Relativistic Quantum Mechanics through Frame-Dependent Constructions

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This paper is concerned with the possibility and nature of relativistic hidden-variable formulations of quantum mechanics. Both ad hoc teleological constructions and frame-dependent constructions of spacetime maps are considered. While frame-dependent constructions are clearly preferable, a many-maps theory based on such constructions fails to provide dynamical explanations for local quantum events. Here the hidden-variable dynamics used in the frame-dependent constructions is just a rule that serves to characterize the set of all possible spacetime maps. While not having dynamical explanations of the values of quantum-mechanical measurement records is a significant cost, it may prove too much to ask for dynamical explanations in relativistic quantum mechanics.

1. Introduction. It is difficult to find a formulation of quantum mechanics that provides a dynamical account of the process of measurement and the production of determinate measurement records and is compatible with the constraints of relativity (Barrett 2003). This paper concerns the most direct way of providing a hidden-variable formulation of quantum mechanics that is compatible with relativity. The general strategy guarantees determinate measurement records but ultimately forfeits any dynamical explanation of the production of such records or of any other physical process.

One might naturally suppose that a formulation of quantum mechanics is compatible with relativity if it can be given without reference to any preferred inertial frame. In the context of special relativity, one might suppose it to be sufficient that the dynamics assign a unique local quan-

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tum-mechanical state to all regions in Minkowski spacetime. But if this is all one requires, then it is easy, perhaps too easy, to get a formulation of quantum mechanics that is compatible with relativity.

Bloch (1967) provided an early discussion of the difficulties one faces in reconciling quantum mechanics and relativity. He understood the problem as one of finding a collapse formulation of quantum mechanics that (i) was compatible with the constraints of special relativity and (ii) would explain the determinate measurement records generated by particle detection experiments. Using particle counters as quantum measuring devices, Bloch explained how one might get a weak sort of compatibility with relativity by supposing collapses to occur along the backward light cones of measurement interactions.[1]

Bloch concluded his discussion of relativistic quantum mechanics by describing how one could, if one pleased, define a "teleological wave function" by simply stipulating the value of the wave function so that it corresponds to whether or not each particle counter is triggered at each particular location in spacetime where a measurement is made (1967, 156). That is, one might construct an empirically adequate *spacetime map* of the quantum-mechanical state by stipulating that the local value of the wave function in each region of Minkowski spacetime is the corresponding eigenstate of the recording variable wherever and whenever there is in fact a measurement record. One might then complete the spacetime map by filling in local values for the wave function in all other regions subject to the constraints imposed by the values in those regions where there is a determinate record. There are several ways one might do this. If one used the standard unitary dynamics to fill in the values outside the determinate-record regions, then the resultant spacetime map might look as if collapses of the wave function had generated the determinate measurement records. Indeed, such a complete spacetime map might be constructed from Bloch's backward light-cone collapse prescription above if one knew the result of each actual measurement. But there is a sense in which it does not really matter how one completes the spacetime map since one already has the right determinate local measurement records by stipulation. Such a *teleological* spacetime map constructed from observed measurement records would clearly be both empirically adequate (by stip-

1. His discussion here is built on the earlier work of Aharonov, Bergmann, and Lebowitz and directly inspired the later work of Hellwig and Kraus (1970). A closely related approach was also suggested by Schlieder (1968). See Hellwig and Kraus (1970, 569) for a description of how Schlieder's spacetime maps are updated. These proposals also foreshadowed relativistic collapse proposals like Aharonov and Albert's (1981) and subsequent hyperplane-dependent collapse theories.

ulation) and perfectly compatible with special relativity (insofar as it is just a map of local quantum-mechanical states in Minkowski spacetime).

Concerning the construction of such ad hoc teleological spacetime maps, however, Bloch concluded that "such a procedure appears to have little to recommend it" (1967, 156). While one cannot help but agree with this conclusion, it is also unsurprising to find such teleological constructions throughout the literature on relativistic quantum mechanics given the difficulties inherent in finding a dynamical account of the quantum measurement process that is compatible with relativity.

Hellwig and Kraus (1970) proposed adopting precisely the sort of ad hoc procedure that Bloch found objectionable in order to extend Bloch's discussion of particle-detection records to the construction of spacetime maps for quantum field variables. Their proposal amounts to stipulating the corresponding local value of the field variables in those spacetime regions where determinate measurement records are in fact found, then filling in the quantum-mechanical field state map in other regions by applying the collapse dynamics along the backward light cone of each measurement event region in spacetime and applying the standard unitary quantum dynamics everywhere else (1970, 567).

While such a teleological spacetime map provides an empirically adequate model for any collection of actual determinate measurement records and while there is a sense in which they are also compatible with the constraints imposed by special relativity, they are nevertheless blatantly ad hoc. Such a construction guarantees empirical adequacy *by stipulation*. While such a spacetime map may predict and explain our empirical results in the sense of logically entailing the determinate records we in fact find, the predictions are ad hoc and the explanations are the most impoverished imaginable.

The salient question is whether we can do better than such ad hoc constructions of quantum-mechanical spacetime maps. I think we can. In particular, I will argue that frame-dependent constructions of hidden-variable spacetime maps are clearly preferable to teleological constructions. While I take a many-maps formulation of relativistic quantum mechanics to be preferable, it will also limit the sort of explanations available. I will use both basic and generalized Bohmian mechanics to illustrate frame-dependent hidden-variable constructions of many-maps theories. Then I will discuss the relative virtues and vices of such theories.

2. Frame-Dependent Constructions. As the most popular hidden-variable formulation of quantum mechanics, Bohm's theory (1952) provides a convenient context for discussing frame-dependent constructions.

In basic Bohmian mechanics (characterized by Bell 1981 and 1982), a complete physical description consists of the standard quantum-mechanical state ψ together with a specification of the always-determinate position Q of each particle. It is the determinate particle configurations relative to the wave function that are supposed to explain our determinate measurement records in this theory.

According to basic Bohmian mechanics, the standard quantum-mechanical state, always evolves in the standard deterministic unitary way. In the simplest nonrelativistic case, this evolution is described by the time-dependent Schrödinger equation

$$i\hbar \frac{\partial \psi}{\partial t} = \hat{H}\psi, \tag{1}$$

where $\hat{H}$ is the Hamiltonian of the system.

The determinate particle configuration Q also evolves in a deterministic way. For an N particle system, the particle configuration can be thought of as being pushed around in $3N$-dimensional configuration space by the flow of the norm-squared of the wave function (the probability current) just as a massless particle would be pushed by a compressible fluid. More specifically, the motion of the particles is given by

$$\frac{dQ_k}{dt} = \frac{1}{m_k} \frac{\mathrm{Im}(\psi^* \nabla_k \psi)}{\psi^* \psi} \tag{2}$$

evaluated at the current configuration Q, where m_k is the mass of particle k.

While this dynamics is local in configuration space, local in configuration space is not local in Minkowski spacetime. Indeed, since a single point in configuration space represents the simultaneous positions of every particle, one must choose a preferred inertial frame in order to provide a configuration space representation at all. Moreover, according to Bohm's dynamics, the velocity of a particle at a time is typically a function of the simultaneous positions of distant particles. And since it is this feature of the dynamics that explains the correlated results of EPR experiments in Bohm's theory, one might naturally conclude that the Bohmian dynamics is essentially incompatible with relativity.

Since both the evolution of the wave function and the evolution of the particle configuration are fully deterministic in Bohmian mechanics, in order to get the standard quantum probabilities, one must assume a special statistical boundary condition. The distribution postulate requires that there be a time t_0 where the epistemic probability density for the configuration Q is given by $\rho(Q, t_0) = |\psi(Q, t_0)|^2$. If the distribution postulate is satisfied, one can show that Bohm's theory makes the standard quantum statistical predictions as epistemic probabilities for possible particle configurations.

Basic Bohmian mechanics can be generalized to make virtually any discrete physical quantity determinate. In particular, a Bohmian theory can be constructed where field quantities, rather than particle positions, are always determinate. Just as in the basic version of the theory, the standard quantum-mechanical state ψ evolves in the usual unitary deterministic way and an auxiliary dynamics describes the time-evolution of the determinate physical quantity. The only significant difference is that the auxiliary dynamics is typically stochastic.

There are several empirically equivalent ways to specify an auxiliary dynamics for generalized Bohmian mechanics. The following describes the choices made by Bell (1984) and Vink (1993). Suppose that the current value of discrete physical quantity Q is q_m. The probability that the value jumps to q_n in the time interval dt is $T_{mn}dt$, where T_{mn} is an element in a transition matrix that is completely determined by the evolution of the wave function. More specifically, the wave function evolves according to the time-dependent Schrödinger equation

$$i\hbar\partial_t|\psi(t)\rangle = H|\psi(t)\rangle, \tag{3}$$

where H is the global Hamiltonian. The probability density P_n is defined by

$$P_n(t) = |\langle q_n|\psi(t)\rangle|^2 \tag{4}$$

and the source matrix J_{mn} is defined by

$$J_{mn} = 2\mathrm{Im}(\langle\psi(t)|q_n\rangle\langle q_n|H|q_m\rangle\langle q_m|\psi(t)\rangle). \tag{5}$$

Finally, if $J_{mn} \geq 0$, then for $n \neq m$

$$T_{mn} = J_{mn}/\hbar P_m; \tag{6}$$

and if $J_{mn} < 0$, then $T_{mn} = 0$. On analogy with the Bohmian particle dynamics, here one can think of the change in the discrete value of Q as a discrete random-walk in Q-space biased by the flow of a compressible fluid with current J_{mn}. If the distribution postulate is satisfied, then this dynamics makes the standard quantum statistical predictions for the value of the determinate quantity Q as epistemic probabilities (Vink 1993).

That both the basic and generalized formulations of Bohmian mechanics make the same empirical predictions as standard quantum mechanics for whatever physical quantity one takes as determinate has two immediate consequences. While the auxiliary dynamics is incompatible with relativity (in the sense that it requires a preferred inertial frame for its specification), if the distribution postulate is satisfied, then (i) one cannot communicate superluminal signals and (ii) there is no empirical way to detect which preferred inertial frame was used to calculate the evolutions of the determinate physical quantities. There is a sense then in which Bohmian mechanics is *observationally* compatible with relativity.[2] But one can get a stronger sort of compatibility between Bohmian mechanics and relativity by sacrificing the dynamical explanations Bohm's theory is typically taken to provide.

A hidden-variable spacetime map consists in an assignment of a local value of each hidden variable to each region of spacetime. Both the basic and generalized formulations of Bohmian mechanics provide frame-dependent procedures for constructing such spacetime maps.

Basic Bohmian mechanics allows one to construct particle-trajectory spacetime maps. Choose a preferred inertial frame. Use the associated family of spacelike hyperplanes of simultaneity to define a $3N$-dimensional configuration space associated with the preferred frame. Choose an appropriate wave function in configuration space at an initial proper time. Subject to the probabilities specified by the distribution postulate, randomly choose an initial particle configuration. Run the standard non-relativistic unitary dynamics on the wave function in the configuration space associated with the preferred inertial frame and run the auxiliary dynamics on the determinate configuration (using the proper time for the preferred frame in each case). Then map the individual particle trajectories represented by the evolution of the preferred configuration to worldlines in Minkowski spacetime to form a determinate particle-trajectory map.

One can similarly construct the set of *all possible* Bohmian particle-trajectory spacetime maps together with a prior probability distribution over the set. Start with the wave function in the configuration space associated with the preferred inertial frame at an initial time. Suppose that an initial particle configuration has been determined subject to the distribution postulate, but that this is all one knows about the initial configuration. The distribution postulate then determines an epistemic probability distribution over possible configurations at a time in the preferred frame. Rather than tracking the evolution of the actual configuration, which by assumption one does not know here, track the evolution of every possible configuration that is compatible with the initial epistemic probability distribution in configuration space as specified by the distribution postulate. This initial probability distribution might be understood as providing the prior epistemic probabilities for each possible type of particle-trajectory spacetime map in fact describing our physical world.

2. Peter Holland has argued that while some sort of violation of relativistic intuitions is "inevitable in a theory whose basic dynamical equations are defined in configuration space rather than ordinary spacetime," in Bohmian mechanics, relativity is nevertheless "statistically valid" (1993, 498). This sort of compatibility between Bohmian mechanics and relativity has often been noted. See for examples, Albert (1992) and (1999), Bohm and Hiley (1993), Maudlin (1994) and (1996), and Dickson (1998).

These prior probabilities may then be updated by conditioning on what one learns from empirical experience concerning the determinate features of the actual spacetime trajectory map describing our world.

The many-maps theory is a set of possible spacetime maps and a distribution over these maps representing the epistemic probability that a particular type of map correctly describes our physical world. The standard unitary dynamics and the Bohmian auxiliary dynamics are here just part of the prescription for how to construct the set of possible spacetime maps. One might argue that it is natural in statistical theories like Bohmian mechanics to think of the theory as just providing a set of possible physical worlds and a probability measure over the set. In any case, the many-maps theory is nothing more this this.[3]

As in standard nonrelativistic Bohmian mechanics, the epistemic probabilities one gets by conditioning on new empirical evidence in the many-maps theory will agree with the standard quantum probabilities for particle trajectories. And both the actual particle-trajectory spacetime map and the epistemic probabilities over all possible such maps are perfectly compatible with relativity in the sense that each map is just a description of the local value of each determinate physical parameter (here particle position) in each region of Minkowski spacetime and the probabilities are just representations of our uncertainty concerning which spacetime map in fact correctly describes our world.[4]

3. Virtues and Vices. The particle-trajectory spacetime maps produced by frame-dependent constructions in basic Bohmian mechanics certainly fall short of what one should want from a satisfactory hidden-variable spacetime map in relativistic quantum mechanics. While such maps are in some sense perfectly compatible with relativity, the phenomena they represent are manifestly non-relativistic. Such maps do not, for example, account for even elementary relativistic phenomena such as particle creation. But getting the right empirical predictions for such relativistic phenomena here is at least in principle not difficult.

3. The many-maps theory is a spacetime version of the many-threads theory discussed in Barrett (1999) where the connection rule is replaced with a prescription for constructing a spacetime hidden-variable map.

4. Note that quantum nonlocality here is not a dynamical nonlocality. Rather, apparent nonlocality here just amounts to the fact that almost all physically possible worlds will in fact exhibit the standard EPR statistical correlations between space-like separated particle trajectories. Further, that such relativistic particle theories are possible shows one concrete sense in which particle no-go theorems like Malament's (1996) are contingent on exactly how one seeks to explain determinate measurement records in relativistic quantum mechanics. See Dickson (1998, 214–215) and Barrett (2002) for further discussions of this point.

As a first step toward getting the right relativistic predictions, there is good reason to exchange determinate particle-trajectory maps for determinate field-value maps. Generalized Bohmian mechanics might then be used to construct all possible determinate field spacetime maps. Again, there would be a simple matter of fact concerning which determinate field-value spacetime map accurately described our world. One would start with the standard quantum probabilities, given by the distribution postulate, as providing a prior epistemic probability distribution over possible determinate field maps, then update these probabilities by conditioning on empirical evidence concerning which determinate field map in fact describes our world.

In order to get the right relativistic phenomena one would also need to use an appropriate field-theoretic version of the unitary dynamics in the frame-dependent construction. This might be done as follows. Start with any of the standard relativistic versions of the unitary dynamics in Minkowski spacetime. This will provide a spacetime map of the standard quantum mechanical state everywhere in spacetime. Given the best current field theories, this state map will typically describe each local region as possessing an entangled superposition of field values. Next choose a preferred inertial frame $\mathcal{F}$ in which to carry out the frame-dependent construction. Start with a set of determinate field values at an initial time in $\mathcal{F}$. Use the generalized Bohmian dynamics to evolve these determinate field values in the preferred frame, but instead of using a frame dependent version of the unitary dynamics to calculate the probability currents, use the sequence of quantum-mechanical states induced on the preferred hyperplane foliation by the field-theoretic state map in Minkowski spacetime. This construction provides a possible map of determinate field values for all of spacetime. The set of all such maps together with the standard epistemic probabilities of this set is the relativistic field theory. This version of the many-maps theory will predict whatever relativistic phenomena one would have expected given the unitary field dynamics with which one started.

While the determinate field maps predicted by such a theory would typically exhibit unexplained, nonlocal correlations between spacelike separated determinate field values, there remains a sense in which the theory is nevertheless perfectly compatible with relativity. Indeed, any empirically adequate formulation of relativistic quantum mechanics that allows one to represent determinate determinate field values at all must be associated with a map that exhibits just such nonlocal correlations insofar as we in fact observe such correlations. Consequently, if one does not like the spacetime maps associated with the present theory, it must be that one does not like how they are constructed. But here, unlike the teleological spacetime maps considered earlier, the problem is not that frame-dependent maps are ad hoc. They are, after all, constructed using rules that may or may not yield the right empirical predictions. Rather, the problem here is presumably that the rules that are used to construct possible determinate field maps are not dynamical and hence the many-maps theory does not provide dynamical explanations.

While the many-maps theory does not provide dynamical explanations for the determinate events represented in the constructed spacetime maps, the rules used for the frame dependent constructions do code for empirical regularities in a way that provides empirical predictions and exposes the theories to potential empirical refutation. So how comfortable one is with the theory ultimately depends on the sort of explanations one requires from a satisfactory formulation of relativistic quantum mechanics. By opting for frame-dependent rules that do nothing beyond characterizing the set of possible hidden-variable spacetime maps, one is left without the richer dynamical explanations we like to have whenever we can get them. On the other hand, it is not at all clear whether we will be able to get satisfactory dynamical explanations for all physical phenomena. The assumption that we will is particularly suspect in the context of our best spacetime theories (like general relativity) and in the context of quantum mechanics (and hidden-variable formulations of quantum mechanics in particular). Whether dynamical explanations are possible in quantum mechanics also depends on what counts as a dynamical explanation. Indeed, depending on what one requires from a satisfactory dynamical explanation, Bell's theorem and the Kochen-Specker theorem may amount to no-go theorems for such explanations in any empirically adequate formulation of quantum mechanics.[5]

If one takes seriously hidden-variable formulations of quantum mechanics at all, then there may be further explanatory constraints. Michael Dickson has argued that it is at least contentious to claim that Bohmian mechanics predicts nonlocal causal relations since it does not support the sort of counterfactual conditionals one might require in order even to make sense of causal relations (1998, 202–208). In the context of basic Bohmian mechanics, one can only support counterfactual conditionals of the sort represented by "What would have happened if the experiment had been set up differently?" by supposing that at least some particles

5. These theorems suggest that one may not be able to get dynamical, mechanical, or causal explanations in any empirically adequate formulation of quantum mechanics insofar as such explanations require locally mediated interactions and a full set of determinate physical quantities exhibiting the standard functional relationships between their possessed values. But whether or not this is possible clearly depends on exactly what one takes to be essential to each type of explanation. See Bell (1987), Kochen and Specker (1967), and Bub (1997) for discussions of these theorems.

were distributed differently than stipulated by the distribution postulate. But since it is the initial state being selected as stipulated by the distribution postulate that explains quantum probabilities in Bohmian mechanics, the theory cannot support such counterfactual conditionals.

A potential problem with this reconstruction of the argument is that the distribution postulate does not stipulate any particular initial state; rather, it just requires that an initial state be randomly selected subject to the standard quantum probabilities. One might nevertheless defend Dickson's conclusion by noting that the particular initial state required for the analysis of a particular counterfactual conditional is never a state *randomly* selected subject to the distribution postulate. But there are other reasons to suppose that not even basic Bohmian mechanics supports standard causal or dynamical explanations.

Basic Bohmian mechanics requires the distribution postulate to be satisfied in order to get the right quantum statistical predictions given the usual auxiliary dynamics. But one can get essentially the same statistical predictions with a weaker statistical boundary condition if one adds an appropriate stochastic term to the auxiliary dynamics. That is, there is a trade-off between the dynamics and the statistical boundary condition in hidden-variable formulations of quantum mechanics like Bohmian mechanics such that one can get the right empirical predictions with many different *dynamical-law/boundary-condition* pairs. This is closely tied to the fact that there is typically no empirical way to determine what the actual particle dynamics is in a world described by basic Bohmian mechanics (see Barrett 2000). For our purposes, the important point here is that, in a hidden-variable theory like Bohmian mechanics, the boundary conditions and the dynamical laws work together to yield the right statistical consequences. The moral is that there can be little epistemic or methodological justification for arguing that boundary conditions and dynamical laws have an essentially different status in Bohmian mechanics: it is only *together* that they explain the standard quantum statistics.

If the boundary conditions have the same status as the dynamical evolution of the state in Bohmian mechanics, then one cannot analyze causal relations by considering counterfactual boundary conditions since to support a counterfactual conditional by considering a different boundary condition would be akin to supporting a counterfactual conditional by considering a different dynamical law, and a counterfactual conditional supported by considering a counterfactual dynamical law would clearly tell one nothing about the causal structure of the physical world. Secondly, since there is an empirically equivalent trade-off between dynamics and boundary conditions in hidden-variable theories, one could never empirically support a particular dynamical explanation in such a theory since one would never have empirical grounds for selecting one dynamics over all others. Thirdly, we have other physical theories, like general relativity, that may not generally allow for standard dynamical explanations (in this case due to global constraints on the structure of spacetime that cannot typically be inferred from any local state or time slice). And finally, if there is in fact no principled difference in the methodological status of boundary conditions and dynamical laws in a hidden-variable theory, then, insofar as hidden-variable theories are themselves unobjectionable, there can be no principled objection to replacing inadequate dynamical theories with a many-maps formulation of relativistic quantum mechanics.

4. Conclusion. Frame-dependent hidden-variable constructions of spacetime maps are clearly preferable to teleological constructions since the former explain why the statistical properties of the observed measurement records are to be expected while the latter take the observed measurement records as given then simply stipulate an appropriate corresponding spacetime map. There are explanatory costs to settling for frame-dependent rules for characterizing possible spacetime maps and an epistemic probability distribution over the set. Perhaps the most significant is this sort of relativistic hidden-variable formulation of quantum mechanics does not provide the dynamical explanations we like. On the other hand, it is difficult to find any formulation of quantum mechanics where one can provide an empirically adequate dynamical explanation of one's determinate measurement records that is also compatible with relativistic constraints. Perhaps something like the many-maps formulation of relativistic quantum mechanics is the best we can do.

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