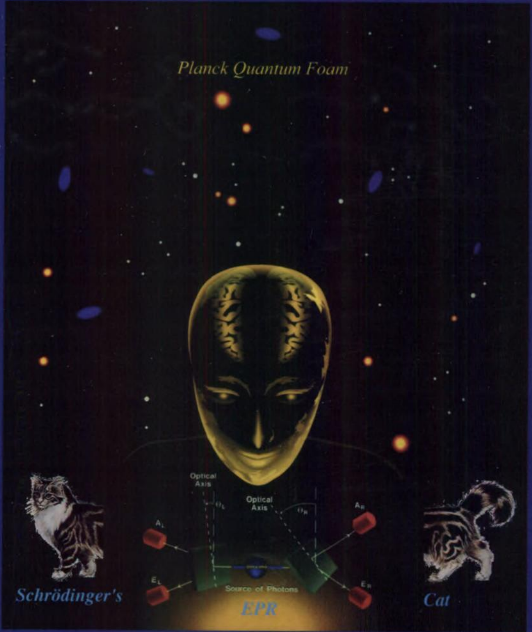
Menas Kafatos • Robert Nadeau

The Conscious Universe

Parts and Wholes in Physical Reality



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Parts and Wholes in Physical Reality

With 30 Illustrations

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Introduction

Imagine that two people have been chosen to be observers in a scientific experiment involving two photons, or quanta of light. These photons originate from a single source and travel in opposite directions an equal distance halfway across the known universe to points where each will be measured or observed. Now suppose that before the photons are released, one observer is magically transported to a point of observation halfway across the known universe and the second observer is magically transported to another point an equal distance in the opposite direction. The task of the observers is to record or measure a certain property of each photon with detectors located at the two points so that the data gathered at each can later be compared.

Even though the photons are traveling from the source at the speed of light, each observer would have to wait billions of years for one of the photons to arrive at his observation point. Suppose, however, that the observers are willing to endure this wait because they hope to test the predictions of a mathematical theorem. This theorem not only allows for the prospect that there could be a correlation between the observed properties of the two photons but also indicates that this correlation could occur instantly, or in no time, in spite of the fact that the distance between the observers and their measuring instruments is billions of light years. Now imagine that after the observations are made, the observers are magically transported back to the source of the experiment and the observations recorded by each are compared. The result of our imaginary experiment is that the observed properties of the two photons did, in fact, correlate with one another over this fast distance instantly, or in no time, and the researchers conclude that the two photons remained in communication with one another in spite of this distance.

This imaginary experiment distorts some of the more refined aspects of the actual experiments in which photons released from a single source are measured or correlated over what physicists term *space-like* separated regions. But if we assume that the imaginary experiment was conducted many times, there is good reason to believe that the results would be the same as those in the actual experiments. Also like the imaginary experiment, the actual experiments were designed to test some predictions made in a mathematical theorem.

The theorem was published in 1964 by physicist John Bell, and the predictions made in this theorem have been tested in a series of increasingly refined experiments. Like Einstein before him, John Bell was discomforted by the threats that quantum physics posed to a fundamental assumption in classical physics: that there must be a one-to-one correspondence between every element of a physical theory and the physical reality described by that theory. This view of the relationship between physical theory and physical reality assumes that all events in the cosmos can be fully described by physical laws and that the future of any physical system can, in theory at least, be predicted with utter precision and certainty. Bell's hope was that the results of the experiments testing his theorem would obviate challenges posed by quantum physics to this understanding of the relationship between physical theory and physical reality.

The results of these experiments would also serve to resolve other large questions. Is quantum physics a self-consistent theory whose predictions would hold in this new class of experiments? Or would the results reveal that quantum theory is incomplete and its apparent challenges to the classical understanding of the correspondence between physical theory and physical reality were illusory? But the answer to this question in the experiments made possible by Bell's theorem would not merely serve as commentary on the character of the knowledge we call physics. It would also determine which of two fundamentally different assumptions about the character of physical reality is correct. Is physical reality, as classical physics assumes, local, or is physical reality, as quantum theory predicts, nonlocal? Although the question may seem esoteric and the terms innocuous, the issues at stake and the implications involved are, as we shall see, enormous.

Bell was personally convinced that the totality of all of our previous knowledge of physical reality, not to mention the laws of physics, would favor the assumption of locality. The assumption states that a measurement at one point in space cannot influence what occurs at another point in space if the distance between the points is large enough so that no signal can travel between them at light speed in the time allowed for measurement. In the jargon of physics, the two points exist in space-like separated regions, and a measurement in one region cannot influence what occurs in the other.

Quantum physics, however, allows for what Einstein disparagingly termed "spooky actions at a distance." When particles originate under certain conditions, quantum theory predicts that a measurement of one particle will correlate with the state of another particle even if the distance between the particles is millions of light years. And the theory also indicates that even though no signal can travel faster than light, the correlations will occur instantaneously, or in no time. If this prediction held in experiments testing Bell's theorem, we would be forced to conclude that physical reality is nonlocal.

After Bell published his theorem in 1964, a series of increasingly refined tests by many physicists of the predictions made in the theorem culminated in experiments by Alain Aspect and his team at the University of Paris-South. When the results of the Aspect experiments were published in 1982, the answers to Bell's questions were quite clear: Quantum physics is a self-consistent theory and the character of physical reality as disclosed by quantum physics is nonlocal.

In 1997, these same answers were provided by the results of twin-photon experiments carried out by Nicolus Gisin and his team at the University of Geneva.[1] The Gisin experiments were quite startling. While the distance between detectors in space-like separated regions in the Aspect experiments was 13 meters, the distance between detectors in the Gisin experiments was extended to 11 kilometers, or roughly 7 miles. Because a distance of 7 miles is quite vast within the domain of quantum physics, these results strongly indicate that similar correlations would exist even if experiments could be performed where the distance between the points was halfway across the known universe.

For reasons that will become clear later, what is most perplexing about nonlocality from a scientific point of view is that it cannot be viewed in principle as an observed phenomenon. The observed phenomena in the Aspect and Gisin experiments reveal correlations between properties of quanta, light, or photons, emanating from a single source based on measurements made in space-like separated regions. What cannot be measured or observed in this experimental situation, however, is the total reality that exists between the two points. Although the correlations allow us to infer the existence of this whole, they cannot in principle disclose or prove its existence.

When we consider that all quanta have interacted at some point in the history of the cosmos in the manner that quanta interact at the origins in these experiments and that there is no limit to the number of correlations that can exist between these quanta,[2] this leads to another dramatic conclusion: that nonlocality is a fundamental property of the entire universe. The daunting realization here is that the reality whose existence is inferred between the two points in the Aspect and Gisin experiments is the reality that underlies and informs all physical events in the universe. Yet all that we can say about this reality is that it manifests as an indivisible or undivided whole whose existence is inferred where there is an interaction with an observer or with instruments of observation.

If we also concede that an indivisible whole contains, by definition, no separate parts and that a phenomenon can be assumed to be real only when it is an observed phenomenon, we are led to more interesting conclusions. The indivisible whole whose existence is inferred in the results of the Aspect and Gisin experiments cannot in principle be the subject of scientific investigation. There is a simple reason why this is the case. Science can claim knowledge of physical reality only when the predictions of a physical theory are validated by experiment. Because the indivisible whole in the Aspect and Gisin experiments cannot be measured or observed, we confront an event horizon of knowledge, where science can say nothing about the actual character of this reality. We will discuss why this is the case in detail later.

If nonlocality is a property of the entire universe, then we must also conclude that an undivided wholeness exists on the most primary and basic level in all aspects of physical reality. What we are actually dealing with in science per se, however, are manifestations of this reality that are invoked or actualized in making acts of observation or measurement. Because the reality that exists between the space-like separated regions is a whole whose existence can only be inferred in experiments, as opposed to proven, the correlations between the particles, or the sum of these parts, does not constitute the indivisible whole. Physical theory allows us to understand why the correlations occur. But it cannot in principle disclose or describe the actual character of the indivisible whole.

Although the discovery that physical reality is nonlocal made the science section of *The New York Times*, it was not front-page news, and it received no mention in national news broadcasts. On these few occasions where nonlocality has been discussed in public forums, it is generally described as a piece of esoteric knowledge that has meaning and value only in the community of physicists. The obvious question is why a discovery that many regard as the most momentous in the history of science has received such scant attention and stirred so little debate. One possible explanation is that some level of scientific literacy is required to understand what nonlocality has revealed about the character of physical reality. Another is that the implications of this discovery have shocked and amazed scientists, and a consensus view of what those implications are has only recently begun to emerge.

The implication that has most troubled physicists is that classical epistemology, also known as Einsteinian epistemology, and an associated view of the character of scientific epistemology, known as the doctrine of positivism, can no longer be considered valid. Classical or Einsteinian epistemology assumes that there must be a one-to-one correspondence between every element in the mathematical theory and every aspect of the physical reality described that by that theory. And the doctrine of positivism assumes that the meaning of physical theories resides only in the mathematical description, as opposed to any nonmathematical constructs associated with this description. For reasons that will soon become obvious, the doctrine of positivism is premised on classical or Einsteinian epistemology, and the efficacy of both has been challenged by results of experiments testing Bell's theorem.

The results of these experiments have also revealed the existence of a profound new relationship between parts (quanta) and whole (universe) that carries large implications. Our proposed new understanding of the relationship between part and whole in physical reality is framed within the larger context of the history of mathematical physics, the origins and extensions of the classical view of the foundations of scientific knowledge, and the various ways that physicists have attempted to obviate previous challenges to the efficacy of classical epistemology. We will demonstrate why the discovery of nonlocality forces us to abandon this epistemology and propose an alternative understanding of the actual character of scientific epistemology originally articulated by the Danish physicist Niels Bohr. This discussion will serve as background for understanding a new relationship between parts and wholes in a quantum mechanical universe and a similar view of that relationship that has emerged in the so-called new biology.

What may prove most significant in this discussion in more narrowly scientific terms are the two chapters on physical cosmology, or the study of the origins and history of the entire universe. According to Niels Bohr, the logical framework of complementarity is not only required to understand the actual character of physical reality; it is also, he claimed, the most fundamental dynamic in our conscious constructions of reality in the mathematical language of physical theories.

Drawing extensively on Bohr's definition of this framework and applying it to areas of knowledge that did not exist during his time, we will attempt to show that his thesis is correct. We will demonstrate that complementarity has been a primary feature in every physical theory advanced in mathematical physics beginning with the special theory of relativity in 1905. And we will make the case that complementarity is an emergent property or dynamic in the life of the evolving universe at increasingly larger scales and times and that new part-whole complementarities emerged at greater levels of complexity in biological life. Based on this evidence, we will advance the hypothesis that future advances in physical theory in cosmology, or in the study of the origins and evolution of the entire universe, will also feature complementary constructs.

We will also make a philosophical argument that carries large implications in human terms that may initially seem very radical. Based on our new understanding of the relationship between parts

If one can accept, along with most physical scientists, these definitions of metaphysical and epistemological realism, most of the conclusions drawn here should appear fairly self-evident in logical and philosophical terms. And it is not necessary to attribute any extra-scientific properties to our new understanding of the relationship between parts (quanta) and whole (cosmos) to embrace the new view of human consciousness that is consistent with this relationship. But since the conditions and results of experiments testing Bell's theorem also reveal that science can say nothing about the actual character of this whole, science can neither prove or disprove that our view of the relationship between part (human consciousness) and whole (cosmos) is correct. One is, therefore, free to dismiss our proposed view of this relationship for the same reason one is free to embrace it—the existence of this whole can only be inferred and the actual relationship of human consciousness to this whole cannot be known or defined in scientific terms.

Science as a Way of Knowing

As previously noted, we will argue that the discovery of nonlocality obliges us to abandon the classical view of one-to-one correspondence between physical theory and physical reality and the associated doctrine of positivism. But this in no way comprises the privileged character of scientific knowledge. Modern physical theories have allowed us to understand the origins and history of physical reality at all scales and times and to predict future events in physical reality with remarkable precision and certainty. Yet there are many well-educated humanists and social scientists, including some philosophers of science, who have adopted assumptions about the character of scientific truths that serve to either greatly diminish their authority or, in the extreme case, to render these truths virtually irrelevant to the pursuit of knowledge.

Those who promote these views typically appeal to the work of philosophers of science, principally that of Toulmin, Kuhn, Hanson, and Feyerabend. All of these philosophers assume that science is done within the context of a *Weltanschauung*, or comprehensive world-view, which is a product of culture and constructed primarily in ordinary, or linguistically based, language. One would be foolish to discount this view entirely. But it can, if taken to extremes, lead to some rather untenable and even absurd conclusions about the progress of science and its epistemological authority.

Although some physicists have taken the views of the *Weltanschauung* theorists seriously, most physicists have not. This entire approach to the philosophy of science also appears to have been largely displaced by historical realism. This approach is characterized, says Frederick Suppe, by "paying close attention to actual scientific practice, both historical and contemporary, all in the aim of developing a systematic philosophical understanding of the justification of knowledge claims."[3] If we were to identify ourselves with the views of any figures in the philosophy of science who practice historical realism, that figure would be, with some reservations, Dudley Shapere.

Shapere's focus is on the reasoning patterns in actual science and on the manner in which physics as a "privileged" form of coordinating experience with physical reality has obliged us to change our views of ourselves and the universe. We also agree with Shapere's view that the cumulative progress of science imposes constraints on what can be viewed as a legitimate scientific concept, problem, or hypothesis, and that these constraints become "tighter" as science progresses. This is particularly true when the results of theory present us with radically new and seemingly counterintuitive findings like those of the Aspect experiments. It is because there is incessant feedback within the content and conduct of science that we are led to counterintuitive results like the discovery of nonlocality as a fact of nature.

We also agree with Shapere's claim that the postulates of rationality, generalizability, and systematizability are rather consistently vindicated in the history of science.[4] Shapere does not dismiss the prospect that theory and observation can be conditioned by extrascientific, linguistically based factors. But he also argues, correctly in our view, that this does not finally compromise the objectivity of scientific knowledge. Although the psychological and sociological context of the scientist is an important aspect of the study of the history and evolution of scientific thought, the progress of science is not ultimately directed or governed by such considerations. Why this is the case should become quite clear in the course of this discussion.

There is, of course, no universally held view of the actual character of physical reality or of the epistemological implications of quantum physics. It would be both foolish and arrogant to claim that we have articulated this view or resolved the debate about quantum epistemology. At the same time, we are convinced that the view of physical reality advanced here is quite consistent with the totality of knowledge in mathematical physics and biology and that our proposed resolution of epistemological dilemmas is very much in accord with this knowledge.

1

Two Small Clouds: The Emergence of a New Physics

> Some physicists would prefer to come back to the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist independently of whether we observe them. That, however, is impossible.
>
> *Werner Heisenberg*

During the summer of 1900, David Hilbert, widely recognized for his ability to see mathematics as a whole, delivered the keynote address at the Mathematics Congress in Paris. Speaking in a hall a few blocks away from the laboratory in which Madame and Pierre Curie were tending their vats of radioactive material, Hilbert set the agenda for the study of mathematics in the twentieth century. There were, he said, twenty-three unsolved problems in mathematics and all of them were amenable to solution in the near future. As Hilbert put it, "There is always a solution. There is no ignoramus."[1]

As it turned out, Hilbert's prediction that we would soon see the logically coherent and self-referential whole of mathematics by eliminating internal inconsistencies and problems was not accurate. The first major indication that this might be the case was the failed effort to resolve Hilbert's tenth problem. The solution to this problem required a mathematical proof that a certain kind of equation was solvable and that the solution could be found in a finite number of steps. This proof was not found, and we now know in principle that it will never be found. The failed attempt to resolve this and other related mathematical enigmas eventually culminated in the realization that the nineteenth-century view of mathematics as a self-referential whole that could prove it's logical self-consistency could not be sustained.

A few years prior to Hilbert's keynote address in 1900, Lord Kelvin, one of the best known and most respected physicists at that time, commented that "only two small clouds" remained on the horizon of knowledge in physics. In other words, there were, in Kelvin's view, only two sources of confusion in our otherwise complete understanding of material reality. The two clouds were the results of the Michelson-Morley experiment, which failed to detect the existence of a hypothetical substance called the ether, and the inability of electromagnetic theory to predict the distribution of radiant energy at different frequencies emitted by an idealized radiator called the "black body." These problems seemed so small that some established physicists were encouraging those contemplating graduate study in physics to select other fields of scientific study where there was better opportunity to make original contributions to knowledge. What Lord Kelvin could not have anticipated was that efforts to resolve these two anomalies would lead to relativity theory and quantum theory, or to what came to be called the "new physics."

The most intriguing aspect of Kelvin's metaphor for our purposes is that it is visual. It implies that we see physical reality through the mathematical description of nature in physical theory and the character of that which is seen is analogous to a physical horizon that is uniformly bright and clear. Obstacles to this seeing, the "two clouds," are likened to visual impediments that will disappear when better theory allows us to see through or beyond them to the luminous truths that will explain and eliminate them. The assumption that the mathematical description of nature can disclose such truths is, however, dependent on the assumption that mathematics is a logically consistent and self-referential system that can prove itself. There is, therefore, an intimate connection between Kelvin's belief that we can see all truths in physical reality and Hilbert's belief that we can see into the whole of mathematics and resolve or clarify all seeming inconsistencies. And the ground on which both beliefs rest is what we will term the "hidden ontology" of classical epistemology.

One reason that Kelvin's metaphor would have seemed quite natural and appropriate is that the objects of study in classical physics, like planets, containers with gases, wires, and magnets, were visualizable. His primary motive for metaphor can be better understood, however, in terms of some assumptions about the relationship between the observer and the observed system and the ability of physical theory to mediate this relationship. Observed systems in classical physics were understood as separate and distinct from the mind that investigates them, and physical theory was assumed to bridge the gap between these two domains of reality with ultimate completeness and certainty.

It is also interesting that light was the primary object of study in the new theories that would displace classical physics. Light in western literature, theology, and philosophy appears rather consistently as the symbol for transcendent, immaterial, and immutable forms separate from the realm of sensible objects and movements. Attempts to describe occasions when those forms and ideas appear known or revealed also consistently invoke light as that aspect of nature most closely associated with ultimate truths.

In the eighteenth century, when Alexander Pope penned the line, “God said, Let Newton be! and all was Light,” he anticipated no ambiguity in the minds of his readers. There was now, assumed Pope, a new class of ultimate truths, physical law and theory, which had been revealed to man in the person of Newton. One irony is that the study of the phenomenon of light in the twentieth century leads to a vision of physical reality that is not visualizable or cannot be constructed in terms of our normative seeing in everyday experience. Another is that attempts to describe the actual behavior of light undermined the view of mathematical physics as a self-referential and logically consistent system that exists outside of and in complete correspondence with the dynamics of physical reality.

Light and Relativity Theory

Equally interesting, studies of light have often been foundational to the cumulative and context-driven progress of science that led to the questions asked in Bell’s theorem. The best known of these experiments is probably that conducted in 1887 by Albert A. Michelson and Edward W. Morley. The intent was to refine existing theory, in this case Maxwell’s electromagnetic theory, and both scientists were terribly disappointed when the effort failed. Light in Maxwell’s theory is visualizable as a transverse wave consisting of magnetic and electric fields that vary in magnitude and direction in ways that are perpendicular to each other and to the direction of propagation of the wave (see Fig. 1). This wave theory of light had been established since the early 1800s and was well supported in experiments on light in which behavior like interference and diffraction had been observed. Interference arises when two waves, like those produced when two stones fall on the surface of a pond, combine to form larger waves when the crests of the two waves coincide. It can also be observed when waves cancel one another out when the crest of one wave corresponds with the trough of another. Diffraction is a wave property evident when waves bend around obstacles, like when ocean waves go around a wave-breaker in a harbor. Perhaps the best way to observe interference and refraction is to listen to sounds of musical notes, associated with sound waves, on a piano. Some combine and become louder while others cancel each other out.

cuit is moving past the magnet. Although some had speculated that the stationary ether could explain this difference, others argued that this did not make sense because the speed of light should also be affected by the presence of the ether. When Foppl addressed this issue, he referred to an experiment conducted by Hippolyte Fizeau in 1851 that showed that the speed of light was completely unaffected when running back and forth through a fast-moving column of water.

Einstein also read Poincare's *Science and Hypothesis,* a remarkably innovative book that was full of carefully reasoned and unsettling ideas. In a discussion of the relationship of geometry to space, Poincare wrote, "There is no absolute space" and "There is no absolute time."[3] He also said that "contradictions between competing theories" of the same phenomena "exist only as images we have formed to ourselves of reality" and that the "electrodynamics of moving bodies" suggest that the ether "does not actually exist."[4]

Sensing that Poincare's speculations may be correct, Einstein concluded that if the ether does not exist and the speed of light is constant, this requires some profound revisions of our understanding of the relationship between space and time. He was aware that the Newtonian construct of three-dimensional absolute space existing separately from absolute time implied that one could find a frame of reference absolutely at rest. And he knew that Newtonian mechanics also implied that it was possible to achieve velocities that corresponded to the speed of light and that the speed of light in this frame of reference would be reduced to zero.

Einstein's first postulate was that it is impossible to determine absolute motion, or motion that proceeds in a fixed direction at a constant speed. The only way, he reasoned, that we can assume such motion exists is to compare it with that of other objects. In the absence of such a comparison, said Einstein, one can make no assumptions about movement. He then concluded that the assumption that there is an absolute frame of reference in which the speed of light is reducible to zero must be false. Sensing that it was Newton's laws rather than Maxwell's equations that required adjustment, Einstein concluded that there is no absolute frame of reference or that the laws of physics hold equally well in all frames of reference. He then arrived at the second postulate of the absolute constancy of the speed of light for all moving observers. Based on these two postulates—the relativity of motion and the constancy of the speed of light—the entire logical structure of relativity theory followed.

Einstein mathematically deduced the laws that related space and time measurements made by one observer to the same measurements made by another observer moving uniformly relative to the first. Although Poincare had independently discovered the space-time transformation laws in 1905, he saw them as postulates without any apparent physical significance. Because Einstein perceived that the laws did have physical significance, he is recognized as the inventor of relativity. In this theory, the familiar law of simple addition of velocities does not hold for light or for speeds close to the speed of light. The reason these relativistic effects are not obvious in our everyday perception of reality, said Einstein, is that light speed is very large compared with ordinary speeds.

The primary impulse behind the special theory was a larger unification of physical theory that would serve to eliminate mathematical asymmetries apparent in existing classical theory. There was certainly nothing new here in the notion that frames of reference in conducting experiments are relative; Galileo had arrived at the same conclusion. What Einstein did, in essence, was extend the so-called Galilean relativity principle from mechanics, where it was known to work, to electromagnetic theory, or the rest of physics as it was then known. To achieve this greater symmetry, it was necessary to abandon the Newtonian idea of an absolute frame of reference and, along with it, the ether.

This led to the conclusion that the "electrodynamic fields are not states of the medium [the ether] and are not bound to any bearer, but they are independent realities which are not reducible to anything else."[5] He concluded that in a vacuum light traveled at a constant speed, *c*, equal to 300,000 km/sec, and thus all frames of reference become relative. There is, therefore, no frame of reference absolutely at rest, and the laws of physics could apply equally well to all frames of reference moving relative to each other.

Einstein also showed that the results of measuring instruments themselves must change from one frame of reference to another. Lorentz had earlier speculated that the reason the Michelson-Morley experiment did not detect differences in the speed of light was that the measuring apparatus was shrinking in the direction of the motion of Earth. He also developed his now famous transformation equations to translate the description of an event from one moving frame of reference to another. What Lorentz did not realize, however, was that "local time" was the only time that could be known in a moving frame of reference and that all other times were relative to it. Einstein realized this was the case and used the Lorentz equations to coordinate measurements in one frame of moving reference with respect to that in another frame. This means, for example, that clocks in the two frames of reference would not register the same time and two simultaneous events in a moving frame would appear to occur at different times in the unmoving frame.

For the observer in the stationary frame, lengths in the moving frame appear contracted along the direction of motion by a factor of $\sqrt{1-v^2/c^2}$*, where* v *is the relative speed of the two frames. Masses, which provide a means to measure inertia, in the moving frame also appear larger to the stationary frame by the factor* $1/\sqrt{1-v^2/c^2}$.

In the space-time description used to account for the differences in observation between different frames, time is another coordinate in addition to the three space coordinates forming the four-dimensional space-time continuum. In relativistic physics, transformations between different frames of reference express each coordinate of one frame as a combination of the coordinates of the other frame. For example, a space coordinate in one frame usually appears as a combination, or mixture, of space and time coordinates in another frame.

Entering the Realm of the Unvisualizable

It was the abandonment of the concept of an absolute frame of reference that began to move us out of the realm of the visualizable into the realm of the mathematically describable but unvisualizable. We can illustrate light speed with visualizable illustrations, like approaching a beam of light in a spacecraft at speeds fractionally close to that of light and imagining that the beam would still be leaving us at its own constant speed. But the illustration bears no relation to our direct experience with differences in velocity. It is when we try to image the four-dimensional reality of space-time as it is represented in mathematical theory that we have our first dramatic indication of the future direction of physics. It cannot be done no matter how many helpful diagrams and illustrations we employ.

As numerous experiments have shown, however, the counterintuitive results predicted by the theory of relativity occur in nature. For example, unstable particles, like muons, which travel close to the speed of light and decay into other particles with a well-known half-life, live much longer than their twin particles moving at lower speeds. Einstein was correct: The impression that events can be arranged in a single unique time sequence and measured with one universal physical yardstick is easily explained. The speed of light is so large compared with other speeds that we have the illusion that we see an event in the very instant in which it occurs.

To illustrate that simultaneity does not hold in all frames of reference, Einstein used a thought experiment featuring the fastest means of travel for human beings at his time—trains. What would happen, he wondered, if we were on a train that actually attained light speed? The answer is that lengths along the direction of motion would become so contracted as to disappear altogether and clocks would cease to run entirely. Three-dimensional objects would actually appear rotated so that a stationary observer could see the back of a rapidly approaching object. To the moving observer, all objects would appear to be converging on a single blinding point of light in the direction of motion.

Yet the train, as Einstein knew very well, could not in principle reach light speed. Only massless photons, or light, can reach light speed due to the equivalence of mass and energy. For a train, or spaceship, to reach this speed, mass would have to become infinite, and an infinite amount of energy would be required as well. While commonsense explanations of this situation may fail us, there is no ambiguity in the mathematical description.

Because light or photons have zero rest mass, they travel exactly at light speed. And in accordance with the Lorentz transformations, the factor $\sqrt{1-v^2/c^2}$ *becomes zero as the relative speed v approaches light speed c.*

The special theory of relativity dealt only with constant, as opposed to accelerated, motion of the frames of reference, and the Lorentz transformations apply to frames moving with uniform motion with respect to each other. In 1915, Einstein extended relativity to account for the more general case of accelerated frames of reference in his general theory of relativity. The central idea in general relativity theory, which accounts for accelerated motion, is that it is impossible to distinguish between the effects of gravity and nonuniform motion. If we did not know, for example, that we were on an accelerating spaceship and dropped a cup of coffee, we could not determine whether the mess on the floor was due to the effects of gravity or the accelerated motion.

This inability to distinguish between a nonuniform motion, like an acceleration, and gravity is known as the principle of equivalence. This principle can also be interpreted as transforming the effects of gravity away as in free-falling frames of reference. In the physics of Einstein, the principle of equivalence explains the familiar phenomenon of astronauts floating in space as they circle Earth as a transformation of gravitational effects. This is quite different from the classical explanation that the effect is due to a balance between opposing forces.

In the general theory, Einstein posits the laws relating space and time measurements carried out by two observers moving uniformly, as in the example of one observer in an accelerating spaceship and another on Earth. Einstein concluded that force fields, like gravity, cause space-time to become warped (see Fig. 3) or curved and hence non-Euclidean in form. In the general theory the motion of material points, including light, is not along straight lines, as in Euclidean space, but along "geodesics" in curved space. The movement of light along curved spatial geodesics was confirmed in an experiment performed during a total eclipse of the sun by Arthur Eddington in 1919.

Here, as in the special theory, visualization may help to understand the situation but does not really describe it. This is nicely illustrated in the typical visual analogy used to illustrate what spatial geodesics mean. In this analogy we are asked to imagine a hypothetical flatland which, like a tremendous sheet of paper, extends infinitely in all directions. The inhabitants of this flatland, the flatlanders, are not aware of the third dimension. Because the world here is perfectly Euclidean, any measurement of the sum of the angles of triangles in flatland would equal 180 degrees, and any parallel lines, no matter how far extended, would never meet.

We are then asked to move our flatlanders to a new land on the surface of a large sphere. Initially, our relocated population would perceive their new world as identical to the old, or as Euclidean and flat. Next we suppose that the flatlanders make a technological breakthrough that allows them to send a kind of laser light along the surface of their new world for thousands of miles. The discovery is then made that if the two beams of light are sent in parallel directions, they come together after traveling a thousand miles.

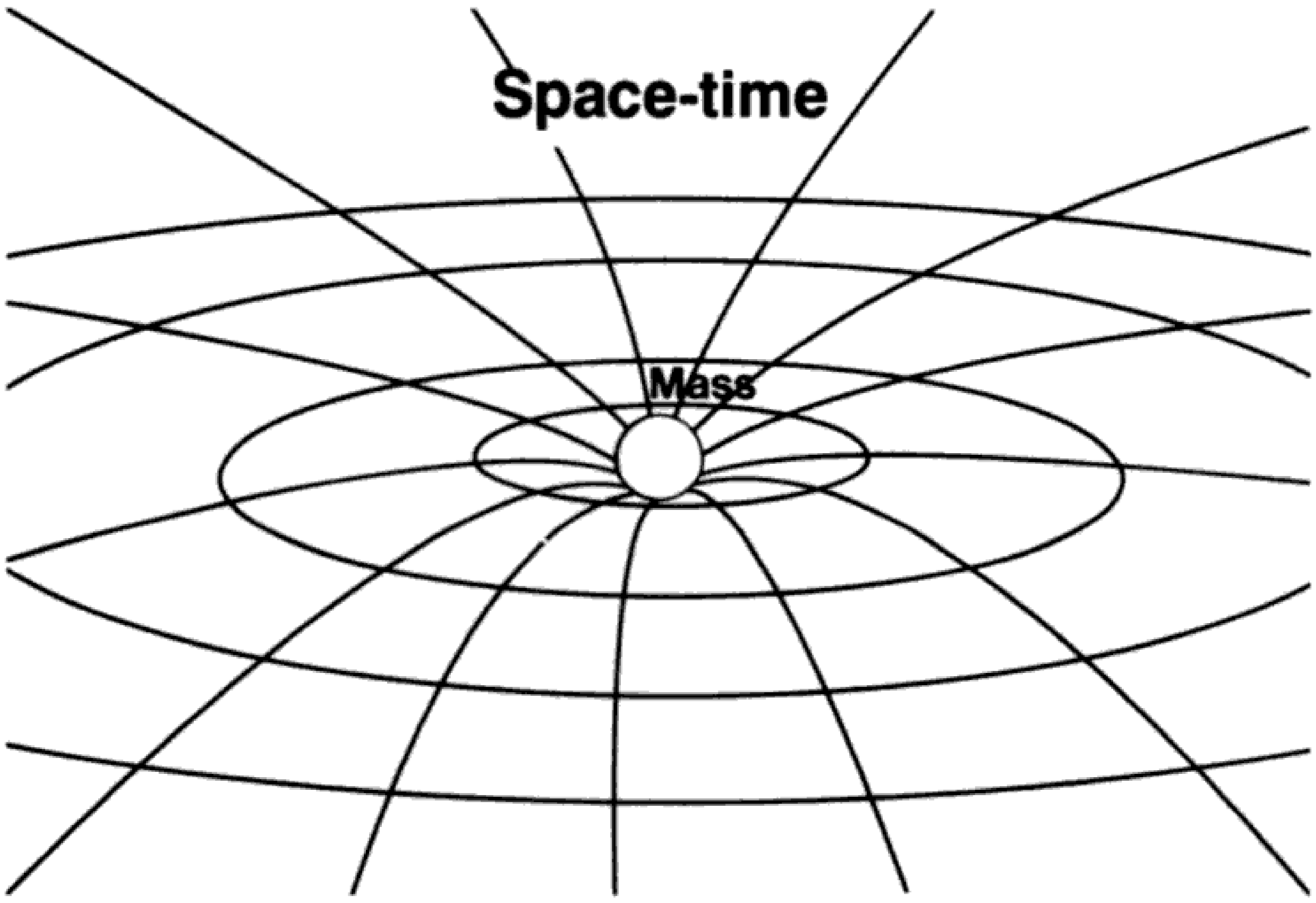

FIGURE 3. Warped space-time around a gravitating mass.

birthday of quantum physics. Planck's new constant, known as the quantum of action, would later be applied to all microscopic phenomena. The fact that the constant is, like the speed of light, a universal constant would later serve to explain the strangeness of the new and unseen world of the quantum.

The next major breakthrough was made by the physicist who would eventually challenge the epistemological implications of quantum physics with the greatest precision and fervor. In the same year (1905) that the special theory appeared, Einstein published two other seminal papers that laid foundations for the revolution in progress. One was on the so-called Brownian movement, the other on the photoelectric effect.

In the paper on the photoelectric effect, Einstein challenged once again what had previously appeared in theory and experiment as obvious, and the object of study was, once again, light. The effect itself was a by-product of Heinrich Hertz's experiments, which at the time were widely viewed as having provided conclusive evidence that Maxwell's electromagnetic theory of light was valid. When Einstein explained the photoelectric effect, he showed precisely the opposite result—the inadequacy of classical notions to account for this phenomenon.

The photoelectric effect is witnessed when light with a frequency above a certain value falls on a photosensitive metal plate and ejects electrons (see Fig. 4). A photosensitive plate is one of two metal plates connected to ends of a battery and placed inside a vacuum tube. If the plate is connected to the negative end of the battery, light falling on the plate can cause electrons to be ejected from the negative end. These electrons then travel through the vacuum tube to the positive end and produce a flowing current.

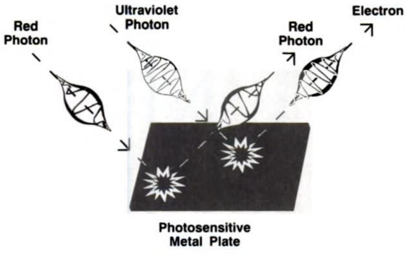

FIGURE 4. The photoelectric effect: A photon of low energy (red) cannot eject an electron but a photon of high-energy (ultraviolet) can.

In classical physics the amplitude, or height, of any wave, including electromagnetic waves, describes the energy contained in the wave. The problem Einstein sought to resolve can be thought about using water waves as an analogy. Large water waves, like ocean waves, have large height or amplitude, carry large amounts of energy, and are capable of moving many pebbles on a beach. Because the brightness of a light source is proportional to the amplitude of the electromagnetic field squared, it was assumed that a bright source of light should eject lots of electrons and that a weak source of light should eject few electrons. In other words the more powerful wave, the bright light, should move more pebbles, electrons, on this imaginary beach. The problem was that a very weak source of ultraviolet light was capable of ejecting electrons while a very bright source of lower-frequency light, like red light, could not. It was as if the short, choppy waves from the ultraviolet source could move pebbles, or electrons, on this imaginary beach, while the large waves from the red light source could not move any at all.

Einstein's explanation for these strange results was as simple as it was bold. In thinking about Planck's work on light quanta, he wondered if the exchange of energy also occurred between particles with mass, like electrons. He then concluded that the energy of light is not distributed evenly over the wave, as classical physics supposed, but is concentrated in small, discrete bundles. Rather than view light as waves, Einstein conceived of light as bundles, or "quanta," of energy in the manner of Planck. The reason that ultraviolet light ejects electrons and red light does not, said Einstein, is that the energy of these quanta is proportional to the frequency of light, or to its wavelength.

In this quantum picture, it is the energy of the individual quanta, rather than the brightness of the light source, that matters. While Planck had quantized only the interaction of matter with energy, Einstein quantized energy itself. Viewing the situation in these terms, individual red photons do not have sufficient energy to knock an electron out of the metal while individual ultraviolet photons have sufficient energy. When Einstein computed the constant of proportionality between energy and the frequency of the light, or photons, he found that it was equal to Planck's constant.

A New View of Atoms

The discovery of the element polonium, by Pierre and Madame Curie in 1898, had previously suggested that atoms were composite structures that transformed themselves into other structures as a result of radioactivity. It was, however, Einstein's paper on Brownian motion that finally enticed physicists to conceive of atoms as something more than a philosophical construct in the manner of the ancient Greeks. The motion is called "Brownian" after the British botanist Thomas Brown, who discovered in 1827 that when a pollen grain floating on a drop of water is examined under a microscope, it appears to move randomly. Einstein showed that this motion obeys a statistical law and the pattern of motion can be explained if we assume that objects, like pollen grains, are moving about as they collide at the microscopic level with tiny molecules of the water. Although Einstein did suggest that molecules and the atoms that constitute them were real in that their behavior had concrete effects on the macro level, nothing of substance was known at the time about the internal structure of atoms.

The suggestion that the world of the atom had a structure enticed Ernest Rutherford in Manchester to conduct a series of experiments in which positively charged "alpha" particles, later understood to be the nuclei of helium atoms, were emitted from radioactive substances and fired at a very thin sheet of gold foil. If there was nothing to impede the motion of the particles, they should travel in a straight line and collide with a screen of zinc sulfide where a tiny point of light, or scintillation, would record the impact.

In this experiment most of these particles were observed to be slightly deflected from their straight-line path. Other alpha particles, however, were deflected backward toward the direction from which they came. Based on an estimate of the number of alpha particles emitted by a gram of radium in one second, Rutherford was able to arrive at a more refined picture of the internal structure of the atom.

The existing model, invented by the discoverer of the electron, J.J. Thomson, presumed that the positive charge was distributed over the entire space of the atom. The observed behavior of the alpha particles suggested, however, that the particles deflected backward were encountering a highly concentrated positive charge, while most particles traveled through the space of the atoms as if this space were empty. Rutherford explained the results in terms of a picture of the atom as being composed primarily of vast regions of space in which the negatively charged particles, electrons, move around a positively charged nucleus that contains the greatest part of the mass of the atom.

Forced to appeal to macro-level analogies to visualize this unvisualizable structure, Rutherford termed the model "planetary." It was soon discovered, however, that there is practically no similarity between the structure or behavior of macro and micro worlds. The relative distances between electrons and nucleus, as compared to the size of the nucleus, are much greater than the relative distances between planets and the sun, as compared to the size of the sun. If one can imagine Earth undergoing a quantum transition and instantaneously appearing in the orbit of Mars, this illustrates how inappropriate macro-level analogies would soon become.

The next step on the road to quantum theory was made by a Danish physicist from whom we will hear a great deal more later in this discussion—Niels Bohr. Developed partly as a result of the work done with Rutherford in Manchester, Bohr provided, in a series of papers published in 1913, a new model for the structure of atoms. Although obliged to use macro-level analogies, Bohr was the first to suggest that the orbits of electrons were quantized. His model was semiclassical in that it incorporated ideas from classical celestial mechanics about orbiting masses. The problem he was seeking to resolve had to do with the spectral lines of hydrogen, which showed electrons occupying specific orbits at specific distances from the nucleus with no in-between orbits.

Spectral lines are produced when light from a bright source containing a gas, like hydrogen, is dispersed through a prism, and the pattern of the spectral lines is unique for each element. The study of the spectral lines of hydrogen suggested that the electrons somehow "jump" between the specific orbits and appear to absorb or emit energy in the form of light or photons in the process. What, wondered Bohr, was the connection?

Bohr discovered that if you use Planck's constant in combination with the known mass and charge of the electron, the approximate size of the hydrogen atom could be derived. Assuming that a jumping electron absorbs or emits energy in units of Planck's constant, in accordance with the formula Einstein used to explain the photoelectric effect, Bohr was able to find correlations with the specific spectral lines for hydrogen. More important, the model also served to explain why the electron does not, as electromagnetic theory says it should, radiate its energy quickly away and collapse into the nucleus.

Bohr reasoned that this does not occur because the orbits are quantized— electrons absorb and emit energy corresponding to the specific orbits. Their lowest energy state, or lowest orbit, is the "ground state" (see Fig. 5). What is notable here is that Bohr, although obliged to use macro-level analogies and classical theory, quickly and easily posits a view of the dynamics of the "energy shells" of the electron that has no macro-level analogy and is inexplicable within the framework of classical theory.

The central problem with Bohr's model from the perspective of classical theory was pointed out by Rutherford shortly before the first paper describing the model was published. "There appears to me," Rutherford wrote in a letter to Bohr, "one grave problem in your hypotheses which I have no doubt you fully realize, namely, how does an electron decide what frequency it is going to vibrate at when it passes from one stationary state to another? It seems to me that you would

This book explores the implications for physics and philosophy of a strange new fact of nature: that particles can be "entangled" over enormous distances, and that measurements made on such entangled particles in one place can have an instantaneous effect in another. Such interactions seem to (but actually do not, as the authors show) violate the principle that nothing can move faster than the speed of light, which is why Einstein called them "spooky interactions at a distance."

The authors provide the necessary background to understand these "nonlocal" interactions, and explain the experiments that confirmed their existence. They discuss how the nonlocal effects depend on the fundamental complementarity of natural phenomena, such as the wave–particle duality. They go on to show that the results have profound implications for our understanding of the foundations of physics and for our view of the universe. In particular, they argue that consciousness can no longer be divorced from our understanding of the way nature works, and they illustrate this new epistemological approach with an attempt to resolve some ambiguities in our view of the origin and evolution of the universe.

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