Absolute Quantum Mechanics[*]

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Abstract

Whereas one can conceive of a relational classical mechanics in which absolute space and time do not play a fundamental role, quantum mechanics does not readily admit any such relational formulation.

Newton's mechanics is formulated against a backdrop of what he called "absolute" space and time. However, absolute position and velocity appear to be unobservable, and there is a long tradition, beginning with Leibniz, of criticizing the postulation of these unobservable properties, and suggesting that mechanics would better be reformulated in a way that does not make reference to them There are several such reformulations (see Earman [1989]), varying in their commitments, which are all typically called "relational". What they have in common is a restriction of the domain of predication of the physical theory to observable quantities. (Where they differ is in what is construed to be "observable". In particular, they differ on whether various sorts of acceleration, including rotation, are deemed to be observable.) "Observable" is cashed out as "relational", where "relational" means a physical quantity that is a relation between two objects or properties. For instance, the distance between two objects is a relational property – the relative position.

What is, or is not, an observable quantity is a matter of much debate. At a minimum, it would seem that relative positions are observable, or physical. Change in relative position with respect to time (usually called "relative velocity") should be observable to the extent that time is observable. And so on. For the purposes of this paper, I will suppose that *any* theory which is relational with respect to spatiotemporal properties will represent relative position as an observable. The point of this paper is simply that it is entirely unclear what would count as a quantum analogue of such a theory. Thus quantum theory seems to require absolute space and time.

Before proceeding, let me note that it is not completely obvious that formulating a theory in a way that makes no reference to an unobservable, absolute space and time means formulating it in a way that would be characterized as fully relational. For instance, it is a matter of some controversy whether to regard general relativity as relational. In that theory, formulating observables

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as diffeomorphism-invariant objects eliminates any reference to the underlying spacetime manifold (arguably making the theory non-absolutist), but not all such observables need be relational in nature (e.g., the ADM energy in asymptotically flat spacetimes).[1]

1 Classical Relationalism

Consider the classical mechanics of point particles $a, b, ...$ moving without constraint in three spatial dimensions. The ordinary Newtonian formulation describes the state S of these particles by describing their configuration $\mathbf{x} = (a_i, a_j, a_k, b_i, b_j, b_k, ...)$ (their arrangement in space) and the rate of change $\dot{\mathbf{x}} = (\dot{a}_i, \dot{a}_j, \dot{a}_k, \dot{b}_i, \dot{b}_j, \dot{b}_k, ...)$ of this configuration with respect to time.[2] Specifying the masses of the particles, along with the forces exerted by the particles on each other, allows one to calculate the locations and velocities at all future and past times.[3]

The relationalist reaction to classical mechanics is rooted in the observation that we never actually observe absolute position or absolute velocity. Thus if we take some state S of these particles and write down a new state $S' = (\mathbf{x}', \dot{\mathbf{x}})$, where $\mathbf{x}' = (a_i + 6, a_j, a_k, b_i + 6, b_j, b_k, ...)$, in which the particles have the same velocities but in which they are translated 6 feet in the i direction, we would be unable to tell the difference — they are observationally equivalent. This, at least, is the relationalist construal. It is based on the idea that an observer is always *part* of the universe, and thus that all actual observations are made relative to some such observer. So, identifying the observer with one of the particles described by S or S', the relationalist insists that S and S' are two different descriptions of the same physical reality, because all physical (here meaning observable) quantities are the same, for the relative positions and velocities of the particles in S and S' are the same.

Clearly, there are difficult issues here, not least of which is the identification of observable equivalence (empirical equivalence) with physical equivalence. Nonetheless, one can certainly understand how the relationalist position may be developed — it proceeds by identifying the observer as a constituent of any complete physical description, and noting that many mathematically different descriptions yield the same observational consequences.

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[1] The seemingly relational quantum mechanics of Aharonov & Kaufherr [1984] has just this feature: there are observables in the theory that are not relational in nature.

[2] Alternatively, we may adopt the canonical (first-order) formalism, and speak of the configuration variables and their conjugate momentum variables.

[3] This is perhaps an overstatement; limitations on determinism in classical physics are discussed in Earman [1986].

2 Quantum Theory

Standard quantum mechanics is, like Newtonian mechanics, constructed against a backdrop of absolute space and time. Whereas a state S in Newtonian mechanics is a specific configuration of particles in absolute space, and a specification of the rate of change in this configuration with respect to time, a state $\psi(\mathbf{x})$ in quantum theory is a function which assigns a complex-valued "amplitude" to each configuration $\mathbf{x}$, the squared-value of which corresponds to the probability (density) of finding that configuration. (Similarly, one can obtain from the state the amplitudes for changes in the configuration with respect to time.)

How are absolute space and time implicated in this conception? The configurations are configurations with respect to classical, absolute space, and the evolution of the state, and the rates of change of the configuration, are given with respect to absolute time. So, for example, one might consider a new quantum state ψ' corresponding to an assignment of the same amplitudes to particle locations (hence configurations) translated 6 feet in some direction (so that $\psi(a_i, a_j, a_k, b_i, b_j, b_k, ...) = \psi'(a_i+6, a_j, a_k, b_i+6, b_j, b_k, ...)$, for example). These are regarded, in ordinary quantum theory, as physically distinct states, just as their analogues are in classical theory. Moreover, these states will, in general, exhibit interference with one another.[4]

Now, in the classical picture, the relationalist approach is motivated by the observation that a uniform translation of all the matter in the universe, including the observer, would be physically unobservable, and thus should not be counted as a physically distinct situation. However, the analogous observation in quantum theory is highly problematic, because, quite simply, it is completely unclear how to describe an observer, and an observation, in quantum theory. (This is the measurement problem.)

In practice, which is to say when actually using quantum theory, one in fact does what the much-maligned Copenhagen interpretation insists that one must do — one treats only part of the world quantum-mechanically, and one treats the observer and the measuring apparatus classically. That is, one treats them as physical systems having definite locations at all times.[5] This allows one, among other things, to say that a measurement took place at some definite place at some definite time. Thus the ordinary usage of quantum theory seems to preclude a fully quantum description of the world.

If one accepts a fragmentation of the physical description of the entire world into classical and

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[4] Since we are treating this as an "active" transformation, we do not transform the operators. One may also view ψ and ψ' as corresponding to the same state in two different coordinate systems—a "passive" transformation. However, in such a case, the representation of the observables changes along with the state, and the expectation values do not change.

[5] In the Bohmian interpretation of quantum theory, however, objects do have trajectories, though the trajectories are nonclassical. See Cushing, Fine & Goldstein [1996] for more information on Bohmian mechanics.

quantum parts, one can motivate a kind of relationalism. Consider a world that is empty but for an electron and a detecting screen. Describe the electron quantum-mechanically (state-vector) and the detecting screen classically (position and velocity). The relationalist will note that certain rearrangments of this physical situation with respect to absolute space and time will be empirically indistinguishable, and will urge a relational formalism that renders them identical. But how is one to do this? The problem is that there *is* no formalism that incorporates both quantum and classical aspects. This is something imposed from outside.

For example, suppose one makes this quantum-classical split, and describes the (absolute) state as some combination of positions and velocities (for the classical objects) and wave-functions (for the particles).[6] One might conceivably rewrite such a state as a "relational" state describing positions as positions *relative* to classical objects. The difficulty, of course, is that old bane of dualism: interaction. What happens when a quantum object interacts with a classical object? Were there a formalism that could accommodate this, it would be one in which classical and quantum objects were subspecies of some more general formal characterization of matter. Lacking such a formalism, however, one can say nothing.

Suppose one decides instead to adopt a purely quantum approach, whereby all matter is treated quantum-mechanically. Here, we have a consistent formalism to start with. But there are at least two major, related problems in constructing a relational version:

1. The original motivation for the relational approach is not at hand. One cannot make statements about formally different but empirically indistinguishable situations because one does not have any unambiguous way of extracting empirical content from a purely quantum theory. (Although I will consider the Everett approach below.)

2. Proceeding on a purely formal basis, on the other hand, is obscure. For example, one approach to the construction of a classical relational theory is to take the original configuration space and "factor out" by the symmetries of physical space. That is, one deems all states which are translations or rotations of the original state to be equivalent. Identifying these (equivalent) points yields a new, reduced configuration space. One can then formally write down a quantum theory in which this reduced configuration space is the domain of the wave-functions. However, in the absence of any physical interpretation, one is at something of a loss as to how to proceed from here. For example, the reduced phase space of the classical theory will be one in which *relative* distances are the "configuration" variables. In the classical theory, these correspond to observable quantities, and one might decide to represent them as "observables", i.e., self-adjoint operators, in the relational quantum theory. Whatever formal appeal this might have, it is far from obvious

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[6] I speak of wave-functions rather than more general state-vectors because I am not concerned with the spin of the electron.

that one should take this route, because it is entirely unclear what an observer is or an observation is in such a theory.

Note that the purely formal approach is even more problematic when one attempts to deal with rotation, the bugbear of classical relationalism. The reason is that quantum theories of the electron, the proton, the photon, etc., all include a non-classical form of angular momentum called "spin". Typical approaches to classical relationalism assign zero angular momentum to the entire universe by fiat. Is one to extend this restriction to the quantum case, where angular momentum includes not only orbital angular momentum but spin? This is unclear.[7]

Finally, *time* is especially problematic for the would-be quantum relationalist. The role of time in ordinary quantum theory is to parametrize the evolution of the quantum state. And just as one uses classically-described objects in the ordinary theory to define spatial positions, one uses classically-described clocks to measure time. Were one to attempt a fully quantum, fully relational theory, one would presumably like some quantum physical system to stand in for the classical clock. However, it is well-known (Unruh & Wald [1989]; also Weinstein [1999]) that there is no quantum observable whose behavior appropriately tracks the absolute time, and which can thus stand in for a clock in the relational theory.

3 Everett/Many Worlds

Attempts have of course been made to extract empirical content from a purely quantum-mechanical description of the universe. Most prominent among these attempts is the set of intepretations which find their inspiration in Everett [1957], and are known as "relative-state" or "many-worlds" or "consistent histories" interpretations. Recent work of Saunders [1997] has emphasized the relational aspects of the Everett's original relative-state formulation.[8] What I would like to point out here is simply that, as currently formulated, this interpretation is every bit as dependent on absolute space and time as the Copenhagen interpretation.

The relational aspect of Everett's interpretation is a relationalism with respect to value-definiteness, as Saunders himself notes. The general idea is that one can think of a universal wave-function as attributing definite properties to certain subsystems of the universe *relative* to definite properties of other subsystems. Consider Schrödinger's cat coupled to a radioactive atom. From this perspective, the cat is definitely-alive relative to the atom being in an excited state, and definitely-dead relative to the atom being in an unexcited (decayed) state. In general, interactions produce correlations between systems such that definite states of one system are correlated with definite states

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[7] It is worth pondering the fact that Planck's constant carries units of angular momentum, and it is the total angular momentum that the classical relationalist is at pains to get rid of.

[8] See also Rovelli [1996] for another interesting take on relationalism in quantum theory.

of the other.

What is important for our purposes, however, is that this Everettian relationalism has nothing *per se* to do with spacetime. The position of one object may be definite relative to some position of another object, but these positions will be positions in absolute space.

4 Conclusion

Space-time relationalism in classical mechanics is motivated by the apparent unobservability of absolute spatial and temporal properties. Though construction of a relational mechanics is not trivial, it is at least a well-defined project in the classical case, because one expects that observers (or, less anthropomorphically, measuring apparatuses), are represented by the theory itself, and furthermore are represented as objects with spatiotemporal trajectories.

In quantum theory, on the other hand, one's hands are tied. The motivation is perhaps in place, in that one cannot claim to observe, say, the location in absolute space of any particular object. But already observation is a tenuous notion in quantum theory, one which has its clearest meaning in the unsatisfactory classical/quantum hybrid description required by the Copenhagen interpretation. When moving to a fully quantum theory, it is very much a challenge to say what observation consists in.

Ultimately, it seems to me, the tenacity of absolute space and time in the quantum context is a result of the fact that we do not know how to extract physical content from quantum theory in the absence of a notion of measurement that makes reference to classically described measuring apparatuses occupying these spacetime points. These objects are not explicitly invoked in the formulation of the theory, but they are implicit in our construction of "observables", for observables are understood to be properties measured by objects or observers which are located *in* space, *at* some time. In a way, absolute space and time are placeholders for these classical objects.

Although many seem to think that the ultimate physical theory will be a quantum theory, it seems to me that it is worth seriously considering the idea that quantum theory is joined at the hip to classical theory, and that further progress in understanding quantum theory will come, not by probing quantum theory proper, but by coming to understand how to move beyond it.

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