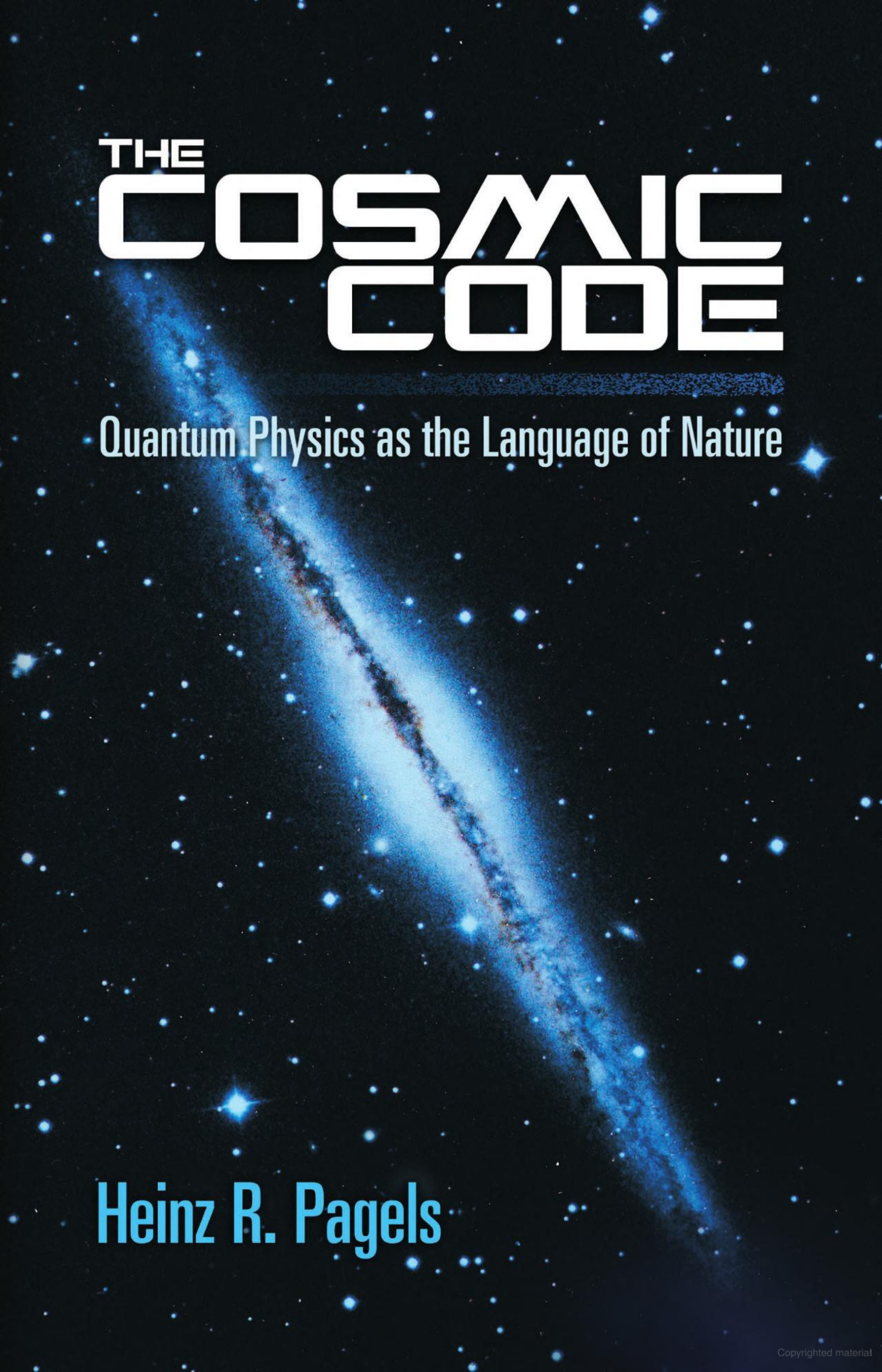

THE COSMIC CODE

Quantum Physics as the Language of Nature

Heinz R. Pagels

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foreword

As a physicist I want to share the excitement of the recent discoveries of physics with other people—discoveries giving insights into the ultimate structure of matter, the origin and end of the universe, and the new quantum reality. In the last ten years physicists have learned more about the universe than in previous centuries—they have seen a new picture of reality requiring a conversion of our imaginations. The visible world is neither matter nor spirit but the invisible organization of energy.

This book is divided into three parts. The first part, "The Road to Quantum Reality," describes the development of the quantum theory of the atom. Grasping quantum reality requires changing from a reality that can be seen and felt to an instrumentally detected reality that can be perceived only intellectually. The world described by the quantum theory does not appeal to our immediate intuition as did the old classical physics. Quantum reality is rational but not visualizable.

Another way the old physics differs from quantum physics is the way the determinism of a clock differs from the contingency of a pinball machine. Albert Einstein, who never accepted the randomness at the foundation of reality implied by the quantum theory, expressed his objection by stating, "I cannot believe that God plays dice." Yet almost every physicist today believes He does. We will look at randomness in the hand of a dice-playing God and see what it implies about reality.

The second part of the book describes "The Voyage into Matter." Physicists, extending human consciousness into the farthest reaches of space and time, deep into the structure of matter, find that beyond the molecule and atom lies a new realm. The core of the atom is the nucleus. The same forces that bind the atomic nucleus together produce a new set of particles—forms of matter never before seen—called hadrons, and these in turn are made out of yet more fundamental particles called quarks. Physicists have voyaged into the realm of quarks and other quantum particles from which everything in the universe can be made. Here, at the smallest distances ever reached by our instruments, they have discovered the basic laws that unify the forces of nature.

Understanding the world of these elementary particles requires combining the quantum theory and Einstein's special relativity theory of space and time. The result of this combination which describes the creation and destruction of the quantum particles is called relativistic quantum field theory. It represents one of the great intellectual accomplishments of this century and realizes a radical new picture of the material world. Physicists have found the unified field theories they have been seeking for decades—theories which use complex and beautiful mathematical symmetries. The language of such physical theories is highly mathematical, and that has been an obstacle to many people in sharing in the excitement of these recent discoveries; but here we will not use mathematics.

Using these new unified field theories, physicists reconstruct the first few seconds of the big bang at the beginning of time when the universe was a swirling fireball of quarks and other quanta. Everything we know came out of that fireball. How our universe was born through a succession of broken symmetries and how it might end is described.

Finally, there is a short third part, "The Cosmic Code," which describes the nature of physical laws and how physicists find them. This part also contains some personal reflections on the meaning of the scientific enterprise—that through the activity of science and technology the discovered order of the universe, what I call the cosmic code, becomes a program for historical change. The modern world is a response to the challenging discoveries of the quantum and the cosmos—discoveries which continue to shape our future and to transform our idea of reality.

New York, New York
Aspen, Colorado 1981

PART I

The Road to Quantum Reality

The Lord may be subtle, but
He is not malicious.
—Albert Einstein

1. The Last Classical Physicist

Still there are moments when one feels free from one's own identification with human limitations and inadequacies. At such moments, one imagines that one stands on some spot of a small planet, gazing in amazement at the cold yet profoundly moving beauty of the eternal, the unfathomable: life and death flow into one, and there is neither evolution nor destiny; only being.
—ALBERT EINSTEIN

AS A YOUNG boy growing up in suburban Philadelphia, I had few heroes. Albert Einstein was one of them. Reading about Einstein in the newspapers and Sunday supplements, I learned he was working on a unified field theory, whatever that was. Before Einstein, scientists thought that space went on forever—that the universe was infinite. But what Einstein proposed, what really excited me, was the notion of the curvature of three-dimensional space, for that meant that the universe could be finite.

Imagine that you are in an airplane flying above the surface of our earth. If you fly long enough in a straight path in any direction, you return to your starting point, going around the world in a circle. The surface of our earth may be viewed as two-dimensional curved space, a finite surface that closes on itself without a boundary or edge. It's harder to visualize a three-dimensional curved space closing on itself in the same way, but we *can* imagine flying into the universe in any direction, maintaining a steady course, and eventually returning to our starting point. As in our round-the-world flight in the airplane we would never encounter a physical boundary, a stop sign that says the universe ends here. Einstein in his general theory of relativity proved that the three-dimensional space of our universe can curve around itself and be finite just like the curved surface of the earth.

My friends and baseball companions thought I was crazy when I explained this to them, but I felt confident and pleased because I had Einstein backing me up. Later I learned that Einstein, anticipating such appeals to his authority, once ironically remarked, "For rebelling against every form of authority Fate has punished me by making me an authority."

I never met Einstein. He had died by the time I went to Princeton University to major in physics. But I have spoken with his friends and collaborators, many of whom were refugees like himself. Einstein was present at the birth of twentieth-century physics. One might say he fathered it.

Twentieth-century physics grew out of the previous "classical" physics inspired by the work of Isaac Newton in the late seventeenth century. Newton discovered the laws of motion and gravitation and successfully applied them to describing the detailed motion of the planets and the moon. In the century following Newton's discoveries, a new interpretation of the universe emerged: determinism. According to determinism, the universe may be viewed as a great clockwork set in motion by a divine hand at the beginning of time and then left undisturbed. From its largest to its smallest motions the entire material creation moves in a way that can be predicted with absolute accuracy by the laws of Newton. Nothing is left to chance. The future is as precisely determined by the past as is the forward movement of a clock. Although our human minds could never in practice track the movement of all the parts of the great clockwork and thus know the future, we can imagine that an all-knowing mind of God can do this and see past and future time laid out like a mountain range.

This rigid determinism implied by Newton's laws promotes a sense of security about the place of humanity in the universe. All that happens—the tragedy and joy of human life—is already predetermined. The objective universe exists independently of human will and purpose. Nothing we do can alter it. The wheels of the great world clock turn as indifferent to human life as the silent motion of the stars. In a sense, eternity has already happened.

As strange as it seems today, complete determinism was the only conclusion that could be reasonably drawn from classical Newtonian physics. Even the great scientific advances of the nineteenth century—the theory of heat called thermodynamics, and the theory of light as an electromagnetic wave by the Scottish physicist, James Clerk Maxwell—were worked out within the framework of deterministic physics. These theories were among the last triumphs of classical physics. They are today still seen as major achievements, but the deterministic world view they supported fell. It fell not because of some new philosophy or ideology, but because by the end of the nineteenth century experimental physicists contacted the atomic structure of matter. What they found was that atomic units of matter behaved in random, uncontrollable ways which deterministic Newtonian physics could not account for. Theoretical physicists responded to these new experimental discoveries by *inventing* a new physical theory, the quantum theory, between 1900 and 1926.

When the earliest version of the quantum theory was formulated in 1900 it was not clear that a clean break with Newtonian physics was inevitable. Attempts were made between 1900 and 1926 to reconcile the quantum theory of atoms with deterministic physics. Physicists hoped that even the tiniest wheels of the great clockwork, the atoms, would obey Newton's deterministic laws. After 1926 it became clear that a radical break with Newtonian physics was required, and determinism fell.

Like Isaac Newton two centuries before him, Albert Einstein is a major transitional figure in the history of physics. Newton accomplished the transition begun by Galileo, from medieval scholastic physics to classical physics; Einstein pioneered the transition from Newtonian physics to the quantum theory of atoms and radiation, a new non-Newtonian physics. But the irony was that Einstein, who opened the route to the new quantum theory that shattered the deterministic world view, rejected the new quantum theory. He could not intellectually accept that the foundation of reality was governed by chance and randomness. Yet Einstein had led the tribe of physicists through a period of struggle into the promised land of the quantum theory, a theory which he could not see as giving a complete picture of physical reality. Einstein was the last classical physicist.

Why did Einstein reject the interpretation of the new quantum physics—the ultimate randomness of reality—when most of his fellow scientists accepted it? Any answer to this question cannot be simple. Einstein's rejection reflects not just his rational choice but also the roots of his personality and character formed during his childhood in Germany. By examining his childhood we find clues to his later persistent adherence to the classical world view.

Einstein was born in Ulm, Germany, on March 14, 1879, into a middle-class Swabian Jewish family. Shortly thereafter, his family moved to Munich, where Einstein's father started a small electrochemical business. Einstein was not an exceptional child and had a poor memory for words, often repeating the words of others softly with his lips. His mind played with spatial rather than linguistic associations; he built card towers of great height and loved jigsaw puzzles. When he was four his father gave him a magnetic compass. Seven decades later, in his "Autobiographical Notes" appearing in the volume *Albert Einstein: Philosopher-Scientist* he recalled the wonder that this compass inspired; it "did not at all fit into the nature of events which could find a place in the unconscious world of concepts. . . ."

Einstein's mother and father encouraged the young boy's curiosity. In a psychoanalytic study of Einstein's childhood, Erik Erikson called him "Albert, the victorious child." Something in Einstein's character and upbringing encouraged a profound sense of trust in the universe and life. That trust and the confidence it brings is the foundation of the autonomous mind living at the boundary of human knowledge.

His family had a liberal secular orientation. They were not especially intellectual but they respected learning and loved music. His parents, not being religiously observant, sent the young boy to a Catholic school, where he became involved with the ritual and symbolism of religion. This involvement was not to last. He wrote about his early emotional and intellectual odyssey from religion toward science when he was sixty-seven. These "Autobiographical Notes" display a simplicity and strength that characterizes his prose:

> Even when I was a fairly precocious young man the nothingness of the hopes and strivings which chases most men restlessly through life came to my consciousness with considerable vitality. Moreover, I soon discovered the cruelty of that chase, which in those years was much more carefully covered up by hypocrisy and glittering words than is the case today. By the mere existence of his stomach everyone was condemned to participate in that chase. Moreover, it was possible to satisfy the stomach by such participation, but not man in so far as he is a thinking and feeling being. As the first way out there was religion, which is implanted into every child by way of the traditional education-machine. Thus I came—despite the fact that I was the son of entirely irreligious (Jewish) parents—to a deep religiosity, which, however, found an abrupt ending at the age of 12. Through the reading of popular scientific books I soon reached the conviction that much in the stories of the Bible could not be true. The consequence was a positively fanatic [orgy of] freethinking coupled with the impression that youth is intentionally being deceived by the state through lies; it was a crushing impression. Suspicion against every kind of authority grew out of this experience, a skeptical attitude towards the convictions which were alive in any specific social environment —an attitude which has never again left me, even though later on, because of a better insight into the causal connections, it lost some of its original poignancy.
>
> It is quite clear to me that the religious paradise of youth, which was thus lost, was a first attempt to free myself from the chains of the "merely personal," from an existence which is dominated by wishes, hopes and primitive feelings. Out yonder

> there was this huge world, which exists independently of us human beings and which stands before us like a great, eternal riddle, at least partially accessible to our inspection and thinking. The contemplation of this world beckoned like a liberation, and I soon noticed that many a man whom I had learned to esteem and to admire had found inner freedom and security in devoted occupation with it. The mental grasp of this extra-personal world within the frame of the given possibilities swam as highest aim half consciously and half unconsciously before my mind's eye. Similarly motivated men of the present and of the past, as well as the insights which they had achieved, were the friends which could not be lost. The road to this paradise was not as comfortable and alluring as the road to the religious paradise; but it has proved itself as trustworthy, and I have never regretted having chosen it.

What this passage reveals is a conversion from personal religion to the "cosmic religion" of science, an experience which changed him for the rest of his life. Einstein saw that the universe is governed by laws that can be known by us but that are independent of our thoughts and feelings. The existence of this cosmic code —the laws of material reality as confirmed by experience—is the bedrock faith that moves the natural scientist. The scientist sees in that code the eternal structure of reality, not as imposed by man or tradition but as written into the very substance of the universe. This recognition of the nature of the universe can come as a profound and moving experience to the young mind.

Many intellectual biographies of the turn of the century record a similar conversion. The symbols of religion and family are replaced by those from literary, political, or scientific culture. The formative event is the assertion of the individual's autonomy against parental, social, or religious authoritarianism. For Einstein this event took the form of liberating himself from a random existence "dominated by wishes, hopes and primitive feelings." He turned to the contemplation of the universe, a magnificent and orderly system that was, in his view, completely determined and independent of human will. The classical world view of reality fulfilled the needs of the young Einstein. The idea that reality is independent of how we question it may have been instilled in him then. This early commitment to classical determinism was to be the theme of his later opposition to the quantum theory, which maintains that fundamental atomic processes occur at random and that human intention influences the outcome of experiments.

When he was twelve Einstein received Euclid's geometry, "the holy geometry book," from his Uncle Jacob, and now Euclid became his Bible. Euclid's geometry appeals to reason, not authority or tradition. The new way of thinking attracted Einstein, and he became strongly antireligious and challenged the school's authoritarianism and discipline. No doubt the boy was a difficult student. He detested the military organization of German schools. He was rarely found in the company of children his own age, and once was even expelled from school by a teacher who said his mere presence in the classroom was sufficient to undermine the educational process.

When Einstein was fourteen, his father's business failed and the family moved to Italy. Albert did not at first join them but remained in Munich during 1894 attempting to finish school at the gymnasium. But he became a school dropout by the end of the year, joined the family in Italy, and spent most of the next year wandering in Italy, assuming his gymnasium teachers' recommendation would suffice to get him into a university. It did not, and he had to take an exam to enter Zurich Polytechnic Institute, which he failed. Then in the fall of 1895 he entered the Cantonal School of Argau, a Swiss preparatory school in the liberal Pestalozzi tradition to which he responded enthusiastically. Here he got his diploma, and in 1896 he entered the Zurich Polytechnic Institute to begin his education as a physicist.

Sometime in this year he first asked himself the question of what would happen if he could catch up to a light ray—actually move at the speed of light. The prevailing theory of light at that time—still valid today—was Maxwell's theory that light is a combination of electric and magnetic fields that move like a water wave through space. Einstein knew Maxwell's theory of light and the fact that it agreed with most experimental data. But if you could catch up to one of Maxwell's light waves the way a surfboard rider catches an ocean wave for a ride, then the light wave would not be moving relative to you but instead be standing still. The light wave would then be a standing wave of electric and magnetic fields that is not allowed if Maxwell's theory is right. So, he reasoned, there must be something wrong with the assumption that you can catch a light wave as you can catch a water wave. This idea was a seed from which the special theory of relativity grew nine years later. According to that theory, no material object can attain the speed of light. It is the speed limit for the universe.

In 1900, Einstein graduated from the university, but only by cramming for final exams. He detested the exams so much that he later commented that it had destroyed his motivation for scientific work for at least a year. He held various teaching jobs and tutored two young gymnasium students. Einstein went so far as to advise their father, a gymnasium teacher himself, to remove the boys from school, where their natural curiosity was being destroyed. He didn't last in that job.

Through a friend, he got a job at the patent office in Bern in 1902 while he worked on his doctorate. He earned his living examining patent applications and in his spare time worked on physics. This arrangement ideally suited him, for he never felt he ought to be paid to do theoretical physics research. In this modest way his career in physics began.

Theoretical physics at that time was dominated by the classical deterministic world view which had produced the great achievements of nineteenth-century physics—the theory of heat and Maxwell's electromagnetic theory. There was every reason to suppose it would continue. A major theoretical problem was how to deduce the laws of mechanical motion of electrically charged particles from the electromagnetic theory.

But experimental physicists had turned up some puzzles that did not have an explanation in terms of the prevailing theories. Radioactivity—the spontaneous emission of particles and rays from specific materials—had been observed. Perhaps the most puzzling observation of all was the sharp lines in the color spectrum of light emitted from different materials. No one had an explanation for that. These observations were like the first drops of rain in a storm that was soon to become a deluge sweeping away classical physics.

The puzzling experiments were indirectly revealing the properties and structure of matter down at the smallest distances beyond where anything could yet be directly seen. Today we know that the structure of matter at these small distances is atomic, but in Einstein's day some physicists still debated the existence of atoms. For over two millennia people had suspected the existence of atoms, but there had never been a way of proving their existence. In spite of all the indications, most especially from chemistry, that the atomic hypothesis—the hypothesis that all matter is made of atoms—was indeed correct, no one had devised a direct test to prove that atoms actually existed. Some leading scientists did not believe in atoms, including Ernst Mach, a philosopher-physicist. He was a positivist who maintained that all physical theory must come only from direct experimental experience, that all ideas that cannot be tested experimentally must be abandoned —the "seeing is believing" approach to physics. Mach did not believe in atoms because he had never seen one—and his strict viewpoint and rigorous thinking had a terrific impact on physics in general and upon Einstein in particular.

Max Planck was the physicist who brought forth the first crucial idea of the quantum theory in 1900, the same year Einstein graduated from the university. Previous to Planck's idea, most physicists conceived of the classical world of nature as a continuum: They thought of the forms of matter blending into one another in a smooth, continuous way. Various physical quantities like energy, momentum, and spin were continuous and could take on any value.

The basic idea of Planck's quantum hypothesis is that this continuous view of the world must be replaced by a discrete one. Because the discreteness of physical quantities is so very small, their discreteness is not perceptible to our senses. For example, if we look at a pile of wheat from a distance it appears to be a continuous smooth hill. But up close, we recognize the illusion and see that in fact it is made of tiny grains. The discrete grains are the quanta of the pile of wheat.

Another example of this "quantization" of continuous objects is the reproduction of photographs in newspapers. If you look closely at a newspaper photo it consists of lots of tiny dots; the image has been "quantized"—something you do not notice if you view the photo from afar.

Planck was struggling with the problem of black-body radiation. What is black-body radiation? Take a material object—a metal bar will do—and put it into a dark, light-tight room. The metal bar is the black body; that is, you cannot see it. If you heat the bar on a fire to a high temperature and return it to the dark room, it ceases to be black, instead glowing a dark red like a burning coal in a campfire. If you heat it to a still-higher temperature, the metal glows white hot. The light coming from the hot metal in a dark room has a distribution of colors which can be measured, resulting in what is called the black-body radiation curve.

Two teams of experimental physicists at the Physikalisch-Technische Reichsanstalt in Berlin made precise measurements of the black-body radiation curve. After fitting their empirical curve using ideas from the theory of heat, Planck tried to understand the physical basis for the new radiation law. Then with an incredible leap of intuition, Planck made the quantum hypothesis, which in his own words he described as "an act of sheer desperation." He supposed that the material of the black body consisted of "vibrating oscillators" (actually those were the atoms out of which the black body is made) whose energy exchange with the black-body radiation was quantized. Energy exchange was not continuous but discrete. Completely without precedent, this idea was one of the great leaps of the rational imagination, and Planck spent the remainder of his long life attempting to reconcile his radiation law with the continuous picture of nature.

Planck specified the amount of discreteness by a number h, later called Planck's constant. It specified, if you like, the size of a single grain in the pile of wheat. If Planck's constant could be set to zero, the grain reduced to zero size, then the continuous nature of the world would reappear. The experimental fact that Planck's constant h is not zero came to mean the world is in fact discrete. Planck, with the aid of his quantum hypothesis and some guesses, deduced the experimentally observed black-body radiation law. The Berlin experimentalists, in their report to the Prussian Academy on October 25, 1900, said the "formula, given by Herr M. Planck after our experiments had already been concluded . . . reproduces our observations within the limits of error." This was the beginning of the quantum theory. Einstein was twenty-one.

The world of theoretical physics that Einstein entered was dominated by the deterministic world view inspired by Newton's mechanics. Planck's work on the quantum broke with the idea of the continuum in nature, which was one of the main reasons for its neglect by physicists. Some puzzling experiments existed, but most physicists did not wish to give up Newton's laws to explain them. Scientific opinion was divided on the existence of atoms.

In 1905, the year he received his doctorate in Zurich, Einstein published three papers in volume 17 of *Annalen der Physik,* altering the course of scientific history. The volume is now a collector's item. Each of the three papers is a scientific masterpiece reflecting one of Einstein's three major interests: statistical mechanics, the quantum theory, and relativity. These papers began the physics revolution of the twentieth century. It would be decades before a new consensus on the nature of physical reality could be formed.

The first paper was on statistical mechanics, a theory of gases invented by James Clerk Maxwell, the Austrian physicist Ludwig Boltzmann and the American, J. Willard Gibbs. According to statistical mechanics, a gas like air consists of lots of molecules or atoms bouncing off each other in rapid random motion like a room filled with flying tennis balls. The tennis balls hit the walls, each other, and anything in the room. This model imitates the properties of a gas. But the atomic hypothesis that a gas actually consists of tiny atoms and molecules too small to see all flying around seems to be incapable of direct test.

It is hard to appreciate the atomic hypothesis because atoms are so small and there are so many of them. For example, in your last breath it is almost certain that you have inhaled at least one atom from the dying breath of Julius Caesar as he lamented, "Et tu, Brute." That is scientific trivia. But the fact is that a human breath contains about one million billion billion (10^{24}) atoms. Even if they mix with the entire atmosphere of the earth, the chances are high that you will inhale one of them.

We can't see or touch atoms; they are not a perceivable part of our world. Yet much of physics is based on the existence of atoms. Richard Feynman, one of the inventors of quantum electrodynamics, once wrote that if all of scientific knowledge were destroyed in some cataclysm except for one sentence which would be passed on to the future, it should be, ". . . all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another."

The problem Einstein addressed was how to prove the existence of atoms. How could he do that when atoms were too small to be seen? Suppose you put a basketball into the room full of flying tennis balls. The big basketball gets bombarded from all sides by the tennis balls, and it begins to move in a random way. Assuming the randomness of the bombardment by the tennis balls, the features of the movements of the basketball can be determined. It jumps and bounces around because of the balls hitting it.

Einstein's paper made use of a similar idea to furnish the first convincing proof of the existence of atoms. He recognized that if you put into a gas or liquid relatively large grains of pollen—which could be seen under a powerful microscope—you could see them move around. The English botanist Robert Brown had observed this movement of pollen grains long before Einstein wrote his paper, but he had no explanation for his observation. Einstein explained that this Brownian movement of the pollen grains is due to atoms hitting the grains. The pollen grains are so small they get bounced and jiggled by the atoms hitting them just as would be a basketball being hit by tennis balls. Perrin, the French experimentalist, did some remarkable experiments that confirmed Einstein's quantitative predictions for the motion of the pollen grains. Many physicists then accepted the atomic hypothesis. Ostwald, the chemist, who didn't believe in atoms for reasons of his own, was converted to atomism by Einstein's analysis and Perrin's experiments. Ernst Mach, the strict positivist, was, however, never convinced of the existence of atoms, maintaining his "incorruptible skepticism" to his death. Physicists today recognize the paper of the patent examiner Einstein as proposing the first convincing test for the existence of atoms. That single paper alone would have made his scientific reputation.

The second bombshell paper of 1905 was Einstein's paper on the photoelectric effect. If a beam of light shines on a metal surface, electrically charged particles, electrons, are emitted by the metal, causing an electric current to flow. This is the photoelectric effect—light produces an electric current. The photoelectric effect is used in automatic elevator doors. A beam of light crossing the elevator door hits a metal surface, causing an electric current to flow. If the current flows, the door will close. But if the beam of light is interrupted by a person walking through the door, the current stops and the door stays open.

In 1905, little was known about the photoelectric effect. It is characteristic of Einstein's genius that he was able to see in this obscure physical effect a deep clue about the nature of light and physical reality. The creative movement in science moves from the specific—like the photoelectric effect—to the general—the nature of light. In a grain of sand one may see the universe.

Einstein, in his paper on the photoelectric effect, used Planck's quantum hypothesis. He went beyond Planck to make the radical assumption that light itself was quantized into particles. Most physicists, including Planck, thought that light was a wavelike phenomenon in accord with the view of nature as a continuum. Einstein's hypothesis implied that actually light was a rain of particles consisting of the light quanta later called photons—little packets of definite energy. Using his idea of light quanta, Einstein deduced an equation to describe the photoelectric effect.

Of the three 1905 papers, Einstein referred only to the paper on the photoelectric effect as "truly revolutionary," and indeed it was. One thing physicists had thought they understood was light; they understood it as a continuous electromagnetic wave. Einstein's work seemed to deny this, to claim instead that light was a particle. This is one reason why other physicists resisted his revolutionary idea. Another reason was that, unlike Planck's formula for black-body radiation, which was immediately checked experimentally, there was simply no way to confirm Einstein's photoelectric equation experimentally—and there wouldn't be until 1915. His introduction of the light quantum seemed gratuitous.

Einstein stood alone for more than a decade on the question of energy quantization of light. When he was recommended for membership in the Prussian Academy of Sciences in 1913, the letter read, "In sum, one can hardly say that there is not one among the great problems, in which modern physics is so rich, to which Einstein has not made a remarkable contribution. That he may have missed the target in his speculations, as, for example, in his hypothesis of the light quanta, cannot really be held too much against him, for it is not possible to introduce really new ideas even in the exact sciences without taking a risk." Millikan, the American experimentalist, spent years working on the photoelectric effect, devising precise measurements to test Einstein's photoelectric equation. In 1915 he said, "Despite . . . the apparent complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it." Einstein held to it. But it was clear that even after his photoelectric equation was experimentally confirmed, other physicists resisted the idea that light is a particle. The "truly revolutionary" idea of the photon, the light particle, needed further experimental confirmation before it could be accepted.

The final confirmation of the photon came in 1923–24. Assuming that light consisted of true particles that had a definite energy and directed momentum like little bullets, Compton, one of the first American atomic physicists, and Debye, a Dutch physicist, independently made theoretical predictions for the scattering of photons from another particle, the electron. Compton performed the scattering experiments, and the predictions based on the light particle assumption were confirmed. Opposition to the photon concept fell rapidly after that. Einstein's Nobel Prize was for his light quantum hypothesis, not for his greatest work, the relativity theory.

Einstein's third 1905 article was on the special theory of relativity. This article changed forever the way we think about space and time. Max Planck said in 1910 of this paper, "If [it] . . . should prove to be correct, as I expect it will, he will be considered the Copernicus of the twentieth century." Planck was right.

The special theory of relativity—as the topic of his 1905 paper was later called—dealt with space and time concepts that philosophers and scientists had devoted much thought to over the ages. Some thought that space was a substance—the ether—which pervaded everything. Others evoked images of the flow of time like a river or sand falling in an hourglass. While such images appeal to our feelings, they have little to do with the concept of time in physics. Understanding space and time in physics requires that we distinguish our subjective experience of space and time from what we can actually measure about them. Einstein said it very simply: Space is what we measure with a measuring rod and time is what we measure with a clock. The clarity of these definitions reveals a mind intent on great purpose.

Armed with these definitions, Einstein asked how the measurement of space and time changes between two observers moving at a constant velocity relative to one another. Suppose one observer is riding on a moving train with his measuring rod and clock and his friend is on the station platform with his rod and clock. The person on the train measures the length of the window on the side of his car. Likewise, the person on the platform measures the length of the same window as it moves by. How do the measurements of the two observers compare? Naively, we would think they must agree—after all, it is the same window that is being measured. But this is incorrect, as Einstein showed by a careful analysis of the measurement process. The person standing on the platform with his measuring rod must "see" the window moving past him. In other words, light which bears information about the length of the moving window must be transmitted to the person standing on the platform, otherwise it can't be measured at all. The properties of light have entered our comparison of the two measurements, and we must first examine what light does.

Even before Einstein, physicists knew the speed of light was finite but very fast, about 180,000 miles per second. But Einstein thought there was something special about the speed of light—that the speed of light is an absolute constant. No matter how fast you move, the speed of light is always the same—you can never catch up to a light ray. To appreciate how odd this really is, imagine that a gun fires a bullet at some high speed. But the speed of a bullet is not an absolute constant, so that if we take off after the bullet in a rocket we can catch up to it and it appears to be at rest. There is no absolute meaning to the speed of the bullet because it is always relative to our speed. But not so with light; its speed is absolute—always the same, completely independent of our own velocity. That is the odd property of light that makes its speed qualitatively different from the speed of anything else.

The assumption of the absolute constancy of the speed of light was the second postulate of the special theory of relativity. The first postulate Einstein made was that it is impossible to determine absolute uniform motion. Uniform motion proceeds in a fixed direction at a constant speed—basically coasting. Einstein's postulate is that you cannot determine if you are coasting unless you compare your motion relative to another object. The two observers, one on the train, the other on the platform, illustrate this postulate. For the person on the platform it is the train that is moving. But the person in the train can just as well suppose he is standing still and the platform and the whole earth with it are moving past him. Uniform motion is only relative—you can only say you are moving relative to something else.

From these two postulates, the constancy of the speed of light and the relativity of motion, the entire logical structure of special relativity followed. But, as Paul Ehrenfest, a physicist and a friend of Einstein's, emphasized, there is implicit a third postulate which states that the first two are not in contradiction. Superficially, it seems that they are. All uniform motions are relative to one another, says one postulate. Except the motion of light, which is absolute, says the other postulate. It is the interplay between the relativity of motion for all material objects and the absoluteness of the speed of light which is at the root of all the unfamiliar features of the world according to special relativity.

Using these postulates, Einstein mathematically deduced the laws that related space and time measurements made by one observer to the same measurements made by another observer moving uniformly relative to the first. He showed that the person on the platform would actually find the length of the window on the moving train is shorter than the person on the train. As the train speeds up, the length of the window would be measured to be shorter and shorter by the person on the platform, until, as the imaginary train approached the speed of light, the length of the window would shrink to zero. Because in our familiar world the speed of most objects, like real trains, is so small compared to the speed of light, we never see such length contractions, which become dramatic only at speeds near that of light.

Einstein's theory of relativity linked space and time. Einstein showed that a moving clock marked time more slowly than one at rest. For the person on the platform, the watch on the wrist of the train's passenger actually moves more slowly—time slows down. If the train was moving near light velocity, time changes would actually slow down to close to zero. Likewise, the person on the train will see the watch of the person on the platform move more slowly. Absolute time is abolished. Time is measured differently for persons moving relative to one another.

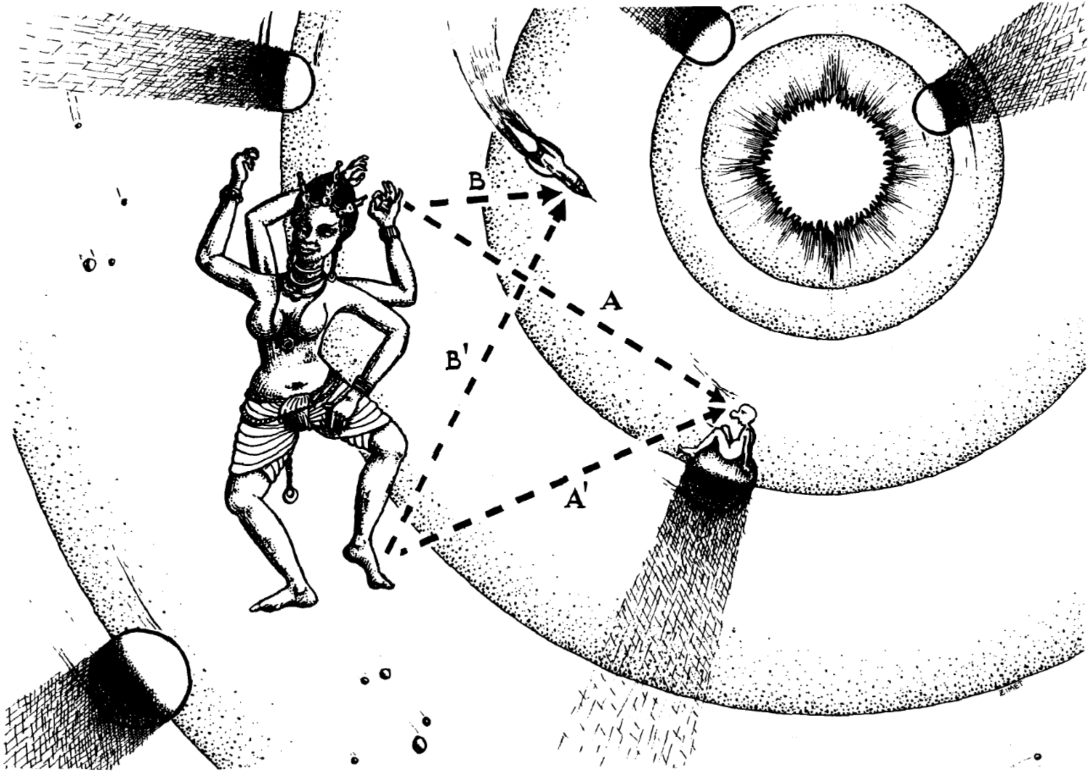
It seems as if the relativity of time poses a paradox—for how can both the passenger on the train and the person on the platform *both* see each other's watches slow down? What happens if now these people meet and compare the time; whose watch has really slowed down? To emphasize this paradox (often called the twin paradox), imagine twins who each set their watches before one of them gets on the train. The train speeds up to nearly the speed of light—at which point each twin will see the other's watch running slower—and then the train slows down and returns to the station. Which twin is older? From the point of view of the twin on the platform, the one on the train has made a round-trip journey, while for the twin on the train, the twin on the platform is the one who has made the round trip. It seems as if the motion of each twin is simply relative to the other's motion. But there is in fact an asymmetry in the motion of the twins, and that is the clue for resolving the paradox. While the train is speeding up it is no longer in uniform motion but is accelerating, and later in the trip it is decelerating. The twin on the platform never experiences such acceleration and deceleration so there is an absolute distinction between the twins' motion. Einstein's special theory of relativity applies only to uniform motions, and the motion of the train is not always uniform. By using Einstein's general theory of relativity, which applies to nonuniform motions like that of the train, one can demonstrate that the twin on the train has actually aged less.

The relativity of space and time disturbs us because it contradicts our intuition. In everyday experience, space and time do not appear to shrink. We might want to think that these odd effects of space and time are merely a mathematical fiction. The French mathematician Poincaré independently discovered the same space-time transformation laws in 1905, but he thought of them as postulates, without physical significance. Einstein was the first to understand the physical implications of those laws; for this reason he is considered the inventor of relativity. He took the physics seriously: clocks really slow down when they move.

One way you might experience the space-time of special relativity, not conceptually but physically, is to imagine you are eleven million miles tall. It takes light about a minute to travel eleven million miles. If you decide to wriggle your toes—assuming nerve impulses could be speeded up to light speed—it would take a minute for the signal to get to your toes and still another minute to return to tell your brain the toes have indeed wriggled. You would feel as if you were in a slow-motion picture with a body made of elastic rubber. If you started walking, the upper part of your leg would move up long before the foot would lift, because the nerve impulses would get there first and to the foot only a half-minute later. Because the speed of light is finite, you could not lift your leg all at once in a coordinated manner—you would simply be unable to signal your foot, knee, and thigh to move together simultaneously. No signal moves faster than light; nothing moves instantaneously.

Or imagine two ordinary-sized people, one on earth, and the other on a spaceship moving at nearly the speed of light. Both have front-row seats to watch a performance of an eleven-million-mile-tall dancer who moves across the solar system as if it were a stage. It is a marvelous performance; and later they discuss it but cannot agree on what they saw. The viewer on the spaceship says the dancer first moved her arm and then her foot, but the viewer on earth saw these events in reverse order. Even if they try to analyze the motion of the dancer taking into account the finite speed of light and the motion of the spaceship and the earth, they cannot agree. The reason is that the second postulate of special relativity—that the speed of light is an absolute constant—denies the existence of a universal time for all observers. Even the order of events in time can be different for observers moving relative to one another; there is no absolute meaning to such time orderings. The consequences of special relativity seem paradoxical compared to our everyday experience. The unfamiliar world of special relativity becomes apparent only when speeds approach that of light; the speeds we encounter in everyday life are not near that. But special relativity is a logically consistent and coherent theory; there are no paradoxes.

Einstein wrote a final, fourth short paper in 1905, the full consequences of which were not developed until 1907. By an analysis of the energy of motion E, of a relativistic particle of mass m, he



An 11-million-mile tall dancer moves across the solar system and is viewed from the earth and from a spaceship moving at nearly light velocity relative to the earth. The observers on earth and on the spaceship cannot agree whether the dancer first moved her hand or her foot. Even after taking into account their relative motion and the finite speed of light they cannot agree which event “really” took place first. Unlike the Newtonian concept of time there is no universal time according to special relativity theory.

showed that the particle had an energy given by $E = mc^2$. The constant c is the speed of light.

Before Einstein, physicists thought of energy and mass as distinct. This seems evident from our experience. What does the energy we expend by lifting a stone have to do with the mass of the stone? Mass conveys the impression of a material presence, while energy does not.

Mass and energy were also quantities that seemed to be separately conserved. In the nineteenth century, physicists discovered the law of conservation of energy—it can neither be created nor destroyed. If you lift a stone, energy has been expended but not lost. The stone has potential energy that is released if the stone is dropped. There was also a separate conservation law for mass—mass could neither be created nor destroyed. If a stone is broken up, the pieces have the same total mass as the original stone. The distinction of energy and mass and their separate conservation was deeply embedded in the thinking of physicists in 1905, because it had enormous experimental support. With that background of thought, the novelty of Einstein's insight may be contrasted.

Einstein discovered that the postulates of relativity theory implied that the distinction between energy and mass and the notion of their separate conservation had to be abandoned. This shattering discovery is what is summarized in his equation $E = mc^2$. Mass and energy are simply different manifestations of the same thing. All the mass you see about you is a form of bound energy. If even a small part of this bound energy were ever released, the result would be a catastrophic explosion like that of a nuclear bomb. Of course, the matter around us is not about to convert itself into energy—it takes very special physical conditions to accomplish that. But at the beginning of time during the big bang that created the universe, mass and energy were freely converting into one another. Today energy and matter only appear distinct, and someday in the far future the matter we see about us may again be freely converting into energy.

How well tested is the theory of special relativity? Today there is a whole technology that depends on the correctness of the theory—practical devices that simply would not work if special relativity were wrong. The electron microscope is one such device. The focusing of the electron microscope takes into account effects of relativity theory. The principles of relativity theory are also incorporated into the design of klystrons, electronic tubes that supply microwave power to radar systems. Perhaps the best evidence that special relativity theory works is the operation of the huge particle accelerators that accelerate subatomic particles like electrons and protons nearly to light velocity. The two-mile-long electron accelerator near Stanford University in California accelerates electrons until their mass increases as predicted by relativity by a factor of forty thousand at the end of their two-mile journey.

One of the oddest predictions of relativity theory is the slowing down of moving clocks. Interestingly, this is one of the most precisely tested predictions of the theory. While we can't accelerate real clocks up to the speed of light, there does exist a tiny subatomic particle, the muon, that behaves just like a tiny clock. After a fraction of a second, the muon disintegrates into other particles. The time it takes the muon to disintegrate may be thought of as a single tick of this tiny clock. By comparing the lifetime of a muon at rest with one that is rapidly moving, we can know how much this tiny clock has slowed down. This was done at CERN, a nuclear laboratory near Geneva, Switzerland, by putting the rapidly moving muons into a storage ring and precisely measuring their lifetime. The observed increase in their lifetime was a precise confirmation of the slowing of moving clocks predicted by special relativity.

These and many other tests confirm the correctness of the early work of Einstein. The young Einstein was a bohemian and a rebel who identified himself with the highest and best in human thought. During his period of intense creativity from 1905 to 1925 he seemed to have a hotline to "the old One"—his term for the Creator or Intelligence of nature. His gift was an ability to go to the heart of the matter with simple and compelling arguments. Separate from the community of physicists but in touch with the perennial problems of his science, Einstein realized a new vision of the universe.

Einstein's papers of 1905 and Planck's paper of 1900 ushered in the physics of the twentieth century. They transformed the physics that went before. Planck's idea of the quantum, further developed by Einstein as a photon, the particle of light, implied that the continuous view of nature could not be maintained. Matter was shown to be composed of discrete atoms. The ideas of space and time held since the age of Newton were overthrown. Yet in spite of these advances, the idea of determinism—that every detail of the universe was subject to physical law—remained entrenched in Einstein and his entire generation of physicists. Nothing in these discoveries challenged determinism.

Einstein's great strength lay not in mathematical technique but in a depth of understanding and a steadfast commitment to principles. That commitment to the principles of classical physics and determinism now moved him from his work on special relativity toward his greatest work, the general theory of relativity.

2. Inventing General Relativity

But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.
—ALBERT EINSTEIN

RECOGNITION FOR EINSTEIN began with the papers of 1905—the test for the existence of atoms, the introduction of the photon as the particle of light, and the special theory of relativity. In the fall of 1909 he left his job in the patent office to accept a faculty position at the University of Zurich followed by positions at the German University in Prague and then at the Zurich Polytechnic. In 1913, Max Planck visited Einstein in Zurich and offered him the best position in Europe for a theoretical physicist, the directorship of the Institute of Physics at the Kaiser Wilhelm Institute in Berlin. Einstein accepted. He was also offered a chair at the Prussian Academy and a professorship at the University of Berlin. In spite of his resistance to returning to Germany and to the academic world he disliked, this position offered him the opportunity of working with the greatest physicists of his time, including Planck.

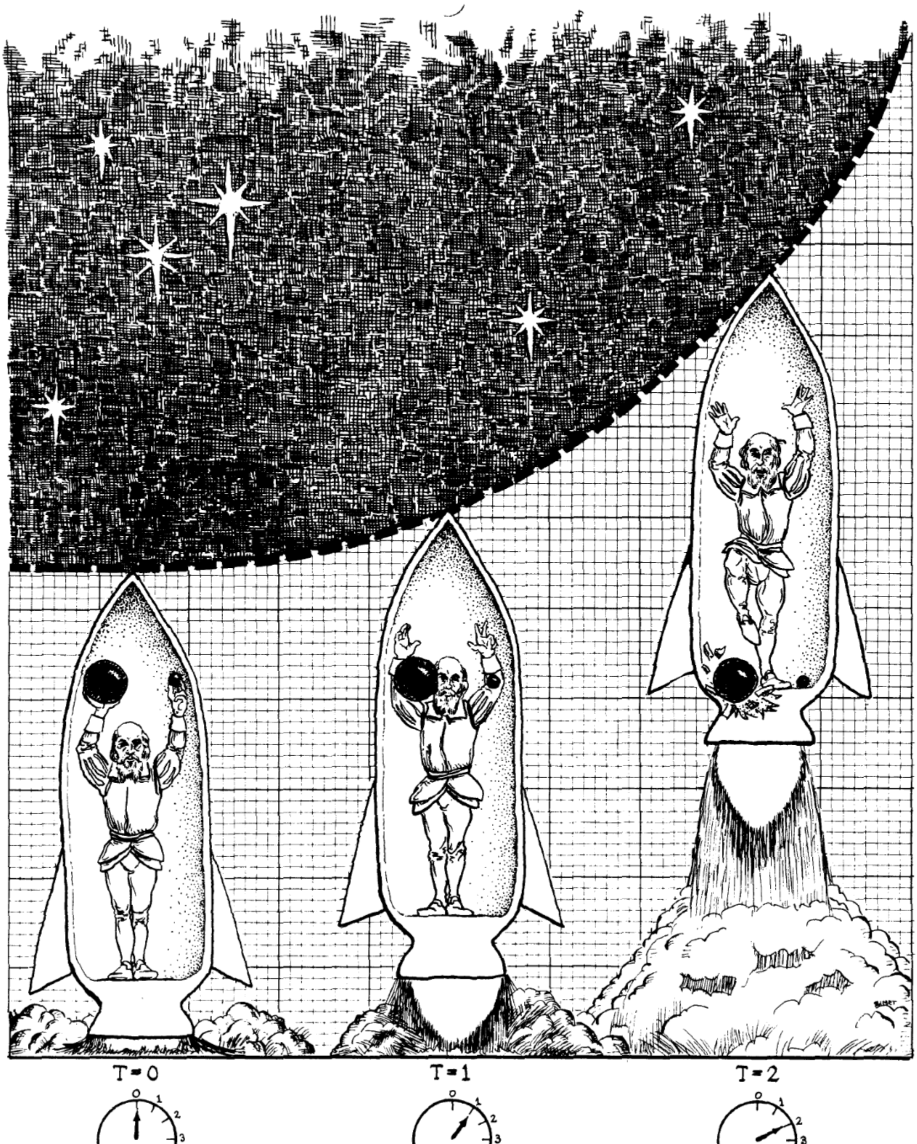
Associating with these physicists was one of the influential experiences of his life. In Berlin, Einstein contributed to the theory of specific heats and gave a new derivation of Planck's black body radiation law. In this latter work he used his new idea of light particles, photons, and introduced the concept of stimulated light emission, the principle on which the modern laser operates.

Einstein completed his greatest work—the general theory of relativity—in Berlin during 1915–1916. This theory extended the concepts of space and time already introduced in his earlier work. Previously, in the special theory of relativity, Einstein had discovered the laws relating space and time measurements between two uniformly moving observers (such as the person on the train and the one on the station platform). A uniform motion is one that proceeds at constant speed and fixed direction. By contrast, a nonuniform motion is one in which the speed is changing (the train accelerates or slows down) or changes direction (the train goes around a curve). But in order to treat such nonuniform motion Einstein realized that he had to go beyond the postulates of special relativity.

Suppose that instead of the train we used to illustrate special relativity we are in a spaceship far from the earth. When the rocket engines are turned on, the spaceship begins to move, slowly at first, then faster and faster. Since the speed is increasing, this is an acceleration—a nonuniform motion of the spaceship. Inside the spaceship we experience this acceleration as a force pressing us to the floor. As long as the rocket engines accelerate the ship we continue to feel the force.

Remarkably, this force, which we know is due to the accelerating spaceship, cannot be distinguished from gravity. If we drop stones of different masses inside the accelerating spaceship, they will fall to the floor at the same rate—just as they do if we drop them here on earth. The moment we release the stones, they cease to be accelerated by the spaceship—they are in free fall—and we may think it is the floor of the spaceship that rushes up to contact them.

This illustrates the first main idea of general relativity—that it is impossible to distinguish the effect of gravity from a nonuniform motion (like that of the accelerating spaceship). Inside the spaceship we feel real gravity. If we didn't know we were in outer space traveling in a spaceship, then we could not determine that the effect of "gravity" we feel was due to the accelerating movement of the entire ship. The fact that we cannot physically distin-



Galileo performs his legendary experiment, not from the leaning tower at Pisa, but inside an accelerating spaceship. He releases two objects of different mass which seem to him to be falling exactly as they would on earth. But notice that the two balls are in fact not accelerating—they are in "free fall" and are not subject to any external forces. It is the floor of the accelerating spaceship that rushes up to meet them. This illustrates the equivalence of accelerated motion and gravity—the first postulate of general relativity theory.

guish a nonuniform motion like an acceleration from gravity is called the principle of equivalence—the equivalence of nonuniform motion and gravity.

Einstein recorded the creative moment, "the happiest thought of my life," when he saw how all this fit together:

> When, in the year 1907, I was working on a summary essay concerning the special theory of relativity for the Yearbook for Radioactivity and Electronics, I tried to modify Newton's theory of gravitation in such a way that it would fit into the theory. Attempts in this direction showed the possibility of carrying out this enterprise, but they did not satisfy me because they had to be supported by hypotheses without physical basis. At that point there came to me the happiest thought of my life in the following form:
>
> Just as in the case where an electric field is produced by electromagnetic induction, the gravitational field similarly has a relative existence. *Thus, for an observer in free fall from the roof of a house there exists, during his fall, no gravitational field* [Einstein's italics], at least not in his immediate vicinity. If the observer releases any objects, they will remain relative to him in a state of rest, or in a state of uniform motion, independent of their particular chemical and physical nature. (In this consideration one must naturally neglect air resistance.) The observer is therefore justified in considering his state as one of "rest."
>
> The extraordinarily curious empirical law that all bodies in the same gravitational field fall with the same acceleration immediately took on, through this consideration, a deep physical meaning. For if there is even one thing which falls differently in a gravitational field than do the others, the observer would discern by means of it that he is falling in it. But if such a thing does not exist—as experience has confirmed with great precision—the observer lacks any objective ground to consider himself as falling in a gravitational field. Rather, he has the right to consider his state as that of rest and his surroundings (with respect to gravitation) as field-free.
>
> The fact, known from experience, that acceleration in free fall is independent of the material is therefore a mighty argument that the postulate of relativity is to be extended to coor-

> dinate systems that are moving nonuniformly relative to one another.

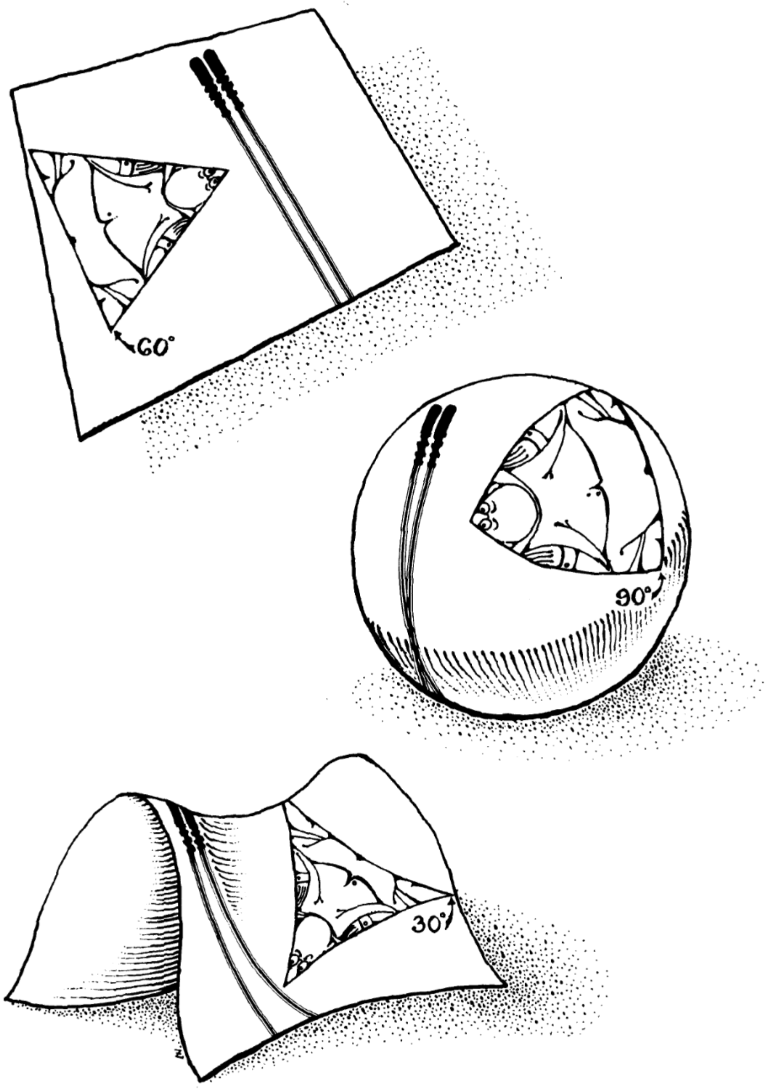
Einstein grasped that the effect of gravity was equivalent to a nonuniform motion. Standing on the earth, we feel gravity pulling us to the ground. If we drop a stone, it falls. But if we fall from the roof of a house, there is no gravity. If we now drop a stone during our fall from the roof, it floats in front of us. It is like being in a spaceship that is not accelerating—we are in free fall and there is no gravity. Astronauts experience a gravity-free environment when the rocket engines are shut off and acceleration ceases.

If we fall or drop a stone in our room on board the accelerating spacecraft, we may perceive that it is the floor that is accelerating up. On the earth it is not obvious that the effect of gravity we experience is equivalent to the ground accelerating up. But it is —gravity is precisely equivalent to nonuniform motion.

In the general theory of relativity, Einstein found the laws relating space and time measurements carried out by two observers moving nonuniformly (one observer in an accelerating spaceship, for instance, and the other floating in gravity-free space). Considering these laws took Einstein into the mathematical discipline of Riemannian geometry—the geometry of curved space. Here Einstein solicited the help of a mathematician friend and former classmate, Marcel Grossman. However, even before Einstein undertook these mathematical investigations to generalize the relativity principle, he already intuited the result. As he remarked, "I first learned of the work of Riemann at a time when the basic principle of the general theory of relativity had already been clearly conceived." The creation of general relativity offers an example of a physicist turning to an existing mathematical discipline to find the right language to express his intuitions.

Why did Einstein need to consider curved space to describe gravity? The curvature of three-dimensional space (four dimensions if we include time) is hard for our minds to grasp. Let us first imagine a space that has only two dimensions, like a tremendous sheet of paper extending infinitely in all directions. The inhabitants of this sheet of paper are flat shadows—they have only two dimensions—and don't know anything about the third dimension. On their sheet of paper they can carry out geometrical measurements. The world they live in has Euclidean geometry—it is flat. If they measure the sum of the angles on the interior of a triangle drawn on the paper they would get 180°, in accord with a theorem of Euclidean geometry. Two parallel lines drawn on this paper would never meet if extended—another feature of flat space.

Now we move our two-dimensional shadow creatures to a new world, the surface of a large sphere. While we, as three-dimensional creatures, can see their sphere as a three-dimensional object in space, the shadow creatures can know only the surface of the sphere—a two-dimensional space similar to the sheet of paper they just left. What is interesting is how our shadow friends come to learn of the difference between the two-dimensional surface of the sphere and that of the sheet of paper. At first, the shadow creatures are quite happy in this new world because it seems so similar to the world they left. If they draw small triangles and measure the angles on the inside as best they can, the angles add up to 180°. Locally their new world is Euclidean and flat. Then the shadow creatures make a technological breakthrough—they discover a kind of laser light that can send out a straight-line beam along the spherical surface of their world for thousands of miles. The first thing they notice is that if two beams of light are sent out in parallel directions, they start coming together after traveling a thousand miles. No amount of adjustment corrects for this. Some shadow creatures argue that light beams don't move in straight lines in the new world. Others insist that a light beam is by definition a straight line: A light beam continues to travel along the shortest path; any other path will be longer. They realize there is nothing wrong with the light beam—rather, the space they move in is curved and not flat. If big triangles are made with these light beams the sum of the angles is now larger than 180°. Clearly, the space is not Euclidean. Eventually the shadow crea-



A two-dimensional scientist explores three different two-dimensional geometrical surfaces. At the top is the open, flat Euclidean geometry for which the sum of the angles of a triangle is 180° and parallel laser beams never meet. In the middle is the closed surface of a sphere—a non-Euclidean space—and the angles can add to more than 180° and "parallel" laser beams must cross. At the bottom is the open, hyperbolic surface geometry, also a non-Euclidean space, for which the angles of a triangle are less than 180° and "parallel" laser beams diverge. The space of our three-dimensional universe can be similarly classified as either flat, spherical, or hyperbolic. It is a difficult experimental problem, as not yet settled, to determine which of these three geometries is actually realized for our universe.

tures invent Riemannian geometry to describe their new curved world.

Our own story is like that of our shadow friends, except that it takes place in three, not two, dimensions of space. We may live in a world that is a curved three-dimensional space. Just as the shadow creatures could not visualize the curved two-dimensional surface of their new world, we cannot visualize a three-dimensional curved space. But, like them, we can use experiments with the laser beams to find out whether our three-dimensional world is in fact curved. Most physicists would bet that if you sent out two parallel laser light beams across intergalactic space they would not remain parallel. They would either diverge or come together. If they diverged, the universe is said to be "open"—space is curved but it goes on forever. If the light beams eventually converged, the universe is "closed"—the three-dimensional analogue of the surface of a sphere. Which of these possibilities corresponds to the real universe is for experimental astronomers to decide. In either case, the space of our universe is non-Euclidean; it is not flat. The geometry of that space is described by Riemannian geometry.

But what does this curvature of space have to do with gravity and nonuniform motions? Once we decide to define a straight line by the path of a light ray we can easily see this relation.

Because a light ray has energy, Einstein's mass-energy equivalence implies it has an effective mass. Everything massive is attracted by gravity. This means if we shoot a light beam near a planet the light path will bend a little toward that planet. We might be tempted to say that the bending of the light path means that light paths really aren't straight lines any more. We would be like those shadow creatures who could not accept that light beams weren't parallel any more and blamed it on the light itself. Actually, the curvature of space—the very geometry of their world—was responsible. Likewise, we could blame the bending of light around a planet on "gravity," a mysterious force. But Einstein saw that gravity was a superfluous concept—there isn't any "gravitational force." What actually happens is that the mass of a planet

—or any mass—curves the space near it, altering its geometry. Light always moves in a straight line—but a straight line as defined in a curved space. Einstein dispensed with the notion of gravity in favor of the geometry of curved space. In effect, he discovered that gravity *is* geometry. That is the central conclusion of general relativity.

We may summarize the main ideas of general relativity as follows. First, we recognize the equivalence principle—that gravity and a nonuniform motion are indistinguishable. Second, as a separate idea, we must recognize that determining the geometry of space is an experimental problem. By shooting laser light beams around we can map out the curved geometry of our space. These two ideas, the equivalence principle and the curvature of space, can be combined if we recognize that the path of light—which we use to determine the curved geometry of space—is subject to the influence of gravity. The nonuniform motion of a light beam—its bending in space—is equivalent to the effect of gravity in that region of space. But rather than thinking that a light path "bends" in the presence of "gravity," we should instead realize that "gravity" is really manifested as curved space and light beams are moving along the shortest path in that curved space. Gravity is the curvature of space.

Einstein in his article on general relativity theory derived a set of equations that specified the curved geometry of space—equivalent to gravity—produced by the presence of matter, like the sun or a planet. These equations precisely determine how space gets curved due to the presence of matter. The old idea—going back to Newton—was that matter, like the earth, produces a gravitational field that attracts other matter to it. This idea is now replaced by Einstein's idea that matter changes the geometry of space from flat to curved in its vicinity.

Einstein proposed three experimental tests for the general theory of relativity—that gravity is the curvature of space and time. These are: (1) a slight bending of light in the gravitational field of the sun, (2) a small shift in the orbit of the planet Mercury, and (3) clocks should run slower in a gravity field.

The first test of general relativity is the bending of light around the edge of the sun. Today scientists perform this experiment using radio interferometers, devices which can precisely measure the position of distant radio sources like certain galaxies and stars as they pass behind the sun. But when Einstein proposed this experiment in 1916, there were no radio telescopes. Arthur Eddington, a British astronomer and member of the Royal Society, heard of Einstein's new theory and wanted to check it by observing a total eclipse of the sun which was to take place on May 29, 1919, in the Southern hemisphere. With the First World War raging, there was no hope for the Royal Society to obtain scarce funds to outfit a solar expedition. But Eddington was a pacifist and an embarrassment to his government; he got his £5,000 probably to get him out of England. The eclipse was observed in Sobral, Brazil, and also at Principe, an island off the coast of West Africa.

During a total eclipse, the field of stars very near the eclipsed sun becomes visible in the darkness, and they can be photographed. The light from those distant stars behind the sun is on a path passing very close to the edge of the sun and hence, according to Einstein, ought to bend in the curved space around the sun. This bending can be revealed if this photograph is compared with a second photograph of the same group of stars taken at night six months later when the sun is not near the light path of the stars. The comparison shows there is a shift in the relative positions of the stars in the two photographs caused by the bending of light in the curved space-time around the sun. In 1919 the Royal Society announced the result that the positions of stars seen during the eclipse both at Sobral and Principe agreed with Einstein's prediction. After two hundred years, Newton's law of gravitation was overthrown, and Einstein's public notoriety began.

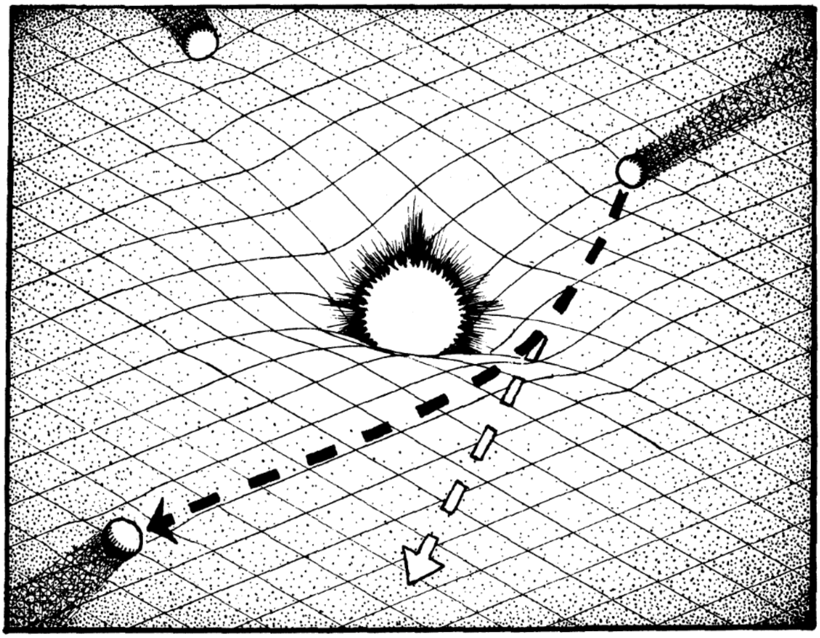
It was not easy for the Royal Society to get the results of this crucial experiment to Einstein in Berlin, because the First World War was just over. The telegram, sent from London, first reached the physicist Hendrik Lorentz, in Holland, which was a neutral country. Lorentz sent it on to Einstein in Berlin. A student of

Einstein's was in his office, and Einstein interrupted his discussion with her to hand her the telegram from the windowsill with the words, "This may interest you." When she read the statement that the British solar expedition had confirmed Einstein's theory, she exclaimed that this was a very important message. But Einstein was not excited and said, "I knew that the theory was correct. Did you doubt it?" The student protested; what would Einstein have thought if the result of the experiment had not confirmed his theory of general relativity? Einstein responded, "Then I would have to be sorry for dear God. The theory is correct." The hotline to "the old One" was still open.

This classic test of relativity was done long ago. But only in the last decade have a number of new tests been devised that very precisely test general relativity. The technology simply didn't exist ten years ago.

Irwin Shapiro and his collaborators at MIT have devised a beautiful test of general relativity. Using a powerful radar beam and computer signal processors, they bounce radar off a planet such as Mercury or Venus just before it is eclipsed by passing behind the sun as seen from the earth. When the planet is eclipsed, no radar beam returns, but just before eclipse it is possible to measure the amount of time it takes for the radar signal (which is the same as a light beam) to leave the earth, reflect from the distant planet, and return to earth. According to general relativity, a light beam has to bend slightly as it passes very near the edge of the sun because of the space curvature. This increases the round-trip time for the light beam over what it would be if the beam did not graze the edge of the sun. As the planet approaches the edge of the sun as seen from earth, it takes a longer time for the radar signal to return, and general relativity has a precise prediction for this delay. Within small experimental errors the prediction is confirmed.

The advent of satellite technology and the exploration of the solar system by unmanned space probes opened new ways of testing general relativity. There is now an orbiter around the planet Mars that sends signals to the earth. Just as the orbiter and



A schematic representation of the curvature of space around the sun. If a radar beam is reflected off a planet passing behind the sun as viewed from the earth, then the beam has to bend, causing a signal delay compared to what it would be if the beam did not pass near the sun. The different paths are indicated by the curved and straight dotted lines. The measured time delay between the curved and straight paths agrees with the general theory of relativity.

Mars are about to pass behind the sun from the viewpoint of the earth, the signals take longer and longer to reach earth because of the space curvature near the sun. Scientists can precisely measure the effective signal delays, and these, too, confirm Einstein's theory.

Perhaps the most dramatic confirmation of the bending of light was the discovery of a gravitational lens in 1979. Because mass causes space to curve in its vicinity, light paths bend near a large mass much as they do in an ordinary glass lens to achieve a focusing or distorting effect. Einstein predicted the gravitational lens effect in 1937. He showed that if a large mass acting like a lens existed on the line of sight between us and a still more distant light source, then we would see a double image of the distant source. Dennis Walsh, Robert Carswell, and Ray J. Weymann in 1979 noticed that one quasar—an extremely distant source of radio and light signals—actually appeared double when viewed by a powerful telescope. The best explanation for this double image of the quasar is that an entire galaxy, lying on the line of sight between us and the quasar, is producing the gravitational lens.

A second test of general relativity is a small shift in the orbit of the planet Mercury called the advance of the perihelion, discovered by the French astronomer Urbain Jean Joseph Le Verrier in 1859. The perihelion is the point of nearest approach to the sun in the elliptical orbit of a planet, and its advance refers to the amount that this point may move around the sun in a given time period. When Le Verrier calculated the influence of all the other planets on the advance of the perihelion of Mercury using Newton's law of gravity, he found about a 1 percent discrepancy between his theoretical calculations and the astronomical observations. Fortunately, he did not disregard this tiny discrepancy and published the result. Other scientists first attempted to discount this discrepancy from Newton's law, arguing that dust around the sun or the possibility that the sun was not perfectly round was responsible. But the dust was never seen and the sun was round. Einstein's general theory of relativity predicted small differences from Newton's law of gravity and gave a number of 43 seconds of arc per century—precisely the discrepancy Le Verrier had found! Today powerful radars can discriminate the mountains from the valleys on the surface of the planet Mercury. Such radars precisely measure Mercury's orbit, and again the perihelion shift agrees with general relativity.

The third test of general relativity is that clocks should run slower in a gravitational field. The stronger the force of gravity is, the slower time flows. Einstein, after all, said that time is what a clock measures. If a clock slows down, so does time. We actually age more slowly in a gravity field than someone in a gravity-free environment. This remarkable effect of the slowing of clocks is very small; only extremely precise clocks can detect it. The most precise clocks that have been made are atomic clocks, more accurate than the ancient standard of the movement of the stars. If two synchronized atomic clocks are left side by side, they will differ by only a fraction of a second after billions of years. We can check how gravity slows these clocks by putting one of the atomic clocks into an orbital trajectory high above the earth where gravity is weaker and then returning it to earth and comparing its elapsed time against a clock on earth where the gravity is relatively stronger. The observed time difference between the two clocks agrees with general relativity. In another version of this experiment, one atomic clock is taken from the National Bureau of Standards in Washington, D.C., near sea level, and moved to Denver, Colorado. The clock rates differ because of the difference in the gravitational force between the two locations, and these again accord with general relativity. By a tiny amount, people in Denver actually age more rapidly than those in Washington, D. C.

The three original tests of general relativity proposed by Einstein have been beautifully confirmed using modern technology. But beyond these predictions, the theory offers further implications which physicists are now investigating.

The theory of general relativity implies the existence of gravity waves, undulations of the curvature of space that propagate at the speed of light across any distance. It would be exciting to detect actual gravity waves, but most of the means of generating gravity waves from catastrophic cosmic events like stars exploding or colliding will generate gravity waves too weak to detect here on earth. One potential source of gravity waves could be black holes consuming stars at the core of our galaxy. Maybe, in a few decades, if there are strong enough gravity waves, we will detect them.

Recently the astrophysicists Hulse and Taylor's analysis of a binary pulsar has suggested some indirect evidence for gravity waves. A pulsar is a star collapsed to enormous density. A thimbleful of pulsar matter would weigh several tons. A binary pulsar is a pulsar orbiting around an ordinary star. Although we can't see the pulsar with an optical telescope, by using a large radio telescope we can detect the radio signals which the pulsar emits. In the case of a binary pulsar, the pulsar swings behind its companion star periodically, an event which blocks its radio signal. By measuring how often the signal is blocked, it's possible to determine the time or period of each orbit of the pulsar around its companion. Astronomers observing one such binary pulsar have measured its period over a number of years and observe that it is slowing down. How can we account for this slowing down?

The binary pulsar may be a gigantic transmitter of gravity waves. As it transmits gravity waves out into space, it loses energy, and this loss of energy is revealed by the pulsar's slowing down its orbital period. Using general relativity, astrophysicists have calculated the energy lost from gravitational waves radiating into space, and this is in remarkable agreement with the observed slowing down. Although indirect, the slowing down of the binary pulsar could be the first evidence for gravity waves.

These and other tests of general relativity have confirmed Einstein's theory. The tests reveal small but important differences from Newton's theory. That is because the gravity fields in our solar system are all weak, and for a weak field Einstein's and Newton's theories differ by only a small amount. Strong gravitational fields, such as those produced by totally collapsed matter in the form of black holes, reveal exciting new features of general relativity. With the strong gravity effects associated with black holes and the origin and expansion of the universe, general relativity finally comes into its own with qualitatively different features from Newton's theory. Through such discoveries we realize that it takes a revolution in our thinking to discover the new laws of nature. These new laws may at first yield only small corrections to the old ones. But the new laws have qualitative implications that extend far beyond the old ideas, as Einstein's theory of general relativity extends far beyond Newton's old theory. If we are ever to understand the beginning and end of the universe, we must go beyond Newton's theory of gravity into Einstein's general relativity.

General relativity, with its emphasis on geometry, opens up a new vision of the nature of the universe, providing the basis for cosmology, the study of the entire universe. For millennia, people have wondered about the universe and its origin. Now a new mathematical tool—the general theory of relativity—is available to cast these questions into a new form and perhaps even to answer them.

Looking out on a clear night we see the heavens filled with stars. The feeling is that we are very small; we know that the universe is far larger than even the visible stars suggest. All the stars we see are part of the Milky Way—our home galaxy—and this is just one of billions of galaxies. How can we study such vastness? We can imagine that the universe is like a gas in which the particles are galaxies. For this simplifying case of a uniform gas of galaxies we can solve the equations of general relativity.

The Soviet physicist Alexander Friedmann was the first to find these solutions to Einstein's equations. In 1922 he found the surprising result that Einstein's theory of general relativity implied the universe could not be static—it had to be changing. The gas of galaxies had to expand or contract. It would be as if our shadow friends had discovered that not only were they living in a curved space, but also that the curvature was changing in time.

Friedmann showed that if the density of the gas of galaxies was below a critical value, the universe was open and would continue to expand forever—the galaxies would move farther and farther apart. If the density of the galaxies was above a critical value, the universe would be closed and would eventually contract.

It is like throwing a stone. If you throw it up fast enough, above a critical velocity (related to the total matter in the earth), it will never return to earth—like the open universe, it never returns. Below that critical velocity the stone always returns to earth—like a closed universe. The best evidence that astronomers have today suggests that we are below the critical density for galactic matter and the universe is open. But should more matter be discovered, the actual density would increase and then we could have a closed universe which would expand and then contract.

At first Einstein didn't believe Friedmann's calculations and thought he'd made a mistake. Like most physicists and astronomers of this time, Einstein thought the universe was static and existed from an eternity in the past to an eternity in the future. A dynamic, evolving universe seemed contrary to experience and a gratuitous novelty. Because he wanted a closed, static universe, Einstein even went so far as to alter his relativity equations, adding a "cosmological term" that allowed for a static solution. He later called this mutilation "the biggest blunder of my life." So it was Friedmann, not Einstein, who had discovered that general relativity required an expanding, moving universe. His dramatic prediction was made seven years before the great cosmological discovery of the American astronomer Edwin Hubble. From a detailed study of distant galaxies, Hubble concluded that the universe was indeed expanding like a gigantic explosion. The universe was evolving!

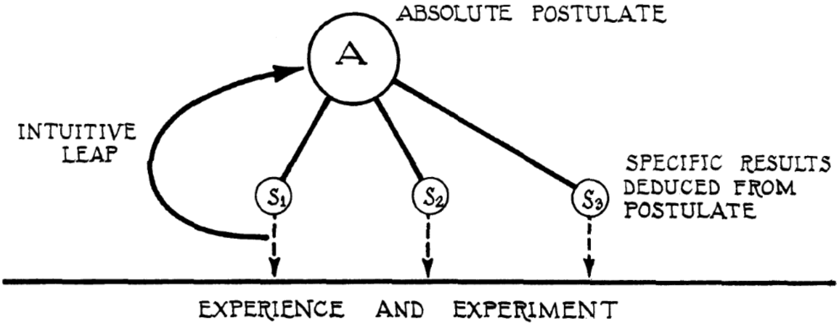
The general theory of relativity was Einstein's greatest accomplishment; it represented the fulfillment of the classical, deterministic world view. While Einstein went beyond the physics of Newton, bringing the ideas of space, time, and matter to their modern form, the framework of his physics was completely deterministic. The great clockwork of Newton's universe was altered by Einstein—the gears and parts were different—but Einstein agreed with Newton that the motion of the clock was still completely determined into the infinite past and future.

It is difficult to imagine that a single person created general relativity. The theory combines the ideas of space, time, energy, matter, and geometry into a coherent whole of enormous scope and implication. How did Einstein invent general relativity?

While he was in Zurich and during his first years in Berlin, Einstein fell under the intellectual influence of the philosopher-physicist Ernst Mach, a major advocate of positivism in physics. Mach taught that theoretical physicists should never use any idea in physics which cannot be given a precise, direct meaning through experimental operations. Ideas without connection to the empirical world were deemed superfluous to physical theory. Mach's method became a guiding force in the development of the new physics. Einstein was a master of this method. Recall his definitions of space and time: Space is what we measure with a measuring rod; time is what we measure with a clock. These definitions, with their direct appeal to measurement, cut through all the excess philosophical baggage that the ideas of space and time had carried for centuries. The positivist insists that we talk only about what we can know through direct operations like a measurement. Physical reality is defined by actual empirical operations, not by fantasies in our heads.

However, after he settled in Berlin, Einstein moved away from the position of strict positivism, and this was only partly due to persuasive arguments offered by his colleague, Planck. It was as much Einstein's own success with the general theory of relativity and the method of thought he used to arrive at it that convinced him of the limitations of the strict positivist method. If Einstein had remained a positivist, I doubt that he would have discovered general relativity. Einstein subsequently described his own method in a letter to the philosopher Maurice Solovine, a friend from his days in Bern at the patent office. This method might be called "Einstein's postulational method."

In his letter to Solovine, Einstein included a diagram which illustrated his method. The diagram is:



The scientist begins with the world of experience and experiments. On the basis of nothing more than physical intuition, he leaps from experience to abstracting an absolute postulate—just as Einstein realized that the equivalence principle implied gravity is geometry. Einstein made this conceptual leap far beyond where any experiment could check it and before he had any supporting evidence. How could there be such evidence? No physicist had even imagined the relation of gravity to geometry. The next step is to use the postulate to deduce specific theoretical results that can be experimentally checked. For general relativity, these results are the predictions such as the shift in the orbit of Mercury. Should an experiment falsify the theoretical results it also brings down the postulate on which they are based. This vulnerability of the absolute postulate to falsification is part of the positivist method.

But a strong antipositivist element central to Einstein's method is the intuitional leap from experience which sets up the absolute postulate in the first place. The theorist cannot rationally deduce the absolute postulate from experience, since it transcends experience. Only intuition, an inspired guess, can invent the postulate. This is what Einstein meant when he said, "For the creation of a theory, the mere collection of recorded phenomena never suffices—there must always be added a free invention of the human mind that attacks the heart of the matter." A great deal of creative work in physics proceeds by this method, which places intuition at the very first step, a nonrational but verifiable aspect of scientific creativity.

In the years following the First World War, Einstein's public fame rose and he became a world figure. The only other figure that I can think of who attracted such notice as a moral leader was Gandhi, and he was a statesman who courted public prominence as a means for leading India out of colonialism. Einstein never wanted to be a public figure—yet when it happened, he used his celebrity to promote causes he believed in. How does one account for this "Einstein phenomenon"?

There are several factors at work here. First was the emergence of the new media of radio and mass-circulation newspapers associated with the rise in literacy. Secondly, Europe was exhausted and devastated by the war; Germany especially had to salvage something from defeat. Popular attention turned to Einstein and his accomplishments, which seemed far removed from the political world and which reminded Germans of their great scientific culture. During the war, Einstein went his own way, apart as always. He was a pacifist at a time when that position was considered tantamount to treason. He was proud to be a Jew at a time when many German Jews were disguising their identity and assimilating. These were unpopular positions, but they established Einstein in the public eye as a man of principle at a time when men of principle were rare. Finally, that time in Europe was a period of ideological debate and conflict. In Russia, there was civil war, an aftermath of the Revolution of 1917. Everywhere fascism was on the rise. Social and religious philosophers sought support for their views in Einstein's new theories, which, it became clear, were the next step in the revelation of nature. Soviet physicists, led by V. Fock, found it necessary to defend relativity against charges of idealism and to point out that it was in strict accord with Lenin's materialism, the ideological basis for Soviet policy. Some scientists in England and America insisted that Einstein's relativity theory had nothing to do with moral or cultural relativism, a philosophy that maintained human moral values were relative to their social and cultural environment. This philosophy was then popular in the universities and was threatening to traditional religions. The astronomer Arthur Eddington, a Quaker himself, assured religious people there was still a place for God and Soul in the universe. In the face of these controversies, Einstein himself reiterated his cosmic philosophy already formulated when he was a teenager, that the universe was indifferent to mankind and its problems. But he asserted that moral questions were of utmost importance for human existence and that humanity must create a moral order for the sake of its survival.

Even as Einstein's eminence grew and his vision of the universe became part of public awareness, physics itself was moving ahead with enormous strides. In the 1920s, the quantum theory of atomic phenomena was created. Einstein rejected it not because it was wrong (it agreed with experiments) but because he felt it gave an incomplete description of physical reality and denied the objectivity and determinism of the world. His great debate with Niels Bohr began; but that is a story for another chapter. In the late 1920s and 1930s, a new generation of physicists emerged who accepted the new quantum theory and applied it with great success. The theory of the chemical bond was discovered; the new quantum theory explained the foundations of chemistry. The theories of solid-state matter, metals, electrical conductivity, and magnetization were developed out of the new quantum theory. Nuclear physics began.

Einstein had little to do with these developments. He was on the sidelines of physics after 1926. Einstein, in fact, thought that the new quantum theory was not radical enough. He thought the quantum theory might be a consequence of a unified field theory —a theory that combined electric, magnetic, and gravitational fields and went beyond general relativity. In 1938 he said, "I have now struggled with this basic problem of electricity for more than twenty years, and have become quite discouraged, though without being able to let go of it." Although he failed to unify electricity and gravity, he was one of the first physicists to emphasize the importance of seeking the unification of all forces in nature, a goal of physics on which great progress has occurred only recently. Of all his work, he felt that everything he had done would have been discovered without him except for general relativity. This was the crown of his creativity and of classical physics as a science. But the road to progress in physics, at least for the next half century, lay elsewhere.

My view is that after 1926, Einstein became involved in the mathematics of the unified field theory. For the rest of his life he could not resist the conceptual power and beauty of general relativity. The influence of this creation and the method of thought he used to arrive at it dominated all his subsequent thinking. He lost contact with "the old One" and the creative physical intuition he possessed for more than twenty years. The delicate balance between innocence and experience, prerequisite for creativity, tipped toward experience. As the physicist Paul Ehrenfest said when he heard of Einstein's opposition to the new quantum theory, "We have lost our leader."

Einstein held the classical view of determinism to the end of his life. For him, it was unthinkable that there was arbitrariness and chance in the fundamental structure of the universe. His vision of the cosmic code—the eternal laws of nature that govern all existence—left no room for chance or the intervention of human will and purpose. He felt that the quantum theory was superficial and that beyond the random play of atomic particles it described, we would find a new deterministic physics. While most other physicists are open to the possibility of revising the quantum theory, they do not believe that deterministic physics will ever return. Einstein, even as the leader of the physicists before 1926, was apart from them. After 1926, he was not only apart but also alone.

As a teenager I admired Einstein as a hero of science, a god in a distant pantheon of the intellect. Now through older eyes I see another side of him—his loneliness and emotional exile from capricious human feelings. He required that distance to forge the instruments of his immense genius, a genius which showed us a universe far greater and more bewildering than was previously imagined. His vision of the cosmos, stretching across the vast emptiness of space and time, indifferent to our humanity, now haunts us all. But I still wonder about the man that first saw this vision and look for clues to his character.

Einstein loved the music of Mozart. Both these men shared the sense of the ultimate vulnerability of all life but never lost their sense of play or a ready laugh. They knew that in this world the reality of life is that it need not be. Yet what we might learn from such men is that we too can celebrate our creative existence in the full awareness of its extinction. And that is the essence of irony.

With the rise of the tribal madness of National Socialism, Einstein left Germany on a forced emigration to the United States, a country he had already visited. Along with many other of the most brilliant European scientists, he brought to America a spirit of scientific inquiry centuries in the making. Talented Americans became willing students.

Einstein never felt at home in the United States. A product of the great German intellectual renaissance at the turn of the century, he did not adjust to the new ways. Once he remarked with his usual irony, "To the Jews I am a saint, to the Americans an exhibition piece, to my colleagues a mountebank."

Einstein knew that he had no choice in being born but his death could be his choice. Upon learning of his terminal illness, Einstein refused an operation. He died in Princeton, New Jersey, his American home, on April 18, 1955, attended by a nurse who could not understand his last words, which he spoke in German.

Michele Besso was Einstein's oldest friend from his days in the Bern patent office. They kept up a correspondence through fifty years. Einstein's unique acknowledgment in his 1905 paper on special relativity was for conversations with his friend Besso. What an honor! Einstein's friend died a month before he did, in Switzerland. Expressing his world view of absolute determinism, Einstein wrote movingly to Besso's son and sister, "Now he has departed from this strange world a little ahead of me. That means nothing. People like us, who believe in physics, know that the distinction between past, present, and future is only a stubbornly persistent illusion."

3. The First Quantum Physicists

By Zeus, Soddy, they'd have us out as alchemists!
—Ernest Rutherford

As a college freshman I had my first contact with the quantum theory by purchasing a copy of *Quantum Mechanics* by Leonard Schiff, who became my teacher in graduate school. I read his book and worked out the problems. Quantum mechanics was for me an exercise in solving differential equations. To my freshman's mind, unencumbered by any bias from the older, classical physics, the quantum theory presented no problems. It was simply an abstract mathematical description of atomic processes. I had no sense of the "quantum weirdness" of the atomic world; it was the earlier theory of special relativity, with its space contractions and time dilations, that seemed bizarre to me. But as I continued my study my reaction reversed—relativity seemed less bizarre and more in accord with common sense, while the quantum theory seemed more and more "weird." Pursuing the mathematics of the quantum theory, I felt pushed beyond common sense into unimagined areas. Later, I found out that my experience paralleled that of the physicists who first discovered the new quantum theory. First they discovered the mathematical equations of the quantum theory which worked experimentally; then they pondered the equations and their meaning for the real world, developing an interpretation which departed radically from naive realism. As I realized what the abstract mathematics of quantum theory was actually saying, the world became a very strange place indeed. I became uncomfortable. I would like to share that discomfort with you.

What is this quantum weirdness? The physics of the new quantum theory can be contrasted with the older Newtonian physics which it replaced. Newton's laws brought order to the visible world of ordinary objects and events like stones falling, the motion of the planets, the flow of rivers and the tides. The primary characteristics of the Newtonian world view were its determinism —the clockwork universe determined from the beginning to the end of time—and its objectivity—the assumption that stones and planets objectively exist even if we do not directly observe them; turn your back on them and they are still there.

In the quantum theory these common-sense interpretations of the world (like determinism and objectivity) cannot be maintained. Although the quantum world is rationally comprehensible, it cannot be visualized like the Newtonian world. And that is not just because the atomic and subatomic world of quanta is very small, but because the visual conventions we adopt from the world of ordinary objects do not apply to quantum objects. For example, we can visualize that a stone can be both at rest and at a precise place. But it is meaningless to speak of a quantum particle such as an electron resting at a point in space. Furthermore, electrons can materialize in places where Newton's laws say they can't be. Physicists and mathematicians have shown that thinking about quantum particles as ordinary objects is in conflict with experiment.

Not only does quantum theory deny the standard idea of objectivity but it also has destroyed the deterministic world view. According to the quantum theory, some events such as electrons jumping around atoms occur at random. There just isn't any physical law that will ever tell us when an electron is going to jump; the best we can do is to give the probability of a jump. The smallest wheels of the great clockwork, the atoms, do not obey deterministic laws.

The inventors of the quantum theory found yet another contrast with the Newtonian world view—the observer-created reality. They found that the quantum theory requires that what an observer decides to measure influences the measurement. What is actually going on in the quantum world depends on how we decide to observe it. The world just isn't "there" independent of our observing it; what is "there" depends in part on what we choose to see—reality is partially created by the observer.

These properties of the quantum world—its lack of objectivity, its indeterminacy, and the observer-created reality—which distinguish it from the ordinary world perceived by our senses I refer to as "quantum weirdness." Einstein resisted quantum weirdness, especially the notion of an observer-created reality. The fact that an observer was directly involved with the outcome of measurements clashed with his deterministic world view that nature was indifferent to human choices.

Something inside of us doesn't want to understand quantum reality. Intellectually we accept it because it is mathematically consistent and agrees brilliantly with experiment. Yet the mind is not able to rest. The way in which physicists and others have trouble grasping quantum reality reminds me of the way children respond when confronting a concept they do not yet grasp. Jean Piaget, the psychologist, studied this phenomenon in children. If a child of a certain age is shown a collection of transparent vessels all of very different shape filled with a liquid to the same level, the child thinks that all the vessels have the same amount of liquid. The child does not yet grasp that the amount of liquid has to do with volume, not just height. If the correct way of viewing the problem is explained to the child, the child will often understand it but immediately reverts back to the old way of thinking. Only after a specific age, around six or seven years, is the child able to grasp the relation between amount and volume. Coming to grips with quantum reality is like that. After you think you have grasped it and some picture of quantum reality forms in your mind, you immediately revert back to the old, classical way of thinking, just like the children in Piaget's experiment.

It is important to realize that the microworld of atoms, electrons, and elementary particles is not entirely unlike the classical world, the physical world of naive realism. A single atom can be isolated in a box; electrons and other particles leave tracks on photographic emulsions or in cloud chambers. We can push them around using electric and magnetic fields. Experimentalists can measure certain properties of these tiny objects, such as their mass, electric charge, spin, and magnetization. Physicists, like most people, think of microworld particles in just that way. They are just tiny little things. We can make particle beams of them or bounce them off each other and make them dance to our tune. Where is the quantum weirdness? What is so hard to grasp?

The quantum weirdness comes when you start to ask certain kinds of questions about atoms, electrons, and photons. And it comes only when you ask these special questions and set up experiments to try to answer them. For example, if you try to measure precisely both the position of an electron and its velocity by repeated measurements, you find it can't be done. Every time you measure its position the velocity changes, and vice versa—the electron has a kind of quantum slipperiness. If the electron were an ordinary object, you would be able to determine simultaneously both its position and its velocity. But the electron is a quantum particle, and the ordinary idea of objectivity fails. Until you start asking detailed questions about quantum particles, such as what is the precise position and velocity of a particle, you can live happily in a paradise of naive realism.

Once a person recognizes that the quantum weirdness of the microworld is unavoidable, he can take two attitudes. The first is to forget it and stick to the mathematics of quantum theory. In that way he will find the right answers and make progress in discovering the laws of the microworld. Most theoretical physicists, following the lead of Paul Dirac and Werner Heisenberg, who laid the mathematical foundations of the new quantum theory, take this attitude. The second attitude is the philosopher's approach, which tries to interpret the quantum weirdness of the microworld in terms of physical reality. They are interested in developing a conceptual picture of the quantum world that is intelligible as well as mathematically consistent. Niels Bohr founded that attitude for modern physics, and he had much to say about the interpretation of reality.

The story of the discovery of the quantum theory began with Max Planck's determination of the black-body radiation law, the giant first step in 1900. The main feature of the old quantum theory was that it represented attempts on the part of physicists to fit the idea of Planck's quantum—that there was a discrete element in nature—into classical Newtonian physics. In his work on black-body radiation, Max Planck introduced a new constant into physics, called h, which was a measure of the amount of discreteness in atomic processes. When Planck did his work, in 1900, physicists thought that atoms could have any value for their total energy—energy was a continuous variable. But Planck's quantum hypothesis implies that energy exchange was quantized. Although the introduction of a quantum of energy had no basis in classical physics, it was not yet clear that the new theory required a radical break with classical concepts. Theoretical physicists first tried to reconcile Planck's quantum hypothesis with classical physics.

Physicists are conservative revolutionaries. They do not give up tried and tested principles until experimental evidence—or an appeal to logical and conceptual simplicity—forces them into a new, sometimes revolutionary, viewpoint. Such conservatism is at the core of the critical structure of inquiry. Pseudoscientists lack that commitment to existing principles, preferring instead to introduce all sorts of ideas from the outside. Werner Heisenberg commented, "Modern theory did not arise from revolutionary ideas which have been, so to speak, introduced into the exact sciences from without. On the contrary, they have forced their way into research which was attempting consistently to carry out the program of classical physics—they arise out of its very nature." The old quantum theory represented a program to reconcile the quanta with classical physics.

Einstein took up Planck's idea in his 1905 paper on the photoelectric effect. Planck assumed the sources of light exchanged quantized energy. Einstein, going a step further, assumed that light was itself quantized—light consisted of particles called photons. This revolutionary idea broke with the then well-established wave theory of light—reason enough for most physicists to reject it. Other physicists resisted Einstein's proposal because it only explained the photoelectric effect, which was hardly direct evidence for the photon. But Einstein held firm to the notion of a wave-particle duality for light and attempted reconciling these apparently contradictory properties of light but without success.

The theoretical ideas of Planck and Einstein which advanced the quantum theory were a response to experiments which opened a whole new realm of natural phenomena. By the end of the nineteenth century a great number of puzzling new properties of matter were discovered; for the first time, scientists were making direct contact with atomic processes. Roentgen discovered the penetrating X-rays in 1895. Henri Becquerel discovered radioactivity in 1896, and the Curies isolated radium in 1898. In 1897, J. J. Thomson discovered the electron, a new elementary particle. A puzzling discovery was that under certain circumstances atoms emit spectral lines of light. If a substance is heated or if an electric current is passed through a gas of atoms, the substance or gas will emit light. If the spectrum of the light is analyzed by a prism that splits off the various colors, only definite colored lines appear in the spectrum. Neon colored lights offer one example. Each chemical element has a definite and unique set of colored lines, called its line spectrum. No one had any explanation for this phenomenon in the nineteenth century. Yet here lay the experimental clue to the structure of the atom.

Ernest Rutherford was already a famous experimentalist for his discovery of the radioactive transformation of elements with Frederick Soddy when he came to Manchester University. Rutherford and Soddy had found that chemical elements, previously thought to be immutable, changed in the process of radioactivity. Soddy suggested they should call the new process "radioactive transmutation." Transmutation of the elements, such as lead into gold, was an ancient alchemical dream already discredited by nineteenth-century chemists and physicists. Soddy's suggestion was met by Rutherford's sharp reply, "By Zeus, Soddy, they'd have us out as alchemists!" But in fact they had discovered transmutation of the elements.

At Manchester, Rutherford was studying alpha particles, stable positively charged helium nuclei that are emitted by radioactive substances. Rutherford, who did not have the patience to do long hours of counting scintillations on a screen that detected alpha-particle bombardment, unleashed a young assistant, Marsden, on an experiment. The experiment is beautiful for its simplicity. A radioactive source of alpha particles is placed near a metal foil (Marsden used gold foil). The alpha particles are projectiles, like little bullets being fired at the foil. Most of the alpha particles go straight through the foil and are detected on a screen. However, on a hunch, Rutherford asked Marsden to look for alpha particles that were strongly scattered by the foil and widely deflected. By placing the detecting screen away from the line of sight to the alpha source, Marsden found a few deflected alphas. He observed that some even scattered back toward the alpha source. It would be like firing bullets at a piece of tissue paper only to find some bullets bounced backward. This discovery initiated a series of experiments.

What caused some alpha particles to scatter backward from the gold foil? Rutherford knew the alpha particles were positively charged. In the gold foil these particles would sometimes pass close to the atomic nuclei, also positively charged. Since like charges repel each other, this caused the large deflections of some alpha particles off the atomic nuclei. By carefully studying these deflections, Rutherford determined the major features of atomic structure. A window on the microworld opened.

The idea of atoms, held by many people, was that they were without parts, completely elementary, the end of all material structure—a building block for the rest of matter. While a few theoretical physicists speculated about the possibility of atomic structure, there was no experimental support for such speculations. Rutherford's simple scattering experiment gave humankind its first glimpse into the structure of the atom.

The picture of the atom Rutherford announced in May 1911 was that most of the mass of the atom was concentrated in a tiny, positively charged core, later called the nucleus, while the negatively charged electrons, with very small mass, formed a large cloud about the nucleus, accounting for the size of the atom. The massive nucleus was ten thousand times smaller than the atom. Rutherford's atom was like a little solar system with the nucleus as the sun and the electrons as the planets and with electric forces instead of gravity binding the system together.

Although Rutherford's scattering experiments were compelling, from the standpoint of classical physics his planetary picture of the atom was completely unstable. According to classical physics, the electron in orbit about the nucleus should radiate away its energy in the form of electromagnetic waves and fall rapidly into the nucleus. Physicists knew that according to the laws of classical physics, Rutherford's atom ought to collapse. But there it was nevertheless. This unsatisfactory situation soon changed dramatically. Around 1912, Rutherford wrote from Manchester to his friend Boltwood, "Bohr, a Dane, has pulled out of Cambridge and turned up here to get some experience in radioactive work." Niels Bohr, a student of J. J. Thomson's at Cambridge, actually spent less than half a year at Manchester before returning to his native Copenhagen. However, in spite of his brief visit, Rutherford made an impact on the young Dane.

Bohr, challenged by the problem of atomic structure, took an imaginatively daring step: He simply dispensed with some of the rules of classical physics and instead applied the quantum theory of Planck and Einstein to the problem of atomic structure. Remarkably, the few features of the quantum theory already known at the time could solve the problem—as long as one did not worry about the conflict with classical physics. Bohr simply assumed that the electrons in orbit about the nucleus do not radiate light and that the light emitted by atoms is due to some other physics. He showed that Planck's idea of energy quantization implied that only specific orbits for the electrons are allowed. In order to ensure the stability of atoms, Bohr postulated a lowest orbit beyond which the orbiting electron could not fall. When an electron drops from a higher orbit to a lower one, thereby losing energy, the atom containing that electron emits light, which carries off the lost energy. Because only certain electron orbits are allowed, only certain jumps of the electron between orbits can take place, and consequently the energy of the emitted light is quantized. Since the energy of light is related to its color, only specific colors of light can be emitted by atoms. In this way Bohr's theoretical model of the atom accounts for the existence of the mysterious spectral lines. The experimentally observed fact that each different atom emitted light with unique and distinct colors revealed the quantum structure of atoms.

One way of imagining the energy levels of Bohr's atom is to think of a musical stringed instrument like a harp. Each string when plucked has a definite vibration or sound. Similarly, when an electron jumps orbits in an atom there results the emission of a light wave with a definite vibration or color. That is the origin of the discrete light spectrum.

Bohr applied his novel ideas to the simplest atom, hydrogen, which consists of a single proton with a single electron in orbit about it. The advantage of studying such a simple atom is that the allowed orbits of the electron could be precisely calculated and hence the spectrum of light from hydrogen determined. Bohr's calculations of the hydrogen light spectrum based on his theoretical model of the atom agreed adequately with the experimentally observed spectrum. Such agreement between theory and experiment could not be an accident. It meant that the combination of ideas Bohr took from the quantum theory really worked—the scientific imagination made its first successful step into the quantum structure of the atoms. The ancient capability of the human mind to comprehend a new environment, in this case the atomic structure of matter, was again powerfully reinforced.

Theoretical physicists seized Bohr's ideas and applied them to more complicated atoms. But Bohr's model, like every great scientific advance, raised many new questions—questions that couldn't be asked before. When does an electron change its orbit and cause light to be emitted from the atom? What causes a particular jump? What direction does the emitted light take off in, and why? These questions troubled Einstein. According to classical physics, the laws of motion precisely determine the future behavior of a physical system like an atom. But atoms emitting light seemed to behave spontaneously and undeterminedly. Atoms jump. But why and in what direction? The same spontaneity, Einstein realized, characterized radioactivity.

At first, physicists tried to fit the behavior of atoms into the framework of the classical theory of electromagnetism and made desperate attempts to answer the enigma of the quantum jumps without using light quanta. In 1924, Niels Bohr, Hendrick Kramers, and John Slater wrote an article advocating this approach at the expense of abandoning the laws of energy and momentum conservation at the level of the atom—a revolutionary proposal, because these laws are among the most well-tested physical laws. At the time of this proposal there had been no direct experimental evidence that these conservation laws worked for individual atomic processes. However, it soon came. Arthur H. Compton and A. W. Simon scattered individual photons, the light particles, from electrons. Using a Wilson cloud chamber, a device that displayed the tracks of individual electrons, they verified to a high degree of accuracy the conservation laws for individual atomic processes. For most physicists, these experiments done in 1925 vindicated Einstein's 1905 proposal of the light quantum.

Through a multitude of new atomic experiments such as Rutherford's and Compton's, the structure of the atom was revealed. These experiments forced theoretical physicists into a new and unfamiliar world; the usual rules of classical physics no longer seemed to work. In the atom the human mind was shown a new message—a new physics revealed in the structure of the atomic microworld. The world view of determinism, supported by centuries of experiment and physical theory, was about to fall.

Bohr accepted the results of the experiments of Compton and of Simon, both the correctness of the conservation laws and the existence of the light quantum or photon. He concluded, in July 1925, "One must be prepared for the fact that the required generalization of the classical electrodynamical theory demands a profound revolution in the concepts on which the description of nature has until now been founded." Bohr was ready for the revolution. It soon came. The first shot had already been fired on a small island in the North Sea.

4. Heisenberg on Helgoland

If God has made the world a perfect mechanism, He has at least conceded so much to our imperfect intellect that in order to predict little parts of it, we need not solve innumerable differential equations, but can use dice with fair success.
—MAX BORN

HELGOLAND IS A small island in the North Sea, not far from the North German industrial city of Hamburg, with high red cliffs and fresh sea breezes. It was here that Werner Heisenberg invented matrix mechanics—the first step of the new quantum theory. Heisenberg belonged to a new generation of physicists who came out of the First World War with a different outlook, which included a distrust of the previous generation. He was among the many German students who set out to find something of value, something uncorrupted by the recent past. His father, a classicist, instilled in him a love of Greek philosophy and literature. The young Heisenberg with his clear eyes, brush-cut hair, shorts, and keen sense of competition was the image of the postwar German youth movement. In spite of his strong attraction to classics, Heisenberg was drawn to science. He went to study in Munich with Arnold Sommerfeld, who invited him in 1921 to hear Niels Bohr lecture in Göttingen at what was known as the "Bohr Festival." Heisenberg was tempted to become a pure mathematician; but through long discussions with Bohr he became fascinated with the problem of atomic theory and decided instead to become a theoretical physicist. Heisenberg realized that the realm of abstract mathematics could be applied to the most difficult new problems in physics—a connection between pure ideas and the real world that excited him. Reflecting on this, Heisenberg later said, "I also learned something perhaps even more important, namely that in science a decision can always be reached as to what is right and wrong. It is not a question of belief, or Weltanschauung, or hypothesis; but a certain statement could be simply right and another statement wrong. Neither origin nor race decides this question: It is decided by nature, or if you prefer by God, in any case not by man." Like Einstein a generation before him, Werner Heisenberg had encountered the cosmic code, the internal logic of the universe. Through physics he could know the very soul of the universe, a knowledge far removed from those political events which had caused so much recent human suffering. After completing his doctoral work with Sommerfeld in 1924, Heisenberg went to join Bohr in Copenhagen and work on the new atomic theory.

Bohr had always wanted a place, like Rutherford's lab in Manchester which he had visited, where physicists could discuss their problems without the formal student-professor relation interfering. In 1920, through donations from Danish businesses, including the Carlsberg brewery, Bohr realized his vision and founded an institute in Copenhagen which became known as the Niels Bohr Institute. Bohr gathered about him young, bright students from Europe, America, and the Soviet Union to study the problems of atoms. Here Heisenberg found an intellectual environment that challenged his creative power—a community of geniuses that would soon become the new scientific establishment. These students were a brilliant, arrogant, and penniless lot. The general public had little interest in or understanding of their work, but this lack of attention did not discourage them. They were convinced they were creating a scientific revolution which would transform the understanding of reality.

After a year with Bohr, Heisenberg left to become an assistant to Max Born, director of the physics institute at Göttingen University in Germany. Like many physicists, Heisenberg was wrestling with the puzzle of atomic spectral lines. He was also struggling with a bout of spring hay fever in Göttingen and decided to go to Helgoland to clear his head. Here the lightning struck, and in one day and night Heisenberg invented a new mechanics. His paper was completed in July 1925. Similar to Planck's earlier idea of the quantum in 1900, there was no historical precedent for Heisenberg's idea. A single rock had been loosened by the lightning. An avalanche followed.

Heisenberg was interested in Greek philosophy, especially Plato and the atomists, who thought of atoms conceptually, not as things with parts. Most physicists tried to make physical pictures of atoms, but Heisenberg, like the Greeks, felt it was necessary to dispense with all pictures of atoms, of electrons circulating about the nucleus with definite radii like little solar systems. He did not think about what atoms were but what they did—their energy transitions. Proceeding mathematically, he described the energy transitions of an atom as an array of numbers. Applying his remarkable mathematical resourcefulness, he found rules that these arrays of numbers obeyed and used these rules to calculate atomic processes. Before leaving again for Copenhagen, he showed his work to Max Born.

Born recognized in Heisenberg's arrays of numbers the mathematics of matrices. A matrix is a generalization of the idea of a simple number to a square or rectangular array of numbers. Consistent algebraic rules for multiplying and dividing such matrices had been worked out by the mathematicians. Born solicited the aid of his student Pascual Jordan, and together they worked out the details. Born and Jordan wrote a paper extending Heisenberg's ideas, pointing out the importance of matrix algebra for describing atomic energy transitions. Somehow matrices rather than simple numbers were the correct language for describing the atom.

In classical physics the physical variables that describe the motion of a particle are simple numbers. For example, the position (q) of a particle from a fixed point might be 5 feet ($q = 5$); its momentum (p = mass of the particle times its velocity) might be designated by 3 ($p = 3$). Simple numbers like 5 and 3 obey the commutative law of multiplication: that is, $3 \times 5 = 5 \times 3 = 15$ —the order of multiplication does not matter. Likewise for the position and momentum of a particle in classical physics; these variables, since they were always simple numbers, obeyed the commutative law, $p \times q = q \times p$.

The main idea of the new matrix mechanics is that physical variables like the position q and momentum p of a particle were no longer simple numbers but *matrices.* Matrices do not necessarily obey the commutative law of multiplication—$p \times q$ does not have to equal $q \times p$. Born and Jordan's paper contained a relation for the matrices that represented the position q and momentum p of a particle which implied that the difference between $p \times q$ and $q \times p$ was proportional to Planck's constant, h. If we lived in a continuous world in which h was zero, then the matrices p and q would obey the commutative law like simple numbers—just as in the old classical physics. But because h was different from zero, although very small in the real world, the position q and momentum p of a particle could no longer be thought of as simple numbers—they had to be represented as matrices and obeyed the noncommutative laws of the new matrix mechanics, not the commutative law of classical mechanics. What could this possibly mean? Physicists, like most people, think of the position of a particle as having a definite value specified by a simple number. But in the new matrix mechanics the position of a particle was described by a matrix—not a simple number. What then was the "real" position of a quantum particle? Here, for the first time, arose the astonishing problem of physically interpreting the mathematics of the new mechanics, a problem quantum physicists would be struggling with in the coming years.

Heisenberg, in Copenhagen, when he heard of the recent work of Born and Jordan, did not know what a matrix was; but he quickly learned. Later in the same year, 1925, Heisenberg visited the Cavendish Laboratory at Cambridge, England, and gave a seminar on his recent work in the study of Peter Kapitza, a visiting Soviet experimentalist. In the audience was Paul Dirac, twenty-three years old and a brilliant mathematical physicist. Dirac understood the essence of Heisenberg's work immediately. Soon after Heisenberg left Cambridge, Dirac wrote a lucid paper formulating the new matrix mechanics and showed how it was a complete dynamical theory that replaced classical mechanics.

Meanwhile, in Göttingen, Born and Jordan, working in collaboration by letter with Heisenberg in Copenhagen, arrived at the same conclusions but by a slightly different route. The two papers, one by Dirac and the other co-authored by Born, Jordan, and Heisenberg—both sparked by Heisenberg's insight on Helgoland—mark the beginning of matrix quantum mechanics.

The new matrix mechanics was the mathematical modification of Newton's classical mechanics that physicists sought—it provided a mathematical description of moving particles, just like the earlier classical theory. But it also went beyond it. Theoretical physicists had created a new mathematical theory, and now, with great excitement, they turned to face the question: Did the new theory actually describe nature—was matrix mechanics the right quantum theory of the atom?

Heisenberg, in Copenhagen, worked hard to apply the new matrix methods to determining the light spectrum of the hydrogen atom. Bohr had already solved this problem, but it was of interest to see if the new method would yield the same result. The solution of this problem fell to the brash and brilliant young physicist Wolfgang Pauli. One colleague remarked of Pauli that it was not possible to distinguish his rudeness from his politeness. He was a ruthless critic of ideas, sometimes signing his letters "The Wrath of God." While a student with Arnold Sommerfeld in Munich, Pauli had already acquired a scientific reputation for a clear encyclopedia article he had written on the special theory of relativity. Once Einstein came to lecture at Munich and at the end of the lecture the nineteen-year-old Pauli stood up and said, "You know, what Mr. Einstein said is not so stupid. . . ." Later when he went to Copenhagen to work with Bohr, Pauli would get into long discussions with Bohr. Once at the end of a heated argument with Bohr he said to Bohr, "Shut up! You are being an idiot." "But

Pauli . . ." Bohr protested. "No, it's stupidity. I will not listen to another word." That is the kind of man he was. No intellectual dissembler or shoddy thinker could last long with Pauli around; unfortunately even physicists with correct ideas could be defeated by Pauli if he thought they were wrong.

Pauli quickly mastered the mathematics of matrices, solved the problem of the light spectrum of the hydrogen atom, and obtained the same result that Bohr had found earlier. Pauli also determined the light spectrum of a hydrogen atom placed in an electric or magnetic field, a problem that had previously resisted solution. The power of the new matrix mechanics was evident.

Physicists didn't get a picture of the atom or of quantum processes from the new matrix mechanics—it was invented precisely to avoid making a physical picture. The attitude of Dirac and Heisenberg was that a consistent mathematical description of nature was the road to truth in physics. The need to visualize the atomic world was a holdover from classical physics not appropriate to the new matrix theory. Many physicists felt dissatisfied with this attitude, and while Bohr, Born, Jordan, Heisenberg, Dirac, and Pauli were working on the new matrix mechanics, an alternate theory of the atom was developed, resulting in the invention of wave mechanics.

Einstein, we recall, theorized that light was a particle in 1905, an idea which flew in the face of the fact that light was an electromagnetic wave. As early as 1909, he suggested that the future theory of light would fuse the particle and wave theory of light, but there had been little progress in this direction. It seemed that light should be either a particle or a wave.

The next step was taken by Louis de Broglie, a French prince whose intellectual interests took him to the frontiers of physics. He reasoned by analogy that if light, which seemed so clearly to be a wave, could sometimes behave like a particle—the photon—then an electron, clearly a particle, could sometimes behave like a wave. The crucial ideas were presented in two papers of September 1923, in which de Broglie deduced the wavelength of the electron. He suggested that his idea could be experimentally confirmed if electrons showed diffraction phenomena like true waves. Diffraction of a wave around an obstacle, like an ocean wave hitting the edge of a jetty, refers to its bending behind an obstacle, unlike a particle beam, which casts sharp shadows. Sound is a wave, and that is why we can hear around corners; it "bends" around them. The papers became de Broglie's doctoral thesis, and a copy of the thesis was sent to Einstein by an examiner, Paul Langevin. Einstein thought highly of the thesis and did much to bring de Broglie's novel ideas to the attention of other physicists.

One of the physicists who heard about de Broglie's electron waves was the Austrian Erwin Schrödinger. He pondered the significance of the wave idea and devised an equation that the electron wave shape would have to obey if the electron was part of the hydrogen atom. Using his equation, he deduced the light spectrum of hydrogen—it was the same that Bohr had found years earlier. The strange notion that the electron was a wave was quantitatively vindicated. Schrödinger's paper appeared in January 1926 and marks the beginning of wave mechanics, another completely general way of formulating the new mechanics of the atom.

The "Schrödinger equation" applied to all sorts of quantum problems. A series of experiments supported Schrödinger's and de Broglie's thesis that electrons exhibited diffraction—there was no doubt that true waves were involved. But waves of what? The problem of the interpretation of the de Broglie—Schrödinger waves became the central puzzle of the new wave mechanics.

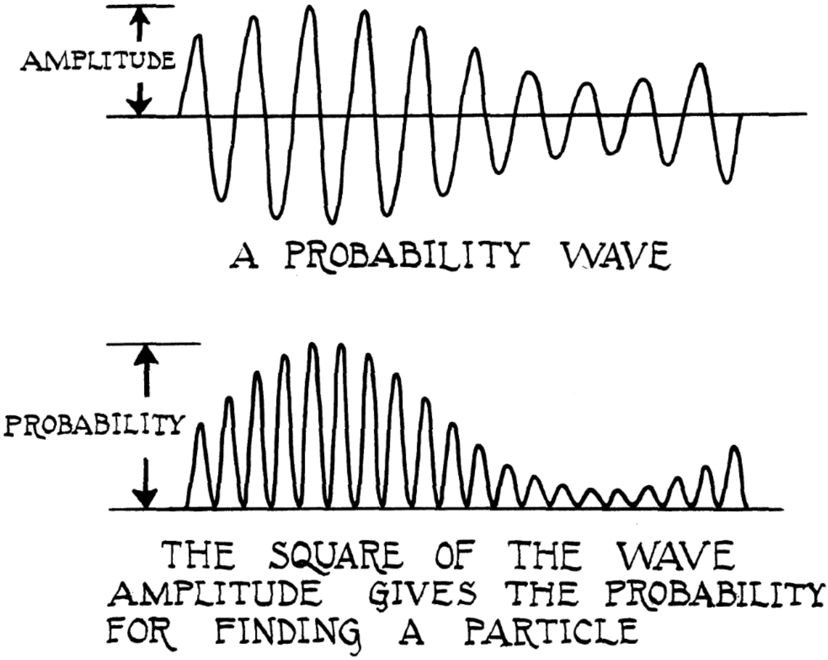
Schrödinger himself offered one of the first interpretations: The electron is not a particle, he argued, it is a matter wave as an ocean wave is a water wave. According to this interpretation the particle idea is wrong or only approximate. All quantum objects, not just electrons, are little waves—and all of nature is a great wave phenomenon.

This matter-wave interpretation was rejected by the Göttingen group led by Max Born. They knew that one could count individual particles with a Geiger counter or see their tracks in a Wilson cloud chamber. The corpuscular nature of the electron—the fact it behaved like a true particle—was not a convention. But what, then, were the waves?

It was Max Born himself who answered that perplexing and crucial question. His interpretation marks the birth of the God who plays dice and the end of determinism in physics. It occurred in June 1926, six months after Schrödinger's paper, and profoundly distressed the community of physicists. Born interpreted the de Broglie–Schrödinger wave function as specifying the probability of finding an electron at some point in space.

Think of a wave moving through space. Sometimes the wave height is just higher than the average level and sometimes lower. The height of the wave is called its amplitude. What Born said was that the square of the wave amplitude at any point in space gave the probability for finding an individual electron there. For example, in regions of space where the wave amplitude is large, the probability of finding an electron there is also large; perhaps one out of two times an electron will be found there. Similarly, where the wave amplitude is small the probability of finding the electron is also small—say one in ten. The electron is always a true particle and its Schrödinger wave function only specifies the probability for finding it at some point in space. Born realized the waves are not *material,* as Schrödinger wrongly supposed; they are waves of *probability,* rather like actuarial statistics for the creation of individual particles that can change from point to point in space and time. This description of the motion of quantum particles is inherently statistical—it is impossible to track them precisely. The best physicists could do was to establish the probable motion of a particle. Born demonstrated the consistency of his interpretation by a careful analysis of atomic collision experiments.

How are we supposed to think about the atomic world of the quanta? Atoms, photons, and electrons really exist as particles, but their properties—such as their location in space, momentum, and energy—exist only on a contingency basis. Imagine that an individual atom is a deck of cards and a specific energy level of



According to Max Born's statistical interpretation of the de Broglie-Schrodinger wave, the height or amplitude of the wave when squared gives the probability for finding the particle at that position. All that quantum theory could do was predict the wave shape and hence the probability that a quantum particle would have certain properties; it could not predict with certainty the outcome of single measurements of those properties, as did the old classical physics.

that atom corresponds to a specific poker hand dealt from the deck. Poker hands have probabilities that can be calculated—using the theory of card playing it is possible to determine precisely the possibility of a given hand's being obtained from the dealer. The theory does not predict the outcome of a particular deal. Demanding this latter kind of determinism requires looking into the deck—cheating. According to Born, the de Broglie–Schrödinger wave function specifies the probability that an atom will have a specific energy level just as the theory of card playing specifies the probability of a certain hand. The theory does not say whether in a particular single measurement the atom will in fact be found in a specific energy level, just as the theory of card playing can't predict the outcome of a specific deal. Classical physics, in contrast to the new quantum theory, claimed to be able to predict the outcome of such specific measurements. The new quantum theory denies that such individual events can be determined. As Born said, it is only the probability distribution of events that is causally determined by quantum theory, not the outcome of specific events.

An important feature of the probability distributions in quantum theory—and one which distinguishes them from the probability distributions of card hands—is that quantum probabilities can propagate through space and change from point to point; this is the Schrödinger wave. The predictive power of the quantum theory is that it determines precisely the shape of the wave and how it moves—how the probabilities change in space and time. Here we see for the first time the new idea of causality in quantum theory—it is probability that is causally determined into the future, not individual events.

Born was excited by his statistical interpretation of the wave theory but found himself alone. When Schrödinger heard of Born's interpretation, he remarked that he might not have written his paper if he had known the consequences—he never accepted indeterminism. Max Planck agreed with Schrödinger's matter waves and when Schrödinger accepted Planck's chair in Berlin, the retiring Planck praised him as the man who had brought determinism back to physics. In late 1926, Einstein wrote to Born, "Quantum mechanics is certainly imposing. But an inner voice tells me it is not yet the real thing. The theory says a lot, but does not really bring us closer to the secret of 'the old One.' " Born was especially disappointed by Einstein's rejection of the statistical interpretation. But Born was right.

This indeterminism was the first example of quantum weirdness. It implied the existence of physical events that were forever unknowable and unpredictable. Not only must human experimenters give up ever knowing when a particular atom is going to radiate or a particular nucleus undergo radioactive decay, but these events are even unknown in the perfect mind of God. Physicists, irrespective of their belief, may invoke God when they feel issues of principle are at stake because the God of the physicists is cosmic order. The indeterminism of the quantum theory is an issue of principle, of what is knowable and unknowable, not experimental technique—that is what distressed Einstein. Even God can give you only the odds for some events to occur, not certainty. About this time Einstein started stating his objection to the new quantum theory with the remark that he didn't believe God plays dice. Max Born, who always considered Einstein his physics master, later responded, "If God has made the world a perfect mechanism, He has at least conceded so much to our imperfect intellect that in order to predict little parts of it, we need not solve innumerable differential equations, but can use dice with fair success." The door to the indeterminate universe opened.

So there were now two explanations of atomic phenomena, Heisenberg's matrix mechanics and Schrödinger's wave mechanics. How could this be? It was Dirac who showed that the matrix and wave mechanics were completely equivalent through his transformation theory—they were simply different representations within the same theory. Physicists refer to them as Heisenberg (matrix) representation and the Schrödinger (wave) representation.

A good way to get across the significance of Dirac's transformation theory is by the analogy between language and mathematics. They are both symbolic means of representing the world; language is richer, while mathematics is more precise. Suppose someone describes a tree in the English language while someone else describes it in Arabic. The English and Arabic descriptions are different symbolic representations of the same object. If you want to describe the tree, you must pick at least one language or representation. Once you have one representation you can find the others by the rules of translation or transformation. That is how it is in the mathematical description of quantum objects like electrons. Some representations emphasize the wavelike properties, others the particlelike properties, but it is always the same entity that is being represented. That different representations are subject to laws of transformation is a profound idea. It is by varying the symbolic representations through transformations that we arrive at the notion of *invariants*: those deep, intrinsic properties of an object which are not just artifacts of how we describe it. We learn what makes a tree in any language. Invariants establish the true structure of an object.

Wave mechanics and matrix mechanics employ different representations to describe the same behavior. The complete theory, including Dirac's transformation theory, finally became called quantum mechanics or quantum theory, a new mathematically consistent dynamics which replaced classical physics. The labor of nearly three decades had yielded a new world dynamics. The mathematical formalism was intact and triumphed experimentally. But what did it mean? What was the interpretation of quantum mechanics, and what was it saying about physical reality? Heisenberg commented, "Contemporary science, today more than at any previous time, has been forced by nature herself to pose again the old question of the possibility of comprehending reality by mental processes, and to answer it in a slightly different way."

5. Uncertainty and Complementarity

It is wrong to think that the task of physics is to find out how Nature is. *Physics concerns what we can say about Nature.*
—NIELS BOHR

DETERMINISM—THE WORLD view that nature and our own life are completely determined from past to future—reflects the human need for certainty in an uncertain world. The projection of that need is the all-knowing God some people find in the Bible, a God who knows the past and future down to the finest detail—like a film that has already been developed. We may not have seen the film, but what it holds for us is already fixed.

Classical physics supported the world view of determinism. According to classical physics the laws of nature completely specify the past and future down to the finest detail. The universe was like a perfect clock: once we knew the position of its parts at one instant, they would be forever specified. Human beings could not, of course, know the positions and velocities of all the particles in the universe at one instant. But invoking the medieval concept of "the mind of God," we could imagine that this perfect mind knows the configuration of all the particles, past and future.

With Max Born's statistical interpretation of the de Broglie–Schrödinger wave function, physicists finally renounced the deterministic world view of nature. The world changed from having the determinism of a clock to having the contingency of a pinball machine. Physicists realized that the concept of the perfect all-knowing mind of God has no support in nature. Quantum theory

—the new theory that replaced classical physics—makes only statistical predictions. But is there a possibility that beyond quantum theory there exists a new deterministic physics, described by some kind of subquantum theory, and the all-knowing mind uses this to determine the world? According to the quantum theory this is not possible. Even an all-knowing mind must support its knowledge with experience, and once it tries to experimentally determine one physical quantity the rest of the deck of nature gets randomly shuffled again. The very act of attempting to establish determinism produces indeterminism. There is no randomness like quantum randomness. Like us, God plays dice—He, too, knows only the odds.

It is this very randomness that makes the determinist recoil. Physics, as it was conceived of for centuries, was supposed to predict precisely what can happen in nature. In the quantum theory, only probabilities are precisely determined, and the determinist finds it difficult to renounce the hope that behind quantum reality a deterministic reality exists. But in fact the quantum theory has closed the door on determinism.

The randomness at the foundation of the material world does not mean that knowledge is impossible or that physics has failed. To the contrary, the discovery of the indeterminate universe is a triumph of modern physics and opens a new vision of nature. The new quantum theory makes lots of predictions—all in agreement with experiment. But these predictions are for the distribution of events, not individual events—it is like predicting how many times a specific hand of cards gets dealt on the average. Probability distributions are causally determined, not specific events.

After Born's statistical interpretation, other physicists struggled to deepen the understanding of the new quantum theory. What knowledge of nature was possible in the framework of the new theory? For example, the mathematics of quantum theory permitted both a particlelike and a wavelike representation for the electron. But clearly these two representations were opposed and in conflict with any common-sense ideas. Is the electron a wave or a particle? Bohr, Heisenberg, and Pauli in Copenhagen and many others debated these questions for over a year. Frustration set in, but Bohr's persistent optimism kept up a spirit of inquiry. Finally, by the beginning of February 1927, Bohr was exhausted and needed a break from Heisenberg, and he took a vacation, collecting his thoughts. While on vacation, Bohr had a primary insight into the meaning of the quantum theory. Likewise Heisenberg, in the absence of Bohr but under the lash of Pauli's criticism, came to his own interpretation of the quantum theory. Bohr and Heisenberg each in his own style had come to new breakthroughs in understanding which were conceptually equivalent. Heisenberg had discovered the uncertainty principle, and Bohr had discovered the principle of complementarity. Together these two principles constituted what became known as the "Copenhagen interpretation" of quantum mechanics—an interpretation that convinced most physicists of the correctness of the new quantum theory. The Copenhagen interpretation magnificently revealed the internal consistency of the quantum theory, a consistency which was purchased at the price of renouncing the determinism and objectivity of the natural world.

Heisenberg's forte was expressing physical intuitions in precise mathematical terms. His discovery of the uncertainty relation was an example of this. It came out of the existing mathematical formalism of quantum mechanics and served profoundly to clarify the meaning of that formalism.

Heisenberg, you will recall, invented the matrix mechanics in which the physical properties of a particle such as its energy, momentum, position, and time were represented by mathematical objects called matrices, generalizations of the idea of simple numbers. Simple numbers obey the commutative law of multiplication —the result of the multiplication does not depend on the order in which it is carried out: $3 \times 6 = 6 \times 3 = 18$. But matrix multiplication *can* depend on the order in which it is carried out. For example, if A and B are matrices, then $A \times B$ does not have to equal $B \times A$.

What Heisenberg showed was that if two matrices representing different physical properties of a particle, like the matrix q for the position of the particle and the matrix p for its momentum, had the property that p × q did not equal q × p, then one could not simultaneously measure both these properties of the particle with arbitrarily high precision. To illustrate this, suppose that I build an apparatus to measure the position and momentum of a single electron. The readout of the apparatus consists of two sets of numbers, one marked "position," the other "momentum." Every time I push a button the apparatus simultaneously measures the position and momentum of the electron and prints out two long numbers, the result of the measurements. For any single measurement, let's say the first one, the two numbers printed out can be as long as I like and hence highly precise. I might think that I have simultaneously measured both the position and momentum of the electron with incredible accuracy. However, to get an idea of the error or uncertainty in this first measurement, I decide to repeat the measurement and push the button again. Again two long numbers are printed out representing the position and the momentum of the electron. Remarkably, they are not exactly the same as for the first measurement, although perhaps the first several digits of each position and momentum measurement agree. By pushing the button again and again I assemble more and more such measurements. Then I can calculate the uncertainty of the position and momentum of the electron by a statistical averaging procedure over the entire set of measurements, so that the quantity denoted by Δq is the spread or uncertainty of position measurements about some average value and likewise Δp is the spread of momentum measurements about an average value. The uncertainties Δq and Δp have meaning only if one does a large set of measurements so that one can compare the differences between individual measurements. What the Heisenberg uncertainty relation asserts is that it is impossible to build an apparatus for which the uncertainties so calculated, over a large series of measurements, fail to obey the requirement that the product of the uncertainties, $(\Delta q) \times (\Delta p)$, is greater than or equal to Planck's constant, h. This is expressed mathematically by the relation:

$$(\Delta q) \times (\Delta p) \geq h$$

A similar uncertainty relation is found for the uncertainty in the energy, ΔE, of a particle and the uncertainty in the elapsed time, Δt:

$$(\Delta E) \times (\Delta t) \geq h$$

Heisenberg derived these formulas directly from the new quantum theory.

To see what these relations imply, suppose we try to measure the position of an electron with arbitrarily high accuracy. This means that our uncertainty in the position of the electron is zero, $\Delta q = 0$—we know its location exactly. But the Heisenberg uncertainty relation says that the product of Δq and Δp, the uncertainty in the momentum, must be greater than a fixed quantity, Planck's constant. If Δq is zero, this means Δp must be infinite—that is, the uncertainty in our knowledge of the momentum of the particle is infinite. Conversely, if we knew precisely that the electron was at rest, so the uncertainty in the momentum is zero, $\Delta p = 0$, then the position uncertainty, Δq, must be infinite—we have no idea where the particle is located. As Heisenberg remarked, the uncertainty in position and momentum are like "the man and the woman in the weather house. If one comes out the other goes in." Notice that if Planck's constant h were equal to zero in the real world rather than a tiny number, then we could simultaneously measure both the position and momentum of a particle, because the uncertainty relation would be $(\Delta q) \times (\Delta p) \geq 0$ and both Δq and Δp could be zero. But because Planck's constant is not zero, this is impossible.

I have always thought that wet seeds from a fresh tomato illustrate the Heisenberg relation. If you look at a tomato seed on your plate you may think that you have established both its position and the fact that it is at rest. But if you try to measure the location of the seed by pressing your finger or a spoon on it the seed will slip away. As soon as you measure its position it begins to move. A similar kind of slipperiness for real quantum particles is expressed mathematically by the Heisenberg uncertainty relations.