Chapter 3

STYLE AND SCIENTIFIC DISCOVERY

When Einstein was a sixteen-year-old boy, he began to wonder what would happen if one could travel at the speed of light. He quickly observed that there was something very puzzling about the idea, for if one could travel at such a velocity, light itself would disappear.

The year was 1895. Physicists had known for some time that light was a form of electromagnetic radiation; it consisted of oscillating electric and magnetic fields. When these oscillations struck the retina of the eye, or interacted with a piece of laboratory apparatus, light was observed.

Einstein realized that if one could move at the velocity of light, the oscillations would no longer seem to exist. They would become frozen. Where a stationary observer would see a series of alternating crests and troughs as a light wave moved past him, an observer who was traveling at the same speed as the light wave would see only a motionless crest, or a motionless trough, and nothing else. Einstein saw that there was something very paradoxical about such an idea. Motionless “oscillations” simply did not exist in nature. Consequently, he began to wonder if velocities equal to that of light were possible.

This adolescent thought experiment suggested to Einstein that
motion at velocities equal to that of light was not possible. It may have motivated him to seek a theory which explained why such a thing could not happen. However, it does not explain how Einstein happened to think of the specific postulates upon which the special theory was based. It no more explains the genesis of his theory than the anecdote about Newton and the apple explains the discovery of the inverse-square law of gravitational attraction.

How do scientific discoveries come about? Does the theoretical scientist depend primarily on logical deduction? If Einstein had never been born, could the special theory of relativity have been discovered by any physicist who was acute enough to realize that the idea of travel at the speed of light was paradoxical? Or does theoretical discovery depend upon a kind of creative imagination similar to that of the artist or the poet?

The question of how Einstein happened to think of the special theory of relativity has no obvious answer. It is a topic about which scholars still argue. However, the other questions are not so difficult to answer. It appears to be fairly obvious that most significant discoveries depend both upon logical thinking and upon creative leaps of imagination.

There are a few relatively "pure" examples of one or the other. Planck's discovery of the quantum theory of light seems to have depended primarily upon deduction. Planck began by deriving a mathematical formula that would accurately describe blackbody radiation. Next, he attempted to see what the theoretical consequences of the formula were. Although intuition must have played a role of some sort, it was probably a relatively minor one.

On the other hand, De Broglie's hypothesis about matter waves was so much of an intuitive leap that it was practically a shot in the dark. At the time, there was no experimental evidence which would have indicated that particles would exhibit wave characteristics. De Broglie's theory was not the result of deduction; it was an inspired guess.

The examples of Planck and of De Broglie are rather atypical, however. In most cases, both logical analysis and creative imagination play important roles in scientific discovery. New theories rarely come about because one scientist or another has expended a great deal of effort analyzing experimental data. They just as rarely depend upon insight alone. Typically, scientific discovery is a two-part process. The first thing that happens is that a scientist experiences a sudden insight. Then, if he is lucky, he finds that the insight has logical consequences that will clear up an outstanding scientific problem, or explain baffling experimental results.

I say "if he is lucky" because not every scientific idea is a good one. Insights can be accurate, and they can be totally misleading. One could even go so far as to say that the majority of the scientific theories that have been proposed, or thought of, have been wrong, just as the majority of the poems that have been written and the majority of the pictures that have been painted were not very good. Great scientists and great artists sometimes have bad ideas. Mediocre scientists and artists have them frequently.

There are more parallels between science and the arts than immediately strike the eye. Like artists, scientists often have unique styles. Furthermore, their ideas of what a good scientific theory should be like are strangely reminiscent of artistic convictions. Admittedly, the concept of "style" is not often applied to the sciences. Nevertheless, when one looks at the work of Planck, of Bohr and of Einstein, it is difficult to avoid being struck by the differences between them. It is apparent that these three men attempted to understand the universe in three stylistically very different ways.

Planck was a conservative classical physicist. Although he was the instigator of the twentieth-century revolution in physics, he was a reluctant revolutionary. He was the originator of the quantum theory, yet he was so committed to classical nineteenth-
century ideas that he spent ten years of his life trying to find a way to do away with the concept of quanta entirely.

It wasn’t a desire for innovation that led Planck to the discovery of the quantum emission of light. He made the discovery because he perceived that the blackbody problem represented a glaring gap in scientific knowledge. He labored for years to plug that gap, and finally proposed that light was emitted in packets only because he could see no way to avoid that conclusion.

It would be a mistake to view Planck as an old fuddy-duddy. He was a brilliant, imaginative physicist. He was the first to appreciate the significance of Einstein’s special theory of relativity. He was on hand when Einstein’s rather unconventional paper arrived at the offices of the journal *Annalen der Physik*, and he defended Einstein’s theory in print the following year. Yet although he understood Einstein’s imaginative ideas, he distrusted his own insight.

Relativity, after all, represented an extension of ideas that had been accepted for a long time. When Einstein propounded the special theory, he reached some surprising conclusions. But he did not break with the old ideas the way Planck did when he formed the quantum hypothesis. Interestingly, Planck, who endorsed relativity with enthusiasm, remained skeptical when Einstein proposed that light traveled through space as photons. Above all, Planck seems to have wanted to preserve the concepts of classical physics.

If Planck perceived the laws of nineteenth-century science as absolute truths that could be expanded upon but not overthrown, Einstein was willing to question anything in the structure of science. By proposing his theory of special relativity, he showed that he was willing to make audacious assumptions. In his paper on quantum theory, published the same year, he suggested that light was made up of particles, even though he knew that there was conclusive evidence that it was a wave phenomenon. When he endorsed de Broglie’s matter-wave hypothesis, he showed that he was willing to consider an idea that most physicists would have rejected out of hand.

In Einstein’s view, only one thing was important. Physics had to be made into something that was logical and coherent. If his quest for an inner logic led to ideas that seemed outlandish, Einstein would happily conclude that the world was stranger than it seemed to be. It seems never to have occurred to him that a quest for logical structure could lead to conclusions that were incorrect.

Planck and Einstein also differed in the emphasis they placed on experiment. Planck began to work on the blackbody problem because he saw that theory and experiment did not agree. On the other hand, Einstein paid little attention to experimental results. Like the ancient Greek philosophers, he believed that pure thought could grasp the structure of reality. If a theory was elegant and logically compelling, then it had to be true. If experiment indicated otherwise, then so much the worse for experiment.

In 1906 the German physicist Walter Kaufmann published the results of a long series of experiments in which he had measured the mass of moving electrons. His results agreed with some theories and disagreed with others. In particular, they failed to substantiate the predictions of the special theory of relativity. There was a small but significant difference between Kaufmann’s findings and Einstein’s calculations.

But Einstein was not troubled. Commenting on the two theories that Kaufmann’s results did support, he wrote, “In my opinion both theories have a rather small probability because their fundamental assumptions concerning the mass of moving electrons are not explainable in terms of theoretical systems which embrace a greater complex of phenomena.”

In other words, no matter what the experiments said, the competing theories could not be true because they did not fit into far-reaching, clear-cut theoretical patterns. In Einstein’s eyes, the logical structure of a theory was more important than results that were obtained in the laboratory.

Einstein became even more dogmatic about the primacy of theory over experiment when he heard of the results of an experimental test of the general theory of relativity. In 1919 a group
of astronomers headed by Arthur Eddington went to Africa to observe the path followed by starlight that grazed the surface of the sun during a solar eclipse. Einstein's theory had predicted that the starlight would be deflected by a certain amount. His prediction of the bending of starlight in the sun's gravitational field could be checked only during a total eclipse because at other times the light of the sun blotted out the images of nearby stars.

Although the observations were difficult, Eddington managed to obtain results that confirmed Einstein's theory within the limits of experimental error. One might expect that Einstein would have been overjoyed when he heard of this. But he wasn't; he was relatively unmoved. When one of his students, Ilse Rosenthal-Schneider, asked him why he did not seem to be as excited as she was, Einstein replied, "But I knew that the theory is correct." When she asked him how he would have reacted if the theory had not been confirmed, he said, "Then I would have been sorry for the dear lord—the theory is correct."

Einstein did sometimes make mistakes. However, his greatest error was not the result of paying too little attention to observational data. It came about when he paid too much attention to them.

In 1917, Einstein set himself the task of using his general theory of relativity to find equations that would describe the structure of the universe. To his surprise, he found that his theory indicated that the universe had to be in a state of either contraction or expansion.

In 1917, all the astronomical observations that had ever been made seemed to indicate that the universe was static. It had been known for thousands of years that the constellations did not change in size or appearance. The heavens seemed to be unalterable; one spoke of the "fixed stars" to distinguish them from the moving planets. It had apparently not yet occurred to anyone that the universe might evolve on a time scale that was much longer than the time spans by which events were measured on earth. No one realized that the universe might be changing, that the only reason it appeared static was that it was seen in slow motion.

Einstein didn't realize this either. Rather than follow where his theory led him, he accepted the conclusion that the universe must be static. Since his equations indicated that it could not be, he decided to "fix them up." Einstein accomplished this by introducing a quantity that he called the cosmological constant. This constant was the mathematical representation of a force that balanced out the effects of gravity at large distances. Once this force was "put in," a static universe became mathematically possible.

Twelve years later, in 1929, the American astronomer Edwin Hubble discovered that the universe was in a state of rapid expansion. Hubble's observations indicated that the light from distant stars was reddened. This Doppler shift, or red shift, indicated that distant galaxies were rushing away from the earth. Since it was ludicrous to assume that the earth occupied any special position in the center of the universe, only one conclusion was possible. Galaxies and clusters of galaxies were moving apart. The universe was expanding.

It wasn't long before Einstein realized that if he had only trusted his own theory, he could have predicted this result twelve years before Hubble discovered it. By 1931, Einstein had rejected the concept of a cosmological constant. In later years he was to speak of the introduction of the quantity as "the greatest blunder of my career."

But the story does not end here. After Hubble had made his discovery, some cosmologists began to wonder if there might not be good reasons for retaining Einstein's constant after all. It seemed that Hubble's results gave an age for the universe that was much too young. The cosmologists observed that if the universe was expanding, then there must have been a time when all the matter in it was compressed together. If one took Hubble's figures and worked backward, it was possible to calculate that approximately 2 billion years had passed since the expansion began.

However, this result did not agree with determinations of the age of certain terrestrial rocks. Radioactive dating methods showed that some of these rocks were 3.5 billion years old. This contradicted the 2-billion-year figure for the age of the universe.
It was absurd to assume that rocks found on the surface of the earth could be older than the universe itself.

There seemed to be only one way out of the dilemma. If one reintroduced Einstein’s cosmological constant into the calculations, the theoretical age of the universe could be extended. If there existed another long-range force besides gravity, the expansion would proceed at a different rate. If the cosmological force was of the right strength, it was possible to obtain an age for the universe that was greater than 3.5 billion years.

But Einstein refused to accept this as a way out. He was now convinced that the introduction of the cosmological constant had been a mistake, that it created a flaw in the logical structure of his theory. It should not be brought back in merely to bring theory into agreement with astronomical data. Although Einstein could suggest no method of resolving the contradiction, he remained adamant. He had blundered once, and he was not going to do it again.

Einstein’s obstinacy seems almost pigheaded. And yet he turned out to be right in the end. During the 1950s, two American astronomers, Allan Sandage and the German-born Walter Baade, demonstrated that there had been systematic errors in Hubble’s distance measurements. When Hubble had done his work, astronomical knowledge—at least in some areas—had been in a relatively primitive state. Lack of knowledge had caused Hubble to confuse certain kinds of stars that were really quite different from each other. Since he had used the brightness of these stars to calculate the distances to nearby galaxies, his results for the expansion rate had been inaccurate. And if the expansion rate had been determined incorrectly, the estimate for the age of the universe would be wrong too.

Sandage and Baade corrected the age of the universe to 10 billion years. Although this was still a bit too small—the modern estimate is 18 billion—it was large enough to account for 3.5-billion-year-old rocks. It became apparent that Einstein’s intuition had not failed him. There was no discrepancy, and the cosmological constant did not have to be brought back in.

Until Einstein reached the age of thirty-five or forty, he seemed to have an almost clairvoyant insight into the workings of nature. When Einstein decided that a theoretical idea “felt right,” it almost invariably turned out to be true. He seemed to have the mysterious ability to penetrate beyond the world of appearances and to see, in his mind, the hidden laws that explained natural phenomena.

Einstein often spoke in a manner that would have seemed more appropriate for a mystical philosopher, or for an Eastern seeker after enlightenment, than for a Western scientist. When he talked of his attempts to understand the laws of nature, he often expressed himself in enigmatic ways. On one occasion, he spoke of his attempts to discover the “secrets of the Old One.” “God is subtle, but not malicious,” he said on another, when he wanted to express the idea that although natural laws were sometimes difficult to discover, they were never incomprehensible.

Perhaps an Eastern mystic would not have used the words “Old One.” But when Einstein did so, he was not speaking of God as though He were an individual. Einstein had lost his belief in the personal God of Judaism and Christianity while he was still an adolescent. When he spoke of “God,” he was simply referring to the logical patterns that were observed in nature. In Einstein’s eyes, the natural universe partook of the divine. Perhaps this idea can best be expressed in Einstein’s own words. In 1929, in response to an inquiry from a Rabbi Goldstein in New York, Einstein stated that he believed in “Spinoza’s God who reveals himself in the harmony of all that exists, not in a God who concerns himself with the fate and actions of men.”

One should not conclude that Einstein was infallible. He very definitely wasn’t. In fact, after he passed the midpoint of his life, his intuition began to fail him. He spent his last forty years in an attempt to discover a unified field theory that would combine the laws of gravity and electromagnetism. Today, it is apparent that Einstein was following a blind alley. Although there is hope that a unified theory might be possible, it has become apparent that the theoretical methods employed by Einstein are not likely to produce one.
Einstein's search for such a theory during the second half of his life caused him to become isolated from the community of physicists. Most of Einstein's contemporaries felt that the approach was misguided. Einstein, on the other hand, pursued the chimera with such single-minded purpose that he had little time to consider the problems that other scientists thought to be much more important. Einstein was still seeking a unified field theory when he died at the age of seventy-six; at that time he was not much nearer his goal than he had been at the age of forty.

Although Einstein's intuitive feelings about the order of the universe propelled him toward his great achievements, they sometimes brought him into conflict with other physicists, particularly with Niels Bohr. Bohr had convictions about the natural world too. His views and Einstein's did not always coincide.

The arguments between Bohr and Einstein began in 1927 at a conference on physics sponsored by the Belgian industrialist Ernest Solvay. Just a few weeks earlier, Bohr had presented his ideas on complementarity at another conference in Como, Italy. Einstein had not been present at the Como meeting. However, he was in attendance when the Solvay congress opened in Brussels.

The Solvay conference drew many of the most notable physicists of the day. One after another, they gave talks on recent discoveries and theoretical speculations. Einstein did not participate in any of the discussions that followed the lectures. It wasn't until Bohr spoke about complementarity that he rose to take issue.

Einstein's opposition to Bohr's interpretation of quantum mechanics was immediately obvious. In particular, he would not accept the idea that atomic processes were indeterministic. If quantum mechanics could give only statistical predictions, Einstein argued, this meant that it was not a complete theory. When a better, more comprehensive theory was found, the concept of probability would no longer be needed, and determinism would be restored.

Einstein also argued against the acceptance of the Heisenberg uncertainty principle. The idea was logically inconsistent, he claimed. In principle, he said, the position and momentum of a particle could be simultaneously determined. Then he gave a theoretical argument in which he attempted to show that this was so.

When Bohr was able to find a flaw in the argument against the uncertainty principle, Einstein was not deterred; he promptly invented a second one. Bohr found a hidden fallacy in that one too. But Einstein still would not give up. His opposition continued long after the Solvay meeting; he continued to dream up new arguments over the course of several years.

By 1930, Einstein was ready to admit that his attempts to prove the inconsistency of the uncertainty principle had been unsuccessful. However, he continued to maintain that the indeterminism of quantum mechanics implied that it could not be a complete theory. "God does not play dice," he would say, over and over again. On one occasion, Bohr became so exasperated that he admonished Einstein, "Stop telling God what to do!"

It is really not surprising that Bohr and Einstein should have argued with each other so vehemently. Their ways of doing physics were too different to permit easy agreement. Einstein was the mystic who could comprehend the universe only in terms of clear-cut pictures which displayed some compelling inner logic. Bohr was the philosopher who was delighted to discover that reality was more profound and paradoxical than it appeared to be. One suspects that Bohr and Einstein did not so much disagree as fail to understand each other. Each was guided by his own inner voice. But the voices did not speak the same language.

Neither outlook on physics can be said to be better than the other. As students of mystical philosophy are fond of pointing out, there is more than one path to the truth. However, the majority of physicists today tend to think that it was Bohr, not Einstein, who was right about quantum mechanics. No deterministic hidden-variable theory of quantum behavior has been found. Or at least, none has been found that seems adequate. The Copenhagen interpretation remains the standard interpretation of quantum mechanics; physicists generally accept the idea that the
behavior of subatomic particles can be interpreted only in terms of probabilities.

In 1927, the problem that confronted physicists was one of interpretation. It was already apparent that quantum mechanics would be a successful theory. It contained a mathematical formalism that could be used to perform accurate calculations which had already been verified by experiment. However, the mathematical formulas didn't tell physicists what an electron or a photon "really was." Bohr had developed his ideas on complementarity to fill this gap. The only way to gain a true understanding of quantum reality, he maintained, was to assume that quantum systems could possess contradictory properties. They did not behave like the objects one encountered in the macroscopic world. Concepts that could not simultaneously be applied to ordinary large systems might very well have to be combined if one wanted to understand events in the atomic realm.

The doctrine of complementarity did not represent Bohr's first attempt to introduce apparently contradictory ideas into physics. He had already done this when he proposed a theory of the hydrogen atom in 1913.

Although this theory of Bohr's was eventually superseded by quantum mechanics, it was quite an advance at the time. It was the first successful attempt to apply Planck's ideas about quanta to atomic structure. Bohr's theory did work. It was only when one tried to extend it to atoms that were more complicated than hydrogen that it ran into trouble.

In 1911, the British physicist Ernest Rutherford had discovered the nucleus of the atom. Prior to this time, it had been thought that atoms were tiny balls of positively charged matter in which the negatively charged electrons were embedded. This idea was sometimes referred to as the plum-pudding model: the positively charged sphere was the pudding, and the electrons were the plums.

Rutherford discovered that this model was incorrect. He carried out a series of experiments which demonstrated that the positive charge was confined to a tiny sphere in the center of the atom. Presumably, the electrons revolved around this nucleus in the same manner in which planets revolve around the sun.

But there was one very significant difficulty. This planetary model seemed to imply that atoms did not exist. According to the laws of classical physics, the orbiting electrons would radiate energy. They would radiate so much so rapidly that they would quickly lose their energy of motion and fall into the nucleus. The planetary model seemed to contain a serious contradiction.

The problem was solved by Bohr in a very surprising way. He simply assumed that the laws of classical physics did not apply. Electrons in atoms did not continuously radiate away their energy, he said, even though free electrons would do so under similar circumstances.

Furthermore, Bohr suggested, the motion of the electrons was quantized. Only certain specific orbits were possible; an electron could not follow any path that lay between them. If one made this assumption, Bohr pointed out, then Planck's quanta of light could easily be explained. An atom emitted a photon when an electron jumped from one orbit to another. The different orbits had different energies. If an electron jumped from a higher energy state to a lower one, the difference was equal to the energy of a particle of light.

Bohr's theory was at least as audacious as any of Einstein's. If this description was accurate, it implied that an electron could vanish and reappear somewhere else. After all, if intermediate orbits were not allowed, that was the only kind of motion between orbits that would be possible.

Bohr's theory embodied several different sets of contradictory ideas. First, Bohr assumed that a free electron could radiate energy, but that electrons in atoms did not (except when they jumped). He assumed that electrons revolved around the nucleus with a smooth, continuous motion, but that the emission of light was associated with motion that was discontinuous. Finally, although a free electron could presumably occupy any position in space, atomic electrons could exist only in a certain set of allowed orbits.
The theory sounded outlandish. However, it won acceptance quickly, for it worked. It explained why hydrogen gas could emit light only at certain specific wavelengths, and it accurately predicted just what those wavelengths should be.

When quantum mechanics superseded Bohr's theory, the idea of electron orbits was dropped. The discovery that the positions of electrons were defined by probability waves made such an interpretation impossible. Bohr's concept of electron jumps was retained, however. Although physicists no longer speak of electron orbits, they still talk about transitions from one quantum state to another. There are no orbits in the classical sense of the term. However, configurations of probability waves can undergo discontinuous change.

It is not surprising that a physicist who could develop a theory like this should be the one who would later develop an interpretation of quantum mechanics which depended upon the application of contradictory ideas. The principle of complementarity seems to have been a natural outgrowth of Bohr's outlook. Indeed, he was always interested in the application of contradictory ideas, in any field. He was intrigued by philosophical writers who dealt with such notions, and he was interested in the Chinese concept of yin and yang. Bohr was no mystic, and he was not a devotee of Eastern philosophy. Nevertheless, he placed the yin-yang symbol on the coat of arms that he was required to devise when he was awarded the Danish Order of the Elephant in 1947. Above the symbol, he inserted the legend CONTRARIA SUNT COMPLEMENTA. Contraries are complementary.

If Bohr's outlook on physics was unlike those of Planck and of Einstein, his working methods were different too. While Planck and Einstein worked in solitude, Bohr developed many of his most important ideas in conversation with other physicists. His favorite method of working was thinking aloud. In order to do this, he needed a listener. Bohr's ideas about complementarity were developed, to a large extent, in conversations that he had with such scientists as Heisenberg, Schrödinger and Pauli at his institute in Copenhagen. One suspects that Bohr did most of the talking. A cartoon drawn by the Russian émigré physicist George Gamow shows Bohr with another physicist who has been gagged and bound to a chair. "Please, please," Bohr says, "may I get a word in?"

Bohr, Einstein and Planck had different approaches to the solution of theoretical problems in physics. Sometimes these differences were reflected in their personal lives. Bohr, who was so preoccupied with the role of contradictory ideas in physics, seems to have become interested in the reconciliation of seemingly incompatible ideas while he was still quite young. As an adolescent, he was already pondering such problems as the determinism/free-will dichotomy, coming to the conclusion that the two concepts were really not irreconcilable. In later years, he applied the notion again and again in his work on physics that an idea and its opposite could both be profound truths.

On the other hand, Einstein seems to have looked for solutions that were more clear-cut. In physics, he demanded that a theory be unambiguous and that its meaning be transparent. Like Bohr, he extended this outlook to areas outside of physics. Rather than try to reconcile contraries, as Bohr did, he would opt for one solution or another. For example, after pondering the question of free will, he seems to have decided that it was most logical to conclude that it did not exist. In his book The World as I See It, Einstein wrote:

I do not at all believe in human freedom in the philosophical sense. Everybody acts not only under external compulsion but also in accordance with inner necessity.

Such a point of view is certainly philosophically permissible. However, it is the sort of idea with which Bohr would not have been able to agree.

The differences between Einstein and Planck were dramatic too, although they expressed themselves in different ways. Compared with Einstein and with Bohr, Planck was a conservative physicist. He appears to have been equally conservative in other
matters. Planck had great respect for authority, and his manner was reserved and formal. He wore dark clothing, and shirts that were heavily starched. He lived a life that was characterized by its order. He would leave home for his office at the university at exactly the same time every day. A visitor in his household once observed that every morning, just as a clock in the hall was sounding, Planck would emerge from his room and make his way down the stairs to the front door. A part of Planck's day was always reserved for a walk, and he regularly devoted thirty minutes to playing the piano.

The analogy between Planck’s life and his work in physics is striking. Unlike Bohr, he did not try to impose his philosophical ideas on physics. His work as a scientist was characterized by a search for order. He seems to have been attracted to the blackbody problem because it appeared to be such a blemish in the structure of theoretical knowledge. It is almost as though he felt that he could not rest until the blemish was removed.

Einstein, on the other hand, was a rebel who never seemed to fit in. As a child, he insisted on going his own way. The very same trait expressed itself again in his later life, when he insisted on laboring away at his unified field theory even though most of his colleagues doubted that he would have any success. If anything, he exhibited an even greater rebelliousness as a young man, when he propounded new ideas that toppled long-balked scientific theories.

As a boy, Einstein rebelled against the regimentation that was common in German schools. As a result, he never did manage to graduate from the Gymnasium (academic high school); he had already decided to drop out when he was expelled on the ground that “your presence in the class is disruptive and affects the other students.”

Einstein’s lack of a Gymnasium diploma was not the impediment that it might be today. He was able to attend the Swiss Federation Polytechnic School in Zurich, which offered one of the best scientific educations of any university in Europe outside of Germany. But the same problems soon reasserted themselves. Ei-
scientist both make use of intuitive leaps. But it is not so easy to see why scientific intuition such as that possessed by Bohr, or by Planck, or by Einstein should have turned out to be unerringly accurate so often.

We commonly demand that works of art be imaginative. Significant new scientific ideas need to be imaginative as well. In addition, they must possess another quality. They must be correct. However brilliantly imaginative a scientific theory may be, it is worthless if it is wrong.

A correct theory is one that can presumably be verified by experiment. And yet, in some cases, scientific intuition can be so accurate that a theory is convincing even before the relevant experiments are performed. Einstein—and many other physicists as well—remained convinced of the truth of special relativity even when Kaufmann’s experiments seemed to discredit it.

How can such things be? Science is supposed to depend upon experimental verification. Scientists habitually remain skeptical of unproven ideas. Can there really be any justification for the acceptance of theoretical ideas that are not backed up by a mass of evidence?

Justified or not, it is something that happens all the time. Since the beginning of the scientific renaissance of the sixteenth century, numerous scientific theories have seemed so plausible that they have won acceptance long before the relevant experiments could be performed. There have been other theories which seemed so implausible that most scientists did not think it worth their while to check them.

Naturally, there have been mistakes. However, scientific intuition has proved to be unerringly accurate on a surprising number of different occasions. Although scientists, like other human beings, often blunder, they have been astonishingly successful in finding significant patterns in the natural world even when they used no tools other than creative thought.

The ancient Babylonians were superb astronomers. Although they had no telescopes or clocks, or any of the other instruments that can be found in a modern observatory, some of their observations had an accuracy that was not equaled until the nineteenth century. The Babylonians were infallible in their forecasts of lunar eclipses; they could even predict how complete an eclipse of the moon would be. Some of the calculations performed by the Babylonian astronomer Kidinna in the fourth century B.C. have turned out to be more accurate than those made by European astronomers as late as 1887.

But the Babylonians had no theory to explain why the bodies in the solar system moved the way they did. They could predict eclipses and conjunctions of planets, but they had no idea what a planet was. It wasn’t until astronomy was taken up by the ancient Greeks that the first attempts were made to find theoretical explanations for the motions that were observed in the heavens.

By modern standards, the Greek theories were not very good ones. Although the Greeks made an important advance when they realized that celestial events must have logical explanations, they relied a little too much on principles they thought to be
DISMANTLING
The Nature

THE UNIVERSE
of Scientific Discovery

Richard Morris