# Einstein, and the World Beyond

## Second-Order Thought Experiments and the Rationalization of the Transcendent

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Note: This is a draft of Lecture 2 of seven lectures with the general title: *Mind and World: From Newton, Einstein, & Darwin to Principles of Mind* to be given by Roger N. Shepard as the William James Lectures at Harvard Univerisity during October and November 1994, and then to be published in book form. The following Page 2 gives the projected titles of all seven lectures. Drafts of some of the subsequent lectures may follow, separately. (Some of the material to be covered in Lectures 4-6 has already been summarized in Santa Fe Institue Reprint 93-11-073, "Perceptual-Cognitive Universals as Reflections of the World.") Comments and corrections on any of these reports will be greatly appreciated!

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## Titles of the seven William James Lectures

# MIND AND WORLD

## From Newton, Einstein, & Darwin to Principles of Mind

Roger N. Shepard

### I. PRINCIPLES OF THE WORLD AS EMERGENTS IN MIND

Lecture 1. Newton, and the World Perceived
First-Order Thought Experiments
and the Rationalization of the Sensible

**Lecture 2. Einstein, and the World Beyond**
**Second-Order Thought Experiments**
**and the Rationalization of the Transcendent**

Lecture 3. Darwin, and the World Within
Evolutionary Epistemology, Consistency,
and the Rationalization of the Rationalizer

### II. PRINCIPLES OF MIND AS EMERGENTS IN THE WORLD

Lecture 4. Principles of Perception
Internal Representation of Things Present
and of the Manners of their Presentation

Lecture 5. Principles of Generalization
Internal Representation of Things Hidden
and of the Probabilities of their Manifestation

Lecture 6. Principles of Transformation
Internal Representation of Things Possible
and of the Paths to their Realization

### III. THE NATURE AND RELATION OF MIND AND WORLD

Lecture 7. Unresolved Philosophical Issues
Necessary versus Arbitrary Principles
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# 2. Einstein, and the World Beyond

## Second-Order Thought Experiments and the Rationalization of the Transcendent

By such elaborate inventions, and at such a cost to the
imagination, do men succeed in making for themselves
a world in which real things shall be coerced
per fas aut nefas under arithmetical law.

--William James (1890)

There is only the way of intuition, which is helped
by a feeling for the order lying behind the appearance.

--Albert Einstein

... the task is, not so much to see what no one has yet seen;
but to think what nobody has yet thought,
about that which everybody sees.

--Erwin Schrödinger (1952)

In my first lecture I considered the first four of what I styled "The Seven Wonders of Physical Science." These four culminated in a theory of the world as a system of material bodies governed by Newtonian laws of motion in Euclidean space. I tried to make the case that the essential ideas underlying each of these developments were derivable -- and perhaps were largely derived -- from thought experiments about the behavior of macroscopic objects long familiar to us in the terrestrial environment or, in the case of statistical mechanics, thought experiments about the behavior of microscopic particles obeying the same laws. In this second lecture I consider the remaining three Wonders of Physical Science: electrodynamics, relativity, and quantum mechanics. These pose successively greater challenges for the thesis of these first two lectures -- namely, the thesis that the fundamental principles governing the physical world are discoverable through thought. Beyond the sensible realm of macroscopic motion, mixing, and temperature equalization familiar to our ancestors and ourselves, we have had to accept the existence in the physical world of ever more strange realms: the electrodynamic realm of invisible fields and undulations in empty space; the relativistic realm of increasingly non-Euclidean space-time as we approach the speed of light, super-massive objects, or cosmological distances; and the quantum mechanical realm in which a submicroscopic entity may have no determinate state until a certain interaction occurs with that entity or, astonishingly, with a second entity that had once itself interacted with the first entity but that has since traveled billions of light years away from it across the universe.

I shall argue, however, that each of these three theories now appears to be required for the explanation of phenomena that although previously overlooked, had long been a salient part of the everyday world of scientists and nonscientists alike. The scientists' limited theoretical perspective, at each stage, may have blinded them to the problem posed by the otherwise obvious phenomena. Perhaps for this reason, each new theory arose, instead, from a struggle with more subtle inconsistencies that although less salient in the everyday world, loomed larger under the selective lense of existing theory.

## Second-Order Thought Experiments

The thought experiments that I put forward as leading to Newtonian mechanics concerned familiar operations on familiar objects -- pushing blocks, dropping bricks, or throwing apples. I call these first-order thought experiments. From here on, more and more of the crucial thought experiments seem not to be of this concrete first-order type. Increasingly, the objects on which the mental operations are performed are the more abstract objects posited in the theories already constructed on the basis of first-order thought experiments. These "objects" may be a space-filling "ether" or its luminiferous vibrations, a non-Euclidean four-dimensional space-time manifold, or electrons or protons conceptualized as particles or waves -- all objects of which neither we nor our ancestors have ever had any direct experience. These I call second-order thought experiments. They have been particularly helpful in revealing previously unsuspected inconsistencies in existing theories. Thus, they motivate the search for more general theories capable of yielding a consistent treatment of a still wider range of phenomena.

Albert Einstein made particularly effective use of second-order thought experiments in developing his theories of relativity. First-order thought experiments were no longer sufficient because the conditions that most clearly reveal certain ways in which Newton's mechanics and Maxwell's electrodynamics need to be modified become appreciable only at near-luminal velocities, stellar masses, or cosmological scales never actually experienced on earth. Similarly, the development of quantum mechanics depended on second-order thought experiments because the conditions that most clearly reveal certain other ways in which Newton's mechanics and Maxwell's electrodynamics need to be modified become appreciable only in the never directly experienced subatomic realm. I already reviewed the development of Newton's mechanics in my first lecture. But before proceeding to relativity and quantum mechanics, I must briefly review the development of Maxwell's electrodynamics, which turned out to play crucial roles in the thought experiments leading to those theories. Moreover, the development of electrodynamics itself seems to have depended on mental operations that were, in a way, transitional between first- and second-order thought experiments.

## Maxwell's Demon

The beginnings of such a transition can already be discerned in the thought experiment (which I described at the end of my first lecture) in which Boltzmann imagined the motions of invisible molecules following the removal of a partition that had separated them into two types (such as fast and slow). I cannot proceed directly to the discovery of the laws of electrodynamics by the Scottish theoretical physicist James Clerk Maxwell without first mentioning a particularly famous 1871 thought experiment by Maxwell that seemed to raise the possibility that contrary to

Boltzmann's conclusion, the second law of thermodynamics might not be universal after all.

Maxwell, pictured a container of gas already in its expected equilibrium condition of uniform termperature and, then, imagined dividing the container by a partition equiped with one tiny aperture and a weightless, frictionless shutter operated by a comparably tiny "demon." The demon was to monitor all molecules that happened to be moving toward the aperture from either side and to open the shutter only if they were approaching from the right chamber with higher than average velocity or approaching from the left chamber with lower than average velocity. Over time, the selective passage and entrapment of the more frenzied molecules on the left and the more lethargic ones on the right would be felt by a macroscopic observer as a rising temperature in the left compartment and a falling temperature in the right, in flagrant contravention of the second law. It was not until after Maxwell's death that ways were found to exorcise Maxwell's demon and, thus, to reaffirm the universality of the second law of thermodynamics. One of these ways was based, as we shall see, on Maxwell's own electromagnetic theory.

## Maxwell's Electrodynamics

### Unexplained phenomena

A number of phenomena (beyond those of mixing and temperature equalization, considered in my first lecture), though also familiar at the time of Newton, remained unexplained by Newton's laws of motion. These included: the solid, liquid, or gaseous states of matter; the spherical forms assumed by liquid droplets and bubbles; the rigid, moldable, or springy properties of solids; the irreversibility of fracturing and breakage; the chemical transformations of combustion and oxidation; the biological processes of growth, reproduction, and death; the refraction of light (which causes a slanting stick to appear bent where it enters water, or enables the lense of a telescope or of an eye to form an image); and, most directly, magnetic and electrostatic attraction and repulsion, and lightning discharges (of which, on earth alone, there are estimated to be some 40 million per day). Although some of these phenomena were as "striking" as "a bolt from the blue," none could be accounted for in terms of gravitational interactions among material bodies. They are all governed by the quite different electromagnetic interactions between electrons and light.

In fact, the mutual attractions between material objects attributable to magnetism and static electricity were both known long before those attributable to gravitation. Partly, this may have been because electromagnetic forces, unlike gravitation, do not operate universally between all material bodies. Naturally, given that most macroscopic objects, being magnetically or electrically neutral, do not manifest noticeable attraction or repulsion, attention was "attracted" to those exceptional cases such as the lodestone or brushed hair on a dry winter's day that did exhibit appreciable attraction or repulsion.

The overriding reason for the failure to appreciate the ubiquity of gravitation, however, was simply that electromagnetic forces vastly exceed gravitational force in intrinsic strength. Electrostatic force causes a bit of paper to leap to a stick of amber that has been rubbed by a piece of silk, and magnetic force causes an iron filing to leap to a magnet. But the gravitational attraction between any two objects of comparable size is far too weak to cause any detectable motion. We now know that the electrostatic attraction between the negatively charged electron and the positively charged proton of an hydrogen atom exceeds the gravitational attraction between those same two particles by a factor of $10^{27}$ -- that is, over a billion, billion, billion to one.

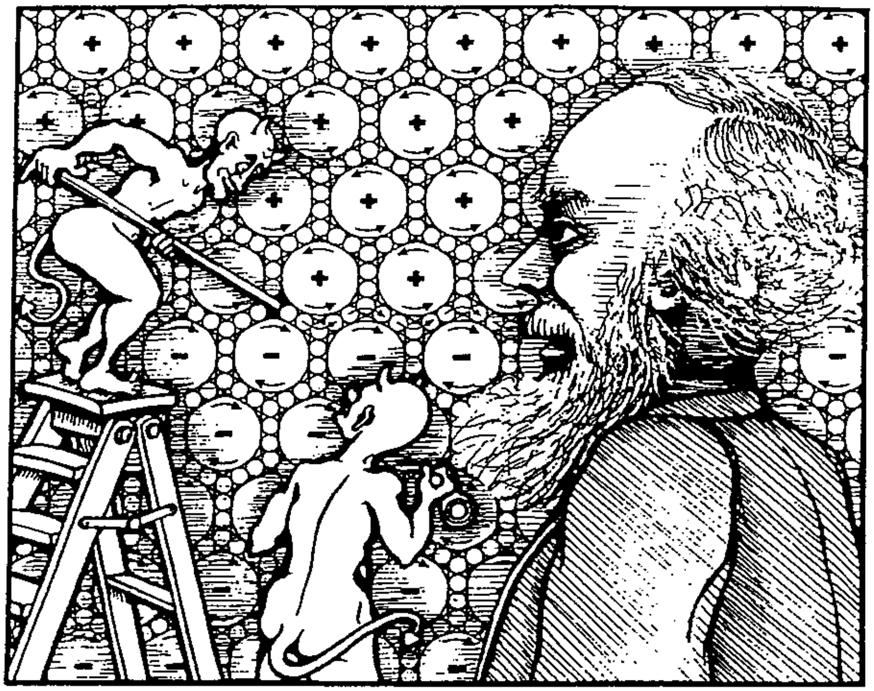
If Newton's mechanics ignored a force of such enormously greater intrinsic strength than the force of gravitation, why did so many scientists and philosophers after Newton believe, with Lagrange, that Newton had discovered <u>the</u> "system of the world"? The answer is simple: Gravitational force is always attractive, whereas electromagnetic force is just as often (you should pardon the expression) repulsive. Although feeble within each atom, gravitation therefore cumulates to become dominant near a massive body, such as the earth, consisting of some $10^{50}$ atoms. Thus, what is holding you to your seats right now is only the gravity of the earth (if not the occasional levity of my remarks). In contrast, because electromagnetic force is attractive only between unlike charges and repulsive between like charges, negatively charged electrons accumulate around each positively charged nuclus until a balance of charge is achieved within each atom, leaving little if any net electromagnetic attraction or repulsion to be felt at the macroscopic level (except when some electrons, only weakly bound to their nuclei, are temporarily transferred from the surface of one object to the surface of another -- as by rubbing a stick of amber).

## Maxwell

In his efforts to understand the phenomena of electricity and magnetism, Maxwell began with what he had learned from Michael Faraday (whose own experiments and formulations were reportedly guided by his imagining of electric and magnetic fields as lines of force or, even more concretely, as fluid flows through curved invisible tubes, in space). Maxwell proceeded to carry out thought experiments on a series of more and more refined hydrodynamic and then micromechanical models of the invisible "ether" -- a nonconducting (dielectric) medium that was generally supposed to fill all of Newton's absolute space and to be the carrier of electric and magnetic fields and (since Thomas Young's confirmation of its wave-like character) light. Maxwell's final and most refined model (Figure 2.1) was a space-filling array of slender cylinders, whose rotation (in a + or - direction, as marked on their circular ends in the figure) represented magnetic force, and intervening ball bearings, whose correlated motion at right angles, represented electric force. I portray Maxwell imagining his demons creating a disturbance in the ether by pushing the electrically charged balls to the right (causing counterrotations in the adjacent magnetic force cylinders) or by rotating one of the magnetic force cylinder (causing lateral motion in the adjacent electrically charged balls).

In order to provide a mechanistic account of the nonconducting but wave-carrying capacity of the ether -- conceived as a kind of all-pervading invisible and intangible jelly -- Maxwell imagined his cylinders and balls to be elastically bound so that on removal of the disturbing force, they would spring or rotate back, overshoot, and then settle into their former positions through a transient quiver of damped oscillations. In a brilliant stroke, Maxwell saw that such an oscillation would propagate through this medium as a transverse wave of alternating electric and magnetic force at right angles to each other. Based on the dielectric constant of empty space (determined from the ratio between measured electric and magnetic forces), he calculated the velocity of propagation of such an electromagnetic undulation and found that "within the limits of experimental error," it was "the same as that of light."

(Granted, the speed of light itself had been determined not by a thought experiment but by astronomical measurements. The first successful measurements were made by Newton's Danish contemporary Ole Rømer, based on the shorter or longer time that elapsed between the observations of Jupiter's eclipses of its moons, when the earth had moved closer to or farther from Jupiter, respectively. In retrospect, however, we could also say that the speed of light was determinable through Maxwell's thought experiments together with a laboratory measurement of the dielectric constant, which did not require an observation of light itself.)



*Maxwell*
*imagines creating an electromagnetic disturbance*
(Figure 2.1)

Physical implications of Electrodynamics

Now light, unlike the direct but macroscopically weak electrostatic and magnetic forces, has always been one of the most obvious features of the terrestrial environment. For Newton, the sun was not only the principal source of gravitation in our solar system but also the principal source of light. Indeed, having given the first general theory of gravitation in his 1687 Principia, Newton provided what may have been the most complete scientific treatment of light in his 1704 Opticks. Yet

Newton did not achieve a synthesis of the two. Light could not be reduced to particles moving in accordance with Newtonian laws:

•The direction in which a slanting beam of light deviates from a straight path as it passes from one transparent medium into another -- namely, toward a line at right angles to the surface, on passing from a less dense medium (such as air) into a more dense medium (such as water or glass) and away from such a line on passing from the more dense to the less dense medium -- is not what one would expect if light were composed of material particles but follows directly from the wave theory of light, if the velocity of light is less in the more dense medium, as Huyghens showed.

•The closely space concentric colored rings that Newton himself observed upon illumination of a convex lens placed against a reflecting surface and that have since been known as "Newton's rings" are best explained as the result of interference of reflected light waves -- akin to the "interference fringes" that in Thomas Young's later double-slit experiment, definitively confirmed Huyghens's wave theory.

•Moreover, as special relativity was later to make explicit, if light were composed of tiny material "corpuscles" of non-zero rest mass, as Newton evidently supposed, at the velocity of light each such corpuscle would have infinite kinetic energy and, so, would blast a path of death and destruction through any other material body.

Newton had conjectured that all "the phaenomena of Nature ... depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards one another ... or are repelled and recede from one another ..." But it was Maxwell who provided us with the first set of universal laws, in the spirit of Newton's Principia, to account for electromagnetic attraction and repulsion and, as it turned out, the undulatory nature of light. (Maxwell's theory of electromagnetic radiation was later confirmed when Helmholtz's student Heinrich Hertz demonstrated the transmission of radio waves.) When Maxwell had succeeded in giving an explicit mathematical formulation of his electromagnetic laws, he dispensed with the imaginary hydraulic and mechanical models on which he had performed his thought experiments. For posterity, he offered only the four abstract, beautiful, and symetrically related differential equations of electromagnetism now universally known and celebrated simply as "Maxwell's equations."

Today, our entire technological infrastructure -- including power, heating, lighting, transportation, communication, and computation -- depends entirely on electromagnetic interactions among electrons and photons. No wonder that Richard Feynman, perhaps the foremost architect of quantum electrodynamics, has said, "ten thousand years from now -- the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics."

### Psychological implications of Electrodynamics

Ironically, Maxwell's own electromagnetic theory was found (by Leo Szilard, Leon Brillouin, and others) to preclude the possibility that his thermodynamic demon could use electromagnetic energy to perform its nefarious task of subverting the second law of thermodynamics by opening or closing a small shutter between two compartments depending on whether each approaching molecule was fast or slow. Corresponding to the temperature, T, of a body of gas in thermodynamic equilibrium, Maxwell's electromagnetic theory required that the agitated gas molecules give rise to and remain in thermal equilibrium with electromagnetic radiation. Against the background of this radiation, Brillouin said, "the demon ... would never see the molecules." (Subsequent analyses have shown that even if the demon had a way of discriminating fast and slow molecules without depending on electromagnetic radiation, in its thermal environment it would be unable to dissipate the heat associated with discarding its accumulating burden of information. Losing its "cool," it would be unable to sustain the information processing essential to its sorting task.) In retrospect, it even appears that if Maxwell had fully worked through the implications of his own electromagnetic theory, he might himself have achieved not only the end of his demon but also (as I shall suggest) the beginnings of relativity and of quantum mechanics. As onetime Harvard physicist Steven Weinberg observed, "often ... our mistake is not that we take our theories too seriously, but that we do not take them seriously enough."

## Einstein's Theories of Relativity

### Unexplained phenomena

At the beginning of the 20th century, science was once again seen by many as accounting for just about everything in the physical world. Newton had reconciled terrestrial with celestial motions, Boltzmann had reconciled apparently irreversible processes with Newton's time-symmetric laws, and Maxwell had reconciled the diverse phenomena of electricity, magnetism, and light under one set of Newtonian-like laws. Nevertheless, some facts still remained to be explained. And two of these were, quite literally, as plain as night and day.

The first of these was that days are so bright. Maxwell had offered a theory of what electromagnetic radiation is, but he had not explained how the sun (and other stars) could producè so much of it. The total amount of radiant energy emitted by the sun just during the period required for the evolution of terrestrial life (which depends on sunlight for its energy) exceeded, according to calculations by Kelvin, what could have been available in the total amount of matter in the sun in the two forms of potential energy known at that time -- namely, gravitational and chemical.

The second of the two obvious but unexplained facts was that nights are so dark. If we follow Giordano Bruno in taking the logical next step beyond Copernicus and admit that there is no reason to suppose that our sun, any more than the earth, occupies a privileged position in the universe and that our sun may in fact be just one of indefinitely many suns (the countless stars we see at night), then the universe should look much the same from the vicinity of any other star as it appears from earth. On the largest scale, matter might then be expected to have a statistically uniform distribution throughout the universe. But the appearance of any luminous surface (such as the flame of a candle) becomes only smaller, not less bright, with increasing distance from us. (Relative to a square luminous panel at a given distance, four such luminous panels arranged edge-to-edge into a larger square with twice the height and twice the width situated at twice the distance, would project a square image on the retina that is not only of the same size but within which each photoreceptor would receive the same amount of radiant energy per unit time.) Consequently, every line of sight into the night sky should eventually encounter a stellar surface with retinal brightness comparable to that produced by the closest star, our sun. If that were the case, however, the whole night sky would blaze with the brilliance of the sun itself. The fact that it does not is known as Olber's paradox.

Einstein's 1905 special theory of relativity provided an explanation of the obvious fact of the sun's enormous energy output and, also, of the much more subtle failure of Michelson and Morley's "ether-drift" interferometer to find any evidence of the earth's movement relative to a stationary ether. (Maxwell's theory required that the travel time be slightly longer for that portion of a beam of light that was being reflecting back and forth between mirrors at the ends of an arm aligned with the direction of the earth's motion than for that portion of the light beam that was being reflected back and forth between mirrors at the ends of an arm at right angles to that motion. But the interference fringes produced when the two portions of the beam were brought together again showed none of the shift predicted to occur as the orientation of the instrument was varied with respect to the earth's motion.) And, Einstein's 1916 general theory of relativity led to a theoretical explanation of the obvious darkness of night sky and, also, of the much more subtle 43-seconds-of-arc-per-century unexplained rotation of the major axis of Mercury's elliptical orbit. Yet none of these four unexplained phenomena, whether obvious or subtle, seems to have played a significant role in Einstein's original development of his theories of relativity.

## Special theory of relativity

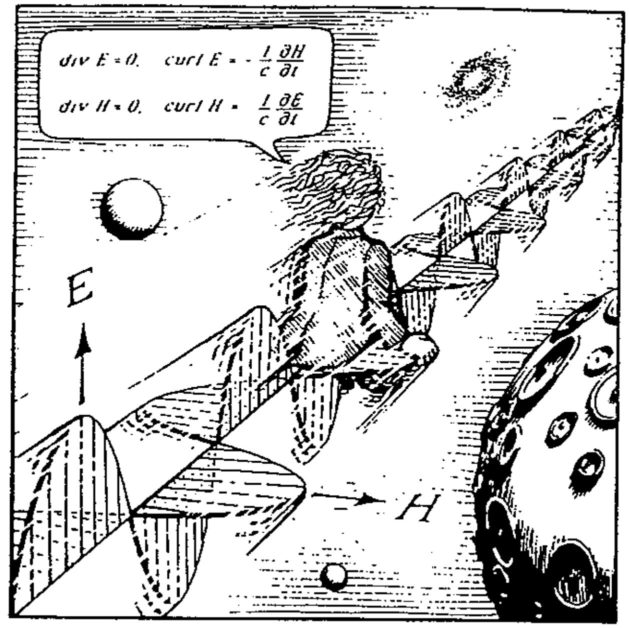
Much as Copernicus formulated his heliocentric theory by imagining himself standing on the sun, Einstein had the first insights that were to lead to his formulation of relativity theory by imagining himself riding a wave of light (Figure 2.2). In imagining what he would experience in thus flashing through space at this almost unimaginable speed (of some 186,000 miles per second), Einstein confronted anomalies that had not previously been noticed. According to Maxwell's theory, Einstein realized, he would not be able to see his own image in a mirror that he held in front of himself. Any light scattered from his face toward the mirror could never catch up to the mirror, which was already moving away at the speed of light. Moreover, the electromagnetic wave, which to a stationary observer must play out as an oscillation in the stationary ether, would not oscillate for the co-moving observer but would remain frozen throughout its flight.

Such anomalies were unsatisfying for Einstein. According to him, Galileo's principle that everything that could be observed within the closed cabin of a ship is the same whether the ship is at anchor or in full sail, should extend even to a space ship travelling at close to the speed of light. In the absence of force-induced accelerations or decelerations (such as those caused by waves at sea), the laws of physics -- including the velocity of light -- should remain the same regardless of the velocity at which the laboratory as a whole is travelling through space. In his desire for such universally invariant laws, Einstein carried out a number of thought experiments on sending light signals between spatially separated observers in various states of motion. I describe one that leads quite simply and directly to the basic idea of special relativity, and that also illustrates the non-Euclidean character of relativistic space-time (Figure 2.3).

It is sufficient to consider just the two-dimenensional plane through four-dimensional space-time in which the horizontal axis represents the spatial dimension along which a motion is to take place and the vertical axis represents time -- multiplied by the invariant speed of light, c. Without this rescaling of the vertical axis, the oblique line corresponding to anything as swift as a pulse of light would be virtually horizontal in the diagram. With this rescaling, a pulse of light, here represented by a wavy line, always traverses a 45∞ line.

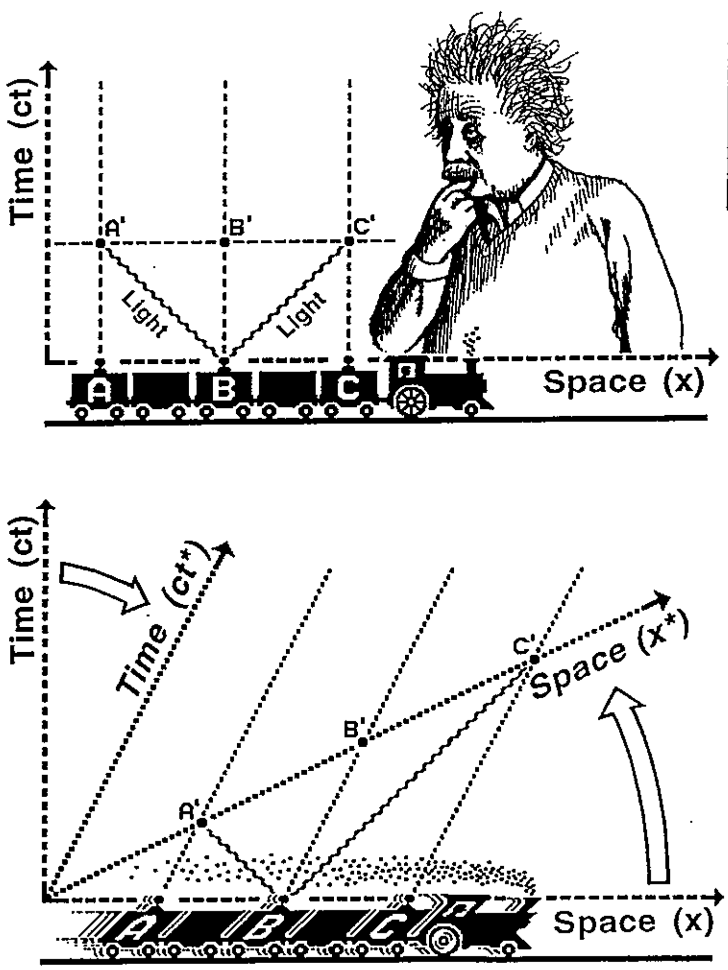
Following Einstein, we now imagine three observers, A, B, and C, at equally-spaced locations in a rigid inertial frame that can be considered at rest or (with thanks, here, to James Watt) undergoing uniform motion at any desired velocity along the x axis. We further imagine that at a given moment, Observer B briefly uncovers a lantern, simultaneously sending light signals in opposite directions to Observers A and C. Those two observers, being equally distant from B, would receive those light signals at exactly the same later moment. In case the observers are in a stationary frame (upper diagram), this is immediately obvious by symmetry. The x-coordinates of the three observers are then constant, and the passage of time is simply represented by a purely upward motion of all three observers along the three vertical lines parallel to the time axis in the diagram. As shown, the light signals diverging from B must intersect the vertical lines for Observers A and C at the points A' and C' on the same horizontal line at the later time. Likewise, if Observers A and C immediately sent back confirmatory light signals, those signals would converge back on Observer B simultaneously at a time that is still later and, hence, higher in the diagram.

But what would be the experience of the same three observers if the rigid frame on which they were riding were rushing along the x axis at a significant fraction of the speed of light? Adding his principle of the invariance of the speed of light to Galileo's principle that all observations made within an inertial frame are independent of the velocity of that frame, Einstein was immediately led to the situation illustrated in the lower diagram. By hypothesis, the light signals are still represented by 45∞ lines, but the three observers, by virtue of their common rightward motion, trace out lines in the space-time diagram that are no longer strictly vertical but leaning to the right. Consequently, the signals from Observer B no longer intersect the lines for Observers A and C in points falling on a horizontal line (as in the upper diagram). Instead B's signals intersect the lines for Observers A and C in points that determine a line slanting upward to the right. Nevertheless, in agreement with Galileo's principle, the experiences of the three observers remain exactly as before. Again, if Observers A and C immediately respond to the signals from B, their confirmatory signals will converge back on Observer B simultaneously at an appropriately later time, just as in what was considered the stationary case.




*Einstein*
*imagines riding and electromagnetic wave*

(Figure 2.2)




*Einstein*
*imagines light signals between moving observers*

(Figure 2.3)

Nothing in the experience of the three observers would enable them to distinguish between the cases illustrated in the two diagrams. Hence, there is no epistemological basis for distinguishing absolute states of motion or rest. It is this relativity of all motion that gives Einstein's theory its name. For any two states of relative motion (such as are illustrated in the two diagrams), there is a geometrical transformation, the Lorentz transformation, that will carry either state into the other. In the lower diagram the large curved arrows illustrate how this Lorentz transformation rotates the axes for time and space toward each other to yield new coordinates, x* and ct*. The line representing each observer's continuation over time is parallel to the transformed time axis. Thus, in the transformed coordinate system, the three observers regard themselves as at rest (just as we regard ourselves at rest relative to the local surface of the earth even though the earth is rotating about its axis and moving about the sun and, with other stars, about the galaxy and, with othe galaxies, through space). Relative to the transformed system, what were previously described as stationary observers in the upper diagram are now regarded as moving uniformly to the left. But, because the lines of simultaneity are different in the two cases (horizontal above, tilted below), two separated events in space-time will be characterized as having different temporal orders by observers in the two relatively moving frames. And, because neither frame has a privileged status, simultaneity has no objective, observer independent meaning.

This is a departure from Newton, who had said: "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external. "Absolute space, in its own nature, without relation to anything external, remains always similar and immovable." Equally, it is a departure from Maxwell, who had assumed that his own all-pervading "ether" remained in a globally absolute state of rest in Newton's Euclidean space. Suddenly, in order to maintain invariance of physical laws up to the velocity of light, Einstein's special relativity required that Euclidean space (after an unprecedented reign of 23 centuries) be replaced by a non-Euclidean four-dimensional space-time. The mathematician Hermann Minkowki summed it up: "Hereafter space in itself and time in itself sink to mere shadows, and only a union of the two retains an independent existence." (Yet, the four-dimensional geometry of relativistic space-time bears a simple relation to four-dimensional geometry of the more familiar Euclidean type. Reasoning from an analogy with the Pythagrean formula for the length of the hypotenuse of a right triangle, Minkowski himself showed that if instead of representing time by the real-valued coordinate ct, we represent it by the imaginary coordinate ict, where i = ÷-1, the seemingly exotic Lorentz transformations become isomorphic to rigid rotations in Euclidean space.)

Einstein's theory of space and time came as a shock to physicists and geometers alike (with the possible exception of the Dutch physicist Hendrik Lorentz and the French mathematician Henri Poincaré, who at about the same time as Einstein had each independently glimpsed parts of the truth). Other thinkers, having evolved in the three-dimensional terrestrial world of objects of only modest velocities, had not carried out sufficient thought experiments concerning the implications of relative motion at near-luminal velocities -- thought experiments that as we have just seen, can quite directly reveal that physical space and physical time are inextricable and partially interchangeable aspects of one unified physical structure.

## Physical implications of the special theory

The special theory of relativity entailed many counterintuitive implications:

•However swiftly we race a beam of light, it will continue to pass us by at a constant, undiminishable relative velocity, c, (approximately 186,000 miles per second).

•As we approach the velocity of light, relative to an external observer our spatial extension in the direction of motion shrinks toward zero, our physical (and, hence, mental) processes slow toward a standstill, and our mass increases without limit.

•Because increasing expenditures of additional energy are required for each increment in speed of this increasing mass, nothing can exceed the speed of light.

•There is no objective basis for attributing simultaneity to spatially separated events; relatively moving observers assign different temporal orders to such events.

•To exceed the speed of light would even entail the reversal of cause-effect relations and all the logical paradoxes that follow from the possibility of altering past events.

•Matter or energy are not separately conserved; there is conservation only of mass/energy -- each bit of matter being potentially convertible into an enormous amount of energy proportional to its mass times the speed of light squared, $E = mc^2$.

Despite their counterintuitive character, these conclusions follow quite directly from Einstein's thought experiments.

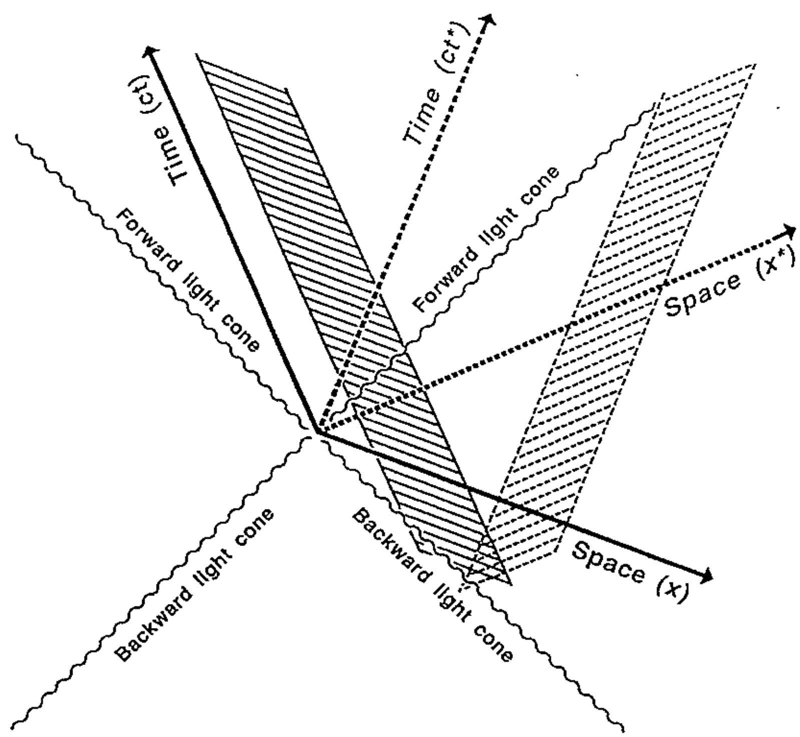
In order to understand the motion-induced contraction, we need only consider two objects that are extended along the x-axis of space and that are moving away from each other along that axis at an appreciable fraction of the speed of light (Figure 2.4). Of course, the circular or spherical wave front expanding in all directions from a point-source in two-dimensional x, y plane or three-dimensional x, y, z space (as opposed to the one-dimensional x space shown in the diagram) traces out a conical surface (or hypersurface) in, respectively, three- or four-dimensional x, y, z, ct space-time. The central assumption of special relativity -- that the speed of light is invariant -- implies that all such "light cones" are identical for all observers. Any event within the cone of light emitted from an observer at a given instant is in the absolute future of that observer at that moment, any event within the (backward) cone of light received by that observer is in the absolute past, and any event outside both these (forward and backward) cones is in the observer's potential present in the sense that for some state of motion, the observer would regard that event as occuring at his or her own present moment. (In the diagram, the two wavy lines forming a V represent the intersection of the x, ct plane with the forward light cone, and the two wavy lines forming an inverted-V represent the intersection of that plane with the backward light cone.)

We can think of the extended, relatively moving objects as the two trains portrayed in the earlier figure. The train moving to the left can be regarded as stationary in its own inertial frame, indicated by the solid-line x and ct axes. The train itself is indicated, for successive time slices, by the solid-line segments that are all parallel to the corresponding (solid-lined) space axis. The train moving to the right can be regarded as stationary in its Lorentz-transformed inertial frame, indicated by the broken-line x* and ct* axes. This train is indicated, for successive time slices, by the broken-line segments that are all parallel to the corresponding (broken-line) space axis. (The interpretation of each train as at rest in its own inertial frame corresponds to the parallelism of the path of successive line segments and the associated time axis, ct or ct*.)

The lengths of the two trains are exactly the same when measured at rest in their own intertial frames; that is, the solid-line segments parallel to the solid-line x axis all have exactly the same lengths as the broken-line segments parallel to the broken-line x* axis. When each train is viewed from the inertial frame of the other train, however, it appears to be contracted in the direction of motion; the band corresponding to the space-time existence of that train has a shorter intersection with the other space axis, x* or x, than with its own space axis, x or x*.

This relative contraction becomes more and more extreme as the relative velocities approach the speed of light; that is, as the solid-line axes x and ct diverge toward alignment with the left-going 45° light line and the broken-line axes x* and ct* converge toward alignment with the right-goint 45° light line in the diagram.

According to the special theory of relativity, it is the space-time bands or "world lines" of the two objects that have an invariant physical reality. The way an object appears to a particular observer at a particular moment is just that -- an appearance. It will be quite different for differently moving observers, and no observer's viewpoint is more valid than any other. (More justifiably, then, the space-time bands representing the two trains should be filled not with lines parallel to any particular spatial axis but with a homogeneous gray shading.) Indeed, rather than regarding a moving object as having suffered a contraction, we might better say that the external observer's unit of length is expanded relative to the transformed space direction (x*) of the moving object.




*Relativistic contraction*
*of moving objects*

(Figure 2.4)

By a similar geometrical argument (omitted here), we can say that the external observer's unit of time is expanded relative to the transformed time direction (ct*) of the receding object. Thus it is that to the external observer, temporal processes in a receding system appear to be slowed. The external observer will also attribute to the moving object a greater mass than that attributed to the object by an observer moving along with the object. For such a co-moving observer, Galileo's principle still holds; a given push to the object in the direction in which it is already moving with respect to the external observer's fame will produce the usual increment in the object's motion in the co-moving fame. When measured with respect to the observer's expanded scales of length and time, however, that increment in motion is reduced. That a smaller spatial increment occurs during a longer temporal interval for the same applied force is attributed to an augmentation of the object's resistive mass.

I may have made the spatial contraction, temporal dilation, and increased mass seem as nothing more than a kind of optical illusion when viewed by an hypothetical observer moving relative to the object at close to the speed of light. These effects nevertheless have very real physical consequences for such an observer. Granted, we cannot physically realize exactly these thought experiments. Our swiftest rockets approach velocities of no more than a ten-thousandth the speed of light (that is, .0001 c). Still, Stanford's linear accelerator has propelled electrons to as close to the speed of light as .999,999,98 c. Every day, the predicted increases in mass at such speeds are verified by the energies required to further accelerate the particles or to deflect them from their rectilinear path, as well as by the energies released when such speeding particles collide with a stationary target; and the predicted dilations of time are confirmed in the retarded decays of other accelerated particles, such a mesons, that (unlike the stable electrons) are normally very short lived when not traveling at these enormous speeds. But the consequence of the special theory of relativity that has given rise to some of our brightest hopes and darkest fears is the equivalence that Einstein discovered between energy and mass, $E = mc^2$. This equivalence follows from the relativistic increase in mass with motion.

(Briefly, in an inelastic collision of two spherical bodies, such as balls of wax, of equal rest mass but hurtling toward a mutual collision at an appreciable fraction of the speed of light, symmetry, here realized as the conservation of momentum, requires that the combined body resulting from the inelastic collision be stationary in the frame with respect to which the two bodies had been symmetrically moving. The relativistically augmented masses of the two moving bodies must be conserved in some form in the resulting merged body -- here, in the form of thermal energy, as discussed in my first lecture. But according to relativity theory, for velocities not too close to c, the relativistic augmentation of the masses is approximately proportional to the square of their kinetic energies of motion divided by by the speed of light squared. This leads directly to Einstein's most famous equation, $E = mc^2$.)

Despite its counterintuitive implications, the special theory of relativity was ultimately accepted for both theoretical and empirical reasons: Its laws, unlike Newton's and Maxwell's, were the same for all observers, regardless of their (uniform) relative motions. And its predictions, unlike Newton's and Maxwell's, have passed all tests. In particular, special relativity requires the observed absence of shift in interference fringes when Michelson and Morely rotated their ether-drift interferometer because, in effect, the expected slower transit time of light along the direction of the earth's motion is exactly compensated for by the (minute) relativistic contraction of the apparatus in that same direction. And the sun's long continuing output of radiation has been fueled not by gravitational contraction or chemical combustion but by the gradual but more efficient conversion (through nuclear fusion) of a portion, m, of the sun's prodigious mass -- amplified by the speed of light, c, squared -- into a still more stupendous amount of energy, E, in accordance with $E = mc^2$. Even at its present estimated loss of mass through radiation at the rate of some $4 \times 10^{11}$ tons per day, the sun still has enough reserve mass to go on shining for a few hundred million years.

## Psychological implications of the special theory

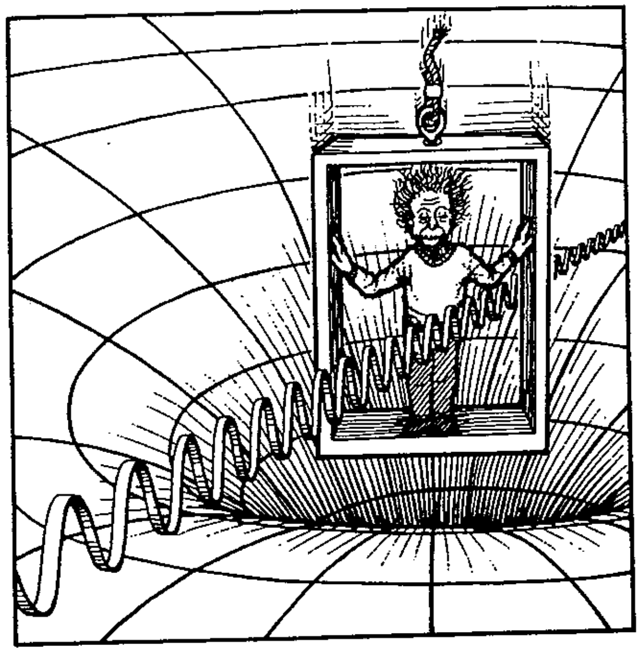
Perhaps most difficult to reconcile with everyday experience is the implication of the special theory of relativity that neither what we call "the present moment" nor its "motion" from past to future can have objective reality. Of all the events that have or will ever occur in the universe, the subset that can be said to be "occurring now" is entirely subjective in that the subset differs from one observer to another. What is objective -- that is, true for all observers -- is only the entire past and future structure of the universe taken as a four-dimensional whole. Strictly, there are no moving objects; the history of each object exists as a static "world line" resembling a thread frozen in a four-dimensional block of ice. This is in contrast even to the Newtonian "clockwork" universe where, Laplace notwithstanding, there had always been at least the logical possibility of an intervention (whether through quantum fluctuations, free will, or God). But the frozen four-dimensional universe of special relativity, having no objective "now" and, hence, no objective past or future, leaves no crack for the insertion of a decision or a choice. Moreover, the lonely astronaut hurtling through the depths of interstellar space who, thinking of one she left behind, asks herself, "I wonder what he is thinking at just this moment?" can only feel more alone when she realizes that "this moment" has no application to the distant earth. No wonder Einstein himself once confessed that he regarded the problem of the "now" as the most perplexing in all of physics.

In addition to its direct implications for mind, the special theory of relativity suggests analogies for understanding the functioning of the brain. In particular, William Hoffman and others (including Harold Lindman, Terry Caelli, Mari Riess Jones, and I) have noted that the consequences that the limiting velocity of electromagnetic transmission in space has for the motions of physical objects at near-luminal velocities should have analogs in the consequences that the limiting velocity of neuronal transmission in the brain has for the perceptual representation of objects at ordinary terrestrial velocities. I shall return to this in when, in a later lecture, I consider perceptual phenomena of visual apparent motion.

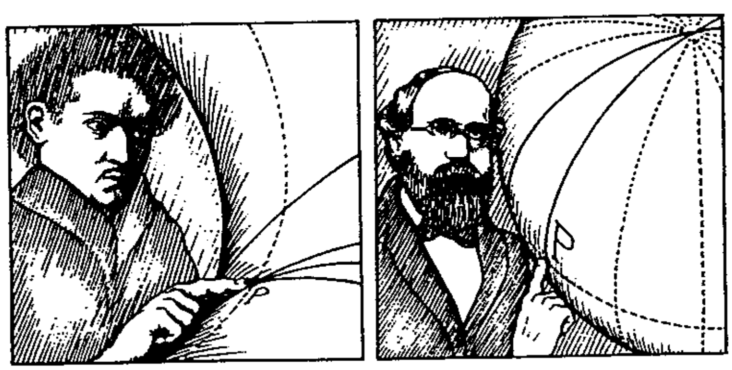
## General theory of relativity

The general theory emerged ten years after the special theory following additional thought experiments, in which, for example, Einstein imagined riding in an elevator free-falling in a strong gravitational field (figure 2.5). He realized that if the laws of physics are to be invariant for all observers, a beam of light passing through the elevator must appear to traverse a straight path relative to that free-falling frame. But, because the elevator's downward motion is accelerating in the gravitational field, any path that appears straight relative to the accelerating elevator will of geometrical necessity appear curved relative to a stationary external observer. To such an observer, therefore, a beam of light bends in passing through a gravitational field. The predicted bending was confirmed in 1919 when a solar eclipse expedition led by Eddington measured the shift in the apparent positions of stars close to the image of the sun (where they could now be seen because the glare of the sun was masked by the eclipsing moon). More recently, such bending has been further confirmed by the discovery of the remarkable multiple, arc, and ring images that had been predicted to arise when a galaxy situated by chance along our line of sight to an enormously distant quasar acts as a "gravitational lense."

In order to achieve physical laws that are invariant in the general case of observers in a gravitational field or undergoing arbitrary accelerated motion, Einstein found that those laws could no longer be formulated with respect to a "flat"



*Einstein*
*imagines riding a free-falling elevator*
(Figure 2.5)



*Lobachevsky & Riemann*
*imagine spaces of negative and positive curvature*
(Figure 2.6)

space (whether Euclidean or Minkowskian). Invariance required formulation with respect to a curved four-dimensional space such as had never even been imagined until Lobachevsky and Riemann devised geometries that, although violating Euclid's fifth postulate, were each internally consistent (Figure 2.6).

Here, I depict Lobachevsky and Riemann each imagining a two-dimensional "plane" taken from their respective spaces in which Euclid's Parallel Axiom is violated in one of two ways: Instead of there being, for any line L, exactly one line through an external point P that does not meet L (as in Euclidean space, with its zero curvature), there either are infinitely many such lines, as in the negatively curved Lobachevskian (or "hyperbolic") space, or not even one such line, as in the positively curved Riemannian (or "elliptic") space (where, as on the globe of the earth, the meridians, which all make right angles with the equator, necessarily intersect each other at each of the two poles).

These non-Euclidean two-dimensional "planes" are easy for us to picture only because their saddle-shaped and spherical curvatures can be depicted in familiar three-dimensional space. The possibility that three-dimensional space itself might be curved had not occurred to previous geometers or philosophers (evidently including Immanuel Kant). Again, as Einstein remarked "... the human race is poor in ... creative imagination." This particular failure of imagination is understandable, however. Given the small portion of the whole universe visible from earth and given no ultramassive objects in the immediate vicinity of earth, the curvature of the portion of three-dimensional space with which we and our ancestors have ever had direct experience (like the curvature of a local portion of the two-dimensional spherical surface of the earth itself) has been negligible. Under these conditions there has been little or no selection pressure favoring the emergence of neuronal machinery either for the representation of curved space or for the representation of a higher-dimensional space in which curvature of three-dimensional space might be concretely visualized. Even Newton is said to have regarded the truth of Euclid's propositions, presumably including the parallel axiom, as "obvious ... at the first glance." Einstein remarked, "When the blind beetle crawls over the surface of a globe, he doesn't notice that the track he has covered is curved. I was lucky enough to have spotted it."

Actually, general relativity required a four-dimensional Riemannian manifold in which the curvature varies from point to point depending on the mass distribution in the vicinity of each point. Kepler's aphorism, "Where there is matter, there is geometry," thus took on a meaning never anticipated by Kepler himself.

Material bodies and light waves, alike, were no longer to be considered as moving in response to a Newtonian gravitational force acting instantaneously across empty space. (Newton himself admitted, "That gravity should [act] at a distance through a vacuum, without the mediation of anything else, ... is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it," and further confessed, "the cause of gravity is what I do not pretend to know, and therefore would take more time to consider of it.") Einstein eliminated gravitational force. For him, what we regard as a material body or a light wave is just a (momentary) spatial slice through a thread-like "world line" stretched over the shortest possible path (called a geodesic) in the four-dimensional space-time manifold -- curved and warped as it is by the surrounding distribution of matter/energy. In addition to the bending of light by the sun, Einstein's revision of Newtonian mechanics accounted for the otherwise unexplained rotation of the major axis of Mercury's orbit. Echoing William James, we might well say, "By such elaborate inventions and cost to the imagination, has Einstein coerced the world per fas aut nefas under geometrical law."

To make possible physical laws that remain invariant not only near luminal velocities but also near stellar masses or at cosmological scales, the four-dimensional Minkowski space of special relativity was thus superseded, after only ten years, by the four-dimensional curved Riemannian manifold of general relativity. Yet the Euclidean theory of space, like the Newtonian theory of motion in space, remains valid as a remarkably close approximation under the conditions of velocity, mass, and size normally prevailing in the terrestrial environment. This illustrates the uniquely cumulative character of science. In the evolution of scientific theories, as in the evolution of biological species, developments may be slow in coming but, when at last they come, they can be truly revolutionary and, at the same time, highly conservative.

General relativity also led to a natural explanation for the darkness of the night sky. Einstein, who had assumed the universe to be unchanging in its global structure, was dismayed to find that the equations of his own theory did not admit a stable solution corresponding to such a universe. The Russian cosmologist Alexander Friedmann, nevertheless accepting this implication, went on to develop a general-relativistic model of a universe that although spatially homogeneous, must be either expanding or contracting in time (except for a possible transitory stasis at the time, if any, when the expansion slows to a stop and begins to contract). Historically, the expanding alternative was selected over the contracting one for our current universe based on Hubble's 1929 discovery (using the world's then largest telescope) that the fainter and presumably more distant a galaxy, the more its light tended to be shifted toward longer wavelengths (the cosmological "red-shift").

Significantly, with regard to the thesis I am developing here, however, the expanding alternative was already implicated by the familiar fact, requiring no telescope at all, that the night sky is dark and cold. Only in a globally expanding universe, are the radiations from distant sources effectively stretched in wavelength or "red-shifted" until, for sufficiently distant sources, they become too degraded in energy to be seen or felt. The "big-bang" cosmologist Lemaître well expressed our situation: "Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds."

Actually, a universe governed by Newton's laws is similarly unstable, as Newton himself recognized: "the hypothesis of matter's being at first evenly spread through the heavens, is ... inconsistent with the hypothesis of ... gravity." The mutual gravitation of material bodies would cause them eventually to fall together, unless such collapse were prevented by some external intervention or initial condition not specified within Newtonian mechanics. The theistic Newton invoked the intervention of a "supernatural power" to counteract gravitational collapse. But a less ad hoc explanation, whether regarded as natural or supernatural, would be that all material bodies had been sent rushing out into Euclidean space, from some stupendous explosion in the remote past, with velocities sufficient to prevent or, at least, to delay gravitational collapse. In retrospect, we thus see that the darkness of the night sky could in principle have been explained by Newton; the recession of very distant sources would have taken away from the energy of any light corpuscles arriving from them (or, as we would say now, their light waves would be doppler shifted toward the lower-energy red wavelenghts). But Newton had not thought of Olber's paradox and, perhaps for theological reasons, had evidently assumed (as Einstein initially did) that the universe is stable.

In models of the universe based on general relativity, in contrast, galaxies are not regarded as having been hurled into empty space from some localized explosion. Instead, matter/energy is assumed always to have homgeneously pervaded all space; it is the space itself that has been expanding. For easier visualization, the reduced-dimensional analogy of the surface of an inflating balloon is helpful: On such a surface, randomly distributed spots, representing the galaxies, become increasingly separated from each other; and undulating lines, representing light waves, become increasingly stretched and, hence, red-shifted.

Because the expanding alternative implies a beginning of the universe at a finite time in the past, it is also true that our lines of sight necessarily encounter not the infinite number of stars originally assumed for Olber's paradox but only the finite number of stars that have formed within the light cone extending back just to the time when stars first formed (after the "big bang"). Still, any line of sight that does not encounter a stellar surface must eventually encounter the space-filling flash of radiation that decoupled from matter when the expanding universe had cooled to about 3,000° Kelvin -- a temperature that is itself comparable to that of a stellar surface. But, this primordial radiation, too, has been stretched by the subsequent expansion of the universe until, by our present epoch, its temperature has been reduced a thousand fold, from the blazing 3000° K specified by Olber's paradox to a feeble 3∞ K radio noise undetectable by human eye or skin. Although this residual cosmic background radiation was theoretically predicted as early as 1948 (by Alpher and Herman) as a necessary vestige of the big bang, it was not physically detected until 1964, when Penzias and Wilson who, unaware of the prediction, strove unsuccessfully to eliminate an annoying static that persisted in their huge Bell Laboratories microwave antenna, no matter where they pointed it in the sky.

The developments in cosmology between 1929 and 1964 seemed, however, to raise, again, the question of the universality of the second law of thermodynamics. For, the view that emerged during that period (and which still prevails), is that the early universe, though intensely hot and dense, was in a state of virtually complete spatial uniformity of matter, energy, and temperature. Such a homogeneous state would seem to be one of maximum entropy -- exactly the opposite of the low entropy required, since Boltzmann, to account for the increasing entropy we now observe in all branch subsystems in the world. The resolution of this apparent inconsistency was achieved, only later, by considering the entropic consequences of the gravitational tendency (manifested, particularly, with the expansion and cooling of the universe) of matter to coalesce into clumps and, ultimately, to collapse into black holes -- objects obeying laws whose uncanny formal resemblance to the laws of thermodynamics led Bekenstein and Hawking to generalize Clausius's concept of entropy well beyond the great generalization that had been achieved by Boltzmann.

### Physical implications of the general theory

General relativity brought its own additional counterintuitive implications:

•Physical space, though manifesting no noticeable departure from Euclidean "flattness" in our local environment, partakes of a larger scale space-time curvature.

•The moon in apparently orbiting the earth, and the earth in apparently orbiting the sun are both only tracing out the straightest possible paths in this curved space-time.

•Time runs slower in the vicinity of a massive body -- so much so that from the perspective of a remote observer, the time of a person falling into a black hole slows toward a complete standstill as the unfortunate astronaut approaches the "event horizon" (beyond which the roles of space and time are effectively interchanged).

•After an interstellar excursion at close to the speed of light, the still youthful astronaut would return to find her stay-at-home twin already old and gray.

•And, if the universe should happen to have a globally "nonorientable" topology (like that of a two-dimensional Möbius strip or Klein bottle), a circumnavigating astronaut could return in enantiomorphic form -- with left and right interchanged, writing backward in reversed letters, with DNA twisting in the opposite way, and possibly with matter converted to antimatter (in which case, a hug from her stay-at-home twin would have all the warmth of the detonation of a hydrogen bomb!).

•Depending on the still insufficiently determined density of its dark matter, the universe either has globally nonpositive curvature, infinite size, and the destiny of interminable expansion toward utter coldness, darkness, and emptyness; or has globally positive curvature, finite volume, and the destiny of a decelerating expansion followed by accelerating contraction toward a blinding implosion into the infinite pressure and heat of a mathematical point.

(So, in the meantime: Have a nice day!) As Steven Weinberg has said, "The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy."

## Psychological implications of the general theory

The extension from the special to the general theory of relativity becomes necessary when the physical system of interest is in an intense gravitational field or is undergoing extreme acceleration (such as would be induced in such a field). The already noted paradoxes of time that arise under such conditions apply to all physical processes, including those of the brain and, hence, of the mind. The general theory does however reopen a way, seemingly closed by the special theory, to a specification of global simultaneity and, hence, of contemporaneousness of conscious experience between widely separated loved ones. In the special theory, there was no basis for singling out a particular inertial frame and its associated hyperplane of simultaneity. In the general theory, however, the status of being at rest in the universe as a whole may be uniquely assignable to that inertial frame for which the cosmic background radiation left over from the big bang has the same temperature in all directions.

In the general theory of relativity (much as in the special theory), we may also find useful analogies for formalizing mental laws. In particular, in a later lecture I shall argue that in representing the motions of objects in space (in both apparent and imagined transformations), our mental processes traverse a geodesic path in an abstract, non-Euclidean space of the possible positions of the object.

## Quantum Mechanics

### Unexplained phenomena

After Newtonian mechanics had been extended to statistical mechanics, after it had been supplemented by electrodynamics, and even after it had been superseded by special and general relativity, some highly significant facts, though long taken for granted in daily life, still lacked scientific explanation. There was, in particular, the fact, well known to every human being since well before the time of Newton, that matter exists in the structurally stable forms of familiar macroscopic objects -- sticks and stones, birds and bees, levers and wheels.

There are two irony's here. The first is that clockworks have for so long been taken as the examples par excellence of a Newtonian system. For, neither the rigidity of the component shafts, wheels, cogs, and levers essential for the operation of an actual clockwork nor the tension in the spring that may provide its driving force are explainable in terms of the laws formulated by Newton -- or, in fact, by Newton's successors, Maxwell or Einstein. The force of a stretched or compressed spring (described by Hooke's law) is not a manifestation of gravitational force but of the enormously stronger electromagnetic forces operating within and between atoms. The same holds for rigidity -- the condition exemplified, after all, by an arbitrarily stiff spring. (What I have portrayed in Figure 2.7 might not serve as a suitably rigid wheel for a clockwork.)

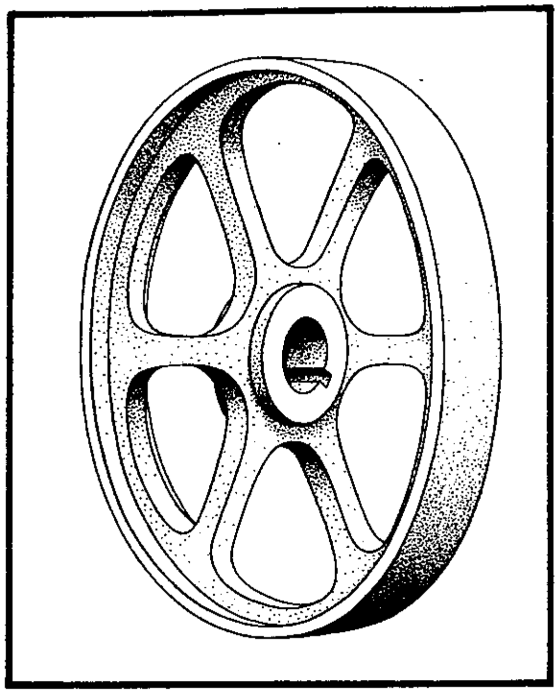
The second irony is that quantum mechanics is universally characterized, in contrast with Newtonian mechanics, as being probabilistic, indeterminate, and fuzzy. For it is quantum mechanics, as we shall see, that confers structural stability on a system that otherwise -- that is, if governed solely by Newtonian and Maxwellian laws of attraction and repulsion -- would not possess the enduring order essential to clockworks or, indeed, to life. Making the connection with thermodynamics, the quantum theorist Erwin Schrödinger (in his little book What is life?) remarked: "Clockworks are capable of functioning 'dynamically,' because they are built of solids, which are kept in shape by London-Heitler forces, strong enough to elude the disorderly tendency of heat motion at ordinary temperature."

But it evidently is not just the strength of the forces that is critical. Newton had long before conjectured that it must be through "certain forces [that] the particles of bodies ... are ... mutually impelled towards one another, and cohere in regular figures." Yet, electromagnetic forces, however strong, fall off, like Newton's gravitational force, with the inverse square of distance. Such forces can explain how a congeries of separate particles form a spiraling galaxy or a vortex of ionized gas. But, to explain how a rigid lever maintains -- or how a flexed spring tends to return to -- the arbitrary "regular figure" into which it was originally cast or cut, required a new kind of physics, never imagined by Newton or Maxwell. This is the physics is called quantum mechanics.

## Bohr

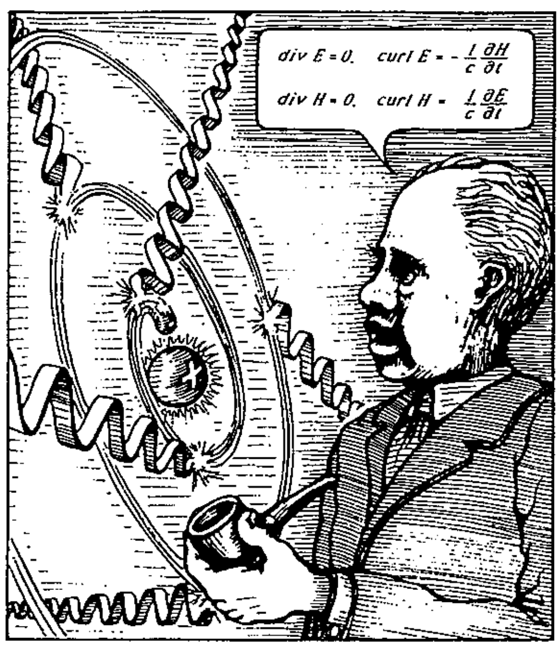
In considering what maintains or restores the shape of an object, it is natural to repeat Democritus's thought experiment of dividing the object into smaller and smaller pieces, and to ask what properties of its irreducible constituent atoms or molecules and their interconnections could explain the structural stability of the macroscopic whole. (Newton had said, "that Nature may be lasting, the changes of corporeal things are to be placed only in the various separations and new associations and motions of ... permanent particles.") The Danish physicist Niels Bohr (Figure 2.8) performed what might be regarded as the crucial second-order thought experiment concerning the planetary model of the atom that had recently been advanced by Ernest Rutherford. In this model, negatively charged particles were imagined to circle a positively charged nucleus under the inverse-square (Coulomb) force of mutual electrical attraction, much as the planets circle the sun under the (much weaker) inverse-square force of mutual gravitational attraction.

Bohr was aware that according to Maxwell's equations (once again), a charged particle that is forced to deviate from uniform rectilinear motion necessarily creates an electromagnetic disturbance that then propagates away at the speed of light. The



*Wheel for a nonrigid clockwork?*

(Figure 2.7)




*Bohr*

*imagines the radiative collapse of an atom*

(Figure 2.8)

energy carried away in this radiation can only come from the kinetic energy of the orbiting electron. As a result of its loss of orbital momentum, the electron would be expected to spiral into the positively charged nucleus. There, the mutual anihilation of the positive and negative charges would entail the collapse not only of the atom but of the residual electromagnetic forces between neighboring atoms responsible for the macroscopic rigidity or springiness we feel. The modern theory of the atom was born when Bohr concluded that new constraints must take precedence over Maxwell's electromagnetic equations at the atomic level, enabling electrons to conserve their kinetic energies in the vicinity of a nucleus. Such constraints, later formalized in Wolfgang Pauli's 1925 exclusion principle, explained, for the first time, the stability of atoms, hence of interatomic bonds, and thence of macroscopic objects. They also explained the structure of the periodic table of the elements, which the Russian chemist Dmitri Mendeleyev hit upon on February 17th, 1869 (when, on arranging the elements in order of their atomic weights, he discovered a repeating patten in their chemical properties), and which has since provided the foundation for all of chemistry. Finally, they explained the biological stability of microscopic cells and their macromolecular components (such as DNA and RNA) that are crucial for the existence of life, and hence of mind and science itself.

## Planck

Historically, however, it was a more subtle inconsistency that at the very beginning of the 20th century, first intimated the fundamentally quantum character of nature and provided a basis for Bohr's theory of the atom. This inconsistency, too, stemmed from a familiar fact: On being withdrawn from a fire, a heated object such as an iron poker comes to thermodynamic equilibrium with the cooler surrounding space by radiating its heat away in the form of electromagnetic energy. The distribution of emitted wavelengths depends on the object's temperature. Heated to a sufficiently high temperature, a poker, like the electrically heated filament of a light bulb, emits wavelengths spanning the visible spectrum and, hence, glows white hot. As the object cools, the distribution of emitted wavelengths shifts progressively toward the longer, less energetic wavelengths -- through orange, to red, to infrared (which though invisible to the eye can still be felt by the skin). Simply by mentally exploring the implications of the relevant theories available at the time, however, those theories were found to entail something that could not possibly be the case.

According to the kinetic theory, the heat of a solid object is in the form of vibrations of its elastically bound constituent particles. The good news was that according to Maxwell's equations, any electrically charged particles that are forced to vibrate more vigorously must give off electromagnetic energy at the expense of their augmented kinetic energy. The familar glowing and cooling of a hot body thus furnished support for the kinetic and electromagnetic theories as well as for Rutherford's assumption that the basic constituents of matter are charged particles. The bad news was that a more careful analysis (by Lord Rayleigh) of the kinetic theory revealed that vibrations with finite energies should occur at all frequencies, however high. This implied that the total amount of emitted energy (integrated over all possible wavelengths, however short) would be infinite. Such an "ultraviolet catastrophe" (the first of many infinities to torment the developers of quantum mechanics) could be declared impossible without making any physical measurements.

The first halting step toward quantum mechanics came in 1900, when the German physicist Max Planck, going beyond Rayleigh, tried an ad hoc hypothesis. He asked what would happen if, out of the previously assumed continuum of possible energies of vibration, each constituent particle could only vibrate with energies that were integer multiples of the product of that particle's natural frequency, n, and some constant, h. The new constant h could of course be set to zero, but Planck then obtained Rayleigh's distribution with its unacceptable ultraviolet catastrophe. For any finite positive value of h, however, Planck found the total energy remained finite, and the catastrophe was avoided. Indeed, if he set h at a particular, extremely small value of $6.6 \times 10^{-27}$ (about a billionth of a billionth of a billionth of an erg-second -- the unit of <u>action</u>), he found that the predicted wavelength distribution matched the empirically measured distribution exactly. Since then, the resulting theoretical distribution (Planck's "black body" radiation law) has become one of the basic laws of physics, and the corresponding constant h (Planck's quantum of action) has become the fundamental constant of quantum mechanics.

## <u>Einstein (again)</u>

Still, this was just the beginning. The second step toward quantum mechanics was taken by Einstein in 1905 (the same year that he introduced the special theory of relativity). Whereas Planck had reluctantly come to the conclusion that matter is somehow constrained to emit thermal radiation in packets having only certain discrete energies, Einstein boldly proposed that light itself exists only in discrete packets, for which he introduced the term "quanta." Einstein was thereby able to explain various electromagnetic phenomena, including not only Planck's thermal emission, but also the photoelectric absorption of light, in which the energy of electrons knocked off a metalic surface by ultraviolet light are independent of the intensity of that light. It was, in fact, primarily for his quantum theory of light, rather than for his theory of relativity, that Einstein was awarded the Nobel Prize.

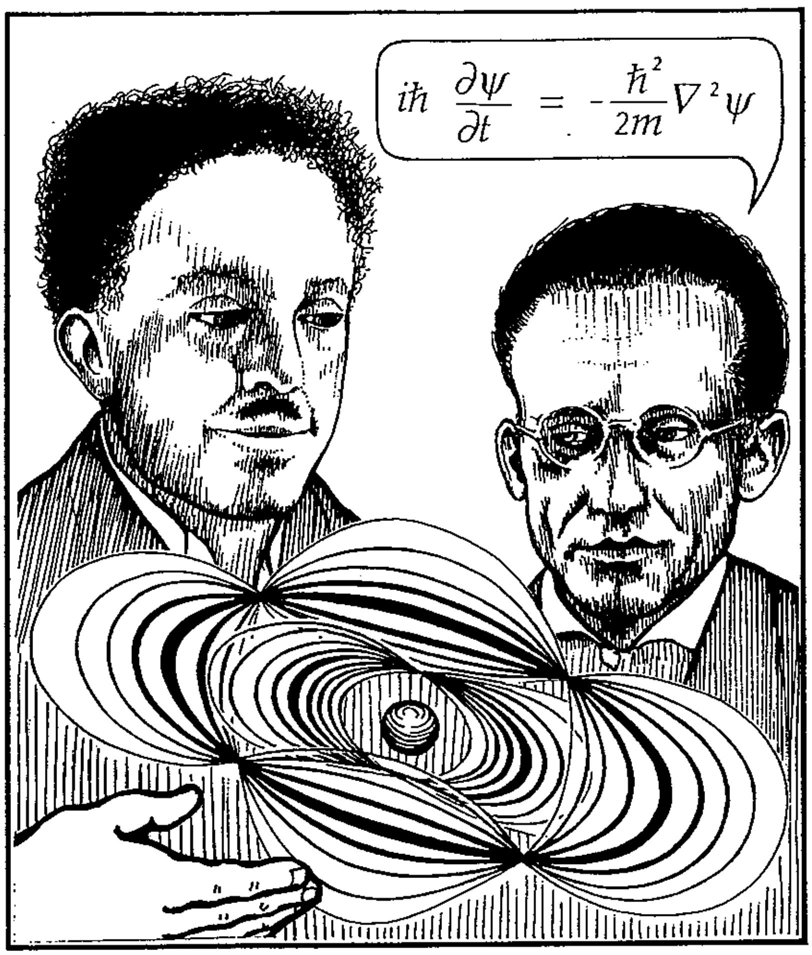
## Bohr (again)

Like a heated iron poker, heated hydrogen gas cools by giving off electromagnetic radiation. The energy thus carried away must be compensated for by a decrease in the kinetic energy of the gas. But the stability of hydrogen atoms implies, as Bohr noted, that there is a natural ground state below which the orbital energies of the electrons cannot be reduced. Moreover, the series of discrete wavelengths that Johann Balmer had found to be characteristic of the light emitted (or absorbed) by hydrogen implied, in agreement with Planck's radiation law and Einstein's photoelectric theory, that the kinetic energy levels between which the electrons in the hydrogen atoms could shift take on only certain discrete values. Bohr calculated that if these energy levels could only be multiples of Planck's constant, the previously mysterious Balmer series was immediately obtained. Each emitted wavelength was directly determined by the difference in energy between the two levels through which an electron could jump in the cooling of a thermally excited atom. It was an example of the kind of insight that, according to Bohr's onetime American associate John A. Wheeler, could lead Bohr to exclaim, "What fools we've been! We have only to recognize (such-and-such) and we see that absolutely everything has to be exactly as it is."

## de Broglie

A different second-order thought experiment led the French physicist Louis de Broglie to a possible mechanism for Bohr's new principle. De Broglie asked himself: What if not just photons, as proposed by Einstein, but all elementary particles have both a wave and a particle aspect? In imagining what would happen when the negatively charged "matter wave" of an electron was captured by a positive nucleus (Figure 2.9), de Broglie realized that the picture of a particle orbiting the nucleus in the manner of a planet circling the sun would have to be replaced by the picture of a standing wave surrounding the nucleus.

As I have schematically tried to suggest in my (oversimplified, two-dimensional) illustration, such a standing wave would necessarily consist of an integral number of oscillating lobes separated by stationary nodes around the nucleus -- much as the vibration of the string of Pythagoras's musical instrument equally divides the whole string into 1, 2, 3, etc. equal vibrating segments. And, somewhat as the different modes of vibration of a string give rise to the harmonic series of musical tones, spontaneous shifts between the alternative modes of vibration of an electron's matter wave would give rise to the Balmer series of spectroscopic lines. De Broglie had only to reinterpret the momentum of the electron as being proportional to the frequency of its wave (and, hence, to the reciprocal of its wavelength), with the factor of proportionality being, again, Planck's constant, h. The one-lobed, two-lobed, etc. modes of vibration thus constituted the lowest energy, next-higher energy, etc. states of the atom. The discrete values of the energies of emitted or absorbed quanta of radiation in Bohr's model thus found a more intuitive and less ad hoc explanation as shifts between modes of vibration.




*de Broglie and Schrödinger*
*imagine electron waves around a nucleus*

(Figure 2.9)

## Schrödinger

De Broglie's idea was soon taken up by the Austrian physicist Erwin Schrödinger who, while secluded in a cabin in the Alps, succeeded in formalized the intuitive idea into a full-blown "wave mechanics." The fundamental equation that Schrödinger derived has since proved so successful in accounting for atomic (and molecular) phenomena that it has acquired a status comparable to that long held by Maxwell's equations. Despite its predictive success, however, the ontological status of the wave described by Schrödinger's equation continues to be disputed. De Broglie (and, subsequently, David Bohm and his associates) regarded the wave as a physical disturbance that accompanies and somehow guides its associated point-like particle. Schrödinger hoped, instead, to replace the notion of a point-like particle altogether, with the equally physical but spatially extended wave itself (much as Maxwell had proposed to replace the light corpuscle of Newton by and electromagnetic wave). But Max Born, noting that while Schrödinger's wave spreads out in space, the physical detection of a photon only occurs at some localized point, argued that Schrödinger's equation does not describe any physical wave. Rather, declared Born, the equation is purely a calculational device for telling us, for each possible position and momentum of the point-like particle, an "amplitude" that, when squared, yields the probability that the particle would be found to have that particular position or momenum -- if the appropriate measurement operation were to be performed.

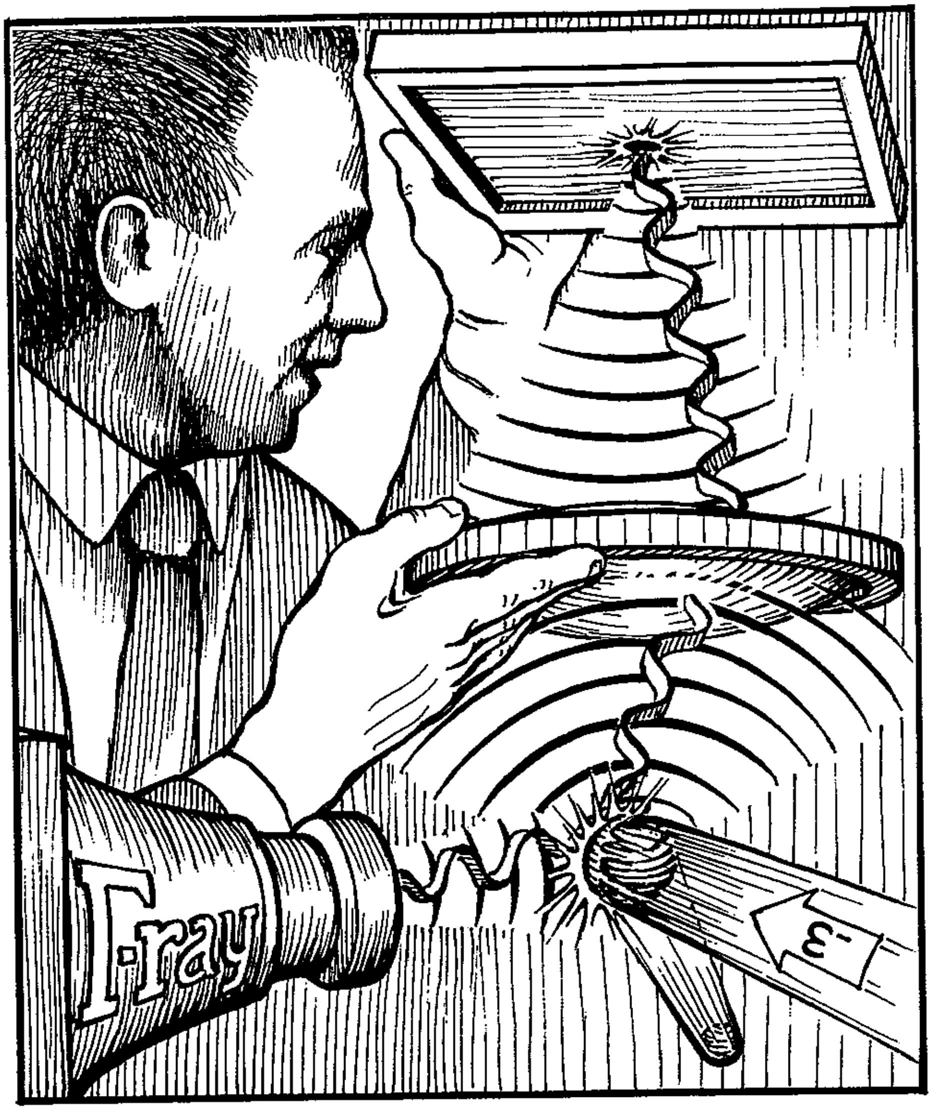
## Heisenberg

Independently seeking a mathematical basis for Bohr's atomic principles but based only on quantities that (unlike de Broglie and Schrödinger's hypothetical waves) were directly observable, the young German physicist Werner Heisenberg, while working in seclusion at an island retreat, had devised, through some combination of deparation, genius, and sheer luck, an entirely different "matrix mechanics." (Much as Einstein remarked that theories were the "free creations of the human intellect" guided by an intuitive "feeling for the order lying behind the appearance," Heisenberg said, "I must start not from detail but from ... a feeling I have about the way things should be.") Schrödinger later proved, however, that Heisenberg's matrix mechanics was in fact formally equivalent to his own wave mechanics. (In practice, Schrödinger's wave mechanics has continued to be used, often in preference to Heisenberg's matrix mechanics, because Schrödingers differential equation was more in the spirit of classical physics, more accessible to physical intuition, and, for many purposes, more amenable to computation.)

It was nevertheless Heisenberg who formulated the celebrated uncertainty principle, which has since served as an inviolate cornerstone of quantum mechanics. Moreover, he did this by performing a thought experiment. With regard to the nature and behaviors of such unseen entitites as waves and particles, physicists had found it tempting to think that if only they could actually observe what those shifty little miscreants were actually doing down there at the subatomic level, they could clear up the nagging puzzles posed by quantum phenomena. All right, said Heisenberg (in effect), let us imagine using a super microscope designed to observe an electron, so to speak, 'up close and personal' (Figure 2.10).

In the standard optical microscope (originally perfected by Hooke), an objective lense gathers the light scattered off a tiny object of interest and (usually with the aid of additional lenses) focuses that light on the image plane, where, by the time of Heisenberg, a photographic plate or other recording medium could be positioned. In principle, an electron, too, could be observed by means of the electromagnetic waves it scatters back. Unfortunately, however, the electron is much smaller than the wavelength of visible light. For this reason, a satisfactory image of the electron could be obtained only by probing it with electromagnetic energy of a much shorter wavelength -- shorter than that of ultraviolet light or even X-rays. The extremely short wavelengths of gamma rays would be required. But the energy of an electromagnetic wave varies directly with the frequency of the wave and, hence, inversely with its wavelength. As a consequence, a single gamma photon would pack enough punch to knock the electron right out of the microscope's "ballpark."

Worse, the speed and direction of the electron's recoil would depended on the exact position and momentum of the electron at the time of the collision, which were just the things that were to be determined by the observation. Hence, the motion of the electron would remain unknown. In short, we would have to make a choice: We might determine the electron's position at a given moment by probing it with high energy photons and thereby forfeit knowledge of its motion; or we might determine the electron's motion by probing it with long wavelength photons and thereby forfeit knowledge of its position. We could not determine both the position and the momentum of the electron. In quantitative terms, Heisenberg's mathematical analysis revealed that the product of the uncertainty ($\Delta x$) in determining the electron's location and the uncertainty ($\Delta p$) in determining the electron's momentum could never be reduced below Planck's constant, h, (formally, $\Delta p.\Delta x \geq h$).




*Heisenberg*
*imagines a microscope for observing an electron*
(Figure 2.10)

## Physical implications of quantum mechanics

Over the ensuing decades, the full formalization of quantum mechanics took shape bit by agonizing bit, through the titanic struggles of Bohr, Heisenberg, Schrödinger, Born, Pauli, Dirac, Feynman, and many others. The theory that has emerged, though not reconciled with general relativity even today, has led to the successful prediction -- if not of large things such as previously unknown planets -- of very small things such as previously unknown kinds of elementary particles, beginning with Dirac's positron and Pauli's neutrino. (It is relevant to note, incidentally, that Dirac's positing of the positron came as a result of his search for a generalization of Schrödinger's equation consistent with special relativity.)

Moreover, despite three-quarters of a century of more and more exacting tests, quantum mechanics has so far had its every prediction not only confirmed but confirmed to unprecedented and ever increasing levels of accuracy. Feynman made this precision vivid by noting that the emprically measured value of Dirac's magnetic moment for the electron was matched by its theoretically calculated value (even back in 1983) to within a theoretical uncertainty of only one part in several billion -- roughly the accuracy of specifying the distance between New York and Los Angeles to within the thickness of a human hair.

But the implications of quantum mechanics have proved to be at least as counterintuitive as those of relativity. The prevailing orthodox or "Copenhagen" view of quantum mechanics -- articulated principally by Bohr and Heisenberg, based on Heisenberg's uncertainty principle, Born's probability interpretation of Schrödinger's equation, and the conviction that nothing can be known about what cannot in principle be observed -- proclaims that we should not even consider a submicroscopic entity to possess such properties as position or momentum until its mathematical wave function is "collapsed" by an operation of physical measurement. Throughout the whole prior history of science, the world was always presumed to have a determinate state at each moment; it was only our lack of knowledge of that state that forced us to introduce probabilities into our theories. Now, for the first time, probabilities were taken to reflect an indeterminacy inherent in the physical world itself.

The original formulators of quantum theory all recognized the bizzare nature of the theory to which they were being driven. Bohr remarked that anyone who doesn't find quantum phenomena incomprehensible hasn't understood them. When Pauli, after proposing some ideas about subatomic phenomena, said "You will probably think that what I said is crazy," Bohr's response reportedly was, "Yes, but unfortunately not crazy enough." Heisenberg wrote that following one particularly agonizing late night discussion with Bohr, he took a long solitary walk during which he asked himself, again and again, "Can nature possibly be [this] absurd?" And Schrödinger, who balked at the suggestion that the deterministic waves described by his beautiful equation should be subject to unpredictable "collapse," lamented, "Had I known that we were not going to get rid of the damned quantum jumping, I never would have involved myself in this business." And Einstein never did accept the "spooky action at a distance" of quantum mechanics or its implication that, in Einstein's well known phrase, "God playes dice" with the universe. But now, after living with the enigmas of quantum mechanics for many decades, physicists have mostly come to accept them with some equanimity. In his lectures about quantum electrodynamics, Feynman even seemed to delight in saying, "You won't understand it. I don't understand it. Nobody does." So, "I hope you can accept Nature as She is -- absurd."

All of this poses, of course, a daunting challenge for the thesis I have been developing in these first two lectures. Because the principles governing the submicroscopic realm are so different from those familiar to us at the macroscopic level, many commentators have reasonably enough concluded that quantum mechanics could only have been forced on us by the results physicists unexpectedly obtained when they physically probed the submicroscopic realm. Surely, it seems, no mere thought experiments based on intuitions gained solely from past interactions with macroscopic objects could yield a clue as to the bizarre practices in which electrons and photons engage in the privacy of their subatomic domain.

Might it be, however, that this conclusion overlooks the "bootstrapping" to knowledge that may be possible through a conjunction of second-order thought experiments and the search for over-all mathematical consistency. In the library of the Santa Fe Institute (where I was preparing a draft of this lecture), I came across a 1979 book by Sir Rudolf Peierls, an eminent theoretical physicist (and former associate of Bohr). The title, "Surprises in Theoretical Physics," seemed to bode ill for my thesis. Opening the book with some trepidation, however, I was myself surprised to find, right there in the Preface, a statement that nicely echoed Bohr's own exclamation, "Everything has to be exactly as it is!" For, Peierls warns the reader, "all the surprises I discuss have rational explanations, and these are mostly very simple ... In other words, we should not have been surprised if only we had thought sufficiently deeply about our problem in advance."

## A possible least-action path to quantum mechanics

When (at the Santa Fe Institute) I suggested that even quantum mechanics might be guessed at through thought alone, visiting astrophysicist Piet Hut (from the Princeton Institute for Advanced Study), ventured that one route to such a guess might be through the principle of least action. As I have already noted, the most fundamental constant of quantum mechanics, Planck's constant, has the units of action -- energy times time. (Technically, action is the "space integral" of the total momentum of a system from one time to another.) Remarkably, more and more of physics has been found to be derivable from the single principle that any system evolves over time in such a way as to minimize its total action during that time. The principle has a long history -- beginning in 1658 with Fermat's least-time principle for light, and continuing through Maupertuis's (1747) least-effort principle for mechanics, Hamilton's more general least-action principle (also known as Hamilton's Principle), Einstein's minimum-length principle for the (geodesic) world lines of light and of material bodies in four dimensional space-time, to a grand culmination in the quantum-mechanical formalisms of Schwinger, Tomonaga, and Feynman. Indeed, the similarity between Fermat's principle in optics and Hamilton's principle in mechanics contributed to the later quantum-mechanical idea that matter might have, just as light, a wave aspect.

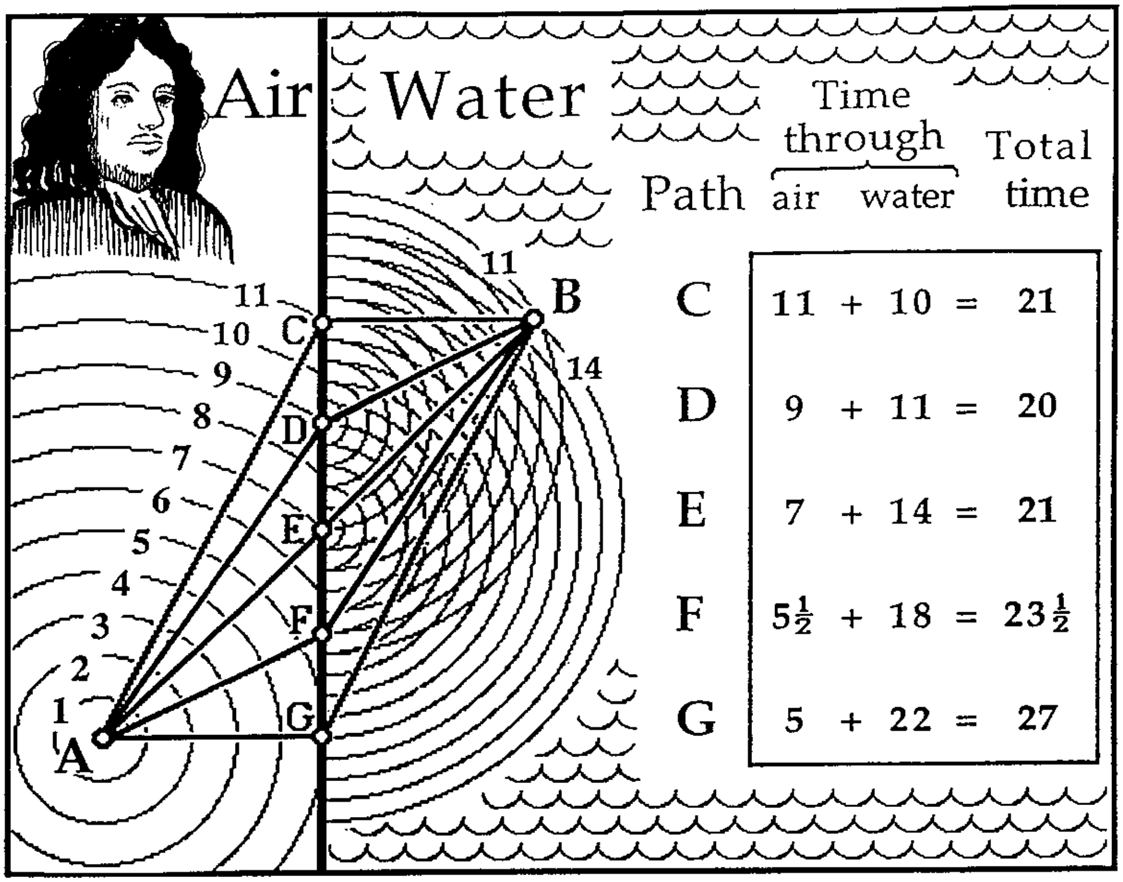
In the standard conception of physical theories, as I have so far presented them here, the evolution of a system over time is determined by two things. One is the set of boundary conditions taken to specify the initial state of the system and any prevailing external forces (such as a local gravitational or magnetic field). The other is the fixed set of laws (as formalized in Newton's, Maxwell's, or Schrödingers differential equations) assumed to govern the deterministic evolution of the system from each state to its immediately succeeding state, starting from any given initial state. Thus the preceding state and the prevailing boundary conditions are taken together to constitute the complete cause of each new state.

In contrast, the least-action conception has a quite different, teleological character reminiscent of Aristotle's "final cause." Instead of starting just with a given state, A, and asking what subsequent state will evolve from that state at any specified later time, we start with both the given state, A, and a goal state, B, into which the system does in fact evolve and we ask what path the system takes in reaching that goal state. The remarkable fact is that the system always "selects" (so to speak) the unique path that minimizes the total action. Fermat's original least-time principle, which explains the angles through which light is refracted as it passes from each medium to the next, affords a simple illustration that admits both the standard causal and the teleological interpretation (Figure 2.11).

Fermat imagined light traveling, from a point A in a rarified medium (say air) to a point B in a denser medium (say water). Supposing that light travels through the denser medium with (for example) just half its velocity through the tenuous medium, he finds that the quickest path from A to B is not the shortest, straight path AEB but the longer, bent path ADB. The reason is simple: The wave front of a pulse of light emitted at A expands outward during successive equal time intervals through the concentric circles labelled 1, 2, 3, ... on the left of the figure, thus reaching the interface with the denser medium at point G, F, E, D, and C after (let's say) 5, 5 $^1/_2$ , 7, 9, and 11 time units, respectively (in agreement with the concentric circles). Following Huyghens, Fermat could then imagine that from each of those interface points at its corresponding time, a new wave front begins expanding in the denser medium (as illustrated just for the two points E and D). But, because the wave fronts in the denser medium expand only half as rapidly, the concentric circles which they reach at successive time intervals will be separated by just half the distance of those in the more tenuous medium. The times to B from C, D, E, F, and G would accordingly be 10, 11, 14, 18, and 22, respectively -- just twice the previous values (as confirmed in the figure by the circles around D and E). As tabulated at the right, then, the total light travel times from A to B over the paths through C, D, E, F, and G would be 21, 20, 21, 23 $^1/_2$ , and 27 units, respectively. The shortest time (20 units) is thus for the bent path via D.

As given, this causal account is not complete, however. It leaves the impression that the arrival at B of the light pulse over the quickest path via D will be followed by the arrivals of luminous pulses over all other possible paths with corresponding delays (of, for example, 1, 1, 3 $^1/_2$ , and 7 time units for paths through C, E, F, and G). In fact, no such delayed pulses are detected at B. The light waves over the alternative paths mutually interfere in just such a way that only the wave that traverses the least-time path through D survives to reach B uncanceled.

The teleological interpretation is quite different. Recurring to an analogy that I remember once seeing somewhere, we can think of a lifeguard on the beach at A who spots a swimmer desparately flailing in the water at B. To minimize the time to reach the distressed swimmer, the lifeguard should not take the spatially shortest path through the point E at the water's edge. Instead, if the lifeguard can run, let's say, twice as fast through air as swim through water, she should run to the point D and then swim the shorter distance to the goal B. (If the ratio between the velocities in the first and second media is not just 2-to-1 but becomes infinitely large or small, the least-time path will approach the limiting points C or G, respectively, each minimizing the distance through whichever is the slower medium.)




*Fermat*

*imagines alternative light paths from A to B*

(Figure 2.11)

The teleological account becomes more compelling in the general case in which the total action is not simply equivalent to the total time. When, for example, a material body (whether a pendulum, planet, or hurled apple) moves in accordance with Newton's laws, the total energy (expressible as the kinetic energy plus the potential energy) remains constant, but the action (expressible, now, as the kinetic energy minus the potential energy) varies from moment to moment. Yet, the motion of the pendulum, planet, or apple is always that one for which the total action, integrated along the path of motion between the beginning and end states, is the minimum possible. It is as if the physical system itself first performs "thought experiments" of moving over each possible path to the end state and then elects actually to traverse the one path to that goal that would require the least total effort.

Quantum mechanics, though introducing a probabilistic indeterminism, preserves this teleological quality. We cannot say that a particle (such as an electron) emitted at A and then detected at B took any particular path (such as through one rather than the other of two slits in an intervening screen). It is tempting to say, rather, that a proxy wave corresponding to the emitted particle simultaneously "explored" all possible paths from A and then, based on the resulting interference pattern, "opted" to gather itself together and to deposit all its energy at the single point B -- with probability computed, in accordance with Feynman's "sum over paths" method, as the square of the sum of the amplitudes for all paths leading to B. Thus it is not just light that comes only in discrete packets (as stumbled upon by Planck and embraced by Enstein). All action comes in irreducible quanta.

Is it not possible, then, that a sufficiently intelligent being could arrive at the basic ideas of quantum mechanics, in the absence of an experimental probing of the subatomic domain, through a combination of analogical reasoning, bold conjecture, and mathematical analysis? The essential insights might include the following:

•Light is a kind of wave, exhibiting phenomena of propagation and interference analogous to the familiar phenomena of water waves on the surface of a pond.

•This wave hypothesis explains the way in which light is refracted on passing from one medium to another (as well as other phenomena, including Newton's rings).

•Material particles obey a least-action principle directly analogous to that governing the refraction of light; hence, such particles may have a similar wave-like character.

•Much as there are irreducible atoms of matter (as suggested by the original thought experiment of Democritus) there may also be irreducibe "atoms" or quanta of action.

•A submicroscopic system may therefore evolve like a wave propagating through all possible paths in parallel, but (assuming that action is irreducibly quantal) yield a macroscopically observed event that is necessarily discrete, localized, and unitary.
•Such an event can therefore be only probabilistically determined by the distributed wave pattern, with the possibility for each alternative observable event given by the "amplitude" of the interferring wave pattern for that corresponding event.

## Psychological implications of quantum mechanics

Implications for the nature of mind and its relation to the world arise most clearly from those interpretations of quantum mechanics (currently taken for granted by most working physicists) that assign a fundamental and indispensable role to the observer. The orthodox Copenhagen interpretation, in particular, conceptually divides the world into two distinct realms: the observable realm of familiar macroscopic objects, including the instruments, photographic plates, bubble chambers, scintillation counters, and the like that physicists use in detecting submicroscopic events; and the unobservable realm of those submicroscopic events themselves. Three basic tenets of the Copenhagen interpretation are, first, that the macroscopic instruments are describable in the terms of classical (pre-quantum-mechanical) physics; second, that nothing can be known about the submicroscopic events beyond the macroscopic photographic images, bubble tracks, scintillation counts, etc. recorded by these macroscopic instruments; and third (in accordance with Bohr's "correspondence principle"), that the quantum mechanical laws proposed to predict such observable events must yield the laws of classical physics as a suitable limit (as when the system under consideration is large enough that the value of Plank's constant h, though nonzero, has negligible effect).

The hungarian-born mathematician John Von Neuman provided a mathematical formalization of quantum mechanics based on this interpretation in which it is the operation of observation or measurement that results in the so-called "collapse" of Schrödinger's wave equation (or, in von Neuman's terms, the reduction of the quantum mechanical state vector in infinite-dimensional Hilbert space). But according to this formalization, the alternative outcomes of the observation or measurement exist only as an abstract linear superposition of possibilities until the moment of the collapse into one concrete alternative. Exactly where the division between the quantum mechanical and the classical and, hence, exactly where this irreducibly probabilistic collapse takes place in the long chain of events leading from the submicroscopic process, through the emergence, say, of alternative spots on the photographic plate, to the registration of only one of these alternative spots in the mind of the physicist who inspects the plate is not, however, specified by von Neuman's formalism.

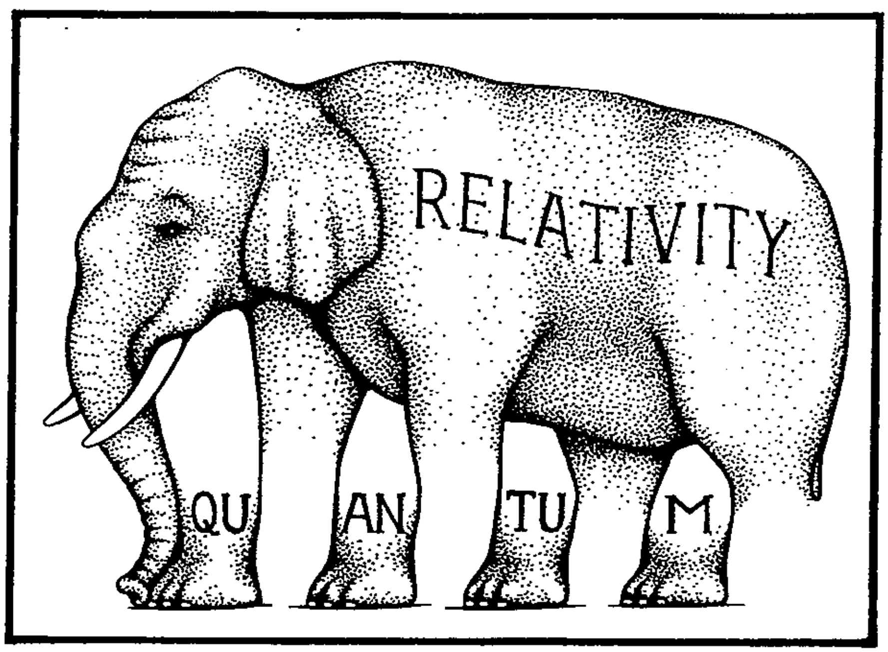
Ironically, when Eugene Wigner (another hungarian-born theorist and major contributor to the mathematical formulation of quantum mechanics) took von Neuman's analysis of the most widely accepted interpretation of quantum mechanics to what seems to be its logical conclusion, the conclusion was not one that most quantum theorists were willing to embrace. Arguing that the only nonarbitrary point in this causal chain is where it crosses from the physical realm into the mental, Wigner proposed that the purely physical realm (whether microscopic or macroscopic) evolves purely deterministically, in accordance with Schrödinger's wave equation, as a superposition of possibilities; and that the collapse of the wave function to one concrete alternative (out of these possibilities) is an inherently mental event. Not surprisingly, few physicists were ready to concede that physics may reduce in this way to psychology. Many also pointed out that Wigner's proposal raises questions of exactly what mind is required to precipitate the collapse of the wave function. (Must it be the mind of the physicist who happens first to inspect the plate? Could it be the physicists young child, who looked first, though knowing nothing of what the alternative spots might mean? Could it be a fly that visually registered the spot while buzzing past the apparatus? Or could it be a robot that had been programed to monitor the apparatus and record the outcome of the measurement?) But other alternative interpretations of quantum mechanics, such as the "relative state" or "many worlds" interpretation of Hugh Everett (and his followers), or its related "many minds" interpretation, or the hidden variable or pilot-wave interpretation of Bohm (and his associates) have so far not gained universal acceptance either. I must leave further consideration of the connections between quantum mechanics and mind for my final lecture. I hope I have said enough to suggest, at least, the relevance of such further consideration.

## A Theory of Everything?

Time and again, it has been tempting to think that the basic laws of the universe were almost within our grasp. After Newton's mechanics, after the addition of Maxwell's electrodynamics, and again after the replacement of those theories by relativity and quantum mechanics, it seemed that we might be close to a "theory of everything." Each time, however, further thought experiments revealed inconsistencies between our best theories, or between them and familiar but previously ignored facts about the world. And each time, the inconsistencies could be removed only by yet another major theoretical reconceptualization.

True, no empirical violation of predictions has yet been reported for either of our currently two best theories: general relativity and quantum mechanics. But, neither has anyone succeeded in reconciling these two theories with each other. Attempts at a unified theory have so far entailed irrepressible infinities. Furthermore, whereas the standard formulations of quantum mechanics have presupposed a fixed spacetime geometry, if that geometry is to be the basis of gravitation (as required by general relativity), then quantum mechanics requires that that geometry itself be subject to quantum fluctuations -- leading to a difficult circularity that no one has yet seen how to break.

Einstein once characterized someone's grand but (in Einstein's estimate) not very well grounded theory as resembling "a stately statue of a horse with one leg." In a similar vein, however, we could say of the entire present edifice of theoretical physics, that while Einstein's own general theory of relativity is like the body of a magnificent elephant supported on the four well grounded legs of quantum mechanics (Figure 2.11), the interconnection between the body and the legs remains problematic.




*L'egs-istential quandary of relativity & quantum mechanics*

(Figure 2.12)

Presumably, a more inclusive and self-consistent theory is possible. The world that has so far failed to reveal any discrepancy from the predictions of either theory does exist! If, as we have been led to hope from past successes, the world is ultimately governed by laws, those laws, like the world itself, must be mutually consistent. As Newton once remarked, "Those things which men understand by contradictious phrases may be ... in nature without any contradiction at all." Given the conservative nature of scientific revolutions, such a more general theory would be expected to subsume the two theories as special cases -- just as quantum mechanics subsumed classical physics as the special case in which Planck's constant h is taken to be zero, just as general relativity subsumed special relativity as the special case in which mass/energy density is taken to be zero, and just as special relativity subsumed Newtonian mechanics as the special case in which the speed of light is taken to be infinite. Nevertheless, the reconciliation of general relativity and quantum mechanics may require a reconceptualization (possibly in some form of superstring theory) as great as the reconceptualizations that originally led to the theories of relativity and quantum mechanics themselves.

## Unexplained phenomena

Moreover, there are still (as there have been all along) some highly salient and undeniable facts that appear to remain unaccounted for by all physical theories that have so far been proposed, including those of relativity and quantum mechanics. These facts include the qualitative "feels" of conscious experience -- such subjective qualia as colors, pains, and pleasures (which seem irreducible to any such things as particles, waves, or space-time curvatures). Then, too, there remains what is surely the most staggering of all facts: that rather than just nothingness, there exists anything at all -- let alone the incomprehensibly vast, possibly infinite, universe of galaxies that glimmer ever more faint, red-shifted, and numerous out to the limits of our largest telescopes. But, although I find some of these facts to be as undeniable as any, I must defer what little I am able to say about them to my last lecture.

For now, I note only that successive major theoretical reconceptualization have become, in Einstein's words "steadily more abstract and remote from experience." Correspondingly, the thought experiments needed for further advances become more and more difficult for the brains furnished to us by our evolution on earth. It is not therefore surprising that "the human race is poor in independent thinking and creative imagination," as Einstein remarked. Possibly our meagre endowment will ultimately suffice to enable us to converge on one consistent "system of the world," "wave function of the universe," or "theory of everything." At present, however, we cannot rule out the possibility that in what Einstein has described as our "struggle for a complete and unitary penetration of natural events by thought," our search for an overall consistent theory will only take us deeper and deeper into what John Wheeler once envisioned as "wheels within wheels, caverns measureless to man, world without end."

## Thought Experiments and the Mind

In these first two lectures I have explored the possibility that the most fundamental principles we have so far discovered behind the "rebellious appearances" of physical reality are discoverable through thought alone. But how does the mind come by this mysterious power to gain knowledge about the external world merely by thinking about it? There are two ways in which thought experiments may be able to inform us about the mind. First, just as thought experiments about the physical world have helped us to formulate consistent theories of the physical world, thought experiments about the mind may help us to formulate consistent theories of the mind. I defer consideration of this possibility to my last lecture. Second, if thought experiments (of the sort I have already been considering) can yield true knowledge about the physical world, without actually making observations or performing experiments on that external world, this must imply something quite significant about the mind. In my next lecture, I address the question of how the human mind -- in apparently flagrant violation of the central tenet of empiricism -- came to have the power of discovering principles governing the physical world through thought alone.