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Relational Quantum Mechanics and the Determinacy Problem

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ABSTRACT

Carlo Rovelli's relational interpretation of quantum mechanics holds that a system's states or the values of its physical quantities as normally conceived only exist relative to a cut between a system and an observer or measuring instrument. Furthermore, on Rovelli's account, the appearance of determinate observations from pure quantum superpositions happens only relative to the interaction of the system and observer. Jeffrey Barrett ([1999]) has pointed out that certain relational interpretations suffer from what we might call the 'determinacy problem', but Barrett misclassifies Rovelli's interpretation by lumping it in with Mermin's view, as Rovelli's view is quite different and has resources to escape the particular criticisms that Barrett makes of Mermin's view. Rovelli's interpretation still leaves us with a paradox having to do with the determinacy of measurement outcomes, which can be accepted only if we are willing to give up on certain elements of the 'absolute' view of the world.

1 Introduction

Quantum mechanics describes certain systems as being in superpositions of their properties, yet every measurement on every system that we are able to perform apparently yields a unique, determinate result. The 'orthodox' formulation of the theory builds this in by including a postulate that such superpositions 'collapse' at the time of measurement. This strategy fails to really explain why such measurements are determinate, is unacceptably imprecise, and makes observation basic in fundamental physical theory, which seems like the wrong level to describe the process. The problem of the interpretation of quantum

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mechanics is the problem of finding a more satisfactory understanding of the formalism in the face of these problems.

Carlo Rovelli's (Rovelli [1996]; Laudisa and Rovelli [2005]) relational interpretation of quantum mechanics holds that a system's states[1] or the values of its physical quantities as normally conceived only exist relative to a cut between system and observer (alternatively: measurement system, exosystem, metasystem, measurement frame). Furthermore, on Rovelli's account, the appearance of (absolutely) determinate observations from superposed quantum states happens only relative to the interaction of the system with the exosystem.

Jeffrey Barrett ([1999]) has pointed out that certain 'relational' interpretations suffer from what we might call the 'determinacy problem', but the interpretations that Barrett considers make facts relative to branches of the universal wave function rather than to cuts. Barrett misclassifies Rovelli's interpretation by lumping it in with Mermin's view, as Rovelli's view is quite different and has resources to escape the particular criticisms that Barrett makes of Mermin's view; nevertheless, the relational interpretation still results in a paradox. The problem manifests itself for Rovelli's interpretation not as a problem of determinate experience, as Barrett puts it, and it doesn't arise for the same reason it arises in interpretations of Everett or on Mermin's interpretation, but it instead results from our inability (on Rovelli's account) to give any absolute or gods-eye-view descriptions of events.

First, I will give a brief description of the view, following Rovelli's presentation. Next, I will discuss Barrett's criticisms of David Mermin's interpretation, and then contrast Rovelli's interpretation with Mermin's in a way that draws out further features of Rovelli's interpretation as well as showing how it escapes Barrett's criticisms. In the next section, I discuss a further puzzle for Rovelli's interpretation, and I finish by considering two strategies for dissolving the puzzle that the relationalist can employ (the second better than the first).

2 Relational Quantum Mechanics

Rovelli's version of quantum theory ([1996]) takes a cue from Einstein,[2] particularly Einstein's landmark 1905 paper on special relativity. Einstein accomplishes

[1] I speak of the 'state' of the system throughout the paper, though, in the considered view of both the supporters of the relational interpretation (Laudisa and Rovelli [2005]) and myself, it is infelicitous to call the wavefunction/Hilbert-space vector of the system 'the state' or to treat it as what corresponds to the classical state. Better to speak of the quantities of physical variables or operators like 'position' and 'momentum' as those things that have reality (relationally speaking). Nevertheless, as nothing crucial is lost in the translation for the purposes of this paper, I speak of states in order to stick closer to Rovelli's original presentation ([1996]) and achieve maximal familiarity.

[2] He is not the first to have done so. Both Heisenberg and Bohr saw themselves as making moves analogous to Einstein's relativity. See also (Finkelsten [1996], [unpublished]).

two things in his paper on special relativity that inspire Rovelli. First, Einstein provides an interpretation of an already existing formalism (the Lorentz transformations), answering the charges that the formalism is unreasonable or inconsistent by criticizing an implicit assumption (absolute simultaneity) that is 'inappropriate to describe reality when velocities are high' (Rovelli [1996], p. 2). Second, Einstein does not merely tack an interpretation on to the formalism, but he attempts to understand or in some sense derive the formalism on the basis of some simple physical principles (ones that may seem contradictory given the inappropriate assumptions: in the case of special relativity, 'equivalence of inertial observers and universality of the speed of light', Rovelli [1996], p. 2).

Rovelli is interested in following Einstein's strategy in both respects when giving his interpretation of quantum mechanics. His program would start with some simple physical assertions, showing that they entail a rejection of some inappropriate assumption(s), and then derive the formalism of quantum theory from them. He admits that this project is not yet completely successful, and so splits the discussion into two parts: a motivation of some basic ideas about quantum mechanics from a discussion of the 'third person problem', the conjunction of which lead us to the discovery of the inappropriate assumptions that form our uneasy attitude toward quantum mechanics, and an attempt to reconstruct the formalism (somewhat informally) from a small number of postulates suggested by the first discussion, dealing with the information systems have about each other.[3] I will focus on the first part of Rovelli's discussion.

Before diving in to Rovelli's own presentation, consider the following formulation of the basic principles of 'orthodox' quantum theory (using Schrödinger's formulation):

1. **The Eigenstate–Eigenvalue rule:** The system has a certain value for a property if and only if it is in an eigenstate corresponding to that value.
2. **The unitary Schrödinger dynamics (Process II):** The system's state evolves in time according to the Schrödinger equation.
   - $H(t)|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$
   - This evolution is linear and deterministic and allows systems to evolve into superpositions.

[3] So Rovelli's project is incomplete in three ways: the principles fail to be motivated independently of the formalism, the postulates do not fall directly out of the first discussion, and the derivation lacks some rigor, especially with the *ad hoc* introduction of the principle that allows for superpositions. Despite Rovelli's failure to meet his own desiderata, his view does address familiar problems in an interestingly new way, and may have merits on its own that forgive this incompleteness. In my view, Rovelli provides a full-fledged interpretation of quantum theory based on *just* the first part. The attempt to derive the theory from informational principles is a separate (or separable) project, discussed in (Grinbaum [2003], [2005], [2007]).

3. **The collapse postulate (Process I):** At the time of measurement, the system collapses into one of its eigenstates.

As it stands, we have a problem, based in two facts. First, the term 'measurement' is crucially vague: what counts as a measurement? Second, we're led into an apparent contradiction when we consider measurements from different perspectives, as in the cases of Schrödinger's cat and Wigner's friend.

It is precisely these kinds of considerations from which Rovelli draws his main conclusions. He discusses the 'third person problem', which goes as follows:[4] Suppose observer (or measuring apparatus) O is measuring a property of system S. Let's take as an example a Stern–Gerlach apparatus measuring the x-spin of an electron, with possible values of spin-up and spin-down. We'll represent the two eigenstates of that property as $|\uparrow\rangle_S$ and $|\downarrow\rangle_S$. If S is in the arbitrary state

$$|\psi\rangle_S = \alpha\ |\uparrow\rangle_S + \beta\ |\downarrow\rangle_S \tag{1}$$

when O measures the electron's x-spin, he will find the value 'up' (with probability $|\alpha^2|$) or 'down' (with probability $|\beta^2|$). Now, suppose that O measures S and in fact finds it to be up. We usually represent this with the following state transition:

$$\begin{gathered} t_1 \rightarrow t_2, \\ \alpha\ |\uparrow\rangle_S + \beta\ |\downarrow\rangle_S \rightarrow |\uparrow\rangle_S. \end{gathered} \tag{2}$$

Here we have what is referred to in orthodox expositions of quantum theory as the 'collapse of the state/wavefunction' (von Neumann's *Process I*).

Now consider observer P who treats both the observer and system from our previous discussion as the quantum mechanical system $S + O$. P tracks both the state of the system S as well as the measuring device of O, which has the eigenstates $|ready\rangle_O$, $|up\rangle_O$, and $|down\rangle_O$ corresponding to its readout of 'ready', 'up', and 'down'. If P has not performed a measurement at t_2, and instead only knows that there is an interaction, then just given the linearity of quantum mechanics, the state transition according to P ($|\psi\rangle_{SO}$) will be

$$\begin{gathered} t_1 \rightarrow t_2, \\ |ready\rangle_O(\alpha\ |\uparrow\rangle_S + \beta\ |\downarrow\rangle_S) \rightarrow \alpha|up\rangle_O\ |\uparrow\rangle_S + \beta|down\rangle_O\ |\downarrow\rangle_S. \end{gathered} \tag{3}$$

This process, unlike (1), proceeds entirely according to the linear dynamics (von Neumann's *Process II*).

From this discussion, Rovelli derives the following principle (what he calls the 'main observation'):

[4] This is just the Wigner's friend case, without any reference to human agents or consciousness. S is the system, O is the friend, and P is Wigner.

R1 : 'In quantum mechanics different observers may give different accounts of the same sequence of events' (Rovelli [1996], p. 4).[5]

The sequence of events from t_1 to t_2 is described quite differently from the perspective of O and P. Particularly, O reports an event at t_2 where there is a measurement of a determinate property, while P reports an interaction between two quantum systems without any determinacy in the property of either subsystem (O or S).

Rovelli takes this principle and then analyzes various interpretations of quantum mechanics as attempts to weasel out of **R1**, that is, as attempts to say that (1) and (2) can't both be true. Collapse theories, which postulate a physical mechanism of collapse, say that (1) but not (2) is true, because interaction with the macroscopic measuring device (or something) causes the collapse of S's state. They thus deny the applicability of the Schrödinger dynamics for some systems that haven't been measured (like the joint S-O system). Versions of Everett's theory say that (2) but not (1) is true, because wavefunctions never collapse, thus denying the collapse postulate.[6] If the formalism really implies (1) and (2), all such theories constitute a denial of the validity of the quantum formalism in some circumstances. (Other interpretations, according to Rovelli, deny the basic formalism in some other way. These discussions are a little more complex, and their details need not concern us here. The discussion of collapse and Everettian theories will serve to show the general point.)

Rovelli counters with a quite strong realism about the ordinary formulation of quantum theory, described by the following principle (which he calls 'Hypothesis 2' or 'Completeness'):

R2 : 'Quantum mechanics provides a complete and self-consistent scheme of description of the physical world, appropriate to our present level of experimental observations.' (Rovelli [1996], p. 7).

where quantum mechanics, for Rovelli, is just the formalism as it is normally used in basic applications.[7] The conjunction of **R1** and **R2**, understood

[5] As pointed out to me in comments on an earlier draft of this paper, this principle bears some resemblance to Bohr's principle of complementarity, which should be carefully distinguished from the 'orthodox' interpretation. For Bohr and for Rovelli both, 'observer' is defined entirely in terms of a *physical apparatus* making measurements, and so for both of them, different observers will give different (but complementary) accounts.

[6] Thus, Rovelli's 'Relational Quantum Mechanics' and Everett's 'Relative-State Interpretation', despite similar-sounding names, have little in common. Everett relies on the wave function of the entire universe; Rovelli countenances no such entity. Everett denies collapses in any circumstances, relying entirely on the Schrödinger evolution; Rovelli allows them in system–metasystem interactions. Given an interaction of this sort, Everett still allows for multiple 'realities'; in this case, Rovelli regards the physical state to be uniquely determined. For more detailed discussions of the differences and relations between Rovelli and Everett, see (Rovelli [1996], p. 5; and Laudisa and Rovelli [2005], Section 5.4).

[7] It is crucial to note the significance of the formalism *as it is normally used*. In particular, you will not see ordinary physics textbooks discussing the wave function of the Entire Universe, nor will

in conjunction with the rest of the discussion, leads us to the following conclusion:

> *Quantum mechanics is a theory about the physical description of physical systems relative to other systems, and this is a complete description of the world.* (Rovelli [1996], p. 7)

This is sensible enough; after all, it would seem that the only obvious way for different observers to give different *but correct* accounts would be to make the truth of accounts relative to different observers. So, we must include information about the system/metasystem cut when we specify states, observables, and quantities. That is, we must introduce a new indexical into the formalism: we speak of $|\psi\rangle_{S/O}$ and $|\psi\rangle_{SO/P}$, not $|\psi\rangle_S$ and $|\psi\rangle_{SO}$ simpliciter. At t_2 in the example above, we consider the following state ascriptions:

$$|\psi\rangle_{S/O} = |\uparrow\rangle_S,$$
$$|\psi\rangle_{SO/P} = \alpha|up\rangle_O\ |\uparrow\rangle_S + \beta|down\rangle_O\ |\downarrow\rangle_S.$$

From this conclusion it quickly follows that 'the notion of observer-independent description of the world' (ibid.) is inappropriate. Giving up this notion (like giving up the notion of absolute simultaneity in the case of special relativity) is supposed to put our worries about quantum mechanics at ease.

Put yet another way, Rovelli's interpretation amounts to complete acceptance of the principles given above, specifying 'measurement' as any system–metasystem interaction, and stressing that the Schrödinger dynamics applies only to the system in isolation.

3 Barrett on Relational Interpretations

Rather than discussing Rovelli's view explicitly, Jeffrey Barrett ([1999]) assimilates Rovelli's interpretation to David Mermin's view, which he discusses in detail. According to Barrett, Mermin tries to 'understand quantum mechanics in terms of statistical correlations *without there being any determinate correlata that the statistical correlations characterize*' (Barrett [1999], p. 217). Expanding further, he says that on Mermin's view,

> [P]hysics, properly understood, is about correlations and only correlations. It is not about correlations between determinate physical records nor is it about correlations between any other determinate physical properties.

such a wave function play a role in any familiar application of the formalism. It is an entity that is quite familiar to philosophers of physics, but one that Rovelli would see as entirely outside the normal usage. The formalism as normally used relies on a system/observer split, where only the system (in some sense) is described in the formalism. As we will see later on, this understanding of quantum mechanics is crucial to understanding Rovelli's position.

> Rather, physics is about correlations without correlata. According to Mermin, 'Correlations have physical realty; that which they correlate does not'.[8] (Barrett [1999], p. 217)

To put it another way, just as we normally index quantum states to times, views like Mermin's introduce an additional index into the variables of the theory that refers to the branch of the wave function relative to which the variable has a certain value. In the cases above, O would say that S is spin-up relative to S being $|\uparrow\rangle_S$, and S would be $|\uparrow\rangle_S$ relative to O observing it to be so, while O measures S as spin-down relative to S being $|\downarrow\rangle_S$, and S is $|\downarrow\rangle_S$ relative to O observing it to be so. All that we can say 'absolutely' is that S and O are correlated in a certain way; any further statements are relative to choice of a certain branch.

Barrett makes three major arguments against Mermin's account (Barrett [1999], pp. 218–9): (i) relations are necessarily relations between determinate relata, that is, a relations-without-relata view is (either metaphysically or analytically) incoherent; (ii) on Mermin's interpretation, there are no determinate physical records, and thus there are no determinate mental records (if mental states supervene on physical states in the ordinary way), and thus there are no determinate experiences, and thus the theory makes no determinate empirical predictions; (iii) Mermin's version of the theory does not even predict the right correlations since it does not tell us how to update the quantum state after a measurement. These criticisms are quite damning, if accurate. It is not my purpose to say whether Barrett gives a fair account of Mermin's view, nor to give responses on behalf of Mermin. Instead, I will examine how Rovelli's account differs from Mermin's view (as presented by Barrett), and ask whether Barrett's criticisms apply to Rovelli's account as well.

It turns out that there are a number of differences between Rovelli's view and the view that Barrett attacks. The most important thing to notice is that Rovelli does not index facts to branches, but to a system/metasystem cut. Rovelli's account admits a distinction between types of relations: on the one hand, there are system–system relations, and, on the other, there are system–observer relations. System–system relations are interactions among elements of the system that can become entangled quantum-mechanical correlations. System–observer relations are interactions between the system and observer such that a property of the system becomes actualized for the observer. While there is always in principle an observer who can treat any system–observer relation as a system–system relation (e.g., moving from O to P), that new observer will have different information about the system than the first, including different information about the determinacy of properties of the system.

[8] Barrett quotes (Mermin [1998], p. 2).

To make it sound less epistemic, the new observer will define a different cut between system and observer, and so the states, properties, etc., will, in general, be different.

From this, we can see that Rovelli would say something different about determinacy and relata/correlata. Insofar as we are looking for absolutely determinate relata, then Rovelli would agree that there are no such things. Rovelli's relations do hold between relata (different physical systems), and those relata *can be* determinate *relative* to system–observer relations. Determinacy is not entirely absent; it is just relativized to certain observer–system cuts. Furthermore, by performing the proper measurements (that is, by interacting with the system in the right ways), the observer can find determinate answers to any well-formed question (that is, the observer can render any particular property of the system determinate). What is more, different observers can get together and compare notes about their determinate results and they will find that they agree (though more on this later).

We can understand the peculiar relativity of determinacy better by asking why the unitary dynamics fails to apply in the system–observer interactions. This happens because of the incompleteness of *O*'s description of the interaction. As Rovelli puts it:

> From the point of view of [*P*], the measurement is therefore a fully unitary evolution, which is determined by the interaction Hamiltonian between *O* and *S*. An interaction is a measurement that brings the states to a correlated configuration. On the other hand, *O* gives a dynamical description of *S* alone. Therefore he can only use the *S* Hamiltonian. Since between times t_1 and t_2 the evolution of *S* is affected by its interaction with *O*, the description of the unitary evolution of *S* given by *O* breaks down. *The unitary evolution does not break down for mysterious physical quantum jumps, due to unknown effects, but simply because O is not giving a full dynamical description of the interaction.* *O* cannot have a full description of the interaction of *S* with himself (*O*), because his information is correlation, and there is no meaning in being correlated with oneself. (Rovelli [1997], p. 205, emphasis in original)

We can make a useful analogy to thermodynamics. So long as I am dealing with a closed system, the second law of thermodynamics applies. Once I open the system up to an influx of energy from outside, the second law breaks down, but that is only because I am not giving a full description of the interaction. I can bring the energy source into my description of the system, and it 'becomes' a closed system again, to which the second law applies perfectly well. Just as the order in an open system can increase, even though a closed-system description would not allow this, a non-dynamical description of a quantum system (i.e., one in which a measurement, and thus an intervention, has been made) can lead to a determinate result, even though a dynamical description (i.e., one that includes both system and measuring device) would not describe a determinate result.[9]

We can now provide answers to Barrett on Rovelli's behalf. First, counter to (i), it is not the case that relations necessarily depend on determinate relata. Models of relations with relata of a nondeterminate nature date back at least to Plato's *Theaetetus*, if not further.[10] Similarly, it seems that if we look at the perfect symmetry between defining volumes by integrating over points, or defining points as by series of smaller and smaller volumes, or the symmetry between defining graph-structures by listing their edges or their vertices, and other such symmetries,[11] it appears that there is no more problem giving primary reality to relations and abstracting relata from them, than there is giving primary reality to relata and showing how relations supervene on them. Or consider the following possibility: we have discovered that things can be broken down into molecules, molecules into atoms, atoms into subatomic particles, those particles into more fundamental particles. One might suppose it likely that this process of discovering smaller-and-smaller constituents will bottom out somewhere (and some believe that we have already arrived at this level, even if we haven't discovered all its members). But it is also imaginable that there exist sub-quark particles, and sub-sub-quark particles, and . . . so on and so on with no end.[12] It would certainly be a strange world, but nothing seems obviously incoherent or inconceivable about it. In such a case, we would have compounds without (non-compound) constituents, a special case of relations without relata.[13] Most recently, these issues have been explored in depth by structural realists, such as (Stachel [2002]; Saunders [2003]; Esfeld [2004]; Ladyman and Ross [2007]). Those who defend what Ladyman calls 'ontic structural realism' in particular have argued for the claims that Barrett simply dismisses as incoherent.[14]

[9] This analogy is not completely felicitous, because one can with some justification call the closed system in thermodynamics the *complete* description, and treat the effects in the open-system description as merely artifacts of an incomplete description. This option is not available in the quantum case, which will be described below.

[10] Plato describes the Protagorean/Heraclitean theory of perception as being one built on relations between non-determinate relata (so-called 'pure flux').

[11] Perhaps including the symmetry between neo-Humeanism (e.g., David Lewis) and Causal Structuralism (see Hawthorne [2001]). Humeans begin with simple intrinsic properties and take causal relations to be defined by them (supervene on them); only the intrinsic properties are essential, whereas causal relations or causal powers are contingent. Causal Structuralists like John Hawthorne take causal relations or powers to be essential, and properties to be defined entirely in terms of these causal profiles. Put this way, the symmetry between the ideas is striking.

[12] This is just Paul Churchland's 'onion-world' from (Churchland [1985]) or Jonathan Schaffer's 'metaphysic of infinite descent' (Schaffer [2003]). Schaffer brings up and answers many fundamentalist objections to such worlds. While the controversy still rages, it seems implausible to dismiss such views as simply incoherent.

[13] That is, relations without *non-relational* relata. But it seems obvious that no relationalist could insist that there were *no* relata, just that there are no relata that aren't themselves exhaustively captured by the relations they stand in.

[14] Many thanks to an anonymous referee of *BJPS* for drawing the connection between this discussion and the work of structural realists.

Whether such theories have their difficulties, it is not the case that they can be dismissed summarily, without looking to the specifics of each view.

Whether relations-without-relata views hold up is itself probably beside the point for Rovelli, because, counter to (ii), determinate physical records *do* exist (relative to a cut), as do determinate experiences. Attempting to understand whether this determinacy is enough will occupy the remainder of this essay, as there still may be a sort of determinacy problem. But one should note that this view is crucially different from Mermin's view, because relations are *not* the only thing that have physical reality. In addition to relations, there are interventions that produce determinate physical records. Now, *these* records are themselves *relational* in the sense that their determinacy is relative to a cut, but this relationality is different from Mermin's correlations (as seen above), and the description that focuses on the correlations (i.e., the one that treats the elements in question under the dynamics) is no more fundamental than the other (and in fact, a description that was entirely at the level of the dynamics would never get any information about determinate properties).

Counter to (iii), Rovelli (unlike Mermin) can tell each observer how to update his states after a measurement: just as the standard formalism tells us to. That is, when measurement-system O performs a measurement on system S, there is a reduction of the state function $|\psi\rangle_{S/O}$ according to the Collapse Postulate (Process I). On the other hand, relative to measurement-system P which has not yet had a measurement interaction with the $S+O$ system, the state $|\psi\rangle_{SO/P}$ continues to evolve according to the Schrödinger dynamics, governed by the appropriate Hamiltonian for the interaction of S and O. For any further system/observer cuts,[15] the question of how to update states after measurement depends on where the boundary lies. If, like P, a further measurement system treats S and O as parts of the system of study, then the interaction between S and O will be covered by the Schrödinger dynamics. On the other hand, if all or part of O is left out of the system of study, and thus is on the measurement-system side of the cut, then the Collapse Postulate will again play a role.

Suppose we decompose O (in our example above, the Stern–Gerlach apparatus for measuring spin) into two parts, O'_1 and O'_2. We treat the new system under study as $S+O'_1$ and the measurement system as O'_2. Once the measurement is complete, we will have a reduction of the state function $|\psi\rangle_{SO'_1/O'_2}$ according to the Collapse Postulate (though, since the cut is rather unnatural from the point of view of the standard practice of quantum mechanics, it may be quite difficult in practice to describe the pre-measurement and post-measurement states). This measurement may differ in some details from the original measurement (e.g., in the time that the measurement will have been

[15] My thanks to an anonymous referee of *BJPS* for raising this issue, allowing me to expand on and further clarify Rovelli's account of measurement.

said to occur—see Rovelli [1998]; See also the puzzle raised in the next section), but in both cases, since the measurement system has an interaction with the system being described, Rovelli tells us there will be a collapse. When we have an observer–system cut, relational quantum mechanics tells us that it is the system that we describe quantum mechanically, and that any time the observing system 'interferes' with the system under description, that constitutes a 'measurement' event for the purposes of the standard formalism.[16]

It is important here to qualify a point made earlier: Rovelli, perhaps incautiously, says that O does not give 'a full dynamical description of the interaction' of O with S. One could read this with emphasis on the description not being *full* (i.e., complete). This leads to the question: how could an incomplete *description* solve the problem of *metaphysical* determinacy. This brings into question whether Rovelli has a satisfactory answer to the question about determinate measurement records (ii). Furthermore, one would also be led to ask: why would anyone ever be justified in using an incomplete description if one knows (or knows that there could be) a more complete description?[17] I suggest that if this move is going to do what Rovelli thinks it does, we must instead read the point at issue with emphasis on the description not being *fully dynamical*. Here, we have two different types of description: partially dynamical description plus non-dynamical[18] intervention versus fully dynamical description.[19] We haven't got a distinction between more and less complete descriptions of the same thing, because, first, the two descriptions are different, relying on different information, but neither is more complete than the other, and second, O can gather more information than P at certain points in the process (like the determinate state of S at t_2), and, third, because they aren't descriptions of the *same* thing in the sense of the same *state*, since states are individuated relative to cuts, not independent of them (though, of course, it is the same *system*). The state of S relative to S/O is not identical to the state of S relative to SO/P. States are relational creatures, relative to cuts, and thus two different cuts define two distinct states.

On a certain reading of criticism (iii), though, the objection might stand: namely, the theory doesn't give us a fully dynamical or deterministic way of updating 'the quantum state', taken as a perspective-free entity (such as

[16] It is an important consequence of Rovelli's interpretation that complete self-measurement is impossible (Rovelli [1996], p. 17). As Rovelli points out, this accords with a general theorem proved by Breuer demonstrating this impossibility for classical, quantum, deterministic, and stochastic systems (Breuer [1995]).

[17] Thanks to Jeff Barrett and Craig Callender for pointing out the problems with this reading.

[18] In the sense of 'dynamical' defined by the Schrödinger dynamics.

[19] Even this is not quite right. The first type is not really even a description, because quantum mechanics cannot describe what *will* happen in an intervention, only that there is some probability of certain options. And whereof quantum mechanics cannot speak, it just so happens that it is silent.

Everettians might take it). Given the 'wave function of the universe', no information about system–observer cuts will lead you to determinate outcomes, but Rovelli doesn't regard this as an admissible entity of quantum mechanics. If the requirement is instead the rather more tractable task, that the formalism give us the requisite information about how to update the states as used in ordinary quantum mechanical practice, which (says Rovelli) are implicitly defined by the cut between system of study and measurement system then Rovelli's interpretation does indeed tell us how to update our states: Before a measurement interaction, update states according to the Schrödinger dynamics; after measurement interaction, 'collapse' the state into the eigenstate it was found to actually be in.

4 A Puzzle about Relative States

We can recapture a similar worry about relational quantum mechanics by comparing what happens at t_2 for O to what happens at the time of P's measurement, t_3. As noted by von Neumann ([1932]), no matter where one places a cut, the probabilities will always agree, so, prior to the actual measurements, O and P will agree on the probabilities of finding states associated with the electron's being spin-up. According to the Malus–Born law, at t_2 there is a probability of $|\alpha^2|$ that O will find S to be x-spin-up and a probability of $|\beta^2|$ that O will find it down. Now suppose that O measures 'up'. So, according to the relational interpretation, the state of S for O is actually $|\psi\rangle_{S/O} = |\uparrow\rangle_S$. Further, according to the relational interpretation, the state of $S{+}O$ for P is $|\psi\rangle_{SO/P} = \alpha|up\rangle_O\ |\uparrow\rangle_S + \beta|down\rangle_O\ |\downarrow\rangle_S$. According to the Malus–Born law, the probability that P will find the state at t_3 to be $|up\rangle_O\ |\uparrow\rangle_S$ (electron spin-up and O indicating 'up') is $|\alpha^2|$, and the probability of $|down\rangle_O\ |\downarrow\rangle_S$ is $|\beta^2|$. So, as von Neumann taught us, the *probabilities* agree. But notice: if we are to take **R2** seriously, *nothing* said so far prevents it from being the case that P finds $|down\rangle_O\ |\downarrow\rangle_S$ at t_3, and thus S being spin-down for P, *even though S was spin-up for O!*

Things get even more interesting. P will never know that S was spin-up for O, because, for P, S was spin-down for O. That is, P measures not S's state in isolation ($|\psi\rangle_{S/P}$), but $S{+}O$. And, for P, O's state is 'down.' So, for P, O's observation is consistent with P's own observation of S (as part of the $S + O$ system). So, while O observed 'up' according to O, O observed 'down' according to P. Any subsequent observations P does are going to be consistent with all the other observations that P has done. But here's the puzzle: we have parallel sets of consistent events relative to O and P, which nevertheless disagree. Consider a case where O is Schrödinger's cat and P is the evil experimenter. The cat could be dead for the cat, while he's alive for P. If you think that there is a problem with spontaneous reanimation (or, perhaps, since the cat remains dead *for the* *cat*, a certain kind of undead zombie), then you might think there is a problem with the relational interpretation.

You might think that one could solve the 'dispute' between P and O at t_2 over whether the state of S has collapsed, at least in principle. After all, we know we can specify an observable that will distinguish between S being in a superposition and S having collapsed without doing anything that would actually collapse S or reveal its state. Indeed, as Wigner has shown, it is possible to do so, and so it might be possible to adjudicate the dispute. This too fails, however, because the observable must be specified relative to a cut. It is not the case that there is some $\hat{A}$ that each observer could apply to $|\psi\rangle_S$. Instead, there is $\hat{A}_{S/O}$ that P can apply to $|\psi\rangle_{S/O}$ and $\hat{A}_{SO/P}$ that P can apply to $|\psi\rangle_{SO/P}$. Now, according to Rovelli, the former observable at (or just after) t_2 will indicate that the system is not in a superposition, while the latter will indicate that it is. This renders no contradiction, as both the observables and the states they are applied to are different.

One might put the point in a somewhat different way.[20] There *is* actually some $\hat{A}$ that each observer could apply to S to determine how the collapse went, whether the cat collapsed it or the scientist did. But if one could measure $\hat{A}$, the description and the result would be relative to some enormous measuring apparatus (if such was even possible). Say that $\hat{A}$ tells you that S was in a superposition at t_2. This is entirely compatible with S being in a determinate state at t_2 relative to O.

So we won't solve the puzzle this way. In other words, the puzzle is not a violation of *anything* observable.

5 Canonical Cuts

One way to solve the problem might be to suppose that there are canonical ways to cut up particular physical situations. In all the contexts we're interested in, it will be obvious where to place the cut between system and metasystem. This response shares affinities with Bohr's interpretation, which insists on careful specification of the measuring apparatus and the system in a way that lends itself to an unambiguous interpretation and communication of the measurement.

If I'm interested in testing some predictions about superconducting nanobelts, I will go down to the lab down in the basement of the physics building, get out my sample, position it among various standard bits of equipment, and start running some tests. It is obvious what the system whose states or properties I'm interested in is: the sample of nanobelts. It is equally obvious what counts as part of the measurement system: the various bits of lab equipment that I use to perform the experiment. One could argue that this

[20] I'm indebted to Craig Callender for this alternative.

will be the case for any physical situation of interest, and thus that there are canonical observer–system cuts. Furthermore, canonical cuts may be helpful in explaining experience, if we can explain how such cuts match up with our ordinary perspectives.

There is something dissatisfying, and perhaps even *ad hoc* about this solution. Must we really introduce such canonical cuts? Are there really canonical cuts in *all* physical situations of interest, or merely in a narrow class of circumscribed experimental situations? On the very frontiers of science, experimentalists must work very hard to design measuring equipment that can actually isolate interesting phenomena. It is very far from obvious how to separate system from observer. What happens if we insist that any old cut will do?

6 Is Quantum Consistency Enough?

Without adverting to something like a canonical cut, the relationalist has a ready answer to this paradox: the problem only gets off the ground if one assumes some absolute standpoint from which to view the situation. Because of the self-consistency of the quantum framework, any possible standpoint is going to predict consistent results among any subsystems of the system under consideration. This consistency is taken as a cardinal virtue of the relational interpretation by its adherents:

> This internal self-consistency of the quantum formalism is general, and it is perhaps its most remarkable aspect. This self-consistency is taken in relational quantum mechanics as a strong indication of the relational nature of the world. (Laudisa and Rovelli [2005])

Just as a number of seeming paradoxes in relativity disappear when we let go of the notion of absolute simultaneity, this paradox disappears when we let go of the absolute standpoint, of absolute states, quantities, and events. Once we give up the idea of absolute state, we are unable to state the paradox; any description allowable by quantum mechanics will allow full consistency. We can describe the match between *S* and *O* from the point of view of *P*, and we can compare the points of view of *O* and *P* from yet another observer, *Q*, and in all of these situations the results will come out consistent. It is only if we assume that different observers are embedded in a larger, non-quantum view-from-nowhere that paradoxes arise. As Rovelli says,

> [T]he notion 'A system *O* has information about a system *S*' is a physical notion that can be studied experimentally (by a third observer), in the same way as any other physical property of a system. In particular, the question 'Do observers *O* and [*P*] get the *same* answers out of a system *S*?' is a *meaningless* question. It is a question about the *absolute state* of *O* and

> [*P*]. What is meaningful is to reformulate this question in terms of some observer. (Rovelli [1997], p. 204)

That *O* observed 'spin-up' is not a fact that can be stated absolutely. We cannot make a statement about *O*'s knowledge without reference to another observer. From t_2 to t_3, we can consider questions about the answer that *O* gets from the standpoint of *O*, who will arrive at a determinate answer because of the breakdown of the unitary dynamics, and we can consider from the standpoint of *P*, where *O* will at first be correlated with the superposed states of *S*, and then become determinate when the dynamics breaks down because of *P*'s own intervention.

The move here can again be understood by analogy, this time to special relativity (so, we end where we begin). In special relativity, certain paradoxes arise, where observer *Q* observes event *A* to precede event *B*, while observer *R* sees *A* following *B*. The contradiction disappears when we give up the notion of absolute simultaneity. Likewise, the contradictions disappear in relational quantum mechanics when we give up the notion of absolute state or absolute physical quantities. In special relativity, certain invariants remain, like the worldlines of particles through spacetime. Likewise, in relational quantum mechanics, the physical relations between systems remain invariant. (*O* and *P* agree about the relation of *O* to *S*, but at t_2 they disagree about the determinacy of each.)

The view has its attractions. Unlike realistic-collapse theories, it takes the predictions of the formalism with full seriousness. It will in fact conflict with collapse theories when it comes to whether *P* could measure a superposition ($\hat{A}$) at t_2. Unlike ordinary no-collapse theories, it gives us determinate measurement records (as determinate as we could want) without adverting to a dualistic solution to do so, for the theory posits no extra entities beyond what the ordinary formalism requires, nor does it require any quantum minds or divergent worlds, actuality-markers or Bohmian particles, or any such contrivances. The theory doesn't even require reference to consciousness or any human agents whatsoever. The processes of measurement considered are mundane old physical interactions, ones that can (from a certain point of view) be described quantum-mechanically. On the other hand, we fail to capture the security of the unified world of classical mechanics. Maybe the price isn't so much to pay, given the dismal array of alternative options.

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References

Barrett, J. A. [1999]: *The Quantum Mechanics of Minds and Worlds*, Oxford: Oxford Univeristy Press.

Breuer, T. [1995]: 'The Impossibility of Accurate State Self-Measurements', *Philosophy of Science*, **62**, pp. 197–214.

Churchland, P. M. [1985]: 'Conceptual Progress and Word/World Relations: In Search of the Essence of Natural Kinds', *Canadian Journal of Philosophy*, **15**, pp. 1–17.

Esfeld, M. [2004]: 'Quantum Entanglement and a Metaphysics of Relations', *Studies in History and Philosophy of Modern Physics*, **35**, pp. 601–17.

Finkelsten, D. R. [1996]: *Quantum Relativity: A Synthesis of the Ideas of Einstein and Heisenberg*, Berlin: Springer.

Finkelstein, D. R. [unpublished]: 'Finite Quantum Relativity', <http://www.physics.gatech.edu/people/faculty/finkelstein/FQR02.pdf>.

Grinbaum, A. [2003]: 'Elements of Information-Theoretic Derivation of the Formalism of Quantum Theory', *International Journal of Quantum Information*, **1**, pp. 289–300.

Grinbaum, A. [2005]: 'Information-Theoretic Principle Entails Orthomodularity of a Lattice', *Foundations of Physics Letters*, **18**, pp. 563–72.

Grinbaum, A. [2007]: 'Reconstruction of Quantum Theory', *British Journal for the Philosophy of Science*, **58**, pp. 387–408.

Hawthorne, J. [2001]: 'Causal Structuralism', *Noûs*, **35**, pp. 361–78.

Laudisa, F. and Rovelli, C. [2005]: 'Relational Quantum Mechanics', in E. N. Zalta (*ed.*), Fall 2005, *The Stanford Encyclopedia of Philosophy*, <http://plato.stanford.edu/archives/fall2005/entries/qm-relational/>.

Ladyman, J. and Ross, D. [2007]: 'Ontic Structural Realism and the Philosophy of Physics', in *Every Thing Must Go: Metaphysics Naturalized*, Oxford: Oxford University Press, pp. 130–89.

Mermin, N. D. [1998]: 'What Is Quantum Mechanics Trying to Tell Us?', *American Journal of Physics*, **66**, pp. 753–67.

Rovelli, C. [1996]: 'Relational Quantum Mechanics', *International Journal of Theoretical Physics*, **35**, pp. 1637–78. Page references are to later revised version (24 Feb 1997), <arxiv.org/abs/quant-ph/9609002v2>.

Rovelli, C. [1997]: 'Halfway Through the Woods: Contemporary Research on Space and Time', in J. Earman and J. D. Norton (*eds*), *The Cosmos of Science: Essays of Exploration*, Pittsburgh, MA: University of Pittsburgh Press, pp. 180–223.

Rovelli, C. [1998]: '"Incerto Tempore, Incertisque Loci": Can We Compute the Exact Time at Which a Quantum Measurement Happens?', *Foundations of Physics*, **28**, pp. 1031–43.

Saunders, S. [2003]: 'Structural Realism Again', *Synthese*, **136**, pp. 127–33.

Schaffer, J. [2003]: 'Is There a Fundamental Level?', *Nous*, **37**, pp. 498–517.

Stachel, J. [2002]: '"The Relations between Things" versus "The Things between Relations": The Deeper Meaning of the Hole Argument', in D. Malament (*ed.*), *Reading Natural Philosophy: Essays in the History and Philosophy of Science and Mathematics*, Chicago and LaSalle, IL: Open Court, pp. 231–66.

von Neumann, J. [1932]: *Mathematische Grundlagen der Quantenmechanik*, Berlin: Julius Springer.