ALSO BY FRANK WILCZEK

A Beautiful Question

The Lightness of Being

Fantastic Realities

Longing for the Harmonies

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PREFACE: BORN AGAIN

I

This is a book about fundamental lessons we can learn from the study of the physical world. I've met many people who are curious about the physical world and eager to learn what modern physics says about it. They might be lawyers, doctors, artists, students, teachers, parents, or simply curious people. They have intelligence, but not knowledge. Here I've tried to convey the central messages of modern physics as simply as possible, while not compromising accuracy. I've kept my curious friends and their questions constantly in mind while writing the book.

To me, those fundamental lessons include much more than bare facts about how the physical world works. Those facts are both powerful and strangely beautiful, to be sure. But the style of thought that allowed us to discover them is a great achievement, too. And it's important to consider what those fundamentals suggest about how we humans fit into the big picture.

II

I've selected ten broad principles as my fundamentals. Each forms the theme of one chapter. In the body of each chapter, I explain and document that chapter's theme from different

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perspectives, and then make some informed guesses about its future development. Those informed guesses were fun to create, and I hope they're exciting to read. They are meant to convey another fundamental message: that our understanding of the physical world is still growing and changing. It is a living thing.

I've been careful to separate speculations from facts and, for the facts, to indicate the nature of the observations and experiments that establish them. For perhaps the most fundamental message of all is that we *do* understand many aspects of the physical world very deeply. As Albert Einstein put it, "The fact that [the universe] is comprehensible is a miracle." That, too, was a hard-won discovery.

Precisely because it is so surprising, the comprehensibility of the physical universe must be demonstrated, not assumed. The most convincing proof is that our understanding, though incomplete, has let us accomplish great and amazing things.

In my research, I try to fill gaps in our understanding and to design new experiments to push the frontiers of possibility. It's been a joy for me, in writing this book, to step back and reflect, wonderstruck, on some highlights of what generations of scientists and engineers, cooperating across time and space, have already accomplished.

III

Fundamentals is meant, as well, to offer an alternative to traditional religious fundamentalism. It takes up some of the same basic questions, but addresses them by consulting physical reality, rather than texts or traditions.

Many of my scientific heroes—Galileo Galilei, Johannes Kepler, Isaac Newton, Michael Faraday, James Clerk Maxwell—were devout Christians. (In this they were representative of

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their times and surroundings.) They thought that they could approach and honor God by studying His work. Einstein, though he was not religious in a conventional sense, had a similar attitude. He often referred to God (or “the Old One”), as he did in one of his most famous quotations: “Subtle is the lord, but malicious he is not.”

The spirit of their enterprise, and mine here, transcends specific dogmas, whether religious or antireligious. I like to state it this way: In studying how the world works, we are studying how God works, and thereby *learning what God is*. In that spirit, we can interpret the search for knowledge as a form of worship, and our discoveries as revelations.

IV

Writing this book changed my perception of the world. *Fundamentals* began as an exposition but grew into a contemplation. As I reflected on the material, two overarching themes emerged unexpectedly. Their clarity and depth have astonished me.

The first of those themes is abundance. The world is large. Of course, a good look at the sky on a clear night is enough to show you that there’s lots of space “out there.” When, after more careful study, we put numbers to that size, our minds are properly boggled. But the largeness of space is only one aspect of Nature’s abundance, and it is not the one most central to human experience.

For one thing, as Richard Feynman put it, “there’s plenty of room at the bottom.” Each of our human bodies contains far more atoms than there are stars in the visible universe, and our brains contain about as many neurons as there are stars in our

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galaxy. The universe within is a worthy complement to the universe beyond.

As for space, so also for time. Cosmic time is abundant. The quantity of time reaching back to the big bang dwarfs a human lifetime. And yet, as we'll discuss, a full human lifetime contains far more moments of consciousness than universal history contains human lifespans. We are gifted with an abundance of inner time.

The physical world is abundant, as well, in hitherto untapped resources for creation and perception. Science reveals that the nearby world contains, in known and accessible forms, far more energy and usable material than humans presently exploit. This realization empowers us and should whet our ambitions.

Our unaided perception brings in only a few slivers of the reality that scientific investigation reveals. Consider, for example, vision. Our sense of vision is our widest and most important portal to the external world. But it leaves so much unseen! Telescopes and microscopes reveal vast treasure troves of information, encoded in light, that ordinarily come to our eyes unrecognized. Moreover, our vision is limited to one octave—the span of visible light—from an infinite keyboard of electromagnetic radiation, which runs from radio waves to microwaves to infrared on one side, and from ultraviolet to x-rays and gamma rays on the other. And even within our one octave, our color vision is blurry. While our senses fail to perceive many aspects of reality, our minds allow us to transcend our natural limits. It is a great, continuing adventure to widen the doors of perception.

V

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The second theme is that to appreciate the physical universe properly one must be “born again.”

As I was fleshing out the text of this book, my grandson Luke was born. During the drafting, I got to observe the first few months of his life. I saw how he studied his own hands, wide-eyed, and began to realize that he controlled them. I saw the joy with which he learned to reach out and grasp objects in the external world. I watched him experiment with objects, dropping them and searching for them, and repeating himself (and repeating himself . . .), as if not quite certain of the result, but laughing in joy when he found them.

In these and many other ways, I could see that Luke was constructing a model of the world. He approached it with insatiable curiosity and few preconceptions. By interacting with the world, he learned the things that nearly all human adults take for granted, such as that the world divides into self and not-self, that thoughts can control movements of self but not of not-self, and that we can look at bodies without changing their properties.

Babies are like little scientists, making experiments and drawing conclusions. But the experiments they do are, by the standards of modern science, quite crude. Babies work without telescopes, microscopes, spectroscopes, magnetometers, particle accelerators, atomic clocks, or any other of the instruments we use to construct our truest, most accurate world-models. Their experience is limited to a small range of temperatures; they are immersed in an atmosphere with a very special chemical composition and pressure; Earth’s gravity pulls them (and everything in their environment) down, while Earth’s surface supports them . . . and so forth.

Babies construct a world-model that accounts for what they experience *within the bounds of their perception and environment*. For practical purposes, that’s the right plan. To

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cope with the everyday world, it is efficient, and reasonable, when we are children, to take lessons from the everyday world.

But modern science reveals a physical world very different from the model we construct as babies. If we once again open ourselves up to the world, curious and without preconceptions — if we allow ourselves to be born again—we come to understand the world differently.

Some things, we must learn. The world is built from a few basic building blocks, which follow strict but strange and unfamiliar rules.

Some things, we must unlearn.

Quantum mechanics reveals that you cannot observe something without changing it, after all. Each person receives unique messages from the external world. Imagine that you and a friend sit together in a very dark room, observing a dim light. Make the light very, very dim, say, by covering it with layers of cloth. Eventually, both you and your friend will see only intermittent flashes. But you will see flashes at different times. The light has broken up into individual quanta, and quanta cannot be shared. At this fundamental level, we experience separate worlds.

Psychophysics reveals that consciousness does not direct most actions, but instead processes reports of them, from unconscious units that do the work. Using a technique known as transcranial magnetic stimulation (TMS), it is possible to stimulate the left or right brain motor centers in a subject's brain, at the experimenter's discretion. A properly sculpted TMS signal to the right motor center will cause a twitch of the left wrist, while a properly sculpted TMS signal to the left motor center will cause a twitch of the right wrist. Alvaro Pascual-Leone used this technique ingeniously in a simple experiment that has profound implications. He asked subjects, upon receiving a cue, to decide whether they wanted to twitch their

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right or their left wrist. Then they were instructed to act out their intention upon receiving an additional cue. The subjects were in a brain scanner, so the experimenter could watch their motor areas preparing the twitch. If they had decided to twitch their right wrist, their left motor area was active; if they decided to twitch their left wrist, their right motor area was active. It was possible, in this way, to predict what choice had been made before any motion occurred.

Now comes a revealing twist. Occasionally Pascual-Leone would apply a TMS signal to contradict (and, it turns out, override) the subject's choice. The subject's twitch would then be the one that TMS imposed, rather than the one he or she originally chose. The remarkable thing is how the subjects explained what had happened. They did *not* report that some external force had possessed them. Rather, they said, "I changed my mind."

Detailed study of matter reveals that our body and our brain —the physical platform of our "self"—is, against all intuition, built from the same stuff as "not-self," and appears to be continuous with it.

In our rush to make sense of things, as infants, we learn to misunderstand the world, and ourselves. There's a lot to unlearn, as well as a lot to learn, on the voyage to deep understanding.

VI

The process of being born again can be disorienting. But, like a roller-coaster ride, it can also be exhilarating. And it brings this gift: To those who are born again, in the way of science, the world comes to seem fresh, lucid, and wonderfully abundant. They come to live out William Blake's vision:

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To see a World in a Grain of Sand
And a Heaven in a Wild Flower
Hold Infinity in the palm of your hand
And Eternity in an hour

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INTRODUCTION

I

The universe is a strange place.

To newborn infants, the world presents a jumble of bewildering impressions. In sorting it out, a baby soon learns to distinguish between messages that originate from an internal world and those that originate from an external world. The internal world contains both feelings, such as hunger, pain, well-being, and drowsiness, and the netherworld of dreams. Within it, too, are private thoughts, such as those that direct her gaze, her grasp, and, soon, her speech.

The external world is an elaborate intellectual construction. Our baby devotes much of her time to making it. She learns to recognize stable patterns in her perception that, unlike her own body, do not respond reliably to her thoughts. She organizes those patterns into objects. She learns that those objects behave in somewhat predictable ways.

Eventually our baby, now a child, comes to recognize some of the objects as beings similar to herself, beings with whom she can communicate. After exchanging information with those beings, she becomes convinced that they, too, experience internal and external worlds and, remarkably, that all of them share many objects in common, and that those objects obey the same rules.

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II

Understanding how to control the common external world—in other words, the physical world—is, of course, a vital practical problem, with many aspects. For example, to thrive in a hunter-gatherer society, our child would have to learn where to find water; which plants and animals are good to eat, and how to find, raise, or hunt them; how to prepare and cook food, and many other facts and skills.

In more complex societies, other challenges arise, such as how to make specialized tools, how to build lasting structures, and how to keep track of time. Successful solutions to the problems posed by the physical world get discovered, shared, and accumulated over generations. They become, for each society, its "technology."

Nonscientific societies often develop rich and complex technologies. Some of those technologies enabled—and still do enable—people to thrive in difficult environments, such as the Arctic or the Kalahari Desert. Others supported the construction of great cities and impressive monuments, such as the Egyptian and Mesoamerican pyramids.

Still, throughout most of human history, prior to the emergence of the scientific method, the development of technologies was haphazard. Successful techniques were discovered more or less by accident. Once stumbled upon, they were transmitted in the form of very specific procedures, rituals, and traditions. They did not form a logical system, nor was there a systematic effort to improve them.

Technologies based on "rules of thumb" allowed people to survive, reproduce, and, often, to enjoy some leisure and achieve satisfying lives. For most people, in most cultures, over most of history, that was enough. People had no way to know

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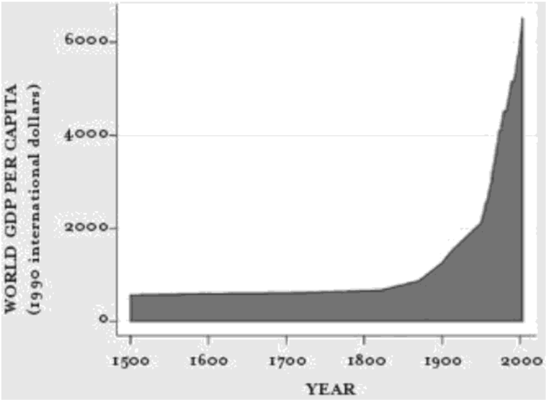
what they were missing, or that what they were missing might be important to them.

But now we know that they were missing a lot. This figure, which shows the development of human productivity with time, speaks for itself, and it speaks volumes.



III

The modern approach to understanding the world emerged in Europe in the seventeenth century. There were partial anticipations earlier, and elsewhere. But the constellation of breakthroughs known as the Scientific Revolution provided inspiring examples of what could be achieved by human minds creatively engaged with the physical world, and the methods and attitudes that led to those breakthroughs gave clear models for future exploration. With that impetus, science as we know it began. It has never looked back.

The seventeenth century saw dramatic theoretical and technological progress on many fronts, including in the design of mechanical machines and ships, of optical instruments (including, notably, microscopes and telescopes), of clocks, and

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of calendars. As a direct result, people could wield more power, see more things, and regulate their affairs more reliably. But what makes the so-called Scientific Revolution unique, and fully deserving of the name, is something less tangible. It was a change in outlook: a new ambition, a new confidence.

The method of Kepler, Galileo, and Newton combines the humble discipline of respecting the facts and learning from Nature with the systematic chutzpah of using what you think you've learned aggressively, applying it everywhere you can, even in situations that go beyond your original evidence. If it works, then you've discovered something useful; if it doesn't, then you've learned something important. I've called that attitude Radical Conservatism, and to me it's the essential innovation of the Scientific Revolution.

Radical Conservatism is conservative because it asks us to learn from Nature and to respect facts—key aspects of what is called the scientific method. But it is radical, too, because it pushes what you've learned for all it's worth. This is no less essential to how science actually works. It provides science with its cutting edge.

IV

This new outlook was inspired, above all, by developments in a subject that even in the seventeenth century was already ancient and well developed: celestial mechanics, the description of how objects in the sky appear to move.

Since long before the beginning of written history, people have recognized such regularities as the alternation of night and day, the cycle of seasons, the phases of the Moon, and the orderly procession of stars. With the rise of agriculture, it became crucial to keep track of seasons, in order to plant and

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harvest at the most appropriate times. Another powerful, if misguided, motivation for accurate observations was the belief that human life was directly connected to cosmic rhythms: astrology. In any case, for a mixture of reasons—including simple curiosity—people studied the sky carefully.

It emerged that the vast majority of stars move in a reasonably simple, predictable way. Today, we interpret their apparent motion as resulting from Earth rotating around its axis. The "fixed stars" are so far away that relatively small changes in their distance, whether due to their own proper motion or to the motion of Earth around the Sun, are invisible to the naked eye. But a few exceptional objects—the Sun, the Moon, and a few "wanderers," including the naked-eye planets Mercury, Venus, Mars, Jupiter, and Saturn—do not follow that pattern.

Ancient astronomers, over many generations, recorded the positions of those special objects, and eventually learned how to predict their changes with fair accuracy. That task required calculations in geometry and trigonometry, following complicated, but perfectly definite, recipes. Ptolemy (c. 100–170) brought this material together in a mathematical text that became known as *Almagest*. (*Magest* is a Greek superlative meaning "greatest." It has the same root as "majestic." *Al* is simply Arabic for "the.")

Ptolemy's synthesis was a magnificent achievement, but it had two shortcomings. One was its complexity and, related to this, its ugliness. In particular, the recipes it used to calculate planetary motions brought in many numbers that were determined purely by fitting the calculations to observations, without deeper guiding principles connecting them. Copernicus (1473–1543) noticed that the values of some of those numbers were related to one another in surprisingly simple ways. These otherwise mysterious, "coincidental" relationships could be

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explained geometrically, if one assumed that Earth together with Venus, Mars, Jupiter, and Saturn all revolve around the Sun as center (and the Moon further revolves around Earth).

The second shortcoming of Ptolemy's synthesis is more straightforward: It simply isn't accurate. Tycho Brahe (1546–1601), in an anticipation of today's "Big Science," designed elaborate instruments and spent a lot of money building an observatory that enabled much more precise observations of planetary positions. The new observations showed unmistakable deviations from Ptolemy's predictions.

Johannes Kepler (1571–1630) set out to make a geometric model of planetary motion that was both simple and accurate. He incorporated Copernicus's ideas and made other important technical changes to Ptolemy's model. Specifically, he allowed the planetary orbits around the Sun to deviate from simple circles, substituting ellipses, with the Sun at one focus. He also allowed the rate at which the planets orbit the Sun to vary with their distance from it, in such a way that they sweep out equal areas in equal times. After those reforms, the system was considerably simpler, and it also worked better.

Meanwhile, back on the surface of Earth, Galileo Galilei (1564–1642) made careful studies of simple forms of motion, such as the way balls roll down inclined planes and how pendulums oscillate. Those humble studies, putting numbers to positions and times, might seem pitifully inadequate to addressing big questions about how the world works. Certainly, to most of Galileo's academic contemporaries, concerned with grand questions of philosophy, they seemed trivial. But Galileo aspired to a different kind of understanding. He wanted to understand *something* precisely, rather than *everything* vaguely. He sought—and found—definite mathematical formulas that described his humble observations fully.

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Isaac Newton (1643–1727) weaved together Kepler's geometry of planetary motion and Galileo's dynamical description of motion on Earth. He demonstrated that both Kepler's theory of planetary motions and Galileo's theory of special motions were best understood as special cases of general laws, laws that apply to all bodies everywhere and for all time. Newton's theory, which we now call classical mechanics, went from triumph to triumph, accounting for the tides on Earth, predicting the paths of comets, and empowering new feats of engineering.

Newton's work showed, by convincing example, that one could address grand questions by building up from a detailed understanding of simple cases. Newton called this method *analysis and synthesis*. It is the archetype of scientific Radical Conservatism.

Here is what Newton himself had to say about that method:

> As in mathematics, so in natural philosophy the investigation of difficult things by the method of analysis ought ever to precede the method of composition. This analysis consists of making experiments and observations, and in drawing general conclusions from them by induction. . . . By this way of analysis we may proceed from compounds to ingredients, and from motions to the forces producing them; and in general from effects to their causes, and from particular causes to more general ones till the argument end in the most general. This is the method of analysis: and the synthesis consists in assuming the causes discovered and established as principles, and by them explaining the phenomena preceding from them, and proving the explanations.

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V

Before leaving Newton, it seems appropriate to add another quotation, which reflects his kinship with his predecessors Galileo and Kepler, and with all of us who follow in their footsteps:

> To explain all nature is too difficult a task for any one man or even for any one age. ’Tis much better to do a little with certainty & leave the rest for others that come after you.

A more recent quotation from John R. Pierce, a pioneer of modern information science, beautifully captures the contrast between the modern concept of scientific understanding and all other approaches:

> We require that our theories harmonize in detail with the very wide range of phenomena they seek to explain. And we insist that they provide us with useful guidance rather than with rationalizations.

As Pierce was acutely aware, this heightened standard comes at a painful price. It involves a loss of innocence. “We will never again understand nature as well as Greek philosophers did. . . . We know too much.” That price, I think, is not too high. In any case, there’s no going back.

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I

What There Is

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1

THERE'S PLENTY OF SPACE

PLENTY OUTSIDE *AND* PLENTY WITHIN

When we say that the something is big—be it the visible universe or a human brain—we have to ask: Compared with what? The natural point of reference is the scope of everyday human life. This is the context of our first world-models, which we construct as children. The scope of the physical world, as revealed by science, is something we discover when we allow ourselves to be born again.

By the standards of everyday life, the world "out there" is truly gigantic. That *outer plenty* is what we sense intuitively when, on a clear night, we look up at a starry sky. We feel, with no need for careful analysis, that the universe has distances vastly larger than our human bodies, and larger than any distance we are ever likely to travel. Scientific understanding not only supports but greatly expands that sense of vastness.

The world's scale can make people feel overwhelmed. The French mathematician, physicist, and religious philosopher Blaise Pascal (1623–1662) felt that way, and it gnawed at him. He wrote that "the universe grasps me and swallows me up like a speck."

Sentiments like Pascal's—roughly, "I'm *very* small, I make no difference in the universe"—are a common theme in literature, philosophy, and theology. They appear in many

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prayers and psalms. Such sentiments are a natural reaction to the human condition of cosmic insignificance, when measured by size.

The good news is that raw size isn't everything. Our *inner plenty* is subtler, but at least equally profound. We come to see this when we consider things from the other end, bottom up. There's plenty of room at the bottom. In all the ways that really matter, we're abundantly large.

In grade school, we learn that the basic structural units of matter are atoms and molecules. In terms of those units, a human body is huge. The number of atoms in a single human body is roughly 10^{28}–1 followed by 28 zeros: 10,000,000,000, 000,000,000,000,000,000.

That is a number far beyond what we can visualize. We can name it—ten octillion—and, after some instruction and practice, we can learn to calculate with it. But it overwhelms ordinary intuition, which is built on everyday experience, when we never have occasion to count that high. Visualizing that many individual dots far exceeds the holding capacity of our brains.

The number of stars visible to unaided human vision, in clear air on a moonless night, is at best a few thousand. Ten octillion, on the other hand, the number of atoms within us, is about a million times the number of stars in the entire visible universe. In that very concrete sense, a universe dwells within us.

Walt Whitman (1819–1892), the big-spirited American poet, felt our inner largeness instinctively. In his "Song of Myself" he wrote, "I am large, I contain multitudes." Whitman's joyful celebration of abundance is just as grounded in objective facts as Pascal's cosmic envy, and it is much more relevant to our actual experience.

The world is large, but we are not small. It is truer to say that there's plenty of space, whether we scale up or down. One

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shouldn't envy the universe just because it's big. We're big, too. We're big enough, specifically, to contain the outer universe within our minds. Pascal himself took comfort from that insight, as he followed his lament that "the universe grasps me and swallows me up like a speck" with the consolation "but through thought I grasp it."

The abundance of space—both its outer and its inner plenty—is the main topic of this chapter. We'll look deeper into the hard facts, and then venture a bit beyond.

OUTER PLENTY: WHAT WE KNOW AND HOW WE KNOW IT

Prelude: Geometry and Reality

Scientific discussion of cosmic distances is built on the foundation of our understanding of physical space and how to measure distance: the science of geometry. Let us begin, therefore, with the relationship between geometry and reality.

Direct, everyday experience teaches us that objects can move from place to place without changing their properties. This leads us to the idea of "space" as a kind of receptacle, wherein nature deposits objects.

Practical applications in surveying, architecture, and navigation led people to measure distances and angles among nearby objects. Through such work, they discovered the regularities on display in Euclidean geometry.

As practical applications got more extensive and demanding, that framework held up impressively. So successful was Euclid's geometry, and so majestic is its logical structure, that critical tests of its validity as a description of physical reality were rarely undertaken. In the early nineteenth century, Carl

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If you review all the steps, you'll see that the engineers who designed the Global Positioning System built on many non-obvious assumptions. The system relies on the idea that the speed of light is constant. It uses atomic clocks, whose design and interpretation relies on advanced principles of quantum theory, to do accurate timing. It uses the tools of classical mechanics to calculate the position of the satellites it deploys. It also makes corrections for the effect, predicted by general relativity, that the rate of clocks depends slightly on their elevation above Earth. Clocks run slower near Earth's surface, where its gravitational field is stronger.

Since the Global Positioning System relies on so many other assumptions in addition to the validity of Euclidean geometry, we cannot claim that it provides a clean, pure test of that geometry. Indeed, the success of GPS is not a clean, pure test of any single principle. It is a complicated system, whose design relies on a tangled web of assumptions.

Any of those assumptions might be wrong or, to put it more diplomatically, only approximately true. If any of the assumptions that engineers assumed to be "approximately true" were significantly wrong, GPS would give inconsistent results. For instance, you might derive different positions from triangulating on different sets of satellites. Hard use can reveal hidden weaknesses.

Conversely, to the extent that GPS works, its success reinforces our confidence in *all* the underlying assumptions, including the assumption that Euclidean geometry describes, with good accuracy, the reality of spatial geometry on earthly scales. And so far, GPS has worked flawlessly.

More generally, science builds. The most advanced, adventurous experiments and technologies rely on tangled webs of underlying theories. When those adventurous applications hold up, they increase our confidence in their supporting webs.

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The fact that fundamental understanding forms a tangled, mutually reinforcing web of ideas will be a recurring theme in what follows.

Before concluding this prelude, I must add a qualification. When we come to consider space on gigantic cosmic scales, as we're about to do, or with exquisite precision, or in the vicinity of black holes, Euclidean geometry stops matching reality. Albert Einstein, in his special and general relativity theories (in 1905 and 1915, respectively), exposed its inadequacies theoretically and suggested how to get beyond them. Since then, his theoretical ideas have been confirmed in many experiments.

Einstein taught us, in special relativity, that when we claim to measure "distance" we must consider carefully what it is we're measuring and how we are measuring it. Real measurements take time, and things can move in time. What we can actually measure is separations between *events*. Events are located in both space and time. The geometry of events must be constructed within that larger framework: space-time, not just space. In general relativity, we learn further that the geometry of space-time can be warped by the influence of matter, or by waves of distortion that travel through it. (More on this in chapters 4 and 8.)

Within the more comprehensive frameworks of space-time and general relativity, Euclidean geometry serves as an approximation to more accurate theories. It is accurate enough for use in the many practical applications mentioned above. Surveyors, architects, and designers of space missions use Euclidean geometry because they can get away with it, and it eases their work. The more comprehensive theories, while more accurate, are much more complicated to use.

The fact that Euclidean geometry fails to provide a complete model of reality does not detract from its mathematical

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consistency nor invalidate its many successes. But it does confirm the wisdom of Gauss's fact-checking, radically conservative approach. The relationship between geometry and reality is a question for Nature to settle.

Surveying the Universe

Having taken the measure of nearby space, we can proceed to survey the cosmos. The primary tools in this endeavor are various kinds of telescopes. Besides the familiar telescopes that employ visible light, astronomers use telescopes that gather "light" from many other parts of the electromagnetic spectrum, including radio waves, microwaves, infrared, ultraviolet, x-rays, and gamma rays. There are also more exotic eyes on the sky, not based on electromagnetic radiation, notably including a very recent addition, gravitational wave detectors. I'll say more about those in later chapters.

Let me begin by highlighting the amazingly simple conclusions of this survey. Then I'll review how astronomers reached them. That is more complicated—though, given the context, still amazingly simple.

The most fundamental conclusion is that we find the same kind of material everywhere. Furthermore, we observe that the same laws apply everywhere.

Second, we find that matter is organized into a hierarchy of structures. Everywhere we look, we can recognize stars. They tend to cluster into galaxies, which commonly contain anywhere from a few million to billions of stars. Our own star, the Sun, has a retinue of planets and moons (and also comets, asteroids, the beautiful "rings" of Saturn, and other debris). Jupiter, the largest planet, has about one-thousandth the weight of the Sun, while Earth has about three-millionths the

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weight of the Sun. Despite their modest share of mass, planets and their moons should be especially dear to our hearts. We live on one, of course, and there are reasons to suspect that others might support new forms of life—if not in our solar system, then elsewhere. Astronomers have long suspected that other stars might have planets, but it is only recently that they've developed the technical strength to detect them. By now, hundreds of extrasolar planets have been discovered, and new discoveries keep flooding in.

Third, we find that all this stuff is sprinkled nearly uniformly throughout space. We find roughly the same density of galaxies in all directions, and at all distances.

Later we will refine and supplement these three fundamental conclusions, notably to bring in the big bang, "dark matter," and "dark energy." But their central message endures: One finds the same sorts of substances, organized in the same sorts of ways, spread uniformly over the visible universe, in vast abundance.

By now you may be wondering how astronomers arrive at such far-reaching conclusions. Let's have a closer look, while filling in concrete values of the sizes and distances.

It is not immediately obvious how to measure the distance to very distant objects. Obviously, you can't lay down rulers, stretch tape measures into the sky, or monitor time-stamped radio transmissions. Instead, astronomers use a bootstrap technique, called the *cosmic distance ladder*. Each rung of the ladder takes us to larger distances. We use our understanding at one rung to prepare us for the next.

We can start by surveying distances in the immediate neighborhood of Earth. Using similar techniques to GPS—that is, bouncing light (or radio signals) around, and measuring transit times—we can determine distances on Earth, and distances from Earth to other objects in the solar system. There

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are several other ways to do this, including some ingenious, though not very accurate, methods invented by the ancient Greeks. For present purposes, it is enough to note that all of these methods give consistent results.

Earth itself is a near-perfect sphere, whose radius is roughly 6,400 kilometers, or 4,000 miles. In this age of air travel, that is a readily comprehensible distance. It is roughly equal to the overland distance between New York and Stockholm, or slightly more than half the distance between New York and Shanghai.

There is another way of stating distance, which is beautifully adapted to astronomy and cosmology, and is widely used in those subjects. Namely, to specify a distance we can specify how long it would take a light beam to travel that distance. For Earth's radius, that computes to about one-fiftieth of a second. We say, therefore, that Earth's radius is equal to one-fiftieth of a light-second.

At higher rungs in the cosmic distance ladder it becomes more practical to measure distances in light-years, rather than light-seconds. To get started with that, and for comparison purposes, let me record now that Earth's radius is roughly one-billionth of one light-year. Keep that tiny number in mind as we expand our survey of the world. It will soon encompass whole light-years, and then hundreds, millions, and finally billions of them.

Our next milestone length is the distance from Earth to our Sun. That distance is about 150 million kilometers, or 94 million miles. It is also 8 light-minutes, or about 15 millionths of one light-year.

Notably, the distance from Earth to the Sun is about 24,000 times Earth's radius. That startlingly large number emphasizes that even within the solar system, all of Earth, let alone a single human, really is "swallowed like a speck."

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