Informational characterizations of quantum theory as clues to Wheelerian emergence

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1 Wheeler's vision

Many thinkers have proposed that existence and experience are indissolubly linked. Berkeley, for instance, proposed a tight—probably too tight—metaphysical link ("to be is to be perceived"), while Kant famously tried—although not entirely successfully—to derive *a priori* some properties of reality, at least as it appears to us, and including aspects of the physics of his day, as conditions of the very possibility of experience.

More recently John Wheeler proposed, based not, or at least not only, on *a priori* grounds but on empirical grounds involving the nature of quantum physics, than the physical world and information concerning that world come into being through their mutual interdependence. It is a vision of the universe itself as created by myriad acts or events of measurement, of answerings of "yes/no questions" posed by agents, or at least by their apparatus. Wheeler's slogan of "it from bit" may be a slightly inaccurate summary of his vision, which he often described in terms of a "meaning circuit" in which it and bit both arose as each others' necessary partners. His vision was a proposal, not anything like a finished theory, but something that could change, or turn out to be the seed of a more developed and confirmed theory that in some ways might look radically different. "Start her up and see why she don't go," he liked to say.

It's possible that Wheeler's vision was not radical enough. An important part of "the message of the quantum" may be that the world is stranger than the notions of "it" and "bit" — of material object, of definite answer to a yes-no question, or even and perhaps especially, of that staple of physics that may share properties with both,

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the mathematically described object — can tell. These notions (like, perhaps, any set of notions) may be inadequate to wholly capture existence and experience, even while proving extraordinarily useful in grappling with it or with part of it, capturing aspects of it, and participating in it. But it is well worth seeing how much insight we can get into the world, its physics and our place in it, by attempting to make more concrete and precise the Wheelerian vision.

2 Information

As Chris Timpson has eloquently argued, we should take care to distinguish at least two uses of "information": the one involving meaning, as when we inform someone of something, and the one used in Shannon-style information theory, in which it is at most the *potential* for conveying meaning that is at issue—although the quantitative analysis of this capacity proceeds in terms of "answers to yes-no questions" without burdening itself with further analysis of the notion of meaning. Both notions were important to Wheeler. While information in the semantic sense may not "be physical", there may be physical preconditions for its storage, processing, or communication; this, as well the semantic aspect itself, is relevant to the Wheelerian vision.

3 Quantum and classical

Wheeler viewed the interdependence of it and bit as manifested most clearly in quantum phenomena. Indeed, he thought that an understanding of how the universe can come into existence would explain "how come the quantum?", in that the quantum would turn out to be necessary to that coming-into-existence. In the next section, we will look at some modest, but concrete, attempts to understand "how come the quantum" which do not yet add up to an explanation of how the universe can come into existence, but which do at least connect it to principles concerning information, so that they might constitute a step towards realizing the broader vision. But first, it is useful to think about the extent to which even classical theory involves an interdependence between informational and ontological concepts, in order too see which aspects of quantum theory might be crucial.

Even the Laplacean vision of *classical* physics is shot through with the interdependence of "it" and "bit", as indeed, arguably is the Western religous-philosophical tradition at least since another John wrote: "In the beginning was the word. And the word was with God, and the word was God."

The "objects" of classical physics do share some properties of ordinary material objects. They are conceived of as having definite positions and moving at definite velocity, and indeed Newtonian physics may be applied fairly straightforwardly to such objects as rocks and baseballs, though the description is somewhat complicated by phenomena like friction, air resistance, etc.. that are, however, viewable at least in priniciple as due to interactions with additional objects such as gas particles. These objects, however, have the informational aspect that they are susceptible to a mathematical description, and perhaps the even more "informational/mindlike" aspect that they are viewed as "obeying laws".

Inasmuch as material objects each have — as it seems they do — their own particularity beyond any universal properties they may have or laws they may obey, then arguably quantum mechanics may be pointing us back toward particularity, quiddity, something in each part of nature with which we interact that is its own *sui generis* mode of existence, action, reaction. Some, notably Chris Fuchs, locate part of that particularity in the probabilistic nature of our interactions with objects. In the classical Laplacean picture, however, it is presumably located in their structure, and perhaps also in their relations to other objects, both traceable ultimately to the initial conditions of the universe.

The structures we interact with, become conscious of, and indeed the structures that we are, are generally understood to be emergent ones. Indeed that is partly implicit in the word structure: a structure is made of constituents, perhaps ones described in explicit mathematical terms as objectively existing and obeying universal laws, but the structure itself is not one of the constituents, nor inherent in the laws. Rather — in a Newtonian/Laplacean picture — it is inherent in the initial conditions — and perhaps in some way best manifested as it develops over time while conforming to the dynamical laws. There is a widely held account — or better put, idea for an account — of consciousness, thinking, becoming aware of information — that locates it in certain types of structures built up from such law-obeying constituents—structures that exhibit certain types of behavior, that function in certain ways, for example, that instantiate a computer running a certain type of program on certain types of inputs. Broadly, such accounts are called "functionalist". Such accounts, particularly if construed in a sophisticated way, do seem to capture important aspects of consciousness, information, and so forth, though I'm not convinced that they are the whole story. The computational version of functionalism seems particularly weak to me, as it seems that embodiment, and interaction with an environment, are probably crucial for things to have a mental aspect, though it might be possible to achieve the effect of these within a rich enough virtual world.

It is sometimes said that functionalism gives us an account of how consciousness, thought, or what have you, arises from unthinking matter that itself has no mental aspect. I can see some virtue in this view, but find more in the view that the material constituents must have some mental aspect in order for mental phenomena to arise from their combination. The solution to this apparent contradiction may be more trivial than one might hope: "following a law" is already a rather metaphysical, even "mental" image of the behavior of constitutents, and it may just be this that is the "mental" aspect of the constituents: in virtue of their ability to follow universal laws, they can be constituents of structures whose functioning endows them with consciousness.

Thinkers such as Daniel Dennett have given valuable accounts of how phenomena such as free will, consciousness, and selfhood might arise in a deterministic, classical universe. Potentially crucial to these accounts, although not always emphasized as explicitly as it could be, is *computational complexity*, which is entwined with *emergence* in that, although our doings may *be* the workings out of mechanical processes set in motion with particular initial conditions, we cannot *understand* them under such a description, but must use higher-level ("emergent") concepts. Computational complexity may make it infeasible to *simulate* these workings out in sufficient detail for useful prediction. Perhaps deeper, though, is the point that simulation is not equivalent to understanding: seeing that a simulation gives a certain result is not the same as understanding *why* it does. It is tempting to suppose, though, that if our brains really did have the capability to simulate, perhaps it would appear to us from inside as understanding, even though when we simulate something on a computer, it need not give understanding. But it is not clear this is so.

The very idea of a physical law usually involves counterfactuality: "how something would behave if". It is, in ways we may not fully understand, linked to notions of freedom (to tweak the physical conditions and see what ensues, as indeed we do in experiments), to the doings of agents whose theories it is part of. The Dennettian thought experiments and computational experiments that are supposed to support emergence of mind and freedom from deterministic rule-governed systems, involve observing emergent, "life-like" phenomena in, for instance, cellular automata such as Conway's game of "Life". But in this setting, we assume by fiat that the constitutents follow rules. In reality, the rules are part of our theory as to how things behave. Standard quantum theory makes this perhaps even more explicit, as the rules are probabilistic, and probabilities are perhaps best understood as advice to a decision maker. Still, I would argue that in many situations quantum theory does give us "the facts" about how agents with particular information should "bet".

Evolution is crucial to the emergence of complex structures having mental aspects, and evolution requires randomness to act upon. However on the Laplacean view we may take this randomness to consist in our lack of knowledge of the initial conditions...so that the complex structure already resides, in some sense, in the details of these conditions.

It is tempting to suppose that the role of the quantum in an account of how existence emerges from experience (and vice versa in a Wheelerian circuit) is to allow the particularity embodied in emergent structures, which in the Laplacean picture is in some sense already present in full detail in the initial conditions, to emerge instead in a manner distributed over spacetime, in acts of quantum observation or interaction. In the Laplacean picture, the emergence of structure over time might seem like a "redundant representation". The structure was already present in the initial conditions and one might think that its actual unfolding should perhaps be "modded out" in the most succinct description of reality, as in a gauge-independent representation of a field theory. In quantum theory, the distributed nature of the randomness might make such a modding out impossible, giving events occuring throughout spacetime a more substantive, non-redundant kind of reality. I suspect there is something to this, but it must be tempered by the abovementioned role of computational complexity in emergence on the Laplacean picture. The process of evolution over time would seem to be crucial in order that the details embodied in the initial condition can manifest themselves in a manner understandable to conscious beings, thus perhaps reaching a fuller kind of existence. Also, in defense of a certain amount of "redundance" one might observe that consciousness and meaning are related to representation of aspects of the world in, or by, an agent—in other words, to certain correlations being induced between the agent and that part of the world. It is perhaps crucial, though, that these correlations are partial—not every aspect of that part of the world is represented by the agent. In this way, perhaps, the content of consciousness can be emergent. We therefore cannot be certain that a Laplacean understanding of the emergence of "bit from it" over time (or in timelike directions in spacetime, on a relativistic account) is inadequate, but the quantum is suggestive that it might be.

In the next section, we will take up efforts to give information-related answers to Wheeler's question "how come the quantum?", but we should not forget to keep in mind that as we have just seen, while there are some suggestions that we may need quantumness, as opposed to classicality, in order for experiencing subject and experienced object to emerge through mutual interdependence, it is not *prima facie* obvious that we do.

4 Informational derivations of "quantum theory"

One concrete research area that holds great promise for helping realize Wheeler's vision is the project of mathematically characterizing quantum theory as the unique theory, or one of a limited class of theories, satisfying particular principles concerning information and the processing of information. There has been strongly renewed interest in this area since the advent of quantum information and computation—a field which to a remarkable degree owes its early development to students of Wheeler. There are by now various derivations of finite-dimensional quantum theory over the complex field from fairly natural principles concerning information. (The finite dimensionality is technically convenient but probably not conceptually essential to most of these.)

The most common framework for such investigations is what is often called the *convex operational* or *general probabilistic* framework for theories. A main purpose of a theory in this framework is to specify the probabilities of the various possible outcomes of a measurement made on a system that has been prepared in a given state.

The theory specifies a set of possible systems, each of which is described as having a convex, compact set Ω of *states*, and a set of real-valued affine functionals on the state space, that correspond to measurement outcomes. The probability of the outcome represented by functional e, when the system has been prepared in state ω, is just $e(\omega)$. The theory further specifies what dynamics a system may undergo, and how it may be combined with other systems to get composite systems. There is a strong structural and interpretive analogy to "Alice 'n Bob" style quantum information theory. Explicitly or not, this usually gives something close to a *symmetric monoidal category* of such systems in which the scalars are real numbers interpreted as probabilities. Theories can also be studied more abstractly in terms of properties of such categories without presupposing real scalars, as done by Samson Abramsky and Bob Coecke, Chris Heunen, and others, but even then specializing to the probabilistic case can help concretize and clarify the significance of such properties.

An example of this sort of work in the convex framework is my work with Markus Mueller and Cozmin Ududec, in which we use the assumptions: (1) every state has a spectral decomposition in terms of a "classical set" of perfectly distinguishable pure states and (2) every such ordered set of perfectly mutually distinguishable pure states can be taken to any other such ordered set by a reversible dynamical evolution allowed by the theory. Several alternatives for a third assumption then narrow things down to a choice between quantum theory or classical theory from among the vastly broader set of imaginable theories. One such principle is local tomography—the idea that the state of a system composed out of two subsystems, such as a pair of entangled photons or atoms, can be determined by separately measuring each subsystem, and looking (over many experimental instances of preparation and measurement of the same state) at the correlations between the measurements on the two systems. (This principle has sometimes been claimed to be necessary for the very possibility of doing science, though I am not convinced.) Other possible assumptions, including ones not involving composite systems, get us to Jordan-algebraic systems—a class of systems introduced by Jordan in the 1930s and studied by Jordan, von Neumann, and Wigner as a possible mathematical setting for quantum theory, which includes, besides the usual quantum systems over the complex numbers, quantum-like systems over the real or quaternionic numbers, and a very limited class of other systems. We showed that one such assumption is the absence of what Rafael Sorkin called "higher-order interference": interference between three or more possibilities that cannot be explained in terms of "two-way" interference between pairs of the possibilities. In the context of our first two axioms, this postulate—obviously related to the interference experiments which Wheeler thought revealed the essence of the message of the quantum, but perhaps somewhat obscure in its informational implications—is equivalent to others of a more information-theoretic flavor, such as the principle that the "filters" that (given our first two axioms) can tell us which "classical subspace" of its state space our system is in, without disturbing states that are already in the subspace, preserve purity, that is, do not introduce any additional randomness not associated with pre-existing uncertainty about which subspace the system has been prepared in.

Given Jordan algebras, we can, as noted for example in Alfsen and Shultz' *Geometry of State Spaces of Operator Algebras*, narrow things down further to standard complex quantum theory without invoking local tomography, by requiring that the generators of all the reversible dynamical evolutions allowed by the systems (which would usually be identified as the energy of a system undergoing such an evolution) be an observable.

Our spectrality assumption could be viewed as a requirement that classical information be representable within operational systems, and indeed that every state can be described in terms of classical ignorance about *some* observable that is classical in the strong sense that preparations yielding definite values for it can, in principle, be perfectly distinguished. The overall system is still nonclassical because *which* observable this is depends on the state of the system.

Our very strong symmetry postulate is perhaps somewhat less well motivated. My research, in progress, suggests that with spectrality and the observability of energy it allows for a very perspicuous account of statistical mechanics and thermodynamics along fairly standard lines.

5 Operational axiomatics and spacetime

Such investigations are only one approach to the problem of attaining a more concrete understanding of how "it" could emerge along with "bit" in a "meaning circuit" that can result, for example, in yes-no questions being posed by parts of reality and acquiring definite answers. They are likely to be most fruitful when combined with continued consciousness of the possible limitations of the "operational" framework within which they take place. At the least subtle level, these investigations have taken place primarily in a framework that abstracts "Alice and Bob" style quantum information theory, and it is important to look at how they might be integrated into a more explicitly spacetime picture. Some of this has been done, in a "circuit" picture, in which there is a fixed causal diagram represented by a directed acyclic graph, with a "no-signaling from the future" condition imposed on systems connected by a "causal" arrow, and a "no-signaling, period" condition imposed on systems not connected by any directed causal path. (The explicit workings out of this sort of picture I am familiar with are by Hardy, and by D'Ariano, Chiribella, and Perinotti.) Hardy has also investigated operational structures in which the causal structure is not predefined, a potentially important step toward combining quantum theory with general relativity.

One promising, relatively conservative, direction to investigate is whether interesting constraints are imposed on operationally described systems by an attempt to use them in generalizations of algebraic, or topological, quantum field theories. In AQFTs, for example, quantum fields in a fixed (usually flat Minkowski) background spacetime are described by associating algebras of observables with certain spacetime regions, along with natural requirements on how these algebras relate to the causal and set-theoretic structure of spacetime regions (they commute if spacelike separated, for example, and subsets correspond to subalgebras). The fact that these regions have a spatial extent means that the operational interpretation of the observables in them is a subtle matter. Rafael Sorkin has pointed out that superluminal signaling is possible if one simply assumes all observables within a spacetime region to be instantaneously measurable. Indeed, such instantaneous measurability hardly seems physically realistic given that that the region is extended in spacetime. Still, there is hope that the attempt to generalize these constructions to operational structures more general than algebras of quantum observables might shed light, both on how one should implement realistic operational restrictions in the context of standard algebraic QFT, and on why the operational structures associated with spacetime regions might need to have a structure similar to that of standard quantum theory. A similar exercise could be performed with topological quantum field theories, in which the spacetime might be modelled by a Riemannian or Lorentzian manifold, usually compact, and the quantum structures (e.g. Hilbert spaces, or associated algebras of observables, or group representations, or quantum group representations) associated with cobordisms representing the manifold as glued together from two pieces which might be thought of as "observer" and "observed". One might attempt to generalize this construction, which involves a functor from a category of cobordisms describing the possible "splittings" of the manifold into two parts, to a category of Hilbert spaces (or algebras or representations), to one in which the target of the functor is a category of probabilistically described operational systems. Again one might expect interesting restrictions on the sort of operational systems that can support such a construction.

We need to keep in mind possible limitations of the operational approach. For starters, "making a measurement" is a complex physical process that presumably doesn't happen instantaneously, but is extended over space and time, requiring physical resources. The operational approach is just one way of viewing quantum theory as informational. It's a remarkable property of quantum theory that one seems to always be able to represent the measurement process within the theory—at the cost of representing it as the establishment of correlation between system and observer, but not representing which particular outcome was obtained. But it's possible that we need to represent correlations between spacetime regions more than we do operations performable "within" such regions—indeed the TQFT structure suggests that interpretation.

The need to represent correlations, or the use of operational systems to represent "local" events suggests a "histories" interpretation of quantum theory... but quantum theory itself does not seem to give us a *precise* statement of what the histories are about — what the *beables* are, as John Bell liked to say, other than that whatever else they include, they should include the outcomes of measurements and the setup of experimental apparatus (or at least allow us to describe the latter sorts of things as structures built from the beables). Indeed Wheeler seemed to view the lack of a precise definition of what the beables are as potentially deeply connected to the "it from bit" vision, as the very nature of what becomes definite about the history of a quantum system may depend on the measurements we choose to make on it. Furthermore, a simple histories formulation in which the "events" are taken to correspond to some set of projectors or coarsegrained effects associated with some grid of small spacetime regions—or more elegantly, some weak-measurement continuum analogue of this sort of thing—might well be associated with too-easily-observable decoherence.

I view it as more likely that the "decoherence" associated with particular histories will be associated with the effective, and indeed probably in-principle, impossibility, within an adequate theory integrating the quantum with spacetime, of performing the interference experiments required to verify the putative coherence of, for example, the live and dead versions of Schrödinger's cat. We do not yet have a clear understanding of this — which might after all amount to a resolution of the quantum measurement problem — but it would appear to involve a remarkable mixing of scales, relating macroscopic phenomena such as the setup of experimental apparatus, to what we can say about microscopic systems — just the sort of thing Wheeler thought crucial.

In this regard, one important "clue", to use Wheelerian terminology, to what may be going on, is thermodynamics and the second law. These provide a bridge between microscopic and macroscopic physics, and are connected to irreversibility. I have already suggested that there is a close relation between the operational, probabilistic structure of finite-dimensional quantum theory, and a standard statistical account of thermodynamics. This relation can also probably be understood in terms of the representability of mixed states as arising from pure states of larger systems, and of irreversible dynamics as arising from reversible dynamics on larger systems. The most detailed investigation of these latter properties in the operational framework, though not of their thermodynamic implications, has been by Chiribella, D'Ariano, and Perinotti, who use them, along with other properties such as local tomography, to axiomatically characterize quantum theory.

6 Conclusion

It is clear that most of Wheeler's project remains to be done, if indeed it can be done. But some concrete progress has been made, stimulated by the advent of quantum computation and quantum information theory. An important part of this progress has involved various characterizations of quantum theory in terms of postulates or properties stated in terms of information or information processing. This work has mostly viewed quantum theory as an operational theory describing systems in terms of preparation procedures, operations, measurement outcomes, and probabilities associated with them. Further progress will likely require intensive efforts—some of which are under way—to understand the place of these operational structures, and the informational principles and characterizations of quantum theory associated with them, to spacetime physics, capturing some of the physics embodied in quantum field theories, and hopefully even integrating them with some of the physics, such as gravitation, which is currently not integrated with quantum theory. Of course the operational structures and axiomatic characterizations may need to be modified to be suitable in these spacetime settings. An important clue to the future of the project is probably in the importance to these operational results of the availability of a very rich set of reversible dynamics and the probable relation of this to statistical physics and thermodynamics. A closely related clue is the importance of the representability of measurement-like and irreversible processes by reversible ones on larger systems. Still another is the potential importance, even in classical accounts of emergence, of computational complexity, and the need to take it more seriously than is usually done in the operational approach.