CAN LIFE EXPLAIN QUANTUM MECHANICS?

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I would like to try, if not an entirely new path, at least a new detour in approaching the measurement problem in quantum mechanics, as well as the more general problem of how physical description is dependent on the epistemological interpretation of the *matter-symbol* relationship.

Quantum theory has proven to be exceptionally stable, as theories go, and resistant to 'going beyond' which is what the title of this symposium suggests we try to do. I would like to emphasize that my basic interest has not been the foundations of quantum mechanics, but the origin of life. I am looking for a clear physical reason why living matter is so manifestly different from lifeless matter in spite of the evidence that both living and lifeless matter obey the same set of physical laws. I would have been very happy to accept quantum theory as it exists, but the origin and nature of life is unavoidably dependent on the writing and reading of hereditary records at the single molecule level, and on the sharp distinction between the genetic description and the phenotypic construction processes. The physical meaning of a *recording process* in single molecules cannot be analysed without encountering the measurement problem in quantum mechanics, nor can the symbolic aspects of the genetic description be understood without an interpretation of the *matter-symbol* relation at an elementary physical level. In short, the physical distinction between living and non-living matter turns out, as one might reasonably have expected, to depend on the most fundamental physical and epistemological concepts.

The measurement problem as it has recently been attacked using ergodic principles to justify a quantum treatment of classical bodies, may indeed prove to be a helpful path (e.g., reference (5)). On the other hand, there still remains the problem of our apparently unavoidable primary dependence on classical concepts, and what Bohr, calls the 'ordinary language' in which we communicate about the process of measurement. We may perhaps make a simple classification of arguments over the foundations of quantum theory by dividing them according to the relative primacy attributed to the microscopic quantum description as opposed to the 'ordinary language' classical description. Toward one extreme, we have theories which assume the primacy of quantum mechanics and proceed to derive classical behaviour from the ergodic properties of quantum statistics. Toward the other extreme, we have the assumption that the conceptual world cannot be divorced from the way it actually appears to human observers and their measuring devices, and that quantum 'theory' is only a useful algorithm to be followed in certain microscopic situations, rather than a picture of the underlying reality.

I am well aware that my own contribution is not likely to 'solve' such a fundamental problem, especially after great efforts by the most competent physicists have failed to produce agreement. But my primary reason for attacking this problem, as I have said, is simply that I have not been able to avoid it in the context of life. It is because the problem of measurement reappeared entirely *independently* of ordinary physics that I believe there is a chance that this detour may add some insights to the basic difficulties.

Living matter behaves differently from non-living matter. I will put the problem of the origin of life as simply as possible for this discussion. Living matter is distinguished from non-living matter only by its *collective behaviour in the course of time*. We know from the detailed experiments of molecular biology that there is almost certainly no microscopic or short-time reaction or interaction within living cells which does not follow the laws of ordinary physics and chemistry. Many molecular biologists conclude from these experiments that life differs from non-life only because life is very complicated dynamically compared to ordinary physical systems. This may have some quantitative degree of truth, but what is qualitatively exceptional about living matter is not the complexity of the detailed dynamics but the time evolution of *constraints* which harness these motions to execute *simple* collective functions. We recognize this simplicity of function which integrates itself out of extremely complex detailed dynamics as the evolution of hierarchical control.[10] In other words, beginning with a common set of dynamical laws for the microscopic motions, we observe living matter evolving hierarchies of collective order, and non-living matter evolving a collective disorder. Even the 'true believer' in total reductionism must agree that this aspect of living matter is different from non-living matter. Unless this crucial difference is explained in terms of physical laws, no one can claim to have reduced life to physics. Therefore the essential question of the origin of life is to find a physical basis for this clear, empirical dichotomy in the behaviour of matter. In particular we may ask: *what is the simplest set of physical conditions that would allow matter to branch into two pathways—the living and lifeless—but under a single set of microscopic, dynamical laws?*

Events and records of events. It is clear that under infinitely precise initial conditions and strictly deterministic and complete laws of motion the concept of more or less order is meaningless. We know that disorder appears in physical systems only when we assume dispersion in the values of initial conditions or where the variables themselves are defined as statistical averages. These two modes of description of matter—the strictly deterministic and the statistical—provide already one type of 'branching' in physical systems. However, this branching is to a large degree a subjective matter depending on the amount of detail the observer chooses to take into account. In other words, this type of branching has its source in the modes of description used only by a highly evolved observer, and it is difficult to imagine this branching problem arising in the primæval molecules which originated life. We shall see, however, that the origin of records from a deterministic system must also involve a second mode of description. The problem is to first explain how statistical modes arise spontaneously, and second—the difficult part—to explain how the 'vital' statistical mode leads to increasing organization whereas the ordinary statistical description leads to increasing disorganization.

The epistemological position, which I shall assume in this discussion, is that the concept of probability is inseparable from the concept of *measurement* itself. In other words, whereas the idea of a strictly deterministic trajectory is an acceptable abstraction, the concept of an infinitely precise measurement is not. How do we justify this? Simply by the assertion that a measurement must be a *record* of an event and not the event itself. Consequently while a record of an event may be in error, it is unthinkable that the event could itself be in error. The evolution of disorder in collections of inanimate matter may therefore be attributed to the propagation of error in records of initial conditions. The equations of motion remain deterministic and reversible, but any *records* of initial conditions are probabilistic and lose their accuracy or significance irreversibly in the course of time. This concept of error in measurement has been carefully developed by Born [3] and Brillouin. [4]

If you accept loss of records as the source of increasing disorder in the course of time, then it is reasonable that increasing order in the course of time must require the accumulation of records. In biological terminology we describe the recording process as the accumulation of genetic information by natural selection. But this accumulation is now apparent only in highly evolved cells in complex ecosystems. The origin of life problem is to explain how this record accumulation began and why it can survive the universal tendency toward loss of records which occurs in non-living matter. What is the simplest physical system in which a persistent recording process constrains future events? By stating the origin of life problems in this way, it is clear that we need to know more precisely what we mean by the 'simplest recording process'.

What is a record? I believe we must follow the reasonable assumption that the first records were in single molecules, since that is the way they occur in modern cells. The essentially new condition in this origin of life formulation of the recording or measuring problem is that no human observer, no physicist, no philosopher, nor any macroscopic measuring instrument designed by biological organisms can exist in the beginning. We imagine only the motions and interactions of the elementary matter, so we can only ask, how does matter record its own behaviour without the intervention of a physicist. Or in other words: How does the motion of matter lead to *records* of these motions?

Someone will probably object that the observer has not really disappeared in this formulation, and that I have only hidden the observer by imagining the existence of an objective recording process which is operationally meaningless, since it is still the human observer who decides when a record has been made. Here I shall simply admit to being a realist, that is, a person who believes that there are aspects of the world which exist independent of this observer's description of the world. I must accept as a meaningful concept supported by empirical evidence that life did not always exist on the earth, and that it was the accumulation and transmission of hereditary records at the molecular level that eventually led, only after billions of years, to observers like myself. But I must therefore add—and this is the central point—that not only matter, but also *records* existed long before physicists started thinking about matter and making large measuring devices.

At first sight this origin of records problem may appear more difficult than the more familiar problem of how physicists now obtain records of elementary motions of matter; but I think this is an illusion created by our familiarity with highly evolved and abstract languages. In effect, all symbols are records in so far as they are marks which stand for something else. We express all our physical laws in terms of symbols without thinking at all about the *physical limits on symbols.* But even though we have evolved from the first recording process, which occurred some billions of years ago, we cannot use the mere passage of time to evade this circle of self-reference of the matter-symbol problem.

In fact, I believe that one source of our difficulties in clarifying fundamental epistemological questions such as the matter-symbol and measurement problems is that we usually start with the most complex evolved systems we know—namely, the symbolic systems created by the brain of man. Our symbolic languages are deceptive because they achieve great *functional* simplicity, like any highly evolved organ of the body, but only through many hierarchical levels of complex integrated dynamical constraints, achieved only after long periods of selective evolution. This is not only true for the externalized written forms of language but applies as well to all the complex internal biological constraints or boundary conditions which had to evolve before written language was possible. It is no wonder we are puzzled, since the symbols and records we talk about are removed from elementary physical systems by billions of years of biological evolution. This is a gap which we should not expect to bridge in one jump.

It is my central idea that the essence of the matter-symbol problem and the measurement or recording problem must appear at the origin of living matter. Symbols and records have existed since life existed. If this view is correct, then it is a more hopeful strategy to begin by asking what we mean by the *first* primitive record rather than question what we mean by our most sophisticated and abstract records. In effect, this strategy forces us to make an objective criterion for a recording process. We must make a distinction between the record of an event and the event itself in terms of the properties of a physical system, without regard to the higher purposes of experimental physicist, philosophers, or logicians. We must be prepared to consider the concept of record without too many sophisticated restrictions. In particular, we must convince ourselves that the time evolution of the physical system with a primitive recording process can lead to a distinctly different path than similar systems in which no such records occur.

The physics of records. What can we mean by a primitive recording process in terms of physical description? In normal usage, the concept of a recording process implies three steps which we may call (1) writing, (2) storage, and (3) reading. The storage of records is usually accomplished by a relatively time-independent set of constraints which forms structures or marks. The smallest record storage we know is embodied in a single molecule like nucleic acid. Largely because of the relative stability and permanence of storage structures, their significance in the total recording process is usually overemphasized. For example, many investigators think of the origin of life problem primarily in terms of an abiogenic synthesis of the first nucleic acids, as if the appearance of the same type of molecule which now *stores* genetic records were equivalent to originating the crucial writing and reading processes. Actually, as we shall see, it is the physics of *writing* and *reading* records which are the difficult concepts, while the physics of the storage, or of the symbol vehicle, is relatively trivial. In the same way, it is the design and dynamics of the measuring apparatus which is complicated and not the mark or indication of the stored result.

The mathematician Emil Post [13] saw the essence of writing symbols as the preservation in space of time-dependent activity. 'Activity in time' is the source of symbols, but this '. . . activity itself is frozen into spatial properties'. In a simple physical system this writing process could be described as a *selective freezing-out of degrees of freedom*. The key word here is 'selective'. We do not mean freezing-out degrees of freedom as in a phase transition or condensation. These latter processes are statistical events which are not dependent on the detailed motions of the particles involved. Then what can we mean by 'selective' in this context? In what type of physical system does the selection of a new constraint depend on the motions of the system?

Consider the formation of a chemical bond which requires the proper initial positions and velocities of the reactants. Is this what we mean by the 'selective' freezing-out of some degrees of freedom? No, I think not, since initial conditions are by definition the arbitrary or rule-free conditions in our description of a physical system. While it is grammatically correct to say that we have 'selected a number arbitrarily', what this means physically is that we have no rule for selection at all. So we must modify our concept of writing a symbol to exclude selection on the basis of rule-free initial conditions. What we mean by 'writing' is that we must have a *rule of selection to remove* *degrees of freedom which is independent of initial conditions*. Now in what sense can any dynamical process be independent of initial conditions? This is a question which we must formulate carefully, since the answer to it contains the necessary conditions for a measurement or recording process.

First, we ask the question in terms of the maximum possible detail. We could ask: what properties of the microscopic physical world are invariant with respect to initial conditions? In a strictly detailed sense, the answer we must give is that only the *laws of motion* are invariant to initial conditions. Or as Wigner has put it,[17] the other way around, invariance principles are possible only because we divide the world into two categories: the initial conditions and the laws of nature. Now it is at least logically clear that to the extent that we require by 'writing a symbol' or 'making a measurement' some selective dynamical process which is invariant to initial conditions, we must, in effect, introduce a new 'equation of motion' for the system, and this is clearly contradictory if we have assumed the original equations of motion are complete and deterministic.

All records are statistical. One way out of this contradiction is, as we know, to relinquish the detailed description and, through a postulate of ignorance, define new variables as 'averages' over an extended time interval or over a collection of microscopic degrees of freedom. These statistical dynamical descriptions 'almost do not depend' on the microscopic initial conditions. Using such macroscopic variables, it is at least not contradictory to introduce *non-holonomic* equations of constraint which may be defined as non-integrable relations between the new macroscopic coordinates and momenta which must be preserved throughout the motion. Such constraints must, of course, have a physical structure to maintain these relations. In effect, then, such artificial 'invariants' of the motion can selectively reduce the number of dynamical degrees of freedom, and therefore can fulfil our condition for *writing*. But in return for our ability to selectively control degrees of freedom in a macroscopic system, we must accept a corresponding *dissipation* so as not to violate the statistical laws of our macroscopic coordinates. That is, for every binary selection or bit recorded, there must be $(\ln 2)\, kT$ of energy dissipated. If this were not the case then we know that we could design non-holonomic 'demons' which would violate the Second Law of Thermodynamics (e.g. references (14) and (8)). Thus the classical concept of writing or recording demands a classical non-holonomic constraint which is inherently statistical in its structure and dissipative in its operation.

The quantum analogue of writing, of course, runs immediately into difficulty since a non-holonomic constraint between the microscopic degrees of freedom could have no physical basis. Even postulating such constraints in quantum mechanics, as we would expect, leads to serious difficulties. Eden has shown how the quantum formalism can be modified to accept non-holonomic conditions,[6] but the constraints do not in general commute with the Hamiltonian, leading to path-dependent values for the wave functions, and 'observables' which have a definite value even though no observation is actually made (i.e. an operator with an effect depending partly on the history of the state on which it operates).

But however we may choose to describe a selection process in physical terms, we must accept the inherent irreversibility of the concept, and hence a relaxation time or some dissipative process must occur in its physical representation. We must therefore conclude that it is logically and physically inconsistent to think of writing a symbol or a record in the strictly deterministic world governed by complete, microscopic laws of motion. The writing of records and symbols is an inherently irreversible classification process, and its physical representation is therefore probabilistic.

The classical ideal of machines and symbols. This interpretation of symbolic systems as inherently probabilistic or incomplete is contrary to our traditional usage. As the classical idea of laws of nature developed from the times of Galileo and Newton, the concept of determinism was almost always associated with the behaviour of machines. The universe, even including living matter, was compared to a gigantic machine, in spite of the fact that the machine is only found as an invention of the most highly evolved living organisms.

The growth of statistical mechanics did not alter the machine analogy since it was generally assumed that the loss of detail was the result of the practical inability of physicists to measure all the degrees of freedom. It was only with the recognition of the inescapable indeterminacy of conjugate variables that the machine analogy to physics broke down. But the machine concept remains an ingrained part of our thought.

We have compounded this trouble by relating our concepts of symbolic precision and computability so closely to the ideal of the classical machine that we are unable to clarify the basis of either formal or mechanical logics. Thus all of our logical and mathematical symbols are assumed to be strictly deterministic both as records as well as in their syntactical rules for manipulation. But in spite of enormous efforts to clarify the foundations of logic and mathematics we still find the intuitive ideas of a 'formal system' of symbols based on the entirely classical concept of a strictly deterministic 'mechanical procedure' (e.g. references (15) and (7)) even though this is a physical impossibility. While we may, like Laplace, imagine an ideal determinism for the detailed events of the universe, it is precisely the assumed completeness and symmetry in time of this dynamic description in which any inherently irreversible process of classification is unimaginable. Thus *all* recording processes, can only *approximate* the ideal of determinism by minimizing the effects of error produced by the fluctuations of irreversible systems. However small we may make this error, it is especially appropriate to remember Planck's warning to use words like 'certain' or 'sure' with great caution: '*For it is clear to everybody that there must be an unfathomable gulf between a probability, however small, and an absolute impossibility.*' [11]

Where does this gulf begin? The apparent paradox of quantum and classical concepts is that on the one hand, we consider all laws and measurements describing the truths of quantum mechanics as recorded and transmitted by the machines and symbols of the classical world, while on the other hand, we find this classical world is only an approximation to the 'truer' quantum world. One established school attempts to evade this paradox by postulating that the 'classical world' always be taken to the limit of ideal determinism when discussing the symbols and records of the quantum world. For example, Bohr requires,[2] '...the unambiguous use of the concepts of classical physics in the analysis of atomic phenomena'. This requirement is fulfilled, Bohr continues, '...by the use, as measuring instruments, of rigid bodies sufficiently heavy to allow a completely classical account of their relative positions and velocities'. Such a postulate implies that the source of deterministic behaviour in nature is in 'ordinary language' and 'heavy machines', while the origin of probabilistic events is in the interaction of these machines with the quantum world. It is very easy then to slip into the false logical conclusion that the quantum world itself is necessarily probabilistic.

A second school attempts to evade the paradox by avoiding the classical world altogether, or at least treating classical concepts as a kind of useful, but basically unreal link between the quantum level and the consciousness of the observer which remains 'shrouded in mystery'. To a greater or lesser degree, this interpretation has been seriously considered by Heisenberg, von Neumann, Wigner,[16] and other founders of modern quantum theory. Since consciousness is not even defined, this attitude does indeed evade the paradox, but replaces it with the mystery of the origin and nature of consciousness.

Without in any way minimizing the intellectual efforts which have produced these acceptable levels of consistency or at least a safe obscurity in the epistemological interpretations of quantum theory, I detect a sense of extremism in these schools of thought which may be born more of the frustration of years of unresolved arguments than of practical strategies for future developments. In effect it appears that each of these interpretations of the quantum-classical paradox introduces a different location for the 'unfathomable gulf' not so much to clarify the problem, but rather, to more cleanly separate two modes of description which otherwise produce unresolvable confusion.

My own approach, as the title of this paper suggests, is more biological than physical. I have said nothing so far that bridges the gulf. I am not proposing so much how to cross the gulf, as *where to place it*. I would place the gulf where it must be narrow—at the origin, between lifeless and living matter. In other words, between physical events and the *most simple*, natural records of these events. Of course our attitude must also be modified to suit the new location. We must relinquish many traditional concepts which have meaning only in the highly evolved world of human life. These include not only 'consciousness' but also the ideal 'classical machine' and the entirely abstract 'symbol'.

I believe that any attempt to describe the origin of life in physical terms will show that the traditional deterministic classical machine analogy to life is used precisely backwards! As Polanyi has so clearly pointed out,[12] all our macroscopic machines and symbolic languages exist only as the product of highly evolved living matter. Classical machines and symbolic systems are in essence *biological* constraints, not physical constraints. It is a simple, but non-trivial observation that classical machines and languages do not occur in the inanimate world. The fact that our classical machines and symbolic systems can be constructed with high accuracy and reliability is not a tribute to classical determinism but to biological ingenuity, or to put it more modestly, it is the *end* product of evolution by natural selection. This evolution does not *begin* with classical languages and classical machines but with the integrated dynamics of *molecular* languages and *molecular* machines. Single molecules function as the writing, storage, and reading constraints in all present living cells and perhaps even in the brain. Furthermore, it is reasonable to expect that some billions of years ago these recording processes were first accomplished with even smaller molecules. In any case, it is certainly clear that the origin of life's records could not have depended on 'rigid bodies sufficiently heavy to allow a completely classical account of their relative positions and velocities'. Let me emphasize that I do not mean that we, as external observers of life, cannot make some useful classical descriptions of life as is now done extensively in the area of 'molecular biology'. What I am saying is that life itself could not exist if it depended on such classical descriptions or on performing its own internal recording processes in this classical way.

Can we experiment with the gulf? How can we expect to make progress with the matter-symbol problem or the measurement problem in quantum mechanics in a scientific sense without experimental criteria for success? Is there such a thing as an 'epistemological experiment' or are epistemological questions inherently metaphysical? Or to put the matter more pragmatically: can any of these interpretations of quantum and classical concepts be distinguished by a measurable effect? There is no doubt that theoretical discussion will continue on such fundamental issues, and no one can say whether experiments will ever resolve the problems. However, it is clear that these problems have taken their present form because of experimental results, and only on the basis of history, it would be a good guess that further experiments will alter the form of these epistemological questions.

A serious difficulty with the strict separation of quantum and classical concepts by a 'classical limit' or a 'consciousness limit' is that no experimental test appears possible. The Complementarity Principle has in fact been represented as an interpretation of the formalism '...covering automatically any procedure of measurement...'.[1] In a totally informal sense, but with similar results, the insistence on including the conscious observer in the physical system leaves any experimental result open to so many 'soft' interpretations that no disproofs could be possible.

Unlike all other interpretations of the measurement problem that I have understood, the placement of the matter-symbol gulf at the *origin of life does suggest connections with possible experiments*. For reasons which I have more fully explained elsewhere [9], [10] I would expect a selective, macromolecular catalyst or proto-enzyme to exhibit a simple 'writing' process. Briefly stated, such a catalyst selectively removes degrees of freedom by forming a chemical bond many orders of magnitude more rapidly than it would form without the catalyst. Furthermore, the selection process, in keeping with our requirements, is not strongly dependent on the initial position or velocity of the reactants, but only on their inherent structure. This structure is recognized or classified by the catalyst in the sense that of the many collisions with other potential reactants, only the one with the proper structure will trigger the catalytic dynamics which produces the permanent 'record' in the form of a new chemical bond. The dynamical structure of the catalytic molecule may be described in the classical approximation as a non-holonomic constraint which maintains an 'invariant' rule (perhaps over as many as 10^9 catalytic reactions) for producing records of selected collisions with its environment.

In the context of the quantum measurement problem, many questions immediately arise: (1) To what degree is the quantitative dynamics of specific catalysis derivable from classical laws? Specifically, is a random phase assumption (i.e. the Born–Oppenheimer approximation) sufficient to quantitatively account for the selectivity and catalytic power, or does the correlation of phases play an essential role? (2) To what extent do the dissipative or relaxation processes involved in the collisions with reactants and the reset of the catalyst after each reaction involve heat, radiation, or loss of phase correlations? (3) Does the uncertainty relation limit or account for the accuracy of recognition and speed of catalysis? All of these questions are of course inseparable from the problem of the relation of the dynamical to the statistical modes of description, and we must therefore be careful to distinguish time averages which are 'convenient' for us, functioning as calculators or theorists, and those which are 'essential' for the natural functioning of the selective catalyst.

It is possible that the distinction between the dynamical and statistical descriptions will turn out to be an unfathomable gulf in the human brain even though we are looking at the simplest recording molecule; yet I cannot believe it would not be illuminating to know the dynamics and statistics as far as possible in a *natural* recording situation not designed by the human brain. Averages over short time intervals or small numbers of variables may be displeasing to the mathematician, but quite effective for molecular catalysis. There are certainly all levels of selectivity and catalytic rates—all degrees of error, speed, reliability, and permanence in a recording or measurement process which might be modified in an experiment. With such ideas in mind, it should be possible to simplify models of selective catalysts and to design experimental tests on existing tactic catalysts or enzymes which may at least help us approach a clearer understanding of the primary physical conditions for a natural recording process.

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QUANTUM THEORY AND BEYOND

ESSAYS AND DISCUSSIONS ARISING FROM A COLLOQUIUM

EDITED BY
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CAMBRIDGE
AT THE UNIVERSITY PRESS
1971