# KARL POPPER AND FALSIFICATIONIST CRITICISM

This book focuses on Karl Popper's falsificationist thesis of scientific criticism. It also examines his particle-propensity interpretation of the quantum theory, which he advances as an alternative to the Copenhagen interpretation, and discusses the influence of the physicist Alfred Landé.

Karl Popper (1902-1995) was born in Vienna, Austria. He enrolled in the University of Vienna in 1918, where he studied physics, mathematics, and philosophy. In 1928 he received his Ph.D. for a dissertation titled *On the Problem of Method in the Psychology of Thinking*. He never returned to the subject of psychology again during his professional career, because he became convinced that methodology of science is exclusively a matter of logic and objective knowledge instead of psychology. Popper was personally acquainted with Rudolf Carnap and other members of the Vienna Circle, and although he had been invited to address the group at a meeting in which he set forth his philosophy of science, he was never a member of the Circle. In 1937 he was appointed a senior lecturer to Canterbury University College in Christchurch, New Zealand, and then in 1945 he was appointed to a readership at the London School of Economics, University of London. In 1949 he was made professor of logic and scientific method at the London School. He was knighted in 1964.

**Einstein's Influence and the Falsificationist Thesis of Criticism**

In his intellectual autobiography in Schilpp's *The Philosophy of Karl Popper* (1974) Popper states that Einstein was the most important influence on his thinking. The influence was not a personal one, since Popper and Einstein did not actually meet until 1950; the influence was through Einstein's published works. The year 1919 was the fateful year in Popper's intellectual life. At that time he was interested in the views of several thinkers including Marx's theory of history, Freud's theory of psychoanalysis, and Alfred Adler's theory called "individual psychology." Popper relates in his "Science: Conjectures and Refutations" (1957) in *Conjectures and Refutations* (1963), that he had come into personal contact with Alfred Adler and cooperated with Adler in the latter's social work with children and young people in the working class districts of Vienna during the last years of the Austrian Empire and the subsequent revolution. In the summer of 1919 Popper became dissatisfied with the views of Marx, Freud and Adler, because the persons who accepted and advocated these theories were strongly impressed by the theories' purported explanatory power, and because study of these theories had the effect of an intellectual conversion or revelation. Most objectionable to Popper was the fact that once the reader's eyes were opened to the theory, he found that the theory was verified everywhere one might think of applying it. Unbelievers were dismissed as persons who could not see the verifications. In Popper's view the apparent strength of these theories' purported "explanatory" power is their principal weakness.

Popper saw in Einstein's theory a striking contrast to the situation he found in the views of Marx, Freud and Adler. Eddington's solar eclipse observations in 1919 brought the first important test to bear upon Einstein's relativity theory of gravitation. This test was distinctive, because in the test there was a risk involved in the theory's prediction. Had Eddington's observations showed that the predicted effect is definitely absent, then Einstein's theory would simply have been refuted. And the risk in Einstein's case was very great, since the predicted effect was different from what was expected from Newton's theory, which had long demonstrated great success culminating with the discovery of the planet Neptune. In his autobiography Popper said that what impressed him most was Einstein's own clear statement that he should regard his theory of relativity as untenable, if it should fail certain tests. This was an attitude that was very different from the dogmatic attitude of the Marxians, Freudians, and Adlerians. Einstein was looking for crucial experiments where agreement with his predictions would by no means establish his theory, but where disagreement with his predictions, as Einstein was the first to say, would show his theory to be untenable. Thus in 1919 Popper concluded that the critical attitude, which does not look for verifications but rather looks for crucial tests that can refute the tested theory, is the correct aim for science, even though the crucial tests can never establish the theory. This is Popper's falsificationist philosophy of scientific criticism, the central thesis of his philosophy of science.

**Explanation, Information, and the Growth of Science**

Popper's philosophy recognizes the dynamic character of science that is not recognized in the philosophy of the positivists, who were interested only in the result, as they understood it. His statements on the dynamics of science are found in appendices to the 1968 edition of his *Logic of Scientific Discovery*, in his "Truth, Rationality, and the Growth of Scientific Knowledge" in his *Conjectures and Refutations*, and in "The Rationality of Scientific Revolutions" in *Problems of Scientific Revolutions* (ed. Harre, 1975) as well as elsewhere in his literary corpus. His falsificationist thesis is not only a philosophy of scientific criticism and scientific explanation, but is also a philosophy of the growth of scientific knowledge. As a philosophy of scientific criticism, it says that the empirical test outcome can never establish or "verify" a scientific theory, but can only refute or "falsify" the theory. And even before a theory's claims are considered for testing, it is possible to determine whether or not it is a scientific explanation: it is not a scientific explanation if it is not empirically testable.

Another way that Popper describes this condition is that what makes a theory scientific is its power to exclude the occurrence of some possible events, and he calls the singular statements that describe these excluded events "potential falsifiers". This way of speaking introduces his idea of various degrees of explanatory power: the more that a theory forbids or excludes and therefore the larger the class of potential falsifiers, then the more the theory tells us about the world. Popper calls the variability of degree of explanatory power the "amount of information content" of a theory or explanation. The idea of the amount of information content may be illustrated by reflection on the logical conjunction of two statements $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$. It is intuitively evident that the conjunction $\boldsymbol{\alpha}$ $\boldsymbol{\beta}$ has no lesser amount of information content than do the component statements taken separately, and it usually has more information content than its components. This is because there are more potential falsifiers for the conjunction than for the component statements taken separately; the conjunction is false if either component is false. In some contexts Popper calls information content "empirical content", and he calls the falsifiability of the theory its "testability." All of these terms refer to a logical relation between a theory or a hypothesis and its class of potential falsifiers.

Popper relates the idea of information content to probability theory. He says that the amount of information content is inversely related to the degree of probability that may be associated with a hypothesis. This view can be illustrated also by the logical conjunction: if the probability value **P(α)** is associated with the statement **α** and the probability value **P(β)** is associated with the statement **β**, then by the probability calculus the probability **P(α β)** associated with the conjunction **α β** must be less than the separate probability values **P(α)** and **P(β).** Therefore as the information content of a theory increases, the associated probability must decrease. Popper maintains that the whole problem of the probability of hypotheses as viewed by Carnap is misconceived, because on Carnap's idea of degree of confirmation, scientists should prefer statements having higher associated probabilities, while on Popper's view scientists should prefer theories with higher information content. Therefore in contrast to Carnap's idea of degree of confirmation Popper advances the idea of "degree of corroboration", although in some contexts Popper also uses the phrase "degree of confirmation" in a sense that is synonymous with his idea of degree of corroboration. On the corroboration thesis a scientific theory that has greater information content (because it is more universal, or because it is more accurate than an alternative theory) also has a higher degree of corroboration, if when it is tested it is not falsified. Like the idea of information content, the idea of corroboration is based on the idea of falsifiability, but a theory would not be said to have been corroborated until it had been tested and found to have no falsifying test outcome; the degree of corroboration actually attained does not depend only on the degree of falsifiability. A statement may be falsifiable to a high degree yet it may be only slightly corroborated or it may be falsified.

The measures for corroboration, **C(h,e),** and probability, **P(h,e),** for hypothesis **h** and for basic statement **e** of evidence describing a test outcome, are related by certain equations. The inverse relation between the measures of corroboration and probability is related as follows:

**C(h,e) = 1- P(h,e)**

 

and Popper is willing to admit a proposal by Kemery in the Journal of Symbolic Logic (1954) that the relation may also be expressed in terms of information science concepts as:

**C(h,e) = 1- log P(h,e).**

Popper states that the measure of the degree of corroboration, **C(h,e),** may be interpreted as a measure of the rationality of belief in the statistical hypothesis**, h,** in the light of test outcomes, **e,** only if **e** consists of reports of the outcome of sincere attempts to refute the hypothesis by the severest test that can be devised, rather than attempts to verify **h.** But the degree of corroboration does not measure the degree of rationality in our belief in the truth of **h,** since **C(h,e)=0** whenever **h** is logically true. Rather, it is the measure of accepting tentatively a problematic guess. On the other hand the measure of explanatory power, **E(h,e),** may be interpreted as the measure of the explanatory power of **h** with respect to **e,** even though **e** is not a report of any genuine and sincere attempts to refute **h.** The measure **E(h,e)** is a purely logical relation to the infinite class of potential falsifiers, and in an appendix to his *Logic of Scientific Discovery* (1959) Popper relates **E(h,e)** positively to **C(h,e)** as follows:

**E(h,e) = C(h,e)/[1+ P(h) P(h,e)].**

The concepts of relatively greater or lesser degrees of information content and falsifiability provide the basis for Popper's ideas on scientific progress, the growth of scientific knowledge, and the aim of science. He advances a "metascientific" criterion of progress that enables the scientist and methodologist to know in advance of any empirical test, whether or not a new theory would be an improvement over existing theories, were the new theory able to pass crucial tests, in which its performance is compared to older existing alternatives. He calls this criterion the "potential satisfactoriness" of the theory, and it is measured by the degree or amount of information content. Simply stated, his thesis is that the theory that tells us more is preferable to one that tells us less, and the theory that tells us more is also one which is most falsifiable. From this it follows that **the aim of science is high empirical information content as well as successful performance in tests**.

 

It is the criterion of high information content that makes the growth of science rational. The aim of science is not high probability, and the rationality of science does not consist of constructing deductive axiomatic systems, since there is little merit in formalizing a theory beyond the requirements for testing it. Nor does the growth of science consist of the accumulation of observations. Rather **the growth of science consists of the repeated overthrow of scientific theories and their replacement by more satisfactory theories**. The continued growth and progress of science is essential to the rational and empirical character of scientific knowledge. The growth is continuous, because criticism of theories, which are proposed solutions, in turn generates new problems. Scientific problems occur when expectations are disappointed. Science starts from problems, not from observations, although unexpected observations give rise to new problems. Popper views science as progressing from old problems to new problems having increased depth, when it progresses from old theories to new theories having increased information content. He also views progress in science as approaching more and more closely to the truth understood as a correspondence with the facts and as a regulative idea. Just as there are degrees of information content, so too there are degrees of approach to the truth that he calls "verisimilitude."

In his "Rationality of Scientific Revolutions" Popper therefore sets forth two criteria for the rationality of scientific revolutions, which are also two logical properties that enable the scientist to evaluate any new theory even before it is tested. The **first** criterion may be called a criterion of discontinuity: the new theory must conflict with the old one in the sense that it leads to conflicting results. Popper says that in this sense scientific progress is always revolutionary, and that Trotsky's refrain "revolution in permanence" is applicable to science. The **second** criterion may be called a criterion of continuity: the new theory must be able to explain fully the success of its predecessor in the sense that either there are applications in which the old theory must appear to be a good approximation to the results of the new theory, or there are cases where the new theory yields different and better results than the old one. Scientific revolutions are rational because unlike ideological revolutions, which are sociological, the former cannot simply break with tradition.

**Against Psychologism, Induction, and Naturalistic Semantics**

 

## POPPER AND LANDÉ

Popper's philosophy of knowledge is a critique of psychologism and a defense of the objectivity of knowledge. In the opening chapter of *Logic of Scientific Discovery,* which is titled "A Survey of Some Fundamental Problems", he devotes a section to the elimination of psychologism. This section follows the opening section on the problem of induction, which he views as a fallacy resulting from the psychologistic philosophy of knowledge. He sets forth his own theory of knowledge in the fifth chapter titled "The Problem of the Empirical Basis", and the opening section is a critique of the psychologistic view that perceptual experiences are the empirical basis for science. In his "Demarcation Between Science and Metaphysics" (1955) in *Conjectures and Refutations* he criticizes Carnap's theory of meaninglessness, which he describes as a "naturalistic theory of meaningfulness" of linguistic expressions. The linguistic expressions of particular relevance are those singular statements that are used for describing observations in science. All of these ideas are interrelated according to Popper: induction as the logic for making generalizations and hypotheses, psychologism which proposes perception as the empirical basis of observation in science, and the naturalistic theory of the semantics of language. Popper rejects all of them together. In his "Epistemology Without a Knowing Subject" (1967) and his "On the Theory of the Objective Mind" (1968) published as chapters three and four in his *Objective Knowledge* (1972), in Part I of *The Self and Its Brain* (1977), and also in an appendix to *The Open Universe* (1982), Popper sets forth his own philosophy of the three "worlds" of reality which locates subjective psychology and objective knowledge in different worlds.

The development of Popper's own philosophy of science began with the objective of demarcating empirical science and pseudoscience (*e.g.*, astrology, Marxism, Freudianism, and Adlerian psychology). His solution to the problem of demarcation is the criterion of empirical falsifiability, which he also uses to demarcate empirical science from metaphysics, and he contrasts this criterion with the criterion of meaningfulness that Carnap and other logical positivists used for distinguishing science from metaphysics. Carnap's criterion of meaningfulness is based on the naturalistic philosophy of language. Popper argues that the positivists have never succeeded in distinguishing science from metaphysics or in distinguishing theory from observation, that metaphysics need not be meaningless even though it is not a science, and that positivism excludes scientific theories as meaningless while failing to exclude metaphysics as meaningless.

 

Popper maintains that **there is no observation without theory**, and that the **observation terms occurring in observation language are "theory impregnated",** such that observation terms are a type of theoretical term that Carnap calls disposition terms, which is in effect just another way of saying that all concepts are universal. The reason that the positivists have not succeeded in distinguishing science from metaphysics, is that they cannot define meaningfulness, and they cannot define meaningfulness because they interpret the problem in a naturalistic way, as though it were a problem in natural science or psychology. Popper maintains that the positivists have confused the psychology of knowledge with the logic of knowledge, which is to say that they have adopted a psychologistic philosophy of knowledge. Popper rejects both behaviorism and psychologism, and maintains that the content of thought, the meanings of words, the semantics of language, are not determined either by the natural laws of the physical world or by the natural laws of psychology. The world of objective knowledge, which is governed by the laws of logic, is a third world that is autonomous from the world of objective physical nature and also from the world of subjective psychology.

In *The Self and Its Brain* he argues against behaviorism and physicalist reductionism by the display of ambiguous drawings that he emphasizes may be interpreted in different ways by voluntary action, in order to demonstrate the existence of world 2, the world of the mind and of subjective mental experiences. He argues against the psychologistic view by stating that the objects of world 3 are intersubjectively testable. Hence there are the three separate worlds which cannot be reduced to one another: world 1 is the world of objective physical nature, world 2 is the subjective world of psychological experience, and world 3 is the objective world of human artifacts or creations including knowledge. Popper emphasizes that while the three worlds interact through world 2, nevertheless the world of objective knowledge is autonomous of the world of subjective psychological experience including perceptual experiences. Advocates of psychologism and the naturalistic theory of the semantics of language fail to recognize the autonomy of world 3 from the other two worlds.

More recently in his "The Foundations of Information Science: Philosophical Aspects" in *The Journal of Information Science* (1980) the information scientist Bertram C. Brookes proposed that the task of information science as a discipline can be defined as the exploration of the world of objective knowledge understood as Popper's world 3, and that this discipline is distinct from documentation and library science, the customary home of information science.

Popper's rejection of inductive logic is based on his thesis that world 3 is autonomous from worlds 1 and 2. He references Einstein's stated view that there is no logical path leading to the universal laws that scientists search for, and that these laws can only be reached by intuition. Popper accepts Hume's thesis that singular statements describing observations cannot justify universal statements, and he rejects the early Wittgenstein's verifiability criterion of meaningfulness adopted by Carnap and the other logical positivists of the Vienna Circle. He also rejects the probabilistic inductive logic developed by Carnap and set forth in the latter's *The Logical Foundations of Probability,* and he expresses dismay that anyone would ever write such a book. In Popper's view there is no logic of scientific discovery; there is only a psychology of scientific discovery. He explains that the title of his own book, *The Logic of Scientific Discovery* in not about the psychological processes involved in inventing new scientific theories, but rather is about the growth of scientific knowledge by conjectures and refutations, the proposal and criticism of new theories.

Popper's philosophy of scientific knowledge is a sustained attack on positivism, but it is not just a critical rejection; he has his own alternative philosophy of observation. The positivists maintained that there is a clear distinction between theory and observation, such that one could separate the language of theory from the language of observation with each containing its own distinctive vocabulary and its own class of universal of statements. The universal statements containing only observation terms are produced by inductive generalization, while those containing theoretical terms are invented by the scientist's creative imagination. However, with the recognition that theory determines what is observed, the separation between theory language and observation language can no longer be sustained, and the ideas of theory and observation must be reconsidered. And since the existence of an observation language was thought to be the empirical basis for science, the empirical basis for science also must be reconsidered.

The positivists had attempted to base empirical science on "atomic statements", "protocol statements" and "judgments of perception" stated in the observation language. Popper rejects these ideas with his rejection of the naturalistic philosophy of meaning. Instead he proposes the idea of the "basic statement", which he defines as a singular statement which together with the universal statements of theory can serve as a premise in an empirical falsification of a theory. The basic statement is fundamentally different in concept from Carnap's protocol statement. The protocol statement is thought to be justified by perceptual experiences and thereby to constitute a foundation for science. But Popper maintains that this is confusion between the subjective psychological aspect of knowledge and the objective logical aspect. Perceptual experiences are subjective and psychological; they can motivate a decision and hence an acceptance or a rejection of a statement, but a basic statement cannot be justified by them any more than it can be justified by thumping on a table. Basic statements are objective in the sense that they can be intersubjectively tested by repetition of the conditions that occasioned them. And they can be falsified, since they operate as premises from which other statements can be deduced, which in turn can be tested. As a result there can be no ultimate statements in science, as the positivists believed; any statement in empirical science can be refuted by falsifying conclusions that may be deduced from them.

But it is not necessary that a basic statement should be tested in order for it to be accepted; it is only necessary that the basic statement be testable. The function of basic statements is to test theories. Every test of a theory must stop at some basic statement, which the scientists have agreed to accept at least for the present time. To the extent that the basic statements are accepted on the basis of agreement, they are conventional. But the agreement is not arbitrary or capricious; the decision is made by reference to a theory and the problem that the theory is proposed to address. Theory dominates experimental work from its initial planning to its completion in the laboratory. Popper summarizes his views on the empirical basis of science by means of a memorable metaphor: There is nothing absolute about science; it does not rest upon solid bedrock, as it were. The bold structure of its theories rises as it were above a swamp like a building erected on piles, which in turn are driven down to whatever depth is found to be satisfactory to carry the structure for the time being.

Popper's reconceptualization of the empirical basis of science is also a reconceptualization of the concept of theory in science. Unlike the positivists, Popper does not define the concept of scientific theory in terms of theoretical terms. Instead he views theories as universal statements, and rejects any distinction between empirical laws and theories, since there is no longer any distinction between theory language and observation language based on a distinction between theoretical terms and observation terms. All the universal statements in science are conjectures that are testable and falsifiable. These conjectures are invented by the human mind, and none of them are produced by inductive generalization. To give a causal explanation of an event means to deduce a statement which describes the event using as premises of the deduction one or more universal laws as theories together with singular basic statements that describe the initial conditions. Popper's ideas for such terms as "theory", "law", and "cause" are fundamentally different from the positivists' ideas for these terms, because Popper's ideas are separated from the subject matter or ontologies described by the sciences.

Empirical science is not purely formal like mathematics or logic, but neither is it defined in terms of certain substantive concepts about reality as it is described by science today. Future science may revise the substantive content of today's science, and yet science will still be science as Popper has defined it. As Popper says in reply to Kuhn's concept of science in "Normal Science and Its Dangers" in *Criticism and the Growth of Knowledge* (1970), **"science is subjectless".** Such could not be said of science by the positivists, for whom the naturalistic philosophy of the semantics of language requires that certain substantive concepts permanently established by observation must always be retained as definitive of the empirical character of science. The rejection of the naturalistic philosophy of the semantics of language implies the reconceptualization of such metascientific terms as "theory", "law", "explanation", and "cause" in a manner that disassociates these ideas from any particular ontology that the semantics of science may describe at any point in history. Empirical science becomes a sequence of alternative ontologies instead of a specific ontology. And with his criterion of increasing information content Popper believes that the sequence of ontologies is not a disconnected random sequence, but rather is one that reveals objective and rational scientific progress. Curiously Popper himself did not follow through on these ideas when he supported Einstein's criticism of the Copenhagen interpretation of quantum theory, and he advanced his own "commonsense realism" ontology.

 

## On Computers, Induction Machines, and Scientific Discovery

In his *Logical Foundations of Probability* and elsewhere Carnap proposed using a computer to make empirical generalizations with inductive logic. Throughout his career Popper has rejected the idea of inductive logic, but in *Realism and the Aim of Science* (1982) he admits to induction machines of a certain type. For such a machine he postulates a simple universe containing individuals and a limited number of properties that the individuals can have. This universe furthermore operates with a number of so-called "natural laws." Popper says that for this universe a machine can be created, such that in some reasonable period of time it will discover the laws that are valid in the postulated universe during the time period. If the laws of its universe are modified, the machine will show its capacity for finding a new set of laws. It would be capable of drawing up statistics about various distinguishable occurrences and of calculating averages. If the postulated universe is complicated further to include among its natural laws, the laws of succession, the general or conditional frequencies having a certain degree of stability, etc., then the machine can be enhanced to be able to formulate hypotheses, to test the hypotheses, and to eliminate those that should be eliminated. Such a machine can learn from experience.

But Popper emphasizes that this inductive machine is limited to the universe that its architect has created for it. The architect of the universe decides what are to be individual events, and what constitutes a property or a relation. In general it is the architect of the machine who decides what the machine can recognize as a repetition. And even more fundamentally it is the architect of the machine who decides what kinds of questions the machine is to answer. All these considerations mean that the more important and difficult problems are already solved by the human designer, when he constructs the machine and the universe it can recognize. Things that positivists such as Carnap had thought simply to be given by nature, the meanings that according to the naturalistic theory of the semantics of language are delivered by the natural operation of human perception, are in Popper's view the product of the creative and imaginative powers of the human designer. These powers enjoy a freedom that is permitted by the artifactual character of objective knowledge, and that is necessary for the creation of the hypotheses and theories that have characterized the growth of knowledge by science.

 

The basis of this freedom is the nondeterministic relation between world 3 on the one hand and worlds 1 and 2 on the other. Carnap had admitted that an induction machine cannot create hypotheses, and that theories are inventions created by the human mind. But Popper does not admit to the positivists' separation between empirical generalizations on the one hand and theories on the other; he maintains that there is no observation without theory. He also argues that no human or computer can predict the future growth of scientific knowledge without committing the fallacy of historicism. In his *Poverty of Historicism* (1975) as well as in *Realism and the Aim of Science* he maintains that historicism involves unconditional predictions, and he says that such predictions are impossible, because prediction in science requires universal laws, which are always conditional.

As it happens, the computerized development of hypotheses and conjectures is precisely what information scientists attempt to accomplish by their "artificial-intelligence" computer systems, which Herbert Simon calls "discovery systems". These computer systems are instrumental to the scientist's development of hypotheses. They are not historicist, but are conditioned upon inputs that require preparation or initial conditions like those Popper says are needed for what he calls an "induction machine." But Popper rejects the related theses of induction as the logic for making generalizations and hypotheses, of psychologism which proposes perception as the empirical basis of observation in science, and of the naturalistic theory of the semantics of language. This places him in opposition to the cognitive psychologists including Simon, Thagard, Langley and their ilk. Like Popper, Hickey accepts the artifactual view of semantics, and he is thus sympathetic to Popper's views of knowledge. Hickey therefore locates computational philosophy of science and its discovery systems more closely to computational linguistics than to cognitive psychology, and he views discovery systems as generative grammars.

## The Schism in Physics and Metaphysical Research Programmes

The term "schism" in the context of the philosophical discussions of the quantum theory did not originate with Popper; Heisenberg introduced it. In his "Recent Changes in the Foundations of Exact Sciences" (1934) in *Philosophical Problems of Quantum Mechanics* Heisenberg notes a "peculiar schism", that he says is inescapable in the investigation of atomic processes. He is not referring to a sociological phenomenon in the physics profession or to an issue that must be resolved; he views the schism positively as a development in physics. As Heisenberg uses the term "schism", it refers to the different concepts used by classical physics and quantum physics and to the different ontologies they describe. On the one hand he has said as part of his doctrine of closed-off theories that there is a need for macrophysical classical concepts of space and time in quantum physics for the description of experiments and of the apparatus of measurement in experiments. On the other hand he says that there is the mathematical expression suitable for the representation of microphysical reality, the wave function in multidimensional configuration spaces that allow of no easily comprehensible interpretation. Heisenberg says that the dividing line between the classical and the quantum physics is the statistical relation.

Popper's earlier views on quantum theory are set forth in his *Logic of Scientific Discovery* (1959 [1934]) and his more mature statement is set forth in his *Postscript to the Logic of Scientific Discovery* (1982). The latter work is a collection of three volumes: *Realism and the Aim of Science, The Open Universe: An Argument for Indeterminism,* and *Quantum Theory and the Schism in Physics.* Popper brings to statistical quantum theory a prior ontological commitment, which he calls "commonsense realism". In Popper's view physics has historically developed out of one or another metaphysical view which he calls a "metaphysical research programme." A metaphysical research programme is a set of ideas that are currently untestable, and that he therefore calls "metaphysical." In Popper's philosophy the demarcation between science and metaphysics is testability thus giving metaphysics a residual status relative to science.

The metaphysical research programme supplies the physicist both with a metaphysical view or ontology about the general structure of the world and with a metascientific view about such things as the criteria for a satisfactory scientific explanation based on the ontology contained in the metaphysical research programme. Science needs metaphysical research programmes, because they largely determine its problem situations. Popper cites Einstein's way of looking at the Lorentz transformation as an example of how a metaphysical research programme can supply a new way of looking at things that may change science completely. Metaphysical research programmes change and are replaced as some parts become testable and are incorporated into science. The relation between the testable theory and the metaphysical research programme is part of the history of problem situations of the science, along with the problems arising from inconsistency among theories and empirical falsifications of theories.

Unlike Heisenberg, Popper views the schism in physics in more sociological terms and in terms of the issues that have given rise to the schism. And unlike Heisenberg, he does not view the current schism in physics favorably. In his opinion the acceptance of the Copenhagen interpretation and the rejection of what he calls the Faraday-Einstein-Schrödinger metaphysical research programme have left physics without any unifying picture of the world, without any theory of change, and without any general cosmology. The current schism in physics is a clash between two metaphysical research programmes, neither of which in his view seems to be doing its job. In *Quantum Theory and the Schism in Physics* he summarizes the current schism in terms of three issues: (1) indeterminism vs. determinism, (2) realism vs. instrumentalism, and (3) objectivism vs. subjectivism. All three issues are closely related to one another and to the interpretation of the probability function in the statistical quantum theory.

The schism has its orthodox group, and it has a variety of dissenters. On the dissenting side of the schism he locates the views of Einstein, de Broglie, Schrödinger and Bohm, which he characterizes together as determinist, realist and subjectivist. On the orthodox side of the schism he locates the Copenhagen school including Bohr, Heisenberg, Pauli and Born, which he characterizes together as indeterminist, instrumentalist and objectivist. He does not consider Heisenberg's views to be realist, and he effectively lumps Heisenberg together with Bohr, who was explicitly instrumentalist in his view of the formalism of quantum theory. This amounts to a misrepresentation of Heisenberg.

Popper proposes a new and unifying metaphysical research programme that he says offers a consistent ontology for both macrophysics and microphysics. Such an ontology has been the Holy Grail of nearly every critic of the Copenhagen school. In his autobiography he states that his views on quantum theory were greatly influenced by those of the physicist Alfred Landé, and he states in the *Postscript* that Landé anticipated his own interpretation of the quantum theory. Therefore, a brief examination of Landé's interpretation of the statistical quantum theory is in order before proceeding further in the discussion of Popper's particle-propensity interpretation.

**Landé's New Foundations of Quantum Physics**

A brief biography of Alfred Landé (1888-1975) can be found in an obituary published in *Physics Today* (May 1976). Landé was a German-born American physicist, who received a doctorate in physics in 1914 from the University of Munich, where he studied under Sommerfeld. In 1918 he co-authored a paper with Born that refuted Bohr's model of coplanar electronic orbits. In 1931 he migrated to the United States, where he taught theoretical physics at Ohio State University until his retirement in 1960. Landé originally advocated the Copenhagen interpretation of quantum theory, but publicly disassociated himself from it with the publication of his *Foundations of Quantum Theory* (1955). His most mature statement of his views is his *New Foundations of Quantum Mechanics* (1965), which includes ideas published in his previous papers.

As a physicist Landé had his own agenda: the solution of what he calls "The Quantum Riddle", which is the derivation of the laws of quantum mechanics from a nonquantal and nondeterministic basis without the *ad hoc* assumptions that he finds in the Copenhagen interpretation. In his deductive explanation of quantum laws from three nonquantal postulates, he maintains that uncertainty is a physical principle for both classical and quantum physics, and he advances and defends a particle interpretation of both Heisenberg's indeterminacy relations and Schrödinger's wave function. Both of these views were central to Popper's philosophy of science twenty years before Landé rejected the Copenhagen interpretation of quantum theory, and Landé references Popper's views in his own literary corpus. However, Landé maintains a contrary ontology with respect to the reality of the waves associated with the Schrödinger wave function.

In "Probability in Classical and Quantum Theory" in *Scientific Papers Presented to Max Born* (1953) Landé argues that classical thermodynamics cannot be reduced to deterministic mechanics, and that it is futile to search for hidden causes behind any distribution that satisfies the rules of probability either in classical or quantum physics. To illustrate his thesis he describes an experiment in which ivory balls are dropped through a tube onto the center of a steel blade, resulting in an observed 50:50

 

average ratio of balls falling to the left or right. On the determinist view the 50:50 ratio is possible only if it is already contained in the initial conditions, which in turn either implies an infinite regress to still prior conditions; otherwise the ratio is left unexplained. Landé rejects both these options. Instead he concludes that random distribution is a physical reality, and that determinism is a purely academic construction, because a program of giving a deterministic theory of statistically distributed events leads nowhere. Statistical theory can only reduce one probability distribution to another, and when there are ensembles of events conforming to error theory, these events are not reducible to deterministic mechanics.

In *New Foundations* he states that the belief in determinism is as much beyond the domain of physics as the belief in indeterminism, because both ideas are metaphysical theses. Observation only shows that equal preparation, as far as equality can be achieved, always leads to unpredictably different results. Landé elevates this general insight to the physical principle of uncertainty. In contrast to ordinary experience, classical mechanics was deterministic, while on the other hand ordinary experience and quantum mechanics agree. Unpredictability understood as the acausality of individual events must be seen as an irreducible feature of natural science. Statistical mechanics can describe predictable averages for unpredictable individual events. In quantum mechanics it is Heisenberg's great merit that he established quantitative limits for the uncertainty of prediction, but Landé also states that unpredictability of future events does not preclude the reconstruction of past individual cases using a deterministic theory.

Landé rejects Heisenberg's thesis that between two observations in atomic physics the electron is nowhere. In his discussions of uncertainty and measurement in *New Foundations* he admits that while in classical physics a measurement value can be attributed to the object immediately before, during, and after the measurement, in quantum physics there is an active, unpredictable, and unavoidable participation of the instrument or "meter" in producing the result, in which the microphysical object is thrown from its previous state into a new state. Therefore in quantum physics the measured value can be ascribed to the atomic object only immediately after the measurement is completed, and any subsequent measurement erases all traces of the first state and produces an entirely new situation. Nevertheless Landé maintains that it is always possible to reconstruct one and only one path between the two space-time positions according to the laws of classical mechanics *post factum*, even though the path cannot be predicted. He distinguishes between direct and indirect measurements; the former are coincidences in space and time, and are the basis for all other measurements, which are indirect measurements. Energy, momentum, and velocity are relevant examples of indirect measurements; velocity by definition requires measuring two adjacent positions at two adjacent times.

Landé rejects the Copenhagen thesis that effectively equates "indirectly observed" with "not observed", and then with "not observable", and finally with "nonexistent" and "meaningless". The Copenhagen school wrongly maintains that only direct measures count as observation. To say as they do, that position and momentum cannot be measured simultaneously is only a half-truth. If one includes "directly", then it is trivial because momentum can never be measured directly. And without the word "directly" the statement is wrong, because the momentum value acquired within a given position increment can be determined by reconstruction of space-time data with the help of theory. The root of the difficulty with reconstructing values of indirect observables is the ambiguity of their definition, which always requires theory. Landé maintains that classical theory can be used to make the indirect measurements needed to describe the path of an electron. The controversy about the meaning of an atomic measurement is due to an erroneous connecting of the first measurement with a set of possible future measurements. When the wave function is used as a mathematical representation of just one physical state, there is no confusion. But when it is used to connect one measurement with a set of future possible measurements, misunderstanding occurs, which results in different interpretations of the wave function including the Copenhagen dualistic thesis that the wave function describes a physical state of matter, which is spread out in space and time, and which suddenly contracts to one point when the particle is measured.

Landé rejects subjective interpretations, and states that quantum physics deals with records of instruments rather than any observer's consciousness, with physical objects rather than mental pictures, and with statistical distributions rather than lack of knowledge by human observers. Knowledge and conscious reading by observers are as irrelevant in atomic physics as they are in any other branch of physical science. Echoing Einstein's programmatic aim of all physics (but without referencing

 

Einstein), Landé says that the object of natural science is to suppose that the real world exists without human advice and consent, and then to search for general regularities which may help to manipulate things and events. The significance of all that quantum theory stands for, is to provide formulas, tables, and other rules of correlation between events, and in particular between probabilities of transition. To speak of the contraction of the wave packet upon an observation is as senseless in Landé's opinion as to speak of a sudden contraction of a statistical mortality table upon an individual fatality. A probability wave does not guide actual events any more than a mortality table guides actual mortalities, and it shrinks no more than a mortality table shrinks when an actual death occurs. In Landé's view the subjectivist confusion begins when the material body used as a measuring instrument is regarded as a subject, and when it is then said that quantum theory has changed the relation between subject and object. This makes a great impression on those who mistakenly identify statistical distributions recorded by instruments with knowledge or lack of knowledge of observing subjects.

Landé advances a particle interpretation of the Heisenberg uncertainty relations and the Schrödinger wave function, and he criticizes the Copenhagen dualistic interpretation. A central part of his criticism is his alternative interpretation of the two-slit experiment, in which the diffraction pattern is construed by the Copenhagen school as an interference pattern, that must be taken as evidence for the wave nature of the electron, which in turn must also be construed as a particle before its entry into the slit and then again upon its impact on the photographic plate. Landé references the Stern-Gerlach experiment (1922), the theory of William Duane (1923), and the work of Paul Ehrenfest and Paul S. Epstein (1924). He explains that Duane's quantum theory was not immediately recognized as a way out of the Copenhagen duality paradox, because Duane's proposed statistical particle theory of diffraction pertains to X-rays in support of the photon theory of light, and also because in 1923 diffraction of electrons was not yet discovered. Landé references a letter written to him by Born stating that Duane's 1923 paper on the particle theory of X-ray diffraction was well appreciated at the time of its publication, and stating that it is a riddle as to why its significance was overlooked when the diffraction of matter was discovered a few years later. Landé remarks that he could not find any hint of recognition in any of the works of Bohr, Born, de Broglie, Dirac, Einstein, Heisenberg, Pauli, or Schrödinger, that Duane's quantum rule is relevant to the alleged dilemma of matter diffraction and duality.

According to Duane's quantum rule for linear momentum, the incident matter particles do not spread out as continuous matter waves or manifest themselves as though they do. It is the crystal slit with its parallel lattice planes, which is already spread out in space, and which reacts as one rigid mechanical body to the incident particles, that produces the diffraction pattern. Duane's rule yields the same observed diffraction directly without appealing to any wave interlude. Therefore, the idea of a dualistic change from matter particles to waves and then back to particles is a quite unnecessary and fantastic invention in Landé's opinion. According to his criteria for scientific criticism the scientific value of a theory is measured not only by its power to account for observed data, but also by the criterion of simplicity, freedom from *ad hoc* assumptions, and reducibility to more general postulates.

As a result of Duane's theory, quantum physics has discovered that even such wave-like phenomena as matter diffraction through crystals can be understood in a consistent unitary way as produced exclusively by matter particles obeying the conservation laws of mechanics under special restrictions known as quantum rules, matter particles which react to bodies such as crystals containing periodicies in time and space. Landé thus states that electrons always behave as particles, and never misbehave as waves; he calls Duane's quantum rule the "missing link" between wave-like appearances and particle reality. To the two recognized general quantum postulates, Planck's rule for energy exchange and Sommerfeld-Wilson's rule for angular momentum exchange, Landé adds Duane's quantum rule for linear impulse changes as the third postulate for quantum physics. Landé thus answers the problem of the two-slit diffraction experiment, the problem of which of the two slits did the particle pass through. He states that for its contribution to the diffraction pattern, it does not make any difference where exactly the diffraction takes place. The electron changes its momentum in reaction to the harmonic components of the matter distribution of the crystal screen with two slits as a whole. All that is important is the conservation of charge and of total momentum in the reaction between electron and diffractor.

 

For these reasons Landé maintains that the Copenhagen school starts from "wrong physics", when they maintain that wave-like appearances of matter diffraction are due to the periodic wave action of the electron. The correct view is that the appearances are due to the periodic structure of the bodies in space (the crystal) and in time (the oscillators) via the three corresponding quantum rules for the momentum and energy activity of the periodic bodies. He calls his particle interpretation "practical realism", and offers reinterpretations of Heisenberg's and Schrödinger's equations. The Heisenberg indeterminacy relations describe objective statistical dispersion. Heisenberg's claim that simultaneous exact position and momentum measurement pairs, is meaningless and nonexistent, is incorrect because it confuses lack of predictability (which is true) with lack of measurability (which is false). Unpredictable data including position and momentum measurement pairs can be reconstructed which are more accurate than Planck's constant. And what can be measured exists. The doctrine of the indeterminacy of existence is a "semantic artifice" rather than legitimate physics. Nor is denying that a particle always is somewhere, warranted by diffraction experiments, because each particle reacts to a space-extended periodic component in the matter distribution of the diffractor. To say that the particle is nowhere is a "linguistic extravaganza" and not a philosophical innovation.

As for Schrödinger's equation, Landé says that it does not deal with matter waves, but with probability amplitudes; it is a probability table not essentially different from any mortality table. The real constituents of matter are discrete particles that occasionally give the appearance of wave action, and that the real constituent of light is a continuous electromagnetic field that sometimes gives the appearance of photonic particles. The Schrödinger wave function is a probability curve describing betting odds for future events; it is not a real thing even when the curve looks wave-like.

Landé uses the phraseology of Dr. Samuel Johnson (a critic of Bishop Berkeley's *esse est percipi* philosophy, who kicked a great stone and exclaimed "I refute him thus") saying that you can kick a stone, and you can kick an electron and even a water wave and an electromagnetic wave, and be hurt by them, thus proving their reality. But you cannot kick or be hurt by a wave-like curve representing probabilities of events. For Landé, physical interaction is the only correct ontological criterion for physical reality. He also takes exception to Born, his former colleague, who had initially developed the statistical interpretation of the Schrödinger wave function as a probability amplitude for particles, but who later made what Landé calls "belated concessions" to the Copenhagen dualistic interpretation. He references Born's "Physical Reality" appearing in *Philosophical Quarterly* (1953) in which Born sets forth his own ontological criterion, the criterion of invariance. In this article Born is not explicitly opposing Landé, but rather is opposing the idealist metaphysics and the logical positivist philosophy of phenomenalism.

Born explains his criterion of invariance as follows: Most measurements in physics are not concerned with things that ordinarily interest us, but are concerned with some kind of projection which is defined in relation to a system of reference. In every physical theory there is a rule which connects the projections of the same object on different reference systems. The rule is called a law of transformation, and all transformations have the property of forming a "group", where the sequence of two consecutive transformations is a transformation of the same kind. Invariants are quantities having the same value for any system of reference, and therefore are independent of the transformations. The main advances in the conceptual structure of physics consist in the discovery that some quantity formerly regarded as the property of a thing, is in fact only the property of a projection.

The long historical development of the theory of gravitation from pre-Newtonian physics to relativity theory is one example. Another example is the development of quantum physics. An observation or measurement in quantum physics does not refer to a natural phenomenon as such, but to its projection on a system of reference which is the whole apparatus used in the experiment. By use of instruments the physicist can obtain certain restricted but well described information, which is independent of the observer and of his apparatus, namely the invariant features of a number of properly devised experiments. Bohr's complementarity principle means that the maximum knowledge of the quantum can only be obtained by a sufficient number of independent projections of the same physical entity. The final result of complementary experiments is a set of invariants characteristic of the entity, and these invariants are called "charge", "rest mass", "spin", etc. In every instance, when we are able to determine these quantities, we decide we are dealing with a definite particle. The words "photon", "electron", etc. signify definite invariants that can be constructed by combining a number of observations.

Born maintains that the idea of invariance is the clue to a rational concept of reality, not only in physics but also in every aspect of the world. The power of the mind to neglect the differences of sense impressions and to be aware only of their invariant features is the most impressive fact of man's mental structure. He proposes translating the term "*gestalt*" not as "shape" or "form" but as "invariant". And he proposes speaking of invariants of perception instead of sense impressions as the elements of our mental world. In the closing paragraph of his article Born considers the reality of waves according to his ontological criterion of invariance. He says that we regard waves on a lake as real, though they are nothing material but are only a certain shape of the surface of the water. The justification for this view is that they can be characterized by certain invariant quantities like frequency and wavelength, or as a spectrum of these. Born says that the same thing holds for light waves, and he asks rhetorically why the physicist should withhold the epithet "real" even if the waves represent in quantum theory only a distribution of probability.

In his *New Foundations* Landé replies to Born's rhetorical question from the viewpoint of his own criterion of interaction: Particles are real while Schrödinger waves are not real, for the same reason that sick people are real things while the wave-like curve which symbolizes the probability distribution during a fluctuating epidemic is not a real thing. Landé says that a given formalism can always be interpreted in a variety of ways. At the conclusion of his *New Foundations* he gives seven alternative interpretations of the Schrödinger wave function including Schrödinger's, de Broglie's, Bohm's, Heisenberg's subjective interpretation, Heisenberg's objective interpretation, Bohr's instrumentalist interpretation, and Landé's own particle interpretation. He does not include Popper's propensity interpretation. He states that this list is indicative of the present confusion regarding the wave function, and paraphrases Mao Tse Tung saying that while it may be good politics to let a hundred flowers bloom and let a hundred schools contend, it is not good enough for science. He asserts that only his interpretation stands up to realistic criticism in accordance with "monolithic" quantum mechanics, *i.e.*, quantum theory with an ontology that is consistent with the rest of physics. However, unlike Landé and Popper's criterion of interaction for physical reality, Born's criterion of invariants is consistent with the contemporary pragmatist thesis of ontological relativity, because Born's subordinates ontology to the empirically adequate theory describing the invariants.

## Popper's Particle-Propensity Interpretation of Quantum Theory

Popper explains the basis for the schism in physics as follows: On the one hand Einstein was a determinist, who believed that the statistical nature of quantum theory is due to the physicist's ignorance of the underlying deterministic laws, which have not yet been discovered. Therefore Einstein chose a subjective interpretation of probability based on the scientist's ignorance. On the other hand Heisenberg was an indeterminist, but because the only objective interpretation of probability available at the time was the frequency interpretation. His introduction of the observer's disturbance of the quantum phenomenon by the measurement apparatus resulted in the combination of both the objective and subjective interpretations of the probability function in the Copenhagen interpretation of the quantum theory. But the frequency interpretation is applicable only to mass phenomena, while the quantum theory pertains to singular events. Therefore in order to describe the single quantum event, it seemed necessary to view probability as describing the scientist's ignorance resulting from the disturbance. For this reason according to Popper the Copenhagen interpretation also relies on the subjective interpretation of probability. Popper's propensity hypothesis advances an objective interpretation of the probability calculus and of probabilistic theories in physics, and it is an objective interpretation that is applicable to singular events. Popper has arguments for probability interpretations that are exclusively objective, but any objective interpretation requires a realistic philosophy with a nondeterministic ontology. Therefore he also advances arguments for realism and indeterminacy as well as for objectivism.

Popper has several arguments against the subjective interpretation of probability and for an objective interpretation. Firstly some quantum theorists such as Pauli introduce the idea of induction into discussions about the statistical nature of quantum theory. Popper rejects this application of inductivism for the same reasons that he rejects all applications of the idea of induction; induction is psychologistic and confuses world 2 with world 3. Secondly he also argues that the idea of explaining the statistical outcomes of experiments and predictions in terms of the ignorance of the physicist is absurd. Empirical science absolutely never explains anything in terms of the researcher's ignorance; it always explains phenomena in terms of other phenomena. While this argument of Popper's is true and may apply to some subjective interpretations of the quantum theory, it does not apply to interpretations such as Heisenberg's, which invoke the subjective interpretation of probability only to address the problem of measurement errors, thus giving the subjective interpretation a metalanguage status instead of the object-language status of an explanation in physics.

Popper's argument for realism is based on his falsificationist thesis of scientific criticism. Simply stated, he argues that the possibility of falsification is evidence of the existence of the real world that is independent of human knowledge. He furthermore argues that the fact that theories are conjectures does not imply that they do not describe the real world. Rational criticism results in better theories that have greater verisimilitude. Popper argues against instrumentalism, which he associates with both Bohr and Heisenberg. In "Three Views Concerning Human Understanding" in *Conjectures and Refutations* Popper references Heisenberg's thesis that physical theories such as Newton's are not falsified, but rather have had their applicability restricted by later theories such as relativity and quantum mechanics.

This view is an aspect of Heisenberg's doctrine of closed-off theories, although Heisenberg did not set forth his doctrine of closed-off theories as an instrumentalist thesis. In a footnote in this paper Popper states that Heisenberg's instrumentalism is far from consistent, and that he has many anti-instrumentalist remarks to his credit, but that Heisenberg's view of quantum theory necessarily leads to an instrumentalist philosophy by neglecting falsification and stressing application. A mere instrument cannot be falsified, and the instrumentalist view may be used *ad hoc* to rescue a theory threatened by falsifications. Popper maintains that such an evasion was the reason that Bohr advanced his principle of complementarity, the renunciation of the attempt to interpret atomic theory as a description of anything; the self-consistent formalism need not be reconciled with its inconsistent applications, if it is left uninterpreted. On Popper's view the unfalsifiability thesis of the instrumentalist view makes instrumentalism incapable of explaining scientific criticism and scientific progress. Only by reaching for refutations can science hope to learn and to advance.

 

## POPPER AND LANDÉ

Popper argues against determinism, and in this respect he takes exception to Einstein, although he says that he may have changed Einstein's mind about determinism in a conversation at Princeton in 1950. Popper distinguishes between metaphysical determinism, which is a thesis about the whole world, and scientific determinism, which is a thesis about the part of the world described by a scientific theory. He classifies Einstein as a metaphysical determinist, and reports that in his discussions with Einstein he referred to him by the name Parmenidies, because like the ancient philosopher Parmenidies, Einstein's metaphysical determinism implies that the future is entirely contained in the past, and that change is not real but is merely an appearance.

Popper also argues against scientific determinism, and specifically he denies that Newtonian mechanics implies a deterministic ontology. He describes the theories of classical physics as *prima facie* deterministic, by which he means that the deterministic character is a property of the theory and not of the real world. He maintains that classical physics does not imply real determinism any more than quantum physics does, because there is always an irreducible and stable statistical element in any predictions made with a *prima facie* deterministic theory. It is always necessary to add to the deterministic theory a probability assumption to explain the statistical component in the prediction, because statistical conclusions require statistical premises. Popper quotes at length Landé's description of the experiment with the ivory balls and steel blade, which Landé uses to argue that statistical results require statistical assumptions about the initial conditions. Therefore Popper rejects attempts to explain the statistical outcomes subjectively by reference to lack of knowledge of the experimenter for the reasons given above, and he maintains that the law-like behavior of statistical sequences is for the determinist ultimately inexplicable.

Popper developed his propensity interpretation of probability in 1950 specifically to address the interpretation problem arising from statistical quantum theory, but it is also intended to be applicable to all physics. While it is but one of many interpretations for the probability calculus, it is the best for physics in Popper's view. Popper distinguishes three objective interpretations of the probability calculus: the classical interpretation, the frequency interpretation, and his propensity interpretation. The classical interpretation is that the probability measure **P(α, β)** is the proportion of equally possible cases compatible with the event **β** that are also favorable to the event **α**. The frequency interpretation is that **P(α, β)** is the relative frequency of the events **α** among the events **β**. The propensity interpretation is a refinement of the classical interpretation. In the classical interpretation experimentation is not needed, because it deals with equally possible cases, such as the two sides of a coin or the six faces of a die.

The propensity interpretation substitutes weights for equally possible cases in the classical interpretation, where the weights are experimentally determined measures of the propensity or tendency of a possibility to realize itself upon repetition. In the propensity interpretation the measure **P(α, β)** is the propensity of **α** given experimental conditions **β**. It is the sum of the weights of the possible cases that satisfy the condition **β** which are also favorable to **α**, divided by the sum of the weights of the possible cases that satisfy **β**. The propensity interpretation is closely related to the frequency interpretation; the latter is about frequencies in actual finite sequences of experiments, while the former is about virtual finite sequences. In the propensity interpretation probability statements are about some measure of a physical property of the whole repeatable experimental arrangement, a measure of a virtual frequency, and the probability distribution is taken to be a property of the single experiment. The fact that the probability distribution in the propensity interpretation is a property of a single experiment is the strategic characteristic of this interpretation for quantum theory. Previously in *Logic of Scientific Discovery* Popper had attempted to modify the frequency interpretation so that it could address single events by means of what he called "formally singular statements." He abandoned this idea, when he developed the propensity interpretation. Now he says that the frequency measurements function to test the conjectured virtual frequency, which is a conjecture like any other scientific hypothesis.

The propensity interpretation is consistent with Popper's particle interpretation of the quantum theory that he had advanced years before in *Logic of Scientific Discovery*. According to Popper`s particle interpretation the Heisenberg indeterminacy relations are statistical scatter relations that describe the lower limits of the dispersion of particles; they are not the upper limits of the accuracy of measurements, as Popper construes Heisenberg's view. The indeterminacy relations apply only to the magnitudes that belong to the particle after the disturbing measurement has been made. The particle always has position and momentum, and has both these properties up to the instant of measurement, which can be ascertained in principle with unlimited accuracy. It is not the impossibility of precise measurement, but the statistical scatter that makes it impossible to predict the path of the particle after the disturbing measurement operation. The scatter relations are statistical predictions about paths, and the paths must be measurable in order to test the statistical theory. For these reasons Popper rejects the view he incorrectly attributes to Heisenberg's view that the uncertainty relations express limits to our subjective knowledge instead of expressing objective statistical scatter relations, and that measurements are impossible due to the nonexistence of the entities measured. What is impossible is producing dispersion-free quantum states. The statistical laws add to our knowledge. They do not set limits to our knowledge; they set limits to the scatter relations and tell us that the scatter is an objective reality that cannot be suppressed.

The propensity interpretation purports to solve the problem of the relationship between particles and their statistics, and between particles and waves. Popper calls the Copenhagen wave-particle dualistic interpretation the "great quantum muddle." The great quantum muddle results from the mistake of taking the probability distribution function as a physical property of the elements of the population. Popper believes that this mistake is historically due to the fact that the works of de Broglie and Schrödinger led physicists to view the wave as the structure of the particle, and thus to view the particle as a "wave packet" or a "wavicle". Popper maintains that the statistical wave function is a property characterizing a sample space and not a property of the elements of the sample space. The elements have the properties of a particle. The propensity interpretation achieves the application of probability theory to single cases, but it does not do this by speaking about single electrons or protons; it speaks about propensities, which are properties of each instance of the whole repeatable experimental situation involving a single particle.

Propensity statements in physics describe properties of the situation, and are testable if the situation is typical. Popper accepts Landé's explanation of the two-slit experiment, and he references what he calls the Duane-Landé space periodicity formula. The two-slit experiment is a space periodicity experiment, in which the particle interacts with the whole experimental situation including the crystal. More specifically from the viewpoint of the propensity interpretation, it is the whole experimental arrangement that determines the propensities. The possible results of any one experiment are different in the case of both slits being open from the case where only one is open; propensities are dependent on possibilities, such that the results will differ with different experimental arrangements, one slit or two. Thus in the two-slit arrangement the particle will pass through only one of the slits and in a sense will remain unaffected by the other slit. What the other slit influences are the propensities of the particle relative to the entire experimental arrangement and not relative to the particle itself: the propensities for reaching the one point or the other point on the screen with the two slits. The Schrödinger wave equation enables the physicist to determine the propensities, and it entails the Heisenberg scatter relations, which limit the possible predictions.

Popper states that Schrödinger had anticipated one of the most important aspects of the propensity interpretation, namely the objectivity and reality of the waves in configuration space. One of the features of Popper's propensity interpretation is his thesis that the propensities are real, just as forces are real, and he speaks of propensity fields, just as contemporary physicists are accustomed to speak of force fields. The propensities are dispositional relational properties of the experimental set up. The waves are propensities of the particles to take up certain states under the conditions of the experimental set up, and the propensity waves are therefore no less real than electromagnetic waves. Landé believes that if he admitted to the reality of the Schrödinger wave, then like Born he would have to make what he called "concessions" to the Copenhagen dualistic thesis. Therefore Landé maintains that the Schrödinger wave function interpreted as a probability wave is merely a statistical function that is no more real than a mortality table, which Landé did not view as real. But Popper uses Landé's criterion of interaction, and argues that because the probability waves can interact to produce interference, they must be real, and are not merely mathematical tables. Popper supports Landé's rejection of the Copenhagen dualism, but contrary to Landé, Popper says that he prefers to speak of the particle and its associated propensity fields, instead of speaking of the particle and its associated mathematical probability function.

**On Crucial Experiments and Scientific Revolutions**

 

Unlike the positivist philosophy of science, which has been interred to its resting place in the history of philosophy, Popper's philosophy of science is still a living philosophy in the sense that it is still accepted and debated in the professional literature. Popper has addressed more than one generation of philosophers during his lifetime. Initially his philosophy was a critique of the positivists, who viewed his philosophy as an unconventional novation, while today his philosophy is criticized by the contemporary pragmatists, who view his philosophy as the conventional wisdom. The central contemporary issue in which Popper represents the conservative position is the problem of the decidability of scientific criticism including most notably the decidability of crucial experiments. The origin of the problem is the thesis shared by both Popper and the wholistic pragmatists, and also enunciated by Einstein, that theory decides what the physicist can observe. To these pragmatists this thesis implies that the description of the observed results from an experimental test cannot be understood in the same way by different scientists who maintain alternative theories in an experimental test, which is crucial in the sense that it purportedly decides between the alternative theories. If theory determines what is observed, then scientists maintaining different theories do not observe the same thing, and the observed outcome from the crucial experiment cannot decide between the alternative theories. To Popper on the other hand, Eddington's 1919-eclipse experiment, which is widely regarded as the historic crucial experiment deciding on behalf of Einstein's theory of relativity, demonstrates conclusively that crucial experiments are decisive.

It should be noted at the outset that even in his earliest writings Popper maintained that falsification is never finally and permanently conclusive, because the singular basic statements that are potential falsifiers may be revised, thus occasioning the revision of a falsifying test outcome. The empirical test may be said to be conclusive only to the extent that interested scientists agree to accept certain basic statements. Popper states that in some cases it has taken scientists a long time before a falsification is accepted, and that it was often not accepted until a falsified theory had been replaced by the proposal of a new and more adequate theory. But Popper does not find this historical fact to be problematic, even though in his view it is responsible for having led the pragmatists to accept irrationalism and relativism in philosophy of science. In his introduction to *Realism and the*

 

*Aim of Science* he gives several examples of successful falsifications that furthermore have led to important scientific revolutions.

Just as the development of Einstein's relativity theory can be said to be the formative influence in Popper's philosophy of science, the development of the quantum theory can be said to be the formative influence in the contemporary pragmatist philosophy of science. The topic of crucial experiments has assumed its controversial status in the professional literature due to the Copenhagen interpretation of quantum theory. The Copenhagen interpretation denies that a crucial experiment can decide between the wave and particle interpretations of microphysics, because the electron has the properties of both wave and particle. Quine invoked Duhem's philosophy of physical theory not only due to Duhem's rejection of the decidability of crucial experiments for establishing a theory, but also more fundamentally due to Duhem's thesis of the organic character of the semantics of theory language in physics. In his "Two Dogmas of Empiricism" Quine extended Duhem's thesis of the organic or wholistic character of the semantics of physical theory, to make it a general theory of the semantics of language as such, including the language used by physicists to describe observed experimental test outcomes.

As a result of this extended thesis, which is now conventionally called the Duhem-Quine thesis, the wholistic character of the semantics of language explains why crucial experiments are undecidable not only in the wave-particle issue in quantum theory, but also more generally for all scientific criticism. Even where one of the alternatives is the Copenhagen dualistic interpretation, as in Landé's list of seven interpretations, the crucial experiment cannot effectively decide among them, according to the wholistic version of the contemporary pragmatist philosophy. The issue of crucial experiments has become a focal point in philosophy of science for the larger issues of the decidability of scientific criticism and of the nature of the semantics of language in general.

The historic transition from the positivists' naturalistic philosophy of the semantics of language to the contemporary artifactual philosophy of the semantics of language has thus resulted in two alternative artifactual philosophies of the semantics of language: The one is the organic or wholistic thesis advocated by some pragmatists, which they use to attack the decidability of crucial experiments and of scientific criticism in general.

 

The other is the mechanistic or logical thesis advocated by Popper, which he uses to defend the decidability of crucial experiments for eliminating theories and for defending the rationality of scientific criticism in general.

In his “Three Views Concerning Human Knowledge” (1956) reprinted in his *Conjectures and Refutations* Popper discusses Duhem’s views on crucial experiments. He notes that Duhem shows that crucial experiments cannot establish a theory simply by refuting its alternatives, and emphasizes that Duhem does not say that theories cannot be refuted in crucial experiments. Popper maintains that crucial experiments can be used to decide between alternative theories, as occurs when a new theory is proposed as a superior alternative to an older theory. The new theory is tested by applying it to cases for which it yields results that are different from what is expected from the older theory. He says that such cases are “crucial” in the Baconian sense that they indicate the crossroads between two or more theories, but not in the Baconian sense that any theory can be conclusively established.

Popper then turns to Duhem’s thesis that in every test it is not only the theory under investigation that is tested, but also the whole system of assumptions made by the theory, such that it is never possible to be certain which of the assumptions is refuted by the test. Popper states that if the scientists consider each of the two theories in the crucial test together with all the background knowledge assumed by both theories, then the scientists decide between the two systems, which differ only over the two alternative theories in the test. Popper adds that scientists do not assert the refutation only of one of the theories by the test, but rather the theory together with the background assumptions. By this he does not mean that every statement in the theory and its assumed background is refuted, but only that there is at least one statement that is erroneous, and that it may be in either the theory or the assumed common background. Thus he also says that in future tests parts of the background knowledge may be rejected as responsible for the falsification of the theory in the current crucial test.

Popper then proposes to “characterize the theory under investigation” in the crucial test precisely as that part of the vast system of knowledge for which the scientist has an alternative in mind, and for which he has therefore designed the crucial test. This may be taken as Popper’s basis for individuating theories: theory **α** is distinguished from theory **β**, because **α** makes a claim or statement than is an alternative to that made by **β**, and because **α** consists in the language that makes it an alternative to **β**. Thus it may be said that Popper individuates theories by reference to the theories' semantical properties as manifested in the crucial-test situation.

However, Popper does not define theory language by reference to the crucial test situation as such; he often states that the background knowledge includes theories other than the tested one. In his philosophy, therefore, theory language is any testable general statement regardless of whether or not it is being tested, which is to say that he defines theory by reference to its syntactical property of universal quantification and not by reference to its semantics or its pragmatics. Furthermore Popper's concept of theory language may be contrasted with that of the positivists, who believed that it is possible to define theory in terms of its semantical properties by means of their distinction between theoretical and observation terms; Popper rejects this basis for their distinction.

In his "Truth, Rationality, and the Growth of Knowledge" (1961) reprinted in *Conjectures and Refutations* Popper turns to Quine's use of Duhem's philosophy. Quine maintains a wholistic view of empirical testing, and in his "Two Dogmas of Empiricism" in *From A Logical Point of View* he states that our statements about the external world face the tribunal of experience not individually but as a corporate body. Popper replies that this wholistic view of tests, even if it were true, would not create a serious problem for the falsificationist philosopher of science. He repeats his thesis that to say scientists take a vast amount of background knowledge for granted, is not to say the scientist must uncritically accept it, because the background knowledge too may be challenged and tested. Even though all of the background assumptions may be challenged, it is quite impossible to challenge all of the assumptions at the same time. All criticism must be "piecemeal", which Popper says is only another way of saying that the fundamental maxim of every critical discussion is that one should "stick to the problem", because the misguided attempt to question all background assumptions merely leads to a breakdown of critical debate. Critics such as Feyerabend will view this thesis as the parallel postulate of Popper's philosophy of science to be replaced with a pragmatist philosophy of language.

 

Furthermore even though the falsification of a theory does not reveal where the error is, it is still possible to find the hypothesis that is responsible for the refutation, *i.e.*, to find which hypothesis is responsible for the falsified prediction. The fact that such logical dependencies may be discovered is established by the existence of independence proofs for axiomatized systems; these are proofs that show that certain axioms of a system cannot be derived from the others in the axiomatic system. Popper argues that the existence of such proofs shows that Quine's wholistic view of the global character of all empirical tests is untenable, and that it explains why even without axiomatized physical theories, the scientist may still have an inkling of what has gone wrong with the theory. In *Realism and the Aim of Science* Popper affirms as historical fact, that scientists are sometimes highly successful in attributing to a single hypothesis the responsibility for the falsification of a complex theory or of a system of theories, and he argues that this success remains to be explained if one adopts the wholistic view of empirical testing.

In 1962 Thomas Kuhn wrote *Structure of Scientific Revolutions* in which he used the wholistic thesis to interpret the history of science. And in 1970 Kuhn defended his wholistic interpretation against critics in *Criticism and the Growth of Knowledge*. The leading critic in this later book was Popper, who contributed "Normal Science and its Dangers." In his earlier statements in defense of the decidability of crucial tests Popper did not explicitly address the basis of the wholistic view of testing, namely the thesis that the semantics of language is wholistic. The wholistic thesis of the semantics of language means that the meanings of terms are mutually determined in the context of the discourse in which they occur, such that alternative contexts consisting of alternative theories produce a semantic ambiguity or equivocation that is propagated through all of the related language. In other words when considering the alternative theories investigated in a crucial test, all that constitutes the background assumptions is ambiguous.

Therefore there is really no common background, because one semantical interpretation is given to the language expressing the background assumptions by one of the theories in the test and another interpretation is given by the other theory in the same test. However, Quine also says that the propagation of change is damped by vagueness in language. Often the two alternative semantical interpretations are spoken of as two different languages, and there is said to arise a problem of translation from one to the other. This thesis is strategic to Kuhn's critique of the positivists, because the lack of any common semantics for alternative theories that makes impossible a common background for crucial tests, also makes impossible a common observation language for decidable testing.

Kuhn maintains that the kind of scientific progress that Popper describes with its crucial experiments and falsifications can occur only within a linguistic framework, and he calls this type of scientific progress "normal science", which Kuhn opposes to another type which he calls "extraordinary science" or "revolutionary science". Revolutionary science is a transition from one language framework to another, where the term "framework" in the discussion refers to discourse having a univocal semantical interpretation and associated ontology. Popper rejects this theory of scientific revolution as irrational, when he criticizes Kuhn in *Criticism and the Growth of Knowledge*. While admitting that "normal science" as a behavior in Kuhn's sense does exist, Popper argues that such normal science is dogmatic. He says that science is essentially critical, that it consists of bold conjectures controlled by criticism, and that it may be called revolutionary in this rational sense. He rejects Kuhn's relativism, the thesis that the linguistic framework cannot be critically discussed, and he calls this "the myth of the framework." Comparison of different frameworks is always possible on Popper's view, and so is critical discussion therefore. Even totally different languages are not untranslatable.

Thus Popper argues that it is simply false to say that the transition from Newton's theory of gravitation to Einstein's theory is an irrational leap, and that the two are not rationally comparable; the transition to Einstein's theory was genuine progress in comparison with Newton's. Popper concludes that the myth of the framework is in our time the central bulwark of irrationalism, and that it exaggerates a difficulty with communication and criticism into an impossibility. In place of criticism as is found in Popper's falsification thesis, Kuhn proposes turning for enlightenment concerning the aim of science to psychology and sociology. But Popper rejects this proposal, and states that compared with physics, sociology and psychology are riddled with fashion and with uncontrolled dogmatism. He believes that such a proposal is a backward regression that cannot solve the difficulty.

 

In his "The Rationality of Scientific Revolutions" in *Problems of Scientific Revolution* Popper distinguishes between the sociological and the logical or rational dimensions in the history of science, when he distinguishes ideological from scientific revolutions. By an ideology he means any nonscientific theory, creed, or view of the world that is attractive or interesting to people including scientists. He cites the Copernican and Darwinian revolutions as examples of scientific revolutions that gave rise to ideological revolutions, because each changed man's view of his place in the universe. But these were also scientific revolutions in so far as each overthrew a dominant scientific theory, the one a dominant astronomical theory, the other a dominant biological theory. He also cites Einstein's relativity theory as a revolution, a truly scientific revolution that gave rise to operationalism and supported positivism, even though Einstein later rejected these ideologies. And Popper also refers to the subjectivist interpretation of quantum theory as an ideology.

The wholistic thesis of the semantics of language is used by many pragmatists to explain events that have been observed in the history of science: the impediment that language creates both to the development of new theories and to the communication of new theories within a profession. However, Popper relegates all semantical analysis to the status of a variation on the essentialist metaphysical thesis; in his autobiography in *Philosophy of Karl Popper* he admonishes the reader never to let himself be "goaded" into taking seriously problems about words and their meanings. He maintains that words "merely" play a technical or "pragmatic" rôle in the formulation of theories, just as the letters in written words play such a rôle in the formation of the words. Contrary to Popper contemporary pragmatists do not believe that language has such a passive rôle in concept formation and in human cognitive processes. And it may be noted that contemporary pragmatists are as anti-essentialist as Popper; one need only recall Quine's rhetorical ridicule that an essence is merely a "meaning wedded to a word". Regrettably Popper's philosophy does not offer a theory of semantical description to reconcile the phenomenon of semantical change with his views on the decidability of criticism.

## The Philosophy of Science

Popper's philosophy comprehensively addresses the four functional topics of philosophy of science. His explicit rejection of the positivist and naturalistic philosophies of the semantics of language represents a basic problem shift, a reconceptualization of science as viewed by academic philosophy of science.

***Scientific Criticism***

The central feature of Popper's philosophy of science is his falsificationist criterion, as well as its consequent rejection of the naturalistic thesis of the semantics of language and redefinition of the concept of theory to mean any universally quantified statements. Theories are conjectures that are created by the human imagination, and similarly the meanings associated with the theories' constituent terms must also be created artifacts distinguished as world 3 objects. The theories do not originate by any natural process such as induction, and similarly the constituent meanings are not determined by any natural process such as perception. The theories are not permanently established by verification or confirmation, and similarly the meanings are not permanently established by virtue of any foundational ontology. The logic of criticism is the *modus tollens* form of argument, in which a theory is falsified, if the antecedent clause of the conditional statement is true and the consequent clause is false. Theories are routinely falsified as a part of the progress of science. The paradigmatic case for Popper is the transition from Newton's mechanics to Einstein's relativity theory. Einstein's theory does not include Newton's as a special case, but rather contradicts and corrects Newton's theory, and therefore describes an alternative ontology. And in such cases the new theory offers a higher degree of information content as indicated by the relative sizes of the classes of potential falsifiers, such that even before empirical tests are attempted it is possible to recognize that the new theory is preferable if it survives the test.

Crucial experiments are methodologically and historically important decision procedures in the progress of science. In the case of the transition from Newton's theory to Einstein's theory a crucial experiment was performed in 1919, in which Einstein's theory made the more accurate prediction within the range in which the deviation between the two theories was experimentally distinguishable. Crucial experiments are not only effective for deciding between theories, but are characteristic of the growth of science toward greater information content and verisimilitude. Popper rejects the wholistic variation on the artifactual theory of meaning, because it implies that crucial experiments are invalid, since the alternative theories cannot share common background assumptions with univocal semantics, and since it implies in general that scientific criticism is undecidable. Both in his 1982 introduction to *Realism and the Aim of Science* and as early as his 1934 *Logic of Scientific Discovery* Popper maintained that the falsifying basic statements like all empirical statements cannot be verified, and that therefore it is impossible to prove conclusively that an empirical scientific theory is false. He also states that every falsification can be retested to motivate an agreement among interested scientists about the test outcome.

Popper maintains that there have historically been successful scientific revolutions, which were occasioned by successful falsifications, and he rejects the view that falsification plays no rôle in the history of science. But he offers no theory of meaning description that would enable him to reconcile the phenomenon of semantical change with his thesis of crucial experiments and the rational growth of science. Contrary to Kuhn, Popper maintains that communication problems are merely difficulties and not impossibilities. But without a metatheory of semantical description for analyzing semantical change, Popper cannot explain why communication is not impossible, because he cannot explain why it is merely difficult.

### *Scientific Explanation*

Popper's theory of scientific explanation has been called the hypothetico-deductive thesis. It is not altogether unique to Popper. In his chapter on theories in *Logic of Scientific Discovery* he states that to give a causal explanation of an event means to deduce a statement that describes the event, using as premises of the deduction one or more universal laws together with certain singular statements called initial conditions. Later in "Aim of Science" in *Ratio* (1957), reprinted both in *Objective Knowledge* and in *Realism and the Aim of Science*, he defines a causal explanation as a set of statements by which one describes a state of affairs to be explained, statements which he calls the "*explicandum*", by deduction from a set of explanatory statements, which he calls the "*explicans*". The logic of explanation is the *modus ponens* form of argument, in which a true antecedent clause describing initial conditions and an empirically valid tested and nonfalsified conditional law or theory implies an *explicandum* consequent clause. The *explicans* must logically entail the *explicandum*, and it must not be known to be false. Furthermore, the *explicans* must be independently testable, so that it is not *ad hoc*.

The logical positivist concept of explanation is also described as hypothetico-deductive in the above sense. But there are fundamental differences between Popper's and the logical positivists' views. Of central importance to Popper's concept of scientific explanation is the thesis that causal explanation need not describe certain things, or in other words that it need not have a certain semantics describing a certain ontology needed to supply science with foundations, such as the phenomenolist ontology. Or as Popper says, "science is subjectless". Popper's view therefore differs from the positivist view that causal explanation must have a semantics with such ontological categories as sensations, elementary phenomena, or sense data. And it also differs from the romantic view of causal explanation in social science, which requires a mentalistic ontology. In *Poverty of Historicism* Popper rejects the romantic requirement of intuitive understanding of purpose and meaning produced by sympathetic imagination. In its *verstehen* version this mentalistic ontological requirement for causal explanation in social science becomes a theory of scientific criticism. He maintains that this requirement goes beyond causal explanation, and he proposes his doctrine of the unity of method in both natural and social science, the method that he describes in *Logic of Scientific Discovery*. In Popper's philosophy of science "causal explanation" is defined in terms of the function that theories perform in realizing the aim of science, and not in terms of some foundational ontology.

His view of causal explanation is the result of his rejection of the naturalistic philosophy of meaning. Without the naturalistic theory of semantics there is no basis for requiring any particular ontology including the particular ontology's concept of causality, in order to be able to give a causal explanation. Rejection of the naturalistic thesis implies the rejection of all ontological criteria for causal explanation as well as the rejection of the semantical distinction between observation language and theory language and of the idea of the existence of an ontological foundation for science. Thus Popper says that explanation is of the known by the unknown in the sense of conjectural, instead of by the known in the sense of the permanently established foundation. In this respect Popper is in the company of the contemporary pragmatists; Quine for example calls the view that there are ontological criteria for causal explanation the "genetic fallacy."

Popper's rejection of ontological criteria for causal explanation became complicated in later years by his idea of metaphysical research programmes. The metaphysical research programme is not atemporal and eternal like the ontological foundations demanded by essentialists or by the positivists. It is part of the historical problem situation at a particular juncture in the history of a science, and it is also untestable at the point in time, and therefore "metaphysical" in Popper's residual sense. Most notably in Popper's view, at the given point in the history of the science the metaphysical research program functions as an ontological criterion for what constitutes a satisfactory explanation.

This complication arises from Popper's way of demarcating between science and metaphysics, which appeared many years before he introduced the idea of metaphysical research programmes into his philosophy of science, as he did in his later discussions of quantum theory. As early as 1955 in "Demarcation Between Science and Metaphysics" in *Conjectures and Refutations* he states that all physical theories say much more than the physicist can test, and that whether this "more" belongs to physics or should be eliminated as a metaphysical element is not easy to say. And in 1958 in "On the Status of Science and of Metaphysics" reprinted in the same book he says that one can discuss irrefutable metaphysical theories rationally in the sense that one can discuss their ability to solve the problems that they purport to solve, that is, in relation to their problem situation.

This complication has its origin in the residual status of metaphysics in Popper's philosophy. Metaphysics for him contains a great heterogeneity of types of knowledge, which need have nothing in common, but their irrefutable character and therefore their nonscientific status. Historically philosophers have not treated metaphysics in so residual a manner, but instead have offered positive characterizations of metaphysics, which have sometimes been called "transcendental metaphysics", and which are not typically viewed merely as protoscience. For example futile arguments such as realism versus idealism are viewed as transcendental and as incapable of empirical resolution at any time. In the concluding paragraph of the concluding section of the concluding volume of the *Postscript*, Popper states that there may be a criterion of demarcation within metaphysics between what he calls "rationally worthless" metaphysical systems on the one hand, and metaphysical systems that are worthy of discussion on the other hand.

He does not characterize the basis for such a demarcation within metaphysics, but his motivation for recognizing the existence of protoscientific metaphysics within residual metaphysics clearly shows the influence of Kuhn. In the 1982 "Introductory Comments" in *Quantum Theory and the Schism in Physics* Popper compares metaphysical research programmes to Kuhn's concept of paradigm, while stressing that metaphysical research programmes must be seen in terms of a situation that can be rationally reconsidered, and that scientific revolutions viewed as changes of paradigms are due to rational criticism. In this context he references his 1975 "Rationality of Scientific Revolutions", where he distinguishes between scientific and ideological revolutions, and then sets forth his criteria for rational criticism of scientific revolutions like Einstein's that are applicable even before any experimental testing is attempted.

### *Aim of Science*

Popper's concept of scientific explanation and the rejection of the naturalistic theory of meaning implied by the falsificationist thesis of scientific criticism, in turn imply a new concept of the aim of science, which is very different from the views of the positivists. In his philosophical development two different types of statements of the aim of science may be distinguished, firstly the logical statement and secondly the later institutional statement. As early as 1934 in his discussion of the degrees of testability in the *Logic of Scientific Discovery* he states that theoretical science aims to obtain theories that are easily falsifiable in the sense that the theories have a large class of potential falsifiers and thus a large information content. This concept of the aim of science is integral to Popper's view of the growth of scientific knowledge. Similarly in "Truth, Rationality, and the Growth of Knowledge" he states that the task of science is to search for interesting truth in the sense of truth that has a high degree of explanatory power, *i.e.*, empirical information content. In his later statements Popper added to these ideas of the aim of science the rôle of the historical problem situation with his idea of the metaphysical research programme.

 

In the introductory chapter to *Realism and the Aim of Science* he describes science as a social institution that results from human actions that are unforeseen and unintended. He states that science grows through the institutionalized cooperation and competition of scientists, who are not only motivated by their own subjective curiosity but also by their motivation to make a contribution to the growth of objective knowledge. The phrases "social" and "unforeseen and unintended" seem to refer to Popper's views on the nature of social science and to his rejection of all historical relativism. Popper defines social science as the study of the unintended consequences of social behavior. And what are unforeseen in the growth of science are the new theories that result from conjectural scientific research. The content of theories in future science is in principle unpredictable in Popper's view, and he rejects all historicisms that purport to predict history including the history of science.

The strategic relevance of Popper's reference to the institutional character of science in the context of objective knowledge becomes evident when contrasted with Kuhn's view that in the history of science the ontology of a prevailing theory assumes institutional status. It seems likely that Popper was led to think of the aim of science in institutional terms in reaction to Kuhn's views. Kuhn's thesis that the prevailing theory or paradigm assumes institutional status means that the ontology of the prevailing paradigm functions as the criterion for scientific criticism, and that therefore commonly recognized revolutionary developments in the history of science, which introduce a new theory and ontology into a science, must be viewed as institutional changes with no larger framework providing continuity.

In Popper's view this radical discontinuity is historical-relativist and irrational. In his "Rationality of Scientific Revolutions" he quotes Trotsky, saying that the growth of science is "revolution in permanence", but Popper intends this phrase to mean that there exists criteria for scientific criticism that are invariant through even the most revolutionary developments that make scientific change rational and meaningfully progressive. Thus the force of Popper's statement that the growth of objective scientific knowledge is a social institution is that the objective nature of science makes revolutionary scientific change occur within an enduring set of institutional value standards, instead of a breakdown of the institution. The criteria for scientific criticism that operate as the institutional values of the scientific community are in Popper's view independent of the semantics and ontology of the prevailing theory or paradigm. As he says in "Normal Science and Its Dangers" in *Criticism and the Growth of Knowledge*, science is "subjectless". In his 1982 "Introductory Comments" to *Quantum Theory and the Schism in Physics* Popper compares his idea of metaphysical research programmes to Kuhn's idea of paradigms, but nevertheless maintains that metaphysical research programmes can be rationally reconstructed and rationally criticized, even though they cannot yet be empirically tested.

***Scientific Discovery***

Popper's rejection of the naturalistic theory of meaning had the unfortunate consequence of leading him to exclude consideration of the topic of scientific discovery from philosophy of science. He viewed philosophy of science as entirely a matter of logic and objective knowledge, while he believes that the topic of scientific discovery is exclusively a psychological and therefore subjective matter. The conjectures resulting from the discovery process belong to world 3, but the discovery process itself belongs to world 2, and events in world 2 cannot determine the contents of world 3. While this view offers very adequate recognition to the freedom in the creative discovery process, it also relegates a whole area of interest for philosophers to the empirical studies of the psychologists. And as it happens, the topic of discovery has become a central concern of the emerging specialty of cognitive psychology, although Popper would reject the cognitive psychologists' explicit psychologism.

Popper's exclusion of discovery is perhaps due also to his identification of traditional discussions of discovery with the "logic" of induction. When he rejects inductive logic, he therefore rejects all logic from the discovery process. He later modified this view, when he explained what he would admit to be possible with an "induction machine." Considering the work done by contemporary information scientists working in what is generically called "artificial intelligence" Popper's later statements are more plausible. Up to the present time at least, these information scientists would find it difficult to deny that the discovery system user must firstly conceptualize the input to the system. The discovery systems are not unconditioned much less historicist, and must draw from the current discourse of the science under investigation to develop state descriptions containing their input language. Thus an alternative to psychologistic analysis is linguistic analysis, which has been characteristic of twentieth-century philosophy. And linguistic analysis using mechanized generative grammars enables discovery.

## Comment and Conclusion

Popper's philosophy was occasioned by Einstein's development of relativity theory, a milestone episode in the history of science that Popper took to be paradigmatic of scientific progress. And Popper's philosophy is also a milestone in the history of philosophy, because it represents a fundamental problem shift. While Carnap and other positivists continued their efforts to establish theoretical science including Einstein's theory, on firm semantical and ontological foundations, Popper rejected the naturalistic theory of meaning that supposedly supplies such a foundation, and accepted the revision of scientific explanation as a matter of course. Positivist foundational problems, such as the problem of the meaningfulness of theoretical terms, became pseudo problems or what Heisenberg called "false questions" as a result of Popper's problem shift, while the problem addressed by Popper, the rational growth of science without foundations, has become central to philosophy of science.

Popper's philosophy was not occasioned by the development of the modern quantum theory, and he spent much of his professional career attempting to reconcile his philosophy and the modern quantum theory. It may be said that just as Carnap had attempted to reconcile positivism and Einstein's relativity theory, Popper had attempted to reconcile his philosophy and the new quantum theory, except that Popper also presumed to revise the semantical interpretation of quantum theory. In the meanwhile the pragmatist philosophers have taken up a rôle relative to quantum physics, accepting it as the paradigm of modern physics, that Popper had taken up relative to Einstein's relativity theory. As a result Popper's philosophy now represents the conservative position in the contemporary professional literature of philosophy, a position that casts him in the rôle of more the defensive rearguard than the aggressive vanguard he had been.

One of the distinctive aspects of the historical development of quantum theory is the persistent plurality of semantical and ontological interpretations compatible with both the same experimental measurements and mathematical formalism. This plurality has caused lengthy controversies among the physicists; Landé's list of seven alternative interpretations may be taken as indicative of this plurality. Popper's response to this situation in modern microphysics was to create still another interpretation for the quantum theory, his particle-propensity interpretation, because like Einstein he rejects the schism in physics and believes that a uniform ontology for both microphysics and macrophysics is imperative.

The history of physics has since evolved differently than Popper had imagined. Since the 1990's there has been a successful replacement of the traditional language with its classical concepts by a new language, which is better adapted to the mathematics of quantum theory. In his *Understanding Quantum Mechanics* Princeton University physicist Roland Omnès reports that recent conceptual developments using the Hilbertian framework have enabled all the features of classical physics to be derived directly from Copenhagen quantum physics. And he says that this mathematics of quantum mechanics is a "universal language of interpretation" for both microphysical and macrophysical description. This deductive relationship has not only resolved Heisenberg's "everyday" language, but because it is deductive, it has even further resolved the vagueness in the semantics of the vocabulary in both macrophysics and microphysics.

The pragmatists reacted differently than Popper. For them the quantum theory is the paradigmatic episode in the history of science, and their more accepting attitude has occasioned another problem shift in philosophy of science. While some pragmatists express reason to advocate one or another particular interpretation of quantum theory as distinctively interesting from the viewpoint of philosophy of science, the reason is not the particular philosopher's prior ontological commitments. Rather it often proceeds from a belief in the importance of the particular interpretation for scientific discovery. As Hanson noted at the opening of his *Patterns of Scientific Discovery*, the issue for physics affects the strategies for future research. (Discovery, remember, is the topic that Popper did not consider even being a part of philosophy of science). The focus on the problem of scientific discovery has in turn occasioned the problem shift: philosophers have reconsidered the semantical and ontological pluralism represented by the different interpretations of quantum theory. They have concluded that the pluralism is an inevitable outcome of the empirical underdetermination of language, and that it is therefore a strategic condition for continuing the growth of science. (Growth is the topic that Popper considered being central to philosophy of science). In brief – Popper's approach is to attempt to adjust the semantics and ontology of quantum physics to his philosophy of science, while the pragmatists' approach has been to attempt to adjust philosophy of science to account for the phenomenon of semantical and ontological pluralism in science and to identify its function.

As it happens, Popper's rejection of the naturalistic theory of meaning supplied the pragmatist philosophers with the point of departure for addressing this phenomenon of semantical pluralism, and they did so in ways that Popper did not accept. The philosophical view that affirms an artifactual character of the relativized semantics of language admits to a wholistic variation that introduces an unresolvable cultural and historical relativism into science, which in turn makes problematic the intersubjective objectivity and rationality that Popper considers to be necessary for the growth of science. Popper recognized the philosophical views of the historian of science, Thomas Kuhn, as paradigmatic of this semantical wholism. The affirmation of this wholistic variation and its consequent ambiguity is occasioned by the thesis that scientific change involves semantical change. Popper's philosophy does not address the problem of semantical change, because he identifies all attempts at semantical description or "meaning analysis" with disreputable essentialism. As a result contemporary philosophers of science have moved on to new problems that Popper was unprepared and unwilling to address. More importantly neither Popper nor pragmatists such as Hanson, Kuhn or Feyerabend had any concept of componential semantics as an alternative to wholism.

Finally some comments are in order about Popper and the positivists' truth-functional logic. In addition to criticizing the logical positivists for their positivism, Popper also refrained from using their favorite logic, the Russellian symbolic logic. This logic is called a truth-functional logic, because the truth value of any compound statement, such as a conditional "material implication", can be determined by reference to the truth-values of its component elementary statements. Therefore in the truth-functional logic the truth tables for all compound statements are complete for all combinations of truth-values of the component statements, thus enabling the symbolic logic to have the closure of an algebra, which is very desirable for a mathematical system including mathematical logic. Originally the agenda of the symbolic logicians was to make logic the foundation for mathematics. Ironically these Russellians had firstly to make logic into mathematics before they could make their symbolic logic a foundation of mathematics. In contrast the nontruth-functional conditional statement affirms the existence of a dependency connection between the truth-values of the antecedent and consequent clauses, such that the truth of the conditional compound statement is not determined merely by the truth-values of the component clauses for combinations of truth-values.

The affirmed dependency connection might for example be a logical one, as obtains between the premises and conclusion of the categorical syllogism. The conditional statement expressing a syllogism would have an antecedent clause consisting of the conjunction of the major and minor premises and a consequent consisting of the conclusion. As is well known, the conditional connection is the logical inference, which may be valid independently of the truth of its constituent statements – either in the conjunction of the premises in the antecedent clause or in the conclusion in the consequent clause. The logical inference may be invalid such that the conditional statement is false, while both of the premises in the antecedent and the conclusion are be true. Thus the conditional statement's connection is not truth-functional.

But of greater interest in philosophy of science are those cases in which the nontruth-functional connection is an empirical hypothesis affirming a causal connection instead of a logical connection. In the *modus tollens* form of argument, if the antecedent clause describing the initial conditions of a test is false, then the truth of the conditional statement expressing the tested theory is irrelevant or unknown, because the empirical test is not valid when it is not executed in accordance with its test design described in the antecedent clause. But if the antecedent is true, the test is valid, and if the test outcome is not a falsification, then the theory can reasonably be believed to be true for the time being, but its truth is not *logically* established. The truth condition of the nontruth-functional conditional statement is logically implied from the truth of its component statements only in the event of falsification.

Consider the stereotypic universal "Every raven is black", which Popper would consider a theory, since the statement is universal and because he considers all descriptive terms to be a type of theoretical term which the positivists called "disposition terms." Then re-express the universal categorical proposition as a conditional statement in the form of a material implication **A ⊃ B** of the Russellian predicate calculus:

**(x) (xRaven ⊃ xBlack).**

This is conventionally rendered in English as "For all ***x*,** if ***x*** is a raven, then ***x*** is black", or more colloquially as "For every entity, if the entity is a raven, then it is black." Popper's falsificationist thesis of scientific criticism requires a nontruth-functional logic in which only the falsehood of the universally quantified conditional can be determined from knowledge of the truth values of its component elementary statements. In this case the conditional is a hypothesis or theory proposed for empirical testing.

Thus the truth tables for truth-functional conditional and the corresponding nontruth-functional conditional logical forms are different. The Frege-Russellian "logistic" agenda to reduce mathematics to logic motivated the symbolic logicians to construct the truth-functional logic that is a closed mathematical algebra. Thus the irony noted above: the "logisticians" who wanted to make logic a foundation for mathematics firstly had to make their logic a branch of mathematics. The result misled many philosophers of science. The logical positivist philosophers had deluded themselves into thinking that they are very sophisticated and impressively technical by using the Russellian mathematical logic, and they exercised themselves with their favorite problem of the significance of so-called theoretical terms. The truth-functional truth table dictates that the truth of the antecedent and consequent atomic sentences can logically conclude to the truth of the material implication conditional expressing an empirical universal statement.

Yet these philosophical descendents from Hume eventually recognized that their Russellian conditionals are not eternal verities like their observation sentences. Nonetheless for decades the symbolic logic ostentatiously littered the pages of the *Philosophy of Science* and *British Journal of Philosophy of Science* journals with its chicken tracks, and rendered their ostensibly "technical" papers fit for the bottom of a birdcage. Finally even the lesser lights among the positivists came to recognize that the technical pretenses of the Russellian logic could not supply the façade of sophistication that had formerly masked its sophistic claim to be the logic for science, and the Russellian symbolic logic has largely fallen into disuse. Good riddance to bad rubbish!

 