RUSSELL HANSON, DAVID BOHM AND OTHERS ON THE SEMANTICS OF DISCOVERY

Norwood Russell Hanson (1924-1967), born in New Jersey, was a U.S. Marine Corps fighter pilot during the Second World War, who earned the rank of major, and was awarded the Distinguished Flying Cross and the Air Medal for flying combat missions over Japan. Afterward he studied at the University of Chicago, Columbia University, and Yale University in the United States, and then studied at both Oxford University and Cambridge University in England. He received a Ph.D. from Oxford in 1955 and a Ph.D. from Cambridge in 1956, and was afterward a fellow at the Institute for Advanced Study at Princeton. He accepted a faculty appointment at Indiana University in 1957, where he was founder and chairman of Indiana University's Department of History and Logic of Science from 1960 to 1963. He then accepted a professorship on the philosophy department faculty of Yale University, which he had at the time of his premature death at the age of forty three in a crash of his private airplane in 1967. His principal works are *Patterns of Discovery* (1958) and *Concept of the Positron* (1963). At the time of his death he left an uncompleted textbook in philosophy of science intended for first-year college students, which was edited by Willard C. Humphreys, a former student of Hanson, and then published as *Perception and Discovery* (1969). A year after his death a complete bibliography of his publications appeared in a memorial volume of *Boston Studies in the Philosophy of Science*, Volume III (1968).

David Bohm (1917-1992) was born in Wilkes-Barre, PA, and received his doctorate in physics from the University of California. He taught physics at Princeton, and eventually moved to England. He was professor of theoretical physics from 1961 at Birkbeck College, University of London, where he was professor emeritus from 1983 until his death in 1992. A brief biography may be found in the "General Introduction" in *Quantum Implications* (ed. B.J. Hiley and F. David Peat, 1987), and a three-hundredfifty page biography by Peat was published under the title *Infinite Potential: The Life and Times of David Bohm* (1997). Bohm's initial statement of his interpretation was published in 1952 in two articles in the *Physical Review*, in which he reports that the interpretation was originally stimulated by a discussion with Einstein in 1951. His principal statements of his hidden-variable interpretation of quantum theory are set forth in two of his books. The earlier is a brief monograph of only one-hundred-forty pages titled *Causality and Chance in Modern Physics* published in 1957, and the more recent is his more elaborate *Undivided Universe* co-authored with Basil Hiley and posthumously published in 1993. After publishing his seminal articles in 1952, he found that his interpretation had been anticipated in important respects in 1927 by Louis de Broglie (1892-1987). De Broglie's interpretation had been criticized severely, and he had consequently abandoned it, but Bohm had further developed the thesis enough that the fundamental objections confronting de Broglie had been answered. Bohm's interpretation was shown to be consistent with all the essential characteristics of the quantum theory, and additional suggestions were made by Vigier, a colleague of de Broglie. De Broglie then returned to his original proposals, since he believed that the decisive objections against them had been answered. Bohm and Vigier then published a joint paper setting forth the interpretation in the *Physical Review* in 1954, and de Broglie wrote a "Foreword" to Bohm's 1957 book. Bohm was one of the physicists who recognized nonlocality in the quantum theory. Peat's generally sympathetic biography shows how the idea of nonlocality led Bohm firstly to his wholistic ontology for physics, then to his process metaphysics, and finally to his mysticism of the implicate order, according to which mind and matter are indivisibly united. To the dismay and consternation of his friends and colleagues, this mysticism was encouraged by Bohm's long-time association with an Indian guru, and also led Bohm to take seriously the mind-over-matter exhibitions of a stage magician.

Hanson takes very seriously the question of the interpretation of the modern quantum theory, and he truculently defends the Copenhagen interpretation. In "Appendix II" to his *Patterns of Discovery* he notes that while for most practical microphysical problems Born, who accepted the Copenhagen interpretation, and Schrödinger, who did not, would have made the same theoretical calculations. Nevertheless, their alternative interpretations organized their thinking differently, and consequently influenced their future research work in very different ways: after 1930 Born was led to work on collision behavior, on the statistical analysis of scattering matrices, while Schrödinger pursued investigation of the so-called ghost waves of the elementary particles. The interpretations, therefore, are important because each supplies an agenda that influences the direction of future research in physics. Hanson does not view all interpretations as equally worthy of consideration, and he considers particularly unfortunate is the "hidden-variable" interpretation developed by David Bohm. In contrast to the Copenhagen interpretation with its duality thesis that the wave and particle are two manifestations of the same physical entity, Bohm's alternative interpretation is that the wave and particle are different physical entities, even though they are never found separately, and that the wave oscillates in an as yet experimentally undetected and therefore hidden subquantum field. In the context of the topic of scientific discovery Bohm's views are interesting, because they illustrate the semantical approach to scientific discovery and theory development in physics. They illustrate the use of figures of speech as a technique for theory development based on certain postulated basic similarities between the macrophysical and microphysical orders of magnitude, similarities that are denied by advocates of the Copenhagen interpretation. Consider firstly Bohm's early advocacy of the Copenhagen interpretation, and then his later agenda for future physics including his hidden-variable interpretation for quantum theory.

Bohm's Early Copenhagen Views

The hidden-variable thesis is Bohm's more mature view. He started out as an advocate of the Copenhagen interpretation, which he also calls the usual interpretation, and then changed his mind after the talk with Einstein in 1951, the year in which his textbook titled *Quantum Theory* was published setting forth his earlier view. There are at least two noteworthy features of this early book. The first is Bohm's distorted understanding of Bohr's philosophy of quantum theory. The second is his ontology for quantum theory, the ontology of potentialities, which anticipated Heisenberg's similar ontology of *potentia* by seven years.

In the “Preface” to his *Quantum Theory* Bohm says that as a result of the work of Neils Bohr, it has become possible to express the results of quantum theory in terms of comparatively qualitative and imaginative concepts, which are totally different from those appearing in the classical theory. He rejects the view that the quantum properties of matter imply the renunciation of the possibility of their being understood in the customary imaginative sense, and that they imply the sufficiency of only a self-consistent mathematical formalism which can in some mysterious way correctly predict the numerical results of experiments. The eighth chapter of the book is titled "An Attempt to Build a Physical Picture of the Quantum Nature of Matter", and Bohm writes in a footnote that many of the ideas appearing in the chapter are an elaboration of material in Bohr's *Atomic Theory and the Description of Matter*. However, Bohm's understanding of Bohr is distorted. Bohr maintained an instrumentalist view of the equations of quantum theory, which rejects any semantics or ontology for quantum theory, and he repeatedly denied explicitly that quantum phenomena are pictureable. From Bohm's statement in his 1952 articles that his hidden-variables thesis was the result of a talk with Einstein in 1951, it is reasonable to speculate that Einstein had read Bohm's book, had recognized that Bohm was ripe for disillusionment with the views in Bohr's philosophy, and had concluded that Bohm was ready for induction into the ranks of Bohr's critics. In any event whatever may have been Einstein's unreported comments to Bohm in their private conversation, the ultimate outcome after forty years was Bohm's *Undivided Universe: An Ontological Interpretation of Quantum Theory* (1973), a book in which Bohm explicitly says he is supplying an ontology to replace Bohr's epistemological interpretation.

The ontology for quantum theory that Bohm described in 1951 is a wholistic ontology of potentialities, in which the world is an indivisible unit where quanta have no component parts describable by hidden variables, and are not even separate objects, but are only a way of talking about indivisible transitions. This metaphysics is also called monism. At the quantum-mechanical level the properties of a given object do not exist separately in the quantum object alone, but rather are potentialities which are realized in a way that depends on the systems with which the object interacts. Thus the electron has the potentiality for developing either its particle-like or its wave-like form, depending on whether it interacts with an apparatus that measures either its position or momentum. Bohm's views are also realist; he does not maintain that the quantum phenomenon has its properties because it is being measured. He says that a quantum-mechanical system can produce classically describable effects not only in a measuring apparatus, but also in all kinds of systems that are not actually being used for the purpose of making measurements. Throughout the process of measurement the potentialities of the electron change in a continuous way, while the forms in which these potentialities can be realized are discrete. The continuously changing potentialities and the discontinuous forms in which the potentialities may be realized are complementary properties of the electron.

Bohm anticipated Heisenberg's idea of potentiality, which Heisenberg did not propose until his *Physics and Philosophy* in 1958, the only place in Heisenberg's literary corpus where the idea is mentioned. But there are differences in their ideas of potentiality, because unlike Bohm's, Heisenberg's is not a wholistic version. In the 1951 book Bohm said that potentiality makes quantum theory inconsistent with the hidden-variables thesis, because the hidden-variables view is based on the incorrect assumption that there are separately existing and precisely defined elements of reality. The idea of potentiality is much more integral to Bohm's earlier interpretation than to Heisenberg's, and it had distinctive implications for Bohm. One implication is Bohm's thesis that mathematics is inadequate for physics. He says that the interpretation of the properties of the electron as incompletely defined potentialities finds its mathematical reflection in the fact that the wave function does not completely determine its own interpretation until it interacts with the measuring device, and that the wave function is not in one-to-one correspondence with the actual behavior of matter, but is merely an abstraction reflecting only certain aspects of reality. He believes that to obtain a description of all aspects of the world, one must supplement the mathematical description with a physical interpretation in terms of the incompletely defined potentialities.

Shortly afterwards he accepted the hidden-variables idea, and in the second chapter of his *Undivided Universe*, where he mentions in a footnote his anticipation of Heisenberg's idea of potentiality, he rejects altogether the potentiality thesis that the particle itself is created by the measurement process. In Bohm's hidden-variables view, the particle is not a wave-packet or otherwise created out of the wave; the particle is in reality distinct from the wave. His later view is not wave *or* particle, but wave *and* particle. That is, the wave and particle are not two alternative aspects of the same entity, but are different and separate entities.

Bohm's Agenda for Future Microphysics

Bohm's hidden-variable interpretation is an agenda for future microphysics, and his *Causality and Chance* (1957) sets forth three related objectives in this agenda. His first objective is the relatively modest one of demonstrating that an alternative to the Copenhagen interpretation is possible, in the sense that it is not the only one that is consistent with the formalism and measurements of modern quantum theory. He states this objective not only because he has another interpretation in mind, but also because he maintains that the development of alternative views is important for the advancement of science, while advocates of the Copenhagen interpretation deny that any alternative view including one involving a subquantum level of magnitude is conceivable. For example in his "Questions of Principle in Modern Physics" (1935) in *Philosophical Problems of Quantum Physics* Heisenberg states that the uncertainty principle must be taken as a question of principle making other formulations into false and meaningless questions, just as in relativity theory it is supposed that it is in principle impossible to transmit signals at speeds greater than the velocity of light. But Bohm maintains that without alternatives the physicist is constrained to work along accepted lines of thought in the hope that either new experimental developments or lucky and brilliantly new theoretical insights eventually will lead to a new theory. In contrast Bohm maintains that one of the functions of criticism in physics is to suggest alternative lines of research that are likely to lead in a productive direction. He thus sees criticism with alternatives to be integral to scientific discovery. This objective is particularly attractive to the philosopher of science Paul Feyerabend, once an advocate of Bohm's interpretation, who to the end of his life maintained that creating alternatives is necessary for the advancement of science.

Bohm's second objective is to propose an interpretation of the history of physics, which shows successful precedents for the research strategy represented by his hidden-variable interpretation of quantum theory. The paradigmatic historical precedent he invokes is the atomic theory of matter, which postulated the existence of atoms unobservable at the time the theory was proposed. Analogously Bohm’s strategy consists of postulating that there exists an order of physical magnitude below the quantum order of magnitude containing the quantum of action represented by Planck's constant. Bohm postulates that this subquantum order contains new types of qualitative phenomena governed by more deterministic laws than do those known to exist at the quantum level of magnitude. The existence of this postulated subquantum level of microphysical phenomena is denied by the Copenhagen interpretation advocates, and since there is as yet no experimental detection of any such subquantum phenomena, the theory that postulates them is said to have hidden variables.

Bohm opposes his historical interpretation to another that he calls mechanistic, a term that is unfortunately ambiguous in both philosophical and scientific usage, but which has a specific and somewhat elaborate meaning in Bohm’s book. According to the objectionable mechanistic philosophy opposed by Bohm the qualitative diversity of things in the world can be reduced completely, without approximation, and in every possible domain of science to nothing more than the effects of some definite and limited general framework of quantitative laws, which are regarded as absolute and final. Prior to the development of quantum theory these quantitative laws were assumed to be deterministic; then with the development of the Copenhagen interpretation of quantum theory these laws were assumed to be indeterministic. Hence there are both deterministic and indeterministic varieties of mechanism. In the former variety causal laws are thought to be fundamental, while in the latter probability laws are thought to be fundamental. Indeterministic mechanism prevails today, because physicists have accepted Heisenberg's thesis that the indeterminacy principle represents an absolute and final limitation on our ability ever to define the state of things by any kind of measurement.

In *Causality and Chance* Bohm maintains that both causality and chance are fundamental and objective, and that both determinism and indeterminism are merely idealizations. Thus he departs from Einstein's determinism. He also rejects the subjective interpretation of probability, which says that the appearance of chance is a result of human ignorance. And he rejects the idea common to both deterministic and indeterministic varieties of mechanism that there is only one general framework of laws and a limited qualitative diversity. Bohm maintains that there are different levels of depth or orders of magnitude with each level having its own laws and qualitative diversity. In the history of physics revolutionary developments have occurred when laws and qualities at a higher level are explained by those of a lower level. Experiments may disclose a breakdown of an entire scheme of laws by the appearance of chance fluctuations not originating in anything at the higher level, but instead originating in qualitatively different kinds of factors at a lower level. For example in classical physics a particle such as an electron follows the classical orbit only approximately, while in a more accurate treatment it is found to undergo random fluctuations in its motions arising outside the context of the classical level. Thus Bohm affirms by way of historical analogy and on the basis of his nonmechanistic interpretation of the history of science that there is a still deeper level, a subquantum level, which in turn explains the randomness that is detected at the higher quantum level of magnitude.

Bohm’s hidden-variable interpretation is both an alternative interpretation of quantum theory motivated by this prior ontological commitment and also a discovery heuristic for which there is historical precedent. He maintains that new work is considerably facilitated by his thesis of a hidden subquantum order of magnitude, because the physicist can imagine what is happening, and can thereby be led to new ideas not only by looking directly for new equations but also by a related procedure of thinking in terms of concepts and models that will help to suggest new equations, equations which would not likely be suggested by mathematics alone. And he uses his postulated subquantum ontology as a basis for figures of speech such as analogy, which are a central feature in his discovery strategy. These figures aid in formulating new hypotheses for future physics both on the basis of similarities between the macrophysical and microphysical orders of magnitude and on the basis of past developments in the history of physics, which he believes justifies his hidden-variables ontology.

Bohm's third objective is to use the hidden-variable interpretation as a guide for future research for a new microphysical theory that will resolve what he sees as the current crisis in quantum physics. This crisis manifests itself in Dirac's relativistic quantum theory, when the wave equation is applied to the description of particle scattering with very high energies and at short distances. For the Schrödinger wave equation to be used in such applications, an *ad hoc* mathematical adjustment called renormalization is necessary. Furthermore the behavior of very high-energy particles in experiments reveals that there exist many new kinds of particles not previously known, and that they are unstable, since they decay into one another and create other particles. Nothing like this is accounted for by current quantum theory. To Bohm these problems for the current quantum theory suggest that elementary particles are not really elementary. The concept of a subquantum level justifies the physicist considering a whole range of qualitatively new kinds of theories that approach the currently accepted theory only as approximations, which hold in limiting cases. He believes that the current crisis in quantum theory portends a revolution in microphysics, and that the hidden-variable interpretation offers a superior guide for research that promises to resolve the crisis.

These three objectives of Bohm's agenda represent successively more ambitious claims. The first claim is merely that an alternative to the

Copenhagen semantical interpretation describing a subquantum level of magnitude is conceivable in the sense that it is consistent with the data and formalism of the current quantum theory. The second claim states more ambitiously that the history of physics reveals that postulating lower levels of magnitude supplies an analogy, which is a productive strategy to guide new research. The third claim is still more ambitious; it states that a new scientific revolution in microphysics is at hand, and that the hidden-variable semantical interpretation will produce a new microphysical theory that will resolve the current crisis in quantum theory. As de Broglie said in the closing sentence of his "Foreword" to *Causality and Chance* (1957), Bohm's book comes at exactly the right time. Thirty-five years later in his *Undivided Universe* Bohm was still predicting this impending revolution. No such revolution has yet occurred, but more recent experiments based on John Stuart Bell's inequality have occasioned reconsideration of the merits of Bohmian mechanics.

Bohm's Hidden-Variable Interpretation of Quantum Theory

Consider next a brief overview of the hidden-variable interpretation, Bohm's means for implementing his three-point agenda for future microphysics. Bohm's hidden-variable interpretation is the Schrödinger wave equation plus trajectories for individual particles, as in Newton's second law of motion, thus rendering both the wave and particle as real and completely causal. Measurement does not realize the particle, and there is no wave collapse to a particle. Bohm postulates that there exists a subquantum-mechanical order of magnitude containing hidden phenomena, and that the statistical character of the current quantum theory originates in random fluctuations of new kinds of entities existing at this lower subquantum-mechanical level. Thus Heisenberg's indeterminacy principle and his particular statistical treatment of it pertain only to phenomena at the quantum-mechanical level. Bohm believes that indeterminacy is a measurement problem like the measurement problems found in Newtonian mechanics, and that by broadening the context of physical theory to include a subquantum-mechanical level, it will become possible to diminish indeterminacy below the limits set by Heisenberg's indeterminacy principle. Bohm states that subquantum processes may be detectable in the domain of very high energies and very small distances, even though at lesser energies and greater distances the high degree of approximation permitted by the laws of the quantum level means that the entities at the subquantum level cannot be playing a very significant role in quantum-level events. He postulates that associated with each electron there is a particle that has a precisely definable and continuously varying values of position and momentum, and that is so small that at the quantum-mechanical level it can be approximated as a mathematical point, just as in the earliest forms of atomic theory the atom was so described. He also postulates that associated with the particle there is a quantum-level wave that oscillates in a real subquantum field, and which satisfies the Schrödinger wave function. In his later works he also refers to the subquantum field as the quantum field. In summary Bohm says he regards the quantum-mechanical system as a synthesis of a precisely definable particle and a precisely definable subquantum field which exerts a force or potential on the particle.

Bohm uses figures of speech, which he imprecisely calls analogies, and these analogies are not merely illustrative of fully formed thoughts, but have had a self-consciously formative role in his thinking. In his *Causality and Chance* Bohm uses an analogy with Brownian movements of particles in a gravitational field, and illustrates what Heisenberg’s indeterminacy principle would mean in terms of a subquantum-mechanical field. In the case of Brownian motion a smoke particle is subject to random fluctuations originating in collisions with the atoms that exist at a lower order of magnitude than the smoke particle. As a result of these random collisions the motion of the smoke particle cannot be completely determined by the position and velocity of the particle at the level of the Brownian motion itself. Bohm cites a 1933 paper by the German physicist, R. Furth, who showed that the lack of determination in Brownian motion is not only qualitatively analogous to that obtained in the quantum theory, but is also quantitatively analogous to the mathematical form of the indeterminacy relations. Thus, for a short-time interval with random fluctuations of a given magnitude in the mean position and a given magnitude in the mean momentum, the magnitudes satisfy a relationship involving a constant that depends on the state of the gas, and the relationship is mathematically analogous to Heisenberg's indeterminacy relation involving Planck's constant. The quantum-level force produces a tendency to pull the particle into regions where the subquantum-level field has its strongest intensity, as described by Born's probability distribution. But this tendency is also resisted by random motions analogous to Brownian motions, which originate at the subquantum level. The origin of these motions is not important; it is sufficient they have the property such that the average of their motions satisfies the Schrödinger wave equation, and that they are communicated to the particle. The net effect of the quantum-level force and the subquantum-level random motions in the subquantum field is a mean distribution in a statistical ensemble of particles, which favors the regions where the quantum-level force field is most intense, but which still leaves some chance for a typical particle to spend some time in the regions where the field is relatively weak. This result is analogous to the classical Brownian motion of a particle in a gravitational field, where the random motion which tends to carry the particle into all parts of the container, is opposed by the gravitational field, which tends to pull it towards the bottom of the container.

Using these concepts Bohm proposes his alternative explanation of the two-slit experiment. When the particle passes through a slit, it follows an irregular path, because subquantum random motions affect it. After a large number of particles have passed through the slit system with both slits open, a pattern forms with particles accumulating on a screen where the subquantum field intensity is greatest due to the effects of the quantum force, as described by Born's probability distribution. The pattern is different if only one slit is open, than if both are open. Closing one of the two slits influences the particles that pass through the open slit, because it influences the quantum-level force felt by the particle as it moves between the slit system and the screen. Thus the hidden-variable interpretation can explain how the appearance of the wave-particle duality originates, while the Copenhagen interpretation requires acceptance without further discussion of the fact that electrons enter the slit system and appears at the screen with an interference pattern.

In *Causality and Chance* Bohm also comments on Heisenberg's gamma-ray microscope thought experiment. He maintains that Heisenberg's indeterminacy principle should not be regarded as expressing the impossibility of making measurements of unlimited precision. Rather it should be regarded as expressing the incomplete degree of self-determination characteristic only of entities that can be defined in the quantum-mechanical level. The subquantum-mechanical processes involving very small intervals of time and space will not be subject to the same limitations as those of the quantum-mechanical processes, and the unpredictable and uncontrollable disturbances caused by a measurement apparatus at the quantum level can either be eliminated or be controlled and corrected. Thus when the physicist measures processes at the quantum-mechanical level, the process of measurement will have the same limits on its degree of self-determination as every other process at this level. But if the microphysical theory is generalized to include the subquantum order of magnitude, then the problem of measurement attributed to the uncertainty principle should be regarded not as an inherent limitation on the precision with which it is possible to conceive the simultaneous definition of position and momentum, but rather as merely a practical limitation, because measurement precision in violation of the uncertainty relations is conceivable.

Bohm also gives another analogy with Brownian motion. Bohm compares quantum phenomena with Brownian motion by describing the wave and particle as entities that interact in a way that is essential to their modes of being. He says that this seems plausible, because that fact that wave and particle are never found separately suggests that they are both different aspects of the some fundamentally new kind of entity, which is likely to be quite different from a simple wave or particle. Thus if Brownian motion were viewed not as a motion of particles, but as a motion of a very fine droplet of mist, then the indeterminacy of the droplets in a vapor at its critical temperature, where the distinction between liquid and gaseous states disappears, is a fluctuation in which the droplets are always forming and disappearing. This is an indeterminacy in the very existence of the droplets. Similarly at the quantum level it may be found that the very mode of existence of the electron is indeterminate. The fact that the electron shows its characteristic wave-particle duality in its behavior suggests that the particle showing this critical opalescence is the relevant concept of particle. It is unclear whether or not Bohm is attempting at this stage of his thinking in terms of hidden variables to use this alternative Brownian analogy to reconcile his original potentiality idea with his newer hidden-variables idea. In his later view in *Undivided Universe* potentiality is the presence of the information in the quantum wave, which is inactive except when the particle uses it as a guidance condition for its movement.

Bohm says that because the subquantum level is inadmissible in the Copenhagen interpretation, one is restricted to making blind mathematical manipulations with the hope that somehow one of these manipulations will lead to a new and correct theory. He says that if the subquantum level is admitted, where there are processes of very high energy and very high frequency faster than the processes taking place at the quantum-mechanical level, then the details of the lower level would become significant, and the current formulation of the quantum theory would break down. The creation of a particle such as a meson may thus be conceived as a well defined subquantum-level process, in which the field energy is concentrated in a certain region of space in discrete amounts, while the destruction of the particle is just the opposite process. At the quantum-mechanical level the precise details of this process are not significant, and therefore can be ignored. This in fact is done in the current quantum theory, which discusses the creation and destruction of particles as merely a kind of popping in and out of existence with special creation and destruction operators in the mathematics. However, with very fast high-energy processes the results may well depend on these subquantum-mechanical details. And if this should be the case, then the current quantum theory would not be adequate for the treatment of such processes.

The original analogy used by Bohm for developing the idea of the subquantum field is a postulated similarity with the electromagnetic field. The analogy appears in his 1952 articles in *Physical Review*, and reappears often in later works. The subquantum field exerts a force on the particle in a way that is analogous to the way that the electromagnetic field exerts a force on a charge. And just as the electromagnetic field obeys Maxwell's equations, so too the subquantum field obeys Schrödinger's equation. In both cases a complete specification of the field at a given instant over every point in space determines the values of the fields for all times. And in both cases once the physicist knows the field fluxions, he can calculate the force on a particle, so that if he also knows the initial position and momentum of the particle, he can calculate its entire trajectory. Physicists are not yet able to make experiments that localize the position and momentum to a region smaller than that in which the intensity of the hidden subquantum field is applicable. Therefore Bohm notes that they cannot yet find clear-cut experimental evidence that the hypothesis of the hidden variables is necessary.

There are also noted dissimilarities from the electromagnetic wave (or negative analogies as Hesse would say). These dissimilarities are the distinctive aspects of the quantum world in contrast to the classical world. One noteworthy dissimilarity is that the Schrödinger equation is homogeneous while Maxwell's equations are inhomogeneous, with the result that unlike the electromagnetic field, the subquantum field is not radiated or absorbed, but simply changes its *form* while its intensity remains constant. In his later works Bohm says that the quantum wave does not impart energy to the particle, but instead functions as a guidance condition, while the particle moves with its own energy. This feature gives rise to Bohm's concept of active information, which he introduces in his later book, *Undivided Universe*. He describes the concept of active information by an analogy with a radio wave which guides a ship propelled by its own much greater energy while piloted under the guidance of the radio signal. Similarly the elementary particle moves by its own energy under the guidance of the quantum wave. The quantum wave does not push or pull the particle, but rather guides it like the radio wave guides the ship. Bohm explains the two-slit interference experiment in terms of active information. If both slits are open, the quantum wave passes through both slits while the particle passes through only one slit, and the quantum wave contains information about the slits. As the particle reaches certain points in front of the slits, it is informed to accelerate or decelerate accordingly. Bohm says that the electron particle with its own energy source may have a complex and subtle inner structure, perhaps comparable to a radio receiver.

Quite notably Bohm says the fact that the action of the quantum potential upon the particle depends only on its form and not on its magnitude, implies the possibility of a strong nonlocal connection of distant particles and a strong dependence of the particle on its general environmental context. The forces between particles depend on the wave function of the whole system, so that there is what Bohm calls indivisible wholeness, reminiscent of the organic wholeness of a living being in which the very nature of each part depends on the whole. This absence of the mutual externality and separability of all elements which is characteristic of the classical world, makes the quantum world very elusive to the grasp of the physicists' instruments. But Bohm says it is real and more basic than the classical world. According to Bohm's theory the classical world's autonomy emerges wherever the quantum potential is so relatively small that it can be neglected. But the classical subworld is actually an abstraction from the subtle quantum world, which is the ultimate ground for existence. These considerations lead to Bohm's thesis of the implicate order, the order in the quantum world, which supersedes the Cartesian order of the classical world and its mathematics.

In several of his publications Bohm uses the analogy of the lens and the hologram to illustrate the implicate order in ordinary experience. The classical world is like a lens, which produces an approximate correspondence of points on an object to points on an image. In contrast the quantum world is like a hologram, in which each region of the hologram makes possible an image of the whole object. The hologram does not look like the represented object at all, but rather the image is implicit or enfolded. Bohm adds that the term enfolded is not merely a metaphor, but is to be taken literally, and that the order in the hologram is implicate. He also says that there are algebras of the implicate order, and he exemplifies some in his *Undivided Universe*.

Bohm's most noteworthy analogy is given in the third chapter of Undivided *Universe*, where he develops the basic principles of his ontological interpretation in the context of the one-body system. He begins with what is known as the WKB approximation for the classical limit in quantum mechanics, and concludes with an equation of motion containing separate terms for both classical and quantum forces, and describing the electron as a particle that has a well defined position that varies continuously, is causally determined, and is never separated from a new type of quantum field that affects the particle. Peat, Bohm's editor, explains Bohm's development of this analogy in his biography's seventh chapter titled "Hidden Variables". Bohm later rejected Einstein's idea that the probabilistic results of quantum theory are the result of underlying deterministic motions of smaller particles, as in the Brownian motion analogy. Bohm knew that something analogous to the quantum theory's wave-particle ambiguity already existed in classical physics. In the nineteenth century the Irish mathematician W.R. Hamilton had shown that it is mathematically possible to recast Newton's laws about the movement of particles into a description involving waves. Bohm also knew that Hamilton's approach is used in quantum theory as an approximation which simplifies calculations, the WKB approximation, which Peat says has a position midway between classical and quantum mechanics with its assumption that quantum particles move along actual trajectories. Unlike most physicists, Bohm took the WKB approximation realistically instead of instrumentally, i.e. as merely a convenient approximation. Peat reports that Bohm's strategy was to ask what would have to be added to Hamilton's approach in order to transform this mathematical approximation technique into an equation that can reproduce all the results of quantum theory exactly, and that Bohm's answer was to introduce his radically new quantum potential, in order to explain all the nonclassical effects. Peat reports that Bohm thus dispensed with metaphysical ideas like Heisenbergian potentialities and actualities, collapsing wave functions, and irreducible probabilities.

Bohm's Critique of Heisenberg's Copenhagen Interpretation

Shortly after the publication of Heisenberg's *Physics and Philosophy: The Revolution in Modern Science* (1958) Bohm wrote an article in *The British Journal for the Philosophy of Science* (February, 1962) titled "Classical and Nonclassical Concepts in the Quantum Theory." In a footnote Bohm comments that his article was originally planned as a review of *Physics and Philosophy*, but since he and Heisenberg had on previous occasions criticized one another's views, Bohm decided to subtitle his article "An Answer to Heisenberg's *Physics and Philosophy*." On the first page of his article Bohm says that since Heisenberg's book presents the basic features of the Copenhagen interpretation in such a clear light that it constitutes a useful basis on which further criticisms can be developed. And in this paper Bohm sets forth his own criticisms, one ontological and the other semantical. In summary Bohm's ontological criticism is that in the exposition of his Copenhagen interpretation Heisenberg introduces ideas that are subjectivist and inconsistent. Bohm believes that in expounding his doctrine of *potentia* Heisenberg states that whereas possibilities can exist outside the human mind, physical actuality can only exist when someone perceives it. To assess Bohm's criticism, it is necessary firstly to examine Heisenberg's own statements about the role of subjectivism in quantum theory.

Heisenberg's version of the Copenhagen interpretation is set forth in the third chapter of his *Physics and Philosophy*, which is titled "The Copenhagen Interpretation of Quantum Theory." He begins by comparing experiments in classical and quantum physics. In both types of experiments there are errors of measurement observation, which can be described by probability functions. The error is not a property of the observed system, but is the experimenter's ignorance or lack of knowledge of the true measurement. Thus Heisenberg invokes a subjective interpretation of the probability function describing measurement error. He then states several times in his exposition that in the case of a quantum experiment the probability function combines both objective and subjective elements in the experimental situation, or as he also says, it represents both statements of a fact and statements of our knowledge of the fact. The statement of our incomplete knowledge of the fact is the measurement error, which is subjective, and it may be different for different experimenters, presumably because the different experimenters do not make exactly the same errors when making their measurements. And he comments that the subjective element in the probability function may be practically negligible as compared with the objective element, and the physicist can then speak of a pure case. The statement of fact is a statement about possibilities or tendencies, and he references Aristotle's concept of *potentia*. The *potentia* or potential is completely objective and does not depend on any observer. The realization of the potential, the transition from the possible to the actual, takes place during the act of observation, as soon as the of object interacts with the measuring device. Heisenberg explicitly issues some caveats, namely that this transition applies to the physical and not to the psychical act of observation, that it is not connected with the act of registration of the result by the mind of the observer, and that quantum theory does not contain genuinely subjective features, because it does not introduce the mind of the physicist as a part of the atomic event. These comments would suggest that Heisenberg wishes to preclude any metaphysical idealism such as Berkeley's *esse est percipi*. But Bohm argues that these caveats are inconsistent with Heisenberg's preceding statements about subjectivism in these passages.

While denying that the transition from the possible to the actual in the measurement operation is connected with the act of registration of the measurement result by the mind of the observer, Heisenberg states that the discontinuous change in the probability function due to the second measurement takes place with the act of registration, because it is a discontinuous change of our knowledge in the instant of registration, a change that has its image in the discontinuous change in the probability function. Bohm quotes this passage in his article, and he concludes that until an observer actually perceives the result of observation, so that he can write a new wave function representing the actual state to which the previous possibilities have collapsed as a result of his perception, there is no actuality at all as far as anything that can appear in the theory is concerned, but only the set of possibilities. Bohm illustrates his view of Heisenberg's subjectivism with a hypothetical experiment involving a set of Geiger counters arranged in a grid and toward which a free electron is directed. He supposes a point in time at which the electron has already entered the grid system and has triggered off one of the counters, and furthermore supposes that no observer has yet looked to see which counter has been triggered. Bohm says that on Heisenberg's view, at the supposed point in time when no observer has seen which counter has been triggered, one knows the objective possibilities, namely that the counter in question must be one of those located where the amplitude of the electron wave function is appreciable; but if one tries to describe the physical actuality of which counter has been triggered, there is no way in the theory to do so, because the probability function describes only psychic actualities. In other words until an observer actually perceives which counter has operated, so that he can write a new wave function representing the actual state to which the previous possibilities have collapsed as a result of his perception, there is no actuality described by the theory but only the set of possibilities. Thus the physical actualities play no part at all in the theory, because no predicted result would be changed if the theory were developed without mentioning the physical actualities. It is noteworthy that Bohm seems not merely to be saying that the Copenhagen interpretation is subjectivist because it is probabilistic; he is not merely criticizing Heisenberg's Copenhagen interpretation by assuming the subjectivist interpretation of probability as the only probability interpretation. Bohm's criticism is the claim that the subjectivism is in Heisenberg's Copenhagen interpretation, and that Heisenberg's argument unintentionally but logically implies that to be is to be perceived by the registering mind of the observer. In fact this is not Heisenberg's view. Heisenberg's thesis is that to be is to be produced by the disturbing physical apparatus used by the observer. Thus Bohm's thought experiment involving the grid of Geiger counters demonstrates only that there may be a time interval between production and perception of the new actuality.

The confusion seems to arise from Heisenberg's decision to give the quantum probability function both a subjective and an objective interpretation. Normally these two interpretations are distinguished as alternatives, and for good reason: On the objective interpretation the probability function is a statement in the object language like any other theory in physics with a semantics describing the real physical world. Thus interpreted the probability function is an object language statement with a semantics describing the *potentia* ontology and the ontology of indeterminism. On the subjective interpretation the probability function is a statement in a metalanguage for physics with a semantics describing the physicist's state of knowledge or ignorance expressed by the object language, and it consists of statements making statistical estimates of measurement error. Heisenberg chose to combine these two interpretations, presumably because in quantum theory it is not possible to write a separate probability function for the measurement error. In classical physics, which traditionally assumes an ontology of determinism, variations in repeated measurements under the same experimental conditions are assumed to be due entirely to randomly distributed measurement errors. These could be represented statistically by the standard deviation about the calculated mean of the measurement values, also known as the standard error of the estimate of the true measurement value, or by a probability function based on a normalization inversely related to the deviations from the mean. In quantum theory, on the other hand, the indeterminist ontology introduces a random variation not originating in measurement errors even though the indeterminacy operates in the measurement process. Therefore, the two sources of variation are inseparable, and the effects of both are taken up in the probability function of quantum theory. What is noteworthy is that Heisenberg does not state in his exposition that the discontinuity in the probability function is due to measurement errors occurring in the second measurement. He says it is a discontinuous change in our knowledge in the instant of registration that has its image in the discontinuous change of the probability function, and that is occasioned by the disturbance produced by measurement process. Thus the objective interpretation would seem to be the operative one in this passage, because the probability function is viewed as constituting the experimenter's knowledge rather than describing that knowledge. The knowledge that Heisenberg says is the image of the new probability function is the semantics that describes the new physical actuality realized by the action of the measurement apparatus.

However, Bohm prefers to construe this passage to mean that the probability function should be taken with a subjective interpretation, and that it describes knowledge, which Heisenberg calls psychical instead of physical. This places the quantum theory entirely in the metalanguage for physics. Thus Bohm says that the physical actualities play no part whatsoever in the theory, since no predicted result would be changed in any way at all, if the theory were developed without mentioning them. Then Bohm says that to avoid subjectivism, Heisenberg adopts the completely metaphysical assumption of physical entities, which play no part in the theory, but which are introduced to avoid what would otherwise be an untenable philosophical position.

Having exposed to his satisfaction the inconsistency in the Copenhagen interpretation, namely the subjectivism he believes implied in Heisenberg's exposition and contradicted by Heisenberg's *ad hoc* attempt to introduce physical actuality, Bohm then goes on to say that it was due to this problem that he himself was led to criticize the Copenhagen interpretation years earlier, and that while trying to find a way to remedy the absence of the actuality function, he developed his own alternative interpretation. In his alternative interpretation, namely the hidden-variable interpretation, he proposes in addition to the Schrödinger wave function the existence of a particle having a well defined position and momentum, which interacts with the wave in a certain prescribed manner. The position of this particle plays the part of an actuality function in the sense that, when the wave function spreads out over many possibilities, this particle function determines which of these possibilities is actually present.

Consider next Bohm's semantical critique of Heisenberg's version of the Copenhagen interpretation. His semantical critique is distinctive, because it exploits Heisenberg's distinction between on the one hand everyday concepts and on the other hand the Newtonian concepts of classical physics that are said to be refinements of the everyday concepts. Bohm rejects the Copenhagen thesis that the classical concepts are necessary for describing macrophysical objects such as the equipment used in microphysical experiments, and thus maintains that alternatives to the Copenhagen interpretation are conceptually possible. He maintains contrary to Heisenberg that the everyday concepts actually used in ordinary experience including the physicist's description of his laboratory equipment may be refined to topological concepts, and need not be the Cartesian-coordinate concepts of Newtonian physics. He therefore believes that the topological concepts are more fundamental in the mathematical sense for the description of space and time than the Cartesian concepts, and that the latter must be translated from the former for Newtonian physics.

Bohm exemplifies this idea with the problem of location an ordinary pencil. The location is not ordinarily stated in terms of a coordinate system such as latitude and longitude. What is actually done in ordinary experience is to locate the pencil as laying upon a desk within a certain room in a certain house, which is located on a certain street, etc. Thus the pencil is located with the aid of a series of topological relations, in which one entity is within or upon another entity. He then says that the laboratory physicist also uses topological relations in his work. In no experiment does he ever locate anything by giving an exact coordinate, which is to say an infinite number of decimals. Rather what he does in practice for making a measurement is to place a pointer between certain marks on a scale, thus locating it by the topological relation of between. In every experiment the notion of precisely defined coordinates is just an abstraction, which is approximated when a topologically described experimental result is translated into the Cartesian language of continuous coordinates. Bohm adds that everyday concepts could be refined in other ways than to topological concepts, but that for description of space and time, the topological concepts are most appropriate for physical theory.

Bohm then suggests a topological formulation of the quantum theory, and says that these nonclassical concepts make possible new kinds of experimental predictions, which cannot be considered in the framework of the Copenhagen interpretation, and which according to Heisenberg's conclusions are not possible. Bohm says that there is a remarkable analogy between the mathematics of topology and that of the modern quantum mechanical field theory, and that utilization of this analogy can make possible the development of a topological formulation, which while leading to the results of the usual quantum theory in suitable limiting cases, nevertheless possesses certain genuinely novel features with regard both to its mathematical formalism and to its experimental predictions. He also says that he cannot go into the details in this paper, and he is not known to have done so in any other paper he has published. This novation with or without the inspiring analogy is a promissory note backed by an as-yet-unearned income, because Bohm does not set forth an explicit topological formulation of the quantum theory. If he actually had set forth such a new formulation, and if its novel experimental predictions were found to be superior to those made by the current quantum theory, such as resolving the renormalization problem, then his new topological formulation would be a revolutionary development in microphysical theory, and much more than merely a new interpretation of the quantum theory.

Bohm and Bell on the EPR Experiment and Nonlocality

In 1935 Einstein, Podolsky and Rosen (conventionally abbreviated as "EPR") published an article in the *Physical Review* titled "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" Their negative answer implies that the current statistical quantum theory is inadequate, and that further development is needed that would presumably involve identifying presently unknown factors conventionally referred to as hidden variables. The authors firstly set forth a necessary condition for completeness, according to which every element of the physical reality must have a counterpart in the physical theory. And they secondly set forth a sufficient ontological condition for affirming the reality of a physical quantity, which consists in the possibility of predicting with certainty the physical quantity under investigation without disturbing the physical system. The three authors propose a hypothetical or *gedanken* experiment, now conventionally known as the "EPR experiment", which assumes among other things the experimental correctness of the quantum theory and Heisenberg's indeterminacy relations, but which concludes to a demonstration of the present quantum theory's incompleteness.

There are several equivalent versions of this now famous experiment including some that have since actually been performed. The authors postulate two particles initially interacting, such that their properties are correlated, and then subsequently separated spatially by being sent off in opposite directions, so that they can no longer interact but still retain their correlated properties. One of the implicit assumptions of the argument is that there is no instantaneous action at a distance, so that the spatial separation of the two particles precludes the measurement of one particle from disturbing the other particle in any way. This assumption has been called either separability or locality. In this thought experiment the noteworthy properties are the noncommuting observables, position and momentum. If the *momentum* of one of the particles is measured, then since its momentum is correlated to the momentum of the second particle, the momentum of the second is also known by the measurement of the first. Or if the *position* of the first particle is measured, then since its position is correlated to the position of the second particle, the position of the second is also known by the measurement of the first. But according to Heisenberg's indeterminacy relations no quantum wave/particle can simultaneously have both position and momentum as determinate properties The selection of which quantity is determinate is made by the measurement action, a selection which is the free and arbitrary choice of the experimenter. The second particle has no interaction with the first at the time that the first particle is measured, so the second particle cannot know, as it were, which of the noncommuting properties the experimenter selected as the determinate property of the first particle. Yet paradoxically the second particle's determinate property is always correlated to that of the first. The authors, Einstein, Podolsky and Rosen, conclude that the paradox can only be resolved by recognizing that in fact both particles always had both determinate position and determinate momentum from the time of their separation, and that the current quantum theory fails to represent the physical reality of the situation completely. The current quantum theory, in other words, is incomplete.

Bohr responded to this argument in an article with the same title appearing in a later issue of the same journal in the same year. He takes issue with EPR's criterion for physical reality, reaffirms his principle of complementarity, and maintains contrary to EPR that quantum theory is not incomplete. He says that because it is impossible to control the reaction of the object on the measuring instruments, the interaction between object and measuring devices conditioned by the very existence of the quantum of action entails the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality. Bohr discusses this aspect of measurement in the context of the two-slit experiment of electron diffraction, which is not a hypothetical experiment but an actual one. He references Heisenberg's uncertainty principle, and says that the uncertainty of momentum of the incident particle is inseparably connected with an exchange of momentum between the particle and the diaphragm. This impossibility of a closer analysis of the reactions between the particle and the measuring instrument is an essential property of any arrangement where there is a feature of individuality completely foreign to classical physics. Any attempt to take into account the momentum exchanged between the particle and the separate parts of the apparatus, would imply conclusions about the course of such phenomena, such as what particular slit the particle passes on its way to the photographic plate. This would be quite incompatible with the fact that the probability of the particle reaching a given place on the photographic plate is determined not by the presence of any particular slit, but by the position of all the slits. Bohr explains that complementarity is due to this impossibility in the field of quantum theory of accurately controlling the reaction of the object on the measuring instrument, i.e. the transfer of momentum in the case of position measurements and the displacement in the case of momentum measurements. And he concludes that in such cases the physicist is not dealing with an incomplete description characterized by the arbitrary picking out of different elements of physical reality at the cost of sacrificing other such elements, but with a rational discrimination between essentially different experimental arrangements which are suited either for an unambiguous use of the idea of space location or for the legitimate application of the conservation laws of momentum. There is nothing in this rebuttal by Bohr that was not previously known to physicists and to EPR at the time of their famous paper, and Bohr's arguments cannot be said to have been responsive to the particulars of EPR's thought experiment.

In a section titled "The Paradox of Einstein, Podolsky and Rosen" in his *Quantum Theory* Bohm says that the EPR criticism of quantum theory has been shown to be unjustified, and in a footnote to this statement he references Bohr's critique of EPR published in *Physical Review*. At this time Bohm was sympathetic to the Copenhagen interpretation, and critical of

Einstein's views. In addition to EPR's necessary condition for a complete physical theory and their sufficient condition for recognizing an element of reality, Bohm says that there are two additional assumptions implicit in the EPR argument. These assumptions are firstly that the world can be correctly analyzed in terms of distinct and separately existing elements of reality, and secondly that every one of these elements must be a counterpart of a precisely defined mathematical quantity appearing in a complete theory. Bohm attacks these two implicit assumptions. He says that the one-to-one correspondence between mathematical theory and well defined elements of reality exist only at the classical level. At the quantum level, on the other hand, the properties described by the wave function are not well defined properties, but are only *potentialities* which are more definitely realized in interaction with an appropriate classical system such as a measuring apparatus.

For his own critique of EPR, Bohm offers a modified but equivalent version of the EPR experiment for his analysis. His version considers the spin of the two separated and correlated particles. The second particle's spin is always correlated to the measurement axis, i.e. the spin component, chosen for measurement of the first particle, regardless of the component selected by the experimenter for measurement. On the EPR interpretation precisely defined elements of reality must therefore exist in the second particle corresponding to the simultaneous definition of all three dimensional components of spin. And since the Schrödinger wave function can specify at most only one of these components at a time with precision, it cannot provide a complete description of all elements of reality existing in the second particle. But Bohm maintains that the wave function provides the most complete description of physical reality consistent with the actual structure of matter, because on his view *no* component of spin of a given variable exists with a precisely defined value until interaction with the measuring apparatus has taken place. As soon as the first particle interacts with the measuring apparatus a given spin component is determined. As a result the definite phase relations between the wave functions of the two particles are destroyed, and the wave function of the other particle will take a form that guarantees the development of the opposite value of spin, if the second particle interacts with an apparatus measuring the same component of spin. Bohm therefore says that wave function describes the propagation of correlated potentialities.

Bohm's proposed resolution to the EPR paradox involving his rejection of the two implicit assumptions he believed contained in the EPR argument resulted in his ontological thesis of potentialities, his wholistic philosophy of nature, and his belief that mathematics is of limited value for physics. Contrary to Einstein's ontology, Bohm maintains the wholistic view that there are no distinct and separately existing elements of reality, and that the present form of the quantum theory implies that the world cannot be put into one-to-one correspondence with any conceivable kind of precisely defined mathematical quantities. Therefore a complete theory will always require concepts that are more general than those for an analysis into precisely defined elements. Thus to obtain a description of *all* aspects of the world, one must supplement the mathematical description with a physical interpretation in terms of incompletely defined potentialities. He later refers to such supplementary description as informal language. Bohm's conclusion that mathematical physics must be supplemented with informal nonmathematical discourse, may be contrasted with the approach of Dirac, who never doubted the adequacy of mathematics for physics, and who instead admitted a new type of variable into mathematical physics, namely the quantum or *Q* variables, as he called them, as opposed to the traditionally classical or *C* variables. Finally to cope mathematically with the indeterminacies in microphysics Bohm introduces in his *Undivided Universe* his thesis that quantum theory is an implicate algebra.

In his early statement of his hidden-variable thesis published in *Physical Review* in 1952 Bohm revised his view of Bohr's thesis. He says that Bohr's interpretation of the quantum theory leaves unexplained the correlations between the two separated particles in the EPR experiment, and that the quantum theory needs to be completed by additional elements or parameters. This is the hidden-variables thesis, but there is no mention of potentiality in noncommuting variables or ontological wholism, although there is recognition of the nonlocality implication in his new thesis, and Bohm seems to have been one of the first to recognize it. He states that on his new interpretation, the EPR experiment is describable in terms of a combination of a six-dimensional wave field, the subquantum field, and a precisely definable trajectory in a six-dimensional space. Thus when the experimenter measures either the position or the momentum of the first particle, he introduces uncontrollable fluctuations in the wave function for the entire system, which through the quantum-mechanical forces bring about corresponding uncontrollable fluctuations in the position or momentum respectively of the other particle. And he notes that these quantum-mechanical forces transmit the disturbances *instantaneously* from one particle to the other through the medium of the subquantum field. But Bohm does not conclude that the instantaneously transmitted disturbances involve signals having velocities greater than that of light. He says that where the quantum theory is correct, his interpretation cannot lead to inconsistencies with relativity theory, and that where the quantum theory may break down in cases of high velocities and short distances, Lorentz invariance may serve as a heuristic principle in the search for new physical laws.

Before examining Bohm's later statements in his *Undivided Universe*, consider firstly Bell's locality inequality and actual EPR experiments. John Stewart Bell (1928-1990), a theoretical physicist associated with CERN in Geneva, Switzerland, is an advocate of the hidden-variable interpretation of the quantum theory, who further developed Bohm's analysis of the EPR experiment. In 1987 Bell published his collected papers under the title *Speakable and Unspeakable in Quantum Mechanics*, in which each chapter is a previously published paper. In the chapter titled "Six Possible Worlds of Quantum Mechanics" (1968) Bell distinguishes six interpretations of the quantum theory, which he divides into the romantic and the unromantic views. The romantic views are those that are principally of interest to journalists, and the unromantic ones are those of interest to professional physicists. The three romantic views are 1) Bohr's complementarity thesis, 2) the mentalistic views of Wigner and Wheeler, and 3) the many-worlds thesis of Everett. The three unromantic views are 1) the pragmatic view that is the philosophy of physicists who work with the quantum theory, 2) a new and not-yet developed classical nonlinear Schrödinger wave equation that makes microscopic and macroscopic physics continuous, and 3) the pilot wave of de Broglie and Bohm. This last alternative, which is the hidden-variable interpretation, makes the whole physical universe classical, and the probability outcome is due entirely to the experimenter's limited control over the initial conditions. Bell says that the pilot wave thesis seems so natural and simple for resolving the wave-particle dilemma that it is a great mystery to him why it had been ignored.

In a chapter titled "Introduction to the Hidden-Variable Question" (1971) Bell discusses his motivations for defending and developing the hidden-variable thesis. His first reason, and the one that he finds most compelling, is the possibility of a homogeneous account of the physical world, which is to say, a single uniform ontology for microphysical and macrophysical domains based on classical concepts. Bell denies that there is a boundary between classical and quantum worlds, the boundary that Heisenberg had called the schism in physics, and Bell agrees with Einstein that the wave function is an incomplete and provisional microphysical theory. His second motivation concerns the statistical character of quantum mechanical predictions. Once the incompleteness of the wave function is suspected, then the seemingly random statistical fluctuations may be viewed as determined by the extra hidden variables, which are hidden because at the present time physicists can only conjecture their existence. His third motivation is the peculiar character of some quantum-mechanical predictions considered in the famous *gedanken* experiment formulated by EPR, and a refinement proposed by Bohm in 1951, in which Stern-Gerlach magnets are used to measure selected components of spin revealed by the deflections of particles moving simultaneously away from each other in opposite trajectories from a source. The experiment permits the observer to know in advance the result of measuring one particle's deflection by observing the other's deflection even at great distance. The implication intended by Einstein is that the outcomes of such measurements are actually determined in advance by variables over which the physicist has no control, but which are sufficiently revealed by the first measurement that he can anticipate the result of the second. Therefore, contrary to the Copenhagen view there is no need to regard the performance of one measurement as a causal influence on the result of the second distant measurement, and the situation can be described as local.

Heisenberg's indeterminacy principle says no quantum-mechanical state can be dispersion free for every variable. On the other hand the hidden-variable theory says that all observations are fully determined, such that each quantum-mechanical state must correspond to an ensemble of states each with different values of the hidden variables with the component states dispersion free. Therefore, one way to formulate the hidden-variable problem is to search for a formalism permitting such dispersion-free states. Bell proposes such a formalism, a modification of the Schrödinger wave function with a set of hidden variables added, which he says provides an explicit causal mechanism by which operations on one of the two measuring devices in the apparatus can influence the response of the other distant device. However, this revision establishes that the measurement does not reveal some property previously possessed by the quantum system, but rather reveals something that comes into being in the combination of system and apparatus. It is local in configuration space, but nonlocal in ordinary three-dimensional space thus providing an explicit causal mechanism by which one of the two measuring devices in the EPR experiment can influence the response of the distant device. This is the opposite of the resolution hoped for by EPR, who had envisaged that the first device could serve only to reveal the character of the information already stored in space and propagating in an undisturbed way toward the other detecting equipment.

In a paper titled "On the Einstein-Podolsky-Rosen Paradox" (1964) Bell set forth his locality inequality, the theoretical accomplishment for which he is best known. This probabilistic expression assumes in agreement with EPR that the separated particles and thus their measured properties are statistically independent of one another. The noteworthy consequence is that the values admitted by the inequality are inconsistent with the quantum theory. Bell thus concludes that no local deterministic hidden-variable theory can reproduce all the experimental predictions of the quantum theory. Several years after Bell's 1964 paper physicists began to design and perform actual EPR experiments to test Bell's locality inequality. The first proposed EPR experimental design was published under the title "Proposed Experiment to Test Local Hidden-Variable Theories" in *Physical Review Letters* by J.F. Clauser, M.A. Horne, A. Shimony, and R.A. Holt. These experiments examined the statistical behavior of separated photons with polarization analyzers. The most reliable experiments of the several actually performed have outcomes favoring quantum mechanics, thus violating Bell's locality inequality.

In his "Metaphysical Problems in the Foundations of Quantum Mechanics" in the *International Philosophical Quarterly* (1978) one of these experimenters, Abner Shimony, affirms a realistic interpretation based on the idea that the measurement produces a transition from potentiality to an actuality in both the separated photons. Echoing Bohm's early explanation Shimony adds that the only changes that have occurred concerning the second photon are a transition from indefiniteness of certain dynamical variables to definiteness, and not from one definite value to another. He concludes that there seems to be no way of utilizing quantum nonseparability and action at a distance for the purpose of sending a message faster than the velocity of light. He prefers the idea of wormholes previously proposed by J. A. Wheeler in 1962. Shimony describes wormholes as topological modifications of space-time whereby two points are close to each other by one route and remote by another. Thus the two photons in the EPR experiment are not only distantly separated as ordinary observation shows, but may also be more closely connected through a wormhole.

In "Bertlmann's Socks and the Nature of Reality" (1981) Bell considers four possible positions in connection with nonlocality. The first is that Einstein was correct in rejecting action at a distance, because the apparatus in any EPR experiment attempted to date is too inefficient to offer conclusive results. But Bell says that the experimental evidence is not encouraging for such a view. The second position is that the physicist's selection of dynamical variables is not truly an independent variable in the EPR experiment, because the mind of the experimenter influences the test outcome. Bell seems unsympathetic to this position. He merely comments that this way of arranging quantum mechanical correlations would be even more mind boggling than one in which causal chains go faster than the speed of light, and that it implies that separate parts of the world are deeply entangled including our apparent free will. A third position that he considers is Bohr's view that there does not exist any reality below some classical or macroscopic level. He says that on Bohr's thesis fundamental physical theory would be fundamentally vague until concepts like macroscopic are made sharper than they are currently. And in an "Appendix" to this article Bell adds that he does not understand the meaning of such statements in Bohr's 1935 rebuttal to EPR. Clearly Bell's polite and reserved response is not intended as a confession of his ignorance, but rather as a criticism of Bohr's obscurantism.

Finally Bell considers the position that causal influences do in fact travel faster than light, and this is the position he prefers. In "Speakable and Unspeakable in Quantum Mechanics" (1984) he says that the problem of quantum theory is not how the world can be divided into the speakable macrophysical apparatus, which we can talk about, and the unspeakable quantum system, which we cannot talk about. The problem is to explain how the consequences of events at one place propagate to other places faster than light, which is in gross violation of relativistic causality. Most notably he says that Aspect, Dalibard, and Roger, who published the findings from their EPR experiments in 1982, have realized specific quantum phenomena which require such superluminal explanation in the laboratory. Bell concludes that there exists an apparent incompatibility at the deepest level between the two fundamental pillars of contemporary physical theory, and that a real synthesis of quantum and classical theories requires not just technical developments but a radical conceptual renewal.

Consider next Bohm's final statements of his views on nonlocality in his *Undivided Universe* (1993). Bohm had affirmed the nonlocality thesis even before he adopted the hidden-variable interpretation, and nonlocality remained a basic feature of his mature view. While nonlocality and wholeness are often associated with Bohr's Copenhagen interpretation, and are opposed to EPR's criticism, Bohm's ideas of nonlocality and wholeness are not the same as Bohr's. On Bohr's view an attempt to analyze a quantum process in detail is not possible, because the experimental conditions and measurement of the experimental results are a whole that is not further analyzable. Bohm on the other hand not only proposes his hidden-variable interpretation as an analysis of the individual quantum phenomenon, but he also offers a philosophically sophisticated critique of Bohr's rebuttal to EPR in the seventh chapter titled "Nonlocality". Bohm replies that on Bohr's view it is not possible even to talk about nonlocality, because nothing can be said about the detailed behavior of individual systems at the quantum order of magnitude. In his critique Bohm attacks Bohr's philosophy of language, according to which physical phenomena must be described with concepts from classical physics. Bohm references Einstein's statements that concepts are a free creation of the human mind, and says that there is no problem in assuming the simultaneous reality of all properties of the separated particles in the EPR experiment, even though these properties cannot be simultaneously observed. Contemporary philosophers of science refer to these different semantical views expressed by Bohr and Einstein and discussed by Bohm as the naturalistic and the artifactual theses of the semantics of language respectively. Notwithstanding Bohm's minority status among physicists, his philosophy of language is as sophisticated as may be found in the views of any contemporary academic philosopher of science.

Bohm's adoption of the hidden-variable interpretation led him to modify his original explanation of nonlocality. In his *Undivided Universe* he says that the nonlocal connection between the separated particles which causes the correlation in the EPR experiment is the quantum potential in the subquantum field. And he also maintains that the nonlocal quantum potential cannot be used to carry a signal. By signal he means a controllable influence, and he says that there is no way to control the behavior of the remote second particle by anything that might be done to the first particle. This is because any attempt to send a signal by influencing one of the pair of particles under EPR correlations will encounter difficulties arising from the irreducibly participatory nature of all quantum processes due to their wholistic nature. To clarify his view on signals, he says that if an attempt were made in some way to modulate the wave function in a way similar to what is done to make a radio wave signal, the whole pattern of this quantum wave would change radically in a chaotic and complex way, because it is so fragile.

Bohm takes up the relation between nonlocality and special relativity in "On the Relativistic Invariance of Our Ontological Interpretation", the twelfth chapter of *Undivided Universe*. He says that since a particle guided in a nonlocal way is not Lorentz invariant, physicists must either accept nonlocality, in which case relativity is not fully adequate in the quantum domain, or they must reject nonlocality, in which case quantum theory is not fully adequate in the relativistic domain. Bohm does not renounce nonlocality, but instead concludes that physicists must assume the existence of a unique frame in which the nonlocal connections are instantaneous. He says that he does not regard this unique frame to be intrinsically unobservable, but that these new properties cannot be observed presently in the statistical and manifest domains in which the current quantum theory and relativity theory are valid. Just as the observations of atoms became possible where continuity of matter broke down, so the observation of the new properties will become possible where quantum theory and relativity theory break down. He says that the idea of a unique frame fits in with an important historical tradition regarding the way in which new levels of reality, e.g. the atoms, are introduced into physics to explain older levels, e.g. continuous matter, on a qualitatively new basis. Bohm admits it will take time to demonstrate experimentally the existence of the subquantum fields and the unique frame of reference implied by nonlocality. He also considers that the speed of the quantum connection is not actually instantaneous, but is nonetheless much faster than the speed of light, and he proposes the development of the EPR experiment reminiscent of the Michelson-Morley experiment to measure the superluminary velocity of the quantum connection between distant particles. He says such a test might demonstrate the existence of the unique frame, indicate a failure of both quantum and relativity theories, eliminate quantum nonlocality, and indicate a deeper level of reality in which the basic laws are neither those of quantum theory nor relativity theory.

The new EPR experiments using Bell's locality inequality are empirical developments that have supplied ample grist for the philosophy dissertation mills. Nonetheless, their interesting findings are of greater significance to physicists than to philosophers of science. They may be the Michelson-Morley experiment for the contemporary physicists' theory of relativity, but they present no anomalies for the contemporary philosopher's Pragmatist philosophy of science. The modern quantum theory brought down the Positivist philosophy by occasioning the rejection of the naturalistic thesis of the semantics of descriptive language including notably those terms that the Positivists called observation terms. This was analogous to rejecting the parallel postulate in Euclidian geometry, and it brought in its train the development of the contemporary Pragmatist philosophy of science based on the thesis that the semantics of descriptive language is artifactual. Following this development in philosophy of science, however, the new EPR experiments have not warranted any revision to the contemporary Pragmatist philosophy of science. For the contemporary Pragmatist, the EPR experimental findings may be viewed as business as usual for science. In view of Bell's sympathy for Bohm's hidden-variable thesis, it is ironic that the experiments performed using Bell's inequality have yielded findings that contradict the expectations of Einstein, Podolsky and Rosen.

Bohm on Perception and Metaphor in Scientific Discovery

For forty years following his initial 1952 statement of his hidden-variable interpretation Bohm continued to expound his views in philosophy of science, metaphysics, and epistemology. His statements that are most relevant to the subject of scientific discovery are found in *Science, Order and Creativity*, particularly in the introductory chapter and in the two succeeding chapters, which altogether take up about half of the book. There he also sets forth his philosophy of perception, which is explicitly opposed to that of the Logical Positivists, and is characteristic of contemporary post-Positivist philosophy of science. It also reveals some influence from Einstein, because he says perception takes place in the mind and in terms of theories. For example the observational data obtained by Archimedes in his bath had little value in themselves. What was significant was their meaning as perceived through the mind in an act of creative imagination. The principal historical change that has occurred in modern science is that this mental perception is more mediated through elaborate instruments that have been constructed on the basis of theories. Bohm's philosophy of perception is central to his views on scientific discovery and he assigns a special role for metaphor.

Bohm believes that the development of science is now obstructed by fragmentation that is caused by subliminal rigidities in thought that he calls the tacit infrastructure of scientific ideas. One example of the tacit infrastructure of scientific ideas is the Newtonian notions of space and time that led Lorentz to preserve both the idea of the constancy of the velocity of light and the ideas of absolute space and time by explaining the anomalous results of the measurements of light by postulating changes in the measuring apparatus as the apparatus moves through the ether. He notes that the tendency of the scientist's mind to hold to what is familiar is reinforced by the fact that the overall tacit infrastructure is interwoven in the institutions on which depends the professional security of the scientist. The means for breaking out of the tacit infrastructure of scientific ideas and to create new theories is metaphor. Bohm defines metaphor as the simultaneous equating and negating of two concepts. Metaphor is especially important for Bohm, since he maintained that microphysics and macrophysics should have the same basic ontology, such that features from the latter domain projected into the former enables a discovery strategy. This role of metaphor in discovery is possible because the realm of physics is now that of perception through the mind, and theory dominates experiment in the development of the scientific perception of nature. Bohm says that metaphor occasions creative perception, and he also refers to metaphoric perception. Metaphoric perception brings together previously incompatible ideas in radically new ways. He says that the unfolding of a metaphor that equates different and even semantically incommensurable concepts can be very fruitful. In using the term incommensurable Bohm references Kuhn, and he equates his own thesis of the tacit infrastructure of scientific ideas with Kuhn's thesis of scientific paradigm. A paradigm is not just the articulate theory, but also the scientist's whole way of working, thinking, communicating, and perceiving with the mind. However, Bohm rejects Kuhn's thesis that normal science is without any creativity, and that revolution is completely discontinuous. Bohm maintains that semantic incommensurability can be overcome with metaphor. He furthermore says that revolution occurs when a new metaphor is developed, and normal science is the creative unfolding of that new metaphor. In Bohm's view there is much more creativity in normal science, than Kuhn admits. Bohm also criticizes Popper's thesis of falsifiability. He maintains that today an excessive emphasis is being placed on falsifiability in the sense that unless a theory can immediately or very shortly be falsified, then that theory cannot be regarded as properly scientific. A new idea with broad implications may require a long period of gestation before falsifiable consequences can be drawn from it.

Bohm also maintains that communication is essential to perception in science. He understands communication in a very broad sense to include the individual's own articulate mental dialogue with himself. The scientist engages in an inner dialogue with himself as well as with his colleagues, and in this dialogue he is disposed in his thinking by the social background.

Insights enfolded in this inner dialogue must be unfolded by discourse with colleagues and eventually by publishing. Fragmentation may proceed to the point that communication becomes blocked, because the tacit infrastructure of ideas not only limits the individual but also the whole scientific community in their creative acts of perception. Both paradigms and specialization may cause fragmentation in this way. One very central thesis of Bohm’s is that a fragmentation has occurred in modern microphysics between mathematical formalism and informal discourse in microphysics. Differences in the informal discourse gave rise to an issue between Bohr and Einstein, as well as among later physicists. Bohm considers communication to be so central to perception that he speaks of perception-communication. The change in the language of physics occasioned by the development of quantum theory has led to a communication breakdown. Both Bohr and Einstein agreed on the mathematical formalism, but there is still no common informal language. Bohm believes that if Bohr and Einstein had been willing to entertain a free dialogue to eliminate the rigidities that block communication, then perhaps a new creative metaphor might have emerged for microphysics. In such a dialogue each person must be able to hold several points of view in a sort of active suspension, while treating others' views with the consideration he gives to his own. This would lead to the intellectual free play needed for a new creative metaphor.

Bohm proposes his hidden-variable interpretation for consideration in this spirit. He maintains that the interpretation of a formalism is something that is in the informal discourse, not in the measurements or the equations. This view is fundamentally contrary to Hanson's, who says the exact opposite. In Bohm's view all the available interpretations of the quantum theory, as with any other physical theory, depend fundamentally on implicit or explicit philosophical assumptions, as well as on assumptions that arise in countless other ways. The image of the hard-nosed scientist, who does not admit to the existence of the philosophical assumptions in the informal language, is just another example of the subliminal influence that is exerted on scientists by the tacit infrastructure of ideas shared by the scientific community at large.

Bohm on Mathematics and Scientific Discovery

In *Science, Order and Creativity* Bohm maintains that there is no difference between science and philosophy. While Hanson also states that physics is natural philosophy, Bohm's statement means something very distinctive. Bohm explicitly rejects the prevailing view of the aim of physics, which he says is to produce mathematical formalisms that can correctly predict the results of experiments. He maintains that, since quantum theory and relativity theory were never understood adequately in terms of what he calls physical concepts, physics gradually slipped into the practice of talking about equations. And he states that Heisenberg gave this practice an enormous boost with the idea that science can no longer visualize atomic reality in terms of physical concepts, and with the idea that mathematics is the basic expression of our knowledge of reality. Bohm maintains that the current emphasis on mathematics has gone too far. In stating that science is the same as philosophy, Bohm means that as philosophy had traditionally done, now science must unify knowledge instead of offering physicists a fragmentation as it has today. In times past there was a general vision of the universe, of humanity, and of man's place in the whole. But specialization in modern science became narrower and led eventually to the present approach, which is fragmentary. Bohm also opposes what he sees as another wayward aim of modern physics, which is to analyze everything into independent elements that can be dealt with separately. This further contributes to fragmentation. Bohm believes that the time has come to change what is meant by science. This change is to be implemented by a creative surge that will eliminate the fragmentation.

In the fourteenth chapter of *Undivided Universe* Bohm offers a somewhat more balanced statement of the relation between physical concepts and mathematical concepts. Again he says that the prevailing attitude today is take the present mathematical formalism of quantum theory as an essential truth, and then to try to derive the physical interpretation as something that is implicit in the mathematics. He denies that his own approach is simply a return to the historically earlier view that the mathematics merely enables the physicist to talk about the physical concepts more precisely. His view is that the two types of concepts represent two extremes, and that it is necessary to be in a process of thinking that moves between these extremes in such a way that they complement one another. He says he does not regard such physical concepts as particle, quantum wave, subquantum field, position, and momentum as mere imaginative displays of the meaning of the equations. He maintains that what he is doing with his hidden-variable interpretation, is moving to the other side of the extreme in the thought process and taking the physical concepts as a guide for the development of new equations. He says that the clue for a creative new approach may come from either side, and may flow back and forth indefinitely between them.

Bohm's Philosophy of Science

Aim of Science

Bohm's view of the aim of science contains a fundamental ambiguity. One aim is to supply a basically uniform and consistent ontology for science admitting variations at different orders of magnitude. But it does not admit to the inconsistency or pluralism that exists between quantum theory and relativity theory, which Heisenberg called the schism in physics, and which Bohm called fragmentation. This is the integrating aim that Bohm has in mind when he says that physics is philosophy. The other aim is the more conventional one in contemporary physics, the aim of producing more empirically adequate equations. Bohm maintains that these two aims of science need not and should not be divergent, even though lamentably they presently diverge. And he says that the fragmentation in contemporary physics is due to an exclusive concern with the formal language, the equations of mathematical physics.

Discovery

Bohm's philosophy of scientific discovery follows from these views on the aim of science. The fragmentation-produced divergence between these aims will be eliminated *and* both aims will be more adequately realized, if physicists attend to both the formal and the informal language, to both the mathematical and physical concepts. Employing figures of speech such as analogy and metaphor containing physical concepts will facilitate developing better equations.

Criticism

Bohm's views on scientific criticism do not lead him to invalidate the empirical adequacy of the Schrödinger wave function. Like other critics of the Copenhagen interpretation he advocates developing an alternative interpretation for the equations of the quantum theory. He never denies that the second aim of science, the production of empirically superior equations, is realized by the equations of the quantum theory. But just as there is an ambiguity in his aim of science, so too there is a corresponding dualism in his criteria for scientific criticism. He spent most of his career attempting to persuade the physics profession that there exists another criterion that is unabashedly philosophical. That criterion is the integrated, consistent ontology for both microphysics and macrophysics. And some physicists like John Bell have been persuaded to pursue this agenda.

Explanation

Bohm does not set forth an explicit statement of his philosophy of scientific explanation. But if satisfaction of the criteria for scientific criticism is taken as yielding a scientific explanation, then Bohm's philosophy of scientific explanation follows from his views on criticism. The salient consideration in this context is the role for a uniform and consistent ontology in his integration aim of science and its associated criterion for scientific criticism.

Hanson on the Copenhagen Interpretation and Scientific Discovery

Hanson rejects all three of the objectives in Bohm's agenda for future physics. His argument against Bohm's third objective that a future hidden-variable theory will resolve the difficulties in current quantum theory, is that Bohm and other advocates of alternatives to the Copenhagen interpretation offer nothing but promises. In *Quanta and Reality* Hanson calls Bohm's proposal a congeries of excitingly vague, bold-but-largely-formless, promising-but-as-yet-unarticulated speculations. The Copenhagen interpretation on the other hand is a working theory however imperfect it may be, and a speculation is never an alternative to a working theory.

Hanson's argument against Bohm's first objective that an alternative to the Copenhagen interpretation is possible, is similar to his criticism of the third objective. Hanson denies that an alternative to the Copenhagen interpretation is possible until a new mathematical quantum theory formalism is developed, because on his thesis the Copenhagen interpretation is not a semantics supplied by related philosophical or metaphysical ideas about the subject, but rather is the semantical interpretation resulting from the logicogrammatical form of the theory's mathematical formalism. Therefore contrary to physicists such as Bohm and Lande, and contrary to philosophers such as Feyerabend and Popper, the Copenhagen interpretation even after disengagement from what Hanson calls Bohr's naive epistemology, is not just one of several alternative semantical interpretations; it is a unique interpretation that is defined by the relationships in the mathematical formalism. In *Concept of the Positron* and elsewhere Hanson distinguishes the Copenhagen interpretation from what he calls the Bohr interpretation. He rejects efforts by philosophers such as Feyerabend to include what Feyerabend admits are the dogmatic elements of the Bohr interpretation in the Copenhagen interpretation. The dogmatic elements consist particularly in what Hanson calls Bohr's naive epistemology with its forms of perception. Perhaps it could be said with caution that with the rejection Bohr's naive epistemology Hanson's philosophy of quantum theory is one that Heisenberg might have formulated, had Heisenberg rejected Bohr's epistemological ideas which he included in his doctrine of closed-off theories, and instead followed through on Einstein's admonition that theory decides what the physicist can observe. With his rejection of the Bohr interpretation Hanson places himself in agreement with Bohm and Feyerabend, when the latter maintain that the quantum theory is not permanently valid, and he agrees that the current quantum theory may be superseded. But contrary to these authors he considers the wave-particle duality to be the defining characteristic of the Copenhagen interpretation and integral to the formalism. Because he maintains that the Copenhagen interpretation is defined by the logicogrammatical form of the mathematical formalism itself, he defends it as the only interpretation that works. He therefore says that in the absence of any algebraically detailed and experimentally adaptable alternative, the Copenhagen interpretation represents the conceptual possibilities currently open to practicing physicists, and that it will not be abandoned until it is completely replaced by an alternative, completely detailed, algebraically articulated theory.

Bohm's second objective in his agenda for future physics is that the history of physics suggests (contrary to a mechanistic thesis, as he uses that term) that the future microphysical theory will describe phenomena at the lower level of magnitude than does the current quantum theory, and that his proposal of a hidden-variable theory of the subquantum level may serve as a heuristic for future microphysics. The idea of developing a heuristic for future scientific discovery or theory development is closely related to Hanson's interest, and Hanson does not attack Bohm's second objective in terms of Bohm's antimechanistic historical thesis. But he has his own historical thesis influencing his views on scientific discovery. His analyses are greatly influenced by the Cambrian physicist Paul A. Dirac. Dirac (1902-1984) was a theoretical physicist at Cambridge University, who shared the Nobel Memorial Prize for physics in 1933 with Schrödinger. Dirac had published a methodological statement on the future of physics in his "The Evolution of the Physicist's Picture of Nature: An account of how physical theory has developed in the past and how, in the light of this development, it can perhaps be expected to develop in the future" (*Scientific American*, May, 1963). In this brief paper Dirac contrasted the theory development approaches of Schrödinger and Heisenberg. Dirac was much more sympathetic to the former's approach, according to which the development of physical theory should be guided by the aesthetics of the mathematics of the theory, in contrast to the latter's approach in which a mathematical formalism is developed by data analysis.

However, this is not the issue in Dirac's views that influenced Hanson, who was actually much more sympathetic to Heisenberg's approach in which theory originates with the experimental data. Hanson was influenced by Dirac's historic accomplishment, the transformation theory developed by Dirac in 1928, which not only combines relativity and quantum mechanical descriptions of electron properties, but also enables physicists to exhibit the wave-particle duality by transforming mathematically the wave description into the quantum description and vice versa. Both in his "Copenhagen Interpretation of Quantum Theory" in the *American Journal of Physics* (1959) and in his chapter "Interpreting" in *Concept of the Positron*, Hanson states that objections to the Copenhagen interpretation arise from a failure to appreciate the historical and conceptual role it had played in Dirac's 1928 paper, and he reports that in conversation with Dirac, Dirac told him that the Copenhagen interpretation figured essentially in his development of his relativistic quantum field theory, and not as merely a philosophical after-thought appended to the mathematical formalism. This personal conversation with Dirac more than anything explains Hanson’s motivation for maintaining that the Copenhagen interpretation is integral to the formalism of the quantum theory. He argues against Feyerabend that even if it were possible to have a minimum statement of quantum theory with no more interpretation than is required barely to describe the facts, this is what Dirac felt he had, and Dirac's paper would not have been the paper that it actually was, had its assumptions been purified of the Copenhagen interpretation, as Feyerabend advocates. But for his thesis of scientific discovery Hanson turned not to Dirac's aesthetic thesis, but to the logical thesis proposed by the founder of Pragmatism, Charles S. Peirce.

Peirce, Retroductive Logic, and Semantical Constraints in Discovery

Hanson was influenced by Charles S. Peirce, but he did not accept Peirce's views on observation. In his "How to Make Our Ideas Clear" (1878) Peirce set forth his pragmatic maxim, which says that our conception of the practical effects that we conceive an object might have, is the whole of our conception of that object. He distinguishes observed facts from judgments of fact, and says that observations have to be accepted as they occur, while judgments of fact are controllable. According to Peirce's theory of scientific discovery, hypotheses are judgments of fact expressed in propositions, and all such propositions are additions to observed facts that are sense impressions of singular events associated with particular circumstances. That which is added to observed facts by propositions Peirce calls practical knowledge, and it is something that is controllable and subject to error. Hypotheses are the result of inference, and Peirce distinguishes inductive and abductive types of inference. Abduction (which Hanson also calls retroduction) involves both formulating of hypotheses and then selecting of one hypothesis by testing its ability to account for surprising facts. The difference between abduction and induction is that the former involves guesswork and originality, while the latter only tests a suggestion previously made. Once the hypothesis is formulated, abduction is an inference that satisfies the following form: 1) a surprising fact, *C*, is observed; 2) if *A* were true, then *C* would be a matter of course; 3) hence, there is reason to hypothesize that *A* is true. This is actually a logical fallacy known as affirming the consequent clause of the conditional statement. Peirce says that Kepler's development of his three laws is the greatest piece of retroductive reasoning ever performed. He rejects J. S. Mill's view that Kepler merely generalized on Tycho's data, and that there was no reasoning in Kepler's procedure. Peirce maintains that at each step of Kepler's investigation, Kepler had a theory which approximated the data, that Kepler modified his theory to make his theory closer to the observed facts, and that the modifications were never capricious. Hanson adds that given a choice between two hypotheses, the simpler is preferable, where simplicity is to be understood not as a logical simplicity but rather as an instinctive simplicity, because unless man has a natural bent in accordance with nature's, he has no chance of understanding nature at all.

In his chapter on theories in *Patterns of Discovery* Hanson rejects both the hypothetico-deductive and the Positivists' inductive accounts of scientific discovery. He rejects the inductivist thesis that scientific theories are developed by an enumerating and summarizing of observable data, as the Positivists maintained for the development of empirical generalizations; he states that empirical laws explain, they do not simply summarize. He also rejects the hypothetico-deductive thesis that scientists start from hypotheses for the development of theories, as Popper maintained; he says that scientists do not start from hypothesis, but rather they start from data. The initial inference is not from higher level hypotheses to observations, but the other way around. The article setting forth his most mature views on retroduction is "Notes Toward A Logic of Discovery" in *Perspectives on Peirce* (ed. Bernstein, 1965), which includes summaries of Hanson's earlier papers. The logic of retroduction pertains to the scientist's actual reasoning, which proceeds from an anomalous situation to the formulation of an explanatory hypothesis that fits into an organized pattern of concepts. In *Patterns of Discovery* Hanson refers to the pattern of concepts as a conceptual *gestalt*, which functions to make the anomalous situation appear intelligible. The conceptual *gestalt* supplies the semantics for the theory or hypothesis. In Hanson's philosophy the semantics of observation is variable, while in Peirce's it is fixed and uncontrollable.

In “Notes...” he says that the formal criteria for the retroductive logic of discovery are the same as those for the hypothetico-deductive logic of explanation. They both contain the same elements: a hypothesis, statements of initial conditions, and the conclusion deductively derived from the hypothesis and statements of initial conditions. One difference between them is the direction of the inference. In the hypothetico-deductive logic the inference is from the hypothesis and statements of initial conditions of an experiment, to the statements describing the observed outcome of the experiment as a conclusion. This process is used for experimental testing, and if the results are not anomalous, it also serves as the logic of the explanation of the resultant phenomenon. But in the retroductive logic the direction of inference is in the opposite direction. The statement reporting an observed experimental outcome describes an anomaly relative to what is expected, and the problem is one of finding the hypothesis capable of functioning in a hypothetico-deductive account that will explain the anomalous situation as occurring as a matter of course. But the difference between the hypothetico-deductive and the retroductive types of inference is not just a matter of the directionality of the inference. They are also different because the former is determinate, while the latter is not. In hypothetico-deductive inference consistent premises must produce consistent and unique conclusions, while in the retroductive inference there may be many alternative and mutually inconsistent hypotheses that are able to explain deductively the formerly anomalous test outcome from the same set of statements of initial conditions. From this nondeterminate character of retroductive inference Hanson concludes that retroduction cannot yield a uniquely specific and detailed hypothesis. But he maintains that it can yield an indication of the type of hypothesis that is most plausibly to be considered as worthy of serious attention. And the decision about what type of hypothesis is the most plausible depends in turn on the structure of presently accepted theories and on the shape of the most reliable conceptual frameworks that highlight hypothesis types for the problem solver. Therefore, much as it is only against the background of the intelligible and the conceptually comprehensible offered by existing theories that the anomalies stand out at all, so it is also in these same terms that the scientist comes to know which types of hypotheses will do the job and which do not. Reflection on this analysis reveals why Hanson defends the Copenhagen interpretation, understood as the semantics that is defined by the formalism of the quantum theory. The Copenhagen interpretation is the type of hypothesis that (in Hanson's view) will most plausibly resolve the current anomalies to Dirac's relativistic quantum theory, just as it had enabled Dirac to develop his quantum theory in 1928.

Hanson also maintains that the conceptual *gestalten* constituting the semantics for currently accepted theories not only supply some guidance for the creation of new theories, but also offer what he calls conceptual resistance, which must be overcome for scientific discoveries. The development of a new theory requires a new *gestalt* just as in the reinterpretation of the ambiguous drawing, and similarly there is a resistance to such a change. In *Patterns of Discovery* Hanson illustrates this in the historical episode in which Kepler developed the theory that the orbit of Mars is elliptical. In formulating this theory Kepler had to reject the traditional belief held since Aristotle that the orbits of the planets are circular, because unlike sublunar motions the celestial motions are perfect. This is also the thesis in Hanson's most significant historical analysis set forth in his *Concept of the Positron*. This work is original historical research in which Hanson interviewed several physicists including the three principals in the episode: Carl Anderson, P.A.M. Dirac, and P.M.S. Blackett. All three physicists discovered the positron, but only Blackett recognized that the particle discovered experimentally by Anderson was the same one that was postulated theoretically by Dirac. Dirac's 1928 paper offered a relativistic quantum theory that was Lorentz-invariant, but it also contained negative energy solutions that could not be eliminated. Originally he had hoped that these strange solutions could be construed as protons, and then he thought of them as vacancies which are positive charge solutions with the mass of the electron. This constituted the gradual development of his prediction of the existence of positive electrons before they were observed. Anderson made photographs of electron tracks in the cloud chamber, and he concluded that one of them showed a positive electron, because the change of the particle was positive while its mass was too small to be that of a proton. Dirac had published his theoretical paper on the positron in 1931, a year before Anderson's photograph. In 1933 Blackett and Occhialini reported that the Anderson particle and the Dirac particle are the same thing, by using the new photographic technique in which the particles took photographs of themselves.

Hanson states that one reason Anderson did not recognize any connection between his cloud chamber experiments and Dirac's quantum theory, is that such experiments rely on concepts that are largely classical in nature such as track-leaving particles. But the greatest conceptual constraint, the one that led many physicists to reject the idea of the positive electron, was in the semantics of the concept of the electron. That semantics was such that an intimate association between the electron and the proton, and between the two basic units of electricity, negative and positive, made the very idea of a particle other than a proton or an electron very difficult to conceive. Just as positive/negative exhaust the totality of electrical charge, so too the proton/electron was thought to exhaust the totality of charged particles, since the proton and the electron came to be viewed not as carrying the charge but as being the charge. Hence there was a conceptual resistance to the idea of a third charged particle built into the structure of classical electrodynamics and the elementary particle theory.

Hanson on Perception, Observation and Theory

Hanson defends the Copenhagen interpretation, and he criticizes the hidden-variable interpretation and Bohm's agenda. He maintains that in microphysics all the limitations placed on our conceptions of what the microphysical world is like and what we can observe, are really limitations arising out of the linguistic features of the formal languages available. Such is particularly the case with Heisenberg's uncertainty relations. The uncertainty relations and Heisenberg's thought experiment involving a gamma-ray microscope are often said to state limits to the possibility of observation within microphysics. Hanson says that this is true in an unsuspecting way: there never have been nor could there ever be experiments or observations pertinent to the establishment of the uncertainty relations, because these relations are the conceptual or logical consequence of the language of quantum theory. In the formalisms for modern quantum physics there is a logicolinguistic obstacle to any attempt to describe with precision the total state of an elementary particle, and if there is a conceptual limit to such a description, then there is *ipso facto* a limit to such observation. The conceptually impossible is observationally impossible. Hanson's thesis is that theory is integral to observation or, as he also says, observation is theory-laden. This is also implied by Einstein's admonition to Heisenberg that it is the theory that decides what the physicist can observe. Hanson's is the same philosophy of observation that Einstein told Heisenberg in 1925, and that Heisenberg used to develop the uncertainty relations.

But Hanson was not led to develop his philosophy of observation by reflection on Heisenberg's autobiographical chronicles, in which Heisenberg relates his discussion with Einstein and the use that he made of it. Hanson identified Heisenberg's views on observation with those of Bohr, which Heisenberg included in his explicit and systematic philosophy. Nor was Hanson led to develop his philosophy in response to Feyerabend's criticisms of Bohr's dogmatic interpretation of quantum theory; Hanson's philosophy of observation was developed many years previously. His philosophy of observation was drawn from Wittgenstein's *Investigations* and from the *gestalt* psychology. It is necessary, therefore, to consider briefly Wittgenstein's ordinary-language philosophy and Hanson's use of it in his philosophy of science. Ludwig Wittgenstein (1889-1951) was a somewhat reclusive individual who wrote a somewhat unsystematic philosophy of language in a somewhat obscure style, and who is thought to have anticipated certain ascendant trends in philosophical thinking. In fact Wittgenstein seems twice in his lifetime to have anticipated successfully an ascendant trend in philosophical thought with his two principal works: firstly his *Tractatus Logicus-Philosophicus* (1922) and then later his *Philosophical*

Investigations (1953). The thesis of the latter explicitly includes a repudiation of the thesis of the former, yet each work gathered its own retinue of sympathetic interpreters and devout disciples. Both the *Tractatus* and its author attracted the attention of Schlick and his Vienna Circle (with the noteworthy exception of Carnap, who after his one and only meeting with Wittgenstein was unforgettably unimpressed). But in spite of Schlick's invitations to join the Vienna Circle, Wittgenstein remained aloof from them, just as he remained aloof from all other sublunar states of affairs.

About thirty years later the *Investigations* inspired philosophers who were becoming disillusioned with the technical pedantics of Logical Positivism, and its thesis occasioned the formation of a new philosophy of language. Conventionally historians of philosophy now refer to the two opposing dogmas in these two books as the ideal-language tradition and the ordinary-language tradition respectively. The ideal-language view set forth in the *Tractatus* has a reformist flavor, which accords special status to symbolic logic, such as may be found in Russell's *Principia Mathematica*. The *Tractatus* advanced an ideal (not metaphysical Idealist) interpretation for symbolic logic, consisting of what is called a picture-theory semantics. This is one of many variations on the naturalistic theory of the semantics of language, and it is also the most naive. This first book also advanced a constructionalist view of language. It described all sentences in the ideal language as consisting of elementary sentences, which in turn consist of semantically independent names of simple objects. All nonelementary sentences are constructable from the elementary ones. The former is said to be truth functional, which means that the truth of the constructed compound sentences depends completely on that of their component elementary sentences. As a result of this semantical atomism and logical constructionalism, the understanding of any sentence ultimately reduces to knowing its logical structure and what its constituent names reference. This is a variation on the mechanistic philosophy of the semantics of language, and was called logical atomism. The principal argument in defense of the ideal-language tradition is that ordinary language is unsuitably vague and misleading for philosophy, just as it is unsuitable for empirical sciences like modern physics, which rely on mathematics. The initial attractiveness of symbolic logic to philosophers of science was the expectation that it could serve philosophy as mathematics serves physics. This programme evolved into the Logical Positivist reductionist programme of Carnap and others such as Feigl and Hempel, in which the controlling agenda was the logical reduction of theories to a semantically significant observation language, in order to demonstrate the meaningfulness and semantics of the scientific theories.

But experience with the reformist efforts of the ideal-language philosophers, notably the Logical Positivists, led some younger philosophers to charge that ideal languages are even more unsuitable than ordinary language for philosophy, and that philosophical analysis should be directed toward the examination of colloquial language. The outcome was a new folk philosophy that is self-consciously naive. Wittgenstein anticipated this reaction, perhaps because it was also his own reaction to his own *Tractatus*, and he was led to develop his ordinary-language philosophy. Early statements of his new philosophy were set down in a set of notebooks later published as *The Blue and Brown Books* (1958), and the more mature statement is the *Investigations*. The latter work describes philosophy as a kind of empirical linguistics, and its main themes are (1) the variety of uses of language, (2) the need for the philosopher to consider statements not in isolation but in the context that occasions their utterances, and (3) the definition of meaning in relation to usage. Wittgenstein maintained that the problems of philosophy originate in philosophers' misunderstanding of certain crucial terms such as “know", "see", "free", "true", "reason", and that the resolution of these problems requires examination of the uses of these words as they occur in ordinary-language discourse. The later Wittgenstein seems clearly to have rejected the naturalistic theory of the semantics of language. He asks rhetorically in the *Investigations*, if the formation of concepts can be explained by facts of nature, then should the philosopher not be interested not in grammar, but rather in that in nature which is the basis of grammar. He answers that the philosopher is not interested in natural science or in natural history, and he affirms an artifactual theory of the semantics of language stating that a concept is comparable to a style of painting. But the artifactual theory that he accepts seems to be a wholistic one, since he states in the opening pages of *The Blue and Brown Books* that understanding a sentence means understanding a language.

Hanson was of the generation of philosophers who took their professional education after the Second World War, and he was also one of those who looked to Wittgenstein's new philosophy to rise above the inadequacies of the Logical Positivist philosophy of science. He was not an ordinary ordinary-language philosopher; he was firstly a philosopher of science, and if there was an ordinary language of interest to him, it was the language ordinary to contemporary physics including most notably microphysics. He was specifically drawn to Wittgenstein's comments in the

Investigations about seeing, in order to re-approach the subject of observation in physics, which modern quantum theory had made so problematic. Hanson's discussions about observation and theory are set forth in *Patterns of Discovery*, in "Observation and Interpretation" in *Philosophy of Science Today* (1967), and in *Perception and Discovery*. Hanson rejects the Positivist view that seeing is merely a matter of predetermined sensations, sense data, phenomena, or retinal reactions in the eye, and that interpretation is something added to the predetermined perception as a secondary and discrete step in the perceptual process. Instead he says there is more to seeing than meets the eye, and he follows Wittgenstein's view that interpretation is an integral component of seeing instead of something forced on it. The significance of this point is that perception is not predetermined and fixed by nature but is variable, and he illustrates this variability in perception by using both Wittgenstein's and others' ambiguous drawings that admit to reversible optical interpretations. He explicitly invokes Gestalt psychology (something that Wittgenstein did not do), to explain the reversibility of interpretations of ambiguous drawings as changes in the conceptual organization of what is observed. In this context Hanson references Duhem's example in *The Aim and Structure of Physical Theory* of the layman visiting a physicist's laboratory. The layman would have to learn physical theory before he could observe what the trained physicist observes. Duhem had described this commonplace state of affairs in terms of his Positivist semantics of observation and theory. But Hanson is a critic of Positivism, and he does not maintain any such two-tiered semantical thesis, as Duhem had. Hanson maintains that the postulated laboratory situation reveals that the elements of the laboratory in the visitor's field of perception are not organized as they are for the trained physicist. Physical theory provides the physicist with patterns within which data appear intelligible; it is what makes possible observation of phenomena as being of a certain kind and as related to other phenomena.

To illustrate his thesis that perception is theory-laden, Hanson uses the example of the second-century and the seventeenth-century astronomers who both look at the dawn. They both have the visual experience of the rising sun, but they do not see the same thing, because each believes different astronomical theories: the former, Ptolemy, believes in the geocentric theory, the latter, Galileo, in the heliocentric theory. Nevertheless, it can still be said that they see the same thing, since the sun could be described by both as a brilliant yellow disk. Hanson calls this latter kind of description phenomenal seeing, but he maintains contrary to the

Positivists that such phenomenal seeing is not the ordinary way of seeing. It is something that requires special effort, because seeing is normally interpretative, and is used when the observer is confronted with a new seeing experience in which case what is seen cannot be characterized by reference to his background knowledge. Observation in science aims to pass beyond the phenomenal seeing occurring in the case of the new experience, and to get the visual experience to cohere against a background of accepted knowledge.

The differences between *gestalten* are due to differences in previously acquired background knowledge, knowledge that involves language. Hanson is therefore led to follow Wittgenstein's ordinary-language analysis, because examination of commonly used locutions in colloquial discourse reveals the relation between language and the variability of interpretation in observation. The locution "seeing as" reveals that seeing is to see an object as a certain kind of thing, which is brought out by the verbal context in which the locution occurs. The text in its context supplies the interpretation. But his thesis is still stronger than merely stating that language reveals an interpreting conceptual component; he invokes the locution "seeing that" to exhibit a necessary role for language in interpretation. The idea of "seeing that" explains the relation of "seeing as" and the observer's background knowledge: to see something as a certain kind of thing is to see that it behaves in a certain known and expected manner. The "seeing that" locution supplies a statement of the background knowledge, which can be true or false. Seeing is therefore a theory-laden activity in the sense that the seeing is interpreted by reference to our background knowledge. Without a linguistic component to seeing, nothing we saw could be relevant to our knowledge. Before the wheels of knowledge can turn relative to a given visual experience, some assertive or propositional aspect of the experience must have been advanced. Only statements can be true or false; visual experiences must be cast into the form of a language to be considered in terms of what we know to be true, i.e. in terms of our theories.

Furthermore, Hanson's thesis is not only that language is necessary for the interpretation that is integral to perception, but also that the logicogrammatical form of the language used for description exercises a formative control over the interpretative thinking that occurs in perceiving. Just as seeing may be stated locutions which are "that..." clauses, so too can facts and theories. For this reason Hanson says that Ptolemy could not express in the second century what were facts for Galileo fifteen centuries later. Physical concepts are intimately connected with the formalisms and notations in which scientists express them, including the formalisms used today in contemporary microphysics. The dependence of physical concepts on the mathematical formalisms is a very strategic consideration in Hanson's rejection of attempts by Bohm and Feyerabend to propose interpretations of the uncertainty relations and the Schrödinger wave function that are alternatives to the Copenhagen interpretation of modern quantum theory. For Hanson the Copenhagen interpretation is precisely that interpretation which is supplied by the formalism of the modern quantum theory, because contrary to both the Positivists and to Bohr, it is the formalism that supplies the intelligible patterns and conceptual organization in perception for the observations relevant to microphysics. Interestingly in his *Primer of Quantum Mechanics* (1992) Chester Martin explicitly exhibits Dirac’s notational system as a language, and references the linguistic philosophy of Benjamin Lee Whorf.

Hanson further follows Wittgenstein when he maintains that the meaning of a sentence is its use, and that there are multiple uses for a sentence. Thus he states that the laws and theories of physics have many uses, and not just one, as most philosophers have maintained. The contingently empirical status of a statement is one of the uses of the theory in science. Another is to make the phenomena cohere in an intelligible way, such that empirical disconfirmation does not result in the negation of the concept described by the theory, but rather results in no coherent concept at all. The dynamical laws of classical physics, for example, are a system of propositions that are empirically true, and the fundamental propositions on which the system rests are empirically true. But these fundamental propositions are also treated as axioms, such that the system delimits and defines its subject matter. Then nothing describable within the system could refute its law statements; disconfirmatory evidence counts against the system as a whole, and only shows that the system does not hold, where formerly it was thought to hold. Hanson calls this use of laws and theories functionally *a priori*. These ideas are reminiscent of Heisenberg's comments in "Questions of Principle in Modern Physics", in which he says that it is not the validity but only the applicability of classical laws, which is restricted by modern relativity and quantum physics. Hanson does not reference Heisenberg, but his thesis of the functionally *a priori* use of laws and theories is in this respect similar to Heisenberg's doctrine of a closed-off theories, with the noteworthy exception that Hanson does not reserve certain axiomatic systems such as classical mechanics for observation in physics, as does Heisenberg in his explicit philosophy of physics. Heisenberg's philosophy of observation in his doctrine of closed-off theories does not admit the variability in perception that Hanson's philosophy asserts. Instead in his explicit philosophy Heisenberg followed Bohr's thesis that there are forms of perception that are found only in colloquial language and in its refinements in classical physics.

Hanson's semantical investigations sometimes took a turn away from the wholistic approach of Gestalt psychology. In the chapter on classical particle physics in *Patterns of Discovery* he considers the idea that the meanings of some names have their properties built into them, such that falsification of statements predicating those properties of the named substances is effectively impossible. And in "Newton's First Law: A Philosopher's Door into Natural Philosophy" in *Beyond the Edge of Certainty* (1965), he states that rectilinearity, motion *ad infinitum*, and free force, are conceptions within classical mechanics that are interdependent, in such a way that it is possible to treat the idea of uniform, rectilinear motion *ad infinitum* as itself built into the notion of free force, as part of the latter's semantical content. The terms in Newton's first law are semantically linked: the meaning of some of its component terms unpacks sometimes from one or two of the others, but then sometimes the meaning of these unpacks from that of the first. Which are the contained and which are the semantical containers can affect the logical exposition of any mechanical theory built thereon. These are semantical decisions which guarantee that in different formalizations of Newton's theory different meaning relations will hold between the law's constituent terms. The term “unpack” in connection with semantical analysis is a phrase used by the early Pragmatist philosopher William James, although Hanson does not reference James. It is unclear whether or not Hanson ever thought of this type of semantical analysis as an alternative to his frequent recourse to Gestalt psychology. Nevertheless it is an alternative approach in semantical analysis, because it is not wholistic. On the *gestalt* thesis it is not possible to unpack a *gestalt* into its component parts, because the *gestalt* is more than a mechanical organization of its parts. In his discussions of quantum theory Hanson never exploited this mechanistic or logical analysis of meanings into component parts.

HANSON, BOHM AND OTHERS

Hanson's Philosophy of Science

Aim of Science and Discovery

Hanson's ideas about the aim of science pertain to what he calls research science, as opposed to what he calls almanac science, and are integral to ideas of scientific discovery. In his "Introduction" in *Patterns of Discovery* he states that in a growing research discipline, inquiry is directed not to rearranging old facts and explanations into more elegant formal patterns, but rather to the discovery of new patterns of explanation. The idea that observation is theory-laden is strategic to this purpose. In the chapter titled "Observation" in *Patterns of Discovery* he states that the scientist aims to get his observations to cohere against a background of established knowledge. This kind of seeing is the goal of observation. And similarly in the last chapter titled "Elementary Particle Physics", the area of contemporary physics that he says is presently a research science, he states that intelligibility is the goal of physics, the conceptual struggle to fit each new observation of phenomena into a pattern of explanation. Often the pattern precedes recognition of the phenomena, as Dirac's theory of 1928 preceded discovery of the positron, the antiproton, and the antineutron. But then Dirac's pattern was itself the outcome of an effort to find a suitable explanation for prior phenomena, namely a unified, relativistically invariant theory of electron spin, which would give the correct fine structure formula, explain the Zeeman effect of the doublet atoms, describe the Compton scattering, and supply a model of the hydrogen atom.

Explanation

Hanson offers an evolutionary perspective on scientific explanation. In the third chapter of *Concept of the Positron* he states that the concept of scientific explanation has experienced a historical evolution that follows upon the historical development of physics. Leibniz denied that Newton's theory offers explanation, even though he admitted that it offers acceptable predictions. Today the concept of explanation advanced by the Positivists, such as Hempel, is based on the concepts of Newton's physics including notably the deterministic thesis that explanation implies deterministic prediction. The concept of explanation implied in the nondeterministic quantum theory is not yet accepted. Hanson states that if just after Leverrier had predicted the existence of the planet Neptune in 1847, a time when

Newtonian physics had reached its apex, some physicist who had proposed a new theory that explained all that Newton's theory explained and furthermore explained several minor flaws in Newton's theory, the new and better theory would have been viewed as merely a predictive device, not an explanation. But if Newton's theory then began to show major weaknesses, while the new theory succeeded where Newton's had failed, still these accomplishments would decide nothing. The scientists would begin to show increasing reliance on the new theory, yet it would not be accepted as an explanation. All the same, younger physicists would develop the new theory further. Finally if Newton's physics had begun to fall apart while the new theory opened up new branches of science, focused on problems never before perceived, fused disciplines previously thought to be distinct, and sharpened experimental techniques to an unprecedented degree, then the very pattern of thinking in an inquiry properly called scientific would reflect the new physics with its new concept of scientific explanation; to be able to cope with a scientific problem at all, would be to have become able to build it into the conceptual framework of the new physics.

Hanson distinguishes three stages in this process of the evolution of a new concept of explanation; they are the black box, the gray-box, and the glass box. In the first stage, the stage of the black box, there is an algorithmic novelty, a new formalism, which is able to account for all the phenomena that an existing formalism can account for. Scientists use this technique, but they then attempt to translate its results into the more familiar terms of the orthodoxy, in order to provide understanding. In the second stage, the stage of the gray box, the new formalism makes superior predictions in comparison to the older alternative, but it is still viewed as offering no understanding. Nonetheless it is suspected as having some structure that is in common with the reality it predicts. In the third stage, the stage of the glass box, the success of the new theory will have so permeated the operation and techniques of the body of the science that its structure will also appear as the proper pattern of scientific inquiry. Hanson says that quantum theory is in the second stage, because scientists have not yet ceased to distinguish between the theory's structure and that of the phenomena themselves. This evolution is the gradual adoption of the practice of scientific realism, in which (to mix metaphors) the glass becomes the spectacles through which reality is seen. Explanatory langauge is customarily thought to be explanatory, because it describes the real causes of the phenomena explained. Therefore, the concept of causality also undergoes the kind of evolution that occurs with the concept of explanation. In the chapter titled "Causality" in *Patterns of Discovery* Hanson says that cause words are theory-laden; they are the details in an intricate pattern of concepts. Causes are connected with effects, but only because theories connect them, not because the universe is held together with a cosmic glue. Questions about the nature of causation are to a large degree questions about how certain descriptive terms in definite contexts coupled together complement and interlock in a pattern of other terms. The elements of explanation, causation, and theorizing become worked into a comprehensive language pattern.

Criticism

Hanson's discussion of scientific criticism is principally concerned with the topic of crucial experiments. He takes up the topic in a chapter in *Concept of the Positron* in which he discusses the different concepts of light in the history of physics, and he discusses it again later in a special chapter in *Perception and Discovery*. Hanson's rejection of the idea of crucial experiments has its basis in his thesis that observation is theory-laden. A commonly referenced example of a crucial experiment is Foucault's 1850 crucial test between the wave and particle concepts of light. In that experiment Foucault demonstrated that light travels more rapidly in air than in water. According to the doctrine of the crucial experiment the corpuscular hypothesis should have been banished forever. But this has not happened. The photoelectric effect and the Compton effect can only be explained on a corpuscular theory of the nature of light. The experiments are not crucial, because the observations are important only against the assumptions, theories, and hypotheses that are in the balance before the experiment is performed. One of the assumptions is that light cannot be both wave and particle. The crucial test is a test of the alternative hypotheses together with all of their assumptions, just as in ordinary scientific observation there is a pure registration or sensation plus all of the assumptions necessary to give those sensations meaning. If we were forced to revise our assumptions, then the crucial experiment must be re-interpreted, so that it need not decide against one of the hypotheses. Some of the most profound revolutions in modern science have consisted not in the criticisms of old hypotheses, but in the criticism of the assumptions underlying the hypotheses. Crucial experiments are crucial against some hypothesis only in relation to a stable set of assumptions that we do not wish to abandon. But no set of assumptions is permanently valid. Hanson says that crucial experiments are out of the same bag as pure observations and uninterpreted facts; they are philosophers' myths.

Wittgenstein said language has many uses. Hanson's discussions of crucial experiments pertain only to theories that may intelligently be disconfirmed. Although in principle all statements of science are testable and can be falsified, in practice theories often have another use or function. Following Wittgenstein's thesis that language may have many uses, Hanson maintains that theories functioning as pattern statements supplying a conceptual *gestalt* will not yield an intelligible statement negating the theory, if the theory is viewed as disconfirmed. This is because the theory gives the phenomena their intelligibility; and this explains why scientist will not reject a theory even while they recognize the existence of anomalies that are not intelligible in the theory. What scientists do in practice is to attempt to save the theory with small modifications or wait until a new and more adequate theory is proposed that explains all that the old theory explains as well as the anomalies to the old theory. Anomalies do not make scientists give up intelligibility. It is for this reason that physicists have not given up the Copenhagen interpretation in spite of the anomalies confronting Dirac's theory. Thus Hanson, opposing Bohm in the "Postscript" chapter in *Quanta and Reality*, states that dropping orthodox quantum theory right now would be to stop doing microphysics altogether. Then Hanson immediately adds that should the heretics (Bohm *et al*.) succeed in accounting for everything that orthodox theory now describes, and do so without the divergence difficulties and the renormalization nuisance even without the uncertainty relations and the irreducibly statistical laws, should they do all this, then physicists of the world will be at their feet, and science will have ascended to a new plane of power and fertility.

Hesse on Models and Analogy

Quanta and Reality (1962) is a collection of discourses initially broadcast as a radio series by the BBC in 1961. It includes a dialogue involving Bohm, a "Postscript" commentary by Hanson, and a commentary titled "Models and Matter" by the Cambridge University philosopher of science, Mary B. Hesse. Hanson's comments are generally critical of Bohm; Hesse’s are more sympathetic. This alignment among the participants is not limited to the specifics about the contemporary quantum theory; it divides along issues about the semantics of scientific theories in general and also about the role of semantics in scientific discovery. All participants have much to say about the semantics involved in scientific discovery.

On Hanson's view the semantics of a theory is determined completely by the mathematical formalism and the measurements that the equations of the formalism relate. The relations expressed by the theory including its grammatical/mathematical form determine the conceptual *gestalt*, which constitutes the semantics of the theory. And in the case of quantum theory the Copenhagen semantical interpretation with its wave-particle duality thesis is integral to the mathematical formalism of the quantum theory. Furthermore the semantics of the quantum theory so understood is strategic to the further development of microphysics, as evidenced by the fact that Dirac said he relied on it for his development of his field quantum theory. Hanson does not deny that there may also be other language about the microphysical domain explained by the equations of the quantum theory, language that does not contradict the quantum theory. But he views such supplementary language as mere philosophy, and not as part of the theory itself. He places Bohr's naive epistemology in this category of supplementary philosophical language.

Opponents to the Copenhagen interpretation agree with Hanson that semantics has a strategic role in scientific discovery. But they do not agree that the Copenhagen interpretation is integral to the formalism of the theory. They are motivated to disagree not only because some of them propose alternatives to the wave-particle duality thesis, but also because in general they maintain that there is more that determines the semantics of theories than just the formalism and measurement concepts. The source of this additional semantics that they say is found in many if not all theories, is the nonliteral figurative and often imaginative language, which they find historically characteristic of theories in physics. This figurative language involves analogies and metaphors, and the distinctively additional semantics is often called a model. This is one of several common meanings for the term model, and in the present context the term functions to articulate the different views on the issue at hand. Unlike Hanson, Hesse views the ideas of waves and particles as theoretical models for quantum theory, and her view proceeds from a sophisticated examination of these questions.

Hesse's views about the semantics of theories are influenced by her former mentor at Cambridge, R. B. Braithwaite, a Logical Positivist philosopher of science. Their views are similar but not the same. Both Hesse and Braithwaite are Positivists, and thus distinguish observation and theoretical terms, although Hesse’s views evolved beyond Positivism later in her career. The distinction between observation and theoretical terms produces for Positivists the peculiar problem as to how theoretical terms contained in a semantically uninterpreted formal calculus can be meaningful instead of meaningless or metaphysical. In his *Scientific Explanation* (1953) Braithwaite distinguishes two sources of semantical interpretation for an uninterpreted formal calculus containing theoretical terms: Firstly the formal calculus may receive its semantical interpretation that makes it a meaningful scientific theory containing theoretical terms, when the logically posterior statements of implied consequences, the observation sentences, determine the meaning of the theoretical terms in the calculus of the logically prior premises. Theoretical terms are thus said to receive indirect meaning, since their meanings are determined by their contexts in relation to one another and to the sentences expressing the observable directly testable outcomes, which the experimentalist can logically derive from them. In other words the meanings of the theoretical terms are indirect, because they receive all their semantics contextually and not ostensively, as do observation terms. Braithwaite labeled this view contextualism. Yet Braithwaite also maintains that a good theory is capable of growth, such that it must be an alternative way of describing the empirical statements upon which it is based. Therefore he admits that the meanings of the theoretical terms need not be limited to being contextually defined explicitly, because the indirect contextual interpretation does not satisfy this growth criterion for theories.

Then Braithwaite states secondly that a theory may furthermore be given an interpretation by another source called a model. A model is additional language that contributes meaning to the terms, both those occurring in the premises and those in the conclusions, both to the theoretical terms and the observation terms. Most notably, unlike the contextual definition the model is not a *literal* interpretation for the domain explained by the theory. Thus Braithwaite says that theories and models have different epistemological structures, even when they have the same calculus. It might also be said that the introduction of the model makes the theoretical terms equivocal with one meaning the literal one defined in context and another the nonliteral one defined by the model language. For example according to Braithwaite the solar system may serve as a model for the hydrogen atom, even though it is understood that the atom is not literally to be taken as a solar system. Braithwaite says that thinking of theories by means of models is always "as-if" thinking, e.g. thinking of the atom as if it were a solar system. But he makes an exception for quantum theory: he says that for the physicist, Schrödinger's wave function is exhaustively interpreted in terms of its use in the calculus of the quantum theory, and he states in a footnote that no one supposes that the wave function denotes a wave in any ordinary sense of wave. In Braithwaite's view modern quantum theory does not have any model.

Hesse's semantical theory is set forth in her *Models and Analogies* (1953) and also in her article "Models and Analogies in Science" in *The Encyclopedia of Philosophy* (1967). There she compares two earlier conflicting protagonists in the issues of models and the semantical interpretation of theories. One is Duhem, and the other is Campbell whose views on the semantics of theories is more like Hesse's than Braithwaite's. In his *Aim and Structure of Physical Theory* Duhem had argued a view similar to Hanson's that the semantics of a physical theory is determined only by the equations and measurement concepts, and that even if models based on analogy with more familiar phenomena have served some heuristic value for developing the new theory, nonetheless these models are not part of the theory itself and may be discarded after the theory is constructed.

On the other hand in his *Physics, The Elements* (1920) the Cambrian philosopher Norman R. Campbell argued that analogically based models are not merely dispensable aids, but rather are indispensable to a theory, because they assist in the continuous extension of the theory. He argued that the Positivists' hypothetico-deductive form of explanation alone is insufficient to account for the role of theory in science. He maintained that in addition to the three elements, (1) the formal deductive system of hypothesized axioms and theorems, (2) the dictionary for translating some of the descriptive terms in the formal system into experimental terms, and (3) the experimental laws such as the gas laws, which are confirmed by empirical tests and also can be deduced from the system of hypothesis plus dictionary, there is a fourth element in theories, namely (4) the analogy, such as may be exemplified in gas theory by the model of point particles moving at random in the vessel containing the gas. The motivating intent behind this view is that scientific theories are not static museum items, but rather are always growing as an integral part of the growth of science; and this latter view, which might be called the Cambrian thesis, is the one that is accepted by both Braithwaite and Hesse.

But her views are not quite the same as Braithwaite's. Most notably unlike Braithwaite, Hesse does not distinguish the semantics of theoretical terms from the semantics of models. In fact for Hesse it is the models that supply the indirect meaning had by the theoretical terms. And since extrapolation on the basis of the models explains how the theories grow, Hesse's interest in the semantics of theoretical terms leads her into the topic of scientific discovery. Hesse also differs with Braithwaite about the interpretation of quantum theory. She believes that the concepts of wave and particle supply modern quantum theory with two contrary models. In her examination of analogical models Hesse distinguishes three parts to an analogy, which she calls the positive analogy, the negative analogy, and the neutral analogy. The positive analogy consists of those aspects of some familiar phenomena which are known to apply to the phenomenon explained by the theory. These include the similarities that have occasioned recognition of the analogy in the first place. The negative analogy consists of those aspects of the familiar phenomena that are known not to apply or are known to be irrelevant to the phenomenon explained by the theory, and the theorist ignores them. Hesse views the neutral analogy as strategic for scientific discovery. The neutral analogy consists of those aspects of the familiar phenomena whose relevance to the problematic phenomena in the domain of the theory is presently unknown, and therefore whose explanatory potential for further development of the theory is not yet known. She calls the semantics supplied by the neutral analogy, i.e. the concepts and conceptual relations not present in the empirical data alone, what she also calls the “surplus” meaning. She also uses the phrase open texture property of meaning without referencing any previous usage of the phrase in the literature. The further theoretical exploration of the problematic phenomena will be guided by the neutral analogy. Exploitation of the model for scientific discovery consists in investigating this neutral analogy, because it suggests modifications and developments of the theory that can be subsequently tested empirically. Such in Hesse’s view is how neutral analogies enable theories to grow.

In "Models and Matter" Hesse says that in quantum theory the wave and particle models are such that what is positive analogy in the one model is negative analogy in the other. She also says without elaboration that in the two models there are still features that physicists cannot classify as either positive or negative, and that it is due to these features that the particle and wave models are yet essential. Like Bohm, Hesse says that if physicists were forbidden to talk in terms of models at all, then they would have no expectations, and would be imprisoned forever inside the range of existing experiments. In her discussion of subquantum theories in the chapter “Modern Physics” in her *Forces and Fields: The Concept of Action at a Distance in the History of Physics* (1962) she expresses agreement with Bohm’s thesis that a new quantum theory postulating a subquantum order of magnitude is possible. Specifically she rejects the Copenhagen thesis that current formulations of quantum theory and current models of physical reality are unalterable. She says that if two models each turn out to be unsatisfactory in isolation, but usable when regarded as complementary to each other, it is curiously conservative to assert that no other models can be conceived and to elevate the principle of complementarity to a quasimetaphysical status, when it should instead be regarded as a consequence of the poverty of our imagination. She adds that it may be very difficult to conceive new models, especially when it is remembered that they cannot be entirely abstract formalisms because they must be tied to the observable at some level, but difficulty does not entail logical impossibility.

Hesse on Metaphor

The thesis that analogically created models supply nonliteral interpretation for theoretical explanations leads Hesse to consider also the semantics of metaphorical language. In her "Explanatory Function of Metaphor" in *Logic, Methodology and Philosophy of Science* (ed. Bar-Hillel, 1965) she states that her views are significantly influenced by the interactionist concept of metaphor proposed by her Cambrian colleague Max Black in his *Models and Metaphors* (1962). Black opposes his interactionist view to the comparison view. On his rendering of the comparison view the metaphorical statement is nonliteral for two reasons: Firstly if it is taken literally, it is a false statement. Secondly it can be restated as an exhaustive list of similes, which are literal statements expressing the similarities implied in the metaphor. In other words in rejecting the comparison view Black rejects the thesis that metaphors are elliptical similes. In her paper on the function of metaphor in theoretical explanation Hesse distinguishes a primary system and a secondary system, where both systems may be taken as real or physical systems that are described literally. The metaphoric use of language to describe the primary system consists of transferring to the description a word or words that normally are used in connection with the literal description of the secondary system. In a scientific theory the primary system is the domain of the *explanandum*, the statements that describe the explained phenomenon in an observation language, while the secondary system is the domain of the *explanans*, the statements constituting the explanation and containing either observation language or a familiar theory from which the explanatory model is taken. The explanation of the *explanandum* for the primary system consists of statements that metaphorically use vocabulary describing the secondary system and that are applied to the primary system on the basis of some similarity or analogy.

In his statement of his interactionist thesis Black lays down a criterion for the literal equivalence of a metaphor: the metaphor can be re-expressed as an exhaustive list of statements expressing all the similarities in the metaphor as literal similes. Then he rejects the possibility of reducing the metaphor to such a list of similes, because such a list can never be exhaustive. This inexhaustibility is especially important to Hesse, because the possibility of indefinitely extending and explaining the metaphor constitutes the fruitfulness of the explanatory model containing the metaphorical language. But the thesis that metaphor cannot be reduced to literal language is not all there is to Black's interactive view of metaphor. The interactive thesis is called interactive, because the metaphorical use of language is seen as changing the literal meanings of the words that are used metaphorically; there is an interaction of the meanings of the words in their descriptions of both the primary and secondary systems. For example the metaphorical statement "Man is a wolf" makes wolves seem more human and men seem more vulpine. This is contrasted with the comparison thesis, which purportedly assumes that the literal description of both primary and secondary systems is unaffected by the metaphor, such that the meanings of the terms remain semantically invariant. In Hesse's view the semantical variance postulated by the interaction view of metaphor is relevant to scientific explanation, because metaphor changes the semantics of the observation language. This thesis distances Hesse from the Positivists, for whom the observation language must remain completely uncontaminated by theoretical language. Hesse sees this meaning variance in the observation language as contrary to the assumptions of the hypothetico-deductive account of explanation, in which it is assumed that descriptive laws pertaining to the domain of the explanandum remain empirically independent and semantically invariant through all changes of explanatory theory. She therefore advances the view that the deductive model of explanation should be modified and supplemented by a view of theoretical explanation as metaphoric redescription of the domain of the explanation.

The interactive view of metaphor advanced by Black and used by Hesse, is not the prevailing view. Conventionally metaphor is construed as an elliptical simile containing implicitly the idea of an underlying similarity that can be explicitly and literally expressed by a simile with the words "like" or "as". For example in his *Philosophy of Language* (1964) William

P. Alston sets forth what may be taken as the comparison thesis of metaphor. Like Black and Hesse, Alston maintains that metaphor has an indeterminacy in it that is inexhaustible. But he also maintains that it is a mistake to believe that metaphorical and literal language are different kinds of meaning. On Alston's view the difference between metaphorical and literal language is one of degree, where literal language may be identified with established usage and metaphor is a new usage that is derived from established usage. All meanings are literal meanings, and the derived and unconventional usage in a metaphor may be expressed literally with greater or lesser extent of explanation. When the new usage is forgotten, the metaphor becomes a dead metaphor in the sense that it is dead and buried. But when it has become part of the established usage, then the metaphor has become a dead metaphor in the sense that it has become part of the conventional literal language, and explanation of its derivation from the original established usage becomes an exercise in etymology. Furthermore unlike Black or Hesse, Alston does not say that metaphor must be capable of being reduced to an exhaustive list of similes, in order to be reduced to literal use, because there is indeterminacy in literal language as well as in metaphor. Alston references Friedrich Waismann's "Verifiability" in *Logic and Language* (1952) stating that literal words denoting physical objects have an inexhaustible vagueness which remains even after all attempts at clarification. This vagueness remains because in addition to actual cases of indeterminacy of application, one can think of an indefinite number of possible cases in which one would not know what to say. Waismann calls this inexhaustible vagueness the “open texture” of descriptive language. Alston denies that metaphor is simply vagueness, but he says that in both metaphorical and established language there is an inexhaustible indeterminacy due to the fact that it is impossible to decide in advance on every possible usage of a word.

The conclusion to be drawn from this is that Black's criticism for the reduction of metaphor to literal language by means of an exhaustive list of similes is not a feasible criterion, because it would demand more determinateness of nonliteral language than of literal language. A weaker criterion therefore is in order. It would seem sufficient to require only that a metaphor be re-expressible with at least one simile that makes explicit an implicit underlying similarity, presumably but not necessarily the similarity that is intended by the speaker or writer initiating the metaphor. Furthermore semantical variability or meaning variance must therefore be a property of both metaphorical and literal language, or it must be a property of neither, since the former is merely the elliptical expression of the latter.

These considerations are relevant to Hesse's thesis about metaphor in theoretical explanation in science. Her tacitly assumed premise is that meaning variance does not occur in literal language, i.e. in the absence of metaphor. On this premise the nonreducibility of metaphor to literal language is strategic to her rejection of the adequacy of the hypothetico-deductive thesis of theoretical explanation, and it is strategic to her reliance on metaphor to account for semantical change or meaning variance in the language for description of observed phenomena. On the other hand if as Alston says metaphor is reducible to literal language, then semantical variability must be a property of both metaphorical and literal language, or it must be a property of neither. And it is clearly a property of metaphor; otherwise there would be no dead metaphors indicating that the new metaphorical use has either been forgotten or has become a new alternative literal use. Thus the reducibility of metaphor to conventional literal language implies that metaphor cannot satisfactorily be used as a general explanation of semantical change in science, even if it can serve to indicate that semantical change has occurred relative to currently established meaning. The theory-laden character of observation discourse resulting from theory revision is a much more general aspect of the semantics of language than just its metaphorical usage. The explanation of semantical change or meaning variance demands a general theory of semantical description for all literal language. At the same time metaphor seems clearly to have a role in occasioning semantical change, and it may have a strategic utility for the development of new theories in science.

Two decades after these 1960's-vintage papers on analogy, metaphor, and models Hesse finally reconciled herself to the artifactual thesis of the semantics of language and the phenomenon of pervasive meaning variance in the semantics of descriptive terms. But her pathway was a circuitous one. In her *Construction of Reality* (1986), co-authored with Michael A. Arbib, she says that her starting point is Max Black's interaction theory of metaphor as modified in the light of Wittgenstein's family-resemblance theory of meaning. At the end of her philosophical trek she is not consistent with Black's irreducible separation of literal and metaphorical meanings, although she continues to advocate it. Firstly she rejects literal meaning understood as invariant meaning, and announces (placing her own words in quotes) that all language is metaphorical, a phraseology that she says some will find shocking. It might better have been described as mocking the meaning of literal. Her thesis is that the use of general terms is always metaphorical in the sense of relying on perceived similarities and differences between various individuals, similarities that are family resemblances for which a term has been acceptably used in the past. She dichotomously opposes Wittgenstein's family-resemblance thesis to the Aristotelian natural-kinds thesis. She says that either the world is really Aristotelian, such that objects really fall into sharply discriminated species; or in practice we allow that language works by capturing *approximate* meanings, such that *degrees* of similarity and difference are sufficiently accessible to perception to avoid confusion in ordinary usage. Hesse believes that the second option is more realistic. She adds that it implies we lose potential information every time we use a general descriptive term - either information that is present to perception but neglected for purposes of the description (e.g. no one discriminates *every* potential shade of red), or information present in reality but below the level of conscious perception. In the latter case the information may later be made accessible by instrumental aids such as microscopes, etc. Understood in terms of the family-resemblance analysis, metaphorical shifts of meaning depending on similarities and differences between objects are pervasive in language - not deviant - and some of the mechanisms of metaphor are essential to the meaning of any descriptive language whatever. She explains that this is what she means by her thesis that all language is metaphorical. This peculiar outcome is due to her identification of the naturalistic thesis of the meaning of terms, which she calls semantical naturalism, with the concept of literal meaning, and is also due to her earlier conclusion that metaphor enables a nonliteral redescription of observed phenomena in scientific explanation.

Yet she does not abandon altogether the intuitively recognized distinction between literal and metaphorical usages in language. Having firstly rejected the meaning-invariant idea of literalness she then secondly redefines the meaning of "literal" by making the distinction between literal and metaphoric pragmatic instead of semantic. And it is here that Black's interactionist thesis would seem to serve her no longer, because what now distinguishes metaphor from the literal is not Black's semantical irreducibility but rather conventionality. In fact rejecting Black's irreducibility thesis would seem implied by a pragmatic distinction, because she says that her new definition of "literal" merely enshrines the use that is most frequent in familiar context - the use that least disturbs the network of meanings. It is the one generally put first in dictionary entries, where it is followed by comparatively dead metaphors. And metaphor denotes particular forms of literary expressions that depend on explicit recognition of similarities and analogies. For example "Richard is a lion" is a metaphor, because it based on elaborate analogy between particular human and animal dispositions, in which the obvious differences between human beings and lions are consciously discarded. A metaphor in this sense is usually recognized only when it is newly minted. When metaphors become entrenched in a language, they become a new literal usage. Such is the fate of dead metaphors.

Hesse says scientific language conforms closely to her metaphorical model of meaning. Not only is theoretical explanation a metaphoric redescription of the domain of the phenomena, as she said in the 1960's, but now she also says that scientific revolutions are metaphoric revolutions. In her earlier years as a Positivist, Hesse had been critical of Kuhn often referring to his views pejoratively as historicist. Now using the Kuhnian terminology and referencing Kuhn she says that in the development of science a tension always exists between normal and revolutionary science: normal science seeks to reduce instability of meaning and consistency and to evolve logically connected theories. Revolutionary science makes metaphoric leaps that are creative of new meanings and applications and that may constitute genuine theoretical progress. Ironically in his later writings Kuhn rejected Hesse's thesis that all meaning is metaphorical, and he embraced Black's interactionist view.

Comment and Conclusion

Contrary to often expressed opinion the topic of scientific discovery has not been a neglected one in philosophy of science. The above survey reveals that many philosophers and scientists have addressed it with a semantical approach using figures of speech. But no application of a metatheory of scientific theory development using a purely semantical approach has yet succeeded in generating a new and successful scientific theory in any science, even though many noteworthy historic scientific discoveries have resulted from the intuitive use of such semantical devices as analogy and metaphor. To date the only metatheories that are sufficiently practical to function as applicable procedures for scientific discovery are those based on the discovery-systems approach, and most of these have been academic exercises involving the reconstruction of existing or historical theories. Only a few discovery systems have actually been used to make new theories at the contemporary frontier of a science. Due to his semantical views Hanson had not examined the use of figures of speech, and very few discovery systems existed before his death in 1967. But in his examination of historical episodes in the history of science he recognized and documented cases in which semantics has operated as a *constraint* upon discovery, and he understood that this phenomenon implies the need for a reconsideration of the nature of scientific language, especially the language for observation. However, he himself had only suggested a metatheory of semantical description in his discussion of the semantics of Newton's mechanics.

The following commentary is divided into five topics: Firstly Hanson's attempt at a logic of discovery with his wholistic *gestalt* semantics is critiqued. Secondly Hanson's defense of the Copenhagen interpretation with its duality thesis is considered in the context of semantical change in science. Thirdly Hanson's principal criticism of Bohm's hidden-variable thesis is viewed in historical retrospect. Fourthly some comments are given on Bohm's and Hesse's use of metaphor, and Wittgenstein's family-resemblance theory of meaning is critiqued. And finally a semantical metatheory of analogy, metaphor, and simile is set forth.

Consider firstly Hanson's proposed logic of scientific discovery, which took as its point of departure Peirce's investigations. Peirce's abductive (AKA retroductive) logic of discovery does not conclude to a unique theory from a given set of premises as deductive logic concludes to a unique theorem. And Hanson does not propose that there exists a resolution for this indeterminacy, much less does he supply one. But Hanson adds something to Peirce, namely the controlling role of logical syntax in the determination of semantics, which in turn strongly influences the selection of possible hypotheses available for abduction. Thus he says that the mathematical formalism or syntax of the empirically adequate quantum theory defines the conceptual possibilities for any future development of microphysical theory, while paradoxically he also maintains that it offers a conceptual resistance to any future development of an alternative microphysical having a different formalism. This controlling role for syntactical structure in statements and equations believed to be true implies an artifactual thesis of the semantics of language. But in spite of the importance that Hanson places on semantics, he never used or developed a systematic philosophy of language. His principal inspiration was Wittgenstein's *Investigations*, which is not without its insights but is an aphoristic approach to philosophy of language. In his discussion of "seeing" Wittgenstein employed ambiguous drawings such as are commonly used in texts on *gestalt* psychology, and Hanson developed a semantics of language based on the idea of the conceptual *gestalt*. Unfortunately Gestalt psychology is a very blunt instrument for semantical analysis, because it is a wholistic approach to semantical description.

Hanson's philosophy of scientific discovery was greatly influenced by the physicist Paul Dirac. Dirac had told Hanson that the Copenhagen interpretation figured essentially in his development of the formalism of his relativistic quantum theory. Hanson therefore took the position that the Copenhagen interpretation (without Bohr's naive epistemology based on forms of perception) is that one, unique, and distinctive semantical interpretation supplied by the formalism itself, and is not merely some philosophical idea appended to the formalism. However, the *gestalt* semantics is not adequate to the defense of Hanson's view of that Copenhagen interpretation is integral to the formalism of the modern quantum theory. Had Dirac said just the opposite of what Hanson reports he said about the Copenhagen interpretation's relation to the formalism of quantum theory, then the *gestalt* semantics would have been neither more nor less serviceable for a semantical analysis of quantum theory. This is because the conceptual *gestalt* is wholistic and does not enable the philosopher of science to separate or even distinguish the semantics that may in some way be integral to the quantum theory's formalism, from that which may not be integral to the formalism but is merely appended to the formalism - what Hanson calls mere philosophy and Bohm calls informal language. In fact Hanson's *gestalt* semantics does not even offer him a basis for his distinction between the Copenhagen interpretation and the Bohr interpretation. The wholistic character of the conceptual *gestalt* makes it impossible to partition the semantics of the quantum theory into parts, to identify those parts that are integral to the formalism and those parts that are not, or those parts that are properly called the Copenhagen interpretation and those parts that are distinctive to the Bohr interpretation. In *Patterns of Discovery* Hanson had a brief flirtation with the idea that the meanings of terms contain each other as parts, but he failed to explore the idea. Had he done so, he would have found that semantics can be as analyzable as the syntax of any semantically interpreted and empirically warranted text.

The wholistic character of the conceptual *gestalt* also thwarts Hanson's attempt to explain scientific discovery. On the one hand the conceptual *gestalt* offers conceptual resistance to any change to a new *gestalt* and therefore to any new theory. In other words it is an impediment to the semantical change integral to scientific discovery. On the other hand it is also a guide to scientific discovery, because it informs the scientist of the kind of hypothesis that may satisfy the retroductive logic of scientific discovery. Semantics may function in both of these contrary ways, but the *gestalt* psychology cannot explain how. More specifically in connection with the modern quantum theory, the *gestalt* psychology does not explain why Hanson should be defending the Copenhagen interpretation as a guide instead of attacking it as an impediment to the discovery of a new and more empirically adequate quantum theory. The reason for this problem is the basic fact that the wholistic *gestalt* cannot function in a logic of scientific discovery or in any other application of logic, because its wholistic character deprives the retroductive logic of any procedural character. Retroduction can only describe the conditions that the new *gestalt* must satisfy after it has been hit upon, which is to say that it is a statement of a scientific problem that the discovery must solve rather than a procedure for obtaining a solution. On the *gestalt* view the discovery itself is a transition that does not admit to a procedure, just as the transition from one interpretation of an ambiguous drawing to another does not admit to a procedure. Just as there could never be a logical or mathematical formalism to describe the transition occurring in a change of a substantial form described in Aristotle's physics, so too there could never be a logical formalism to describe the change in a change of a *gestalt* form in modern physics. In both cases the transition from one form to the other is a substitution, which is instantaneous, whole and complete, and with no intelligible continuity to warrant calling it a process instead of a simple replacement.

Turn next to the second topic, Hanson's defense of the Copenhagen interpretation and his view that the formalism of the equations and statements of the theory necessarily imply it. The central question is whether the semantics of physical theory is exhaustively specified by the equations of the theory together with the statements describing the measurement apparatus and procedures used to obtain the measurement data related by the equations, or whether additional discourse is involved characterizing the domain of the equations and measurements. Hanson rejects any semantical role in scientific explanation for any discourse other than the equations of the theory and the statements required for experimental description and measurement procedures. Accordingly he maintains that the wave-particle duality, which is the distinctive characteristic of the Copenhagen interpretation, is not some semantics added to the formalism of the quantum theory by those statements that he calls mere philosophy, but rather is an ontological claim that is expressed by the formalism due to the formalism’s control of the semantics of the theory. His motive for stating this position is Dirac's statement made personally to Hanson that the wave-particle duality is integral to the formalism, and that it was strategic in Dirac's development of his own relativistic quantum theory. And it is built into the syntax of Dirac's operator calculus.

There are physicists who disagree with Hanson's view. Some disagree because they do not recognize the occurrence of semantical change. Hanson illustrates the phenomenon of semantical change in the first chapter of his *Concept of the Positron*, where he gives a brief historical overview of the wave and particle theories of light. He notes that Newton did not have a semantics for the terms "wave" and "particle" making the concepts dichotomous or mutually exclusive, when Newton proposed his theory of fits. Only later did these concepts assume their dichotomous implications, when the experiments of Foucault, Frenzel, and Young were believed to have the force of crucial experiments that persuaded the physicist that they must decide between one and the other characterization. Thus the concepts of wave and particle had undergone semantical change with the advance of physical experiment and theory. By the twentieth century the wave-particle dichotomy had become very well established even though the discoveries of Planck's quantum constant in 1900, Einstein's equation for the photoelectric effect for light in 1905, Compton's equation for his Compton effect for light in 1922, and de Broglie's relation for matter waves in 1924 enabled physicists to express the wave-particle duality mathematically prior to development of the modern quantum theory by Heisenberg and Schrödinger. Interestingly in his *Conceptual Development of Quantum Mechanics* (1966) Max Jammer observed that Bohr had come to his complementarity principle by consideration of these earlier equations, and he references a four-page postscript to a paper written by Bohr in 1925. This is one year before Heisenberg reports that Bohr had developed his complementarity principle.
Yet in spite of having been led by these considerations to conclude that wave and particle are alternative manifestations of the same physical reality, the inconsistent concepts were retained by Bohr, because he retained the classical concepts of wave and particle in his complementarity principle and relegated mathematical formalism to an instrumentalist status, even as he affirmed the wave-particle duality. His complementarity principle is a contradiction resulting from his belief in the naturalistic philosophy of perception, which in turn implies that like all classical concepts, those of wave and particle cannot be changed. And the complementarity principle is an example of the philosophical discourse defining the semantics in a way that is inconsistent with the semantics defined by acceptance of the mathematically expressed theory. After some weeks of disagreement with

Bohr, Heisenberg concluded that he could accommodate Bohr's complementarity thesis by accepting the idea that the wave-particle duality is expressed by the uncertainty principle, save that the mathematical formalism of the uncertainty principle is consistent while the complementarity principle is inconsistent. Heisenberg made this accommodation, because he accepted Bohr's naturalistic philosophy of perception. Yet in so doing, he was himself philosophically inconsistent, since unlike Bohr, he did not construe the formalism instrumentally. Instead by accepting Einstein’s admonition that the theory decides what the physicist can observe, Heisenberg let his theory decide what the physicist observes, and furthermore following Einstein's precedent applying scientific realism to the concept of time in relativity theory, Heisenberg likewise attempted to construe his indeterminacy relations realistically.

The only way the Copenhagen wave-particle duality thesis can be affirmed consistently is to let the equations control the semantics of the terms "wave" and "particle", as these terms relate to the descriptive variables in the mathematically consistent formalism. Accepting this mathematical context produces a semantical change in the meanings of the terms with the result that they no longer stand for classical concepts and are therefore no longer antilogies. The empirical adequacy of the quantum theory demonstrated after testing enables its equations to function as definitions. This amounts to using the equations of the theory in a functionally *a priori* manner and as pattern statements, as Hanson said, and to letting the theory decide what is observed, as Einstein said. Heisenberg may have been approaching the recognition of the semantical change, when in his "Questions of Principle" (1935) he said the restrictions on classical concepts as enunciated in the uncertainty relations acquire their “creative value” only by making them questions of principle, such that they can have the freedom necessary for a noncontradictory ordering of experience. In the light of his autobiographical description of his development of the uncertainty relations, his phrase “creative value” may be taken to refer to the role of the mathematical equations in defining the semantics, when the concepts of the formalism are used for observation as in the case of his reconsideration of the tracks in the Wilson cloud chamber. In other words he recognized that the formation of a new semantics is integral to the new scientific discovery. In this paper Heisenberg also states that the system of mathematical axioms of quantum mechanics entitles the physicist to regard the question the simultaneous determination of position and impulse values as a false problem, just as Einstein's relativity theory makes the question of absolute time a false question in the sense that they are devoid of meaning. Clearly the reason Heisenberg said such questions become devoid of meaning, is that the meanings of the variables have been changed by the in-principle maneuver of giving semantical control to the new theory.

Hanson reiterates Heisenberg's in-principle approach. In the chapter "Elementary Particle Physics" in his *Patterns of Discovery* he states that one cannot maintain a quantum-theoretic position and still aspire to the day when the difficulties of the uncertainty relations have been overcome, because this would be like playing chess and yet hoping for the day when the difficulties of having but one king piece will have been overcome. But Hanson proceeds beyond Heisenberg. Heisenberg's explicit and systematic theory of semantical change, his doctrine of closed-off theories developed under the influence of Bohr, was not only intended to explain semantical change, but was also intended to explain semantical permanence for classical concepts used for observation. In contrast Hanson said that the uncertainty principle is built into every observation of every fruitful experiment since 1925. In Hanson's explicit and systematic philosophy of science, unlike Heisenberg's, the theory controls even the semantics of the language used for description of observed phenomena. Hanson states how a theory has its creative value in ways that Heisenberg actually used and chronicled in his development of the uncertainty principle, but which Heisenberg did not incorporate into his explicit and systematic philosophy, his doctrine of closed-off theories. Heisenberg was inconsistent when he viewed the semantics of the variables in the mathematical quantum theory as classical concepts with restricted applicability for observation.

One problematic and indeed controversial outcome of the semantical change resulting from giving semantical control to the formalism of the theory, as Hanson advocates, is a complication in the problem of how empirical control is also exercised over the theory in scientific criticism, such that independent evidence enabling empirical decidability is possible and tautology is prevented. This is a problem that still vexes those contemporary Pragmatists who employ a wholistic thesis of the semantics of language. Hanson could have called upon his thesis of theory-independent phenomenalist seeing as an observation language. But he never invokes this idea to defend the empiricism of science, even while he never doubts either the empirical decidability of science or the theory-laden character of observation language. Instead he regrettably invokes Wittgenstein's idea of the multiple uses of language with theory language having a concept-defining function for observation only in some uses and a testing function in others. This seems no better than Heisenberg's inconsistency.

Letting the consistent mathematical formalism of the theory control its semantics and thus the ontology its semantics describes, enables the new theory to supply a new semantics and ontology. But recognition of semantical change does not resolve the central ontological issues associated with the quantum theory. In fact there is no compelling evidence either from experiment or from the formalism of the quantum theory for the Copenhagen ontology. Whether the wave and particle are two alternative manifestations of the same entity, as Bohr and Heisenberg say, or whether they are copresent but separate entities, as de Broglie and Bohm say, or whether the particle is the only real entity, as Lande says, or whether the wave is the only real entity, as Schrödinger says - are all different ontological commitments that cannot be decided by reference to the mathematical syntax, because mathematics does not reference entities, or in Carnap's phraseology it is not a "thing language". The mathematical syntax does not express instantiation in things or entities like the syntax of the Aristotelian categorical logic, the Russellian predicate calculus, or ordinary language.

In the mathematical equations the semantically interpreted calculus expresses the universal claim, when no numeric measurement values are assigned to the descriptive variables. And the claim is made particular when any of the variables are assigned numeric values either by measurement actions of the experimenter or by calculation with the equation from measurement values assigned to other descriptive variables in the equation. The individual measurement action is the referenced instance at a specific place and time, and no claim is made about instantiated entities. In categorical logic on the other hand entities are explicitly referenced by the subject term, which is quantified, and their existence is claimed by the copula, a form of the verb "to be", when the considered categorical statement is proposed as true. Similarly in the Russellian predicate calculus quantified (or bound) variables also reference entities, although in the Russellian predicate calculus ontology and quantification are commingled so that the syntax implies nominalist ontology, such that one may blithely ignore such subtleties as simple or personal supposition, and say with Quine that in the Russellian predicate calculus to be is to be the value of a variable. In ordinary substantive discourse reference to entities is often implicit, but can be made explicit with terms such as "thing" or "entity".

In order for any mathematically expressed theory to make ontological claims about entities, it is necessary to supplement its mathematical language with additional thing-language discourse having the syntactical categories that enable reference to entities. This could be as elementary as a statement of a measurement procedure in terms of counting certain types of entities, such as members of a population. Even if the mathematics were set theory, it would be necessary to add information identifying which sets have elements as entities. Thus there is merit in Bohm's thesis that the interpretation of a mathematical formalism is something that is in the informal language and not in the measurements or the equations themselves. And he was furthermore correct in maintaining that the informal language contains philosophical assumptions, because the statements of test design used to make quantum-theory measurements do not describe the microphysical entities adequately to decide between the various ontological interpretations. Thus any discourse purporting to describe the one or more microphysical entities in terms of wave and particle attributes must be relegated to what Hanson called mere philosophy. In this respect whether or not Bohm's hidden-variable interpretation is the correct interpretation, he seems to have been philosophically correct in stating that the interpretation is in the informal language, and that the discourse is philosophical, because that informal discourse is not yet empirically testable. Thus it is not yet empirically decidable - and the ontological debate goes on.

In conclusion the thesis of scientific realism is that the descriptive terms occurring in universally quantified statements accepted as true describe reality, because the statements are empirically warranted. Thus each ontological interpretation for quantum theory can be construed as realist, but only to the extent that the theories are empirically warranted. Thus scientific realism does not resolve issues of ontology. Due to ontological relativity the empirical under-determination of language carries over into ontology, and the unresolved ontological issues in quantum theory result from the empirical underdetermination of the theory and its associated test design language. Consider the following analogy for the quantum theory measurement problem: A survey researcher asks a respondent to express his agreement (or disagreement) about a viewpoint using a scale of 1 to 10. The respondent answers stating a value on the scale, and the interviewer dutifully records the measurement. Two ontological scenarios are possible in this measurement situation: 1. The respondent had an opinion and made his response by recalling his opinion. 2. The respondent had no opinion but formed one upon being asked, and issued his response accordingly. Both scenarios yield the same response and valid empirical measurement, just as the quantum measurements are empirically valid. The issue of when the respondent's opinion was formed is a supplementary consideration to be resolved by further inquiry. So too with the time of the formation of the electron's wave or particle manifestations or its position or momentum. In anticipation of empirical evidence from future inquiry the physicist like the survey researcher can indulge in ontological speculation. And both Einstein and Heisenberg like many others indulged in such speculation. Einstein's realist ontology resembles the first survey respondent scenario, and Heisenberg's realist ontology of *potentia* the second.

Thirdly consider Hanson's principal criticism of Bohm's hidden-variable interpretation of quantum theory. Hanson's criticism is that Bohm has not developed any new empirically testable equations. Initially Bohm had proposed his hidden-variable hypothesis as a heuristic for developing new microphysical equations that would resolve the renormalization problem, as well as unify physics with an ontology that is consistent for both macrophysics and microphysics. For forty years he elaborated his interpretation of the existing quantum theory formalism, while the postulated subquantum field has remained remote from experimental detection, and while the renormalization problem remains unsolved. In his "Hidden Variables and the Implicate Order" in *Quantum Implications* Bohm admits that his proposed hidden-variable interpretation did not catch on among physicists, since it gives exactly the same predictions for all experimental results as does the Copenhagen interpretation, which he calls the usual theory.

Hanson's critique of Bohm's hidden-variable interpretation in his "Postscript" in *Quanta and Reality* seems to have been vindicated to date by the behavior of the physics profession in the years that have since elapsed notwithstanding Bell's nonlocality theorem. There is no shortage of sociological and conspiracy theories about the exclusion of Bohm and his supporters. Some philosophers of science as well as supporters of Bohm claim that the advocates of the Copenhagen interpretation have imposed some kind of hegemony on the physics profession. Bohm claims in his *Undivided Universe*, that the Copenhagen interpretation prevails only because it was prior to his interpretation, and says that it is merely a historical circumstance if not an accident that the Copenhagen interpretation was chronologically prior to his alternative interpretation.

But such claims reveal a failure to understand the institutional value system of empirical science that guides and motivates scientists' opportunistic decisions - including the decision by the majority to ignore Bohm's hypotheses about phenomena occurring at an order of magnitude that is still experimentally undetectable. Physicists exhibit what Bell calls a pragmatic attitude. Feynman's sum-over-paths approach to quantum theory notwithstanding, physicists are not interested in alternative interpretations for their own sake, i.e. interpretations that are not associated with new and empirically testable equations that solve problems which the current mathematical physics has yet to solve. In fact the whole issue of alternative semantical and ontological interpretations for the quantum theory's formalism is often ignored in textbooks on quantum theory. Instead researchers in microphysics have allocated their time and effort to theorizing about the wealth of new data made available with the particle accelerators by developing the standard model and by developing string theory to account for gravitation as well. Eventually new experimental techniques and apparati will enable physicists to detect and examine subquantum phenomena (it would be quite remarkable if in fact absolutely *nothing* actually exists at subquantum orders of magnitude, as Bohr had thought). The question as to whether Bohm's hidden-subquantum-field thesis or the string theory thesis elementary point particle composition will eventually enjoy the glorious destiny of the hidden-atomic theory of matter, or whether it will eventually suffer the inglorious denouement of the hidden-ether theory of light, remains to be seen.

Finally consider Bohm and Hesse's comments on metaphor. Their differences not withstanding, Bohm and Hanson have a common belief underlying their interests in scientific discovery. Traditionally it was thought that language has merely a passive role, such that firstly a discovery is made by observation of nature, and then language is employed to report the discovery. But Hanson, Bohm, and later Hesse rejected the naturalistic philosophy of the semantics of language, which assigns to language such a passive role in scientific discovery. Instead they recognized that language has an active role that enables language construction to function as an instrument or heuristic and thus to admit to a discovery strategy. In their writings retroduction, analogy, and metaphor represent such semantical discovery strategies. But to date neither their semantical strategies using figures of speech nor even Thagard's computational efforts employing his analogical discovery strategy, have yielded new and consequential theories for any science. The inspiring muses of ancient Greek mythology are still as operative in the use of figures of speech for scientific discovery, as they are for poetry and music. While metaphor is not yet serviceable as a discovery *procedure*, it may be recognized as an outcome of mechanized discovery procedures due to the very unconventional statements generated as system outputs.

Hesse's reliance on Wittgenstein's family-resemblance theory of meaning, however, is unfortunate. Wittgenstein noted that humans are able to distinguish individuals without articulately characterizing the individuals' distinguishing features or attributes, and to group of individuals without characterizing their common features or attributes that make them similar and that serve as the basis for grouping. But so too can dogs and cats, neither of which practice scientific research. Hesse draws upon this banal observation, and then confronts her readers with the dichotomous choice between Aristotle's natural-kinds doctrine and Wittgenstein's family-resemblance doctrine. This is a false dichotomy. It is also a rhetorical one, since Aristotle's philosophy of natural kinds, substantial forms, and species has accumulated a long baggage train of implications and associated ideas during the interim two thousand years, and few contemporary philosophers would welcome being harnessed to pull this baggage train. But Wittgenstein's family-resemblance theory of meaning is a poor alternative. As a wholistic theory of meaning, it is an exercise in vagueness about vagueness. Furthermore semantical differences are not reducible to only differences in *degree* of similarity or difference. Few concepts are like the color words, such as shades of red, which Hesse uses as an example. If meanings may be said to be approximate, as Hesse maintains, it is because they are vague. And if meanings may be said to be similar or different, it is because they are fundamentally complexes that may share many or only a few discrete semantic components, which may be called semantic values. When they share many components, or semantic values, they are similar, and when they share few, they are dissimilar. Furthermore, Hesse is not even consistent with her Wittgensteinian theory of meaning. For example in a discussion of how science can reclassify observed phenomena she notes the case in which whales become classified as mammals and not fish, because the property of suckling their young comes to be a more salient property than the fact that they live in the sea. Clearly this property of suckling young is a difference between mammals and fish that is not a matter of degree or reducible to such. A more adequate theory of meaning description than the family-resemblance thesis is needed, and a proposed alternative is set forth immediately below.

Consider the following metatheory of meaning and of figures of speech such as metaphor, which does not propose that meanings are somehow continuous with one another such that differences and similarities are fundamentally matters of degree. As a linguistic phenomenon metaphor may be explained with the semantical thesis that the meanings of descriptive terms have complex composition. For purposes of analysis metaphor may be viewed in the context of predication to form a sentence. Other modes of expression such as phrases or texts larger than sentences may reveal metaphorical use, when these expressions are transformed grammatically into the subject-predicate sentence form. One of the identifying features of a metaphorical description is that if the term that is metaphorically predicated of a subject is taken in its literal, i.e. conventional sense, then the statement is false, although this is a feature only for metaphors occurring in affirmative predications. For example in his *Mental Leaps* Thagard notes that the statement “No man is an island” is not literally false, even though “island” is also denied metaphorically of “man” in the statement. Another feature is that when the statement is false, it is not an unrecognized mistake; it is deliberately issued with no intention to deceive and for the purpose of revealing something believed to be true. Thus, there is merit to Bohm’s definition of metaphor as the simultaneous equating and negating of two concepts. The central problem, therefore, is how the metaphorical description can be both true and false. One possible answer is that metaphor is a kind of equivocation, and this proposal seems inevitable so long as meanings are viewed as simple wholes, such that the metaphorical description is completely true on its one meaning and completely false on its other.

A more suggestive way to formulate the question is to ask how the metaphorical predication can be partially true and partially false rather than simply true and simply false simultaneously. This suggests an alternative to simple equivocation, because it suggests that meanings have parts. A metaphorical predication invokes only part of the meaning complex associated with the descriptive predicate, and it excludes the remainder of the meaning complex. A speaker's conventional linguistic usage associates the entire meaning complex with the predicate term, and the metaphor is false if the term is predicated with its full and conventional semantics. But the speaker or writer of the metaphor recognizes the part of the meaning which is truly predicated of the subject, and he implicitly expects the hearer or reader to suspend other parts of the predicate's semantics, while the speaker or writer uses the portion that he wishes for describing the subject. A listener or reader may or may not succeed in understanding the metaphorical use of the predicated term depending on his ability to select the applicable parts of the predicate's semantics intended by the speaker or writer. Some authors discussing metaphor, such as Max Black, render it as a kind of esoteric mode of speech, which cannot be reduced to literal language. But in fact metaphors are explained in literal (i.e. conventional) terms to the uncomprehending listener or reader. To explain the metaphorical predication of a descriptive term to a subject, is to list those sentences or clauses believed to be true of the subject, which may substitute for the predicated metaphor, and which set forth precisely those parts of the predicate's meaning that the issuer intends to be applicable. And the explanation may also be elaborated by listing those sentences or clauses that are not believed to be true of the subject, but which are conventionally associated with the predicated term when it is predicated literally. These negative sentences state what is intended to be excluded from the predicate's meaning complex in the metaphorical usage.

For example to explain the metaphor "Man is a wolf", the speaker may say, "Man is a wolf, because man is ..., and man is ..., and..." where in the clauses he substitutes predicates that identify those characteristics of wolf that he intends to be applicable to man. And if in this substitute predication he finds himself further using metaphorical descriptions, then the substitution process is repeated with other clauses, until the entire explanation is literal. The explanation may be elaborated for clarity by the sentence "Man is not a wolf, because man is not..., and man is not..., and...." Substitutions in this negative sentence results in subordinate clauses that have predicates describing characteristics conventionally associated with wolves, but which the issuer of the metaphor does not intend to be truly predicated of men. The affirmative explanatory sentence sets forth those parts of the meaning associated with "wolf" that are intended to describe man in the metaphorical use of "wolf", and the negative explanatory sentence sets forth whatever parts of the conventional or literal meaning associated with "wolf" that the issuer intends to suspend for metaphorical purposes. Semantical change for the term "wolf" occurs when the metaphorical predication becomes conventional, and this produces an equivocation. The equivocation consists of two literal meanings, the original one and a second meaning, which is now a dead metaphor. As a dead man is no longer a man, so too a dead metaphor is no longer a metaphor; it is a meaning from which the suspended parts have become conventionally excluded to produce a second literal meaning. The dead metaphor may also be a change of meaning in which the first meaning has become archaic. This may occur in some cases of scientific discovery or theory development. The new theory supersedes an old one, such that the old meaning becomes as archaic as the old theory containing it, and the new meaning eventually becomes the only conventional meaning applicable to the subject of the superseding theory. However, the change cannot be a complete semantical change, if the fact that the new and old theories address the same subject cannot even be detected. The semantical change applies only to some parts of the term's meaning with other parts providing the needed semantical continuity, namely those supplied by statements of test design.

Simile is similar to metaphor except that the occurrence of the terms “like” or “as” alerts the listener that only part of the meaning complex is applicable, and with explanatory elaboration it may furthermore inform him of which parts. With the listener thus alerted, his awareness of the partial applicability of the predicate’s meaning complex enables him to retain the term’s conventional semantics. Unlike metaphor the simile is not partly true and partly false, but is wholly true, if it is true at all, even if the expressed similarity signified by the applicable part of the meaning intended by the issuer of the simile, is not the same as the meaning part selected by the listener. Thus the simile "Man is like the wolf" may be explained with the sentence "Man is like the wolf, because man is..., or man is..., or.…” The terms “like” or “as” alone only inform the listener that the full meaning of “wolf” is not applicable, but the added “because…” clause explains what parts of the meaning complex are applicable.

Consider next analogy. In a conventional generic sense the term “analogy” might include metaphor and simile, because they are all figures of speech expressing similarity. But in its more restrictive sense based on the idea of a grammatical form, it is a compound sentence having two independent clauses connected with the conjunction “as”. The typical form is “A is to B as C is to D.” For example: “The electron is to the atomic nucleus as a planet is to the sun.” This sentence may have appended to it a subordinate “because” clause explaining the underlying similarity consisting of both electrons and planets moving in orbits around a center having a relatively greater mass. There may be many such explanatory clauses explaining various underlying similarities, and perhaps also describing dissimilarities. Hesse’s thesis of positive, negative, and neutral analogy would seem to pertain to such explanatory clauses. The positive analogy is what is expressed in the explanatory clauses, the negative analogy is what is expressed in the clauses describing dissimilarities, and the neutral analogy consists either in what is not yet considered, or more usefully what is actually considered and expressed with much more hypothetical attitude than the affirmed similarities and dissimilarities. It is the neutral analogy that Hesse considers to be of distinctive value for formulating scientific theories as hypotheses proposed for testing. In the research context, instead of the literary or poetic context motivated by aesthetic considerations, the central feature of the analogy statement is that one of the independent clauses connected by "as" is believed to be true with a high degree of confidence if not conviction, while the credence status of the other independent clause is much more hypothetical in the judgment of the issuer. Historically in the above example of analogy, the solar-system description involving planets in orbits around the sun was believed much more firmly than the description of the atom in terms of electrons moving in orbits around the nucleus of the atom, which at the time was a much more tentative hypothesis. And semantically the predicate "planet" in the clause with the higher degree of credence has the idea of orbits built into its associated meaning complex, while the more hypothetical attitude toward the description of the atom deprived the predicate "electron" of the idea of orbits as a component part.

Both metaphor and simile too may be said to have positive, negative, and neutral aspects in the context of scientific discovery. The positive aspect of either a metaphor or a simile consists of those parts of the meaning complex associated with the predicate term that are also conventionally included in the meaning complex associated with the subject term, and that are the basis for the affirmed similarity. Conversely the negative aspect consists of those parts of the meaning complex associated with the predicate term that are not also conventionally included in the meaning complex associated with the subject term. And the neutral aspect consists of those parts of the meaning complex that the issuer has not considered in connection with the meaning complex associated with the subject term, but which he may consider at a later time. As a figure of speech, this later consideration involves reflection on the semantics associated conventionally with the predicate terms. But if the later consideration involves new empirical research either by formulating a new hypothesis or by examination or consideration of a test outcome, then there is a semantical change that has not yet become conventional. For example at one time a proposed metaphor was "the electron is a small orbiting planet", and the corresponding simile is "the electron is like a small orbiting planet." At that time these components of meaning were not conventionally included in the concept of electron.