THE LIGHTNESS OF BEING

Big Questions, Real Answers

Frank Wilczek

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About the Title

THE UNBEARABLE LIGHTNESS OF BEING is the title of a famous novel by Milan Kundera—one of my favorite books. It is about many things, but perhaps above all the struggle to find pattern and meaning in the seemingly random, strange, and sometimes cruel world we live in. Of course Kundera's approach to these problems, through story and art, looks very different from the one I've taken in this book, through science and (light) philosophy. For me at least, coming to understand the deep structure of reality has helped to make Being seem not merely bearable, but enchanted—and enchanting. Hence, *The ~~Unbearable~~ Lightness of Being.*

There's also a joke involved. A central theme of this book is that the ancient contrast between celestial light and earthy matter has been transcended. In modern physics, there's only one thing, and it's more like the traditional idea of light than the traditional idea of matter. Hence, *The **Lightness** of Being.*

Reader’s Guide

THE CORE PLAN OF THIS BOOK couldn’t be simpler: it is meant to be read chapter by chapter, from beginning to end. But I’ve also supplied:

- An extensive glossary, so that you don’t get tripped up by unfamiliar words or have to search for the place fifty pages back where they were introduced. It can also be mined for cocktail party nuggets. It’s even got a few jokes.
- Endnotes that elaborate on fine points, follow some important tangents, or provide references.
- Three appendices. The first two take discussions in Chapters 3 and 8, respectively, into deeper waters; the third is a first-person account of how a key discovery reported in Chapter 20 occurred.
- A web page, itsfrombits.com, where you’ll find additional pictures, links, and news related to the book.

You can detour to the appendices as their chapters come up, but if you prefer to get on with the story instead, you should still find it comprehensible. I considered offloading more of the material in Chapter 8, but in the end I couldn’t bring myself to do it. So in that chapter you’ll find *much* ado about Nothing.

PART I

The Origin of Mass

MATTER IS NOT WHAT IT APPEARS TO BE. Its most obvious property—variously called resistance to motion, inertia, or mass—can be understood more deeply in completely different terms. The mass of ordinary matter is the embodied energy of more basic building blocks, themselves lacking mass. Nor is space what it appears to be. What appears to our eyes as empty space is revealed to our minds as a complex medium full of spontaneous activity.

1

Getting to *It*

The universe is not what it used to be, nor what it appears to be.

WHAT'S IT ALL ABOUT? People reflecting upon the wide world around them, the varied and often bewildering experience of life, and the prospect of death are driven to ask that question. We seek answers from many sources: ancient texts and continuing traditions, the love and wisdom of other people, the creative products of music and art. Each of these sources has something to offer.

Logically, however, the first step in the search for answers should be to understand what "it" is. Our world has some important and surprising things to say for itself. That's what this book is about. I want to enrich your understanding of just what "it" is that you and I find ourselves within.

Senses and World-Models

To begin, we build our world-models from strange raw materials: signal-processing tools "designed" by evolution to filter a universe swarming with information into a very few streams of incoming data.

Data streams? Their more familiar names are vision, hearing, smell, and so forth. From a modern point of view, vision is what samples the electromagnetic radiation that passes through tiny holes in our eyes, picking up only a narrow rainbow of colors inside a much broader spectrum. Our hearing monitors air pressure at our eardrums, and smell provides a quirky chemical analysis of the air impinging on our nasal membranes. Other sensory systems give some rough information about the overall acceleration of our body (kinesthetic sense), temperatures and pressures over its surface (touch), a handful of crude measures of the chemical composition of matter on our tongue (taste), and a few other odds and ends.

Those sensory systems allowed our ancestors—just as they allow us—to construct a rich, dynamic model of the world, enabling them to respond effectively. The most important components of that world-model are more-or-less stable objects (such as other people, animals, plants, rocks,… the Sun, stars, clouds,…) some of them moving around, some dangerous, some good to eat, and others—a select and especially interesting few—desirable mates.

Devices to enhance our senses reveal a richer world. When Antonie van Leeuwenhoek looked at the living world through the first good microscopes in the 1670s, he saw totally unsuspected, hidden orders of being. In short order he discovered bacteria, spermatozoa, and the banded structure of muscle fibers. Today we trace the origin of many diseases (and of many benefits) to bacteria. The basis of heredity (well, half of it) is found within the tiny spermatozoa. And our ability to move is anchored in those bands. Likewise, when Galileo Galilei first turned a telescope to the sky in the 1610s, new riches appeared: he found spots on the Sun, mountains on the Moon, moons around Jupiter, and multitudes of stars in the Milky Way.

But the ultimate sense-enhancing device is a thinking mind. Thinking minds allow us to realize that the world contains much more, and is in many ways a different thing, than meets the eye. Many key facts about the world don't jump out to our senses. The parade of seasons, in lock-step with the yearly cycle of sunrise and sunset, the nightly rotation of stars across the sky, the more intricate but still predictable motions of the Moon and planets, and their connection with eclipses—these patterns do not leap to the eye, ear, or nose. But thinking minds can discern them. And having noticed those regularities, thinking minds soon discover that they are *more* regular than the rules of thumb that guide our everyday plans and expectations. The more profound, hidden regularities lend themselves to counting and to geometry: in short, to mathematical precision.

Other hidden regularities emerged from the practice of technology—and, remarkably, of art. The design of stringed musical instruments is a beautiful and historically important example. Around 600 BCE, Pythagoras observed that the tones of a lyre sound most harmonious when the ratio of string lengths forms a simple whole-number fraction. Inspired by such hints, Pythagoras and his followers made a remarkable intuitive leap. They foresaw the possibility of a different kind of world-model, less dependent on the accident of our senses but more in tune with Nature's hidden harmonies, and ultimately more faithful to reality. That is the meaning of the Pythagorean Brotherhood's credo: "All things are number."

The scientific revolution of the seventeenth century began to validate those dreams of ancient Greece. That revolution led to Isaac Newton's mathematical laws of motion and of gravity. Newton's laws permitted precise calculation of the motion of planets and comets, and provided powerful tools for describing the motion of matter in general.

Yet the Newtonian laws operate in a world-model that is very different from everyday intuition. Because Newtonian space is infinite and homogeneous, Earth and its surface are not special places. The directions “up,” “down,” and “sideways” are fundamentally similar. Nor is rest privileged over uniform motion. None of these concepts matches everyday experience. They troubled Newton’s contemporaries, and even Newton himself. (He was unhappy with the relativity of motion, even though it is a logical consequence of his equations, and to escape it he postulated the existence of “absolute” space, with respect to which true rest and motion are defined.)

Another big advance came in the nineteenth century, with James Clerk Maxwell’s equations for electricity and magnetism. The new equations captured a wider range of phenomena, including both previously known and newly predicted kinds of light (what we now call ultraviolet radiation and radio waves, for example), in a precise mathematical world-model. Again, however, the big advance required a readjustment and vast expansion of our perception of reality. Where Newton described the motion of particles influenced by gravity, Maxwell’s equations filled space with the play of “fields” or “ethers.” According to Maxwell, what our senses perceive as empty space is actually the home of invisible electric and magnetic fields, which exert forces on the matter we observe. Although they begin as mathematical devices, the fields leap out of the equations to take on a life of their own. Changing electric fields produce magnetic fields, and changing magnetic fields produce electric fields. Thus these fields can animate one another in turn, giving birth to self-reproducing disturbances that travel at the speed of light. Ever since Maxwell, we understand that these disturbances are what light *is*.

These discoveries of Newton, Maxwell, and many other brilliant people greatly expanded human imagination. But it’s only in twentieth and twenty-first century physics that the dreams of Pythagoras truly approach fruition. As our description of fundamental processes becomes more complete we see more, and we see differently. The deep structure of the world is quite different from its surface structure. The senses we are born with are not attuned to our most complete and accurate world-models. I invite you to expand your view of reality.

Power, Meaning, and Method

When I was growing up, I loved the idea that great powers and secret meanings lurk behind the appearance of things.[1] I was entranced by magic shows and wanted to become a magician. But my first magic kit was a profound disappointment. The secret of the magic, I learned, was not genuine power, just trickery.

Later, I was fascinated by religion: specifically, the Roman Catholic faith in which I grew up. Here I was informed that there are secret meanings behind the appearance of things, great powers that can be swayed by prayer and ritual. But as I learned more about science, some of the concepts and explanations in the ancient sacred texts came to seem clearly wrong; and as I learned more about history and historiography (the recording of history), some of the stories in those texts came to seem very doubtful.

What I found most disillusioning, however, was not that the sacred texts contained errors, but that they suffered by comparison. Compared to what I was learning in science, they offered few truly surprising and powerful insights. Where was there a vision to compete with the concepts of infinite space, of vast expanses of time, of distant stars that rival and surpass our

Sun? Of hidden forces and new, invisible forms of "light"? Or of tremendous energies that humans could, by understanding *natural* processes, learn to liberate and control? I came to think that if God exists, He (or She, or They, or It) did a much more impressive job revealing Himself in the world than in the old books—and that the power of faith and prayer is elusive and unreliable compared to the everyday miracles of medicine and technology.

"Ah," I hear the traditional believer object, "but scientific study of the natural world does not reveal its *meaning*." To which I reply: Give it a chance. Science reveals some very surprising things about what the world is. Should you expect to understand what it means, before you know what it is?

In Galileo's time, professors of philosophy and theology—the subjects were inseparable—produced grand discourses on the nature of reality, the structure of the universe, and the way the world works, all based on sophisticated metaphysical arguments. Meanwhile, Galileo measured how fast balls roll down inclined planes. How mundane! But the learned discourses, while grand, were vague. Galileo's investigations were clear and precise. The old metaphysics never progressed, while Galileo's work bore abundant, and at length spectacular, fruit. Galileo too cared about the big questions, but he realized that getting genuine answers requires patience and humility before the facts.

That lesson remains valid and relevant today. The best way to address the big ultimate questions is likely to be through dialogue with Nature. We must pose pointed sub-questions that give Nature a chance to respond with meaningful answers, in particular with answers that might surprise us.

This approach does not come naturally. In the life we evolved for, important decisions had to be made quickly using the information at hand. People had to spear their prey before they *became* the prey. They could not pause to study the laws of motion, the aerodynamics of spears, and how to compute a trajectory. And big surprises were definitely *not* welcome. We evolved to be good at learning and using rules of thumb, not at searching for ultimate causes and making fine distinctions. Still less did we evolve to spin out the long chains of calculation that connect fundamental laws to observable consequences. Computers are much better at it!

To benefit fully from our dialogue with Nature, we must agree to use Her language. The modes of thought that helped us to survive and reproduce on the African savannah of 200000 BCE will not suffice. I invite you to expand the way you think.

The Centrality of Mass

In this book we'll explore some of the grandest questions imaginable: questions about the ultimate structure of physical reality, the nature of space, the contents of the Universe, and the future of human inquiry. Inspired by Galileo, however, I will address these questions as they arise in the course of a natural dialogue with Nature, about a specific topic.

The topic that will be our doorway into much bigger questions is *mass*. To understand mass deeply, we'll move past Newton, Maxwell, and Einstein, calling on many of the newest and strangest ideas of physics. And we'll find that understanding mass allows us to address very fundamental issues about unification and gravity that are at the forefront of current research.

Why is mass so central? Let me tell you a story.

Once upon a time there was something called matter that was substantial, weighty, and permanent. And something else, quite different, called light. People sensed them in separate data streams; touching one, seeing the other. Matter and light served—and still do serve—as powerful metaphors for other contrasting aspects of reality: flesh and spirit, being and becoming, earthy and celestial.

When matter appeared from nowhere, it was a sure sign of the miraculous, as when Jesus served the multitude from six loaves of bread.

The scientific soul of matter, its irreducible essence, was mass. Mass defined matter's resistance to motion, its inertia. Mass was unchangeable, "conserved." It could be transferred from one body to another but could never be gained or lost. For Newton, mass *defined* quantity of matter. In Newton's physics, mass provided the link between force and motion, and it provided the source of gravity. For Lavoisier, the persistence of mass, its accurate conservation, provided the foundation of chemistry, and offered a fruitful guide to discovery. If mass seems to disappear, look for it in new forms—*voilà*, oxygen!

Light had no mass. Light moved from source to receptor incredibly fast, without being pushed. Light could be created (emitted) or destroyed (absorbed) very easily. Light exerted no gravitational pull. And it found no place in the periodic table, which codified the building blocks of matter.

For many centuries before modern science, and for the first two and a half centuries *of* modern science, the division of reality into matter and light seemed self-evident. Matter had mass, light had no mass; and mass was conserved. As long as the separation between the massive and the massless persisted, a unified description of the physical world could not be achieved.

In the first part of the twentieth century, the upheavals of relativity and (especially) quantum theory shattered the foundations beneath classical physics. Existing theories of matter and light were reduced to rubble. That process of creative destruction made it possible to construct, over the second part of the twentieth century, a new and deeper theory of matter/light that removed the ancient separation. The new theory sees a world based on a multiplicity of space-filling ethers, a totality I call the Grid. The new world-model is extremely strange, but also extremely successful and accurate.

The new world-model gives us a fundamentally new understanding of the origin of the mass of ordinary matter. How new? Our mass emerges, as we'll discuss, from a recipe involving relativity, quantum field theory, and chromodynamics—the specific laws governing the behavior of quarks and gluons. You *cannot* understand the origin of mass without profound use of all these concepts. But they all emerged only in the twentieth century, and only (special) relativity is really a mature subject. Quantum field theory and chromodynamics remain active areas of research, with many open questions.

High on their success, and having learned much from it, physicists enter the twenty-first century with ideas for further syntheses. Today, ideas that go far toward achieving a unified description of the superficially different forces of nature, and toward achieving a unified account of the superficially different ethers we use today, are ready for testing. We have some subtle, tantalizing hints that those ideas are on the right track. The next few years will be their time of trial, as the great accelerator LHC (Large Hadron Collider) begins to operate.

> listen: there's a hell of a good universe next door; let's go.
> — e e cummings

2

Newton's Zeroth Law

What is matter? Newtonian physics supplied a profound answer to that question: matter is that which has mass. While we no longer see mass as the ultimate property of matter, it is an important aspect of reality, to which we must do justice.

IN *MATHEMATICAL PRINCIPLES OF NATURAL PHILOSOPHY* (1686), the monumental work that perfected classical mechanics and sparked the Enlightenment, Isaac Newton formulated three laws of motion. To this day, courses on classical mechanics usually begin with some version of Newton's three laws. But these laws are not complete. There is another principle, without which Newton's three laws lose most of their power. That hidden principle was so basic to Newton's view of the physical world that he took it not as a law that governs the motion of matter, but as the *definition* of what matter *is*.

When I teach classical mechanics, I start by bringing out the hidden assumption I call Newton's zeroth law. And I emphasize that it is wrong! How can a definition be wrong? And how can a wrong definition be the foundation for great scientific work?

The legendary Danish physicist Niels Bohr distinguished two kinds of truths. An ordinary truth is a statement whose opposite is a falsehood. A profound truth is a statement whose opposite is also a profound truth.

In that spirit, we might say that an ordinary mistake is one that leads to a dead end, while a profound mistake is one that leads to progress. Anyone can make an ordinary mistake, but it takes a genius to make a profound mistake.

Newton's zeroth law was a *profound* mistake. It was the central dogma of an Old Regime that governed physics, chemistry, and astronomy for more than two centuries. Only at the beginning of the twentieth century did the work of Planck, Einstein, and others begin to challenge the Old Regime. By mid-century, under bombardment from new experimental discoveries, the Old Regime had crumbled.

That destruction opened the way to a new creation. Our New Regime frames an entirely new understanding of what matter is. The New Regime is based on laws that differ from the old ones, not merely in detail but also in kind. This revolution in basic understanding, and its consequences, are what we'll be exploring.

But to justify the revolution we must first bring the shortcomings of the Old Regime into clear focus. For its mistakes are, in Bohr's sense, profound. The Old Regime of Newtonian physics gave us relatively simple and easy-to-use rules with which we could govern the physical world pretty effectively. In practice, we still use those rules to administer the more peaceful, well-settled districts of reality.

So, to begin, let's take a close look at Newton's hidden assumption, his zeroth law—both its tremendous strength and its fatal weakness. That law states that mass is neither created nor destroyed. Whatever happens—collisions, explosions, a million years of wind and rain—if you add up the total mass of all the material involved at the beginning, or at the end, or at any intermediate time, you will always get the same sum. The scientific jargon for this is that mass is conserved. The standard, dignified name for Newton's zeroth law is *conservation of mass*.

Of course, to translate the zeroth law into a meaningful, scientific statement about the physical world, we have to specify how masses are measured and compared. We'll do that momentarily. But let me first highlight why the zeroth law is not just another scientific law, but a strategy for understanding the world—a strategy that looked very good for a very long time.

It's revealing that Newton himself usually used the phrase *quantity of matter* for what we now call mass. His wording implies that you can't have matter without mass. Mass is the ultimate measure of matter; it tells you how much matter you've got. No mass, no matter. Thus the conservation of mass expresses—indeed, is equivalent to—the persistence of matter. For Newton, the zeroth law was not so much an empirical observation or experimental discovery as a necessary truth; it was not a proper law at all, but a definition. Or rather, as we'll see in a moment, it expressed a religious truth—a fact about God's method of creation. (To avoid misunderstanding, let me emphasize that Newton was a meticulous empirical scientist, and he carefully checked that the consequences of his definitions and assumptions described Nature as accurately as the measurements of the day could test them. I'm not saying that he let his religious ideas trump reality. It's more subtle: those ideas gave him his intuition about how reality works. What motivated Newton to suspect that something like the zeroth law had to be true was not painstaking experiments but, rather, powerful intuition, derived from his religion, about how the world is built. Newton had no doubt about God's existence, and he saw his task in science as revealing God's method of governing the physical world.)

In his later *Opticks* (1704), Newton was more specific in expressing his vision of the ultimate nature of matter:

> It seems probable to me, that God in the beginning formed matter in solid, massy, hard, impenetrable, moveable particles, of such sizes and figures, and with such other properties, and in such proportions to space, as most conduced to the ends for which He formed them; and that these primitive particles being solids, are incomparably harder than any porous bodies compounded of them, even so very hard, as never to wear or break in pieces; no ordinary power being able to divide what God Himself made one in the first creation.

This remarkable passage contains a few points we should notice. First: Newton takes the property of having a fixed mass as one of the most basic properties of the ultimate building blocks of matter. He calls it being “massy.” Mass, for Newton, is not something you should try to explain in terms of something simpler. It is part of the ultimate description of matter; it reaches bottom. Second: Newton ascribes the changes we observe in the world entirely to *rearrangements* of elementary building blocks, elementary particles. The building blocks themselves are neither created nor destroyed— they just move around. Once God has made them, their properties, including their mass, never change. Newton’s zeroth law of motion, the conservation of mass, follows from those two points.

Getting Real

Now we must return from these heady philosophico-theological ideas about why conservation of mass might be true, or must be true, to the ordinary business of measuring to see whether it *is* true.

How do we measure mass? The most familiar way is to use a scale. One sort of scale, the kind dieters have in their bathrooms, compares how much bodies (that is, dieters' bodies) can compress a spring. Closely related are the scales that anglers use, which compare how much dangling bodies (that is, fish) stretch a spring. The amount the spring stretches (or, for the dieter, compresses) is proportional to the downward force the body exerts, which is what we call the body's weight, which is proportional to its mass.

In this very concrete and practical framework, conservation of mass simply says that a closed system will continue to stretch a spring by the same amount, whatever is going on inside. This is precisely what Antoine Lavoisier (1743–1784) verified—using, to be sure, more sophisticated and accurate scales than you'll find in your bathroom—in the many painstaking experiments that earned him the title "father of modern chemistry." Lavoisier checked, in a wide variety of chemical reactions, that the total weight of all the stuff you started with was equal to the total weight of what you had after the reaction took place, within the accuracy he could measure (typically one part in a thousand or so). Through the discipline of accounting for *all* the matter in a reaction—capturing the gases that might escape, collecting the ashes of explosions, and so forth—he discovered new compounds and elements. Lavoisier was guillotined during the French Revolution. The mathematician Joseph Lagrange said, "It took them only a moment to cut off that head, but France may not produce another like it in a century."

Using scales to compare masses is practical and effective, but it won't do as a general, principled definition of mass. For example, if you take your body out into space, its weight as measured by a scale will get smaller, but its mass will stay the same. (Scales will lie, but waistlines won't shrink.) Mass had better stay the same, if the law of conservation of mass is going to be true! And that superficially circular assertion has real content, because you can compare masses in other ways. For example, you can compare how fast two cannonballs start to fly after you launch them out of the same cannon. According to Newton's other laws of motion, a given impulse will give rise to a velocity inversely proportional to the mass. So if one cannonball comes out twice as fast as the other, it has half the mass—whether you do the experiment at the surface of Earth or in space.

I won't go further into the technicalities of measuring mass, except to say that there are many ways to do it besides using scales and shooting things from cannons, and many checks of their mutual consistency.

Downfall

Newton's zeroth law was accepted by scientists for more than two centuries, and not just because it fit in with some philosophical or theological intuitions. It was accepted because it worked. Together with Newton's other laws of motion and his law of gravitation, the zeroth law serves to define the mathematical discipline—classical mechanics—that accounts with wonderful precision for the motion of the planets and their moons, the bewildering behavior of gyroscopes, and many other phenomena. And it works brilliantly in chemistry, too.

But it doesn't always work. In fact, the conservation of mass can fail quite spectacularly. At the Large Electron-Positron Collider (LEP), which operated at the CERN laboratory near Geneva through the 1990s, electrons and positrons (antielectrons) were accelerated to velocities within about one part in a hundred billionth (10^{-11}) of the speed of light. Speeding around in opposite directions, the particles smashed into each other, producing a lot of debris. A typical collision might produce ten π mesons, a proton, and an antiproton. Now let's compare the total masses, before and after:

$$\text{electron} + \text{positron: } 2 \times 10^{-28}\ \text{gram}$$
$$10\ \text{pions} + \text{proton} + \text{antiproton: } 6 \times 10^{-24}\text{gram}$$

What comes out weighs about *thirty thousand times* as much as what went in. Oops.

Few laws have ever appeared more fundamental, more successful, and more carefully verified than the conservation of mass. Yet here it's gone completely awry. It's as if a magician dropped two peas into her hat and pulled out a few dozen rabbits. But Mother Nature is no cheap trickster; her "magic" is deep truth. We've got some explaining to do.

Does Mass Have an Origin?

As long as mass was thought to be conserved, there was no sense in asking what its origin is. It's always the same. You might as well ask what the origin of 42 is. (Actually there is an answer of sorts. If mass is conserved except when God manufactures elementary particles, then God is the origin of mass. That was Newton's answer. But it's not the kind of explanation we'll be pursuing in this book.)

In the framework of classical mechanics, no answer to the question "What is the origin of mass?" could possibly make sense. Trying to build massive objects from massless ones leads to contradictions. There are many ways to see this. For example:

- The soul of classical mechanics is the equation $F = ma$. This equation relates the dynamical concept of force (F), which summarizes the pull and tug felt by a body, to the kinematic concept of acceleration (a), which summarizes how the body moves in response. The mass (m) mediates between those two concepts. In response to a given force, a body with a small mass will pick up speed faster than a body with a large mass. A body of zero mass would go crazy! In order to figure out how it should move, it would have to divide by zero, which is a no-no. So bodies had better have mass to begin with.
- According to Newton's law of gravitation, each body exerts gravitational influence that is proportional to its mass. In trying to imagine that a body with nonzero mass can be assembled from building blocks without mass, you run smack into a contradiction. The gravitational influence of each building block is zero, and no matter how many times you add zero influence to zero influence you still get zero influence.

But if mass is not conserved—and it's not!—we can seek its origin. It's not bedrock. We can dig deeper.

3

Einstein's Second Law

Einstein's "second law," $m = E/c^2$, raises the question whether mass can be understood more deeply as energy. Can we build, as Wheeler put it, "Mass Without Mass"?

WHEN I WAS ABOUT TO BEGIN TEACHING at Princeton, my friend and mentor Sam Treiman called me into his office. He had some wisdom to share. Sam pulled a well-worn paperback manual from his desk and told me, "During World War II the Navy had to train recruits to set up and operate radio communications in a hurry. Many of those recruits were right off the farm, so bringing them up to speed was a big challenge. With the help of this great book, the Navy succeeded. It's a masterpiece of pedagogy. Especially the first chapter. Take a look."

He handed me the book, opened to the first chapter. That chapter was titled "Ohm's Three Laws." I was familiar with one Ohm's law, the famous relation $V = I R$ that connects voltage (V), current (I), and resistance (R) in an electric circuit. That turned out to be Ohm's first law.

I was very curious to find out what Ohm's other two laws were. Turning the fragile, yellowed pages, I soon discovered that Ohm's second law is $I = V/R$. I conjectured that Ohm's third law might be $R = V/I$, which turned out to be correct.

issues about the possibility of explaining mass in terms of energy.

Question 1: If $E = mc^2$, then mass is proportional to energy. So if energy is conserved, doesn't that mean that mass will be conserved, too?

Answer 1: The short answer is that $E = mc^2$ really applies only to isolated bodies at rest. It's a pity that this equation, the equation of physics that is best known to the general public, is actually a little cheesy. In general, when you have moving bodies, or interacting bodies, energy and mass aren't proportional. $E = mc^2$ simply doesn't apply.

For a more detailed answer, take a look at Appendix A: "Particles have Mass, the World has Energy."

Question 2: How can something made from massless building blocks feel gravitational forces? Didn't Newton tell us that the gravitational force a body feels is proportional to its mass?

Answer 2: In his law of gravitation, Newton indeed told us that the gravitational force felt by a body is proportional to its mass. But Einstein, in his more accurate theory of gravity, general relativity, tells us something different. The complete story is quite complicated to describe, and I won't try to do it here. Very roughly speaking, what happens is that where Newton would say the force is proportional to m, Einstein's more accurate theory says it's proportional to E/c^2. As we discussed in the previous question and answer, those aren't the same thing. They are almost equal for isolated, slowly moving bodies, but they can be very different for interacting systems of bodies, or for bodies moving at close to the speed of light.

In fact, light itself is the most dramatic example. The particles of light, photons, have zero mass. Nevertheless light is deflected by gravity, because photons have nonzero energy, and gravity pulls energy. Indeed, one of the most famous tests of general relativity involves the bending of light by the Sun. In that situation, the gravity of the Sun is deflecting massless photons.

Carrying that thought a step further, one of the most dramatic consequences of general relativity is that you can imagine an object whose gravity is so powerful that it bends photons so drastically as to turn them completely around, even if they're moving straight out at the start. Such an object traps photons. No light can escape it. It is a black hole.

4

What Matters for Matter

What is the world made of? We'll be explaining the origin of matter's mass from pure energy, with 95% accuracy. To attain that sort of precision, we'll have to be very clear about what it is we're talking about. Here we'll be specific about what normal matter is, and what it isn't.

"NORMAL" MATTER IS THE STUFF WE STUDY in chemistry, biology, and geology. It is the stuff we use to build things, and it's what we're made of. Normal matter is also the stuff that astronomers see in their telescopes. Planets, stars, and nebulae are made from the same kind of stuff that we find and study here on Earth. That's the greatest discovery in astronomy.

Recently, however, astronomers have made another great discovery. Ironically, the new great discovery is that normal matter is *not* all there is in the Universe. Not by a long shot. In fact, most of the mass in the Universe as a whole is in at least two other forms: so-called dark matter and dark energy. The "dark" stuff is actually perfectly transparent, which is why it managed to escape notice for hundreds of years. So far it's been detected only indirectly, through its gravitational influence on normal matter (that is, stars and galaxies). We'll have much more to say about the dark side in later chapters.

If you just count up mass, then normal matter is a minor impurity, contributing only 4–5% of the total. But it's where the vast bulk of the structure, information, and love in the world reside. So I hope you'll agree it's an especially interesting part. And it's the part we understand best, by far.

In the next few chapters we'll account for the origin of 95% of the mass of normal matter, starting from massless building blocks. To make good on that promise, we'll have to be quite specific about what it is we're explaining. (After all, we're quoting numbers.)

Building Blocks

Speculation that matter[1] could be analyzed down to a few types of elementary building blocks goes back at least to the ancient Greeks, but solid scientific understanding came only in the twentieth century. Matter, people ordinarily say, is made of atoms. The great physicist Richard Feynman, near the beginning of his famous *Feynman Lectures on Physics*, made a big point of it:

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or atomic *fact*, or whatever you wish to call it) that *all things are made of atoms*… (italics in original).

The great and most useful "fact" that all things are made of atoms is, however, incomplete in three important ways. (Like Newton's zeroth law, or the greatest discovery in astronomy, it's a profound truth in Bohr's sense—that is, it's also *profoundly* false.)

One aspect of its incompleteness is the existence of dark matter and dark energy, as we've already mentioned. Their existence was barely suspected in 1963, when Feynman's lectures were published. A few astronomers, starting with Fritz

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1. I still do!

2. Both protons and neutrons are always spinning: we say they have an intrinsic, fundamental spin. We'll have much more to say about the property of fundamental spin later. It plays a crucial role in modern ideas about the ultimate unification of forces.

1. The flavors of quarks should not be confused with their color charges. Color charge is a different, additional property. There are *u* quarks with a unit of red color charge, *u* quarks with a unit of blue color charge, and so forth. Thus with 3 flavors and 3 colors, we have $3 \times 3 = 9$ kinds altogether.

5. When Gross and I discovered asymptotic freedom we were young and naive, and we didn't fully appreciate the importance of naming things in catchy ways. If I had it to do over, I'd call asymptotic freedom something sexy, like "Charge Without Charge." "Asymptotic freedom" was suggested by my good friend Sidney Coleman, whom I forgive.

6. They were much more challenging in 1973 than they are today, because technique has improved.