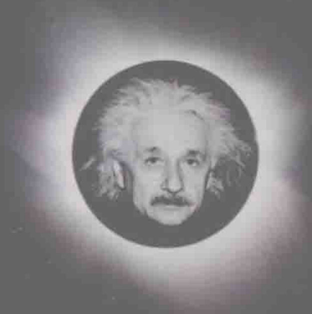

SIMPLY EINSTEIN

Relativity Demystified

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PREFACE

Have you ever heard it said of a difficult idea that "it would take an Einstein to understand this"? What could be more incomprehensible to us non-Einsteins than Albert Einstein's own work, the theory of relativity?

But relativity *is* comprehensible, and not just to scientists. At the heart of relativity is an extraordinarily simple idea—so simple that a single English sentence suffices to state it all. Some consequences of that statement are disturbing because they violate our deeply held, commonsense notions about the world. Yet those consequences flow inexorably from a single principle so simple and obvious that it will take me just a few pages to convince you of its truth.

This book's title, *Simply Einstein,* reflects the fact that the basic ideas of Einstein's relativity are accessible to nonscientists and make eminent sense. Even relativity's startling implications about the nature of space, time, and matter follow so directly from those basic ideas that they, too, become not only comprehensible but also logically inevitable.

Relativity is behind many of the hot topics at the frontiers of modern physics, astrophysics, and cosmology—topics ranging from black holes to the ultimate fate of the Universe to the prospects for time travel. I'll touch on these topics here, and you'll see how they flow from the essential ideas of relativity. But my main purpose is not to explore the latest frontiers of physics. There are plenty of good books on those topics, and I've included some in the Further

Readings. Rather, this is a book that aims to give you, its reader, a clear understanding of just what it was that Einstein said about the ultimate nature of physical reality. To help you get there, we'll be exploring together the history of ideas that culminated in Einstein's simple but remarkable vision. Then you'll see how that vision alters your commonsense notions of space and time in ways that would let you travel a thousand years into the future in just a few short hours. You'll come to a new understanding of "past" and "future" that might surprise historians, and you'll begin to feel at home in the four-dimensional universe of relativistic spacetime. Along the way I'll anticipate your frequent questions: Why can't anything go faster than light? Will I really age more slowly, or is this just something that happens to physicists' clocks? Can I go backward in time? What does $E = mc^2$ really mean? Finally, in the end, we'll return to some of those contemporary hot topics that show just how prescient was Einstein's visionary insight.

You don't need to do math to grasp the essence of Einstein's relativity, and you don't need math to understand this book. Occasional numbers can help make some points more concrete, and I'll use them sparingly. What's important here are the big ideas—and they're all expressed in words. Grasp those ideas, and you know what Einstein's relativity is all about. Enjoy!

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SIMPLY EINSTEIN

CHAPTER 1

THE SELF-CREATING UNIVERSE AND OTHER ABSURDITIES

Could the Universe have created itself? What an absurd idea! Did the Universe even have a beginning? That question, too, has an absurd ring. If there was a beginning, what came before? Wasn't that part of the Universe too? Or has the Universe always existed, begging the question of its own origin?

Whatever the answers to these questions, modern astrophysics makes one thing clear: our Universe hasn't existed forever unchanged. Rather, it's evolved from an earlier state of extreme temperature and density. Some 14 billion years ago, all the "stuff" that makes up ourselves, our planet Earth, and all the stars and galaxies was crammed into a volume far smaller than a single hydrogen atom or even the tiny proton at its core. The expansion of that extreme state is the Big Bang that describes the Universe's subsequent evolution and ultimately accounts for the origin of stars, galaxies, planets, and intelligent life.

What came before the Big Bang? What created that early, extreme state? We're back to the primordial question: Did the Universe have a beginning, or has it always existed—albeit an existence marked by evolutionary change?

To some cosmologists—scientists who concern themselves with the origin and evolution of the Universe—the start of the Big Bang marks the start of time itself. For them, it makes no sense to ask what came before because the concept of "before" is meaningless if there's no such thing as time. Others have envisioned an ever existing Universe that undergoes a series of oscillations. Each begins with a Big Bang and subsequent expansion—the phase we're now in—then eventually contracts toward a Big Crunch of extreme density and temperature that starts another cycle.

In 1998 Princeton physicist J. Richard Gott and his student Li-Xin Li published a novel answer to the ultimate question of the Universe's origin. Their paper, "Can the Universe Create Itself?," shows how the laws of physics may allow a *time loop*, in which time goes round and round in a circlelike structure rather than advancing inexorably into a never-before-experienced future. Like Bill Pullman's character in the film *Groundhog Day*, an occupant of the time loop might go to bed at night and wake up on the morning of the day before! The "new" day would unfold, night would come, and again the morning would bring the already familiar day. In this loop, time advances circularly into a future that is a recycling through past events. There's no earliest event, any more than any point on a circle can be called the beginning of the circle or any point on Earth's surface is the place where our planet "starts."

Gott's time loop doesn't sound like a description of our Universe, but hold on—there's more. Time, in Gott's theory, can branch, providing different paths to different futures. Gott envisions a universe whose earliest epoch includes a time loop. Every point on the loop both precedes and follows every other point. There is no beginning instant, because one can always trace time further back round the loop. But there's a branch out of the time loop, a branch into a more normal realm of time that advances, without repetition, to a future of never-before events. That's the kind of time we know, with an as-yet-unknown, yet-to-occur future. Figure 1.1 depicts Gott's time-loop, multibranched universe.

It's the branching that reconciles Gott's time loop with the more ordinary time we experience today. The time loop unambiguously precedes our present, and in that sense it's closer to the beginning. But trace time backward, through the branch and onto the loop. You can keep tracing back but you'll never find a beginning. Instead, events repeat as your historical exploration circles backward around the loop. There's no one event that marks the creation

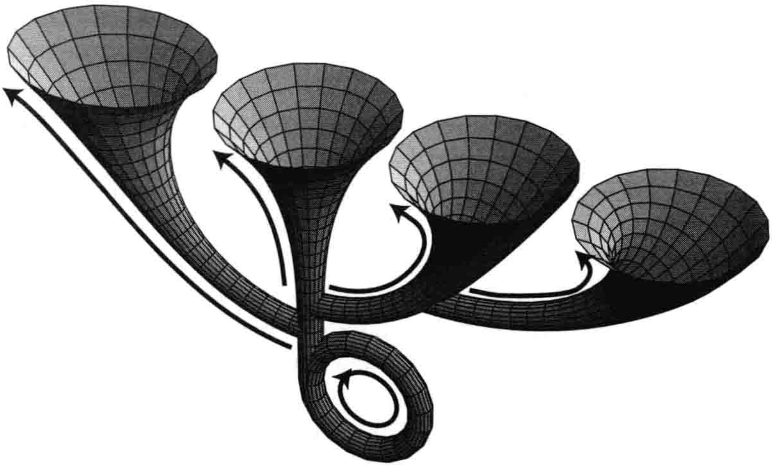

Fig. 1.1 Gott's time-loop universe. Arrows represent multiple directions of time, including the circular time loop at the beginning, in which time goes round and round in an ever repeating sequence. Circular cross sections of the "trumpets" represent position in a single spatial dimension, and each trumpet is its own universe. Is this absurd? Maybe not, says the theory of relativity. (Adapted with permission from J. Richard Gott and Li-Xin Li, "Can the Universe Create Itself?" *Physical Review D* 58 (1998), p. 3501.)

of this universe. Every event on the time loop precedes every other event, and in that sense Gott's universe creates itself. Absurd!

How Many Universes Did You Order?

Surely, "The Universe" encompasses all that there is. That's the root meaning of the word, as in "universal." But not according to Stanford University cosmologist Andrei Linde. For the Russian-born Linde, our Universe is but one small branch of a possibly infinite *Multiverse*. What we think of as the Big Bang origin and evolution of *the* Universe is, to Linde, simply the "budding" and subsequent expansion of a new branch from a pre-existing cosmos. That branch is our Universe. Other branches are different universes, each of which has had its own big bang and its own evolutionary scenario. Remarkably, each universe may even have its own laws of physics. The budding that produces a new universe may result in mutations from the laws that govern the parent branch. Together, all these interconnected universes form the Multiverse or, in Linde's more dynamic phrasing, the "self-replicating inflationary universe." Our own Universe may someday spawn new buds that become entire universes; in fact, it may already have done so. It might not even take much effort to initiate such a bud. Cosmologist Alan Guth of MIT has suggested that with an ounce of material, crushed to high enough density, you might start a new universe right in your own garage! Perhaps we and our whole Universe are just the results of someone's experimentation in another branch of the Multiverse.

Linde's Multiverse provides yet another answer to the question of the Universe's origin. *Our* Universe, according to Linde, clearly had a beginning in the budding event that was the start of *our* Big Bang. But that budding occurred from one branch of a Multiverse that may have existed forever—as if the structure in Figure 1.1, instead of starting with the time loop, just continued backward forever in a jumble of budding and branching universes. That self-replicating Multiverse in some ways resembles a biological system. It's forever spawning new buds—"baby universes"—some of which grow to become full-blown universes like our own, which then produce their own babies. Others are stillborn, withering to collapse before they've had a chance to evolve complex structure and intelligent life. Universes come and go, so there are multiple beginnings. Creation isn't a one-time story. But the Multiverse persists forever, and, despite the birth and demise of individual universes, the large-scale picture may remain unchanged for eternity.

Contact!

In the film *Contact*, based on Carl Sagan's novel with the same title, actress Jodi Foster plays the first astrophysicist to detect interstellar signals from an advanced civilization. The signals convey a message—instructions for building some sort of machine. Machines are built, against a backdrop of political and religious intrigue, and eventually Foster's character boards one for a ride into the unknown. The machine takes her through a wormhole in spacetime and deposits her on a distant world where she learns that entire galaxies are actually cosmic engineering projects. She rides the wormhole machine back to Earth only to find that no one believes her story because, for folks on Earth, no time has elapsed while she was ostensibly touring the cosmos.

Contact looks like science fiction. But many of its key ideas, including wormholes through space and time, are based in sound physics. In fact, author Sagan—a scientist himself—consulted colleagues about the validity of the sci-fi ideas at the basis of *Contact*. As a result, Sagan's novel spurred a flurry of interest in wormholes and in the possibility of time travel. By the turn of the century, leading researchers had published scores of papers on these subjects in the most respected physics journals. Some show how wormholes might connect seemingly distant parts of the Universe that are actually less than an inch apart in a hidden dimension. Others debate the mathematical possibility and philosophical implications of time machines that might let us travel into the past. That's getting pretty speculative, but another form of time travel is solidly established. Read on.

Escape to the Future

In the 1970s, scientists sent a very accurate atomic clock on a trip into the future. How? By flying the clock around Earth on commercial airplanes. When the clock returned to its starting point, it showed less elapsed time than a companion clock that hadn't made the journey. So what? That time difference means the traveling clock had somehow jumped into the future, arriving back at its starting place at a time that was further advanced than its own reading would suggest. For the traveling clock the difference amounted to some 300 billionths of a second. No big deal!

But we're convinced that the same idea would work in a more dramatic context, allowing you to "leapfrog" into the distant future.

Here's the scenario: You and I, who are about the same age, collaborate in building a high-tech spaceship capable of traveling at close to the speed of light (about 186,000 miles per second). You board the ship, zoom off to a star in our galactic neighborhood, and return. As far as you're concerned, the trip takes a few days. But on return, you find me some 20 years older than when you left. You pick up a newspaper, and it's dated 20 years after your departure. You look around and see that planet Earth and all of human society have advanced 20 years during your several-days trip. Somehow you, like the atomic clock, have jumped into the future. This time the jump isn't a negligible fraction of a second but a goodly chunk of a human lifetime. Take that spaceship further—say, to the center of our Milky Way galaxy—and when you return, weeks later as far as you're concerned, you'll find yourself some 60,000 years in the future!

Alas, there's no going back—at least not with this form of time travel. If you don't like what you find thousands of years in the future, you can either put up with it or jump further into the future.

The Universe as Telescope

Much of what we know about the Universe beyond our home planet comes from telescopes—instruments that collect and analyze light and other forms of radiation from the cosmos. Before the early twentieth century, telescopes were too weak to see very clearly beyond our own Milky Way galaxy. That changed with the completion of the 100-inch Mount Wilson telescope in 1917, and within 10 years observations from Mount Wilson had radically enlarged humankind's conception of the Universe—a conception that included, for the first time, hints that the Universe had a beginning.

Mount Wilson reigned for three decades as the world's most powerful telescope, until the 1949 opening of the 200-inch Mount Palomar instrument quadrupled astronomers' powers of observation. (Those 100-inch and 200-inch figures are the diameters of the telescopes' mirrors; the amount of light they collect depends on the mirror area, which quadruples for each doubling of its diameter.) Today's largest ground-based telescopes have mirror diameters of 10 meters, or nearly 400 inches. With their huge but flexible mirrors, prime mountaintop sites, and a host of advanced technological features, these modern instruments greatly extend our vision of the Universe.

The 1990 launch of the Hubble Space Telescope gave astronomers an exciting new tool for probing the Universe. Its location above the distorting effects of Earth's atmosphere more than compensates for Hubble's modest 94-inch mirror. Hubble continues to churn out discoveries, ranging from dust storms on Mars to black holes in neighboring galaxies to objects at the very edges of space and time.

Today Hubble and all its Earth-based companions have been bested—reduced to the role of eyepieces for a "telescope" vastly greater in scale. This "telescope" consists of a cluster of some 10,000 galaxies, located 2 billion light-years from Earth, that acts as a vast cosmic lens. The gravity of this huge assemblage of matter bends light rays and thus concentrates light from more distant objects, making them visible to the paltry telescopes of our own making. In 2001, this cosmic telescope led to the discovery of a "baby galaxy" that formed some 13.4 billion years ago—only 600 million years after the Big Bang and in a realm of time astronomers call the "Dark Ages" because most stars had not yet formed. The cosmic telescope provides a 30-fold enhancement of the light from the baby galaxy; without this effect, the galaxy would be utterly invisible even to the most advanced human-made telescopes. By the way, the cosmic lensmaker didn't make this lens quite perfect; like other *gravitational lenses*, the huge galactic cluster that focuses light from the distant baby galaxy forms distorted and often even multiple images of objects that lie beyond it. In fact, it was through such multiple imaging that gravitational lenses were first identified.

A Common Absurdity

Time loops? A time before time? A many-branched Multiverse? Wormholes? Leapfrogging into the future? Galactic telescopes peering to the edge of space and time? What do all these seeming absurdities have in common? All require conceptions of space and time that boggle our common sense. All require that space and time bend, warp, and distort in ways that have no counterparts in our everyday experience. All require that we give up our tenth-grade notions of geometry, with straight lines and perfect triangles. Straight lines through space, from here to there? Not in a Universe where cosmic lenses focus multiple images of the same object! Straight lines through time, from now to then? Not in a Universe with wormholes, time loops, and high-speed star trips!

The geometry of space and time is not, in fact, the geometry you learned in tenth grade. It's a much richer geometry that allows for the curving, bending, or warping of space and time. That richness, in turn, enables a host of new phenomena: time loops that bend time back on itself; black holes, where spacetime curvature becomes infinite; gravitational lenses that create multiple paths for light from distant sources to reach Earth; high-speed travel that's a shortcut to the future. The strange geometry of spacetime is not some unfathomable mystery, though. It's described precisely by Einstein's theory of relativity—a theory that is as much about the geometry of space and time as it is about phenomena of physics. In fact, relativity suggests that we think of geometry as a branch of physics rather than mathematics, setting the spacetime "stage" on which we and the rest of physical reality strut and fret our roles in the larger Universe.

So what is this relativity theory that mixes geometry into physical reality and leads to mind-boggling possibilities like time loops, wormholes, and cosmic telescopes? Ultimately, the idea behind relativity is a very simple one—so simple that I can state it in a single sentence. But it's a very big idea, too—an idea whose consequences and philosophical implications go far beyond the confines of physics. In the next chapter I will introduce you to the simple Principle of Relativity, and I'll convince you that you already grasp and even embrace this idea at the heart of relativity. From there we'll explore how relativity came to be, what it really means, and why its consequences fly in the face of common sense. At the end, I'll return to the cosmic implications of relativity to show how exotic phenomena like wormholes, time loops, and gravitational lenses follow from your newfound understanding of Einstein's remarkable vision.