WERNER HEISENBERG AND THE SEMANTICS OF QUANTUM MECHANICS

This book examines Werner Heisenberg's interpretation of quantum theory and the influence of Albert Einstein. Heisenberg's semantical view is the chrysalis of the contemporary pragmatist philosophy of language.

Heisenberg (1901-1976) was born in Wurzburg, Germany, and studied physics at the University of Munich, where he wrote his doctoral dissertation under Arnold Sommerfeld in 1923 on a topic in hydrodynamics. He became interested in Niels Bohr's atomic theory and went to the University of Göttingen to study under Max Born. In 1924 he went to Bohr's Institute for Theoretical Physics in Copenhagen, where he developed the quantum matrix mechanics in 1925, and then developed the indeterminacy principle in 1927. From 1927 to 1941 he was a professor of physics at the University of Leipzig. In 1932 he was awarded the Nobel Memorial Prize for Physics. In the Second World War, he was the director of the Kaiser Wilhelm Institute for Physics in Berlin. After the war he established and became director of the Max Planck Institute of Physics initially at Göttingen, and then after 1958 at Munich. His principal publications in which he set forth his philosophy of physics consist of the "Chicago Lectures of 1930" published as *The Physical Principles of the Quantum Theory* (1950, [1930]), *Philosophical Problems of Nuclear Science* (1952) currently published under the title of *Philosophical Problems of Quantum Theory* (1971), *The Physicist's Conception of Nature* (1955), an interpretative history of physics, *Physics and Philosophy: The Revolution in Modern Science* (1958), his intellectual autobiography published as *Physics and Beyond* (1971), and *Across the Frontiers* (1974).

Heisenberg's philosophy of science was not significantly influenced by the doctrines of academic philosophers, although he was a positivist early in his career and later rendered Bohr's view of observation in neo-Kantian terms, even though neither he nor Bohr were metaphysical idealists. The formative intellectual influences on his philosophy were Einstein and Bohr. These two philosophical influences were contrary to each other, and each pulled Heisenberg's thinking in opposite directions. Therefore, consider firstly the philosophical views of Einstein and Bohr.

Heisenberg's Discovery and Einstein's Semantical Views

Reference was made in BOOK II in the discussion of Mach's philosophy about the influence of Einstein's aphorism on Heisenberg's development of the indeterminacy relations. This episode in the history of science, which Heisenberg relates in "Quantum Mechanics and a Talk with Einstein (1925-1926)" in *Physics and Beyond*, is a watershed event for the contemporary pragmatist philosophy of science. His description of his personal experience and thought processes deserves close examination.

He had initially believed that he could develop a quantum theory exclusively on the basis of observed magnitudes. He writes that in the summer of 1924 he had attempted to guess the formula that might successfully describe the line intensities of the hydrogen spectrum using methods involving the idea of electron orbits, which he thought would be successful in view of the previous work of Kramers in Copenhagen. When use of these methods hit a dead end, he became convinced that he should ignore the idea of electron orbits. He decided instead that he should treat the frequencies and amplitudes associated with the spectral line intensities as substitutes, because the line intensities are observable directly, while the electron orbits are not. He was led to this approach because he recalled a conversation years earlier in which a friend told him that Einstein had emphasized the importance of observability in relativity theory. In May of 1925 Heisenberg suffered a severe hay fever attack and had to absent himself from his academic duties. While recuperating on the island of Heligoland he continued to work on the problem by considering nothing but observable magnitudes, and during this period of isolation he developed his matrix-mechanics version of quantum theory.

About a year later he was invited to give a lecture at the University of Berlin physics colloquium to present his matrix mechanics. Einstein was in the assembly, and after the lecture Einstein asked Heisenberg to discuss his views with him in his home that evening. In that discussion Einstein argued that it is in principle impossible to base any theory on observable magnitudes alone, because in fact the very opposite occurs: ***it is the theory that decides what the physicist can observe***. Einstein argued that when the physicist claims to have observed something new, he is actually saying that while he is about to formulate a new theory that does not agree with the old one, he nevertheless must assume that the new theory covers the path from the phenomenon to his consciousness and functions in a sufficiently adequate way, that he can rely upon it and can speak of observations. The claim to have introduced nothing but observable magnitudes is actually to have made an assumption about a property of the theory that the physicist is trying to formulate. Einstein objected that Heisenberg was using his idea of observation as if the old descriptive language could be left as it is.

Heisenberg replied that Einstein was using language a little too strictly, and that until there is a link between the mathematical quantum theory and the traditional language, physicists must speak of the path of an electron by asserting a contradiction, notably Bohr's wave-particle "complementarity" description. Heisenberg also replied by referencing Mach's view that a good theory is no more than a condensation of observations in accordance with the principle of thought economy. Einstein replied that Mach thought a theory combines complex sense impressions just as the word "ball" does for a child. He also stated that the combination is not merely a psychological simplification but is also an assertion that the ball really exists, because it makes assertions about possible sense impressions that may occur in the future. Einstein thus affirmed a realistic philosophy, and criticized Mach for neglecting the fact that the real world exists, that our sense impressions are based on something objective, and that observation cannot be just a subjective experience. Heisenberg accepted Einstein's realism on these grounds, and admitted that theory reveals genuine features of nature and not just of our knowledge.

In the "Preface" to his *Physics and Beyond* Heisenberg stated that his purpose is to convey even to readers who are remote from atomic physics, some idea of the mental processes that have gone into the genesis and development of science. In the chapter titled "Fresh Fields (1926-1927)"

Heisenberg offers a description of his own mental processes in his development of the indeterminacy relations. To the contemporary reader this description has value apart from his systematic and explicit philosophy. Just as Newton attempted to philosophize about his work with his denial that he created hypotheses, so too did Heisenberg attempt to philosophize about his work with his own systematic and explicit philosophy of language – his doctrines of closed-off theories and of perception. But the recollections of his cognitive experiences in “Fresh Fields (1926-1927)” in *Physics and Beyond* are not an attempt at a systematic philosophy. They are more simply his recollection of his own cognitive experiences as a central participant in the development of the quantum theory, and they are valuable as an historical document. As it happens, in the contemporary pragmatist philosophical perspective these recollections are far more valuable than Heisenberg’s explicit attempt to philosophize on the nature of language and perception.

These writings reveal that his development of the indeterminacy relations was occasioned by several historical circumstances. One of these that he discusses in “Fresh Fields” was the development of the wave mechanics by Schrödinger and its disturbing effects on the thinking of the physicists at Copenhagen. The wave equation did not contain Planck’s constant as did Heisenberg’s matrix mechanics, while Planck’s constant was thought by Bohr and the Copenhagen physicists to be central and necessary for any modern microphysical theory. Then Max Born, formerly a teacher of Heisenberg, proposed a probability interpretation of the wave equation, such that for each point in space and instant in time the wave equation gives the probability of finding an electron at the given point and instant. The upshot was that while neither the matrix mechanics nor the wave mechanics could be rejected for empirical reasons, they nevertheless seemed to be logically incompatible.

In addressing this problem Bohr and Heisenberg took different approaches. Bohr attempted to admit simultaneously to the validity of both theories by maintaining that both the classical wave and the classical particle concepts used to describe the experimental observations are necessary for characterizing atomic processes, even though in the language both of ordinary discourse and of classical physics these two concepts are mutually exclusive. A wave is spread out in space, while a particle is concentrated nearly at a point. This semantic inconsistency became Bohr’s "complementarity" principle. But Heisenberg relates that he did not like this approach, and that he wanted a "unique", that is, a consistent and unequivocal physical interpretation of the magnitudes in the mathematical formalism, one that is logically derivable from the matrix mechanics. Heisenberg reports that this objective was one of the reasons that led him to derive the indeterminacy relations.

A second reason leading him to the indeterminacy relations was the fact that neither the wave mechanics nor the matrix mechanics seemed capable of explaining the observed track of the electron in the Wilson cloud chamber. The cloud chamber developed by C.T.R. Wilson in 1912 consists of a chamber containing a saturated vapor under pressure. When the pressure is rapidly reduced, the vapor cools and becomes supersaturated, as the temperature drops below the dew point. The passage of a charged particle, *i.e.*, an electron, through the vapor causes ion pairs to form droplets. A string of these droplets mark the track of the passage of the charged particle. But such ideas as tracks and orbits do not figure in the mathematical formulations of the matrix mechanics, and the wave mechanics could only be reconciled with the existence of a densely packed beam of matter, if the beam is spread over volumes that are much larger than the dimensions of an electron. This problem of the observed track in the cloud chamber led Heisenberg to reformulate the questions he was asking himself in his statement of the problem. He attempted to relate the observed track of the electron in the cloud chamber to the mathematics of the matrix mechanics.

In February and March of 1927 Bohr was vacationing in Norway and Heisenberg was again alone with his thoughts, as he had been when he had earlier developed the matrix mechanics. At this time his attempt to relate the cloud chamber observations to the matrix mechanics bought to mind his discussion with Einstein the prior year in Berlin, and specifically Einstein's statement that **the theory decides what the physicist can observe**. In "Fresh Fields" he describes his thinking processes when he attempted to employ Einstein's advice. Firstly he reconsidered the idea that what is observed in the cloud chamber is a track. The idea of a track is a concept in Newtonian physics. Therefore, when he thought that he was observing the track of an election in the cloud chamber, the theory that was deciding what was being observed was the Newtonian theory, not his quantum theory.

Then secondly after reconsidering the Newtonian observations and recognizing that it is not necessary to think in Newtonian terms, he viewed the phenomenon as merely a series of ill defined and discrete spots through which the electron had passed, somewhat like the water droplets which of course are very much larger than the dimensions of the electron. Then thirdly he reformulated his problem, and asked how quantum theory instead of Newtonian theory can represent the fact that an electron finds itself approximately in a given place and that it moves approximately with a given velocity. Using Einstein's thesis that the theory decides what the physicist can observe, Heisenberg concluded that the processes involved in any experiment or observation in microphysics must satisfy the laws of quantum mechanics. The magnitude of the observed water droplets suggested room for approximation for the minute electron, and Heisenberg asked whether it is possible to imagine these approximations so close that they do not cause experimental difficulties. He then derived the indeterminacy relations in which the approximations are limited by Plank's constant.

Heisenberg had formulated his indeterminacy principle by the time Bohr had returned to Copenhagen from his vacation in Norway. Initially Bohr objected to the idea, while at the same time Heisenberg disliked the complementarity idea that Bohr had developed. After several weeks of argument they finally agreed that the two approaches are related. The indeterminacy principle reconciles at the microphysical level and in the mathematical formalism of quantum mechanics, what cannot be avoided yet what cannot be stated consistently in the language supplied by classical physics and everyday language, which is suitable only to describe phenomena at the macrophysical level. What is expressed consistently with the mathematical formalism of the indeterminacy principle is the impossibility of measuring simultaneously both the position and the impulse of the electron with a degree of accuracy greater than the limit imposed by Planck's constant, a limit that is imposed by virtue of the nature of the microphysical phenomenon itself and not merely by limits of measurement technique. What are described inconsistently at the macrophysical level and in the language of classical physics by means of complementarity, are the observable wave and particle manifestations of the unitary phenomenon. This concession to Bohr was at variance to Heisenberg's acceptance of Einstein's semantical thesis that the theory decides what the physicist can observe. Heisenberg tried to reconcile the dilemma, but never did.

Heisenberg's description, which is based on his own experience of the interpretative character of all perception and observation and of the rôle of scientific theory in determining the interpretation, articulates one of the most characteristic features of the contemporary pragmatist philosophy of science. It is more valuable than Duhem's exemplification of the theoretical interpretation of the laboratory apparatus in the opening passages of the chapter titled "Experiment in Physics" in *Aim and Structure of Physical Theory*, not only because Duhem's explanation is positivist with his two-tier semantics, but also because Heisenberg's description of his experiences is given in the context of his development of the indeterminacy principle, one of the most noteworthy achievements of twentieth-century physics.

As it happens, Heisenberg did not like the pragmatism he encountered at the University of Chicago during his visit to the United States and described in "Atomic Physics and Pragmatism (1929)" in *Physics and Beyond*. Even though his description of the interpretative character of perception and observation actually contributed to the contemporary pragmatism, Heisenberg himself was still influenced by Bohr in ways that impeded his developing a philosophy of language that is consistent with Einstein's thesis that theory decides what the physicist can observe. This influence places Heisenberg's explicit philosophy of science closer to the positivist philosophy than either Einstein's or the pragmatists' views. This influence originated in Bohr's naïve naturalistic philosophy of the semantics of language. And the result was Bohr's thesis of "forms of perception" and Heisenberg's consequent neo-Kantian rendering of Bohr's philosophy of perception.

Heisenberg's Discovery and Einstein's Ontological Criteria

An ontology consists of the entities and aspects of the real world that are described by the semantics of a discourse, such as a scientific theory that is believed to be true. Unlike Bohr, who took an instrumentalist view of the equations of the quantum theory, Heisenberg maintained that quantum theory describes ontology, that is, that the equations constituting the language of the theory describe aspects of the real world. Thus he maintained that the quantum theory describes nondeterministic microphysical reality and the Copenhagen wave-particle duality, the thesis that wave and particle manifest two aspects of the same physical entity and do not represent two separate physical entities.

Initially, however, Heisenberg's ontological views were not based in the language of the mathematically expressed quantum theory, but were based in the everyday language that can be used to express experimental findings. In the opening sentence of the "Introduction" chapter of his *Physical Principles of the Quantum Theory* (1930), a book based on lectures he gave at the University of Chicago in the Spring of 1929, Heisenberg says that the experiments of physics and their results can be described in the language of daily life. He adds that if the physicist did not demand a theory to explain his results and could be content with a description of the lines appearing on photographic plates, then everything would be simple and there would be no need for an epistemological discussion. He states that difficulties arise only in the attempt to classify and synthesize the results, to establish the relations of cause and effect between them – in short, to construct a theory.

Heisenberg maintained that the everyday description of certain experimental findings implies the Copenhagen ontology, and he proceeds to give a brief description of several experiments including Young's two-slit experiment, which show that both matter and radiation sometimes exhibit the properties of waves and at other times exhibit the properties of particles. He notes that it might be postulated that two separate entities, one having all the properties of a particle and the other having all the properties of wave motion, are combined in some way. But he then adds that such a theory is unable to bring about the "intimate relation" between the two entities, which seems required by the experimental evidence. He argues that wave and particle are a single entity, and that the apparent duality, the properties described in Newtonian mechanics as "wave" and "particle", is due to the limitations of language. Such recourse to the limitations of language reveals the influence of Bohr's philosophy. For Heisenberg both quantum experiments and quantum mechanics redefines the meaning of the word "entity". Other physicists such as Einstein, de Broglie, and Bohm did not agree with Heisenberg's view that there is any such compelling experimental evidence for the Copenhagen duality ontology. Both philosophers and scientists have had different ontological commitments, often because they maintain different philosophies of language.

Einstein's ontological view influenced Heisenberg's ontological ideas. Therefore briefly consider Einstein's views. It may be said that Einstein had two different ontological criteria for physics, one explicitly set forth by him, and another that he tacitly used and which therefore may be called his implicit criterion. In Newtonian physics and in relativity theory these two different criteria are not easily distinguished, because in each case they yield similar ontologies, but in quantum theory they yield fundamentally different ontologies. Einstein's **explicit** ontological criterion for deciding what is physically real is set forth in his "Can Quantum Mechanical Description of Physical Reality be Considered Complete?" in *Physical Review* (1935), in his "Physics and Reality" in *The Journal of the Franklin Institute* (1936), and in his "Reply to Criticisms" in *Albert Einstein* (ed. Schilpp, 1949). There are several statements.

One that he states as his "programmatic aim of all physics" is his criterion of logical simplicity, which he sets forth as the aim of science: The aim of science is a comprehension as complete as possible of the connections among sense impressions in their totality, and the accomplishment of this aim by the use of a minimum of primary concepts and relations. He goes on to say that the essential thing about the aim of science is to represent the multitude of concepts and theorems that are close to experience, as theorems logically deduced from and belonging to a basis as narrow as possible, of axioms and fundamental concepts that themselves can be chosen freely. This is a coherence concept of the aim of science as the logical unity of the world picture, and it might be described as an aspiration to what today is called a "theory of everything". Einstein interprets the history of physics as an evolution under the direction of this aim of science. This criterion requires that microphysical and macrophysical theories affirm one single consistent ontology, and use the same basic concepts of what is physically real. Einstein thus maintains that the conviction that deterministic field theory is unable to give a solution to the molecular structure of matter and to the quantum phenomenon, is a false prejudice. He demands that the ontology of field theory supply this uniform fundamental ontology, and he uses this explicit ontological criterion to criticize the nondeterministic Copenhagen interpretation.

In a famous article titled "Can Quantum Mechanical Description of Physical Reality be Considered Complete?" in *Physical Review* co-authored with Podolsky and Rosen, Einstein describes the Copenhagen interpretation as "incomplete". By this he meant that further research is needed to make quantum theory consistent with the ontology of field physics, the ontology of deterministic causality and of the physical space-time continuum in four dimensions. The argument in this paper, often called the "EPR argument" after the three co-authors, includes a thought experiment, which is based on explicit criteria for completeness and for physical reality. The completeness criterion says that a physical theory is complete, only if every element of the physical reality has a counterpart in the physical theory. The criterion for physical reality in turn is that if without in any way disturbing a system, one can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity. This criterion's reference to independence of any act of observation is repeated in a later statement of the programmatic aim of all physics in "Remarks" in Schilpp's *Albert Einstein: Philosopher-Scientist.* The thought experiment in the EPR argument attempts to demonstrate that the quantum theory's satisfaction of the reality criterion does not result in satisfaction of the completeness criterion.

The stated criteria for completeness and for physical reality are defined such that field theory satisfies both criteria while quantum theory does not. The point of departure, the basic premises of the argument, is Einstein's ontological preferences. In an article with the same title also appearing in Schilpp's *Albert Einstein* Bohr argued that the phrase "without in any way disturbing a system" in Einstein's criterion for physical reality is ambiguous, because its meaning in classical physics is not the same as that in quantum physics. Bohr maintained that in quantum measurements the object measured and the observing apparatus form a single indivisible system that defies any further analysis at the quantum level. A large literature developed around the technicalities of the physical thought experiment, but in practice even today many physicists chose their ontological premises according to their preferences about the ontological conclusions, depending on whether one agreed or disagreed about Einstein's view that quantum theory must have the same ontology as field physics.

On the other hand Einstein's **implicit** ontological criterion was operative in his development of the special theory of relativity. This criterion (stated explicitly) is that the empirically adequate scientific theory must be interpreted realistically. Unlike Einstein's explicit criterion, which subordinates a scientific theory and its interpretation to a preconceived ontology, the implicit criterion subordinates ontological commitment to the outcome of empirical scientific criticism. This is the contemporary pragmatist view, which Quine calls "ontological relativity". Heisenberg applied this same ontological criterion to the mathematical expressions of the quantum theory to defend the Copenhagen dualistic ontology against Einstein's criticism based on the latter's explicit ontological criterion for physical reality. In this defense based on the mathematical language of the quantum theory instead of the everyday language of the microphysical experiments, Heisenberg referenced Einstein's realistic interpretation of the Lorentz transformation equation. In his discussions about Einstein's special theory of relativity in *Physics and Philosophy* and in *Across the Frontiers* Heisenberg describes as the "decisive" step in the development of special relativity, Einstein's rejection of Lorentz's distinction between "apparent time" and "actual time" in the interpretation of the Lorentz transformation equation, and Einstein's taking Lorentz's "apparent time" to be physically real time, while rejecting the Newtonian concept of absolute time as real time. In other words this decisive step consisted of taking the Lorentz transformation equation realistically, and of letting it describe the ontology of the physically real due to its empirical adequacy.

Nowhere does Heisenberg write that he was consciously imitating Einstein at the time Heisenberg developed the indeterminacy relations. But in his "History of Quantum Theory" in *Physics and Philosophy* he describes his use of the same strategy. In this description of his thought processes Heisenberg does not refer to his conversation with Einstein in Berlin in 1926. He states that his thinking in the discovery experience of the indeterminacy principle consisted of his turning around a question. Instead of asking himself how one can express in the Newtonian mathematical scheme a given experimental situation, notably the Wilson cloud chamber experiment, he asked whether only such experimental situations can arise in nature as can be described in the formalism of the matrix mechanics. The new question is about what can arise or exist in reality. Later in "Remarks on the Origin of the Relations of Uncertainty" in *The Uncertainty Principle and Foundations of Quantum Mechanics* (p. 42.) he explicitly states that this meant that there was not a Newtonian path of the electron in the cloud chamber. Heisenberg's strategic answer to the new question, the indeterminacy relations, resulted from this realistic interpretation of the quantum theory. Similar remarks are to be found in "The Development of the Interpretation of the Quantum Theory" in Pauli's *Niels Bohr and the*

Development of Physics (P. 15) where Heisenberg says that he inverted the question of how to pass from an experimentally given situation to its mathematical representation, by using the hypothesis that only those states that can be represented as vectors in Hilbert space can occur in nature and be realized experimentally. And he immediately adds that this method had its prototype in Einstein's special theory of relativity, when Einstein had removed the difficulties of electrodynamics by saying that the apparent time of the Lorentz transformation is real time. He similarly assumed in quantum mechanics that real states can be represented as vectors in Hilbert space (or as mixtures of such vectors), and that the indeterminacy principle is the simple expression for this assumption.

If at the time he developed the indeterminacy principle, Heisenberg was not consciously imitating the discovery strategy that Einstein used for development of special relativity, it is nevertheless not difficult to imagine how Heisenberg hit upon it independently. For the realist it is a small step from Einstein's semantical thesis that theory decides what can be observed, to the ontological thesis that theory decides what is physically real, where the theory in question is empirically warranted, as was Heisenberg's matrix mechanics. This strategy in which the empirical adequacy of a scientific theory as revealed by scientific criticism decides the ontology to be accepted, is a reversal of the more traditional relation in which currently accepted ontological and metaphysical views are included among the criteria for scientific criticism, and operate prior to or even in disregard of the outcome of empirical criticism. Heisenberg explicitly compares his realistic interpretation of quantum theory to Einstein's realistic interpretation of the Lorentz transformation equation, when he defends the ontology of his Copenhagen interpretation against Einstein's explicit ontological criterion for physical reality.

In his "Criticism and Counter-proposals to the Copenhagen Interpretation of Quantum Theory" in *Physics and Philosophy* Heisenberg characterizes the ontology advanced explicitly by Einstein as the ontology of "materialism", which he says rests upon the "illusion" that the kind of existence familiar to us, the direct actuality of the world around us, can be extrapolated into the atomic order of magnitude. In the closing paragraphs of this chapter of his book he states that all counterproposals offered in opposition to the Copenhagen interpretation must sacrifice what he calls the position-momentum symmetry properties of the quantum theory. He explicitly states that like Lorentz invariance in the theory of relativity, the Copenhagen interpretation cannot be avoided, if these symmetries are held to be genuine features of nature.

Another example of Heisenberg's practice of scientific realism is his *potentia* ontology given in his summary of the Copenhagen interpretation of the quantum theory in "The Copenhagen Interpretation of Quantum Theory" in his *Physics and Philosophy*. This might be taken as his redefinition of the meaning of "entity". Heisenberg invokes Aristotle's idea of *potentia* to express the thesis that wave and particle do not appear simultaneously, and are wave or particle manifestations of the same entity. His interpretation of the probability function is that it has both a subjective and an objective aspect. The subjective aspect makes statements about the observer's incomplete knowledge, while the objective aspect makes statements about what Heisenberg calls "tendencies" and "possibilities", and it is in this latter aspect that he refers to the idea of *potentia*. The probability function in the quantum theory is subjective and represents incomplete knowledge, because observers' measurements are always inaccurate. The subjective reason that they are inaccurate is the ordinary errors of measurement, the empirical underdetermination that occurs both in both classical physics and quantum physics. But the objective reason is distinctive to quantum physics, and it is the inaccuracy caused by a disturbance introduced by the apparatus in the measurement process.

Heisenberg illustrates this objective aspect by means of an ideal experiment involving a gamma-ray microscope used to observe an electron. In the act of observation at least one quantum of the gamma ray must have passed the microscope, and must first have been deflected by the electron. Therefore the electron must have been impacted by the quantum and must have changed its momentum. The indeterminacy relations give the indeterminacy of this momentum change. When the probability function is written down, it includes both the objective and subjective inaccuracies, and there must be at least two such disturbing observations in an atomic experiment. The objective element in the probability function is not like the description of motion in classical physics. The classical physicist would like to say that between the initial and the second observation the electron has described an unknown path. But Heisenberg says that between the two observations the electron has not described any path in space and time, since the electron has not been anywhere. The probability function does not represent a course of events in the course of time, but rather represents statistical possibilities or tendencies, which are actualized by the second act of observation. The transition from the possible to the actual takes place with the act of observation involving the interaction of the electron with the measuring device. Heisenberg also notes that the transition applies to the physical and not to the psychological act of observation, and that certainly quantum theory does not contain "genuine subjective features" in the sense that it introduces the mind of the physicist as a part of the atomic event.

Heisenberg attributes the objective aspect of the quantum theory to duality, which he construes as a transition from possible to actual. In his *Physics and Philosophy* Heisenberg illustrates duality by the two-slit experiment, the historic interference experiment firstly performed by Thomas Young in 1801. It involves passing monochromatic light through a screen with two holes or slits in it, and then registering the light on a photographic plate. Viewed as a wave phenomenon there are primary waves entering the slits, and then there are secondary spherical waves starting from the two slits, which interfere with each other to produce an interference pattern on the photographic plate. But the registration on the plate is a quantum process, a chemical reaction. If the quantum particle passes through either slit, the other one would normally be viewed as irrelevant. But the existence of the other slit is in fact relevant, because the photographic plate registers the interference pattern. Therefore the statement that any light quantum must have gone through either just one or just he other slit is problematic. Heisenberg maintains that this problematic outcome shows that the concept of the probability function does not allow a description in space and time of what happens between the two observations. The description of what "happens" is restricted to the measurement observation process in which there occurs the transition from the possible or *potentia* to the actual. David Bohm had also proposed construing indeterminacy realistically as potentiality in his *Quantum Theory* (1951), written while he accepted the Copenhagen interpretation and before proposing his alternative hidden-variables thesis. But Heisenberg does not reference Bohm for his own thesis of *potentia*, and he seems to have derived the idea independently, probably from his reading of Aristotle's philosophy.

Bohr's Influence on Heisenberg and Issues with Einstein

Niels Bohr was one of the leading atomic physicists of the first half of the twentieth century. He had studied in England under J.J. Thompson and Lord Rutherford, and received the Nobel Memorial Prize for Physics in 1922 for his theory of the structure of the atom. He founded the Copenhagen Institute for Theoretical Physics in 1920, and as its director was actively recruiting talented staff members, when he accepted an invitation to deliver a series of lectures on atomic physics at the University of Göttingen in the summer of 1922.

In "Quantum Theory and its Interpretation" in *Niels Bohr* (1963) Heisenberg reports that he first met Bohr at these Göttingen lectures, which he attended with his teacher, Arnold Sommerfeld. At the time Heisenberg was a twenty-two year old student at the University of Munich. Heisenberg came to Bohr's attention, because in the discussions following one of the lectures, he dissented from Bohr's optimistic assessment of a theory developed by Kramers at Copenhagen. Heisenberg relates that Bohr was sufficiently worried about the objection, that after the discussion he asked Heisenberg to take a walk with him for a conversation. During the walk Bohr talked about the fundamental physical and philosophical problems of modern atomic theory.

The encounter resulted in an invitation for Heisenberg to visit the Institute at Copenhagen for a few weeks, and later to hold a position. Heisenberg describes Bohr as primarily a philosopher rather than a physicist, and he states that he found Bohr's philosophy to be fascinating, although he also states that he and Bohr had different views on the rôle of mathematics in physics.

Bohr's philosophy of atomic physics is set forth in his *Atomic Physics and the Description of Nature* (1934), "Discussions with Einstein" in *Albert Einstein* (ed. Schilpp, 1949), *Atomic Physics and Human Knowledge* (1958), and *Essays 1958/1962 on Atomic Physics and Human Knowledge* (1963). Bohr's philosophical views may have been influenced by some casual reading of the philosophical literature, but he never references any philosopher in his writings. His views seem largely to be the product of his own reflections on his research in atomic physics and on the work of his staff at Copenhagen. In "Quantum Theory and Its Interpretation" Heisenberg states that Bohr had developed views on the semantics of language and scientific theory many years before he met Bohr and before he developed his matrix mechanics.

Bohr's mature philosophy of science included two theses: Firstly that the mathematical formalisms of microphysics cannot describe the microphysical domain that lies beyond ordinary experience. Secondly that the only language that is capable of a descriptive semantics is the language of ordinary discourse and its refinement in classical Newtonian physics. Heisenberg did not accept the first thesis, because he had a different concept about the abstract nature of mathematics. But Bohr's second thesis had a lifelong influence on him, an influence that had a retarding effect on his development of his own philosophy of microphysics.

Bohr gives various reasons why in his view the mathematical formalisms of microphysics have no descriptive semantics and are only symbolic instruments for making calculations and predictions. One reason given in "Discussions with Einstein" is the occurrence of a complex number in the formalism. Apparently he believed that reality could be described only by equations having variables and parameters that admit only real numbers. Another reason given in "The Solvay Meetings and the Development of Quantum Theory" (1962) in his *Essays 1958/1962* is the interpretation of the statistical wave function in a configuration space of more than four dimensions. Like Einstein, Bohr believed that real physical space-time has no more than four dimensions.

But the basic reason why Bohr interpreted the mathematical formalism of quantum theory instrumentally is his belief that only the language of everyday discourse and its refinement in classical physics can have descriptive semantics. He maintained that ordinary language and classical physics must be used to describe any experimental set up in physics, while at the same time he believed that classical physics is too limited to describe the microphysical domain beyond ordinary experience. It is limited not only because Newtonian physics is inadequate as a microphysical theory, but also due to the inherent nature of human cognitive perception. This is a philosophy of the semantics of language that is a naturalistic thesis. Due to Bohr's philosophy of perception, Einstein as well as many philosophers of science were led to conclude that Bohr's philosophy of science is positivist.

If Bohr's philosophy of science is a positivist philosophy, it is a peculiar one. His statements of his philosophy that are most often referenced in this connection by philosophers of science are those in *Atomic Physics and the Description of Nature*. In the opening "Introductory Survey (1929)" he states that both relativity theory and quantum theory are concerned with physical laws that lie beyond ordinary experience, and which therefore present difficulties to our "accustomed forms of perception". In quantum theory the limitations of these forms of perception are revealed by the need for complementary, the inconsistent Newtonian description of the quantum phenomenon as both a wave and a particle. Both of these two forms based on classical physics are necessary for a complete description, even though they are inconsistent in classical physics. Yet these "customary" forms of perception cannot be dispensed with, since all human cognitive experience must be expressed in terms of them. The fundamental concepts of classical physics therefore will never become superfluous for the description of physical experience; they must be used to describe experiments and to relate the mathematical symbolisms to the perceptions in experience.

In Einstein's attack on Bohr's philosophy of quantum theory the central issue is the ontology of the Copenhagen interpretation, which Einstein critiqued with his programmatic aim of all physics. The explicit criterion set forth in the programmatic aim of science is the "complete" description of any individual situation, as it supposedly exists irrespective of any act of observation or substantiation. Accordingly he characterized the Copenhagen interpretation as a version of Bishop Berkeley's idealist thesis "*esse est percipi"*, a characterization that is not accurate, because Bohr did not maintain that the atomic phenomenon is produced by a cognitive process but rather by the physical processes of measurement in the experimental set up. In this matter Einstein seems to have confused an epistemological issue with a physical one.

But Bohr is not blameless for the confusion. For example in "Introductory Survey (1929)" he opens with statements emphasizing the subjectivity of all experience and the difficulties in distinguishing between phenomena and their observation; and he concludes the chapter with the statement that "to be" and "to know" lose their unambiguous meanings. From an epistemological viewpoint some of Bohr's statements are ambiguous as to whether he is advancing a realist or an idealist philosophy.

Some of Heisenberg's earlier statements are also suggestive of an idealist position. For example he writes in the opening chapter of *The Physicist's Conception of Nature*, that since we can no longer speak of the behavior of the particle independently of the process of observation, the natural laws formulated in the quantum theory no longer deal with the elementary particles themselves, but only with our knowledge of them. But later Heisenberg is very clear about avoiding any metaphysical idealism. In "The Copenhagen Interpretation of Quantum Theory" in *Physics and Philosophy* he states explicitly that quantum theory does not contain genuinely subjective features, since it does not introduce the mind of the physicist as part of the atomic event, and that the transition from possible to actual in the act of observation is in the physical and not the psychical act of observation.

Any metaphysical idealist/realist ambiguity notwithstanding, however, Einstein's central ontological thesis is that the statistical quantum theory is incomplete in the sense that further theoretical research is necessary, in order to develop a complete theory that would give Heisenberg's indeterminacy relations a status in future physics, which he thought should be analogous to the status had by statistical mechanics. It is noteworthy that Einstein admits the indeterminacy principle is not empirically incorrect, even as he rejects the Copenhagen nondeterministic ontology, because it does not conform to his explicit ontological criterion. In the 1949 "Reply to Criticisms" Einstein conceded that his incompleteness thesis is the minority view among physicists; many contemporary philosophers as well as physicists have accepted the indeterminacy thesis of the Copenhagen interpretation of the statistical quantum theory, and have rejected the deterministic ontology advocated by Einstein. When confronted with the dilemma of having to choose between an established ontological criterion and a new but empirically adequate quantum theory, both the contemporary physicists and the contemporary pragmatist philosophers of science opt for the latter, contrary to Einstein's arguments for the former.

In addition to the ontological issue between Bohr and Einstein about what is physically real, there is also a related epistemological issue about the relation between sense perception and intellectual concepts. Einstein had portrayed Bohr as a positivist due to Bohr's views about perception and the semantics of language. This portrayal is debatable, because positivists do not usually speak of what Bohr called "forms of perception", and particularly about the limitations of such forms of perception for physics. But in his 1934 book Bohr writes of the necessity of these forms of perception for science to reduce our "sense impressions" to order. Even though Einstein himself uses the phrase "sense impressions" in his statement of the aim of science in "Physics and Reality" in 1936, he seems to have taken Bohr's discussion referencing sense impressions to mean that there are no concepts or categories in perception.

Einstein opposed this view, and stated in 1949 in his "Reply to Criticisms" that thinking without positing categories and concepts is as impossible as breathing in a vacuum. He furthermore states that his philosophy differs from Kant's since he does not view categories as unalterable and as predetermined by the faculty of understanding, but rather views them as "free conventions". The philosopher of science may ask whether Einstein's neo-Kantian views without Kant's idealism and a priorism is still recognizably Kantian. But the point to be emphasized is that Einstein's thesis that concepts are necessary for perception and that they are free conventions amounts to a restatement of what he told Heisenberg in 1926, when he said that theory decides what the physicist can observe. In this earlier statement Einstein might consistently have told Heisenberg that observation without theory is as impossible as breathing in a vacuum. Perhaps it was in response to Einstein's criticisms in these matters that Bohr refrains in his later writings from using the phrase "sense impressions". Instead Bohr merely describes the concepts of classical physics as a refinement of the concepts of ordinary discourse, so he is no longer misunderstood as saying that perception occurs without any concepts.

Nonetheless there is still a fundamental difference between the semantical views of Bohr and Einstein. Einstein's thesis that concepts are free conventions is intended to mean that there are none of the inherent limitations in observation or in language that Bohr had maintained. In Bohr's phrase "customary forms of perception", the term "customary" does not mean the same thing as the term "convention" in Einstein's phrase "free conventions". The limitations that Bohr said these customary forms of perception impose on descriptive language are not temporary limitations, which will be removed with the change in language customs resulting from the further development of theory. Rather these limitations are inherent in the nature of the human cognitive processes of perception and consequently in the semantics of descriptive language. They are therefore permanent. There is no such permanence according to Einstein's view; the free conventions of human thought, in the concepts and categories in language and scientific theory, are not only conventions that are free to change, but are destined to change with the advancement and further development of scientific theory. The difference between Bohr's and Einstein's semantical views is the difference between the naturalistic and the artifactual philosophies of the semantics of language.

Semantical Revision and Heisenberg's Doctrine of Closed-off Theories

Heisenberg called quantum theory "closed", while Einstein in contrast said it is "incomplete". An earlier and a later version of Heisenberg's semantical doctrine of "closed-off theories" may be distinguished. The earlier version is given in his "Questions of Principle in Modern Physics" originally given as a lecture at the University of Vienna in 1935 and since published in his *Philosophical Problems of Quantum Physics*, where he sets forth the central questions that are addressed by his philosophy of physics. He firstly asks how it is possible for there to have occurred the strange revision of the fundamental concepts of physics during the preceding thirty years. Then secondly he asks what is the truth content of classical physics and of modern physics in view of this conceptual revision. He notes that these are also the questions that were posed and discussed by Bohr, who approached them from the fundamental premises of quantum theory. It is noteworthy that Heisenberg's philosophy of science addresses questions formulated by Bohr. The formulation of the questions in terms of how a conceptual revision is possible suggests a naturalistic philosophy of the semantics of language as a point of departure, since on the artifactual thesis the possibility of a fundamental semantical revision is not problematic. When concepts and meanings are understood to be cultural artifacts, then semantical change may be expected as a matter of course.

As it happens, in his doctrine of closed-off theories Heisenberg did not depart very far from the naturalistic thesis. He developed a theory of semantical revision, but it is also a theory of semantical permanence. Heisenberg has an earlier and a later version of his doctrine of closed-off theories. In the **earlier** 1935 version he maintains that classical physics is permanently valid, and that its concepts are necessary for experimentation in physics. He states that classical physics is based on a system of mathematically concise axioms, whose physical content is fixed by the choice of words used in them. These words determine unequivocally the application of the system of axioms to nature. Wherever concepts like mass, velocity and force can be applied, there Newton's law, **F=ma**, will be true. The validity of the claim of this law is comparable to Archimedes law of the simple lever, which today forms the theoretical basis for all load-raising machines, and which will be true for all time. Therefore in spite of the fact that there has been a revision of mechanics, the axiomatic system developed by Newton is still valid. The revision pertains to the limits encountered in the application of the axiomatized system of concepts of classical physics; it is not the validity but only the applicability of classical laws that has come to be restricted by relativity theory and quantum theory.

Having thus described how he believes that the axiomatized mathematical system of classical physics is permanently valid, Heisenberg then describes how revision is possible. The revision of classical physics is possible due to a "lack of precision" in the concepts used in the system. While the quantitative variables **x**, **t**, and **m** used in the Newtonian system are linked without ambiguity by the system of equations, which contain no degree of freedom apart from initial conditions, the words "space", "time", and "mass", which are attributed to those quantities are tainted with all the lack of precision that may be found in their **everyday** use. The validity of classical physics is limited by the lack of precision of the concepts contained in its axioms. As a result of this lack of precision science may be forced into a revision of its concepts as soon as it leaves the field of common experience; the concepts currently used may lose their value for the orderly presentation of new experience. But this revision cannot be known in advance.

He notes for example that before the experiences of quantum theory the results of the Wilson cloud chamber experiments could unhesitatingly be expressed as "we see in the cloud chamber that the electron has described such and such a path", and this simple description could be accepted as an experimental fact. It was only later that physicists came to know from other experiments the problematic nature of the phrase "path of an electron". Scientific progress consists initially in the unhesitating use of existing terms for the description of experience, and then subsequently in the revision of those terms as demanded by new experience. The lack of precision contained in the systems of concepts of classical physics is necessary, and therefore even the mathematically exact sections of physics represent only tentative efforts to find our way among a wealth of phenomena.

Central to the doctrine of closed-off theories is the thesis that classical concepts must be retained for experimentation in physics. So far as the concepts of space, velocity and mass can be applied unhesitatingly, as in everyday experiences, Newtonian principles still apply. The Newtonian laws represent an "idealization" achieved by taking into account only those parts of experience that can be ordered by the concepts of space, time and mass on the assumption of objective events in time and space. Therefore they always remain the basis for any exact and objective science. Since we demand of the results of science that they can be objectively demonstrated, we are forced to express these results in the language of classical physics. For example for an understanding of relativity theory, it is necessary to stress that the validity of Euclidian geometry is presupposed in the instruments that are used to show the deviation from Euclidian geometry, *i.e.*, the measure of the deviation of light (an apparent reference to Eddington's 1919-eclipse experiment to test relativity theory). Furthermore the very methods used for the manufacture of these instruments enforce the validity of Euclid's geometry for these instruments within the range of their accuracy. Similarly we must be able to speak without hesitation of objective events in time and space in any discussion of experiments in atomic physics. Heisenberg concludes that while the laws of classical physics seen in the light of modern physics appear only as limiting cases of more general and abstract connections, the concepts associated with these laws remain an indispensable part of the language of science, without which it is not possible even to speak of scientific results. Therefore, while mathematically exact sections of classical physics are tentative, the classical concepts must nevertheless be used for the description of experiments.

Heisenberg offers a **later** version of his doctrine of closed-off theories in several later articles and chapters in his books. In his earlier version meanings found in everyday words, which are associated with variables in mathematically expressed axiomatic systems of physical theories, retain their vagueness in Newtonian physical theory. In his later version association of the vague everyday meanings with the terms in the axiomatic system **resolves their vagueness**, because the axiomatic systems have a definitional function. This development represents his transition to context-determined relativized semantics, where the relevant context is the axiomatic system of a physical theory.

In "The Notion of a 'Closed Theory' in Modern Science" in *Across the Frontiers* he discusses the criteria for scientific criticism and the evolution of the aim of science. He writes that when Einstein developed his special theory of relativity, it was evident that Maxwell's theory of electromagnetic phenomena could not be traced back to mechanical processes that obey Newton's laws, and the inference seemed unavoidable that either Newtonian mechanics or Maxwell's theory must be false. Physicists concluded that Newton's theory is strictly speaking false. This mislead many scientists into unwittingly attempting to describe the phenomena of the world exclusively by means of the concepts of field theory. This represented an aim of science that is commonly accepted from Newton's theory that science should proceed by means of a unitary conceptual scheme, except that now the concepts should be those of field theory instead of classical mechanics.

But in both cases the concepts supplied an objective and causal description of the process involved, and were therefore thought to be universal. These common concepts were rejected by quantum theory for the description of the atom, although they must still be used to describe the results of an observation while standing in a complementary relation to one another. Thus Heisenberg concludes that physicists no longer say that Newton mechanics is false and must be replaced by quantum mechanics which is correct. Instead they say that classical mechanics is a consistent self enclosed scientific theory, and that it is a strictly true and correct description of nature, whenever its concepts can be applied. Quantum theory has only restricted the applicability of Newtonian mechanics, and has made classical physics a "closed-off" theory. Heisenberg says that in contemporary physics there are four great disciplines that have closed-off theories. They are firstly Newtonian mechanics, secondly Maxwell's theory and special relativity, thirdly the theory of heat and statistical mechanics, and fourthly nonrelativistic quantum mechanics, atomic physics and chemistry. General relativity is not yet closed off.

Heisenberg then turns to a discussion of the properties of a closed-off theory and of its truth content. A closed-off theory is consistent as an axiomatized mathematical system. The most celebrated example is

Newton's *Principia Mathematica*. And the concepts of the theory must be directly anchored in experience. Before the axiomatic system is developed, concepts describing everyday life remain firmly linked to the phenomena and change with them; they are compliant toward nature. But when they are axiomatized, they become rigid, and they "detach" themselves from experience. This is the distinctive aspect of his later version of the doctrine of closed-off theories. The system of concepts rendered precise by axioms is still very well adapted to a wide range of experiences, but axiomitization of concepts sets a decisive limit to their field of application. The discovery of these limits is part of the development of physics. Yet even when the boundaries of the closed theory have been encountered and overstepped, and when new areas of experience are ordered by means of new concepts, the conceptual scheme of the closed theory still forms an indispensable part of the language in which the physicist speaks of nature. The closed theory is among the presuppositions of the wider inquiry; we can express the result of an experiment only in the concepts of earlier closed theories. Heisenberg summarizes the properties of closed-off theories as follows: Firstly the closed-off theory holds true for all time. Whenever experience can be described by the concepts of the closed-off theory, even in the most distant future, the laws of this theory will always be correct. Secondly the closed-off theory contains no perfectly certain statements about the world of experiences; its successes are contingent. Thirdly even with the indeterminacy of its contingency, the closed-off theory remains a part of scientific language, and therefore is an integrating constituent of our current understanding of the world.

Heisenberg sees the evolution of modern science differently than Einstein's description in "Physics and Reality". Heisenberg says the historical process that gave rise to the whole of modern physics since the conclusion of the Middle Ages, consists in a succession of intellectual constructs, which take shape as if from a "crystal nucleus", out of individual queries raised out of experience, and which eventually once the complete crystal has developed, again detach themselves from experience as purely intellectual structures that forever illuminate the world for us as closed-off theories. Thus the history of science is like the history of art, where the goal is to illuminate the world by means of intellectual constructs. In his "The End of Physics" in *Across the Frontiers* he adds that while physics consist of many closed-off systems, it is not possible to close off physics as a whole. Today it is necessary to seek out new and still more comprehensive closed-off theories or "idealizations" as he also calls them, which will include both relativity theory and quantum theory as limiting cases.

Closely related to his thesis of closed-off theories is Heisenberg's theory of abstraction. In "Abstraction in Modern Science" in *Across the Frontiers* he defines abstraction as the consideration of an object or a group of objects under one viewpoint while disregarding all other properties of the object. All concept formation depends on abstraction, since it presupposes the ability to recognize similarities. Primitive mathematics developed from abstraction, *e.g.*, the concept of the number three. Mathematics has formed new and more comprehensive concepts, and thereby ascended to ever higher levels of abstraction. The realm of numbers was extended to include the irrational and complex numbers. This view is quite different from Bohr's, who believed that the mathematical formalisms used in physics have no descriptive semantical value but are merely symbolic, *i.e.*, semantically vacuous, instruments for calculation and prediction, particularly if they contain complex numbers or represent more than four dimensions as in quantum theory. In Heisenberg's philosophy abstraction, the consideration of the real from a selective viewpoint, produces idealizations of reality which are axiomatic mathematical structures that become closed-off, as the historical development of science reveals the limitations of their applicability and occasions the creation of new theories.

In expounding his semantical doctrine of closed-off theories Heisenberg departed from Bohr. Comparison of their views reveals essential similarities, but it also reveals differences. Bohr's semantical views are stated in "Discussions with Einstein" where he says that Planck's discovery of the quantum of action makes classical physics an "idealization" that can be unambiguously applied only in the limit, where all actions involved are large in comparison with the quantum. A more elaborate statement is given in "The Solvay Meetings" in *Essays 1958/1962*. There he firstly says that unambiguous communication of physical evidence demands that the experimental arrangement and the reading of observations be expressed in common language suitably refined by the vocabulary of classical physics. Then secondly he states that in all experimentation this demand is fulfilled by using as measuring instruments bodies like diaphragms, lenses, and photographic plates, which are so large and heavy that notwithstanding the decisive rôle of the quantum for stability and properties of such bodies, all quantum effects can be disregarded in the account of their position and motion. Finally and thirdly he says that in classical physics we are dealing with an idealization according to which all phenomena can be arbitrarily subdivided, and all interaction between measuring instruments and the object under investigation can be neglected or compensated for. Bohr seems to be using the term "idealization" as Heisenberg does, but he reserves it for the classical physics. Bohr does not admit a separate set of distinctively quantum concepts, because he maintains an instrumentalist interpretation of the quantum theory mathematical formalism. In his view there are no quantum concepts defined by the equations of the quantum theory, but rather there are only classical concepts, while the semantically uninterpreted mathematical formalism generates predictions expressed in classical terms.

Bohr's "Forms of Perception" and Neo-Kantianism

Having based his doctrine of closed-off theories on Bohr's philosophy of observation, Heisenberg attempted to relate Bohr's philosophy to the history of philosophy, and specifically to Kantianism. Heisenberg's statements are found in his "Recent Changes in the Foundations of Exact Science" (1934) in *Philosophical Problems of Quantum Physics*, in his "The Development of Philosophical Ideas Since Descartes in Comparison with the New Situation in Quantum Theory" in *Physics and Philosophy*, in his "Quantum Physics and Kantian Philosophy (1930-1932)" in *Physics and Beyond*, and in his "Planck's Discovery and the Philosophical Problems of Atomic Theory" in *Across the Frontiers*. Like Einstein, Heisenberg rejects the positivist phenomenalism and advocates realism; he was never a metaphysical Idealist, Kantian or otherwise. In "Planck's Discovery" he states that quantum theory does not consider sense impressions to be the primary given, and that if anything is the primary given in quantum theory, it is the reality described with the concepts of classical physics. And in "Development of Philosophical Ideas Since Descartes" he describes his realistic variation on Kant's views with the phrase "practical realism", since in Heisenberg's view things rather than perceptions are the given for the human mind.

But while Heisenberg is opposed to positivism as much as Einstein, his referencing the philosophy of Kant is not motivated by his antipositivism. Heisenberg is interested merely in relating Kantianism to the philosophy of observation he took from Bohr and incorporated in his doctrine of closed-off theories. In "Recent Changes in the Foundations of Exact Science" he says that in the field of philosophy of perception, Kant's philosophy has been put into a new light as a result of the critique of absolute time and Euclidian space by relativity theory and by the critique of the law of causality by quantum theory, and that the question of the priority of the forms of perception and of the categories of the understanding must be reconsidered. He states that there are two apparently contradictory propositions that must be reconciled: On the one hand relativity theory and quantum theory have shown that our space-time forms of perception and the category of causality are not independent of all experience in the sense that they must for all time remain essential constituents of every physical theory. On the other hand, as Bohr taught, the applicability of the classical (*i.e.*, Kantian) forms of perception and the law of causality are the premises of every objective experience even for modern physics. The physicist can only communicate the course of an experiment and the result of a measurement by describing the necessary manual operations and instrument readings as objective events taking place in the space and time known to our intuition. And he could not infer the properties of the observed object from the result of measurement, unless the law of causality guaranteed an unambiguous connection between measurement and object. Heisenberg resolves the contradiction between the two statements as follows: Physical theories can have a structure differing from classical physics, only when their aims are no longer those of immediate sense perception; that is to say, only when they leave the field of common experience dominated by classical physics.

In "Quantum Physics and Kantian Philosophy" Heisenberg views Kant's philosophy of perception as a closed-off theory, as he elsewhere describes closed-off theories in physics. He compares the validity of Kant's philosophy to the validity of Archimedes' theory of the lever, and he states that Kant's theory is eternally true, just as Archimedes' theory is eternally true. Kant's analysis of perception represents true knowledge that applies wherever thinking beings enter into the kind of contact with their environment called "experience". Relativity theory and quantum theory have defined the limits of the a priori in the exact sciences in ways that could not have been known to Kant. The a priori has not been eliminated from physics, and Kant's analysis of how we come by our experiences is essentially correct. But the a priori has become "relativised" in the sense that classical concepts are a priori conditions for relativity and quantum theory, since classical concepts are necessary for experiments. Remarkably

Heisenberg says that the progress of science has changed the structure of human thought, and has taught us the meaning of "understanding". In the closing paragraph of his "Quantum Physics and Kantian Philosophy" Heisenberg states that he has described the relationship between Kant's philosophy and modern physics from the perspective of Bohr's teachings.

On Scientific Revolutions

Heisenberg considers the development of modern quantum theory to be one of the two great scientific revolutions in twentieth century physics; the other in his view is relativity theory. Few would disagree. The complete title of his 1958 book is *Physics and Philosophy: The Revolution in Modern Science*. But by the 1960's the term "revolution" as used in connection with the development of science had become what Heisenberg calls a "vogue word" due to some similarities between scientific revolutions and social revolutions. Possibly the vogue status of the term is due in part to the popular monograph, *Structure of Scientific Revolutions*, written by Thomas Kuhn in the United States in 1962, but Heisenberg never references Kuhn, and their views are not the same. Heisenberg discusses his idea of revolution in science in a lecture delivered to the Association of German Scientists in Munich in 1969, which was published in English in 1974 as "Changes of Thought Pattern in the Progress of Science" in his *Across the Frontiers*. Heisenberg recognizes the operation of sociological forces in the scientific professions, but his views are different from those of Kuhn.

Heisenberg defines a "revolution" in science as a change in thought pattern, which is to say a semantical change. He states that a change in thought pattern becomes apparent, when words acquire meanings that are different from those they had formerly, and when new questions are asked. He does not reference his semantical thesis of closed-off theories in this context, although the episodes in the history of post-Newtonian physics that he cites as examples of scientific revolutions are the same as those that he also says resulted in new closed-off theories in the history of physics. And the semantical change that occurs in the transition to a new axiomatic theory and the closing off of the old one, is the change involved in the transition to a new thought pattern. The central question that Heisenberg brings to the phenomenon of revolution in science understood as a change in thought pattern, is how the revolution is able to come about. The occurrence of the revolution is problematic due to resistance to the change in thought pattern offered by the cognizant profession. Heisenberg also expresses the question in more sociological terms, when he asks how a small group of physicists are able to "constrain" other physicists to make the change in thought pattern in spite of the latter's resistance to do so. Firstly he discusses the reasons for resistance. Then he discusses various proposed explanations about how the resistance is overcome.

In his discussion of the reasons for resistance he states that there have always arisen strong resistances to every change in the pattern of thought. The progress of science proceeds as a rule without much resistance or dispute; the scientist has by training been put in readiness to fill his mind with new ideas. But the case is altered when new groups of phenomena compel changes in the pattern of thought. Here even the most eminent of physicists find immense difficulties, because a demand for change in thought pattern may create the perception that the ground is to be pulled from under one's feet. A researcher who has achieved great success in his science with a pattern of thinking he has accepted from his young days, cannot be ready to change this pattern simply on the basis of a few novel experiments. Heisenberg states that once one has observed the desperation with which clever and conciliatory men of science react to the demand for a change in the pattern of thought, one can only be amazed that such revolutions in science have actually been possible at all. Undoubtedly the case in Heisenberg's experience is the desperation that he saw in Schrödinger's and especially Einstein's opposition to the new thought pattern represented by the Copenhagen interpretation of the quantum mechanics.

He then considers several possible answers to the question of how scientific revolutions can come about in spite of the resistances, of how the resistances are overcome. One answer that he rejects is that the revolution is due to a strong revolutionary personality. He maintains that no such strong personality could overcome the profession's resistance. Another answer that he rejects might be described as a variation on the conspiracy thesis, the view that a small group of physicists intended from the outset to overthrow the existing state of the science. He states that never in its history has there ever been a desire for any radical reconstruction of the edifice of physics; this is because at the onset of a revolution there is a very special, narrowly restricted problem, which can find no solution within the traditional framework. The revolution is brought about by researchers who are genuinely trying to resolve the special problem, but who otherwise wish to change as little as possible in the previously existing physics. It is precisely the wish to change things as little as possible, which demonstrates in Heisenberg's opinion that the introduction of novelty is a matter of being compelled by the facts. The change of thought pattern is imposed by the phenomena. He concludes therefore that the way to make a scientific revolution is to try to change as little as possible: it is an error to demand the overthrow of everything existing due to the risk of attempting a change that nature makes impossible. Small changes on the other hand show what is compelled by the facts, and in the course of years or decades enforce a change in thought pattern and shift the foundation of the science. The relevant example of such a small change is Planck's quantum of action, which years later resulted in the modern quantum theory.

Having rejected the view that scientific revolution occurs due to a conspiracy either with or without a strong revolutionary personality, Heisenberg then considers the answer that the resistances to revolution are overcome simply because there is a "right" and a "wrong" in physics, and the new theory is right while the old theory is wrong. It is noteworthy that Heisenberg does not reject the thesis that there is a right and a wrong in the sense of a correct and an incorrect, and in view of his thesis of closed-off theories, it would be remarkable if he did. Furthermore he had explicitly rejected historical relativism in his "Quantum Physics and Kantian Philosophy". Still he finds that there is a problem with this answer as an explanation for overcoming resistances, namely that historically the right theory has not always prevailed. He cites as an example the dominance of the geocentric theory of Ptolemy over the heliocentric theory of Aristarchus, who lived in the third century BC.

Therefore, while there are absolute standards for criticism of scientific theories, there still remains the question of why some correct theories succeed in gaining acceptance over the strong forces of resistance, while others do not, even though the rejected theories may be correct. Heisenberg then proposes his own answer. Scientists perceive that with the new pattern of thought, they can achieve greater success in their science than with the old; the new system proves to be more fruitful. Heisenberg states that once anyone has decided to be a scientist, he wants above all to get ahead, to be on hand when the new roads open up; it does not satisfy him merely to repeat what is old and has often been said before. Consequently the scientist will be interested in the kind of problems where there is something to be done, where he has the prospect of successful work. That is how relativity theory and quantum theory came to prevail according to Heisenberg. He describes this as a "pragmatic criterion of value", and he states that while one cannot always be certain that the right theory will always prevail, nevertheless these are forces that are strong enough to overcome the resistances to a change in thought pattern.

Since Heisenberg is a principal participant in one of the great scientific revolutions in modern physics, his views based on his personal experience deserve singular consideration. He was undoubtedly impressed by the resistances offered to the Copenhagen interpretation by Schrödinger and especially by Einstein. While few contemporary philosophers of science accept Heisenberg's doctrine of closed-off theories with its naturalistic view of observation, which he uses to interpret his experience of scientific revolution, they recognize the operation of sociological forces including the thrust of opportunistic careerism. And they also recognize that semantical change occurs in scientific revolutions, and that the adjustment it imposes on the affected profession operates as a cause of resistance within it, even though they do not accept Heisenberg's theory of semantical change and permanence. Unlike others such as Kuhn, Heisenberg does not identify the institutionalized criteria for scientific criticism with the existing thought pattern, and he does not maintain that the revolution is a change with no institutional framework controlling it. Heisenberg avoids the historical relativism found by many in Kuhn's thesis, and which is explicitly embraced by Feyerabend. And one would not expect the proponent of the doctrine of closed-off theories and the advocate of Bohr's theory of observation to find the process of scientific criticism very problematic. The scientist is simply compelled by the facts, and the semantics of the statements of fact are not a problematic matter. Failure of the correct theory to overcome the forces of resistance, and indeed the very existence of those resistances, is due to the professional failure of those who cannot adjust to new thought patterns when the facts compel, and not to any inherently problematic character in the process of scientific criticism itself.

One can only wonder what Heisenberg might have said, were he to have followed through with Einstein's thesis that it is the theory that decides what the physicist can observe; how he would have addressed the consequent problem that the concepts used to describe the facts are supplied by the choice of thought patterns expressed in the new theory.

Heisenberg's Philosophy of Science

Heisenberg's rich and extensive philosophical writings can be related to the four functions performed in basic-scientific research:

Aim of Science

The aim of science has a special importance in Heisenberg's philosophy, because it was explicitly developed to defend the Copenhagen interpretation of quantum theory against Einstein's explicitly formulated programmatic aim of all physics. Heisenberg's views are expressed in his "Notion of 'Closed Theory' in Modern Science" and in his "On the Unity of the Scientific Outlook on Nature" (1941) in *Philosophical Problems of Quantum Physics*. Einstein used his programmatic aim of physics to claim that the statistical quantum theory is "incomplete" in the sense that it does not represent an adequate explanation for the problem that it addresses, and that further research work is still needed. The reason he said it is still incomplete is that it is not consistent with the ontology of field physics, which describes physical reality as continuous in four dimensions and deterministic.

But Heisenberg denied Einstein's contention that the microphysical theory must employ the same ontological concepts as those used in macrophysical field theory, and his doctrine of closed-off theories was motivated by his desire to show how multiple ontologies can co-exist in physics. This is Heisenberg's thesis of pluralism in science. The Copenhagen interpretation of quantum theory is complete in Heisenberg's view, because it is a closed-off theory. And like all closed-off theories it is not only a complete solution to the problem that it addresses, but it is also a permanently true solution. In Heisenberg's philosophy the aim of science is to progress through a sequence of closed-off theories, and it is not, as Einstein maintained, to progress toward a single and all-inclusive ontology. The result of physics pursuing its aim as Heisenberg views it, has been his architectonic scheme for physics, a scheme of closed-off theories which he delineates in his “Relation of Quantum Theory to Other Parts of Natural Science” in *Physics and Philosophy*.

Scientific Discovery

In Heisenberg’s treatment of scientific discovery two aspects may be distinguished: One is the syntactical or structural aspect, and the other is the semantical or the interpretative aspect that also implies ontological considerations. The structural aspect pertains to the development of the new mathematical theory. The new quantum theory formal structure was the result of repeated failures of conservative attempts by the researchers to extend the classical theory, in order to explain phenomena at the microphysical order of magnitude. But eventually research resulted in the revolutionary development that is quantum mechanics.

Closely related to the first aspect is the second, the interpretative problem. When extension of Newtonian physics could not solve the problem of microphysics, and after Heisenberg eventually developed the matrix mechanics, the semantical and ontological interpretation of the new matrix mechanics still remained problematic. Using Einstein’s thesis that the theory decides what the physicist can observe, Heisenberg reinterpreted the observed tracks in the Wilson cloud chamber experiment, and developed the indeterminacy relation with its nondeterministic and duality ontology. The new interpretation was accomplished by taking the new quantum theory realistically, as a description of the ontology of the microphysical world. When Einstein attacked the statistical quantum theory, he attacked only the second aspect, the Copenhagen interpretation with its nondeterministic ontological claim; he rejected indeterminacy as a valid ontological claim.

Scientific Explanation

Heisenberg’s views on the issue of scientific explanation are implicit in his position against Einstein’s objections to the Copenhagen interpretation. Einstein’s objection to the Copenhagen interpretation is that it is incomplete as a scientific explanation. This objection is a very traditional type of objection, because historically the concept of scientific explanation has been defined in terms of one or another ontology, and Einstein demanded conformity to the ontology defined by the concepts in Newtonian and field physics. Bohr placed himself and his Copenhagen colleagues at a disadvantage, when he employed the vocabulary of their critics by referring to the statistical quantum theory as “noncausal”, because he accepted the definition of causality in terms of the deterministic ontology of classical physics and field theory.

But Heisenberg also maintained that the revolutionary developments in physics include interpreting the new mathematical formalism realistically. He saw this in Einstein who accepted the field as real, accepted relativistic time as real time, and abandoned the concept of absolute time. Invoking Einstein’s practice as his precedent, Heisenberg likewise accepted his indeterminacy relation as describing the real microphysical world as nondeterministic. This amounts to separating the concept of scientific explanation from any preconceived ontology. Such separation had occurred previously in the history of physics, but its recognition was quite radical in microphysics after the lengthy domination of Newtonian physics, even though it is now the common property of the contemporary pragmatist philosophers of science in their thesis of ontological relativity.

Scientific Criticism

In striking contrast to his radical concept of scientific explanation, Heisenberg’s treatment of the question of scientific criticism is very conservative. Actually it is anachronistic, because he believed that his doctrine of closed-off theories enables him to explain how scientific theories can be permanently true. His views of explanation and of criticism represent a very unusual combination of views. Historically philosophers and scientists have maintained that scientific explanations are permanently true, because as explanations they purport to describe correctly the one and only true ontology. Heisenberg’s philosophy of scientific criticism includes a semantical thesis, which is a thesis of both semantical change and semantical permanence. Whether or not this semantical thesis is a sustainable one is certainly questionable, particularly when it depends on such curious processes as the semantics of words becoming “detached” from the variables occurring in the closed-off axiomatic theories, when the theories encounter the limits of their applicability.

A philosopher of science such as Popper would dismiss such a thesis as a “content-decreasing” stratagem. If when a theory is criticized by an experimental test, the words expressing the test outcome describe something contrary to what the theory had predicted, then a later attempt to save its truth claim by equivocation, by the "detachment" of the meanings describing the experimental outcome from the terms in the theory, only makes the theory tautological. In other words Heisenberg's doctrine in effect says a theory is true where it is true, and that where it is not true, it is not falsified, because it becomes silent, detached and inapplicable

Comment and Conclusion

In "Bohm and the 'Inevitability' of Acausality" in *Bohmian Mechanics and Quantum Theory: An Appraisal* (1996) Mara Beler takes a cynical perspective to Heisenberg's inconsistency, arguing that he had neither belief nor commitment, but only a selective and opportunistic use of Bohrian doctrine for the finality of the Copenhagen orthodoxy. Such might be the appearances, but Heisenberg was not cynical. A new philosophy does not spring forth as from the brow of Zeus – coherent, complete, and finally formed. It struggles to emerge from the confusion produced by the inevitable conflict between new seminal insights and old conventional concepts. It is not surprising, therefore, that there should exist an inconsistency between the seminal insights in Heisenberg's philosophical reflections described in his autobiographical accounts, and the conventional concepts in his systematic philosophy of science described in his doctrine of closed-off theories.

Naturalistic vs Artifactual Semantics for Observation Language

There is indeed an inconsistency in Heisenberg's philosophy, and it is due to the conflicting influences of Bohr and Einstein. The conflict has its basis in two fundamentally different philosophies of the semantics of language; particularly where the relevant language is the vocabulary used to conceptualize the sense stimuli delivered in observations. The philosophy of language in contemporary pragmatist philosophy of science is the artifactual thesis of semantics, and the traditional philosophy is the naturalistic thesis. Bohr's naturalistic philosophy of language is that the semantics of language is the natural product of perception, such that concepts used for observation are what in *Atomic Theory and the Description of Nature* he calls the "customary forms of perception", which have their information content determined by nature and the natural processes of perception, and which therefore relegate the mathematical quantum theory to instrumentalist status. Einstein's artifactual philosophy of language on the other hand is that the semantics of language is an artifact, a "free convention", a cultural product instead of a natural product, such that concepts and categories used for observation in physics do not have their information content specifically determined by the natural processes of perception, and are therefore changeable.

It was evident to Heisenberg as well as to every other physicist at the time that revolutionary revisions had been made in twentieth-century physics. Heisenberg wanted to explain how such developments in the history of science could produce correspondingly revolutionary revisions in the semantics of the language of physical theory. Heisenberg's response was his doctrine of closed-off theories, and the philosophy of language that he used for this semantical theory was due to the influence of Niels Bohr. This doctrine restricts semantical revision to the description of phenomena that lie beyond ordinary perception, and thereby retains semantical permanence for the description of phenomena accessible to ordinary observation and described by the language and concepts of Newtonian physics. According to Heisenberg's doctrine of closed-off theories Newtonian physics is permanently valid and serves as the observation language for physics, because it is necessary for reporting experimental measurements and other observations.

Thus Heisenberg believed that all observation must be with concepts supplied by either classical physics or "everyday" language. In his mature version of his doctrine of closed-off theories these concepts are not the same. The everyday concepts have a "lack of precision" or vagueness, while the concepts of classical physics have their semantics rigidly and precisely defined by the context consisting of the laws of Newtonian physics. The concepts of quantum physics also have their content fixed by the context consisting of the laws of quantum physics. What is significant is that the laws of classical and quantum physics are mutually inconsistent. And most notably in Heisenberg's view the quantum concepts are not merely alternative resolutions of the vagueness in everyday concepts, but they cannot be used for observation. The fact that classical and quantum concepts occur in mutually inconsistent laws implies that, when these concepts are associated with the same descriptive term or variable, they are alternative meanings making that common term equivocal.

The equivocal relation between classical and quantum concepts is illustrated in the cases of the terms "position" and "momentum", which occur in both classical and quantum physics. The advocates of the Copenhagen interpretation of the quantum theory argue that in practice the concepts of classical physics must operate in descriptions of the macrophysical experimental apparatus and observation measurement. This classical semantics includes the idea that nature is fundamentally continuous, and the idea that in principle the measurements can be indefinitely accurate, notwithstanding the fact that in practice the degree of accuracy is always limited. They also argue that there are meanings for these terms that are distinctive of quantum physics, and this semantics, which is defined by the context supplied by the indeterminacy relations, includes the ideas that nature is fundamentally discontinuous and that the accuracy of the joint measurement of momentum and position is limited by Planck's constant. Therefore, on Heisenberg's philosophy of closed-off theories, in order for observation to be possible in quantum physics there must exist an equivocation for every term common to classical and quantum physics, such that for every quantum concept determined by the context of quantum physics there must be a corresponding classical concept for observation determined by the context of classical physics. Such is the unfortunately equivocal outcome of Heisenberg's explicit and systematic philosophy of science.

Yet Heisenberg's use of Einstein's aphorism for describing the tracks in the Wilson cloud chamber, which led to his subsequent development of the indeterminacy relations, does not agree with the observation language required by his doctrine of closed-off theories. Einstein's aphorism is the semantical thesis that **the theory decides what the physicist can observe**, and for microphysical experiments this thesis implies that **the quantum theory contributes to defining the semantics for observational description.**

The Contemporary Pragmatist Alternative

Contrary to Heisenberg's semantical doctrine of closed-off theories, classical concepts are not necessary for observation, variables in the quantum laws are not equivocal, and all the concepts in the quantum theory are quantum concepts that are operative in observational description. It is possible with a metatheory of semantical description to follow through with Einstein's aphorism and to say that theory decides what the physicist can observe, because the concepts used for observation are quantum concepts. Such a new semantical theory is needed, because like Bohr, Heisenberg had premised his doctrine of closed-off theories on the naturalistic philosophy of language. Attempts to preserve a permanent semantics for observation, while at the same time to explain the semantical revisions produced by the revolutionary developments in theory, result in a positivist philosophy of language that attributes equivocation to language that in practice physicists are routinely able to use unambiguously. The historic twentieth-century scientific revolutions have motivated post-positivist philosophers of science to reject the naturalistic philosophy of the semantics of language, and to accept the artifactual philosophy instead. It is necessary to consider further how to describe the semantics both of quantum theory and of experimental observation, in order to exhibit how concepts are culturally determined as linguistic artifacts instead of predetermined as products of nature, and to explain why semantical change occurs in observation reporting without involving complete equivocation.

False Assumptions in Closed-off Theories Doctrine

Heisenberg's doctrine of closed-off theories contains certain basic assumptions that are in need of reconsideration. The first is the tacit assumption that all **concepts are indivisible or simple wholes**, that must be either completely different or completely the same, such that classical and quantum concepts are simply and wholly equivocal. The second is the explicit assumption that **observation language must be exclusively associated with macroscopic phenomena**. Both of these assumptions contain errors.

Firstly it is incorrect to assume that the meanings of terms in physics or in any other discourse are simple wholes that cannot be analyzed into component parts. **Secondly** it is necessary to reconsider the Copenhagen school's basis for dividing the relevant language into statements of experiment and statements of theory. Specifically rejection of the naturalistic philosophy of language implies rejecting two mental associations that occur in Heisenberg's doctrine of closed-off theories. The first is the **classical-macroscopic-observation association**, and the second is the **quantum-microscopic-theoretical association**. Consider firstly the pragmatist alternative to the wholistic view, and how it affects Heisenberg's thesis of equivocation.

Semantical Wholism Rejected

Conventional habitual meanings of words are synthetically experienced wholistically. However reflection on the common occurrence of looking up words like a common noun in a unilingual dictionary reveals that the meanings of words are not simple wholes, but rather have component parts that are identified by the defining words occurring in the dictionary definition or lexical entry. Dictionary definitions that are not proper names give semantical descriptions of the meanings they define, and in order to function in this way they always must have the force of universally quantified statements accepted as true. Furthermore dictionary definitions are often viewed as describing the complete meaning of the term, but dictionary definitions are actually minimal statements, and by no means give complete meaning. Usually the understanding of the meaning of a univocal term, especially a technical term, requires a larger context consisting of a discourse having many statements containing the term. Today such larger context may be examined extensively with the aid of a key-word-in-context computer program.

Since Quine rejected the analytic-synthetic distinction, all universal empirical or "synthetic" statements accepted as true may also be viewed as definitional or "analytic". Thus if one were to make a list of logically consistent universally quantified affirmative categorical statements containing a univocal descriptive term as their common subject term with each statement accepted as true, then the predicates in each of the mutually consistent statements constituting the list describe part of the meaning of the common subject term, and the entire list as well as each statement in it may be called a "semantical description" of the univocal common subject term's meaning. In summary **a semantical description consists of the language context, in which a descriptive term's meaning is determined and described by a set of universal affirmations believed to be true.**

This contextual determination of the semantics of language is the essence of the artifactual thesis. Quine calls this context the "web of belief". A term is equivocal if any of the universal affirmations in the semantical description are mutually inconsistent. This equivocation is made explicit, when the predicates of the inconsistent universal affirmations can be related to one another by universal negations accepted as true. The several different meanings in the equivocation each have separate semantical descriptions, which can be exhibited when the original list is subdivided into mutually exclusive subsets with each subset containing only mutually consistent universal affirmations. Then each subset is a semantical description of one of the several different meanings of the equivocal term instead of each subset functioning as a description of different parts of the one meaning of a univocal term.

The equivocations postulated by Heisenberg's doctrine of closed-off theories as applied to microphysics are the result of the logical inconsistency between the theories of classical and quantum physics. Thus there exists equivocation with each theory context constituting a separate semantical description list for any term common to the two theories, terms such as "position" or "momentum".

In addition to the properties of equivocation and univocation there is another aspect of language called vagueness. Equivocation and univocation are properties of terms, while vagueness and clarity are properties of meanings. Meanings are more or less clear or vague. Two concepts are clear in relation to one another, if they can be related to each other by universal affirmations or negations accepted as true, and they are vague in relation to each other if they cannot be so related by any universal statements. And adding any universal affirmations or negations believed to be true to a single univocal term's semantical description list has the effect of reducing the vagueness in the concept associated with the term by explicitly adding or excluding meaning.

Every meaning is always vague and admits to further clarifying resolution, because potentially its semantical description can always be increased by additional universal statements believed to be true. This becomes evident when instances are encountered about which no decision had been made regarding the applicability of the term in question. Friedrich Waismann has called this inexhaustible residual vagueness the "open texture" of concepts. What Heisenberg calls "everyday language" is merely language which has a degree of vagueness or "lack of precision" that is greater than the degree of vagueness in Newtonian and quantum concepts due to the latter's contexts consisting of their respective equations. However no terms that are part of a language including everyday terms can be utterly without any defining context such as is found in the term's lexical entry in a dictionary.

Naturalistic "Observation" and "Theory" Rejected

Consider next the relation between the language of observation and the language of theory, the second basic assumption in the doctrine of closed-off theories. Scientists and philosophers still conventionally use the word "theory" to refer to Newton's "theory" of gravitation, to Einstein's "theory" of relativity, and to the quantum "theory", even though the physics profession had decided many years ago either to accept or to reject these expressions as physical laws and explanations. As Norwood Russell Hanson, Yale University pragmatist philosopher of science and advocate of the Copenhagen interpretation of quantum mechanics, notes in this conventional usage the term "theory" does not function as it did when these expressions were firstly advanced for testing as proposed explanations of problematic phenomena in research science. When they were firstly proposed, these expressions represented statements that had a much more hypothetical status in the judgment of the cognizant professions than they do today, and they were typically topics of controversy.

There is, therefore, an ambiguity between "theory" understood as an accepted or rejected explanation in what Hanson called "catalogue science", and "theory" understood as a tentative proposal submitted for empirical testing in what he called "research science". In the "Introduction" to his pioneering *Patterns of Discovery: An Inquiry into the Conceptual Foundations of Science* (1958), Hanson wrote that earlier philosophers of science had mistakenly regarded as paradigms of inquiry finished systems like planetary mechanics instead of the unsettled, dynamic research sciences like contemporary microphysics. He explains that the finished systems are no longer research sciences, although they were at one time. He therefore says that distinctions applying to the finished systems ought to be suspect when transferred to research disciplines, and that such distinctions afford an artificial account of the activities in which Kepler, Galileo and Newton were actually engaged. He thus maintains that ideas such as *theory*, *hypothesis*, *law*, *causality* and *principle*, if drawn from what he calls the finished "catalogue-sciences" found in undergraduate textbooks, will ill prepare one for understanding research-science.

Only the functional meanings as found in what Hanson calls "research science" are strategic in the contemporary pragmatist philosophy of science, even though the conventional or "almanac" meaning of "theory" occurs even in its own expository discourse such as herein. From this functional view theory language that has been tested and not falsified by a decisive test ceases to be a theory and has thereby been given the status of a law that can be used in an explanation. Due to empirical underdetermination there may nonetheless be multiple tested and nonfalsified former theories that address the same problem, and that therefore also have the status of explanations accepted by some scientists in the same profession. Some scientists are uncomfortable with this pluralism, but the contemporary pragmatist philosophers recognize such pluralism as historically characteristic of science.

In an empirical test of a theory the semantics of the vocabulary in all the relevant discourse is controlled by a strategic decision that is antecedent to the performance of the test. This is the functional decision as to what statements are **presumed** for testing and what statements are **proposed** for testing. The former language is the explicit statements of test design together with usually many tacit assumptions. The latter language is the explicit statements of the theory. This decision is entirely pragmatic, since it is not based on the syntactical or the semantical characteristics of language, but rather is based on the use or function of the language in basic research, namely empirical testing. The test-design statements are those that by prior decision and agreement among cognizant members of the profession have the status of definitions. These statements are presumed to be true regardless of the outcome of the test, and serve to identify the subject of investigation and to describe the test execution procedure throughout the test. The theory is the language that by prior decision and agreement among the cognizant members of the profession has the less certain status of a hypothesis. The hypothesis is believed to be true to the extent that it is considered worthy of testing, although the developer and his entourage of cheerleading advocates may be quite firmly convinced. But if the test outcome is a falsification, then by prior agreement among scientists who accept the test design, it is the statements of theory and not the statements of test design that are judged to have been falsified and in need of revision.

However, a falsification may lead some interested scientists, such as the theory's developer and advocates, to reconsider the beliefs underlying the test design, even while admitting that the test was executed in accordance with its design. This is a rôle reversal between test design and theory, which may result in productive research. In such cases when the falsified theory is made a test-design statement characterizing the problematic phenomenon, the problem has become reconceptualized. As James Conant recognized to his dismay in his *On Understanding Science: An Historical Approach*, the history of science is replete with such prejudicial responses to scientific evidence that have nevertheless been productive and strategic to the advancement of basic science in historically important episodes.

The decision distinguishing test-design language and theory language made prior to the experiment may but need not result in identifying mathematical equations as the statements of theory and of identifying colloquial discourse as the statements of test design. The decision is not based on syntactical characteristics of the language, and the test-design statements often include mathematically expressed statements together with statements in colloquial language describing the measured phenomenon, the measurement procedures, and the design and operation of the measurement apparatus. Even more relevantly the decision is not based on semantical criteria, as advocates of the naturalistic philosophy of the semantics of language believe. Contrary to both Bohr and the positivists the decision is not based on any purportedly inherent distinction between observation and theory, whether or not, as in the case of quantum mechanics, the observation concepts are called "classical" or "macroscopic", and the theoretical concepts are called "quantum" or "microscopic". The distinction between statements of test design and statements of theory is neither syntactical nor semantical; it is distinctively and entirely pragmatic.

Test Language Before Test Execution

With the above concepts in mind and at the expense of some repetition consider the language of an empirical test **before the test is executed and its outcome is known.** In order for the test-design statements to characterize evidence independently of the theory proposed for testing, the test-design statements and the theory statements must be logically independent; *i.e.*, neither set of statements may be merely a logical or mathematical transformation of the other. The test-design statements, the language presumed for testing, may neither deductively imply nor contradict the theory or any of its alternatives. In the case of quantum mechanics this means that the test-design language for experiments cannot be from Newtonian physics, which postulates matter to be infinitely divisible and its physical laws to be deterministic. Test-design language must be silent about such claims, and must be given the status that Heisenberg called "everyday" language, which is silent, *i.e.*, vague, about these Newtonian claims. Furthermore the statements of the quantum theory proposed for testing are too hypothetical to function as definitions except for the developer and other advocates of the theory, who may believe in the theory as strongly as they believe in the truth of the test-design statements.

But for all the critical researchers for whom the test is contingent and functions as a decision procedure, the semantical consequence of the logical independence and greater hypothetical status of a theory proposed for testing relative to the universal statements of test design, is that each of the terms common to both the test-design statements and theory statements have their semantics defined only in relation to the meanings of the other terms in the test-design statements, such that they characterize the subject matter of the experiment, but do not have their semantics defined in relation to the meanings of the terms in the theory proposed for testing. In other words by strategic decision for testing, the theory statements are not included in the same semantical description list as the test-design statements, even though both sets of statements are mutually consistent and contain the same common subject terms. The meaning of each term common to the test-design and theory statements is therefore vague with respect to the meanings of the other terms of the theory.

And on the artifactual thesis of the semantics of language the observation language in turn is merely the test-design statements with their logical quantification changed from universal to particular, to enable their application to describe the particular ongoing or historical experiment performance. The test-design statements similarly supply the vocabulary that describes the observed test outcome, especially if the outcome contradicts and thus falsifies the claims of the tested theory.

Test Language After Test Execution

Consider next the language of the empirical test **after the test is executed and its outcome is known.** When the test is executed, a falsifying test outcome produces no semantical change except for the developer and advocates of the tested theory, who had been convinced of the theory's truth, and who decide to reconsider their belief in the theory due to the test outcome. The latter's belief revision causes a semantical change. But a nonfalsifying outcome produces a semantical change, especially for the critics of the theory for whom the test is a decision procedure. After the test the theory no longer has the greater hypothetical status that it formerly had merely as a proposal, but assumes the status of a law that may operate in an explanation, which is neither more nor less contingent than other accepted universal empirical statements including the test-design statements. The semantical outcome is that both the test-design statements and the theory statements (now elevated to the status of a law) are semantical rules exhibiting the composition of the meanings of the univocal terms common to both sets of statements. Those component parts contributed by the test-design statements remain included. But the semantical descriptions for these terms now include not only the test-design statements but also the statements constituting the tested and nonfalsified former theory. These former theory statements are additional information learned from the successful test outcome that resolves some of the vagueness in the vocabulary terms common to both the theory and the test-design statements.

In summary: the descriptive terms common to both test-design and theory statements have part of their semantics defined by the test-design statements throughout the test, both before, during, and after the test is executed. And these common terms have their semantics augmented and thus defined by the statements of the tested and nonfalsified former theory added after the test, such that the test-design concepts have their vagueness resolved by the tested and nonfalsified former theory.

Semantics and Quantum Theory Tests

In Heisenberg's doctrine of closed-off theories the naturalistic philosophy of language requires retention of the Newtonian concepts for observation in any quantum-theory experiments. But the resulting equivocation is unnecessary. Newtonian concepts are never involved, since the Newtonian theory is a falsified microphysical theory or at least an alternative to the quantum theory. **Before the test outcome is known it is sufficient to use a vaguer or less precise vocabulary that Heisenberg calls "everyday" words used by physicists, in order to describe the experimental set up, which is a macrophysical phenomenon.** The meanings of these "everyday" concepts are vague, because they do not describe the fundamental constitution of matter. **After the test outcome is known, the tested and nonfalsified quantum theory is recognized as empirically adequate, and the vagueness in these everyday concepts is**

resolved by the equations constituting the quantum theory. The quantum mechanics is the tested and nonfalsified former theory, which after the test as a law became a semantical rule contributing meaning parts to the complex meanings of the **univocal terms** used to describe the experimental set up such as the Stern-Gerlach or two-slit apparatuses. This effectively makes the meanings quantum concepts, whether or not quantum effects are empirically detectable or operative in the description of the macroscopic features of the experimental set up.

Even if some Newtonian laws are employable for their now known lesser truth, in order for this resolution of vagueness to occur in the terms used for description of the macroscopic features of the experimental set up, it is not necessary for the Newtonian macrophysical laws to be made logical extensions of quantum mechanics by logical reduction procedures, because the Newtonian theory is falsified as a microphysical theory. Nor is it necessary for the Newtonian macrophysical laws to be replaced by macrophysical laws that are an extension of the quantum laws. The univocal quantum semantics neither implies nor requires any logical reductionist or extensional development of macrophysical quantum mechanics, *i.e.*, a macrophysical theory that is deductively or reductively a logical extension of the microphysical quantum mechanics. **It is sufficient merely that the scientist realize that the nonfalsifying test outcome has made quantum mechanics and not classical mechanics an empirically warranted microphysical theory.**

Heisenberg's doctrine of closed-off theories is incorrect, and Einstein's semantical thesis expressed in his aphorism to Heisenberg is correct, because the vocabulary used for macroscopic observation after quantum mechanics' acceptance is a univocal vocabulary with meaning parts contributed by quantum mechanics. The descriptive terms in the equations of the quantum mechanics contribute to, and thereby resolve some of the vagueness in the meaning complex associated with the descriptive terms used for observation. **Thus as Heisenberg maintained, quantum mechanics decides what the scientist observes in the Wilson cloud chamber.** The macrophysical description is not antilogous to the microphysical quantum mechanics including the indeterminacy relations. In summary **the quantum semantic values are included in the univocal meaning complexes associated with the observation description, and the**

Newtonian concepts were never included, because the macrophysical description never affirmed a Newtonian microphysical theory.

Heisenberg's Last Statements on Semantics

In his "Remarks on the Origin of the Relations of Uncertainty" in a memorial volume dedicated to him titled *The Uncertainty Principle and Foundations of Quantum Mechanics* (1977), which was in press at the time of his death in 1976, Heisenberg says in this brief four-page article that there have been attempts to replace the traditional language with its classical concepts by a new language which would be better adapted to the mathematical formalism of quantum theory. But he adds that during the preceding fifty years, physicists have preferred to use the traditional language in describing their experiments with the precaution that the limitations given by the indeterminacy relations should **"always be kept in mind".** He concludes that a "more precise" language has not been developed and in fact it is not needed, since there seems to be general agreement about the conclusions and predictions drawn from any given experiment in the field. In other words the semantics of terms like "momentum" and "position", "wave" and "particle" have evolved much like the semantics of the term "atom" has evolved in the history of physics, even as the vocabulary has been retained.

Regrettably Heisenberg never repudiated his doctrine of closed-off theories. But contrary to his doctrine of closed-off theories, Heisenberg's statement that the contemporary physicist must keep quantum effects "in mind" when the physicist is describing macrophysical objects, even while not explicitly accounting for quantum effects that are experimentally undetectable in the circumstances, is *ipso facto* a semantical change in the univocal vocabulary used to describe experiments due to the development of quantum mechanics. In other words a language in which the limitations given by the indeterminacy relations are "always be kept in mind", means that a "more precise" language with a less vague semantics has in fact been evolved. This semantical evolution consists in the fact that the concepts employed for observational description contain component parts, *i.e.*, semantic values, contributed from quantum mechanics. That is how the limitations of the indeterminacy relations are "always kept in mind": **they have become built into the semantics of those terms, even when those terms are used to describe macrophysical observations including but not limited to cloud chamber tracks.**

Double-Think Rejected

Heisenberg's semantical theory of equivocation in his and Bohr's philosophy of observation language is the result of the acceptance of the naturalistic philosophy of the semantics together with the assumption that meanings are simple, indivisible wholes. However, all such views are untenable, because they imply what can only be called "double think". The equivocation thesis demands that the modern physicist indulge in a contrived cognitive duplicity with himself, a pretense at simultaneously both knowing and not knowing the modern quantum theory. But concepts are not known like physical objects to which one may simply close one's eyes; they **are** knowledge. Scientists never did in practice carry on the kind of cognitive duplicity that the equivocation semantical theses require, and since the ascendancy of the contemporary pragmatism, philosophers no longer expect that they should.

Heisenberg might have obtained greater utility from his insightful idea of "everyday" concepts, had he rejected Bohr's philosophy of observation language, and realized that neither these "everyday" concepts nor the Newtonian concepts nor any other concepts are inherently observational. Heisenberg's term "everyday" is admittedly awkward, because the everyday man in the street does not perform quantum experiments. But in the pragmatist perspective Heisenberg's "everyday" concepts are distinctive only because they are vague in a very strategic fashion: they are the concepts used in test-design statements, and are vague relative to the concepts in the theories proposed for testing **prior to execution of the test and prior to the production of a nonfalsifying test outcome.** More specifically, in the case of the quantum-mechanics experiments, everyday test-design concepts are vague because they are not defined by either the Newtonian or the quantum theories or of any other proposed microphysical theory prior to the execution of the tests. **After execution of the test and after production of a nonfalsifying test outcome**, the vagueness of the "everyday" concepts is resolved with respect to microphysical phenomena and become quantum concepts, such as Heisenberg used for observing the electron tracks in the cloud chamber.

In "On the Methods of Theoretical Physics" in *Ideas and Opinions* (1933) Einstein said that if you want to find out anything from the theoretical physicists about the methods they use, stick closely to one principle: don't listen to their words, but rather fix your attention on their deeds. This is good advice for anyone attempting to understand Heisenberg's writings in philosophy of science. The philosophy of language that was instrumental to Heisenberg's "deeds", *i.e.*, his development of his indeterminacy relations as a result of Einstein's influence and that is chronicled in his autobiographical works, is historically more important and more revealing than the "words" he expounded as a result of Bohr's influence and set forth as his doctrine of closed-off theories, because pragmatism is the philosophy of language that Heisenberg practiced.

Quantum physicists are like the Biblical characters who had been driven out of the Garden of Eden. They have eaten from the forbidden fruit of the **tree of quantum knowledge**, the fruit forbidden by Newtonian physics. They have consumed such findings as uncertainty, duality, and nonlocality, so that today they simply know too much to return to the their former state of blissful nineteenth-century innocence, in which Newtonian concepts had been used for the semantics for observational reporting. Now the semantics they must use in their conceptualization of the sense stimuli that produce their observational reporting language, is penetrated, permeated and suffused with semantic values from quantum theory.

A New Language Developed

Roland Omnès is presently Professor Emeritus of Theoretical Physics in the Faculté des sciences at Orsay at the Université Paris. In his *Understanding Quantum Mechanics* (1999) Omnès writes that since the 1980's there has been a renewal in both experiments and theory due to a transition from a period when Bell's ideas and the hidden variables issues were dominant, to the current period when the interpretation of Copenhagen quantum mechanics has become the dominant interest.

Omnès says that the renewal involves three theoretical ideas: the decoherence effect, the emergence of classical physics from quantum theory, and the constitution of a universal language of "interpretation" by means of consistent histories. The decoherence effect, which was recently observed, explains the absence of macrophysical interference and solves the Schrödinger's cat problem. The emergence of classical physics from quantum theory using the Hilbertian framework explains the relation between quantum and classical physics, and reconciles determinism with probabilism. The constitution of a universal language of "interpretation" by the method of consistent histories provides a logical structure for quantum and classical physics, and it supplies the universal language of "interpretation" initially sought by the members of Bohr's Copenhagen Institute for Physics, but which Bohr's complementarity cannot supply. Omnès has been instrumental in developing the consistent histories and quantum decoherence approaches. He writes that when these three ideas are combined, they provide a genuine theory of interpretation, in which everything is derived directly from four basic principles using the Hilbert-space framework to deduce theorems including the rules of measurement theory, and he sets forth a set of axioms.

It may be said that Omnès' deductive system not only resolves the relatively vague semantics of Heisenberg's "everyday" language, but because it is deductive, it **further** resolves the vagueness in the semantics of the vocabulary in both macrophysics and microphysics. Omnès' logical integration of physical theory may satisfy long-standing psychological yearnings for intellectual coherence expressed by both physicists and philosophers. But while Omnès reports that it depends on recent experimental results, he does not report any new testable proposals much less new empirical findings. Yale University's Norwood Russell Hanson would likely have dismissed Omnès and his ilk as mere "axiomitizers". Only time will tell whether or not Omnès' *tour de force* yields any new testable proposals or new empirical findings.

Heisenberg's Practice of Ontological Relativity

Unlike Bohr, Heisenberg effectively practiced what Quine called "ontological relativity", when he reported that he interpreted the quantum mechanics equations realistically by replicating Einstein's realist interpretation for special relativity. Heisenberg said the "decisive step" in the development of special relativity was Einstein's rejecting the distinction between apparent time and actual time in the interpretation of the Lorentz transformation equation, taking Lorentz's apparent time to be physically real time, and rejecting the Newtonian absolute time as real time. Heisenberg said he took the same kind of decisive step, when he inverted the question of how to pass from an experimentally given situation to its mathematical representation by affirming that only those states represented as vectors in Hilbert space can occur in nature and be realized experimentally. Heisenberg's indeterminacy principle says that no quantum-mechanical state can be dispersion free for every variable. He thus believed that his decisive step affirms that microphysical reality is nondeterministic. He likewise maintains that Young's two-slit experiment affirms the duality thesis of quantum mechanics, and that wave and particle are manifestations of the same entity that is indeterminate until subject to a measurement action.

Hanson and Heisenberg

In his *Patterns of Discovery* (1958) Norwood Russell Hanson (1924-1967) dismissed what he called Bohr's "naïve epistemology", and like Einstein he believed that observation is what Hanson called "theory laden". It may be said that Hanson's philosophy of quantum theory is what Heisenberg could have formulated, had Heisenberg rejected Bohr's naturalistic semantics, which Heisenberg used for his doctrine of closed-off theories, and instead followed through on Einstein's aphorism that theory decides what the physicist can observe.

Hanson defended the Copenhagen duality thesis by reference to the mathematical transformation theory developed in 1928 by Paul A. Dirac (1902-1984), who was a theoretical physicist at Cambridge University, and who shared the Nobel Memorial Prize for physics in 1933 with Schrödinger. Hanson had interviewed Dirac at Cambridge for writing his *Concept of the Positron* (1963). Dirac's transformation theory enables physicists to exhibit the wave-particle duality by mathematically transforming the wave description into the quantum description and vice versa. Hanson thus says that 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, such that quantum mechanics makes the dualistic ontology the only conceivable one. This thesis of Hanson echoes Heisenberg's thesis of false questions set forth in his paper "Questions of Principle" (1935), in which he says 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.

Hanson's philosophy is discussed in BOOK VII below.

