we have basically already answered this. In Section 1.5, we considered Russell's Paradox, which

showed that not just any things can be collected into a set. (In particular, there is no set containing all sets.) We also considered how the argument can be generalized to prove *Cantor's Theorem* (Exercise 1.5.3):

For any set A , there is no onto function from A to PA .

So we can draw the following conclusions.

4.5.2 Exercise (Cantor's Theorem Version 2)

For any set A , there are strictly more *subsets* of A than *elements* of A . That is:

$$A < PA$$

4.5.3 Definition

A set A is **uncountable** iff A is not countable. Equivalently: $\mathbb{N} < A$.

4.5.4 Exercise

- (a) The set of all sets of natural numbers, $P\mathbb{N}$, is uncountable. (Cantor's Theorem Version 3)
- (b) If A is any infinite set, then A has uncountably many subsets: that is, PA is uncountable.

4.5.5 Exercise

- (a) If A is infinite and B has at least two elements, then the set of all functions from A to B is uncountable.
- (b) For any set A , if A has at least two elements, the set of all infinite sequences in A (that is, $A^{\mathbb{N}}$) is uncountable.

4.5.6 Technique (Counting Arguments)

The natural numbers are an infinite yardstick for measuring sets. Whether a set is countable or uncountable provides a good first approximation of what that set is like. One common way we use this is based on a very simple principle: if A is countable, and B is uncountable, it follows that A and B are *not the same set*. In particular, If A is a countable subset of B , and B is uncountable, then it follows that B has elements *besides* those in A . (Indeed, B has *uncountably many* elements which aren't in A .) So a handy trick for showing that there are B 's that aren't A 's is to show that A is countable, and B is uncountable.

This is a more specific version of the general kind of counting argument we intro-

duced in Section 1.5.

4.5.7 Exercise

Suppose that L is some set of strings, which we'll call *descriptions*. (For example, L could consist of strings that make grammatical English noun-phrases, like the set of all prime numbers.) Suppose furthermore that there is a function d that takes each description in L to a set of numbers: for any string s , we'll call ds the set **described** by s . Show that there are sets of numbers which are not described by *any* description in L .

4.5.8 Exercise

Let L be a signature, and let S be an L -structure with domain D . Recall from Definition 3.5.11 that a function $f : D \rightarrow D$ is *simply definable* iff there is some term $t(x)$ that has f as its extension. (That is, $\llbracket t \rrbracket_S d = f(d)$ for every object $d \in D$.) Use a counting argument to show that, if D is infinite, then there is some function $D \rightarrow D$ which is *not* simply definable in S .

4.5.9 Exercise

Let I be the set of **real numbers** between 0 and 1. We won't need to worry too much about what real numbers are like, but here is one fact about them: we can represent a real number using an infinite sequence of digits. Let D be the set of base 10 digits, $D = \{0, 1, \dots, 9\}$. The standard way of representing numbers with sequences of decimal digits isn't quite one-to-one: for example, 0.4999... and 0.5 are both the same number. In order to get a one-to-one representation, we'll need to block this case. So let X be the set of all infinite sequences of digits that eventually end in just 9's. This is the key fact that you can take for granted about the decimal representation of real numbers:

There is a one-to-one correspondence between $D^{\mathbb{N}} - X$ and I .

To be explicit, X is the set

$$X = \{s \in D^{\mathbb{N}} \mid \text{for some } n \in \mathbb{N}, \text{ for every } k > n, s(k) = 9\}$$

There is also a **division** function. This function takes each ordered pair of natural numbers $(m, n) \in \mathbb{N} \times \mathbb{N}$ such that $m < n$ to a real number in I (namely, the number m/n). A real number in I is called **rational** iff it is in the range of this division function. Otherwise, it is called **irrational**.

Prove that there are uncountably many irrational numbers.

Notice that the same argument that tells us that there are more *sets* of numbers than there are numbers ($\mathbb{N} < P\mathbb{N}$) can be applied again. There are more *sets of sets* of numbers than there are sets of numbers: that is, $P\mathbb{N} < P(P\mathbb{N})$. And we can keep on going:

$$\mathbb{N} < P\mathbb{N} < PP\mathbb{N} < PPP\mathbb{N} < \dots$$

So just starting with *one* infinite set ends up introducing us to *infinitely many* different sizes of infinity.

In fact, this ladder of infinite sets only reaches up to some of the lowest levels of abstract reality. *All* of these infinitely many infinite sets are puny compared to some of the vast collections that mathematical set theory has to offer. In this course we'll explore some “small” infinite sets, but we won't climb very high at all into Plato's heaven. (For a glimpse of some of the upper reaches, see Chapter 10.)

Another very interesting question is whether there are other sizes of infinity *in between* the rungs in this ladder we get by taking sets of sets of sets ... The claim that there are no infinite sets intermediate in size between \mathbb{N} and $P\mathbb{N}$ is called *Cantor's Continuum Hypothesis*. The question of whether it is true is a famous open question. One reason the question is so striking is that as it turns out, we know that it is *impossible* to answer this question using standard mathematical methods. See Chapter 10 for more about this.

4.6 Induction and Infinity*

In Chapter 2, we considered a fundamental infinite set—the set of numbers—and a second fundamental way of producing infinite sets, by forming finite sequences. Each of those ideas had an axiom that went with it: the Axiom of Numbers and the Axiom of Sequences. In this chapter we have considered a more general perspective on infinity, based on Hilbert's hotel. This suggests an alternative, more abstract axiom we might have used instead.

4.6.1 Axiom of Infinity

There is an infinite set.

It's an important foundational fact that we don't really need to assume all three of these as axioms: in fact, any one of them is strong enough to prove the other two as consequences.

4.6.2 Exercise

- (a) Explain why the Axiom of Numbers implies the Axiom of Infinity.
- (b) Explain why the Axiom of Sequences implies the Axiom of Infinity.

The other direction—from a general infinite set to numbers or sequences—is not quite so straightforward.

4.6.3 Proposition

The Axiom of Infinity implies the Axiom of Numbers.

Proof

Recall first what the Axiom of Numbers says: that there is some set we call “ \mathbb{N} ”, which has an element we can call “zero”, and a function we can call “successor”, where together these have the Inductive and Injective Properties.

Suppose that the Axiom of Infinity is true. This means that there is a set A and a function $f : A \rightarrow A$ which is one-to-one but not onto. Since f is not onto, there is some element $z \in A$ which is not in the range of f . Then we can define the set of “numbers” to be consist of z , fz , $f(fz)$, and so on. To make this precise, we define a set N *recursively*.

$$\overline{z \in N} \quad \frac{n \in N}{fn \in N}$$

Then we will let the “successor” function be the restriction of f to N . That is, define a function $s : N \rightarrow N$:

$$sn = fn \quad \text{for each } n \in N$$

We now just have to check that N , z , and s have the Inductive and Injective Properties. The recursive definition of N automatically gives us this inductive property:

For any set $X \subseteq A$, if

- (a) $z \in X$, and
- (b) for any $n \in X$, we also have $fn \in X$

then $N \subseteq X$.

The Inductive Property for N , z , s follows from this immediately. (In the case where $n \in X \subseteq N$, sn and fn are the same thing.) The Injective Property is also straightforward. (Check this!) \square

This proof raises a philosophical question. We came up with a set of “numbers” from some *arbitrary* infinite set. It could have been a set of strings, or sets, or space-time points, or whatever. But it would be surprising if numbers turned out to be the same thing as strings, or sets, or points. And surely numbers can’t be *all* of these things. If the number zero is the string ABC, it can’t also be the string CBA, since these strings are different. But we could have picked either one of these strings as our “zero” element in the proof. So this abstract proof can’t really have shown us what the numbers really *are*. Even though we have “reduced” the Axiom of Numbers to the Axiom of Infinity, we have not really given what philosophers would call a *reduction* of the numbers to something else. But the Axiom of Numbers was not a claim about what the numbers really *are*. It was a claim about the *existence* of a set \mathbb{N} , an element 0, and a function suc with the right properties. We have now proved that this existence claim follows from existence of any infinite set at all. Furthermore, this existence claim is enough for our technical purposes. Whatever the numbers may be, as long as they have the Inductive and Injective Properties, that is all we need to prove anything else that has to do with numbers in this text. So for our purposes, we don’t need to answer the philosophical question about the true nature of numbers. We just need to know there is something or other that has the *structure* of numbers. That isn’t an *answer* to the philosophical question of what we are really talking about wide open. This is a deep issue. But it at least gives us an excuse to keep going without an answer to that question.

This move is characteristic of modern mathematics, as a departure from older ways of thinking. Once upon a time we tried to put the subject on firm *metaphysical* foundations, by giving a reductive account of the ontology of abstract mathematical objects. Nowadays, we generally settle instead for putting the subject on firm *methodological* foundations, by giving a *structural* account of the basic properties we need our abstract mathematical objects to have, and then convincing ourselves that there is *something or other* with the right structure.

4.6.4 Proposition

The Axiom of Numbers implies the Axiom of Sequences.

Proof

Let A be any set. We want to show that there are some things which have the right structural properties for finite sequences.

There is a set S , an element $e \in S$, and a function $\text{app} : S \times A \rightarrow S$ which have the Inductive and Injective Properties for Sequences.

Here is one way to do that. We can completely describe the sequence (Al, Bea,

Cece) by saying

Element 0 is Al, element 1 is Bea, element 2 is Cece, and that is all.”

(We’re counting elements from zero just for convenience.) The sequence is completely described by specifying a certain *function* from the first three numbers $\{0, 1, 2\}$ to the set of elements, which says which element appears at each position in the sequence:

$$[0 \mapsto \text{Al}, \quad 1 \mapsto \text{Bea}, \quad 2 \mapsto \text{Cece}]$$

We can do the same thing with any finite sequence.

[TODO. I should officially introduce partial functions in chapter 1.]

Let S be the set of all *partial functions* f from \mathbb{N} to A such that the domain of f is the set $\{k \in \mathbb{N} \mid k < n\}$ for some $n \in \mathbb{N}$. Let $e \in S$ be the function with the empty domain. And for $f \in F$ and $a \in A$, where the domain of f is $\{k \in \mathbb{N} \mid k < n\}$, let $\text{app}(f, a)$ be the function in S with domain $\{k \in \mathbb{N} \mid k < \text{suc } n\}$ such that

$$\begin{aligned}\text{app}(f, a)(k) &= f(k) && \text{for every } k < n \\ \text{app}(f, a)(n) &= a\end{aligned}$$

We just need to prove that S, e, app have the Inductive and Injective Properties for Sequences.

The Injective Property is straightforward. (*Exercise.*)

To prove the Inductive Property for Sequences, suppose that $X \subseteq S$ is a set such that $e \in X$ and for every $s \in X$ and $a \in A$, $\text{app}(s, a) \in X$. Let S_n be the set of all functions from $\{k \in \mathbb{N} \mid k < n\}$ to A . Then we can use induction on *numbers* to prove:

For every $n \in \mathbb{N}$, $S_n \subseteq X$.

(This is also an exercise.) Since every element of S is in A^n for some $n \in \mathbb{N}$, we are done. \square

A similar philosophical issue arises for sequences as for numbers. In this case, our proof did give us a way of “constructing” sequences, as certain functions from numbers. But this is not the only way we could have done it, and it seems a bit weird and arbitrary to suppose that sequences really *are* certain functions. Once again, while questions like these about the nature of abstract objects are philosophically important, fortunately we don’t have to answer them in order to use the Axiom of Sequences. Again, all we will really care about is that there is *some* set \mathbb{S} with the

right structural features. It won't really matter what that set's elements really *are*, as far as our proofs go. So, for the purposes of this text, we can duck the ontological question.

4.6.5 Exercise

Put the pieces together to show that the Axiom of Numbers, the Axiom of Sequences, and the Axiom of Infinity are equivalent.

We can use the ideas from Section 3.4 to present another general way of thinking about these infinity axioms. We discussed there that, in general, the inductive and injective properties for an L -structure S are equivalent to a “universal property”: for every L -structure T , there is exactly one homomorphism $r : S \rightarrow T$. So another way of stating the Axiom of Numbers or the Axiom of Sequences is as the existence of an appropriate universal structure. But now we can conclude something more general still:

4.6.6 Exercise

The Axiom of Infinity implies that for any signature L , there exists a **universal L -structure**. That is, there is an L -structure S such that for any L -structure T , there is a unique homomorphism $r : S \rightarrow T$.

Hint. Recall that we already proved in Section 3.3;Section 3.4 that the *term* structure \mathbb{T}_L has the Inductive and Injective Properties for Terms, and that these imply the Recursion Theorem for Terms. Furthermore, all we needed to prove these things was the existence of *strings*, which follows from the Axiom of Sequences.

This gets us all sorts of “inductive structures” in one fell swoop, including numbers, sequences, trees, and so on. We just have to choose appropriate signatures.

4.7 Review

Key Techniques

- One way to show that there is some element of A which is *not* an element of B is to use a **counting argument**: show that A has *strictly more* elements than B ($A > B$). One way to do this is to show that A is *uncountable*, and B is *countable*. (Technique 4.5.6)

Key Concepts and Facts

- We can compare the sizes of sets:

- **A has the same number of elements as B** ($A \sim B$) iff there is a one-to-one correspondence between A and B .
- **B has at least as many elements as A** ($A \lesssim B$) iff there is a one-to-one function from A to B .
- **B has strictly more elements than A** ($A < B$) iff $A \lesssim B$ and $A \not\sim B$.
- **Cantor's Theorem (Version 2).** Every set has strictly more subsets than it has elements. That is, $A < P A$.
- An infinite set is one with a “**Hilbert's hotel**” function: intuitively, you can rearrange the elements of the set in a way that leaves some extra room left over. More officially, if A is an infinite set, there is a function from A to A which is *one-to-one but not onto*.
 - The set \mathbb{N} of all numbers is **infinite**. So is the set \mathbb{S} of all strings.
- A **countable** set has no more elements than there are natural numbers. Some infinite sets are countable, and some infinite sets are **uncountable**.
- The following sets are countable:
 - \mathbb{N} , the set of all numbers
 - \mathbb{S} , the set of all strings
 - For countable A and B , the set $A \times B$ of ordered pairs of elements of A and B .
 - For countable A , the set A^* of all finite sequences of elements of A .
- The following sets are uncountable:
 - For any infinite set A , the set $P A$ of all subsets of A . In particular, $P \mathbb{N}$ (the set of all sets of numbers) and $P \mathbb{S}$ (the set of all sets of strings).
 - $A^{\mathbb{N}}$, the set of all infinite sequences of elements of A , as long as A has at least two elements
 - For A infinite and B containing at least two elements, the set $A \rightarrow B$ of all functions from A to B .
- In any infinite structure, there are some functions (uncountably many!) which are not the extension of any term. (Exercise 4.5.8)

Chapter 5

Truth and Consequence

What then is truth? It is the notion of existence applied to something that exists and that of non-existence with respect to something that does not exist. Grasping what is as what is, there is truth, the “as it is”, the “uncontroverted.” Likewise, grasping what is not as being what is not, there is truth, the “as it is”, the “uncontroverted.”

Vātsyāyana, *Nyāyasutra Bhāshya* (*Commentary on the Principles of the Nyaya School of Logic*, 2nd or 3rd century CE(?))

In this chapter we return to the project of carefully describing the relationship between language and the world. In Chapter 3 we described some very simple languages. These languages included terms which we can use to refer to particular objects, or to define functions in a structure using variables. Now we’ll build up a more sophisticated language that we can use to *say* things about these objects and functions and how they are related to each other—using *sentences*.

In particular, we’ll be studying a *first-order* language (with function symbols and identity). What this means is that we have a way of making generalizations about all of the objects in an entire structure, using “for all” statements. (“First-order” contrasts with “higher-order” languages, which can also say things about all *sets* or *properties* of objects in a structure. See Chapter 9.)

Just like with terms, when it comes to sentences there are two main things we need to look at. The first thing is the internal structure of the language: the way its simple

pieces can be put together to produce complicated expressions. This is called *syntax*. The second thing is the way the language is related to the world, and in particular the way that sentences can be true or false. This is called *semantics*.

Once we have looked at these two aspects of the first-order language, we can apply them to look at the *logic* of this language, which is about special relationships between different sentences. For example, we can ask whether some sentences are inconsistent with each other, or whether a conclusion follows from some premises.

Nowadays first-order logic is a standard part of the philosopher’s toolkit (as well as the mathematician’s toolkit, the linguist’s toolkit, and the computer scientist’s toolkit). You can do a lot with it: it’s a pretty powerful tool. But it has its limits. In later chapters, we will examine some things it *can’t* do.

5.1 Syntax

I hope the language of first-order logic is already familiar to you (though some of the details in this section will probably be new). Here are some examples of sentences in first-order logic (with identity) in the language of arithmetic.

$$\begin{aligned} & \forall x \forall y \forall z (x + (y + z) = (x + y) + z) \\ & \exists x (\forall y (x + y = y) \quad \& \quad \forall y (y + x = y)) \\ & \forall x \forall y \exists z (x + z = y) \end{aligned}$$

Intuitively, the first sentence says that addition is associative, in the sense that the order of parentheses doesn’t matter. The second says there is an additive identity—something which makes no difference when added to anything—that is, zero. The third says that any two things have a difference, which can be added to one to reach the other. (This principle is *false* about the natural numbers, because if y is smaller than x then there is no natural number you can add to x to reach y . But the principle is true about the *integers*, which include negative numbers.)

These examples are all *sentences*, but they have as part of their internal structure things which aren’t sentences, like

$$\forall y (x + y = y)$$

Here x is what we call a *free variable*, which doesn’t correspond to any quantifier within the expression. A “sentence fragment” like this is called a **formula**.

We have already defined the syntactic structure of *terms*. These are an important building block for making sentences, so let’s start by refreshing our memory of this definition. Let L be a signature.

For each name c in L , we have this rule:

$$\frac{}{c \text{ is an } L\text{-term}}$$

For each one-place function symbol f in L , we have this rule:

$$\frac{a \text{ is an } L\text{-term}}{f(a) \text{ is an } L\text{-term}}$$

And for each two-place function symbol f in L , we have this rule:

$$\frac{a \text{ and } b \text{ are } L\text{-terms}}{f(a, b) \text{ is an } L\text{-term}}$$

Remember also that this definition works just the same way if L happens to be a signature that includes *variables*.

Now we'll give a recursive definition for *formulas*.

5.1.1 Definition

We will recursively define “ **A is a first-order L -formula**”.

Let L be any signature L . First, there are three rules for putting terms together to build the simplest formulas—our “base cases”. (These are sometimes called *atomic formulas*.) For any L -terms a and b , we have this rule:

$$\frac{}{a = b \text{ is an } L\text{-formula}}$$

For each one-place L -predicate F , and L -term a , we also have this rule:

$$\frac{}{F(a) \text{ is an } L\text{-formula}}$$

And for each two-place L -predicate R and L -terms a and b , we have this rule:

$$\frac{}{R(a, b) \text{ is an } L\text{-formula}}$$

(It's easy, and standard, to generalize these rules to allow predicates with more than two places. But we'll stick to one and two, because that's all we happen to need, and it will keep our notation simpler.)

Next, we have two more rules for building up complex formulas from simpler formulas.

$$\frac{A \text{ is an } L\text{-formula}}{\neg A \text{ is an } L\text{-formula}}$$

$$\frac{A \text{ is an } L\text{-formula} \quad B \text{ is an } L\text{-formula}}{(A \& B) \text{ is an } L\text{-formula}}$$

Finally, there is one more rule which is a little more complicated. Let x be a *variable*. We have this final *quantifier rule*:

$$\frac{A \text{ is an } L(x)\text{-formula}}{\forall x A \text{ is an } L\text{-formula}}$$

We will use the notation \mathbb{F}_L for the set of all L -formulas. Similarly, let $\mathbb{F}_L(x)$ be the set of all $L(x)$ -formulas, etc.

We call an L -formula a **sentence** when L does not include any variables. (Since there isn't really an official distinction between variables and other names, this really just means that we are not *thinking* of any of the names in L as variables.)

Some notes about this definition:

1. As with terms, while we need official rules, in practice we often take some notational liberties when we are writing down formulas—just like we did with terms. We may drop parentheses or modify spacing a bit, if that makes things more reader-friendly. There is also a notational issue with relation symbols. Normally we write some relation symbols, like \leq , in between the two terms it applies to, as in $0 \leq \text{suc } 0$. But again, it is more convenient to only ever do things one way in our official notation, and our official choice is “prefix” notation. So again, *officially*, we would write that formula as $\leq(0, \text{suc}(0))$. But we will hardly ever bother to be official.
2. Notice what's going on in the last syntax rule, the rule for the quantifier \forall . When we put $\forall x$ in front of $F(x)$, we take a formula $F(x)$ that has a free variable x in it to a *sentence* $\forall x F(x)$, which has no free variables: the variable x is *bound*. In general, the quantifier $\forall x$ takes an $L(x)$ -formula to an L -formula, in which x is no longer available to use as a free variable. This also works

if we have extra variables on the side. For example, the formula $R(x, y)$ has two free variables, x and y . But the *quantified* formula $\forall y R(x, y)$ has just *one* free variable, dangling loose: just x . In this case, we put $\forall y$ in front of an $L(x, y)$ formula, and get an $L(x)$ formula. (Notice how this fits the pattern in the general rule: if L' is the signature $L(x)$, then $\forall y$ takes an $L'(y)$ -formula to an L' -formula.)

3. Another subtle thing to notice is that, even if a signature L includes some free variables, an L -formula doesn't *have* to include all of the variables that L gives it. So, for example, $x \leq x$ is a formula in $L_{\mathbb{N}}(x)$ (where $L_{\mathbb{N}}$ is the language of arithmetic); but it is *also* a formula in $L_{\mathbb{N}}(x, y)$, or $L_{\mathbb{N}}(x, y, x_2)$, or a signature with whatever extra variables you like, as long as x is included in there.
4. One more thing to notice is that many standard connectives don't appear in these official formation rules, such as the conditional \rightarrow , or the existential quantifier \exists . That's because we can define them up from the basic materials in the definition. For example, later on we'll define $\exists x (x + x = x)$ to be just a notational shortcut for the official formula $\neg \forall x \neg (x + x = x)$. We'll go over these abbreviations in the next section. It's helpful to do things this way, because it means that when we are proving things inductively about formulas we only need to consider a small number of formation rules.

5.1.2 Example

The **first-order language of arithmetic** consists of the first-order formulas with the signature of the language of arithmetic, $L_{\mathbb{N}}$ (namely, \emptyset , **suc**, $+$, \cdot , and \leq).

The **first-order language of strings** consists of the first-order formulas with the signature of the language of strings, $L_{\mathbb{S}}$ (namely, \emptyset , \sqsubseteq , the name for the empty string "" , and the name c_a for each symbol $a \in \mathbb{A}$ in the standard alphabet).

5.1.3 Example

Let L be the signature containing a one-place function symbol f and a two-place relation R . Use the definitions to show, step by step, that the following is a first-order $L(z)$ -formula.

$\forall x (\forall y y = z \ \& \ R(f(x), z))$

Proof

We will apply the formation rules for formulas one by one. This is a bit trickier than you might expect.

First, y and z are both $L(z, x, y)$ -terms. Remember that in general that any L -term is also an term for any signature that *expands* L . So since y is an $L(y)$ -term, it is also an $L(z, x, y)$ -term. (But why are we talking about this signature at all? You'll see.) So, using the identity rule for formulas:

1. $y = z$ is an $L(z, x, y)$ -formula.

Next, notice that $L(z, x, y)$ is what you get if you add one variable, y , to the signature $L(z, x)$. To put that another way, $y = z$ is an $L'(y)$ -formula, where $L' = L(z, x)$ and y is a variable that does not appear in L' . This means we can apply our quantifier rule to conclude:

2. $\forall y \ y = z$ is an $L(z, x)$ -formula.

Similarly, $f(x)$ and z are both $L(z, x)$ -terms. Since R is an L -predicate, it is also an $L(z, x)$ -predicate. So we can apply the rule for two-place relations to conclude:

3. $R(f(x), z)$ is an $L(z, x)$ -formula.

Now we have two formulas with the same signature, so we can put them together using the conjunction rule:

4. $(\forall y \ y = z \ \& \ R(f(x), z))$ is an $L(z, x)$ -formula.

Finally, $L(z, x)$ adds the variable x to the signature $L(z)$. So we can use the quantifier rule once again:

5. $\forall x \ (\forall y \ y = z \ \& \ R(f(x), z))$ is an $L(z)$ -formula.

Notice how as we go, the free variables in signature are *bound* by quantifiers, one by one, resulting in the end in a formula with fewer free variables. \square

5.1.4 Exercise

Use the definitions to show, step by step, that the following is a formula in the first-order language of strings, with the free variable x . (That is, it is an $L_S(x)$ -formula.)

$\forall y \ \forall z \ \neg(y \odot z = x \ \& \ y = "A")$

As with numbers, strings, and terms, formulas have an Inductive Property and an Injective Property. The Inductive Property intuitively says that every formula can be produced in at least one way from these rules, and the Injective Property intuitively says that every formula can be produced in at most one way from these rules.

At this point, we won't go through the fuss of being totally official about these properties. The thing that matters is that our two familiar friends—inductive proof and recursive definition—also work for formulas. We'll do some examples of induction and recursion for formulas very soon.

(The *Inductive Property* for Formulas follows from our recursive definition of “formula.” The *Injective Property* for Formulas is more complicated to prove: we would have to prove another parsing theorem, like the one for terms in Section 3.3. This parsing theorem would show that our particular system of notation for writing down formulas is not ambiguous: no two different ways of applying the rules ever produce the same string by accident. Since this proof of the parsing theorem for formulas is very similar to the analogous proof for terms, we won't bother going into it.)

5.1.5 Exercise

Write out the Inductive Property and the Injective Property for Formulas, based on the formation rules in Definition 5.1.1. (You can use the Inductive Property and the Injective Property for terms as a model.)

In Section 3.5, we showed that each L -term is also an $L(x)$ -term, for any variable x . As an example of our new kind of induction, let's prove the analogous fact for formulas.

5.1.6 Example

For any signature L and variable x (not in L), every L -formula is an $L(x)$ -formula.

Proof

Since the recursive definition of formulas has six parts, so does this inductive proof.

1. *Identity.* Let a and b be L -terms. So they are also $L(x)$ -terms. Thus by the identity rule, $a = b$ is an $L(x)$ -formula.

The steps for one-place and two-place predicates go the same way as identity, so we will skip them.

4. *Negation.* Let A be an L -formula. Suppose for the inductive hypothesis that A is an $L(x)$ -formula. Then by the negation rule, $\neg A$ is also an $L(x)$ -formula.
5. *Conjunction.* Let A and B be L -formulas, and suppose for the inductive hypothesis that A and B are also $L(x)$ -formulas. Then by the conjunction rule, $A \& B$ is also an $L(x)$ -formula.
6. *Quantification.* Let y be a variable, let $A(y)$ be an $L(y)$ -formula. We assume for the inductive hypothesis that $A(y)$ is also an $L(y, x)$ -formula. (Notice—

we *don't* assume it's an $L(x)$ -formula! For the inductive hypothesis we're assuming the principle for formulas with a *different* signature.) Then by the quantifier rule, $\forall y A(y, x)$ is an $L(x)$ -formula. \square

A free variable is like a hole in a sentence. One thing we often want to do is plug a term into that hole, to see what the formula “says about” a certain thing. For instance, take the formula

$$\neg(x = 0) \ \& \ \forall y \ \neg(x + y = y)$$

Intuitively this says, “ x is not zero, and adding x to anything never gives you the same thing back”. We can plug the term $\text{suc } 0$ into the x slot, to get the sentence

$$\neg(\text{suc } 0 = 0) \ \& \ \forall y \ \neg(\text{suc } 0 + y = y)$$

which says: “one is not zero, and adding one to anything never gives you the same thing back.” The basic idea is that each free occurrence of the variable x gets replaced with the term $\text{suc } 0$. This basically works just like it did with terms back in Section 3.5.

As we did with terms, we will often use the notation $A(x)$ to emphasize that A is a formula with the signature $L(x)$, which includes x as a free variable. (But in general, L may also include other variables besides x . Also, remember that the variable x isn't *required* to appear in an $L(x)$ -formula.)

5.1.7 Definition

Let L be a signature, let $A(x)$ be an $L(x)$ -formula (for some variable x not already in L), and let t be an L -term. The **substitution instance** $A(t)$ is an L -formula which is defined recursively as follows.

$$\begin{aligned} (a = b)(t) &= a(t) = b(t) && \text{for terms } a(x) \text{ and } b(x) \\ (R(a, b))(t) &= R(a(t), b(t)) && \text{for terms } a(x) \text{ and } b(x) \\ (\neg A)(t) &= \neg A(t) && \text{for a formula } A(x) \\ (A \ \& \ B)(t) &= A(t) \ \& \ B(t) && \text{for formulas } A(x) \text{ and } B(x) \\ (\forall y A)(t) &= \forall y A(t, y) && \text{for an } L(x, y)\text{-formula } A(x, y) \end{aligned}$$

Notice that the notation $A(t)$ relies on the variable x being made clear in context. Occasionally we find ourselves in contexts where it is *not* very clear which variable we are talking about; in that case, we can use the more explicit substitution notation $A[x \mapsto t]$ instead.

[TODO. Add this notation for terms, too.]

5.1.8 Example

Let L be the signature containing one two-place predicate R and one name c . Let $F(x, y)$ be the formula

$$\forall z \ (\neg R(z, x) \ \& \ R(z, y))$$

Use the definition to find the substitution instance $F(x, c)$.

Proof

We will work our way up, starting from the atomic formulas. $\neg R(z, x)$ is a $L(x, y, z)$ -formula, and z and x are $L(x, y, z)$ -terms. By the definition of substitution for terms, $z[y \mapsto c]$ is just z , and $x[y \mapsto c]$ is just x again. (These are also both $L(x, z)$ -terms.) So, by the clause for predicates in the definition of substitution,

$$(R(z, x))[y \mapsto c] = R(z, x)$$

Then by the negation clause,

$$(\neg R(z, x))[y \mapsto c] = \neg R(z, x)$$

Now we'll work on $R(z, y)$. Again, $z[y \mapsto c]$ is z . Also, by the definition of substitution for terms, $y[y \mapsto c]$ is c . So by the predicate clause of the definition of substitution,

$$(R(z, y))[y \mapsto c] = R(z, c)$$

Putting this together and applying the conjunction clause, we get:

$$(\neg R(z, x) \ \& \ R(z, y))[y \mapsto c] = (\neg R(z, x) \ \& \ R(z, c))$$

And this is an $L(x, z)$ -formula. Finally, by the quantifier clause,

$$(\forall z \ (\neg R(z, x) \ \& \ R(z, y)))[y \mapsto c] = \forall z \ (\neg R(z, x) \ \& \ R(z, c)) \quad \square$$

5.1.9 Exercise

Let $F(x, y)$ be the following $L_{\mathbb{S}}(x, y)$ -formula (in the language of strings):

$$\forall z \ (\neg(z \leq x) \ \& \ \forall s \ \neg(y \oplus s = x))$$

Use the definition to work out the substitution instance $F(x, m \oplus x)$, step by step.

5.1.10 Exercise

Let A be an L -formula. By Example 5.1.6, it is also an $L(x)$ -formula for any variable x , which we can write $A(x)$. Prove by induction on A that for any term t , $A(t)$ is the very same formula as A .

[TODO. I actually skipped the analogous fact about terms in chapter 3, so I need to go back and add it. You can take it for granted: if a is an L -term, and thus also an $L(x)$ -term $a(x)$, then $a(t) = a$.]

5.2 Semantics

Consider the standard model of arithmetic \mathbb{N} . A truth about this structure is that every number has a successor, and not every number *is* a successor. This is a truth which we can formalize in the first-order language of arithmetic:

$$\forall x \exists y (y = \text{suc } x) \quad \& \quad \neg \forall x \exists y (\text{suc } y = x)$$

(We haven't officially introduced the existential quantifier \exists yet, but we will very soon.) What makes *this* sentence a good description of \mathbb{N} ? And what makes this *other* sentence a bad description of \mathbb{N} ?

$$\forall x \forall y \exists z (x + z = y)$$

This one says that for any numbers, there is a *difference* which added to the first produces the second. This is a false claim about the natural numbers structure: for example there is no natural number you can add to 3 to get 1. (Of course, there is another sense in which any two numbers *do* have a difference, which is formalized by this sentence:

$$\forall x \forall y \exists z ((x + z = y) \vee (y + z = x))$$

This is called the *absolute* difference between two numbers.)

Our goal in this section is to give a precise definition of “The first-order sentence A is true in the structure S ,” and then check that this definition works the way it should.

Most of this definition is pretty straightforward, using recursion on formulas. For example, one of our semantic rules will look like this:

For any L -formulas A and B , $A \wedge B$ is true in S iff A and B are both true in S .

The trickiest bit is the step for quantifiers. Before we give an official definition, let's work through a concrete example. Sticking to the standard model of arithmetic, consider this sentence:

$\forall x \ x \leq x$

What does it take for this sentence to be true? What it says is that *everything* in the domain has a certain property—the property expressed by the formula of one variable $x \leq x$. Here is another way of saying this. Suppose we add the name x to our language. Then *whatever number* x might stand for, the resulting sentence $x \leq x$ would be true. So what our rule will say is that the L -sentence $\forall x A(x)$ is true in a structure S iff, *for every way of expanding S* , by letting x stand for some object in the domain of S , the resulting sentence $A(x)$ is true. Intuitively, $\forall x \ x \leq x$ amounts to saying (in the context of the structure \mathbb{N}):

Let x be any number. Then $x \leq x$.

Recall from Section 3.5 our definition of the *expansion* of a structure: $S[x \mapsto d]$ is the $L(x)$ -structure you get by starting with an L -structure S , and letting the new name x stand for the object d in the domain.

Here is how the step of our definition of truth for quantified formulas will go:

For any variable x (not already in L), and any $L(x)$ -formula $A(x)$,
 $\forall x A(x)$ is true in S iff, for every object $d \in D_S$, $A(x)$ is true in
 $S[x \mapsto d]$.

For example, $\forall x \ x \leq x$ is true in \mathbb{N} iff, for every number $n \in \mathbb{N}$, $x \leq x$ is true in the expanded structure $\mathbb{N}[x \mapsto n]$ that lets x stand for n .

5.2.1 Definition

For a signature L , an L -structure S , and an L -formula A , we will recursively define the relation A is true in S as follows.

1. For any L -terms a and b :

$a = b$ is true in S iff $\llbracket a \rrbracket_S = \llbracket b \rrbracket_S$.

2. For any one-place predicate F and L -term a :

$F(a)$ is true in S iff $\llbracket a \rrbracket_S \in F_S$, the extension of F in S .

3. For any two-place predicate R and L -terms a and b :

$R(a, b)$ is true in S iff the ordered pair $(\llbracket a \rrbracket_S, \llbracket b \rrbracket_S)$ is in the extension R_S .

4. For any L -formula A :

$\neg A$ is true in S iff A is not true in S .

5. For any L -formulas A and B :

$A \ \& \ B$ is true in S iff A and B are each true in S .

6. For any variable x (not already in L) and any $L(x)$ -formula $A(x)$:

$\forall x \ A(x)$ is true in S iff, for every object d in the domain of S ,
 $A(x)$ is true in the expanded structure $S[x \mapsto d]$.

Just like with the denotation of terms, we have a nice alternative way of talking about truth in expanded structures that is usually a bit more intuitive.

5.2.2 Definition

Let L be a signature and let S be an L -structure. Let $A(x)$ be an $L(x)$ -formula, and let d be an object in D_S . We say $A(x)$ is **true of d in S** iff $A(x)$ is true in $S[x \mapsto d]$. Similarly, we say $A(x, y)$ is true of (d_1, d_2) in S iff $A(x, y)$ is true in $S[x \mapsto d_1][y \mapsto d_2]$. And so on.

(This terminology requires that not just the variables x and y , but also their intended *order* is made clear in context.)

Another synonym for “ $A(x)$ is true of d ” is “ d **satisfies** $A(x)$ ”.

Using this lingo, we can restate the quantifier part of the definition of truth more concisely:

$\forall x \ A(x)$ is true in S iff $A(x)$ is true of each object in the domain of S .

Likewise, for formulas with extra variables we can say things like this:

$\forall y \ A(x, y)$ is true of d in S iff $A(x, y)$ is true of (d, d') for every object d' in the domain of S .

We can also restate the other rules for the case of formulas containing a variable, given an object d in the domain of S :

$a(x) = b(x)$ is true of d in S iff $\llbracket a(x) \rrbracket_S(d) = \llbracket b(x) \rrbracket_S(d)$.

$A(x) \ \& \ B(x)$ is true of d in S iff $A(x)$ and $B(x)$ are each true of d in S .

And similarly for all the other rules.

5.2.3 Example

Use the definition to show that $\forall x \neg(\text{suc } x = 0)$ is true in the standard model of arithmetic \mathbb{N} .

Proof

Let n be any number. By the definition of the denotation function:

$$\llbracket \text{suc } x \rrbracket_{\mathbb{N}}(n) = \text{suc} \llbracket x \rrbracket_{\mathbb{N}}(n) = \text{suc } n \neq 0 = \llbracket 0 \rrbracket_{\mathbb{N}}(n)$$

We already know that $\text{suc } n \neq 0$. (This is a statement about arithmetic, not a statement about the semantics of any language.) So by the identity clause of Definition 5.2.1, this tells us that $\text{suc } x = 0$ is not true of n in \mathbb{N} .

Thus, by the negation clause of Definition 5.2.1, $\neg(\text{suc } x = 0)$ is true of n in \mathbb{N} .

So we have shown:

For every number n in the domain of \mathbb{N} , $\neg(\text{suc } x = 0)$ is true of n in \mathbb{N} .

Thus, by the clause for quantifiers in Definition 5.2.1, it follows that $\forall x \neg(\text{suc } x = 0)$ is true in \mathbb{N} . \square

5.2.4 Exercise

Use Definition 5.2.1 to show, for each of the following sentences, whether it is true or false in the standard string structure \mathbb{S} .

- (a) $\forall x (x \oplus \text{""} = x)$
- (b) $\forall x \forall y (x \oplus y = y \oplus x)$

TODO. I'm sorry PHIL 450, I switched t and a around here in what follows, compared to how it was done in chapter 3. Later I'll go back and switch chapter 3 to match this.

In Exercise 3.5.10, we showed how two different notions of “plugging something into” a term fit nicely together. Say you have a term $a(x)$, and another term t . If you plug the *term* t into $a(x)$, you get the term $a(t)$. This denotes some object, $\llbracket a(t) \rrbracket_S$. If you plug the thing that term t stands for into the *function* that $a(x)$ stands for, this will also give you some object, $\llbracket a \rrbracket_S \llbracket t \rrbracket_S$. The Substitution Lemma said that these are both the same object:

$$\llbracket a(t) \rrbracket_S = \llbracket a \rrbracket_S \llbracket t \rrbracket_S$$

Something similar to this also holds for formulas. We have the same two ways of “plugging something into” a formula $A(x)$: substituting some term into a formula

to get $A(t)$, or evaluating whether $A(x)$ is true of a the object which is denoted by t . Again, these two notions play well together.

5.2.5 Lemma (Substitution Lemma for Formulas)

Let S be an L -structure, let $A(x)$ be an $L(x)$ -formula, and let t be an L -term. Then the L -formula $A(t)$ is true in S iff $A(x)$ is true of $\llbracket t \rrbracket_S$ in S .

Proof sketch

We can prove this by induction on the formula $A(x)$. Because there are six different syntax rules for formulas, this inductive proof has six parts.

1. *Identity.* Let $a(x)$ and $b(x)$ be $L(x)$ -terms. The L -formula $a(t) = b(t)$ is true in S iff

$$\llbracket a(t) \rrbracket_S = \llbracket b(t) \rrbracket_S$$

The Substitution Lemma (Exercise 3.5.10) tells us that the left side of this is equal to $\llbracket a(x) \rrbracket_S \llbracket t \rrbracket_S$, and the right side is equal to $\llbracket b(x) \rrbracket_S \llbracket t \rrbracket_S$. So $a(t) = b(t)$ is true in S iff

$$\llbracket a(x) \rrbracket_S \llbracket t \rrbracket_S = \llbracket b(x) \rrbracket_S \llbracket t \rrbracket_S$$

This is precisely what it takes for $a(x) = b(x)$ to be true of $\llbracket t \rrbracket_S$.

2. *One-place predication. Exercise.* Let F be a one-place predicate and let $a(x)$ be an $L(x)$ -term. Use Exercise 3.5.10 to show the following:

$F(a(x))$ is true of $\llbracket t \rrbracket_S$ in S iff $F(a(t))$ is true in S .

3. *Two-place predication.* This goes basically the same way as step 2, so we'll skip it.
4. *Negation. Exercise.* (Compare the step for conjunction.)
5. *Conjunction.* Let $A(x)$ and $B(x)$ be $L(x)$ -formulas. Assume the following two inductive hypotheses:

- (a) $A(t)$ is true in S iff $A(x)$ is true of $\llbracket t \rrbracket_S$ in S .
- (b) $B(t)$ is true in S iff $B(x)$ is true of $\llbracket t \rrbracket_S$ in S .

We now consider the conjunction

$$A(t) \& B(t)$$

This is true in S iff $A(t)$ and $B(t)$ are both true in S . By (a), $A(t)$ is true iff $A(x)$ is true of $\llbracket t \rrbracket_S$. By (b), $B(t)$ is true iff $B(x)$ is true of $\llbracket t \rrbracket_S$. Furthermore,

$$A(x) \& B(x)$$

is true of $\llbracket t \rrbracket_S$ iff both of those two parts hold.

6. *Quantification.* This is the trickiest part. This time, we'll let $A(x, y)$ be an $L(x, y)$ -formula. For the inductive hypothesis, what we will suppose is that for any $L(y)$ -structure S' ,

$$A(t, y) \text{ is true in } S' \text{ iff } A(x, y) \text{ is true of } \llbracket t \rrbracket_{S'} \text{ in } S'.$$

Now, let S be an L -structure. First, suppose that

$$\forall y \ A(t, y) \text{ is true in } S$$

We will show that $\forall y \ A(x, y)$ is true of $\llbracket t \rrbracket_S$ in S .

Let d be any object in D_S . By the definition of truth (Definition 5.2.1), $A(t, y)$ is true of d in S . In other words, $A(t, y)$ is true in the expanded structure $S[y \mapsto d]$. Call this structure S' for short. Then the inductive hypothesis tells us that this implies that $A(x, y)$ is true of $\llbracket t \rrbracket_{S'}$ in S' . Since t is an L -term and S' is an expansion of S , Example 3.5.2 tells us that $\llbracket t \rrbracket_{S'} = \llbracket t \rrbracket_S$. Call this object d' . Then to say that $A(x, y)$ is true of d' in S' means the same thing as saying $A(x, y)$ is true in $S[x \mapsto d][y \mapsto d']$, which is the same structure as $S[y \mapsto d'][x \mapsto d]$. Since this holds for arbitrary $d \in D_S$, Definition 5.2.1 tells us that $\forall y \ A(t, y)$ is true in $S[y \mapsto d']$. In other words,

$$\forall y \ A(x, y) \text{ is true of } d' \text{ in } S$$

Since $d' = \llbracket t \rrbracket_S$, this is what we wanted to show.

The other direction goes very similarly, and is left as an exercise. \square

5.2.6 Exercise

Do the remaining parts of the proof of Lemma 5.2.5:

- (a) One-place predicates
- (b) Negation
- (c) The other direction for quantifiers

5.2.7 Exercise

Suppose t and t' are L -terms, and $A(x)$ is an $L(x)$ -formula. Use Lemma 5.2.5 to show that, if t and t' denote the same object (in a structure S) then $A(t)$ and

$A(t')$ have the same truth-value (in S). In short:

If $\llbracket t \rrbracket_S = \llbracket t' \rrbracket_S$ then $A(t)$ is true in S iff $A(t')$ is true in S

5.2.8 Exercise

By Example 3.5.2, any L -formula is also an $L(x)$ -formula. Let A be an L -formula, let S be an L -structure, and let $S[x \mapsto d]$ be an expansion of S . Prove that A is true in S iff A is true in $S[x \mapsto d]$.

Notice that all of this works just fine if L happens to include some extra variables on the side. And we can apply the Substitution Lemma (Lemma 5.2.5) more than once, to get things like this, for two terms t and u :

$A(t, u)$ is true in S iff $A(x, y)$ is true of $(\llbracket t \rrbracket_S, \llbracket u \rrbracket_S)$ in S .

So far we've just been working with our “primitive” logical symbols: \vee , \neg , $\&$, and $=$. These are the only logical symbols in our official first-order language. But this isn't a serious limitation. For example, consider “or”: say we want to formalize the claim $x = 0$ or $x = 1$. We can unpack this statement in terms of “and” and “not”:

$\neg(\neg(x = 0) \& \neg(x = 1))$

This has exactly the same truth conditions as the “or” statement: the only way it can be false is if both $x = 0$ and $x = 1$ are false. But in practice, we don't want to write out this complicated expression every time we want an “or” statement. So we'll just introduce a handy shorthand: we'll write $A \vee B$ as an abbreviation for the official formula $\neg(\neg A \& \neg B)$. This means that when we write down certain strings, we're really officially talking about the string you get by unpacking all of the abbreviations. But we've already been allowing ourselves a bit of this kind of laziness—for example, by leaving off parentheses, or using “infix” notation for operators and relation symbols.

We can use similar tricks for other logical connectives.

5.2.9 Definition

For any formulas A and B , terms a and b , and variable x :

- The **material conditional** $A \rightarrow B$ abbreviates the formula $\neg(A \& \neg B)$.
- The **biconditional** $A \leftrightarrow B$ abbreviates the formula $(A \rightarrow B) \& (B \rightarrow A)$.
- The **disjunction** $A \vee B$ abbreviates the formula $\neg A \rightarrow B$.
- The **standard truth** \top is the formula $\forall x (x = x)$.

- (e) The **standard falsehood** \perp is the formula $\neg T$.
- (f) The **existential generalization** $\exists x A$ abbreviates the formula $\neg \forall x \neg A$.
- (g) The **unique existential** $\exists !x A(x)$ abbreviates the formula

$$\exists y \forall x (x = y \leftrightarrow A(x))$$

(where y is a distinct variable from x).

- (h) $a \neq b$ abbreviates the formula $\neg a = b$.

5.2.10 Example

Let L be any signature (left implicit), let S be any structure.

- (a) For any formulas A and B , the formula $A \rightarrow B$ is true in S iff either A is false in S , or B is true in S .
- (b) For any formula of one variable $A(x)$, the formula $\exists x A(x)$ is true in S iff there is some d in the domain of S such that $A(x)$ is true of d .

Proof of (a)

Let A and B be formulas. By Definition 5.2.9, $A \rightarrow B$ abbreviates the formula

$$\neg(A \& \neg B)$$

Using the definition of truth (Definition 5.2.1),

$$\begin{aligned} \neg(A \& \neg B) \text{ is true in } S \\ \text{iff } A \& \neg B \text{ is not true in } S \\ \text{iff } A \text{ and } \neg B \text{ are not both true in } S \\ \text{iff } \text{either } A \text{ is false in } S \text{ or } B \text{ is true in } S \end{aligned}$$

□

Proof of (b)

By Definition 5.2.9, $\exists x A(x)$ abbreviates

$$\neg \forall x \neg A(x)$$

Using Definition 5.2.1 again,

$$\begin{aligned} \neg \forall x \neg A(x) \text{ is true in } S \\ \text{iff } \forall x \neg A(x) \text{ is not true in } S \end{aligned}$$

This holds iff it is *not* the case that for every $d \in D$, $\neg A(x)$ is true of d in S . That is, this holds iff there is *some* $d \in D$ such that $\neg A(x)$ is *not* true of d in S . Furthermore $\neg A(x)$ is not true of d (in S) iff $A(x)$ is true of d (in S). Putting this together, $\neg \forall x \neg A(x)$ is true in S iff there is some $d \in D$ such that $A(x)$ is true of d in S , which is what we wanted to show. \square

5.2.11 Exercise

Prove the following, using Definition 5.2.9 and Definition 5.2.1. Let L be any signature, let S be any L -structure, and let A and B be L -formulas.

- (a) $A \leftrightarrow B$ is true in S iff A and B have the same truth-value in S .
- (b) $A \vee B$ is true in S iff at least one of A and B is true in S .
- (c) \top is true in every structure.
- (d) \perp is false in every structure.
- (e) For any $L(x)$ -formula $A(x)$, $\exists ! x A(x)$ is true in S iff there is exactly one d in the domain of S such that $A(x)$ is true of d .

5.3 Metalogic

A sentence can be true or false in a structure. One reason we care about this is because we care about the truth. If we are using a certain language to talk about a certain structure S , then we can find out what is true by investigating which sentences are true in S . But there is also another important reason we care about truth-in-a-structure: we also care about what *follows* from what. Which arguments are logically valid? Which theories are logically consistent? One of the neat insights of modern logic (originally from Tarski [1936] 2002) is that that we can understand logical consequence and logical consistency by looking at what is true in different structures. (This isn't the only way to do it. In Chapter 8 we'll consider an alternative, older approach to logical consequence and logical consistency, using *proofs* instead of structures.)

Here's the basic idea. The sentence

`Snow is white`

is true. But the sentence

If snow is white, snow is white

is not only true, but *logically* true. We can tell that it is true without knowing anything about the color of snow, and indeed without even knowing what the word “snow” means. This is because, no matter *what* “snow” and “white” happen to mean, the sentence will still be true. Typically, whether a sentence is true depends on its actual “intended” interpretation. But if a sentence is *logically* true, then it is true on *every* possible reinterpretation—including alternative “unintended” interpretations. Even if we perversely interpret snow to mean “water” and white to mean “impenetrable”, we would still understand If snow is white, snow is white to express something true (namely, that if water is impenetrable, water is impenetrable). The basic idea is that a sentence is logically true if it is true according to *every* interpretation. Since a structure (for a signature L) provides us with a way of interpreting a sentence (in the language with signature L), this means that if an L -sentence is logically true, it should be true in every L -structure.

(But what if we also perversely interpret the word *if* to mean “unless”? Then we could end up understanding the sentence as saying something false. The more precise idea is that a logical truth is true according to every reinterpretation of its *non-logical* expressions. But this raises the difficult question of what is supposed to count as a *logical* expression. What do we hold fixed, and what do we allow to vary? It’s not clear how to answer this question in general. But for our present purposes, we do have a precise answer. We are talking specifically about first-order sentences, and instead of “interpretations” in general we are talking specifically about *structures*. That means we are only looking at reinterpretations of the basic symbols in the *signature* of our language: the basic names, function symbols, and relation symbols. These are the only bits of the language whose extensions are allowed to vary from structure to structure. You could explore how things go with other choices of what to reinterpret. For example, maybe you don’t like fixing the same interpretation of *identity* in every structure, or maybe you think we should also fix the interpretation of some extra things, such as a predicate Set. You can do that, and if you do, you will end up with different logical systems with different things counting as “logical truths.” But for now we are just studying one particular logical system: *first-order logic* with identity.)

Our definitions of *logical consistency* and *logical consequence* are based on the same idea as this definition for logical truth. Logical *consistency* means being true according to *at least one* interpretation. Logical *consequence* means having *no counterexamples*, where a counterexample to an argument is an interpretation according to which every premise is true, but the conclusion is false.

Now let's do this officially.

5.3.1 Definition

Let L be a signature, and let A be an L -formula.

- (a) A is a **logical truth** (or **valid**) iff A is true in every L -structure.
- (b) A is **logically consistent** iff A is true in some L -structure.

We can also extend these notions to sets of sentences, in a natural way.

5.3.2 Definition

Let L be a signature. Let X be a set of L -formulas, and let A be an L -formula. We'll leave the L 's implicit.

- (a) A structure S is a **model of X** iff every formula in X is true in S .
- (b) X is (**semantically**) **consistent** iff X has a model. (That is, some structure is a model of X .) Otherwise X is (**semantically**) **inconsistent**.
- (c) A is a **logical consequence** of X (for short, $X \models A$) iff A is true in every model of X .

5.3.3 Example

Consider a signature with one name c , and one one-place function symbol f . This set of sentences is consistent:

$$\{ \forall x \neg(f(x) = x), \quad f(f(c)) = c \}$$

Proof

We can show this by explicitly providing a model, like the one in (Fig. 5.1).

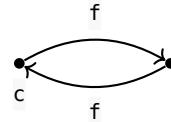


Figure 5.1: An example model.

The domain of this structure S has two elements—for concreteness, say the domain is $\{0, 1\}$. Let c_S (the extension of the name c) be 0, and let f_S be the function that takes 0 to 1 and 1 to 0.

There are, of course, many other models for this set of sentences. But to prove they are consistent, we just have to provide one. \square

5.3.4 Example

This set of sentences is inconsistent:

$$\{ \forall x \neg(f(x) = x), f(f(f(c))) = c \}$$

Proof

We can't prove this just by providing examples of structures which are *not* models: rather, we have to give a general argument that there is *no* structure where both of these sentences are true. Here's one way of arguing for this.

Suppose (for reductio) that S is a model of these sentences. Then in particular, $\forall x \neg(f(x) = x)$ is true in S . This means that for each d in the domain of S , $\neg(f(d) = d)$ is true of d in S . In particular, let d be the element that is denoted by $f(c)$ in S . Since $\neg(f(d) = d)$ is true of d in S , and $f(c)$ denotes d , it follows (from the Substitution Lemma, Lemma 5.2.5) that $\neg(f(f(c)) = f(c))$ is true in S . Thus $f(f(c)) = f(c)$ is false in S . Since S was an arbitrary structure, we have shown that no structure is a model of both $\forall x \neg(f(x) = x)$ and $f(f(c)) = f(c)$. \square

5.3.5 Exercise

Let c be a name and let f be a one-place function symbol. Show whether each of the following sets of sentences is consistent or inconsistent.

- (a) $\{ \exists x (f(x) = c), \exists x \neg(f(x) = c) \}$
- (b) $\{ f(c) = c, \forall x \neg(f(x) = c) \}$
- (c) $\{ \forall x \neg(f(c) = x) \}$
- (d) $\{ \forall x \neg(f(x) = c), \forall x \forall y (f(x) = f(y) \rightarrow x = y) \}$

5.3.6 Notation

When we use the “turnstile” notation $X \models A$ for logical consequence, it's common to take a few notational shortcuts. In this context, we usually leave out set brackets, and we use commas instead of union signs. If X and Y are sets of sentences, and A , B , and C are sentences, then instead of these—

$$\{A, B\} \models C \quad X \cup \{A\} \models B \quad X \cup Y \cup \{A, B\} \models C \quad \emptyset \models A$$

—we'll usually write these simplified versions:

$$A, B \models C \quad X, A \models B \quad X, Y, A, B \models C \quad \models A$$

(For these shortcuts to make sense, we have to make it clear in context which letters stand for sentences and which letters stand for sets of sentences.)

5.3.7 Example

Let X be a set of sentences and let A be a sentence. Show that $X \models A$ iff $X \cup \{\neg A\}$ is inconsistent.

Proof

$X \cup \{\neg A\}$ is *consistent* iff some structure S is a model of $X \cup \{\neg A\}$. This means that every sentence in X is true in S and $\neg A$ is true in S , which means that S is a model of X in which $\neg A$ is true, or equivalently, S is a model of X in which A is not true. So $X \cup \{\neg A\}$ is *inconsistent* iff there is no such S : that is, A is true in every model of X . That's just what $X \models A$ means. \square

5.3.8 Exercise

- (a) X is inconsistent iff $X \models \perp$.
- (b) A is a logical truth iff $\models A$ (that is, A is a logical consequence of the empty set of premises).

5.3.9 Example

Let L be any signature. Let A and B be any L -formulas, and let X and Y are any sets of L -formulas. Prove the following facts about logical consequence.

- (a) **Assumption**

$$X, A \models A$$

- (b) **Weakening**

$$\text{If } X \models A \text{ then } X, Y \models A$$

- (c) **Conjunction Introduction**

$$\text{If } X \models A \text{ and } X \models B \text{ then } X \models A \And B$$

- (d) **Modus Ponens**

$$A, A \rightarrow B \models B$$

Proof of (a)

We want to show that A is true in every model of $X \cup \{A\}$. This is obvious: if S is a model of $X \cup \{A\}$, that means that every element of $X \cup \{A\}$ is true in S , so in particular A is true in S . So we're done. \square

Proof of (b)

Suppose that $X \vDash A$: that is, A is true in every model of X . We want to show that $X, Y \vDash A$: that is, that A is true in every model of $X \cup Y$. So suppose that S is a model of $X \cup Y$. That means that every formula in $X \cup Y$ is true in S . But every formula in X is a formula in $X \cup Y$, so S is also a model of X . So A is true in S . This is what we wanted to show. \square

Proof of (c)

Suppose that $X \vDash A$ and $X \vDash B$, and suppose that S is a model of X . Then since $X \vDash A$, it follows that A is true in S , and since $X \vDash B$, it follows that B is true in S . By Definition 5.2.1, this means that $A \& B$ is true in S . So $A \& B$ is true in every model of X , which is what we wanted to show. \square

Proof of (d)

Suppose that S is a model of $\{A, A \rightarrow B\}$: that is, A is true in S , and $A \rightarrow B$ is true in S . By Exercise 5.2.11, the truth of the conditional tells us that either A is false in S , or B is true in S . But A is not false in S , so B must be true in S . This shows that B is true in every model of $\{A, A \rightarrow B\}$. \square

5.3.10 Exercise

Prove the following facts about logical consequence, where A , B , and C are any L -formulas, and X and Y are any sets of L -formulas (for an arbitrary signature L).

(a) **Cut**

$$\text{If } X \vDash A \text{ and } Y, A \vDash B \text{ then } X, Y \vDash B$$

(b) **Conjunction Elimination**

$$\text{If } X \vDash A \& B \text{ then } X \vDash A \text{ and } X \vDash B$$

(c) **Double Negation Elimination**

$$\text{If } X \vDash \neg\neg A \text{ then } X \vDash A$$

(d) **Proof by Contradiction (Reductio)**

$$\text{If } X, A \vDash B \text{ and } X, A \vDash \neg B \text{ then } X \vDash \neg A$$

(e) **Conditional Proof**

If $X, A \vDash B$ then $X \vDash A \rightarrow B$

5.3.11 Example (Leibniz's Law)

Let a and b be L -terms, and let $A(x)$ be an $L(x)$ -formula.

If $X \vDash a = b$ and $X \vDash A(a)$ then $X \vDash A(b)$

Proof

Let S be any model of X . Given that $X \vDash a = b$, we know $a = b$ is true in S . This implies tells us that $\llbracket a \rrbracket_S = \llbracket b \rrbracket_S$. Given that $X \vDash A(a)$, we know that $A(a)$ is true in S . By the Substitution Lemma (Lemma 5.2.5) this implies that $\llbracket a \rrbracket_S$ satisfies $A(x)$ in S . Thus $\llbracket b \rrbracket_S$ satisfies $A(x)$ in S , and so (using the Substitution Lemma a second time) $A(b)$ is true in S . \square

5.3.12 Exercise

Let X be a set of L -formulas, let a be an L -term, and let $A(x)$ be an $L(x)$ -formula.

(a) **Reflexivity.**

$X \vDash a = a$

(b) **Universal Instantiation.**

If $X \vDash \forall x A(x)$ then $X \vDash A(a)$

(c) **Universal Generalization.** By Example 5.1.6, we know that each formula in X is also an $L(x)$ -formula. Prove:

If $X \vDash A(x)$ then $X \vDash \forall x A(x)$

Hint. Use Exercise 5.2.8.

Notice that all of the definitions and facts we've proved in this section work even for signatures that happen to include extra variables (besides the ones we've explicitly mentioned). So, for example, it makes sense to say that $x = x$ is a logical truth, since it is true in every $L(x)$ -structure.

5.4 Theories and Axioms

The ancient Greeks knew a lot about geometry. Around 300 BCE, the Greco-Egyptian mathematician Euclid systematized this knowledge by showing how a huge variety of different facts about figures in space could be derived from a very small collection of basic principles—or *axioms*—about points, lines, and circles. It was a beautiful accomplishment, and since then Euclid’s “axiomatic method” has been deeply influential. It’s a wonderful thing when we can find a simple set of basic principles with far-reaching implications—and this kind of thing has been done over and over again with remarkable success in mathematics, in empirical science, and in philosophy. Consider just a few examples from the history of philosophy. In the 18th century Isaac Newton (among others) gave elegant principles describing space, time, and the motion of material objects. In the 19th century John Stuart Mill (among others) gave elegant principles describing which actions are best. In the 20th century, Ruth Barcan Marcus (among others) gave elegant principles describing essence and contingency—about what particular objects could have been like.

(Of course in each case, there are important questions about whether the principles these philosophers gave are *true*. Lots of false statements are “axioms” in some theory or other. Calling certain statements “axioms” and their consequences a “theory” isn’t taking any stand on whether they are true or false.)

We now have some tools to help us understand how this works. Later on we will also encounter some striking ways that it *doesn’t* work (especially in Section 7.7 and Section 8.5).

There are two parts to this deep idea: “a simple set of basic principles,” and “far-reaching implications”. In the previous section we worked out an account of implications—that is, an account of first-order logical consequence. The set of everything that logically follows from certain principles is called a *theory*.

5.4.1 Definition

Let T be a set of L -sentences.

- (a) Let X be a set of sentences. We say X **axiomatizes** T iff T includes all and only the logical consequences of X . That is,

$$T = \{A \in \mathbb{F}_L \mid X \vDash A\}$$

We call the elements of X **axioms** for T , and we call the elements of T **theorems** of T .

(b) T is a **theory** iff there is some set of sentences X that axiomatizes T .

Here are some examples.

5.4.2 Definition

The **minimal theory of arithmetic**, called Q for short, is axiomatized by the following sentences. (Here and throughout, whenever we present an axiom with free variables, we should understand this as implicitly adding universal quantifiers to the front as needed to turn the open formula into a sentence.)

```

 $\emptyset \neq \text{suc } x$ 
 $\text{suc } x = \text{suc } y \rightarrow x = y$ 

 $x + \emptyset = x$ 
 $x + \text{suc } y = \text{suc } (x + y)$ 

 $x \cdot \emptyset = \emptyset$ 
 $x \cdot \text{suc } y = (x \cdot y) + x$ 

 $\neg(x < \emptyset)$ 
 $x < \text{suc } y \leftrightarrow (x < y \vee x = y)$ 

 $x < y \vee x = y \vee y < x$ 
 $x = \emptyset \vee \exists y (x = \text{suc } y)$ 

```

(See CITE BBJ 16.2.) The first two axioms capture the Injective Property of Numbers. The next three pairs capture the recursive definitions of addition, multiplication, and less-than, respectively. The last two axioms give us a kind of exhaustiveness conditions. (But they are not nearly as powerful as our full-fledged exhaustiveness condition, the Inductive Property of Numbers.)

5.4.3 Definition

The **minimal theory of strings**, or S for short, has the following axioms.

Remember that the language of strings includes a name for each one-symbol string. We start off with a long list of axioms of the form

```
 $c_a \neq c_b$ 
```

for each pair of names for distinct symbols a and b in the alphabet \mathbb{A} . (For example, this includes the axioms " $A \neq B$ ", " $A \neq C$ ", " $B \neq C$ ", and so on.)

We will use $\text{Sym}(x)$ as an abbreviation for the long formula

$$x = "A" \vee x = "B" \vee \dots \vee x = c_a \vee \dots$$

which lists out all of the names c_a that stand for a single symbol $a \in \mathbb{A}$. Next we have two axioms corresponding to the Injective Property of strings.

$$\begin{aligned} \text{Sym}(x) &\rightarrow x \oplus y \neq \text{""} \\ \text{Sym}(x_1) \rightarrow \text{Sym}(x_2) &\rightarrow x_1 \oplus y_1 = x_2 \oplus y_2 \rightarrow (x_1 = x_2 \ \& \ y_1 = y_2) \end{aligned}$$

We then state some basic properties of joining together strings.

$$\begin{aligned} \text{""} \oplus x &= x \\ x \oplus \text{""} &= x \\ (x \oplus y) \oplus z &= x \oplus (y \oplus z) \end{aligned}$$

Next, we have some axioms for the “no-longer-than” relation \leq .

$$\begin{aligned} \text{""} &\leq x \\ x \leq \text{""} \leftrightarrow x &= \text{""} \\ \text{Sym}(x_1) \rightarrow \text{Sym}(x_2) &\rightarrow x_1 \oplus y_1 \leq x_2 \oplus y_2 \leftrightarrow y_1 \leq y_2 \\ x \leq y \vee y &\leq x \end{aligned}$$

Finally, we have an axiom that says *every* string is either empty, or else the result of adding some symbol to the beginning of another string.

$$x = \text{""} \vee \exists y \exists z (\text{Sym}(y) \ \& \ x = y \oplus z)$$

The theory Q does not include all of the truths of arithmetic—just some of them. Likewise, the theory S just includes a small fragment of the first-order truths in the standard string structure \mathbb{S} . These theories are important because, while they are both pretty simple,¹ at the same time they also turn out to be strong enough to represent lots of interesting structure. They will be important players in Chapter 6 and Chapter 7.

¹The list of axioms for S is not short: because we are using such an extravagantly large alphabet with over 100,000 basic symbols, the full list of axioms would take more than 10 billion symbols to write out explicitly! Of course, if we cared about doing things more efficiently we could really do everything important with a much, much smaller alphabet. If we decided to be super-efficient and write everything using a two-symbol alphabet (“binary code”), then the fully-written out sentence that axiomatizes the theory analogous to S would comfortably fit on a single page.

5.4.4 Exercise

Let T be a set of L -sentences. T is a theory iff, for every L -sentence A , if $T \vDash A$ then $A \in T$.

Notice that it isn't built into the definition of a theory that its axioms have to be *simple*. For example, we could count every single truth of arithmetic as an "axiom", as far as the definition goes. But theories with simple axioms are especially nice. These two examples of theories do have simple axioms: in particular, we can give all of the axioms in a short list.

5.4.5 Definition

A theory T is **finitely axiomatizable** iff there is some finite set of sentences X that axiomatizes T .

5.4.6 Example

The minimal theory of arithmetic Q and the minimal theory of strings S are each finitely axiomatizable.

5.4.7 Exercise

Suppose that T is a finitely axiomatizable theory with axioms A_1, \dots, A_n . Then for any sentence B , B is a theorem of T iff

$$(A_1 \And \dots \And A_n) \rightarrow B$$

is a logical truth.

You might think that *only* finitely axiomatizable theories are simple enough to be useful for humans. But that isn't true: some infinite sets of axioms are also practically useful. Here is an important example:

5.4.8 Definition

First-order Peano arithmetic PA is the theory with the following axioms. There are two parts. The first part is the same as in minimal arithmetic Q (leaving off just the last two axioms, which will no longer be needed):

$$\begin{aligned} \text{suc } x &\neq 0 \\ \text{suc } x = \text{suc } y \rightarrow x &= y \\ \\ x + 0 &= x \\ x + \text{suc } y &= \text{suc } (x + y) \end{aligned}$$

$$\begin{aligned}
 x + 0 &= 0 \\
 x + \text{suc } y &= (x + y) + x \\
 \\
 \neg(x < 0) \\
 x < \text{suc } y &\leftrightarrow (x < y \vee x = y)
 \end{aligned}$$

For the second part, we have some axioms that are intended to capture the Inductive Property of Numbers. For any formula $A(x)$, we have an axiom of this form:

$$(A(0) \ \& \ \forall x (A(x) \rightarrow A(\text{suc } x))) \rightarrow \forall x A(x)$$

Axioms of this form are called **instances of the induction schema**.

(To be more precise, the formula $A(x)$ in the induction schema is allowed to have extra variables on the side besides just x . For example, here is an instance of the induction schema:

$$(y \leq 0 \ \& \ \forall x (y \leq x \rightarrow y \leq \text{suc } x)) \rightarrow \forall x y \leq x$$

Remember that this means in the fully spelled out axiom we put universal quantifiers out front to bind all the extra variables—in this example, that means putting $\forall y$ at the beginning of the sentence.)

First-order Peano arithmetic has infinitely many axioms. So we can't simply list all of them. But we can still *describe* all of the axioms using a simple rule. It is easy to tell whether a sentence is an instance of the induction schema just by looking at its syntactic structure. There have been many foundational debates about whether some principle should or should not be taken for granted in mathematical reasoning (let alone philosophical reasoning!) and many of these debates are very difficult to resolve. But there shouldn't be any dispute over whether a certain formula is an axiom of *Peano arithmetic*, as we have officially defined it. If any dispute like this comes up, we have clear rules that we can use to settle it.

A theory like this is called *effectively axiomatizable*: what counts as an axiom can be checked using some straightforward procedure. But we won't give an official definition of this notion until after we have said more about the idea of a “straightforward procedure” in Chapter 7.

We can do something similar with the theory of strings. We can also do proof by induction on strings, and this fact was officially captured by the Inductive Property of Strings. This says, intuitively, that if the empty string has a property, and adding a single symbol always takes you from a string with the property to another string

with that property, then *every* string has the property. Again, we can try to capture this kind of reasoning using an axiom schema. For any formula $A(x)$, this will give us an axiom of this form:

$$A(\text{“““}) \ \& \ \forall y \ \forall x \ (\text{Sym}(y) \ \& \ A(x) \rightarrow A(y \oplus x)) \rightarrow \forall x \ A(x)$$

(The same point about allowing formulas with extra side variables applies here, too.) If we add these axioms to the minimal theory of strings, we get a theory which is effectively axiomatizable (even though it isn't *finitely* axiomatized). We'll call this theory the **first-order inductive theory of strings**, or SI when we want an abbreviation. (As it happens, this axiomatization is a little redundant, since two of the original axioms from the minimal theory of strings can be proved using the induction axiom schema, but we won't worry about this detail. *Exercise:* which two?)

There is one more important example of a theory which is effectively axiomatizable, but not finitely axiomatizable. In principle, we could formalize all the reasoning we have been doing throughout this textbook. We have set out some axioms—some basic principles about sets, functions, numbers, sequences, and so on. We could formalize all of these principles in a first-order language in a signature with predicates like **Set**, **Element**, **Number**, and so on. And then we could show that the various exercises and lemmas and theorems we have proved are logical consequences of these axioms. But we couldn't do this with just a *finite* set of axioms. You may remember from way back in Chapter 1 that we had a couple of axioms that talked about *properties*—namely, Separation and Choice. Here's how we stated the Axiom of Separation:

Let F be any property. For any set A , there is a set B such that, for any thing a : a is an element of B iff a is an element of A that has the property F .

This looks like a “second-order” axiom, about arbitrary properties. If we are going to formalize this axiom in a *first-order* language, we can use the same trick as in first-order Peano arithmetic. We can replace this single axiom with an axiom *schema*. We could formalize it like this: for any formula $F(x)$ in the first-order language we use to formalize our reasoning, we have an axiom of this form:

$$\forall x \ (\text{Set}(x) \rightarrow \exists y \ (\text{Set}(y) \ \& \ \forall a \ (a \in y \leftrightarrow F(a))))$$

There are infinitely many different axioms of this form, but they are all described by the same simple rule.

The system of axioms we have used in this book is a lot more complicated than what

people usually use to formalize mathematical reasoning. In general, there is a trade-off between how *simple* an axiomatization is and how straightforward it is to use to prove things—and we have gone with usability over simplicity. The axiom system people standardly use is much more austere. It is a *pure set theory*: according to this theory, everything is a set. Functions, numbers, sequences, and so on, are all defined to be certain special kinds of sets. Instead of using many different predicates, like **Set**, **Function**, and **Number**, it uses just one basic predicate: \in , for being an element of a set. And instead of many different axioms spelling out the important properties of sets, functions, numbers, sequences, and so on, all separately, it has just eight axioms.

This very austere formal system is called ZFC. It is described informally in “starred” Section 1.6, and we present a more official version in Chapter 10. But the details are really not important for our purposes. What *is* important is that, in principle, you *can* formalize all of the reasoning we have been doing in this textbook in a first-order theory. And even though this theory is not *finitely* axiomatizable, it is still reasonably simple, in the sense of being *effectively* axiomatizable. (Again, we will explain this concept more precisely in Section 7.7.)

But not all theories are simple. One way of describing a theory is “bottom-up”, by starting with some nice set of axioms that generates the whole theory. But we can also describe a theory “top-down”, by starting with a *structure* (or a set of structures). For example, the set of *all truths of arithmetic* is a theory, since anything that follows from the truths of arithmetic is another truth of arithmetic.

5.4.9 Definition

Let S be a structure. The **first-order theory of S** is the set of all sentences which are true in S . We call this $\text{Th } S$ for short.

5.4.10 Example

- (a) The **first-order theory of arithmetic** is $\text{Th } \mathbb{N}$, the set of all sentences that are true in the standard model of arithmetic.
- (b) The **first-order theory of strings** is $\text{Th } \mathbb{S}$, the set of all sentences that are true in the standard string structure.

Notice that we’ve used the word “theory” in this definition, but we haven’t really justified using this word yet. Is the theory of a structure really a theory in the sense of Definition 5.4.1—a set of sentences that are the consequences of some axioms (perhaps infinitely many)? Yes: the first-order theory of any structure is a theory. But not every theory is the theory of some structure. The following exercises show

these facts.

5.4.11 Definition

A set of L -sentences X is **negation-complete** iff for every L -sentence A , either $A \in X$ or $\neg A \in X$ (or both).

5.4.12 Exercise

Suppose X is a set of sentences.

- (a) Suppose X is the first-order theory of some structure S .
 - (i) X is consistent,
 - (ii) X is negation-complete, and
 - (iii) X is a theory.
- (b) If X is consistent and negation-complete, then X is the theory of some structure: that is, there is some structure S such that $X = \text{Th } S$.

5.4.13 Exercise

For each of the following, either give an example or explain why there is no example.

- (a) A theory which is not negation-complete.
- (b) A theory which is not consistent.
- (c) A consistent and negation-complete set of sentences which is not a theory.

Here's an important question: when can a structure be completely described using simple axioms? Can we come up with a simple system of axioms from which we can derive *all* of the truths? For example, First-Order Peano Arithmetic looks like a reasonable candidate for a set of axioms that might capture all of the truths of arithmetic. (In that case, First-Order Peano Arithmetic would be the very same theory as the complete first-order theory of arithmetic $\text{Th } \mathbb{N}$.) Likewise, the first-order inductive theory of strings looks like a reasonable candidate for an axiomatization of the complete theory of strings, and ZFC looks like a reasonable candidate for a set of axioms that captures all of the truths of pure set theory. But do they really? We will answer this question in Section 8.5. But here's a preliminary result.

5.4.14 Exercise

If S is a finite structure, then $\text{Th } S$ is finitely axiomatizable.

Note. This exercise is harder than most.

5.5 Review

Key Techniques

- **Syntax.** Formulas in a first-order language make up another inductive structure.
 - We can prove things about all formulas by induction.
 - We can define functions on all formulas by recursion.
- **Semantics.** First-order formulas can be *true or false* in a structure, or true or false of certain objects. Truth has a recursive definition. We can use this to prove things about the truth conditions of different sentences.
- **Metalogic.** We can prove things about validity, logical consequence, and consistency, using the idea of *truth in a structure* and a *model* of a set of sentences.

Key Concepts and Facts

- For a signature L , the set of **L -formulas** has a recursive definition (Definition 5.1.1). An **L -sentence** is an L -formula with no free variables.
- Being **true in a structure** also has a recursive definitions (Definition 5.2.1).
- **The Substitution Lemma for Formulas:** for a structure S , a formula $A(x)$, and a term t , $A(t)$ is *true* in S iff $A(x)$ is *true of* the denotation of t in S .
- For a set of L -formulas X :
 - A **model** of X is a structure in which every formula in X is true.
 - X is (**semantically**) **consistent** iff X has a model.
 - A formula A is a **logical consequence** of X (written $X \models A$) iff A is true in every model of X .
- A **theory** is the set of all logical consequences of some set of sentences, which are called *axioms*.
 - The **theory of a structure S** (written $\text{Th } S$) is the set of all sentences that are true in S .

- A set of sentences X is the theory of some structure iff X is a consistent, negation-complete theory.

Chapter 6

The Inexpressible

If you have not realized that not all things can be verbally expressed, then you will lack the look of the Buddhas and Ancestors, and you will lack the bones and marrow of the Buddhas and Ancestors.

Dōgen (1200–1253), *The Shōbōgenzō*, “Dotoku”
(*Expression of the True Principles*, “The Moral Way”)

This chapter works up to two important results about the limits of what can be said. *Truth* in a structure cannot be described within that same structure. More generally no theory can fully describe itself. (For concreteness, we’re working with *first-order* theories, but it turns out that not very many of the main points in this chapter turn on that detail. Similar facts hold for many other kinds of precise logical theories.)

Before we can state these limits on expressibility, we’ll think about the “expressive power” of logic more generally. What kinds of things—in particular, what sets and functions—can be described within a structure? What sets and functions can a theory represent?

6.1 Explicit Definitions

We have been gradually formalizing more and more of the things we do when we are doing logic, and speaking and reasoning more generally. First we introduced terms, as a toy model of our practice of *naming* things. Then we introduced first-order formulas and sentences, as a toy formal model of our practice of *saying* things

about what the world is like. Then we introduced logical consequence and theories and axioms, as a toy formal model of *valid reasoning*, particularly when we deduce conclusions from premises.

Now we will formalize yet another important thing we do: our practice of *giving definitions*. We have been doing this kind of thing since way back in Chapter 1. For example, we said things like this:

For any sets A and B , A is a **subset** of B iff every element of A is an element of B .

When we do this, some magic happens. Before we said this incantation, “subset” was meaningless. We couldn’t use the word in our proofs, or in our definitions, or in true or false statements about the world. After we said it, though, we could do all of those things. Our language has *expanded*. Not only that, but our *knowledge* has expanded: we immediately know some important facts about subsets, “by definition”. For a start, we know that the thing we just said was true: if A is a subset of B , then every element of A is an element of B , and vice versa. And we went on to derive other important truths about subsets just from this definition, such as that every set is a subset of itself.

This is very similar word-magic to what we discussed in Section 5.1. In our proofs, we often say things like this:

Let n be any number.

Before we say this, n might be a meaningless symbol. But after we say it, we can use n just like any other term in our language. Again, our language expands.

Let’s think about how we can formalize this magic in the context of our formal theories. Look again at our example:

$$A \text{ is a subset of } B \iff \text{every element of } A \text{ is an element of } B.$$

On the left-hand side, we introduce our new predicate, “subset”, which is supposed to pick out a certain relation between sets. On the right-hand side, we have an alternative way of expressing this same relation *without* using the word “subset”. This is the simplest kind of definition (not the only kind!)—it is called an *explicit definition*. In this kind of definition, we already have some equivalent way of describing the relation in our *old* language. We can think of the *new* word “subset” as effectively just an abbreviation for this more complex description.

Similarly, we might say:

$$\text{A number } n \text{ is even iff there is some number } k \text{ such that } n = k + k.$$

(Notice that this *explicit* definition of *even* is different from the *recursive* definition of *even* that we gave in Section 2.2. We will get to recursive definitions in Section 6.3.) We can also formalize this definition using first-order logic: the formula

$$\exists y \ y + y = x$$

is true of every even number in the natural number structure \mathbb{N} , and it is not true of any odd number. Accordingly, even though the language of arithmetic does not include any basic *predicate* that applies to just the even numbers, it does have a way of *defining* the even numbers, using this formula. In short, we can say that the set of even numbers is *definable in \mathbb{N}* .

6.1.1 Definition

Let S be an L -structure, and let $X \subseteq D_S$ be a set of elements of the domain of S . We say that X is **definable in S** iff there is an $L(x)$ -formula $A(x)$ such that

$$d \in X \text{ iff } A(x) \text{ is true of } d \text{ in } S \text{ for every } d \in D_S$$

Similarly, a set of pairs $X \subseteq D_S \times D_S$ is definable in S iff there is an $L(x, y)$ -formula $A(x, y)$ such that

$$(d_1, d_2) \in X \text{ iff } A(x, y) \text{ is true of } (d_1, d_2) \text{ in } S \text{ for every } (d_1, d_2) \in D_S \times D_S$$

And so on for sets of n -tuples of any length.

6.1.2 Example

- (a) The set of prime numbers is definable in \mathbb{N} . This is because the following formula is true of all and only the prime numbers:

$$x \neq \text{suc } 0 \ \& \ \forall y \ (\ \exists z \ (x = y + z) \rightarrow (y = 1 \vee y = x) \)$$

- (b) The set of pairs of strings that are both the same length is definable in \mathbb{S} , as shown by this $L_{\mathbb{S}}(x, y)$ formula:

$$x \leq y \ \& \ y \leq x$$

- (c) The set of all pairs of strings (s, t) such that s is an *initial substring* of t is definable in \mathbb{S} :

$$\exists z \ (x \oplus z = y)$$

6.1.3 Exercise

Show that the following are definable in \mathbb{S} .

- (a) The set of non-empty strings.
- (b) The set of pairs (s, t) such that s is a substring of t .
- (c) The set of pairs of strings (s, t) such that t is exactly twice as long as s .

6.1.4 Exercise

For any signature L and any L -structure S , if the domain of S is infinite, then it has undefinable subsets. (In fact, it has uncountably many undefinable subsets!)

Besides properties and relations, we have also defined lots of *functions*. For example, say we want to define the *predecessor* function for natural numbers, which takes each number to the number immediately before it. Since zero doesn't have a number before it, we'll let zero be its own honorary predecessor. In other words,

For any numbers m and n , $\text{pred}(x) = y$ iff either x is the successor of y , or else x and y are both zero.

Again, we can formalize the right-hand side of this definition in the language of arithmetic:

suc $y = x \vee (x = 0 \ \& \ y = 0)$

So we can say that the predecessor function is definable in \mathbb{N} .

6.1.5 Definition

Let S be an L -structure, and let $f : D_S \rightarrow D_S$ be a function on its domain. We say that f is **definable in S** iff the set of ordered pairs (d_1, d_2) such that $f(d_1) = d_2$ is definable in S . (In Exercise 1.3.6 we called this set the *graph* of f .) In other words, there is some $L(x, y)$ formula $A(x, y)$ such that

$$A(x, y) \text{ is true of } (d_1, d_2) \text{ iff } f(d_1) = d_2 \text{ for every } (d_1, d_2) \in D_S \times D_S$$

We can split this up into two conditions. First:

$$A(x, y) \text{ is true of } (d, fd) \text{ for every } d \in D_S$$

Second, $A(x, y)$ is **functional in S** , in the sense that for each $d_1 \in D_S$, there is exactly one $d_2 \in D_S$ such that $A(x, y)$ is true of (d_1, d_2) .

Similarly, if $f : D_S \times D_S \rightarrow D_S$ is a two-place function, we say f is **definable in S** iff the set of ordered triples $(d_1, d_2, d_3) \in D_S^3$ such that $f(d_1, d_2) = d_3$ is definable in S . And so on for functions with more arguments.

6.1.6 Example

- (a) The function that takes each non-zero number to its predecessor, and which takes zero to itself, is definable in \mathbb{N} . This is witnessed by the following formula (with signature $L_{\mathbb{N}}(x, y)$):

$$\text{suc } y = x \vee (x = 0 \ \& \ y = 0)$$

- (b) The function that takes each string to the same string repeated three times is definable in \mathbb{S} . This is demonstrated by the formula

$$x \oplus x \oplus x = y$$

6.1.7 Exercise

The “dots” function from Exercise 2.4.13, which takes each string to a string of the same length containing just the repeated symbol \bullet , is definable in \mathbb{S} . (*Hint.* Your function *won’t* be recursive this time. You can help yourself to things that were defined in Example 6.1.2.)

6.1.8 Exercise

A formula $A(x, y)$ is functional in S iff the sentence

$$\forall x \exists !y \ A(x, y)$$

is true in S .

6.1.9 Exercise

Recall from Definition 3.5.11 that a function $f : D_S \rightarrow D_S$ is *simply definable* iff there is some term $t(x)$ that has f as its extension in S . Show that if f is simply definable, then it is also definable in the sense of Definition 6.1.5.

It can also be useful to define *partial* functions, which are not defined for the whole domain of the structure. This is a little bit tricky, because the way we have defined structures, we function symbols are always required to have *total* functions as their extensions. So what we will say is that a partial function is definable iff there is some way of extending it to a definable total function. Basically, we just don’t care what the definition ends up doing beyond the domain of the function we are defining.¹

¹Something to be careful about is that different textbooks use slightly different definitions and terminology for “definable”, particularly when it comes to partial functions. The same goes even more so for “representable”, which we will encounter in Section 6.9.

6.1.10 Definition

Let $X \subseteq D_S$ be a subset of the domain and $f : X \rightarrow D_S$ is a function, we say that f is **definable** iff there is some definable function $g : D_S \rightarrow D_S$ such that $g(d) = f(d)$ for every $d \in X$ in the domain of f .

6.1.11 Example

- (a) The function that takes each number $n \geq 2$ to its smallest prime divisor is definable in \mathbb{N} . We already know that the set of prime numbers is definable, so let's introduce a new predicate `Prime` with this extension. We can use this to show that the relation of being a prime divisor is also definable in \mathbb{N} , with this defining formula:

$$\text{Prime}(y) \ \& \ \exists z \ (y \cdot z = x)$$

Then we can expand the language again with a two-place predicate `PrimeDivisor`, which has the same extension as this formula. Next, we have this formula in the expanded language:

$$\text{PrimeDivisor}(y, x) \ \& \ \forall y_2 \ (\text{PrimeDivisor}(y_2, x) \rightarrow y \leq y_2)$$

The extension of this formula is the set of pairs (m, n) such that n is the greatest prime divisor of m (and $m \geq 2$, since otherwise m has no prime divisors).

- (b) The function that takes each non-empty string to its first symbol is definable in \mathbb{S} . We already showed that the set of length-one strings is definable, so we can introduce a predicate `Sym` that applies to just these strings. Then we can use this formula to define the function:

$$\text{Sym}(y) \ \& \ \exists z \ (y \oplus z = x)$$

Let's look again at what happens when we state a definition, like this one:

A number n is *even* iff there is a number k such that $n = k + k$.

As we discussed above, we can formalize the right-hand side of this definition with the formula $\exists y \ y = x + x$. But what is happening with the definition as a complete sentence? We can formalize this, too, like this:

$$\forall x \ (\text{Even}(x) \leftrightarrow \exists y \ y + y = x)$$

But this is not quite a sentence in the language of arithmetic. That language doesn't include a predicate `Even`. Rather, this is a sentence in an *expansion* of the language of arithmetic, which adds in the new predicate `Even`. In general, when we define a new expression, we expand our language. Symbols that may have been meaningless

before magically gain meanings.

Back in Section 3.5, we discussed how we can expand a signature by adding new names, and we can expand a structure by assigning an extension to that new name. In just the same way, we can expand a signature by adding a new *predicate* or *function symbol*, and we can expand a structure by assigning extensions to the new symbols.

6.1.12 Definition

Let L be a signature.

- (a) We call a signature L^+ an **expansion** of L iff L^+ includes all of the names, function symbols, and predicates from L , and possibly more besides. For a token F which does not already appear in L , $L(F)$ is the expansion of L that we get by just adding the new predicate F to L . Likewise, $L(f)$ is the expanded signature we get by just adding the new function symbol f to L .

(This notation requires that we make clear in context what *kind* of symbol we're adding to the language—whether it is a new variable, or a one-place or two-place function symbol, or a predicate. Usually our choice of notation will make this clear—whether we call it something like x or f or F .)

- (b) Let L^+ is an expansion of L , let S be an L -structure, and let S^+ be an L^+ -structure. We say that S^+ is an **expansion** of S iff S^+ has the same domain as S , and the same extensions for each name, function symbol, and predicate in L .

We use the notation $S[F \mapsto X]$ for the $L(F)$ -structure that expands S by assigning the set of objects $X \subseteq D_S$ as the extension of the new predicate F . Similarly, for a function $g : D_S \rightarrow D_S$, $S[f \mapsto g]$ is the $L(f)$ -structure that expands S by assigning the function g as the extension of the new function symbol f .

Definitions correspond to a particularly important kind of expanded structure. Remember that a structure represents an interpretation of a language. When we explicitly define a new predicate, we switch from one structure to an expanded structure, with the meaning of the new predicate fixed by its definition.

6.1.13 Definition

Let S be an L -structure, and let S^+ be an L^+ -structure, where L^+ expands L . We call S^+ a **definitional expansion** of S iff S^+ is an expansion of S , such that, the extension in S^+ of every L^+ -symbol is definable in S . In other words:

- (a) For each one-place L^+ -predicate F , there is some $L(x)$ -formula $A(x)$ such that

$$d \in [F]_{\$^+} \text{ iff } A(x) \text{ is true of } d \text{ in } S \text{ for every } d \in D_S$$

- (b) For each two-place L^+ -predicate R , there is some $L(x, y)$ -formula $A(x, y)$ such that

$$(d_1, d_2) \in [R]_{\$^+} \text{ iff } A(x, y) \text{ is true of } (d_1, d_2) \text{ in } S \text{ for every } (d_1, d_2) \in D_S \times D_S$$

- (c) For each one-place L^+ -function symbol f , there is some $L(x, y)$ -formula $A(x, y)$ which is functional in S , and

$$A(x, y) \text{ is true of } (d, fd) \text{ in } S \text{ for every } d \in D_S$$

- (d) For each two-place L^+ -function symbol f , there is some $L(x, y, z)$ -formula $A(x, y, z)$ which is functional in S , and

$$A(x, y, z) \text{ is true of } (d_1, d_2, f(d_1, d_2)) \text{ in } S \text{ for every } (d_1, d_2) \in D_S \times D_S$$

When we expand our language with an explicit definition, the incantation we spoke—

A number n is even iff there is some number k such that $n = k + k$
not only becomes *meaningful*, but it is also *true* in the new expanded language.

6.1.14 Exercise

Let S be an L -structure.

- (a) Let $A(x)$ be an $L(x)$ -formula.

Let X be the set of all $d \in D_S$ such that $A(x)$ is true of d in S . (This is called the **extension** of $A(x)$.) Let F be a predicate not in L . Then $S[F \mapsto X]$ is a definitional expansion of S . Check that

$$\forall x (F(x) \leftrightarrow A(x))$$

is true in $S[F \mapsto X]$.

- (b) Let $A(x, y)$ be an $L(x, y)$ -formula which is functional in S , and for each $d \in D_S$, let $g(d)$ be the unique $d' \in D_S$ such that $A(x, y)$ is true of (d, d') in S . Let f be a new function symbol. Check that

$$\forall x \forall y (f(x) = y \leftrightarrow A(x, y))$$

is true in the definitional expansion $S[f \mapsto g]$.

An important fact about explicit definitions is that, in principle, we could do without them. We could just replace our *defined* predicate with the original formula we used to define it. Take our earlier example of an explicit definition:

For any sets A and B , A is a **subset** of B iff every element of A is an element of B .

One of the things this let us prove was this:

For every set A , A is a subset of A .

But instead of saying that, using the word **subset**, we could instead “unpack the definition”, and say this:

For every set A , every element of A is an element of A .

(And this is a logical truth!)

To make the idea of “unpacking definitions” precise, we can use a new kind of *substitution*: instead of replacing a *variable* with some *term*, we can replace a *predicate* with some *formula*. For example, consider the formula

$$(Even(x) \& Prime(x)) \rightarrow x = 2$$

This uses two predicates: `Even` and `Prime`. We have a definition for `Even`, and we can “unpack” it by replacing each occurrence of `Even(x)` with the formula

$$\exists y (y + y = x)$$

The result looks like this:

$$(\exists y (y + y = x) \& Prime(x)) \rightarrow x = 2$$

Like before, we can officially define this kind of substitution using recursion. But the details are tedious, and not especially illuminating. For completeness’s sake, we’ll put them in the starred Section 6.2.

This is also true for definitions of functions: they don’t really increase the expressive power of our language—they just lets us say things more succinctly. We can always “unpack” the definition of the function. But this isn’t quite as straightforward as with sets. For example, consider the definition of the predecessor function again:

$$\forall x \forall y (\text{pred } x = y \leftrightarrow (\text{suc } y = x \vee (x = 0 \& y = 0)))$$

Now consider some sentence using `pred`, like this one:

$$\forall x (\text{pred } x \leq x)$$

When we unpack the definition of `pred`, we get this sentence:

$$\forall x \exists y ((\text{suc } y = x \vee (x = 0 \& y = 0)) \& y \leq x)$$

Notice that we *can't* simply replace every occurrence of a function symbol with its defining formula—formulas and function symbols have different syntax. Function symbols show up as parts of terms, but formulas don't. So the rule for “unpacking” definitions of functions is a bit more complicated. What we did instead is replace the term `pred x` with a new *variable*. Instead of saying “`pred x` is ...”, instead we can say “there is some y that stands in the predecessor relation to x such that y is ...”.

Here is the basic recipe for how to do it. Say we have a function symbol f with a defining formula $F(x, y)$.

1. Look for an occurrence of f in your formula. If there aren't any, then we're done.
2. Otherwise, our formula must contain some *atomic* formula (either an identity formula or a predication) which has the form $A(f(a))$, for some atomic formula $A(x)$ and some term a . We can replace this atomic formula with a new formula like this, where y is a new variable:

$$\exists y (F(a, y) \& A(y))$$

This is equivalent (in our structure S) to the atomic formula we started with, and so the result of swapping it into the place of the atomic formula in our “big” formula is also equivalent.

3. Repeat until there are no remaining occurrences of f .

At each step, we have removed one occurrence of f from the formula. So eventually we'll be done.

This idea is made into a more precise recursive definition in Section 6.2.

6.1.15 Proposition

Let S^+ be a definitional expansion of S . For every $L^+(x)$ -formula $A(x)$, there is a

corresponding $L(x)$ -formula, called the **translation** of $A(x)$, such that:

$$A(x) \text{ is true of } d \text{ in } S^+ \quad \text{iff} \quad A^*(x) \text{ is true of } d \text{ in } S \quad \text{for every } d \in D_S$$

Proof

See Section 6.2. □

Proposition 6.1.15 tells us that if we define new predicates and function symbols, in a structure S , then any formula in the *expanded* language is equivalent to some formula in the *original* language. Intuitively, definitions don't add any extra *expressive power* to our language. Anything you could say using the new predicate is something you could have said instead by unpacking the definition of that predicate in the original language. Defining new words makes no difference to what properties we can express—only how long it takes us to express them.

Practically speaking, this means that once we have shown that a set is *definable* in a structure, we can go ahead and add a basic predicate to our language which stands for that set—we know that we'll always be able to get rid of it in the end. Similarly for definable functions.

6.1.16 Exercise

Use Proposition 6.1.15 to show that, if a set $X \subseteq D_S$ is definable in a definitional expansion of a structure S , then X is also definable in S .

We have worked a lot with some very simple languages—the language of arithmetic, and the language of strings. Each of these has a simple set of constants, function symbols, and predicates. But it turns out that these simple languages are really quite powerful: we can express a lot of interesting properties, relations, and functions on numbers and strings using them. Let's start simple. We will turn to this in Section 6.3.

6.2 Unpacking Definitions*

UNDER CONSTRUCTION

6.2.1 Definition

Let $A(F)$ be a formula in the expanded language $L(F)$, where F is a new one-place predicate. Let $B(x)$ be an $L(x)$ -formula. Then we define the **(predicate) substitution instance or translation** $A(F \mapsto B)$ recursively as follows. (Hopefully there are no surprises here.)

1. *Identity.* For L -terms a and b ,

$$(a = b)(F \mapsto B) = a = b$$

2. *Predication.* For an L -term a ,

$$(F(a))(F \mapsto B) = B(a)$$

For any one-place predicate G other than F ,

$$(G(a))(F \mapsto B) = G(a)$$

3. *Two-place predication.* This case goes similarly.

4. *Negation.* For an $L(F)$ -formula A ,

$$(\neg A)(F \mapsto B) = \neg A(F \mapsto B)$$

5. *Conjunction. Exercise.*

6. *Quantification.* For an $L(F, y)$ -formula A ,

$$(\forall y A)(F \mapsto B) = \forall y A(F \mapsto B)$$

What is important about this notion of “plugging something into a predicate” is that it has the right semantics. Say we have a sentence that uses some predicate symbol. If we have another formula with the same *meaning* as that predicate, then replacing the predicate with the formula should give us a sentence with the same meaning as the one we started with. This is an analogue of our familiar Substitution Lemmas for terms and formulas.

6.2.2 Lemma (Substitution Lemma for Predicates)

Let S be an L -structure. Let A be an $L(F)$ -formula, where F is a new one-place predicate not in L . Let $B(x)$ be an $L(x)$ -formula, and let X be the extension of $B(x)$ in S . Then:

$$A(F \mapsto B) \text{ is true in } S \text{ iff } A \text{ is true in the expanded structure } S(F \mapsto X)$$

To put that another way,

$$\llbracket A(F \mapsto B) \rrbracket_S = \llbracket A \rrbracket_{S(F \mapsto \llbracket B \rrbracket_S)}$$

Proof

We can prove this by induction on formulas, using the recursive definition of substitution for predicates. The proof is long and tedious, but it's a good exercise for checking that we really understand how the definitions all work.

1. *Identity.* For L -terms a and b , by Definition 6.2.1

$$(a = b)(F \mapsto B) = a = b$$

TODO Finish this. □

6.2.3 Exercise

Fill in this missing steps of the proof of Lemma 6.2.2.

Notice that this same fact holds if A has free extra variables in it. We can put it like this.

6.2.4 Proposition

Let S be an L -structure. Let x be a variable and let \bar{y} be a sequence of variables.

Let A be an $L(F, \bar{y})$ -formula. Let $B(x)$ be an $L(x)$ -formula, and let

$$X = \llbracket B(x) \rrbracket_S$$

That is, X is the extension of $B(x)$ in S . Then the extension of $A(F \mapsto B)$ in S (in which we have replaced the predicate F with the formula $B(x)$ everywhere) is the same as the extension of A in $S(X)$. In short:

$$\llbracket A(F \mapsto B) \rrbracket_S = \llbracket A \rrbracket_{S(F \mapsto X)}$$

This follows from Lemma 6.2.2. Things look a little more complicated, because we have to do some extra variable-management, but it goes essentially the same way. For example, suppose A is an $L(F, y)$ -formula. Let S be any L structure, and let d be any object in its domain. Then let S' be the expanded $L(y)$ -structure $S(d)$. Then we can apply Lemma 6.2.2 to the signature $L(y)$:

$$A(F \mapsto B) \text{ is true in } S(d) \iff A \text{ is true in } S(d)(F \mapsto \llbracket B(x) \rrbracket_{S(d)})$$

Since $B(x)$ doesn't use the variable y , $\llbracket B(x) \rrbracket_{S(d)} = \llbracket B(x) \rrbracket_S$. So we can rewrite this:

$$A(F \mapsto B) \text{ true of } d \text{ in } S \iff A \text{ is true of } d \text{ in } S(F \mapsto \llbracket B(x) \rrbracket_S)$$

Now let's consider how all of this goes for function symbols.

TODO. Finish writing this up.

6.3 Recursive Definitions

In Section 6.1 we discussed *explicit* definitions. But we have also extensively used a different kind of definition in this book. For example, consider the set of terms in the language of arithmetic. We defined this set of strings *recursively*, using the following four rules:

$$\begin{array}{c} \text{---} \\ \textcolor{green}{0} \text{ is a term} \end{array} \qquad \begin{array}{c} t \text{ is a term} \\ \text{---} \\ \textcolor{orange}{suc} \ t \text{ is a term} \end{array}$$

$$\begin{array}{c} t_1 \text{ is a term} \qquad t_2 \text{ is a term} \\ \text{---} \\ (t_1 \textcolor{orange}{+} t_2) \text{ is a term} \end{array} \qquad \begin{array}{c} t_1 \text{ is a term} \qquad t_2 \text{ is a term} \\ \text{---} \\ (t_1 \textcolor{brown}{\cdot} t_2) \text{ is a term} \end{array}$$

Every term in the language of arithmetic is the result of applying these rules some number of times. Each term can be built up step by step, where each step uses one of these rules to build up a more complicated string from earlier steps.

It turns out that *the language of strings* is powerful enough to capture recursive definitions like this. In fact, each recursive definition in the language of strings can be reduced to an equivalent *explicit* definition. This is what we will work through now—though, to keep from getting too bogged down in the details, we will set some of them aside in the starred section Section 6.4.

In particular, the *syntax* we have done in this book uses recursive definitions all over the place—terms, formulas, quotation, substitution. So an important upshot, which we will take up further in Section 6.6, is that syntax can be formalized in our simple language of strings.

Take the recursive definition of the terms in the language of arithmetic again. A term in this language is anything you can reach by applying the rules step by step, any finite number of times. So we can try to make this idea precise. For example, $(0 + (\text{suc } 0 + 0))$ is a term. We can show this by considering a list of terms:

```
0
suc 0
(suc 0 + 0)
(0 + (suc 0 + 0))
```

Each line in this sequence is derived by applying some rule from the recursive definition of terms, where if we need any “inputs” to the rule, we find them on earlier lines. We get $\mathbf{0}$ from the zero rule (which is a base case). Then we get $\mathbf{suc } \mathbf{0}$ by applying the **suc** rule to the previous line. Then we get $(\mathbf{suc } \mathbf{0} \mathbf{+ } \mathbf{0})$ by applying the **+** rule to both of these lines. Finally we get $(\mathbf{0} \mathbf{+ } (\mathbf{suc } \mathbf{0} \mathbf{+ } \mathbf{0}))$ by applying the **+** rule to lines 1 and 3.

Let’s call a sequence of strings like this a *derivation*. Intuitively, a derivation spells out the results of repeatedly applying the formation rules. Each element of the sequence is the result of applying one of the formation rules to earlier elements of the sequence.

6.3.1 Exercise

A sequence of strings (s_1, \dots, s_N) is a $L_{\mathbb{N}}$ -**derivation** (or just *derivation* for short) iff for each $k \leq N$, one of the following four conditions holds:

- $s_k = \mathbf{0}$,
- For some $i < k$, $s_k = \mathbf{suc } s_i$,
- For some $i < k$ and $j < k$, $s_k = (s_i \mathbf{+ } s_j)$, or
- For some $i < k$ and $j < k$, $s_k = (s_i \mathbf{- } s_j)$.

Show that for any string s , s is a term in the language of arithmetic iff s is an element of some derivation.

Hint. Each direction of the “iff” uses a different kind of induction. It may be helpful to use the following facts, which follow straightforwardly from the definition.

- (a) If s and t are derivations, then $s \oplus t$ is also a derivation.
- (b) Any initial subsequence of a derivation is also a derivation.

This means that in order to write down something equivalent to the recursive definition of terms in the language of arithmetic, it’s enough to come up with a formalized definition of a *derivation*. And this is something we can do in just the language of strings. We can do it by representing a derivation as one big string, instead of a sequence of smaller strings.

We can let an $L_{\mathbb{N}}$ -*derivation string* be the result of separating the strings in a derivation by newlines, and then joining them all together. (Notice that no term in the language of arithmetic uses any newline symbols itself.)

6.3.2 Exercise

- (a) The set of pairs (s, t) such that s is a complete line in the string t is definable in \mathbb{S} . (That is, either s appears at the beginning of t followed by a newline, s appears at the end of t immediately after a newline, or else s appears somewhere in the middle of t with a newline both before and after it.)
- (b) The set of pairs (s, t) such that s consists of the first n lines of t , for some n , is definable in \mathbb{S} .
- (c) The set of all $L_{\mathbb{N}}$ -derivation strings is definable in \mathbb{S} .
- (d) The set of terms in the language of arithmetic is definable in \mathbb{S} .

We can use the same idea to show that for *any* finite signature L , the set of all L -terms is definable. A particularly important case is the language of strings—we will come back to this in Section 6.6. We can also use the same idea for lots of other recursive definitions. First we define a notion of a *derivation* corresponding to the rules in the recursive definition, and then we can use $L_{\mathbb{S}}$ to define a set of derivation strings.

The way we used strings to represent derivations for terms is simple: just stick all the elements of a derivation sequence together as lines in one big string. That's good enough for terms, but it's not quite general enough for everything we need. The trouble is that we also will want to write down recursive definitions of sets of strings that are *allowed to contain newline symbols*. If we just stick these strings together, we'll end up with ambiguity—the same string would represent more than one different derivation, and this will mess up our definition.

Fortunately, we have already figured out a way to solve this problem, back in Section 4.1. The trick is to first replace each string in a sequence with its *quotation*—a term in the language of strings, which is guaranteed not to include any newlines. For example, the quotation of AB is `"A" ⊕ "B"`. The quotation of the multiline string

```
AB
C
```

is the string `"A" ⊕ "B" ⊕ new ⊕ "C"`—which does not contain any newlines. Then we can stick together all these *quoted* strings as lines in one big string.

To do it this way, though, first we need to check that the *quotation* function for strings is definable in \mathbb{S} . Our official definition of this function, back in Exercise 3.2.16, was *recursive*. So to keep from getting stuck in a loop here, we'll need

to come up with a way to redescribe quotation without any recursion—just in terms of the basic operations of joining together strings and comparing lengths. This bit of logic engineering involves a bit of hackery, and the details aren’t super important, so we’ll tuck them away in the starred section Section 6.4. For the moment, let’s take this point on faith.

6.3.3 Proposition

The function that takes each string s to its quotation $\langle s \rangle$ is definable in \mathbb{S} .

Proof

See Section 6.4. □

Now we can represent *any* sequence of strings with a single string: just take the sequence (s_1, \dots, s_n) to the string $\langle s_1 \rangle \oplus \text{new} \oplus \dots \oplus \text{new} \oplus \langle s_n \rangle \oplus \text{new}$. (The extra newline at the end will help keep our definitions uniform.) Use the notation $\langle (s_1, \dots, s_n) \rangle$ for this string representation. We just need to check a few things.

6.3.4 Exercise

- (a) For any sequences of strings s and t , $\langle s \oplus t \rangle = \langle s \rangle \oplus \langle t \rangle$. Joining together the strings that represent two sequences gives us the same thing as the string representation for joining the two sequences together.
- (b) The set of pairs of strings (s, t) such that s and t each represent sequences, and s represents an initial subsequence of the sequence represented by t , is definable in \mathbb{S} .
- (c) The set of pairs of strings (s, t) such that s is an element of the sequence represented by t is definable in \mathbb{S} . (Take Proposition 6.3.3 for granted.)

Now we can define all sorts of derivation sequences, for all sorts of recursive definitions.

6.3.5 Example

The set of *palindromes* is defined recursively as follows:

$$\overline{() \text{ is a palindrome}}$$

For each symbol $a \in \mathbb{A}$,

$$\overline{(a) \text{ is a palindrome}}$$

And for each symbol $a \in \mathbb{A}$,

$$\frac{s \text{ is a palindrome}}{(a) \oplus s \oplus (a) \text{ is a palindrome}}$$

Show that the set of palindromes is definable in \mathbb{S} .

Proof sketch

Let a *palindrome-derivation* be any sequence of strings (s_1, \dots, s_n) with the property that, for each $1 \leq k \leq n$, one of the following three cases holds:

- (i) $s_k = ()$;
- (ii) $s_k = (a)$ for some $a \in \mathbb{A}$;
- (iii) There is some $i < k$ such that $s_k = (a) \oplus s_i \oplus (b)$

We can check that a string is a palindrome iff it is an element of some palindrome-derivation. We can also show that the set of string representations for palindrome-derivations is definable in \mathbb{S} . [TODO. Add a bit more detail here.]

Consider a definitional expansion of \mathbb{S} where `DerivElem` is a two-place predicate that applies to just the ordered pairs (s, t) where t is a string representation for a palindrome-derivation that includes s as an element. The set of palindromes is the extension in this structure of the $L_{\mathbb{S}}(x)$ -formula

`Ǝy ElemDeriv(x, y)`

Moreover, anything definable in a definitional expansion of \mathbb{S} is definable in \mathbb{S} . \square

We can also extend these same ideas to capture recursive definitions of *functions*.

6.3.6 Example

Consider the function

$$f(s) = \langle \text{length } s \rangle \quad \text{for every } s \in \mathbb{S}$$

which takes each string to the numeral that stands for the length of s . For example:

$$\begin{aligned} f(\bullet) &= \text{suc } 0 \\ f(ABC) &= \text{suc suc suc } 0 \end{aligned}$$

Show that this function f is definable in \mathbb{S} .

Proof sketch

First, let's write down a recursive definition of this function.

$$\begin{aligned} f() &= 0 \\ f(s, a) &= \text{suc } f(s) \quad \text{for each } a \in \mathbb{A} \end{aligned}$$

Next, remember that what it takes for a function f to be definable is just for the set of all ordered pairs $(s, fs) \in \mathbb{S} \times \mathbb{S}$ to be definable. Call this set X . We can turn the recursive definition of the function f into a recursive definition of this set X . (This is similar to what we did in Section 2.3.)

$$\frac{}{(\(), \mathbf{\emptyset}) \in X} \quad \frac{(s, t) \in X}{((s, a), \mathbf{suc } t) \in X}$$

Let an f -derivation be a sequence of strings (s_1, \dots, s_N) in which each s_k is the string representation for some *ordered pair* of strings (x, y) which has one of the following two properties:

- (i) $x = ()$ and $y = \mathbf{\emptyset}$, or else
- (ii) There is some $i < k$ such that s_i is the string representation for an ordered pair (x', y') , and

$$\begin{aligned} x &= (x', a) \quad \text{for some symbol } a \in \mathbb{A}, \\ y &= \mathbf{suc } y' \end{aligned}$$

We can then check (using two simple inductive arguments) that for any strings x and y ,

$\text{len } x = y$ iff the string representation for the pair (x, y) is an element of some f -derivation.

Then all we need to do is translate this definition of f -derivation into the language of strings, in the same way as in Exercise 6.3.2. \square

In general, any property, relation, or function that has a *recursive* definition in terms of definable operations on strings can also be defined in the string structure \mathbb{S} . But the precise statement of this general claim, and its proof, is rather abstract. This is in the starred section Section 6.5. The main idea is that whenever we want to translate a recursive definition into the language of strings, we can always do it by defining the corresponding kind of derivation sequence.

Even though the basic language of strings is very simple—it just has basic symbols for the empty string, each length-one string, the “join” operation, and the “no longer than” relation—it turns out to be a pretty powerful tool for describing languages. It is powerful enough to define simple languages, like the terms of arithmetic, and basic operations on these terms. It is even powerful enough to define the language of strings itself! In Section 6.6 we will consider some important consequences of this idea.

6.4 Defining Quotation*

In Section 6.3, we skipped the proof that the *quotation label* function, which takes each string s to a term $\langle s \rangle$ in the language of strings that stands for it, is definable in \mathbb{S} . In this section we'll fill that in.

We have usually been writing out terms using unofficial shortcuts, like “infix” notation for \oplus , and dropping parentheses. For this part, though, we had better write out our official labels explicitly, since it's the *official* label function that we are trying to define. For example, the label function officially does this:

- The string \bullet has the label $\textcolor{brown}{\oplus}(\textcolor{brown}{"\bullet"}, \textcolor{brown}{""})$.
- The string ABC has the label $\textcolor{brown}{\oplus}(\textcolor{brown}{"A"}, \textcolor{brown}{\oplus}(\textcolor{brown}{"B"}, \textcolor{brown}{\oplus}(\textcolor{brown}{"C"}, \textcolor{brown}{""})))$.

Our original definition of this function was recursive. But looking at how it works, we can describe the pattern of what it does in a different way.

6.4.1 Exercise

For any string s , there are strings t_1, \dots, t_n and u such that the canonical label $\langle s \rangle$ has the form

$$t_1 \oplus \cdots \oplus t_n \oplus \textcolor{brown}{""} \oplus u$$

where

- (i) Each string t_i has the form $\textcolor{brown}{\oplus}(c_{-i}, \textcolor{brown}{")})$, where c_i is the constant in the language of strings that denotes the i th symbol in s , and
- (ii) u is the same length as s and contains only right parentheses $)$

Hint. This can be proved by induction, using the original recursive definition of the quotation function.

6.4.2 Exercise

Each symbol $a \in \mathbb{A}$ in the standard alphabet has a corresponding constant symbol c_a in the language of strings. Show that the relation

c is the constant for the symbol a

is definable in \mathbb{S} .

For example, this relation applies to each of the following pairs

("A",	A)
("B",	B)
(quo,	")
(lpa,	()
("",)()

Finally, we can use a hack. In the language of strings, all of the constants for single symbols have the same *length*: each of them is three symbols long. That means that each “chunk” t_i in the canonical label which corresponds to the i th symbol is exactly six symbols long. We can use this fact to “line up” each symbol with the relevant part of its string representation. In order to check if a string t is the canonical label for s , we just have to compare initial substrings of the string s with initial substrings of t which are *exactly six times as long*.

6.4.3 Exercise

The relation

s is exactly six times as long as t

is definable in \mathbb{S} .

6.4.4 Exercise

Let s be any string. Then the canonical label $\langle s \rangle$ is the unique string of the form $t \oplus \text{ " } \oplus u$ for some strings t and u such that

- (i) For each pair of an initial substring $s' \leq s$ and an initial substring $t' \leq t$ which is exactly six times as long as s' , for any symbol a , if $s' \oplus a$ is also an initial substring of s , and c is the constant that stands for a in the language of strings, then the string $t' \oplus (c ,$ is also an initial substring of t .
- (ii) u has the same length as s and contains only the symbol $)$

6.4.5 Exercise

The function that takes each string s to its quotation $\langle s \rangle$ is definable in \mathbb{S} .

6.5 Recursive Definitions, in General*

Let's consider how we can generalize the idea from Section 6.3 to other recursive definitions.

Suppose F is a set of operations on some set A . That is, each element $f \in F$ is a function from $A^n \rightarrow A$ for some n or other. Recall from Section 2.3 that there is a (unique) *F -recursively defined* set $X \subseteq A$, which is closed under all of the F operations and which has inductive property that corresponds to F . That inductive property tells us that we can show that *every* element of X has a certain property by showing

6.5.1 Definition

Let F be a set of operations on a set A . An **F -derivation** is a sequence (x_1, \dots, x_N) such that for each number $k \leq N$, there is some n -place operation $f \in F$ and some numbers $i_1, \dots, i_n < k$ such that

$$x_k = f(x_{i_1}, \dots, x_{i_n})$$

6.5.2 Exercise

Check:

- (a) For any F -derivations s and t , the joined sequence $s \oplus t$ is also an F -derivation.
- (b) If s is an F -derivation, any initial subsequence of s is also an F -derivation.

6.5.3 Exercise

Let F be a set of operations on a set A . Let $X \subseteq A$ be the F -recursively defined subset of A . Then for each $a \in A$,

$$a \in X \text{ iff } a \text{ is an element of some } F\text{-derivation.}$$

6.5.4 Exercise

Let F be a set of operations on \mathbb{S} . Suppose that each operation $f \in F$ is definable in \mathbb{S} . Then the F -recursively defined set of strings X is also definable in \mathbb{S} .

This also shows that recursively defined *functions* are definable in \mathbb{S} (as long as each of its defining rules is definable), since each recursively defined function straightforwardly corresponds to a recursively defined set of ordered pairs.

6.6 Representing Language

‘You are sad,’ the Knight said in an anxious tone: ‘let me sing you a song to comfort you.

‘Is it very long?’ Alice asked, for she had heard a good deal of poetry that day.

‘It’s long,’ said the Knight, ‘but it’s very, very beautiful. Everybody that hears me sing it—either it brings the tears into their eyes, or else—’

‘Or else what?’ said Alice, for the Knight had made a sudden pause.

‘Or else it doesn’t, you know. The name of the song is called “*Haddocks’ Eyes*”.’

‘Oh, that’s the name of the song, is it?’ Alice said, trying to feel interested.

‘No, you don’t understand,’ the Knight said, looking a little vexed. ‘That’s what the name is *called*. The name really *is* “*The Aged Aged Man*”.’

Lewis Carroll, *Through the Looking Glass* (1871)

We use language to represent the world. But language is also *part* of the world, and it is one of the things that we talk about. We don’t just use words to talk about other things; we can also use words to talk about words themselves.

We have been doing this a lot: as we have been building up little formal languages, we have talked about them a lot, using ordinary English. But these little formal languages can *also* talk about language. We can look at formal languages which include names for sentences, and which include sentences that say things about names, and so on. This means we can use these formal languages as a model of what we ourselves have been doing all along, as logicians. We can turn the tools of logic onto logic itself.

In fact, we have already been working with a theory with these capabilities since early on. We represent terms and formulas of formal languages as strings of symbols. These are all elements of the domain of \mathbb{S} , the standard string structure. So the string structure \mathbb{S} and the first-order language of strings are good tools for a *formalized theory of syntax*. The language of strings is a formal language that can describe formal languages.

Here are some important facts:

6.6.1 Proposition

Let L be a finite signature. The following sets are definable in \mathbb{S} .

- (a) The set of L -terms.
- (b) The set of L -formulas.

Each of these sets has a recursive definition. So showing that they are definable is tedious, but not difficult, using the same strategy for translating recursive definitions into the language of strings that we discussed in Section 6.3 and Section 6.5. The same goes for the following recursively defined syntactic operation.

6.6.2 Proposition

Let L be a finite signature. The **substitution function** is the two-place function that takes an L -formula $A(x)$ and a closed L -term b to the L -sentence $A(b)$. The substitution function is definable in \mathbb{S} . That is to say, there is a definitional extension of \mathbb{S} that includes a two-place function symbol **sub** such that

$$\llbracket \mathbf{sub}(x, y) \rrbracket_{\mathbb{S}}(A(x), b) = A(b)$$

for each L -formula $A(x)$ and L -term b . (Remember, formulas and terms are *strings*—so $A(x)$, b , and $A(b)$ are each elements of the domain of the string structure \mathbb{S} .)

6.6.3 Exercise

Without going through all the details, explain why Proposition 6.6.2 is true. Consider Example 6.3.6 as a model, and refer to the recursive definitions of substitution for terms and formulas (Definition 3.5.4 and Definition 5.1.7).

In fact, Proposition 6.6.2 follows from an even more general fact about the expressive power of the string language. It turns out that *any* operation on strings which can be systematically worked out step by step is definable in \mathbb{S} . (This is called the Definability Theorem, Exercise 7.7.5.) Since the substitution function is systematic in this way, the fact that it is definable in \mathbb{S} will follow as one particular application of this general result.

As we have discussed, each string s has a *quotation label*, a term in the language of strings that denotes s , which we call $\langle s \rangle$ (see Section 4.2 and Section 6.3). Since formulas and terms are strings of symbols, they have canonical labels in the language of strings. If A is any L -formula, $\langle A \rangle$ is a term in the language of strings that denotes A (in the string structure \mathbb{S}). Similarly, if t is an L -term, then $\langle t \rangle$ is a term in the language of strings that denotes the string representation for a .

We can describe the syntax of any language L that has finitely many primitive symbols in the first-order theory of the string structure \mathbb{S} . In particular, then, we can apply all of these ideas to the language of strings itself. This language only has finitely many primitives (\oplus , \sqsubseteq , ``'' , and one constant for each symbol in the standard alphabet \mathbb{A} , which is finite). Thus the language of strings is a language that can describe itself. The string language has terms that denote the very strings of symbols that we use to write that language down. In the language of strings, for each formula A , there is a *quotation term* $\langle A \rangle$ that denotes A .

6.6.4 Example

Consider the formula $x = x$. The quotation term for this string, $\langle x=x \rangle$, is

$\text{``x''} \oplus \text{``=''} \oplus \text{``x''} \oplus \text{``''''}$

Or in officially spelled out notation:

$\oplus(\text{``x''}, \oplus(\text{``=''}, \oplus(\text{``x''}, \text{``''''})))$

6.6.5 Notation

In what follows, when I'm talking about quotation labels, I'll sometimes hide extra brackets. Things like $A(\langle s \rangle)$ look ugly, so I'll instead write this as $A\langle s \rangle$. Similarly, instead of $A(\langle s_1 \rangle, \langle s_2 \rangle)$ I'll usually write the simplified version $A\langle s_1 \rangle\langle s_2 \rangle$.

6.6.6 Exercise

Use the definition of the quotation function $\langle \cdot \rangle$ to explicitly write out each of the following expressions.

- $\langle \neg \forall x \ x = 0 \rangle$, which is the quotation of the formula $\neg \forall x \ x = 0$ (in the language of arithmetic).
- $\langle \langle () \rangle \rangle$, which is the canonical label of the *canonical label* of the empty string.
- $A\langle A(x) \rangle$, where $A(x)$ is the formula $x = x$.

Since we began talking about strings, it's been important for us to be careful about the difference between *use* and *mention*: when we are using some symbols to say something, and when we want to talk about those symbols themselves. We've used notation like `We've used notation like` to mark this distinction. Now, though, we need to be extra careful, because the formal language we are talking about—the language of strings—can *also* talk about language. *Within* this “object language” there is also a distinction between use and mention: between ways formulas and

terms come up as part of the language, and ways formulas and terms come up as part of what this language is understood as being *about*.

For example, for any formula A , this sentence is true in \mathbb{S} :

$$\langle A \rangle \oplus \text{""} = \langle A \rangle$$

This says, intuitively, that joining the empty string to the formula A gives you back the same formula A . But *this* isn't even a well-formed sentence:

$$A \oplus \text{""} = A$$

This sticks a *formula* A in a spot where a term should be, and the result is gibberish.

For another example, let's examine these first-order sentences.

$$\begin{aligned} \forall x \ (x \oplus \text{""} &= x) \\ \forall x \ (x \oplus \langle () \rangle &x) \\ \forall x \ (x \oplus \langle \text{""} \rangle &= x) \end{aligned}$$

The first sentence is true (in \mathbb{S}): it says that appending the empty string to the end of any string gives you the same thing back (a generalization of the fact above). The second sentence is, in fact, the very same sentence as the first. Since $\langle () \rangle$, the label for the empty string, is "" , this notation just means to stick the string "" in the middle of the string. The third sentence, in contrast, is false (in \mathbb{S}). Intuitively, it says that appending the *quotation label* for the empty string—the length-two string $\text{""}\text{"}$ —to any string gives you the same thing back. If we unpack it, what the third sentence says is

$$\forall x (x \oplus (\text{quo} \oplus \text{quo} \oplus \text{""}) = x)$$

This is false in \mathbb{S} : for example, the string $\text{ABC}\text{""}$ is not the same as the string ABC . This kind of issue can be subtle, and it's important to get the hang of these distinctions.

For any formula A , its label $\langle A \rangle$ is some complex term. We can use this term $\langle A \rangle$ just like any other term to build up other formulas, such as this one:

$$\exists x \ (x \lhd \langle A \rangle \ \& \ \neg(\langle A \rangle \lhd x))$$

(“Some string is strictly shorter than the formula A ”). We can also substitute $\langle A \rangle$ into another formula $B(x)$, just like any other term, to get a formula $B\langle A \rangle$. For example, suppose $B(x)$ is the formula $x = x$, and A is the sentence $\text{0} = \text{0}$. Then the substitution instance $B\langle A \rangle$ is $\langle A \rangle = \langle A \rangle$. Since $\langle A \rangle$ is the term

"0" ⊕ "≡" ⊕ "0" ⊕ ""

the fully spelled out sentence $B\langle A \rangle$ is this monstrosity:

"0" ⊕ "≡" ⊕ "0" ⊕ "" = "0" ⊕ "≡" ⊕ "0" ⊕ ""

(As usual, to simplify the notation, I'm leaving out some redundant parentheses, and using infix notation.)

We can even plug formulas into *themselves*. If $A(x)$ is a formula of one variable, we can substitute the quotation term $\langle A(x) \rangle$ into the formula $A(x)$, to get the formula $A\langle A(x) \rangle$. Here's how this would work in English, rather than our formal language. Say $A(x)$ is the English formula of one variable x is great, and $\langle A(x) \rangle$ is its quotation-name "x is great". Then the substitution instance $A\langle A(x) \rangle$ is the sentence

"x is great" is great

This is a sentence that says that a certain English formula is great.

This provides us with more examples of syntactic operations which are definable in \mathbb{S} . In Proposition 6.3.3 we showed that the *quotation* function is definable in \mathbb{S} : that is, there is a definitional extension of \mathbb{S} that adds a one-place function symbol *quote* such that

$$\llbracket \text{quote} \rrbracket_{\mathbb{S}} s = \langle s \rangle$$

for every string $s \in \mathbb{S}$. Equivalently, for each string s , the following sentence is true in \mathbb{S} :

$$\text{quote}(s) = \langle \langle s \rangle \rangle$$

In particular, this holds when the string s happens to be a *formula*.

6.6.7 Exercise

Let the **self-application function** (also called **diagonalization**) be the function that takes any formula of one variable $A(x)$ to the sentence $A\langle A(x) \rangle$, which results from plugging the label for $A(x)$ into $A(x)$ itself. Show that the self-application function is definable in \mathbb{S} .

In other words, show that there is some formula $F(x, y)$ in the language of strings (or in a definitional extension) such that, for each formula $A(x)$, and any string $s \in \mathbb{S}$,

$$F(x, y) \text{ is true of } (A(x), s) \text{ in } \mathbb{S} \text{ iff } s = A\langle A(x) \rangle.$$

Hint. Use Proposition 6.6.2 and Proposition 6.3.3.

We now have a systematic way, within the very simple language of strings, to describe syntax. This is a simple *formalization* of the thing we have been doing all along through this text: using language to describe the structure of language itself. Next we will explore some consequences.

6.7 Self-Reference and Paradox

Remember our old friend the *Liar sentence*, the sentence L which says L is not true. Is L true? If L is true, then since what L says is that L is not true, it should follow that L is not true. That's a contradiction, so it must be that L is not true. But again, since what L says is that L is not true, and L is not true, it should follow that L is true. That's a contradiction. Moreover, we derived that contradiction just using the following principles:

- There is a sentence $L = L$ is not true
- L is not true is true iff L is not true.

The second principle is an instance of a more general schema. Here is another famous instance:

- Snow is white is true iff snow is white.

On the left hand side we are *mentioning* a certain sentence. On the right hand side we are *using* that very sentence to say something about snow, rather than saying something about a sentence. In general, for any sentence A , if $\langle A \rangle$ is a label for A , then we can assemble a sentence with this form:

$\langle A \rangle$ is true iff A

The left hand side of the biconditional uses a label for a sentence, and the right hand side uses that very sentence. Sentences like this are called instances of the **T Schema**.

For a long time, many people assumed that the problem of the Liar Paradox arose because there was something defective about “self-referential” sentences like L . In English we can say things like this very sentence, or what I am saying right now. The trick, many people thought, was to just avoid saying things like this, at least whenever we were speaking “seriously”, like in mathematics. In proper official languages, there just shouldn't be any sentence like $L = L$ is not true. Sentences shouldn't be allowed to mention themselves.

But it turns out that this natural idea won't work: in an important sense, *self-reference is inevitable*. This follows from **Gödel's Fixed Point Theorem** (which is also known as the *Diagonal Lemma*). One caveat: what the theorem really shows is not *exactly* that there is a sentence which mentions itself, but rather that there is a sentence which is *equivalent* to one that mentions it. But this is plenty to raise the interesting problems.

Let's start with a warm-up. As we discussed back in Section 1.5, there is a paradox called "Grelling's Paradox" which is very similar to the Liar Paradox, but doesn't involve any self-reference. Instead of self-reference, we can use *self-application*. Now we have some logical resources that will help us make this idea precise.

Let $H(x)$ be the English formula `the self-application of x is not true`. And let G be the self-application of $H(x)$, that is, $H(H(x))$. Spelled out:

`The self-application of "The self-application of x is not true"
is not true`

Is G true? If G is true, then this seems to say that the self-application of $H(x)$ is not true. But that's what G is! So if G is true, then G is not true. So G must not be true. But *this* seems to say that the self-application of $H(x)$ is true—and thus G is true after all. And so we have a contradiction.

Now we can use the first-order language of strings to formalize Grelling's paradox. As we discussed in the previous section, we can *self-apply* a formula of one variable $A(x)$ to get a sentence $A(A(x))$. This self-application function is standardly called **diagonalization**. This syntactic operation is *definable* in the string structure \mathbb{S} : that means we can definitionally extend the string structure \mathbb{S} to introduce a new function symbol **diag**, such that, for any $L_{\mathbb{S}}(x)$ formula $A(x)$,

$$\llbracket \text{diag} \rrbracket(A(x)) = A(A(x))$$

Call this definitionally expanded structure $\mathbb{S}(\text{diag})$.

Now, suppose that *truth* was definable in \mathbb{S} . That would mean we could definitionally extend \mathbb{S} with a *truth predicate* **True**, which would apply to just the true sentences (in \mathbb{S}). Using this predicate, we could then formalize the Grelling formula `x is not true of x` like this:

`¬True(diag(x))`

Intuitively, this formula says, "The result of applying x to itself is not true". It would be true of a string s iff it is *not* the case that s is a formula in the language of strings whose self-application is true.

This formula $\neg\text{True}(\text{diag}(x))$ is an expression in an *expanded* language, a definitional extension of the language of strings, adding **True** and **diag**. But since these were definable, we can eliminate them, and get back an extensionally equivalent formula in the original language of strings. Let's call this formula in the original language $H(x)$. Again, $H(x)$ is true (in \mathbb{S}) of each string s which is not a formula with a true self-application.

Now, just like in Grelling's paradox, we can ask again: what happens when we apply this formula $H(x)$ to itself? Consider the “diagonalized” sentence $H(H(x))$ —call it G . Since $H(x)$ has the same extension in \mathbb{S} as $\neg\text{True}(\text{diag}(x))$, it follows that G has the same truth-value as

$\neg\text{True}(\text{diag } \langle H(x) \rangle)$

But $\text{diag } \langle H(x) \rangle$ denotes the sentence $H(H(x))$, which is just G again! So (by the Substitution Lemma), this sentence is true (in the definitional extension of \mathbb{S}) iff the formula $\neg\text{True}(x)$ is true of G . But we also just said that G has the same truth-value as this sentence. Thus:

G is true iff $\neg\text{True}(x)$ is true of G

This self-application sentence G is just as bad as the self-referential Liar sentence L . In fact, if **True** really does apply to just the true sentences, then our conclusion is contradictory. So our original supposition must have been false: there must *not* be any way of defining this new predicate **True**.

We just showed that the tricky sentence G is a “fixed point” of the formula $\neg\text{True}(x)$. Intuitively, we can think of $\neg\text{True}(x)$ as denoting a function from strings to truth-values. This function maps G to the same truth-value as G itself has. But most of the reasoning we just went through—all of it except the very last step—didn't depend on anything special about *truth*. We can use the very same ideas to prove a more general, quite beautiful theorem.

6.7.1 Exercise (Gödel's Fixed Point Theorem, aka the Diagonal Lemma, Version 1)

Let $F(x)$ be any formula in the language of strings.

- (a) There is some first-order sentence G in the language of strings with **diag** added such that

G is true in $\mathbb{S}(\text{diag})$ iff $F(x)$ is true of G in $\mathbb{S}(\text{diag})$

Hint. Work through the same reasoning as above, generalizing from the

specific formula $\neg\text{True}(x)$ to an arbitrary formula $F(x)$.

- (b) The same goes for the unexpanded language of strings. That is, there is a first-order sentence G in the language of strings with diag added such that

$$G \text{ is true in } \mathbb{S} \quad \text{iff} \quad F(x) \text{ is true of } G \text{ in } \mathbb{S}$$

Hint. Remember that any formula in the language of a definitionally expanded structure can be translated back to an equivalent formula in the original language—Proposition 6.1.15.

6.7.2 Exercise (Tarski's Theorem Version 1)

Use Exercise 6.7.1 to show that the set of sentences which are true in the standard string structure \mathbb{S} is not definable in \mathbb{S} .

In short, *truth is undefinable*. The property of being a true sentence in the string structure is not expressible by any first-order formula in the language of strings.

These are our first, preliminary versions of Gödel's Fixed Point Theorem and Tarski's Theorem. Next we'll generalize these ideas, and consider their implications.

6.8 Definitions in a Theory

Consider again our definition of *even* from Section 6.1:

$$\forall x (\text{Even}(x) \leftrightarrow \exists y y + y = x)$$

When we define a new predicate like *Even*, this expands our language. We get a new meaningful word. It also gives us a new truth—the definition statement. But this statement isn't just *true*—it's also something we *know*. This definition is a new principle that we can legitimately use in our proofs, just like *axioms*. We can assert this sentence, with the justification of just “by definition.”

Now we're going to formalize this aspect of our practice of introducing definitions. The simple formal model of *proving* things that we have right now is just the notion of logical consequence, and specifically the notion of a *theory*—the set of logical consequences of some axioms. (In Chapter 8 we'll introduce a finer-grained model of proofs.)

First, recall this definition from Section 6.1.

6.8.1 Definition

Let L be a signature, let $A(x)$ be any $L(x)$ -formula, and let F be a new predicate,

not in L . A **definition** of F by $A(x)$ is the following sentence:

$$\forall x \ (F(x) \leftrightarrow A(x))$$

We also had a similar definition of a definition of a *function*. For example, in Section 6.1 we defined a function symbol `pred`:

$$\forall x \forall y \ (\text{pred } x = y \leftrightarrow \text{suc } y = x \vee (x = 0 \ \& \ y = 0))$$

For this to work, we needed the relation described on the right-hand side of the definition to be *functional*. That is, we required that this is true:

$$\forall x \exists !y \ (\text{suc } y = x \vee (x = 0 \ \& \ y = 0))$$

But really, for the function definition to be justified, in the context of giving a proof, it's not enough that the functionality claim be *true*—it must first be *proven*. It should be a *theorem*.

6.8.2 Definition

Let L be a signature, let $A(x, y)$ be any $L(x, y)$ -formula, and let f be a new function symbol not in L . Let T be an L -theory, and suppose the “functionality sentence”

$$\forall x \exists !y \ A(x, y)$$

is a theorem of T . In this case, the following sentence is a **definition** of f by $A(x, y)$ in the context of the theory T :

$$\forall x \forall y \ (f(x) = y \leftrightarrow A(x, y))$$

Things go similarly for a definition of an n -place function symbol by a formula of $n + 1$ variables.

6.8.3 Definition

If T is an L -theory, we call a theory T^+ a **definitional extension** of T iff it consists of the set of all logical consequences of $T \cup X$, where each sentence in X is a definition.

(These definitions must each be of distinct predicates or function symbols—defining the same symbol twice is not allowed).

This notion of a definitional extension of a *theory* is closely related to our notion of a definitional expansion of a *structure*.

6.8.4 Exercise

If T^+ is a definitional extension of T , then any model of T has a definitional expansion which is a model of T^+ .

Hint. It's enough to show that this is true when a single definition of a predicate or function symbol is added. To do this, it will be useful to recall Exercise 6.1.14.

This lets us prove some important fact about definitions. In Section 6.1, we pointed out that definitions don't increase the expressive power of a language: if S^+ is a definitional extension of S , then any formula in the expanded language has the same extension in S^+ as some formula in the original language—its *translation*. Something analogous holds for adding definitions to *theories*.

6.8.5 Exercise

Let L be a signature, let T be an L -theory, and let T^+ be an L^+ -theory which definitionally extends T . For every L^+ -formula A , its translation A^* (in the original language L) is equivalent to A in T^+ . That is,

$$A \equiv_{T^+} A^*$$

Hint. Use Exercise 6.8.4 and Proposition 6.1.15.

There is also another way in which definitions are “tame”. Just as they don't really increase the *expressive* power of our language, they also don't really increase our power to *prove* things. In particular, if we can use our new definitions get a theorem that we can state in our *old* language, then that sentence was already a theorem of the original theory without those definitions.

6.8.6 Exercise

Let L be a signature, and let L^+ be an expansion of L . Let T^+ be a definitional extension of T . Then for every L -sentence A (in the smaller language), A is a theorem of T^+ iff A is a theorem of T . In this case, we say that T^+ **conservatively extends** T .

In particular, for any L -formulas A and B (in the original language),

$$\text{If } A \equiv_{T^+} B \text{ then } A \equiv_T B$$

6.9 Theories of Syntax

Definability in a *structure* effectively lets us use all of the truths in that structure to pin down facts about particular sets and functions. Definability in a *theory* just lets us use *some* of the facts—the axioms and their logical consequences. One reason this is important is that picking out all of the truths in a structure can be very difficult in practice, while picking out just a few useful truths is much easier.

Here's an example. We've been focusing mainly on definability in the string structure \mathbb{S} . As we'll see in Section 7.7, there is a sense in which the true statements in this structure are intractably complicated. But it turns out that we can still do a lot with a lot less. We can consider some simple axioms that don't pick out all of the truths about sequences, but do pick out enough of them for many purposes. For instance, there are still enough facts there to describe operations on numbers, sequences, and syntax. Not only can the full *structure* \mathbb{S} define these operations, but there is a much simpler *theory* of strings that can represent these operations. We introduced this theory in Section 5.4: *minimal theory of strings S* (Definition 5.4.3). This is a finitely axiomatized theory that includes some important basic facts about how strings are put together.

Consider a simple example. The set of all non-empty strings is definable in \mathbb{S} , using this formula:

$$x \neq \text{""}$$

This formula is true of each non-empty string, and false of the empty string. Here is another way of saying that. We can also restate this using quotation terms. Since the quotation $\langle s \rangle$ denotes s in \mathbb{S} , it follows that for each non-empty string s , the sentence

$$\langle s \rangle \neq \text{""}$$

is true in \mathbb{S} . Likewise, if s is empty, then

$$\langle s \rangle \neq \text{""}$$

is false in \mathbb{S} .

But we don't need all the truths about \mathbb{S} to get these simple facts. In fact, the fact that $\langle s \rangle \neq \text{""}$ is true if s is non-empty, and false otherwise, follows from some very basic facts about strings. Each of these things is in fact a theorem of the minimal theory of strings S . For this example, we just need to recall that S includes an axiom of this form,

$$\forall x \forall y (\text{Sym}(x) \rightarrow x \oplus y \neq "")$$

where $\text{Sym}(x)$ is an abbreviation for the long formula

$$x = "A" \vee x = "B" \vee \dots$$

which lists out all of the constants for one-symbol strings. In particular, for each symbol $a \in \mathbb{A}$, if c_a is its corresponding constant, we have a theorem of S of the form

$$\forall y (c_a \oplus y \neq "")$$

6.9.1 Example

Let $A(x)$ be the formula $x \neq ""$. For each string s ,

if s is non-empty, $S \models A(s)$
 otherwise, $S \models \neg A(s)$

Proof

Let s be any string. For the first part, suppose s is non-empty. In that case, $s = \text{cons}(a, t)$ for some string t and some symbol $a \in \mathbb{A}$ in the standard alphabet. So $\langle s \rangle$ is the term $c_a \oplus \langle t \rangle$, where c_a is the constant for the symbol a . So $A(s)$ is the formula

$$c_a \oplus \langle t \rangle \neq ""$$

This immediately follows by universal instantiation from the theorem of S :

$$\forall y (c_a \oplus y \neq "")$$

For the second part, suppose s is empty. In this case the label $\langle s \rangle$ is the term $" "$. So $\neg A(s)$ is the formula $\neg (" " \neq "")$, which is a logical truth—and thus of course it is a logical consequence of S . \square

The formula $x \neq ""$ applies to the right things to define the set of non-empty strings—and this fact is something that the minimal theory of strings S “knows”, using quotation terms. Let’s generalize this idea.

6.9.2 Definition

Let T be a theory, either in the language of strings, or in some expansion of that language.

- (a) Let X be a set of strings, and let $A(x)$ be a formula of one variable. Then T **represents** X iff there is some formula $A(x)$ such that, for each string $s \in \mathbb{S}$,

$$\begin{aligned} \text{If } s \in X &\text{ then } T \models A(s) \\ \text{If } s \notin X &\text{ then } T \models \neg A(s) \end{aligned}$$

- (b) Let f be a partial function from strings to strings. (That is, $f : X \rightarrow \mathbb{S}$ for some set of strings $X \subseteq \mathbb{S}$.) Then T **represents** f iff T has some definitional extension T^+ with a new function symbol g such that, for each string $s \in X$ in the domain of f ,

$$T^+ \models g(s) = \langle f(s) \rangle$$

To put that another way, this means that there is some formula $A(x, y)$ such that

$$T \models \forall x \exists ! y A(x, y)$$

and, for each string $s \in X$,

$$T \models A(s) \langle f(s) \rangle$$

Things go similarly for sets of n -tuples and n -place functions.

6.9.3 Exercise

- (a) If X is any set of strings, then X is definable in \mathbb{S} iff $\text{Th } \mathbb{S}$ represents X .
- (b) If f is any function from strings to strings, then f is definable in \mathbb{S} iff $\text{Th } \mathbb{S}$ represents X .

6.9.4 Example

Consider the function that appends a stroke to the beginning of a string:

$$\text{delimit } x = | \oplus x$$

This function is representable in the minimal theory of strings \mathbb{S} . We can extend \mathbb{S} with a function symbol `delimit` with this definition:

$$\forall x \forall y (\text{delimit } x = y \leftrightarrow " | " \odot x = y)$$

Equivalently, and more succinctly:

$$\forall x \text{ (} \text{delimit } x = " | " \oplus x \text{)}$$

To justify this, we have to check that \mathbb{S} includes the existence and uniqueness claim:

$$\forall x \exists ! y \text{ (} " | " \oplus x = y \text{)}$$

In fact, this is a logical truth.

Now what we need to show is, for any string s , we have this as a theorem of \mathbb{S} :

$$" | " \oplus \langle s \rangle = \langle | \oplus s \rangle$$

In fact, the right-hand side $\langle | \oplus s \rangle$ is defined to be $" | " \oplus \langle s \rangle$ (because $" | "$ is the constant for the symbol $|$). So in fact this identity sentence is a logical truth of the form $(a = a)$. So of course it is a logical consequence of the axioms of \mathbb{S} .

6.9.5 Exercise

Let X and Y be sets of strings, and suppose that T is a theory that represents each of X and Y . Then T also represents the following sets:

- (a) The union $X \cup Y$.
- (b) The intersection $X \cap Y$.
- (c) The difference $X - Y$.

6.9.6 Exercise

Suppose a theory T' extends T : that is, the set of theorems of T is a subset of the set of theorems of T' . If T represents X , then T' represents X .

In Section 6.6, we discussed the fact that some important syntactic operations are definable in the standard string structure \mathbb{S} . The string structure can describe how to substitute terms into formulas, as well as the function that takes each string to its quotation label. As it turns out, the minimal theory of strings \mathbb{S} can do this, too. This theory includes enough information to *represent* these basic syntactic operations.

The reason this is true is that, as it turns out, the minimal theory of strings includes every truth-in- \mathbb{S} which is *syntactically simple enough*. Section 6.10 explains what this means in more detail, and walks through the details of how to prove it. The important upshot is that any set or function that is definable in \mathbb{S} using a *simple enough* expression can also be represented in the minimal theory of strings \mathbb{S} . (The officially stated version of this fact is Exercise 6.10.16.) And in fact, if we work

through the definitions of substitution and the label function, it is possible to do it in a way that only uses these simple-enough formulas. The minimal theory also includes enough formulas to define lots of other interesting operations, as we will discuss in Section 7.7.

For the moment, we will take the following facts on faith:

- (a) The substitution function, which takes a formula $A(x)$ and a term b to the sentence $A(b)$, is representable in S .
- (b) The quotation function, which takes a formula A to its quotation term $\langle A \rangle$, is representable in S .

Then this follows:

- (c) The *self-application* function (or *diagonalization*), which takes a formula $A(x)$ to the sentence $A\langle A(x) \rangle$, is representable in S .

It will be helpful later on to have concise way of referring to this important property of S . Let's restate it:

6.9.7 Definition

Let T be a theory in the language of strings (or an expansion of that language). We will say that T **represents syntax** iff it represents the self-application function $A(x) \mapsto A\langle A(x) \rangle$. In other words, T has a definitional extension T^+ with a function symbol **diag** such that, for any L -formula $A(x)$,

$$\text{diag}\langle A(x) \rangle \underset{T^+}{\equiv} \langle A\langle A(x) \rangle \rangle$$

So this is another way of stating the main fact that we are taking on faith, for now:

6.9.8 Theorem

The minimal theory of strings S represents syntax.

We haven't proved this yet, though in principle there's nothing stopping us. It's a matter of writing out the complicated formula $F(x, y)$ that defines self-application, and checking that S has two kinds of theorem. First, we need the "functionality" claim

$$\forall x \exists ! y F(x, y)$$

Second, for each formula $A(x)$, we need the theorem

$$F\langle A(x) \rangle \langle A\langle A(x) \rangle \rangle$$

This ensures that F really applies to each pair of a formula and its diagonalization. But rather than working through all of this now, we'll wait until we prove the more general Representability Theorem in Section 6.9.

Now we can prove some powerful generalizations of the theorems from Section 6.7. If T represents syntax, then let's go to a definitional extension T^+ with a function symbol **diag**, such that

$$\text{diag}\langle A(x) \rangle \underset{T^+}{\equiv} \langle A\langle A(x) \rangle \rangle$$

We can use diagonalization to come up with a “self-referential” sentence, basically the same way as before.

6.9.9 Exercise (Gödel's Fixed Point Theorem Version 2)

Suppose that T is a theory that represents syntax. Let $F(x)$ be any formula. Then there is some first-order sentence G such that

$$G \underset{T}{\equiv} F\langle G \rangle$$

Hint. Use the same strategy as in Exercise 6.7.1. You'll need to use Exercise 6.8.5 and Exercise 6.8.6 to get back from the extended language T^+ , which includes the **diag** function symbol, to the original language.

6.9.10 Exercise (Tarski's Theorem Version 2: The Liar Paradox)

Suppose T represents syntax. Let $\text{True}(x)$ be a formula, and suppose that for each sentence A ,

$$T \models \text{True}\langle A \rangle \leftrightarrow A$$

Then T is inconsistent.

Hint. Use Exercise 6.9.9 with the same idea from the Liar Paradox as in the proof of Exercise 6.7.2.

6.9.11 Exercise (Tarski's Theorem Version 3)

Suppose T represents syntax, and suppose furthermore that T represents the set of all theorems of T . Then T is inconsistent.

Hint. Use the Fixed Point Theorem and the Liar Paradox idea again. |

Notice that our earlier version of Tarski’s Theorem, the undefinability of truth-in-the-string-structure (Exercise 6.7.2), follows from this generalized version. We can let T be $\text{Th } \mathbb{S}$, the set of all sentences which are true in \mathbb{S} . This theory is consistent: it has \mathbb{S} as a model. It also represents syntax. So $\text{Th } \mathbb{S}$ must *not* be representable in $\text{Th } \mathbb{S}$, which means that $\text{Th } \mathbb{S}$ —which is the set of all truths in \mathbb{S} —is not definable in the string structure \mathbb{S} .

Before we move on, here’s one more “bonus” version of the Fixed Point Theorem. It allows you to more directly formalize statements like

$$L = L \text{ is not true}$$

in the language of strings. So we can get sentences that are *really* self-referential, instead of just *equivalent* to a sentence about it. The cost is that the sentence may not be in the same language as the original theory, but rather in a definitional extension of it.

6.9.12 Exercise (Gödel’s Fixed Point Theorem Version 3)

Suppose that T is a theory that represents syntax. Let $F(x)$ be any formula. Then T has a definitional extension T^+ that includes a term a such that

$$T^+ \models a = \langle F(a) \rangle$$

Hint. You can use the same formula $H(x)$ as before. This time, though, you want to use a *term* that represents the result of “diagonalizing” $H(x)$, instead of a sentence. |

Notice that Version 3 of the Fixed Point Theorem implies Version 2, as well. If you have a term a which is equivalent to $\langle F(a) \rangle$ in T , then $F(a)$ is equivalent to $F\langle F(a) \rangle$ in T . But the converse doesn’t hold: the sentence version does not imply the term version. You might think that if G is a fixed-point sentence, then $\langle G \rangle$ is a fixed-point term. But that doesn’t follow. Just because G is *equivalent* to $F\langle G \rangle$ in T —that is, $G \leftrightarrow F\langle G \rangle$ is a theorem of T —that doesn’t mean that the *identity* $\langle G \rangle = \langle F\langle G \rangle \rangle$ is a theorem of T . Different sentences can be logically equivalent to each other. So the term version of the Fixed Point Theorem is going a bit beyond the sentence version. In the original language, *without* the defined function symbol **diag**, you might not have a fixed point term, even if you do have a fixed point sentence.

TODO. Add some philosophical discussion about the relationship to the definition of truth in Section 5.2.

6.10 Representability in the Minimal Theory of Strings S^*

The full theory of strings ($\text{Th } \mathbb{S}$) is very complicated, and the minimal theory of strings (S) is relatively simple—it has just finitely many axioms. (In Chapter 7 and Chapter 8 we will be able to say more about the ways in which the minimal theory of strings is “simpler.”) Even so, it turns out that the minimal theory of strings can do a whole lot of what the full-fledged theory of strings can. It is expressively pretty powerful. So lots of interesting things that can be *defined* in the standard string structure can also be *represented* in the minimal theory of strings. This includes the syntactic operations that Gödel’s Fixed Point Theorem relies on—but that’s just one example. In this section we will examine how this works in general.

There are lots of truths about strings which are not theorems of the minimal theory of strings S . But as it turns out, the minimal theory of strings includes all of the truths about strings which are *syntactically simple enough*, in a sense that we will make precise. For example, S includes every truth about strings that can be expressed in a sentence (in the language of strings) without any *quantifiers*.

If a set of strings X is definable in the string structure \mathbb{S} , this means that there is a certain formula $A(x)$ which is true of each string which is in X , and false of each string which is not in X . Equivalently, $A\langle s \rangle$ is true in \mathbb{S} for each string $s \in X$, and $\neg A\langle s \rangle$ is true in \mathbb{S} for each string $s \notin X$. This means that if the formula $A(x)$ is *syntactically simple enough*, then these sentences are each theorems of the minimal theory of strings, as well. So this tells us that any set which is definable in the standard string structure *using a syntactically simple enough formula* is also representable in the minimal theory of strings. Something similar goes for representing functions, as well.

For now, the most important application of these facts is about representing syntax. The syntactic operations of substitution and labeling are definable in the standard string structure. But if we pay attention to how we do it, we can show that they are definable using *syntactically simple* formulas. (To use the technical term we will define later in this section, they are Σ_1 -definable.) This tells us the main fact we took on faith in Section 6.9: the minimal theory of strings represents syntax. In Section 7.7 there will be another very important application, which generalizes this. It turns out that *any* operation on strings that can be systematically computed step by step is representable in the minimal theory of strings.

How can we show that S includes all the “syntactically simple enough” truths about strings? Let’s start small. We’ll start by showing that the minimal theory S knows enough to “unpack” each closed term in the language of strings. Remember that

a term in this language is either $\text{“}a\text{”}$, a constant for some single symbol a , or else a term $t_1 \oplus t_2$ for some terms t_1 and t_2 . Remember also that each string s has a quotation $\langle s \rangle$. For example, the quotation of ABC is the term

$$\text{“}A\text{”} \oplus (\text{“}B\text{”} \oplus (\text{“}C\text{”} \oplus \text{“}\text{”}))$$

We can repeatedly apply the axioms of S to convert an arbitrary term to its quotation term. In particular, S has these axioms for joining strings:

$$\begin{aligned} \text{“}\text{”} \oplus x &= x \\ x \oplus \text{“}\text{”} &= x \\ (x \oplus y) \oplus z &= x \oplus (y \oplus z) \end{aligned}$$

We can apply these axioms to “normalize” the term $(\text{“}A\text{”} \oplus \text{“}\text{”}) \oplus \text{“}B\text{”}$. Using the last of these axioms, instantiating x with $\text{“}A\text{”}$, y with $\text{“}\text{”}$ and z with $\text{“}B\text{”}$):

$$(\text{“}A\text{”} \oplus \text{“}\text{”}) \oplus \text{“}B\text{”} = \text{“}A\text{”} \oplus (\text{“}\text{”} \oplus \text{“}B\text{”})$$

Then, since $\text{“}\text{”} \oplus \text{“}B\text{”} = \text{“}B\text{”}$ and $\text{“}B\text{”} \oplus \text{“}\text{”}$ follow from the first and second axioms, by Leibniz’s Law we have this as a theorem of S:

$$(\text{“}A\text{”} \oplus \text{“}\text{”}) \oplus \text{“}B\text{”} = \text{“}A\text{”} \oplus (\text{“}B\text{”} \oplus \text{“}\text{”})$$

The right-hand term is the canonical label for the string $\langle ABC \rangle$, which is the string denoted by the left-hand term.

6.10.1 Exercise

- (a) Let s_1 and s_2 be strings. Show by induction on the length of s_1 that

$$\langle s_1 \rangle \oplus \langle s_2 \rangle = \langle s_1 \oplus s_2 \rangle$$

is a theorem of S.

- (b) Let t be any term in the language of strings, and let $s = \llbracket t \rrbracket_S$ be the denotation of t in S. Show by induction on the structure of the term t that

$$t = \langle s \rangle$$

is a theorem of S.

- (c) Let t_1 and t_2 be any terms in the language of strings. If

$$t_1 = t_2$$

is true in \mathbb{S} , then it is a theorem of \mathbb{S} . |

We can also show similar things about *distinctness*. We have these axioms of \mathbb{S} (which correspond to the Injective Property for strings).

$$\begin{aligned} \text{Sym}(x) &\rightarrow x \oplus y \neq \text{""} \\ \text{Sym}(x_1) \rightarrow \text{Sym}(x_2) &\rightarrow x_1 \oplus y_1 = x_2 \oplus y_2 \rightarrow (x_1 = x_2 \ \& \ y_1 = y_2) \end{aligned}$$

And for each pair of *distinct* symbols $a_1 \neq a_2 \in \mathbb{A}$, we have an axiom for their corresponding constants c_1 and c_2 :

$$c_1 \neq c_2$$

We can use these axioms to show the following. It follows that \mathbb{S} has these theorems, for any distinct single-symbol constants c_1 and c_2 :

$$\begin{aligned} c_1 \oplus x &\neq \text{""} \\ c_1 \oplus x &\neq c_2 \oplus y \end{aligned}$$

6.10.2 Exercise

- (a) Show by induction that for any string s_1 , if s_2 is a distinct string from s_1 , then

$$\langle s_1 \rangle \neq \langle s_2 \rangle$$

is a theorem of \mathbb{S} .

- (b) Let t_1 and t_2 be any terms in the language of strings. If

$$t_1 \neq t_2$$

is true in \mathbb{S} , then it is a theorem of \mathbb{S} . |

We can do similar things with our other basic kind of formulas. The theory \mathbb{S} also has some axioms that say how the “no-longer-than” relation should work:

$$\begin{aligned} \text{""} &\leq x \\ x \leq \text{""} &\leftrightarrow x = \text{""} \\ \text{Sym}(x_1) \rightarrow \text{Sym}(x_2) &\rightarrow x_1 \oplus y_1 \leq x_2 \oplus y_2 \leftrightarrow y_1 \leq y_2 \end{aligned}$$

6.10.3 Exercise

Show by induction that for any strings s_1 and s_2 :

- (a) If s_1 is no longer than s_2 , then

$\langle s_1 \rangle \text{ } \textcolor{orange}{\leq} \text{ } \langle s_2 \rangle$

is a theorem of S .

- (b) If s_1 is longer than s_2 , then

 $\textcolor{blue}{\neg}(\langle s_1 \rangle \text{ } \textcolor{orange}{\leq} \text{ } \langle s_2 \rangle)$

is a theorem of S .

- (c) Let t_1 and t_2 be terms in the language of strings. If the sentence

 $t_1 \text{ } \textcolor{orange}{\leq} \text{ } t_2$

is true in \mathbb{S} , then it is a theorem of S . If it is false in \mathbb{S} , then

 $\textcolor{blue}{\neg}(t_1 \text{ } \textcolor{orange}{\leq} \text{ } t_2)$

is a theorem of S .

This shows that the minimal theory S “knows” the truth-value of every basic sentence in the language of strings, which is either an identity sentence or a “no-longer-than” sentence. Next we can extend this to slightly more complex sentences, which also use the propositional connectives $\textcolor{blue}{\neg}$ and $\textcolor{blue}{\&}$.

6.10.4 Exercise

Let A be any *quantifier-free* sentence in the language of strings: that is, A is built up using just identity sentences, relational sentences (using $\textcolor{orange}{\leq}$), negation, and conjunction. If A is true in \mathbb{S} , then $S \models A$, and if A is false in \mathbb{S} , then $S \models \textcolor{blue}{\neg}A$.

Hint. Use induction on formulas.

This means S knows the truth-value of every sentence in the first-order language of strings that doesn’t use any quantifiers. But we’ll need more than this—the formulas we used to define computable functions use quantifiers, too. It would be natural to try adding the quantifiers back in as well—but in fact, this won’t work. There are some sentences using quantifiers that are true in \mathbb{S} , but are not theorems of S . (We won’t prove this now, but it will turn out to be a consequence of Gödel’s First Incompleteness Theorem, Exercise 8.5.6.)

But not all sentences using quantifiers are out of reach. For example, consider this sentence:

$$\forall x \ (x \leq "••" \rightarrow (x \leq "A" \vee "BB" \leq x))$$

This uses a universal quantifier. But the quantifier is *restricted* to just the strings of length at most two. So, effectively, instead of quantifying over the infinite domain of all strings, this sentence only “cares about” those finitely many strings which are no longer than $\bullet\bullet$. It turns out that the minimal theory S can handle sentences like this just fine. The trick is that, since there are only finitely many different strings of length at most two, we can list them all out (though it’s a long finite list, because our alphabet is large):

$$s_1, s_2, \dots, s_n$$

Then, if we abbreviate the right-hand side $x \leq "A" \vee "BB" \leq x$ as $A(x)$, we can rewrite the quantified sentence as a long conjunction, like this:

$$A(s_1) \And A(s_2) \And \dots \And A(s_n)$$

The quantified sentence is true in \mathbb{S} if and only if this long conjunction is true in \mathbb{S} . Furthermore, we can show that \mathbb{S} “knows” this equivalence. And since the conjunction doesn’t have any quantifiers, we have already shown that \mathbb{S} knows its truth-value, too. Thus this particular quantified sentence is also a theorem of \mathbb{S} .

In general, we can use this idea to show that any sentence that uses only *bounded* quantifiers is still within the ken of the minimal theory \mathbb{S} .

6.10.5 Definition

Let t be a term, let A be a formula, and let x be a variable. Let

$$\forall x \leq t A$$

abbreviate the **bounded universal generalization**

$$\forall x \ (x \leq t) \rightarrow A$$

Similarly,

$$\exists x \leq t A$$

abbreviates the **bounded existential generalization**

$$\exists x \ x \leq t \And A$$

Call a formula in the language in the language of strings (without definite descriptions) **bounded** iff it is built up just using identity formulas, length formulas, conjunction, negation, and *bounded* universal quantification.²

²Other standard names for bounded formulas include Δ_0 -formulas, Σ_0 -formulas, and Π_0 -formulas.

Here is the final axiom of the minimal theory \mathbb{S} .

$$x = " \quad v \quad \exists y \exists z (\text{Sym}(y) \And x = y \oplus z)$$

We can use this, along with things we have already shown about what \mathbb{S} knows about the no-longer-than relation, to show the following.

6.10.6 Exercise

- (a) Let s be any string, and let s_1, \dots, s_n be *all* of the strings which are no longer than s . Prove by induction on s that

$$\forall x (x \leq \langle s \rangle \leftrightarrow (x = \langle s_1 \rangle \vee \dots \vee x = \langle s_n \rangle))$$

is a theorem of \mathbb{S} .

- (b) Let t be a term, and let $A(x)$ be a quantifier-free formula of one variable x . There is a quantifier-free formula B such that

$$B \leftrightarrow \forall(x \leq t) A(x)$$

is a theorem of \mathbb{S} .

6.10.7 Exercise

Let A be any bounded sentence. If A is true in \mathbb{S} , then $\mathbb{S} \models A$, and if A is false in \mathbb{S} , then $\mathbb{S} \models \neg A$.

Finally, we can go one step further, by adding some *unbounded* quantifiers. But this time we can't do quite as much. We can only add *existential* quantifiers, we can only do it once, and we only get half as strong a conclusion. So far, we have shown that \mathbb{S} knows the truth-value of every bounded sentence. But for the final step, we will only get one direction: for each of these slightly more complicated sentences, if it is *true*, then \mathbb{S} knows it is true—but if it is *false*, then \mathbb{S} might not know it. (That's why we can't use this result to keep building up to even *more* complicated sentences. We have reached a limit.)

6.10.8 Exercise

Suppose $A(x)$ is a bounded formula. If

$$\exists x A(x)$$

is true in \mathbb{S} , then it is a theorem of \mathbb{S} .

It's helpful to have a word for formulas which are slightly more complicated than

bounded formulas in this way.

6.10.9 Definition

A formula is Σ_1 (pronounced “sigma-one”) iff it has the form $\exists x \ A$, for some bounded formula A . That is, a Σ_1 formula is a bounded formula with an unrestricted existential quantifier in front.³

So in other words, what Exercise 6.10.8 tells us is that, if A is Σ_1 , and A is true in \mathbb{S} , then A is a theorem of S . But, to reiterate, in general if A is *false* in \mathbb{S} , we *don't* know that $\neg A$ is a theorem of S .

Intuitively, if there *is* an example of something that satisfies a bounded formula $B(x)$, then eventually S can find it, by plugging away through the structure of individual strings. But if there is *no* example of something that satisfies $B(x)$, then no matter how long you plug away finding consequences of S , you may never succeed in “proving the negative”.⁴

6.10.10 Exercise

Say a formula is Σ_1 -**equivalent** iff it has the same extension in \mathbb{S} as some Σ_1 -formula. If A and B are Σ_1 formulas, and t is a term, then the following are Σ_1 -equivalent formulas.

- (a) $A \vee B$
- (b) $A \wedge B$
- (c) $\exists x \ A$
- (d) $\forall x \ s \ t \ A$

³The Greek letter capital sigma is often used to represent existential quantification, and the subscript one indicates that we have just used existential quantification once.

The Greek letter capital pi Π is often used to represent universal quantification. So similarly, a Π_1 -formula is a bounded formula with an unbounded universal quantifier in front.

This is just the beginning of a hierarchy of more and more complex formulas. A Σ_2 -formula is what you get by adding an existential quantifier to a Π_1 formula. A Π_2 -formula is what you get by adding a universal quantifier to a Σ_1 -formula. And you can go on this way to recursively define Σ_n and Π_n formulas for every number n . Every formula is equivalent (in S) to something that shows up at some stage in this hierarchy. This gives us a useful general notion of a formula’s “quantificational complexity”.

⁴In Section 7.6 we will discuss a very closely analogous distinction, between *decidable* sets and *semi-decidable* sets. In a sense, the bounded sentences are “decidable in S ”, while the Σ_1 sentences are only “semi-decidable in S ”. (But this is an alternative sense of “decidable” and “semi-decidable” that has to do with *logical consequences*, rather than programs.)

6.10.11 Exercise

- (a) Let X be a set of strings which is definable in \mathbb{S} using a bounded formula. That is, there is a bounded formula $A(x)$ which is true of each string in X , and false of each string not in X (in the structure \mathbb{S}). Then $A(x)$ also represents X in \mathbb{S} .
- (b) Let X be a set of strings which is definable in \mathbb{S} using a Σ_1 -formula $A(x)$. Then $A(x)$ also represents X in \mathbb{S} “in one direction”. That is, for each string $s \in X$, $A(s)$ is a theorem of \mathbb{S} , and for each string $s \notin X$, $A(s)$ is not a theorem of \mathbb{S} .

(Similar facts hold for sets of n -tuples and formulas of n variables, but there is no need to show this separately.)

We'll also need to show some related things about representable *functions*, rather than sets.

6.10.12 Definition

Let f be a partial function from strings to strings. Say that f is **Σ_1 -definable** iff there is a Σ_1 formula $A(x, y)$ such that, for each string s in the domain of f , $f(s)$ is the unique string such that $A(x, y)$ is true of $(s, f(s))$ in \mathbb{S} .

The next bit involves a bit of tricky logic engineering. Let $f : \mathbb{S} \rightarrow \mathbb{S}$ be a function, and suppose there is a “functional” Σ_1 -formula $A(x, y)$ as in the definition: so for each string s , $f(s)$ is the unique string such that $A(x, y)$ is true of $(s, f(s))$. We want to show that \mathbb{S} represents f . The trouble is that we aren't guaranteed to be able to use the formula $A(x, y)$ as a *definition* in the context of \mathbb{S} . To do this, it isn't enough that the formula $A(x, y)$ is functional—the theory \mathbb{S} needs to “know” that it is functional, by including this theorem:

$$\forall x \exists !y A(x, y)$$

The problem is that this “functionalit” sentence is not Σ_1 —it involves two unrestricted universal quantifiers. So even if it is true in \mathbb{S} , there is no guarantee that it is a theorem of the minimal theory.

But there is a way to avoid this. The basic idea is that we can use a *different* formula as our definition—call it $B(x, y)$. This formula $B(x, y)$ will be extensionally equivalent to $A(x, y)$, but it will be written in a form that makes it more obvious that it has to be functional. It doesn't have to be Σ_1 : instead, we can choose $B(x, y)$

so that for every string s , we have

$$S \models A(s)\langle f(s) \rangle \rightarrow B(s)\langle f(s) \rangle$$

So if $A(x, y)$ is Σ_1 , that will be enough to get us all of the theorems we need: we can use $B(x, y)$ as our definition for f , and we will be able to prove each of the identities $f\langle s \rangle = \langle f(s) \rangle$ that we need.

Here is how to modify our formula. First we'll handle uniqueness, and then existence. The basic idea for uniqueness is that if t is the only string such that (s, t) satisfies $A(x, y)$, then t is also the *shortest* string such that (s, t) satisfies $A(x, y)$. Moreover, the axioms of S are enough to guarantee that there can be at most one *shortest* string with a certain property.

To show this, we'll need to use the last axiom of S :

$$x \leq y \vee y \leq x$$

6.10.13 Exercise

Let $A(x)$ be a formula, and let $B(x)$ be the formula

$$\forall(x' \leq x)(A(x') \leftrightarrow x = x')$$

Show that

$$\forall x \forall y ((B(x) \& B(y)) \rightarrow x = y)$$

is a theorem of S .

For the existence part, we can add on an extra “default” output value, which is the output in a case where otherwise there wouldn’t be any output.

6.10.14 Exercise

Let $A(x)$ be a formula, and let $B(x)$ be the formula

$$A(x) \vee (\neg \exists x A(x) \& x = \text{"Nothing"})$$

Show that

$$S \models \exists x B(x)$$

(In fact, this is a logical truth.)

Now we can put these two ideas together.

6.10.15 Exercise

Let $A(x, y)$ be a formula of two variables. Let $B(x, y)$ be the formula

$$\begin{aligned} \forall(y' \leq y) (\ A(x, y') &\leftrightarrow y = y') \\ \vee (\ \neg\exists y' \ A(x, y') &\& y' = \text{"Nothing"}) \end{aligned}$$

Show:

(a)

$$S \models \forall x \ \exists ! y \ B(x, y)$$

(b) If $A(x, y)$ is Σ_1 , then for any strings s and t ,

$$S \models A(s)(t) \rightarrow B(s)(t)$$

Now we can finally show what we wanted to show.

6.10.16 Exercise

If f is Σ_1 -definable, then f is representable in S .

Here's the key application of all of this. The substitution function is not just *definable* in the string structure S : in fact, it is Σ_1 -*definable*. The same goes for the labeling function. Thus by Exercise 6.10.16, these two functions are representable in the minimal theory of strings S . So the diagonalization function is also representable in S . That is, S represents syntax.

There will be a second important application in Section 7.7, which is much more general.

6.11 Syntax and Arithmetic

We have one central example of a theory that represents syntax: the minimal theory of strings S (though, again, we have deferred the proof of this until Chapter 7). But there are many other theories that will do the same job.

Recall what it means for a theory T to represent syntax: what we need is a definitional extension that includes a function symbol **diag** that represents the diagonalization function. To get this definitional extension, what we need is some formula $F(x, y)$ with two properties:

$$T \models \forall x \ \exists ! y \ F(x, y)$$

And for every formula $A(x)$,

$$T \models F(A(x))\langle A(A(x)) \rangle$$

That is, T “knows” that F is functional, and that F applies to each pair of a formula and its diagonalization.

It is clear, then, that if T represents syntax, then any theory that *extends* T will also represent syntax. If each of those sentences are theorems of T , then they are also theorems of any stronger theory. So, for example, the *complete* theory of strings $\text{Th } \mathbb{S}$ also represents syntax.

But what about theories in other languages, besides the language of strings? Many of these also represent syntax. To see this, note that it doesn’t matter whether the symbols ,,, , \oplus , and so on that appear in \mathbb{S} are really *primitive* symbols. You could replace each of them with some more complex term—indeed, with some complex term in another language. The result of doing this is called a *translation*. If a theory includes suitable *translations* of the sentences in \mathbb{S} , then in particular its language includes a translation of the formula $F(x, y)$ that defines diagonalization, and the theory also includes corresponding translations of each of the relevant theorems of \mathbb{S} . So a theory like this also represents syntax.

We’ll call a theory like this **sufficiently strong**: a sufficiently strong theory is one that includes some suitable translation of the minimal string theory \mathbb{S} . Thus any sufficiently strong theory represents syntax.

We can make this idea more precise using the idea of definitional extensions, again.

6.11.1 Definition

Let T_1 be an L_1 -theory, and let T_2 be an L_2 -theory. The theory T_1 **interprets** T_2 iff T_1 has a definitional extension that extends T_2

The idea here is that, within the theory T_1 , we can introduce definitions of all of the basic terms that appear in T_2 , and then we can use those definitions to prove all of the theorems in T_2 as well. (Notice that this also covers the case where T_1 simply adds to T_2 , since a theory is trivially a definitional extension of itself.)

6.11.2 Exercise

Let T_1 and T_2 be theories, and let T_2^+ be a definitional extension of T_2 .

- (a) Suppose $T_1 \supseteq T_2$. (That is, every theorem of T_1 is also a theorem of T_2 .) Then T_1 also has a definitional extension T_1^+ such that $T_1^+ \supseteq T_2^+$.

Hint. Notice that any definition in T_2 will also count as a definition in T_1 .

- (b) If T_1 interprets T_2 , then T_1 also interprets T_2^+ .

6.11.3 Definition

A theory T is **sufficiently strong** iff T interprets the minimal theory of strings S . That is, T has a definitional extension T^+ that extends S .

In that case, in particular, the language of T^+ includes each of the quotation labels for strings $\langle s \rangle$. If T is sufficiently strong, and X is a set of strings, we say that T **represents** X iff such a definitional extension T^+ represents X in the usual sense: there is some formula $A(x)$ in the expanded language such that $T^+ \models A\langle s \rangle$ for each string $s \in X$, and $T^+ \models \neg A\langle s \rangle$ for each string $s \notin X$. Likewise for sets of n -tuples and functions.

6.11.4 Exercise

If T is sufficiently strong, then T has a definitional extension that represents syntax. That is, T has a definitional extension T^+ in a language that includes all of the quotation labels in the language of strings, as well as a function symbol **diag** such that

$$\text{diag}\langle A(x) \rangle \equiv_{T^+} \langle A\langle A(x) \rangle \rangle$$

6.11.5 Exercise (Gödel's Fixed Point Theorem Version 4)

If T is a sufficiently strong theory in a language L , then for any $L(x)$ -formula $F(x)$, there is an L -sentence G such that

$$G \equiv_{T^+} F\langle G \rangle$$

Hint. By Exercise 6.11.4, T has a definitional extension T^+ that represents syntax. This is enough to tell us that $F(x)$ has a fixed point in the *expanded* language of T^+ . But to get a fixed point sentence in the original language L , we'll need to repeat the proof of Gödel's Fixed Point Theorem Version 2 (Exercise 6.9.9), slightly generalizing it.

6.11.6 Exercise

If T has an inconsistent definitional extension, then T is inconsistent.

6.11.7 Exercise (Tarski's Theorem Version 4)

If T is sufficiently strong, and T represents the set of theorems of T , then T is inconsistent.

Hint. Again, this doesn't quite follow directly from our earlier versions of Tarski's Theorem. But we can just repeat the proof of Tarski's Theorem Version 3, using our generalized Fixed Point Theorem.

Now let's turn to an especially important example of a sufficiently strong theory.

We've been using strings to represent syntax. But Gödel originally did something a bit different. Gödel was primarily interested in the foundations of mathematics, rather than the philosophy of language, and so he was especially interested in *arithmetic*. So Gödel came up with a way of describing syntax *in arithmetic*. This is called "the arithmetization of syntax"—or "Gödel numbering". We won't be making any extensive use of this, because arithmetic isn't really our central focus, but it's good to know about it, because this is a much more common way of presenting Gödel's and Tarski's results.

In Definition 5.4.2 we presented the *minimal theory of arithmetic* \mathbf{Q} , which is a very simple theory with just ten axioms. As it turns out:

6.11.8 Theorem

The minimal theory of arithmetic \mathbf{Q} is sufficiently strong.

The proof of this fact involves finding a way to uniquely represent *strings* and string operations using *numbers* and numerical operations. This involves some non-trivial number theory—in particular, some facts about prime factors and remainders. Since this isn't a number theory course, we won't go into these details. (You can find a sketch of the proof in CITE BBJ, Lemma 16.5.)

One thing to note, though, is that you really only need the fancy number theory if you insist on just using the primitive operations $(0, \text{suc}, +, \cdot)$. If you help yourself to other operations—such as *exponentiation*—then things get a lot easier. If you have that (and a few more axioms about how exponentiation works), then instead of Gödel's fancy encoding based on prime factors, you can use the same kind of *binary* encoding that computers use. The basic idea is to think of numbers as sequences of "bits" (one and zero, or "on" and "off"); then you can use those sequences to encode sequences of sequences of bits, and so on. The basic reason exponentiation helps with this is because the "join" operation for sequences of bits, that takes, say, 10110 and 110 to 10110110 , corresponds to the operation on *numbers* defined by $x \cdot 2^n + y$,

where n is the length of the binary representation of y . But calculating 2^n (for arbitrary n) uses exponents, and not just straightforward addition and multiplication.

6.11.9 Exercise

Using Theorem 6.11.8, show:

- \mathbb{Q} does not represent \mathbb{Q} .
- Any theory that interprets \mathbb{Q} is sufficiently strong. In particular, the theory of arithmetic $\text{Th } \mathbb{N}$ is sufficiently strong.
- $\text{Th } \mathbb{N}$ does not represent $\text{Th } \mathbb{N}$. Likewise, no definitional extension of $\text{Th } \mathbb{N}$ represents $\text{Th } \mathbb{N}$.

In a moment we'll derive one more important consequence, let's prove one more important fact about the relationship between definitional extensions of *structures* and definitional extensions of *theories*.

6.11.10 Proposition

If S^+ is a definitional extension of S , then $\text{Th } S^+$ is a definitional extension of $\text{Th } S$.

Proof

Each new symbol in the language of S^+ is definable in S . So each has a corresponding *definition*. Let T be the definitional extension of $\text{Th } S$ using these definitions. We can show that $T = \text{Th } S^+$. Let $A \in \text{Th } S^+$; that is, A is any sentence which is true in S^+ . Let A^* be its translation back to the original language of S , using these definitions, as in Section 6.2. We know two important things about this translation:

- A^* is extensionally equivalent to A in S^+ .

Thus, since A is true in S^+ , so is A^* . Since A^* is a sentence in the original language, it must also be true in the original structure S . So $A^* \in \text{Th } S$.

- A^* is logically equivalent to A given T .

In particular $T \vDash A^* \rightarrow A$. So $A \in T$.

For the other direction, note that if $A \notin \text{Th } S^+$, then $\neg A \in \text{Th } S^+$, and thus by the reasoning we just gave $\neg A \in T$. Since T is consistent (it is a conservative extension of a theory that has a model), $A \notin T$.

So $\text{Th } S^+ = T$, which is a definitional extension of $\text{Th } S$. □

It follows that if \mathbb{N}^+ is any definitional extension of the *structure* \mathbb{N} , then $\text{Th } \mathbb{N}^+$

does not represent $\text{Th } \mathbb{N}$.

Since the minimal theory of arithmetic Q interprets S , this means that Q^+ has a definitional extension of Q that extends S . We also have a standard *model* of arithmetic, \mathbb{N} , which in particular is a model of Q . So \mathbb{N} has a definitional extension \mathbb{N}^+ which is a model of Q^+ (Exercise 6.8.4). This adds the language of strings onto the language of arithmetic. In particular, it provides an interpretation of the quotation label $\langle s \rangle$ for each string s : each of these terms in the language of *strings* also denotes some *number*. We call this a **Gödel number** for the string.

6.11.11 Exercise (Tarski's Theorem Version 5)

For any definitional extension \mathbb{N}^+ of \mathbb{N} which is a model of S , we call the function that takes each string $s \in S$ to its denotation $\llbracket \langle s \rangle \rrbracket_{\mathbb{N}^+}$ a **Gödel numbering**.

We call a set of numbers **arithmetically definable** iff it is definable in \mathbb{N} .

For any Gödel numbering, the set of Gödel numbers of true first-order sentences of arithmetic is not arithmetically definable.

Hint. Show that if this set were definable in \mathbb{N} , then $\text{Th } \mathbb{N}^+$ would represent $\text{Th } \mathbb{N}$, and derive a contradiction.

Chapter 7

The Undecidable

But the science of operations ... is a science of itself, and has its own abstract truth and value; ... This science constitutes the language through which alone we can adequately express the great facts of the natural world, and those unceasing changes of mutual relationship which, visibly or invisibly, consciously or unconsciously to our immediate physical perceptions, are interminably going on in the agencies of the creation we live amidst.

Ada Lovelace, notes on *Sketch of The Analytical Engine Invented by Charles Babbage* (1842)

For some questions, there is a systematic procedure you can follow that will eventually bring you to an answer. For example, suppose you want to know whether a certain number n is prime. To answer this, you can try dividing n by each number less than it, one by one, and see if there is a remainder in each case. If you find a number $k < n$ such that dividing n by k leaves no remainder, then n is prime. Otherwise, n is not prime. What we have just described is an *algorithm* for answering the question of whether a number is prime. An algorithm is a list of instructions for how to find the answer to a question. If a question can be systematically answered somehow or other, then it is called **effectively decidable**.

We can also think about questions which have different sorts of answers. For instance, the question “What is the remainder when m is divided by n ? ” has a number as its answer. Many of us learned the long-division algorithm in elementary school, which provides a systematic way of answering any question of this form. A

family of questions like this, the answers to which can be arrived at systematically, is called **effectively computable**.

We can describe these “families of questions” as *functions*, whose values are answers to the question. The remainder function takes a pair of numbers (m, n) to the number which is the remainder when m is divided by n . Similarly, the question “Which numbers are prime?” can be represented by the function takes each number n to either True or False. Alternatively, using the correspondence between sets and two-valued functions from Exercise 1.2.13, we can represent this question with the *set* of all prime numbers.

The main thing we’ll be working up to in this chapter is a central result about certain undecidable questions in logic. It turns out that the question “Which first-order sentences are true in the standard model of arithmetic?” is *undecidable*: there is no systematic way of answering it in general. The question “Which first-order sentences are logically consistent?” is also undecidable. (So there will always be work left for logicians to do!)

7.1 Programs

An algorithm is a general systematic “recipe” for answering a question. (This is also called an “effective procedure”.) For example, given a string like ABC, what is the string of the same symbols in reverse order? For this example, the answer is CBA. How can we work out the answer in general, for an arbitrary string? One approach is to follow these steps.

1. Set the result to the empty string.
2. Go through the symbols in the string one by one, from left to right. For each symbol x , set the result to be the old result with x appended to the end.

We can also describe algorithms using formal languages: these are called **programming languages**, and a formal description written in such a language is called a **program**. The first programs were written by Ada Lovelace (and a few other people) in the 1840’s, about a century before the first programmable computers were built. Nowadays programs are everywhere. There are millions of lines of programming code that make your phone work, and about a hundred million for a new car. Hundreds of different programming languages have been developed for different purposes: Javascript, C++, Python, Lisp, Haskell, and so on. Here is an example of a program in the Python programming language that describes (or “implement”) the algorithm for reversing a string that we just described. (Don’t worry about the

details yet. We'll systematically work through how this language works in the next two sections.)

```
result = ""
for symbol in x:
    result = symbol + result
```

Modern programming languages like Python are relatively easy to use to write complex programs—that's exactly what they're designed for. The downside is that giving a full description of the syntax and semantics for any of these languages would take a whole lot of work, because they are so complicated and have so many features.¹ In this chapter, what we're primarily interested in isn't *writing* programs, but rather *analyzing* programs—showing certain properties they have. So for our purposes, it makes sense to look at a much simpler programming language than any of these. It turns out that this simple programming language can answer any question that any of the others can. (We won't prove this ourselves, since that would involve the very complicated task of saying precisely what questions Javascript or Python or Haskell can answer. But computer scientists have done this—and it turns out that the answer is: exactly the same questions as our simple language.) In fact, for most purposes we could think of *any* of these languages as just our little language, with a whole lot of convenient abbreviations.

So our first job is to describe a simple programming language. Programs are expressions in a formal language. This language is very similar in spirit to the first-order languages we've been using already—for example, this language also uses variables. But the details are a bit different. For example, we don't have any quantifiers—because typically, finding out whether *there is* something of a certain sort practically involves *looking* for it, in some systematic way. If our domain is infinite, then there's no guarantee ahead of time that a search through the whole domain will ever end. In fact, as we'll show later on, some things we can say using quantifiers aren't decidable at all. So unrestricted quantifiers over an infinite domain aren't a good fit for programming languages.

The most important thing about these basic programs we'll describe is that they only do things that can be worked out mechanically and systematically—given enough time and space to write things down. So if we can write a program in this little language that answers a certain question, this shows that the question is *effectively decidable*.

The language we'll use is a very simple subset of the Python language. We'll call

¹For example, formally defining a denotation function for a simplified version of the Python language is the topic of a hundred-page master's thesis (see Smeding 2009).

it **Py**. Because it's a subset of real Python, that means you can enter our programs into any Python interpreter and they should run. This is a useful way to check your work.²

There is a very small set of basic rules for forming Py-programs. This is convenient for proving things about the language: we don't have to go through zillions of special cases in our proofs. But to actually write programs in this language, it will be useful to introduce shorthand expressions that encapsulate common patterns. This situation is analogous to what we did for the syntax of first-order logic: we used a very small set of basic syntax rules, and then we treated other symbols (like \rightarrow , v , and \exists) as abbreviations for expressions that just use the basic symbols. We'll discuss some of these shorthands along the way.

In this section we'll take an informal tour of how programs can be written in Py, looking at some examples and getting a bit of practice writing programs. In the next section we'll give a more formally precise description of the syntax and semantics for programs.

Py has two different syntactic categories. This is analogous to the distinction in first-order logic between terms and formulas. In Py, the three kinds of expressions are called **terms** and **programs**.

²For example, you can use this one: <https://repl.it/languages/python3>

There's one catch: we have a few operations that aren't built into standard Python. So to make our programs work in a standard Python interpreter, you need to add these lines to the beginning of your code:

```
def head(x): return x[0]
def tail(x): return x[1:]
quo = "\\""
com = ","
rpa = "("
lpa = ")"
new = "\n"
```

After that, everything should work ok.

You can use the statement `print(x)` in your programs to show the value of the variable `x` on the screen at any stage of computation. This is helpful for keeping track of how your program is working.

Another thing to watch out for is that Python interpreters are picky about white space. If you are typing programs into a Python interpreter, you should make sure to always indent using four spaces—not “tabs”—and watch out that your `while`, `for`, and `if` blocks are correctly lined up. A good text editor will help take care of these things for you automatically. See https://en.wikipedia.org/wiki/Source-code_editor#Notable_examples

Terms

Terms stand for things—in particular, terms in Py stand for strings. Here are some examples of terms:

```
""  
x  
"A"  
x + y  
head(x)  
tail(y)
```

The terms in Py are very similar to the terms in the language of strings, but there are some slight differences to fit with Python conventions. We use `+` rather than `⊕` to represent the result of joining two strings together end to end. (Python syntax uses the same symbol `+` both for adding together numbers and also for joining together strings.) The term `""` denotes the empty string.

The term `x` is a variable, and it denotes whatever value happens to be assigned to the variable. In first-order logic we officially use the strings `x`, `y1`, `z`, etc., for variables. When we’re writing programs it’s customary to use longer and more informative variable names. For instance, we might use names like `result`, or `sequenceOfPrimeNumbers`, or `awesomeString`, or pretty much whatever we want.

The term `"A"` denotes the singleton string `A`. We have a term like this for each symbol in the standard alphabet, just like in the first-order language of strings. (Remember, our standard alphabet is the Unicode Character Set. Conveniently, this is the same standard alphabet that Python interpreters use.) In almost every case, we get this term by putting quotation marks around the symbol itself. (Once again, there are a few exceptions: we use `quo` for `"`, `com` for `,`, `lpa` for `(`, `rpa` for `)`, and `new` for the newline symbol.)³

All of these terms so far are basically familiar from the language of strings. Besides these, we have two new term-formers. The term `head(x)` denotes the string containing just the first symbol from the string denoted by `x`, as long as that string is non-empty. Otherwise, the program will crash with an error message. The term `tail(x)` denotes all of the rest of the string denoted by `x`, *except* the first symbol—again, unless the string denoted by `x` is empty, in which case we crash with an error message.

³In fact, there are a few other exceptions for how Python interpreters handle some other special symbols, but we can ignore these.

We can build up complex terms in Py by putting together these basic pieces in arbitrary combinations, just like before. For example, we can build up these complex terms:

```
"A" + (x + "")  
head(y + "A" + "B")  
tail(head(tail(head("A" + "B" + new + "C" + "D"))))
```

Let Statements

A **statement** is an instruction, which says to do something. This is a bit different from the sentences we've been talking about so far, which describe how things already are. A statement describes a way of *changing* the way things are.

There are two basic kinds of statement. The first kind of statement is a “let” statement, which looks like this:

```
x = a
```

You should read this as an *imperative* sentence—“let *x* be *a* from now on”—and *not* as a *declarative* sentence “*x* is *a*”. (It’s a bit confusing that programmers use the `=` sign this way—rather than something else for the purpose, like `x := a`—but unfortunately this is almost completely standard. “Let” statements are also called “assignments”, which is also unfortunately confusing terminology.)⁴ So we can write things like

```
x = x + "A"
```

If we read this as a declarative sentence (“*x* is identical to the result of joining *x* with *A*”) then it is false, no matter what *x* stands for. No finite string is one symbol longer than itself. But the *imperative* reading means “*change* the value of *x*: from now on, let *x* stand for the string which results from appending the string `"A"` to the end of the string that *x* stood for until now.” Whatever string *x* used to stand for, make it now stand for a longer string than that. In imperative programs, the values of variables can change.

A **program** is a string of statements joined together, which means to do what each of the statements says, one after another. For example, we can chain together “let” statements like this:

⁴I don’t know if this is true, but I’ve heard that this conventional use of `=` rather than `:=` was settled on for an incredibly dumb reason: the language designers analyzed some code, and concluded that programmers use “let” statements *more often* than they use actual equality—and they wanted to save a keystroke.

```

foo = ""
bar = "A"
bar = bar + bar
result = head(bar)

```

First, this sets the variable `foo` so it denotes the empty string. Second, this sets the variable `bar` so it denotes the string `A`. Third, this changes the variable `bar` so it instead denotes `AA`. Finally, this sets the variable `result` to the value `A`.

You can think of the program as a list of instructions for someone who has a sheet of paper that lists all of the variables and their values—for example:

<code>foo</code>	(the empty string)
<code>bar</code>	<code>A</code>

The person follows the instructions one by one. When they reach a “let” statement, they write in some new value in the right-hand column, erasing whatever might already been written there. For instance, when they see the third instruction

```
bar = bar + bar
```

they will change the table to look like this:

<code>foo</code>	
<code>bar</code>	<code>AA</code>

After the final instruction, the table will then say:

<code>foo</code>	
<code>bar</code>	<code>AA</code>
<code>result</code>	<code>A</code>

The idea is that when they reach the end of the instructions, they’ll tell you what is written in the `result` row of the table, which represents the “output” of the program.

7.1.1 Example

The following Py-program sets the `result` variable to the second symbol in whatever string is initially represented by `x` (if the length of `x` is at least two).

```
allButFirst = tail(x)
result = head(allButFirst)
```

7.1.2 Exercise

Write Py-programs that set the `result` variable to the following values.

- (a) The third symbol in the string represented by the variable `x` (if the length of this string is at least three.)
- (b) The string which has the same first two symbols as the string that `x` stands for and is followed by all but the first two symbols of the string that `y` stands for (when `x` and `y` both stand for strings with length at least two.)

Say we want to write a program that uses a specific string, such as `True`. One way to do this would be to write this:

```
trueString = "T" + "r" + "u" + "e"
```

But that's a bit of a nuisance, so we'll use this handy shorthand.

```
trueString = "True"
```

Officially, `"True"` is just an abbreviation for `"T" + "r" + "u" + "e"`. Similarly, `"ABC"` is an abbreviation for `"A" + "B" + "C"`, and so on. This is just like how we used symbols like `→` in first-order logic as abbreviations for expressions using only our “official” logical symbols. We are keeping our official language very simple, to make it easy to prove things about it, and then introducing shorthands that make the language easier to use. Programmers call this “syntactic sugar.”

Loops

Py has two basic kinds of statements. We just discussed the first kind: let statements. The second basic kind of statement is a *loop*. Loops let us write programs that do the same steps over and over again, until some “halt” condition is met.

7.1.3 Example

This program takes a string and returns the same string in reverse order. The basic idea is that we’re going to go through the symbols in the string one by one from left to right, and paste them together into a new string going from right to left.

Here’s how it works in more detail. First, set the result to the empty string. Then we do the following steps over and over until `x` stands for the empty string: remove

the first symbol from the `x`-string, and add it onto the left side of the result.

Here's the whole program:

```
result = ""
while x != "":
    result = head(x) + result
    x = tail(x)
```

The symbol `!=` is how we write “is not equal to” (that is, \neq) in Python syntax. Whatever value `x` starts out with, when the program reaches the end, `result` will have that same string in reverse order.

In general, for any terms a and b , and any block of statements A , we can build this kind of statement:

```
while a != b:
    A
```

This means to repeatedly do what A says as long as the values of a and b are different. We don't stop repeating the block until a and b have the same value.

In general, we'll think of a program as taking certain “input” variables (in this case `x`), doing some work, and finally putting the result in an “output” variable (`result`).

“Let” statements and “while” loops are the only basic kinds of statements we need for our programming language. But writing programs with just these statements can get pretty cumbersome. To write complicated programs, it's very helpful to introduce some more abbreviations for common patterns. At this point we're done with the “low-level” programming language: our basic tools. The rest of this section introduces some “higher-level” programming structures, which helps show what our programming language is capable of.

Branching

One important thing we can do is *branching*. We can write programs that can go in two different alternative directions, depending on whether two strings are the same.

```
if a == b:
    flag = "True"
else:
    flag = "False"
```

Again, the meaning of this is different from the conditional in first-order logic, because it is an *imperative* statement meant to change the world, rather than a *declarative* sentence meant to describe it. Here's what it means. First, evaluate whether the terms `a` and `b` denote the same string. (Note that we use a double equals sign `==`. This is because the single equals sign `=` was already taken for "let" statements.) If `a` and `b` have the same value, then we do the statements in the first block—in this case, we set the value of the variable `flag` to `True`. If `a` and `b` denote different strings, then instead we do the statements after the `else`—in this case, we set `flag` to `False`.

Here's another example:

```
if s == "":
    result = "It's empty!"
else:
    result = head(s)
```

If `s` is not empty, then this statement sets the value of `result` to its first symbol. Otherwise, it just sets the result to be an error message.

We don't need to include `if` statements as basic building blocks, because we can always replace them using let statements and `while` loops. The trick is to write loops that are guaranteed to only happen at most one time. In general, if A and B are programs and a and b are terms, we can treat this

```
if a == b:
    A
else:
    B
```

as an abbreviation for this:

```
x = a
finished = "False"

while x != b:
    B
    x = b
    finished = "True"

while finished != "True":
    A
```

```
finished = "True"
```

Here `x` and `finished` should be variables that aren't used elsewhere in the program. The idea is that we have a loop for *B* that runs once if *a* and *b* have different values, and a second loop for *A* that runs once if the first loop didn't run.

Sometimes we don't care about the `else` part of an `if`-statement: we don't want to do anything in that case. We can indicate this by just leaving out the `else` part. That is, this program:

```
if a == b:
    A
```

means just the same thing as this one:

```
if a == b:
    A
else:
    ()
```

where the `else` block is the empty program. We can also write

```
if a != b:
    A
```

as a synonym for

```
if a == b:
    ()
else:
    A
```

(Remember that `!=` is Python's standard way of writing “not equal”.) Sometimes it's also useful to chain together `if` statements. The Python abbreviation for this looks like this (`elif` is short for `else if`).

```
if a1 == b1:
    A1
elif a2 == b2:
    A2
elif a3 == b3:
    A3
```

This means the same thing as

```
if a1 == b1:
    A1
else:
    if a2 == b2:
        A2
    else:
        if a3 == b3:
            A3
```

The shorthand is nice to keep the indentation from getting out of control.

7.1.4 Exercise

Show the following questions are decidable by writing a program that returns `True` if the answer is “yes”, and `False` if the answer is “no”, using `if` statements.

- (a) Are the values of `s` and `t` both equal to `True`?
- (b) Are either of the values of `s` or `t` equal to `True`?
- (c) Is the length of `s` at least two?

It will be useful to have names for the first two programs, to refer back to them later on: in particular, let’s abbreviate them `and(s, t)`, and `or(s, t)`.

Bounded Loops

A common pattern in programs is to go through each of the symbols in a string one by one, do something with each symbol, and stop when we reach the end of the string. This is called a `for` loop.

For example, this program decides whether every symbol in a string is `A`.

```
result = "True"
for symbol in s:
    if symbol != "A":
        result = "False"
```

The `for` loop goes through the elements of the string represented by `s` one by one, and stores each symbol as the value of the variable `symbol`. This is similar to a `while` loop, but it is more specialized. One important feature of a `for` loop is that it is guaranteed to eventually stop, when it gets to the end of the string. In contrast,

in principle a `while` loop might go on running forever, if the equality test is never passed.

Again, though `for` loops are very useful, we don't need to include them as an extra primitive in our programming language, because they can be eliminated using `while` loops. In general, suppose x is any variable, a is any term, and A is some program. We can understand this notation—

```
for x in a:
    A
```

—as a shorthand for this, where y is a variable that is not used elsewhere in the program—

```
y = a
while y != "":
    x = head(y)
    y = tail(y)
    A
```

7.1.5 Example

This program takes a string and repeats each symbol an extra time. For instance, it takes ABC to AABBCC.

```
result = ""
for symbol in s:
    result = result + symbol + symbol
```

7.1.6 Example

We can rewrite the `reverse` program a bit more concisely using a `for` loop.

```
result = ""
for symbol in x:
    result = symbol + result
```

Function Calls

There's another abbreviation which is useful for chaining programs together to make more complex programs. We have already written a program that reverses a string, and a program that repeats each symbol. We can stick these two programs together to produce a program that repeats the symbols *and* reverses their order. The obvious way to do this is to cut and paste, with one program immediately following the other:

```

result = ""
for symbol in s:
    result = result + symbol + symbol

x = result

result = ""
for symbol in x:
    result = symbol + result

```

Note that to make this work, we needed to add one extra line in between the original two programs: `x = result`. This feeds the *output* value of the first program to the *input* variable for the second program.

We can represent this program much more concisely using *function call* notation. The first step is to introduce a name for each of the two simple programs. Python has a standard notation for this. We can write the definitions of our two programs like this:

```

def reverse(x):
    result = ""
    for symbol in x:
        result = symbol + result
    return result

def repeatSymbols(s):
    result = ""
    for symbol in s:
        result = result + symbol + symbol
    return result

```

With each program, we've added an extra `def` line before it, and an extra `return` line after it. (We've also indented the whole program.) The `def` line tells us what *shorthand* we're planning to use for this program later on, and what the "input" variables are. The final `return` line tells Python where the program ends, and that the value of the `result` variable should be treated as the program's output.

Once we've done this, we can stick the two programs together using this concise shorthand:

```
finalResult = reverse(repeatSymbols(s))
```

Here we are using `repeatSymbols(s)` as a complex term, and `reverse(repeatSymbols(s))` as a more complex term. The idea is that `repeatSymbols(s)` stands for whatever final output you get by running the `repeatSymbols` program with the input `s`. Similarly `reverse(repeatSymbols(s))` means the final output of first getting the value of `repeatSymbols(s)`, then feeding that as an input to the `reverse` program. (The intuitive idea here is very similar to the idea of *substitution* for formulas in first-order logic.)

7.1.7 Example

This program returns `True` for an empty string, and `False` for a non-empty string.

```
def empty(s):
    if s == "":
        result = "True"
    else:
        result = "False"
    return result
```

Then suppose we write this later:

```
x = empty("ABC")
```

Then this abbreviates

```
s = "ABC"
if s == "":
    result = "True"
else:
    result = "False"
x = result
```

This program has the result of assigning `False` to `x`.

Here's the general recipe for unpacking “function call” notation. Suppose we have a program `A` which we have called `programName`, with the input variables `x` and `y`. (That is, we have used the line `def programName(x, y):`.) Then say we have a let statement like this one:

```
z = programName(a, b)
```

We can unpack it like this:

```
x = a
y = b
A
z = result
```

(In fact, the real rule is a little trickier than this: *first*, we should modify all the variable names used in *A* so that we don't have any clashes.) If we use the shorthand more than once, we can just follow these rules as many times as we need to.

When you are writing programs, feel free to use all of the shorthands we have introduced: complex terms, `if ... elif ... else` branching, `for`-loops, and function call notation. Since we know that each of these *can* be eliminated and replaced with simple let and `while` statements, this means that for practical purposes we don't have to eliminate them from our programs.

7.1.8 Exercise

Write a program that computes the “dots” function from Exercise 2.4.13. For example, the output of the program for input ABC should be `•••`.

7.1.9 Exercise

Write programs to show that the following questions are decidable.

- (a) Is *s* at least as long as *t*?
- (b) Are *s* and *t* the same length?

7.2 Syntax and Semantics

Syntax for Programs

Here's a summary of the official syntactic rules for terms and programs in the language Py.

We'll start with terms. Remember that in Section 3.2 we chose some constants for the language of strings: `""` for the empty string, and constants like `"A"`, `"B"`, `quo`, and `new` for single-symbol strings. Py is also a language for talking about strings, so we will use each of these same constants as Py-terms. But we will also add in two extra function symbols `head` and `tail` for “unpacking” strings. (These functions were definable in the first-order language of strings, so we didn't need to include them there—but the definition used quantifiers, which we don't have in our programming language.)

As with terms and formulas, it will be helpful to explicit about what *variables* a term or program uses. For terms, this works the same way as before: if \bar{x} is a finite sequence of variables, we will talk about the **(Py) terms of \bar{x}** . These are the variables whose values are provided as “inputs” for the term. Recall, though, that a term doesn’t *have* to use every input variable that it’s provided with. For example, $x + x$ is a term of (x) , but it also counts as a term of (x, y, z) .

7.2.1 Definition

For a sequence of tokens \bar{X} , The **Py-terms of \bar{x}** are the L -terms of \bar{x} , where L is the signature including every constant in the language of strings, the two-place function symbol $+$, and additionally two one-place function symbols **head** and **tail**.

Next we’ll give a recursive definition of Py programs. Again, we want to do a bit of variable management. Unlike in first-order logic, variables in programs have two different roles to play: they can be *inputs* or *outputs*. We will want to keep track of which variables are available to play either of these roles. If \bar{x} and \bar{y} are two sequences of variables, we will define the **(Py) programs from \bar{x} to \bar{y}** . For short, we will let $\text{Py}(\bar{x} \rightarrow \bar{y})$ be the set of all such programs.

A program doesn’t *have* to use all of its outputs, and it is allowed to set the values of variables that are not considered to be outputs.

If a program has just one input variable x , or just one output variable y , we will usually talk about a program “from x to y ” instead of “from (x) to (y) ”, using length-one sequences.

In what follows, let \bar{x} and \bar{y} be any sequences of variables.

7.2.2 Definition

If every variable in \bar{y} appears somewhere in \bar{x} :

The empty string $()$ is a program from \bar{x} to \bar{y} .

The empty program does not set any new variables, so the only things that it gets to pass on as an output is whatever is already passed to it as an input.

$$\begin{array}{c} z \text{ is a variable} \quad t \text{ is a term of } \bar{x} \quad A \text{ is a program from } z, \bar{x} \text{ to } \bar{y} \\ \hline z = t \quad \text{is a program from } \bar{x} \text{ to } \bar{y} \\ A \end{array}$$

A let statement sets the value of a new variable z . So the program that comes after the let statement can now use the value of that variable, even if it wasn't already provided as an input. Whatever outputs the subsequent program has are also available as outputs for the program as a whole. (This is analogous to the quantifier in first-order logic: the variable z is “bound” by a let statement, which makes it available to the subsequent program even if it wasn't already available.)

t_1 and t_2 are terms of \bar{x}	A is a program from \bar{x} to \bar{x}	B is a program from \bar{x} to \bar{y}
	$\text{while } t_1 \neq t_2:$ $\quad A$ $\quad B$	is a program from \bar{x} to \bar{y}

In this case, the A program is going to run as a loop, updating the values of the variables that it is provided with each time that it runs. Then these updated values are passed on to the subsequent program B .

7.2.3 Example

Consider our familiar “reverse” program.

```
result = ""
while x != "":
    result = head(x) + result
    x = tail(x)
```

To see how the definition works, let's work through it step by step to show that this is indeed a program from the input variable x to the output variable $result$. We will work backwards.

The clause for “let” statements tells us that it is enough to show two things:

1. $" "$ is a term of x —which is clearly true.
2. The remaining program is a program from $(result, x)$ to $result$:

```
while x != "":
    result = head(x) + result
    x = tail(x)
```

To show this, we need:

1. x and $" "$ are each terms of $(result, x)$ —which is again clearly true.
2. This inner block is a program from $(result, x)$ to $(result, x)$:

```
result = head(x) + result
x = tail(x)
```

3. The remaining program—that is, the empty string—is a program from (result, x) to result . This is true, since the output result is included in the sequence of input variables.

That leaves part 2. To show that, we need:

1. $\text{head}(x) + \text{result}$ is a term of (result, x) .
2. $x = \text{tail}(x)$ is a program from $(\text{result}, \text{result}, x)$ to (result, x) . (The fact that result gets repeated here is kind of annoying, but it doesn't really matter, so we'll just let it be for now. TODO. Next pass---try to smooth this out?)

So then what we need to show is:

1. $\text{tail}(x)$ is a term of $(\text{result}, \text{result}, x)$
2. The empty string is a program from $(x, \text{result}, \text{result}, x)$ to (result, x) —which is true.

So we're done.

Syntax Details*

That should get the idea across, but before we move on, let's get clear on a few details about what this definition means. (You can skip over these details, but they're important if you're going to do some of the parsing exercises in Section 7.4.)

Programs are strings. (Just like always, we can ask, is a program *really* just a string, or are programs some other structure that can be *represented* by a string? This is a fair question, but it will make things easier if we suppose that a program just *is* a certain string.) A string is just a bunch of symbols, one after another. But because programs can get pretty long, it would be a pain to write out a program in a single line of text. That's no problem, though: we have a special symbol in our alphabet that means “start a new line”. So, for example, take this program:

```
y = x
z = y
```

We could spell out the sequence of symbols in this string very explicitly like this:

$(y, \text{ }, =, \text{ }, x, \text{new line}, z, \text{ }, =, \text{ }, y, \text{newline})$

In general, we can spell out the syntax rule for let statements very explicitly like this: if x is a variable, t is a term, and A is a program, then

$$x \oplus = \oplus t \oplus \text{newline} \oplus A$$

is also a program.

A second note is that our syntax uses *indentation* to indicate the structure of a **while** loop. Like writing programs in multiple lines, this “white space” convention makes programs easier to read. Each statement within a while loop should be moved over to the right by adding some white space to the beginning of the line (officially, the space symbol four times).

Let’s be explicit. For any program A , there is a unique sequence of strings (s_1, s_2, \dots, s_n) which are the *lines* of A (see Exercise 4.3.4). None of these strings contains any newline symbols, and

$$\begin{aligned} A = & s_1 \oplus \text{newline} \\ & \oplus s_2 \oplus \text{newline} \\ & \vdots \\ & \oplus s_n \oplus \text{newline} \end{aligned}$$

Then

$$\begin{aligned} \text{indent}(A) = & \quad \oplus s_1 \oplus \text{newline} \\ & \oplus \quad \oplus s_2 \oplus \text{newline} \\ & \vdots \\ & \oplus \quad \oplus s_n \oplus \text{newline} \end{aligned}$$

(To be even *more* explicit, we could define this indent function recursively. Compare the “tokenization” function from Section 4.3.)

Now we can state the syntax rule for **while** statements more explicitly. If t_1 and t_2 are terms, and A and B are programs, then this is also a program:

$$\text{while } \oplus t_1 \oplus != \oplus t_2 \oplus : \oplus \text{newline} \oplus \text{indent}(A) \oplus B$$

That’s it for the syntax of programs.

As with first-order logic, an important fact about these definitions is that there is no syntactic ambiguity in our notation. Py-terms and programs also each have an Injective Property. (This can be officially proved by writing and checking a parsing function, as in Section 3.3.) But we will skip over these details.

Semantics for Programs

So far we've been working with an intuitive sense of how programs work. Now let's give a precise account of the *meaning* of the programming language. Just like we did with first-order logic, we can recursively define a *denotation* function for Py-terms and programs.

For terms, things are pretty easy.

7.2.4 Definition

Let the *expanded string structure* \mathbb{S}^+ be the same as the ordinary string structure, but with the two additional function symbols **head** and **tail**. The extension of **head** is the function that takes each non-empty string to its first symbol, and which takes the empty string to itself. The extension of **tail** is the function that takes each non-empty string to the whole string *except* its first symbol, and which again takes the empty string to itself.

The denotation of a Py term t (of a sequence of variables \bar{x} , with respect to a sequence of strings \bar{s}), is just the same as its denotation in the expanded string structure \mathbb{S}^+ (with respect to \bar{s}).

$$\llbracket t \rrbracket \bar{s} = \llbracket t \rrbracket_{\mathbb{S}^+ \bar{s}}$$

The denotation of a *program* is a function—in particular, a function from a sequence of (string) values for its *input* variables, to a sequence of (string) values for its *output* variables.

For example, consider this very simple program:

```
x = x + "A"
```

The result of running it is to change the value of x by adding the letter A to the end: for example, it takes A to AA, or UCL to UCLA. This is a program from x to x , and its denotation is the function that takes each string s to the extended string $s \oplus A$.

Let's state the general semantic rule for a “let” program. First, recall the syntactic rule:

$$\frac{\begin{array}{c} z \text{ is a variable} \\ t \text{ is a term of } \bar{x} \\ A \text{ is a program from } z, \bar{x} \text{ to } \bar{y} \end{array}}{z = t \quad \text{is a program from } \bar{x} \text{ to } \bar{y}}$$

Since we are giving a recursive definition, we can assume that we already know what function the subsequent program A denotes. The “let” statement just needs to

provide the right value of the variable z to this function—namely, the string denoted by t .

$$\left[\begin{array}{c} x = t \\ A \end{array} \right] = \llbracket A \rrbracket(\llbracket t \rrbracket \bar{s}, \bar{s})$$

What this says is to get the string denoted by t , put this string together with the rest of the input strings, and give this sequence of inputs to the rest of the program.

We skipped over the semantics of the empty program. Intuitively, this program doesn't do anything at all. But its denotation is not totally trivial, because the empty program can have different input and output variables. So the empty program denotes different functions depending on which variables we are interested in. (Really, there is more than one different denotation function: for each pair of sequences of variables \bar{x} and \bar{y} , we have a denotation function that takes the set of programs $\text{Py}(\bar{x} \rightarrow \bar{y})$ to the set of (partial) functions from sequences of strings to sequences of strings.) So the empty program denotes the function that picks out the appropriate output values from among the input values.

Spelling this out precisely is a little bit complicated, but in practice it's very simple. If the input variables are \bar{x} , then each of the output variables \bar{y} for the empty program has to be included somewhere in \bar{x} . So there is a function h that takes each index between 1 and the length of \bar{y} to some index between 1 and the length of \bar{x} : $h(i)$ is the first position where y_i appears in \bar{x} . Then:

$$\llbracket () \rrbracket \bar{s} = (s_{h(1)}, s_{h(2)}, \dots, s_{h(n)})$$

That is, we just pick out the values in the input sequence that correspond to the variables in the output sequence.

Finally, we have **while** loops. Recall the syntactic rule:

t_1 and t_2 are terms of \bar{x}	A is a program from \bar{x} to \bar{x}	B is a program from \bar{x} to \bar{y}
$\text{while } t_1 \neq t_2:$	A	B is a program from \bar{x} to \bar{y}

Intuitively, what this should do is run the function denoted by A as many times as it takes until t_1 and t_2 denote the same string. Except this isn't guaranteed to *ever* happen. Some programs go into infinite loops—like this one:

```
while "A" != "B":
    x = x
```

And some programs go into infinite loops for *some* inputs, but not for others—like this one:

```
while x != "B":  
    x = x
```

If the input value of `x` is `B`, then this program halts, and if it is anything else then it runs forever.

So far we have ignored this, but we can do so no longer: in general, the denotation of a program is a *partial* function, which may be undefined for some inputs. We'll write $f(s) = *$ to indicate that f does not have any output for the input s , and we'll adopt the convention that $f(*) = *$.

Consider a while block

$$\begin{array}{c} \textbf{while } t_1 \neq t_2 : \\ \quad A \\ \quad B \end{array}$$

Let's start by considering what happens if the `while` loop runs forever. We can define a function that says what the output looks like after any number of steps. We'll call the result after k steps $\llbracket A \rrbracket^k$, and define it recursively:

$$\begin{aligned}\llbracket A \rrbracket^0(\bar{s}) &= \bar{s} \\ \llbracket A \rrbracket^{k+1}(\bar{s}) &= \llbracket A \rrbracket(\llbracket A \rrbracket^k(\bar{s}))\end{aligned}$$

Note that if this result is ever $*$, then it stays $*$ forever after.

Now there are two different cases to consider.

1. There is some smallest number k such that

$$\llbracket t_1 \rrbracket(\llbracket A \rrbracket^k(\bar{s})) = \llbracket t_2 \rrbracket(\llbracket A \rrbracket^k(\bar{s}))$$

In this case,

$$\left[\begin{array}{c} \textbf{while } t_1 \neq t_2 : \\ \quad A \\ \quad B \end{array} \right] (\bar{s}) = \llbracket B \rrbracket(\llbracket A \rrbracket^k(\bar{s}))$$

That is, we keep applying the function denoted by A until we get a result with respect to which t_1 and t_2 have the same denotation, and then we apply the function denoted by B to that result.

2. There is no such k . In this case,

$$\llbracket \begin{array}{c} \text{while } t_1 \neq t_2 : \\ \quad A \\ \quad \quad \quad \end{array} \quad B \end{array} \rrbracket = *$$

That completes the official semantics.

7.2.5 Definition

The *denotation* of a program A from variables \bar{x} to variables \bar{y} is the partial function from sequences of strings to sequences of strings defined recursive by the three rules just described.

A program A **halts** for input \bar{s} iff $\llbracket A \rrbracket(\bar{s})$ is defined; that is, $\llbracket A \rrbracket(\bar{s}) \neq *$.

Now that we have a formal definition of the semantics of programs, we can ask: which functions can be expressed by a program? In other words, which functions are *computable* using Py programs?

7.2.6 Definition

- (a) A (partial) function $f : \mathbb{S} \rightarrow \mathbb{S}$ is **Py-computable** iff it is the denotation of some program.
- (b) A set of strings $X \subseteq \mathbb{S}$ is **Py-decidable** iff its characteristic function is Py-computable: that is, the function that takes each string $s \in X$ to **True** and each string $s \notin X$ to **False** is the denotation of some program.

The definitions are similar for n -place functions and sets of n -tuples.

These definitions are closely analogous to our earlier definitions of *definable* functions and sets. The key difference is just what kind of language we are using: then, we were talking about the extensions of terms and formulas in a first-order language, and now we are talking about the extensions of programs. In a slogan, we could say that a *computable* function is one that is definable using a *programming language*, rather than a first-order language, and likewise, a decidable set is one that is definable using a programming language.

7.2.7 Example

Prove that the following program halts, for any initial value for x .

```
while x != "A":
    x = "A"
result = tail(x)
```

Proof

We'll work this one out in tedious detail, to show how all the pieces are working.

Let's work from the inside out. Start by looking at the inner block,

```
x = "A"
```

The definition of the denotation function for “let” assignments (and for the empty program) tells us that the denotation of this block is the function that takes any assignment g to the assignment

$$g[x \mapsto A]$$

That is, this block updates the value of the variable x to the string A .

Next, let's use this to evaluate the **while** statement,

```
while x != "A":
    x = "A"
```

To show that this halts, we need to show that there is some *finite loop sequence* for the terms x and "A" and the inner block. Let g be an assignment. There are two cases: either $g(x)$ is A , or it is something else. If $g(x) \neq A$, then we can easily show that this length-two sequence (g_0, g_1) meets the three conditions of the definition of a finite loop sequence.

$$(g, g[x \mapsto A])$$

First, g_1 is clearly given by applying the denotation of the inner block to the assignment g_0 . Second, $g_0(x) \neq A$ by assumption. Third, clearly $g_1(x) = A$.

On the other hand, if $g(x) = A$, then we can show that the length-one sequence (g) meets all the conditions. The first and second conditions are both vacuously true, since there is no number $i < 0$. The last condition is obvious: $g(x) = A$.

In either case, there is a finite loop string for the **while** loop starting with g , and so the loop halts. Note also that whether or not $g(x) = A$ for the initial assignment, for the final assignment h in the sequence, $h(x) = A$; in particular, this is not empty. Now evaluate the final “let” statement (which is followed by the empty program):

```
result = tail(x)
```

The denotation of this program, given the assignment h , is

$$h[\text{result} \mapsto [\![\text{tail}(x)]\!] h]$$

To ensure that this is defined, we just need to check that $[\![\text{tail}(x)]\!] h$ is defined. And this is true: looking at the definition for the denotation of **tail** terms and variables, we see that this is defined as long as $h(x)$ is not empty, which we have already shown is true.

In short, for any string s , $[\![A]\!] s$ is defined, which means that A halts for every input. \square

7.2.8 Exercise

Give an example of a program that does not halt for any input, and use the definition of the denotation function for programs to prove this.

7.2.9 Definition

We will use the notation $A(x)$ for a program from the input variable x to our conventional output variable **result**.

- (a) Let $A(x)$ be a program and let t be a term. Then $A(t)$ is the program that adds a let statement to the beginning of $A(x)$:

```
x = t
A(x)
```

(The idea here is similar to substitution for first-order formulas.)

- (b) Similarly, for programs $A(x)$ and $B(y)$, let $B(A(x))$ be the program

```
A
y = result
B
```

7.2.10 Exercise

- (a) For any program $A(x)$ and term t ,

$$[\![A(t)]\!] = [\![A]\!]([\![t]\!])$$

That is, the result of running the program $A(t)$ is the same as the result of running the program $A(x)$ with the denotation of t as its input.

- (b) For any programs $A(x)$ and $B(y)$ and any string s , $B(A(x))$ is a program from x to `result`, and

$$\llbracket B(A(x)) \rrbracket(s) = \llbracket B \rrbracket(\llbracket A \rrbracket(s))$$

Hint. Use induction on the program B .

7.3 The Church-Turing Thesis

If we want to show that a question is decidable, we can write a program to answer it. But how would we show that a question is *undecidable*? To do this, we wouldn't just need to show that no program in our little language Py answers the question—we'd need to show that no program in *any* reasonable programming language can answer it. If a question is undecidable, then there isn't any systematic algorithm for solving it at all.

Alonzo Church and Alan Turing each hypothesized that there are *universal* programming languages: languages which are expressive enough to describe *every* systematic algorithm. In fact, they didn't just hypothesize that such languages exist: they proposed some specific candidates. (In Church's case, these consisted of a small family of operations on functions of natural numbers. In Turing's case, the “language” consisted of **Turing Machines**—hypothetical devices for reading and printing on a long tape.) These proposals amounted to giving a formal analysis of the intuitive concept of a decidable question. You might doubt whether such an analysis could succeed. (Surely any conceptual analysis like this would have counterexamples!) But in fact, we have very strong evidence that Church and Turing's proposal is right.

The key philosophical claim is called the **Church-Turing Thesis**. The first bit of evidence for it is packed right into its name. Church's and Turing's theses look *different*: they are apparently different analyses of the concept of a decidable question. But they turned out to be equivalent to one another. That is, any question which is decidable using a Turing Machine is also decidable using Church's functions, and vice versa.

Today we have hundreds more examples—formal languages like C++ or Python or Haskell and so on: these *also* turn out to be equivalent to Turing and Church's languages. This also means that we get a little bit more empirical evidence for the truth of the Church-Turing Thesis every time a programmer takes a precisely described algorithm and implements it in their favorite programming language. The Church-Turing Thesis is thus a hypothesis which is extraordinarily well-confirmed

by the practice of modern programming.

(Besides this empirical evidence, there are also some very strong *philosophical* arguments for the Church-Turing Thesis. CITE Smith, Kripke. We have some clear and precise *sufficient* conditions for a question to be effectively decidable: it's enough to show that we can write a program, for example, in our little language Py. There are also interesting arguments for some precise *necessary* conditions on decidability. But it turns out that we can prove that these sufficient conditions and these necessary conditions are equivalent! So this argument would show that Py-decidability is a necessary and sufficient condition for decidability, just as the Church-Turing Thesis says. TODO: explain this a bit.)

Even so, it's worth remembering that it is a philosophical thesis—an extraordinarily successful philosophical thesis, but not officially a theorem. We can prove lots of theorems about various kinds of formal languages. But the Church-Turing Thesis is about the relationship between these formal languages and the intuitive notion of a decidable question.

In particular, our little language Py is equivalent to each of these other programming languages: a function is Py-computable if and only if it is computable using a Turing Machine, if and only if it is computable using Church's functions, if and only if it can be computed by a program in C++ or any other standard programming language. So if any of these languages is a universal programming language, so is Py. So according to the Church-Turing Thesis, whatever can be done in any systematic way—by any algorithm at all—can also be done using humble Py.

7.3.1 The Church-Turing Thesis

- (a) A partial function $f : \mathbb{S} \rightarrow \mathbb{S}$ is effectively computable iff f is Py-computable.
- (b) A set $X \subseteq \mathbb{S}$ is effectively decidable iff X is Py-decidable.

In what follows, we will freely appeal to the Church-Turing Thesis (though it's generally a good idea to be clear about when exactly we're relying on it). This is extremely useful in two ways.

First, this lets us deduce the existence of programs, even without formally writing them out. In order to show that a question is decidable, it's enough to informally give some reasonably careful description of a systematic procedure for answering it. But even once we've done this much, transforming an informal description of an algorithm into a formal program can still be pretty tricky. (That's what professional programmers are for.) Given the Church-Turing Thesis, we can deduce the

existence of a program from the existence of an algorithm, even when we haven't worked out exactly how to write that program. We'll do this in what follows: rather than writing out fully detailed programs in our little language, we can just outline how a program ought to work, and posit that *some* program does in fact work that way, appealing to the Church-Turing Thesis.⁵

Second, this lets us prove results about undecidability. We can mathematically prove that every Py-decidable set has certain properties. Then, using the Church-Turing Thesis, we can conclude that every *decidable* set has those properties as well, or to put that the other way around, any set without those properties is undecidable.

7.3.2 Exercise

Given the Church-Turing Thesis, prove that there are uncountably many effectively undecidable sets of strings.

7.4 The Universal Program

Programs operate on strings: they take strings as input, and spit out strings as output. But a program also *is* a string of symbols itself. This means we can use programs themselves as the input or output for other programs. Programs that manipulate programs might sound recherché, but it's actually very common and practical. When we write a program in Python, what we are doing is typing in a certain string of symbols. When we then want to *run* that program, we are providing this string as an argument to a Python *interpreter*—which is some other program. Somebody wrote that program, too, in some programming language. In fact, the interpreter might be written in Python itself!

Even our little language Py can do this. We can write a “Py-interpreter” in Py. This is a program `run(program, inputValue)` with two input variables. The first input should be a Py-program A , and the second input is an input value s to provide to A . Then the final result of `run` is the same as the final result of running A with the input s . At least, it has this result if A *has* any final result. It could be that A crashes or goes into an infinite loop. In that case, the interpreter will also just crash or run forever. In short, for any program A and string s ,

$$\llbracket \text{run} \rrbracket(A, s) = \llbracket A \rrbracket(s)$$

Basically, what we're doing is precisely describing the denotation function for Py, within Py! This is very close to what Tarski's Theorem showed we *couldn't* do, for

⁵Peter Smith CITE calls these “labor-saving” uses of the Church-Turing Thesis.

sufficiently strong theories: we can represent the semantics of Py within Py. A key difference is that Py programs (unlike first-order sentences) can *crash*. We'll come back to this point in Section 7.5 and Section 7.6.

First, let's introduce some tools which are analogous to what we did in Chapter 6. Officially, our Py-programs only have one “data type”: strings. But there are natural ways of using strings to represent other things—like numbers, or sequences of strings.

7.4.1 Exercise

In Section 6.3 we defined a string representation function for sequences of strings. Show that the following functions are computable:

- (a) The function that takes the string representation of a non-empty sequence of strings to its first element.
- (b) The function that takes a the string representation for a sequence of strings s , and a string t , and returns `True` if t is an element of the sequence s , and otherwise returns `False`.

For the universal program, we'll need string representations for one other important kind of thing: *assignment functions*. There are many ways to do this, but here's one. We have already discussed a way of representing a sequence of strings using a single string in Section 6.3. We can represent an assignment function as a sequence of strings like this one:

`(x:hello, result:, s:ABC)`

This represents the assignment function

$$\left[\begin{array}{l} x \mapsto \text{hello} \\ \text{result} \mapsto \text{the empty string} \\ s \mapsto \text{ABC} \end{array} \right]$$

Each element of the sequence joins up a *variable* with its *value* string, separated by the symbol `:`. (For this to work out right, it's important that we have stipulated that the symbol `:` can't ever show up within a variable name.) Then we can use the string representation function for sequences to represent a key-value sequence like this as a single string.

(We'll only ever need to worry about assignment functions that are defined for just finitely many variables—which is a good thing, because there is no way to represent arbitrary *infinite* assignment functions using finite strings. There are too many of them.)

7.4.2 Exercise

The following functions are computable, with respect to the string representation function defined above.

- (a) The function that takes a string representation of an assignment function g and a variable x to its value gx . That is, this function takes the string representation for a sequence of strings s , and a “key” string k which does not include the symbol `:`, and returns a string v such that $k:v$ is an element of the sequence s , if there is any such string v .
- (b) The function that takes an assignment function g , a variable x , and a string s , to the new assignment $g[x \mapsto s]$, which modifies g by setting the value of x to s .

7.4.3 Lemma

The **denotation function** takes a pair of a program A and an assignment g and returns the denotation $\llbracket A \rrbracket g$ (when this is defined). The denotation function is Py-computable.

Proof Sketch

We won’t write out a full program for this, but we will informally describe an algorithm for doing this. By the Church-Turing Thesis, this algorithm can be implemented by some program.

The first part of this project is called *parsing*. We need to take a program (or a term), and split it up into its meaningful parts. We can write a bunch of small programs to handle basic parsing tasks. Here’s our to-do list. (We won’t actually do all of this: the goal here is just to make it apparent that the interpretation function is *computable*, not to actually write a complete parser and interpreter. But if you have the time and interest, it’s fun to work out some of these details in front of a computer.)

1. Write a program that takes a program as input, and returns `empty` if it is the empty program, `let` if it begins with a let statement, or `while` if it begins with a `while` loop.
2. Write three programs that each take as their input a program that begins with a let statement, and return (a) the variable on the left side of the equals sign, (b) the term on the right side of the equals sign, and (c) the rest of the program after the let statement.
3. Write four programs that take a program beginning with a `while` loop, of the form

```
while a != b :
    A
    B
```

and return (a) the first term a , (b) the second term b , (c) the inner block A , and (d) B the remaining lines of the program after the while loop.

(One slightly tricky part here is figuring out where the inner block ends. As we noted earlier, in Python this depends on the indentation.)

4. (a) Write a program that takes a Py-term as input and identifies whether it is a variable, a constant (either the constant `""` for the empty string, or else one of the constants like `"A"` for a one-symbol string) or a term of the form `head(t)`, `tail(t)`, `(t1 + t2)`.
- (b) For `head` and `tail` terms we should also write programs that return the inner term t , and in the case of `+` we should write programs that return each of the inner terms t_1 and t_2 .
- (c) For constant terms, we should also write a program that tells us which string the constant stands for. (In most cases, this just means stripping off the outer quotation marks, but remember that there are a few special cases.)

The components we have described so far just analyze the syntax of programs. To calculate what a program *does*, we'll need to keep track of an assignment function, and work out how each part of a program ends up modifying it. For this purpose we'll use the programs from Exercise 7.4.2 that manipulate assignment functions: we have a program `getValue` for looking up the value of a variable in an assignment, and a program `updateAssignment` for updating the value of a variable in an assignment.

We can build our interpreter by putting all these components together. There will be two parts: a term-evaluator, and a program-interpreter.

The term-evaluator takes an assignment and a term and returns the string that the term denotes (with respect to that assignment). We start by figuring out which form the term has. If it's a variable, then we look up the value of the variable in our assignment (using function 6 above). If it's one of the constants like `""`, `"A"`, or `quo`, then we return the corresponding string—either the empty string, or a one-symbol string.

The other cases—terms built from `head`, `tail`, or `+`, are a little trickier, because

these terms include other terms. The most natural way to handle this would be with a *recursive* program that can call itself (see Section 7.5). Since recursive programming isn't a part of basic Py, we need to be a little devious. Here's the trick. We can easily evaluate a term if it's simple enough—if it doesn't nest `+` or `head` or `tail`. But we can always break down a complicated term into simple terms, by introducing extra let statements. In order to evaluate a complex expression like `"A" + head(x)`, we can break it into two steps: first, set an intermediate variable `temp` to the value of `head(x)`, and then evaluate `"A" + temp` instead.

So the idea is that, before we try to interpret a program, we can start by simplifying its terms. Say we have a program that begins with this statement:

```
x = "A" + head(y + z)
```

Then we can break this up into simpler let statements, like this:

```
temp1 = "A"
temp2 = y + z
temp3 = head(temp2)
x = temp1 + temp3
```

In this simplified program, we never embed any term *other than variables* inside more complex terms.

Say a term is **simple** iff it has no subterms other than variables. That is to say, a simple term is either (a) a variable, (b) a constant, (c) of the form `head(x)`, `tail(x)`, or `(x + y)` for some *variables* *x* or *y*.

Say a *program* is simple iff all of the terms that appear in its first line are simple (or else it is the empty program). That is, a simple program is either empty, or else of the form

```
x = t
A
```

for a simple term *t*, or else of the form

```
while t_1 != t_2 :
    A
B
```

for simple terms *t*₁ and *t*₂.

Then we can add these syntactic manipulations to our to-do list.

5. Write a program that takes a program as input, and returns `True` iff it is simple.
6. Write a program that takes a program which is not simple as input, and returns an equivalent simpler program. For example, this will take a program of the form

```
x = t_1 + t_2
A
```

to a new program with this form:

```
y = t_1
z = t_2
x = y + z
A
```

(where y and z are variables which are not already used in the original program). This result might not be simple yet: t_1 might still be another complex term. But if we do this enough times, eventually the resulting program will be simple. We'll call this program `simplify`.

The `simplify` program is a reasonably straightforward bit of syntactic manipulation, though it would take some work to write out. (If you're going to try to write it yourself, one thing you'll need to do first is write a program that takes a program as input, and returns a "new" variable which is not used in that program.)

Now we can just write our term-evaluator for *simple* terms, which is pretty straightforward, once we have the parsing and assignment-wrangling tools from our to-do list.

```
def evaluateSimpleTerm(term, g):
    kind = kindOfTerm(term)
    if kind == "variable":
        result = getValue(g, term)
    elif kind == "constant":
        result = getStringFromConstant(term)
    elif kind == "head":
        x = innerTermOfHead(term)
        result = head(getValue(g, x))
    elif kind == "tail":
        x = innerTermOfTail(term)
```

```

        result = tail(getValue(g, x))
    elif kind == "join":
        x = firstTermOfJoin(term)
        y = secondTermOfJoin(term)
        result = getValue(g, x) + getValue(g, y)
    return result

```

Here's how our program-interpreter will work. First, we'll check if the program is simple or not. If it isn't simple, then our first job is to simplify it. After that we'll try again.

Once we have a simple program, we'll look at its first statement to decide what to do. If it doesn't have any first statement—the program is empty—then we're already done. If it's a let statement $x = t$, then first we use our term-interpreter to evaluate the (simple) term t , and we use our “update an assignment” program to set the value of x to whatever value t denotes.

Next, suppose it's a `while`-statement, so the program has the form

```

while t_1 != t_2:
    A
B

```

Then we'll start by evaluating the (simple) terms t_1 and t_2 . If they have the same value, then we're done with the loop, so we just go on to run the rest of the program B . If they have different values, though, then we will add another copy of the subprogram A to the beginning of our program (including this `while` loop) and keep going. That is, in this case we'll run the program

```

A
while t_1 != t_2:
    A
B

```

Let's spell this out in more detail. The whole interpreter goes in one big `while` loop. We'll keep track of an assignment g as we go, and step through the statements we need to evaluate one by one, updating g as we go.

```

def interpretProgram(program, g):
    while program != "":
        if simpleProgram(program) == "False":
            program = simplify(program)

```

```

else:
    kind = kindOfProgram(program)
    if kind == "let":
        variable = variableInLetStatement(program)
        term = termInLetStatement(program)
        value = evaluateSimpleTerm(term, g)
        g = updateAssignment(g, variable, value)
        program = remainderAfterLetStatement(program)
    elif kind == "while":
        a = firstTermInWhileStatement(statement)
        b = secondTermInWhileStatement(statement)
        block = blockInWhileStatement(statement)
        value1 = evaluateSimpleTerm(a, g)
        value2 = evaluateSimpleTerm(b, g)
        if value1 == value2:
            program = block + program
        else:
            program = remainderAfterWhileStatement(program)
    return g

```

And that about finishes it up, aside from the details we skipped over. So the denotation function for Py-programs is computable. \square

7.4.4 Exercise

The **Py-interpretation function** is the function that takes each pair of a program $A(x)$ and a string s to the result $\llbracket A \rrbracket(s)$, whenever this is defined, and which is undefined otherwise. Use Lemma 7.4.3 to show that the Py-interpretation function is Py-computable.

7.5 The Halting Problem

Recall that a program *halts* if and only if it has some well-defined value. A program that halts is one that neither crashes with an error nor “hangs” in an infinite loop. Here is perfectly sensible question: which programs halt? The Py-interpretation function is a precisely defined partial function. The “halting problem” is the precise question of which programs are in the domain of this function. For any particular program A , either A has some final value, or it doesn’t.

This is a practically important question. If you've been working through the exercises, by now you've probably accidentally written some programs that crash or hang. It would be extremely useful to have a program-checking program: a program that determines whether your program will go into a never-ending `while` loop, or not.

Unfortunately, there is no such program. The question of which programs halt—while it is a perfectly precise question with a correct answer—is effectively undecidable. There is no systematic method for determining, in general, which programs are going to eventually return a value.

This fact is very closely connected to Tarski's Theorem about the undefinability of truth. (Remember that decidability and definability are very closely related: the difference is that one uses a programming language, while the other uses a first-order language.) The proof is also very similar.

Let's introduce some notation to make the analogies more obvious. Just like in the first-order language of strings, in our programming language we have a standard term for each string, like `"A" + "B" + "C" + ""`. As before, let's call this a string's **canonical label** (in Py), and use the notation $\langle s \rangle$. (Using the abbreviation we introduced in Section 7.1, we can abbreviate this term as `"ABC"`.)

We can also plug these terms into programs: $A\langle s \rangle$ is the program that runs the program $A(x)$ with the input s . (That is, $A\langle s \rangle$ is the program consisting of the let statement $x = \langle s \rangle$ followed by $A(x)$.) Similarly, anything that has a standard string representation—such as sentences or programs—has a canonical label in Py, which is just the canonical label for its string representation. This is easy to check:

7.5.1 Proposition

For any string s ,

$$\llbracket \langle s \rangle \rrbracket = s$$

7.5.2 Exercise

For any program $A(x)$ and string s ,

$$\llbracket A\langle s \rangle \rrbracket = \llbracket A \rrbracket(s)$$

The first step is to write some programs to do basic syntactic manipulations. First, just as the label function was *definable* in the sequence theory, similarly it is *computable* in Py. We can show this by writing a program.

7.5.3 Exercise

The function that takes each string s to its canonical label $\langle s \rangle$ is computable.

7.5.4 Proposition

The “substitution” function that takes any program $A(x)$ and term t to the program $A(t)$ is computable.

Proof

Here is a program:

```
def substitution(program, term):
    result = "x = " + term + new + program
    return result
```

7.5.5 Exercise

The “diagonalization” function that takes any program $A(x)$ to the program $A\langle A(x) \rangle$ is computable. That is, there is a program $\text{Diag}(y)$ such that, for any program $A(x)$,

$$\llbracket \text{Diag} \rrbracket(A(x)) = A\langle A(x) \rangle$$

Let’s be very clear about what this means. The program $\text{Diag}(y)$ is a syntax-manipulating program. It takes a program as its input, and then it modifies that program to produce another program as output. The new program simply adds a line of the form $x = t$ to the beginning of $A(x)$, where specifically the term t is the canonical label for the program $A(x)$ itself. For example, suppose $A(x)$ is this very simple program:

```
z = x
```

Then the result of applying the “diagonalization” function to $A(x)$ is this slightly more complex program:

```
x = "z = x" + new
z = x
```

(Note in particular that while x was a free “input” variable in $A(x)$, the diagonalized program $A\langle A(x) \rangle$ does not have any free variables.)

7.5.6 Exercise (Kleene's Fixed Point Theorem)

Let $F(x)$ be any program. Then there is a program A such that

$$\llbracket F \rrbracket(A) = \llbracket A \rrbracket$$

That is, the result of running the program $F(x)$ with the “fixed point” program A as its input is the same as the result of running A itself.

Hint. Refer back to the proof of Gödel’s Fixed Point Theorem (Exercise 6.9.9). It may also be helpful to remember Exercise 7.2.10.

Notice in particular that if A is a “fixed point” of $F(x)$ in the sense of Kleene’s Theorem, then A halts iff $F(x)$ halts for the input A .

7.5.7 Exercise

Write a program $\text{Flip}(x)$ which does not halt for the input `True`, and which halts for any input besides `True`.

7.5.8 Exercise (Turing’s Theorem)

The set of programs that halt is undecidable (given the Church-Turing thesis).

Hint. Suppose that there is a program $\text{Halt}(x)$ such that

$$\llbracket \text{Halt} \rrbracket(A) = \begin{cases} \text{True} & \text{if } A \text{ halts} \\ \text{False} & \text{otherwise} \end{cases}$$

Then you can use Kleene’s Theorem and the program $\text{Flip}(x)$ to derive a contradiction, using similar reasoning to the proof of Tarski’s Theorem or the Liar Paradox.

We used Kleene’s Fixed Point Theorem as a lemma on the way to proving Turing’s Theorem. But this is also an important result in its own right, because it provides a foundation for *recursive* programming. It’s often handy to write programs that call themselves. For example, here’s another way of writing the reverse program:

```
def reverse(x):
    if x == "":
        result = ""
    else:
        reversedTail = reverse(tail(x))
        result = reversedTail + head(x)
    return result
```

This program calls the `reverse` program itself. Since each time `reverse` calls itself, the string passed along as the value of `s` gets shorter, eventually these recursive self-calls will bottom out at the empty string. So even though the program calls itself, it will always end up halting. This is very similar to the kind of recursive definitions we've given for functions on numbers and strings.

Self-calling programs like this one are not an official part of Py. But Kleene's theorem shows us how to unpack programs like this in Py, using a *fixed point*. First, we need to state a slightly more general version of Kleene's Theorem, which allows us to also pass a “side argument”:

7.5.9 Proposition (Kleene's Fixed Point Theorem Version 2)

Let $F(x, y)$ be a program. Then there is a program $A(y)$ such that, for any string s ,

$$\llbracket A \rrbracket(s) = \llbracket F \rrbracket(A(y), s)$$

This can be proved in basically the same way as Exercise 7.5.6

Now, suppose we want to write the recursive program `reverse`. Let's start by modifying it a bit. At the point where we wanted to call the `reverse` program itself, instead we can run some *arbitrary* program which is provided as an extra argument.

```
def protoReverse(program, x):
    if x == "":
        result = ""
    else:
        reversedTail = run(program, tail(x))
        result = reversedTail + head(x)
    return result
```

(Here `run` is the Universal Program from Exercise 7.4.4.) Then Proposition 7.5.9 tells us that there is a program $R(x)$ which has the same effect as running the `protoReverse` program with $R(x)$ itself as the first argument.

$$\llbracket R \rrbracket(s) = \llbracket \text{protoReverse} \rrbracket(R(x), s)$$

In other words, $R(x)$ is equivalent to a program that calls $R(x)$ itself! So the simple Py-program $R(x)$ has the same behavior as the recursive program `reverse`. In general, we can construct a recursive program as a fixed point of a “higher-order” program like `protoReverse`. (For this reason, Kleene's Fixed Point Theorem is also known as Kleene's *Recursion Theorem*.)

7.6 Semi-Decidable and Effectively Enumerable Sets

Here is a point that might be a little confusing. The denotation function for programs is computable; but the question of whether a program halts is undecidable. Why can't we use the Universal Program `run` to decide whether a program halts?

We can clarify the relationship between these two facts by introducing another notion: this is something which is less demanding than decidability, but still goes a long way toward it. A *semi-decidable* set is one that can be “decided in one direction”. What that means is that there is an algorithm such that, for any given d , if d is in the set, then the algorithm will eventually tell you so—and the algorithm won't ever tell you something is in the set which really isn't—but if d is *not* in the set, then there is no guarantee that the algorithm will tell you anything at all. The algorithm will tell you the good things are good, and it won't say any bad things are good, but the bad things might just end up crashing or hanging your program instead.

7.6.1 Definition

A **semi-decision procedure** for a set X is a program A such that, for each string $s \in \mathbb{S}$,

$$\llbracket A \rrbracket(s) = \text{True} \quad \text{iff} \quad s \in X$$

But note that if s is *not* in X , $\llbracket A \rrbracket(s)$ isn't guaranteed to return any value at all: it is just required *not* to return the value `True`. A set X is **semi-decidable** iff there is some semi-decision procedure for X .

It follows directly from the definition that every decidable set is semi-decidable. But as the next exercise shows, the converse does not hold.

7.6.2 Exercise

The set of programs that halt is semi-decidable. Thus there is a set which is semi-decidable, but not decidable.

7.6.3 Exercise

Uncountably many sets of strings are not even semi-decidable.

7.6.4 Exercise (Bounded Search)

Let $A(x, y)$ be a program which halts for every input. Use this to write another program $B(y, \text{bound})$ such that, for any strings t and u ,

$\llbracket B \rrbracket(t, u) = \text{True}$ if there is some string s which is no longer than u , such that $\llbracket A \rrbracket(s, t) = \text{True}$.

$\llbracket B \rrbracket(t, u) = \text{False}$ otherwise.

Hint. You can help yourself to a variable called `alphabet` whose value is a long string containing every symbol in the standard alphabet. Actually writing this out would require you to write a very long first line of your program:

```
alphabet = "A" + "B" + "C" + ...
```

One elegant strategy for writing this program uses a *recursive* self-calling program. (We know that recursive self-calls can be eliminated in principle using Kleene's Theorem.)

7.6.5 Exercise (Unbounded Search)

Let $A(x, y)$ be a program which halts for every input. Use Exercise 7.6.4 to write another program $C(y)$ such that, for any string t ,

$\llbracket C \rrbracket(t) = \text{True}$ iff there is some string s (of any length) such that
 $\llbracket A \rrbracket(s, t) = \text{True}$.

If there is no such string, C does not have to return any value at all.

7.6.6 Exercise

Let $X \subseteq \mathbb{S} \times \mathbb{S}$ be a set of pairs of strings. Let

$$X^{\exists} = \{t \in \mathbb{S} \mid \text{there is some } s \in \mathbb{S} \text{ such that } (s, t) \in X\}$$

If X is decidable, then X^{\exists} is semi-decidable.

Hint. Use Exercise 7.6.5.

Semi-decidability is closely linked to another idea. Some sets can be *listed*. The idea is that we can write a program that spits out each element of X one by one. One way to make this idea precise is with computable functions from the natural numbers. For a “listable” set X , we can take any number n and spit out an element of X , such that every element of X shows up for some number n . This is very similar to the idea of a *countable* set—which is a set which is the range of some function from natural numbers. But now we're not just interested in *arbitrary* functions: what we want is a “counting function” which is a nice *computable* function.

If you can decide which things are in a set, then you can list it. If X is decidable,

then one way to list its elements is to go through *every* string one by one in some fixed order, and for each string check whether it's in X . If it is, then spit it out, and if it isn't, then don't spit anything out, and go on to the next string.

But just because you can *list* a set doesn't guarantee that you can determine whether any particular thing is in it. You might try just going through the list looking for the thing you want. This half works. If the thing you want is in the list, then by going through the list one by one, eventually you'll find it, and you can return `True`. But if the thing you want *isn't* in the list, then you'll never find it. But at any point in your search you'll only have looked at finitely many things, so there's no point in your search where you know you never *will* find it, later on. So every effectively enumerable set is *semi*-decidable. But this doesn't mean that every effectively enumerable set is decidable.

We can make these ideas a bit more official.

7.6.7 Definition

A set of strings $X \subseteq \mathbb{S}$ is **effectively enumerable** iff X is the range of some computable total function.

7.6.8 Theorem

If X is effectively enumerable, then X is semi-decidable.

Proof

If X is effectively enumerable, then X is the range of some computable total function f . That is to say,

$$X = \{t \in \mathbb{S} \mid \text{there is some } s \in \mathbb{S} \text{ such that } fs = t\}$$

But also, if f is a computable total function, then the set $Y = \{(s, t) \in \mathbb{S} \mid fs = t\}$ is *decidable*—just calculate fs , and then check whether the result is the same string as t . Since $X = Y^3$, using Exercise 7.6.6 we can conclude that X is semi-decidable. \square

We can also show that this works the other way around: every semi-decidable set is effectively enumerable. But this direction takes significantly more work to officially prove.

7.6.9 Theorem

If X is semi-decidable, then X is effectively enumerable.

Proof Sketch

Suppose that X is semi-decidable: this means we have some program that returns

`True` just for inputs that are in X . We'll use this to show that X is effectively enumerable.

Here's the basic idea. We can go through strings one by one in some fixed order. The obvious thing to try is to check each string, and print it out if we get `True`. The problem with this approach is that the semi-decision program might go into an infinite loop. The first time this happens, the whole program will stop working, which means we'll never get to strings that come later in the list. So we need to make sure we never allow the semi-decision program to go on forever.

Here's how we can do this. We can run a *modified* program, which replaces each `while` loop with a `for` loop that only runs n times, for some number n , and returns `Fail` if the loop-ending condition still hasn't been met at that point. Call this the **n -bounded variant** of a program. If a program halts, then each of its `while` loops only goes through finitely many steps, which means there is *some* number n such that the n -bounded program succeeds.

So here's what we can do. We can go through the *pairs* (s, n) of a string and a number, one by one. For each pair, we'll try to run the n -bounded semi-decision program with input s . If we get `True`, then we print out s . If we get `False` or `Fail` then we don't print out s (yet) and we go on to the next pair. Because we are using bounded programs, the computation we do for each pair can only take finitely many steps. So we'll eventually reach every pair, and so eventually every string that the semi-decision program returns `True` for will get printed out. \square

7.6.10 Exercise

Suppose that X is a decidable set, and Y is a subset of X . Suppose furthermore that Y and $X - Y$ (the set of strings in X but not in Y) are *both* semi-decidable. Then Y is decidable.

TODD. This exercise `is` probably too hard. I would like to refactor this section again.

7.7 Decidability and Logic

Now that we have come to grips with the fundamental ideas of computability, we can apply these ideas to some important questions in logic.

Here's a common problem. You have some premises that you take to be true, and you want to know whether a certain conclusion logically follows from them. In

other words, given some *axioms*, we want to know whether a certain sentence is a *theorem*. This is a task philosophers face all the time, as they are trying to figure out how certain philosophical conclusions fit together with various philosophical starting points. It's an even larger part of what mathematicians do. The question of which conclusions follow from which premises is at least somewhat important in essentially every field of inquiry, and it is often very tricky to answer.

Part of Leibniz's distinctive rationalist vision was that *all* fields of inquiry could be reduced to the problem of determining what follows from what. He wrote:

The only way to rectify our reasonings is to make them as tangible as those of the Mathematicians, so that we can find our error at a glance, and when there are disputes among persons, we can simply say: Let us calculate, without further ado, to see who is right. [CITE "Art of Discovery" 1685, trans. Wiener.]

Leibniz imagined that "reasoning in morality, physics, medicine, or metaphysics" could be reduced to the problem of determining what logically follows from what. And he thought that solving the problem of what logically follows from what was a matter of mere calculation—and so, in principle, *every* question could be systematically answered.

In 1928, the mathematicians David Hilbert gave a challenge to the world. Can you give a general, systematic procedure that can take any statement in first-order logic, and determine whether or not it is a logical truth? If you can do this, you can also solve the more general problem: given any finite set of premises X which are formalized in first-order logic, and given any other first-order sentence A , determine whether A is a logical consequence of X . If we could do this, then we would have a general purpose tool for determining which arguments are valid, as long as we know how to formalize those arguments in first-order logic. This would be extremely handy! This problem is called Hilbert's *Entscheidungsproblem* (which is German for "decision problem").

Unfortunately, Hilbert's challenge can't be met. Like the problem of determining which programs have infinite loops, the problem of deciding which arguments are logically valid in first-order logic is *effectively undecidable*. This fact is called Church's Theorem—and we will prove it now.

The important idea is that we can link up the key concept of this chapter—*computability*—with the two key concepts of the last chapter—*definability* and *representability*. What we have to do is connect *programs* to *formulas*. For every program, there is a corresponding formula in the first-order language of strings that precisely describes what that program does. Once we've made these

connections, the exciting results will basically follow as simple consequences of Tarski’s Theorem from Chapter 6.

The basic idea is very similar to the idea of the Universal Program. We will explicitly represent the state of a program—that is, an assignment function—using a string. Then we will use formulas to describe what each kind of statement in our programming language does. That is, for each step of a program, we can describe the relationship between its “input” and “output” assignments using first-order logic.

We have already discussed how to represent an assignment function as a sequence of strings in Section 7.4, and also how to represent a sequence of strings with a single string in Section 6.3. One thing we’ll need to do is come up with expressions in first-order logic that do the same work as some of the programs we discussed earlier.

7.7.1 Exercise

Recall from Section 7.4 that we can represent a (finite) assignment function as a sequence of key-value strings. Thus we can represent an assignment using a single string, using the idea in Section 6.3 for representing sequences of strings. Show that the following functions are *definable in \mathbb{S}* , with respect to this representation:

- (a) The function that takes each assignment function g and variable x to its value gx .
- (b) The function that takes each assignment function g , variable x , and string s , to the updated assignment function $g[x \mapsto s]$.

Hint. Back in Section 6.3 we showed that certain sequence operations are definable in \mathbb{S} . It will be helpful to use some of those facts.

7.7.2 Exercise

Show that for each Py-term t , the corresponding function that takes each assignment function g to its denotation $\llbracket t \rrbracket g$ is definable in \mathbb{S} .

By the Church-Turing Thesis, we can assume that every computable function is the extension of some Py-program. So to show that every computable function is definable in \mathbb{S} , we just have to show that every *Py-program* has a definable extension. And we can show *this* by induction on the structure of programs. That is, we can prove that every computable function is definable in \mathbb{S} by showing three things:

1. The denotation of the empty program is definable.

2. If the denotation of A is definable, so is the denotation of

$$\begin{array}{c} t_1 = t_2 \\ A \end{array}$$

3. If the denotations of A and B are definable, so is the denotation of

$$\begin{array}{c} \text{while } t_1 \neq t_2 : \\ \quad A \\ \quad B \end{array}$$

The trickiest part is step 3. Recall from Definition 7.2.5 that definition of the denotation of a `while` block uses the idea of a *finite loop sequence*. For terms t_1 and t_2 and a program A , (g_0, \dots, g_n) is a finite loop sequence iff the following three conditions hold:

$$\begin{aligned} g_{i+1} &= \|A\|g_i \quad \text{for each } i < n \\ \|t_1\|g_i &\neq \|t_2\|g_i \quad \text{for each } i < n \\ \|t_1\|g_n &= \|t_2\|g_n \end{aligned}$$

The denotation $\|A\|g$ is the last element of a finite loop sequence whose first element is g , if there is one.

7.7.3 Exercise

Let t_1 and t_2 be Py-terms, and let A and B be programs. Suppose the denotations of A and B (that is, the functions $[g \mapsto \|A\|g]$ and $[g \mapsto \|B\|g]$) are each definable in \mathbb{S} .

- (a) The set of finite loop sequences for t_1 , t_2 , and A is definable in \mathbb{S} .
- (b) The function that takes each assignment g to the denotation

$$\left[\left[\begin{array}{c} \text{while } t_1 \neq t_2 : \\ \quad A \\ \quad B \end{array} \right] \right] g$$

is definable in \mathbb{S} .

7.7.4 Exercise (The Definability Theorem)

Given the Church-Turing Thesis, every computable function is definable in the standard string structure \mathbb{S} .

7.7.5 Exercise

Use Exercise 7.7.4 to show that every decidable set of strings is definable in the string structure \mathbb{S} .

This fact has several important applications. For instance, we can use it to show the definability of certain functions we discussed in Chapter 5—like substitution, the labeling function, and translation functions. To show they’re definable, we just need to show that they’re *computable*. And to show this, we just need to describe some systematic algorithm for computing them. For this, their standard recursive definitions are pretty much already enough.

We can also combine the Definability Theorem with what we showed in the last chapter about *undefinable* sets, in order to derive another important result about *undecidability*.

7.7.6 Exercise

The set of true first-order sentences in the string structure, $\text{Th } \mathbb{S}$, is undecidable.

7.7.7 Exercise

Show that the set of programs that halt is definable in the structure \mathbb{S} . So there are sets of strings which are definable but undecidable.

In fact, we can strengthen these results. We don’t really need the *whole* theory of \mathbb{S} to describe computable functions. Just a pretty small simple piece of this theory is enough.

Let’s start by recalling some definitions from Section 6.9. Each string $s \in \mathbb{S}$ has a *quotation term*, which is a term $\langle s \rangle$ in the language of strings. If f is a partial function from \mathbb{S} to \mathbb{S} , then a theory T **represents** f iff there is a formula $F(x, y)$ such that

$$\begin{aligned} T \models \forall x \exists !y F(x, y) \\ T \models F(\langle s \rangle, \langle f(s) \rangle) \quad \text{for each } s \text{ in the domain of } f \end{aligned}$$

Intuitively, this means that the theory T “knows”, first, that F is functional, and second, that F relates each input string s to the correct output string $f(s)$.

The next thing to remember is the idea of a *sufficiently strong theory* (Section 6.11): this is a theory that interprets the minimal theory of strings \mathbb{S} . (We will focus here on theories that are already expressed in the language of strings, or an expansion of that language, in order to avoid complications involving definitional extensions.)

Sufficiently strong theories can be quite simple—for example, S itself, and the minimal theory of arithmetic Q are each finitely axiomatizable theories that are sufficiently strong. These are much simpler than the full theory of the string structure $\text{Th } \mathbb{S}$. Even so, sufficiently strong theories are powerful enough to describe lots of things. Anything which is *definable* in the string structure \mathbb{S} using a *syntactically simple enough* expression is also *representable* in S , and thus in a sufficiently strong theory. To use the technical term introduced in Section 6.10: anything that is Σ_1 -*definable* in \mathbb{S} is representable in S . A Σ_1 -formula consists of a formula that uses only *bounded* quantifiers—quantifiers that are restricted to strings with a certain maximum length—plus just one unbounded existential quantifier out front.

We can use this fact to prove a stronger generalization of the Definability Theorem:

7.7.8 Representability Theorem, version 1

Any sufficiently strong theory represents every computable function.

To prove the Definability Theorem, we showed that lots of different functions are definable in \mathbb{S} —functions that pick out elements of sequences, update assignments, and so on. We can prove the Representability Theorem by working our way back through this proof, and checking that at each step we can get by using *syntactically simple enough* expressions—that is, just Σ_1 formulas. We won’t work through this in detail. (If you have worked through the “starred” section Section 6.10 and the proof of the Definability Theorem, then you have everything you need to do it yourself.) But let’s think about an intuitive explanation for why this really *should* work out.

The basic idea is that, even though the theory S doesn’t include *all* the truths about strings, it does include all of the “basic” truths, about what any particular string is like internally. For example, for any particular string s , the theory S knows what substrings s has, or how long it is, or whether it contains an A somewhere before a B , and so on. Furthermore, it turns out these kinds of “basic” truths about strings are enough to pin down the behavior of computable functions. Suppose A is a program that returns some value $\llbracket A \rrbracket(s)$ for an input sequence of strings s . Then it turns out that the value of $\llbracket A \rrbracket(s)$ is determined by what *one specific string* is like. There is a string that represents the whole finite sequence of “states” that A steps through (that is, sequences of strings, representing the values of variables), starting with s . Call this sequence of assignments an *A -computation sequence*. (This is an extension of the idea of a *finite loop sequence* that we considered earlier.) We can verify that a string has all the right features to represent an A -computation sequence just by examining its internal structure—ignoring the rest of the infinite universe of

alternative strings. And as we noted, these “internal” facts about a specific string are the sort of thing that the theory S can verify all on its own. More specifically, we can formalize the property of being an A -computation sequence using a *bounded* formula—we don’t need to look at any strings longer than the string that represents the computation sequence itself. Similarly we can formalize the property of being the first or last element of such a sequence using another bounded formula. Then to represent the relation $\llbracket A \rrbracket(s) = s'$, we can use a formula that says this:

There is some string that represents an A -computation sequence whose first element is s , and whose last element is s' .

This has just one unbounded existential quantifier.

That is all we’ll say here about the proof of the Representability Theorem. From here on, we will take the theorem to be established, and use it to show some other important things.

Here’s one immediate application. Remember that in Chapter 6 we used the fact that the minimal theory of strings S represents *syntax*: that is, it represents the substitution function and the labeling function. We can now get these facts as corollaries of the Representability Theorem. It is clear that these functions are *effectively computable*. Indeed, the recursive definitions themselves already amount to an effective method for calculating the results of substitution and labeling. Thus, by the Church-Turing Thesis these functions are *Py-computable*, and thus by the Representability Theorem they are representable in S .

7.7.9 Exercise (Representability Theorem, version 2)

Use the Representability Theorem (version 1) to show that, if X is a decidable subset of \mathbb{S} and T is a sufficiently strong theory, then T represents X .

Hint. Recall this definition: for T to represent X means that there is some formula $F(x)$ such that

$$\begin{aligned} &\text{for each string } s \in X, T \models F\langle s \rangle \\ &\text{for each string } s \notin X, T \models \neg F\langle s \rangle \end{aligned}$$

Note also that if T is sufficiently strong, then

$$T \models \langle \text{True} \rangle \neq \langle \text{strFalse} \rangle$$

7.7.10 Exercise (The Essential Undecidability Theorem)

No sufficiently strong theory is both consistent and decidable.

Hint. Use Tarski’s Theorem.

7.7.11 Exercise (Church’s Theorem)

The set of first-order logical truths (in the language of strings) is undecidable.

Hint. Here are two useful facts to bear in mind. First, the theory S is finitely axiomatizable and sufficiently strong. Second, if A_1, \dots, A_n is some finite list of sentences, then the function that takes each sentence B to the sentence

$$(A_1 \ \& \ \dots \ \& \ A_n) \rightarrow B$$

is computable.

Church’s Theorem shows that Hilbert’s general “decision problem” is impossible. There is no general systematic way to decide which statements are logical consequences of a given set of axioms.

The Essential Undecidability Theorem, which we used to prove Church’s Theorem, is also going to be very important in Chapter 8, so take a bit of time to meditate on what it says. Take any theory T that is strong enough to describe some basic string operations (or a bit of basic arithmetic) but *not* so strong that it includes logical contradictions. Then there is no general systematic method, even in principle, to determine what exactly T says. To put it another way, there is no decidable theory anywhere “in between” the minimal theory of strings (or if you prefer, the minimal theory of arithmetic) and the inconsistent theory. In particular, the minimal theory of strings itself is undecidable (it is a sufficiently strong consistent theory). But furthermore, it is *essentially* undecidable, in the sense that you can’t consistently add anything to it that would make it come out decidable again.

This amounts to a refutation of the strong form of Leibniz’s rationalist vision. *Even if* all questions in “morality, physics, medicine, or metaphysics” can be reduced to questions of logic, this would not make answering them a matter of mere “calculation”—because questions of logic are effectively undecidable.

Chapter 8

The Unprovable

Thus they argued, and intended to go on, but the Empress interrupted them: I have enough, said she, of your chopped logic, and will hear no more of your syllogisms; for it disorders my reason, and puts my brain on the rack; your formal argumentations are able to spoil all natural wit.

Margaret Cavendish, *The Blazing World* (1668)

So far we've been thinking about logic in terms of *structures*: A is a logical consequence of X iff A is true in every structure where each sentence in X is true. To put it another way, a logically valid argument is one with no *counterexamples*, where a counterexample is a structure where the premises are true and the conclusion is false. We'll now look at a different approach to logic, which instead uses the idea of a *formal proof*. A formal proof builds up a complicated argument by chaining together very simple steps. The basic steps are chosen so that they are very closely connected to the basic roles of our logical connectives. Because of this, many people have thought that proofs are in some sense conceptually more basic than structures.

One of the central facts about first-order logic is that these two different ways of thinking about logic perfectly line up. An argument from premises X to a conclusion A has a proof if and only if it has no counterexamples. (This is called **Soundness and Completeness**.) This fact is important because it lets us go from facts which are obvious about provability to corresponding facts about structures which are less obvious, and vice versa. For instance, it will be obvious from the way we

build up proofs that no proof relies on infinitely many premises. From this we can deduce the less obvious fact that no *logical consequence* essentially relies on infinitely many premises. (This is called the **Compactness Theorem**.) Similarly, we can show that a certain argument is not logically valid by coming up with a specific counterexample. From this we can deduce the less obvious fact that the argument has *no proof*.

We can also combine provability with the other ideas we've been exploring. A key fact about our proof system—and indeed, any reasonable system of proofs that a finite being could use to establish results—is that the question of what counts as a correct proof of a certain conclusion is *effectively decidable*. This basic fact, together with the things we have already established about undecidability in Chapter 7, has deep and important consequences. First, we can show that the set of logical truths is effectively enumerable—basically, because proofs are the sort of thing we can systematically list one by one. (This means, in light of Church's Theorem ((Exercise 7.7.11)), that the set of logical truths is another example of a set that is semi-decidable, but not decidable.) More generally, consider any “reasonably simple” theory: a theory that consists of just the logical consequences of some effectively decidable set of *axioms*. Any theory like this is also effectively enumerable. But this leads us directly to Gödel's First Incompleteness Theorem: *no* theory is “reasonably simple”, sufficiently strong, consistent, and complete. Notice in particular that the set of *truths* is sufficiently strong, consistent, and complete (in all but the most impoverished languages); so it follows that the truth cannot be simple. There is no hope, for example, for a rationalist project of writing down elegant axioms from which all truths can be systematically derived. (That is—systematically derived by *finite beings*. Perhaps, as Leibniz believed, God can know some truths by way of *infinite proofs*, which are not covered by this theorem.)

8.1 Proofs

A proof is an expression in a formal language: a string of symbols built up systematically from certain basic pieces using certain rules. In this respect, proofs are just like terms, formulas, and programs. Just like we did with those other formal languages, we will give a recursive definition of the structure of proofs, which will specify some “basic” proof steps and some rules for putting them together. Since the point of a formal proof is to make it very clear and easy to check that a conclusion follows from some premises, there shouldn't be too many different proof rules, and no particular rule should be too complicated. Even so, proofs are our most complicated formal language so far: they are built up from formulas, which are already a bit complicated, and there are multiple proof rules for each one of the

basic logical connectives we use to build up formulas ($\&$, \neg , $=$, and \forall). So we'll take it slow.

There are many different formal proof systems for first-order logic, which make different trade-offs. We'll use what's called a *natural deduction* system. The key feature of natural deduction systems is that they let us make intermediate suppositions in our proofs—the kind of step that we express in our ordinary informal proof using the word “suppose”. We do this when we use the technique of proof by contradiction. Here's a classic example—the reasoning of Russell's Paradox:

Suppose x is a set such that for any y , y is an element of x iff y is not an element of y . So, in particular, x is an element of x iff x is not an element of y . We can derive a contradiction from this claim. First, suppose that x is an element of x . In that case, by the claim, x is not an element of x . This is a contradiction, so it follows that x is not an element of x . But in that case the claim implies that x is an element of x . This is a contradiction again. So the claim must be false. This shows that there is no set x such that, for any y , y is an element of x iff y is not an element of y .

In a natural deduction system, the formalized version of the proof has basically the same structure as the informal proof. It's a bit more austere, a bit more repetitive, and some steps get rearranged a bit. It looks like this.

```
for arbitrary x:
  suppose  $\forall y (y \in x \leftrightarrow \neg(y \in y))$ :
    suppose  $x \in x$ :
       $x \in x$  Assumption
       $\forall y (y \in x \leftrightarrow \neg(y \in y))$  Assumption
       $x \in x \leftrightarrow \neg(x \in x)$  \forall Elim
       $x \in x$  Assumption
       $\neg(x \in x)$  \leftrightarrow Elim
       $\neg(x \in x)$  Reductio
       $\forall y (y \in x \leftrightarrow \neg(y \in y))$  Assumption
       $x \in x \leftrightarrow \neg(x \in x)$  \forall Elim
       $x \in x$  \leftrightarrow Elim

    suppose  $x \in x$ :
       $x \in x$  Assumption
```

$\forall y (y \in x \leftrightarrow \neg(y \in y))$	Assumption
$x \in x \leftrightarrow \neg(x \in x)$	$\forall E$ lim
$x \in x$	Assumption
$\neg(x \in x)$	\leftrightarrow Elim
$\neg(x \in x)$	Reductio
$\neg\forall y (y \in x \leftrightarrow \neg(y \in y))$	Reductio
$\forall x \neg\forall y (y \in x \leftrightarrow \neg(y \in y))$	\forall Intro

The main difference from the informal version is that we have formalized all of the logical connectives, and we have cut out almost all of the other words. We use indentation to help keep the structure of the proof clear without transition words like “in that case.” Another difference is that our official proof syntax is a bit more restrictive than you may be used to when it comes to *order* you put the steps of the proof in. (The reason for this is just because it makes our official definitions simpler, which will make it a little easier to prove things *about* formal proofs.) Each rule has to come immediately below the parts of the proof that it relies on. This also has the effect of making our proofs extra repetitive. For example, in this proof, the subargument for $\neg(x \in x)$ is repeated twice. That’s because this conclusion is really used twice in the proof: once on the way to the first conclusion $x \in x$, and a second time to state the contradictory conclusion $\neg(x \in x)$. Our official proof syntax will require us to prove things over again each time we use them.

In practice, a convenient notational shorthand is to leave out redundant subproofs, and instead just refer to the line number where we originally derived that step. (We have to be careful not to cheat, though, and refer to conclusions from within **Reductio** subproofs that wouldn’t actually be correct in the current context.) Using this convention a lot lets us rewrite the formal proof in a way which is much more concise, and maybe a bit less alien-looking.

1	for arbitrary x :
2	suppose $\forall y (y \in x \leftrightarrow \neg(y \in y))$:
3	suppose $x \in x$:
4	$x \in x \leftrightarrow \neg(x \in x)$ $\forall E$ lim (2)
5	$\neg(x \in x)$ \leftrightarrow Elim (3, 4)
6	$\neg(x \in x)$ Reductio (3, 5)
7	$x \in x \leftrightarrow \neg(x \in x)$ $\forall E$ lim (2)
8	$x \in x$ \leftrightarrow Elim (6, 7)
9	$\neg\forall y (y \in x \leftrightarrow \neg(y \in y))$ Reductio (8, 6)
10	$\forall x \neg\forall y (y \in x \leftrightarrow \neg(y \in y))$ \forall Intro

Another detail is that **\leftrightarrow Elim** is not really one of the *basic* rules of our system—

indeed, \leftrightarrow is not officially one of our basic connectives. So what we have written here is an abbreviation of the full official proof, which would spell out the biconditional using $\&$ and \neg , and derive the rule of \leftrightarrow from the corresponding basic proof rules for those connectives. We'll see how this works very soon.

Proof systems that don't allow intermediate assumptions are called "Hilbert-style" systems. The main advantage of natural deduction proofs over Hilbert-style proofs is that they are more intuitive to read and write. The main disadvantage is that natural deduction proofs are a bit more structurally complex than Hilbert-style proofs. A natural deduction proof isn't just a "flat" list of statements: it has interesting syntactic structure. But by this point we have plenty of experience handling complex syntax.

Our proof system has twelve rules. We can group them into five families—one family for each basic logical connective ($\&$, \neg , $=$, and \vee) plus a few extra "structural" rules for putting pieces together. We'll start by taking a quick informal tour of these rules and how to use them, after which we'll give an official definition that summarizes them.

The main point of a proof is to show that a certain conclusion follows from certain premises—in particular, that the conclusion is *provable* from the premises. If X is set of formulas and A is a formula, the notation $X \vdash A$ means that the conclusion A is provable from premises in X . We use the same notational shortcuts for the "single turnstile" notation for provability as we have been using for the "double turnstile" notation for logical consequence. For instance, $X, A, B \vdash C$ means the same thing as $X \cup \{A, B\} \vdash C$. The official definition of provability will come later—after we have gone through all the pieces of the definition of proofs. But we will be able to show lots of things about provability before we get that far, as we build up some particular examples of formal proofs. (This is just like how we could go ahead and show certain things about *decidability* long before we had finished our full official definition of *programs*.)

Assumption

The simplest kind of proof just asserts something we already know—either because it is one of our premises, or because we have supposed it for *reductio*. We call this rule **Assumption**.

8.1.1 Example

For any formula A , and any set of formulas X ,

$$X, A \vdash A$$

Proof

A Assumption

Obviously we can't do very much with the **Assumption** rule all by itself. But we usually need it to get a more complicated proof started.

Something to notice right away is that a proof of A from some premises X doesn't actually have to explicitly use all of those premises. It's okay to just ignore some premises. (In this way, classical logic is unlike *relevant logic*, which does require every premise to actually play a role in the argument.) So, for example, consider the proof

$\forall x (\text{suc } x \neq 0)$ Assumption

This counts as a proof of $\forall x (\text{suc } x \neq 0)$ from just the premise $\forall x (\text{suc } x \neq 0)$ itself, but it also counts as a proof of this conclusion from *bigger* premise sets that include this particular formula—for example, the set of all the axioms of minimal arithmetic.

Conjunction Rules

Next we have some rules for reasoning about conjunction. The ideas are simple. If we have proved A and B , then we can deduce the conjunction $A \& B$. We call this rule Conjunction Introduction, or **&Intro** for short. For example:

- | | | |
|---|-----------------------------|------------|
| 1 | $1 + 0 = 1$ | Assumption |
| 2 | $1 \neq 0$ | Assumption |
| 3 | $(1 + 0 = 1) \& (1 \neq 0)$ | &Intro |

In general, to prove $A \& B$, first we write down a proof of A , then we write down a proof of B , and finally we deduce the conjunction.

8.1.2 Example

For any formula A ,

$$A \vdash A \& A$$

Proof

A Assumption
 A Assumption
 $A \& A$ &Intro

Something to notice is that our official proof repeats the assumption *twice*. We have a proof of A , and then *another* proof of A (though of course really it's the same proof) and finally we deduce the conjunction. In practice, this is the sort of thing we might abbreviate, like this:

1	A	Assumption
2	$A \ \& \ A$	&Intro (1, 1)

This indicates that we're using the same subproof (the one ending at line 1) twice over. \square

Another basic proof rule is that, if we have proved $A \ \& \ B$, then we can deduce A . Likewise, if we have proved $A \ \& \ B$, we can deduce B . These two rules are called &Intro1 and &Intro2. (Notice that we really need *two* rules here. As always, even though $A \ \& \ B$ and $B \ \& \ A$ are logically equivalent, that doesn't make them the same formula.)

8.1.3 Example

For any formulas A and B ,

$$A \ \& \ B \vdash B \ \& \ A$$

<i>Proof</i>		
1	$A \ \& \ B$	Assumption
2	B	&Elim2 (1)
3	A	&Elim1 (1)
4	$B \ \& \ A$	&Intro (2, 3)

If we spell out the repetitive steps explicitly, it looks like this:

$A \ \& \ B$	Assumption
B	&Elim2
$A \ \& \ B$	Assumption
A	&Elim1
$B \ \& \ A$	&Intro

8.1.4 Example

For any formulas A , B , and C ,

$$A \ \& \ (B \ \& \ C) \vdash (A \ \& \ B) \ \& \ C$$

Proof

Notice that in the officially spelled out proof, the premise $A \And (B \And C)$ gets used three times, and so there are three repeated **Assumption** lines.

$A \And (B \And C)$	Assumption
A	$\And\text{Elim1}$
$A \And (B \And C)$	Assumption
$B \And C$	$\And\text{Elim2}$
B	$\And\text{Elim1}$
$A \And B$	$\And\text{Intro}$
$A \And (B \And C)$	Assumption
$B \And C$	$\And\text{Elim2}$
C	$\And\text{Elim2}$
$(A \And B) \And C$	$\And\text{Intro}$

Notice the structure of this proof. Before the last line

$(A \And B) \And C$	$\And\text{Intro}$
---------------------	--------------------

there are two subproofs: first, a proof of $(A \And B)$, and second, a proof of C . Similarly, the line

$A \And B$	$\And\text{Intro}$
------------	--------------------

comes after two subproofs; first, a proof of A , and then a proof of B . □

The rules for conjunction follow a pattern. We have one *introduction rule*, which lets us derive a conjunction as a conclusion. We also have two *elimination rules*, which let us use a conjunction as a premise to derive something else. This pattern is typical: we will also have introduction and elimination rules for other logical connectives, like $=$ and $\forall x$. (Negation is a bit special, though.)

8.1.5 Exercise

For any formula A ,

$A \And A \vdash A$

Negation Rules

Our tool for “proving a negative” is proof by contradiction, also called *reductio ad absurdum*, or **Reductio** for short. To prove $\neg A$, suppose A , and then derive a contradiction from this supposition.

8.1.6 Example

For any formulas A and B ,

$$\neg A \vdash \neg(A \ \& \ B)$$

Proof

1	suppose	$A \ \& \ B$:
2		$A \ \& \ B$	Assumption
3		A	&Elim1
4		$\neg A$	Assumption
5		$\neg(A \ \& \ B)$	Reductio

In this proof, we add an extra assumption, $A \ \& \ B$. We use this assumption to derive a contradiction: that is, first we have a subproof for A , and then we have another subproof for $\neg A$. Then we can conclude that our original assumption was false.

In general, **Reductio** looks like this. To get a proof of $\neg A$, first we write down **suppose** A :. Then we write down two subproofs: a proof of some formula B (this can be any formula we want), and a proof of its negation $\neg B$. These subproofs can use A as an **Assumption** step wherever we want (in addition to any other assumptions we already had available). Finally, we write down our conclusion, $\neg A$ by **Reductio**. Here is the template:

suppose	A	:
	:	
	B	
	:	
	$\neg B$	
	$\neg A$	Reductio

We'll state the rules more rigorously in Section 8.2.

An alternative label for **Reductio** is **¬Intro** (following the same **Intro/Elim** naming pattern as conjunction). Feel free to use it if you prefer. But I'll stick with the traditional medieval name.

We don't have a proof rule that lets us derive conclusions from an arbitrary negated premise. Instead, we have *double-negation elimination*, or **¬¬Elim** for short. If we have a proof of $\neg\neg A$, then underneath it we can write the line

$$A \quad \neg\neg\text{Elim}$$

8.1.7 Exercise (Explosion)

$A, \neg A \vdash B$.

Remember, officially our language only includes the connectives $\&$ and \neg . Formulas using other connectives, like \rightarrow and \vee , are officially considered to be abbreviations of formulas using $\&$ and \neg . Similarly, we will only officially have basic *proof rules* for the connectives $\&$ and \neg . But we can use the definitions of these other connectives to derive their standard proof rules, as well.

8.1.8 Example (Modus Ponens)

For any formulas A and B ,

$$A, (A \rightarrow B) \vdash B$$

Proof

Recall that we defined the conditional $A \rightarrow B$ to be an abbreviation for $\neg * A \& \neg B$. So what we want to show is

$$A, \neg * A \& \neg B \vdash B$$

□

We can show this by providing a formal proof.

suppose	$\neg B$:
	A	Assumption
	$\neg B$	Assumption
	$A \& \neg B$	$\&Intro$
	$\neg(A \& \neg B)$	Assumption
	$\neg\neg B$	$\neg\text{Reductio}$
	B	$\neg\text{--Elim}$

8.1.9 Exercise (Modus Tollens)

For any formulas A and B ,

$$A, (A \rightarrow \neg B) \vdash \neg A$$

8.1.10 Exercise (Disjunction Introduction)

For any formulas A and B ,

$$A \vdash (A \vee B)$$

$$B \vdash (A \vee B)$$

(Recall that $A \vee B$ is officially an abbreviation for $\neg\neg A \& \neg B$.)

It's also useful to show some relationships between different provability facts. For example:

8.1.11 Example (Conditional Proof)

If $X, A \vdash B$, then $X \vdash A \rightarrow B$.

(This is also sometimes called the Deduction Theorem.)

Proof

Suppose that P is a proof of B from the premises $X \cup \{A\}$. We want to use P to build up a more complex proof of $A \rightarrow B$ which only relies on the premises X . Remember, $A \rightarrow B$ is officially an abbreviation for $\neg * A \& \neg B$. So we can schematically put together a proof like this.

```

1 suppose A & ~B :
2   A & ~B      Assumption
3     A          &Elim1
4
5   suppose A :
6     P          # This is a proof of $B$ from $X$ and $A$
7
8     A & ~B    Assumption
9     ~B          &Elim2
10    ~A          Reductio
11  ~( A & ~B )  Reductio

```

Notice in particular that this proof does not rely on the assumption A : this assumption is available within the inner `Reductio` subproof, but not outside of it. So this is a proof of $\neg * A \& \neg B$ that just relies on the premises X . (The whole proof uses these premises because the subproof P uses them and they have not been caught by any `suppose` line.) \square

8.1.12 Exercise (Contraposition)

$X, A \vdash B$ iff $X, \neg B \vdash \neg A$.

Identity Rules

We also have an introduction rule and an elimination rule for the identity symbol $=$. The introduction rule says that we can always prove a thing is identical to itself (from no premises). That is, we can always write a one-line proof of $a = a$, where a is any term. The pattern-following name for this is [=Intro](#), and the traditional name is simply [Identity](#). (Feel free to use either one.)

The elimination rule says (putting it a bit roughly) that if we know a and b are the very same thing, and we have also proved that a has a certain property, then we can conclude that b has the property as well. Our more official version doesn't say anything about *properties*, though: instead we do it by substituting the terms a and b into a certain formula.) If we have a proof of $a = b$ and a proof of $A(a)$, then we can stick those proofs together and then deduce $A(b)$. This is called either [=Elim](#) or [Leibniz's Law](#).

8.1.13 Example

For any terms a and b ,

$a = b \vdash b = a$	
Proof	
$a = b$	Assumption
$a = a$	=Intro
$b = a$	=Elim

In this proof, we have a one-line subproof of $a = b$, then another one-line subproof of $a = a$. We can think of this second proof as saying that a has the property of being identical to b —so the last line concludes that b also has this property. More officially, what's going on is that the second line is the result of plugging a into the formula $x = a$, and the third line is the result of plugging b into that same formula. \square

8.1.14 Exercise (Euclid's Property)

For any terms a , b , and c ,

$$a = b, a = c \vdash b = c$$

Quantifier Rules

Finally, the universal quantifier also has an introduction rule and an elimination rule. Let's consider the elimination rule first, because it's easier. If we know that *everything* has a certain property, then we also know that each particular thing has that property. Again, our official version of the rule doesn't say anything about "properties", and uses substitution instead. Given $\forall x \ A(x)$, we can deduce $A(a)$.

$$\text{AElim} : \forall x \ A \vdash A[x \mapsto a]$$

8.1.15 Exercise (Existential Generalization)

For any term a and formula $A(x)$,

$$A(a) \vdash \exists x \ A(x)$$

(Recall that $\exists x \ A(x)$ is officially an abbreviation for $\neg \forall x \ \neg A(x)$.)

The final rule is the subtlest. First, we should call attention to something that has been in the background so far. In our proof system, the steps of a proof can include *free variables*—they don't have to be whole sentences. For example, this is a perfectly fine proof.

1	$x = 0 + x$	Assumption
2	$x > 0$	Assumption
3	$0 + x > 0$	=Elim

Here we have used the free variable x and the open term $0 + x$ as our terms a and b for an application of Leibniz's Law (=Elim, plugging each of these terms into the formula $y > 0$). Variables, and terms that include variables, can be used just like any other terms in our proofs.

It might seem odd to allow this, but it actually reflects an important aspect of our informal proofs. Remember the example we considered earlier—the reasoning of Russell's paradox. It looked like this.

Suppose x is a set such that y , y is an element of x iff y is not an element of y . So [more reasoning here, where we derive a contradiction from this assumption]. This shows that there is no set x such that, for any y , y is an element of x iff y is not an element of y .

We were trying to prove a certain generalization: there is *no* set with a certain property. (We could formalize this "no" claim as a universal generalization: $\forall x \ \neg \forall y \ (y \in x \leftrightarrow \neg(y \in y))$.) In order to do it, we introduced an informal

variable with the statement “Let x be a set”. We then went on to prove things “about x ”—that is, we made a bunch of statements that used that variable. But the variable isn’t meant to stand for any particular thing, the way a name would. (Indeed, we show in the end that there *isn’t* anything with the property we are supposing. It isn’t as if x were a name for a non-existent Russell-set.) It’s really a hard philosophical problem to say exactly what the variable x means in this kind of reasoning.¹ But in any case we can understand why the reasoning is correct: what we are showing is that x has certain properties, given certain assumptions, *no matter what x might be*.

Our formalization of this reasoning looks like this.

```

1  for arbitrary x:
2    suppose ∀y (y ∈ x ↔ ¬(y ∈ y)):
3      :   # This is where we derived a contradiction
4      ¬∀y (y ∈ x ↔ ¬(y ∈ y))          Reductio
5  ∀x ¬∀y (y ∈ x ↔ ¬(y ∈ y))          ∀Intro

```

(The systematic name for this rule is `∀Intro`. Its traditional name is [Universal Generalization](#).)

In this argument, we consider an *arbitrary* thing x . We then go on to prove that this arbitrary x does not have the Russell-set-property, and so we can conclude that *nothing* has the Russell-set-property—that is, there is no Russell set.

What does it mean for x to be “arbitrary”? In our formal proofs, what it means is that we don’t rely on any special assumptions about what x is like. The key feature that lets us generalize in the last step is that the subproof within the “for arbitrary x ” bit does not rely on any assumptions in which x is a free variable.

(This constraint is a little bit subtle. We *can* have x as a free variable in an [Assumption](#) line within that subproof, if it’s an assumption we’ve introduced for [Reductio](#). But we can’t use any assumptions about x that we bring in “from outside.”)

The general form of the rule looks like this:

```

for arbitrary y :
:
A(y)
∀ x A(x)  ∀Intro

```

¹For example, see Breckenridge and Magidor (2012).

The inner subproof should prove $A(y)$ without relying on any assumptions that include y as a free variable. The details of this rule are explained more precisely in Section 8.2.

8.1.16 Exercise

- (a) $\vdash \top$.
- (b) $\bot \vdash A$, for any formula A .

(Recall that \top is an abbreviation for the standard truth, $\forall x (x = x)$, and \bot is an abbreviation for the standard falsehood $\neg\top$.)

8.1.17 Exercise (Change of Variables)

For any variables x and y , and for any formula $A(x)$ in which y does not occur free,

$$\forall x A(x) \vdash \forall y A(y)$$

8.1.18 Exercise (Existential Instantiation)

Suppose x is not free in B or in any formula in X . Then,

$$\text{If } X, A(x) \vdash B \text{ then } X, \exists x A(x) \vdash B$$

This fact corresponds to a kind of reasoning we've often used in our informal proofs. Suppose we know that there is something with the property A . Then we can "give it a name"—we suppose in particular that x has the property A . The sequent $X, A(x) \vdash B$ corresponds to reasoning that uses the assumption that x , in particular, is one of the A 's. The name we choose had better be "arbitrary", in the sense that we haven't made any other assumptions about x already. If we can draw a conclusion B that doesn't say anything specifically about x , then that conclusion *also* follows from the mere existential claim that *something* is A .

8.2 Official Syntax

Now that we have gone over the rules for putting together proofs informally, it's time to give an official definition. The informal bits and pieces are enough when we want to show particular things are provable. But the official recursive definition is important for proving things about *all* proofs. There are three main facts about provability that we will show using the recursive definition.

1. *Compactness*. No formal proof essentially relies on infinitely many premises.

2. *Soundness.* If you can formally prove a conclusion from some premises, then the conclusion is a *logical consequence* of those premises in the sense we defined in Chapter 5. In other words, no argument has both a proof and a counterexample.
3. *Decidability.* The question of what counts as a formal proof is effectively decidable. The question of what is *provable* from a decidable set of premises is not always decidable, but it is at least *semi-decidable*. (We'll return to this one in Section 8.5.)

8.2.1 Definition

We recursively define the relation ***P* is a proof of *A* from the premises *X***, or ***P* proves $X \vdash A$** for short, where *X* is any set of sentences and *A* is any sentence.

1. For any sentence *A* and any set of sentences *X*,

A	Assumption
---	------------

proves $X, A \vdash A$.

2. If *P* proves $X \vdash A$, and *Q* proves $X \vdash B$, then

P	
Q	
A & B	&Intro

proves $X \vdash A \& B$.

3. If *P* proves $X \vdash A \& B$, then

P	
A	&Elim1

proves $X \vdash A$.

4. If *P* proves $X \vdash A \& B$, then

P	
B	&Elim2

proves $X \vdash B$.

5. If *P* proves $X, A \vdash B$, and *Q* proves $X, A \vdash \neg B$, then

```
suppose A :
  P
  Q
   $\neg A$       Reductio
```

proves $X \vdash \neg A$.

6. If P proves $X \vdash \neg\neg A$, then

```
P
A      \neg\negElim
```

proves $X \vdash A$.

7. For any term a ,

```
a = a      =Intro
```

proves $X \vdash a = a$.

8. For any terms a and b , and any formula A (in which x is free for both a and b), if P proves $X \vdash a = b$, and Q proves $X \vdash A[x \mapsto a]$, then

```
P
Q
A[x → b]      =Elim
```

proves $X \vdash A[x \mapsto b]$.

9. For any term a and formula A (in which a is free for x), if P proves $X \vdash \forall x A$, then

```
P
A[x → a]      \forall Elim
```

proves $X \vdash A[x \mapsto a]$.

10. Suppose P proves $X \vdash A[x \mapsto y]$, where y is a variable which is not free in any formula in X , and y is free for x in A . Then

```
for arbitrary y :
  P
   $\forall x A$       \forall Intro
```

proves $X, Y \vdash \forall x A$, for any set of formulas Y .

(Typically x and y will just be the same variable, but the official rule is more flexible to help us avoid variable name clashes that come up once in a while.)

As in any recursive definition, we can say “that’s all”: P proves $X \vdash A$ *only* when this statement can eventually be reached by applying these rules.

Those are our official syntax rules. These rules are pretty rigid, but there are a bunch of ways in which we relax these official rules when we are writing out formal proofs in practice. (These shortcuts are analogous to the notational flexibility we have allowed ourselves for terms, formulas, and programs.)

- We are rather free with whitespace.
- We use all of our usual notational shortcuts for writing down formulas and terms.
- We use “derived rules” like Modus Ponens as if they were part of our basic repertoire.
- In rules like `&Intro`, `=Elim`, and `Reductio` that have two subproofs P and Q , we sometimes mix up the order of the two subproofs.
- Instead of repeating a whole proof of a statement, sometimes we will just write the line number where the statement was previously proved (as long as that earlier proof didn’t use any assumptions that aren’t available for our subproof). When we use this style, we also can just refer to the line number of a `Suppose` line to indicate that we are using a corresponding one-line proof by `Assumption`.

8.2.2 Definition

- We say P is a **proof** iff there are some X and A such that P proves $X \vdash A$.
- We say A is **provable from** X (abbreviated $X \vdash A$) iff there is some proof P such that P proves $X \vdash A$.

8.2.3 Example (Standard truth)

$X \vdash \top$ for any set of formulas X .

Proof

Recall that `T` is an abbreviation for $\forall x (x = x)$. We can write a formal proof:

```
for arbitrary x:
  x = x      =Intro
   $\forall x$  (x = x)   $\forall$ Intro
```

Let's explicitly check that this is a proof of $X \vdash \forall x x = x$, using Definition 8.2.1.

First, the subproof $x = x$ =Intro is a proof of $\emptyset \vdash x = x$. Furthermore, the variable x does not appear free in any formula in the empty set. Thus the whole thing proves $X \vdash \forall x x = x$.

(One detail to notice is that the \forall Intro rule lets us add in the extra premises from X , which aren't used in the subproof. This is important, because in general those premises might include the free variable x , in which case we aren't allowed to use them in the inner proof.) \square

8.2.4 Example

For any set of formulas X and any formula A ,

If $X, \neg A \vdash \perp$ then $X \vdash A$

Proof

Remember that \perp is an abbreviation for $\neg T$. Suppose that P proves $X, \neg A \vdash \neg T$. We can use this to put together a proof for $X \vdash A$, as follows. Let Q be the proof given by Example 8.2.3 for $X, \neg A \vdash T$. Then the following proves $X \vdash A$.

```
suppose  $\neg A$  :
  Q
  P
   $\neg\neg A$       Reductio
  A             $\neg\neg$ Elim
```

To be explicit: since

Q proves $X, \neg A \vdash T$
 P proves $X, \neg A \vdash \neg T$

this means the Reductio part proves

$X \vdash \neg\neg A$

Thus the whole proof with the $\neg\neg$ Elim step proves

$X \vdash A$ \square

We have spelled out a definition of how proofs are put together, and what each proof proves. But often what we are most interested in is not the details of what *proofs* are like, but just what is *provable* somehow or other. So it's helpful to summarize the recursive definition of proofs (Definition 8.2.1) just in terms of what it tells us about what is provable, leaving out all the syntactic details about what the proof that proves it happens to look like. This straightforwardly follows from (Definition 8.2.1).

8.2.5 Proposition

Provability is closed under each of the following rules.

$$\begin{array}{c}
 \frac{}{X, A \vdash A} \text{Assumption} \\
 \\
 \frac{X \vdash A \quad X \vdash B}{X \vdash A \& B} \text{\&Intro} \quad \frac{X \vdash A \& B}{X \vdash A} \text{\&Elim1} \quad \frac{X \vdash A \& B}{X \vdash B} \text{\&Elim2} \\
 \\
 \frac{X, A \vdash B \quad X, A \vdash \neg B}{X \vdash \neg A} \text{Reductio} \quad \frac{X \vdash \neg \neg A}{X \vdash A} \text{\neg\negElim} \\
 \\
 \frac{}{X \vdash a = a} \text{=Intro} \quad \frac{X \vdash a = b \quad X \vdash A[x \mapsto a]}{X \vdash A[x \mapsto b]} \text{=Elim} \\
 \\
 \frac{X \vdash A[x \mapsto y]}{X, Y \vdash \forall x A} \text{\forallIntro}, \text{ where } y \text{ is not free in } X \quad \frac{X \vdash \forall x A}{X \vdash A[x \mapsto a]} \text{\forallElim}
 \end{array}$$

Taking this perspective, we can give more elegant (informal) proofs of (formal) provability facts, which abstract from the details of what particular proofs look like. For example, we can redo the proof of Example 8.2.4 much more compactly, by leaving out all of the syntactic details of proofs.

Second proof

We want to show:

If $X, \neg A \vdash \perp$ then $X \vdash A$

We do this as follows.

$X, \neg A \vdash \top$	Standard truth exercise
$X, \neg A \vdash \neg \top$	by assumption
$X \vdash \neg \neg A$	Reductio
$X \vdash A$	$\neg \neg$Elim

□

Another common presentation style for this kind of proof uses a diagram. Here is a third way of presenting the same proof of Example 8.2.4.

Third proof

$$\frac{\begin{array}{c} X, \neg A \vdash \top \\ \hline \end{array} \text{Standard truth exercise} \quad \begin{array}{c} X, \neg A \vdash \neg \top \\ \hline \end{array} \text{Reductio}}{\frac{X \vdash \neg \neg A}{X \vdash A} \text{ } \neg \neg \text{Elim}} \quad \square$$

□

Each line in the diagram corresponds to some fact we know about provability—either from the definition, or from things we have already shown. This spare presentation style is common in proof theory. (But it is entirely optional.)

8.2.6 Exercise

Use Proposition 8.2.5 to show

$$A, (A \rightarrow B) \vdash B$$

(Recall that $(A \rightarrow B)$ is officially an abbreviation for $\neg * A \& \neg B$.)

Proofs and provability are defined recursively. This means we can do yet another kind of proof by induction: induction on *proofs*. This works essentially the same way as induction on terms, formulas, or programs. Let's start with an example.

8.2.7 Example (Weakening)

For any sets of formulas X and Y , and any formula A , if $X \vdash A$, then $X, Y \vdash A$.

Proof

Let Y be any set. We will prove the following by induction on proofs:

For any P , X , and A such that P proves $X \vdash A$, P also proves $X, Y \vdash A$.

This proof is long and tedious, but not difficult. This is typical of induction on proofs. The proof has ten steps, corresponding to the ten rules for putting together proofs.

1. (**Assumption**) Consider a proof

A	Assumption
---	------------

which proves $X, A \vdash A$. Then clearly this same proof also proves $X, Y, A \vdash A$. (Note that $(X \cup Y) \cup \{A\}$ and $(X \cup \{A\}) \cup Y$ are the very same set of premises—the order doesn’t matter.)

2. (**&Intro**) Let P prove $X \vdash A$ and let Q prove $X \vdash B$. We *suppose* (for the inductive hypothesis) that P also proves $X, Y \vdash A$ and Q also proves $X, Y \vdash B$. We want to *show* that the proof

P
Q
A & B &Intro

also proves $X, Y \vdash A \& B$. This immediately follows from the part of Definition 8.2.1 for **&Intro**.

3. (**&Elim**) Let P prove $X \vdash A \& B$. *Suppose* for the inductive hypothesis that P also proves $X, Y \vdash A \& B$. We want to *show* that

P
A &Elim1

proves $X, Y \vdash A$. Again, this is clear from the part of Definition 8.2.1 for **&Elim1**.

4. (**&Elim2**) This step goes just like **&Elim1**.

5. (**Reductio**) Let P prove $X, A \vdash B$ and let Q prove $X, A \vdash \neg B$. *Suppose* that P also proves $X, Y, A \vdash B$ and Q also proves $X, Y, A \vdash \neg B$. (Again, note that the order of premises doesn’t matter.) We want to *show* that

suppose A :	
P	
Q	
¬A Reductio	

also proves $X, Y \vdash \neg A$. Again, this follows from Definition 8.2.1.

And so on. The remaining steps continue in just the same way. For each rule, we suppose for our inductive hypothesis that each component proof can be “weakened” by adding more unused premises, and then we put these “weakened” component proofs back together using the very same rule. The only step that is slightly trickier is **\forall Intro**.

10. (**\forall Intro**) Let P prove $X \vdash A[x \mapsto y]$ where y is not free in X . Suppose that P also proves $X, Y \vdash A[x \mapsto y]$. We want to *show* that

```
for arbitrary y:
  P
  ∀x A      ∀Intro
```

also proves $X, Z, Y \vdash \forall x A$. In this case, we can just ignore the inductive hypothesis: since P proves $X \vdash \forall x A$ and x is not free in X , the definition tells us that this **\forall Intro** proof also proves $X, Z, Y \vdash \forall x A$. \square

8.2.8 Technique (Proof by induction on proofs)

Suppose you want to prove that *every* proof of a conclusion from premises is *nice*. That is, you want to show that whenever P proves $X \vdash A$, the triple of P , X , and A is nice. You can show this in ten steps, one for each proof rule. In each step, you consider a proof put together from subproofs using one of the ten rules. Suppose that each of the subproofs are nice, and *show* that this implies the whole proof is nice as well. Then you are done.

Sometimes you use this technique to show something that isn’t explicitly about *proofs* at all, but just about what is *provable*. The trick is that, in order to show

Whenever $X \vdash A$, _____

(fill in the blank) it is enough to show

Whenever P proves $X \vdash A$, _____

You can show this by induction on the syntax of proofs.

8.2.9 Example (Provability is Compact)

If $X \vdash A$, then there is a finite subset $X_0 \subseteq X$ such that $X_0 \vdash A$.

The basic reason for this is that each proof has just finitely many steps, and each step of a proof only relies on finitely many premises, so the proof can only rely on finitely many premises all together. This is intuitively clear enough. But to get

some practice with provability-induction, let's go ahead and show this fact in detail. It's a little trickier than you might expect.

Proof

We prove this by induction on proofs. Again, there are ten steps, and again this proof is long and tedious, but easy. We'll just spell out a few parts of it, to get the idea. We will show more specifically that whenever P proves $X \vdash A$, there is some finite subset $X_0 \subseteq X$ such that P proves $X_0 \vdash A$ as well.

1. (**Assumption**) Any proof by assumption of $X, A \vdash A$ is also a proof of $A \vdash A$, and $\{A\}$ is a finite subset of $X \cup \{A\}$.
2. (**&Intro**) Let P prove $X \vdash A$ and let Q prove $X \vdash B$. Suppose for the inductive hypothesis that there are finite subsets $X_0 \subseteq X$ and $Y_0 \subseteq X$ such that P proves $X_0 \vdash A$ and Q proves $Y_0 \vdash B$. By Weakening, we also have

$$\begin{aligned} P \text{ proves } X_0, Y_0 \vdash A \\ Q \text{ proves } X_0, Y_0 \vdash B \end{aligned}$$

and $X_0 \cup Y_0$ is also a finite subset of X . Then the proof

P
Q
A & B &Intro

proves $X_0, Y_0 \vdash A \& B$ as well.

We'll skip steps 3–8, since they all go basically the same way.

9. (**VElim**) Let P prove $X \vdash \forall x A$. Suppose for the inductive hypothesis that there is a finite subset $X_0 \subseteq X$ such that

$$P \text{ proves } X_0 \vdash \forall x A$$

Then

P
A[x ↦ t] VElim

proves $X_0 \vdash A[x \mapsto t]$.

10. (**VIntro**) Let P prove $X \vdash A[x \mapsto y]$ (where y is not free in any formula in X) and suppose that there is a finite subset $X_0 \subseteq X$ such that

$$P \text{ proves } X_0 \vdash A[x \mapsto y]$$

Then

```
for arbitrary y:
  P
   $\forall x \ A$        $\forall \text{Intro}$ 
```

also proves $X_0 \vdash \forall x \ A$, and X_0 is a finite subset of $X \cup Y$.

That completes the induction. \square

8.2.10 Exercise

Fill in the steps for `Reductio`, `$\neg\neg\text{Elim}$` , and `=Intro` in the inductive proof of Example 8.2.9.

8.2.11 Exercise

Let X be a set of formulas. Use the fact that Provability is Compact to show that, if every finite subset of X is consistent, then X is consistent (in the proof-theoretic sense).

Here's another important fact: you can stick two proofs together to get a proof. If you have a proof of a conclusion A , and another proof that uses A as a premise, then you can stick those together into one proof. Spelling that out a bit more, suppose you have a proof of $X \vdash A$, and another proof of $Y, A \vdash B$, which uses the conclusion of the first proof as a premise. Then by "sticking together" these proofs, we get a proof of $X, Y \vdash B$. That is, our conclusion is still B , but we don't rely on A as a premise anymore—since it is proved along the way. Instead, we have whatever premises the first proof used to prove A .

8.2.12 Example (Cut)

If $X \vdash A$ and $Y, A \vdash B$, then $X, Y \vdash B$.

Proof

We'll prove this by induction on proofs again. This time, we have to choose which of the two statements to do the induction on—the "upper proof" $X \vdash A$, or the "lower proof" $Y, A \vdash B$. The intuitive idea is that we can add the steps of the lower proof onto the upper proof, one by one. This gives us a clue that the lower proof is the one we want to do induction on. In other words, we will prove:

Whenever P proves $Y, A \vdash B$, if $X \vdash A$, then $X, Y \vdash B$.

It might be helpful to put that even more explicitly in the "official" form for a state-

ment to proved inductively. Let X be a set of formulas, and let A be a formula, and suppose $X \vdash A$. We want to show that every triple (P, Y', B) such that P proves $Y' \vdash B$ has the following property:

For any set of formulas Y , if $Y' = Y \cup \{A\}$, then $X, Y \vdash B$.

What we have to show is that every proof *inherits* this property from its subproofs. As usual there are ten parts to this proof. It is still long and tedious, but not quite as straightforward as some of the others. We'll go through some of the steps, and leave the rest as exercises.

In order to avoid some messiness (in the `VIntro` step in particular), we'll make a simplifying assumption: no variable x is both *free* in some formula in X , and also used as an *arbitrary* variable somewhere in the proof P (appearing in a line `for arbitrary x ::`). If a clash like this did come up, we could always just switch to using a different variable in the proof P . This would still be a perfectly good proof of the same conclusion from the same premises.²

(But what if X is an infinite set that uses up *all* of the free variables? To avoid this case, we can start by finding a finite subset $X_0 \subseteq X$ such that $X_0 \vdash A$. This is guaranteed to only have finitely many free variables. Then we can use the same argument we give below to prove that, if $Y, A \vdash B$, then $X_0, Y \vdash A$. Finally, $X, Y \vdash A$ follows by Weakening.)

1. Consider a proof of $Y, A \vdash B$ by `Assumption`. This means B must be an element of $Y \cup \{A\}$. That is, either B is A , or else $B \in Y$.

If $A = B$, then since we have already assumed that $X \vdash A$, we know $X \vdash B$. So by Weakening, $X, Y \vdash B$.

If $B \in Y$, then in fact the same proof by `Assumption` also proves $Y \vdash B$. So again by Weakening, $X, Y \vdash B$.

In either case, we have $X, Y \vdash B$, which is what we needed to show for this part.

2. Consider a proof of $Y, A \vdash B \And C$ by `&Intro`. This has two subproofs:

P proves $Y, A \vdash B$

Q proves $Y, A \vdash C$

²This complication in our proof of Cut is very closely parallel to the complication that “captured” variables introduced for our definition of substitution in formulas (Definition 5.1.7). In general, there is a close analogy between Cut and substitution. *Premises* in proofs are closely analogous to *free variables* in terms and formulas. This is part of a family of analogies called the “Curry-Howard correspondence.”

For the inductive hypothesis, we suppose that each of these subproofs have the property. This means:

$$\begin{aligned} X, Y \vdash B \\ X, Y \vdash C \end{aligned}$$

Then we can put together these two new proofs into another proof using **&Intro**: this shows

$$X, Y \vdash B \And C$$

This is what we needed to show.

The steps for **&Elim1** and **&Elim2** are left as an exercise.

5. Consider a proof by **Reductio** of $Y, A \vdash \neg B$. This also has two subproofs (for some formula C):

$$\begin{aligned} P \text{ proves } Y, A, B \vdash C \\ Q \text{ proves } Y, A, B \vdash \neg C \end{aligned}$$

In this case our inductive hypothesis says:

$$\begin{aligned} X, Y, B \vdash C \\ X, Y, B \vdash \neg C \end{aligned}$$

Then we can put these back together with **Reductio**, to conclude:

$$X, Y \vdash \neg B$$

Again, this is what we needed to show for this part.

6. Consider a proof by **\neg\neg-Elim** of $Y, A \vdash B$. This has one subproof:

$$P \text{ proves } Y, A \vdash \neg\neg B$$

We suppose for the inductive hypothesis:

$$X, Y \vdash \neg\neg B$$

Then we can use **\neg\neg-Elim** again to conclude

$$X, Y \vdash B$$

The steps for **=Intro**, **=Elim**, and **\forall Elim** are left as exercises. The only step with some fiddly business is **\forall Intro**.

10. Consider a proof by $\forall\text{Intro}$ of $Y, A \vdash \forall x B$. This has one subproof. The premises of this subproof are a subset of $Y \cup \{A\}$ in which the variable y is not free. So there are two cases, depending on whether this subset includes A . There is a subset $Z \subseteq Y$, in which y is not free, such that either

$$P \text{ proves } Z \vdash B[x \mapsto y]$$

or else

$$P \text{ proves } Z, A \vdash B[x \mapsto y]$$

But the first case also implies the second case, by Weakening. So either way, our inductive hypothesis tells us

$$X, Z \vdash B[x \mapsto y]$$

We want to show that $X, Y \vdash \forall x B$. Here is where we'll use our simplifying assumption: since the variable y is used an arbitrary variable in this proof, by assumption it is not also a free variable in any formula in X . This means we can use $\forall\text{Intro}$ again to conclude

$$X, Y \vdash \forall x B$$

□

8.2.13 Exercise

Fill in the missing steps in the proof of Cut (Example 8.2.12).

Cut is handy for putting different provability facts together.

8.2.14 Example

TODO.

One important thing about formal proofs is that they line up with the notion of logical consequence we introduced in Section 5.3. Remember, there we said that A is a logical consequence of X iff the argument from X to A has no *counterexamples*: there is no structure in which every sentence in X is true, and A is false. In first-order logic, proofs and structures fit together neatly. First, if an argument has a *proof*, then it *has no counterexamples*. This fact is called *Soundness*. Second, if an argument *does not* have a counterexample, then it *does* have a proof. This fact is called *Completeness*. Putting the two facts together, they tell us that every argument has a proof or a counterexample, but not both.

The Completeness Theorem takes quite a bit of work to prove; this is in Section 8.3. But at this point we already have everything we need to prove the Soundness Theorem pretty straightforwardly.

8.2.15 Theorem (Soundness)

Let X be a set of formulas, and let A be a formula. If A is provable from X , then A is true in every model of X . In short:

$$\text{If } X \vdash A \text{ then } X \vDash A$$

Proof beginning

We will prove by induction that every proof P of $X \vdash A$ has the property that $X \vDash A$. To show this, we need to show that this property is inherited from subproofs.

It will be helpful to refer back to some facts about logical consequence that we showed back in Section 5.3.

1. (**Assumption**) For this step, we need to show that $X, A \vDash A$. This is clearly true: A is true in every model of $X \cup \{A\}$.
2. (**&Intro**) For this step, we suppose that $X \vDash A$ and $X \vDash B$, and show that $X \vDash A \& B$. We already proved that this follows in Section 5.3.
3. (**&Elim1**) For this step, we suppose that $X \vDash A \& B$, and prove that $X \vDash A$. Again, we proved this in Section 5.3.

Checking the steps for the remaining proof rules is left as an exercise. □

8.2.16 Exercise

Fill in the remaining steps of the proof of the Soundness Theorem, using facts about logical consequence from Section 5.3.

Before we move on, we should check a few more basic facts about provability that we will need later on.

8.2.17 Example (Contraposition)

If $X, A \vdash B$ then $X, \neg B \vdash \neg A$.

Proof

$$\frac{\frac{X, A \vdash B}{X, \neg B, A \vdash B} \text{ Weakening}}{X, \neg B \vdash \neg A} \quad \frac{}{X, \neg B, A \vdash \neg B} \text{ Assumption} \\ \frac{}{X, \neg B \vdash \neg A} \text{ Reductio}$$

□

8.2.18 Exercise

The following are equivalent:

$$\begin{aligned} & X \vdash \perp \\ & X \vdash A \text{ and } X \vdash \neg A \quad \text{for some } A \\ & X \vdash A \quad \text{for every } A \end{aligned}$$

In Section 5.3 we defined “consistent” to mean “has a model”. For this section and the next, we’ll use a different definition of “consistent” instead.

8.2.19 Definition

A set X is **inconsistent** iff $X \vdash \perp$. (Exercise 8.2.18 gives us two other equivalent ways of saying this.) Otherwise X is consistent.

When we want to contrast the two meanings of “consistent”—this definition using proofs, and our earlier definition using models—we can distinguish *proof-theoretic* consistency and *model-theoretic* consistency. It is also common to call these *syntactic* consistency and *semantic* consistency, respectively. (But this terminology, while standard, is less transparent and more philosophically loaded.)

In the next section we’ll show that in fact these two definitions exactly line up for first-order logic. That’s why it isn’t usually such a big deal to have two different definitions for the same word. But until we’ve proved that fact, we will need to be careful about which one we are talking about. And while we are showing things about formal proofs, it will be convenient to keep the word “consistent” reserved for the proof-theoretic notion.

8.2.20 Exercise

If X has a model, then X is proof-theoretically consistent: that is, $X \not\vdash \perp$.

8.3 The Completeness Theorem

The Soundness Theorem shows that no argument has *both* a proof *and* a counterexample. There are “not too many” proofs or counterexamples, so they don’t come into conflict with one another. What we’ll now show is that every argument has one or the other: any argument with no countermodels has a formal proof. There are “enough” proofs and countermodels to settle the validity of every argument. The proof of this fact—the Completeness Theorem—is quite a bit trickier than the proof of the Soundness Theorem. For Soundness, we just needed to go through all the basic proof rules and make sure none of them led to trouble. For Completeness, though, we need to start with something that *doesn’t* have a proof, and show that it *does* have a countermodel—and in this case induction on the structure of proofs is no help.

(Note that this is a different sense of the word “complete” from our earlier definition of a (negation-)*complete theory*—that is, a theory that includes each sentence or its negation. The two senses of “complete” are related, though. If you have a negation-complete theory, you can’t add any extra sentences without introducing inconsistencies. If you have a complete proof system, you can’t give proofs for any extra arguments without adding proofs for invalid arguments.)

Our strategy is to show that *any proof-theoretically consistent set of sentences has a model*. Given a set of sentences X which does not prove any contradictions, we can build up a structure in which every sentence in X is true. We’ll do this in four stages: we’ll start by constructing models for sets of very simple formulas, and work up to more complicated formulas little by little.

- **Stage 1.** First, suppose X is a set of formulas which don’t include any logical symbols at all: X only contains *relation* formulas of the form $R(a, b)$. We’ll start by constructing a model for X in this simple case.
- **Stage 2.** Next, we’ll show how we can extend the idea of Stage 1 so it also works for a set X that contains *identity* formulas, of the form $a = b$. This is called a **canonical model**.

(A formula which is either of the form $R(a, b)$ or of the form $a = b$ is called an **atomic formula**.)

- **Stage 3.** Next, we’ll allow X to include formulas with the other logical connectives (\neg , $\&$, and \vee). But we’ll make the further assumption that, not only is X consistent, but also X is *completely specific*, in two different senses.

The first sense is that X has an answer to every “yes-or-no” question. For

each formula A , either A or $\neg A$ is in X . (That is, X is **negation-complete**.)

The second sense is that X has an answer to every “which” question. For each formula $A(x)$, either X names some particular example of a thing that satisfies $A(x)$ —that is, X includes some substitution instance $A(t)$ —or else X says that *nothing* satisfies $A(x)$ —that is, X includes $\forall x \neg A(x)$. (In this case we say X is **witness-complete**.)

We can show that if X is consistent and specific in both of these ways, then X has a model. (In fact, the same model we constructed in Stage 2 turns out to work.)

- **Stage 4.** We’ll show that *any* consistent set of sentences X can be *extended* to a consistent set of formulas X^+ which is completely specific in those two senses. Since Stage 3 shows that this extended set X^+ has a model, this will also be a model of the smaller set X .

Stage 1: Relation Formulas

Our first job is to show how to come up with a model for a set of relational formulas. Suppose we are given a set X that just contains formulas of the form $R(a, b)$. We want to come up with a model of X . We want to come up with some objects for our formal language to “talk about”, and some way of interpreting each of the basic pieces of vocabulary in this language. This doesn’t have to be a *plausible* interpretation of the language: it’s fine for us to interpret the constant symbol \emptyset as denoting a fish or a mountain or whatever we want. We just have to come up with some structure or other that satisfies X .

How can we do this? We want a very general recipe that is going to work for *any* consistent theory. But this seems a bit magical. All we know about our set of formulas is that it doesn’t prove any contradictions. Just given this, we have to conjure some domain of real things for the language to talk about! What sort of things are guaranteed to exist, just given an abstract formal language?

Here’s the trick: we can use the *expressions of the language itself* as the domain of a structure. (Of course the existence of a consistent theory guarantees the existence of *linguistic* things!) It turns out that we can interpret the language as talking about *itself!*

8.3.1 Definition

Suppose X is some set of relational L -formulas (of the form $R(a, b)$ where R is an L -predicate and a and b are L -terms). Let the **simple model** for X be the pair of a structure S and an assignment function g given as follows.

1. The domain D_S is the set of all L -terms.
2. For each constant symbol c in L , the extension c_S is the constant term c itself.
3. For each one-place function symbol f , the extension f_S is the function that takes each L -term a to the L -term fa .
4. For each two-place function symbol f , the extension f_S is the function that takes each pair of L -terms a and b to the L -term $f(a, b)$.
5. For each relation symbol R in L , the extension R_S is the set of pairs (a, b) of a term a and a term b such that $X \vdash R(a, b)$.
6. The assignment function g is the function that takes each variable x to itself.

8.3.2 Exercise

Let X be a set of relational formulas, and let S and g be the structure and assignment from Definition 8.3.1.

- (a) Every L -term a denotes itself: that is, $\llbracket a \rrbracket_{Sg} = a$.
- (b) For every L -formula A , (S, g) satisfies A iff $X \vdash A$.

Stage 2: Identity Formulas

Now we'll try to come up with a model that will also work for *identity* formulas. Suppose, for example, that X includes the sentence $\text{suc } 0 = \text{suc } 0 + 0$. Notice that the simple model from Stage 1 definitely won't satisfy this sentence. On the “linguistic” interpretation, $\text{suc } 0$ denotes itself, the term $\text{suc } 0$, while $\text{suc } 0 + 0$ denotes the term $\text{suc } 0 + 0$, and these two terms are different. So on the “self-referential” Stage 1 interpretation, $\text{suc } 0 = \text{suc } 0 + 0$ will come out false. So we'll need to modify the Stage 1 structure to make it possible for *different* terms to denote the same thing.

What we want to do is “blur together” some of the different elements of the domain of the Stage 1 structure. There is a neat general trick for doing this, called the method of *equivalence classes*. Instead of using the terms themselves as the elements of our domain, we can use special *sets* of terms. Each set will contain some terms that are *equivalent* to one another, in the sense that X says that $a = b$. The key observation here is that, even if a and b are two different terms, if a and b are equivalent, then *the set of terms that are equivalent to a* , and *the set of terms that are equivalent to b* are the very same object. So *sets* of terms can do the job of satisfying the right identity formulas.

8.3.3 Definition

Let X be a set of L -formulas.

1. Terms a and b are **equivalent** given X iff $X \vdash a = b$.
2. For any term a , the **equivalence class** of a is the set of all terms which are equivalent to a given X : that is,

$$E(a) = \{b \in L\text{-terms} \mid X \vdash a = b\}$$

(So E is a function that takes each L -term to a set of L -terms.)

8.3.4 Exercise

For any L -terms a and b , $E(a) = E(b)$ iff a and b are equivalent in X .

8.3.5 Exercise

- (a) For any L -terms a and b , if $E(a) = E(b)$, then for any one-place function symbol f , $E(fa) = E(fb)$.
- (b) State the generalization of (a) for two-place function symbols. (But you don't have to prove this separately.)

8.3.6 Definition

Let X be a set of atomic formulas. The **canonical model** for X is the pair (S, g) of a structure and assignment constructed as follows.

1. The domain of S is the range of E . That is, D_S is the set of all equivalence classes of L -terms.
2. For each constant c , the value c_S is the equivalence class $E(c)$.
3. For each one-place function symbol f , the extension f_S is a function from equivalence classes to equivalence classes, defined so that for each term a :

$$f_S(E(a)) = E(fa)$$

This is well-defined, because if $E(a) = E(b)$, then $E(fa) = E(fb)$ as well.

4. The clause for two-place function symbols is similar.
5. For each relation symbol R , the extension R_S is the set of pairs

$$\{(E(a), E(b)) \mid X \vdash R(a, b) \text{ for any } L\text{-terms } a \text{ and } b\}$$

6. For each variable x , the assignment g takes the variable x to its equivalence class $E(x)$.

8.3.7 Exercise

Let X be a set of atomic formulas, and let (S, g) be the canonical model for X .

- (a) Every L -term a denotes its own equivalence class:

$$\llbracket a \rrbracket_{Sg} = E(a)$$

- (b) For any two-place relation symbol R and any L -terms a and b ,

$$(S, g) \text{ satisfies } R(a, b) \quad \text{iff} \quad X \vdash R(a, b)$$

- (c) For any L -terms a and b ,

$$(S, g) \text{ satisfies } a = b \quad \text{iff} \quad X \vdash a = b$$

8.3.8 Exercise

Is the domain of the canonical model countable or uncountable? Explain.

Stage 3: Negation-Complete and Witness-Complete Theories

The Stage 2 model correctly handles atomic formulas, including identity. But so far it doesn't "know about" the rest of logic.

For example, consider the set $X = \{\exists x (f(x) = c)\}$. This set X doesn't imply any identities for *any* two distinct terms. So in fact, the canonical model for X has as its domain the singleton sets for every term, and in this structure the extension of the function symbol f takes each set $\{t\}$ to the singleton set $\{f(t)\}$. This function doesn't map anything to the singleton set $\{c\}$. So if we construct the canonical model for X in the same way as Stage 2, the existential claim $\exists x (f(x) = c)$ will turn out to be *false*, even though X "says" that it's true.

The trouble here is that X includes an "unwitnessed" generalization: it says that *something* has to satisfy a condition (getting mapped to c), but it doesn't provide any specific example of a thing that satisfies that condition. We can avoid this problem if we add an extra specificity constraint, that insists that every generalization has a specific "witness". For Stage 2, we want to consider a "completely specific" set of formulas. Here's what that means.

8.3.9 Definition

Let X be a set of L -formulas.

1. X is **negation-complete** iff for every L -formula A , either $A \in X$ or $\neg A \in X$.
(This is the same as our earlier definition of “complete” from Section 5.3.)
2. X is **witness-complete** iff for every L -formula $A(x)$, either there is some L -term t such that $A(t) \in X$, or else $\forall x \neg A(x) \in X$.

8.3.10 Exercise

If X is consistent and negation-complete, then $X \vdash A$ iff $A \in X$.

8.3.11 Exercise

Suppose that X is consistent, negation-complete, and witness-complete.

- (a) $\neg A \in X$ iff $A \notin X$.
- (b) $A \& B \in X$ iff $A \in X$ and $B \in X$.
- (c) $\forall x A(x) \in X$ iff for every term t , $A(t) \in X$.

8.3.12 Exercise

Suppose that X is consistent, negation-complete, and witness-complete. Let X_0 be the set of atomic formulas in X , and let (S, g) be the canonical model for X_0 (as in Definition 8.3.6). For any formula A ,

$$(S, g) \text{ satisfies } A \quad \text{iff} \quad A \in X$$

Hint. Use induction on the complexity of A . Exercise 8.3.7 and Exercise 8.3.11 will help.

8.3.13 Lemma

Suppose X is a consistent, negation-complete, and witness-complete set of formulas. Then X has a model.

Proof

By Exercise 8.3.12, the canonical model for the set of atomic formulas in X is a model of X . \square

Stage 4: Extending a Consistent Set

The last step is to get from an *arbitrary* consistent set to a bigger set which is also negation-complete and witness-complete. To do this, we'll use the following three facts about consistency.

8.3.14 Exercise

If $X \cup \{A\}$ is inconsistent, and $X \cup \{\neg A\}$ is inconsistent, then X is inconsistent.

8.3.15 Exercise

If $X_0 \subseteq X_1 \subseteq X_2 \subseteq \dots$ is a chain of consistent sets, then their union $\bigcup_n X_n$ is consistent.

Hint. Recall this fact from back in Chapter 2: if Y is a *finite* subset of $\bigcup_i X_i$, then there is some number n for which Y is a subset of X_n .

8.3.16 Lemma

Suppose that X is a consistent set of formulas. Then X has a consistent and negation-complete extension.

Proof

The idea is that we can go through all the formulas one by one, and in each case if it's consistent with what we already have we can add it in, and otherwise we can add in its negation. We can make this idea precise with an inductive argument. There are countably infinitely many formulas: so we can put them all in an infinite sequence, so each formula is A_n for some number n . Then we can recursively define a sequence of sets, as follows:

$$\begin{aligned} X_0 &= X \\ X_{n+1} &= \begin{cases} X_n \cup \{A_n\} & \text{if this is consistent} \\ X_n \cup \{\neg A_n\} & \text{otherwise} \end{cases} \end{aligned}$$

We start with our original consistent set X , and go through all the formulas adding it or its negation. We can prove by induction that for every number n , X_n is consistent. For the base case, X_0 is consistent by assumption. For the inductive step, we need to show that if X_n is consistent, then either $X_n \cup \{A_n\}$ is consistent or else $X_n \cup \{\neg A_n\}$ is consistent. This follows from Exercise 8.3.14: this exercise showed that if both of these two sets are *inconsistent*, then X_n must also be inconsistent.

So each set X_n is consistent. Furthermore, these sets form a chain $X_0 \subseteq X_1 \subseteq X_2 \subseteq \dots$. Thus, by Exercise 8.3.15, it follows that their union $X^+ = \bigcup_n X_n$ is

also consistent. Furthermore, it's clear that for every formula A , either $A \in X^+$ or $\neg A \in X^+$: so X^+ is a consistent, negation-complete extension of X . \square

8.3.17 Exercise

Suppose that y is not free in any formula in X or in $A(y)$. If $X \cup \{A(y)\}$ is inconsistent, and $X \cup \{\forall x \neg A(x)\}$ is inconsistent, then X is inconsistent.

8.3.18 Lemma

Suppose that X is a consistent set of *sentences*. Then X has a consistent witness-complete extension. That is, there is some consistent and witness-complete set of formulas Y such that $X \subseteq Y$.

Proof

The reason we start with *sentences* and end up with *formulas* in this case is that we'll use free variables in order to come up with enough terms to have a specific instance of every generalization—so we need to guarantee that we haven't already “used up” too many variables to start out with.³

The proof is very similar to Lemma 8.3.16. Once again, we'll list the formulas A in an infinite sequence, so each formula is $A_n(x)$ for some number n . We'll also come up with a sequence of variables: for each n , let y_n be a variable which is not free in any of the formulas $A_0(x), \dots, A_n(x)$, and which is distinct from each of the earlier variables y_0, \dots, y_{n-1} . There is always such a variable, because there are only finitely many free variables in each formula, and there are infinitely many variables to choose from.

Then, as before, we can recursively define a sequence of sets X_n , as follows:

$$\begin{aligned} X_0 &= X \\ X_{n+1} &= \begin{cases} X_n \cup \{A_n(y_n)\} & \text{if this is consistent} \\ X_n \cup \{\forall x \neg A_n(x)\} & \text{otherwise} \end{cases} \end{aligned}$$

First, note that for each n , the variable y_n is not free in any formula in X_n . (This

³This restriction to just sets of sentences is avoidable. Instead, we could add infinitely many new *constants* to our language in order to get enough fresh terms to serve as witnesses to every generalization. But if we did things that way, we would need to prove some (easy, but tedious) facts about the relationship between consistent sets of formulas in *different languages*. Alternatively, we could start with a “relettering” step, switching around all of the free variables in a way that leaves infinitely many variables unused. But this approach also depends on proving tedious consistency facts about relettered sets of formulas.

relies on the fact that no variables are free in X_0 .) Then we can show by induction that each set X_n is consistent. For the inductive step, we need to show that for any consistent set, we can always consistently add either $A_n(y_n)$ (with an unused variable y_n), or else $\forall x \neg A_n(x)$. This follows from Exercise 8.3.17: if both of these additions are inconsistent, then so is the original set. Since we have assumed that X_0 is consistent to begin with, by induction every set X_n is consistent.

It then follows that the union $X^+ = \bigcup_n X_n$ is also consistent. Furthermore, it's clear from the construction that for every formula $A(x)$, either $A(y) \in X^+$ for some term y , or else $\forall x \neg A(x) \in X^+$. So X^+ is a consistent and witness-complete extension of X . \square

8.3.19 Exercise (Henkin's Lemma)

If X is a consistent set of sentences, then X has a model.

Hint. Put the previous three lemmas together (in the right order).

8.3.20 Exercise (The Completeness Theorem)

If $X \models A$, then $X \vdash A$.

8.3.21 Exercise (The Compactness Theorem)

If $X \models A$, then there is a finite subset $X_0 \subseteq X$ such that $X_0 \models A$.

Before we move on, we should note another neat consequence of the way we proved the Completeness theorem. We didn't just show that every consistent set has some model or other. In fact, for any consistent set of sentences X we gave a specific recipe for a *canonical* model for a set of formulas that includes X . An important feature of this model is that it is not too big. So we can prove the following fact as well.

8.3.22 Exercise (The Downward Löwenheim-Skolem Theorem)

If X has a model, then X has a *countable* model.

As you might guess from the name, there is also an “upward” version of this theorem. Here is what it says:

8.3.23 The Upward Löwenheim-Skolem Theorem

If X has a model with an infinite domain D , then for any set D^+ with at least as many elements as D , X has a model with domain D^+ .

Putting both directions together, we get this result:

8.3.24 The Löwenheim-Skolem Theorem

If X has an infinite model, then X has a model of every infinite size.

Proving the “upward” theorem uses ideas that go beyond this text. (See CITE.) The basic idea is that we can add in lots of harmless copies of the elements of the structure without affecting any of the first-order truths.

8.4 Models of Arithmetic*

UNDER CONSTRUCTION

Discuss: the Inductive Principle, first-order PA and induction schema.

Discuss: the standard model, and standard models of arithmetic more generally. (Isomorphism. Give an example: domain is $\{2, 3, 4, \dots\}$, addition given by $(m + n - 4)$, etc.)

8.4.1 Exercise

Consider a structure S for the language of arithmetic. If S is a standard model of arithmetic, then every element of the domain of S is the denotation of some numeral:

$$0 \quad \text{suc } 0 \quad \text{suc suc } 0 \quad \dots$$

8.4.2 Exercise

Consider the signature of the language of arithmetic with one additional constant symbol c . The theory

$$\text{Th } \mathbb{N} \cup \{c \neq 0, c \neq 1, c \neq 2, \dots\}$$

has a model.

8.4.3 Exercise

There is a non-standard model of arithmetic: that is, there is a structure which is a model of $\text{Th } \mathbb{N}$ and which is not isomorphic to the standard model \mathbb{N} .

TODO. Discuss the gap between the induction schema and the Inductive Principle.

8.5 The Incompleteness Theorem

One nice feature of formal proofs is that they are computationally tractable—much more so than structures. We can systematically check whether any particular string of symbols is a proof, and, if so, what it proves. This gives us another important connection between two of the main ideas of this course: *decidability* and *provability*. Furthermore, the Soundness and Completeness Theorems tell us that *provability* exactly lines up with *logical consequence* (in our earlier sense involving structures). This lets us—at last!—use things we have learned about undecidable sets to find logical limits on simple theories.

What is a simple theory? Earlier (Section 5.4) we considered some theories that consisted of the logical consequences of a finite set of axioms. We also considered some theories like PA and ZFC which *aren't* finitely axiomatizable, but are still “simple” in the important sense. Now that we have the tools of computability theory at our disposal, we can describe this more carefully. Even though the set of axioms of First-Order Peano Arithmetic isn't a *finite* set, it is still a *decidable* set: there is a simple mechanical rule for answering the question “Is this an axiom of PA?”. Very often that is enough.

Recall that a set of sentences X *axiomatizes* T iff T is the set of all of the logical consequences of X . Using Soundness and Completeness, we can now equivalently say that X axiomatizes T iff, for every sentence A ,

$$A \in T \quad \text{iff} \quad X \vdash A$$

8.5.1 Definition

A theory T is **effectively axiomatizable** iff there is some effectively decidable set of sentences X that axiomatizes T . We usually just say “axiomatizable” for short.

So instead of our loose notion of a “simple theory”, we now have the precise notion of an *axiomatizable* theory.

8.5.2 Exercise

Suppose that X is an effectively decidable set of formulas. Explain why the set of pairs (P, A) such that $P : X \vdash A$ is effectively decidable, using Definition 8.2.1.

(Officially showing this in detail—by writing a program—would be a big job. You don't have to do that: just describe the basic idea of an algorithm for checking whether P is a proof of A from X .)

For the following exercises, it will be helpful to refresh your memory of the things we showed about semi-decidable and effectively enumerable sets in Section 7.6.

8.5.3 Exercise

- (a) Suppose that X is a decidable set of formulas. Show that the set of formulas A such that A is provable from X is semi-decidable.

(Thus the set of formulas which are provable from X is also effectively enumerable.)

- (b) Give an example of a decidable set of formulas X such that the set of formulas that are provable from X is not decidable. Explain.

8.5.4 Exercise

- (a) Any effectively axiomatizable theory is effectively enumerable.
 (b) The set of logical truths is effectively enumerable.

8.5.5 Exercise

If X is a set of sentences which is effectively enumerable, consistent, and negation-complete, then X is decidable.

8.5.6 Exercise (Gödel's First Incompleteness Theorem)

No theory is sufficiently strong, axiomatizable, consistent, and complete.

8.5.7 Exercise

For each of the following theories, say (i) whether it is axiomatizable, and (ii) whether it is negation-complete. Briefly explain.

- (a) The theory of strings $\text{Th } \mathbb{S}$.
- (b) The theory of arithmetic $\text{Th } \mathbb{N}$.
- (c) The minimal theory of strings \mathbb{S} .
- (d) First-order Peano Arithmetic PA.
- (e) First-order set theory ZFC (supposing this is consistent and sufficiently strong, which we have not shown).
- (f) The set of all logical truths.
- (g) The set of all sentences.

8.6 Gödel Sentences

Lots of interesting theories are sufficiently strong, axiomatizable, and consistent. The minimal theory of strings is like this, and so is the minimal theory of arithmetic. So are lots of reasonable axiomatic theories that extend or interpret these, like Peano Arithmetic, first-order set theory, or many formalized physical theories. Gödel's First Incompleteness Theorem tells us that no theory like this is complete: for any theory like this, there are sentences that can be neither proved nor disproved.

Our version of “Gödel's First Incompleteness Theorem” is a bit anachronistic. What we proved is a little different from what Gödel proved in 1931, and the way we proved it is also a bit different.⁴ In several respects, we actually proved a bit more than Gödel did (with the benefit of hindsight). But in one important respect, we did a bit less. Consider the theory of Peano Arithmetic (PA). We know that there *exist* sentences in the first-order language of arithmetic which PA neither proves nor disproves. But so far we haven't actually given any *example* of such a sentence. In this sense, unlike Gödel's proof, our proof of the First Incompleteness Theorem was not *constructive*. Can we do better?

Let's start by trying to reverse engineer the proof we already gave. We showed, first, that if a theory T is effectively axiomatizable, then its theorems are effectively enumerable. Second, if T is also consistent and complete, then T is *decidable*. This means that if T is also sufficiently strong, then T can *represent* the set of sentences that are provable from T 's axioms. In other words, there is some formula $\text{Prov}_T(x)$

⁴In fact, to be historically accurate, all three of the notions “sufficiently strong”, “effectively axiomatizable”, and “consistent” in the statement of the theorem need some qualification.

1. Gödel didn't know about the theories Q or S (in particular, he didn't know that theories quite as simple as this could represent every decidable set). So he used a different definition of “sufficiently strong”, which referred to a much richer formal theory: the one given in Russell and Whitehead's *Principia Mathematica*, PM. Since PM interprets Q, Gödel's notion of “sufficiently strong” follows from ours.
2. Gödel didn't know about Church and Turing's definitions of computable functions and decidable sets, or the Church-Turing Thesis—and certainly not our programming language Py. (Church and Turing's definitions were both developed in 1936. In fact, Gödel also developed his own equivalent definition of computability in 1933.) So instead of talking about an “effectively axiomatizable” theory (which has a *decidable* set of axioms), he talked about a theory that has a *primitive recursive* set of axioms. This turns out to be equivalent to what can be expressed in Py using only `for` loops, instead of `while` loops. Every primitive recursive set is also decidable.
3. Gödel's proof turned on a stronger consistency requirement, called ω -consistency. We'll discuss this below.

that represents T within T :

$$\begin{array}{ll} T \vdash \text{Prov}_T(A) & \text{if } T \vdash A \\ T \vdash \neg \text{Prov}_T(A) & \text{otherwise} \end{array}$$

Then, by Gödel's Fixed Point Theorem, we have a sentence G which is equivalent (in T) to $\neg \text{Prov}_T(G)$. But this implies that T is inconsistent (by Tarski's Theorem).

But in fact, in a theory T which is consistent, running that last step backwards tells us that there really isn't any formula $\text{Prov}_T(x)$ that represents T within T . This is exactly what Tarski's Theorem (Exercise 6.11.7) tells us. So of course we can't really get an example of an undecidable sentence G by taking a fixed point of the negation of this non-existent formula.

But we can still do something very similar! Here's something else we know: if T is effectively axiomatizable, then the relation “ P is a proof of A from T 's axioms” is decidable. For short, call this the **T -proof relation**. So, if T is sufficiently strong, we can represent this relation in T , using a formula $\text{Proof}_T(x, y)$.

$$\begin{array}{ll} T \vdash \text{Proof}_T(P)(A) & \text{if } P \text{ is a proof of } A \text{ from } T \text{'s axioms} \\ T \vdash \neg \text{Proof}_T(P)(A) & \text{otherwise} \end{array}$$

Now consider the formula $\exists x \text{ Proof}_T(x, y)$. It's customary to call this formula $\text{Prov}_T(y)$ —the *provability* formula for T . But we have to be very careful about this. As we just said, by Tarski's Theorem we know that this formula can't really represent provability in T (unless T is inconsistent). But it does still have an important close relationship to provability. In a sense, provability is “representable in one direction”. (This notion of one-way representability also came up in Section 6.9. It's analogous to *semi-decidability*.)

8.6.1 Exercise

Suppose that $\text{Proof}_T(x, y)$ represents the T -proof relation in T . Let $\text{Prov}_T(y)$ be $\exists x \text{ Proof}_T(x, y)$.

- (a) For any sentence A , if $T \vdash A$, then $T \vdash \text{Prov}_T(A)$.
- (b) Suppose furthermore that the theory T is *true* in the standard string structure \mathbb{S} . In that case, if $T \not\vdash A$, then $T \not\vdash \text{Prov}_T(A)$.

Notice the difference between clause (b) in this exercise and the definition of “represent”. In a case where A isn't provable, it isn't that T says that A is *not* provable—but at least T *doesn't* incorrectly say that A *is* provable.

8.6.2 Definition

Let T be a sufficiently strong, effectively axiomatizable theory. Let $\text{Proof}_T(x, y)$ be a formula that represents the T -proof relation in T . (There is such a formula, by the Representability Theorem (7.7.8).) Let $\text{Prov}_T(y)$ be the provability formula $\exists x \text{ Proof}_T(x, y)$.

A **Gödel sentence** for T is a fixed point of the negation of the provability formula: that is, it is a sentence G_T such that

$$G_T \equiv \frac{T}{\neg} \text{Prov}_T(G_T)$$

8.6.3 Lemma

Any sufficiently strong, effectively axiomatizable theory T has a Gödel sentence G_T .

Proof

This immediately follows from Gödel's Fixed Point Theorem (Exercise 6.9.9). \square

8.6.4 Exercise

Let T be a sufficiently strong, effectively axiomatizable theory, and let G_T be a Gödel sentence for T .

- (a) If T is consistent, then $T \not\vdash G_T$.
- (b) If T is true in the standard string structure \mathbb{S} , then $T \not\vdash \neg G_T$.

We can improve a bit on part (b), by paying attention to exactly how *truth*—that is, truth-in-the-standard-string-structure—comes into the argument. The key thing that this heads off is the following possibility. Suppose there is no proof of G_T . Then, since T represents the T -proofs, for each particular string s , we're guaranteed that T says, “ s is not a proof of G_T ”. But what if T *also* says “But there is a proof of G_T !” This wouldn't be a logical inconsistency: it's not logically impossible for there to be something *else*, something that isn't one of the standard finite strings, which is a proof of G_T . (But even precisely *stating* this possibility goes beyond what we can say in the first-order theory of strings.) Still, even though this wouldn't be formally inconsistent, a theory like this would still be bad in a way. It has a kind of “infinite inconsistency”. A theory like this accepts a generalization, while ruling out every possible instance. This motivates the following definition.

8.6.5 Definition

A theory T is **ω -inconsistent** (pronounced “omega inconsistent”) iff there is some

formula $A(x)$ such that

- (a) $T \vdash \exists x A(x)$
- (b) For every string s , $T \vdash \neg A(s)$.

If there is no such formula, then T is **ω -consistent**.

8.6.6 Exercise (Gödel's First Incompleteness Theorem, Version 2)

Suppose T is a sufficiently strong, effectively axiomatizable theory, and let G_T be a Gödel sentence for T . If T is consistent and ω -consistent, then $T \not\vdash G_T$ and $T \not\vdash \neg G_T$.

So that pretty much gives us what we were hoping for. If a theory T is sufficiently strong, effectively axiomatizable, consistent, *and also ω -consistent*, not only do we know that T is incomplete, but we can give a particular example of a sentence that T neither proves nor refutes: the theory's Gödel sentence.

(A sentence which can be neither proved nor refuted is often called *undecidable*. But watch out—this meaning of “undecidable” is totally different from the notion involving programs.)

8.7 Rosser Sentences*

UNDER CONSTRUCTION.

We've considered two different proofs of Gödel's First Incompleteness Theorem. The first was non-constructive: it didn't give us a concrete example of an undecidable sentence. The second (closer to Gödel's original proof) gave us a specific example of an undecidable sentence, but it used the extra assumption of ω -consistency. It turns out that there is a third proof of Gödel's First Incompleteness Theorem that has the advantages of *both* of the proofs we've already given. It gives us a specific example of an undecidable sentence, and it only depends on ordinary consistency, rather than ω -consistency. The main downside to this proof (the reason we didn't use it as our official proof all along) is that it is extra sneaky.

The trick is to notice that if there is a proof of A , then there is also a *shortest* proof.

8.8 Consistency is Unprovable

What we've shown is that for any sufficiently strong, consistent, axiomatizable theory, there is some true statement that it cannot prove—and we gave an example, the Gödel sentence. But Gödel showed something more: he gave another specific example of an unprovable statement which is of particularly deep importance. Any sufficiently strong axiomatizable theory has the resources to “talk about” what is provable in that very theory, using the provability formula from Section 8.6. So one of the things such a theory can talk about is whether it can prove any contradictions. That is, if T is a sufficiently strong axiomatizable theory, then it includes a sentence that says “ T is consistent”—that is, a sentence which says “no contradiction is provable in T ”. The further thing Gödel showed is that if T really is consistent, then *this* statement is also unprovable. No reasonable theory can prove its own consistency. This is called **Gödel's Second Incompleteness Theorem**.

The basic idea of the proof is that in a sufficiently strong theory T , the proof of Gödel's *First* Incompleteness Theorem can be *formalized*. The steps we went through to justify First Incompleteness Theorem can also be carried out in a formal *proof* from the axioms of T . We won't work through all of the details of the proof of this result, but we will examine the main ideas.

Let's start with a recap of the proof of the First Incompleteness Theorem. Suppose that T is a sufficiently strong theory with a decidable set of axioms X . Then as we discussed in Section 8.6, there is a formula $\text{Proof}_T(x, y)$ such that

$$\begin{aligned} T \vdash \text{Proof}_T(P)(A) &\quad \text{if } P \text{ is a proof of } A \text{ from } X \\ T \vdash \neg \text{Proof}_T(P)(A) &\quad \text{otherwise} \end{aligned}$$

We also noted that this doesn't mean that *provability* can be represented in T . (Indeed, Tarski's Theorem tells us that, if it were, then T would be inconsistent.) But that doesn't stop us from defining a *provability formula*: we can let $\text{Prov}_T(y)$ be $\exists x \text{ Proof}(x, y)$. This doesn't fully represent provability in T , but it does “represent provability in one direction.” If A is provable in T , then A has some proof P . So $T \vdash \text{Proof}_T(P)(A)$, and thus by existential generalization, $T \vdash \text{Prov}_T(A)$. In short, for any sentence A ,

$$\text{If } T \vdash A \text{ then } T \vdash \text{Prov}(A)$$

But, to reiterate, we *don't* get the other half of the definition of representability: if A is *not* provable, there is no guarantee that T “knows” that fact. (Indeed, it will follow from the Second Incompleteness Theorem that T *can't* know that there is no proof of A .)

Remember that a theory T is *inconsistent* iff \perp is provable in T .

8.8.1 Definition

The **consistency sentence** for T is the sentence $\neg \text{Prov}_T(\perp)$. This is abbreviated Con_T . That is, to spell this out, Con_T is the sentence

$$\neg \exists x \text{ Proof}_T(x, \langle \perp \rangle)$$

where $\text{Proof}_T(x, y)$ represents the T -proofs in T .

(Note that while we say “*the* consistency sentence”, this is a bit loose. There are many ways for T to represent the relation “ P is a proof of A ”. Different choices of the formula $\text{Proof}_T(x, y)$ will clearly give rise to different consistency sentences for T . In fact, it can make a difference which one we choose.)

The result we are working toward says that no consistent theory can prove its own consistency sentence. That is:

$$\text{If } T \vdash \text{Con}_T \text{ then } T \vdash \perp$$

For the first step, recall from Section 8.6 that any sufficiently strong, effectively axiomatizable theory T has a **Gödel sentence** G_T , such that

$$T \vdash (G \leftrightarrow \neg \text{Prov}_T(G))$$

Recall also from Exercise 8.6.4 that if T is consistent, then T does not prove its own Gödel sentence. Putting that the other way around:

$$\text{If } T \vdash G_T \text{ then } T \vdash \perp$$

(From here on out, we’ll drop the T subscripts when it’s clear how to fill them in.)

The second step is to show that this first step can be *formalized* in T . To do this, we need to begin by showing that T “knows” some basic facts about how proofs are put together. Here are two basic things we know about provability:

$$\begin{aligned} \text{If } T \vdash (A \rightarrow B) \text{ and } T \vdash A \text{ then } T \vdash B \\ \text{If } T \vdash A \text{ then } T \vdash \text{Prov}_T(A) \end{aligned}$$

That is, provability is closed under modus ponens; and if A is provable, then it is provable that A is provable. Our proof of the Second Incompleteness Theorem relies on T also “knowing” both of these two facts.

8.8.2 Definition

A theory T satisfies the **derivability conditions** iff

$$\begin{aligned} T \vdash \text{Prov}\langle A \rightarrow B \rangle &\rightarrow \text{Prov}\langle A \rangle \rightarrow \text{Prov}\langle B \rangle \\ T \vdash \text{Prov}\langle A \rangle &\rightarrow \text{Prov}\langle \text{Prov}\langle A \rangle \rangle \end{aligned}$$

The first condition formalizes the claim that provability is closed under modus ponens. The second condition formalizes the claim that if A is provable, then it is provable that A is provable.

Showing exactly which theories satisfy the derivability conditions involves some fiddly details that we are going to skip over. We are just going to take this for granted in what follows. (In particular, it can depend a bit on the details of the theory T and the way in which we define the formula $\text{Proof}(x, y)$. I'm ignoring some complications here.) But here's one important example: first-order Peano Arithmetic PA satisfies the derivability conditions.

8.8.3 Notation

We are going to do some fairly intricate reasoning about proofs about provability. For this purpose it can be helpful to introduce some more concise notation, inspired by modal logic. We can use the “box” notation $\Box A$ as an abbreviation for the sentence $\text{Prov}\langle A \rangle$. Using box notation, we can summarize the key facts about provability more concisely like this:

$$\begin{aligned} T \vdash G &\leftrightarrow \neg \Box \neg G \\ \text{If } T \vdash G \text{ then } T \vdash \perp \\ \text{If } T \vdash A \rightarrow B \text{ and } T \vdash A \text{ then } T \vdash B \\ T \vdash \Box(A \rightarrow B) &\rightarrow \Box A \rightarrow \Box B \\ \text{If } T \vdash A \text{ then } T \vdash \Box A \\ T \vdash \Box A &\rightarrow \Box \Box A \end{aligned}$$

We can also rewrite the consistency sentence Con_T as $\neg \Box \perp$.

8.8.4 Exercise

Here is a pretty basic logical fact: for any sentence A ,

$$\text{If } T \vdash A \text{ and } T \vdash \neg A \text{ then } T \text{ is inconsistent}$$

Use the facts about provability to show that T “knows” this fact. That is:

$$T \vdash \text{Prov}\langle A \rangle \rightarrow \text{Prov}\langle \neg A \rangle \rightarrow \text{Prov}\langle \perp \rangle$$

In box notation:

$$T \vdash \Box A \rightarrow \Box \neg A \rightarrow \Box \perp$$

8.8.5 Exercise

We have already proved this fact (Exercise 8.6.4 (a)):

$$\text{If } T \vdash G \text{ then } T \vdash \perp$$

In this exercise, we’ll show that the proof of this fact can be carried out within T .

- (a) $T \vdash \Box G \rightarrow \Box \neg \Box G$
- (b) $T \vdash \Box G \rightarrow \Box \perp$

8.8.6 Exercise (Gödel’s Second Incompleteness Theorem)

Use the previous exercise and Exercise 8.6.4 (a) to show that if T proves the consistency sentence for T , then T is inconsistent. That is:

$$\text{If } T \vdash \text{Con}_T \text{ then } T \vdash \perp$$

Or in other words:

$$\text{If } T \vdash \neg \Box \perp \text{ then } T \vdash \perp$$

Chapter 9

Second-Order Logic*

Ever and anon we are landed in particulars, but this is
not what I want.

Plato (c. 428–c. 248 BCE), *Meno*

UNDER CONSTRUCTION

Overview:

1. The idea of second-order logic
2. Semantics for second-order logic
3. Second-order Peano Arithmetic (PA_2) does not have non-standard models
4. Thus PA_2 is negation-complete
5. Thus PA_2 is not effectively enumerable
6. Thus second-order logic has no sound and complete proof system
7. Type theory

9.1 Syntax and Semantics

- Second-order variables.
- Atomics of the form $Xt_1\dots t_n$.
- Second-order quantifiers.
- Second-order assignments.
- Semantic clauses for atomics and quantifiers.
- Second-order logical consequence and consistency. (\models_2)
- The second-order theory of a structure. (Th_2)

- Observe that Gödel's Fixed Point Theorem, Tarski's Theorem, the Representability Theorem, the Essential Undecidability Theorem, and Church's Theorem all still apply.

9.2 Second-order Peano Arithmetic

Contrast the Inductive Property (of numbers) and the first-order induction schema again.

Write out PA_2 . The induction axiom:

$$\forall X(X0 \rightarrow \forall n(Xn \rightarrow X(\text{suc } n)) \rightarrow \forall n Xn)$$

Note that PA_2 is sufficiently strong.

9.2.1 Definition

... isomorphism ...

9.2.2 Definition

A theory is **categorical** iff all of its models are isomorphic to one another.

9.2.3 Exercise

PA_2 is categorical.

9.2.4 Exercise

Second-order consequence is not compact. That is, there is an infinite set of second-order sentences X such that every finite subset of X has a model, but X does not have a model.

9.2.5 Exercise

- $PA_2 = \text{Th}_2 \mathbb{N}$
- PA_2 is negation-complete.

9.2.6 Exercise

Note that the Essential Undecidability Theorem implies that PA_2 is undecidable (since it is sufficiently strong and consistent). Show:

- PA_2 is not semi-decidable.
- There is a decidable set X such that the set of sentences A such that $X \models_2 A$

is not semi-decidable.

9.2.7 Definition

Let a **proof system** be a set of triples (π, X, A) —we say that π is a *proof* of A from assumptions X —which satisfies the further principle that for any decidable set of sentences X , the set of pairs (π, A) such that π is a proof of A from X is *decidable*.

9.2.8 Definition

Let \models be any relation between a set of formulas and a formula.

- (a) A proof system is **sound** for \models iff, for any X and A , if there is a proof of A from X , then $X \models A$.
- (b) A proof system is **complete** for \models iff, for any X and A , if $X \models A$, then there is a proof of A from X .

9.2.9 Exercise

No proof system is sound and complete for second-order logical consequence.

9.3 Further Directions

- The plural interpretation
- Type theory
- Higher-order identity. Extensionality and intensionality
- Henkin models

Chapter 10

Set Theory*

There is no doubt in my mind that in this way we will get farther and farther ahead, never reaching an unsurmountable limit, but also attaining not even an approximate grasp of the absolute. The absolute can only be acknowledged, but never known, not even approximately.

Georg Cantor, “Fundamentals of a General Theory of Manifolds: A Mathematical-Philosophical Study in the Theory of the Infinite” (1883)

UNDER CONSTRUCTION

10.0.1 Definition

The **first-order language of pure set theory** is a first-order language with just one relation symbol \in . **First-order set theory**, or ZFC, is the theory in this language with the following axioms. As usual, we add universal quantifiers to bind the free variables, and A can be any formula in this first-order language of sets. We’ll use $z \subseteq x$ as an abbreviation for $\forall w (w \in z \rightarrow w \in x)$.

(This axiomatization is pretty old-school. It’s stated in a way which avoids mentioning ordered pairs or functions directly, which makes things a bit harder than you might expect.) Each axiom has a name.

Extensionality.

$$\forall z(z \in x \leftrightarrow z \in y) \rightarrow x = y$$

Separation.

$$\exists y \forall z (z \in y \leftrightarrow (z \in x \wedge A))$$
Power Set.

$$\exists y \forall z (z \in y \leftrightarrow z \subseteq x)$$
Union.

$$\exists y \forall z (z \in y \leftrightarrow \exists w (w \in x \wedge z \in w))$$
Choice.

$$\begin{aligned} \forall y (y \in x \rightarrow \exists z (z \in y)) \rightarrow \\ \exists w \forall y (y \in x \rightarrow \exists ! z (z \in y \wedge z \in w)) \end{aligned}$$
Infinity.

$$\begin{aligned} \exists x (\exists y (y \in x) \wedge \\ \forall y (y \in x \rightarrow \exists z (z \in x \wedge y \subseteq z \wedge y \neq z))) \end{aligned}$$
Foundation.

$$\exists y (y \in x \rightarrow \exists y (y \in x \wedge \neg \exists z (z \in y \wedge z \in x)))$$
Replacement.

$$\forall y (y \in x \rightarrow \exists ! z A) \rightarrow \exists w \forall y (y \in x \rightarrow \exists z (z \in w \wedge A))$$

Overview:

1. First order set theory ZFC.
 2. Set theory has no *intended* model.
 3. If ZFC is consistent, it has countable models. Skolem's Paradox.
 4. If there are large cardinals, ZFC is consistent.
 5. Thus (by Gödel's Second Incompleteness Theorem) ZFC does not prove there are large cardinals.
 6. Some independence results (stated without proof): large cardinals, the Continuum Hypothesis.
-
6. Second-order set theory ZFC_2 .
 7. ZFC_2 does not have countable models

8. Zermelo's categoricity theorem.
9. Kreisel's Principle.

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