ecules, the entropy—or disorder—will keep increasing until, eventually, the system reaches a state of maximum entropy, also known as "heat death"; in this state all activity has ceased, all material being evenly distributed and at the same temperature. According to classical physics, the universe as a whole is going toward such a state of maximum entropy; it is running down and will eventually grind to a halt.

This grim picture of cosmic evolution is in sharp contrast to the evolutionary idea held by biologists, who observe that the living universe evolves from disorder to order, toward states of ever increasing complexity. The emergence of the concept of evolution in physics thus brought to light another limitation of the Newtonian theory. The mechanistic conception of the universe as a system of small billiard balls in random motion is far too simplistic to deal with the evolution of life.

At the end of the nineteenth century Newtonian mechanics had lost its role as the fundamental theory of natural phenomena. Maxwell's electrodynamics and Darwin's theory of evolution involved concepts that clearly went beyond the Newtonian model and indicated that the universe was far more complex than Descartes and Newton had imagined. Nevertheless, the basic ideas underlying Newtonian physics, though insufficient to explain all natural phenomena, were still believed to be correct. The first three decades of our century changed this situation radically. Two developments in physics, culminating in relativity theory and in quantum theory, shattered all the principal concepts of the Cartesian world view and Newtonian mechanics. The notion of absolute space and time, the elementary solid particles, the fundamental material substance, the strictly causal nature of physical phenomena, and the objective description of nature—none of these concepts could be extended to the new domains into which physics was now penetrating.

3 · The New Physics

At the beginning of modern physics stands the extraordinary intellectual feat of one man—Albert Einstein. In two articles, both published in 1905, Einstein initiated two revolutionary trends in scientific thought. One was his special theory of relativity; the other was a new way of looking at electromagnetic radiation which was to become characteristic of quantum theory, the theory of atomic phenomena. The complete quantum theory was worked out twenty years later by a whole team of physicists. Relativity theory, however, was constructed in its complete form almost entirely by Einstein himself. Einstein's scientific papers are intellectual monuments that mark the beginning of twentieth-century thought.

Einstein strongly believed in nature's inherent harmony, and throughout his scientific life his deepest concern was to find a unified foundation of physics. He began to move toward this goal by constructing a common framework for electrodynamics and mechanics, the two separate theories of classical physics. This framework is known as the special theory of relativity. It unified and completed the structure of classical physics, but at the same time it involved radical changes in the traditional concepts of space and time and thus undermined one of the foundations of the Newtonian world view. Ten years later Einstein proposed his general theory of relativity, in which the framework of the special theory is extended to include gravity. This is achieved by further drastic modifications of the concepts of space and time.

The other major development in twentieth-century physics was a consequence of the experimental investigation of atoms. At the turn of the century physicists discovered several phenomena connected with the structure of atoms, such as X-rays and radioactivity, which were inexplicable in terms of classical physics. Besides being objects of intense study, these phenomena were used, in most ingenious ways, as new tools to probe deeper into matter than had ever been possible before. For example, the so-called alpha particles emanating from radioactive substances were perceived to be high-speed projectiles of subatomic size that could be used to explore the interior of the atom. They could be fired at atoms, and from the way they were deflected one could draw conclusions about the atoms' structure.

This exploration of the atomic and subatomic world brought scientists in contact with a strange and unexpected reality that shattered the foundations of their world view and forced them to think in entirely new ways. Nothing like that had ever happened before in science. Revolutions like those of Copernicus and Darwin had introduced profound changes in the general conception of the universe, changes that were shocking to many people, but the new concepts themselves were not difficult to grasp. In the twentieth century, however, physicists faced, for the first time, a serious challenge to their ability to understand the universe. Every time they asked nature a question in an atomic experiment, nature answered with a paradox, and the more they tried to clarify the situation, the sharper the paradoxes became. In their struggle to grasp this new reality, scientists became painfully aware that their basic concepts, their language, and their whole way of thinking were inadequate to describe atomic phenomena. Their problem was not only intellectual but involved an intense emotional and existential experience, as vividly described by Werner Heisenberg: "I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair; and when at the end of the discussion I went alone for a walk in the neighboring park I repeated to myself again and again the question: Can nature possibly be so absurd as it seemed to us in these atomic experiments?"[1]

It took these physicists a long time to accept the fact that the paradoxes they encountered are an essential aspect of atomic physics, and to realize that they arise whenever one tries to describe atomic phenomena in terms of classical concepts. Once this was perceived, the physicists began to learn to ask the right questions and to avoid contradictions. As Heisenberg says, "They somehow got into the spirit of the quantum theory,"[2] and finally they found the precise and consistent mathematical formulation of that theory. Quantum theory, or quantum mechanics as it is also called, was formulated during the first three decades of the century by an international group of physicists including Max Planck, Albert Einstein, Niels Bohr, Louis De Broglie, Erwin Schrödinger, Wolfgang Pauli, Werner Heisenberg, and Paul Dirac. These men joined forces across national borders to shape one of the most exciting periods of modern science, one that saw not only brilliant intellectual exchanges but also dramatic human conflicts, as well as deep personal friendships, among the scientists.

Even after the mathematical formulation of quantum theory was completed, its conceptual framework was by no means easy to accept. Its effect on the physicists' view of reality was truly shattering. The new physics necessitated profound changes in concepts of space, time, matter, object, and cause and effect; and because these concepts are so fundamental to our way of experiencing the world, their transformation came as a great shock. To quote Heisenberg again, "The violent reaction to the recent development of modern physics can only be understood when one realizes that here the foundations of physics have started moving; and that this motion has caused the feeling that the ground would be cut from science."[3]

Einstein experienced the same shock when he was confronted with the new concepts of physics, and he described his feelings in terms very similar to Heisenberg's: "All my attempts to adapt the theoretical foundation of physics to this [new type of] knowledge failed completely. It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built."[4]

Out of the revolutionary changes in our concepts of reality that were brought about by modern physics, a consistent world view is now emerging. This view is not shared by the entire physics community, but is being discussed and elaborated by many leading physicists whose interest in their science goes beyond the technical aspects of their research. These scientists are deeply interested in the philosophical implications of modern physics and are trying in an open-minded way to improve their understanding of the nature of reality.

In contrast to the mechanistic Cartesian view of the world, the world view emerging from modern physics can be characterized by words like organic, holistic, and ecological. It might also be called a systems view, in the sense of general systems theory.[5] The universe is no longer seen as a machine, made up of a multitude of objects, but has to be pictured as one indivisible, dynamic whole whose parts are essentially interrelated and can be understood only as patterns of a cosmic process.

The basic concepts underlying this world view of modern physics are discussed in the following pages. I described this world view in detail in *The Tao of Physics*, showing how it is related to the views held in mystical traditions, especially those of Eastern mysticism. Many physicists, brought up, as I was, in a tradition that associates mysticism with things vague, mysterious, and highly unscientific, were shocked at having their ideas compared to those of mystics.[6] Fortunately, this attitude is now changing. As Eastern thought has begun to interest a significant number of people, and meditation is no longer viewed with ridicule or suspicion, mysticism is being taken seriously even within the scientific community. An increasing number of scientists are aware that mystical thought provides a consistent and relevant philosophical background to the theories of contemporary science, a conception of the world in which the scientific discoveries of men and women can be in perfect harmony with their spiritual aims and religious beliefs.

The experimental investigation of atoms at the beginning of the century yielded sensational and totally unexpected results. Far from being the hard, solid particles of time-honored theory, atoms turned out to consist of vast regions of space in which extremely small particles—the electrons—moved around the nucleus. A few years later quantum theory made it clear that even the subatomic particles—the electrons and the protons and neutrons in the nucleus—were nothing like the solid objects of classical physics. These subatomic units of matter are very abstract entities which have a dual aspect. Depending on how we look at them, they appear sometimes as particles, sometimes as waves; and this dual nature is also exhibited by light, which can take the form of electromagnetic waves or particles. The particles of light were first called "quanta" by Einstein—hence the origin of the term "quantum theory"—and are now known as photons.

This dual nature of matter and of light is very strange. It seems impossible to accept that something can be, at the same time, a particle, an entity confined to a very small volume, and a wave, which is spread out over a large region of space. And yet this is exactly what physicists had to accept. The situation seemed hopelessly paradoxical until it was realized that the terms "particle" and "wave" refer to classical concepts which are not fully adequate to describe atomic phenomena. An electron is neither a particle nor a wave, but it may show particle-like aspects in some situations and wave-like aspects in others. While it acts like a particle, it is capable of developing its wave nature at the expense of its particle nature, and vice versa, thus undergoing continual transformations from particle to wave and from wave to particle. This means that neither the electron nor any other atomic "object" has any intrinsic properties independent of its environment. The properties it shows—particle-like or wave-like—will depend on the experimental situation, that is, on the apparatus it is forced to interact with.[7]

It was Heisenberg's great achievement to express the limitations of classical concepts in a precise mathematical form, which is known as the uncertainty principle. It consists of a set of mathematical relations that determine the extent to which classical concepts can be applied to atomic phenomena; these relations stake out the limits of human imagination in the atomic world. Whenever we use classical terms—particle, wave, position, velocity—to describe atomic phenomena, we find that there are pairs of concepts, or aspects, which are interrelated and cannot be defined simultaneously in a precise way. The more we emphasize one aspect in our description the more the other aspect becomes uncertain, and the precise relation between the two is given by the uncertainty principle.

For a better understanding of this relation between pairs of classical concepts, Niels Bohr introduced the notion of complementarity. He considered the particle picture and the wave picture two complementary descriptions of the same reality, each of them only partly correct and having a limited range of application. Both pictures are needed to give a full account of the atomic reality, and both are to be applied within the limitations set by the uncertainty principle. The notion of complementarity has become an essential part of the way physicists think about nature, and Bohr has often suggested that it might also be a useful concept outside the field of physics. Indeed, this seems to be true, and we shall come back to it in discussions of biological and psychological phenomena. Complementarity has already been used extensively in our survey of the Chinese yin/yang terminology, since the yin and yang opposites are interrelated in a polar, or complementary, way. Clearly the modern concept of complementarity is reflected in ancient Chinese thought, a fact that made a deep impression on Niels Bohr.[8]

The resolution of the particle/wave paradox forced physicists to accept an aspect of reality that called into question the very foundation of the mechanistic world view—the concept of the reality of matter. At the subatomic level, matter does not exist with certainty at definite places, but rather shows "tendencies to exist," and atomic events do not occur with certainty at definite times and in definite ways, but rather show "tendencies to occur." In the formalism of quantum mechanics, these tendencies are expressed as probabilities and are associated with quantities that take the form of waves; they are similar to the mathematical forms used to describe, say, a vibrating guitar string, or sound wave. This is how particles can be waves at the same time. They are not "real" three-dimensional waves like water waves or sound waves. They are "probability waves"—abstract mathematical quantities with all the characteristic properties of waves—that are related to the probabilities of finding the particles at particular points in space and at particular times. All the laws of atomic physics are expressed in terms of these probabilities. We can never predict an atomic event with certainty; we can only predict the likelihood of its happening.

The discovery of the dual aspect of matter and of the fundamental role of probability has demolished the classical notion of solid objects. At the subatomic level, the solid material objects of classical physics dissolve into wave-like patterns of probabilities. These patterns, furthermore, do not represent probabilities of things, but rather probabilities of interconnections. A careful analysis of the process of observation in atomic physics shows that the subatomic particles ~~have~~ no meaning as isolated entities but can be understood only as interconnections, or correlations, between various processes of observation and measurement. As Niels Bohr wrote, "Isolated material particles are abstractions, their properties being definable and observable only through their interaction with other systems."[9]

Subatomic particles, then, are not "things" but are interconnections between "things," and these "things," in turn, are interconnections between other "things," and so on. In quantum theory you never end up with "things"; you always deal with interconnections.

This is how modern physics reveals the basic oneness of the universe. It shows that we cannot decompose the world into independently existing smallest units. As we penetrate into matter, nature does not show us any isolated basic building blocks, but rather appears as a complicated web of relations between the various parts of a unified whole. As Heisenberg expresses it, "The world thus appears as a complicated tissue of events, in which connections of different kinds alternate or overlap or combine and thereby determine the texture of the whole."[10]

The universe, then, is a unified whole that can to some extent be divided into separate parts, into objects made of molecules and atoms, themselves made of particles. But here, at the level of particles, the notion of separate parts breaks down. The subatomic particles—and therefore, ultimately, all parts of the universe—cannot be understood as isolated entities but must be defined through their interrelations. Henry Stapp, of the University of California, writes, "An elementary particle is not an independently existing unanalyzable entity. It is, in essence, a set of relationships that reach outward to other things."[11]

This shift from objects to relationships has far-reaching implications for science as a whole. Gregory Bateson even argued that relationships should be used as a basis for *all* definitions, and that this should be taught to our children in elementary school.[12] Any thing, he believed, should be defined not by what it is in itself, but by its relations to other things.

In quantum theory the fact that atomic phenomena are determined by their connections to the whole is closely related to the fundamental role of probability.[13] In classical physics, probability is used whenever the mechanical details involved in an event are unknown. For example, when we throw a die, we could—in principle—predict the outcome if we knew all the details of the objects involved: the exact composition of the die, of the surface on which it falls, and so on. These details are called local variables because they reside within the objects involved. Local variables are important in atomic and subatomic physics too. Here they are represented by connections between spatially separated events through signals—particles and networks of particles—that respect the usual laws of spatial separation. For example, no signal can be transmitted faster than the speed of light. But beyond these local connections are other, nonlocal connections that are instantaneous and cannot be predicted, at present, in a precise mathematical way. These nonlocal connections are the essence of quantum reality. Each event is influenced by the whole universe, and although we cannot describe this influence in detail, we recognize some order that can be expressed in terms of statistical laws.

Thus probability is used in classical and quantum physics for similar reasons. In both cases there are "hidden" variables, unknown to us, and this ignorance prevents us from making exact predictions. There is a crucial difference, however. Whereas the hidden variables in classical physics are local mechanisms, those in quantum physics are nonlocal; they are instantaneous connections to the universe as a whole. In the ordinary, macroscopic world nonlocal connections are relatively unimportant, and thus we can speak of separate objects and formulate the laws of physics in terms of certainties. But as we go to smaller dimensions, the influence of nonlocal connections becomes stronger; here the laws of physics can be formulated only in terms of probabilities, and it becomes more and more difficult to separate any part of the universe from the whole.

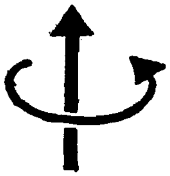
Einstein could never accept the existence of nonlocal connections and the resulting fundamental nature of probability. This was the subject of the historic debate in the 1920s with Bohr, in which Einstein expressed his opposition to Bohr's interpretation of quantum theory in the famous metaphor "God does not play dice."[14] At the end of the debate, Einstein had to admit that quantum theory, as interpreted by Bohr and Heisenberg, formed a consistent system of thought, but he remained convinced that a deterministic interpretation in terms of local hidden variables would be found some time in the future.

Einstein's unwillingness to accept the consequences of the theory that his earlier work had helped to establish is one of the most fascinating episodes in the history of science. The essence of his disagreement with Bohr was his firm belief in some external reality, consisting of independent spatially separated elements. This shows that Einstein's philosophy was essentially Cartesian. Although he initiated the revolution of twentieth-century science and went far beyond Newton in his theory of relativity, it seems that Einstein, somehow, could not bring himself to go beyond Descartes. This kinship between Einstein and Descartes is even more intriguing in view of Einstein's attempts, toward the end of his life, to construct a unified field theory by geometrizing physics along the lines of his general theory of relativity. Had these attempts been successful, Einstein could well have said, like Descartes, that his entire physics was nothing other than geometry.

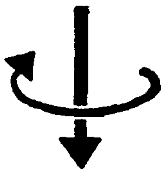
In his attempt to show that Bohr's interpretation of quantum theory was inconsistent, Einstein devised a thought experiment that has become known as the Einstein-Podolsky-Rosen (EPR) experiment.[15] Three decades later John Bell derived a theorem, based on the EPR experiment, which proves that the existence of local hidden variables is inconsistent with the statistical predictions of quantum mechanics.[16] Bell's theorem dealt a shattering blow to Einstein's position by showing that the Cartesian conception of reality as consisting of separate parts, joined by local connections, is incompatible with quantum theory.

The EPR experiment provides a fine example of a situation in which a quantum phenomenon clashes with our deepest intuition of reality. It is thus ideally suited to show the difference between classical and quantum concepts. A simplified version of the experiment involves two spinning electrons, and, if we are to grasp the essence of the situation, it is necessary to understand some properties of electron spin.[17] The classical image of a spinning tennis ball is not fully adequate to describe a spinning subatomic particle. Particle spin is in a sense a rotation about the particle's own axis, but, as always in subatomic physics, this classical concept is limited. In the case of an electron, the particle's spin is restricted to two values: the amount of spin is always the same, but the particle can spin in one or the other direction, for a given axis of rotation. Physicists often denote these two values of spin by "up" and "down," assuming the electron's axis of rotation, in this case, to be vertical.

The crucial property of a spinning electron, which cannot be understood in terms of classical ideas, is the fact that its axis of rotation can-



"SPIN UP"



"SPIN DOWN"

not always be defined with certainty. Just as electrons show tendencies to exist in certain places, they also show tendencies to spin about certain axes. Yet whenever a measurement is performed for any axis of rotation, the electron will be found to spin in one or the other direction about that axis. In other words, the particle acquires a definite axis of rotation in the process of measurement, but before the measurement is taken, it cannot generally be said to spin about a definite axis; it merely has a certain tendency, or potentiality, to do so.

With this understanding of electron spin we can now examine the EPR experiment and Bell's theorem. To set up the experiment, any one of several methods is used to put two electrons in a state in which their total spin is zero, that is, they are spinning in opposite directions. Now suppose the two particles in this system of total spin zero are made to drift apart by some process that does not affect their spins. As they go off in opposite directions, their combined spin will still be zero, and once they are separated by a large distance, their individual spins are measured. An important aspect of the experiment is the fact that the distance between the two particles at the time of the measurement is macroscopic. It can be arbitrarily large; one particle may be in Los Angeles and the other in New York, or one on the earth and the other on the moon.

Suppose now that the spin of particle 1 is measured along a vertical axis and is found to be "up." Because the combined spin of the two particles is zero, this measurement tells us that the spin of particle 2 must be "down." Similarly, if we choose to measure the spin of particle 1 along a horizontal axis and find it to be "right," we know that in that case the spin of particle 2 must be "left." Quantum theory tells us that in a system of two particles having total spin zero, the spins of the particles about any axis will always be correlated—will be opposite—even though they exist only as tendencies, or potentialities, before the measurement is taken. This correlation means that the measurement of the spin of particle 1, along any axis, provides an indirect measurement of the spin of particle 2 without in any way disturbing that particle.

The paradoxical aspect of the EPR experiment arises from the fact that the observer is free to choose the axis of measurement. Once this choice is made, the measurement transforms the tendencies of the particles to spin about various axes into certainties. The crucial point is

that we can choose our axis of measurement at the last minute, when the particles are already far apart. At the instant we perform our measurement on particle 1, particle 2, which may be thousands of miles away, will acquire a definite spin—"up" or "down" if we have chosen a vertical axis, "left" or "right" if we have chosen a horizontal axis. How does particle 2 know which axis we have chosen? There is no time for it to receive that information by any conventional signal.

This is the crux of the EPR experiment, and this is where Einstein disagreed with Bohr. According to Einstein, since no signal can travel faster than the speed of light, it is therefore impossible that the measurement performed on one particle will instantly determine the direction of the other particle's spin, thousands of miles away. According to Bohr, the two-particle system is an indivisible whole, even if the particles are separated by a great distance; the system cannot be analyzed in terms of independent parts. In other words, the Cartesian view of reality cannot be applied to the two electrons. Even though they are far apart in space, they are nevertheless linked by instantaneous, nonlocal connections. These connections are not signals in the Einsteinian sense; they transcend our conventional notions of information transfer. Bell's theorem supports Bohr's interpretation of the two particles as an indivisible whole and proves rigorously that Einstein's Cartesian view is incompatible with the laws of quantum theory. As Stapp sums up the situation, "The theorem of Bell proves, in effect, the profound truth that the world is either fundamentally lawless or fundamentally inseparable."[18]

The fundamental role of nonlocal connections and of probability in atomic physics implies a new notion of causality that is likely to have profound implications for all fields of science. Classical science was constructed by the Cartesian method of analyzing the world into parts and arranging those parts according to causal laws. The resulting deterministic picture of the universe was closely related to the image of nature as a clockwork. In atomic physics, such a mechanical and deterministic picture is no longer possible. Quantum theory has shown us that the world cannot be analyzed into independently existing isolated elements. The notion of separate parts—like atoms, or subatomic particles—is an idealization with only approximate validity; these parts are not connected by causal laws in the classical sense.

In quantum theory individual events do not always have a well-defined cause. For example, the jump of an electron from one atomic orbit to another, or the disintegration of a subatomic particle, may occur spontaneously without any single event causing it. We can never predict when and how such a phenomenon is going to happen; we can only predict its probability. This does not mean that atomic events occur in completely arbitrary fashion; it means only that they are not brought about by local causes. The behavior of any part is determined by its nonlocal connections to the whole, and since we do not know these connections precisely, we have to replace the narrow classical notion of cause and effect by the wider concept of statistical causality. The laws of atomic physics are statistical laws, according to which the probabilities for atomic events are determined by the dynamics of the whole system. Whereas in classical mechanics the properties and behavior of the parts determine those of the whole, the situation is reversed in quantum mechanics: it is the whole that determines the behavior of the parts.

The concepts of nonlocality and statistical causality imply quite clearly that the structure of matter is not mechanical. Hence the term "quantum mechanics" is very much a misnomer, as David Bohm has pointed out.[19] In his 1951 textbook on quantum theory Bohm offered some interesting speculations on the analogies between quantum processes and thought processes,[20] thus carrying further the celebrated statement made by James Jeans two decades earlier: "Today there is a wide measure of agreement . . . that the stream of knowledge is heading towards a non-mechanical reality; the universe begins to look more like a great thought than like a great machine."[21]

The apparent similarities between the structure of matter ~~and the~~ structure of mind should not surprise us too much, since human consciousness plays a crucial role in the process of observation, and in atomic physics determines to a large extent the properties of the observed phenomena. This is another important insight of quantum theory that is likely to have far-reaching consequences. In atomic physics the observed phenomena can be understood only as correlations between various processes of observation and measurement, and the end of this chain of processes lies always in the consciousness of the human observer. The crucial feature of quantum theory is that the observer is not only necessary to observe the properties of an atomic phenomenon, but is necessary even to bring about these properties. My conscious decision about how to observe, say, an electron will determine the electron's properties to some extent. If I ask it a particle question, it will give me a particle answer; if I ask it a wave question, it will give me a wave answer. The electron does not *have* objective properties independent of my mind. In atomic physics the sharp Cartesian division between mind and matter, between the observer and the observed, can no longer be maintained. We can never speak about nature without, at the same time, speaking about ourselves.

In transcending the Cartesian division, modern physics has not only invalidated the classical ideal of an objective description of nature but has also challenged the myth of a value-free science. The patterns scientists observe in nature are intimately connected with the patterns of their minds; with their concepts, thoughts, and values. Thus the scientific results they obtain and the technological applications they investigate will be conditioned by their frame of mind. Although much of their detailed research will not depend explicitly on their value system, the larger paradigm within which this research is pursued will never be value-free. Scientists, therefore, are responsible for their research not only intellectually but also morally. This responsibility has become an important issue in many of today's sciences, but especially so in physics, in which the results of quantum mechanics and relativity theory have opened up two very different paths for physicists to pursue. They may lead us—to put it in extreme terms—to the Buddha or to the Bomb, and it is up to each of us to decide which path to take.

The conception of the universe as an interconnected web of relations is one of two major themes that recur throughout modern physics. The other theme is the realization that the cosmic web is intrinsically dynamic. The dynamic aspect of matter arises in quantum theory as a consequence of the wave nature of subatomic particles, and is even more central in relativity theory, which has shown us that the being of matter cannot be separated from its activity. The properties of its basic patterns, the subatomic particles, can be understood only in a dynamic context, in terms of movement, interaction, and transformation.

The fact that particles are not isolated entities but wave-like probability patterns implies that they behave in a very peculiar way. Whenever a subatomic particle is confined to a small region of space, it reacts to this confinement by moving around. The smaller the region of confinement, the faster the particle will "jiggle" around in it. This behavior is a typical "quantum effect," a feature of the subatomic world which has no analogy in macroscopic physics: the more a particle is confined, the faster it will move around.[22] This tendency of particles to react to confinement with motion implies a fundamental "restlessness" of matter which is characteristic of the subatomic world. In this world most of the material particles *are* confined; they are bound to the molecular, atomic, and nuclear structures, and therefore are not at rest but have an inherent tendency to move about. According to quantum theory, matter is always restless, never quiescent. To the extent that things can be pictured to be made of smaller constituents—molecules, atoms, and particles—these constituents are in a state of continual motion. Macroscopically, the material objects around us may seem passive and inert, but when we magnify such a "dead" piece of stone or metal, we see that it is full of activity. The closer we look at it, the more alive it appears. All the material objects in our environment are made of atoms that link up with each other in various ways to form an enormous variety of molecular structures which are not rigid and motionless but vibrate according to their temperature and in harmony with the thermal vibrations of their environment. Inside the vibrating atoms the electrons are bound to the atomic nuclei by electric forces that try to keep them as close as possible, and they respond to this confinement by whirling around extremely fast. In the nuclei, finally, protons and neutrons are pressed into a minute volume by the strong nuclear forces, and consequently race about at unimaginable velocities.

Modern physics thus pictures matter not at all as passive and inert but as being in a continuous dancing and vibrating motion whose rhythmic patterns are determined by the molecular, ~~atomic,~~ and nuclear configurations. We have come to realize that there are no static structures in nature. There is stability, but this stability is one of dynamic balance, and the further we penetrate into matter the more we need to understand its dynamic nature to understand its patterns.

In this penetration into the world of submicroscopic dimensions, a decisive point is reached in the study of atomic nuclei in which the velocities of protons and neutrons are often so high that they come close to the speed of light. This fact is crucial for the description of their interactions, because any description of natural phenomena involving such high velocities has to take the theory of relativity into account. To understand the properties and interactions of subatomic particles we need a framework that incorporates not only quantum theory but also

relativity theory; and it is relativity theory that reveals the dynamic nature of matter to its fullest extent.

Einstein's theory of relativity has brought about a drastic change in our concepts of space and time. It has forced us to abandon the classical ideas of an absolute space as the stage of physical phenomena and absolute time as a dimension separate from space. According to Einstein's theory, both space and time are relative concepts, reduced to the subjective role of elements of the language a particular observer uses to describe natural phenomena. To provide an accurate description of phenomena involving velocities close to the speed of light, a "relativistic" framework has to be used, one that incorporates time with the three space coordinates, making it a fourth coordinate to be specified relative to the observer. In such a framework space and time are intimately and inseparably connected and form a four-dimensional continuum called "space-time." In relativistic physics, we can never talk about space without talking about time, and vice versa.

Physicists have now lived with relativity theory for many years and have become thoroughly familiar with its mathematical formalism. Nevertheless, this has not helped our intuition very much. We have no direct sensory experience of the four-dimensional space-time, and whenever this relativistic reality manifests itself—that is, in all situations where high velocities are involved—we find it very hard to deal with it at the level of intuition and ordinary language. An extreme example of such a situation occurs in quantum electrodynamics, one of the most successful relativistic theories of particle physics, in which antiparticles may be interpreted as particles moving backward in time. According to this theory, the same mathematical expression describes either a positron—the antiparticle of the electron—moving from the past to the future, or an electron moving from the future to the past. Particle interactions can stretch in any direction of four-dimensional space-time, moving backward and forward in time just as they move left and right in space. To picture these interactions we need four-dimensional maps covering the whole span of time as well as the whole region of space. These maps, known as space-time diagrams, have no definite direction of time attached to them. Consequently there is no "before" and "after" in the processes they picture, and thus no linear relation of cause and effect. All events are interconnected, but the connections are not causal in the classical sense.

Mathematically there are no problems with this interpretation of particle interactions, but when we want to express it in ordinary language we run into serious difficulties, since all our words refer to the conventional notions of time and are inappropriate to describe relativistic phenomena. Thus relativity theory has taught us the same lesson as quantum mechanics. It has shown us that our common notions of reality are limited to our ordinary experience of the physical world and have to be abandoned whenever we extend this experience.

The concepts of space and time are so basic for our description of natural phenomena that their radical modification in relativity theory entailed a modification of the whole framework we use in physics to describe nature. The most important consequence of the new relativistic framework has been the realization that mass is nothing but a form of energy. Even an object at rest has energy stored in its mass, and the relation between the two is given by Einstein's famous equation $E = m c^2$, c being the speed of light.

Once it is seen to be a form of energy, mass is no longer required to be indestructible, but can be transformed into other forms of energy. This happens continually in the collision processes of high-energy physics, in which material particles are created and destroyed, their masses being transformed into energy of motion and vice versa. The collisions of subatomic particles are our main tool for studying their properties, and the relation between mass and energy is essential for their description. The equivalence of mass and energy has been verified innumerable times and physicists have become completely familiar with it—so familiar, in fact, that they measure the masses of particles in the corresponding energy units.

The discovery that mass is a form of energy has had a profound influence on our picture of matter and has forced us to modify our concept of a particle in an essential way. In modern physics, mass is no longer associated with a material substance, and hence particles are not seen as consisting of any basic "stuff," but as bundles of energy. Energy, however, is associated with activity, with processes, and this implies that the nature of subatomic particles is intrinsically dynamic. To understand this better we must remember that these particles can be conceived only in relativistic terms, that is, in terms of a framework where space and time are fused into a four-dimensional continuum. In such a framework the particles can no longer be pictured as small billiard balls, or small grains of sand. These images are inappropriate not

only because they represent particles as separate objects, but also because they are static, three-dimensional images. Subatomic particles must be conceived as four-dimensional entities in space-time. Their forms have to be understood dynamically, as forms in space and time. Particles are dynamic patterns, patterns of activity which have a space aspect and a time aspect. Their space aspect makes them appear as objects with a certain mass, their time aspect as processes involving the equivalent energy. Thus the being of matter and its activity cannot be separated; they are but different aspects of the same space-time reality.

The relativistic view of matter has drastically affected not only our conception of particles, but also our picture of the forces between these particles. In a relativistic description of particle interactions, the forces between the particles—their mutual attraction or repulsion—are pictured as the exchange of other particles. This concept is very difficult to visualize, but it is needed for an understanding of subatomic phenomena. It links the forces between constituents of matter to the properties of other constituents of matter, and thus unifies the two concepts, force and matter, which had seemed to be fundamentally different in Newtonian physics. Both force and matter are now seen to have their common origin in the dynamic patterns that we call particles. These energy patterns of the subatomic world form the stable nuclear, atomic, and molecular structures which build up matter and give it its macroscopic solid aspect, thus making us believe that it is made of some material substance. At the macroscopic level this notion of substance is a useful approximation, but at the atomic level it no longer makes sense. Atoms consist of particles, and these particles are not made of any material stuff. When we observe them we never see any substance; what we observe are dynamic patterns continually changing into one another—the continuous dance of energy.

The two basic theories of modern physics have thus transcended the principal aspects of the Cartesian world view and of Newtonian physics. Quantum theory has shown that subatomic particles are not isolated grains of matter but are probability patterns, interconnections in an inseparable cosmic web that includes the human observer and her*

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* The feminine pronoun is used here as a general reference to a person who may be a woman or a man. Similarly, I shall occasionally use the masculine pronoun as a general reference, including both men and women. I think this the best way to avoid being either sexist or awkward.

consciousness. Relativity theory has made the cosmic web come alive, so to speak, by revealing its intrinsically dynamic character; by showing that its activity is the very essence of its being. In modern physics, the image of the universe as a machine has been transcended by a view of it as one indivisible, dynamic whole whose parts are essentially interrelated and can be understood only as patterns of a cosmic process. At the subatomic level the interrelations and interactions between the parts of the whole are more fundamental than the parts themselves. There is motion but there are, ultimately, no moving objects; there is activity but there are no actors; there are no dancers, there is only the dance.

Current research in physics aims at unifying quantum mechanics and relativity theory in a complete theory of subatomic particles. We have not yet been able to formulate such a complete theory, but we do have several partial theories, or models, which describe certain aspects of subatomic phenomena very well. At present there are two different kinds of "quantum-relativistic" theories in particle physics that have been successful in different areas. The first are a group of quantum field theories which apply to electromagnetic and weak interactions; the second is the theory known as S-matrix theory, which has been successful in describing the strong interactions.[23] Of these two approaches, S-matrix theory is more relevant to the theme of this book, since it has deep implications for science as a whole.[24]

The philosophical foundation of S-matrix theory is known as the bootstrap approach. Geoffrey Chew proposed it in the early 1960s, and he and other physicists have used it to develop a comprehensive theory of strongly interacting particles, together with a more general philosophy of nature. According to this bootstrap philosophy, nature cannot be reduced to fundamental entities, like fundamental building blocks of matter, but has to be understood entirely through self-consistency. All of physics has to follow uniquely from the requirement that its components be consistent with one another and with themselves. This idea constitutes a radical departure from the traditional spirit of basic research in physics which had always been bent on finding the fundamental constituents of matter. At the same time it is the culmination of the conception of the material world as an interconnected web of relations that emerged from quantum theory. The bootstrap philosophy not only abandons the idea of fundamental building blocks of matter, but accepts no fundamental entities whatsoever—no fundamental constants, laws, or equations. The universe is seen as a dynamic web of interrelated events. None of the properties of any part of this web is fundamental; they all follow from the properties of the other parts, and the overall consistency of their interrelations determines the structure of the entire web.

The fact that the bootstrap approach does not accept any fundamental entities makes it, in my opinion, one of the most profound systems of Western thought, raising it to the level of Buddhist or Taoist philosophy.[25] At the same time it is a very difficult approach to physics, one that has been pursued by only a small minority of physicists. The bootstrap philosophy is too foreign to traditional ways of thinking to be seriously appreciated yet, and this lack of appreciation extends also to S-matrix theory. It is curious that although the basic concepts of the theory are used by all particle physicists whenever they analyze the results of particle collisions and compare them to their theoretical predictions, not a single Nobel prize has so far been awarded to any of the outstanding physicists who contributed to the development of S-matrix theory over the past two decades.

In the framework of S-matrix theory, the bootstrap approach attempts to derive all properties of particles and their interactions uniquely from the requirement of self-consistency. The only "fundamental" laws accepted are a few very general principles that are required by the methods of observation and are essential parts of the scientific framework. All other aspects of particle physics are expected to emerge as a necessary consequence of self-consistency. If this approach can be carried out successfully, the philosophical implications will be very profound. The fact that all the properties of particles are determined by principles closely related to the methods of observation would mean that the basic structures of the material world are determined, ultimately, by the way we look at this world; that the observed patterns of matter are reflections of patterns of mind.

The phenomena of the subatomic world are so complex that it is by no means certain whether a complete, self-consistent theory will ever be constructed, but one can envisage a series of partly successful models of smaller scope. Each of them would be intended to cover only a part of the observed phenomena and would contain some unexplained aspects, or parameters, but the parameters of one model might be explained by another. Thus more and more phenomena could gradually be covered with ever increasing accuracy by a mosaic of interlocking models whose net number of unexplained parameters keeps decreasing. The adjective "bootstrap" is thus never appropriate for any individual model, but can be applied only to a combination of mutually consistent models, none of which is any more fundamental than the others. Chew explains succinctly: "A physicist who is able to view any number of different partially successful models without favoritism is automatically a bootstrapper."[26]

Progress in S-matrix theory was steady but slow until several important developments of recent years resulted in a major breakthrough, which made it quite likely that the bootstrap program for the strong interactions will be completed in the near future, and that it may also be extended successfully to the electromagnetic and weak interactions.[27] These results have generated great enthusiasm among S-matrix theorists and are likely to force the rest of the physics community to reevaluate its attitudes toward the bootstrap approach.

The key element of the new bootstrap theory of subatomic particles is the notion of order as a new and important aspect of particle physics. Order, in this context, means order in the interconnectedness of subatomic processes. Since there are various ways in which subatomic events can interconnect, one can define various categories of order. The language of topology—well known to mathematicians but never before applied to particle physics—is used to classify these categories of order. When this concept of order is incorporated into the mathematical framework of S-matrix theory, only a few special categories of ordered relationships turn out to be consistent with that framework. The resulting patterns of particle interactions are precisely those observed in nature.

The picture of subatomic particles that emerges from the bootstrap theory can be summed up in the provocative phrase "Every particle consists of all other particles." It must not be imagined, however, that each of them contains all the others in a classical, static sense. Subatomic particles are not separate entities but interrelated energy patterns in an ongoing dynamic process. These patterns do not "contain" one another but rather "involve" one another in a way that can be given a precise mathematical meaning but cannot easily be expressed in words.

The emergence of order as a new and central concept in particle physics has not only led to a major breakthrough in S-matrix theory, but may well have great implications for science as a whole. The significance of order in subatomic physics is still obscure, and the extent to which it can be incorporated into the S-matrix framework is not yet fully known, but it is intriguing to remind ourselves that the notion of order plays a very basic role in the scientific approach to reality and is a crucial aspect of all methods of observation. The ability to recognize order seems to be an essential aspect of the rational mind; every perception of a pattern is, in a sense, a perception of order. The clarification of the concept of order in a field of research where patterns of matter and patterns of mind are increasingly being recognized as reflections of one another promises to open fascinating frontiers of knowledge.

Further extensions of the bootstrap approach in subatomic physics will eventually have to go beyond the present framework of S-matrix theory, which has been developed specifically to describe the strong interactions. To enlarge the bootstrap program a more general framework will have to be found, in which some of the concepts that are now accepted without explanation will have to be "bootstrapped," derived from overall self-consistency. These may include our conception of macroscopic space-time and, perhaps, even our conception of human consciousness. Increased use of the bootstrap approach opens up the unprecedented possibility of being forced to include the study of human consciousness explicitly in future theories of matter. The question of consciousness has already arisen in quantum theory in connection with the problem of observation and measurement, but the pragmatic formulation of the theory scientists use in their research does not refer to consciousness explicitly. Some physicists argue that consciousness may be an essential aspect of the universe, and that we may be blocked from further understanding of natural phenomena if we insist on excluding it.

At present there are two approaches in physics that come very close to dealing with consciousness explicitly. One is the notion of order in Chew's S-matrix theory; the other is a theory developed by David Bohm, who follows a much more general and more ambitious approach.[28] Bohm's starting point is the notion of "unbroken wholeness," and his aim is to explore the order he believes to be inherent in the cosmic web of relations at a deeper, "nonmanifest" level. He calls this order "implicate," or "enfolded," and describes it with the analogy of a hologram, in which each part, in some sense, contains the whole.[29] If any part of a hologram is illuminated, the entire image will be reconstructed, although it will show less detail than the image obtained from the complete hologram. In Bohm's view the real world is structured according to the same general principles, with the whole enfolded in each of its parts.

Bohm realizes that the hologram is too static to be used as a scientific model for the implicate order at the subatomic level. To express the essentially dynamic nature of reality at this level he has coined the term "holomovement." In his view the holomovement is a dynamic phenomenon out of which all forms of the material universe flow. The aim of his approach is to study the order enfolded in this holomovement, not by dealing with the structure of objects, but rather with the structure of movement, thus taking into account both the unity and the dynamic nature of the universe. To understand the implicate order Bohm has found it necessary to regard consciousness as an essential feature of the holomovement and to take it into account explicitly in his theory. He sees mind and matter as being interdependent and correlated, but not causally connected. They are mutually enfolding projections of a higher reality which is neither matter nor consciousness.

Bohm's theory is still tentative, but there seems to be an intriguing kinship, even at this preliminary stage, between his theory of the implicate order and Chew's S-matrix theory. Both approaches are based on a view of the world as a dynamic web of relations; both attribute a central role to the notion of order; both use matrices to represent change and transformation, and topology to classify categories of order. Finally, both theories recognize that consciousness may well be an essential aspect of the universe that will have to be included in a future theory of physical phenomena. Such a future theory may well arise from the merging of Bohm's and Chew's theories, which represent two of the most imaginative and philosophically profound contemporary approaches to physical reality.

My presentation of modern physics in this chapter has been influenced by my personal beliefs and allegiances. I have emphasized certain concepts and theories that are not yet accepted by the majority of physicists, but that I consider significant philosophically, of great importance for the other sciences and for our culture as a whole. Every contemporary physicist, however, will accept the main theme of the presentation—that modern physics has transcended the mechanistic Cartesian view of the world and is leading us to a holistic and intrinsically dynamic conception of the universe.

This world view of modern physics is a systems view, and it is consistent with the systems approaches that are now emerging in other fields, although the phenomena studied by these disciplines are generally of a different nature and require different concepts. In transcending the metaphor of the world as a machine, we also have to abandon the idea of physics as the basis of all science. According to the bootstrap or systems view of the world, different but mutually consistent concepts may be used to describe different aspects and levels of reality, without the need to reduce the phenomena of any level to those of another.

Before I describe the conceptual framework for such a multidisciplinary, holistic approach to reality, we may find it useful to see how the other sciences have adopted the Cartesian world view and have modeled their concepts and theories after those of classical physics. The limitations of the Cartesian paradigm in the natural and social sciences can also be brought to light, and their exposure is intended to help scientists and nonscientists change their underlying philosophies in order to participate in the current cultural transformation.