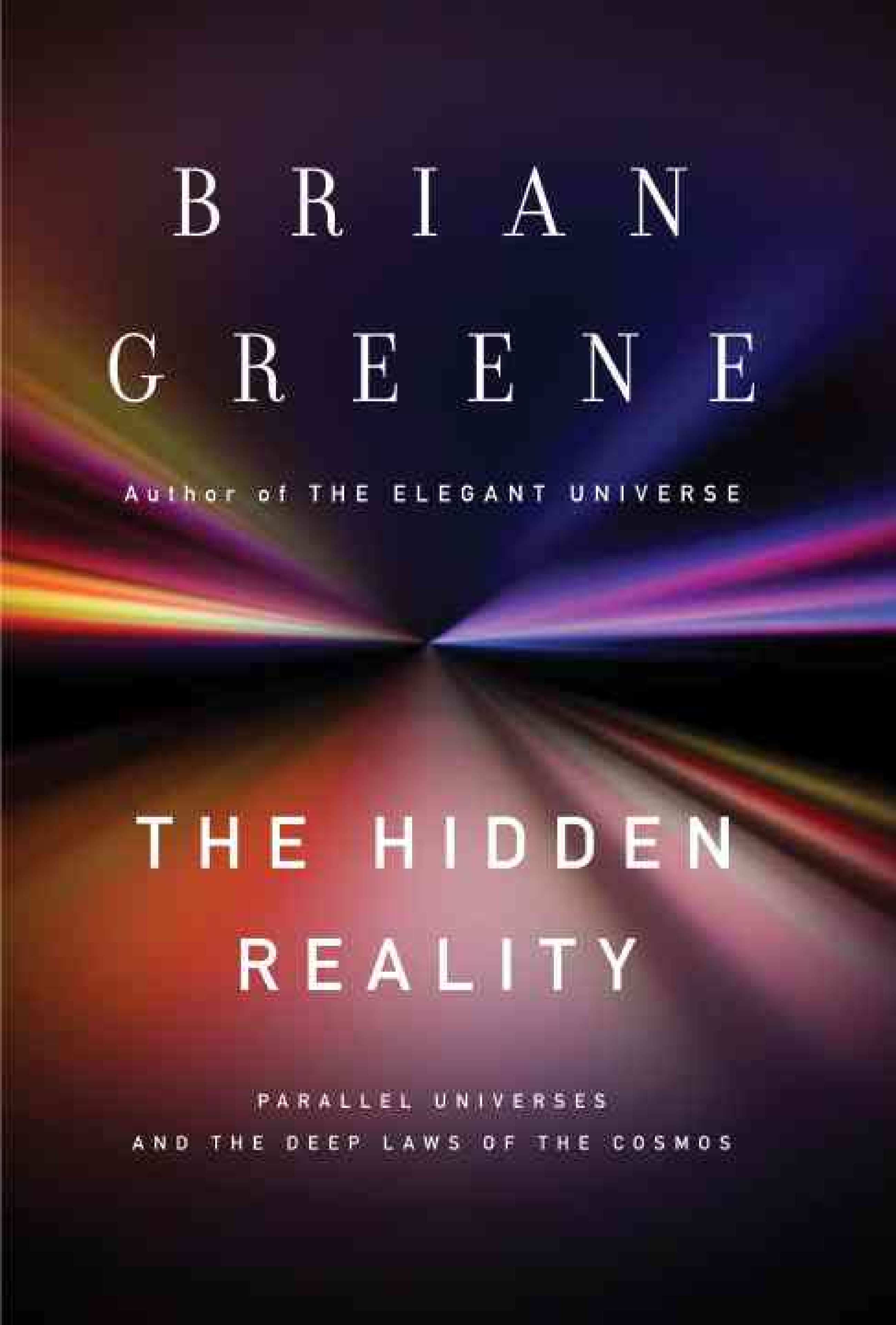
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THE HIDDEN
REALITY
PARALLEL UNIVERSES
AND THE DEEP LAWS OF THE COSMOS

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CHAPTER 1

The Bounds of Reality

On Parallel Worlds

If, when I was growing up, my room had been adorned with only a single mirror, my childhood daydreams might have been very different. But it had two. And each morning when I opened the closet to get my clothes, the one built into its door aligned with the one on the wall, creating a seemingly endless series of reflections of anything situated between them. It was mesmerizing. I delighted in seeing image after image populating the parallel glass planes, extending back as far as the eye could discern. All the reflections seemed to move in unison—but that, I knew, was a mere limitation of human perception; at a young age I had learned of light's finite speed. So in my mind's eye, I would watch the light's round-trip journeys. The bob of my head, the sweep of my arm silently echoed between the mirrors, each reflected image nudging the next. Sometimes I would imagine an irreverent me way down the line who refused to fall into place, disrupting the steady progression and creating a new reality that informed the ones that followed. During lulls at school, I would sometimes think about the light I had shed that morning, still endlessly bouncing between the mirrors, and I'd join one of my reflected selves, entering an imaginary parallel world constructed of light and driven by fantasy.

To be sure, reflected images don't have minds of their own. But these youthful flights of fancy, with their imagined parallel realities, resonate with an increasingly prominent theme in modern science—the possibility of worlds lying beyond the one we know. This book is an exploration of such possibilities, a considered journey through the science of parallel universes.

Universe and Universes

There was a time when “universe” meant “all there is.” Everything. The whole shebang. The notion of more than one universe, more than one everything, would seemingly be a contradiction in terms. Yet a range of theoretical developments has gradually qualified the interpretation of “universe.” The word’s meaning now depends on context. Sometimes “universe” still connotes absolutely everything. Sometimes it refers only to those parts of everything that someone such as you or I could, in principle, have access to. Sometimes it’s applied to separate realms, ones that are partly or fully, temporarily or permanently, inaccessible to us; in this sense, the word relegates our universe to membership in a large, perhaps infinitely large, collection.

With its hegemony diminished, “universe” has given way to other terms that capture the wider canvas on which the totality of reality may be painted. *Parallel worlds* or *parallel universes* or *multiple universes* or *alternate universes* or the *metaverse, megaverse,* or *multiverse*—they’re all synonymous and they’re all among the words used to embrace not just our universe but a spectrum of others that may be out there.

You’ll notice that the terms are somewhat vague. What exactly constitutes a world or a universe? What criteria distinguish realms that are distinct parts of a single universe from those classified as universes of their own? Perhaps someday our understanding of multiple universes will mature sufficiently for us to have precise answers to these questions. For now, we’ll avoid wrestling with abstract definitions by adopting the approach famously applied by Justice Potter Stewart to define pornography. While the U.S. Supreme Court struggled to delineate a standard, Stewart declared, “I know it when I see it.”

In the end, labeling one realm or another a parallel universe is merely a question of language. What matters, what’s at the heart of the subject, is whether there exist realms that challenge convention by suggesting that what we’ve long thought to be *the* universe is only one component of a far grander, perhaps far stranger, and mostly hidden, reality.

Varieties of Parallel Universes

A striking fact (it's in part what propelled me to write this book) is that many of the major developments in fundamental theoretical physics—relativistic physics, quantum physics, cosmological physics, unified physics, computational physics—have led us to consider one or another variety of parallel universe. Indeed, the chapters that follow trace a narrative arc through nine variations on the multiverse theme. Each envisions our universe as part of an unexpectedly larger whole, but the complexion of that whole and the nature of the member universes differ sharply among them. In some, the parallel universes are separated from us by enormous stretches of space or time; in others, they're hovering millimeters away; in others still, the very notion of their location proves parochial, devoid of meaning. A similar range of possibility is manifest in the laws governing the parallel universes. In some, the laws are the same as in ours; in others, they appear different but have a shared heritage; in others still, the laws are of a form and structure unlike anything we've ever encountered. It's at once humbling and stirring to imagine just how expansive reality may be.

Some of the earliest scientific forays into parallel worlds were initiated in the 1950s by researchers puzzling over aspects of quantum mechanics, a theory developed to explain phenomena taking place in the microscopic realm of atoms and subatomic particles. Quantum mechanics broke the mold of the previous framework, classical mechanics, by establishing that the predictions of science are necessarily probabilistic. We can predict the odds of attaining one outcome, we can predict the odds of another, but we generally can't predict which will actually happen. This well-known departure from hundreds of years of scientific thought is surprising enough. But there's a more confounding aspect of quantum theory that receives less attention. After decades of closely studying quantum mechanics, and after having accumulated a wealth of data confirming its probabilistic predictions, no one has been able to explain why only one of the many possible outcomes in any given situation actually happens. When we do experiments, when we examine the world, we all agree that we encounter a single definite reality. Yet, more than a century after the quantum revolution began, there is no consensus among the world's physicists as to how this basic fact is compatible with the theory's mathematical expression.

Over the years, this substantial gap in understanding has inspired many creative proposals, but the most startling was among the first. Maybe, that early suggestion went, the familiar notion that any given experiment has one and only one outcome is flawed. The mathematics underlying quantum mechanics—or at least, one perspective on the math—suggests that *all* possible outcomes happen, each inhabiting its own separate universe. If a quantum calculation predicts that a particle might be here, or it might be there, then in one universe it *is* here, and in another it *is* there. And in each such universe, there's a copy of you witnessing one or the other outcome, thinking—incorrectly—that your reality is the only reality. When you realize that quantum mechanics underlies all physical processes, from the fusing of atoms in the sun to the neural firings that constitutes the stuff of thought, the far-reaching implications of the proposal become apparent. It says that there's no such thing as a road untraveled. Yet each such road—each reality—is hidden from all others.

This tantalizing *Many Worlds* approach to quantum mechanics has attracted much interest in recent decades. But investigations have shown that it's a subtle and thorny framework (as we will discuss in Chapter 8); so, even today, after more than half a century of vetting, the proposal remains controversial. Some quantum practitioners argue that it has already been proved correct, while others claim just as assuredly that the mathematical underpinnings don't hold together.

Such scientific uncertainty notwithstanding, this early version of parallel universes resonated with themes of separate lands or alternative histories that were being explored in literature, television, and film, creative forays that continue today. (My favorites since childhood include *The Wizard of Oz*, *It's a Wonderful Life*, the *Star Trek* episode "The City on the Edge of Forever," the Borges story "The Garden of Forking Paths," and, more recently, *Sliding Doors* and *Run Lola Run*.) Collectively, these and many other works of popular culture have helped integrate the concept of parallel realities into the zeitgeist and are responsible for fueling much public fascination with the topic. But quantum mechanics is only one of numerous ways that a conception of parallel universes emerges from modern physics. In fact, it won't be the first I'll discuss.

In Chapter 2, I'll begin with a different route to parallel universes, perhaps the simplest route of all. We'll see that if space extends infinitely far—a proposition that is consistent with all observations and that is part of the cosmological model favored by many physicists and astronomers—then there must be realms out there (likely *way* out there) where copies of you and me and everything else are enjoying alternate versions of the reality we experience here. Chapter 3 will journey deeper into cosmology: the inflationary theory, an approach that posits an enormous burst of superfast spatial expansion during the universe's earliest moments, generates its own version of parallel worlds. If inflation is correct, as the most refined astronomical observations suggest, the burst that created our region of space may not have been unique. Instead, right now, inflationary expansion in distant realms may be spawning universe upon universe and may continue to do so for all eternity. What's more, each of these ballooning universes has its own infinite spatial expanse, and hence contains infinitely many of the parallel worlds encountered in Chapter 2.

In Chapter 4, our trek turns to string theory. After a brief review of the basics, I'll provide a status report on this approach to unifying all of nature's laws. With that overview, in Chapters 5 and 6 we'll explore recent developments in string theory that suggest three new kinds of parallel universes. One is string theory's *braneworld* scenario, which posits that our universe is one of potentially numerous "slabs" floating in a higher-dimensional space, much like a slice of bread within a grander cosmic loaf.[1] If we're lucky, it's an approach that may provide an observable signature at the Large Hadron Collider in Geneva, Switzerland, in the not too distant future. A second variety emerges from braneworlds that slam into one another, wiping away all they contain and initiating a new, fiery big bang–like beginning in each. As if two giant hands were clapping, this could happen over and over—branes might collide, bounce apart, attract each other gravitationally, and then collide again, a cyclic process generating universes that are parallel not in space but in time. The third scenario is the string theory "landscape," founded on the enormous number of possible shapes and sizes for the theory's required extra spatial dimensions. We'll see that, when joined with the Inflationary

Multiverse, the string landscape suggests a vast collection of universes in which every possible form for the extra dimensions is realized.

In Chapter 6, we'll focus on how these considerations illuminate one of the most surprising observational results of the last century: space appears to be filled with a uniform diffuse energy, which may well be a version of Einstein's infamous cosmological constant. This observation has inspired much of the recent research on parallel universes, and it's responsible for one of the most heated debates in decades on the nature of acceptable scientific explanations. Chapter 7 extends this theme by asking, more generally, whether consideration of universes beyond our own can be rightly understood as a branch of science. Can we test these ideas? If we invoke them to solve outstanding problems, have we made progress, or have we merely swept the problems under a conveniently inaccessible cosmic rug? I've sought to lay bare the essentials of the clashing perspectives, while also emphasizing my own view that, under certain specific conditions, parallel universes fall unequivocally within the purview of science.

Quantum mechanics, with its Many Worlds version of parallel universes, is the subject of Chapter 8. I'll briefly remind you of the essential features of quantum mechanics, then focus on its most formidable problem: how to extract definite outcomes from a theory whose basic paradigm allows for mutually contradictory realities to coexist in an amorphous, but mathematically precise, probabilistic haze. I'll carefully lead you through the reasoning that, in seeking an answer, proposes anchoring quantum reality in its own profusion of parallel worlds.

Chapter 9 takes us yet further into quantum reality, leading to what I consider the strangest version of all parallel universe proposals. It's a proposal that emerged gradually over thirty years of theoretical studies on the quantum properties of black holes. The work culminated in the last decade, with a stunning result from string theory, and it suggests, remarkably, that all we experience is nothing but a holographic projection of processes taking place on some distant surface that surrounds us. You can pinch yourself, and what you feel will be real, but it mirrors a parallel process taking place in a different, distant reality.

Finally, in Chapter 10 the yet more fanciful possibility of artificial universes takes center stage. The question of whether the laws of physics give us the capacity to create new universes will be our first order of business. We'll then turn to universes created not with hardware but with software—universes that might be simulated on a superadvanced computer—and investigate whether we can be confident that we're not now living in someone's or something else's simulation. This will lead to the most unrestrained parallel universe proposal, originating in the philosophical community: that every possible universe is realized somewhere in what's surely the grandest of all multiverses. The discussion naturally unfolds into an inquiry about the role mathematics has in unraveling the mysteries of science and, ultimately, our ability, or lack thereof, to gain an ever-deeper understanding of reality.

The Cosmic Order

The subject of parallel universes is highly speculative. No experiment or observation has established that any version of the idea is realized in nature. So my point in writing this book is not to convince you that we're part of a multiverse. I'm not convinced—and, speaking generally, no one should be convinced—of anything not supported by hard data. That said, I find it both curious and compelling that numerous developments in physics, if followed sufficiently far, bump into some variation on the parallel-universe theme. It's not that physicists are standing ready, multiverse nets in their hands, seeking to snare any passing theory that might be slotted, however awkwardly, into a parallel-universe paradigm. Rather, all of the parallel-universe proposals that we will take seriously emerge unbidden from the mathematics of theories developed to explain conventional data and observations.

My intention, then, is to lay out clearly and concisely the intellectual steps and the chain of theoretical insights that have led physicists, from a range of perspectives, to consider the possibility that ours is one of many universes. I want you to get a sense of how modern scientific investigations—not untethered fantasies like the catoptric musings of my boyhood—naturally suggest this astounding possibility. I want to show you how certain otherwise confounding observations can become eminently understandable within one or another parallel-universe framework; at the same time, I'll describe the critical unresolved questions that have, as yet, kept this explanatory approach from being fully realized. My aim is that when you leave this book, your sense of what might be—your perspective on how the boundaries of reality may one day be redrawn by scientific developments now under way—will be far more rich and vivid.

Some people recoil at the notion of parallel worlds; as they see it, if we are part of a multiverse, our place and importance in the cosmos are marginalized. My take is different. I don't find merit in measuring significance by our relative abundance. Rather, what's gratifying about being human, what's exciting about being part of the scientific enterprise, is our ability to use analytical thought to bridge vast distances, journeying to outer and inner space and, if some of the ideas we'll encounter in this book prove correct, perhaps even beyond our universe. For me, it is the depth of our understanding, acquired from our lonely vantage point in the inky black stillness of a cold and forbidding cosmos, that reverberates across the expanse of reality and marks our arrival.

CHAPTER 2

Endless Doppelgängers

The Quilted Multiverse

If you were to head out into the cosmos, traveling ever farther, would you find that space goes on indefinitely, or that it abruptly ends? Or, perhaps, would you ultimately circle back to your starting point, like Sir Francis Drake when he circumnavigated the earth? Both possibilities—a cosmos that stretches infinitely far, and one that is huge but finite—are compatible with all our observations, and over the past few decades leading researchers have vigorously studied each. But for all that detailed scrutiny, if the universe is infinite there's a breathtaking conclusion that has received relatively scant attention.

In the far reaches of an infinite cosmos, there's a galaxy that looks just like the Milky Way, with a solar system that's the spitting image of ours, with a planet that's a dead ringer for earth, with a house that's indistinguishable from yours, inhabited by someone who looks just like you, who is right now reading this very book and imagining you, in a distant galaxy, just reaching the end of this sentence. And there's not just one such copy. In an infinite universe, there are infinitely many. In some, your doppelgänger is now reading this sentence, along with you. In others, he or she has skipped ahead, or feels in need of a snack and has put the book down. In others still, he or she has, well, a less than felicitous disposition and is someone you'd rather not meet in a dark alley.

And you won't. These copies would inhabit realms so distant that light traveling since the big bang wouldn't have had time to cross the spatial expanse that separates us. But even without the capacity to observe these realms, we'll see that basic physical principles establish that if the cosmos is infinitely large, it is home to infinitely many parallel worlds—some identical to ours, some differing from ours, many bearing no resemblance to our world at all.

En route to these parallel worlds, we must first develop the essential framework of cosmology, the scientific study of the origin and evolution of the cosmos as a whole.

Let's head in.

The Father of the Big Bang

"Your mathematics is correct, but your physics is abominable." The 1927 Solvay Conference on Physics was in full swing, and this was Albert Einstein's reaction when the Belgian Georges Lemaître informed him that the equations of general relativity, which Einstein had published more than a decade earlier, entailed a dramatic rewriting of the story of creation. According to Lemaître's calculations, the universe began as a tiny speck of astounding density, a "primeval atom" as he would come to call it, which swelled over the vastness of time to become the observable cosmos.

Lemaître cut an unusual figure among the dozens of renowned physicists, in addition to Einstein, who had descended on the Hotel Metropole in Brussels for a week of intense debate on quantum theory. By 1923, he had not only completed his work for a doctorate, but he'd also finished his studies at the Saint-Rombaut seminary and been ordained a Jesuit priest. During a break in the conference, Lemaître, clerical collar in place, approached the man whose equations, he believed, were the basis for a new scientific theory of cosmic origin. Einstein knew of Lemaître's theory, having read his paper on the subject some months earlier, and could find no fault with his manipulations of general relativity's equations. In fact, this was not the first time someone had presented Einstein with this result. In 1921, the Russian mathematician and meteorologist Alexander Friedmann had come upon a variety of solutions to Einstein's equations in which space would stretch, causing the universe to expand. Einstein balked at those solutions, at first suggesting that Friedmann's calculations were marred by errors. In this, Einstein was wrong; he later retracted the claim. But Einstein refused to be mathematics' pawn. He bucked the equations in favor of his intuition about how the cosmos *should* be, his deep-seated belief that the universe was eternal and, on the largest of scales, fixed and unchanging. The universe, Einstein admonished Lemaître, is not now expanding and never was.

Six years later, in a seminar room at Mount Wilson Observatory in California, Einstein focused intently as Lemaître laid out a more detailed version of his theory that the universe began in a primordial flash and that the galaxies were burning embers floating on a swelling sea of space. When the seminar concluded, Einstein stood up and declared Lemaître's theory to be "the most beautiful and satisfactory explanation of creation to which I have ever listened."[1] The world's most famous physicist had been persuaded to change his mind about one of the world's most challenging mysteries. While still largely unknown to the general public, Lemaître would come to be known among scientists as the father of the big bang.

General Relativity

The cosmological theories developed by Friedmann and Lemaître relied on a manuscript Einstein sent off to the German *Annalen der Physik* on the twenty-fifth of November 1915. The paper was the culmination of a nearly ten-year mathematical odyssey, and the results it presented—the general theory of relativity—would prove to be the most complete and far-reaching of Einstein's scientific achievements. With general relativity, Einstein invoked an elegant geometrical language to thoroughly refashion the understanding of gravity. If you already have a good grounding in the theory's basic features and cosmological implications, feel free to skip three sections ahead. But if you'd like a brief reminder of the highlights, stay with me.

Einstein began work on general relativity around 1907, a time when most scientists thought gravity had long since been explained by the work of Isaac Newton. As high school students around the world are routinely taught, in the late 1600s Newton came up with his so-called Universal Law of Gravity, providing the first mathematical description of this most familiar of nature's forces. His law is so accurate that NASA engineers still use it to calculate spacecraft trajectories, and astronomers still use it to predict the motion of comets, stars, even entire galaxies.[2]

Such demonstrable efficacy makes it all the more remarkable that, in the early years of the twentieth century, Einstein realized that Newton's Law of Gravity was deeply flawed. A seemingly simpleminded question revealed this starkly: How, Einstein asked, does gravity work? How, for example, does the sun reach out across 93 million miles of essentially empty space and affect the motion of the earth? There's no rope tethering them together, no chain tugging the earth as it moves, so how does gravity exert its influence?

In his *Principia*, published in 1687, Newton recognized the importance of this question but acknowledged that his own law was disturbingly silent about the answer. Newton was certain that there had to be something communicating gravity from place to place, but he was unable to identify what that something might be. In the *Principia* he gibingly left the question "to the consideration of the reader," and for more than two hundred years, those who read this challenge simply read on. That's something Einstein couldn't do.

For the better part of a decade, Einstein was consumed with finding the mechanism underlying gravity; in 1915, he proposed an answer. Although grounded in sophisticated mathematics and requiring conceptual leaps unheralded in the history of physics, Einstein's proposal had the same air of simplicity as the question it purported to address. By what process does gravity exert its influence across empty space? The emptiness of empty space seemingly left everyone empty-handed. But, actually, there is something in empty space: *space*. This led Einstein to suggest that space itself might be gravity's medium.

Here's the idea. Imagine rolling a marble across a large metal table. Because the table's surface is flat, the marble will roll in a straight line. But if a fire subsequently engulfs the table, causing it to buckle and swell, a rolling marble will follow a different trajectory because it will be guided by the table's warped and rutted surface. Einstein argued that a similar idea applies to the fabric of space. Completely empty space is much like the flat table, allowing objects to roll unimpeded along straight lines. But the presence of massive bodies affects the shape of space, somewhat as heat affects the shape of the table's surface. The sun, for example, creates a bulge in its vicinity, much like a metal bubble blistering on the hot table. And just as the table's curved surface induces the marble to travel along a curved path, so the curved shape of space around the sun guides the earth and other planets into orbit.

This brief description glides over important details. It’s not just space that curves, but time as well (this is what’s called spacetime curvature); earth’s gravity itself facilitates the table’s influence by keeping the marble pressed to its surface (Einstein contended that warps in space and time don’t need a facilitator since they *are* gravity); space is three-dimensional, so when it warps it does so all around an object, not just “underneath” as the table analogy suggests. Nevertheless, the image of a warped table captures the essence of Einstein’s proposal. Before Einstein, gravity was a mysterious force that one body somehow exerted across space on another. After Einstein, gravity was recognized as a distortion of the environment caused by one object and guiding the motion of others. Right now, according to these ideas, you are anchored to the floor because your body is trying to slide down an indentation in space (really, spacetime) caused by the earth.[*]

Einstein spent years developing this idea into a rigorous mathematical framework, and the resulting *Einstein Field Equations*, the heart of his general theory of relativity, tell us precisely how space and time will curve as a result of the presence of a given quantity of matter (more precisely, matter and energy; according to Einstein’s $E = mc^2$, in which E is energy and m is mass, the two are interchangeable).[3] With equal precision, the theory then shows how such spacetime curvature will affect the motion of anything—star, planet, comet, light itself—moving through it; this allows physicists to make detailed predictions of cosmic motion.

Evidence in support of general relativity came quickly. Astronomers had long known that Mercury’s orbital motion around the sun deviated slightly from what Newton’s mathematics predicted. In 1915, Einstein used his new equations to recalculate Mercury’s trajectory and was able to explain the discrepancy, a realization he later described to his colleague Adrian Fokker as so thrilling that for some hours it gave him heart palpitations. Then, in 1919, astronomical observations undertaken by Arthur Eddington and his collaborators showed that distant starlight passing by the sun on its way to earth follows a curved path, just the one that general relativity predicted.[4] With that confirmation—and the *New York Times* headline proclaiming LIGHTS ALL ASKEW IN THE HEAVENS, MEN OF SCIENCE MORE OR LESS AGOG—Einstein was propelled to international prominence as the world’s newfound scientific genius, the heir apparent to Isaac Newton.

But the most impressive tests of general relativity were still to come. In the 1970s experiments using hydrogen maser clocks (masers are similar to lasers, but they operate in the microwave part of the spectrum) confirmed general relativity's prediction of the earth's warping of spacetime in its vicinity to about 1 part in 15,000. In 2003, the Cassini-Huygens spacecraft was used for detailed studies of the trajectories of radio waves that passed near the sun; the data collected supported the curved spacetime picture predicted by general relativity to about 1 part in 50,000. And now, befitting a theory that has truly come of age, many of us walk around with general relativity in the palm of our hand. The global positioning system you casually access from your smartphone communicates with satellites whose internal timing devices routinely take account of the spacetime curvature they experience from their orbit above earth. If the satellites failed to do so, the position readings they generate would rapidly become inaccurate. What in 1916 was a set of abstract mathematical equations that Einstein offered as a new description of space, time, and gravity is now routinely called upon by devices that fit in our pockets.

The Universe and the Teapot

Einstein breathed life into spacetime. He challenged thousands of years of intuition, built up from everyday experience, that treated space and time as an unchanging backdrop. Who would ever have imagined that spacetime can writhe and flex, providing the invisible master choreographer of motion in the cosmos? That's the revolutionary dance that Einstein envisioned and that observations have confirmed. And yet, in short order, Einstein stumbled under the weight of age-old but unfounded prejudices.

During the year after he published the general theory of relativity, Einstein applied it on the grandest of scales: the entire cosmos. You might think this a staggering task, but the art of theoretical physics lies in simplifying the horrendously complex so as to preserve essential physical features while making the theoretical analysis tractable. It's the art of knowing what to ignore. Through the so-called *cosmological principle*, Einstein established a simplifying framework that initiated the art and the science of theoretical cosmology.

The cosmological principle asserts that if the universe is examined on the largest of scales, it will appear uniform. Think of your morning tea. On microscopic scales, there is much inhomogeneity. Some H_2O molecules over here, some empty space, some polyphenol and tannin molecules over there, more empty space, and so on. But on macroscopic scales, those accessible to the naked eye, the tea is a uniform hazel. Einstein believed that the universe was like that cup of tea. The variations we observe—the earth is here, there's some empty space, then the moon, yet more empty space, followed by Venus, Mercury, sprinkles of empty space, and then the sun—are small-scale inhomogeneities. He suggested that on cosmological scales, these variations could be ignored because, like your tea, they'd average out to something uniform.

In Einstein's day, evidence in support of the cosmological principle was thin at best (even the case for other galaxies was still being made), but he was guided by a strong sense that no location in the cosmos was special. He felt that, on average, every region of the universe should be on a par with every other and so should have essentially identical overall physical attributes. In the years since, astronomical observations have provided substantial support for the cosmological principle, but only if you examine space on scales at least 100 million light-years across (which is about a thousand times the end-to-end length of the Milky Way). If you take a box that's a hundred million light-years on each side and plunk it down *here*, take another such box and plunk it down way over *there* (say, a billion light-years from *here*), and then measure the average overall properties inside each box—average number of galaxies, average amount of matter, average temperature, and so on—you'll find it difficult to distinguish between the two. In short, if you've seen one 100-million-light-year chunk of the cosmos, you've pretty much seen them all.

Such uniformity proves crucial to using the equations of general relativity to study the entire universe. To see why, think of a beautiful, uniform, smooth beach and imagine that I've asked you to describe its small-scale properties—the properties, that is, of each and every grain of sand. You're stymied—the task is just too big. But if I ask you to describe only the overall features of the beach (such as the average weight of sand per cubic meter, the average reflectivity of the beach's surface per square meter, and so on), the task becomes eminently doable. And what makes it doable is the beach's uniformity. Measure the average sand weight, temperature, and reflectivity over here and you're done. Doing the same measurements over there will give essentially identical answers. Likewise with a uniform universe. It would be a hopeless task to describe every planet, star, and galaxy. But describing the average properties of a uniform cosmos is monumentally easier—and, with the advent of general relativity, achievable.

Here's how it goes. The gross overall content of a huge volume of space is characterized by how much "stuff" it contains; more precisely, the density of matter, or, more precisely still, the density of matter and energy that the volume contains. The equations of general relativity describe how this density changes over time. But without invoking the cosmological principle, these equations are hopelessly difficult to analyze. There are ten of them, and because each equation depends intricately on the others, they form a tight mathematical Gordian knot. Happily, Einstein found that when the equations are applied to a uniform universe, the math simplifies; the ten equations become redundant and, in effect, reduce to one. The cosmological principle cuts the Gordian knot by reducing the mathematical complexity of studying matter and energy spread throughout the cosmos to a single equation (you can see it in the notes).[5]

Not so happily, from Einstein's perspective, when he studied this equation he found something unexpected and, to him, unpalatable. The prevailing scientific and philosophical stance was not only that on the largest of scales the universe was uniform, but that it was also unchanging. Much like the rapid molecular motions in your tea average out to a liquid whose appearance is static, astronomical motion such as the planets orbiting the sun and the sun moving around the galaxy would average out to an overall unchanging cosmos. Einstein, who adhered to this cosmic perspective, found to his dismay that it was at odds with general relativity. The math showed that the density of matter and energy *cannot* be constant through time. Either the density grows or it diminishes, but it can't stay put.

Although the mathematical analysis behind this conclusion is sophisticated, the underlying physics is pedestrian. Picture a baseball's journey as it soars from home plate toward the center field fence. At first, the ball rockets upward; then it slows, reaches a high point, and finally heads back down. The ball doesn't lazily hover like a blimp because gravity, being an attractive force, acts in one direction, pulling the baseball toward earth's surface. A static situation, like a stalemate in a tug-of-war, requires equal and opposite forces that cancel. For a blimp, the upward push that counters downward gravity is provided by air pressure (since the blimp is filled with helium, which is lighter than air); for the ball in midair there is no counter-gravity force (air resistance does act against a ball in motion, but plays no role in a static situation), and so the ball can't remain at a fixed height.

Einstein found that the universe is more like the baseball than the blimp. Because there's no outward force to cancel the attractive pull of gravity, general relativity shows that the universe can't be static. Either the fabric of space stretches or it contracts, but its size can't remain fixed. A volume of space 100 million light-years on each side today won't be 100 million light-years on each side tomorrow. Either it will be larger, and the density of matter within it will diminish (being spread more thinly in a larger volume), or it will be smaller, and the density of matter will increase (being packed more tightly in a smaller volume).[6]

Einstein recoiled. According to the math of general relativity, the universe on the grandest of scales would be changing, because its very substrate—space itself—would be changing. The eternal and static cosmos that Einstein expected would emerge from his equations was simply not there. He had initiated the science of cosmology, but he was deeply distressed by where the math had taken him.

Taxing Gravity

It's often said that Einstein blinked—that he went back to his notebooks and in desperation mangled the beautiful equations of general relativity to make them compatible with a universe that was not only uniform but also unchanging. This is only partly true. Einstein did indeed modify his equations so they would support his conviction of a static cosmos, but the change was minimal and thoroughly sensible.

To get a feel for his mathematical move, think about filling out your tax forms. Interspersed among the lines on which you record numbers are others you leave blank. Mathematically, a blank line signifies that the entry is zero, but psychologically it connotes more. It means you're ignoring the line because you've determined that it's not relevant to your financial situation.

If the mathematics of general relativity were arranged like a tax form, it would have three lines. One line would describe the geometry of spacetime—its warps and curves—the embodiment of gravity. Another would describe the distribution of matter across space, the source of gravity—the cause of the warps and curves. During a decade of ardent research, Einstein had worked out the mathematical description of these two features and had thus filled in these two lines with great care. But a complete accounting of general relativity requires a third line, one that is on an absolutely equal mathematical footing with the other two but whose physical meaning is more subtle. When general relativity elevated space and time into dynamic participants in the unfolding of the cosmos, they shifted from merely providing language to delineate where and when things take place to being physical entities with their own intrinsic properties. The third line on the general relativity tax form quantifies a particular intrinsic feature of spacetime relevant for gravity: *the amount of energy stitched into the very fabric of space itself*. Just as every cubic meter of water contains a certain amount of energy, summarized by the water's temperature, every cubic meter of space contains a certain amount of energy, summarized by the number on the third line. In his paper announcing the general theory of relativity, Einstein didn't consider this line. Mathematically, this is tantamount to having set its value to zero, but much as with blank lines on your tax forms, he seems to have simply ignored it.

When general relativity proved incompatible with a static universe, Einstein reengaged with the mathematics, and this time he took a harder look at the third line. He realized that there was no observational or experimental justification for setting it to zero. He also realized that it embodied some remarkable physics.

If instead of zero he entered a positive number on the third line, endowing the spatial fabric with a uniform positive energy, he found (for reasons I'll explain in the next chapter) that every region of space would push away from every other, producing something most physicists had thought impossible: *repulsive* gravity. Moreover, Einstein found that if he precisely adjusted the size of the number he put on the third line, the repulsive gravitational force produced across the cosmos would exactly balance the usual attractive gravitational force generated by the matter inhabiting space, giving rise to a static universe. Like a hovering blimp that neither rises nor falls, the universe would be unchanging.

Einstein called the entry on the third line the *cosmological member* or the *cosmological constant;* with it in place, he could rest easy. Or, he could rest easier. If the universe had a cosmological constant of the right size—that is, if space were endowed with the right amount of intrinsic energy—his theory of gravity fell in line with the prevailing belief that the universe on the largest of scales was unchanging. He couldn't explain why space would embody just the right amount of energy to ensure this balancing act, but at least he'd shown that general relativity, augmented with a cosmological constant of the right value, gave rise to the kind of cosmos he and others had expected.[7]

The Primeval Atom

It was against this backdrop that Lemaître approached Einstein at the 1927 Solvay Conference in Brussels, with his result that general relativity gave rise to a new cosmological paradigm in which space would expand. Having already wrestled with the mathematics to ensure a static universe, and having already dismissed Friedmann's similar claims, Einstein had little patience for once again considering an expanding cosmos. He thus faulted Lemaître for blindly following the mathematics and practicing the "abominable physics" of accepting an obviously absurd conclusion.

A rebuke by a revered figure is no small setback, but for Lemaître it was short-lived. In 1929, using what was then the world's largest telescope at the Mount Wilson Observatory, the American astronomer Edwin Hubble gathered convincing evidence that the distant galaxies were all rushing away from the Milky Way. The remote photons that Hubble examined had traveled to earth with a clear message: The universe is not static. It *is* expanding. Einstein's reason for introducing the cosmological constant was thus unfounded. The big bang model describing a cosmos that began enormously compressed and has been expanding ever since became widely heralded as the scientific story of creation.[8]

Lemaître and Friedmann were vindicated. Friedmann received credit for being the first to explore the expanding universe solutions, and Lemaître for independently developing them into robust cosmological scenarios. Their work was duly lauded as a triumph of mathematical insight into the workings of the cosmos. Einstein, by contrast, was left wishing he'd never meddled with the third line of the general relativity tax form. Had he not brought to bear his unjustified conviction that the universe is static, he wouldn't have introduced the cosmological constant and so might have predicted cosmic expansion more than a decade before it was observed.

Nevertheless, the cosmological constant's story was far from over.

The Models and the Data

The big bang model of cosmology includes a detail that will prove essential. The model provides not one but a handful of different cosmological scenarios; all of them involve an expanding universe, but they differ with respect to the overall shape of space—and, in particular, they differ on the question of whether the full extent of space is finite or infinite. Since the finite-versus-infinite distinction will turn out to be vital in thinking about parallel worlds, I'll lay out the possibilities.

The cosmological principle—the assumed homogeneity of the cosmos—constrains the geometry of space because most shapes are not sufficiently uniform to qualify: they bulge here, flatten out there, or twist way over there. But the cosmological principle does not imply a *unique* shape for our three dimensions of space; instead, it reduces the possibilities to a sharply culled collection of candidates. To visualize them presents a challenge even for professionals, but it is a helpful fact that the situation in *two* dimensions provides a mathematically precise analog that we can readily picture.

To this end, first consider a perfectly round cue ball. Its surface is two-dimensional (just as on earth's surface, you can denote positions on the cue ball's surface with two pieces of data—such as latitude and longitude—which is what we mean when we call a shape two-dimensional) and is completely uniform in the sense that every location looks like every other. Mathematicians call the cue ball's surface a *two-dimensional sphere* and say that it has *constant positive curvature*. Loosely speaking, "positive" means that were you to view your reflection on a spherical mirror it would bloat outward, while "constant" means that regardless of where on the sphere your reflection is, the distortion appears the same.

Next, picture a perfectly smooth tabletop. As with the cue ball, the tabletop's surface is uniform. Or nearly so. Were you an ant walking on the tabletop, the view from every point would indeed look like the view from every other, but only if you stayed far from the table's edge. Even so, complete uniformity is not hard to restore. We just need to imagine a tabletop with no edges, and there are two ways of doing so. Think of a tabletop that extends indefinitely left and right as well as back and forth. This is unusual—it's an infinitely large surface—but it realizes the goal of having no edges since there's now no place to fall off. Alternatively, imagine a tabletop that mimics an early video-game screen. When Ms. Pac-Man crosses the left edge, she reappears at the right; when she crosses the bottom edge she reappears at the top. No ordinary tabletop has this property, but this is a perfectly sensible geometrical space called a two-dimensional *torus*. I discuss this shape more fully in the notes,[9] but the only features in need of emphasis here are that, like the infinite tabletop, the video-game screen shape is uniform and it has no edges. The apparent boundaries confronting Ms. Pac-Man are fictitious; she can cross through them and remain in the game.

Mathematicians say that the infinite tabletop and the video-game screen are shapes that have *constant zero curvature*. "Zero" means that were you to examine your reflection on a mirrored tabletop or video-game screen, the image wouldn't suffer any distortion, and as before, "constant" means that regardless of where you examine your reflection, the image looks the same. The difference between the two shapes becomes apparent only from a global perspective. If you took a journey on an infinite tabletop and maintained a constant heading, you'd never return home; on a video-game screen, you could cycle around the entire shape and find yourself back at the point of departure, even though you never turned the steering wheel.

Finally—and this is a little more difficult to picture—a Pringles potato chip, if extended indefinitely, provides another completely uniform shape, one that mathematicians say has *constant negative curvature*. This means that if you view your reflection at any spot on a mirrored Pringles chip, the image will appear shrunken inward.

Fortunately, these descriptions of two-dimensional uniform shapes extend effortlessly to our real interest in the three-dimensional space of the cosmos. Positive, negative, and zero curvatures—uniform bloating outward, shrinking inward, and no distortion at all—equally well characterize uniform three-dimensional shapes. In fact, we are doubly fortunate because although three-dimensional shapes are hard to picture (when envisioning shapes, our minds invariably place them within an environment—an airplane *in* space, a planet *in* space—but when it comes to space itself, there isn't an outside environment to contain it); the uniform three-dimensional shapes are such tight mathematical analogs of their two-dimensional cousins that you lose little precision by doing what most physicists do: use the two-dimensional examples for your mental imagery.

In the table below, I've summarized the possible shapes, emphasizing that some are finite in extent (the sphere, the video-game screen) while others are infinite (the endless tabletop, the endless Pringles chip). As it stands, Table 2.1 is incomplete. There are additional possibilities, with wonderful names like the *binary tetrahedral space* and the *Poincaré dodecahedral space*, that also have uniform curvature, but I've not included them because they're harder to visualize using everyday objects. By judicious slicing and paring they can be sculpted from those that I've put in the list, so Table 2.1 provides a good representative sampling. But these details are secondary to the main conclusion: *The uniformity of the cosmos articulated by the cosmological principle substantially winnows the possible shapes for the universe. Some of the possible shapes have infinite spatial extent, while others do not.*[10]

SHAPE	TYPE OF CURVATURE	SPATIAL EXTENT
Sphere	Positive	Finite
Tabletop	Zero (or "flat")	Infinite
Video-Game Screen	Zero (or "flat")	Finite
Pringles Chip	Negative	Infinite

Table 2.1*Possible shapes for space consistent with the assumption that every location in the universe is on a par with every other (the cosmological principle*).

Our Universe

The expansion of space found mathematically by Friedmann and Lemaître applies verbatim to a universe that has any one of these shapes. For positive curvature, use the two-dimensional mental imagery to think of a balloon's surface expanding as it is filled with air. For zero curvature, think of a flat sheet of rubber that is being stretched uniformly in all directions. For negative curvature, mold that rubber sheet into the shape of a Pringles chip and then carry on with the stretching. If galaxies are modeled as glitter evenly sprinkled on any of these surfaces, the expansion of space results in the individual specks of glitter—the galaxies—moving apart from one another, just as Hubble's 1929 observations of distant galaxies revealed.

It's a compelling cosmological template, but if it is to be definitive and complete, we need to determine which of the uniform shapes describes our universe. We can determine the shape of a familiar object, such as a doughnut, a baseball, or a block of ice, by picking it up and turning it this way and that. The challenge is that we can't do so with the universe, and so we must determine its shape through indirect means. The equations of general relativity provide a mathematical strategy. They show that the curvature of space reduces to a single observational quantity: the density of matter (more precisely, the density of matter and energy) in space. If there is a lot of matter, gravity will cause space to curve back on itself, yielding the spherical shape. If there is little matter, space is free to flare outward in the Pringles shape. And if there is just the right amount of matter, space will have zero curvature.[*]

The equations of general relativity also provide a precise numerical demarcation among the three possibilities. The mathematics shows that "just the right amount of matter," the so-called critical density, weighs in today at about 2×10^{-29} grams per cubic centimeter, which is about six hydrogen atoms per cubic meter or, in more familiar terms, the equivalent of a single raindrop in every earth-sized volume.[11] Looking around, it would surely seem that the universe exceeds the critical density, but that would be a hasty conclusion. The mathematical calculation of the critical density assumes that matter is uniformly spread throughout space. So you need to envision taking the earth, the moon, the sun, and everything else and evenly dispersing the atoms they contain across the cosmos. The question then is whether each cubic meter would weigh more or less than six hydrogen atoms.

Because of its important cosmological consequences, astronomers have been trying for decades to measure the average density of matter in the universe. Their method is straightforward. With powerful telescopes, they carefully observe large volumes of space and add up the masses of the stars they can see as well as the mass of other material whose presence they can infer by studying stellar and galactic motion. Until recently, the observations indicated that the average density was on the low side, about 27 percent of the critical density—the equivalent of about two hydrogen atoms in each cubic meter—which would imply a negatively curved universe.

But then, in the late 1990s, something extraordinary happened. Through some magnificent observations and a chain of reasoning we'll explore in Chapter 6, astronomers realized that they had been leaving out an essential component of the tally: a diffuse energy that appears to be spread uniformly throughout space. The data came as a shock to most everyone. An energy suffusing space? That sounds like the cosmological constant, which, as we've seen, Einstein introduced and then famously retracted eight decades earlier. Had modern observations resurrected the cosmological constant?

We still don't know for sure. Even today, a decade after the initial observations, astronomers have yet to establish if the uniform energy is fixed or if the amount of energy in a given region of space varies over time. A cosmological constant, as its name signifies (and as its mathematical representation by a single fixed number on the general relativity tax form implies), would be unchanging. To account for the more general possibility that the energy evolves, and to also emphasize that the energy does not give off light (explaining why it had for so long evaded detection) astronomers have coined a new term: *dark energy*. “Dark” also describes well the many gaps in our understanding. No one can explain the dark energy’s origin, fundamental composition, or detailed properties—issues currently under intense investigation to which we shall return in later chapters.

But, even with the numerous open questions, detailed observations using the Hubble Space Telescope and other earth-based observatories have reached consensus on the *amount* of dark energy that is now permeating space. The result differs from what Einstein long ago proposed (since he posited a value that would yield a static universe, whereas our universe is expanding). That’s not surprising. Instead, what’s remarkable is that the measurements have concluded that the dark energy filling space contributes approximately 73 percent of the critical density. *When added to the 27 percent of criticality astronomers had already measured, this brings the total right up to 100 percent of the critical density, just the right amount of matter and energy for a universe with zero spatial curvature*.

Current data thus favor an ever-expanding universe shaped like the three-dimensional version of the infinite tabletop or of the finite video-game screen.

Reality in an Infinite Universe

At the beginning of this chapter, I noted that we don’t know whether the universe is finite or infinite. The previous sections have laid out the case that both possibilities naturally emerge from our theoretical studies, and that both possibilities are consistent with the most refined astrophysical measurements and observations. How might we one day determine observationally which possibility is right?

It’s a tough question. If space is finite, then some of the light emitted by stars and galaxies might cycle around the entire cosmos multiple times before entering our telescopes. Like the repeated images generated when light bounces between parallel mirrors, cycling light would give rise to repeated images of stars or galaxies. Astronomers have looked for such multiple images but as yet haven't found any. This, in itself, doesn't prove that space is infinite, but it does suggest that if space is finite it may be so large that light hasn't had time to complete multiple laps around the cosmic racetrack. And that reveals the observational challenge. Even if the universe is finite, the larger it is the better it can masquerade as infinite.

For some cosmological questions, such as the age of the universe, the distinction between the two possibilities plays no role. Whether the cosmos is finite or infinite, at ever-earlier times, the galaxies would have been squeezed ever closer together, making the universe denser, hotter, and more extreme. We can use today's observations of the rate of expansion, together with theoretical analysis of how that rate has changed over time, to tell us how long it's been since everything we see would have been compressed into a single fantastically dense nugget, what we can call the beginning. And for either a finite or an infinite universe, state-of-the-art analyses now peg that moment at about 13.7 billion years ago.

But for other considerations, the finite-infinite distinction matters. In the finite case, for example, as we consider the cosmos at ever-earlier times, it's accurate to picture the entirety of space continually shrinking. Although the mathematics breaks down at time zero itself, it's correct to envision that at moments ever closer to time zero, the universe is an ever-smaller speck. For the infinite case, however, this description is wrong. If space is truly infinite in size, then it always has been and always will be. When it shrinks, its contents are squeezed ever closer together, making the density of matter ever larger. But its overall extent remains *infinite*. After all, shrink an infinite tabletop by a factor of 2 and what do you get? Half of infinity, which is still infinite. Shrink by a factor of 1 million and what do you get? Infinity still. The closer to time zero you consider an infinite universe, the denser it becomes at every location, but its spatial extent remains unending.

Although observations leave the finite-versus-infinite issue undecided, I've found that when pressed, physicists and cosmologists tend to favor the proposition that the universe is infinite. Partly, I think this view is rooted in the historical happenstance that for many decades researchers paid little heed to the finite video-game shape, mostly because it is more mathematically complex to analyze. Perhaps the view also reflects a common misconception that the difference between an infinite and a huge-but-finite universe is a cosmological distinction that's only of academic interest. After all, if space is so large that you will only ever have access to a small portion of its entirety, should you care whether it extends for a finite or for an infinite distance beyond what you can see?

You should. The issue of whether space is finite or infinite has a profound impact on the very nature of reality. Which takes us to the heart of this chapter. Let's now consider the possibility of an infinitely big cosmos and explore its implications. With minimal effort, we'll find ourselves inhabiting one of an infinite collection of parallel worlds.

Infinite Space and the Patchwork Quilt

Let's start simply, back here on earth, far from the vast reaches of an infinite cosmic expanse. Imagine that your friend Imelda, to satisfy her penchant for variety in personal attire, has acquired five hundred richly embroidered dresses and a thousand pairs of designer shoes. If each day she wears one dress with one pair of shoes, at some point she will exhaust all possible combinations and duplicate an earlier outfit. It's easy to figure out when. Five hundred dresses and a thousand pairs of shoes yield 500,000 different combinations. Five hundred thousand days is about 1,400 years, so if she lived long enough Imelda would be seen in an outfit she'd already worn. If Imelda, blessed with infinite longevity, continued to cycle through every possible combination, she'd necessarily don each of her outfits an infinite number of times. An infinite number of appearances with a finite number of outfits ensures infinite repetition.

Pursuing the same theme, imagine that Randy, an expert card dealer, has shuffled a gargantuan number of decks, one by one, and neatly stacked each next to the others. Can the order of cards in every shuffled deck be different, or must they repeat? The answer depends on the number of decks. Fifty-two cards can be arranged indifferent ways (52 possibilities for which card will be the first, times 51 remaining possibilities for which will be the second, times

50 remaining possibilities for the next card, and so on). If the number of decks Randy shuffles exceeds the number of different possible card orderings, then some of the shuffled decks would match. If Randy were to shuffle an infinite number of decks, the orderings of the cards would necessarily repeat an infinite number of times. As with Imelda and her outfits, an infinite number of occurrences with a finite number of possible configurations ensures that outcomes are infinitely repeated.

This basic notion is of the essence for cosmology in an infinite universe. Two key steps show why.

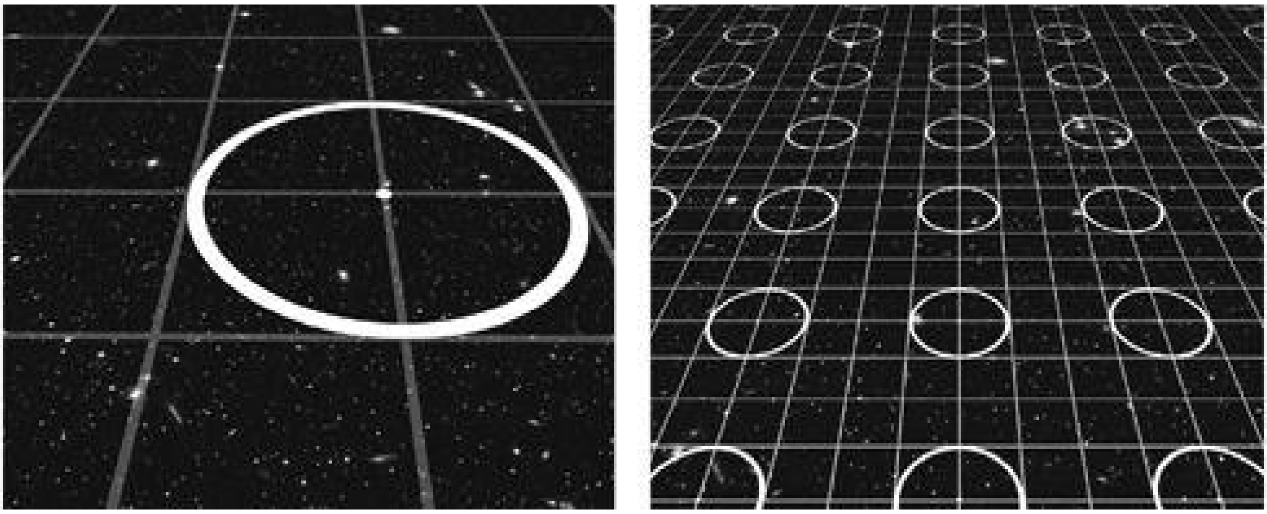
In an infinite universe, most regions lie beyond our ability to see, even using the most powerful telescopes possible. Although light travels enormously quickly, if an object is sufficiently distant, then the light it emits—even light that may have been emitted shortly after the big bang—will simply not have had sufficient time to reach us. Since the universe is about 13.7 billion years old, you might think that anything farther away than 13.7 billion light-years would fall into this category. The reasoning behind this intuition is right on target, but the expansion of space increases the distance to objects whose light has long been traveling and has only just been received; so the maximum distance we can see is actually longer—about 41 billion light-years.[12] But the exact numbers hardly matter. The important point is that regions of the universe beyond a certain distance are regions currently beyond our observational reach. Much as ships that have sailed beyond the horizon are not visible to someone standing on shore, astronomers say that objects in space that are too far away to be seen lie beyond our *cosmic horizon*.

Similarly, the light we've been emitting can't yet have reached those distant regions, so we are beyond their cosmic horizon. And it's not that cosmic horizons solely delineate what someone can and cannot see. From Einstein's special relativity, we know that no signal, no disturbance, no information, no *anything* can travel faster than light—which means that regions of the universe so far apart that light hasn't had time to travel between them are regions that have never exchanged any influence of any kind, and so have evolved completely independently.

Using a two-dimensional analogy, we can compare the expanse of space, at a given moment of time, to a giant patchwork quilt (with circular patches) in which each patch represents a single cosmic horizon. Someone located in the center of a patch can have interacted with anything that lies in the same patch, but has had no contact with anything lying in a different patch (see Figure 2.1a), because they're too far away. Points lying near the border between two patches are closer together than their respective centers and so can have interacted, but if we consider, say, patches in every other row and every other column of the cosmic quilt, all points residing in different patches are now so far from one another that no cross-patch interactions of any kind could have taken place (see Figure 2.1b). The same idea applies in three dimensions, where the cosmic horizons—the patches in the cosmic quilt—are spherical, and the same conclusion holds: sufficiently distant patches lie beyond one another's spheres of influence and so are independent realms.

If space is large but finite, we can divide it into a large but finite number of such independent patches. If space is infinite, then there are an *infinite* number of independent patches. It's this latter possibility that's of particular allure, and the second part of the argument tells why. As we will now see, in any given patch the particles of matter (more precisely, matter and all forms of energy) can be arranged in only a finite number of different configurations. Using the reasoning rehearsed with Imelda and Randy, this means that conditions in the infinity of far-flung patches—in regions of space like the one we inhabit but distributed through a limitless cosmos—*necessarily repeat*.

(a)



(b)

Figure 2.1 (a)*Because of light's finite speed, an observer at the center of any patch (called the observer's cosmic horizon) can have interacted only with things lying in that same patch*. **(b)***Sufficiently distant cosmic horizons are too far apart to have had any interactions, and so have evolved completely independently of one another*.

Finite Possibilities

Imagine it’s a hot summer night and there’s an annoying fly buzzing around your bedroom. You’ve tried the swatter, you’ve tried the nasty spray. Nothing’s worked. In desperation, you try reason. “This is a big bedroom,” you tell the fly. “There are so many other places you could be. There’s no reason to keep buzzing around my ear.” “Really?” the fly slyly counters. “How many places are there?”

In a classical universe, the answer is “Infinitely many.” As you tell the fly, he (or, more precisely, his center of mass) could move 3 meters to the left, or 2.5 meters to the right, or 2.236 meters up, or 1.195829 meters down, or ….. you get the idea. Since the fly’s position can vary continuously, there are infinitely many places it can be. In fact, as you explain all this to the fly, you realize that not only does position present the fly with infinite variety, but so does velocity. At one moment the fly can be here, heading to the right at a kilometer per hour. Or it might be heading to the left at half a kilometer per hour, or heading up at a quarter of a kilometer per hour, or heading down at .349283 kilometers per hour, and so on. Although the fly’s speed is constrained by a number of factors (including the limited energy it possesses, since the faster it flies, the more energy it needs to expend), it can vary continuously and hence provides another source of infinite variety.

The fly isn’t convinced. “I’m with you when you talk about moving a centimeter, or half a centimeter, or even a quarter of a centimeter,” the fly responds. “But when you speak of locations that differ by a ten-thousandth or a hundred-thousandth of a centimeter, or even less, you’ve lost me. To an egghead, those might be different locations, but it flies in the face of experience to say that *here* and a billionth of a centimeter to the left of *here* are really different. I can’t sense such a tiny change in location and so I don’t count them as different places. Same goes for speed. I can tell the difference between going a kilometer per hour and going at half that rate. But the difference between .25 kilometers per hour and .249999999 kilometers per hour? Please. Only a wise fly would claim to be able to tell the difference. Fact is, none of us can. So as far as I’m concerned, those are the same speeds. There’s far less variety available than you’re describing.”

The fly has raised an important point. In principle, he can occupy an infinite variety of positions and attain an infinite variety of speeds. But in any practical sense, there is a limit to how fine the differences in location and speed can be before they go completely unnoticed. This is true even if the fly employs the best of equipment. There is always a limit on how small an increment in position or speed can be and yet still register. And regardless of how fine those minimal increments are, if they’re not zero, they radically reduce the range of possible experience.

For instance, if the smallest increments that can be detected are a hundredth of a centimeter, then each centimeter offers not an infinite number of detectably different locations, but only a hundred. Each cubic centimeter would thus provide $100^3 = 1{,}000{,}000$ different locations, and your average bedroom would offer about 100 trillion. Whether the fly would find this array of options sufficiently impressive to keep away from your ear is difficult to say. The conclusion, though, is that *anything but measurements with perfect resolution reduces the number of possibilities from infinite to finite*.

You might counter that the inability to distinguish between tiny spatial separations or differences in speed reflects nothing more than a technological limitation. With progress, the precision of equipment always improves, so the number of discernibly distinct positions and speeds available to a well-funded fly will also always increase. Here I must invoke some basic quantum theory. According to quantum mechanics, there’s a precise sense in which there *is* a fundamental limit on how accurate particular measurements can be, and this limit can’t ever be surpassed, regardless of technological progress—ever. The limit arises from a central feature of quantum mechanics, the *uncertainty principle*.

The uncertainty principle establishes that regardless of what equipment you use or what techniques you employ, if you increase the resolution of your measurement of one property, there is an unavoidable cost: you necessarily reduce how accurately you can measure a complementary property. As a prime example, the uncertainty principle shows that the more accurately you measure an object’s position, the less accurately you can measure its speed, and vice versa.

From the perspective of classical physics, the physics that informs much of our intuition about how the world works, this limitation is completely foreign. But as a rough analogy, think about photographing that impish fly. If your shutter speed is high, you'll get a sharp image that records the fly's location at the moment you snapped the picture. But because the photo is crisp, the fly appears motionless; the image gives no information about the fly's speed. If you set your shutter speed low, the resulting blurry image will convey something of the fly's motion, but because of that blurriness it also provides an imprecise measurement of the fly's location. You can't take a photo that gives sharp information about position and speed simultaneously.

Using the mathematics of quantum mechanics, Werner Heisenberg provided a precise limit on how imprecise the combined measurements of position and speed necessarily are. This inescapable imprecision is what quantum physicists mean by uncertainty. For our purpose, there's a particularly useful way of framing his result. Much as a sharper photograph requires that you use a higher shutter speed, Heisenberg's math shows that a sharper measurement of an object's position requires that you use a higher energy probe. Turn on your bedside lamp, and the resulting probe—diffuse, low-energy light—allows you to make out the general shape of the fly's legs and eyes; illuminate him with higher energy photons, like x-rays (keeping the photon bursts short to avoid cooking him), and the finer resolution reveals the minuscule muscles that flap the fly's wings. But perfect resolution, according to Heisenberg, requires a probe with infinite energy. That's unattainable.

And so, the essential conclusion is at hand. Classical physics makes clear that perfect resolution is unattainable in practice. Quantum physics goes further and establishes that perfect resolution is unattainable in principle. If you imagine both the speed and the position of an object—be it a fly or an electron—changing by sufficiently small amounts, then according to quantum mechanics, you are imagining something meaningless. Changes that are too small to be measured, even in principle, are not changes at all.[13]

By the same reasoning we used in our pre-quantum analysis of the fly, the limit on resolution reduces from infinite to finite the number of distinct possibilities for an object's position and speed. And since the limited resolution entailed by quantum mechanics is entwined in the very fibers of physical law, this reduction to finite possibilities is unavoidable and unassailable.

Cosmic Repetition

So much for flies in bedrooms. Now consider a larger region of space. Consider a region the size of today's cosmic horizon, a sphere with a radius of 41 billion light-years. A region, that is, which is the size of a single patch in the cosmic quilt. And consider filling it not with a single fly but with particles of matter and radiation. Here's the question: How many different arrangements of the particles are possible?

Well, as with a box of Legos, the more pieces you have—the more matter and radiation you cram into the region—the greater the number of possible arrangements. But you can't cram pieces in indefinitely. Particles carry energy, so more particles means more energy. If a region of space contains too much energy, it will collapse under its own weight and form a black hole.[*] And if after a black hole forms you try to cram yet more matter and energy into the region, the black hole's boundary (its *event horizon*) will grow larger, encompassing more space. There is thus a limit to how much matter and energy can exist fully within a region of space of a given size. For a region of space as large as today's cosmic horizon, the limits involved are huge (about 10^{56} grams). But the size of the limit is not central. What's central is that there *is* a limit.

Finite energy within a cosmic horizon entails a finite number of particles, be they electrons, protons, neutrons, neutrinos, muons, photons, or any of the other known or as yet unidentified species in the particle bestiary. Finite energy within a cosmic horizon also entails that each of these particles, like the annoying fly in your bedroom, has a finite number of distinct possible locations and speeds. Collectively, a finite number of particles, each of which can have finitely many distinct positions and velocities, means that within any cosmic horizon only a finite number of different particle arrangements are available. (In the more refined language of quantum theory proper, which we'll encounter in Chapter 8, we don't speak of particle positions and velocities per se, but rather of the *quantum state* of these particles. From this perspective, we would say there are only a finite number of observably distinct quantum states for the particles in the cosmic patch.) Indeed, a short calculation—described in the notes, if you're curious about the details—

reveals that the number of distinct possible particle configurations within a cosmic horizon is about $10^{10^{122}}$ (a 1 followed by 10^{122} zeros). This is a huge but decidedly finite number.[14]

The limited number of different clothes combinations ensures that with enough outings, Imelda's attire will necessarily repeat. The limited number of different card orderings ensures that with enough decks, Randy's shuffles will necessarily repeat. By the same reasoning, the limited number of particle arrangements ensures that with enough patches in the cosmic quilt—enough independent cosmic horizons—the *particle arrangements, when compared from patch to patch, must somewhere repeat*. Even if you were able to play cosmic designer and tried to arrange each patch to be different from the ones you'd examined before, with a big enough expanse you'd eventually run out of distinct designs and would be forced to repeat a previous arrangement.

In an infinitely big universe, the repetition is yet more extreme. There are infinitely many patches in an infinite expanse of space; so, with only finitely many different particle arrangements, the arrangements of particles within patches must be duplicated an infinite number of times.

That's the result we've been after.

Nothing but Physics

In interpreting the implications of this statement, I should declare my bias. I believe that a physical system is completely determined by the arrangement of its particles. Tell me how the particles making up the earth, the sun, the galaxy, and everything else are arranged, and you've fully articulated reality. This reductionist view is common among physicists, but there are certainly people who think otherwise. Especially when it comes to life, some believe that an essential nonphysical aspect (spirit, soul, life force, chi, and so on) is required to animate the physical. Although I remain open to this possibility, I've never encountered any evidence to support it. The position that makes the most sense to me is that one's physical and mental characteristics are nothing but a manifestation of how the particles in one's body are arranged. Specify the particle arrangement and you've specified everything.[15]

Adhering to this perspective, we conclude that if the particle arrangement with which we're familiar were duplicated in another patch—another cosmic horizon—that patch would look and feel like ours in every way. This means that if the universe is infinite in extent, you are not alone in whatever reaction you are now having to this view of reality. There are many perfect copies of you out there in the cosmos, feeling exactly the same way. And there's no way to say which is *really* you. All versions are physically and hence mentally identical.

We can even estimate the distance to the nearest copy. If the particle arrangements are randomly distributed from patch to patch (an assumption that's compatible with the refined cosmological theory we will encounter in the next chapter), then we can expect that the conditions in our patch will be duplicated as frequently as those in any other. In every collection of 10^{10122} cosmic patches, we thus expect there to be, on average, one patch that looks just like ours. That is, in every region of space that's roughly 10^{10122} meters across, there should be a cosmic patch that replicates ours—one that contains you, the earth, the galaxy, and everything else that inhabits our cosmic horizon.

If you lower your sights and don't seek an exact replica of our entire cosmic horizon, but would be satisfied with an exact copy of a region a few light-years in radius and centered on our sun, the order is more easily filled: on average, in every region that's about 10^{10100} meters across, you should find one such copy. Still easier to find are approximate copies. After all, there is only one way to duplicate a region exactly, but many ways to *almost* duplicate it. Were you to visit these inexact copies, you'd find some that are barely distinguishable from ours, while in others the differences would range from obvious to exhilarating to shocking. Every decision you've ever made is tantamount to a particular particle arrangement. If you turned left, your particles went one way; if you turned right, your particles went the other. If you said yes, the particles in your brain, lips, and vocal cords proceeded through one pattern; if you said no, they proceeded through a different pattern. And so every possible action, every choice you've made and every option you've discarded, will be played out in one patch or another. In some, your worst fears about yourself, your family, and life on earth have been realized. In others, your wildest dreams have come to pass. In others still, the differences arising from the close but distinct particle arrangements have combined to yield an unrecognizable environment. And in most patches, the particle complexion would not include the highly specialized arrangements we recognize as living organisms, so the patches would be lifeless, or at least devoid of life as we know it.

Over time, the size of the cosmic patches laid out in Figure 2.1b will increase; with more time, light can travel farther and so each of the cosmic horizons will grow larger. Ultimately, the cosmic horizons will overlap. And when they do, the regions can no longer be considered as separate and isolated; the parallel universes will no longer be parallel—they will have merged. Nevertheless, the result we've found will continue to hold. Just lay out a new grid of cosmic patches with patch size set by the distance light can have traveled since the big bang through this later moment. The patches will be bigger, so to fill out a pattern like that in Figure 2.1b their centers will need to be farther apart, but with infinite space at our disposal, there's ample room to accommodate this adjustment.[16]

And so we've come to a conclusion that's both general and provocative. Reality in an infinite cosmos is not what most of us would expect. At any moment in time, the expanse of space contains an infinite number of separate realms—constituents of what I'll call the *Quilted Multiverse*—with our observable universe, all we see in the vast night sky, being but one member. Canvassing this infinite collection of separate realms, we find that particle arrangements necessarily repeat infinitely many times. The reality that holds in any given universe, including ours, is thus replicated in an infinite number of other universes across the Quilted Multiverse.[17]

What to Make of This?

It's possible that the conclusion we've reached strikes you as so outlandish that you're inclined to turn the discussion on its head. You might argue that the bizarre nature of where we've gotten—infinite copies of you and everyone and everything—is evidence of the faulty nature of one or more of the assumptions that led us here.

Might the assumption that the entire cosmos is inhabited by particles be wrong? Perhaps beyond our cosmic horizon is a vast realm containing nothing but empty space. It’s possible, but the theoretical contortions required to accommodate such a picture render it thoroughly unconvincing. The most refined cosmological theories, to be encountered shortly, don’t lead us anywhere near this possibility.

Might the very laws of physics change beyond our cosmic horizon, corrupting our ability to perform any reliable theoretical analyses of those distant realms? Again, it’s possible. But as we will see in the next chapter, recent developments yield a compelling argument that although the laws can vary, that variation doesn’t invalidate our conclusions regarding the Quilted Multiverse.

Might the universe’s spatial expanse be finite? Sure. Definitely possible. If space were finite yet large enough, there could still be some interesting patches way out there. But a smallish finite universe could easily fail to have adequate space to accommodate substantial numbers of distinct patches, let alone any that are duplicates of our own. A finite universe poses the most convincing way to upend the Quilted Multiverse.

But in the last few decades, physicists working to push the big bang theory back to time zero—in search of a deeper understanding of the origin and nature of Lemaître’s primeval atom—have developed an approach called *inflationary cosmology*. In the inflationary framework, the argument in support of an infinitely large cosmos, not only garners strong observational and theoretical support but, as we will see in the next chapter, becomes an almost inevitable conclusion.

What’s more, inflation brings to the fore another, even more exotic, variety of parallel worlds.

*It’s easier to envision curved space than curved time, and that’s why many popularizations of Einsteinian gravity focus solely on the former. However, for the gravity generated by familiar objects like the earth and sun, it is actually the curvature of time—not space—that exerts the dominant impact. For an illustration, think of two clocks, one on the ground, the other on top of the Empire State Building. Because the ground clock is closer to the earth’s center, it experiences slightly stronger gravity than the clock that’s high above Manhattan. General relativity shows that because of this, the rate at which time passes on each will be slightly different: the ground clock will run a tiny bit slow (billionths of a second per year) compared to the elevated clock. The temporal mismatch is an example of what we mean by time being curved or warped. General relativity then establishes that objects move toward regions where time elapses more slowly; in a sense, all objects "want" to age as slowly as possible. From an Einsteinian perspective, that explains why an object falls when you let go of it.

*Given our earlier discussion of how matter curves the region in which it is immersed, you might wonder how there can be *no* curvature even though there's matter. The explanation is that a uniform presence of matter generally curves *spacetime;* in this particular case, there is zero space curvature but nonzero spacetime curvature.

*I will discuss black holes more fully in later chapters. Here we'll stick to the familiar notion, by now well ingrained in popular culture, of a spatial region—think of it as a ball in space—whose gravitational pull is so strong that nothing crossing its edge can escape. The bigger the black hole's mass, the larger its size, so when anything falls in, not only does the black hole's mass increase but its size does too.