1. SCIENCE AND HUMAN VALUES.

This book is about what you are, and how you are connected to that which you are not. It is about the impact of the revolutionary developments in physics during the twentieth century upon science's idea of you as a thinking and acting entity, and your linkage to 'the other'.

These questions might appear to belong more to philosophy, metaphysics, or religion, rather than to physics, which is usually assumed to deal only with such tangible items as machines, rockets, transistors, and atomic bombs. But the radical change in our understanding of the physical world that occurred during the twentieth century has transformed connections that formerly had been matters of pure philosophical speculation into issues covered by basic physical theory. The aim of this book is to explain this new idea of the nature of human beings and their causal role in the unfolding of reality to readers with no prior understanding of the quantum character of the world.

Science has improved our lives in many ways. It has lightened the load of tedious tasks and expanded our physical powers, and thereby contributed to a great flowering of human creative energy. On the other hand, it has also given us the capacity to ravage the environment on an unprecedented scale and obliterate our species altogether. Yet along with this fatal power it has provided a further offering which, though subtle in character and still hardly felt in the minds of men, may ultimately be its most valuable contribution to human civilization, and the key to human survival.

Science is not only the enterprise of harnessing nature to serve the practical needs of humankind. It is also part of man's unending search for knowledge about the universe and his place within it. This quest is motivated not solely by idle curiosity. Each of us, when trying to establish values upon which to base conduct, is inevitably led to the question of one's role in nature. The linkage of this philosophical inquiry to the practical question of personal values is no mere intellectual abstraction. Martyrs in every age are vivid reminders of the fact that no influence upon human conduct, even the instinct for self preservation, is stronger than beliefs about one's relationship to the power that shapes the universe. Such beliefs form the foundation of a person's self image, and hence, ultimately, of that person's values.

It is often claimed that science stands mute on questions of values: that science can help us to achieve what we value once our priorities are fixed, but can play no role in fixing these weightings. That claim is certainly incorrect: science plays a key role in these matters. For what we value depends on what we believe, and what we believe is increasingly determined by science.

A striking example is the impact of science upon the system of values promulgated by the church during the Middle Ages. That structure rested on a credo about the nature of the universe, its creator, and man's connection to that creator. Science, by casting doubt upon that belief, emasculated the system of values erected upon it. Moreover, it put forth a credo of its own. In that "scientific" vision we human beings were converted from sparks of divine creative power, endowed with free will, to automatons---to cogs in a giant machine that grinds inexorably along a preordained path in the grip of a blind mechanical process.

Gone from this "scientific" picture of our species is any rational basis for the notion of a person's responsibility for his own actions. Each of us is asserted to be a mechanical extension of what existed prior to his birth. Over that earlier situation one has no control. Hence for what emerges, preordained, from that prior state one can bear no responsibility.

Given this conception of man, the collapse of moral philosophy is inevitable. This notion of human beings provides no rational basis for any value but self interest: behavior promoting the welfare of others, including future generations, becomes rational only to the extent that such behavior serves one's own interests. Hence science becomes doubly culpable: it not only undermines the foundations of earlier value systems, but also strips man of any vision of himself and his place in the universe that could be the rational basis for any elevated set of values.

This mechanical picture of man is the image created by the science that reigned early in the twentieth century. According to that view the physical universe is composed of tiny separate bits of reality, and the unfolding, or evolution in time, of nature is completely fixed by direct contact interaction between these localized microscopic parts. Human beings, insofar as they belong to this physical aspect of nature, are simply conglomerations of these elemental material bits.

During the twentieth-century this simple picture of nature was found to be profoundly wrong: it failed not just in its fine details, but at its fundamental core. In place of the old idea Heisenberg, Bohr, Pauli, and their companions erected a vastly different conceptual framework. They were forced to a radical alteration of the very subject matter of physical theory itself by the strange character of the new mathematical rules, which were invariably validated by reliable empirical data.

The new theory accounts in a uniform manner for all the successes of the earlier physical theories, plus the immense mass of new data where the earlier methods fail abysmally. However, it describes a world built not out of bits of matter, as matter was understood in the nineteenth century, but rather out of bits of information. Straightforwardly interpreted, the quantum rules describe a universe composed of *a new kind of stuff,* whose properties combine features formerly conceived to be imbedded in the physical world with aspects that belong to our streams of conscious thoughts.

The laws that govern the evolution of the world over the course of time differ significantly from the pre-twentieth century idea of these rules. According to the new physics, this evolution is specified not by a single causal process but rather by an interplay between two very different ones. The first of these is analogous to the operation that fixes the development of the material world in classical physics, and it is “locally deterministic”: what occurs at any point is completely fixed by what has just happened at nearby points. But that local rule is not the whole story. At certain instants a *second kind of process* intervenes: a “quantum jump” occurs. This intervention is highly non-local: it involves, in a well specified way, coordinated changes in regions that can lie far apart. The structure of these abrupt changes are mathematically similar to sudden increases in knowledge or information. Indeed, the original, and still orthodox, “Copenhagen” interpretation of quantum theory associates each quantum jump with an actual increase in somebody’s knowledge. Thus our basic scientific theory of the physical world, in its orthodox formulation, has become intrinsically entwined with our streams of conscious knowings.

The existence of this “second process” provides a reprieve from the classical-physics verdict that human thoughts and feelings can make no difference in the flow of physical events. The new theory involves choices that are not determined by any currently known law of nature, but can nevertheless strongly influence the course of physical events. This means that contemporary science accommodates causally efficacious free will. The new physics allows, and in fact demands, the occurrence of happenings that, on the one hand, are fixed by no known law, yet, on the other hand, can influence in mathematically determined ways, both the unfolding of our thoughts and the course of our actions. The details of how this influence works match beautifully with the empirical findings that have accumulated over the past few decades in the field of The Psychology of Attention.

The potency and novelty of the new dynamics both stem directly from the property of “quantum entanglement”, and the closely related feature called “quantum nonlocality”. Entanglement is the property of two (or more) systems that have strongly interacted with each other but then moved far apart, to become, according to the theory, a single unified entity until observations are made that re-establish independent properties for the spatially separated parts.

This entanglement feature leads to the remarkable property of *non-locality*: no theory of nature can both accommodate the predictions of quantum theory and confine all influences of free choices to regions that can be reached by traveling no faster than light.

The upshot of these radical changes is this: Taken at face value, the new mathematical description of the universe portrays a world in which your mind can by free-willed actions influence, although not completely control, what happens in your body/brain. This participatory view contrasts starkly with the earlier science-based image of the human person as a conglomeration of atoms being mindlessly buffeted about by the chance collisions of atoms.

What impact, if any, can this altered idea of what you are have upon your life? Does not a completely rational approach still lead you to value only your own well being? Perhaps so! But this leads to the further question: What is the self whose well being one values?

Values arise from self-image. Generally one is led by training, teaching, propaganda, or other forms of indoctrination, to expand one’s conception of the self: one is encouraged to perceive oneself as an integral part of some social unit such as family, ethnic or religious group, or nation, and to enlarge one’s self-interest to include the interests of this unit. If this training is successful your enlarged conception of yourself as good parent, or good son or daughter, or good Christian, Muslim, or Jew, causes you to give weight to the welfare of the unit as you would yourself. In fact, if well conditioned you may give more weight to the well-being of the group than to that of your bodily self.

In the present context it is not relevant whether this human tendency to enlarge one’s self image is a consequence of natural malleability, instinctual tendency, spiritual insight, or something else. What is important is that we human beings do in fact have the capacity to expand our image of "self", and that enlarged concept can become the basis of a drive so powerful that it becomes the dominant determinant of human conduct, overwhelming every other factor, including even the instinct to survive.

But where reason is honored, belief must be reconciled with empirical evidence. If you seek evidence for your beliefs about what you are, and how you fit into nature, then science claims jurisdiction, or at least relevance. Physics presents itself as the basic science, and it is to physics that you are told to turn. Thus a radical shift in the physics-based conception of man from that of an isolated mechanical automaton to that of an integral participant in the nonlocal process that gives form to the evolving universe is a seismic event of potentially momentous proportions.

The quantum concept, being based on objective science equally available to all, rather than arising from special personal circumstances, has the potential of providing a universal system of values suitable to all people, without regard to the accidents of their origins. With the diffusion of this Quantum Conception of Human Beings, science may fulfill itself by adding to the material benefits it has already provided a philosophical insight of perhaps greater ultimate value.

This issue of the connection of science to values can be put into perspective by seeing it in the context of a very brief historical account. For this purpose let human intellectual history be divided into five periods: traditional, modern, transitional, post modern, and contemporary.

During the “traditional” era our understanding of ourselves and our relation to nature was based on “ancient traditions” handed down from generation to generation: “Traditions” were the chief source of wisdom about our connection to nature. The “modern” era began in the seventeenth century with the rise of what is still called “modern science”. That approach was based on the ideas of Bacon, Descartes, Galileo and Newton, and it provided a new source of knowledge that came to be regarded by many thinkers as more reliable than tradition.

The basic idea of modern science was “materialism”: the idea that the physical world is composed basically of tiny bits of matter whose contact interactions with adjacent bits completely control everything that is now happening, and that ever will happen. According to these laws, as they existed in the early twentieth century, a person’s conscious thoughts and efforts can make no difference at all to what his body/brain does: whatever you do was deemed to be completely fixed by local interactions between tiny mechanical elements, with your thoughts, ideas, feelings, and efforts being a strictly determined high-level consequence of the low-level mechanical process.

This materialist conception of reality began to crumble at the beginning of the twentieth century with Max Planck's discovery of the quantum of action. Planck announced to his son that he had, on that day, made a discovery as important as Newton's.

That assessment was certainly correct: the ramifications of Planck's discovery were eventually to cause Newton's materialist conception of physical reality to come crashing down. Planck's discovery marks the beginning of the "transitional" period.

A second important transitional development soon followed:

In 1905 Einstein announced his Special Theory of Relativity. It denied the validity of our intuitive idea of the instant of time "now", and promulgated the thesis that even the most basic quantities of physics, such as the length of a steel rod, and the temporal order of two events, had no objective "true values", but were well defined only "relative" to some observer's point of view.

Planck's discovery led by the mid twenties to a complete break-down, at the fundamental level, of the material conception of nature. A new basic physical theory was developed, principally by Werner Heisenberg, Niels Bohr, Wolfgang Pauli, and Max Born, and it brought "the observer" explicitly into physics. The earlier idea that the physical world composed in part of tiny particles was abandoned in favor of a theory of natural phenomena in which the consciousness of the human observer is ascribed an essential and independent role. This successor to classical physical theory is called "Copenhagen quantum theory".

This turning away by science itself from the tenets of the objective materialist philosophy lent support to Post-Modernism. That view, which emerged during the second half of the twentieth century, promulgated, in essence, the idea that all "truths" were relative to one's point of view, and were mere artifacts of some particular social group's struggle for power over competing groups. Thus each social movement was entitled to its own "truth", which was viewed simply as a socially created pawn in the power game.

The connection of Post-Modern thought to science is that both Copenhagen Quantum Theory and Relativity Theory had retreated from the idea of observer-independent objective truth: science in the first quarter of the twentieth century had not only eliminated materialism as a possible foundation for objective truth, but had discredited the very idea of objective truth in science. Yet if the community of scientists have renounced the idea of objective truth in favor of the pragmatic idea that "what is true for us is what works for us,” then every group becomes licensed to do the same, and the hope evaporates that science might provide objective criteria for resolving contentious social issues.

This philosophical shift has had profound social ramifications. But the physicists who initiated this mischief were generally too interested in practical developments in their own field to get involved in these philosophical issues. Thus they failed to broadcast an important fact: already by mid-century, a development in physics had occurred that provides an effective antidote to both the ‘materialism’ of the modern era, and the ‘relativism’ and ‘social constructionism’ of the post-modern period. In particular, John von Neumann developed, during the early thirties, a form of quantum theory that brought the physical and mental aspects of nature together as two aspects of a rationally coherent whole. This theory was elevated, during the forties---by the work of Tomonaga and Schwinger---to a form compatible with the physical requirements of the Theory of Relativity.

Von Neumann’s theory, unlike the transitional ones, succeeded in integrating into one coherent idea of reality the empirical data of subjective experience with the basic mathematical structure of theoretical physics. Von Neumann’s formulation of quantum theory is the starting point of all efforts by physicists to go beyond the pragmatically magnificent but ontologically incoherent Copenhagen form of quantum theory.

Von Neumann capitalized upon the key Copenhagen move of bringing human knowings into the theory of physical reality. But, whereas the Copenhagen approach excluded the bodies and brains of the human observers from the physical world that they sought to describe, and renounced the aim of describing reality itself, von Neumann demanded logical cohesion and mathematical precision, and was willing to follow where this rational approach led. Being a mathematician, fortified by the rigor and precision of his thought, he seemed less intimidated than his physicist brethren by the sharp contrast between the nature of the world called for by the new mathematics and nature of the world that the genius of Isaac Newton had concocted.

The common core feature of Copenhagen and von Neumann quantum theory is the incorporation of human knowings into the structure of basic physical theory. How this is done, and what the consequences are, is the subject of this book. But before plunging directly into this topic I shall say a little more about knowings.

2. Knowings

What are you made of? What is reality made of? What does intuition say about this? What does science say?

The deliverance of intuition on these matters is not unambiguous. Western science and philosophy begins with Thales of Miletus, who proclaimed "All is Water!". Other Greeks believed the primordial stuff to be "Air", or "Earth", or "Fire", and Empedocles settled on all four. On the other hand, Leucippus and Democritus thought everything was composed of tiny invisible, immutable atoms. Two millennia later, it looked like the two atomists had gotten it right: Isaac Newton built his sixteenth-century theory of the universe on the idea of enduring miniscule particles, and John Dalton's atomic hypothesis explained many facts of chemistry.

This notion that everything is composed of small bits of matter encountered, however, a serious difficulty. The earlier idea that "air" was a primary ingredient allowed soul or spirit to be construed as constructed out of one of the primitive substances. But it was hard to see how such a thing as a sensation of the color "red" or "green", or a feeling of "pain" or "joy" could be fully described in terms of a collection of tiny immutable bits of matter careening through space. Given even supreme knowledge and comprehension, how could the motions of billions of particles in a person's brain/body be understood to be the very same thing as a conscious sensation, or the *feeling* associated with the grasping of an idea? One can understand all manner of motions of objects, and of their changing shapes, in terms of the motions of their constituent parts, but there is a rationally unbridgeable gap between the purely geometrical concepts of motions of particles in space and the psychological realities of conscious sensations, feelings, and ideas.

Isaac Newton built his theory upon the ideas of the French philosopher Rene Descartes, who resolved this dilemma concerning the psychological realities by conceiving nature to be built out of two sorts of substances: "matter", which was located in and occupied space, and the "mental stuff" that our thoughts, sensations, and feelings are made of.

This sundering of nature worked well in science for more than two hundred years, but was abandoned by physicists during twentieth century. The old idea that the material part of nature is made out of tiny bits of reality whose changes are completely fixed by the prior state of the nearby physical stuff---independently of mind---was replaced by a very different picture. Once it became clear that the old notions could not account for the growing mountain of data concerning the properties of the atoms and their parts the focus shifted to what the experiments were actually telling us. This opened the door to a new approach that dealt directly with *what we could find out* about the systems being examined, rather than with the system itself. An incredibly beautiful and rationally coherent new kind mathematical structure eventually revealed itself, but this new mathematics was understood to describe not a self-sufficient physical reality that can exist independently of all minds, but rather our human knowledge of a reality in which our mental activities reside.

This original way of conceiving and applying the quantum mathematics was created by a group of physicists working closely with the Danish physicist Niels Bohr, and is called the "Copenhagen interpretation". This approach was closely tied to actual experimental procedures, which involve in the end the human experimenters who design the experiments with some purpose in mind, and later record and interpret the results of their investigations. This practical formulation of the theory defines the way the mathematical structure is used operationally, and is the touchstone of all later efforts to retain the original predictive power of the quantum rules, while expanding their scope into the domains of cosmology and neuro-dynamics.

The foundation of all attempts to increase the scope of the theory is the work of the great Hungarian mathematician and logician John von Neumann. But before going on to describe von Neumann's contribution it will be helpful, and also fascinating, to appreciate the tremendous change in outlook instituted already by Werner Heisenberg, Niels Bohr, Wolfgang Pauli, and the other founders. For their insights are preserved and expanded in the work of von Neumann.

In the introduction to his book "Quantum theory and reality" the philosopher of science Mario Bunge (1967) said:
"The physicist of the latest generation is operationalist all right, but usually he does not know, and refuses to believe, that the original Copenhagen interpretation---which he thinks he supports---was squarely subjectivist, i.e., nonphysical."

Let there be no doubt about this point. The original form of quantum theory, which is still alive today, is subjective: it is about relationships among conscious human experiences, and it expressly recommends to scientists that they resist the temptation to try to understand the underlying processes of nature that are responsible for the connections between our experiences that the theory correctly describes. The following brief collection of quotations by the founders give a conspectus of the Copenhagen philosophy:

Heisenberg (1958a): "The conception of objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept but into the transparent clarity of a mathematics that represents no longer the behavior of particles but rather our knowledge of this behavior."

Heisenberg (1958b): "...the act of registration of the result in the mind of the observer. The discontinuous change in the probability function…takes place with the act of registration, because it is the discontinuous change in our knowledge in the instant of registration that has its image in the discontinuous change of the probability function."

Heisenberg (1958b:) "When the old adage `Natura non facit saltus' is used as a basis of a criticism of quantum theory, we can reply that certainly our knowledge can change suddenly, and that this fact justifies the use of the term `quantum jump'. "

Wigner (1961): "the laws of quantum mechanics cannot be formulated...without recourse to the concept of consciousness."

Bohr (1934): "In our description of nature the purpose is not to disclose the real essence of phenomena but only to track down as far as possible relations between the multifold aspects of our experience."

Bohr (1963): "Strictly speaking, the mathematical formalism of quantum mechanics merely offers rules of calculation for the deduction of expectations about observations obtained under well-defined classical concepts."

Bohr (1958): "...the appropriate physical interpretation of the symbolic quantum mechanical formalism amounts only to prediction of determinate or statistical character, pertaining to individual phenomena appearing under conditions defined by classical physics concepts."

The references to `"classical physics concepts" is explained in Bohr (1958): "...it is imperative to realize that in every account of physical experience one must describe both experimental conditions and observations by the same means of communication as the one used in classical physics."

Bohr (1958) "...we must recognize above all that, even when phenomena transcend the scope of classical physical theories, the account of the experimental arrangement and the recording of observations must be given in plain language supplemented by technical physical terminology."

Bohr is saying that scientists do in fact use, and must use, the concepts of classical physics in communicating to colleagues the specifications on how the experiment is to be set up, and what will constitute a certain type of outcome. He in no way claims or admits that there is an actual reality out there that conforms to the precepts of classical physics.

In his book "The creation of quantum mechanics and the Bohr-Pauli dialogue" (Hendry, 1984) the historian John Hendry gives a detailed account of the fierce struggles by such eminent thinkers as Hilbert, Jordan, Weyl, von Neumann, Born, Einstein, Sommerfeld, Pauli, Heisenberg, Schroedinger, Dirac, Bohr and others, to come up with a rational way of comprehending the data from atomic experiments. Each man had his own bias and intuitions, but in spite of intense effort no rational comprehension was forthcoming. Finally, at the 1927 Solvay conference a group including Bohr, Heisenberg, Pauli, Dirac, and Born come into concordance on a solution that came to be called "The Copenhagen Interpretation", due to the central role of Bohr and those working with him at his institute in Denmark.

Hendry says: "Dirac, in discussion, insisted on the restriction of the theory's application to our knowledge of a system, and on its lack of ontological content." Hendry summarized the concordance by saying: "On this interpretation it was agreed that, as Dirac explained, the wave function represented our knowledge of the system, and the reduced wave packets our more precise knowledge after measurement."

Certainly this profound shift in physicists' conception of the basic nature of their endeavor, and the meanings of their formulas, was not a frivolous move: it was a last resort. The very idea that in order to comprehend atomic phenomena one must abandon physical ontology, and construe the mathematical formulas to be directly about the knowledge of human observers, rather than about the external real events themselves, is so seemingly preposterous that no group of eminent and renowned scientists would ever embrace it except as an extreme last measure. Consequently, it would be frivolous of us simply to ignore a conclusion so hard won and profound, and of such apparent direct bearing on our effort to understand the connection of our knowings to our bodies.

Einstein never accepted the Copenhagen interpretation. He said: "What does not satisfy me, from the standpoint of principle, is its attitude toward what seems to me to be the programmatic aim of all physics: the complete description of any (individual) real situation (as it supposedly exists irrespective of any act of observation or substantiation)." (Einstein, 1951, p.667: the parenthetical word and phrase are part of Einstein's statement.);

and "What I dislike in this kind of argumentation is the basic positivistic attitude, which from my view is untenable, and which seems to me to come to the same thing as Berkeley's principle, {\it esse est percipi}. (Einstein, 1951, p. 669). [Transl: To be is to be perceived]

Einstein struggled until the end of his life to get the observer's knowledge back out of physics. But he did not succeed! Rather he admitted that: "It is my opinion that the contemporary quantum theory constitutes an optimum formulation of the [statistical] connections." (ibid. p. 87).

He also referred to: "the most successful physical theory of our period, viz., the statistical quantum theory which, about twenty-five years ago took on a logically consistent form. This is the only theory at present which permits a unitary grasp of experiences concerning the quantum character of micro-mechanical events." (ibid p. 81).

One can adopt the cavalier attitude that these profound difficulties with the classical conception of nature are just some temporary retrograde aberration in the forward march of science: one may imagine, as some do, that a strange confusion has confounded our best minds for seven decades, and that the strange conclusions of physicists can be ignored because they do not fit our classical-physics-based intuitions. Or one can try to claim that these problems concern only atoms and molecules, but not the big things built out of them. In this connection Einstein said: "But the `macroscopic' and `microscopic' are so inter-related that it appears impracticable
to give up this program [of basing physics on the `real'] in the `microscopic' domain alone." (ibid, p.674).

Philosophers have tried for three centuries to understand the role of mind in the workings of a brain conceived to function according to principles of classical physics. We now know no such brain actually exists: neither the brain nor the body nor anything else in the world of nature is composed of those tiny bits of matter that Democritus and Newton imagined the universe to be made of. Hence it is hardly surprising that those endeavors of philosophers have been beset by enormous difficulties, which have led to such positions as that of the `eliminative materialists', who hold that our conscious thoughts do not exist; or of the `epiphenomenalists', who admit that human experiences do exist but claim that they play absolutely no role in how we behave; or of the `identity theorists', who claim that each conscious feeling is exactly the same thing as a motion of the particles that nineteenth century science thought brains and everything else in the universe to be made of. The difficulties in reconciling mental realities with pre-quantum physics is dramatized by the fact that for many years the mere mention of "consciousness" was considered evidence of backwardness and bad taste in most of academia, including, incredibly, even the philosophy of mind.

Given these difficulties with the earlier approach, coupled with the further fact that human experience is now understood to be a central player in our best theory of all purely physical phenomena, the question naturally arises: why not try to understand the role of mind in the workings of the thinking brain?

Success in this endeavour is augured by the fact that the mathematical structure uncovered by quantum physics, although highly counter-intuitive to minds indoctrinated in classical concepts, has an amazing internal logical cohesion, as well as the capacity to correctly predict numbers that can be measured to accuracies of one part in a hundred million. This inner consistency, combined with that incredible precision, means that quantum theory must embody some deep truth about the structure of reality. And this truth brings human experiences into the description of atomic processes. Can one then expect to ignore it in the description of the organ of experience itself?

3. FASTER THAN LIGHT?

"Nonlocality gets more real". This is the provocative title of a bulletin in the December `98 issue of "Physics Today." It reports the completion of experiments performed at Innsbruck, Los Alamos, and Geneva that all confirm to high accuracy some predictions of quantum theory that appear to entail superluminal action at a distance.

The work done in Switzerland is the most spectacular of the three efforts. It got wide press coverage because it confirms the validity of this mysterious holistic quality of nature, not merely at the atomic scale of a billionth of a meter, nor even over a laboratory scale of meters, but now over a geographic scale of more than ten kilometers.

Many experiments of this general kind, but involving shorter distances, have been carried out over the past thirty years. The popular and technical accounts of these works invariably stress that they imply an interconnectedness of the physical universe that contradicts the simple conception of nature that ruled science from the time of Isaac Newton until the dawn of the twentieth century. However, those accounts never provide both a sufficient description of the experiment together with the detailed argumentation that demonstrates their action-at-a-distance implications, and hence the rational need to adopt new ideas about the nature of the world. These experiments do show conclusively that the old notions fail, and fail decisively far beyond the realm of atomic-scale distances.

Surely, no reasonable person should accept on hearsay a radical new idea of reality that overturns everything that has been believed for generations, and is, moreover, wildly counter-intuitive: the physicists who are setting forth this "craziness" might be carried away by enthusiasm, or be so beguiled by the power of their mathematical tools that they lose touch with reality. This abrogation of the formerly well established science has such far-reaching consequences that serious thinkers need to understand for themselves the empirical evidence and its logical implications. Accordingly, I shall now describe in non-technical terms, first very schematically and later in more detail, the experiment performed in Switzerland by members of the Applied Physics Group of the University of Geneva, and then explain how their results contradict the classical-physics principle that bans faster-than-light action at a distance.

Very briefly, the overall general form of the Swiss experiment is this. First, a pair of highly correlated "twin-particles" is created by a special procedure performed in downtown Geneva. One of the two twins is sent to a laboratory in Bellevue, and the other is sent to a laboratory in Bernex. In each lab the arriving twin is sent into one or the other of two devices, which subjects it to one or the other of two alternative possible actions. The choice between these two alternative devices is made in a random fashion. Each twin is then examined in a way that produces one or the other of two alternative possible observable outcomes. The random choices made in the two far-apart regions, and the subsequent actions, are all performed so quickly that no information about which action is chosen in either lab has time to get to the other lab before the experiment there is completed---unless the information travels faster than light.

Classical physics forbids faster-than-light transfer of information. If that condition were satisfied then the behavior of neither twin could depend upon which of the two actions was randomly chosen and performed upon his faraway sibling. However, that condition of non-dependence cannot be reconciled with the predictions validated in this experiment.

Before expanding this cryptic synopsis of the experiment and its implications into a more generous offering it will be helpful to review the theoretical background.

According to Einstein's theory of relativity, any faster-than-light action would, from some point of view, be instantaneous. But instantaneous action at a distance is anathema to many scientists, on aesthetic and intuitive grounds. Of course, Newton's theory of gravity postulated an instantaneous action at a distance over a planetary scale, without any explanation of what was transmitting this action, and Newton's theory was severely criticized on that account. Even Newton himself was troubled by this feature. In a letter to his friend Bentley, he expressed his own skepticism about the notion of non-mediated action at a distance, and by implication, I think, about any instantaneous action at a distance:

",…that one body may act upon another at a distance
through a vacuum, without the mediation of anything else, by
and through which their action and force may be conveyed
from one to another, 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. Gravity
must be caused by an agent acting constantly according to
certain laws, but whether this agent be material or immaterial
I have left to the consideration of my readers."

More than two centuries later Einstein's general theory of relativity explained gravity as being due to the warping of space-time by the presence of matter. According to this theory, the gravitational effect is indeed conveyed from point to point by a local-contact kind of interaction that transfers information no faster than the speed of light. Thus Einstein accomplished what Newton had intuited, the abolition of instantaneous action at a distance. He also enunciated the closely connected principle of no faster-than-light action. But this demand was imposed upon, and was directly relevant to, a conception of nature in which the continuous history of the physical world for all time was determined by certain simple immutable laws from the state of the world at early times.

When quantum theory was created Einstein objected forcefully to the "mysterious action at a distance", which is explicitly built into the normal computational procedures, and which, as we shall now see, directly infects also the predictions derived from those calculations.

The initial phase of the Swiss experiment occurs at a lab in downtown Geneva. That is where the twins are born. This birthing is achieved by directing a laser beam at a crystal. Most of the laser light goes through the crystal, but each laser photon in a small subset is split into a pair of photons, with each member of the pair carrying about half the energy of its laser-photon parent.

For some of these pairs one partner is sent by optical fiber to a lab in the village of Bellevue, while the other partner is sent to a lab in the town of Bernex. These two labs lie more than ten kilometers apart.

At each lab the arriving twin is sent into an "interferometer".

Interferometers are, themselves, very interesting devices, and they need to be understood if the experiment is to be made clear.

These instruments exhibit in a striking way one essential aspect of the quantum mystery: wave-particle duality. What they reveal is similar in principle to what is shown by the famous double-slit experiment. But the double-slit experiment involves many detectors of photons and many possible trajectories that they might traverse. Only two detectors and two paths are needed for an interferometer, and the whole situation is consequently much clearer.

There are different kinds of interferometers. For ease of explanation I shall describe one that is slightly different from what was used in the Swiss experiment. But the principle is the same.

This interferometer involves two ordinary (i.e., fully silvered) mirrors, each of which reflects all the light falling on it, and two half-silvered mirrors, each of which reflects (like a mirror) half the light incident upon it, and transmits (like a plate of clear glass) the other half.

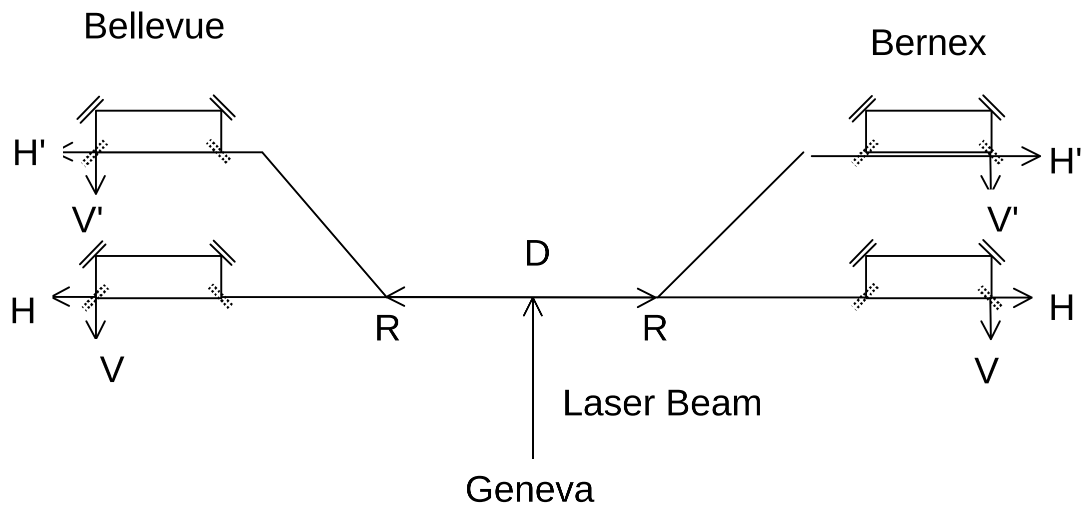
Suppose the beam entering one of these devices is traveling horizontally. Upon entering the interferometer this beam strikes a half-silvered mirror that is slanted at 45 degrees. Half the light goes straight though, while the other half is deflected vertically upwards. The half that goes straight through travels a short distance and then strikes the second half-silvered mirror, which is cocked at 45 degrees in the opposite direction, so that half of that beam goes straight through, and exits the device horizontally, whereas the other half is deflected vertically downward, and exits vertically.

A photon detector is placed in each of these two exit beams. Let the detector placed in the horizontal exit beam be called the horizontal-beam detector H, and the photon detector placed in the vertical exit beam be called the vertical-beam detector V.

The half-beam that was deflected vertically upward at the first half-silvered mirror takes a round-about path, via the two fully silvered mirrors, to the second half-silvered mirror: it is reflected by the first of these two mirrors into a horizontal beam that runs parallel to the original horizontal beam, and is then reflected back downward to the second half-silvered mirror. Thus half of the original beam travels a short route between the two half-silvered mirrors along the bottom side of a rectangle whereas the other half takes a longer path along the other three sides.

At the second half-silvered mirror both halves of the beam, the one traveling the shorter direct route, and the one taking the longer round-about route, both split 50-50, with half going out along the horizontal exit beam and the other half exiting along the (downward-directed) vertical exit beam.

Because there are two interferometers in each village, and each one has two photon detectors, there are four detectors in each village, and hence eight altogether. But for each particle pair the two independent random processes will select only one or the other of the two interferometers in each village.



The Experimental Set up.

[The laser beam is split at D. The two R's indicate the two random processes, each of which randomly sends the photon that arrives in its laboratory to one or the other of the two interferometers. H and V label the photon detectors in the horizontal and vertical exit channels, respectively. The primes indicated alternative possibilities.]

Some of the photons get lost along the way and do not reach a detector. But there are many pairs whose two members both reach detectors, one in Bellevue, the other in Bernex. Signals from those two detectors are sent back by ordinary wires to a central processor in Geneva.

[There is one fine point, which needs mention, but which is not central to the main argument.

The prediction of quantum theory that we want to use concerns the subset of pairs such that both members, one in Bellevue the other in Bernex, take the long path or both take the short path. To distinguish these pairs from the others, the lengths of the various paths are adjusted so that, on a nanosecond time scale, the difference between the times it takes light to traverse the two long paths, one in each village, is equal to the difference between the times it takes light to traverse the two short paths. Consequently, the difference in the arrival times of the two paired pulses, one from each of the two villages, is independent of whether both of the paired photons take the long path in their respective villages or both take the short path. This time difference is measured by fast (nanosecond) electronics. The paired pulses coming from paired photons that both take the long path or both take the short path will have the same time difference, but the pairs such that one partner takes a long path and the other takes a short path will have different time differences.This effect can be used to identify, and cast aside, the pairs such that the member in one village takes a short path and its partner in the other village takes the long path. Retained are those pairs in which both of the twins (one in each village) take the longer path or both take the shorter path. This sample is singled out and analyzed because quantum theory predicts that for the photon pairs in this subset a strong and interesting correlation exists between what happens in the two villages.

The rate at which the pairs are detected is slow enough so that each pair of particles, one detected in Bellevue the other in Bernex, can be distinguished from all the other pairs by fast electronics. A pair is classified as "matched" if both members are detected in a horizontal exit channel or both are detected in a vertical channel. They are "unmatched" if one partner is detected in a horizontal exit channel and its mate is detected in a vertical exit channel.

Quantum theory predicts that the fraction of the pairs that are unmatched will depend on L minus S, where L is the sum of the two long paths, one in each village, and S is the sum of the two short paths. For certain values of L minus S all of the pairs will be unmatched and for other values of L minus S none of the pairs will be unmatched. For intermediate values of L minus S a certain fraction f will be unmatched.

Quantum theory gives a precise formula for this fraction f, and the validity of this formula, for many values of L minus S, was checked by the Swiss experiment. For ease of explanation, I shall use just one simple property of this formula: if for some original value of L minus S none of the pairs are unmatched then for small shifts of L minus S away from this original value the number of unmatched pairs will grow like the square of this small shift. In particular, the fraction f of unmatched pairs will increase faster than linearly, relative to the change in L minus S!

What is so astonishing about that?

What is puzzling and interesting is this: This faster-than-linear growth is impossible to reconcile with the classical idea that the choice of what is done to a twin cannot influence the behavior of its sibling---before the information about which action performed on the one partner can reach the other, without traveling faster than light.

How is this remarkable result proved?

In the actual experimental situation the four alternative kinds of settings come in some random sequence, and the experimenters collect together the experiments with the four alternative combination of settings, in order to check, for each of the four different values of L minus S, that the fraction of unmatched pairs is what quantum theory predicts.

However, within the context of classical physics one has an underlying theoretical structure that allows one to consider a set of four theoretically possible worlds that are identical up until the instant at which the two random processes act. The random processes are supposed to be independent of the system being examined: cosmic rays, or any one of a billion different arbitrary processes could control them. One implements this idea in classical physics (and also in quantum physics) by fixing in slightly different ways the external potential energy in which the system being examined moves. This external potential is set in a way such that a tiny change triggers the choice between the two alternative possible experiments in Bellevue. A second independent potential energy variation is invoked to implement the random choice made in Bernex.

Einsteinian relativistic classical physics is designed so that every physical effect of one of these tiny alterations of the potential is confined to the region of space-time that can be reached by traveling no faster that light from the region of that tiny change. This is how the idea of no-faster-than-light influences is made precise in physics.

The random process in Bellevue directs the photon arriving at Bellevue either into the interferometer BL or into the interferometer BL'. And the random process in Bernex directs the photon arriving in Bernex into either BR or BR'. The subsequent evolution of each of the four alternative possible worlds will continue to be identical to each other, except for the dynamical consequences of these two localized random choices. In classical physics these consequences propagate no faster than the speed of light. Hence under the conditions of the Swiss experiment a change in the random choice made in either region can have no effect at all in the other region until after the detection is made and recorded there. [Recall that the experiment is designed so that the random choice in each region is followed so quickly by the detection and recording there that no effect of the faraway choice upon these two latter processes is possible without superluminal (i.e., faster than the speed of light) action.]

To deduce a contradiction between this no-faster-than-light condition and the predictions validated by the Swiss experiment consider the following arrangement. Let the first alternative interferometers BL and BR in Bellevue and Bernex, respectively, be copies of each other, and let BL' and BR' be copies of each other. Let the short paths in BL, BR, BL' and BR' all have the same lengths. But let the longer path in BL' (hence also in BR') be slightly longer than the longer path in BL (hence also in BR). (This difference is negligible on the nanosecond time scale mentioned earlier.) Let the path lengths in BL (and hence in BR) be fixed so that in the case that BL and BR are chosen by the random processes there will be no "unmatched" pairs: i.e., there will be no pairs such that the twin in one village is detected in a horizontal exit channel and the twin in the other village is detected in the vertical exit channel. This original case will be called Case One.

Case Two is the alternative possible world in which everything is the same as in Case One up until the moment that the two random choices were made, but in which the random choice in Bellevue goes the other way, and BL' is picked by the random process there, rather than BL, but nothing is changed in Bernex. Now a small fraction f of the pairs will be "unmatched". Since nothing has changed in Bernex, this small fraction f of unmatched events must arise from a switching of this fraction f of the events in Bellevue from what they were in Case One. That is, if in a sequence of, say, ten thousand original pairs the sequence of detection events is, say (H, V, V, H, H, H, V, H, etc.) in both Bellevue and Bernex (I shall ignore statistical fluctuations, which do not materially affect the argument) then the fraction f, say 1%, of these values will in Case Two be reversed from their Case One values in Bellevue, but none will be reversed in Bernex. This is the first key consequence of the no-faster-than-light-influence condition: it ensures that the change made in Bellevue does not disturb the outcomes in Bernex.

Case Three is the same as Case One in Bellevue, but BR' is chosen in Bernex instead of BR. Hence the same fraction f of the detection events, but now in Bernex, must be opposite to what they were in Case One.

In case Four Case the changes from Case One that were made in Bellevue alone in Case Two, and in Bernex alone in Case Three, are now made simultaneously in both Bellevue and Bernex. Hence in this final case, Case Four, the changes that occur in Bellevue must be the same as the changes made there in Case Two, since no influence of the choice made in Bernex can be present in Bellevue. Similarly, in this Case Four, the changes made in Bernex must be the same as the changes that were made there in Case Three.
But then the total number of mismatches in Case Four can be no greater than the sum of the number of mismatches in Cases Two and Case Three. Thus the fraction f* of mismatches in Case Four can be no larger than 2f. (Of course, there can be fluctuations, but by taking the numbers of pairs considered to be very large the fluctuations become unimportant.).

On the other hand, in Case Four the empirically validated theoretical formula for this fraction f* is, for small f, proportional to the square of the shift in L minus S from its value in Case One. This shift is the sum of these shifts in L minus S for Case Two and Case Three separately, because L and S are both just sums over the contributions from Bellevue and Bernex individually. Thus this shift in L minus S is twice what it was for Case Two. But this value must be squared to give the empirically validated formula, and 2 squared is 4! Thus theory, and the empirical evidence, say that the fraction of unmatched pair in this Case Four is close to 4f, whereas the no-faster-than-light condition allows it to be no greater than 2f.

This means that both quantum theory and nature are incompatible with the classical notion that what is done to one twin cannot affect the behavior of its faraway mate---faster than the speed of light!

In this particular proof the effect is small when f is small. But in other arrangements the effect can be that locality requires a fraction to vanish that quantum theory predicts to be, say, 99%. In any case, it is the principle that counts not the numerical particulars. And the principle established by this analysis is that the causality concepts of classical physics fail over macroscopic distances.