Quantum Jumps

"The time has come,"
the walrus said,
"To talk of many things:
Of shoes—and ships—
and sealing wax
Of cabbages—and kings—
And why the sea is
boiling hot
And whether pigs
have wings."

LEWIS CARROLL

From: Taking the Quantum Leap: The New Physics for Nonscientists, by Fred Alan Wolf, (New York: Harper and Row), (1981).

A Lord Eats a Raisin Pudding Atom

Planck and Einstein had set the stage. By 1911, the quantum nature of light was already making its way into respectability. Light was a wave that somehow had a particulate graininess associated with it. Using highly developed vacuum techniques and the newest electrical equipment, scientists played with electrical discharges in gases that were sufficiently rarefied to be studied. They were also looking at the light that these electrical discharges produced. Today we call such phenomena "neon signs."

In 1896, J. J. Thomson had discovered the electron by using the vacuum and electrical discharge technique. This discovery was hailed as monumental. The secret of electricity was contained in this tiny bit of matter. By using electric and magnetic fields, Thomson was able to focus and steer a beam of electrons, thus determining the electrical charge and, later, the mass of each electron. These tiny bits were found to be extremely light in weight when compared to atoms of a gas. One atom of hydrogen, the lightest atom known, weighed nearly two thousand times as much as an electron. Thus it seemed natural to suppose that electrons were parts of atoms. Indeed, it was taken for granted that the electrical power used in the electrical discharge in the gases ripped the atomic gases apart and thus produced electrons.

Since matter was assumed to be made of atoms, it was also natural to imagine that heated solid or liquid matter glowed because of the movements of the lighter electrons. These electrons were thought to oscillate back and forth inside of their respective atoms. And these oscillations, it was supposed, broadcast light waves just as Hertz had demonstrated in 1887 that his electrical oscillations broadcast radio waves. The only question was how to picture this. Remember, the Newtonian classical world view of physical processes still persisted in spite of the Planck-Einstein $E = hf$ formula.

The size of the atom was known. It was less than two billionths of an inch in diameter. This diameter is so tiny that it is nearly inconceivable. To grasp how tiny an atom actually is, consider the following imaginative exercise. Suppose you had a golf ball in your hand. And suppose that you could inflate this golf ball—that is, blow it up like a balloon until it was large enough to enable you to see an atom within the golf ball. To be specific, supposed that you wished to blow the golf ball up until one of its atoms was as big as a normal sized golf ball. For that atom to become big enough to hold in your hand, the original golf ball would have to be inflated to the size of our earth! No wonder no one knew what an atom looked like or, in particular, how electrons fit inside of it.

By 1911, J. J. Thomson had become Sir Thomson. He had his own laboratory in England. He was the director of the world-famous Cavendish Laboratory. He also was the leader of a certain school of thought regarding the structure of atoms and the whereabouts of electrons within.

Thomson's atom was pictured as a tiny raisin pudding. Embedded within this "pudding" were even tinier electron "raisins." The number of electrons depended on the particular variety of atom. Hydrogen had just one electron raisin, one bit of negative electrical charge to balance out the observed positive charge and make the atom electrically neutral. By putting the atom into an electrical discharge, that single, negatively charged electron could be pulled out of the pudding and leave behind a positively charged atom "pudding." The result was a hydrogen ion. Helium ions were observed to be doubly charged; thus, it was clear that a helium atom had to have two electrons within it to balance out its charge. And so on.

Another school of thought held that the atom looked more like a miniature solar system than a raisin pudding. Each electron in any given atom was pictured as a planet that moved in a closed orbit about a tiny nucleus at the atom's center. Instead of a more or less random distribution of electron raisins embedded in the large and somewhat soft, tenuous background of a positively charged pudding, there was a well-organized series of electron planets, each in its own orbit, following a well-defined mechanical and repeatable movement. These electron planets moved like real planets. Each had its own respective "years." In other words, there was a periodicity or frequency to their motions. The deciding feature between these two models had to do with the rest of the atom, the positive matter that held the electrons within.

The correctness of the pudding or planetary model of the atom could not be determined from the light emitted by atoms. Nor could anyone shine light on an atom and take a look. Atoms were much too small. The wave lengths of light were thousands of times longer than the diameters of atoms. Such details as the location of electrons or the distribution of the heavier, positively charged atomic matter would never be seen by using light waves. But there were other ways to explore an atom. You could throw other atomic particles at it and observe the scattering and atomic debris that would result from a collision. Just as the debris from a midair collision between airplanes can reveal the cause of the accident, atomic debris can reveal what the insides of the atom look like.

The question of whether matter in an atom was spread out like a pudding or gathered together in a tiny sunlike nucleus at the atom's center was finally given an experimental test in 1911. Within a vacuum enclosure, a beam of helium ions was fired at a very thin foil of gold, and the truth was discovered. The helium ions scattered from the atoms within the gold foil with a pattern that suggested that the atoms of gold had nuclei. The pudding model was dropped.

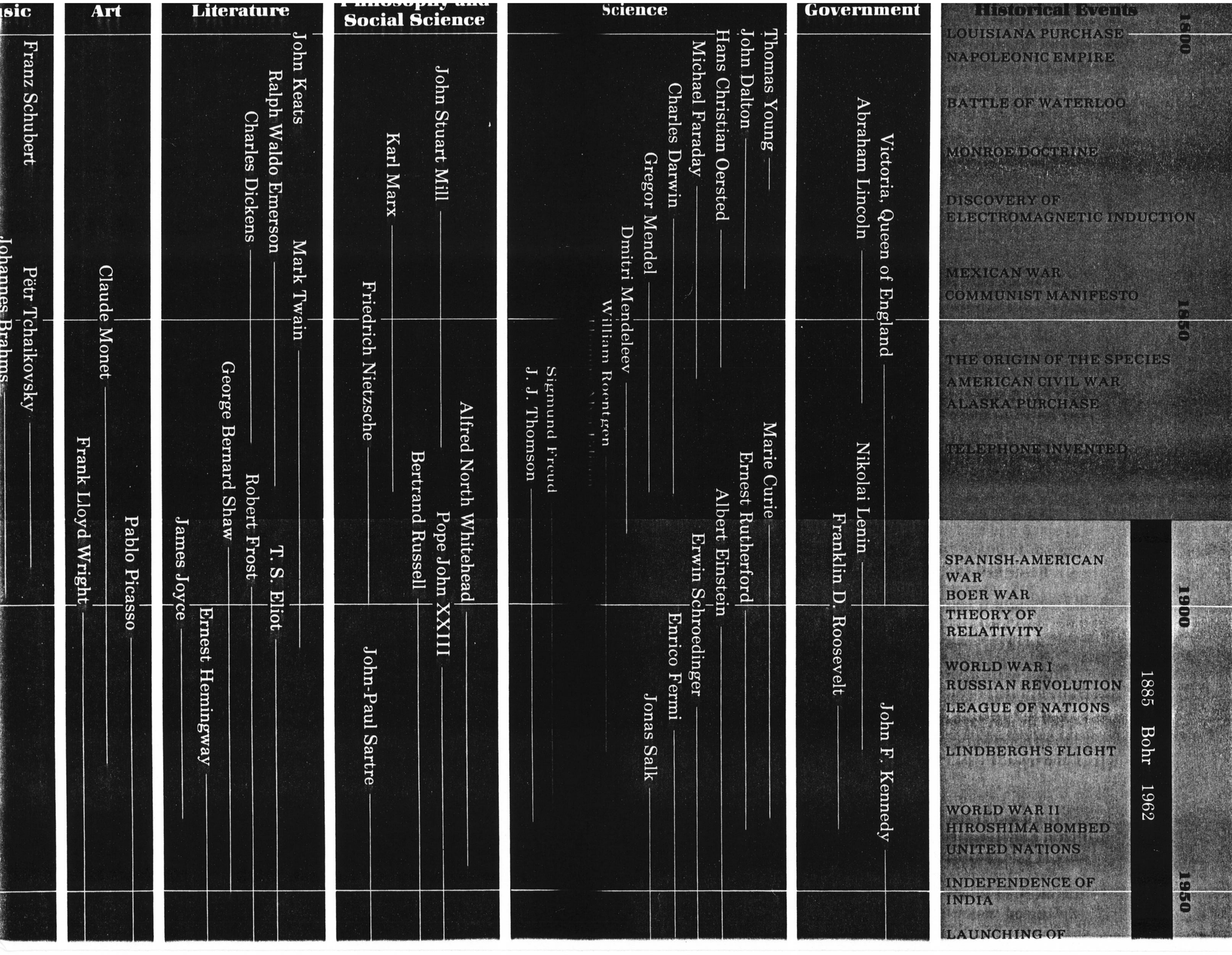
The new atomic model was definitely planetary. The surprising thing of the planetary model was how small the nucleus appeared. If the golf ball-sized atom was once again inflated, this time to the size of a modern sports arena or football stadium, the nucleus of that atom would be the size of a grain of rice. Somehow the electrons whirled about, filling in the vast space within the tiny atomic world.

These experiments were carried out by Lord Ernest Rutherford and his assistant Ernest Marsden.[1] Rutherford was also given his own laboratory in the industrial Midlands of Manchester, England. With the success of what is now called the *Rutherford nuclear atom*, Lord Rutherford led his group of scientists in an attempt to picture how the electron "planets" were able to maintain themselves in orbit and yet radiate energy in the form of light waves. Rutherford's success was, I'm sure, not too palatable for his counterpart, Lord Thomson, down south.

Into this slight animosity a young innocent was about to step. His name was Niels Bohr.

Bohr's Quantum Atom

Dr. Bohr had just completed his doctoral thesis in Copenhagen, Denmark, when he reported to work for J. J. Thomson at the "Cavendish." Lord Thomson, Bohr's first employer, probably



Art
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Frank Lloyd Wright
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James Joyce
Ernest Hemingway
John Stuart Mill
Karl Marx
Friedrich Nietzsche
Alfred North Whitehead
Bertrand Russell
Pope John XXIII
John-Paul Sartre
Thomas Young
John Dalton
Hans Christian Oersted
Michael Faraday
Charles Darwin
Gregor Mendel
Dmitri Mendeleev
William Roentgen
Sigmund Freud
J. J. Thomson
Marie Curie
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RUSSIAN REVOLUTION
LEAGUE OF NATIONS
LINDBERGH'S FLIGHT
WORLD WAR II
HIROSHIMA BOMBED
UNITED NATIONS
INDEPENDENCE OF INDIA
LAUNCHING OF
1885 Bohr 1962

felt less than enthusiastic over meeting the twenty-six-year-old Bohr. Besides possessing an incredible mind, Bohr was quite forthright and outspoken. Thomson's model for an electron had been the subject of Bohr's thesis, and Bohr immediately pointed out some mathematical errors in Thomson's earlier work.

By the autumn of 1911, Bohr found himself, much to Thomson's urging, on his way to Manchester to join Rutherford's group. He quickly joined in with this newly excited group of physicists and began his own search for the electrons within atoms.

The simplest and lightest-known atom in the universe was hydrogen. It contained, according to Rutherford, a tiny nucleus and a single electron orbiting that nucleus. It was hoped that, if a successful model of this atom could be made, all other atoms would fall into line and be explained. So Bohr attempted to make a model of the hydrogen atom.

There was, however, a severe stumbling block in the way of the planetary picture of an atom. The problem was how could the electron keep a stable orbit? If the atom was as big as it appeared to be, its electron would necessarily be whirling around inside it with greatly accelerated changes in speed and direction, filling out the space like the tip of a whirling propeller blade fills out a circle. The electron would have to do this and *not* emit any energy. Certainly, it could not emit its energy continuously. To do so would be a disaster for the model. The reason for this is that the planetary model predicts a spiraling motion of the planet into the sun for any planet that gives up energy continuously. That would mean the electron would crash into its nucleus every time it emitted its light energy. The whole atom would be suddenly deflated and all matter would undergo a rapid collapse. It is amazing to consider how tiny atoms would be if the atomic electrons were gobbled up by their nuclei. A football stadium would be shrunk to a grain of rice. The earth would be shrunk to the size of a football stadium! All matter would thus appear with enormous density. (Neutron stars do appear in our universe with these densities. The force of gravity crushes the atoms together.) And all matter would be dead and lifeless. The light would be gone.

But if the electron could not emit energy continuously, how was it to radiate any light? Light emission took energy. The electron would have to radiate energy sometime or no light would ever be seen. The question was how to make up a planetary model in which the electron would only radiate energy sporadically or in a discontinuous manner. Thus Bohr attempted to visualize under what circumstances the electron would be "allowed" to radiate energy and under what circumstances it would be "forbidden" to do so. This was not an easy decision to make. Bohr's model would have to show a reason for the discontinuity. How could Bohr explain it?

He explained it very simply. He postulated that an atom would only be allowed the privilege of emitting light when an electron jumped discontinuously from one orbit to another. It would be forbidden from doing so otherwise. Like Planck and Einstein before him, Bohr was setting out on a bold path. In fact, he was encouraged by their example. He felt that somehow Planck's h factor had to be involved in the process. He knew that h had been used by both Planck and Einstein to point to the discontinuous movement of light energy in solid matter. Perhaps it could also be used inside of an atom. But how? Bohr found out.

This new secret was actually no mystery to anyone familiar with physics. It had to do with something that physicists call *units*. A unit is a measure of a physical quantity. Any unit can also be composd of other units. Take the common example of a monetary unit. An American dollar is a unit of money, and it is composed of other units as well. For example, a dollar is ten units called dimes, or one hundred units called pennies. Similarly, it is also one-tenth of a unit called a ten dollar bill.

Planck's constant h also was a unit. And it too could be made up of other units. It was a unit of energy-time, something that physicists call *action*, and it was a unit of momentum-distance, just as a dollar is also ten dime units. But Bohr had noticed that h could be viewed as a unit of angular momentum and that observation had a direct bearing on his atomic model.

Angular momentum is a familiar experience for children. It results whenever a moving object passes a fixed point in space. If the moving object joins or connects with the point it is moving past, the object begins to whirl in a circle. Angular momentum can be thought of as momentum moving in a circle. When children run towards a tether ball hanging from a pole, they often leap and swing in a circle about the pole. By hanging on to the tether the children exhibit their angular momentum "about" the pole. Angular momentum is the product of ordinary or linear momentum and the radius or distance from the object to the reference point. Since Bohr's electron was traveling in an orbit about the nucleus, it too was tethered, held to that nucleus by an invisible tether of electrical attraction between the electron and the atomic nucleus. Thus the electron had angular momentum. Could Planck's constant *h* be used as a unit of the electron's angular momentum?

To grasp the significance of this question, imagine that you have a ball attached to a string. Holding the loose end of the string in your hand, whirl the ball around over your head, cowboy style, as if you were about to rope a calf. The faster you whirl the ball, the greater the force you feel, holding on to the rope. When you whirl the ball faster, you increase its angular momentum.

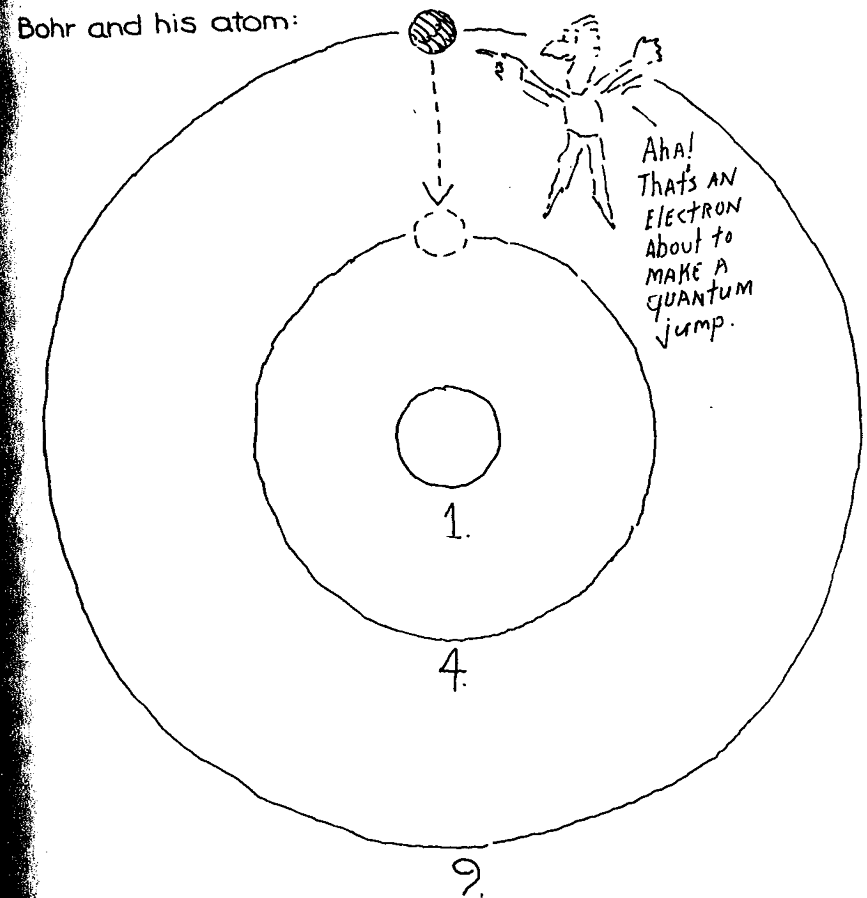
Now picture an ice skater whirling in a spin. Notice that as the skater brings her arms toward her body, she whirls faster. Her arms are acting like balls attached to ropes. But, unlike the whirling balls, although she is spinning faster, her angular momentum remains the same. This is because the distance from her spin axis to her arms has decreased to compensate for her increased speed of rotation.

If you now picture the tiny electron whirling around in its orbit, you will realize that for a given force holding it to its circular path and for a given *fixed* amount of angular momentum, the speed of the electron is determined. The radius of the orbit is also determined. Everything depends on the delicate balance provided by the amount of angular momentum the electron is allowed to possess.

Bohr tried out a calculation imagining a circular orbit for the electron with one unit of angular momentum. He calculated the size of the orbit requiring that the electron have one unit of *h*. The orbit was the correct size; it filled out the atom. He then tried a new orbit with two units of *h*. It proved to be a new orbit with a larger diameter, four times the original orbit. When Bohr calculated an orbit for the electron with three units of *h*, the orbit grew in size to nine times the original orbit. Bohr had discovered a new model for the atom.

In this model there were only certain allowed orbits. By restricting the electron to these special or "quantized" orbits, as they were later called, Bohr successfully predicted the correct size for the atom. Each orbit grew in size as the electron increased its angular momentum. But the scale was correct.

This wasn't the only discovery. Bohr also discovered why the electron wasn't radiating as it whirled in its orbit. In other words he found a reason for the atom's stability. By allowing the electron to have only whole units of *h* and not any other amounts of angular momentum, Bohr discovered the rule that kept the electron in a stable orbit. Only electrons with whole amounts of angular momentum (i.e., integer multiples of Planck's



Each circle represents an orbit for a planetary electron. The orbital diameters are in the ratio 1:4:9. In orbit one, the electron has one unit of h, in orbit two (diameter 4) it has two units of h, and in orbit three (diameter 9) it has three units of h.

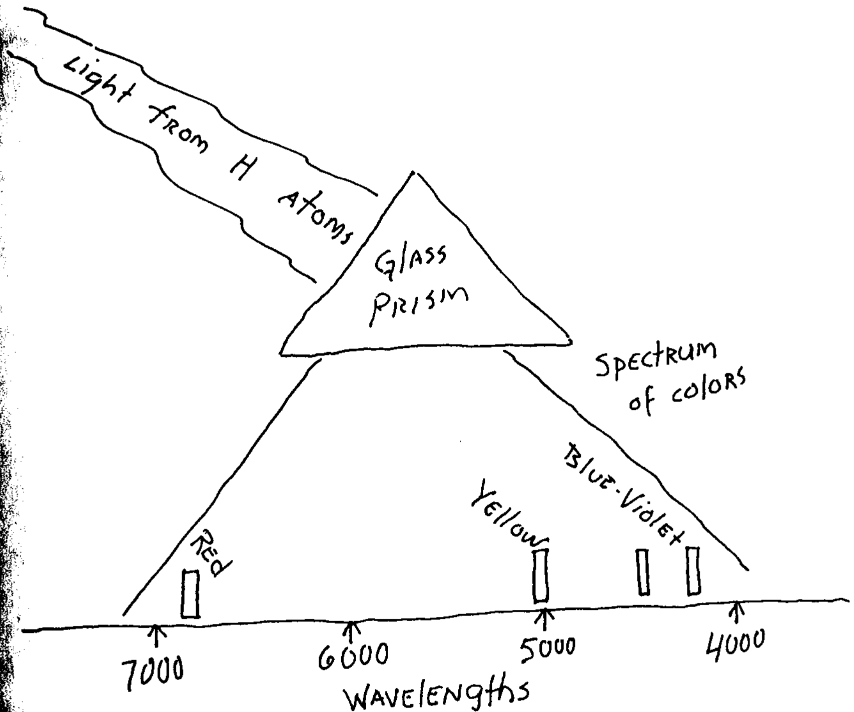
constant: $1h$, $2h$, $3h$, etc.) would be allowed the privilege of orbiting peacefully inside of the atom. These quantized orbits were known as *Bohr orbits*. The integers of 1, 2, 3, and so forth were called the *quantum numbers* of the orbits. A quantum model of the atom had appeared.

The only thing still needed was the "rule" that allowed the electron to radiate light energy. Again, there was no physical reason for the quantization rule that held the electron in a stable orbit. Bohr had made it up. So Bohr again postulated that the electron would radiate light whenever it changed from one orbit to another. He calculated the energy of the electron in each of its possible orbits. By comparing the difference in energies between the orbits and using Planck's $E = hf$ formula, Bohr successfully predicted the frequencies of the light observed whenever an electron made an orbital "jump."

In January of 1913, a former classmate of Bohr's showed him a paper written by a Swiss schoolteacher named Johann Balmer. Balmer had observed light coming from hydrogen gas in 1880. Instead of a continuous spread of colors, the light from hydrogen showed missing colors when it was passed through a prism and analyzed. The spectrum it produced appeared as a horizontal strip containing several vertical lines, like teeth in a comb. Only some teeth were missing. Ordinarily, the light we see—for example, sunlight or light from an incandescent bulb—does not break down into such a spectrum. Instead, sunlight or light from any hot solid or liquid shows a continuous spread of colors like a rainbow. But Balmer's incomplete spectrum had been produced by hydrogen atoms in a gas. Bohr read Balmer's paper on atomic light and became very excited. Not only could he calculate the energy of the electron in each atomic orbit, but he could also calculate the energy that the electron radiated away when it changed orbits.

Balmer's hydrogen spectrum had missing "teeth" because the energy given out by the jumping electron was so well prescribed. Since there were only certain orbits for the electron, there had to be only certain frequencies for the light. The frequency of the light depended on the difference in energies of the electron involved in the quantum jump from one orbit to another. Balmer's atomic light was explained.

All well and good. However, Bohr's successful prediction was based on a very disturbing picture. The electron making the light was not oscillating or orbiting the nucleus to make the light. In fact, it wasn't doing anything that anyone could really imagine. To make the light, it had to jump. It leaped like a



What Balmer saw: Light from hydrogen atoms breaks into a spectrum of colors.

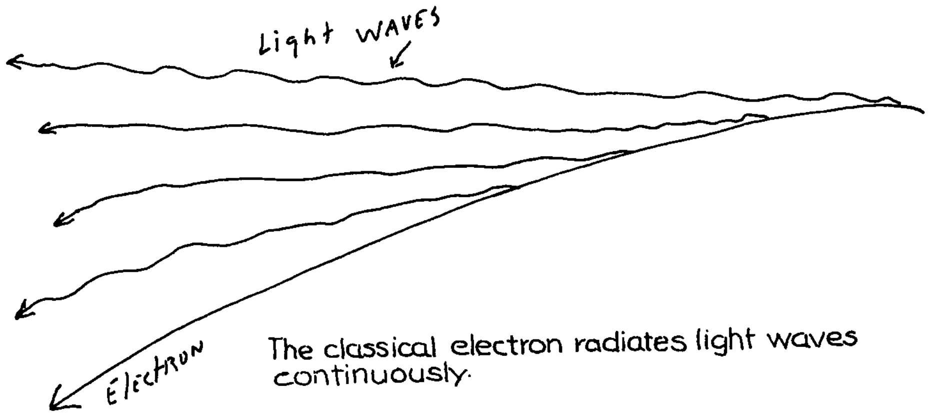
desperate superman from one orbit to another inside the atom. It was not allowed to move in between orbits. Bohr tried to calculate that and failed. The best picture he could come up with was that of a quantum jump, a leap from one place to another without passing in between. As unreasonable as this picture was, it replaced any completely classical mechanical picture of that process.

Yet Newton's mechanics were not to be completely abandoned. Some features of the classical picture were not abandoned at all. First of all, the idea of an orbit and a planetary atom were still classical pictures based upon a continuous movement of the electron. What was not classical was the refusal of the electron to radiate when it was in a Bohr orbit. This was entirely unreasonable for a very important reason: all accelerating electrons have been observed to radiate energy. Either the Bohr-orbiting electrons were accelerating or Newton's second law was being repealed.

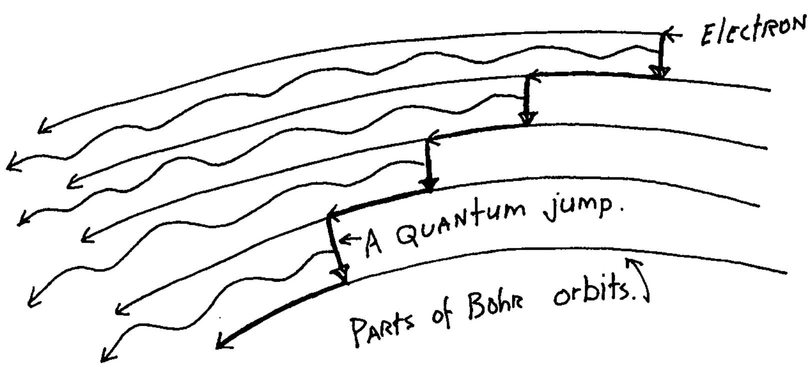
According to Newton, there was a force acting on the electron. That force pulled the electron into a circular orbit, changing the momentum of the electron. Therefore, there had to be an acceleration of the electron. And it also followed that, because the electron was a particle of electricity, the electron had to give out energy whenever it accelerated. Bohr's picture did not seem to correspond with this observed fact.

But Bohr was not to be dissuaded. He noticed that his rule of allowed and forbidden radiation was dependent on the size of the electron's quantum jump. A jump from the second orbit

What looks continuous is really discontinuous.



The classical electron radiates light waves continuously.



The Bohr electron follows a discontinuous path of quantum jumps.

to the first was extremely tiny, but a sizable change on the scale of the first orbital diameter. It was, therefore, a relatively enormous jump. On the other hand, a jump from orbit 10,000 to orbit 9,999 was very large when compared to the first orbital diameter, but an extremely small change in orbit on the scale of the 10,000th orbital diameter. Thus, it was a relatively tiny jump. When Bohr calculated the radiation from a change in orbits between large atomic diameter orbits, the result he found was in agreement with classically predicted results. In other words, the smaller the relative change, the more classical and continuous the result seemed to be.

Bohr had determined another exciting feature of quantum mechanics. It applied just where it was necessary. Wherever the world appeared to be continuous, the quantum "rules" corresponded with classical rules. This was called the *Principle of Correspondence*. Bohr felt very encouraged. He believed that he was on to one of God's secrets. He knew why the world appeared continuous even though it was fundamentally a discontinuous and quantum jumping world. It was all a question of relative scale. To Bohr, discontinuity was a fundamental truth.

But neither were the continuists to be dissuaded. They weren't ready to throw the whole classical towel into the ring. Although Bohr, in his excitement over the correspondence rule, was ready to drop all classical pictures, the continuists felt equally encouraged to find a classical reason for the jumps. Little did they know then that they would have to give up the particle world of matter in their attempts to rid themselves of quantum jumps.

When a Particle Is a Wave

I never saw a moor
I never saw the sea;
Yet I know how the heather looks
And what a wave must be.

EMILY DICKINSON

A Prince Imagines a Wave

The flame of desire for a mechanical model of the atom was about to be refueled. Bohr's orbits were too disturbing. Electrons should have some physical reason for not radiating whenever they are confined to such periodic movements. Furthermore, there must be a natural and physical reason for Planck's mysterious $E = hf$ formula that would relate the energy of Einstein's photon of light with the frequency of that light's wave motion. But what explanation could there be? While classical Newtonian mechanics did not provide any insights, perhaps the "new" mechanics of Einstein's special theory of relativity would shed some light on light. And perhaps this was the desire of one well-to-do prince of the French aristocracy, Louis Victor de Broglie.

De Broglie came from a long line of French royalty.[1] His notable family dated back to the American Revolutionary war, where his ancestors fought for the revolutionaries. Although he completed his education in history by 1910, his brother, a well-known physicist, persuaded him to return to school and study physics. De Broglie soon became fascinated with the quantum controversy and the ideas of Albert Einstein. By 1922, after interrupting his studies to fight in World War I, he published two papers on Einstein's wave-particle concept of light.[2] He called attention to the dual behavior of light. One type of observation, in which the time for observing is spread over many millions of cycles of wave oscillation, shows that light is a wave. Another type of observation, in which there is an instantaneous transfer of energy from light to matter or vice versa, showed that light consisted of particles called *photons*.

De Broglie wished to provide a mechanical explanation for the wave-particle duality of light. Thus, he needed to find a mechanical reason for the photons in the wave to have an energy that was determined by the frequency of that wave. It was while thinking about light that the idea occurred to de Broglie that matter, too, might have a wave nature.

He knew of Bohr's strange result. The electron in a hydrogen atom would orbit its nucleus only in special orbits. In each orbit, the electron had to have a whole number of angular momentum units, multiples of Planck's constant *h*. De Broglie was struck with another wave analogy. He remembered *standing waves*.

If we consider a violin string for a moment, we will see de Broglie's analogy. When the string is plucked or bowed, it vibrates. The string moves up and down in a characteristic manner. The ends of the string, of course, are held down tightly with pegs. If we watch carefully, we will see that the string resembles a wave. The middle of the string vibrates up and down. This kind of wave is called a *standing wave*. It oscillates up and down, but does not move along the string. The sound of the violin string is produced by this standing wave pattern.

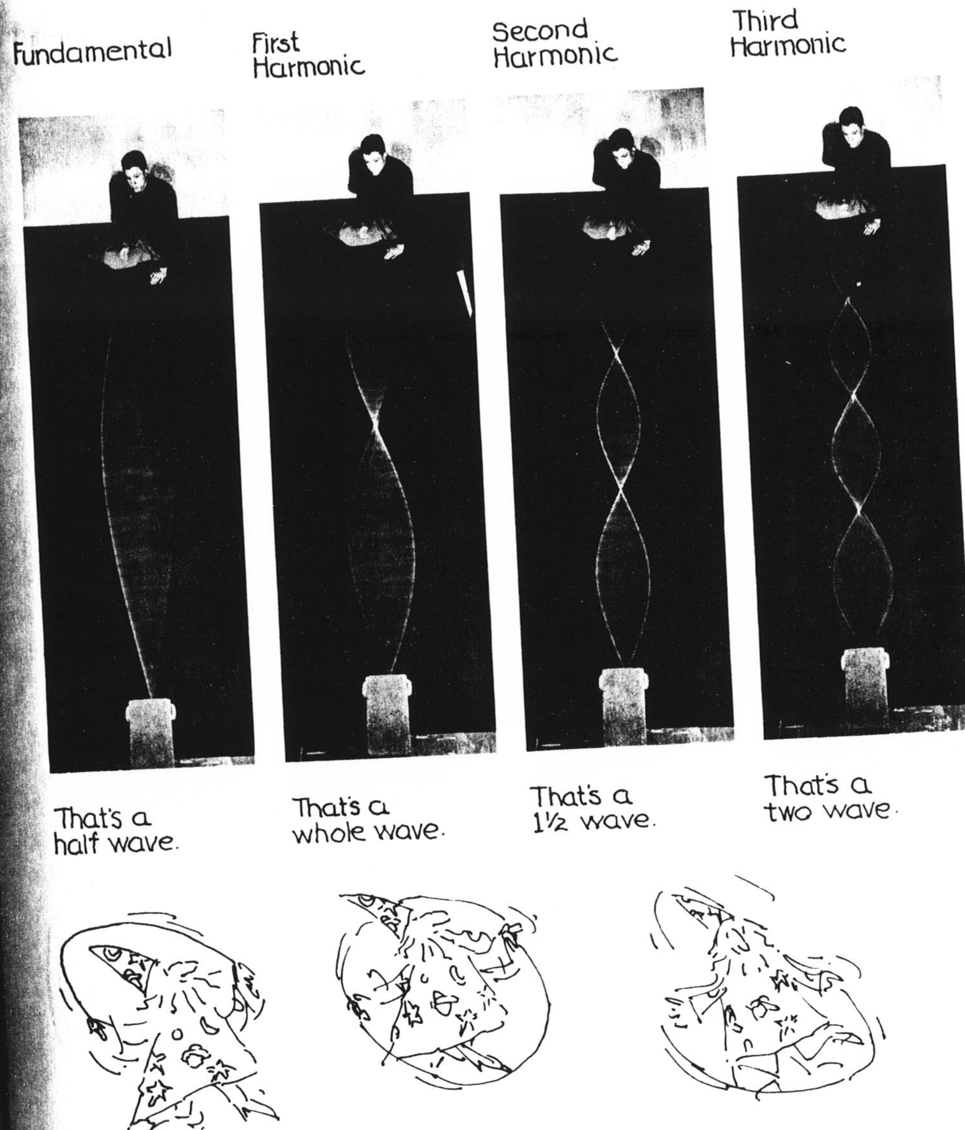
It is also possible to see and hear another vibration on this same string. In this second example, the middle of the string remains at rest while the rest of the string, not including the fixed ends, vibrates. The sound we hear is an octave higher. This standing wave pattern, called the second harmonic, has a higher frequency than the first one. Again, by watching closely we see that there are two up-and-down movements, one on each side of the fixed middle point.

A third harmonic occurs when there are two points along the string, in addition to the endpoints, that remain at rest when the string vibrates. Each resting point on the string is called a node. As the number of nodes on the string increases, the frequency of the standing wave increases and the pitch of the sound wave it produces increases.

De Broglie noticed a connection between the angular momentum of the electron in a Bohr orbit and the number of nodes in a standing wave pattern. The orbiting electron could only have one unit of *h*, two units of *h*, etc. Could these discontinuous changes in the electron's angular momentum, these changes in the amount of *h* allowed, be due somehow to a similar change in standing wave patterns?

What de Broglie had noticed in analogy was that the number of nodes was a whole number for any standing wave pattern. The lowest frequency standing wave had two nodes, the end points of the string. The next higher frequency had three nodes. The next wave had to have four nodes, and so on. Since, according to Planck's $E = hf$ formula, energy was frequency, could the higher energy orbits in the hydrogen atom correspond to higher harmonic matter-wave frequencies?

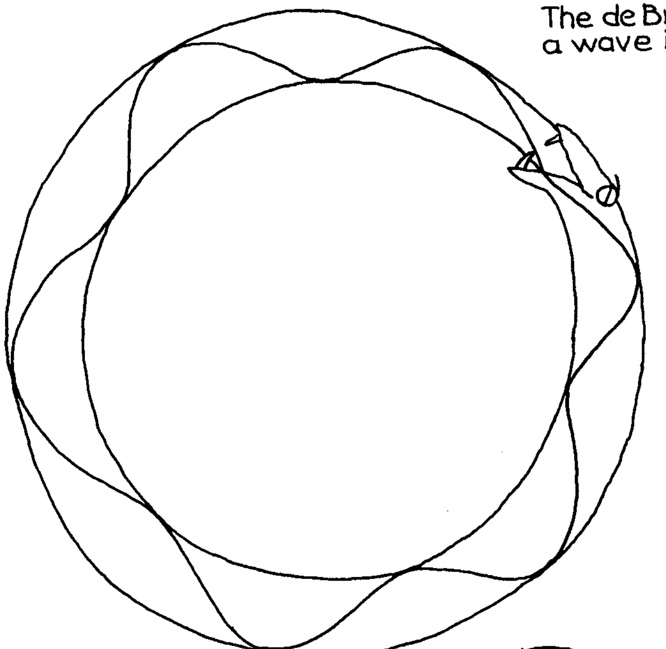
De Broglie realized that the Bohr orbit could be seen as a circular violin string, a snake swallowing its own tail. Would the orbit size predicted by his standing "matter waves" correspond with Bohr's calculated circles? In other words, what would his waves do if they were confined in a circle?

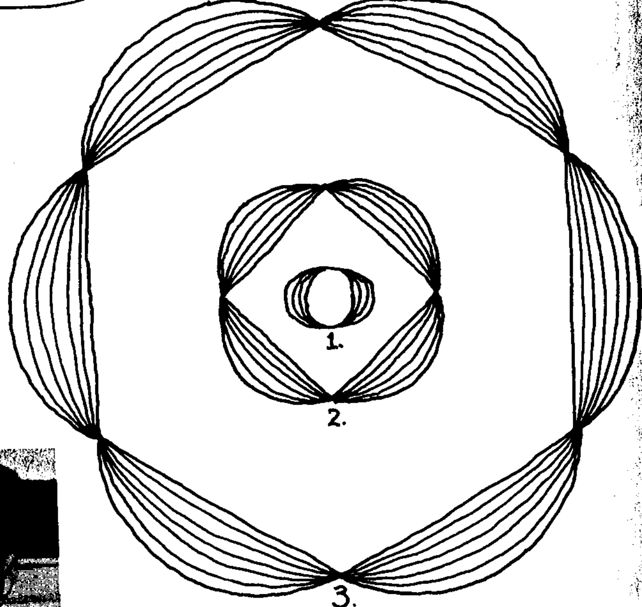


Standing wave patterns for a jump rope.

De Broglie discovered that his matter waves fit Bohr's orbits exactly. When he calculated the wavelength of the lowest orbit, he discovered another astonishing mathematical connection between the wave and the particle. The momentum of the orbiting electron equaled Planck's constant divided by the wavelength. He quickly reviewed his calculation and looked at the next orbit. It had a higher energy. It also checked out the

The de Broglie "orbit": a wave in a circle.





DeBroglie and his atom.

Bohr's orbits are replaced by standing wave patterns. The first orbit has one whole wave, the second has two whole waves, and the third has three.

same. For each Bohr orbit, the electron's momentum equaled h divided by the standing wave's wavelength.

De Broglie had discovered a new formula, one as startling and revolutionary as Planck's formula. It stated that the momentum of a particle p was equal to Planck's constant h, divided by the wavelength L. That is, $p = h/L$.

With this new mathematical discovery, Bohr's orbits could be explained. Each orbit was a standing wave pattern. The lowest orbit had two nodes. The next one had to have four nodes, since an orbit with three nodes would cancel itself out. The third orbit had to have six nodes, and so on. The energy of the electron in each orbit was given by h times the wave frequency. The momentum of the electron in each orbit was given by h divided by the wavelength. The mathematics worked out.

The atom was a tiny tuned instrument. These mathematical relations balanced the tiny electron into a tuned standing wave pattern. Orbits had determined and fixed sizes in order that these distinct, "quantized" *wave patterns* could exist.

Louis de Broglie published his results as a thesis dissertation for his doctorate in physics. He presented it, somewhat reluctantly before the Faculty of Sciences at the University of Paris in 1923.[3] His thesis was certainly original, perhaps a little too original. The study of atoms was a branch of physics, not musical composition. There was no experimental justification for this "crazy" idea. In fact, using such an absurd idea to explain Bohr's absurdity was a little too much for the reserved faculty.

Albert Einstein was called in. Einstein replied, "It may look crazy, but it is really sound!" The thesis was accepted, and a while later, the prince was awarded a Nobel Prize for his dissertation. Someone in America had actually discovered a de Broglie wave.

American Grains of Waves

Einstein welcomed de Broglie's picture. It was a return to continuous mechanism. The wave that guided the electron in the atom had been undetected so far. De Broglie's calculation of the momentum indicated that, for the light-weight, high-speed electron, the wavelength L would be extremely short. In fact, these tiny waves confined to the minuscule orbits within atoms were less than two billionths of an inch long. Even light waves were about five thousand times longer.

De Broglie's wave was envisioned as accompanying any particle wherever the particle went. Like a shadow, the matter wave traveled alongside its particle. The two belonged together. The frequency of the wave could always be determined by the particle energy; the wavelength could be determined from the momentum of the particle. Matter, like light, had a dual nature. This was the wave-particle duality.

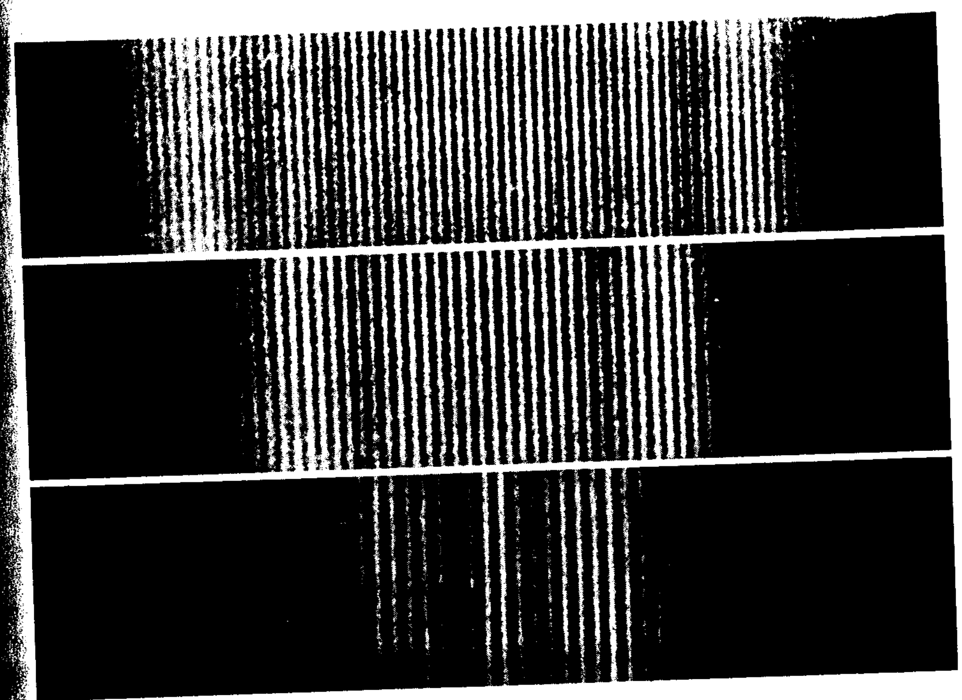
Although these new discoveries were sweeping European science back and forth, little of the furor crossed the Atlantic to the United States. Americans were more concerned with practical discoveries. The Bell telephone laboratories exemplified the practical side of American research. But Clinton Davisson, who worked for Bell,[4] had noticed a peculiarity in his research. He had found that the electrons he was using in his experiments were reflecting from the clean surfaces of nickel crystals in an unexpected pattern. Trusting his results, he published them without offering any explanation.

Davisson's results made their way across the Atlantic. Two German physicists, James Franck and Walter Elsasser, grew excited when they saw these electron reflection patterns.[5] The patterns did not appear to make any sense unless they were wave interference patterns produced by the electron matter waves reflecting from the nickel atoms. By checking the momenta of the electrons that Davisson had used, Franck and Elsasser were able to determine a reflection pattern for the electrons. That pattern depended on the de Broglie calculation of the wavelength in his $p = h/L$ formula. The calculated pattern matched Davisson's measured results. De Broglie's waves had been detected.

Other experiments followed. With the discovery of the neutron, a new particle contained within the atomic nucleus, physicists made neutron diffraction patterns that appeared just like the electron patterns observed by Davisson. Scientists soon realized that any kind of particle would produce a wave pattern if a beam of those particles were directed to an appropriately sized crystal that would allow the waves to interfere with each other.

Matter waves were now accepted. In fact, they were accepted so completely that physicists began to doubt even the existence of particles. Perhaps the waves could be made to interfere with each other and, in so doing, produce a particle. Could this idea be backed up by a careful mathematical analysis?

Such an analysis was needed for another reason as well. De Broglie's waves only held for particle beams and closed Bohr



Matter wave interference patterns. By changing the momentum of each electron, the wavelength changes. The separation between the "teeth" increases as the wavelength gets longer.

orbits. But how does an electron change from one orbit to the next? What is mechanically and continuously going on inside the atom? Newtonian mechanics was not dead; it had only been modified to accommodate a new form of matter—the matter wave. Somehow there had to be a way to describe the movement inside of an atom that would allow the electron to change orbits and radiate away its excess energy as light. To find such an answer, an expert on waves was needed.

Schroedinger's Unimaginable Waves: The End of Pictures

There was certainly something to be said for de Broglie's waves: at least they offered a picture of what was going on inside of an atom. However, more was needed. A way to visualize the shifting patterns of the wave when it changed its energy and produced light was needed. Neither Bohr's jumping electron particles nor de Broglie's wave patterns were enough to explain the light coming from different atoms. But Erwin Schroedinger, an Austrian physicist, found a mathematical equation that explained the changing wave patterns inside an atom.[6]

Schroedinger's equation provided a continuous mathematical description. He viewed the atom as analogous to the vibrating violin string. The movement of the electron from one orbit to another lower energy orbit was a simple change of notes. As a violin string undergoes such a change, there is a moment when both harmonics can be heard. This results in the well-known experience of harmony or, as wave scientists call it, the phenomenon of *beats*. The beats between two notes are what we hear as the harmony. These beats are perceived as a third sound. The vibrational pattern of the beats is determined by the difference in the frequencies of the two harmonics.

This was just what was needed to explain the observed frequency of the light waves or photons emitted when the electron in the atom undergoes a change from one orbit to the other. The light was a beat, a harmony, between the lower and upper harmonics of the Schroedinger-de Broglie waves. When we see atomic light, we are observing an atom singing harmony. With this explanation, Schroedinger hoped to save the continuity of physical processes.

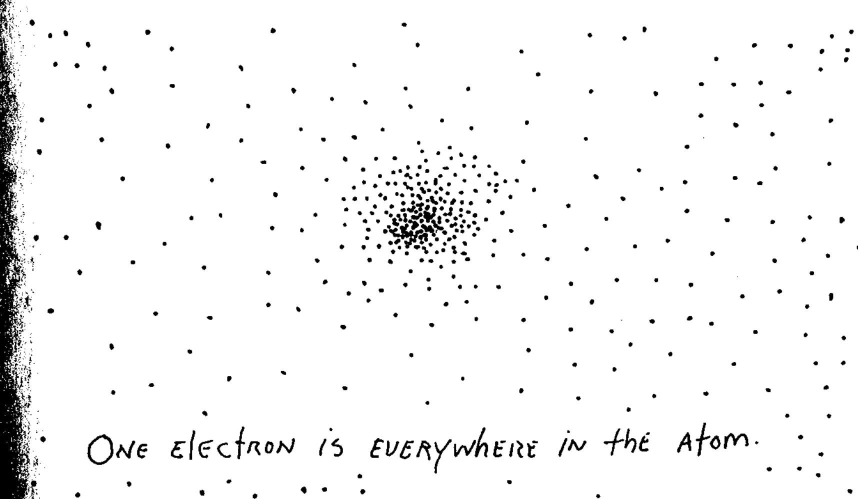
Schroedinger's dancing mathematical waves were in his mind.

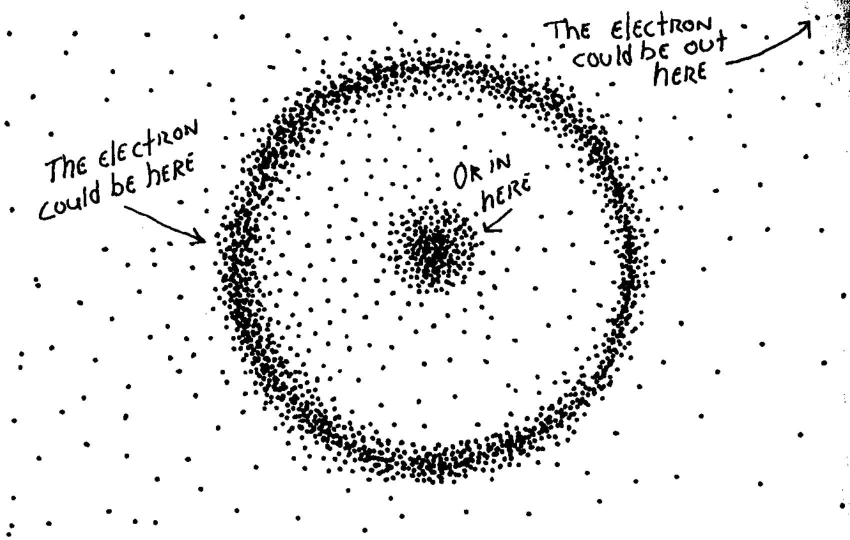
However, physicists were not altogether comfortable with his wave equation. No one could imagine what the waves looked like. They had no medium to wave in, and they had no recognizable form in physical space. They didn't look like water waves or sound waves. Instead, they were abstract, mathematical waves described by mathematical functions.

Although a physical picture of a mathematical function is difficult to imagine, it is not impossible. If you have ever stepped into a shallow wading pool—one that has been recently visited by young children—you may have experienced a disconcerting physical manifestation of a mathematical function due to the children's unfortunate lack of bladder control. As you moved from one place to another in the pool, you undoubtedly noticed that there were warm spots and cold spots. The temperature of the water was not the same everywhere. Temperature was a mathematical function of location in the water. In time, the temperature could even change at a given point in the water. Temperature was also a function of the time of observation. In other words, the temperature was a mathematical function of space and time.

Similarly, Schroedinger's wave was a mathematical function of space and time. The only problem was that no one knew how to look for its "warm and cold spots"—in other words, its troughs and crests. Furthermore, as the atom became more complicated, the wave also became more complicated. For example, the wave

Schroedinger's hydrogen atom: A pattern of probability.





Schroedinger's hydrogen atom: Just before it radiates.

describing one electron is a function of that electron's location in space and time. That's not too difficult. But if we are looking at a helium atom, there are two electrons present, but only one wave. The wave behavior, then, depends on the location of both electrons at the same time. And as the atomic number of an atom increases, the number of electrons contained within that atom increases. Uranium, which has an atomic number of 92, has 92 electrons and only one wave function describing it all. There was simply no convenient way to picture this wave.

But despite its unimaginability, Schroedinger's wave proved indispensable. For it explained a great many physical phenomena to which the classical model could no longer be applied. It was a successful mathematical way to explain light from any atom, molecular vibrations, and the ability of gases to absorb heat at extremely low temperatures. Physicists were excited and eager to apply Schroedinger's mathematics to anything they could get their hands on. They were like a gang of kids who had invaded the kitchen and, after many disappointing attempts to bake a cake, had suddenly discovered mother's cookbook. Schroedinger's formula gave the correct recipe in every physical application imaginable.

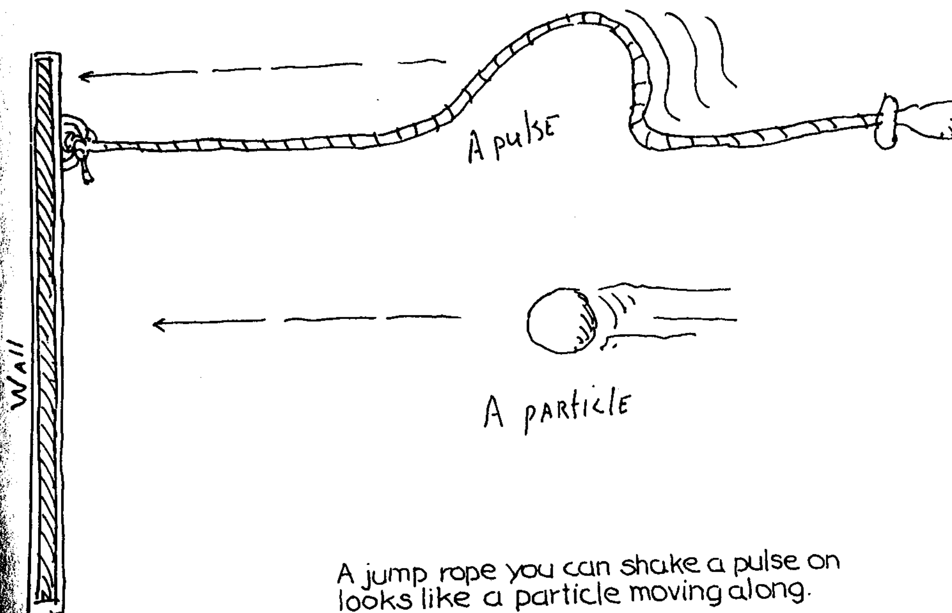
Everyone believed in Schroedinger's wave, even if no one knew how it waved in space and time. Somehow the wave had to exist. But even without a picture, the mathematics was enough—provided you knew how to read the mathematics cookbook. Could

the wave make a particle? Was there a way to use the Schroedinger cookbook to bake a particle? Even that was not impossible for the master chef. But how could one use waves to make a particle? The answer lies in our concept of a particle. It is a tiny object distinguished from a wave by one outstanding characteristic: it is localized. It occupies a well-defined region of space. It moves from one region of space to another. You always know where it is. It exists at one place only at any given time.

Waves are different; they are not localized. They are spread over wide regions of space and can, in fact, occupy any region of space containing many locations at the same instant of time.

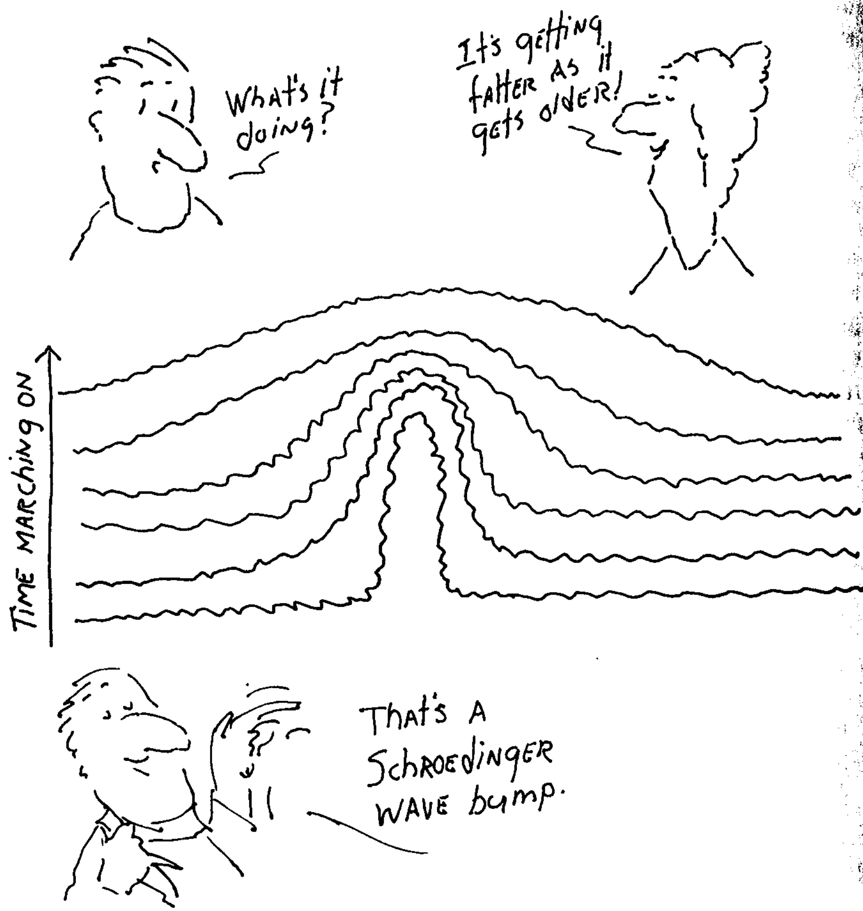
But waves can be added together. And when many waves are added, surprising results can be achieved. Schroedinger waves were no exception to the rule. Schroedinger waves could be added like ingredients to a recipe and produce a *Schroedinger pulse.*

A pulse is a special kind of wave. If you attach one end of a jump rope to a wall and take the other end in your hand, you can make a pulse by stretching the rope taut and giving it a sudden up-and-down movement. The pulse travels from your hand toward the wall and then reflects from the wall. This action resembles that of a ball thrown against the wall and bouncing from it. Perhaps that's all there was to an electron. It was a pulse on an invisible rope.



A jump rope you can shake a pulse on looks like a particle moving along.

But there was something awfully embarrassing about the idea of a Schroedinger pulse: it got fatter as it got older. That is, it spread out and became wider each second it existed. The problem was it had nothing to hold it together. It was made up of other waves, and each of these waves had its own speed. With time, each wave would move apart from the others. The pulse would stay together only so long as the waves remained in harmony with each other.



Schroedinger's free particle: The instant after you find it, it spreads.

Imagine, if you will, the pulse as a closely bunched herd of horses galloping around a racetrack bend. The horses can stay together for only a short time. Eventually, the group spreads out

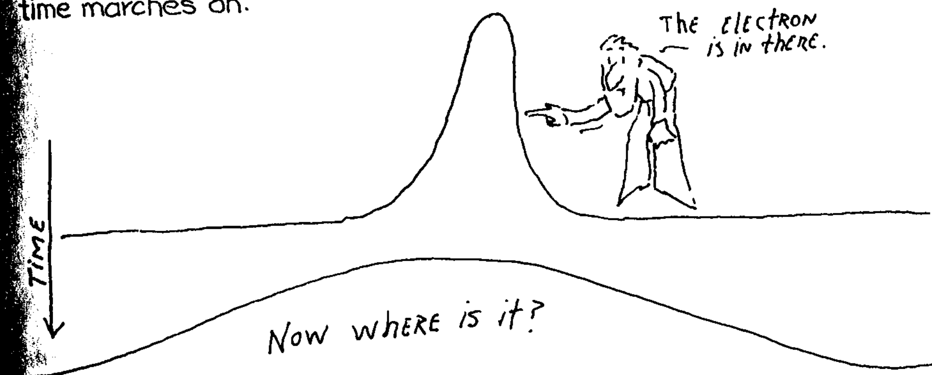
as each horse assumes its own pace. The slowest horses fall to the rear of the group, while the fastest ones move to the front. As time goes on, the distance between the slowest and fastest horses lengthens. In a similar manner, the pulse grows fatter as its slower waves fall out of synchronization with its faster waves.

Though big objects, like baseballs, also were made of waves, the larger the object was initially, the slower its waves spread. Thus a baseball maintained its shape because it was so big to begin with. The Schroedinger pulse describing the baseball was no embarrassment.

But an electron was a horse of a different color. While it was confined within an atom, the electrical forces of the atomic nucleus held its waves in rein. Its waves were only allowed to spread over a region the size of the atom, no further. But when an electron was no longer in such confinement, when it was set free, the waves making up its tiny pulse-particle size would begin to spread at an extremely rapid rate. In less than a millionth of a second, the electron pulse-particle would become as big as the nearest football stadium! But, of course, no one has ever seen an electron that big. All electrons appear, whenever they appear, as tiny spots.

This contradiction between our observations of electrons and Schroedinger's mathematical description of them uncovered a new problem: what prevented Schroedinger's pulses from growing so large? Little did anyone realize that question was to open the doors of paradox and mystery and lead us to a quite different picture of the universe. The answer to the question was: human observation kept them from growing so large. We were on the verge of the discovery of a new discontinuity.

A "skinny" Schroedinger pulse gets wider as time marches on.



No One Has Seen the Wind

The universe is not only queerer than we imagine, but it is queerer than we can imagine.

J. B. S. HALDANE

God Shoots Dice: The Probability Interpretation

It may be difficult for the nonscientist to imagine how repugnant the idea of a discontinuous movement of matter is to physicists who desire continuity. Starting with Einstein, the discontinuity in the movement of light was connected with a mechanical picture. Light consisted of granules. But then came Bohr and his quantum jumping electron inside of the tiny atom. This concept upset continuists because they could not understand how a particle could behave in this fashion. When de Broglie and Schroedinger appeared with their wave interpretation, the continuists breathed a sigh of relief.

Schroedinger's picture of the atom, although complicated and dependent upon a nearly unimaginable wave function, was nevertheless quite reasonable. The atom's electron *was* a wave. The atom radiated, not because its electrons jumped from orbit to orbit, but because of a continuous process of harmonic beats. The light was given out when the atom "music box" played both the upper energy and lower energy frequencies at the same time. The difference between the two electron matter-wave frequencies, which corresponded in Bohr's conception of the atom to the difference in the electron's orbital energies, was exactly the frequency of the light waves observed.

Gradually the upper frequency matter-wave tone quieted down, leaving only the lower harmonic. Thus the atom stopped radiating light. There was no longer a higher harmonic to beat against. The atom simply continued vibrating its electron wave at the lower frequency, which (according to the Planck $E = hf$ formula and the de Broglie $p = h/L$ formula) had to be unobservable and tucked safely away inside of the atom.

Later, Schroedinger's picture would be destroyed, but his equation, his mathematical law, would remain. And he would express to Bohr, after days of long and arduous discussion, his disgust with ever having been involved in this quantum jumping thing. The problem was that, no matter how the wave shook and danced, there still had to be a particle somewhere. Max Born would be the first to provide an interpretation of this "particle" discontinuity. The wave was not the electron. It was a wave of probability.

In 1954, Professor Max Born was awarded the Nobel Prize for his interpretation of the wave function. The award came nearly thirty years after he first offered the interpretation.[1] But then, Nobel Prizes come more slowly for ideas in physics than for experimental discoveries. Born explained his motives for opposing Schroedinger's picture of the atom.[2] He simply had too much connection with experimental work. He knew of the collision experiments being carried out in his own institute at Gottingen, Germany. Sophisticated refinements with vacuum techniques and electrical focusing of beams of electron particles had led to detailed studies of collisions between atoms and electrons. Despite the discovery of electron waves, these collision experiments were convincing evidence that the electron was still very much a tiny particle—literally, a hard nut to crack.

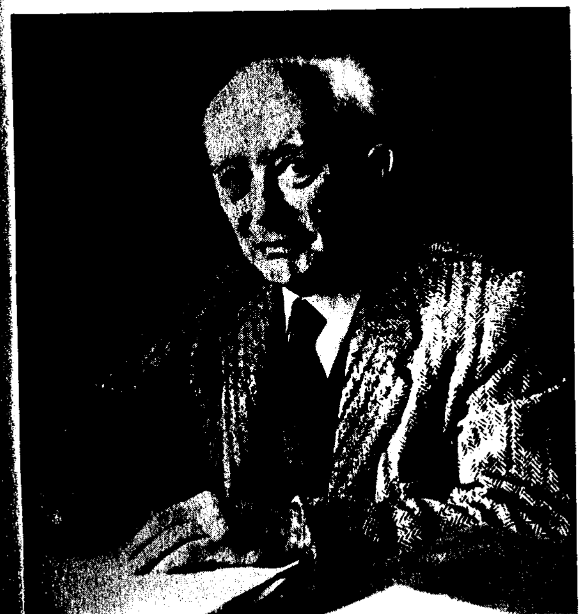
There was no doubt that Schroedinger's mathematics worked. His equation described correctly all observable atomic phenomena. But how could the Schroedinger equation be used in those very same experimental collision studies at Born's institute? In other words, what kind of wave function describes an electron beam colliding with a rarefied gas of atoms? Since the electrons in the beam were not confined within any atoms, they moved freely through space toward their eventual target, atoms.

Schroedinger's pulse describing a single electron was inadequate. It just got too big too quickly. It couldn't be a real tiny electron, the kind seen every day in Born's laboratory. But Born knew his mathematics. Wide electron pulses spread slowly. So if a pulse was wide to begin with, it would hardly spread at all as it moved from one end of the apparatus to the other end. However, since the pulses had to be many times wider than an atom, how could the electron fit inside of an atom?

Born realized that, in the experiments at Gottingen, no one was really able to locate a single electron in a beam of electrons. Could it be that the width of the wave pulse was connected somehow with our knowledge of the location of each electron? When Born allowed the pulses in his mathematical equations to be as wide as the dimensions of the beam, he found that the spreads of the pulses virtually vanished.

Born's efforts suggested that the time had come for a new interpretation of the meaning of the wave. The wave was not the real particle. Somehow the wave was connected with our knowledge of electron locations. It was, in fact, a probability function.

Probability functions are familiar today. They are used to describe the distribution of likely occurrences. A typical example



Max Born viewed Schroedinger's wave as probability in space for finding the electron.

is the probability function for a coin that is spinning in the air. As it falls, the probability function for it to land heads up is .50. Once the coin has landed, the probability function changes. If it has landed heads up, the probability function becomes 1. If it has landed tails up, the probability function becomes 0.

Insurance companies use probability functions to describe the distribution of automobile accidents. The stream of motorists driving into San Francisco each day is intense. That means the probability for any one car to collide with another is large. And the greater the intensity of the stream of motorists, the higher the probability of a collision. The situation is less intense, automotively speaking, in San Diego. Therefore, the probability density or distribution is lower for a collision to occur in that area. If we were to view the entire state of California from a satellite and watch all of the cars driving about, it would be quite easy for us to predict where collisions would be most likely to occur. We would simply note those areas where the flow of traffic was greatest—that is, most intense.

Born pictured the flow of electrons in much the same manner. Wherever there was a greater concentration of electrons in the beam, the Schroedinger wave had a greater intensity. By calculating that intensity, Born found he could predict the probability of a collision between an electron and an atom.

Born's picture made a tremendous impression on his fellow physicists. Again, sighs of relief were heard coming from physics labs all across Europe. But the picture still had a hole in it. Born's system made sense so long as it was applied to a beam or a concentration of actual numbers of particles. Physicists, like insurance actuaries, were quite used to probability ideas when they were dealing with a large number of practically uncountable events. In the experiments at Gottingen, the events were uncountable. But what about just one electron? One atom? How should the Schroedinger wave be interpreted in that case? Did the wave describe a single electron?

Was there a wave in these isolated cases? Was it, in other words, a real wave? And if the wave was a fundamental part of nature that belonged to each individual particle of nature, then who determined where the electron was to be found? Was nature essentially a probability game? Did God play dice with the universe?

A new interpretation was sought. Something was wrong with the probability picture. But what could replace it? The answer to this question had been brewing in Germany since the end of World War I. A new and revolutionary principle of reality was occurring to one man, a principle that was to completely change our thinking about the physical world.

Heisenberg's Uncertainty Principle: The End of Mechanical Models

If I had a time machine and could return to any period of time, which period would I choose? I would pick the Roaring Twenties; however, it would not be the United States that I would return to. No, indeed. Instead, I would go to post–World War I Germany. And because I am fascinated by pseudodecadence and café society, you would find me among such contemporaries as Bertold Brecht and Thomas Mann. Bauhaus art and design would be flourishing and outrageous Dada art would be creating "authentic reality" through the abolition of traditional cultural and aesthetic forms by the technique of comic derision. For, during that period, irrationality, chance, and intuition were guiding principles. Freud was out. Jung and Adler were in. Life had a certain cabaret feeling.

Now add the physicists. Though they numbered perhaps less than a hundred, a new breed of young, enthusiastic fellows was making its way into the new physics. Planck was past sixty. Einstein had seen his fortieth birthday. Bohr was a middle-aged thirty-five. These older and wiser moderates were to be the guiding lights for the new breed. It was time for Dada physics, and it was happening in Gottingen, Germany. In early summer, 1922, Professor Niels Bohr, who then headed a brand-new institute of physics in Denmark called the Copenhagen School, had come to give a lecture.

Among the students who had gathered to hear Bohr was twenty-year-old Werner Heisenberg. This occasion would be the first of many meetings between Heisenberg and Bohr. Together these two would change the meaning of physics. Eager to rid physics of mechanical models, they would herald a new school, a school of discontinuists. Their interpretations would lead to a revolution of thought.

Heisenberg wrote of this first meeting with Bohr in his book, *Physics and Beyond*. After some remarks concerning Bohr's atomic theory, he wrote:

> Bohr must have gathered that my remarks sprang from profound interest in his atomic theory. . . . He replied hesitantly . . . and asked

me to join him that afternoon on a walk over the Hain Mountain. . . . This walk was to have profound repercussions on my scientific career, or perhaps it is more correct to say that my real scientific career only began that afternoon. . . . Bohr's remark [that afternoon] reminded me that atoms were not things. . . .[3]

But if atoms were not "things," then what were they? Heisenberg's answer was that all classical ideas about the world had to be abandoned. Motion could no longer be described in terms of the classical concept of a thing moving continuously from one place to another. This idea only made sense for large objects; it did not make sense if the "thing" was atom-sized. In other words, concepts are reasonable only when they describe our actual observations rather than our ideas about what we *think* is happening. Since an atom was not seen, it was not a meaningful concept.

Heisenberg's thoughts had been influenced by Einstein. In 1905, Einstein had carefully laid out the steps to relativity. He

Young Heisenberg: A vison of uncertainty?

had recognized that, in order to speak about such notions as space and time, one must provide operational definitions—definitions that detailed how these things were measured. For example, space is what a ruler measures and time is what a clock measures. For anyone armed with these empirical and objective forms, space and time lose their mystery. Everyone holding rulers and clocks can agree on the definitions, because they can agree on which operations to do with these instruments.

A concept is useful when we all know how its measurement is to be accomplished. This viewpoint led Heisenberg to question any concept that had no operational definition. Atoms were not observable, but the light coming from them was observable. Thus, Heisenberg developed a new form of mathematical tools based upon the frequencies of the light that was seen, rather than the position and momentum of an unobservable electron within an unseen atom. These new mathematical tools were developed from the mathematics of *operators* and not the mathematics of numbers.

An operator in mathematics performs a duty. It changes or modifies a mathematical function in a defined way. For example, the operator called "square" will multiply any mathematical function by itself. (Thus when "square" operates on "x," it makes "x^2." When it operates on 5, it makes 25, etc. Operators are also capable of being operated upon. Thus "square" can be multiplied by the number 3, which can be an operator as well as a simple number. This makes "3•square," a new operator. When "three•square" operates upon 5 it makes 75 instead of 25. Two or more operators can also be multiplied together.) Heisenberg discovered, with the help of Max Born, that his mathematical operators, which corresponded to the observed frequencies and intensities of the light from atoms, obeyed a strange law of multiplication. The order in which you multiplied the operators was important. If the operators were, for example, A and B, then AB did not equal BA. (If we use the previous example of "three•square," we see that "three•square" is not the same as "square•three." For when "three•square" operates on 5 it gives 75, but "square•three" operating on 5 gives the result of multiplying 3 times 5 and then squaring. This gives 225, instead. Thus three•square does not equal "square•three.") Did that mean that the physical world depended as well upon the order in which you observed things?

Later, Born and Pascual Jordan carried Heisenberg's mathematics a step further. They were guided by Bohr's Principle of Correspondence that showed that the classical mechanical viewpoint would correspond with the quantum mechanical viewpoint whenever the quantum numbers describing the old Bohr orbits were quite large compared with 1. By following this principle, they were able to find mathematical operators for the position and the momentum of the electron instead of the frequencies and intensities used by Heisenberg. The surprising fact was that these operators, too, depended on the order in which they were carried out. A new and previously unsuspected picture of the universe was emerging.

The new tools of operator algebra were later found to be related to the mathematics of matrices. A matrix, an array of numbers, must be handled in a careful, well-defined way. The rules governing the use of matrices were found to be identical to the mathematical rules used to handle operators. Consequently, Heisenberg's development of quantum mechanics came to be called *matrix mechanics*. The wave mechanics of de Broglie and Schroedinger was still being investigated, however, and eventually it became apparent that the two forms of mathematical expression were simply disguised versions of the same thing. Schroedinger discovered this[4] and offered formal mathematical proof of their equivalence. For a while, interest in the purely operational matrix mechanics dropped.

Yet Heisenberg wasn't ready to dismiss the insights he had garnered from his matrix mechanics. He began to explore his observational basis for reality using the Schroedinger wave. Born's probability interpretation suggested how he should proceed, and, following the tradition of Einstein, Heisenberg attempted to describe the method by which the position and momentum of an atom-sized object could be measured.

To see something, we must shine light on it. Determining the location of an electron would require our sense of sight. But for so tiny an object as an electron, Heisenberg knew a special kind of microscope would be needed. A microscope magnifies images by catching light rays, which were originally moving in different directions, and forcing them all to move in much the same direction toward the awaiting open eye. The larger the aperture or lens opening, the more rays of light there are to catch. In this way, a better image is obtained, but the viewer pays a price for that better image.

The price is that we don't know the precise path taken by the light ray after it leaves the object we were trying to view in the first place. Oh, we will see it all right—a fraction after its collision with the little light photon that was gathered up by the

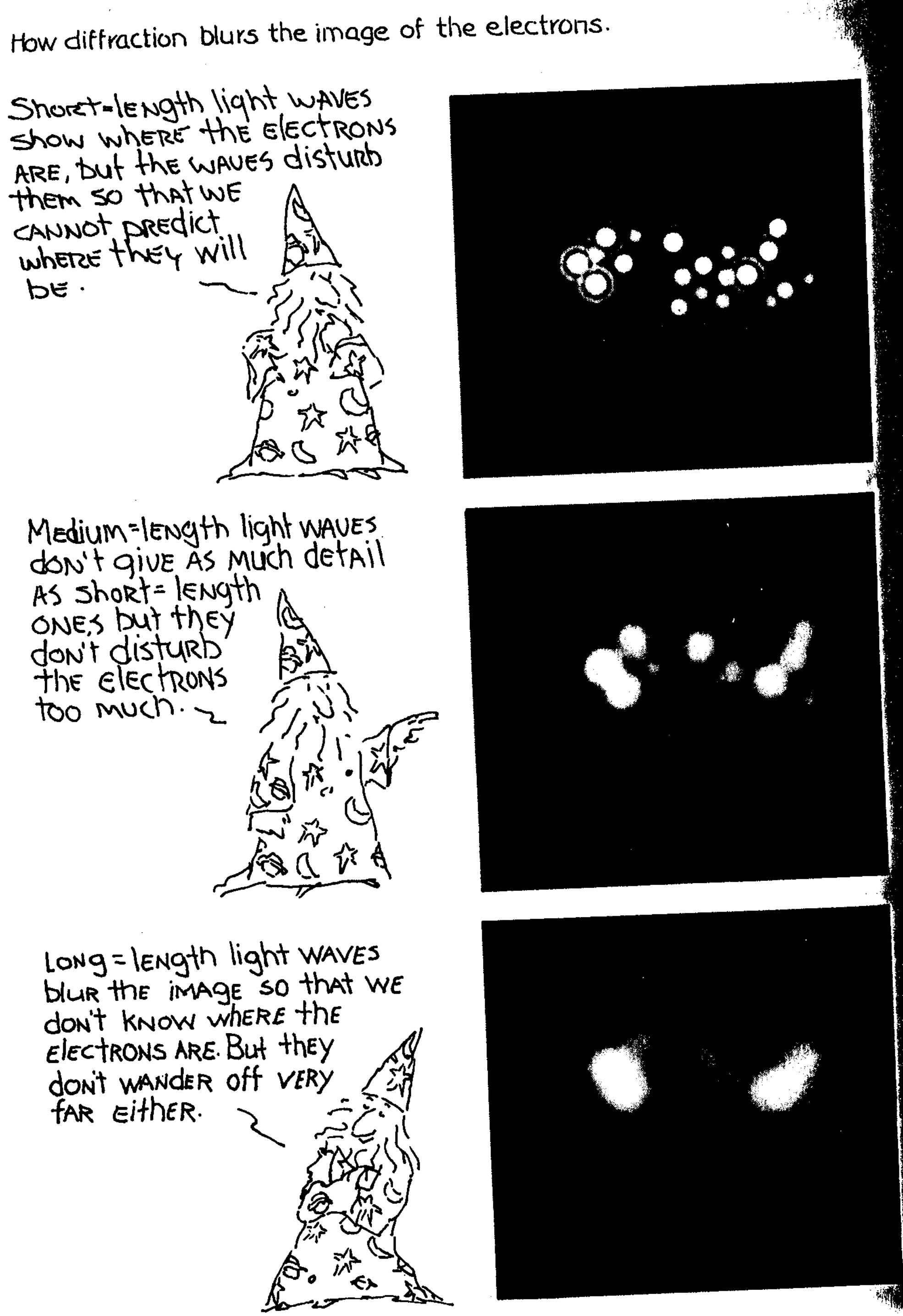
microscope. But was that photon heading north before it was corralled by the lens, was it heading south, or southwest? Once the photon is gathered in, that information gets lost.

But so what? We do get an exact measurement of the position of the electron. We can point out just where it was. Well, not exactly. We still must worry about the kind of light we use.Try to imagine painting a fine portrait the size of a Lincoln penny. What kind of brush would you use? The finer the hairs of your brush, the better your ability to create the miniature. If you were to reduce the size of the portrait even further, you would need an even finer brush.

Different kinds of light vary in their wavelengths in much the same way that brushes vary in the fineness of their hairs. To see something very tiny, you need to use light with a small wavelength. The smaller the object you are looking for, the tinier the wavelength you will need. Since an electron is very tiny, Heisenberg needed to use a kind of light that has a very small wavelength. This light is beyond our normal range of vision, though still detectable in a way similar to ordinary light. But according to de Broglie's formula, the smaller the wavelength of the light, the greater the momentum of the photon. Therefore, for Heisenberg to see the electron, the photon would have to hit it with a tremendous amount of momentum.

In Zen Buddhism, one speaks of using a thorn to remove a thorn as the process of finding out what is real. In Heisenberg's microscope, the tiny wavelengthed photon is as big a thorn as the electron it is inspecting. Thus, if we are able to catch the photon ray in the wide open lens of the microscope and if we are consequently able to "see" the position of the electron, we will have absolutely no idea of where the electron will be next. Our act of viewing the electron disrupts its motion. Though we learn the electron's position, we are left uncertain of its momentum; we simply do not know how fast or in what direction the electron was moving at the instant of impact.

We may attempt to remedy the situation by doing one of two things. First, we can use photons that do not give the electron so big a "kick." That is, we can use light that has a longer wavelength. But this remedy has a disadvantage: we lose information about the precise location of the electron. Like the painter with a brush of coarse hairs, we cannot manage the details of our electron portrait. Our second option is to make the lens opening, the aperture, smaller. For by taking in less light, we are able to determine more accurately the direction the photon takes after its



collision with the electron. Unfortunately, this remedy also has a disadvantage. Light behaves very much like a wave with respect to the aperture. That means it bends or diffracts as it passes through the hole. The narrower the space offered to the light, the worse the bending. Consequently, narrowing the aperture brings us less information about the location of the electron, because the image we receive is distorted by the bent light rays.

If you have ever tried to convince someone to change his way of life, you may have noticed how he had some good reason why the change you suggested could never work. Even though the person sought your advice, he had a ready answer defeating your marvelous idea as soon as you offered it. Your stubborn friend, you probably realized, had simply made up his mind in advance. Similarly, Heisenberg had discovered nature's stubborn streak. Yet there seemed no way to catch her in her act. The more one knew of the position of the electron, the less one knew of its path to the future, its momentum. And the inverse was also true. But was nature just hiding from us? Heisenberg didn't think so.

Remember that we began this section with the premise that we can define only what we can measure. Since we cannot measure both the position and the momentum of any object in this universe with exact precision, the very concepts of "position" and "momentum" are in doubt. So how can these concepts be given any meaning? Heisenberg contended that although the notion of "path" implies clear knowledge of both "position" and "momentum" simultaneously, it could be retained in quantum physics. His rationale was extremely provocative. He said, "The path comes into existence only when we observe it."[5]

To grasp Heisenberg's statement, let us take another look at the Bohr atomic model. Accordingly, if an electron is in an orbit with a large quantum number—say, orbit 10,000—it will behave in a nearly classical manner. The size of this orbit is quite visible with ordinary light, for its diameter is about one-half inch in length. However, the correspondence principle warns us that it will be quite difficult to see any difference between orbit 10,050 and orbit 10,000. These orbits are too close together for us to perceive the difference with ordinary light. Thus, if we shine ordinary light on the atom when the electron has a large orbit, we cannot be certain which orbit we are witnessing.

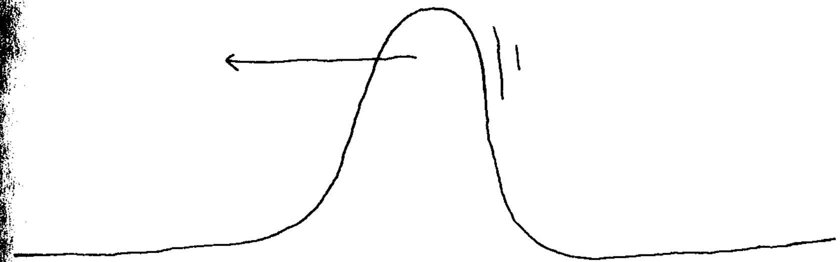
Is the electron in a specific orbit? In other words, does the electron occupy a given point in space at a given time, and does it follow a smooth and continuous trajectory to the future point along that trajectory? According to our observation, we will not be able to determine the actual orbit for the electron. But shall we still assume that it has such an orbit? Certainly we know more about the electron after we observe it than we did before we observed it.

But how did we gain this knowledge? According to Born's interpretation of the Schroedinger wave, the wave describing the electron is a description of our knowledge. In other words, the wave shape and size tell us where the electron is likely to be observed. But, if after we actually observe an electron we know more than we did before we observed it, the Schroedinger wave must have changed its shape and size to correspond to our change of knowledge. But what caused the Schroedinger wave to change, and how?

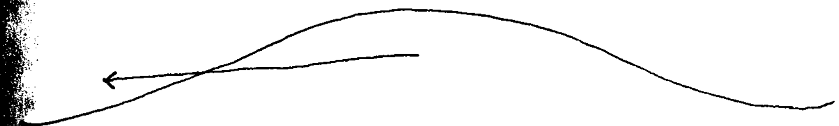
If we imagine that no attempt was made to observe the electron, then the wave pulse composed of those Schroedinger waves, which satisfy the Schroedinger equation, would continue to spread. In fact, they would continue to spread indefinitely. Meanwhile, we are losing information concerning the location of the electron. Even though the light we use is not a very precise guide to determining the electron's location, it is better to light one little match than curse the darkness.

Once we see the light reflecting from the electron, we have a much better idea of its actual location. With our location of the electron, there is a corresponding change in size of the Schroedinger pulse describing the electron. Following Born's interpretation, the size of the pulse is a measure of our knowledge of the electron's location. Since we now have a better knowledge of the electron's location, we must have a correspondingly more narrow Schroedinger pulse describing that electron. But that would mean the Schroedinger pulse describing the electron must have gotten thinner as a result of our observing the electron. It had to thin down because we have more information with the light on than we did without observing the electron. We can see, for example, that the electron is on the right side rather than the left side of an observing screen. Our observation process has somehow reduced the pulse to a smaller size.

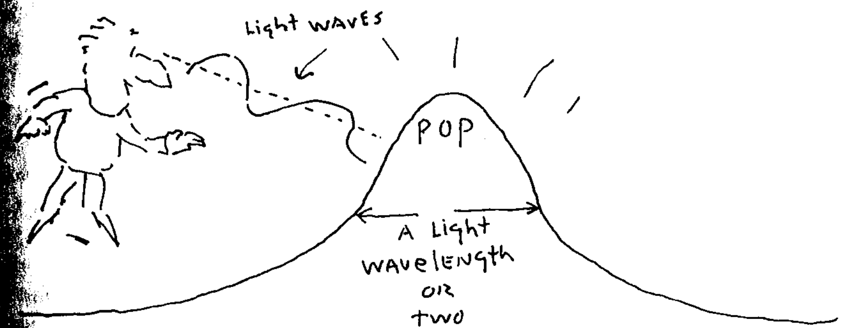
This reduction in pulse size is *not* part of the mathematical description of the electron. We cannot use the Schroedinger wave equation to tell us just where we will find the electron when we observe it. The Schroedinger equation can only tell us about the pulse that is unobserved. It tells us where we are likely to observe the electron. After our observation of the electron, the pulse undergoes a discontinuous change brought on by our observation.



An unobserved electron pulse moves along...



getting wider and spreading as it moves...



until the observer sees it. Then it "collapses" down to size.

If our observation used long wavelength light, the pulse would not have been too thin to start with. Since unobserved, wide pulses do not grow much wider very quickly, our loss of information concerning the location of the electron is not too severe.

In today's electronics industry, electrons are used in a variety of tasks. Engineers have good control of electrons because they work with extremely wide electron wave pulses. Of course, we mean "wide" on an atomic scale. These atomically wide pulses are nevertheless quite definable on a large industrial scale. For example, electrons are used inside of the big cathode ray tube in a typical television set. The Schroedinger pulse describing the electron must travel the length of the tube in about ten billionths of a second. This time is short enough to prevent the electron pulse from spreading too much; particularly since the initial pulse need only be several thousandths of an inch in width. This tiny macroscopic, or large-scale size, is more than a million times larger than an atom. Our modern use of electron microscopes is based not upon the wave nature of the electron, but upon its ability to be a particle for very short time periods and our noninsistence that the electron's wave pulse be too small to begin with.

These practical considerations make the electron appear to be a solid particle. Practical considerations also make nearly every other object that exists on a human-size scale appear "normal." The *spreading time* (that is, the time it takes for a pulse to double its size) depends as well on the mass of the object observed. Large-mass objects on the scale of grams, even if their initial pulses were defined within a millionth of an inch, would need the age of eternity, billions of years, to spread any amount at all. However, such big and heavy pulses are not needed. What about thin and light-weight pulses? Here quantum physics takes its toll. They spread quickly.

When we are dealing with electrons and atoms, we need to consider such things as spreading time. It is just when this time concerns us that we begin to lose our picture of what is going on. The reduction of a fat pulse to a thin pulse is necessary for *any* observation to take place. It is a vital and mysterious process that is ignorable for fat and heavy pulses, but not for initially thin and light-weight pulses. Of course, I am referring to pulses that describe a light-mass particle with only a limited range of possible locations. With such objects, information is lost very quickly. The Schroedinger equation is the only mathematical tool we have to keep track of such objects. But it doesn't do a good job; it simply tells us how we lose information. Once we actually perform an observation, we gain back some of what we lost. This process of gaining back is a discontinuous process.

If we insist that the universe is composed of such tiny objects, then the whole universe comes into existence whenever we observe it. Furthermore, we pay a price for our acts of observation. Each act is a compromise. The more we attempt to measure the position of an electron, the less we can determine its momentum, and vice versa. The Born interpretation was a measure of our uncertainty in this regard.

This uncertainty meant that no matter how accurately one tried to measure the classical quantities of position and momentum, there would always be an uncertainty in the measurement. Predicting or determining the future of atomic objects would be impossible under these circumstances. This was called the Heisenberg Principle of Uncertainty or the Principle of Indeterminism. It had little relevance in the world of ordinary-sized objects. They were hardly bothered by disturbances produced through observation. But the uncertainty principle was serious business when it came to electrons. Indeed, it was so serious that it brought the very existence of electrons into question.

Later the principle was found to apply to any pair of observations, provided that pair of observations never produced the same result when carried out in a reverse order. This included the energy of a particle and the time span over which that energy was to be measured.

As you can expect, the uncertainty principle was quite an upset to the continuists. It signaled the end of mechanical models. How could there be a mechanical universe out there, if the universe changed every time we altered how we observed it? First locating an electron and then finding out how fast it is moving gave an entirely different result than determining the electron's speed and then locating its position. How could a mechanical universe be fundamentally indeterminate?

To answer these questions would require as clear a statement of the issues as possible. That meant a debate. The outcome was destined to affect the entire history of physics.

Resistance to Uncertainty

There is no law except the law that there is no law.

JOHN A. WHEELER

Heisenberg's Principle of Uncertainty could be interpreted nother way: to observe is to disturb. Up to the time of Heisenberg's principle, it was assumed that the "out there" niverse existed quite independently of the observer who easures it. To have a universe that depends upon the observer ho measures it is disturbing on both physical and mental ccounts. After two thousand years, modern physics was faced ith the same dilemma as the early Greeks. It was the old story Zeno and the arrow. How did the arrow move? Continually, id the continuists, with no help from the observer. In jumps, id the discontinuists, with a little and unavoidable help from e observer.

By October, 1927, the issue of the role of the observer had rought together thirty or more well-known physicists. They ere gathered for the fifth Solvay conference (named after elgian industrialist Ernest Solvay, who had sponsored it and ffered considerable financial support). The first four conferences d also dealt with the new quantum mechanics, but this nference promised to be a real showdown. It was the start of e strangest debate in the history of the understanding of the orld. Its protagonists were Niels Bohr for the discontinuists and lbert Einstein for the continuists. Also included were Born, de roglie, Heisenberg, Planck, and Schroedinger. For this was to a top-level discussion on one of the most important problems the time: the meaning of the new quantum theory.

members of the fifth Solvay Congress, 1927.

The first to enter the arena was de Broglie. He argued for the reality of the matter wave. Certainly it was a wave of probability, but it also was a guiding wave determining the real trajectory of the particle in its journey through space and time. The vote was thumbs down. To vote against an idea in such circles is easy enough; all one had to do was not discuss the idea. A year later, de Broglie abandoned his "pilot wave" theory. In fact, in the fall of 1928, when he assumed his post at the Paris Faculty of Sciences, he thought it unjustified to teach in his own course.

After de Broglie, Born and Heisenberg presented their paper on the probability interpretation of the Schroedinger wave. The vote was thumbs up. Next, Schroedinger presented his wave mechanics for a system composed of many bodies in interaction. The climax of the meeting was a general debate. The preliminary bouts were over. The ringmaster Hendrik A. Lorentz opened with his dissatisfaction over the rejection of determinism proposed by the majority of speakers. But it was time for the main bout. Lorentz called on Bohr to address the assembled. Bohr presented his latest ideas on the wave-particle duality for his opening gambit. His words were clearly intended for the ears of one man. Albert Einstein had never before heard Bohr's new ideas on wave-particle duality, a concept that Bohr called *complementarity.*[1] Einstein had not even taken part in any of the preliminary bouts. Even now, at the end of Bohr's presentation, he remained silent.

Several others piped up. Born asked the group to consider the question of reconciling the particle character of matter with the wave character. He referred to the Heisenberg example of observing an electron in an atom. Each time the electron was "seen" the pulse instantly thinned down, redefined within the limits set by the wavelengths of the light. The longer the wavelengths of the light used, the softer the light's impact upon the orbiting electron. The position of the electron was not well defined. Its Schroedinger pulse was large enough to encompass several possible orbits for the electron particle. Somehow the picture was consistent. The particle was defined in its location by the act of observing it.

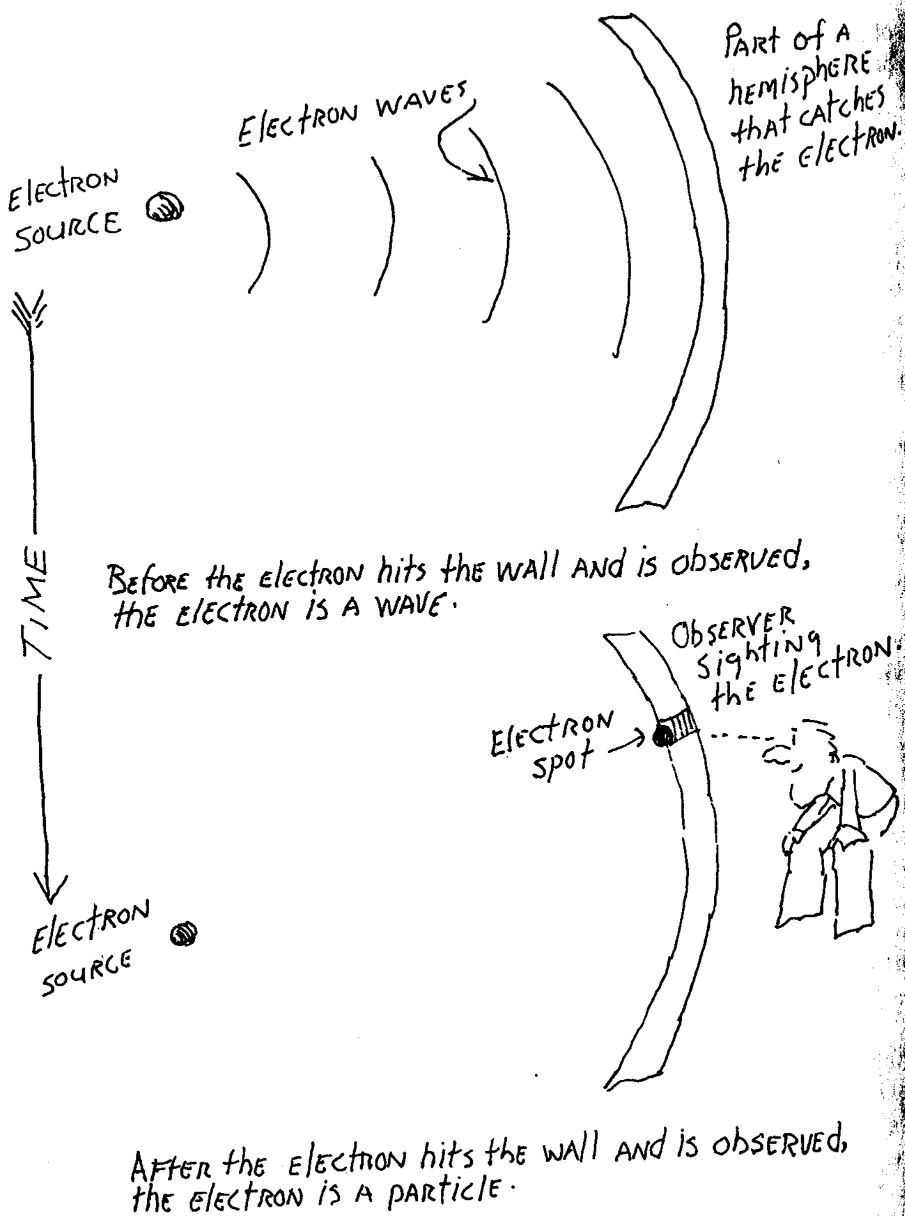
But how did this take place? The pulse would, according to the Schroedinger equation, continue to spread, even after the light interacted with it. The Schroedinger equation did not describe what we would see by shining light on the orbiting electron. It only told of the probability of observing the electron. The actual experience determined the location of the electron insofar as the light's wavelengths could paint the picture. In

other words, Schroedinger's equation did not describe actuality, only potentiality.

The question was how did the spreading waves regroup when an observation took place? This phenomenon was known as the *collapse of the wave function.* The collapse was not contained within the mathematical formulation of quantum mechanics. Yet if the wave description was a reality, the collapse had to occur. Several physicists in attendance attempted to explain the collapse, and someone offered an explanation of an alternative multidimensional space in which no collapse of the wave occurs. But as Born admitted, "This does not lead us very far concerning the basic problem."[2]

It was then that Einstein entered the ring. Rising from his seat, he told the assembly, "I have to apologize for not having gone deeply into quantum mechanics. Nevertheless, I would like to make some general remarks."[3] The seeds of what was to develop had been planted seven years earlier, in the spring of 1920. Now the debate had officially begun. Einstein was clear where Bohr was obscure. Einstein asked the members to consider an experiment, the first of a series of "gedanken (thought) experiments." It was a simple thought experiment in which the group was asked to imagine a particle passing through a very narrow slit. Accordingly, the wave associated with the particle must be diffracted, and like ripples from a dropped pebble in a pond, the wave will spread. Behind the slit is a sensitized screen shaped in the form of a hemisphere. This hemisphere will act as a detector of the particle, for after passing through the slit, the particle must arrive somewhere on the screen. The arrival of the particle is an event whose probability of occurrence at any particular point on the screen depends on the intensity of the wave.

Everyone agreed with these statements, even Bohr. But, Einstein continued, there are two different viewpoints as to what is actually happening. According to the first viewpoint, the wave does not represent a single isolated particle, but rather an ensemble of particles, all of which are distributed through space. The wave intensity corresponds to our usual interpretation of multitudes of similar events: it is a probability distribution no more mysterious than an actuarial table or a census giving the distribution of age and sex among the states and cities. If this first is correct, then the wave describes our real ignorance of things, nothing more, and matter is really material behaving causally and moving so within space and time. But a second view is also possible.



Einstein's thought experiment.

According to this second viewpoint, we are not ignorant of anything, and quantum mechanics is complete in its description of individual events. The particle is a wave moving towards the screen. Thus, Einstein objected, the particle is potentially

present at every point on the screen, with nearly equal probability of appearing anywhere thereon. However, at some point, it becomes localized and appears suddenly to pop up at a single isolated point. "It seems to me," Einstein continued,

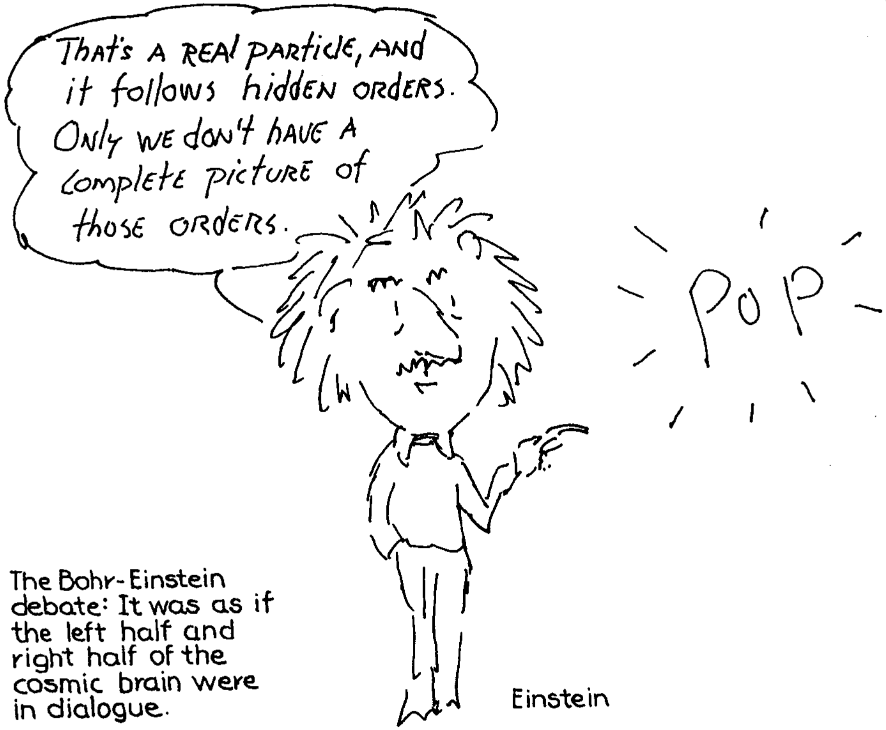
> that this difficulty cannot be overcome unless the description of the process in terms of Schroedinger's wave is supplemented by some detailed specification of the localization of the particle. . . . [The second viewpoint] contradicts the postulate of relativity.[4]

It was the collapse of the wave that most disturbed Einstein. He imagined the wave impinging on the screen like surf on a beach. According to the second viewpoint, a peculiar action-at-a-distance takes place, which prevents the wave from hitting the beach at two or more points at the same time. As a result, the whole wave collapses like a genie into a bottle and beaches itself at one point on the shoreline. Consequently, Einstein favored the first viewpoint.

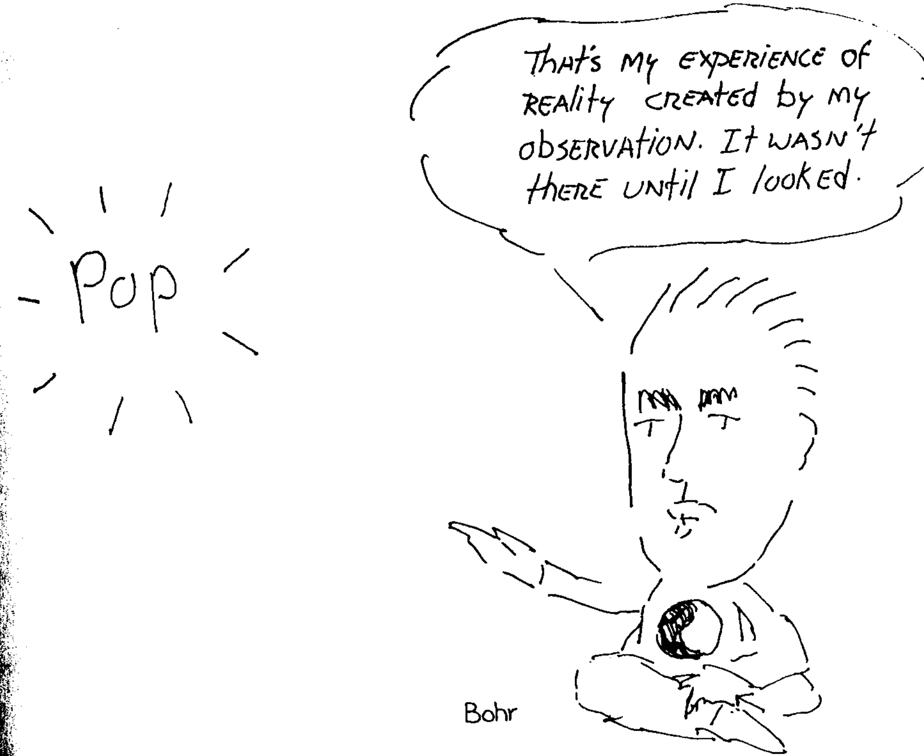
The difference between the two viewpoints was the key fulcrum upon which hung the delicate balance of reality. Though it might not have experimental consequences, still it would have far-reaching effects. The first view suggests unidentified, mechanical, controlling factors called *hidden variables*. The second view denies that anything further can be said. It denies the very need for such factors.

These two views, although couched in the modern terminology of quantum mechanics, were nothing more than the ancient Greek views of continuity and wholeness versus discontinuity and wholeness. The continuists state that the whole is its sum of parts and that any apparent discontinuities can be explained by a continual movement, a smooth mathematical transition from one point to the next. On this, Einstein and Aristotle agreed. Their point of view reaffirms causality, continuity, and a deterministic universe.

The second viewpoint, which Bohr presented and Zeno would have accepted, denies these things. There is no need to explain the collapse of the wave. The wave is not the ultimate reality. The particle is not the ultimate reality. Reality is not the ultimate reality. There is, instead, one unbroken wholeness that appears paradoxical as soon as we observers attempt to analyze it. We can't help but disrupt the universe in our efforts to take things apart. To Bohr, there was no wave to collapse unless the wave was observed, and then no collapse would be seen. He viewed analysis as observation, and observation was fundamentally a discontinuous event. It could not be connected to any past



The Bohr-Einstein debate: It was as if the left half and right half of the cosmic brain were in dialogue.



occurrence. The connection with the past was not a reality.

Although Bohr's position was obscure and difficult to pin down, it provided the groundwork for what is today called the *Copenhagen interpretation of quantum mechanics*. This interpretation is the officially accepted understanding, and it presents a reality that is stranger than we can imagine it to be. Our brains are filled with memories, with a desire for security. Therefore, we have a natural, built-in desire for continuity in all things. But all of this is denied to us by the Principle of Uncertainty. All physical processes are impossible to envision. All physical processes are incompatible with the properties of mechanical models.

This does not mean that we should throw away all of our machines. Just the opposite is true. Our mechanical models work beautifully for large objects because of the smallness of Planck's constant. God's gift is a tiny h. But we must remember that we are the artists in the game of the universe. If h were any larger, the ultimate chaos would overwhelm us. With such a small unit of action, we have just the right amount of freedom to create nearly whatever we want. Just exactly what our limits are is a subject that is still being explored.

Things are only an approximate description of reality. The limits of our description are discovered in the Heisenberg uncertainty principle. Bohr called his philosophy the Principle of Complementarity. The wave-particle duality and the pictures associated with this duality, such as the collapse of the wave and the jumping of the particle, were a result of the fundamental clash between two contrasting mental constructs of the appearance of reality.

Bohr's complementarity views need much room for airing. They are presented in chapter eight. Einstein did not give in to these views. Instead, he adhered to the idea of an orderly universe. God did not play dice, he asserted, and in his later years, Einstein provided the devil's advocacy against Bohr's fundamentally discontinuist view.

Bohr's views offered a new vision of the world. And he carried his ideas of complementarity over into the life sciences. He felt that there was no real contradiction between the humanistic sciences and the natural sciences. The apparent conflict was nothing more than a complex form of the wave-particle duality. In anthropology, for example, there are two modes of behavior: that based upon instinct and that based upon reason. Instinct could be viewed as a sudden discontinuity having no history. Reason, on the other hand, was a process founded upon logic and continuity. In the study of primitive cultures, the observer must be aware of the disturbances he brings into those cultures if he is to extract the "reasons" for those cultures.

In the remaining chapters, we shall further contrast the Bohr and Einstein views. The resistance that each view offered the other resulted in a great deal of new thinking. Scientists would construct exciting parallels between many avenues of life that were previously thought of as very different. However, the debate between Bohr and Einstein has still not ended, though both are now dead. Indeed, the battle of continuity versus discontinuity may never end.

Is There an "Out There" Out There?