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Is Time Asymmetry Logically Prior to Quantum Mechanics?

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Abstract

In trying to imagine how quantum mechanics might be derived from a more fundamental theory, the author is led to consider a framework in which time-asymmetric events, rather than reversible unitary transformations, are taken as basic. In such a scheme it seems likely that quantum mechanics and the second law of thermodynamics would emerge together, both being consequences of a deeper law.

16.1 Introduction

Much of the work prsented at this workshop is aimed at understanding the origin of time asymmetry in quantum mechanical terms, taking the formalism of quantum mechanics as fundamental. In this paper I will pursue a line of thinking that entails precisely the opposite relation between quantum mechanics and time asymmetry, namely, that time asymmetry is fundamental and quantum mechanics is derivative.

To begin, let me recall how it happens that we are faced with a paradox of time asymmetry in quantum mechanics. From a pragmatic point of view, quantum mechanics can be thought of as a theory that predicts probabilities of the outcomes of certain measurements given certain prior measurements. One does not in principle have to talk about what goes on between measurements. However, the theory suggests strongly that something does go on between measurements, namely, a unitary evolution (either of the state vector or of the operators). It is very natural that many of us have come to take this unitary evolution not only as fundamental, but also as inviolable. In the Schrödinger representation, this way of thinking leads to a picture of the universe as an evolving wavefunction with no collapse, that is, the Everett picture. The dynamics of the wavefunction in this picture is reversible. That is, for each possible evolution, there is a corresponding time-reversed evolution which is equally allowed by the laws of physics. And yet our world is manifestly asymmetric in time. Herein lies the paradox of time asymmetry in the quantum context.

However, this view is not the only one possible. According to the Copenhagen interpretation, measurements are not like other processes but have a special status. They do not correspond to reversible unitary transformations but rather to irreversible projections. If one adopts this view, then one appears to have gotten around the paradox of time asymmetry, or at least the most blatant form of the paradox. There is no longer any glaring incongruity between the world we experience and the laws of physics: both are time-asymmetric. (Landau and Lifshitz 1958, p. 31. For a recent review, see Zeh 1989.)

In one respect, this approach to a solution is very appealing. The emergence of a definite outcome of a quantum measurement, if one regards it as a fundamental process, is the only thing in fundamental physics that is not reversible. It is therefore a natural place to look for the origin of time asymmetry.

Of course there are problems with this idea. If measurements are treated as special, then we would appear obligated to say exactly what conditions define a measurement. This obligation brings us directly to the ancient Problem Of Measurement in quantum mechanics. In blaming time asymmetry on the measurement process, one seems to be replacing the problem of time asymmetry with the more formidable problem of measurement, while at the same time excluding from consideration the Everett approach, which many regard as the only viable foundation for quantum cosmology. Moreover, in trying to define "measurement," one would certainly be tempted to invoke the irreversibility of thermodynamics, which is precisely what one wanted to explain in the first place (Zeh 1971).

Despite these objections, I wish to explore briefly in this paper a line of thinking based on the view just presented, to see where it might lead. My main reason for doing so is spelled out in the following section.

16.2 What's Behind Quantum Mechanics?

We usually treat the principles of quantum theory as though they were absolutely fundamental. We do not normally try to explain quantum theory; rather we use it as the underpinning for the rest of physics. However, it seems to me highly unlikely that nature could have chosen the particular structure of quantum mechanics for no particular reason. One can obviously imagine many other possible worlds with very different frameworks for physics: a probabilistic world without complementarity, for example; or a quantum-like world in which all probability amplitudes are real. In this section I would like to try to imagine what answer one might give to the question, "Why quantum mechanics?"

One of the most striking features of quantum theory is its universality. Consider, for example, the quantum mechanics of systems that have just two orthogonal states. Regardless of whether one is thinking of the polarization of a photon, or the spin of a nonrelativistic electron, or the identity of a mixed muon-electron neutrino, the theory is essentially the same: the allowed pure states can be represented by two-component complex vectors; probabilities are computed by squaring inner products between such vectors; and so on. The essential quantum framework is independent of the actual physical system in which it is instantiated. Therefore, if there is to be a reason for quantum mechanics, it should not be a reason that is at all system-specific. The universality of quantum theory suggests that its explanation will rely on only the most central and universal concepts that one finds in physical theory.

The most obvious such concept to consider is that of probability. The framework of quantum mechanics is, after all, ultimately a framework for computing probabilities. Once one abstracts away from all the specific systems to which we apply quantum theory, one is left with what seems to be a summary description of the way in which nature determines probabilities: in brief, nature determines probabilities by squaring complex amplitudes. It is this prescription that one wants to explain.

Now there are at least two possible ways to proceed. One hypothesis is that the above prescription is a convenient summary of some underlying counting process, through which each probability is determined as the ratio of one large integer to another. A model along these lines was proposed many years ago by Penrose (Penrose 1971). He imagined a large network of points connected by lines, with an integer associated with each line. The lines he interpreted as physical systems, the integers being their total angular momenta in units of $\hbar/2$. The network can be used to model the production of a polarized spin-$\frac{1}{2}$ particle by one apparatus and the subsequent measurement of its spin along a different axis by another apparatus. The probabilities of the two possible outcomes of this measurement are computed according to well defined counting rules. Out of this scheme Penrose was able to derive the familiar set of pure states of a spin-$\frac{1}{2}$ particle, along with the standard inner-product rule for computing probabilities.

I should point out that Penrose did not claim that his model should be taken as *the* explanation of quantum mechanics. Too much of the desired result is built into the counting rules, which are somewhat more baroque than one would expect of a basic law of nature. But I think the model serves as a valuable illustration of how one might derive the quantum framework from a combinatorial argument.

The other approach I have in mind is to try to derive the quantum framework from a simple principle. My own work suggests the following principle: The set of pure states of any system constitutes a Riemannian manifold, in which the distance between states is given by their distinguishability (Wootters 1981). This principle, when spelled out more precisely, strongly suggests a vector space structure for the set of states, with probabilities as the squares of components. It does not, however, favor a complex vector space over a real vector space; if anything it does just the opposite. Nevertheless, I regard the relation between distinguishability and the geometry of states as a genuine clue to the underlying explanation of quantum theory. One can imagine a more far-reaching principle which would encompass the one stated above and would yield quantum theory uniquely.

I now come to the main point of this section. No matter which of the above approaches one takes, the aim of the search is to deduce the structure of quantum mechanics *via* the probabilities. That is, one hopes to obtain, from an argument that assumes nothing about Hilbert space or unitary transformations, a relationship among probabilities that is most conveniently *summarized* in terms of Hilbert space and unitary transformations. Probabilities come logically before, not after, state vectors. In particular, the existence of "measurement events," the probabilities of whose outcomes are to be computed, is taken here to be fundamental. Without such events one has nothing to work with, no starting place on which to base a sub-quantum theory. These events thus play a role similar to that played by molecules in the kinetic theory of gases. (This idea is very much in the spirit of Wheeler 1990.) In what follows I will replace the term "measurement event" with the more generic term "branching event," so as not to suggest that anyone actually has to set up an apparatus or see the outcome in order for an event to be allowed in the description. A branching event is any event that (i) defines a set of possibilities and (ii) selects one of these possibilities, such that the outcome becomes an irrevocable component of the history of the universe. A photon encountering a beam-splitter does not constitute a branching event, but the subsequent detection of the photon by a photomultiplier does. (More on this shortly.)

The above considerations lead me to consider the following picture of the world: The world consists, at bottom, of branching events. They are the building blocks. Moreover, each of these branching events carries with it its own direction of time. It has a "before," when the outcome of the event is not determined, and an "after," when it is. A branching event is thus inherently irreversible; so in such a scheme time asymmetry would be built into the very foundations of physics. This asymmetry would be logically prior to quantum mechanics in that quantum mechanics itself would be derived from a sub-quantum principle or construction that is expressed in terms of branching events.

Filling in the picture a bit more, I imagine the history of the world as a network, or graph, of connected branching events. In order to compute the probabilities of the outcomes of a given event, one looks at the outcomes of other events and uses the Great Underlying Probability Law—this is the principle or construction that I assume will be discovered and that underlies quantum mechanics—to compute the probabilities. Moreover, considering that each individual branching event has a temporal orientation, I assume that this orientation plays a non-trivial role: in the network of events, a connecting link can be attached either to the "before" end or to the "after" end of an event, and the Great Underlying Law distinguishes between these two types of connection. The picture is thus quite asymmetric, but a very natural one to consider if one is looking for a sub-quantum theory based on probabilities.

One could object that there is an alternative, "time-free" way to introduce probabilities, namely, to start with a static joint probability distribution over the outcomes of all possible events. Ordinary everyday probabilities would then emerge as conditional probabilities derived from this global distribution. I appreciate the appeal of this approach (cf. Page and Wootters 1983). Note, however, that in order for these conditional probabilities to be usefully applicable to any given event, we must assume that there are observers whose total experience will include both a state of not knowing the outcome and a state of know outcome; that is, there must implicitly be a "before" and an "after." I admit that it is a non-trivial step to transfer this "before" and "after" from the *observers* to the *event*—what this step does in effect is to enforce a certain kind of agreement among the observers—but everything in our experience supports this step, and frankly, if one is trying to derive quantum mechanics, one wants to take advantage of whatever solid ground one can find to stand on. Hence my use of branching events.

Before addressing some of the questions raised by the notion of a branching event, I would like to say a few more words about the business of deriving quantum mechanics. One may well ask: how would we know if we had found the correct sub-quantum theory? Is it not always going to be a matter of aesthetic judgment? I would say that the answer to this question is the same as in any case of finding a deeper theory in physics: one believes the theory to be correct if it brings together parts of physics that were previously disjoint. In the nineteenth century, the atomic theory of matter not only explained the ideal gas law; it also made sense out of the ratios one observed in chemical reactions. Similarly, when we finally understand quantum mechanics in more primitive terms, who knows what other parts of physics will be explained in the same terms? Possibly the dimensionality of spacetime. Possibly even the value of the fine-structure constant. (It has been argued recently that the fine-structure constant, being the low-energy limit of a running coupling constant, appears to be very far removed from the basic laws of physics and is therefore not likely to have a simple explanation (Gross 1989). However, if measurement-like events are taken as fundamental, then the fine-structure constant may be quite close to the foundations of physics.) The uncovering of a such a connection in physics should be the mark of a valid sub-quantum theory.

16.3 What is a Branching Event?

Invoking the notion of a branching event brings us back to the measurement problem. What is it exactly that separates a given branching event from the rest of the history of the universe? How does one know when such an event starts and when it is completed? These questions are difficult enough when the event is a standard quantum measurement, such as the detection of a photon. They are even more difficult when one is talking about, say, the nuclear burning of the sun. Without being completely arbitrary, how could one possibly break up the burning of the sun into elementary branching events?

The only answer that makes any sense is that the representation of the history of the universe as a set of branching events is not unique. The physicist must be free to choose his or her own representation, but within certain limits. One can divide up the world's history rather finely into events, but not arbitrarily finely. In the case of the sun's burning, every measurement we make or can imagine making on the sun without disturbing it allows us to divide the sun's history into more detailed events. But we cannot go so far as to say that an elastic collision between two of its particles constitutes a branching event, because such a collision by itself leaves no definite trace in the history of the universe. It is obvious from this example that there can be no sharp line between what counts as a branching event and what does not. Therefore if one is to take such events as the basic building blocks, one must forsake the goal of mirroring perfectly in one's theory an independently existing reality. The statement, "the world consists of branching events," may have the appearance of an objective description, but in fact there is an unremovable subjective element in the notion of a branching event.

Many people object to such an approach on principle, preferring a framework that claims to be based on a description of objective reality (e.g., the wavefunction of the universe). Without justifying it, let me simply record here my own view that it will probably not be possible to maintain a rigorous separation between the objective and the subjective, but that this limitation need not keep our physical theories from being rigorous.

16.4 The Second Law of Thermodynamics

I conclude by addressing one of the main questions of this conference: what is the origin of the second law of thermodynamics?

In a theory of the sort I am trying to imagine, time asymmetry would be built into the foundations of physics, in the sense that every elementary event would have its own direction of time. One might think that this degree of asymmetry would be sufficient to guarantee the second law of thermodynamics. But I do not think this is the case. Imagine, for example, a beaker of water in which ink initially diffused throughout the water spontaneously collects itself into a localized blob. We have never seen such a process, but we can imagine it. We can also imagine watching this process and taking photographs of it, while the ink continues the whole time to coalesce into a blob, oblivious to the many branching events that we create all around it by our measurements (and to the many other branching events that we do not create). The very fact that we can imagine this scenario suggests that the second law does not follow logically from the asymmetry of the branching events.

It is standard practice to base the second law on the initial state of the universe, which is either assumed or argued to be a very special low-entropy state. But the concept of an initial state of the universe is quite foreign to the framework I am proposing. There is no initial state of the universe. The only things that exist are branching events, their outcomes, and the connections among them. So I cannot invoke the initial state as the origin of the second law.

But remember that there would be in this theory a deep Law, the Great Underlying Probability Law, that would allow one to compute probabilities and would give rise to quantum mechanics. Now, the second law of thermodynamics also concerns the computation of probabilities, e.g., the probability that the ink will spontaneously coalesce. Moreover, there should be only one correct way of computing probabilities, so the same Law that gives rise to quantum mechanics must also be used to compute the probability that the ink coalesces. In other words, I imagine that both quantum mechanics and the second law of thermodynamics emerge at the same logical level, from the same underlying principle.

At this point it would be a great help to my argument if I could produce the Great Underlying Law. Unfortunately I cannot, but the above considerations suggest the following clue: given that the Law has to replace the concept of an initial state of the universe, one should expect to find built into the Law certain regularities of the universe that might otherwise be attributed in part to the initial state. One particular regularity I have in mind is the following fact: our universe is such that we can make all sorts of useful predictions by (i) generalizing from past experience (this is related to Gell-Mann and Hartle (1990), pp. 426-7) and (ii) avoiding unjustified bias (cf. Jaynes 1957). These are very general principles worthy of being incorporated in a fundamental law. Whether such principles, when spelled out precisely, could form the basis of a derivation of quantum mechanics is thoroughly a matter of speculation at this point, but it is nevertheless intriguing to try to imagine such a derivation.

Interestingly, Peres has recently demonstrated a connection between the structure of quantum mechanics and the second law: it turns out that many changes that one can imagine making in the structure of quantum mechanics would lead to violations of the second law (Peres 1990). In a very different context, Gell-Mann and Hartle, building on work by others, have shown that imposing a final condition on the universe would affect not only thermodynamics but also quantum mechanics (Gell-Mann and Hartle 1994, Aharonov et al 1964, Griffiths 1984). These results reinforce the idea that quantum mechanics and the second law of thermodynamics may prove to be two aspects of a single theory.

To repeat the main point of this paper, the attempt to envision a sub-quantum theory suggests a picture of the world in which time-asymmetric events are taken as fundamental. Unitary evolution would appear as a derived concept and would of course not be universal. Many questions remain unanswered, of course, but I am convinced that in the end we will learn much by not taking quantum mechanics for granted.

16.5 Acknowledgments

I would like to thank Ben Schumacher and David Park for very helpful discussions.

Discussion

Lloyd A comment: The entire physical rationale for studying time asymmetry comes from the historical fact that during the nineteenth century, physicists deduced that the underlying equations of motion for physical systems were Hamiltonian and time symmetric. The observed asymmetry in time then became a paradox, rather than the simple fact of dynamics postulated by Aristotle.

Wootters I am going back to thinking of time asymmetry as a simple fact of the world. The challenge for the view I propose will not be to explain time asymmetry but to explain the time symmetric equations of motion.

Griffiths Is there anything in your presentation which does not apply equally well to classical as to quantum mechanics?

Wootters I understand the question: Even if the world ran according to classical mechanics, we would be able to access it only through irreversible measurements, and one could argue that these measurements should be taken as the basic building blocks of the universe. But the motivation for doing this is much greater in quantum mechanics. In classical mechanics, measurements on a system allow one to follow arbitrarily closely the system's evolution, with negligible disturbance of that evolution. But in quantum mechanics this is not the case, and the evolution of a system between measurements takes on much more the character of something that we have constructed.

There is also the question of the initial state of the universe. In classical mechanics it was necessary to assume a complex initial state, in order to produce all the variety we see around us. But in quantum mechanics the initial state can be so simple that one can imagine doing without it altogether.

Davies On a point of information, I believe that a theoretical scheme along the lines you are suggesting has been developed by Alastair Rae of the University of Birmingham.

Wootters I am familiar with Rae's popular book on quantum mechanics, in which he endorses Prigogine's view of irreversibility and applies it to the problem of measurement. Rae does indeed take irreversible measurement processes as fundamental, as I do. One difference between my view and Rae's is that he claims that one can make an objective distinction between reversible and irreversible processes (based on the concept of strong mixing), whereas I do not think such an objective distinction is possible. I would say simply that in order to do physics at all we must have some concrete measurement results—this is the one item we cannot do without—and I assume that we have them.

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