CHAPTER TEN
THE WAR OF THE WORLD-VIEWS

There may be no such thing as the glittering central mechanism of the universe...Not machinery but magic may be the better description of the treasure that is waiting.

John Archibald Wheeler.

What Was At Stake--Both Then And Now

We have seen that from the time of Galileo, Descartes and Newton to the early twentieth century, a certain scientific and philosophical outlook had emerged in Europe and North America, one that had attained dominance. This outlook contained certain central themes:

• Determinism: The past determines the future, without exception. Any element of chance that seems to be present in any event, is only a manifestation of our lack of information.
• Continuity: In moving from one place to another, a material object successively occupies all intervening points in space. These points are packed together with infinite density.
• Causality: Every event that takes place can be thought of as the necessary result of one or more previous events, called "causes."
• Objectivism: Realism--the idea that when we (or the universe) measure(s) or observe(s) a quantity, that quantity is something that is already "there."

Even today, at least 99 out of 100 persons imbued with the culture of Modern Civilization, would consider self-evident the propositions described above: "they stand to reason." But as we shall see, not one of them seems to hold up under close examination. Although these four themes have their roots deep in the Western Philosophical Tradition, their fruiting was delayed until the time of the Scientific Revolution. It was the triumph of Newtonian mechanics, to have melded them together in a definitive pattern; one which scientists went on to employ in the same manner as a team of tailors; a pattern of behavior which we can express in the following way: “Do you remember how we solved that other problem? Well, good! Then we’ll solve this one in the same way”. When such a pattern becomes entrenched, and linked with other compatible patterns, we refer to it as a Paradigm --"a pattern of patterns." This is what began to happen at the time of the Scientific Revolution, and it became what is sometimes called the Newtonian-Cartesian Paradigm. Philosophers Martin Heidegger and Edmund Husserl have referred to the paradigm as The Cartesian Project. We shall discuss this further in a later chapter.

As more and more problems fell before the onslaught of scientists using their new weapon, the Newtonian Method, over time the hypnotic power of the Newtonian Mechanistic Myth became immense. For more than two hundred years it produced a degree of enthusiasm akin to religious fervor among western thinkers. The list of its devoted apostles included such illustrious figures as: Voltaire, Helmholtz, Maxwell, Boltzmann and Freud.
The Mechanistic Myth

The mechanistic myth goes like this: Imagine some kind of isolated physical system under the known influence of what we shall simply call simply: External Forces. Suppose that, besides knowing the Forces, we know the position and velocity of all of the particles in the system at some initial moment in time. Then as time cranks smoothly, continuously forward, all the particles will also move smoothly in their trajectories. To be able to predict all future configurations of that system, forever, all we have to do is apply Newton’s laws of motion to the system. Next, we have to recognize that the Universe itself is a physical system. Its future was therefore considered predictable--hence controllable. According to this scheme, we could (in principle) predict the future of the Universe. Louis de Broglie then, with his theory of waves, was merely upholding the doctrine of Continuity, to keep it from being washed away by a sea of discontinuous quantum jumps. His electron, towed along by its pilot wave, and obeying Newton's laws, would be able to find its deterministic way unerringly to the target. Naturally, an arrangement of this kind must have delighted Einstein, who was determined to uphold the religion of the Newtonians. But what about the waves themselves? How could they be described mathematically? How could one use this kind of idea to predict the point where the electron would actually land? Against what strange shore did those pilot waves break? Schroedinger had found a way to show how his “waves of matter” would move in a deterministic fashion, under the influence of various forces. Einstein, although he had been one of the original founders of the quantum theory, was quite uneasy about the direction that his original line of inquiry had taken. For the moment, though, he believed that in Schroedinger, he had at last found his champion. To be sure, there was still some uneasiness here: Schroedinger had already shown that his “wave mechanics” was mathematically equivalent to the far more radical formalism developed by Werner Heisenberg. Further, it was Heisenberg’s reasoning that had led directly to the Uncertainty Principle—a discovery that was already leading to chilling revelations in Copenhagen--revelations that were chilling for Einstein, to say the least.

Heisenberg And Uncertainty

At this point it is worthwhile for us to examine the Uncertainty Principle in more detail, partly in order to gain an insight into what happens when we actually make a measurement, and partly to
discover the extent to which we must change our way of thinking, to accommodate The Principle. What Heisenberg had found was, that the act of measurement could be regarded as a kind of “operation”—something to be represented by a mathematical artifact called an “operator.” As an example, the act of pulling on your socks is an “operation”; so is the act of putting on your shoes. But if you were to perform these operations in the reverse order, we will all agree that the final results would be vastly different. (People would look at you, and they would talk). A mathematician would say that the two operations “don’t commute”. The same thing is true of measurements of position and momentum; the respective measurement operations don’t commute with each other. To obtain an infinitely “sharp” value of the position requires that the quantum object should take on every possible value of the momentum; and vice-versa. As we have seen, it was Niels Bohr, with his uncanny instinct, who saw the consequences of Heisenberg’s reasoning. Since the act of measurement was necessary to produce, say, the position of the quantum object, what could it mean for the quantum object’s position even to exist in the absence of a measurement? His answer was: It means Nothing at all!

When we make measurements, such as those of position $x$, or momentum $p$, we don’t always get the same values. Instead, we get a statistical distribution of positions or momenta. So we say that there is a “spread” in their values. See figure 10-1, above. What the Heisenberg Uncertainty principle says is that when the spread of position measurements is small, the spread of momentum measurements will be large, and vice-versa. Therefore the two spreads are inversely related to each other. Physicists express the position-momentum Uncertainty Principle algebraically like this: $\Delta x \Delta p \sim \hbar/2\pi$.

What this expression says is that the spread in $x$ times the spread in $p$ is about the size of $\hbar/2\pi$, where $\hbar$ is Planck’s constant. Furthermore, the “spreading” is not the result of any human error; instead, it is inherent in the Very Nature Of Things. This result was certainly unsettling to Einstein and the Continuist faction, as was also the idea of electrons jumping non-deterministically from one orbit to another. It negated the philosophical foundations of classical physics. It was heresy!

Still, Schroedinger initially found himself, together with DeBroglie, in Einstein’s camp, the camp of the Continuists. After all, it was his wave that supposedly guided de Broglie’s deterministic electron. But what he thought he had done, and what he had actually done, were really two very different things, for there were disturbing surprises in store. For one thing, let us ask the question: did the wave represent the electron itself, or was it really something else? True, it is possible, by adding waves of varying wavelengths together, to get a kind of wave form that is all bunched tightly, spike-like, together in one place in space. But is this what the electron really is? We have seen earlier that, to the disappointment of Einstein and the wave enthusiasts, this "spike," according to Schroedinger's equation could be shown, in a short time, to dissipate, spreading uncontrollably out through all space—a most un-particle-like form of behavior! Therefore, we must conclude that there is no way to construct a Schroedinger wave that can also truly be said to represent directly a "particle" (such as an electron). If it does not represent a particle, what, then, does it represent? For an answer, see below. Schroedinger had his own reasons to doubt Einstein’s interpretation of his equation. The mathematical apparatus of Schroedinger’s equation does not refer to the kind of space we imagine ourselves to inhabit. Instead, it refers to an abstract space called “configuration space”, one that is multi-dimensional. This mathematical abstraction carries with it certain disturbing practical consequences. Whenever two quantum particles become involved with each other, their wave functions become permanently “entangled.” This effect marks a decisive, even
radical departure from classical behavior; and it is, in effect, crucial to the Quantum Theory. Schroedinger realized instinctively that this result was no mere artifact of the mathematics, but instead, that it hinted at a fundamental difference between quantum and classical thinking—a chasm vast, and forever unbridgeable. Then, what are we to make of this Schroedinger wave? A strange, but very persuasive interpretation came from Professor Max Born of The University Of Goettingen. An idea that is consistent with all of the observations, said he, is that the square of the height of the Schroedinger wave can be thought of as the probability of our locating the particle within a given small volume of space. "The probability!," you say "But I thought the wave was supposed to be deterministic!" To which I reply: "That's right. The particle's path is non-deterministic, but the probability of finding the particle in space and time is deterministic. A definite: "Maybe." Then Schroedinger's wave is not even a particle, but rather it is a measure of the probability of locating a particle at a point in space when a measurement is being made--in other words, a measure of the available information! Information available to whom or to what? At this writing, three-quarters of a century have gone by, and the answer has never been completely clear. It was this amazing development, which caused the physicist Sir Arthur Eddington to exclaim, that: "The stuff of the world is mind-stuff."

Then we are driven to the conclusion that Schroedinger’s equation must be a description of the evolution of the probability- with respect to time! According to Born, the act of measurement is in a sense an act of destruction; it somehow causes the “collapse of the wave packet”, the Schroedinger wave, and its immediate replacement by a classical event--an event occurring at a single point in space-time. It is an abrupt discontinuity in the amount of available information. Once again, we have a delightful irony. The deterministic faction had wanted to find a truly deterministic equation. And just as they seemed to have one, Nature had played a dirty trick; for the only entity that was propagating deterministically was the probability of locating the quantum object. And a probability is not a thing, like a table or chair. It seems to be a creature whose exclusive habitation is the mind. But whose mind? Thus, quantum probability was, for Einstein, a worst-case scenario.
Ernest Solvay, a Belgian industrialist with a strong interest in science and a philanthropic bent, had endowed a series of scientific conferences. These conferences played an important part in the story of the Quantum Theory, and the story of the upsetting of our classical view of reality. This was the background to the famous Fifth Conference, which began on Monday, 24 October 1927. Although the Conference bore the innocuous title: *Electrons and Photons*, everyone knew what was to be its real business: it was to be a showdown between the Old and the New. The chair at the Conference was the venerable Henryk Antoon Lorentz, the great Dutch physicist. After some preliminary sparring, Louis de Broglie spoke, describing his theory of the pilot wave. But when "certain difficulties" were mentioned⁷, the poor man even began to doubt the validity of his own theory, and was forced to retreat from his position. After de Broglie, Born and Heisenberg spoke, presenting their paper on “matrix mechanics," the arithmetic of operators. They concluded their lecture with a description of the Heisenberg Uncertainty Principle, and with the following words, they threw down the gauntlet before the Continuist faction: “The real meaning of Planck’s constant $\hbar$ is just this: it constitutes a universal gauge of the indeterminism inherent in the laws of nature owing to the wave-particle duality”. Heisenberg illustrated his idea with the following kind of picture: fig. 10-2.
To understand the meaning of this statement we need to imagine a graph, in which we plot momentum along the vertical axis, and position along the horizontal axis. The uncertainties inherent in the position and momentum can be described by visualizing a rectangle. In the one extreme it is tall and skinny when the position is well defined, or at the other extreme it is short and fat when the momentum is well defined. But in every case the area of the rectangle, the product of the uncertainties, remains fixed, and that product is: Planck’s constant $h$, divided by $2\pi$.

Born and Heisenberg concluded with the words: “We maintain that quantum mechanics is a complete theory; its basic physical and mathematical hypotheses are not further susceptible of modifications”. This was, as they say, a way of giving their opponents "The Cut Direct". It meant the following: “Our theory is sufficient to predict the outcome of all quantum-mechanical experiments; everything else is either superfluous or just plain wrong.” It is a matter of fascination to me to reflect that this happened before I was born, and now I am 86 years old. It was revolutionary then, and even today, although scientists make constant use of these ideas in the laboratory, it is very hard to make them central to anyone’s world-view.

The next speaker was Schroedinger, who described his work on “wave mechanics”, stressing the difficulties, the entanglements that arose when more than one quantum state was involved. The Schroedinger wave has a kind of holistic character to it; but once the final measurement occurs, this character abruptly vanishes, and a classical result occurs--one that is not described by his equation. What Schroedinger was getting at was disturbingly clear: he was not at all comfortable with the idea that his Schroedinger wave described the behavior of an actual particle. And of course this was immediately interpreted as giving aid and comfort to those in Bohr’s camp. If there had been a rooting section, a cheer would have gone up.

Lorentz, the gentle patriarch, a man who would not live to see another year, was visibly disturbed by what he was hearing, for the paradigm of the Newtonians had also been his. It was a crisis of faith! He spoke plaintively, saying:

I would always want to retain my determinist faith ... in fundamental phenomena. Is it that a more profound intelligence could not account for the motion of these electrons? Must they necessarily require indeterminism in principle?
These words epitomize the anguish felt by many, even today, at the spectacle of the breaching of the Newtonian Reality, the slow, creaking collapse of the Newtonian-Cartesian paradigm. Wearily, Lorentz invited Niels Bohr to come to the podium to address the meeting. In his usual maddeningly discursive way, Bohr then proceeded to sketch out the outline of the framework of his revolutionary Principle Of Complementarity. After some further discussion by two minor figures, there then came the electrifying moment that everyone had been waiting for. First Max Born rose, and addressed Albert Einstein: “Mr. Einstein once considered the following problem: a radioactive element emits alpha particles into all directions; these are made visible by means of a Wilson Chamber. If, now, a spherical wave is associated with every act of emission, how can it be understood that the trace of each alpha particle appears as an almost straight line? In other words, how can the corpuscular character of a phenomenon be reconciled with its representation in terms of waves?” Born then proceeded to give his own interpretation: the collapse of the wave packet, and after a few further remarks, yielded the floor to Albert Einstein. The tension was electric. “I must apologize,” Einstein said, “for not having gone deeply into quantum mechanics”, (a ripple of nervous laughter in the hall). “Nevertheless, I would like to make some general remarks”. The following treatment was masterful—one that continued to attract supporters for decades afterward. First he pointed out that we can consider the Quantum Theory from two different viewpoints. For clarification he described the following experiment. A particle, such as a photon or an electron, impinges in a perpendicular fashion upon a diaphragm having a small circular hole bored through it. In this way we can think of the Schroedinger wave as being “diffracted” in the hole. Emerging from the hole, the diffracted beam strikes a hemispherically-shaped sensitive screen (similar to the one used by Ernest Rutherford in a previous chapter), which will show the point of arrival of the particle.

![Figure 10-3](image)

The intensity of the diffracted spherical wave at a point of the screen will be proportional to the probability that the particle will arrive there. Of course this hemispherical screen is placed in such a fashion that, at the center of the hemisphere, is the hole to which we have referred. See figure 10-3 above.

**Viewpoint One.** This view is one that is typical of the method used by the insurance company’s actuary. The Schröedinger wave does not describe the probability of finding an individual particle in some small region of space, but it rather describes the behavior of an “ensemble” of particles: the density of a swarm of them. This argument is identical with the manner in which your insurance premiums are computed. The actuary looks at the computerized data for all people in your age group, makes a substantial correction for whether you smoke cigarettes and ride motorcycles, and comes up with a figure. The underlying assumption is that there are always unknown determining factors, such as genetic ones, to which they hope to gain access tomorrow, or the next day—
probability is merely an expression of our ignorance of something that is already there. Similarly, Einstein visualized that the particles themselves may have “wheels within wheels”, although these may be hidden from us at this point in time. How else could you explain the fact that the particles passing through the hole didn’t all end up in the same place? In time, a name was found for this hypothetical phenomenon: it was called: Hidden Variables. It is the notion that we still live in a clockwork 17th century universe; but we just can’t see the clockwork. If we could see it, then we would know—or so Einstein thought.

Viewpoint Two. According to Viewpoint Two, the quantum theory is a complete theory of individual processes; it doesn’t talk about swarms. It is the only answer that can be given to the question: "What is the state of the particle?" The uncertainty already resides in the quantum nature of the particle. Each individual quantum entity traveling to the diaphragm can be described as spread out into a “wave packet” which, after being diffracted at the hole, finally arrives at a certain point $P$ on the hemispherical screen. The square of the amplitude of the Schroedinger wave: $|\Psi(r)|^2$ expresses the probability that at a given moment in time, the particle described by that wave packet can be found at some intermediate distance $r$ between the hole and the screen. If the probability is interpreted according to Viewpoint Two, then, in the absence of any attempt to intercept the particle before reaching the screen, the particle must be considered as potentially present with constant probability over the entire area of the screen. However, as soon as the particle has been detected at a given point, a peculiar action-at-a-distance kind of thing must take place, forever precluding the detection of the particle at any other point. The underlying assumption here is that there aren’t any extrinsic unknown factors. Although it seems that Einstein did not express the matter in quite this way, at the back of his mind must have lurked the following consideration: “Let us suppose that the hemispherical screen was at a long distance from the hole, and therefore very large. Then, when the particle is detected at a given point on the screen (call it A), how will the signal, bearing the news of its arrival, reach all of the other points on the screen, some of them far distant, telling them to collapse the wave packet, that the photon has already arrived, without at the same time violating the Special Theory Of Relativity, which limits the speed of information transfer to the speed of light?” We will find that this latter consideration was to arise eight years later, when Einstein made his final attempt to unseat Bohr’s version of the Quantum Theory. In any event, Einstein made it clear that his sympathies lay solidly with Viewpoint One, and that Viewpoint Two was, for him, an abomination. Although Einstein’s keen intuition went straight to the heart of the matter, neither he nor Bohr was able to resolve the problem. The rest of the physicists returned to their laboratories and proceeded to employ the quantum mechanics derived from the theory of Bohr, Heisenberg and Schroedinger to solve every problem that they could think of, while Bohr and Einstein continued their fateful dialogue. The watchword for young physicists at the time was: “Don’t ask what it all means. Just shut up and calculate.” How long did this ridiculous state of affairs last? For more than a half-century! 

But to understand the course followed by the discussion, we must first return to the famous Two-Slit experiment of Thomas Young, the one that led to the creation of the wave theory of light. This is a necessary pilgrimage, for every quantum mechanical conundrum is like unto this one! It is fair to say that the Two-Slit experiment lies at the very heart of Quantum Reality.
The Celebrated Two-Slit Experiment Revisited

This time we want to leave open the possibility that, in addition to bombarding the slit with light waves, we can also perform the experiment with other projectiles, such as machine-gun bullets or electrons.

1) In The Case Of Machine Gun Bullets.... Imagine the following scenario. At the left side of the diagram is mounted a horizontal array of machine guns, belching a stream of bullets through a narrow slit in a steel plate, against a second plate of steel, located a moderately long distance away from the first one; the second plate is pierced by two more slits, separated by a short distance from each other. Behind this second plate, to the right, is located a kind of backstop, one which absorbs all the bullets which strike it. If we fire the machine gun for a while, a pattern of bullet-holes will become visible on the backstop. If we count the distribution of bullet holes as a function of the position along the backstop, we will get a pattern that look something like this: (see figure 10.4): The spread of the bullet holes into that region of the back-stop which is out of the direct line of fire is due, of course, to the ricocheting of the bullets against the edges of the slits. That is the way bullets behave. (‘Tis their nature).

2) Waves, (such as water waves). This time let’s imagine a kind of water tank. At the left side of the diagram we mount a wave generator—maybe a kind of vibrating instrument, one which agitates the surface of the water, producing waves which go through a first slit, and advance to the right, until they impinge upon a plate pierced with two more slits. Behind the plate, (that is, to the right of it) is a screen, on which we can measure the square of the height of the water waves. If we measure this quantity as a function of the position on the screen, we will get a pattern that looks like this:
3) “Quantum Particles”, (think of electrons\textsuperscript{14} this time, though photons are also quantum particles; but electrons have mass, and we used to think of them as little balls). This time, at the left side of the diagram, we are going to have an electron gun. (This is not fanciful; your TV set has one). In front of the electron gun is a plate with a single small horizontal slit. At a distance to the right is a second plate, pierced by two more slits. The electron beam goes first through the single slit; then it progresses to the right, impinging upon the second plate, with its two slits. Behind the second plate is a screen, along which we can slide an electron detector (a Geiger tube would do). We move the detector across the path of the beam, counting electrons as we go. If we plot the number of electrons per second as a function of the position on the screen, we will get a pattern that looks like this.

This last result should come as a surprise. For surely we expected the electron to behave like a BB-shot; after all, it is supposed to be a particle; but it seems that nature has somehow “played us false.” The individual electrons indeed arrive at very definite points on the screen\textsuperscript{15}. We can even turn down the intensity of the beam until the electrons arrive one at a time, and listen to the individual electrons as they discharge the Geiger tube. But no matter; for eventually our plot of electrons/second versus the distance along the screen will still bear a suspicious resemblance to Fig. 10.5! If we employ the kind of thinking that we habitually apply to material objects, we will say: “The electron had to pass through one slit or the other. After all, that’s the way it is with cars on roads and people going through turnstiles. So what is the meaning of this crazy wave-like interference?” If we ask the question: “Which slit did the electron go through?”, we would be tempted to place detectors at the respective slits; so that we might be able to trace our quarry all the way to the target. But when we try to do this, the interference pattern promptly disappears from the screen, and we get a reprise of Figure 10.4, and the quantum objects, (electrons, etc.) act just like bullets, cars or people. This is the result of the quantum two-slit experiment. The great physicist Richard Feynman described it as a phenomenon “which lies at the heart of quantum mechanics; in reality it contains the only mystery” of the theory, one that cannot be explained in any classical way\textsuperscript{16}.

**The Long Duel Between Einstein And Bohr.**

They were lifelong friends: Bohr and Einstein. The pattern was always the same: Einstein would produce a brilliant conundrum challenging the validity of the Copenhagen Interpretation\textsuperscript{17} of the Quantum Theory; and Bohr would counter by bringing forth an even more brilliant solution. Thirty-five years later, after his sudden death, his co-workers discovered that Bohr had reproduced one of the diagrams that he had used more than twenty-five years before in this duel with Einstein, there on the chalkboard at his Institute. Apparently he had been pondering over the problem, down to his
Notes to Chapter Ten:

(1) At the time of Napoleon there lived a famous scientist, Pierre Simon de Laplace (a kind of Carl Sagan of those times). Laplace was adored in all of the politically correct salons. He once imagined that there is a demon, (a kind of computer), who can compute all of the positions and velocities of all of the objects in the universe. If we allow, (if not by fact, but by hypothesis) that the nature of the forces might be knowable, the demon can predict all future occurrences, to the end of time, and retrodict all past occurrences, to the beginning of all beginnings. But Bohr put Laplace’s demon permanently out of business.

(2) At one time it was considered chic to refer to Schroedinger’s brainchild as a “wavicle”, thereby sidestepping the need to realize that the Schroedinger function does not describe any material object, but rather the probability of finding one. I’m old enough to remember that time!

(3) This is called “forming a superposition”—any irregular-looking wave pulse, any curve, like a breaker in the instant before it strikes the beach, can be thought of as a superposition of sine waves.

(4) Besides, Schroedinger’s wave can describe systems containing more than one object, say, N objects. Such a wave propagates in an abstract multi-dimensional space, (with 6N dimensions!) But the particle, when it finally appears, is located in the customary 3-dimensions plus the time. Measurement, (observation) seems to produce a radical diminution in the number of relevant dimensions. Remember, I warned you that this would be strange! Esse est percipi. (To be is to be perceived!)

(5) Born’s interpretation has stood the test of time, however. It has never been contradicted by laboratory measurements. For 87 years it has withstood all challenges. The Quantum Theory is the Champion Scientific Theory for all time.

(6) Life abounds in delicious ironies. According to Max Jammer, to whose treatise: The Philosophy Of Quantum Mechanics, John Wiley & Sons, NY, 1974, I am indebted for much of the material in this chapter, in a lecture delivered in 1955 Max Born declared that it was Einstein’s idea which he (Born) applied in 1926, to interpret Schroedinger’s wave function in terms of probability! Of course this is the same interpretation that Einstein later opposed so eloquently.

(7) This is a euphemism for: “His views were vigorously attacked”.

(8) Bohr’s position was that knowledge of one aspect of reality will always exclude knowledge of some other complementary aspect; but that both aspects are necessary to give a correct description. This idea, in his mind, was of far more general applicability than to Quantum Theory. See Thematic Origins Of Scientific Thought, by Gerald Holton, Harvard University Press, Cambridge, MA, 1975, p115, The Roots Of Complementarity.

(9) The reference here is to a device called the Wilson Cloud Chamber. It contains a gas whose volume is suddenly expanded. Charged particles passing through the gas will then leave trails of condensation droplets, analogous to the “con-trails” left by jet planes. We do not see the particles, of course; we see only the droplets: condensation events. When we look for objects, we only find events!

(10) When a wave of any kind passes through a hole, we can describe what takes place by thinking of the hole as acting as the source of a new wave—one which will spread out in the shape of a hemisphere. This phenomenon is called “diffraction”.

(11) What an incredible man was Albert Einstein! Even when he was wrong, his insights still proved to be incredibly fruitful.

(12) There is a wonderful book! The title: How the Hippies Saved Physics. The author, David Kaiser, is a Professor at MIT. His Introduction and Chapter One, (entitled “Shut Up And
Calculate”), contain a faithful history of my own discouragement as a student, attempting to understand the Quantum Theory. You see, I had thought all along that everybody else understood it, except me! Thank you, Professor Kaiser!

(13) The definitive exposition of this pivotal experiment was given by the physicist Richard Feynman. It can be found in The Character Of Physical Law, MIT Press, 1965, The Quantum Mechanical View Of Nature. Everyone should read the transcript of this brilliant lecture.

(14) I have suggested electrons, because we have been conditioned by our upbringing to imagine them as charged BB-shot or something of the kind. Prepare to be shocked; they’re not like that at all. Anything, in principle, would serve as a quantum particle, but practical difficulties stand in the way.

(15) There is a very important point to be made here. The electrons are always detected in a very localized way, as having arrived in the form of “particles”. But the interference pattern superimposed upon the random dots, gives away the game; it tells us that some wavelike agency modulated the electrons’ path.

(16) It is always risky to make categorical negative statements. The physicist David Bohm has produced a theory that elaborates upon that of Louis de Broglie, in which the electron is a classical particle, guided by a mysterious, undetectable, ubiquitous “quantum potential”. The purpose of the quantum potential is to guide the electron, in much the way an airplane is guided by radio signals. Using this theory, he was able to reproduce the result of the two-slit experiment. But there are drawbacks to the Bohmian theory. In order to guide a particle, it is necessary to expend some energy. It has been impossible to detect this energy to date. We shall return to this subject in a later chapter.

(17) What is meant by a “thought-experiment”? At the beginning of the twentieth century there lived a very influential philosopher named Ernst Mach. Mach was determined that one should speak only of those sensory inputs which could be directly measured. He was even a bit suspicious about the efficacy of mathematics in the description of experience, since mathematics is not a sensory input. At the time, Mach’s rigid way of thought, called Positivism, was very popular, and produced intense loyalty among scientists. But in order to create, it is essential to relax enough to use one’s imagination. Eventually a kind of compromise was effected, by which one could be free to imagine an experiment, even if there were no way to carry it out in the laboratory, on the condition that one specified with some precision, exactly how the experiment would be done. This kind of exercise is called a “thought-experiment”, after the German word: Gedankenexperiment. At the outset of his career Einstein was much influenced by Mach, and used the thought-experiment with great power and originality in developing his Special Theory Of Relativity. But the rapid development of science in the twentieth century soon made it necessary for Einstein to express himself in abstract terms that were progressively more estranged from the concrete approach of Ernst Mach. Thus when it was pointed out to him that the Bohr-Heisenberg approach “was invented by you in 1905,” Einstein replied: “a good joke should not be repeated too often”.

(17) Copenhagen Interpretation: named in honor of Niels Bohr's native city: a great place!