Advantages and Disadvantages of Various Interpretations of the Quantum Theory

By Henry Margenau

JOSEPH HENRY'S genius was attracted primarily to the great experimental problems of his age. Although he was a professor of natural philosophy, a discipline which a century ago combined the various branches of physical science, he is not known to have indulged in the kind of formal considerations to which the title of this evening's discourse alludes. Yet I am confident that my subject is not wholly inappropriate to the occasion of a lecture in honor of Joseph Henry. For his eminent biographer, Charles Greeley Abbot, describes him as "a man of varied culture, of large breadth and liberality of views, of generous impulses and of great gentleness and courtesy of manner". Hence, while the speculations on which I am about to embark can hardly aspire to honor his memory, we may take comfort in supposing that he would gracefully listen to them and accept them as a small token of respect.

Questions as to fundamental meanings have accompanied the development of the quantum theory from the beginning. They appeared in the controversy over the wave-particle dualism, in the problem of observability posed by Heisenberg's matrix mechanics, in the early pilot wave conjunctures of de Broglie, in the complementary principle of Bohr. They have been revived by the recent publications of Bohm, de Broglie, Vigier, and Weizel. It is the attempts of these latter authors which I should like to appraise in simple philosophic terms.

Contrary to wide-spread belief, the problem in question is not difficult to conceive or to explain. I shall endeavor to present it in its basic features, shunning the artifacts of mathematics which often serve to becloud the scene. The details, it is true, can hardly be treated without analysis. But the details are not in doubt; the controversy concerns their interpretation. It is therefore proper to select for study the simplest possible instances of quantum mechanical reasoning and examine their bearing upon the issues of the present debate.

The first example I propose is the motion of a firefly in a dark summer night. To the eye, the motion of this insect is not continuous; what it presents is a succession of bright spots or streaks at different places in our field of view. The judgment that this phenomenon represents the uninterrupted passage of an object from one point of space to another is based, strictly speaking, on an interpolation between the bursts of luminosity that are actually perceived. Yet common sense, and indeed scientific description, regard themselves fully justified in performing that ideal supplementation of immediate perception which the interpretation of these sporadic darts as continuous motion demands. The chief reasons for this attitude are the following.

First, the hypothesis of continuous motion is testable through other experience. It is possible to watch the firefly in the daytime, when its progression from point to point becomes visible. This settles the issue in large part, although it may not convince the inverterate sceptic who feels that, when unilluminated, the firefly behaves like the angels to whom St. Thomas attributed the ability of emerging at separate points without having to traverse the intervening distance. To answer the sceptic, we must demonstrate the simplicity and convenience of the continuity hypothesis. Thus we add, to the fact of partial testability, a second item of evidence of a more rational sort, namely the simplicity of the geometric curve on which the luminous dots are situated. If the interpolated path were very irregular, showed unlikely curvatures and strange convolutions, doubts as to continuity might remain; the smoothness of the plotted trajectory goes a long way toward removing them.

The validity of every scientific theory, even the simplest, rests ultimately on two kinds of evidence: (1) empirical verifiability of some of its consequences, and (2) rational coherence, economy of thought, or simplicity conveyed by the ideas composing the theory.

Atomic entities, like electrons, present phenomena which, on the purely empirical side, are not unlike the sporadic emergences of a lightning bug at night. To be sure, the electron in an atom cannot be seen. Nevertheless if the results of experiments and observations using the refined techniques of modern physics can be trusted, an electron in what is called a Bohr orbit reveals its position as a random set of points located throughout a region of space in the neighborhood of the classical orbit. More precisely, if a series of position measurements were made while the electron is in the unvarying state known as the ground state of the hydrogen atom, the results would form a probability aggregate of known spatial distribution; the individual positions thus established would dot this region in a curious manner, offering no immediate suggestion as to continuity of motion.

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Thus the question naturally arises: can we regularize those emergences by the same principles which we employed in concluding that the path of the lightning bug was continuous? Or do we confront here a situation calling for entirely different treatment?

Unfortunately, the road leading to empirical verification of the continuity hypothesis is blocked, not merely by incidental obstacles arising from imperfections of measurement or observation, but by infelicities of a fundamental kind. The electron is intrinsically too small to be seen; the act of vision, even if it were possible, requires a time too long for a clear ascertainment of instantaneous positions; last but not least important is the fact that elementary particles are promiscuous entities with a perversity which prevents us from ever being sure that we see the same individual in different observations. If these difficulties seem inessential, if hope still remains that they may be overcome in the future, then we need to remember that their denial contradicts the basic tenets of the quantum theory, the only theory capable of explaining what can in fact be observed about electrons. The conclusion is inescapable: there is no daytime in which the electron's path could be watched.

Let us therefore examine the continuity interpretation from the point of view of simplicity or economy of thought. Here we encounter another failure. A curve drawn through the measured points becomes complicated and aimless, wandering in erratic fashion, with no preference for connecting neighbors, a curve intertwining and crossing itself in obvious labor to accommodate the positions of the particle. Certainly, nothing is gained in ease of conception, in plausibility, or in power of prediction by this familiar artifact.

Thus it is seen that the physical microcosm, the atomic realm, confronts the physicist with a novel kind of problem in interpretation, with a challenge to simplify or rationalize perhaps in ways to which he is not accustomed. And nature is not generous in providing hints for the solution of this methodological puzzle; the difficulties of direct verification we have already noted are so great that theories cannot be readily exposed to test. The sphinx is noncommittal. The physicist has an embarrassing amount of freedom in making his interpretations.

And how happily would he welcome the logical experts on "theory construction", the men who have put scientific procedure in pigeon holes, to whom the facts suggest inductively an hypothesis with computable probability. Here is a place where the principles of theory construction could be tried in vitro, with benefit for science itself. But nothing seems to be happening to relieve the suspicion that there are no recipes for constructing successful theories, that the creative act in factual discovery as well as in theoretical interpretation refuses to be codified. Let us return, then, to the physics of the situation and examine the proposals in terms of which the antics of the electronic lightning bug have thus far been rationalized.

1. The Mechanistic Thesis

THERE are three distinguishable views with possible gradations between them. The first of them, which I have somewhat bluntly called mechanistic, is a continuation of time-honored procedures in classical physics or, in the eyes of its opponents, an obsolete hangover from an unenlightened past. It persists in portraying phenomena continuously in time and space despite the difficulties we have noted; it goes on using visual models where vision palpably fails. It reaffirms the convictions of a number of famous nineteenth century scientists (Maxwell, Kirchhoff) who saw the aim of all science in the discovery of models which allow an understanding of phenomena by their interactions in time and space. De Broglie, one of the foremost advocates of this school, identifies pictorability in time and space with "clarté Cartésien".

The word "mechanistic" is literally applicable only to the simplest variety of space-time interpretations; others are more refined and complex, introduce nonmechanical agencies like fields, both three- and many-dimensional, but continue to avow the real existence of specific world lines, of detailed trajectories in a continuous space-time manifold. These latter formulations, which include the theories of de Broglie and Bohm, might be called quasi-mechanistic; in a deep philosophic sense however they are related to the others and I shall not hesitate to deal with them as special versions of the mechanistic thesis. Our attention must thus be directed, under this heading, to two related attempts at explanation, one simple and the other more refined.

The simple one sees the cause for the firefly behavior of electrons in the havoc wrought by the measuring process. It holds that the electron has a perfectly determinate position at all times, but this position is disturbed by the photon which, on being reflected, carries to the eye or to the measuring device the information where the electron was. The photon imparts to the electron a recoil which in consequence makes the position of the latter object uncertain. It will be recalled that all early explanations of the uncertainty principle invoked mechanical processes of this kind: transfer of momentum, or energy, scattering, lack of temporal precision of the measuring act with consequent uncertainty in the position of the observed object. Furthermore, if the particle aspect did not yield a convincing demonstration of uncertainty, there was always the wave nature of electrons to be drawn upon for further evidence.

The inherent plausibility of this reasoning is strengthened by the circumstance that it shows why atomic particles are erratic and the objects of our daily lives are not. A single photon represents a negligible disturbance when it impinges on bodies of ordinary size, but is a very energetic and disarranging missile when fired upon the miniscule electron. And the quantum theory shows that its energy cannot be made arbitrarily small, its amount being fixed at $h\nu$.

Why, then, does this simple explanation fail to command universal acceptance? Its shortcomings are fairly impressive: In the first place there *are* unquantized missiles such as other particles, for which the last preceding argument does not hold. Secondly, it is hard to see why the measuring disturbance should destroy the state *before* the measurement, why it should not convey information as to what the electron's position was prior to the act of collision. An operation can effect a successful diagnosis of a disease even if it kills the patient! Finally, to extend the criticism, it is possible to show that the uncertainty principle, which we may look upon as a quantitative expression of the erratic behavior in question, is a consequence of the basic laws of quantum mechanics and makes no direct reference to the destructive effects of measurements.

None of these objections, however, is entirely conclusive; they are merely irritating and can be removed by clever reasoning, chiefly by a skillful use of the so-called wave-particle dualism. But the major blow to the simple mechanistic view comes from the realization that, even if it is adopted, it provides no opportunity for *calculating* or *predicting* the mysterious disturbances that confuse the otherwise clean trajectories. It asserts their presence and resigns. It forms an idle embellishment of the facts and yields, perhaps, esthetic, not scientific or philosophic, satisfaction.

The refined version of the mechanistic thesis promulgated by de Broglie, Bohm and Vigier is largely immune to such elementary criticisms. It is far more explicit and does an analytically competent job of interpreting the fundamental equations of quantum mechanics. It seizes upon a well-known connection between the Hamilton-Jacobi equation of classical physics and the Schrödinger equation, splits the latter into a pair of real equations, one of which can be used to define a path for the electron. This path is disturbed, not by interfering measurements, but by a nonclassical field arising from the presence of the electron itself. When a measurement is actually performed, this somewhat mysterious field, in conjunction with the measuring instrument, brings about the emergence of the particle at the place of registration.

Admittedly, such reasoning is complicated and, because of its appeal to an unorthodox and special kind of field, perhaps in need of treatment by Occam's razor. But the formal structure of the theory is without flaws, and it is developing, chiefly through the work of Bohm, into an amazingly consistent formalism. de Broglie, it is true, takes exception to the latest forms of it, but on grounds of extra-scientific convictions and of the lack of plausibility of the quantum field. Briefly, his objections are these.

(a) According to Bohm's interpretation, an electron in an S-state does not move, thus contradicting a notion familiar in physics since the days of the Bohr theory.

(b) The state function (ψ) cannot represent physical reality because it is complex, and it extends in configuration space of many dimensions, not in ordinary space. (This argument can be met by supposing that the forces conveyed by the nonclassical field are complicated many-body forces.)

(c) Finally, de Broglie points out, the physical act called measurement is turned into a mystery, for it involves a sudden, infinitely rapid collapse of the ψ-field, which before the measurement filled all space, upon the immediate locus of the electron.

This is not the place to examine the soundness of the foregoing strictures; some of them have plagued quantum mechanics from its beginning and apply to other interpretations as well. The last point, which adverts to the sudden disappearance of the ψ-field upon measurement, is often made and presents in my opinion an unsurmountable difficulty to every mechanistic interpretation of quantum mechanics. But more of this later. Let it be noted for the present that the controversy involves no questions of empirical fact and that the view here outlined is perfectly tenable in the face of what is now established scientific knowledge.

Before turning to another doctrine I should like to say why I did not follow the custom of calling the interpretation here under review a *causal* one. That adjective is correct but not discriminating, for there is another type of description, outlined in section 3, which in a certain sense is causal too. What characterizes Bohm's ideas is a narrowly mechanistic form of causality, not causality in its widest scope.

2. The Formalistic Thesis

MANY a modern scientist will question the wisdom of indulging in considerations as speculative as the preceding, may even doubt that they have meaning. He will ask: do we not have a formal theory satisfactory for making valid predictions about things that matter? Why bother about interpretations beyond necessity? This positivistic attitude takes what is good and useful in modern theory, systematizes it as well as possible, and does not feel the pangs of conscience that afflict the tenderhearted metaphysician. The view sympathetic to it may be sketched as follows.

It takes the vagaries of the electron as facts. If pressed, it regards them as symptoms of disturbances by measuring devices but grants that every attempt to predict them or to understand them in detail is useless and in need of discouragement. *Particles have positions in space and time under all circumstances,* but atomic nature is so constituted that we often cannot know them. Because of this, a single measurement of position —or in general of any observable attribute—cannot function as the basis of a precise and valid prediction.

To make some sort of prediction possible the physicist introduces his ψ-functions, which are essentially measures of information. Being incomplete as carriers of information, these functions permit only statistical predictions concerning aggregates of future events. Individual events, though always embedded in continuous temporal and spatial sequences, thus lose their effectiveness as causal agents in the physical world. To restore causality in a statistical sense, another description is required, a description in terms of ψ-functions, which are often waves. The universe of happenings is thus divided into two separable strands of development, one consisting of events in space-time with real but unknowable connections between them and devoid of causal nexus, the other a ghostlike space-time manifold of causally evolving states whose relation to observable events is but statistical.

The square of ψ in this interpretation, as in all others, represents a probability; but here a probability of a rather special kind. As is well known, probabilities are sometimes regarded as subjective measures of knowledge or belief, sometimes as objective frequencies (or limits of frequencies). Subjective probabilities change discontinuously with evidence, the others do not. Thus, for example, before a die is thrown, the subjective probability of the appearance of a five is 1/6. After a throw it is either 0 or 1. The objective probability is 1/6 at all times, for the frequency always refers to a large aggregate of throws and is unaltered by a single event. The formalistic view, insofar as it has become explicit on this issue, adopts the subjective meaning of probability. It assumes, for instance, that the ψ-function suddenly collapses from a field-like distribution throughout space to a small, point-like residue at the instant of a measurement.

Bohr's authority stands impressively behind this doctrine. He speaks of it as the principle of complementarity and regards it as the final form of physical analysis. The two modes of describing our experience, irreconcilable in man's mind, are the best we can achieve; the dualism they imply is here to stay. It stands as a memento to the fundamental truth that, in exploring nature, we become disturbing (or, if you will, creative) agents and thereby alter what would otherwise have been the case.

This view, appealing because of its candor and its seeming modesty, is espoused in its essence by the majority of physicists. To acknowledge the dualism has many soothing advantages, as every other form of dualism does. It relieves its advocates of the need to bridge a chasm in understanding by declaring that chasm to be unbridgeable and perennial; it legislates a difficulty into a norm. It is little wonder, therefore, that philosophers at times feel ill at ease when studying this solution of a dilemma, a solution which pays its respects to both horns. But the reward for this accomplishment is quite considerable: it gives the physicist a powerful philosophic tool. Clearly, if the most fundamental of all sciences has to accept complementarity, is it not natural that bifurcation should also pervade the lesser realms? Are not the mind-body problem, the conflict between values and fact, between freedom and necessity, mere manifestations of complementarity?

I fear that my own lack of sympathy with these extrapolations of the formalistic thesis has been ill concealed. Bohr's own cautious formulation does not suffer from such indiscretions. Yet it does commit physics to a dualism which is neither simple nor illuminating.

3. A Third Interpretation

IT is possible to avoid the dualism by an interpretation which is philosophically more radical and more profound, a view that asks for a surrender of certain familiar habits of thought and a few cherished conceptions. To many, this price seems too high. I shall try to make this thesis as reasonable as possible, for it is the one which in view of all present evidence I find most congenial.

Why not simply deny that the electron has a position at all times? The real firefly partakes of "simple location", to use Whitehead's phrase, for the reasons we have mentioned: its path can be directly inspected and the use of continuous interpolation between uninspected points leads to a simple and reasonable theoretical account. Neither is true for the electronic lightning bug! Of course one feels, initially, that somehow the electron must have a position, that position is an essential property of real material things. But this is clearly an example of accepting what Whitehead calls the fallacy of simple location. As we learn more and more about the world, we are asked to sacrifice in increasing measure the facile and picturesque presumptions of what we call so ineptly "common sense". It was common sense that argued that all physical entities, to be real, must occupy space; must have color even if they are smaller than a wavelength of visible light; must have definite shapes even if invisible; it was common sense that said the universe must be Euclidean, simultaneity must be absolute, and there must be an ether. The present situation, it seems, demands the courage and the modesty to disavow common sense; courage in the sense of D'Alembert's admonition, Allez en avant, la foi vous viendra!; and humility to grant that knowledge in one domain does not render us wise enough to foretell another.

In the spirit of these injunctions we ought perhaps to admit that position—and with it many other observables—is undergoing the fate that befell the idea of color: it is not generally applicable to things that are too small or too elusive to be seen. Nor is it proper to ask whether such objects are particles or waves; the very denial of the unrestricted meaningfulness of the concepts position, size, etc., prevents it from being answered. Note, however, that this acknowledgement does not destroy our right to affirm the electron's presence as an objective component of reality. For it merely substitutes certain abstract qualities for those we deemed obvious and immediate; it substitutes mathematical models for mechanical ones. Logically, there is no reason why the character of an entity should be described by a visual image rather than a Hamiltonian.

The view in question is the culmination of a philosophic development of long standing. Galileo introduced the distinction between primary and secondary qualities, Locke and Descartes employed it significantly in their own philosophies. Primary qualities are those which are resident within their object; they are inalienable from it and make up its essence. Secondary qualities arise in the act of perception, are subjective in the simple sense of that word and are therefore less certain. To many of us, size, mass, atomic structure are primary qualities of a material body, whereas heaviness, color, temperature are secondary. But the very recital of such specific examples already tends to be embarrassing, and I for one would not care to defend the assertion that mass is primary and temperature secondary. Yet in early Greek philosophy, Anaxagoras thought it perfectly plausible to assign to his "elements" (homeomerics) the intrinsic property of taste.

Even this superficial account suggests what has in fact taken place throughout the history of natural philosophy. Primary qualities, first posited and affirmed with innocence and scientific blissfulness, engaged in a continual retreat before the onslaught of science. One after another of them was converted into a secondary quality, until today we are wondering whether perhaps the distinction is illusory, whether perhaps all qualities are secondary.

To sharpen this issue, I propose a shift of attention. The distinction between primary and secondary qualities is indeed of lesser interest today and may be regarded as settled, as Jeans believes. But though it be dead, its ghost is still very much alive and amongst us. The contrast, or at any rate the difference, is now between what I have called elsewhere *possessed* and *latent* observables. Possessed are those, like mass and charge of an electron, whose values are "intrinsic", do not vary except in a continuous manner, as for example the mass does with changing velocity. The others are quantized, have eigenvalues, are subject to the uncertainty principle, manifest themselves as clearly present only upon measurement. I believe they are "not always there", that they take on *values* when an act of measurement, a perception, forces them out of indiscriminacy or latency. If this notion seems grotesque, let it be remembered that other sciences, indeed common sense, employ it widely. Happiness, equanimity are observable qualities of man, but they are *latent* qualities which need not be present at all times; they, too, can spring into being or be destroyed by an act of inquiry, a psychological measurement. The third interpretation regards the position of the electronic lightning bug as a latent observable.

It is less committal than the others. For clearly, if the electron did have a determinate position at all times and we could not possibly know it, this view would still stand aright. Likewise, it is compatible with, though again less committal than, the appeal to measurement as bringing about this latency. Perhaps it is an instrumental disturbance that does it, perhaps—and I should favor this conjecture—there is an irreducible haziness in the very essence of perceived phenomena of which Planck's constant h is the quantitative expression. It may be that this latency affects even the identity of an electron, that the electron is not the same entity with equal intrinsic observables at different times. The suggestiveness of the hypothesis is evident, and with it the danger of mysticism. When the view is shorn of its extraneous implications, it avers that the electron *is* where it is measured, that it may be nowhere when it is not measured, that a measurement, properly contrived, may cause it to appear somewhere. The advocate of this view is not entitled to speculate about real trajectories, to follow his mechanistic propensity of picturing the motion of an atomic particle accurately in space and time (except as an approximation). We thereby cut off one horn of the complementarity dilemma and take as the only valid description of reality the ψ-function formulation. Before seeing what that entails, let me insert another word about the difference between possessed and latent observables, a speculative word.

I believe that this contrast, like that between primary and secondary qualities, will ultimately be resolved in favor of the latent observables; that is, the representation of physical observables in terms of operators rather than c-numbers is probably fundamental, and we shall perhaps find suitable operators for charges and masses as we have for positions, momenta, energies, spins and all the rest. The fact that under certain conditions quantization, uncertainty and latency seem to be absent, as in the large-scale world, is guaranteed by Bohr's correspondence principle, which is not a special postulate but can be derived from the axioms of quantum mechanics.

Now, in what sense can the shadowy ψ-functions of the Schrödinger equation be real? Let us translate the question into the familiar terms of the lightning bug phenomenon. The ψ-function, when squared, represents the probability that a speck of luminosity will appear in a specified volume under scrutiny, or, still less technically, the number of times I see a speck divided by the number of times I have looked. There is nothing vague or tentative about such probabilities; they are numbers obtainable by observations just like those which describe all other physical fields. The only difference is that a probability number requires numerous observations in order to be established, whereas an electric field strength can in principle be determined by a single observation. In practice, however, the physicist is able to perform his set of observations in a single act because he has available a large number of similar atomic systems. For example, a single illumination of hydrogen atoms by an x-ray beam produces a pattern on a photographic plate from which the probabilities of position for an electron can be inferred. Hence even the one methodological distinction between a probability field and other fields is largely academic.

Yet physicists, mindful of earlier theories which used probabilities only *à faute de mieux,* have come to associate with them a flavor of ignorance, a mental quality; they often regard them as subjective appraisals of a situation not completely understood, or as intrusions of metaphysics into the objective scheme of things. There are many signs on the horizons of modern science which belie this view, interesting new developments in mathematics, statistical mechanics and information theory that lie beyond the scope of this account. Hence one may well regard the denial of real status and fundamental importance to probabilities, which is so characteristic of classical physics, as an outmoded attitude. This leads me to suggest that we grant consciously to probability the function which in fact it already assumes: to serve as the basic determinant of experiences in a real world.

After all, there is nothing illogical in the seemingly grotesque conception of probabilities flying about in space! Their relation to observational experience is certainly no more remote than the connection between a light wave and its visual manifestation, or indeed between the observed emission of a beta-ray and a neutrino field. Nor does it put any strain upon common sense in the world at large, for the correspondence principle converts all probabilities referring to ordinary objects into δ-functions (i.e. point-like concentrations at the place where the object is conceived to be), and there is no difference between probabilities flying through space in the form of δ-functions and classical objects!

This third interpretation is simple as a philosophic doctrine, monistic by virtue of its rejection of detailed particle trajectories, objective because it takes its probabilities as measurable fields and not as indexes of knowledge or belief; unfortunately, however, it demands a maximum departure from familiar lines of thought. I have chosen not to name this view because it is difficult to label in a simple way. V. F. Lenzen (*Causality in Natural Science,* Charles C. Thomas, 1954) calls it the objective view because it ascribes objective reality to probabilities. This terminology seems to me very appropriate.

On what grounds are we to judge these three interpretations? Is the final verdict as to their validity a matter of personal taste? The state of affairs here is quite different from what it ordinarily is in science, no crucial experiment being available for discrimination. In such cases recourse can and must be taken to the principles of scientific methodology, for in the last analysis these provide the criteria which every good scientific theory must satisfy. I shall therefore give a brief review of these principles.

4. Methodology of Science

SCIENCE serves to make reasonable or understandable as large as possible a portion of our experience. Certain parts of experience, like fleeting sensations, unrelated perceptions and observations, are in themselves devoid of rational order. Science strives to make them coherent, not so much in their direct setting, but by carefully associating with them specific ideal structures sometimes called concepts or constructs, and by endeavoring to reproduce among these meaningfully related structures the perceptory sequence of immediate facts. Permit me, to avoid circumlocutions, to state the essence of scientific method in somewhat arbitrary but pictorial terms (cf. *The Nature of Physical Reality*, McGraw-Hill, 1950).

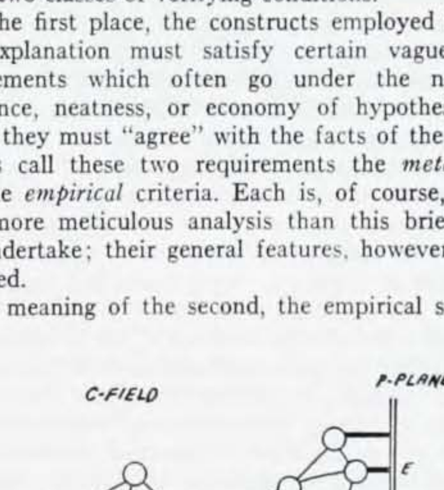
The figure represents what one might call a section of our (cognitive) experience. Its limit is the P-plane (P for "perception" or "protocol" [public record]), the locus of immediate perceptions, observations, data or anything else we deem incontrovertible. It is in a sense a boundary of our experience, because we do not go beyond it to anything more ultimate in science as such. To the left of the P-plane extends a vast domain pervaded, as it were, by rational texture. It is the field of concepts or constructs (C-field), populated by originally ideal entities which habit, plausibility considerations or outright postulation has associated with the data on the P-plane. The linkages between the P-elements and the C-elements will be called rules of correspondence.

Under certain conditions, to be outlined presently, the constructs take on scientific validity, assume an approved status as real entities in the world or, as I shall briefly say, become verifacts. In popular, ontological language, these verifacts "exist".

It is clearly of prime importance to know the criteria under which the transformation from the tentative character of a construct to the approved state of a verifact takes place. These criteria may be found, not in speculative conjectures about first principles or rules of thought, but through a study of the actual procedures in historical science. Such a study, it seems to me, yields two classes of verifying conditions.

In the first place, the constructs employed in scientific explanation must satisfy certain vague formal requirements which often go under the names of coherence, neatness, or economy of hypotheses. Secondly, they must "agree" with the facts of the P-plane. Let us call these two requirements the *metaphysical* and the *empirical* criteria. Each is, of course, in need of a more meticulous analysis than this brief survey can undertake; their general features, however, can be sketched.

The meaning of the second, the empirical set of re-



Constructs (designated by circles) are connected by formal relations (light lines) to one another; some are linked by *rules of correspondence*, which usually are operational definitions, to the plane of perception (P-plane). Metaphysical requirements regulate the C-field; verified sets of connected constructs, i.e., accepted theories, can be traversed by circuits of empirical confirmation, one of which is drawn as E.

quirements, is illustrated by the line E, which starts on the P-plane, moves via rules of correspondence to the C-field and finally returns to P. It represents a typical *circuit* of empirical verification. Some observations (like Newton's falling apple) suggest constructs (mass, acceleration, force of gravitation) which, when combined in accordance with theoretical rules applying to these constructs, allow a return to the P-plane at some other place (motion of the moon). Thus, on the basis of some initial facts, a prediction of other facts has been made. Circuits of this kind are extremely numerous, and each can be traversed in both directions. When a given set of constructs, a theory, has been crossed by a sufficient number of circuits like E, it is said to be empirically valid.

The metaphysical requirements are of another sort, for they do not relate to specific matters on the P-plane. Rather, they constitute ideal devices by means of which the a priori fitness of the constructs is appraised. No attempt will here be made to present them in their fullness. Let us rather discuss the three which are of greatest relevance to the interpretations of the quantum theory.

In the first instance, the constructs of a theory must be so chosen and connected as to permit continuous and uniquely determinable sequences of states. This is often called the postulate of *causality;* it is also regarded by many as differentiating between the mechanistic thesis which is said to obey it, and the other two interpretations which do not. The principle of causality in what seems to me to be its simplest and clearest form requires only this: that physical systems be described in terms of states which are self-unfolding in a determinate manner; that the state of a system at time t be sufficient for a prediction of the state (i.e. the values of the same crucial variables) at any other time t'. The principle does not spell out what these states must be, leaving mechanics free to operate with positions and momenta of particles, electrodynamics to use field variables, hydrodynamics to use pressures and velocities at points. Nor does it discriminate against the use of ψ-functions in quantum mechanics. And these ψ-functions are elements of a causal description whether ψ refers to an ensemble of trajectories as in Bohm's interpretation; or whether it is the probability amplitude of a statistical ensemble. Only if the special mechanistic version of causality, the version which requires that prediction be based on *single* observations or *individual* events, is given unique and preeminent importance, does the third interpretation become noncausal. However, this narrow insistence does violence to a wider methodology of science and is difficult to justify.

Next among the three metaphysical requirements I have chosen to offer for consideration is *extensibility*. A theory must be extensible to a large domain of facts. Science prefers that one among rival theories which is applicable to the greatest number of phenomena. From this point of view Newton's theory of dynamics was preferable to Aristotle's, Maxwell's equations are preferable to theories of Faraday and Ampere, Einstein's general theory of gravitation is preferable to Newton's, the quantum theory to classical dynamics. The principle of extensibility (or extensiveness) itself is vague in logical contour; one cannot say in any given instance whether a theory is sufficiently extensive or not. Its power arises, as with all metaphysical principles, from the fact that the scientist is apparently always able to form an intuitive judgment with regard to sufficiency. Even more effectively can he use the principle in discriminating between competing theories.

Finally, there is the requirement of *simplicity*. Again, I do not feel the need for defining the exact meaning of simplicity, nor do other scientists who use this idea in their appraisal of theories. In practice, and certainly for our present purposes, its intention is clear, I am sure. Galileo's description of free fall was simpler than, say, Tartaglia's; Newton's theory of motion simpler than Aristotle's; Copernicus' astronomy simpler than Ptolemy's; the electromagnetic theory of light simpler than the late ether theories; the S-matrix approach in nuclear theory is simpler than the use of different nuclear potentials on different occasions, and so on. These requirements are felt in all disciplines given to careful thought: even philosophers prefer monism to pluralism because of its better accord with the requirements of extensibility and simplicity.

Having now come to the end of our sketch of the methodology of science, we are perhaps in better position to judge the advantages and disadvantages of the interpretations of quantum mechanics described in sections 1–3. It should be acknowledged, however, that the situation under study differs from those normally met in science, and presents unusual difficulties, because of the paucity of decisive data on the P-plane. For curiously, the *known* facts are explained by all three interpretations, and unknown facts crucial to one thesis and not to the others are extremely difficult to obtain. It is evident, therefore, that we are forced to place an abnormal reliance on the metaphysical principles. By and large, the circuits of empirical verification start at the same points on the P-plane and end at the same points in the three different interpretations. And where the mechanistic thesis does suggest possible discriminating observations, experience is noncommittal.

As a case in point I refer to a paper by Weizel (*Z. f. Phys.*: 134, 264: 1953). This author takes the mechanistic thesis seriously and considers what, in mechanical terms, Bohm's quantum mechanical field might be. He asks: what kind of physical entity, thus far undiscovered, could possibly interact with the invisible firefly in a manner producing its erratic appearances? It must be able to act on the firefly without suffering a reaction itself, and this is a difficult assignment. But Weizel does find a suitable mechanism which he calls a "zeron"; he visualizes it as a sort of jellyfish moving with the speed of light, yet able to absorb an electron if given momentum and to spew it forth again with the same momentum at another place. Needless to say, these zerons have not been found.

5. Assessment of Merits and Demerits

WE now bring the principles of method to bear upon the three interpretations, hoping to reach some verdict. Let us make sure that all the evidence has been heard. I have reason to think that many of you doubt this point and are disposed to say that I have packed the court against the interests of the mechanistic view. For I have said nothing about *pictorability* of constructs as a requirement for a good theory; I have placed an abstract notion, like entropy, field strength or probability, on a par with Rube Goldberg devices. Nothing has been said in favor of visual models. Is this fair?

To be sure, most of us find pictorable models like billiard balls or waves highly desirable and convenient; indeed we often use them in our reasoning when we know we should not. They are suggestive, conducive to clarity of thought. The reason is doubtless psychological: our sensory experience is strongly colored by our visual sense; people learn most easily by seeing. But it is also true that science has carried us very far beyond the range of vision, and to assume that pictures are useful where vision fails is wholly without logical cogency. On the other hand, physics uses nonpictorial elements with great success, as in electrodynamics. This sometimes fails to be recognized because physicists gain familiarity with E and H through use and then mistake what seems familiar for what is pictorable.

My own uneasiness about including pictorability in the list of metaphysical requirements arises from the intolerable way in which it contradicts or curtails both extensiveness and simplicity. If physics were to insist on it, its methods would not embrace the present procedures of Gestaltism and behaviorism in psychology, of social theories and economics. For such constructs as Gestalt, drive, habit, supply and demand have very little in the way of mechanistic pictorialness. This is my primary reason for omitting the (pseudo-) postulate in question.

A while ago I spoke of rendering a verdict; yet this is hardly what the occasion demands. We have seen that the scientific evidence is not complete and that only half the resources of scientific methodology, namely the metaphysical ones, can be drawn upon. Let us therefore temper our judgment with modesty and concede that part of it depends on taste. We are somewhat in the position of a literary critic evaluating three poems and cannot expect finality or general acceptance of our conclusions. Or, with greater optimism, we may consider ourselves in the position of a teacher who grades three themes, themes which he does not fully understand.

Here are the marks I would assign. On the score of causality, the mechanistic thesis gets a perfect mark; but the third interpretation ranks equally, for we have agreed not to discriminate unfairly between mechanical and statistical causation. The formalistic view renounces causality in its space-time description but retains it in the complementary ψ-field. Hence it would seem to merit half-credit on this score, i.e. five out of ten.

Extensibility seems equally great for the second and third interpretations. Bohr's complementarity finds application in many realms of thought; it has been acclaimed even by theologians as casting light on their problems (e.g., freedom of the will). The last view, which regards probabilities as irreducible and admits latent qualities, is very close to the thinking of psychologists, social scientists and modern statisticians. It too is compatible with the possibility of freedom though it provides no solution for it. The mechanistic thesis, on the other hand, is of use primarily in the physical sciences. Furthermore, it makes a paradox of human freedom. Hence a fair rating on the score of extensibility would seem to be: Mechanistic view 2, formalistic view 8, third view 8.

Finally we come to simplicity. Here it appears that the formalistic thesis scores very low, since it resigns itself to a dualistic explanation of nature. I would rate it 20%. The mechanistic thesis does not do much better because it encumbers the conceptual scene with ideas not needed in the third interpretation, which is the simplest of the three. To these two views I would assign, respectively, the marks 50% and 80%. The summary is given in Table I.

Table I

Score Based on Methodological Requirements of Theories

	Principle Interpretation		
	Mechanistic	Formalistic	Third
Causality	10	5	10
Extensibility	2	8	8
Simplicity	5	2	8
Total Score	17	15	26

The outcome of this test will be radically changed in favor of the mechanistic thesis if one or more of several possible contingencies occur. If Vigier, de Broglie, or Bohm succeed in their present endeavor to derive the equations for the quantum field from the principles of general relativity, I should change the mark of 2 on extensibility for that theory to 9. A similar or even greater improvement would result from success of the mechanistic interpretation to explain the puzzling features of nuclear physics or other now mysterious effects by reference to its novel field. Indeed, this would force the other theories to take on modifications and necessitate a rescoring in connection with simplicity as well.

Finally, and this seems most important, experiments might be performed which bring into evidence new physical entities giving verified status to those features of the mechanistic view that count most against it. The likelihood of such evidence for Weizel's zerons is low, but there are surely alternative models. When such discoveries are made the whole status of our problem is changed because advantage can then be taken of new circuits of empirical verification, and a complete reappraisal will be necessary.