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Collapse of the Wave Function

Quantum reality is described by Schrödinger's wave function as a spread-out of superposed, sometimes contradictory possibilities. When the quantum world is measured or observed, these many possibilities become one single actuality—the "quantum hussy" marries and settles down; Schrödinger's cat is found either dead or alive. This transition from many to one, from possibility to actuality, is known as the collapse of the wave function. What happens at, or what causes, the moment of collapse is still a mystery. (See THE MEASUREMENT PROBLEM; A QUANTUM HUSSY.)

Color—What Is It?

Why is it that our world is a rich tapestry of many colors instead of just black and white, or many shades of gray? What are the origin and actual mechanics of color? Why can quantum mechanics explain color when classical physics never could?

The story of color is essentially the story of the atom's structure and how electron energies are balanced and distributed within the atom. In the early 1900s, the atom was known to consist of a heavy, positively charged nucleus and negatively charged electrons held to it by electric forces. The number of electrons, which determines the kind of chemical element the atom represents, varies from one for hydrogen to ninety-two for uranium. The atoms of some artificial elements have even more. Chemical bonds depend upon interactions between the electrons of different atoms.

When an atom is stimulated, by heat or by passing electric sparks through the vaporized element, it gives out visible or ultraviolet light—the yellow glow of sodium-vapor streetlights or the brilliant and varied colors of fireworks. This emitted light is always of a definite wavelength, and patterns of various wavelengths, known as spectral lines, are associated with each chemical element. Physicists imagined that these characteristic wavelengths of light were given off because electrons in the atoms were in some sense being "kicked" onto higher energy "shelves," which they then "fell off" when they returned to a settled state. It was assumed that they gave off photons of light in the course of falling from a higher shelf to a lower one.

In 1913 Niels Bohr presented his famous solar-system model of the atom, in which the nucleus was like the sun and the electrons revolved around it like planets. Physicists attempting to explain color associated the energy shelves onto which electrons climbed with the various electron orbits in the Bohr atom. When a photon was emitted, it must be because the electron was falling from one orbit to another closer to the nucleus.

But this left many questions unanswered. Why, for instance, were there only certain possible orbits in the atom? If there were any number, there would be no distinct energies (colors) emitted; hence everything would be black-and-white or gray, because the colors would all mix together and cancel each other. But why didn't all the electrons of any atom fall into the lowest-energy orbit? Why were they spread around on different orbits?

It took quantum mechanics to answer these questions. Bohr had shown that electrons are restricted to certain orbits because they are "quantized"—that is, each orbit is associated with a definite energy level. In the mid-1920s, Wolfgang Pauli's exclusion principle demonstrated that each electron orbit would allow only a specific number of electrons (two) into any one orbit. And the mathematics of Schrödinger's equation answered the mystery of why only certain electron orbits are possible, rather than an infinite range. (See THE WAVE FUNCTION AND SCHRÖDINGER'S EQUATION.)

We can get an intuitive picture of why electron orbits are quantized by remembering that electrons, like all matter, have both wavelike and particlelike aspects. Considered as a particle, an electron can be knocked from one orbit to another. But when an electron is considered as a wave, any one electron orbit is a wave pattern circulating in a ring around the nucleus, like a snake biting its own tail. A stable wave pattern must join onto itself seamlessly; its "head" and its "tail" must be in the same phase of motion. Hence, there must be a whole number of waves in each circuit, complete cycles with no fractions.

When numerical calculations about the atom's internal structure became possible, the orbits were found to be exactly those that would account for the observed spectral lines (lines of color) associated with each element. This was a triumph for quantum mechanics and its wave/particle duality. (See BOSONS; FERMIONS.)

Complementarity

Waves and particles have radically different behaviors and properties. How can we possibly understand that light is *both* a wave *and* a particle? In what terms can we describe it? Niels Bohr's Principle of Complementarity, which he first proposed publicly in 1927, states that each description excludes the other, but both are necessary—they complement each other. We will, like William Bragg, teach about waves on Mondays, Wednesdays, and Fridays, about particles on Tuesdays, Thursdays, and Saturdays. The course as a whole will add up to a complete picture. Other complementary pairs are position and momentum, and energy and time.

Complementarity quickly became a magic wand that Bohr, and later his followers, waved at all apparent contradictions and conflicts between the emerging world view of quantum mechanics and the older picture of reality offered by classical mechanics. Bohr accepted the fact that quantum experiments require quantum categories, like WAVE/PARTICLE DUALITY and quantum mathematical description, but argued that when we *talk* about reality we can use only classical terms. The quantum and classical worlds complement each other, but we can never unite the two in a single act of understanding.

Bohr used his Principle of Complementarity to argue that there was no point in *trying* to describe the quantum world, or to understand its apparently bizarre picture of reality. Understanding of the way things really are, as opposed to what we see when we measure them, was, he claimed, not the business of physicists. (See THE MEASUREMENT PROBLEM.) His colleague Erwin Schrödinger accused him of trying "to complement away all difficulties" by refusing to discuss them.

If we were to apply the Principle of Complementarity to a particularly complex person, who behaved pleasantly in some circumstances and unpleasantly in others, we would have to say that his or her two sides complement each other. Any psychologist or novelist who tried to get beneath the apparent contradictions to describe "the real person underneath" would be told that there is no such person, or that we were wasting our time trying to describe one.

Bohr himself applied his Principle of Complementarity widely in fields outside physics. In a series of papers and public talks, he argued that many things were complementary or mutually exclusive: thought and action, subjectivity and objectivity, feeling and reasoning, male and female, the truths and values of one culture and those of another. Physicists and philosophers of Bohr's generation liked this way of thinking because it rested within the dualist either/or paradigm of the old world view and required no revolution in thinking. But younger physicists, particularly many of today's philosophers of physics, feel that complementarity is just an excuse for avoiding the kind of both/and thinking that quantum physics makes both possible and necessary.

To accept that light is *both* a wave *and* a particle, and to learn to live conceptually with that kind of ambiguity, is one of the creative leaps quantum physics calls upon us to make. Applied in other fields, both/and thinking requires us to see that there may be two or more mutually contradictory ways of doing something, or of looking at something, *all* of which are valid. Seeing the truth of *all* tells us something more profound about the situation. Some people *may* have both pleasant and unpleasant sides, and learning to see both at once may give us a deeper understanding of the kind of people they are.

Contextualism

The realization that in quantum physics the very existence and identity of a particle are bound up with its overall environment or context is known as contextualism. Like homonyms, words that look the same but have different senses depending upon the context in which they are used, quantum reality shifts its nature according to its surroundings.

In classical physics, things are what they are. In quantum physics, there is more of what a philosopher might call an "existential" dialogue among the particle, its surroundings, and the person studying it. This is one upshot of the WAVE/PARTICLE DUALITY of light and matter.

Light sometimes behaves like a wave, and sometimes like a particle. Which way depends upon the circumstances or, more strongly, how we *want* it to behave, or how we *look* at it. The somewhat eerie reality of this is borne out by one of the most famous experiments in quantum physics, the two-slit experiment.

In this experiment, a stream of photons is emitted from a light source. Just in front of the photon source, the experimenter erects a barrier with two open slits, which allow the photons to pass through. On the other side of the barrier are placed *either* two particle detectors (two photomultiplier tubes near the slits) *or* a wave detector (a screen), with which to observe the photons after they have passed through the slits and met again. If the experimenter selects the particle detectors, thus measuring the photons separately, they travel through *one* of the two slits and cause a click in one of the detectors. If, on the other hand, he or she chooses a screen and thus measures the photons collectively, they travel through *both* slits and leave a wave interference pattern on the screen. If the physicist looks for a particle, a particle is found. If the physicist looks for a wave, that is what's found.

In the two-slit experiment, it is not possible to say that light (the photon) is *really* a wave that sometimes acts like a particle, or vice versa. Light is deeper or richer than either of these partial realities, and which side of its dual *potential* nature it decides to show depends

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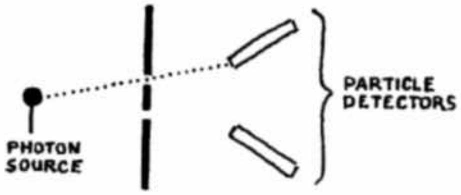

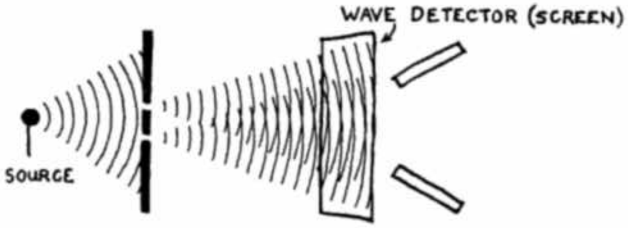

entirely upon the experimental context in which it finds itself. We can never observe light outside of some context.

The wave/particle duality is one of many complementary pairs of variables. (See COMPLEMENTARITY.) For each pair we can devise, there is a context in which one or the other of the pair can be seen or measured.

Though quantum contextualism sounds eerie when we are speaking about elementary particles that change their identity at the drop of a slit, we are very familiar with similar behavior in everyday life. We have all experienced feeling different when at home and when on holiday in some exotic environment. We know that in some relationships, or some jobs, we feel more alive and more creative than in others. Quantum contextualism simply shows us that the adage "Nothing really is as it seems" applies at the most basic level of physical reality. As the French philosopher Maurice Merleau-Ponty put it, when we speak of truth, we can only "define truth within a situation." The same kind of thinking is borne out by Einstein's SPECIAL RELATIVITY.

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rest. It is not absolute space, nor the ether, but it plays some of the roles that the older physics attributed to those absolute constraints. In consequence, the victory of SPECIAL RELATIVITY has not been as complete as it once seemed.

Hadrons

The matter particles called fermions are divided into QUARKS and LEPTONS. Hadrons are composed of quarks. They are either baryons, consisting of three quarks (e.g., the proton or neutron), or mesons, consisting of a quark-antiquark pair. Hundreds of kinds of short-lived hadrons have been produced by particle accelerators.

An older definition of hadrons was "particles that feel the strong nuclear force that holds protons and neutrons together in the atomic nucleus." But we now know that the strong nuclear force itself consists of pi-mesons, which, in turn, consist of quarks and gluons. So the older definition is no longer sufficiently fundamental. (See QUANTUM CHROMODYNAMICS.)

The terminology used to name these various particles is derived from Greek words: hadron ("bulky"), baryon ("heavy"), meson ("middling"), and lepton ("light"). This is generally accurate, although heavy, short-lived leptons ("muons") were discovered in 1937.

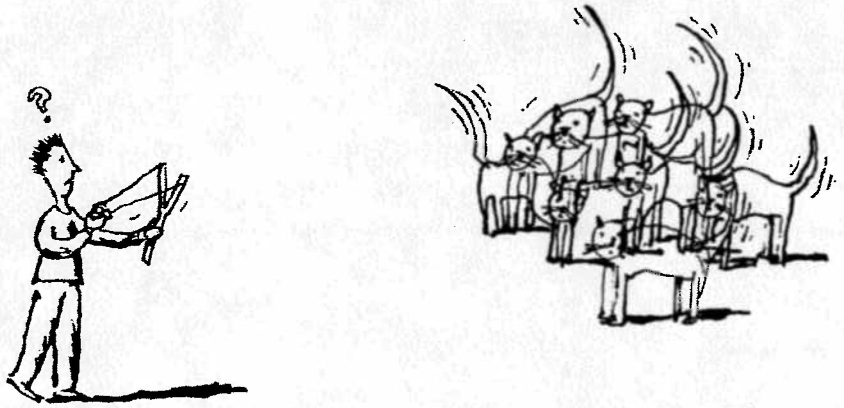
Heisenberg's Uncertainty Principle

How much can we ever know about fundamental physical reality? Are ambiguity and uncertainty inherent features of the real world, or is our knowledge necessarily limited? Heisenberg's Uncertainty Principle addresses questions like these. It may also have wide implications for, and potential applications within, theories of knowledge and organization.

Quantum reality is a strange, uncertain, shadowy realm. The more we try to pin it down, the more it eludes us. The Uncertainty Principle asserts that it must always be so; we must always content ourselves with partial truth and ambiguity when dealing with fundamental physical reality.

A particle was always thought to have both position and momentum. A given particle should always be somewhere (have a location) and is always traveling at a certain speed. But we can never know both. If we measure, or focus on, the position, the momentum becomes unfixed; if we measure the momentum, we lose the position. It is the same with any of the other complementary pairs (see COMPLEMENTARITY) of which quantum reality consists, like waves and particles (see WAVE/PARTICLE DUALITY), energy and time, or continuity and discontinuity. Fixing one member of any pair in place always makes our knowledge of the other member become fuzzy.

A particle is fixed at some exact place in space and time, but this separates or "alienates" it from its neighbors. A wave is spread out over space and time and has an immediate, holistic relationship with its neighbors—and possibly with all waves in the universe—but it can never be located anywhere or anywhen. If we focus on the particlelike



properties of a quantum entity, we get a good sense of the isolated part at the expense of the whole; if we focus on the wavelike qualities, we have a sense of the whole but lose our ability to focus on the part or the particular.

Why does the Uncertainty Principle apply to nature? Why does nature seem to come in complementary pairs of determinate (exact) and indeterminate (fuzzy) aspects? The answer has to do with quantum theory's description of fundamental reality as a wavelike spreading out of infinite possibilities. A particle has the *possibility* of being anywhere or anywhen until it settles into one place or one time. The mathematical description of the particle in quantum theory is known as Schrödinger's equation. (See THE WAVE FUNCTION AND SCHRÖDINGER'S EQUATION.) It *is* a description of all the particle's possibilities. But when any *one* is *actualized,* when the particle settles into just one place or one time, all other possibilities disappear. This is known in physics as the COLLAPSE OF THE WAVE FUNCTION.

In our own lives, we experience something like the Uncertainty Principle. We can focus on the facts of a situation, or we can give ourselves over to the "feel" of it. Focusing on the facts costs us perspective, or a knowledge of the whole; gaining perspective distances us from the details of the situation. We can never be both detached observers and involved participants. In the same way, we find it difficult to focus on one clear and distinct idea (to be analytic) and to entertain a vague train of thought or pattern of loose associations (to be "poetic"). In our organizations we often find that we must choose between imposing rigid rules and tight structure, or allowing things to unfold creatively with a sense of self-organization. Tight structure gives us control but loses us the benefits of innovation. A marketing executive might gain a hard-and-fast knowledge of exact sales figures in the market at a given moment, but perhaps at the cost of understanding the overall drift of factors affecting market demand. In the same way, a pianist must often lose his or her sense of an overall piece of music temporarily in order to concentrate on improving technique for a difficult phrase.

For many years, physicists argued over whether uncertainty and ambiguity are actual features of the real world or merely constraints on our own knowledge and experience. In his "hidden variables theory," David Bohm argued that all variables have definite values, although we are unable to measure them all, but his thinking sits uneasily with the principles of Special Relativity. A series of experiments and complex arguments has led most physicists to believe that reality itself is inherently "fuzzy," or at least that it has both clear and fuzzy aspects at any given time. Trying to focus on it is like trying to grab hold of an evanescent dance.

The Uncertainty Principle has been taken to mean that there is uncertainty, indeterminacy, or unpredictability built into a situation. This use of the term catches the flavor of the actual meaning in physics, but in physics itself the Uncertainty Principle means that we have to *choose* between one or the other of a complementary pair of options.

Holism

The old physics was atomistic; quantum physics is essentially holistic. What does this mean?

Holism as an idea or philosophical concept is diametrically opposed to ATOMISM. Where the atomist believes that any whole can be broken down or analyzed into its separate parts and the relationships between them, the holist maintains that the whole is primary and often greater than the sum of its parts. The atomist divides things up in order to know them better; the holist looks at things or systems in aggregate and argues that we can know more about them viewed as such, and better understand their nature and their purpose.

The early Greek atomism of Leucippus and Democritus (fifth century B.C.) was a forerunner of classical physics. According to their view, everything in the universe consists of indivisible, indestructible atoms of various kinds. Change is a rearrangement of these atoms. This kind of thinking was a reaction to the still earlier holism of Parmenides, who argued that at some primary level the world is a changeless unity. According to him, "All is One. Nor is it divisible, wherefore it is wholly continuous. . . . It is complete on every side like the mass of a rounded sphere."

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~~The coexistence of many, often mutually contradictory, possible movements or possible states is a characteristic feature of quantum reality. But so, too, is the "real" nature of the possible. Just as the fantasies or temptations we entertain in our imaginations often have a real effect on our own or others' behavior, the quantum hussy's "possible" liaisons might lead to real children, as an electron making a temporary transition may collide with another particle, and that particle will remain off course ever after. (See VIRTUAL TRANSITIONS.)~~

~~In the two-slit experiment, each photon goes through both slits at once but ends at one place on the screen. (See CONTEXTUALISM.) The quantum hussy's toddler, likewise, resulted from multiple liaisons superposed.~~

Quantum Physics

Quantum physics is as much a new way of looking at the world as it is a new science. It makes very accurate and very unexpected predictions about the behavior of the physical world, predictions that make sense only in terms of a larger set of new assumptions and expectations about things we find in the world and how they behave and relate to one another.

Elementary quantum mechanics, which was created in stages from 1900 to 1930, was largely the work of six men: Albert Einstein, Niels Bohr, Paul Dirac, Erwin Schrödinger, Max Planck, and Werner Heisenberg. Its first achievements were piecemeal theories formulated to make sense of odd experimental results that could not be fitted into the old classical paradigm. All its early thinking was focused on the microworld, and quantum theory is often misunderstood as a science that applies only to the behavior of very small things. This is untrue.

Quantum theory applies to physical reality on every scale—the very small, the everyday, and the very large. Without it, we cannot make sense of how stars produce nuclear power, why chemical compounds produce the range of colors that they do, why solids have strength and often the capacity to bend (solid-state physics), why electron currents can move along wires, or phenomena like superconductivity and laser light. The whole technology of the microchip is a quantum technology, and quantum effects are increasingly seen as important in biology.

Quantum refers to a little bundle or packet of energy, the smallest discrete amount that can be associated with a single event in the microworld. When an electron moves from one energy orbit to another, it always takes on or gives out an amount of energy that can be measured as so many quanta. Quanta are not, however, divisible. No movement of a particle from one state to another ever uses up one and a half quanta or three quarters of a quantum. Thus the term *quantum leap*, an abrupt movement from one discrete energy level to another. One physicist has described quantum physics as a physics of "lumps and jumps."

Quantum physics' "lumpiness and jumpiness" mark one of its sharp breaks from the Newtonian paradigm. Classical physics represents motion as smooth, continuous change, and energy as increasing or decreasing in a continuous spectrum. The existence of quanta explains why.

During the late 1920s, the piecemeal theories and predictions of quantum mechanics were systematized into a coherent mathematical picture. Quantum theory was born, elegant and complete and able to predict a wide range of physical phenomena accurately to a great many decimal points. But the kind of things, events, and relationships it describes seem to violate all common sense.

Where the old physics describes the world as made of two separate kinds of things, particles and waves, quantum theory postulates a WAVE/PARTICLE DUALITY. The basic building blocks of the universe, whatever form they may take, are "wavicles," indeterminate things with the potentiality to behave like waves in some circumstances and particles in others. Like children who behave well with some adults and badly with others, they manifest one property or the other, depending upon their context or environmental surroundings. (See CONTEXTUALISM.)

A quantum entity is *both* its capacity to manifest itself as a wave, in which case it has momentum, *and* its capacity to manifest itself as

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a particle, which has position. We can never know the position and the momentum of the entity simultaneously. Indeed, it doesn't even possess them simultaneously. If one becomes definite, the other becomes hazy. This is the nub of HEISENBERG'S UNCERTAINTY PRINCIPLE. Trying to view quantum reality is like looking at indistinct figures through blankets of fog.

Classical physics is rigidly determinist, and therefore predictable. The laws of Newton's universe mean that *B* will always follow *A* in the same predictable manner if all other conditions affecting them remain the same. But quantum physics has shown that this is only an approximation of the truth. In quantum theory, *B may* follow *A*, and one can assess the probability that it will do so, but there is no certainty. Quantum events often happen "just as they happen," and there is no way to know what will happen next, or why, or how. (See INDETERMINACY.)

Classical physics reduces all complex things to a few simple components and stressed their absolute, unchanging nature, their actuality or "what is." Quantum physics, by contrast, sees that new properties emerge when simple things combine or relate. The whole is greater than the sum of its parts. There is always the possibility of becoming other or more than what is. Every quantum bit has the potentiality to be here *and* there, now *and* then, a multiple capacity to act on the world. (See ACTUALITY AND POTENTIALITY IN QUANTUM MECHANICS; A QUANTUM HUSSY.) Underlying quantum reality itself is the ground state of being, a "sea of potentiality" described mathematically as a wavelike spread of possibilities. (See THE WAVE FUNCTION AND SCHRÖDINGER'S EQUATION.)

In the old physics and in common sense, things move and events happen as part of a chain of cause and effect. Something is acted upon by a force, or communicated with by a signal, and it responds accordingly. Without such localized action or causation, things remain stationary. But quantum events are often "nonlocal"—that is, they happen without apparent cause, in the absence of any known force or signal. The constituents of quantum reality are somehow correlated; they respond to one another and move harmoniously, as though they are all undulating parts of some larger but invisible whole. (See NONLOCALITY.)

The classical atomistic picture of a world consisting of tiny separate parts, each isolated in its own corner of space and time and linked only through force, is outdated by quantum mechanics. In the quantum universe—and this is the *whole* universe—every "part" is subtly linked to every other, and the very identity—the being, qualities, and characteristics—of constituents depends upon their relation to others. It is impossible, except as an approximation, to apply the part of the scientific method that calls for isolating an entity from its environment when one is investigating quantum entities or systems. The part comes to *be* fully only in the context of the larger whole. (See HOLISM.)

It is also impossible to isolate the observer (or measuring device) from what he or she (or it) observes. Observers have no place in the equations of classical physics. They play no "active" role in the deterministic chain of causal events. But in quantum theory, the observer is *part* of what gets observed. The observer's body and position, his or her choice of experimental design or measuring apparatus, perhaps even his or her conscious mind, are in a mutually creative dialogue with the way quantum reality manifests itself. The phrase "It all depends on how you look at it" takes on a powerful new meaning. The observer actively *changes* physical reality, actively evokes one or another of its underlying potentials. (See PROLOGUE on Schrödinger's cat; THE PARTICIPATORY UNIVERSE.) Exactly how or why this is so, and how it is that quantum reality changes radically to the more familiar reality of everyday experience when it is observed or measured, is the outstanding problem of quantum physics. It is known as THE MEASUREMENT PROBLEM or the observation problem.

Because many features of quantum reality seem to violate common sense, quantum physics has a reputation for being bizarre, an *Alice in Wonderland* physics. Einstein said that it struck him as "the system of delusions of an exceedingly intelligent paranoic." More recently, Nobel physicist Richard Feynman declared that it is impossible to *understand* quantum physics and useless to try. But all this is beginning to change.

In what is almost a third stage of quantum theory's development, philosophers of physics are beginning to understand the wider implications of the theory. Scientists are beginning to see how this physics relates to developments within chaos theory and complexity physics, and contributes to a new overall scientific paradigm. Nonscientists are increasingly aware of how the categories of existence and patterns of

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relationship described by quantum theory serve as meaningful models for our attempts to understand human psychology and relationships. Philosophers of the mind find parallels between quantum reality and the nature of consciousness. Changes in the cultural paradigm, new emphases on holism, and a greater need for a creative dialogue between human beings and the natural world all contribute to bringing quantum physics within the scope of a renewed common sense and everyday concern.

At the high energies of nuclear reactions, particles can be created or destroyed. (See SPECIAL RELATIVITY.) Here, elementary quantum physics must be extended into QUANTUM FIELD THEORY. At still higher energies, physical theories are still provisional. (See THEORIES OF EVERYTHING.) But nobody doubts that the principles of quantum physics will be a part of any future syntheses.

Quantum Theories of Mind

~~Quantum theories of mind stem primarily from philosophical motivations, but they have a scientific aspect and are increasingly the subject of experimental research. Philosophically, they are exciting because they offer a new paradigm for cognitive science, one that seems better suited to our actual mental experience than the dominant mechanistic theories.~~

~~Mechanistic theories of mind are necessarily reductionist. Mental activity is reduced to brain activity, and brain activity is modeled on computers. It is difficult to see how such "mind machines" could be conscious, could exercise intention or free will, or could display the unity of experience that we take for granted. Quantum theories offer an alternative physical theory of mind that many proponents believe gets around these objections.~~

~~The first suggestions that human mental life bears many similarities to the properties of quantum systems were expressed by the biologist J.B.S. Haldane in the 1930s and drawn out in more detail by~~

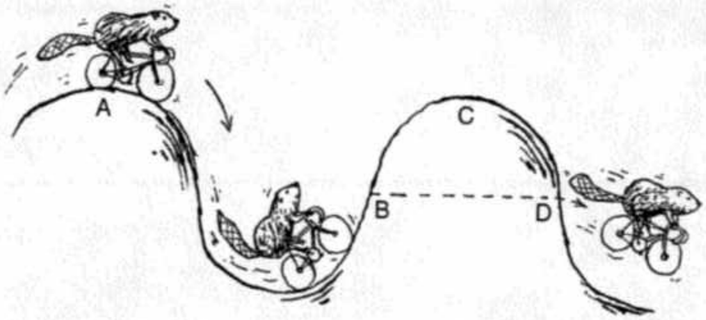
~~LOCALITY might account for this unity. Quantum particle/wave COMPLEMENTARITY offers more viable social and psychological models for how both individuals and groups can be equally important. Roger Penrose (see PENROSE ON NONCOMPUTABILITY) believes there are crucial features of human thinking—insight, intuition, understanding, and dependence upon meaning—that could be accounted for with quantum models of mind, but not with computationalist ones.~~

~~Scientifically, any quantum theory of mind would require the brain to contain a large-scale, body-temperature quantum system that underlies certain mental activities. Neural synaptic activity, especially in the retina, is known to be sensitive to single quanta, but this is not enough to underlie the unity of mental activity. Some large-scale coordinated system analogous to a superconductor or a laser beam would be necessary. Both are examples of BOSE-EINSTEIN CONDENSATION, and most current research concentrates on how there might be Bose-Einstein condensation coordinating subcellular components of neurons. Some theorists suggest that this is concentrated in the water inside neurons; others, inside the molecular membranes of neurons (see FRÖHLICH SYSTEMS); and still others, inside the neural microtubules, or cytoskeletal structure (see NANOBIOLOGY). Microtubules are a "hot" theory at the moment, because anesthetics are thought to act at these sites in the neuron.~~

Quantum Tunneling

How do quantum "particles" travel in regions forbidden to classical ones? How do they jump energy hurdles and sneak through barriers that should be impossible to get beyond? Their common ability to do these things is known as tunneling and is a dramatic consequence of WAVE/PARTICLE DUALITY and HEISENBERG'S UNCERTAINTY PRINCIPLE. It has many practical applications.

In the quantum world, a "particle," which we might expect to be confined to one side of a barrier, can sometimes be found on the other

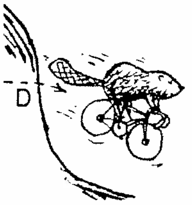


side, as if it had tunneled through like a mole. The barrier in this case is some form of energy constraint, and the likelihood of tunneling becomes less and less as the barrier is made higher or wider.

Imagine, for example, that an electron is riding a bicycle, a very tiny quantum bicycle, over a series of hills. It begins at the top of hill *A* and wants to get to a point *D* on the route without pedaling. In the normal course of classical events, completely discounting any effect from friction, the bicycle will roll down *A*'s slope and have enough potential energy to climb halfway up the next hill to point *B*. At point *B*, the bicycle can climb up to C at the top of the next hill only if it is pedaled—that is, if more energy is pumped into its system. But in the quantum world, the bicycle simply tunnels through hill C and arrives directly at *D*. It goes in one side of the energy barrier and out the other, without ever going over the top. How?

There are two possible intuitive quantum models of how tunneling actually works. Both give the same mathematical predictions. One, relying on the Uncertainty Principle, calls upon us to remember that energy and time are "complementary variables." That means that when one is fixed, the other becomes fuzzy or indeterminate. So it is possible for the energy of the electron on its bicycle to fluctuate by fixing the time the journey will take. The Uncertainty Principle simply requires that the uncertainty in energy *times* the uncertainty in time remain constant ($\Delta e \cdot \Delta t \geq \hbar$, where $\hbar$ is Planck's constant). So one can increase at the expense of the other. In this case, the electron borrows enough energy, for a correspondingly short time, to increase its energy sufficiently to cross the energy barrier.

The other possible model for tunneling relies on an electron's ability to behave sometimes like a particle and at other times like a wave.



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In this scenario, the electron travels up to its energy barrier as a particle, becomes a wave long enough to “wave” through the barrier (waves *can* wave through barriers, as, for instance, sound travels through walls), and then completes its journey as a particle. This, too, is completely possible in the quantum world.

Tunneling effects are common in nature. They include chemical reactions, radioactive decay (the decay particles tunnel through the attractive energy barrier that would keep them within the nucleus), and the processes by which stars generate energy. Technological applications include a special electrical switch called a tunnel diode; the scanning tunneling microscope, which can magnify up to 100 million times; and the Josephson junction, a superconducting ring that magnifies quantum effects and has endless uses from medicine to geology. (See SUPERCONDUCTORS.)

The Quantum Vacuum

In QUANTUM FIELD THEORY, things existing in the universe are conceived of as patterns of dynamic energy. The ground state of energy in the universe, the lowest possible level, is known as the quantum vacuum. It is called a vacuum because it cannot be perceived or measured directly; it is empty of “things.” When we *try* to perceive the vacuum directly, we are confronted by a “void,” a background without features that therefore *seems* to be empty. In fact, the vacuum is filled with every potentiality of everything in the universe.

We can see particles, and we can see waves, but we know that neither of these is primary or permanent. Quantum reality consists of an inaccessible wave-particle dualism, and the waves and particles themselves can transmute one into the other. At high energies, one particle can transmute into another. At the level of perceived existence, everything has a kind of impermanence.

To make sense of this cosmic dance of temporary realities, physicists had to understand what lay beneath it. If particles and waves are

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~~ciples, its essential processes cannot be reduced to laboratory measurements. Life is a holistic process; analysis into components destroys its essential principles. Helmholtz demonstrated that, on the contrary, a wide variety of processes, such as the way in which impulses travel along nerves and the neurological basis of sensations, could all be measured and studied in the laboratory. Another blow to the theory had already come in 1828 when the German chemist Friedrich Wöhler synthesized urea, an organic compound found in the urine of animals. The fact that a compound previously associated only with the life process could be produced by artificial chemical means was seen as the denial of any special principle of life.~~

~~Today, vitalism has been largely discredited in the biological sciences. The principle of Occam's razor dictates that scientific theories should not contain unnecessary assumptions, no matter how seductive. Since biological functions all seem to be explainable in terms of molecular reactions, there is no need to invoke the assumption of a life force. Nevertheless, echoes of vitalism occur in many branches of yoga, acupuncture, and alternative medicine in general; it is generally unclear whether the life energies referred to are reducible to forms of energy known to physics. (See also EMERGENCE.)~~

The Wave Function and Schrödinger's Equation

Quantum systems have many indeterminate aspects (variables) because those features of the system remain unfixed, or unrealized. They are possibilities rather than actualities, things that might be or might happen, rather than things that are. The quantum wave function is a mathematical description of the possibilities associated with a system at any moment.

Consider the situation of Schrödinger's alive/dead cat. Before we open the box to look at the cat, he has two equally "real" possibilities—the possibility that he is alive and the possibility that he is dead.

The cat himself exists in a superposition of these two states. (See PROLOGUE; SUPERPOSITIONS.) The cat's wave function is a mathematical representation of these two possibilities. Graphically, we could draw it as a wave with two humps, each hump representing one possibility. Alternatively, we could draw the wave function of the top card on a full deck of shuffled but as yet unobserved (quantum) cards. This card has fifty-two possibilities, so its wave function would have fifty-two humps.

The wave function is called that for two reasons. If we describe the possibilities associated with a quantum system mathematically, they look like the mathematical description of a set of waves undulating. But more "tangibly," a wave function describes the momentary state of a system that really does consist of some kind of waves. These could be light, sound, or water waves. The quantum wave function describes the wave aspect of matter—that is, its indeterminate aspect, the aspect that is spread out (as waves) all across space and time.

Today physicists even know what the wave aspect of matter is waving in—each wave is an undulation or excitation of the underlying QUANTUM VACUUM, the underlying ground state of physical reality. (See QUANTUM FIELD THEORY.) Mathematically the wave function can be thought of as a menu of possible meals that one might eat, or a list of horses running in a race, each of which might possibly win.

In quantum theory, all events are possible (because the initial state of the system is indeterminate), but some are more likely than others. While the quantum physicist can say very little about the likelihood of any single quantum event's happening, quantum physics works as a science that can make predictions because patterns of probability emerge in large numbers of events. It is more likely that some events will happen than others, and over an average of many events, a given pattern of outcome is predictable. Thus, to make their science work for them, quantum physicists assign a probability to each of the possibilities represented in a wave function. How likely is it that, of the fifty-two possibilities existing, the top card on a fully shuffled deck will be the queen of hearts? How likely is it that when we open the box, we will find Schrödinger's cat alive and well? The answer to these questions is called a probability function, and is arrived at mathematically by squaring the amplitude of each possibility's hump on the wave function.

$$i\hbar \frac{\partial \Psi}{\partial t} = \left(\hat{p}^2/_{2m} + V\right)\Psi$$

Schrödinger's Equation

Both the wave function (also known as Schrödinger's wave function) and the probability function tell us the possibilities and probabilities associated with a quantum system *at any moment*. They are like still snapshots, which catch a segment of action. But all physics is concerned with how things change over time, with how they evolve. To calculate how the wave function evolves through time, quantum theorists use Schrödinger's wave *equation*. (In very high energy situations, a slightly different wave equation must be used, to take account of SPECIAL RELATIVITY effects.)

Schrödinger's equation describes the dynamic unfolding of a set of possibilities over time and tells us the probability of finding any one possibility actualized in a given experimental situation. This is the equation with which physicists can accurately predict the outcome of a large run of quantum events. And while the evolution of a single event is always indeterminate, Schrödinger's equation describes a fully determinate situation—at any given time, as the wave function evolves, the probabilities associated with any possibility are fixed. For a large number of events, these can tell us exactly what to expect.

Schrödinger's equation is like a set of bookmaker's odds, and we can accurately use it as such with two important provisos. First, the equation is calculated on an undisturbed or unmeasured quantum system that exists as an array of possibilities. The moment any one of these possibilities is actualized—through measurement or observation, for instance—the whole equation must be recalculated to give a new set of odds. If there is a one-in-fifty-two chance of the queen of hearts' being drawn from a full deck of cards, the odds change every time a card is drawn that is not the queen of hearts. Once this card is drawn, the possibility of its being drawn again is zero. If there is a 50 percent chance of finding Schrödinger's cat alive before we open the box, this reduces to zero if we open it and find him dead. (See COLLAPSE OF THE WAVE FUNCTION.)

The other limitation on thinking of Schrödinger's equation as a set of bookmaker's odds is ontological; it has to do with the kind of existence found in quantum reality. The events that Schrödinger's equation describes are *more* than mere probabilities. The wave function really is waving in something. In the absence of observation or measurement, its possibilities evolve and interfere (interact) with each other. They have a real effect on the real world. The possibilities are not yet actualities, but they are more than mere mathematical entities. They are a different kind of being—*potentialities*—described for the first time in modern science by quantum physics. (See ACTUALITY AND POTENTIALITY IN QUANTUM MECHANICS.)

Wave/Particle Duality

One of quantum theory's most revolutionary ideas is that all the constituents of matter and light are *both* wavelike *and* particlelike *at the same time*. This is known as the wave/particle duality. Neither aspect of the duality—the wavelike or the particlelike—is more primary or more real. The two complement each other, and both are necessary for any full description of what light and matter really are. (See COMPLEMENTARITY.)

The oldest concept of matter is that it is made up of particles, individual pointlike entities, with a few simple properties such as position, movement, mass, and charge. The early Greeks attributed other properties, such as color, to them, but these were not considered basic in classical physics. For purposes of calculation, particles can be very large, like apples or planets, or very small, like atoms or electrons. Any bulk substance, like a pile of sand or a jug of water, can be seen as composed of myriads of tiny particles. (See ATOMISM.) Bulk properties like weight, pressure, and volume are considered the sum of the properties of the parts.

Waves are almost as familiar as particles, although very different.

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There are sound waves, ripples on the surface of water, electromagnetic waves (light, radio, X rays, and so on), and the vibrations of a guitar string. In classical physics, waves were treated as disturbances or excitations of some material medium, itself composed of particles—air, water, strings, or "the ether," the universal medium believed by classical physicists to fill empty space. But since Einstein proposed SPECIAL RELATIVITY, it has been recognized that electromagnetic waves are not like this (because there is no ether) but have a reality of their own, as fundamental as that of particles.

A wave has a succession of peaks and troughs, a wavelength (the distance between successive peaks), a frequency (the number of peaks per second), and a velocity. Waves carry energy, which depends upon their amplitude (the average height of the peaks in any region). At any given point as it passes, a wave has a phase, which is where, in the cycle of peaks and troughs, it is at that moment.

Particles behave quite differently from waves. They are localized at one point in space and time, and when two particles meet, they bump into each other, clash, and go their separate ways. Waves are not localized; they can be spread out across vast regions of space and time. When two meet, they can overlap and pass through each other. The resulting disturbance at the point of meeting can be increased or decreased as the two disturbances add or subtract, depending on their phase. Two waves meeting produce interference patterns, a patchwork of crisscrossing peaks and troughs where their disturbances add and subtract. Particles are always individuals, but since any two wave patterns add up to make a third, waves are not. Particles are ultimately discrete or irreducible, but a wave can be regarded as the sum of various "components" in an infinity of ways.

Both waves and particles have well-established, quite distinct mathematical descriptions in classical physics. Trying to combine them in some mathematically coherent way is like trying to marry fire and water, yet it was the genius, and the necessity, of quantum physics to do so. The major impetus came from a renewed attempt to understand the nature of light in the face of certain experimental anomalies.

Newton firmly believed that light was a stream of particles, but his view was overridden by nineteenth-century physicists trying to understand how light could bend around corners (diffraction) and give rise to interference patterns. They decided it was a wave undulating in the newly proposed background ether. Light's supposed wavelike nature could not, however, explain the new experimental results associated with black-body radiation: why a body disposed to emit nonpreferentially the full spectrum of colors does so in an observed bell-shaped pattern of intensities, rather than trailing off to infinity as predicted by the wavelike equations of classical theory. Planck's theory that light is absorbed or radiated, not continuously but in little packets called photons each associated with a quantum of action, accurately explained the observations (see QUANTUM), but left physicists with the conclusion that light was behaving like a stream of little "lumps," i.e., *particles*.

Building on Planck's theory, Einstein was able in 1905 to explain another experimental puzzle, the photoelectric effect, by proposing that light is a stream of photon particles, each carrying one quantum of action. His theory that electrons are knocked out of a metal surface by the photons, like coconuts being knocked off a fairground shelf by balls, was verified by the appearance of a photographic plate exposed to a very weak beam of light. The plate shows a patchwork of black spots where each photon has knocked out an electron, rather than a uniform gray exposure as would be expected if the light were a series of continuous waves.

These particlelike interpretations of light's behavior led to a paradox. Unquestionably, light can behave like a stream of particles. There are other times when it behaves like a series of waves (interference and diffraction, for example). This paradox led to confusion until the 1920s, when it was shown to make mathematical, if not common, sense to say that light *sometimes* behaves like a particle, and *sometimes* like a wave. Light itself cannot be said to be either; it must instead be seen as a potentiality to be *both* at any given time, depending upon the circumstances and experimental surroundings in which it finds itself. (See ACTUALITY AND POTENTIALITY IN QUANTUM MECHANICS; CONTEXTUALISM.)

> **"Light seems to behave like a wave on Mondays, Wednesdays and Fridays and like a particle on Tuesdays, Thursdays and Saturdays."**
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> **—WILLIAM BRAGG**

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The opposite paradox arose with solid matter, which can usually be interpreted as consisting of particles, but sometimes behaves as though these had a wavelength. Streams of photons and electrons can, in some experiments, give rise to interference patterns. Even large objects like apples and ourselves have a wavelength, although this is so infinitesimally small as to be of no practical consequence. The wave nature of electrons is the physical basis of the electron microscope, which uses beams of electrons, whose wavelengths are millions of times shorter than those of photons, to view objects too tiny for examination by a light microscope.

Though both light and matter have wave and particle aspects, the two are not identical. Matter is more "solid" than light. (See BOSONS; FERMIONS.) Mathematically, light is described by Maxwell's equation, and solid matter by Schrödinger's equation (see THE WAVE FUNCTION AND SCHRÖDINGER'S EQUATION), or by its relativistic refinements in QUANTUM FIELD THEORY. The analogies are very close.

The both/and, rather than the either/or, nature of light and matter is one of the outcomes of quantum physics that has the most profound philosophical implications. Viewed from within the old paradigm, it seems utterly paradoxical, but taken into our way of thinking and extended through metaphor to things like the individual and relational aspects of the self or society, it gives us a new way of looking at our own experience.

> **"A paradox is not a conflict within reality. It is a conflict between reality and your feeling of what reality should be like."**
>
> **—RICHARD FEYNMAN**

Wormholes

See TIME TRAVEL.