THE GOD PARTICLE

If the Universe Is the Answer, What Is the Question?

LEON LEDERMAN

WITH DICK TERESI

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THE INVISIBLE SOCCER BALL

Nothing exists except atoms and empty space;
everything else is opinion.
— Democritus of Abdera

IN THE VERY BEGINNING there was a void—a curious form of vacuum — a nothingness containing no space, no time, no matter, no light, no sound. Yet the laws of nature were in place, and this curious vacuum held potential. Like a giant boulder perched at the edge of a towering cliff . . .

Wait a minute.

Before the boulder falls, I should explain that I really don't know what I'm talking about. A story logically begins at the beginning. But this story is about the universe, and unfortunately there are *no data* for the Very Beginning. None. Zero. We don't know anything about the universe until it reaches the mature age of a billionth of a trillionth of a second — that is, some very short time after creation in the Big Bang. When you read or hear anything about the birth of the universe, someone is making it up. We are in the realm of philosophy. Only God knows what happened at the Very Beginning (and so far She hasn't let on).

Now, where were we? Oh yes ...

Like a giant boulder perched at the edge of a towering cliff, the void's balance was so exquisite that only whim was needed to produce a change, a change that created the universe. And it happened. The nothingness exploded. In this initial incandescence, space and time were created.

Out of this energy, matter emerged — a dense plasma of particles that dissolved into radiation and back to matter. (Now we're working with at least a few facts and some speculative theory in hand.) Particles collided and gave birth to new particles. Space and time boiled and foamed as black holes formed and dissolved. What a scene!

As the universe expanded and cooled and grew less dense, particles coalesced, and forces differentiated. Protons and neutrons formed, then nuclei and atoms and huge clouds of dust, which, still expanding, condensed locally here and there to form stars, galaxies, and planets. On one planet — a most ordinary planet, orbiting a mediocre star, one speck on the spiral arm of a standard galaxy — surging continents and roiling oceans organized themselves, and out of the oceans an ooze of organic molecules reacted and built proteins, and life began. Plants and animals evolved out of simple organisms, and eventually human beings arrived.

The human beings were different primarily because they were the only species intensely curious about their surroundings. In time, mutations occurred, and an odd subset of humans began roaming the land. They were arrogant. They were not content to enjoy the magnificence of the universe. They asked "How?" How was the universe created? How can the "stuff" of the universe be responsible for the incredible variety in our world: stars, planets, sea otters, oceans, coral, sunlight, the human brain? The mutants had posed a question that could be answered — but only with the labor of millennia and with a dedication handed down from master to student for a hundred generations. The question also inspired a great number of wrong and embarrassing answers. Fortunately, these mutants were born without a sense of embarrassment. They were called physicists.

Now, after examining this question for more than two thousand years — a mere flicker on the scale of cosmological time — we are beginning to glimpse the entire story of creation. In our telescopes and microscopes, in our observatories and laboratories — and on our notepads — we begin to perceive the outlines of the pristine beauty and symmetry that governed in the first moments of the universe. We can almost see it. But the picture is not yet clear, and we sense that something is obscuring our vision — a dark force that blurs, hides, obfuscates the intrinsic simplicity of our world.

HOW DOES THE UNIVERSE WORK?

This book is devoted to one problem, a problem that has confounded science since antiquity. What are the ultimate building blocks of matter? The Greek philosopher Democritus called the smallest unit the *atomos* (literally "not able to be cut"). This a-tom is not the atom you learned about in high school science courses, like hydrogen, helium, lithium, and proceeding all the way to uranium and beyond. Those are big, clunky, complicated entities by today's standards (or by Democritus's standards, for that matter). To a physicist, or even a chemist, such atoms are veritable garbage cans of smaller particles — electrons, protons, and neutrons — and the protons and neutrons in turn are buckets full of still smaller guys. We need to know the most primitive objects there are, and we need to understand the forces that control the social behavior of these objects. It is Democritus's a-tom, not your chemistry teacher's atom, that is the key to matter.

The matter we see around us today is complex. There are about a hundred chemical atoms. The number of useful combinations of atoms can be calculated, and it is huge: billions and billions. Nature uses these combinations, called molecules, to build planets, suns, viruses, mountains, paychecks, Valium, literary agents, and other useful items. It was not always so. During the earliest moments after the creation of the universe in the Big Bang, there was no complex matter as we know it today. No nuclei, no atoms, nothing that was made of simpler pieces. This is because the searing heat of the early universe did not allow the formation of composite objects; such objects, if formed by transient collisions, would be instantly decomposed into their most primitive constituents. There was perhaps one kind of particle and one force — or even a unified particle/force — and the laws of physics. Within this primordial entity were contained the seeds of the complex world in which humans evolved, perhaps primarily to think about these things. You might find the primordial universe boring, but to a particle physicist, those were the days! Such simplicity, such beauty, however mistily visualized in our speculations.

THE BEGINNING OF SCIENCE

Even before my hero Democritus, there were Greek philosophers who dared to try to explain the world using rational arguments and rigorously excluding superstition, myth, and the intervention of gods. These had served as valuable assets in accommodating to a world full of fearsome and seemingly arbitrary phenomena. But the Greeks were impressed too by regularities, by the alternation of day and night, the seasons, the action of fire and wind and water. By the year 650 B.C.E., a formidable technology had arisen in the Mediterranean basin. The people there knew how to survey land and navigate by the stars; they had a sophisticated metallurgy and a detailed knowledge of the positions of stars and planets for making calendars and assorted predictions. They made elegant tools, fine textiles, and elaborately formed and decorated pottery. And in one of the colonies of the Greek empire, the bustling town of Miletus on the west coast of what is now modern Turkey, the belief was articulated that the seemingly complex world was intrinsically simple — and that this simplicity could be discovered through logical reasoning. About two hundred years later, Democritus of Abdera proposed a-toms as the key to a simple universe, and the search was on.

The genesis of physics was astronomy because the earliest philosophers looked up in awe at the night sky and sought logical models for the patterns of stars, the motions of planets, the rising and setting of the sun. Over time, scientists turned their eyes earthward: phenomena taking place at the surface of the earth — apples falling from trees, the flight of an arrow, the regular motion of a pendulum, winds, and tides — gave rise to a set of "laws of physics." Physics blossomed during the Renaissance, becoming a separate, distinct discipline by about 1500. As the centuries rolled by, and as our powers of observation sharpened with the invention of microscopes, telescopes, vacuum pumps, clocks, and so on, more and more phenomena were uncovered that could be described meticulously by recording numbers in notebooks, by constructing tables and drawing graphs, and then by triumphantly noting conformity to mathematical behavior.

By the early part of the twentieth century atoms had become the frontier of physics; in the 1940s, nuclei became the focus of research. Progressively, more and more domains became subject to observation. With the development of instruments of ever-increasing power, we looked more and more closely at things smaller and smaller. The observations and measurements were followed inevitably by syntheses, compact summaries of our understanding. With each major advance, the field divided; some scientists followed the "reductionist" road toward the nuclear and subnuclear domain, while others followed the path to a greater understanding of atoms (atomic physics), molecules (molecular physics and chemistry), nuclear physics, and so on.

THE ENTRAPMENT OF LEON

I started out as a molecules kid. In high school and early college I loved chemistry, but I gradually shifted toward physics, which seemed cleaner — odorless, in fact. I was strongly influenced, too, by the kids in physics, who were runnier and played better basketball. The giant of our group was Isaac Halpern, now a professor of physics at the University of Washington. He claimed that the only reason he went to see his posted grades was to determine whether the A had a "flat top or a pointy top." Naturally, we all loved him. He could also broad-jump farther than any of us.

I became intrigued with the issues in physics because of their crisp logic and clear experimental consequences. In my senior year in college, my best friend from high school, Martin Klein, the now eminent Einstein scholar at Yale, harangued me on the splendors of physics during a long evening over many beers. That did it. I entered the U.S. Army with a B.S. in chemistry and a determination to be a physicist if I could only survive basic training and World War II.

I was born at last into the world of physics in 1948, when I began my Ph.D. research working with the world's most powerful particle accelerator of its time, the synchrocyclotron at Columbia University. Dwight Eisenhower, president of Columbia, cut the ribbon dedicating the machine in June of 1950. Having helped Ike win the war, I was obviously much appreciated by the Columbia authorities, who paid me almost $4,000 for just one year of ninety-hour weeks. These were heady times. In the 1950s, the synchrocyclotron and other powerful new devices created the new discipline of particle physics.

To the outsider, perhaps the most salient characteristic of particle physics is the equipment, the instruments. I joined the quest just as particle accelerators were coming of age. They dominated physics for the next four decades, and still do. The first "atom smasher" was a few inches in diameter. Today the world's most powerful accelerator is housed at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. Fermilab's machine, called the Tevatron, is four miles around, and smashes protons and antiprotons together with unprecedented energies. By the year 2000 or so, the Tevatron's monopoly of the energy frontier will be broken. The Superconducting Super Collider (SSC), the mother of all accelerators, presently being built in Texas, will be fifty-four miles around.

Sometimes we ask ourselves: have we taken a wrong turn somewhere? Have we become obsessed with the equipment? Is particle physics some sort of arcane "cyber science," with huge groups of researchers and megalithic machines dealing with phenomena so abstract that even She is not sure what happens when particles collide at high energies? We can gain confidence and inspiration by viewing the process as following a chronological Road, one that could plausibly have started in the Greek colony of Miletus in 650 B.C.E. The Road's destination is a city where all is understood — where the sanitation workers and even the mayor know how the universe works. Many have followed The Road: Democritus, Archimedes, Copernicus, Kepler, Galileo, Newton, Faraday, all the way to Einstein, Fermi, and my contemporaries.

The Road narrows and broadens; it passes long stretches of nothing (like Route 80 through Nebraska) and curvy sections of intense activity. There are tempting side streets labeled "electrical engineering," "chemistry," "radio communications," or "condensed matter." Those who have taken the side streets have changed the way people live on this planet. But those who stay with The Road find that it is clearly marked all the way with the same sign: "How does the universe work?" It is on this Road that we find the accelerators of the 1990s.

I got on The Road at Broadway and 120th Street in New York City. In those days the scientific problems seemed very clear and very important. They had to do with the properties of what's called the strong nuclear force and some theoretically predicted particles called pi mesons, or pions. Columbia's accelerator was designed to produce lots of pions by bombarding innocent targets with protons. The instrumentation was rather simple at the time, simple enough for a graduate student to understand.

Columbia was a hotbed of physics in the 1950s. Charles Townes would soon discover the laser and win the Nobel Prize. James Rainwater would win the Prize for his nuclear model, and Willis Lamb for measuring the tiny shift in hydrogen's spectral lines. Nobel laureate Isadore Rabi, who inspired all of us, headed up a team that included Norman Ramsey and Polykarp Kusch, both to become Nobel winners in due course. T. D. Lee shared the Nobel for his theory of parity violation. The density of professors who had been anointed with Swedish holy water was both exhilarating and depressing. As young faculty, some of us wore lapel buttons that read "Not Yet."

For me the Big Bang of professional recognition took place in the period 1959-1962 when two of my Columbia colleagues and I carried out the first-ever measurement of high-energy neutrino collisions. Neutrinos are my favorite particles. A neutrino has almost no properties: no mass (or very little), no electric charge, and no radius — and, adding insult to injury, no strong force acts on it. The euphemism used to describe a neutrino is "elusive." It is barely a fact, and it can pass through millions of miles of solid lead with only a tiny chance of being involved in a measurable collision.

Our 1961 experiment provided the cornerstone for what came to be known in the 1970s as the "standard model" of particle physics. In 1988 the experiment was recognized by the Royal Swedish Academy of Science with the Nobel Prize. (Everybody asks, why did they wait twenty-seven years? I don't really know. I used to give my family the facetious excuse that the Academy was dragging its feet because they couldn't decide which of my great achievements to honor.) Winning the Prize was of course a great thrill. But that thrill does not really compare with the incredible excitement that gripped us at the moment when we realized our experiment was a success.

Physicists today feel the same emotions that scientists have felt for centuries. The life of a physicist is filled with anxiety, pain, hardship, tension, attacks of hopelessness, depression, and discouragement. But these are punctuated by flashes of exhilaration, laughter, joy, and exultation. These epiphanies come at unpredictable times. Often they are generated simply by the sudden understanding of something new and important, something beautiful, that someone else has revealed. However, if you are mortal, like most of the scientists I know, the far sweeter moments come when you yourself discover some new fact about the universe. It's astonishing how often this happens at 3 A.M., when you are alone in the lab and you have learned something profound, and you realize that not one of the other five billion people on earth knows what you now know. Or so you hope. You will, *of* course, hasten to tell them as soon as possible. This is known as "publishing."

This is a book about a string of infinitely sweet moments that scientists have had over the past 2,500 years. These sweet moments add up to our present knowledge about what the universe is and how it works. The pain and depression are part of the story, too. Often it is the obstinacy, the stubbornness, the pure orneriness of nature that gets in the way of the "Eureka" moment.

The scientist, however, cannot depend on Eureka moments to make his life fulfilling. There must be some joy in day-to-day activities. For me this joy is in designing and building apparatus that will teach us about this extraordinarily abstract subject. When I was an impressionable graduate student at Columbia, I helped a world-famous professor visiting from Rome build a particle counter. I was the virgin in this and he a past master. Together we turned the brass tube on the lathe (it was after 5 P.M. and the machinists had all gone home). We soldered on the glass-tipped end caps and strung a gold wire through the short, insulated metal straw penetrating the glass. Then we soldered some more. We flushed the special gas through the counter for a few hours while hooking an oscilloscope to the wire, protected from a 1,000-volt power supply by a special capacitor. My professor friend — let's call him Gilberto, because that was his name — kept peering at the green trace of the oscilloscope while lecturing me in faultlessly broken English on the history and evolution of particle counters. Suddenly Gilberto went stark, raving wild. "Mamma mia! Regardo incredibilo! Primo secourso!" (Or something like that.) He shouted, pointed, lifted me up in the air — even though I was six inches taller and fifty pounds heavier than he — and danced me around the room. "What happened?" I stammered. "Mufiletto!" he replied. "Izza counting. Izza counting!" He was probably putting some of this on for my benefit, but he was genuinely excited that we had, with our hands, eyes, and brains, fashioned a device that detected the passage of cosmic ray particles, registered them by small blips in the sweep of the oscilloscope. Although he must have seen this phenomenon thousands of times, he never got over the thrill. That one of these particles may just possibly have started its voyage to 120th Street and Broadway, tenth floor, light-years ago in a distant galaxy was only part of the excitement. Gilberto's seemingly never-ending enthusiasm was contagious.

THE LIBRARY OF MATTER

When explaining the physics of fundamental particles, I often borrow (and embellish on) a lovely metaphor from the Roman poet-philosopher Lucretius. Suppose we are given the task of discovering the most basic elements of a library. What would we do? First we might think of books in their various subject categories: history, science, biography. Or perhaps we would organize them by size: thick, thin, tall, short. After considering many such divisions we realize that books are complex objects that can be readily subdivided. So we look inside. Chapters, paragraphs, and sentences are quickly dismissed as inelegant and complex constituents. Words! Here we recall that on a table near the entrance there is a fat catalogue of all the words in the library —the dictionary. By following certain rules of behavior, which we call grammar, we can use the dictionary words to compose all the books in the library. The same words are used over and over again, fitted together in different ways.

But there are so many words. Further reflection would lead us to letters, since words are "cut-able." Now we have it! Twenty-six letters can make the tens of thousands of words, and they can in turn make the millions (billions?) of books. Now we must introduce an additional set of rules: spelling, to constrain the combinations of letters. Without the intercession of a very young critic we might publish our discovery prematurely. The young critic would say, smugly no doubt, "You don't need twenty-six letters, Grandpa. All you need is a zero and a one." Children today grow up playing with digital crib toys and are comfortable with computer algorithms that convert zeroes and ones to the letters of the alphabet. If you are too old for this, perhaps you are old enough to remember Morse code, composed of dots and dashes. In either case we now have the sequence: 0 or 1 (or dot and dash) with appropriate code to make the twenty-six letters; spelling to make all the words in the dictionary; grammar to compose the words into sentences, paragraphs, chapters, and, finally, books. And the books make the library.

Now, if it makes no sense to take apart the 0 or the 1, we have discovered the primordial, atomic components of the library. In the metaphor, imperfect as it is, the universe is the library, the forces of nature are the grammar, spelling, and algorithm, and the 0 and 1 are what we call quarks and leptons, our current candidates for Democritus' a-toms. All of these objects, of course, are invisible.

QUARKS AND THE POPE

The lady in the audience was stubborn. "Have you ever *seen* an atom?" she insisted. It is an understandable if irritating question to a scientist who has long lived with the objective reality of atoms. I can visualize their internal structure. I can call up mental pictures of cloudlike blurs of electron "presence" surrounding the tiny dot nucleus that draws the misty electron cloud toward it. This mental picture is never precisely the same for two different scientists because both are constructing these images from equations. Such written prescriptions are not user-friendly when it comes to humoring the scientist's human need for a visual image. Yet we can "see" atoms and protons and, yes, quarks.

My attempts to answer this thorny question always begin with trying to generalize the word "see." Do you "see" this page if you are wearing glasses? If you are looking at a microfilm version? If you are looking at a photocopy (thereby robbing me of my royalty)? If you are reading the text on a computer screen? Finally, in desperation, I ask, "Have you ever seen the pope?"

"Well, of course," is the usual response. "I saw him on television." Oh, really? What she saw was an electron beam striking phosphorus painted on the inside of a glass screen. My evidence for the atom, or the quark, is just as good.

What is that evidence? Tracks of particles in a bubble chamber. In the Fermilab accelerator, the "debris" from a collision between a proton and an antiproton is captured electronically by a three-story-tall, $60 million detector. Here the "evidence," the "seeing," is tens of thousands of sensors that develop an electrical impulse as a particle passes. All of these impulses are fed through hundreds of thousands of wires to electronic data processors. Ultimately a record is made on spools of magnetic tape, encoded by zeroes and ones. This tape records the hot collisions of proton against antiproton, which can generate as many as seventy particles that fly apart into the various sections of the detector.

Science, especially particle physics, gains confidence in its conclusions by duplication — that is, an experiment in California is confirmed by a different style of accelerator operating in Geneva. Also by building into each experiment checks and tests confirming that the apparatus is functioning as designed. It is a long and involved process, the result of decades of experiments.

Still, particle physics remains unfathomable to many people. That stubborn lady in the audience isn't the only one mystified by a bunch of scientists chasing after tiny invisible objects. So let's try another metaphor . . .

THE INVISIBLE SOCCER BALL

Imagine an intelligent race of beings from the planet Twilo. They look more or less like us, they talk like us, they do everything like humans -- except for one thing. They have a fluke in their visual apparatus. They can't see objects with sharp juxtapositions of black and white. They can't see zebras, for example. Or shirts on NFL referees. Or soccer balls. This is not such a bizarre fluke, by the way. Earthlings are even stranger. We have two literal blind spots in the center of our field of vision. The reason we don't see these holes is because our brain extrapolates from the information in the rest of the field to guess what *should* be in these holes, then fills it in for us. Humans routinely drive 100 miles per hour on the autobahn, perform brain surgery, and juggle flaming torches, even though a portion of what they see is merely a good guess.

Let's say this contingent from the planet Twilo comes to earth on a goodwill mission. To give them a taste of our culture, we take them to see one of the most popular cultural events on the planet: a World Cup soccer match. We, of course, don't know that they can't see the black-and-white soccer ball. So they sit there watching the match with polite but confused looks on their faces. As far as the Twiloans are concerned, a bunch of short-pantsed people are running up and down the field kicking their legs pointlessly in the air, banging into each other, and falling down. At times an official blows a whistle, a player runs to the sideline, stands there, and extends both his arms over his head while the other players watch him. Once in a great while the goalie inexplicably falls to the ground, a great cheer goes up, and one point is awarded to the opposite team.

The Twiloans spend about fifteen minutes being totally mystified. Then, to pass the time, they attempt to understand the game. Some use classification techniques. They deduce, partially because of the clothing, that there are two teams in conflict with one another. They chart the movements of the various players, discovering that each player appears to remain more or less within a certain geographical territory on the field. They discover that different players display different physical motions. The Twiloans, as humans would do, clarify their search for meaning in World Cup soccer by giving names to the different positions played by each footballer. The positions are categorized, compared, and contrasted. The qualities and limitations of each position are listed on a giant chart. A major break comes when the Twiioans discover that *symmetry* is at work. For each position on Team A, there is a counterpart position on Team B.

With two minutes remaining in the game, the Twiloans have composed dozens of charts, hundreds of tables and formulas, and scores of complicated rules about soccer matches. And though the rules might all be, in a limited way, correct, none would really capture the essence of the game. Then one young pipsqueak of a Twiloan, silent until now, speaks his mind. "Let's postulate," he ventures nervously, "the existence of an invisible ball."

"Say what?" reply the elder Twiloans.

While his elders were monitoring what appeared to be the core of the game, the comings and goings of the various players and the demarcations of the field, the pipsqueak was keeping his eyes peeled for rare events. And he found one. Immediately before the referee announced a score, and a split second before the crowd cheered wildly, the young Twiloan noticed the momentary appearance of a bulge in the back of the goal net. Soccer is a low-scoring game, so there were few bulges to observe, and each was very short-lived. Even so, there were enough events for the pipsqueak to note that the shape of each bulge was hemispherical. Hence his wild conclusion that the game of soccer is dependent upon the existence of an invisible ball (invisible, at least, to the Twiloans).

The rest of the contingent from Twilo listen to this theory and, weak as the empirical evidence is, after much arguing, they conclude that the youngster has a point. An elder statesman in the group — a physicist, it turns out — observes that a few rare events are sometimes more illuminating than a thousand mundane events. But the real clincher is the simple fact that there *must* be a ball. Posit the existence of a ball, which for some reason the Twiloans cannot see, and suddenly everything works. The game makes sense. Not only that, but all the theories, charts, and diagrams compiled over the past afternoon remain valid. The ball simply gives meaning to the rules.

This is an extended metaphor for many puzzles in physics, and it is especially relevant to particle physics. We can't understand the rules (the laws of nature) without knowing the objects (the ball) and, without a belief in a logical set of laws we would never deduce the existence of all the particles.

THE PYRAMID OF SCIENCE

We're talking about science and physics here, so before we proceed, let's define some terms. What is a physicist? And where does this job description fit in the grand scheme of science?

A discernible hierarchy exists, though it is not a hierarchy of social value or even of intellectual prowess. Frederick Turner, a University of Texas humanist, put it more eloquently. There exists, he said, a science pyramid. The base of the pyramid is mathematics, not because math is more abstract or more groovy, but because mathematics does not rest upon or need any of the other disciplines, whereas physics, the next layer of the pyramid, relies on mathematics. Above physics sits chemistry, which requires the discipline of physics; in this admittedly simplistic separation, physics is not concerned with the laws of chemistry. For example, chemists are concerned with how atoms combine to form molecules and how molecules behave when in close proximity. The forces between atoms are complex, but ultimately they have to do with the law of attraction and repulsion of electrically charged particles — in other words, physics. Then comes biology, which rests on an understanding of both chemistry and physics. The upper tiers of the pyramid become increasingly blurred and less definable: as we reach physiology, medicine, psychology, the pristine hierarchy becomes confused. At the interfaces are the hyphenated or compound subjects: mathematical physics, physical chemistry, biophysics. I have to squeeze astronomy into physics, of course, and I don't know what to do with geophysics or, for that matter, neurophysiology.

The pyramid may be disrespectfully summed up by an old saying: the physicists defer only to the mathematicians, and the mathematicians defer only to God (though you may be hard pressed to find a mathematician that modest).

Chapter 2

From Leon Lederman, *The God Particle*.

A TALE OF TWO PARTICLES AND THE ULTIMATE T-SHIRT

When I was ten years old, I came down with the measles, and to cheer me up my father bought me a book with big print called *The Story of Relativity,* by Albert Einstein and Leopold Infeld. I'll never forget the beginning of Einstein and Infeld's book. It talked about detective stories, about how every detective story has a mystery, clues, and a detective. The detective tries to solve the mystery by using the clues.

There are essentially two mysteries to be solved in the following story. Both manifest themselves as particles. The first is the long-sought a-tom, the invisible, indivisible particle of matter first postulated by Democritus. The a-tom lies at the heart of the basic questions of particle physics.

We've struggled to solve this first mystery for 2,500 years. It has thousands of clues, each uncovered with painstaking labor. In the first few chapters, we'll see how our predecessors have attempted to put the puzzle together. You'll be surprised to see how many "modern" ideas were embraced in the sixteenth and seventeenth centuries, and even centuries before Christ. By the end, we'll be back to the present and chasing a second, perhaps even greater mystery, one represented by the particle that I believe orchestrates the cosmic symphony. And you will see through the course of the book the natural kinship between a sixteenth-century mathematician dropping weights from a tower in Pisa and a present-day particle physicist freezing his fingers off in a hut on the cold, wind-swept prairie of Illinois as he checks the data flowing in from a half-billion-dollar accelerator buried beneath the frozen ground. Both asked the same questions. What is the basic structure of matter? How does the universe work?

When I was growing up in the Bronx, I used to watch my older brother playing with chemicals for hours. He was a whiz. I'd do all the chores in the house so he'd let me watch his experiments. Today he's in the novelty business. He sells things like whoopee cushions, booster license plates, and T-shirts with catchy sayings. These allow people to sum up their world view in a statement no wider than their chest. Science should have no less lofty a goal. My ambition is to live to see all of physics reduced to a formula so elegant and simple that it will fit easily on the front of a T-shirt.

Significant progress has been made through the centuries in the search for the ultimate T-shirt. Newton, for example, came up with gravity, a force that explains an amazing range of disparate phenomena: the tides, the fall of an apple, the orbits of the planets, and the clustering of galaxies. The Newton T-shirt reads $F = ma$. Later, Michael Faraday and James Clerk Maxwell unraveled the mystery of the electromagnetic spectrum. Electricity, magnetism, sunlight, radio waves, and x-rays, they found, are all manifestations of the same force. Any good campus bookstore will sell you a T-shirt with Maxwell's equations on it.

Today, many particles later, we have the standard model, which reduces all of reality to a dozen or so particles and four forces. The standard model represents all the data that have come out of all the accelerators since the Leaning Tower of Pisa. It organizes particles called quarks and leptons — six of each — into an elegant tabular array. One can diagram the entire standard model on a T-shirt, albeit a busy one. It's a hard-won simplicity, generated by an army of physicists who have traveled the same road. However, the standard-model T-shirt cheats. With its twelve particles and four forces, it is remarkably accurate. But it is also incomplete and, in fact, internally inconsistent. To have room on the T-shirt to make succinct excuses for the inconsistencies would require an Xtra large, and we'd still run out of shirt.

What, or who, is standing in our way, obstructing our search for the perfect T-shirt? This brings us back to our second mystery. Before we can complete the task begun by the ancient Greeks, we must consider the possibility that our quarry is laying false clues to confuse us. Sometimes, like a spy in a John Le Carre novel, the experimenter must set a trap. He must force the culprit to expose himself.

THE MYSTERIOUS MR. HIGGS

Particle physicists are currently setting just such a trap. We're building a tunnel fifty-four miles in circumference that will contain the twin beam tubes of the Superconducting Super Collider, in which we hope to trap our villain.

And what a villain! The biggest of all time! There is, we believe, a wraithlike presence throughout the universe that is keeping us from understanding the true nature of matter. It's as if something, or someone, wants to prevent us from attaining the ultimate knowledge.

This invisible barrier that keeps us from knowing the truth is called the Higgs field. Its icy tentacles reach into every corner of the universe, and its scientific and philosophical implications raise large goose bumps on the skin of a physicist. The Higgs field works its black magic through — what else? — a particle. This particle goes by the name of the Higgs boson. The Higgs boson is a primary reason for building the Super Collider. Only the SSC will have the energy necessary to produce and detect the Higgs boson, or so we believe. This boson is so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive, that I have given it a nickname: the God Particle. Why God Particle? Two reasons. One, the publisher wouldn't let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing. And two, there is a connection, of sorts, to another book, a *much* older one ...

THE TOWER AND THE ACCELERATOR

> And the whole earth was of one language, and of one speech.
>
> And it came to pass, as they journeyed from the east, that they found a plain in the land of Shinar; and they dwelt there. And they said one to another, Go to, let us make brick, and burn them thoroughly. And they had brick for stone, and slime had they for mortar. And they said, Go to, let us build us a city and a tower, whose top *may reach* unto heaven; and let us make us a name, lest we be scattered abroad upon the face of the whole earth.

> And the Lord came down to see the city and the tower, which the children of men builded. And the Lord said, Behold, the people *is* one, and they have all one language; and this they begin to do: and now nothing will be restrained from them, which they have imagined to do. Go to, let us go down, and there confound their language, that they may not understand one another's speech.
>
> So the Lord scattered them abroad from thence upon the face of all the earth: and they left off to build the city. Therefore is the name of it called Babel.
>
> —Genesis 11:1-9

At one time, many millennia ago, long before those words were written, nature spoke but one language. Everywhere matter was the same — beautiful in its elegant, incandescent symmetry. But through the eons, it has been transformed, scattered throughout the universe in many forms, confounding those of us who live on this ordinary planet orbiting a mediocre star.

There have been times in mankind's quest for a rational understanding of the world when progress was rapid, breakthroughs abounded, and scientists were full of optimism. At other times utter confusion reigned. Frequently the most confused periods, times of intellectual crisis and total incomprehension, were themselves harbingers of the illuminating breakthroughs to come.

In the past few decades in particle physics, we have been in a period of such curious intellectual stress that the parable of the Tower of Babel seems appropriate. Particle physicists have been using their giant accelerators to dissect the parts and processes of the universe. The quest has, in recent years, been aided by astronomers and astrophysicists, who figuratively peer into giant telescopes to scan the heavens for residue sparks and ashes of a cataclysmic explosion that they are convinced took place 15 billion years ago, which they call the Big Bang.

Both groups have been progressing toward a simple, coherent, all-encompassing model that will explain everything: the structure of matter and energy, the behavior of forces in environments that range from the earliest moments of the infant universe with its exorbitant temperature and density to the relatively cold and empty world we know today. We were proceeding nicely, perhaps too nicely, when we stumbled upon an oddity, a seemingly adversarial force afoot in the universe. Something that seems to pop out of the all-pervading space in which our planets, stars, and galaxies are embedded. Something we cannot yet detect and which, one might say, has been put there to test and confuse us. Were we getting too close? Is there a nervous Grand Wizard of Oz who sloppily modifies the archaeological record?

The issue is whether physicists will be confounded by this puzzle or whether, in contrast to the unhappy Babylonians, we will continue to build the tower and, as Einstein put it, "know the mind of God."

> And the whole universe was of many languages, and of many speeches.
>
> And it came to pass, as they journeyed from the east, that they found a plain in

the land of Waxahachie, and they dwelt there. And they said to one another, Go to, let us build a Giant Collider, whose collisions may reach back to the beginning of time. And they had superconducting magnets for bending, and protons had they for smashing.

And the Lord came down to see the accelerator, which the children of men builded. And the Lord said, Behold the people are un-confounding my confounding. And the Lord sighed and said. Go to, let us go down, and there give them the God Particle so that they may see how beautiful is the universe I have made.

— The Very New Testament, 11:1

THE FIRST PARTICLE PHYSICIST

He seemed surprised. "You found a knife that can cut off an atom?" he said. "In *this* town?" I nodded. "We're sitting on the main nerve right now," I said.

— With apologies to Hunter S. Thompson

ANYONE CAN DRIVE (or walk or bicycle) into Fermilab, even though it is the most sophisticated scientific laboratory in the world. Most federal facilities are militant about preserving their privacy. But Fermilab is in the business of uncovering secrets, not keeping them. During the radical 1960s the Atomic Energy Commission told Robert R. Wilson, my predecessor and the lab's founding director, to devise a plan for handling student activists should they arrive at the gates of Fermilab. Wilson's plan was simple. He told the AEC he would greet the protesters alone, armed with a single weapon: a physics lecture. This was lethal enough, he assured the commission, to disperse even the bravest rabble-rousers. To this day, lab directors keep a lecture handy in case of emergencies. Let us pray we never have to use it.

Fermilab sits on 7,000 acres of converted corn fields five miles east of Batavia, Illinois, about an hour's drive west of Chicago. At the Pine Street entrance to the grounds stands a giant steel sculpture created by Robert Wilson, who besides being the first director was pretty much responsible for the building of Fermilab, an artistic, architectural, and scientific triumph. The sculpture, entitled *Broken Symmetry,* consists of three arches curving upward, as if to intersect at a point fifty feet above the ground. They don't make it, at least not cleanly. The three arms meet, but in an almost haphazard fashion, as if they had been built by different contractors who weren't talking to each other. The sculpture has an "oops" feel to it — not unlike our Drive east on Pine Street, away from Wilson Hall, and you come to several other important facilities, including the collider detector facility (CDF), designed to make most of our discoveries about matter, and the newly constructed Richard P. Feynman Computer Center, named after the great Cal Tech theorist who died just a few years ago. Keep driving and eventually you come to Eola Road. Take a right and drive straight for a mile or so, and you'll see a 150-year-old farm-house on the left. That's where I lived as director: 137 Eola Road. That's not an official address. It's just the number I chose to put on the house.

It was Richard Feynman, in fact, who suggested that all physicists put a sign up in their offices or homes to remind them of how much we don't know. The sign would say simply this: 137. One hundred thirty-seven is the inverse of something called the fine-structure constant. This number is related to the probability that an electron will emit or absorb a photon. The fine-structure constant also answers to the name alpha, and it can be arrived at by taking the square of the charge of the electron divided by the speed of light times Planck's constant. What all that verbiage means is that this one number, 137, contains the crux of electromagnetism (the electron), relativity (the velocity of light), and quantum theory (Planck's constant). It would be less unsettling if the relationship between all these important concepts turned out to be one or three or maybe a multiple of pi. But 137?

The most remarkable thing about this remarkable number is that it is dimension-free. The speed of light is about 300,000 kilometers per second. Abraham Lincoln was 6 feet 6 inches tall. Most numbers come with dimensions. But it turns out that when you combine the quantities that make up alpha, all the units cancel! One hundred thirty-seven comes by itself; it shows up naked all over the place. This means that scientists on Mars, or on the fourteenth planet of the star Sirius, using whatever god-awful units they have for charge, speed, and their version of Planck's constant, will also get 137. It is a pure number.

Physicists have agonized over 137 for the past fifty years. Werner Heisenberg once proclaimed that all the quandaries of quantum mechanics would shrivel up when 137 was finally explained. I tell my undergraduate students that if they are ever in trouble in a major city anywhere in the world they should write "137" on a sign and hold it up at a busy street corner. Eventually a physicist will see that they're distressed and come to their assistance. (No one to my knowledge has ever tried this, but it should work.)

One of the wonderful (but unverified) stories in physics emphasizes the importance of 137 as well as illustrating the arrogance of theorists. According to this tale, a notable Austrian mathematical physicist of Swiss persuasion, Wolfgang Pauli, went to heaven, we are assured, and, because of his eminence in physics, was given an audience with God.

"Pauli, you're allowed one question. What do you want to know?"

Pauli immediately asked the one question that he had labored in vain to answer for the last decade of his life. "Why is alpha equal to one over one hundred thirty-seven?"

God smiled, picked up the chalk, and began writing equations on the blackboard. After a few minutes. She turned to Pauli, who waved his hand. "Das ist falsch!" [That's baloney!]

There's a true story also — a verifiable story — that takes place here on earth. Pauli was in fact obsessed with 137, and spent countless hours pondering its significance. The number plagued him to the very end. When Pauli's assistant visited the theorist in the hospital room in which he was placed prior to his fatal operation, Pauli instructed the assistant to note the number on the door as he left. The room number was 137.

That's where I lived: 137 Eola Road.

LATE NIGHT WITH LEDERMAN

Returning home one weekend night after a late supper in Batavia, I drove through the lab grounds. From several points on Eola Road, one can see the central lab building lit up against the prairie sky. Wilson Hall at 11:30 on a Sunday night is testimony to how strongly physicists feel about solving the remaining mysteries of the universe. Lights were blazing up and down the sixteen floors of the twin towers, each containing its quota of bleary-eyed researchers trying to work out the kinks in our opaque theories about matter and energy. Fortunately, I could drive home and go to bed. As director of the lab, my night-shift obligations were drastically reduced. I was able to sleep on problems rather than work on them. I was grateful that night to lie on a real bed rather than having to bunk down on the accelerator floor waiting for the data to come in. Nevertheless, I tossed and turned, worrying about quarks, Gina, leptons, Sophia . . . Finally, I resorted to counting sheep to get my mind off physics: "... 134,135, 136,*137 . . ."*

Suddenly I rose from between the sheets, a sense of urgency driving me from the house. I pulled my bicycle out of the barn, and — still clad in pajamas, my medals falling from my lapels as I pedaled — I rode in painfully slow motion toward the collider detector facility. It was frustrating. I knew I had some very important business to attend to, but I just couldn't get the bike to move any faster. Then I remembered what a psychologist had told me recently: that there is a kind of dream, called a lucid dream, in which the dreamer knows he is in a dream. Once you know this, said the psychologist, you can do anything you want inside the dream. The first step is to find some clue that you're dreaming and are not in real life. That was easy. I knew damn well this was a dream because of the italics. I hate italics. Too hard to read. I took control of my dream. "No more italics!" I screamed.

There. That's better. I put the bike into high gear and pedaled at light speed (hey, you can do anything in a dream) toward the CDF. Oops, too fast: I had circled the earth eight times and ended up back home. I geared down and pedaled at a gentle 120 miles per hour to the facility. Even at three in the morning the parking lot was fairly full; at accelerator labs the protons don't stop at nightfall.

Whistling a ghostly little tune, I entered the detector facility. The CDF is an industrial hangar-like building, with everything painted bright orange and blue. The various offices, computer rooms, and control rooms are all along one wall; the rest of the building is open space, designed to accommodate the detector, a three-story-tall, 5,000-ton instrument. It took some two hundred physicists and an equal number of engineers more than eight years to assemble this particular 10-million-pound Swiss watch. The detector is multicolored, radial in design, its components extending out symmetrically from a small hole in the center. The detector is the crown jewel of the lab. Without it, we cannot "see" what goes on in the accelerator tube, which passes through the center of the detector's core.

What goes on, dead center in the detector, are the head-on collisions of protons and antiprotons. The radial spokes of the detector elements roughly match the radial spray of hundreds of particles produced in the collision.

The detector moves on rails that allow the enormous device to be moved out of the accelerator tunnel to the assembly floor for periodic maintenance. We usually schedule maintenance for the summer months, when electric rates are highest (when your electric bill runs more than $10 million a year, you do what you can to cut costs). On this night the detector was on-line. It had been moved back into the tunnel, and the passageway to the maintenance room had been plugged with a 10-foot-thick steel door that blocks the radiation. The accelerator is so designed that the protons and antiprotons collide (mostly) in the section of pipe that runs through the detector — the "collision region." The job of the detector, obviously, is to detect and catalogue the products of the head-on collisions between protons and p-bars (antiprotons).

Still in my pajamas, I made my way up to the second-floor control room, where the findings of the detector are continuously monitored. The room was quiet, as one would expect at this hour. No welders or other workmen roamed the facility making repairs or performing other maintenance tasks, as is common during the day shift. As usual, the lights in the control room were dim, to better see and read the distinctive bluish glow of dozens of computer monitors. The computers in the CDF control room are Macintoshes, just like the microcomputers you might buy to keep track of your finances or to play Cosmic Ozmo. They are fed information from a humongous "home-built" computer that works in tandem with the detector to sort through the debris created by the collisions between protons and antiprotons. The home-built thing is actually a sophisticated data acquisition system, or DAQ, designed by some of the brightest scientists in the fifteen or so universities around the world that collaborated to build the CDF monster. The DAQ is programmed to decide which of the hundreds of thousands of collisions each second are interesting or important enough to analyze and record on magnetic tape. The Macintoshes monitor the great variety of subsystems that collect data.

I surveyed the room, scanning the numerous empty coffee cups and the small band of young physicists, simultaneously hyper and exhausted, the result of too much caffeine and too many hours on shift. At this hour you find graduate students and young postdocs (new Ph.D.'s), who don't have enough seniority to draw decent shifts. Notable was the number of young women, a rare commodity in most physics labs. CDF's aggressive recruiting has paid off to the pleasure and profit of the group.

Over in the corner sat a man who didn't quite fit in. He was thin with a scruffy beard. He didn't look that different from the other researchers, but somehow I knew he wasn't a member of the staff. Maybe it was the toga. He sat staring into the Macintosh, giggling nervously. Imagine, laughing in the CDF control room! At one of the greatest experiments science has ever devised! I thought I'd better put my foot down.

LEDERMAN: Excuse me. Are you the new mathematician they were supposed to send over from the University of Chicago?

GUY IN TOGA: Right profession, wrong town. Name's Democritus. I hail from Abdera, not Chicago. They call me the Laughing Philosopher.

LEDERMAN: Abdera?

DEMOCRITUS: Town in Thrace, on the Greek mainland.

LEDERMAN: I don't remember requisitioning anyone from Thrace. We don't need a Laughing Philosopher. At Fermilab I tell all the jokes.

DEMOCRITUS: Yes, I've heard of the Laughing Director. Don't worry about it. I doubt if I'll be here long. Not given what I've seen so far.

LEDERMAN: So why are you taking up space in the control room?

DEMOCRITUS: I'm looking for something. Something very small.

LEDERMAN: You've come to the right place. Small is our specialty.

DEMOCRITUS: So I'm told. I've been looking for this thing for twenty-four hundred years.

LEDERMAN: Oh, you're *that* Democritus.

DEMOCRITUS: You know another one?

LEDERMAN: I get it. You're like the angel Clarence in *It's a Wonderful Life,* sent here to talk me out of suicide. Actually, I *was* thinking about slicing my wrists. We can't find the top quark.

DEMOCRITUS: Suicide! You remind me of Socrates. No, I'm no angel. That immortality concept came after my time, popularized by that softhead Plato.

LEDERMAN : But if you're not immortal, how can you be here ? You died over two millennia ago.

DEMOCRITUS: There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.

LEDERMAN: Sounds familiar.

DEMOCRITUS: Borrowed it from a guy I met in the sixteenth century. But to answer your question, I'm doing what you call time traveling.

LEDERMAN: Time traveling? You figured out time travel in fifth-century-B.C. Greece?

DEMOCRITUS: Time is a piece of cake. It goes forward, it goes backward. You ride it in and out, like your California surfers. It's matter that's hard to figure. Why, we even sent some of our graduate students to your era. One, Stephenius Hawking, made quite a stir, I've heard. He specialized in "time." We taught him everything he knows.

LEDERMAN: Why didn't you publish this discovery?

DEMOCRITUS: Publish? I wrote sixty-seven books and would have sold a bunch, but the publisher just refused to advertise. Most of what you know about me you know through Aristotle's writings. But let me fill you in a little. I traveled — boy, did I travel! I covered more territory than any man in my time, making the most extensive investigations, and saw more climes and countries, and listened to more famous men . . .

LEDERMAN: But Plato hated your guts. Is it true he disliked your ideas so much that he wanted all your books burned?

DEMOCRITUS: Yes, and that superstitious old goat nearly succeeded. And then that fire in Alexandria really cooked my reputation. That's why you so-called moderns are so ignorant of time manipulation. Now all I hear about is Newton, Einstein . . .

LEDERMAN: So why this visit to Batavia in the 1990s?

DEMOCRITUS: Just checking up on one of my ideas, an idea that was unfortunately abandoned by my countrymen.

LEDERMAN: I bet you're speaking of the atom, the *atomos.*

DEMOCRITUS: Yes, the a-tom, the ultimate, indivisible, and invisible particle. The building block of all matter. I've been jumping ahead through time, to see how far man has come with refining my theory.

LEDERMAN: And your theory was . ..

DEMOCRITUS: You're baiting me, young man! You know very well what I believed. Don't forget, I've been time-hopping century by century, decade by decade. I'm well aware that the nineteenth-century chemists and the twentieth-century physicists have been playing around with my ideas. Don't get me wrong — you were right to do so. If only Plato had been as wise.

LEDERMAN: I just wanted to hear it in your own words. We know of your work primarily through the writings of others.

DEMOCRITUS: Very well. Here we go for the umpteenth time. If I sound bored, it's because I recently went through this with that fellow Oppenheimer. Just don't interrupt me with tedious musings about the parallels between physics and Hinduism.

LEDERMAN: Would you like to hear my theory about the role of Chinese food in mirror-symmetry violation? It's as valid as saying the world is made of air, earth, fire, and water.

DEMOCRITUS: Why don't you just keep quiet and let me start from the beginning. Here, take a seat next to this Macintosh thing and pay attention. Now, if you're going to understand my work, and the work of all of us atomists, we have to go back twenty-six hundred years. We have to start about two hundred years before I was born, with Thales, who flourished around 600 B.C. in Miletus, a hick town in lonia, which you now call Turkey.

LEDERMAN: Thales was a philosopher, too?

DEMOCRITUS: And how! He was the *first* Greek philosopher. But philosophers in pre-Socratic Greece really knew a lot of things. Thales was an accomplished mathematician and astronomer. He sharpened his training in Egypt and Mesopotamia. Did you know he predicted an eclipse of the sun that occurred at the close of the war between the Lydians and Medes? He constructed one of the first almanacs — I understand you leave this task to farmers today — and he taught our sailors how to steer a ship at night by using the Little Bear constellation. He was also a political adviser, a shrewd businessman, and a fine engineer. Early Greek philosophers were respected not only for the aesthetic workings of their minds but also for their practical arts, or applied science, as you would put it. Is it any different today with physicists?

LEDERMAN: We have been known to do something useful now and then. But I'm sorry to say that our achievements are usually very narrowly focused, and very few of us know Greek.

DEMOCRITUS: Lucky for you I speak English then, yes? Anyhow, Thales, like me, kept asking himself a primary question: "What is the world made of, and how does it work?" Around us we see apparent chaos. Flowers bloom, then die. Floods destroy the land. Lakes become deserts. Meteors fall out of the sky. Whirlwinds appear apparently out of nowhere. From time to time a mountain explodes. Men grow old and turn to dust. Is there something permanent, an underlying identity, that persists through this constant change? Can all of this be reduced to rules so simple that our small minds can understand?

LEDERMAN: Did Thales come up with an answer?

DEMOCRITUS: Water. Thales said water was the primary and ultimate element.

LEDERMAN: How did he figure?

DEMOCRITUS: It's not such a crazy idea. I'm not totally sure what Thales was thinking. But consider: water is essential to growth, at least among plants. Seeds have a moist nature. Almost anything gives off water when heated. And water is the only substance known that can exist as solid, liquid, or gas — as water vapor or steam. Maybe he figured water could be transformed into earth if this process were carried further. I don't know. But Thales made a very great beginning for what you call science.

LEDERMAN: Not bad for a first try.

DEMOCRITUS: The impression around the Aegean is that Thales and his group were given a bad rap by the historians, especially Aristotle. Aristotle was obsessed by forces, by causation. You can hardly talk to him about anything else, and he picked on Thales and his friends in Miletus. Why water? And what force causes the change from rigid water to aethereal water? Why so many different forms of water?

LEDERMAN: In modern physics, er, in the physics of these times, forces are required in addition to —

DEMOCRITUS: Thales and his crowd may well have enmeshed the notion of cause into the very nature of his water-based matter. Force and matter unified! Let's save that for later. Then you can tell me about things you call gluons and supersymmetry and —

LEDERMAN *[frantically scratching his goose bumps]:* Uh, what else did this genius do?

DEMOCRITUS: He had some conventionally mystical ideas. He believed the earth floated on water. He believed that magnets have souls because they can move iron. But he believed in simplicity, that there is a unity to the universe, even though there are many varied material "things" around us. Thales combined a set of rational arguments with whatever mythological hangovers he had in order to give water a special role.

LEDERMAN: I suppose Thales believed the world was being carried by Atlas standing on a turtle.

DEMOCRITUS: Au contraire. Thales and his pals had this very important meeting, probably in the back room of a restaurant in downtown Miletus. After a certain quantity of Egyptian wine, they threw out Atlas and made a solemn agreement: "From this day forth, explanations and theories of how the world works will be based strictly upon logical arguments. No more superstition. No more appeals to Athena, Zeus, Hercules, Ra, Buddha, Lao-tzu. Let's see if we can find out for ourselves." This may have been the most important agreement ever made by humans. It was 650 B.C., probably a Thursday night, and it was the birth of science.

LEDERMAN: Do you think we've gotten rid of superstition now? Have you met our creationists? Our animal rights extremists?

DEMOCRITUS: Here at Fermilab?

LEDERMAN: No, but not far away. But tell me, when did this earth, air, fire, and water idea come in?

DEMOCRITUS: Hold your horses. There were a couple of other guys before we get to that theory. Anaximander, for one. He was a young associate of Thales' in Miletus. Anaximander also earned his spurs doing practical things, such as constructing a map of the Black Sea for Milesian sailors. Like Thales, he sought a primary building block of matter, but he decided it couldn't be water.

LEDERMAN: Another great advance in Greek thinking, no doubt. What was *his* candidate, baklava?

DEMOCRITUS: Have your laugh. We'll get to *your* theories soon enough. Anaximander was another practical genius and, like his mentor Thales, he used his spare time to join in the philosophical debate. Anaximander's logic was fairly subtle. He saw the world as being composed of warring opposites — hot and cold, wet and dry. Water puts out fire; the sun dries up water, et cetera. Therefore the primary substance of the universe cannot be water or fire or anything characterized by one of these opposites. No symmetry there. And you know how we Greeks loved symmetry. For example, if all matter was originally water, as Thales said, then heat or fire could never come into being, since water does not generate fire but obliterates it.

LEDERMAN: Then what *did* he propose as the primary substance?

DEMOCRITUS: He called it the *apeiron*, meaning "without boundaries." This first state of matter was an undifferentiated mass of enormous, possibly infinite, proportions. It was the primitive "stuff," neutral between opposites. This idea had a deep influence on my own thinking.

LEDERMAN: So this apeiron was something like your a-tom— except that it was an infinite substance as opposed to an infinitesimal particle? Didn't this just confuse things?

DEMOCRITUS: No, Anaximander was on to something. The apeiron was infinite, both in space and time, but it was also structureless; it had no component parts. It was nothing but apeiron through and through. And if you're going to decide on a primary substance, it had better have this quality. In fact, my point is to embarrass you by noting that after two thousand years, you are finally coming around to appreciating the prescience of my crowd. What Anaximander did was to invent the vacuum. I think your P. A. M. Dirac finally began to give the vacuum the properties it deserved in the 1920s. Anaxi's apeiron was the prototype of my own "void," a nothingness in which particles move. Isaac Newton and James Clerk Maxwell called it aether.

LEDERMAN: But what about the stuff, matter?

DEMOCRITUS: Listen to this *[pulls a parchment roll out of his toga, perches a pair of discount Magna Vision reading glasses on his nose]:* Anaximander says, "It is neither water nor any other of the so-called elements, but a different substance which is boundless, from which they come into being all the heavens and the worlds within them.

Things perish into those things out of which they have their being . . . opposites are in the one and separated out." Now, I know you twentieth-century types are always talking about matter and antimatter created in the vacuum, also annihilating . . .

LEDERMAN: Sure, but . . .

DEMOCRITUS: When Anaximander says opposites were in the apeiron — call it a vacuum, or call it the aether — and were separated out, isn't that something like what you think?

LEDERMAN: Sort of, but I'm much more interested in what made Anaximander think these things.

DEMOCRITUS: Of course he didn't anticipate antimatter. But in a properly endowed vacuum, he thought that opposites could separate: hot and cold, wet and dry, sweet and sour. Today you add positive and negative, north and south. When they combine, they cancel their properties into the neutral apeiron. Isn't that neat?

LEDERMAN: How about democrat and republican? Was there a Greek named Republicas?

DEMOCRITUS: Very amusing. At least Anaximander attempted to explain the mechanism that creates diversity out of a primary element. And his theory led to a number of sub-beliefs, some of which you might even agree with. Anaximander believed, for example, that man evolved from lower animals, which in turn were descended from creatures in the sea. His greatest cosmological idea was to get rid of not only Atlas but even Thales' ocean that held up the earth. He knew you didn't need to hold up the earth. Picture the thing (not yet given spherical shape) suspended in infinite space. There is no place to go. Totally in accord with Newton's laws if, as these Greeks thought, there was nothing else. Anaximander also figured there had to be more than one world, or universe. In fact, he said there were an unlimited number of universes, all perishable, following one another in succession.

LEDERMAN: Like alternate universes on "Star Trek"?

DEMOCRITUS: Hold your commercials. The idea of innumerable worlds became very important to us atomists.

LEDERMAN: Wait a minute. I'm remembering something you wrote that gave me shivers in light of modern cosmology. I even memorized it. Let's see: "There are innumerable worlds of different sizes. In some there is neither sun nor moon, in others they are larger than in ours, and other worlds have more than one sun and more than one moon."

DEMOCRITUS: Yes, we Greeks held some ideas in common with your Captain Kirk. But we dressed a lot better. I'd rather compare my idea to the bubble universes that your inflationary cosmologists are publishing papers on these days.

LEDERMAN: That's really why I got spooked. Didn't one of your predecessors believe that air was the ultimate element?

DEMOCRITUS: You're thinking of Anaximenes, a younger associate of Anaximander's and the last of the Thales gang. He actually took a step backward from Anaximander and said there was a common primordial element, as Thales did — except Anaximenes said this element was air, not water.

LEDERMAN: He should have listened to his mentor; then he would have ruled out anything as mundane as air.

DEMOCRITUS: Yes, but Anaximenes did come up with a clever mechanism for explaining how various forms of matter are transformed from this primary substance. I understand from my readings that you're one of those experimentalists.

LEDERMAN: Yeah. You got a problem with that?

DEMOCRITUS: I've noticed your sarcasm toward so much of Greek theory. I suspect your prejudice comes from the fact that many of these ideas, while plausibly suggested by the world around us, do not lend themselves to incisive experimental verification.

LEDERMAN: True. Experimenters dearly love ideas that can be verified. It's how we make a living.

DEMOCRITUS: Then you may have more respect for Anaximenes, since his beliefs were based on observation. He theorized that the various elements of matter were separated out of air via condensation and rarefaction. Air can be reduced to moisture and vice versa. Heat and cold transform air into different substances. To demonstrate how heat is connected to rarefaction and cold to condensation, Anaximenes advised people to conduct this experiment: breathe out with your lips nearly closed, and the air will emerge cold. But if you open your mouth wide, your breath will be warmer.

LEDERMAN: Congress would love Anaximenes. His experiments are cheaper than mine. And all that hot air ...

DEMOCRITUS: I get it, but I wanted to dispel your idea that we ancient Greeks never did any experiments. The main problem with thinkers such as Thales and Anaximenes was their belief that substances can be transformed: water can become earth; air can become fire. Can't happen. This snag in our early philosophy wasn't really addressed until two of my contemporaries came along— Parmenides and Empedocles.

LEDERMAN: Empedocles is the earth, air, et cetera guy, right? Remind me about Parmenides.

DEMOCRITUS: He is often called the father of idealism, since much of his thought was picked up by that idiot Plato, but in fact he was a hard-core materialist. He talked a lot about Being, but this Being was material. Essentially, Parmenides held that Being can neither come to be nor pass away. Matter doesn't just pop in and out of existence. It's there and we can't destroy it.

LEDERMAN : Let's go down to the accelerator and I'll show you how wrong he is. We pop matter in and out of existence all the time.

DEMOCRITUS: Okay, okay. But this is an important concept. Parmenides was embracing an idea that was dear to us Greeks: oneness. Wholeness. What exists, exists. It is complete and enduring. I suspect you and your colleagues also embrace unity.

LEDERMAN: Yes, it's an enduring and endearing concept. We strive for unity in our beliefs whenever we can. Grand Unification is one of our current obsessions.

DEMOCRITUS: And, in fact, you don't just pop new matter into existence by will alone. I believe you have to add energy to the process.

LEDERMAN: True, and I have the electric bill to prove it.

DEMOCRITUS: So, in a way, Parmenides wasn't that far off. If you include both matter and energy in what he calls Being, then he's right. It can neither come to be nor pass away, at least not in a total sort of way. And yet our senses tell another story. We see trees bum to the ground. The fire can then be destroyed by water. The hot air of summer can evaporate the water. Flowers appear, then die. It was Empedocles who saw a way around this apparent contradiction. He agreed with Parmenides that matter must be conserved, that it cannot appear or disappear willy-nilly. But he disagreed with Thales and Anaximenes that one kind of matter can become another. How, then, does one account for the constant change one sees around us? There are only four kinds of matter, said Empedocles. His famous earth, air, fire, and water. They do not change into other types of matter, but are unchangeable and ultimate *particles,* which form the concrete objects of the world.

LEDERMAN: Now you're talking.

DEMOCRITUS: Thought you'd like that. Objects come into being through the mingling of these elements, and they cease to be through the separation of elements. But the elements themselves — earth, air, fire, water — neither come into being nor pass away but remain unchanged. Obviously I disagree with him as to the identity of these particles, but in principle he made an important intellectual leap. There are only a few basic ingredients in the world, and you construct objects by mixing them together in a multitude of ways. For example, Empedocles said that bone is composed of two parts earth, two parts water, and four parts fire. How he came up with this recipe escapes me at the moment.

LEDERMAN: We tried the air-earth-fire-water mixture and all we got was hot, bubbling mud.

DEMOCRITUS: Leave it to a "modern" to bring the discussion down a notch.

LEDERMAN: What about forces? None of you Greeks seem to realize you need forces as well as particles.

DEMOCRITUS: I have my doubts, but Empedocles would agree. He saw that you needed forces to fuse these elements into other objects. He came up with two: love and strife — love to draw things together, strife to separate them. Not very scientific, perhaps, but don't the scientists in your age have a similar system of beliefs for the universe? A number of particles and a set of forces? Often given whimsical names?

LEDERMAN: In a way, yes. We have what we call the "standard model." It holds that everything we know about the universe can be explained by the interactions of a dozen particles and four forces.

DEMOCRITUS: There you go. Empedocles' world view doesn't sound all that different, does it? He said the universe could be explained with four particles and two forces. You've just added a couple more, but the structure of both models is similar, no?

LEDERMAN: Sure, but we don't go along with the content: fire, ' earth, strife . . .

DEMOCRITUS: Well, I suppose you have to show something for two thousand years of hard work. But, no, I don't hold with the content of Empedocles' theory either.

LEDERMAN: Then what do you believe in?

DEMOCRITUS: Ah, now we get down to business. The work of Parmenides and

Empedocles set the stage for my own work. I believe in the a-tom, or atom, that which cannot be cut. The atom is the building block of the universe. All of matter is composed of various arrangements of atoms. It is the smallest thing in the universe.

LEDERMAN: You had the instruments necessary to find invisible objects in fifth-century-B.C. Greece?

DEMOCRITUS: Not exactly "find."

LEDERMAN: Then what?

DEMOCRITUS: Perhaps "discover" is a better word. I discovered the atom through Pure Reason.

LEDERMAN: What you're saying is that you just thought about it. You didn't bother to do any experiments.

DEMOCRITUS *[gesturing to indicate the far reaches of the laboratory}:* There are some experiments that the mind can do better than even the largest, most precise instrument.

LEDERMAN: What gave you the idea of atoms? It was, I must admit, a brilliant hypothesis. But it goes way beyond what went before.

DEMOCRITUS: Bread.

LEDERMAN: Bread? Someone paid you to come up with the idea?

DEMOCRITUS: Not that kind of bread. This was in the era before federal grants. I mean real bread. One day, during a prolonged fast, someone walked into my study carrying a loaf of bread just out of the oven. I knew it was bread before I saw it. I thought: some invisible essence of bread traveled ahead and reached my Grecian nose. I made a note about odors and thought about other "traveling essences." A small pool of water shrinks and eventually dries up. Why? How? Can invisible essences of water leap out of the pool and travel long distances like my warm bread? Lots of little things like that — you see, you think, you talk about it. My friend Leucippus and I argued for days and days, sometimes until the sun rose and our wives came after us with clubs. We finally decided that if each substance was made of atoms, invisible because they were too small for our human eyes, we would have too many different types: water atoms, iron atoms, daisy petal atoms, bee foreleg atoms — a system so ugly as to be un-Greek.

Then we got a better idea. Have only a few different styles of atoms, like smooth, rough, round, angular, and have a selected number of different shapes, but have an infinite supply of each kind. Then put them in empty space. (Boy, you should have seen all the beer we drank to understand empty space! How do you define "nothing at all"?) Let these atoms move about at random. Let them move incessantly, occasionally colliding, sometimes sticking and collecting together. Then one collection of atoms makes wine, another makes the glass in which it is served, ditto feta cheese, baklava, and olives.

LEDERMAN: Didn't Aristotle argue that these atoms should naturally fall?

DEMOCRITUS: That's his problem. Ever watch motes of dust dancing in a beam of sunlight that enters a darkened room? The dust moves in any and all directions, just like atoms.

LEDERMAN: How did you imagine the *indivisibility* of atoms?

DEMOCRITUS: It took place in the mind. Imagine a knife of polished bronze. We ask our servant to spend his entire day honing the edge until it can sever a blade of grass held at its distant end. Finally satisfied, I begin to act. I take a piece of cheese . . .

LEDERMAN: Feta?

DEMOCRITUS: Of course. Then I cut the cheese in two with the knife. Then again and again, until I have a speck of cheese too small to hold. Now I think that if I myself were much smaller, the speck would appear large to me, and I could hold it, and with my knife honed even sharper, cut it again and again. Now I must again, in my mind, reduce myself to the size of a pimple on an ant's nose. I continue cutting the cheese. If I repeat the process enough, do you know what the result will be?

LEDERMAN: Sure, a feta-compli.

DEMOCRITUS *[groans]:* Even the Laughing Philosopher chokes on a lousy pun. If I may continue . . . Eventually I will come to a piece of stuff so hard that it can never be cut, even given enough servants to sharpen the knife for a hundred years. I believe the smallest object cannot be cut as a matter of necessity. It is unthinkable that we can continue to cut forever, as some so-called learned philosophers say. Now I have the ultimate uncuttable object, the atomos.

LEDERMAN: And you came up with this idea in fifth-century-B.C. Greece?

DEMOCRITUS: Yes, why? Your ideas today are so much different?

LEDERMAN: Well, actually, they're pretty much the same. It's just that we hate the fact that you published first.