CONTENTS

1 INTRODUCTION

Imagine a future world where computers can create universes—digital environments made from binary ones and zeros. Imagine that within these universes there exist biological forms that reproduce, grow, and think. Imagine plantlike forms, ant colonies, immune systems, and brains, all adapting, evolving, and getting better at solving problems. Imagine if our computers became greenhouses for a new kind of nature. Just think what digital biology could do for us. Perhaps it could evolve new designs for us, think up ways to detect fraud using digital neurons, or solve scheduling problems with ants. Perhaps it could detect hackers with immune systems or create music from the patterns of growth of digital seashells. Perhaps it would allow our computers to become creative and inventive.

Now stop imagining.

We are all becoming blasé about computers. The whirring, chittering box sitting on (or underneath) your table is probably no longer an off-putting device for you. More likely, you regard it as a necessary evil. When working, it becomes part of the furniture, and when not working, it becomes something to hurl abuse at. You cannot even escape it when leaving your office. Everywhere you go, you hear people talking in a new language of e-mails, dot-com domain names, and template files. What existed only in the laboratories of computer scientists ten years ago now forms part of everyday conversation for the least computer literate of us. Computers and computer software are everywhere, and yet, except for a few of the "nerdy types," they are largely ignored or taken for granted by us. Somehow this seems unfair. When some of the most exciting and inspiring new developments of our technology are happening inside the minds of these benign cream-colored boxes, to disregard them is to ignore something wonderful. So I shall not ignore them. I shall do the opposite: I will focus on them. By doing so, I will change the way you think about computers.

Follow me into a different universe—the digital universe of our computers. I will show you the marvels that inhabit this strange new environment. You'll find them familiar, but different. Alike, but diverse. The digital entities I want you to meet are not incomprehensible collections of numbers or equations. They are just the same as you and the natural world that surrounds you. They may live and die within digital domains, but they are every bit as biological as you. Together, they comprise *digital biology*.

To make this journey, we must abandon our physical forms and don digital bodies, for we cannot exist in a digital universe as we are. Ready? Here we go.

THROUGH THE LOOKING SCREEN

The journey from our universe to the digital universe is instantaneous. We open our digital eyes and see ... trees. But these trees are not static. As we watch, we see them grow—from a small seedling to a vast, towering pine. The immense and beautiful complexity of the branches develops before our eyes; leaves form in symmetrical patterns; stems thicken into trunks. A forest grows up around us, the trees all trying to outreach their neighbors in the quest for the sunlight. At our feet are other plants—ivy sending out tendrils to the trees and then swarming up them like leafy snakes. Ferns unfurl themselves, and we see their intricate fractal-like forms spread wide to catch the low level of light at the forest floor. We move through the forest and spot some seashells on the ground. Again, they grow before our eyes, the spirals and patterns emerging like ripples on water. When you pick up one of the shells and put it to your ear, instead of hearing the sea, you hear the pattern of the growing shell, transformed into music. These are not ordinary plants and shells. They are not made from atoms and molecules, and they are not growing in our universe. They are digital plants, made from the flow of electrons within the digital universe of a computer.

Let me slow down time in this digital universe. The growth of the trees and plants slows and stops. Now other movement becomes evident. On the ground we see insects scurrying along. A long line of ants marches forward, each following the pheromone trails left by its companions ahead of it. As we watch, the first few ants reach a specific point on the ground and turn, heading toward a new location, with the ants behind them following like an over-ambitious conga line. As we stand back, we can see that the ants are tracing out a complex and zigzagging route across the ground. Looking up, we see the sky filled with a flock of birds, flying in astonishing formations. They circle around each other, dive up and down, and suddenly all change direction at the same time—yet never does a single bird collide with another. But there are still many more digital marvels in this universe for me to show you. Let me adjust our size.

We shrink rapidly, until the ants tower above us, as high as skyscrapers. Suddenly everything becomes dark. We have been swallowed by some digital creature. Don't be alarmed—I arranged for this to happen. I would like to show you around inside.

We watch the flow of cells from within the veins of the creature. Most are completely normal, but once in a while, we spot a cluster of cells stuck together. In the center of the cluster is a virus or some other unwanted intruder into this creature. It is surrounded by large, colorless cells, which are attacking it. These are the leukocytes—the white blood cells of our digital creature that detect anything that is not regarded as "normal." We move into the bone marrow of the creature. It is here that new white blood cells are constructed. Using the patterns laid down in the DNA of this creature, new cells are created constantly, each configured to attack a different invader. As we watch, a new cell is created and released into the bloodstream. If this cell finds an intruder, it will immediately clone itself, increasing the number of cells designed to attack this particular type of unwanted guest. Throughout the network of veins, an ever-changing police force of white blood cells patrols the creature, ensuring that immunity to all types of attacker is maintained at all times.

We move again inside the digital creature and find ourselves in the brain. Around us is a dazzling electrical storm of activity. Interconnected neurons fire electrical signals at each other in a vastly complicated network, informing their companions to stop or start firing themselves. In parallel, chemical signals are constantly emitted from the cells, and new connections between cells are grown or lost. The unceasing activity around us embraces electrical signals generated by the creature's senses and emits a never-ending stream of signals to the muscles and organs of the creature, causing it to react to its environment and learn, plan, and predict things in its world.

I shrink us again in the digital universe. We are now so small that we are within a single cell of the creature. In fact, we can see molecules within the cell. One vast spiraling molecule dominates the view—a strand of digital DNA held within the nucleus of every cell of the creature. The DNA defines how the creature is grown from a single cell. It also specifies how the creature should mature and controls the production of cells for the immune system. The separate genes in the DNA are rules, designed to turn on and off the production of proteins. The proteins trigger new cells to grow, cause them to differentiate into different types of cell, and even tell cells to die. The DNA of this creature defines a complex recipe of actions and counteractions, safeguards and repair mechanisms.

I grow us back to our original size; the creature we were in shuffles away. Again trees, ants, and birds surround us. Digital DNA is held within all of these aspects of digital biology, defining the growth and behavior of everything we see. But to show you how the genes of the digital DNA are created, I must speed up time in this digital universe.

As the movement of the birds and insects disappears in a blur of activity, once again we see the trees and plants growing around us. I continue to speed up the passage of time, until even the growth of trees becomes too fas tto see properly. Now all we can see is a nebulous landscape of digital biology, with forms appearing and disappearing as their lives are lived in split seconds. And as these biological forms live, as they find their partners and reproduce, they form part of an ever-changing environment. Whether tree or ant, if the offspring inherit some genes that allow them to perform a little better in the digital universe, then they will survive a little longer and on average will have a few more offspring than the others. So the more useful genes become more numerous in the populations, resulting in more successful creatures. This continuous process of change is known as evolution, and it shapes digital biology in the digital universes of our computers just as it shapes the natural world in our own universe. Indeed, as we watch, new types of tree form, changing generation by generation. New types of ant, with subtly different behaviors, emerge, more complex brains develop, more efficient immune systems grow. But our time grows short, so we must depart from the digital universe and return to more familiar surroundings.

NATURAL TECHNOLOGIES

Now that we have left the digital universe, I must come clean. Digital biology does not exist in a single universe, in a single computer. All of the aspects of digital biology I have just described exist in different, isolated digital universes. The digital ants will never meet the flock of birds, nor will they crawl on the ferns in the digital forest. Even the immune system and brain of the creature that swallowed us do not coexist in the same digital universe. But the fact that they do exist is undeniable.

I am one of hundreds of scientists who spend their time understanding the processes of nature and enabling those same processes to happen in computers. To achieve this, we create simple digital universes in computers, using laws of physics laid down in our software. Within these digital universes, we grow a new type of nature. We have harnessed the power of natural processes such as evolution and growth. Digital embryos grow from digital DNA, digital plants evolve, ant colonies swarm, neural network brains learn. We use such digital biology to *evolve* solutions to problems, such as methods for detecting fraud. We explore how immune systems can be created within computer networks and used to attack hackers. We discover how to use colonies of computational ants to search for better solutions to scheduling problems. We examine how architectural designs can be grown from a set of digital genes into adult form. We find out how to use digital neural networks to detect the difference between benign and malignant cancer cells. We learn how to develop colonies of digital cells that have the behavior of fire. By using the natural processes responsible for life within computer software, we are overturning all preconceptions of what computers can and cannot do.

Through our work, we find new and highly efficient ways of solving today's problems. We also learn about the techniques we have borrowed from nature. We find out more about our own origins, about the mechanisms behind evolution and embryology. We learn how plants grow, how animals develop, how our immune systems work, and even how we think.

These new techniques will form the next generation of our technology. By understanding the solutions of nature and using them to solve our own problems, we have found a whole new class of computation, a whole new way of using computers. Digital biology will allow us to survive in the modern world. It will guide us through the ever-growing complexity of our global, interactive, fast-paced, modern lives. These new software techniques will provide us with invaluable assistance from their digital universes. They will find us information, detect crime for us, identify faults, and even repair themselves. They will design new products for us, create art, and compose music. They will have originality, creativity, and the ability to think for themselves. How do I know that these things will happen? Because they already have. Using the methods of digital biology, we have achieved all of these feats.

And in the future? Who knows? But it seems almost certain that the first forms of alien life we see will be not through telescopes but through the windows of our computer screens into digital universes. The first person to hold a conversation with an alien intelligence will not be an astronaut, it will be a computer scientist or computational neuroscientist, talking to an evolved digital neural network. The first glimpses of nonhuman cultures and technologies will occur in our research labs, where the digital biology grows more complex day by day.

Perhaps these grandiose visions will be a long time in coming. But the next time you hear your cream-colored box whirring and clicking to itself, just stop and think what type of digital biology might be blooming inside.

WHAT THIS BOOK IS ABOUT

Think I'm kidding? Or exaggerating? Well, read on. The whole point of this book is to explain, for the first time, how biology and computers have become so closely entwined. Chapter by chapter, I describe how the processes of nature work, to the best of current scientific knowledge. I'll include the voices of the biologists who have discovered and investigated aspects of biology. I'll also tell you how computer scientists, designers, engineers, artists, and many other people make use of the same processes with their computers. You'll read how they have used biology to improve our technology, enabling remarkable new advances in all fields. You'll also read how our use of biology within digital universes is expanding our knowledge of life, the universe, and everything. This new breed of scientist, whom I shall call the digital biologist, creates digital universes, genes, evolution, brains, insect swarms, plants, immune systems, and growth. In doing so, digital biologists learn how these processes work.

My aim in this book is to promote understanding. I hope that when you have read it, you will know the reason that so many of us devote our time, energy, and skills to the development of various aspects of digital biology. It is because of the compelling and overwhelming excitement we feel as we uncover some of the fundamental truths of nature.

The book is organized into seven major chapters that explore natural and digital biology: *Universes, Evolution, Brains, Insects, Plants, Immune Systems,* and *Growth*. Each chapter is designed to stand alone with its own distinctive identity. However, if you truly wish to follow the processes of biology that this book describes, you should read each chapter in order. You should then discover, as I have, how all biological processes are aspects of a single, fundamental process, as described in the final chapter: “Answers.”

Our first step is the beginning of a theme that I shall continue throughout this book: natural and digital biology follow the same processes, just in different universes. Before you can really understand either, you should understand what a universe is.

2 UNIVERSES

THE UNIVERSE WAS A SWARMING MASS of movement. Like the splashes created by raindrops on a lake, ripple-like things grew quickly into existence. Some had regular shapes; others had highly variable and complex characteristics. As the things traveled, they changed, before slowly fading away. The ripples continuously popped into existence, most expanding in size as they moved. Many resembled little explosions as they grew dramatically in all directions. Others resembled flying worms or forks of lightning. They all flew at similar speeds as they chased their companions into the void. There was clearly a maximum velocity, however, with most approaching the limit but none able to exceed it.

The universe followed slightly different rules from our own. Although there were time and space, it contained no solid matter, no light, no gravity. The only objects that could exist were all constantly coming into being through some unknown agency—perhaps in another universe. And the ripple-like things were traveling *through* each other without any effect. There were exceptions to this rule, however. When two identical ripples traveled in exactly opposite directions and flew into each other, they would both cease to exist. When traveling in the same direction and overlapping, the ripples would merge into larger super-ripples.

Despite the beauty and variety of this universe, it was barren. It contained no life. Nothing born to this cosmos could perceive the seething and never-ending activity. The universe and the ripple-like things within it were destined to an eternity of pointless, mindless existence and destruction.

A tragic tale maybe, but this universe is not fictional. Not only does it exist, it is a universe that we have access to. In fact, as you read this, you have sensors dipped into this universe like a periscope, feeding you vital information. I am referring to the universe of *sound*.

As you read this paragraph, activate your periscope: pay a little more attention to the sounds your ears are detecting. If you are in the city, perhaps you can hear the sounds of traffic, a siren, a pneumatic drill, a car horn. Perhaps you hear the sounds of colleagues talking or your children squabbling or crying. Maybe you can hear the music from your CD player while you read this. Perhaps there is just the noise of birds singing or a clock ticking. Whatever you hear, you are experiencing a universe quite different from the one we exist in—a universe comprising only the ripple-like objects that we call sound waves.

This chapter is not about sound; it is about universes. Although it may seem difficult to imagine, the concept of a universe is broader than you might think. There are frames of existence other than the physical universe we experience every day. There are many universes that coexist with or overlap our own. The universe of sound is one, as is the universe of ideas. The digital universe of the computer is another.

We're looking at universes because they help us to understand the full potential of computers. This book is not about the *simulation* of nature or the creation of *virtual* or *artificial* nature. This book is about the use of concepts from nature in a *different universe*—a digital universe. Only by regarding a computer program as a universe in its own right can we take seriously the things that develop and grow within it.

OUR UNIVERSE

How can a computer program be a universe? It sounds a bit unlikely, after all. First let's look more at our own physical universe. It turns out that our universe is a little implausible too.

Using our natural perceptions, we can see much of the universe that affects us. This is no coincidence; evolution has ensured that this is the case. We are aware of solids, liquids, and gases. We can feel the effects of gravity, see light, and feel heat. Nevertheless, there is more to the universe than the things we can see or feel.

Using science, we have broadened our biological perspective of our universe. We know that we live on a (more or less) spherical planet, despite the fact that it looks flat to us. We have worked out that our planet orbits a massive sun. With telescopes we have discovered that there are other planets that also orbit our sun. We know that there are anything from 200 to 500 billion other suns in our galaxy, the Milky Way. In the part of the universe we can observe, there are around 100 billion galaxies. We think that there are a few trillion galaxies in the whole universe. It seems that our universe is *big*.

There's more to the universe than a lot of matter, however. There's also a lot of interesting behavior. Moons orbit planets. Planets orbit stars. Galaxies orbit around themselves and around other galaxies. Light travels very fast, but never faster than a particular speed limit. Matter can emit radiation, and it can be transformed from one substance to another. Electricity can produce magnetism; magnets can produce electricity. Energy can be transformed from light to heat to movement.

Our universe also seems to have a kind of scaffolding to hold everything together. It has spatial dimensions of width, height, and depth, allowing position and size to exist. It also has the fourth dimension of time, allowing past, present, and future to exist. And we know that this scaffolding is a bit bendy. If there is excessive mass (e.g., a star or even a black hole) on one part of the scaffolding, then position, size, and time can become severely distorted.

And as if bendy time weren't enough (although it is normally referred to as Einstein's theory of relativity), it gets worse. Solid is not really solid at all in our universe. We now know that the universe is like an overly ambitious Russian doll. Everything we can touch is made from tiny pieces called molecules. The molecules are made up from even tinier pieces called atoms. The atoms are made from still smaller pieces called electrons, protons, and neutrons. Protons and neutrons are made from even smaller things called quarks. And we think that quarks (and electrons) are points of energy. So the chances are that energy and matter are the same thing.

It seems that our universe is immensely huge and made entirely from energy that seems to interact with itself according to certain rules. If only it were that simple. The trouble is that some things in our universe behave in very peculiar ways. When you perform even quite simple experiments with light, some odd interference patterns emerge. The interference looks exactly like the kind of thing one would expect if other light sources were present, *but there is nothing else there*. We see such mysterious interference even when we do experiments with one photon at a time (light is made from photons). These and other effects have led to the development of quantum theory: that the interference of light looks as though it is caused by the photons in other universes influencing the photons in our own. If we work out the most extreme repercussions of this theory, then we must conclude that there are other universes, parallel to our own. There are parallel versions of me writing this and parallel versions of you reading this. And it seems that there may be an infinite number of these parallel universes out there.

As you may have noticed, this area of science strongly resembles science fiction. There are many other things we know about the universe that are equally hard to accept—the fact that time does not flow, for example. Just as we do not flow through space, our impression of an ever-changing now that moves through time is illusionary. We exist in space-time—a four-dimensional universe comprising all locations and all times. Some theorists assert that every concept of now is exactly equivalent to a parallel universe. But let's not pursue this any further. I have just one more mental punch to throw at you. This one is about the origin of our universe.

One thing we did notice fairly early on was that all the galaxies in our universe appear to be flying away from each other at a considerable rate. When we traced the paths back, it became clear that everything in the universe seemed to originate from a single point in space. This led to the big bang theory, which proposes that a large explosion resulted in the raw components from which everything we see today emerged. Not only did the explosion generate the energy and matter required for the universe, but we think it also laid down the space-time scaffolding. Before the bang, there was no space or time. We do not know for sure exactly what exploded, but it was probably a hyperdense point of energy, the size of a quark. We're also not sure where it came from. Some theories state that there may have been a period of chaos during which certain quantum laws still applied, resulting in the point of energy popping into existence. Certainly for the foreseeable future, the big questions of how and why our universe came into being will remain unanswered.

This is our physical universe—or at least as much of it as we can examine, calculate, and guess at. It is a very different place from the one we actually observe in our day-to-day lives. Trapped in our physical universe as we are, we cannot see far enough to determine the true nature of our home.

WHAT IS A UNIVERSE?

LAWS

Now that you have a sense of what a universe can look like, it is time to generalize. Before you can believe that there are other kinds of universes out there and, more important, that some of them exist in our computers, you need to know what a universe actually is.

If something, then outcome.

The rule tells us that every outcome depends on something. Without that something, the outcome would never happen. With it, the outcome will always happen. Every outcome is caused by a something. This is a simplification, of course. Most real rules define the outcome to vary according to the something, and some rules may even be recursive, with the something being some aspect of the outcome. But this does not matter. The point is that all rules specify that outcomes must depend on something. If they don't, they are not rules. So if our universe is defined by rules, which it is, it follows that each of those rules operates on something to cause an outcome. If I push something, then it will move (or I will). If there is a large mass, it will distort space and time. If energy exists, it can never be lost, only transformed. There are some of the rules of our universe.

We can also learn more about the kinds of rules that define universes by thinking about how they are created. Let's look at the creation of our universe. If we try to find an ultimate cause for our universe, clearly we need a rule that says, "If there is nothing at all —no space, no time, no energy, no other universes—then create a super-dense point of energy and a set of other rules to go with it." Unfortunately, this does not make sense. If there is nothing at all, then where did that rule come from? What created it? Another rule? And what created that? Our universe does not make any sense.

To help understand this, let me show you a universe that does make sense. There's nothing up my sleeve ... abracadabra! Here it is. It is a null universe.

The laws of the null universe are simple—there are none. It has no space-time scaffolding, no energy, nothing, with no behavior. It is a universe without a box and without any contents. It is nothing.

No matter how uninteresting the null universe is to us physical universe dwellers, it does at least make sense. The null universe does explain its own existence. There is nothing there because there are no rules to allow the creation of anything. There is no behavior because there are no rules to give any behavior. There are no rules because there was nothing there to create, derive, or produce the effect of rules. Unlike our own universe, the null universe can explain its own (non) existence *in terms of itself*.

We simply cannot explain the existence of our own universe without some external *something* triggering it into being. And we do need to explain it, for, unlike the null universe, there is a lot to explain. As soon as there is anything—a rule or energy or behavior or matter—we must ask, *why?* Even if the rule is the only conceivable rule, the only possible rule that can define a universe, the only way to know why the rule is there at all, and indeed, what is making the rule actually do anything, is to define the universe with respect to something else. In the same way that you cannot tell if a new color "works" without first having a color scheme, a new universe cannot "work" without first having an existing "scheme."

It seems that this feature is common to all universes except for the null universe. All other universes have laws. In some cases, they define space-time and energy and distortion; in other cases, they define other things. But we will always need an ultimate law or rule to explain what caused those universes, and that rule must always explain the causation in terms of something external to the universe it is explaining. It is not good enough to answer the question “Why does something exist?” with “Because it has always existed.” The answer does not explain the *cause*. It does not explain why the null universe is not here and we are.

Here are some examples of answers that do explain the cause of our universe:

- A chaotic universe prior to ours had a rule that resulted in the creation of our universe.
- A parallel universe “donated” a piece of itself that became our universe.
- God decreed that we should exist.
- A dragon sneezed, and we all came into being.

All of these answers, however believable, rely on an external universe of some kind. Every other answer will also do so, or it will not explain why we are here and the null universe is not.

So it may be that except for my null universe skulking in the corner, it is not possible to explain or even define a universe in terms of itself. Universes are simply not self-contained. They rely on other universes to cause them and make them what they are.

This completes our search for a definition of a universe. From this exploration, we know that a universe is made from a set of rules that define outcomes. We also know that at least one of the rules must be defined in terms of another universe. This two-part definition acts as a key that opens the door to other universes. Now that we know what a universe really is, we can explore some of the large number of universes that coexist with us.

OTHER UNIVERSES

Many other universes exist and overlap with our own. Some we are aware of; some we are not. Some we help create; others we do not. But how do we recognize another universe?

We know that a universe consists of rules, one or more of which must be defined with respect to a different universe. With this definition, we can start to think about other universes. If a set of rules defines our universe, other universes will be defined by other sets of rules. So if we can identify an environment defined by different rules from those that define our universe, *it* may be a different universe. We began this chapter immersed in the universe of sound. Let's briefly return to it and check that it does deserve to be called a universe.

The universe of sound is similar to our own universe. It shares rules that define a very similar space-time scaffolding. It also has some different rules. In our universe, the maximum velocity of everything is the speed of light. In the universe of sound, the maximum velocity is much slower—it is the speed of sound. In our universe, gravity plays a highly significant role. In the universe of sound, there is no clear concept of gravity. In our universe, most things cannot pass through the same space without colliding with each other. In the universe of sound, all things (sound waves) can normally pass through each other without any effect.

Clearly the universe of sound has some different rules from our laws of physics. It is also clear that the rules for the universe of sound are defined in terms of our laws of physics. To an imaginary dweller of the universe of sound, the ripple-like objects spontaneously appear from nowhere. To us, we can see that sounds are generated from vibrations of our molecules in our universe. So the rules defining the universe of sound are defined with respect to another universe—our own. (This is surprisingly similar to those mysterious interference patterns we observe with light. To us, they appear to be spontaneous and without explanation. If the theories are right, then to the dwellers of other universes parallel to our own, our interference patterns are caused by their photons interacting with ours. So our laws of physics may also be defined with respect to other universes in this way.)

Because the universe of sound has different rules from ours and because some of its rules are defined with respect to an external universe, it does qualify for the designation of universe.

Not all universes share quite so many rules with our own. The universe of ideas, or memes, is quite different from ours. The memetic universe, as I shall call it, has a very different scaffolding from ours. Objects (memes) in the memetic universe have no position or size; there are no spatial dimensions. There is a dimension of time, however, so memes can exist at certain times but not at certain locations. Because of this, there can be no movement, no speed, no acceleration, no collisions. But there are some exotic rules that define when memes are created. It seems that as we travel forward along the time axis of this universe, we see more and more memes in existence. Perhaps one rule of this

image
not
available

to blue. Soon a pattern of blue boxes becomes evident among the red. As more and more boxes are carried and glued down by the "ants," a distinct circular wall of blue boxes begins to form around the little gray object in the middle. Despite the apparent random scurrying of the yellow "ants," this wall soon becomes complete as the final red blocks are carried and glued into the last few gaps in the wall. Their task accomplished, all movement ceases. Everything in the universe disappears.

This high-speed universe with its short lifetime has been created and destroyed many times. Similar yellow ants have constructed similar walls many times previously. Indeed, as I write this, the universe has just come into existence again, with its red blocks and scurrying yellow ants going about their mindless activity.

As I'm sure you have guessed, this universe exists in my computer. It is a digital universe. I can never touch a yellow "ant" or pick up one of the red boxes. I will never be able to walk around the smart blue wall and admire its construction. These objects exist in another universe from me. But the fact that they do exist is undeniable.

The digital universe described above has three dimensions: two spatial dimensions and a dimension of time. This simple space-time scaffolding supports a number of objects, where each object has a spatial position at a specific time. We know that the universe is not infinite. We can observe its creation and destruction, so we can see that it exists for only a finite amount of time. We can also see that there seem to be boundaries around the space of the universe, so space is also finite.

Although every object in the digital universe has a position in space, only some can move or be moved. The little gray circular object in the center never moves. The antlike things always move. Red boxes can be moved by the ants. Blue boxes are immovable. And if we could perform some experiments on the objects in the universe, we would find out even more. For example, if we could move the little gray circular object, we would discover that the blue wall would be built in a different place with the gray object still in the center. If we could remove the gray object altogether, we would discover that no wall would ever be built; the ants would never drop their red boxes. With sufficiently ingenious experiments, we might discover why the wall is built at all. We would find out that the little gray object is continuously shouting messages at the yellow ants. The invisible messages inform each ant how far away it is from the gray object. We would also discover that when the ant is carrying a box and happens to be a certain distance away from the gray object, it is instinctively compelled to glue that box to the ground. The ants wander randomly all around the gray object, and all of the ants glue down their boxes when they are the same distance from the object. But they cannot walk through boxes or other objects. These simple rules mean that boxes are always glued in a space on a circle around the gray object. Because there are many ants with many boxes, the behavior results in a circular wall.

These are some of the rules that define this universe. I know that they are correct, because I created those rules. I thought of them, and I wrote them down. I couldn't use English, though, or mathematics. I used a programming language. Why? Because the collection of rules that define this little digital universe is known as a computer program.

MACHINES TO CREATE UNIVERSES

Computers are not like our other machines. Traditionally, each machine has only one behavior. Clocks are often intricately designed, but they only do one thing. They only tell time. The components all do what they were designed to do, but a clock can never vacuum your carpet, just as a vacuum cleaner will never tell you the time. The engine in your car will make the wheels move, but it will never be able to record your voice on a tape. Each of our machines is designed to do something, and that is all that they can ever do. But computers are different.

Computers are machines that can behave in any way you like. Indeed, this is the function of a computer. We don't use computers in order to shuffle electrons around the place, although that is all that they actually do. We use them to behave in ways that are beneficial to us. That is why computers always need software. Without their programs, computers have no behavior. A computer program is the set of instructions that give the computer a behavior.

Every computer program is essentially a collection of rules that defines what can exist and provides a set of behaviors. In other words, each computer program defines a new digital universe. When the computer runs a program and those behavior-defining rules are executed, the computer becomes a universe generator. The program defines the laws of the digital universe, and the computer causes that universe to come into being.

Before we can really explore the nature of digital universes, we need to understand computers a little more. What kind of machine can follow instructions and potentially do different things every time it is used? What kind of machine can generate universes? How do these machines work?

HARDWARE

There are two aspects to every computer: the hardware and the software. Computer hardware is the stuff you can touch, smell, and thump. Computer software is the stuff you feed to the computer to specify behaviors (and define digital universes).

To help me explain how computer hardware works, let me introduce you to four friends of mine: Mary, Al, Reg, and Ian. Mary has a wonderful filing system. Ask her for any information, and she'll provide it after a quick dig around. Al is a bit obsessed with his codebook. Although it may contain only a limited repertoire of codes, he always works out what everything means and gives his friends the results. Reg has an amazing short-term memory: he can repeat small amounts of information in a split second. Finally, Ian is a bossy fellow. He's forever telling Mary to remember things and waiting for information.

My four friends always play the same roles in a conversation. Here's an example of the kind of thing they say to each other. Because Ian is so bossy, he always begins first:

Ian: Mary, please keep the following seven numbers for me in your filing cabinet: 100, 010, 001, 101, 110, 110, 000.

Mary: Okay, Ian.

Ian: Al, why don't you start doing something?

Al: Okay, Ian. Mary, can you tell me the first number that Ian gave you?

Mary: It's 100, Al.

Al: Thanks, Mary. Well, that's interesting. According to my codebook, that means *add the next two numbers together*. Mary, do you want to help me out here?

Mary: The next two numbers are 010 and 001, Al.

Al: Right. Well, according to my codebook, the sum of 010 and 001 is 011. Reg, would you remember the number 011 for me?

Reg: Got it, 011, no problem.

Al: Thanks, Reg. Mary, would you tell me the next number, please?

Mary: It's 101, Al.

Al: Right. According to my codebook, that means *store Reg's number in the place given by the next number*. Mary, I need the next number, please. Reg, could you tell me your number?

Mary: It's 110, Al.

Reg: My number is 011, Al.

Al: Thanks, you two. Mary, could you store 011 in the file 110, please.

Mary: Okay, Al.

Al: Thanks, Mary. Could you give me the next number, please?

generate the output of 011. Alternatively, if the instruction is *add* and the data are 011 and 001, the output of 100 will be produced by the ALU. The execution of every instruction follows a rule (or set of rules) that has been integrated into the circuitry of the ALU.

This is the underlying machinery of a digital universe. The electronic cogs of the computer turn predictably. Every action is the result of electronic circuits directing the flow of electricity. The intricate dances of electrons tracing their way through the myriad circuits that make up our computers are all caused by electronic rules.

SOFTWARE

Computers are machines that perform instructions according to rules. Most computers have between 50 and 200 different instructions in their instruction sets. The instructions usually operate on between zero and four binary numbers at a time, where each number can be anything from 8 to 128 bits long, depending on the word size of the computer. Clearly, the number of different data instruction combinations is an astonishingly large number. (I was certainly astonished when I worked it out.) But however huge this number is, it is not infinite. And yet a computer has an infinite number of different behaviors.

The reason that the behavior of a computer is infinitely variable is that we can choose which instructions the computer should execute, and we can choose the order in which the instructions are carried out. In this respect, instructions are like musical notes. Just as a finite number of different notes can be used to produce an infinite number of different melodies, a finite number of different instructions can be used to generate an infinite number of behaviors. And we tell the computer which instructions it should execute by giving it a *program* to follow.

We have already observed an example of a simple computer program. The conversation among Mary, Al, Reg, and Ian began with Ian providing seven binary numbers. These were examined in turn by Al, who decoded and executed them. The numbers formed a program.

These days, we do not write programs in machine code or specify which of the low-level instructions should be executed in our programs. Instead most of us write programs in high-level languages. These programming languages (such as Pascal, C, C++, Lisp, and Java) are designed to resemble our own language more closely. Using the programming language of our choice, we write computer code in "sentences" so that we can read and understand it ourselves. We then use *compilers* (other programs) to translate our programs into machine code, which the computer can then execute by following the rules embedded in the circuitry of the ALU.

So we define our digital universes using high-level languages. Although every command is executed by the low-level rules within the ALU, more interesting higher-level rules define the digital universes that we shall be exploring in this book. These rules are defined by the commands of the high-level language. Every IF statement, every FOR loop, and every variable declaration helps form the rules that define the current digital universe.

But this does not mean that every programming language defines a different set of digital universes. In fact, it does not matter which high-level language we use. The same high-level rules can be expressed in nearly all of them. To see this, let's create a very simple digital universe using the high-level language C:

```
void main ()
{    int position;
     for (position = 0; position < 80; position++)
     { gotoxy (position, 10);
       printf ("digital nature");
       getch ();
     }
}
```

Here's the same description of a digital universe, this time created by the high-level language Modula 2:

```
MODULE example
VAR position : INTEGER;
BEGIN
    FOR position := 0 TO 80 DO
     GotoXY (position, 10);
     WrStr ('digital nature');
     REPEAT UNTIL KeyPressed ();
    END;
END example.
```

When we compile either piece of code and execute it on the computer, we see a black screen with the white text "digital nature" halfway down on the left. Every time we press a key, the text moves to the right by one character. We can control the speed of the text by how quickly we press a key. When the text has disappeared from the right of the screen, the program ends.

Both programs do exactly the same thing: both define the same digital universe. To understand this, let's look at the laws of physics for this universe. Here are the high-level rules that define this very simple digital universe:

> When something creates the universe, two spatial dimensions capable of supporting objects called *characters* will be created.
>
> If the universe has just been created, then "digital nature" will be written halfway down on the left of the screen.
>
> Every time the user presses a key, the text will move one character to the right.
>
> Once the text has disappeared from the right of the screen, the universe will be destroyed.

The digital universe in the example has only four high-level rules. Both programs follow this set of rules, so both programs define the same digital universe. It is quite normal to describe the working of a program as a set of high-level rules, written in English. Such a description is called an *algorithm*. From now on in the book, we will look only at algorithms; we will not be concerned with which high-level language is used to write down that algorithm.

But can we legitimately call the execution of this algorithm a universe? Recall our definition: a universe is made from a set of rules that define outcomes. At least one of the rules must be defined in terms of another universe. It should be apparent that