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14.1 Introduction: The Ongoing Relativization of Physical Quantities

According to Kuhn ((1962), p. 85), a radical change in our physical worldview is not just due to the invention of a mathematical formalism or to new empirical information coming from novel experiments, but it also implies a thorough modification of the fundamental concepts with which we interpret the world of our experience. This is particularly evident in the scientific revolution ushered by Galileo (Koyré (1978)), which consisted essentially in the discovery of the equivalence between uniform motion and rest, two notions that had always been sharply contrasted, but whose indistinguishability is essential to attribute a counterintuitive state of motion to our planet.

The same moral applies to Einstein's Special Theory of Relativity (STR). Not by chance, Rovelli's relational interpretation of quantum mechanics[1] draws inspiration from the latter theory, by correctly claiming that Einstein's (1905) paper did not change the existing physics, but provided a new interpretation of an already available formalism. As is well known, this interpretation was obtained *via* a critique of an implicit assumption—absolute simultaneity—that is inappropriate to describe the physical world when velocities are significantly close to that

[1] Rovelli (1996); Laudisa and Rovelli (2008)).

of light. It is important to note that it was only thanks to the abandonment of such an assumption—that depends on the "manifest image of the world",[2] and in particular on that belief in a cosmically extended now that percolated in Newton's *Principia*—that Einstein could postulate the two axioms of the theory, namely the independence of the speed of light from the motion of the source (its invariance) and the universal validity of the principle of relativity. What is relevant here is to recall that not only do these axioms imply the *relativization* of velocity, already theorized by Galilei, but also that of the *spatial* and *temporal intervals* (separately considered), a fact that became particular clear with Minkowski's (1908) geometrization of the theory.

The historical theme of the relativization of quantities that were previously regarded as absolute is central also in Rovelli's relational approach to quantum mechanics (RQM), whose metaphysical consequences, strangely enough, have not yet been explored in depth. This is particularly surprising because in his interpretation, Rovelli proposes a much more radical relativization than that required by STR, namely the relativization of the possession of definite physical magnitudes to *interacting physical systems*. Rovelli's relativization is more radical with respect to previous historical cases for at least two reasons:

1) It might be argued that RQM seems to relativize the very notion of "entity", at least to the extent that the possession of some *intrinsically* definite properties is essential to the identity of an object. In the relational quantum world envisaged by Rovelli, the identity of entities might in fact be purely relational or structural, at least for what concerns their state-dependent properties. Assertions like "relative to system *O*, system *S* has value *q*" according to Rovelli are in fact true only relative to *O*. For another system *P* that has not yet interacted with *S*+*O*, *S* has no definite value at all. In STR, on the contrary, at least if one rejects, as nowadays is the case, the verificationist theory of meaning, the fact that "body *B* has length *L* in the inertial system *S* " holds for any possible inertial observer, even those that have no epistemic access to *S*. Of course, the presence of an interaction presupposes that *S* and *O* both exist separately, so that what is in question is not the existence of *two* systems, but rather how we have to interpret their properties and the process of their interaction.

2) Second, and relatedly, while STR imposes a new absolute quantity that replaces the old ones now regarded as relative (the four-dimensional Minkowski metric, or the spatiotemporal interval), Rovelli, as we will see, *seems* to have no new absolute quantity to propose: "In quantum mechanics different observers

[2] Sellars (1962).

may give different accounts of the *same* sequence of events" ((1998), p. 4, italics added).[3] However, how can we identify the "same" sequence of events within a relationist view of quantum mechanics? And furthermore, can a physical theory fail to possess at least some invariant elements that, together with the relevant symmetries, help us to identify what is objective or observer-independent? Can the whole universe be such an invariant?

In this paper, I will try to answer these questions by analyzing some of the metaphysical consequences of relational quantum mechanics (RQM), in particular by focusing on question of the status of the whole (holism and monism) with respect to its parts. My main claim is that *if* Rovelli's interpretation is correct or even plausible, then it does not legitimate the sort of *priority monism* advocated by Schaffer (2010a),[4] since its firm advocacy of locality has radical anti-holistic consequences, in particular on the way we should construe the passage of time.

Here is the plan of the paper. In the second section, I will present in greater detail Rovelli's RQM. In the third I will defend it from some foreseeable objections, so as to clarify its philosophical implications vis-à-vis some rival but closely related interpretations. In particular I will ask whether RQM presupposes a hidden recourse to a duality of both temporal evolutions and ontology (the relationality of quantum world and the intrinsicness of the classical world, which in the limit $\hbar \to 0$ must be recovered from the former). In the fourth section I will concentrate on the pluralistic, antimonistic metaphysical consequences of the theory, due to the impossibility of assigning a state to the quantum universe. Finally, in the last section I will note some interesting consequences of RQM with respect to the possibility of defining a local, quantum relativistic becoming (in flat spacetimes). Given the difficulties of having the cosmic form of becoming that would be appropriate for priority monism, RQM seems to present an important advantage with respect to monistic views, at least insofar far as the possibility of explaining our experience of time is concerned.

14.2 RQM in a Nutshell: Interpreting Rovelli's Interpretation of Quantum Mechanics

Let me begin by summarizing my take on Rovelli's RQM with the help of four slogans: 1) go revisionary about the metaphysical assumptions of common sense; 2) go dispositionalist about isolated quantum systems; 3) go instrumentalist about

[3] The meaning of "observer" and "same" will be clarified below.

[4] As we will see, according to priority monism, the parts exist but the whole has ontic and epistemic priority over the parts.

the wave function; 4) stress the relationality or structural nature of the identity of quantum systems.

I will now present these four points in turn, by warning the reader that I depart somewhat from Rovelli's original formulation of RQM, with the intent of giving it more coherence while exploring at the same time its metaphysical consequences. In particular, we will see that the acceptance of 2) might imply that Rovelli's antirealism about the wave function needs to be qualified.

14.2.1 Go Revisionary About the Metaphysical Assumptions of Common Sense

The first slogan presupposes a methodological and conceptual point. Non-relativistic quantum mechanics has often been regarded as either "wrong" or incomplete. For this reason, in the last 70 years there have been attempts at either changing the formalism of quantum mechanics—*via* nonlinear corrections of Schrödinger's equation—or at adding to an ontology of localized particles "guided" by a new velocity field. Contrary to these endeavours, RQM proposes a move that is similar to Einstein's renunciation of the absoluteness of simultaneity, with a resulting abandonment of important components of the world of our experience. In a word, Rovelli's philosophical strategy can be summarized thus: don't change the formalism of quantum mechanics, but rather your manifest image of the world[5] in accordance with the formalism and the experimental practice of the theory. In this respect, Rovelli's revisionary metaphysics is very similar to Everett's (1957) relative-state approach to quantum mechanics (not to the many-worlds version of it), but with some important differences that will be specified in section 14.3.

According to RQM, the assumption of the manifest image that we need to give up in order to make sense of quantum mechanics is very deep-seated in our cognitive make-up since it is rather well-established in the *classical* world, a world to which we adapted in the course of evolution. The assumption is that objects and events inhabiting the physical world possess intrinsic, definite, and non-purely relational properties. In Rovelli's view, on the contrary, in the quantum world—and in the world simpliciter, to the extent that the classical world is reducible to the quantum world, a question that Rovelli does not treat explicitly but that will be raised in the following—there are no observer-independent properties, where "observer" here is any physical system, of any size (microscopic or macroscopic, quantum or classical) that is able to carry *information* about a quantum system.[6]

[5] The expression is in Sellars (1962).

[6] I don't think that the epistemic notion of "information" is appropriate to look at RQM from a metaphysical viewpoint, but my brief comments about this point will be presented below.

14.2.2 Go Dispositionalist About Isolated Quantum Systems

What do "intrinsic" and "definite" mean here? A table has a shape, and shapes are prima facie intrinsic properties, properties that is, that the objects in question would have even if they were "lonely", that is, the only objects in the universe.[7] Likewise the properties charge or mass appear to be intrinsic; our weight is instead relational, since it depends on whether, for instance, we are on the Moon or here on Earth.

The notion of "intrinsic" that enters in RQM can be formulated in two related ways, a distinction that I think requires a further elaboration of Rovelli's original RQM: either i) it *does not make sense* to talk about a quantum non-interacting system (and if this were our reading, his position would be close to Bohr's), or ii) to put it more metaphysically, both non-interacting quantum systems *S* and observers *O* have no intrinsic properties, except *dispositional* ones. In other words, such systems *S* have intrinsic dispositions to correlate with other systems/observers *O*, which *manifest* themselves as the possession of definite properties *q* relative to those *Os*.

Unlike the standard quantum dispositionalism, however,[8] these manifestations depend also on the contributions of the intrinsic dispositions that the various systems *Os* have to correlate with *S*, in the sense that the role of *O* and *S* is interchangeable. The relation " .. . manifest *q* relative to . . . " holding between "system" and "observer" is therefore fully symmetric, and this is a simple consequence of the hypothesis that in RQM quantum systems and "observers" are on the same level. As already specified above, the latter are not necessarily classical, macroscopic, or conscious, but can also be *quantum* systems.

Consequently, in RQM a quantum disposition is not to be regarded as passive but rather as *active*, a viewpoint that makes very good sense also at the classical level. A match has the disposition of being flammable when struck; oxygen has the disposition to take part in burning processes, but the lighting of the match, the manifestation of these dispositions, is the joint product of a "team work" formed by the dispositions of the oxygen plus those of the match. This view of dispositional properties has been labelled by Mumford and Anjum[9] 'the mutual manifestation model' and considers the manifestation event to be the *joint*

[7] "The intrinsic properties of something depend only on that thing; whereas the extrinsic properties of something may depend, wholly or partly, on something else. If something has an intrinsic property, then so does any perfect duplicate of that thing; whereas duplicates situated in different surroundings will differ in their extrinsic properties," Lewis (1983), pp. 111–12.

[8] A dispositionalist view of quantum mechanics has been variously defended by Heisenberg (1958); Margenau (1954); and, more recently, by Suárez (2004).

[9] (2013), pp. 104–6.

product of the object traditionally regarded as bearing the disposition and of the object traditionally regarded as being the stimulus. In Martin's example, the solution of water and salt is the joint product of the soluble salt and the solvent water, but these substances have many other dispositions, depending on the particular interactions they undergo:

> The reciprocities of these dispositionalities for their mutual manifestations are many, deep and complex. The important point is that for a specific mutual manifestation, any particular dispositional state is itself only one among many other dispositional states that together form reciprocal disposition partners for their particular mutual manifestation.[10]

This reciprocity view is exactly what is needed by RQM, since the manifestations of definite properties are the joint product of the dispositions of *S* with those of *O*. In this way, the manifestation of such dispositions, the definite events *q*, depends also on the dispositions of the "observer", and not just on those of *S*. And in fact, as we will see, for another "observer" *P*, who has not yet interacted with *S*, *S* has no definite properties, and neither does the joint system *S*+*O*. Analogously, the dispositions of *O* depend on the system *S* with which it interacts.

In a word, from this perspective it is possible to conclude that according to RQM, all quantum systems *S* possess merely dispositional (state-dependent) properties to correlate and exchange information with observers *O* in a process in which the flow of information between the two is never unidirectional, even though this flow may vary as a function of the two interacting systems.

It could be retorted that given the philosophical framework of the original formulation of RQM, we should limit ourselves to claiming—*semantically*, or in the *formal* mode—that *descriptions* of isolated quantum systems are meaningless or, less radically, that they lack definite truth-values. Rather than formulating the theory *ontologically* or in the material mode, we should refrain from assuming that RQM refers to the state-dependent features of quantum objects as real, concrete dispositions.[11] Rovelli and Laudisa do not explicitly distinguish between these two modes, and by mixing them in a single sentence, seem to regard them as equivalent:

> The physical world is thus seen as a net of interacting components, where *there is no meaning* to the state of an isolated system. A physical system (or, more precisely, its contingent state) is reduced to the net of relations it entertains with the surrounding systems, and *the physical structure of the world is identified as this net of relationships*.[12]

[10] Martin (2008), p. 2.
[11] The distinction between formal and material mode is in Carnap (1934).
[12] Laudisa and Rovelli (2008), p. 1, my emphasis.

However, to the extent that RQM programmatically wants to be distinguished from the Copenhagen interpretation, and to the extent that one is interested in the metaphysical intimations of RQM, the second (ontological) mode of presentation of the theory is to be preferred. After all, the lack of meaning in the relevant descriptions can be interpreted as a consequence of an ontological fact, which points to the dispositionality of the quantum world, or to the lack of categorical facts about isolated quantum systems.

This dispositionalist move has at least four clear advantages over the merely semantic approach. The first is that in this way it becomes possible to retain some continuity with the ontology of the classical world, even if the latter were not reducible to the quantum world. In fact, properties of macroscopic objects can be identified with their causal powers too.

The second is that to the extent that mass, charge, and spin, which are typically regarded as intrinsic, state-independent properties, can also be viewed as dispositional—and there are good reasons to take this stance[13]—we gain a unified, dispositionalist account of both kinds of *quantum* states. The third advantage over claims of meaninglessness is to favour and even justify an entity-realistic account[14] also of isolated quantum systems and not just of interacting ones. In RQM, despite the possibility that also the above-mentioned intrinsic properties are in the end merely relational,[15] one has to presuppose that *S* and *O* exist for the simple reason that definite reality is the outcome of a correlation. A (cor)relation without the existence of relata is, I take it, rather hard to conceive, if not logically impossible. This entity-realistic commitment distinguishes RQM from the so-called "Ithaca interpretation of Quantum Mechanics", according to which in quantum mechanics only correlations are real, and relata aren't.[16] Rovelli need not deny with the instrumentalists the *existence* of isolated quantum systems (or observers): *qua* carriers of dispositions, such systems can be regarded as real as the table on which I am typing. "Going dispositionalist" as the second slogan recommends ensures both the reality of the isolated systems and the lack of definiteness and relationality of state-dependent magnitudes.

The fourth advantage of talking about dispositions in quantum mechanics is related to a well-known feature of the logical structure of quantum mechanics.

[13] For a dispositional treatment of mass and charge, see Dorato and Esfeld (2015). For a dispositionalist approach to the metaphysics of laws, see Bird (2007a).

[14] See Hacking (1983).

[15] Given the role of Higgs' boson, one might defend the claim that also mass is the product of a correlation with a network of relations.

[16] See Mermin (1998).

This feature forbids the simultaneous attribution of definite properties to quantum systems whose dimensionality is greater than or equal to three.[17] In any interpretation of quantum mechanics, this no-go result forces us to consider some of these properties as *contextual*, that is, as dependent on the kind of measurement we perform. Even in theories in which additional definite magnitudes are provided, like Bohmian mechanics, it is necessary to consider spin as a dispositional property, namely as a contextual property whose manifestation depends on the particular arrangement of the measurement apparatus *O*. Of course, how quantum dispositions are to be understood will depend on the particular interpretation of quantum mechanics.[18] In Bohmian mechanics for instance, the dispositional property "spin" in a certain direction is *reducible* to the positions of the particles constituting *S* and the settings of *O*.[19] In RQM and in other interpretations, dispositions have no categorical basis, and are therefore *irreducible*.

14.2.3 Go Instrumentalist About the Wave Function

The third slogan helps us to distinguish RQM from Everett's relative-state type of interpretations. A first difference is that in Rovelli's view there are real physical interactions between systems and observers that "break" entangled states, while in Everettian approaches the only physical evolution that is admitted is Schrödinger's linear and deterministic one, plus a resort to decoherence, which in any case *preserves* and extends entangled states but just makes them inaccessible to local observers. A second important point is that in Everettian quantum mechanics a universal quantum state is presupposed as *existent*: it is all there is. On the contrary, Rovelli explicitly denies any ontological role to the wave function, which in his opinion must be reduced to a merely predictive device.

In the dispositionalist reading that is suggested here, however, the wave function—while also recording the probabilistic outcomes of previous interactions between systems of a certain kind—might also be taken to represent the dispositional properties of quantum systems in their interaction with "observers". In this paper I have no space to elaborate this hypothesis:[20] what matters here is to note that if it were validated, RQM could not be regarded as giving a thoroughly instrumentalist account of the wave function.[21]

[17] Kochen and Specker (1967).
[18] Dorato (2006b, 2007).
[19] Clifton and Pagonis (1995).
[20] See Dorato and Esfeld (2015).
[21] Here I will not comment on the "spacetime state realism" put forward by Timpson and Wallace (2010), which is another interesting *tertium quid* between wave function realism and full instrumentalism.

Antirealism about the wave function in the restricted sense specified above has its advantages, which will be discussed in the next section. For now, it should be stressed that the "beables" of RQM,[22] its fundamental or *primitive* ontological posits[23] are those *quantum events* that are the manifestation of the dispositions of isolated systems to reveal certain values, relative to other well-identified systems that in turns possess other dispositional properties. For instance, a Stern-Gerlach apparatus revealing spin up is a quantum event. It is important to quote from the following passage, since the language in which the theory is stated ('actualization', 'coming into being') seems to confirm the dispositionalist interpretation of RQM offered above, as well as making room for a view of temporal becoming that will be broached in the last section:

> The real events of the world are the 'realization' (the 'coming to reality', the 'actualization') of the values q, q', q'', . . . in the course of the interaction between physical systems. This actualization of a variable q in the course of an interaction can be denoted as the *quantum event q*.[24]

14.2.4 Stress the Relationality or Structural Nature of the Identity of Quantum Systems

The fourth slogan helps us to realize how the identity of a sequence of events, that is, the *processes* that characterize the evolutions of the primitive ontology of the theory, is relative to the different observers. With obvious notation, suppose that at time t_1 the state of the quantum system S is:

$$|\Psi_S\rangle = a|\uparrow\rangle_S + b|\downarrow\rangle_S$$
$$|a|^2 + |b|^2 = 1$$

Suppose that at time t_2 a physical system O interacts with S and that, relative to O, the spin of S is 'up', that is, $|\uparrow\rangle_S$ Consequently the state of S for O evolves from $|ready\rangle_0|\Psi_S$ at time t_1 to $|\Psi\rangle_{S/O} = |\uparrow\rangle_S$ at time t_2. The index S/O denotes the relativity of the properties of the system S to O. If another physical system P has not interacted with $S+O$ yet, at time t_2 and relatively to P, RQM prescribes that the description of the combined $S+O$ system will not report definite events, since it relies on the linearity of the evolution of the Ψ function ruled by Schrödinger's equation. This means that according to P, the state at t_2 is a superposition of O observing spin up with S being spin up, plus O observing

[22] The term 'be*able*' is in Bell (1993), p. 174, to be contrasted with observ*able*.
[23] For this notion, see Allori et al (2008), who however use it in a rather different philosophical framework.
[24] Laudisa and Rovelli (2008).

being spin down and *S* being spin down, with the same coefficients as before. A remarkable consequence of RQM has already been noted by Brown:

> The state of *S*+*O* for *P* is $|\Psi\rangle_{SO/P} = a|up\rangle_O|\uparrow\rangle_S + b|down\rangle_O|\downarrow\rangle_S$ [at time t_2]. According to the Maus–Born law, the probability that *P* will find the state at [a later time] t_3 to be $|up\rangle_O|\uparrow\rangle_S$ (electron spin-up and *O* indicating 'up') is $|a|^2$, and the probability of $|down\rangle_O|\downarrow\rangle_S$ is $|b|^2$. So, as von Neumann taught us, the *probabilities* agree. But notice: if we are to take RQM 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*![25]

In order to eliminate the charge of inconsistency, recall that the descriptions of all interactions between generic *Ss* and *Os* are *O-dependent*. Therefore the manifestation of *S*'s dispositions resulting in *O* observing spin up (the definite event) need not coincide with the description of the *joint system S*+*O* given by another observer *P*. As a matter of an ontological fact, the dispositions of the joint system S+O in its interaction with *P* are not necessarily identical to those of *S* in its interactions with *O*, and the *mutual* manifestation model explains rather well why this must be the case.

In this sense, it is true that the *same* process, constituted by the interaction between *S* and *O*, receives two different descriptions: its identity is therefore relational or structural. However, the two different descriptions refer to two different interactions. The consistency between the two descriptions can be established *after* a third, *direct* interaction between *S* and *P*. Were they human observers, as a consequence of their meeting they would agree on the following meta-statements: "the interaction between *S* and *O* produced a state such that '*S* was up for *O* and *S*'s spin was up'", while "the interaction between *S*+*O* and *P* produced a state that, relative to *P*, was: '*S* was down for *O* and *S*'s spin was down'."

Finally, the dynamics of the interaction between *S* and *O* cannot be specified for each single instance, as it depends on the specific Hamiltonian that is required by the systems at hand. However, RQM programmatically refuses to offer a *general* explanation of the reasons why a superposed state generates a definite magnitude thanks to an interaction and this may well be regarded as a decisive objection against the theory, to be discussed below. For now it will be sufficient to note that this "omission" is a peculiar characteristic of the theory.

[25] Brown (2009), p. 690, my additions in square parentheses.

14.3 Three Objections to RQM

In order to clarify the consequences of RQM's antirealistic stance about the wave function, as well as the relationalist/dispositionalist accounts of the state-dependent properties in quantum mechanics, three critical remarks are in order. The first concerns the explanatory power of RQM (section 14.3.1), the second the overcoming of typical dualisms of the standard interpretation (section 14.3.2), the third the relationship between relational and invariant, perspective-independent facts in RQM (section 14.3.3).

I should specify at the outset that I will not conclude that RQM is immune to *all* of these objections, but I will try to answer them as best as I can, by pointing out that RQM can solve many extant interpretive problems of quantum mechanics. Not only will these critical remarks help me to compare the merits of RQM vis à vis the other cognate interpretations of the non-relativistic formalism, but my reply to each of them will at the same time justify both the plausibility of Rovelli's view and my antimonistic use of it in the last two sections.

14.3.1 First Objection: The Explanatory Poverty of RQM

First, it could be objected that there must be a physical reason, a deeper explanation, as to *why* the square modulus of the wave function (or simply the Born rule) is so *effective* in giving us accurate predictions of measurement interactions.[26] Shouldn't RQM offer an explanation as to why interactions between an entangled system *S* and an observer *O* manifest quantum events with definite magnitudes with exactly the probability prescribed by the theory?

To this criticism RQM can reply that, temporarily at least, the notion of "physical interaction" between systems and observers has to be regarded as *primitive*: in this way, any such question can be blocked as meaningless, or as one that presupposes a *different* interpretation. Since any interpretation of a formalism must start from somewhere, that is, it must regard certain facts, concepts or events as explanatorily fundamental or primitive, this first objection loses some of its force.

A critic may object that this is *the* main conceptual problem of non-relativistic quantum mechanics, and that by declaring the notion of interaction between systems as primitive and unexplainable in physical terms we sweep the dust under the rug. However, a defender of RQM need not deny that it might be desirable in the future to try to explain the success of Born's rule,[27] but could

[26] Dürr, Goldstein, and Zanghì (1992) is an important explanatory step in this direction.

[27] The origin of the Born rule dates back to Einstein's *Gespensterfeld*: "In the early 1920's, Einstein, in his unpublished speculations, proposed the idea of a 'Gespensterfeld' or a ghost field

simply note, at the same time, that as of now, by accepting the relationality of quantum mechanics, we ought to accept it as a brute metaphysical fact about the world. This means that it cannot be explained in terms of deeper facts or laws: also in the quantum case, as in other scientific revolutions, what needs to be explained changes radically with our change of theories.

Consider that the main scientific revolutions in the history of physics have been possible by the abandonment of a request for an explanation and by a transformation of a seemingly dynamical problem into a postulate of the new theory. For instance, the fact that a body moving in a certain direction with a certain speed tends to maintain its velocity has become an axiom of the modern mechanical view of the world, but for Aristotelian physics it was a problem crying out for an efficient cause: how can something move without a mover? Likewise for the attempts at giving a dynamical explanation for Lorentz contractions: now we accept a purely kinematic account of contractions and dilations, accompanied by structural explanations given in terms of the geometry of Minkowski spacetime.[28] And in general relativity the explanation of gravitational phenomena via a force has been replaced by the geometric notion of curvature: free fall is the "natural", or primitive state of bodies. So the acceptance of certain phenomena as primitive depends on the fruitfulness of the assumption.

Furthermore, the acceptance of the notion of interaction as a primitive and the consequent scepticism about the view that certain algorithms must have a counterpart in the world in quantum theory is not an isolated phenomenon. Take Feynman's diagrams as an example; do not presuppose a realistic stance about, say, the fact that the particles depicted in some of the diagrams have a well-defined trajectory. The standard understanding of them is that they are used to keep track of, and simplify, various difficult calculations in quantum field theories.[29] Even predictive success or empirical adequacy, as Ptolemy's astronomy well demonstrates, is not by itself sufficient for endorsing a realistic stance about the calculating devices that allow the prediction. Of course, in the case of the Ptolemaic system, explaining certain coincidences was a major step in formulating the new Copernican astronomy, but the situation in quantum physics at the

which determines the probability for a light-quantum to take a definite path. In these speculations, the ghost field gives the relation between a wave field and a light-quantum by triggering the elementary process of spontaneous emission. The directionality of the elementary process is fully described by the dynamical properties of the ghost field" (Wódkiewicz (1995)). Born interpreted the ghost field, whose intensity according to Einstein was linked to the direction of the light quantum, as a *probability field*.

[28] For a well-argued contrary view, see Brown (2005).

[29] Brown (1996), but see Meynell (2008) for a contrary opinion and Wüthrich (2010) for an historical reconstruction.

moment seems different: any gain in explanatory force (as in Bohmian mechanics or dynamical collapse models) must be accompanied by clear *independent* evidence for the postulation of the explanans. It is highly desirable that such evidence be gained in the future, but at the moment we ought to recognize that it is still not available, despite the fact that dynamical collapse models yield predictions that are different from those of standard quantum mechanics.

Notice, furthermore, two more arguments siding with Rovelli's anti-realistic view about the wave function. First, the contrary view would commit one to the existence of a 3*n*-dimensional configuration space where the wave function lives in a system with *n* particles, and the daunting task in this case would amount to recovering good old four-dimensional space from the reified configuration space.[30]

Second, the celebrated paper by Pusey, Barrett, and Rudolph (2012) in *Nature Physics*—which tries to prove that the wave function is more than mere information—assumes something that RQM would not accept, namely that isolated systems have well-defined magnitudes (I guess this is what the ambiguous term "real physical state" in the following quotation really amounts to): "The argument depends on few assumptions. One is that a system has a 'real physical state' not necessarily completely described by quantum theory, but objective and independent of the observer. This assumption only needs to hold for systems that are isolated, that is, not entangled with other systems".[31] While this second remark is not a *positive* argument in favour of RQM, it shows at least that this result is not decisive.[32]

14.3.2 Second Objection: The Quantum Mechanical Dualisms

The second criticism addresses the question whether RQM is really successful in overcoming the various types of dualisms of standard quantum mechanics that many interpretations purport to eliminate. I am referring here to dualisms between:

(i) physical systems and epistemic agents;
(ii) quantum systems and classical apparatuses;[33]
(iii) two different kinds of temporal evolutions—a reversible and deterministic one, preserving superposition—and a probabilistic, irreversible and

[30] Albert (1996) thinks that such a task is feasible at least in principle.
[31] Pusey, Barrett, and Rudolph (2012), p. 475.
[32] For a general, critical survey of no-go theorems in the philosophy of quantum mechanics, see Laudisa (2013).
[33] See Bell (1993), p. 176.

possibly non-linear one, implied in measurement interactions, or *S*-*O* correlations;

(iv) the macroscopic classical world, endowed with apparently *intrinsic* properties, and the microscopic world, characterized by merely dispositional or *relational* properties.

While these four types of dualisms are obviously related, it is better to discuss them separately.

14.3.2.1 PHYSICAL SYSTEMS AND EPISTEMIC AGENTS

The first difficulty might be merely terminological. At least programmatically, RQM tries to eliminate any recourse to *real* observers or epistemic agents in the foundations of quantum mechanics: "The observer can be any physical object having a definite state of motion".[34] Let us grant that the interaction between the "observer" *O* and the system *S* does not require the presence of real observers in order to ensure definiteness of results. However, we are told that the physical system *O* interacting with a quantum entity *S* must be capable of storing *information* about *S*.[35] Independently of the remarkable *technical* work that has been done in the field of quantum information,[36] it remains true that "information" is an ambiguous term, which *prima facie* stands for epistemic states of conscious observers. In this way, epistemic agents, that is, conscious observers might be reintroduced from the door after having been dropped outside the window.

In other words, the problem for a philosophical reading of RQM is—exactly as is the case with probability, which has an axiomatic, purely formal treatment too—that we don't know what information is from an ontological viewpoint. In order to avoid this problem, it is better to analyse talk of the "mutual storage of information" that follows an interaction with the more physical idea of correlation of degrees of freedom between *S* and *O*, as Rovelli and Smerlack themselves suggest.[37] Analogous difficulties are raised by Rovelli's reliance on *subjective* probability,[38] given that, unlike Everettian quantum mechanics, RQM seems to bet on an irreducible indeterminism.

[34] Rovelli (1996), p. 3.

[35] "The state † that we associate with a system S is therefore, first of all, just a coding of the outcome of these previous interactions with S. Since these are actual only with respect to [an 'observing' system] A, the state † is only relative to A: † is the coding of the information that A has about S," (Rovelli and Smerlack (2007), p. 3).

[36] See among others Bub (2006). [37] (2007), p. 2.

[38] Rovelli and Smerlak (2007), n. 7.

14.3.2.2 QUANTUM SYSTEMS AND CLASSICAL APPARATUSES

In order to overcome the second form of dualism between quantum and classical systems, originally theorized by Bohr, RQM should explicitly ban Bohr's claim that the distinction between a classical and a quantum realm is purely *contextual*, or dependent on the measurement situation.[39] This, I propose, is the most significant distinction between Bohr's view and RQM. Consequently any sort of contextual dualism between the classical and the quantum ought to be forbidden. In RQM everything is quantum since also classical entities are subject—as we have seen above and we are about to clarify in some more details in (iii)—to the superposition principle.[40] Bohr, on the contrary, needs a classical realm in order to secure the fact that measurement results are *not* subject to Heisenberg's uncertainty relations. Consequently, Bohr also needs a classical spacetime, something that Rovelli's approach to quantum gravity rejects programmatically.[41]

14.3.2.3 TWO DIFFERENT KINDS OF TEMPORAL EVOLUTIONS

Additional questions about the measurement problem are raised by the dualism of evolutions mentioned above. We have just established that any physical system *O* can be treated as a quantum system. But then how can a system *S*—that is in a superposed state, and shows *real* interference—manifest definite properties relative to another quantum system *O* if we don't presupposes *two* different kind of evolutions, one for system-system and one for systems-"observers"?

Brown talks about "two types of relations":

> 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

[39] The contextuality of the distinction between classical and quantum objects that is essential to Bohr's interpretation of quantum mechanics is evident in Bohr (1949) when, discussing the thought experiment proposed by Einstein and involving a double-slit macroscopic screen suspended with springs, Bohr treats the classical slit as a quantum system subject to Heisenberg's uncertainty relation between position and momentum. For a defence of Bohr's contextualism and a critical attitude toward "quantum fundamentalism" (according to which everything is subject to quantum mechanics), see Zinkernagel (2010).

[40] "All systems are equivalent: Nothing distinguishes a priori macroscopic systems from quantum systems. If the observer *O* can give a quantum description of the system *S*, then it is also legitimate for an observer *P* to give a quantum description of the system formed by the observer *O*." (Rovelli (1996), p. 3).

[41] Rovelli (2006). On the other hand, it remains true that also Bohr applies quantum descriptions to classical objects depending on the measurement context (see n. 39), but he would refrain from claiming that a system with which no one has interacted is in an entangled state, since this claim for him would be meaningless.

between the system and observer such that a property of the system becomes actualized for the observer.[42]

Since these two types of relations must be referring to *two different physical evolutions*—one of which (S-O interactions) remains unexplained because it is regarded as primitive—rather than providing *unification*, RQM seems to reproduce that undesirable dualism in the foundations of quantum physics that is already familiar from standard formulations of the theory. It is true, of course, that thanks to the relationism of the theory, these two evolutions do not contradict each other, but they seem to require a principled distinction between systems *S* and "observers" *O*, which it denies to have to rely on. This fact would cause the collapse of RQM into Bohr's contextualism.

As far as I can see, there are three ways out of this conundrum.

The first consists in noting that the two evolutions do not entail a dualism between kinds of systems, but rather a dualism between physical systems that are *internal* to the interaction and those that are *external* to it. The system-system relation referred to by Brown is at the same time a system-observer relation (an *S-O* relation) if described by an observer *O* that has interacted with *S*. Since the entanglement between any two systems *S* and *O* (the latter of which is an "observer" exactly as the former is to the latter) is kept for any other system *P* that has not yet interacted with *S+O*, the composite *S+O* is to be regarded as *external* to the interaction *S+O*, so that the entanglement between them is broken only for observers *P* that interact with *S+O* and are therefore "internal" to the correlation. Importantly, the external/internal difference is *indexical*, since its reference varies with the context, in the sense in which "now" and "here" are indexicals. In terms of Schrödinger's famous thought experiment: if a cat and an observer are isolated in a box, with the usual poison triggered by a radioactive mechanism, the physical systems internal to the box, according to RQM, are all entangled with respect to an external observer. But relative to the observer who has interacted with the cat inside the box the cat is either dead or alive. The "relativization" or the indexing of measurements to "observers" is a way to avoid the contradictions between two descriptions of the same process, as is always the case with relational views of the world: as Plato insisted, the same man can be short and tall relatively to two different persons.

The second way out consists in denying, *à la* Everett, that there is any real physical interaction between *S* and *O*, and insisting on the fact that the only real physical evolution is Schrödinger's linear and deterministic one. However,

[42] Brown (2009), p. 685.

this cannot be Rovelli's position, since the definiteness of outcomes, the actualization of a quantum event, would have to be either a merely *local* phenomenon as in Everettian decoherence approaches, or utterly impossible, a simple illusion.

This fact suggests the exploration of a third way out of the charge of dualism of evolutions, which is not completely successful. On the one hand, denying *some kind of reality* to interference effects of microscopic and mesoscopic systems described by the unitary evolution of Schrödinger's equation is implausible. So it is implausible to claim that in RQM there is only *one* temporal evolution. On the other hand, the dualism of evolutions or relations referred to by Brown is attenuated by the decisive fact that, according to Rovelli, Schrödinger's superpositions-preserving equation is a description of the evolution of probabilities of measurements that does not refer to any ontological posit. Recall that in RQM the wave function, with the provisos referred to above, is merely a bookkeeping device and its evolution is therefore not a physical process: reality is only attributed to the outcomes of interactions between two different systems carrying merely dispositional properties. With this partially instrumentalist reading of the wave function, the dualism in evolution is at least not straightforwardly reflected in a dualistic ontology, despite the fact that interference effects must be regarded as real.

In a word, while this dualism of equations (one of which, prescribed by the so-called Born rule, according to RQM is a primitive fact that cannot be explained) and evolutions seems an ineliminable and in my opinion highly undesirable consequence of RQM, it is possible to reformulate it in such a way as to lessen its negative conceptual impact.[43] Consequently, it is true that the overarching aim of physics (and science) is unification, but if a plausible interpretation of a fundamental physical theory like RQM requires a form of relationism, then there can be as much unification as the theory affords, at least for the time being.

14.3.2.4 THE MACROSCOPIC CLASSICAL WORLD AND THE MICROSCOPIC WORLD

(iv) The dualism of the intrinsicness of the classical and the relationality of the quantum entails two strategies: either claim that also the classical world is through and through relational,[44] or defend a dispositionalist view of both the quantum and the classical world (where all properties are intrinsic dispositions), much in the spirit sketched in the previous section. While I decidedly favour

[43] From the empirical, practical viewpoint obviously RQM has no difficulties, but this is not the perspective adopted here

[44] Dipert (1997).

the second alternative, here I will not insist on this aspect, since the reduction of the classical to the quantum realm is an open problem for all interpretations.

14.3.3 Third Objection: RQM's Lack of Perspective-independent Facts

"Which are the invariants of RQM?" It might be thought that a theory without some invariant or absolute (non-relational) element lacks a desirable component of any physical theory.[45] The special theory of relativity, for example, which is the point of departure for Rovelli's proposal, introduces new invariant elements (the Minkowski metric and the light cone structure) while relativizing spatial and temporal intervals taken separately. However, it regards relations between inertial "observers" and physical magnitudes of objects as invariant: it is true for all inertial observers that "relatively to frame *F* the length of the ruler *R* is *L*", as it is also true for all observers that "the same four-dimensional ruler *R* has length *L* according to observer *O* and a different length L_1 according to observer *P*".

Analogously invariant truths hold also in RQM and this is just what one expects, since the coherence of any form of relationism presupposes the existence of perspective-independent facts about what the facts are from each perspective.[46] In my reconstruction of RQM, the fact *Fa* that "the particular systems *S* and *O* interact by manifesting their mutual dispositions" holds for all other "observers" and is therefore fully invariant.[47] And yet the relativization of magnitudes in RQM is more prominent than that characterizing special relativity, since invariant facts like *Fa* look like a *determinable*, while the four-dimensional ruler *R* is what it is independently of any description provided by an inertial frame. The description of the invariant fact given by the interaction between *S* and *O* depends on whether the interaction of *S* with *O* is described internally or externally by another observer *P*. "Internally", as we saw in section 14.2, the following claim in RQM is true: "relatively to *P* (when she interacts with *S*+*O* at a later time), *O* has found *S* spin up, while relatively to *O*, her previous interaction with *S* resulted in spin down." Note that the fact just stated in scare quotes *is* invariant, that is, it does not hold just for *O* and *P* but for all possible observers. Of course, for yet another observer, *O* and *P* together with their interaction with the apparata are in a superposed state.

Let us look elsewhere for other possible "invariances" that RQM might need for its coherence but don't contradict it. A possible candidate is the meta-

[45] van Fraassen asks: "How can we characterize these systems, in ways that are not relative to something else? That remains crucial to the understanding of this view of the quantum world . . . " (van Fraassen (2010), p. 391).

[46] For this perspicuous way of putting the point, I thank an anonymous referee.

[47] See also Brown (2009), p. 693.

statement or the meta-constraint of the theory, namely that quantum systems have properties only relative to observers. This is obviously not a statement of a *particular* observer, but a principle or constraint that is valid for all observers and for any possible interactions between systems and observers, akin to the special relativistic prescription (a meta-law) to formulate laws that are Lorentz invariant.

Note that the above meta-principle is *not* an objection to RQM, as Bitbol claims within his neo-Kantian reading of RQM,[48] because it does *not* presuppose a "non-located observer" or a non-indexed attribution of a property to a system from God's eye point of view or a Kantian transcendental principle. The constraint, as such, is a sort of meta-law for any quantum mechanical law that can be stated in the object language, a constraint, that is, on how any possible quantum description should be given, in the same sense in which the relativity principle is a meta-law for mechanical and electromagnetic laws. Of course, this meta-theoretical requirement is not a physical invariant as the velocity of light.

A third invariant element of RQM is constituted, as noted by van Fraassen, by the transition probabilities for the two observers *O* and *P* (the modulus square of the coefficients α and β in the example above), which are identical for both. Being calculated in accordance with the mathematical apparatus of quantum mechanics, the element also defines an algebra of observables: not by chance, these are structural, mathematical invariants of the theory.

Finally, whenever a correlation is established between any two systems *S* and *O*, there is coherence between what it is measured in *S* and the properties of *O* that allow detection. It is *never* the case that relative to *P*, *O* has observed that the spin is *up* while the spin of *S* is down.

In a word, the above elements of invariance are sufficient to ensure the coherence of RQM.

14.4 The Anti-monistic Consequences of RQM

From Parmenides to Spinoza, and from to Hegel to Bradley, *monism* is a philosophical view that has a long tradition. Does quantum mechanics *per se* side with monism, given its allegedly *holistic* nature?[49]

[48] "The relational interpretation presupposes . . . a form of absolutisation: the absolutisation of the viewpoint from which all of its metadescriptions are produced . . . one will have to ask *for whom* is the meta-description of a system in relation with an observer valid?" (Bitbol (2007), p. 11 of the manuscript, my translation). According to Bitbol, this is a sort of Kantian condition of possibility for having knowledge of the quantum world.

[49] Healey (1989).

Since one cannot answer this question without presupposing an interpretation of quantum mechanics, in this section I will try to tackle it by choosing RQM as a consistency test. In the previous section I argued that, despite its difficulties, RQM is a plausible interpretation of the theory. Consequently, my choice is not unreasonable, especially if put in the conditional form: *if* RQM is a reasonable interpretation of quantum mechanics, what happens to monism?

According to Schaffer's useful distinction (2010a), there are *two* kinds of monism, one more radical and thought-provoking, the other more reasonable but still interesting, that he himself defends. While the former kind, *existence monism*, claims that the Universe has *no* parts since only the whole exists, *priority monism* grants the non-monist or the pluralist the existence of parts, but holds at the same time "that the whole is prior to its parts, and thus views the cosmos as fundamental, with metaphysical explanations dangling downward from the One".[50] What kind of support, if any, could RQM provide to these two kinds of monism?

Before answering these questions, I have to meet a foreseeable objection: a priori, *metaphysical* positions like monism cannot be confronted with physical theories that are programmatically interpreted in an instrumentalist way. However, as argued above, RQM is not a purely instrumentalist or positivistic interpretation: as such, it qualifies for a confrontation with a metaphysical theory like holism. It is not just RQM's advocacy of entity realism that matters here, but also its metaphysics of dispositions, denying any intrinsic state-dependent properties to physical systems.

Prima facie, RQM seems supported by and not just compatible with priority monism. In RQM, *relata* (isolated quantum systems, or parts) with state-dependent dispositional properties ought to be regarded as existent, since there is no relation without *relata*. The existence of parts on the one hand, and the dependency of the manifestation of definiteness on the mutual interaction between them on the other seems exactly what is required by priority monism. One might even be tempted to claim that the only determinate object in Rovelli's RQM is the quantum universe (the whole web of the interactions among systems) and that every other existing part of the universe depends on it.

In order to make the claim that RQM is incompatible with priority monism as strong as possible, I will begin by providing four additional arguments in favour of the view that RQM *supports* Schaffer's metaphysics. My subsequent rebuttal of each of these arguments will render the claim that RQM is against priority

[50] Schaffer (2010a), p. 31.

monism even more convincing, since it will become evident that I am not fighting against a straw man.

14.4.1 First Argument

The first argument to be rebutted later is as follows: according to RQM, there are many ways to partition the quantum universe *U* in systems *S* and observers *O*. Both *S* and *O* are obviously contained in *U*, since *S*+*O*=*U*. However, each "cut" between a system *S* and the rest of the universe (the observer *O* in this case) is fully arbitrary,[51] in the same sense in which is arbitrary the choice of an inertial system to describe the evolution of a system in Minkowski spacetime. In STR what is real and objective, however, is the *whole*, the block universe, that is, *all* events in Minkowski spacetime (at least in the B-theoretic reading of the theory that I am taking for granted here). If RQM takes inspiration from STR, as Rovelli maintains, an analogue of this kind of invariance should hold also in RQM. It then follows that also in RQM *the universe* (the whole, or the One, to use Schaffer's term) possesses definite magnitudes independently of any relation to anything else and any "cut between the whole is fully arbitrary and dependent on the property of the whole."

14.4.2 Second Argument

The second argument in favour of the claim that RQM is evidence for priority monism is related to the first: there has to be a fact of the matter about the definiteness of the quantum state of the universe, otherwise no quantum cosmology would be possible.

14.4.3 Third Argument

The third argument exploits general cosmological hypotheses that, allegedly, also RQM should accept. If at the Planck scale the initial state of the universe is entangled, any subsequent, evolved state of the universe should also be entangled. However, this consideration pushes toward monism:[52] not only is everything interrelated, but the relation of entanglement between two different relata in the universe is not supervenient on them.[53] This lack of supervenience means that

[51] Decoherence selects a particular basis, but RQM does not rely on decoherence, since superpositions are preserved only if there is no interaction between system and observers. In Everettian quantum mechanics on the contrary, the state of the universe is entangled, and decoherence is needed to explain the definiteness of results to local observers. RQM explains such a definiteness in terms of the primitive, mutual manifestation of dispositional properties presented above.

[52] Esfeld (1999); Schaffer (2010a, b).

[53] Teller (1986); Healey (1989).

systems that are related but not entangled can be exactly in the same state in which entangled systems are (i.e., relata don't fix relations).[54]

14.4.4 Fourth Argument

If all things are internally related (Schaffer 2010b), as it seems to be the case also in RQM, and in priority monism one cannot combine the various parts in an arbitrary way (due to the failure of free recombination), then also Rovelli must accept the view that the universe is not a mere "heap" that *depends* on its proper parts, but is rather *an integrated whole*, exactly as priority monism requires. This notion of dependence will be discussed below.

14.4.5 Replies

In order to respond to these four objections in a single stroke, it is sufficient to recall that in RQM there are no absolute states with definite properties. However such states can be interpreted as being irreducibly dispositional. Therefore, as far as this objection is concerned, one must stress the fact that in RQM there is a purely dispositional, quantum state of the universe, so that quantum cosmology is a legitimate enterprise. From an epistemological point of view, however, quantum cosmology requires that one studies large segments of the universe in relation to other segments. Recall that in RQM there is no fact of the matter about whether two different observers *O* and *P* get the *same* result out of an interaction with the system *S*, since this is a question about the absolute state of *O and P*. If *S* is the whole universe, that is Schaffer's One, then *S*, *qua* isolated system, is also an absolute system with purely dispositional properties that cannot be manifested. Nothing can interact with it in principle, for there is no external observer. Consequently, the quantum universe *S* can be known only by interacting with parts of it *from within*, namely by dividing it into two parts, one of which, *O*, must be *contained* in *S*.[55]

If the quantum universe can be described only from within, we must somehow consider all the *possible compatible perspectives* about it, each of which depends on a cut of the universe into two parts, a system and an observer. This fact has obvious consequences for priority monism as defended by Schaffer, since the whole cannot have *epistemic* priority over the parts. Failure of the *ontic* priority of the One over its parts follows from the fact that there is no consistent sum of all

[54] For an argument in favour of emergent properties of the whole, see Morganti (2009).
[55] For additional arguments against the view that the universe can be described by an external observer, see Smolin (1995).

possible perspectives yielded by the parts, so that there is no definite One whose identity is non-relational or non-structural.

Of course, the priority monist could insist that the necessity of correlations for the existence of definite events required by RQM depends on a purely epistemic limitation on our part, so that the whole has still metaphysical priority over the parts. However, epistemology and ontology should try to go hand in hand as much as possible: consequently, the metaphysical thesis of priority monism would just generate sceptical worries about its a posteriori justification from fundamental physical theories.

The lack of compatibility of the different internal perspectives on the universe can be can be seen in another way. Since the universe *U* has merely dispositional properties, the restriction of such properties to any of its proper parts *S* will have as a consequence that the dispositions of *S* must coincide with those of *U* in the region in which *S* is. Consequently, the events measured by *S* are *self-referential*, in that they are about the rest of the universe *U*-*S* but also about *S* itself, *qua* proper subsystem of *S* that manifests its dispositions in its interaction with *U*-*S*.[56] But in a cosmological application of RQM, there is no observer *S'*6¼ *S* that can interact with *U*-*S* and *S*, since this would imply that a part of the universe *S*' can interact with the universe *U*=*U*-*S*+*S*. Furthermore, if *S*6¼*S'*, the interaction of the dispositions of *S* with those of *U*-*S* will yield definite magnitudes that in general will not coincide with those obtained by *S'* in its interaction with *U*-*S'*, since the dispositions of *U*-*S'* will in general differ from those of *S'*and *U*-*S'*. Consequently, all the perspectives on the universe will not in general produce the same definite outcomes.

An analogous reply holds for section 14.4.3. Schaffer writes: "the argument from quantum entanglement to holism begins from the premise that *the cosmos* forms *one vast entangled whole*".[57] Also this premise, which seems to follow from the fact that shortly after the Big Bang everything interacted with everything else, presupposes an observer external to the universe. However in RQM there is no non-dispositional fact of the matter about the quantum state of the universe, because the state of any quantum system is a codification of outcomes of previous interactions. Due to the impossibility of interacting with something of which we are a proper part, a very large part of the universe can be in an entangled state only relatively to a small, proper part of it. If RQM is correct, it cannot be the case that all fundamental properties are properties of the cosmos (the One), since

[56] I have adapted interesting claims put forward by Breuer (1995) to my dispositionalist approach.

[57] Schaffer (2010a), p. 52.

definite events are a product of the interaction between parts. While priority monism would be correct in insisting that the dispositions of the parts of the universe are restrictions of those of the whole and therefore depend on the whole, there is no fact of the matter about what the dispositions of the whole are at any one time. On the contrary, definite events represent the primitive beables of RQM. The dispositions of the parts therefore are explanatorily prior, since only interactions between parts can produce such beables.[58]

In order to reply to section 14.4.4, consider Schaffer's characterization of *dependence,* which is crucial for his claims that the parts "depend" on the whole and the latter is not a mere *heap.*[59] He treats this notion in a very precise but also in a rather abstract way. Consequently, it is not clear what it is meant by metaphysical dependence unless one enters in detailed considerations about the particular domains to which the notion is applied. The risk of his analysis is that of providing a very general, first-order-logic set of constraints on various domains that however cannot be regarded as alike, because their properties are very different. What does cosmology tell us about the dependence of the whole on its parts? Even if the free recombination principle were to fail because of constraints of non-locality, how could one maintain that there is an essential relation between an internal part of the universe P_1, a different part P_2 and the rest of the universe? (as Schaffer (2010b) requires). If P_1 is the region of the universe in which S and O interact, the rest of the universe that is sufficiently screened off from $S+O$ can remain the same; it is only when another observer O' interacts with the combined system $S+O$ that the part of the universe P_2 in which O' is located changes. So change within the universe is due to the interaction of its parts and not conversely and this confers prior explanatory powers to the parts.

In sum, at least to the extent that the causal isolation of the rest of the universe from two of its coupled subsystems is empirically validated, it is only *via* relations or interactions that entanglement is broken. Rather than guaranteeing monism, the existence of relations between systems breaks holism, since entanglement is the main a posteriori evidence for monism.

14.5 RQM, Quantum Monism, and Relativistic Becoming

Another important field of confrontation between the monistic and the relational view of quantum mechanics concerns time and temporal becoming. Since time is

[58] For other arguments against monism, see also Sider (2007).
[59] See Schaffer (2010b).

important both in the world of quantum-relativistic physics and in our inner world, I assume that both views ought to provide some kind of explanation of our subjective sense of the passage of time. In the context of Relativistic Quantum Mechanics this task has proved rather difficult. I argued (in Dorato (1995)) that as a consequence of quantum non-separability and of Stein's theorem (1991), quantum becoming in Minkowski spacetime is ruled out. According to Albert (2000), no quantum theory at the moment provides an account of the world becoming in time. In order to defend quantum relativistic becoming without a privileged frame, Myrvold (1993) has defended a hyperplane-dependent view of collapse.

In order to evaluate quantum monism and RQM vis à vis temporal becoming, I think that the following three definitions are importantly neutral between the two views.

DEF$_1$ **Absolute becoming.** The claim that an event *e* "becomes" in an absolute sense (or "comes into existence") at a certain time-place simply means that *e* *occurs* or *happens* at that time-place.[60]

DEF$_2$ **the *temporal* becoming** of *a set of temporally separated* (timelike-related) *events* consists in the fact that *such events occur successively,* or at different instants of proper time.

DEF$_3$ **the *spatial* becoming** of *a set of spatially separated* (spacelike-related) *events* consists in the fact that *such events occur* at different locations in spacelike related regions.

If we assume that an interpretation of quantum mechanics that were to rule out the notion of becoming ought to be regarded as unsatisfactory, then we can easily conclude that Schaffer's quantum monism is bound to commit itself to cosmic time, with all the difficulties involved in this notion.[61] On the contrary, RQM is very hospitable to an objective but *local* temporal becoming, for which we need *three* ingredients: 1) Events, regarded as local causal nodes in a relational network; 2) Local successions of events on a worldline, or processes;[62] 3) A de facto irreversible succession.

[60] This first approach to absolute becoming has recently been defended by various scholars, but is originally offered in Broad (1933/38). The other two definitions are in Dorato (2006a).

[61] See Belot (2005) and Dieks (2006).

[62] Notice that in GRW dynamical reduction models based on flashes, there cannot be *local* becoming since, as Esfeld and Gisin have noted, "the becoming of some flashes depends on where other flashes occur at spacelike separated locations, and there is no relativistic answer to the question available of which flashes are subject to such dependency relations (or non-local influences) and which ones are not in these models" (Esfeld and Gisin (2014), p. 257).

As I am about to show, these three ingredients are (either implicitly or explicitly) present in RQM, because RQM *is local*.

Clearly, and firstly, RQM's events are well-defined spatiotemporally extended entities forming a relational causal network since *qua* by-product of the interactions between *S*'s and *O*'s dispositions, they are the beables of the theory.

Secondly, a succession of measurements realized by the interaction between systems provides time with an objective although local and worldline-dependent arrow of time, given by the successive coming into existence or actualization or simply becoming of events. As already argued by Savitt (2001), Dorato (2006a), and Dieks (2006), and first defended by Stein (1991), this type of becoming is relational and strictly local, where local means not extendible to other worldlines of other observers or unanimated physical systems.

Thirdly, RQM in my reconstruction claims that a system *S manifests its dispositions* to display value *q* relatively to the observing system *O* and conversely: the manifestation in question ought to be regarded as *de facto* irreversible, otherwise no stable measurement would be available. The time-asymmetric dispositionalist language defended above is suitable to express this sort of irreversibility, since the manifestation of a disposition is a time-asymmetric process.

What is relevant here is that in order to take quantum non-separability and frame-dependent localizations into account,[63] we don't need to read quantum mechanics as presupposing a privileged frame of[64] as in Bohmian mechanics, and we don't need to have a frame-dependent notion of relativistic becoming, as proposed by Myrvold (2003). The kind of becoming obtained within RQM is compatible with the relativistic constraints of being non-spacelike, but only timelike or lightlike.[65]

However, if the whole set of events (Minkowski spacetime) constituting a classical spacetime were metaphysically and epistemically prior as priority monism would impose, it would be hard to provide a notion of cosmic becoming, the more so when we go to the curved manifolds of general relativity. If holism prevailed, we would not have becoming, not even in the minimal sense, because the notion of cosmic time is not robust enough to give us cosmic becoming.[66]

From the perspective of single worldlines of observers, instead, we can have a description of the successive stages of physical systems, the quantum universe (possibly) included. In the form of relativistic becoming endorsed by RQM what

[63] A frame-dependent sort of becoming cannot be regarded as an account of a Minkowski universe becoming in time, of course, since there are as many histories as there are frames of reference.

[64] Albert (2000).

[65] Savitt (2001); Dieks (2006); Dorato (2006a).

[66] Gödel (1949), and Dieks (2006).

we have is a crisscrossing of little ripples, unrelated to each other, which give us local, non-worldwide becoming (corresponding to the incomplete information that each observer has about the universe, given that she is inside it). The fact that in RQM we have no universal and cosmic tide of becoming also corresponds to the locality of RQM: there is no matter of fact about the distant wing of a Bell-type experiment until a concrete correlation with it is established.[67] If the order of explanation of cosmic time proceeds from the local to the global, how can the parts be dependent on the whole, as priority monism requires?

It could be remarked that the commitment of holism to cosmic becoming holds only for *existence* monism and not for *priority* monism: if there were only an object and it evolved in time, then only cosmic time would be appropriate.[68] The objection to my claim could continue by noting that the priority monist is not subject to this criticism, since she acknowledges the existence of parts. These parts in our case would correspond to individual worldlines encoding the succession of events in which local becoming consists. Consequently, priority monism can also make room for local becoming, and is not necessarily committed to those conventional assumptions that are necessary to construct a cosmic time.

The crucial point, however, is that according to priority monism local clocks ticking proper time should be grounded in, *or dependent* on, cosmic time, whatever dependent means in this context. But in all known constructions of cosmic time in Robertson and Walker's cosmological model,[69] cosmic time is an *average* of, or a construction out of, local times of local observers, and the latter have epistemic and ontic priority over the former, in the same sense in which averages ontically and epistemically depend on the properties of the parts. Even for the measurement of time, one starts from local clocks, based in frequency oscillations of caesium and it is hard to imagine a mechanism thanks to which cosmic time could influence the ticking of local clocks on which physicists base the metric aspects of time.

In a word, to the extent that also priority monism is committed to the existence of some form of cosmic becoming, pluralism, which is based on the secure footings of local becoming, seems a much more plausible way to go in order to explain our subjective experience of time.[70]

[67] Laudisa (2001); Rovelli and Smerlak (2007).

[68] Thanks to Matteo Morganti for this remark.

[69] See Weyl (1923).

[70] I thank an anonymous referee for many useful criticisms. I also thank Federico Laudisa, Matteo Morganti, Carlo Rovelli, Jonathan Schaffer, and audiences in London and Bielefeld for helpful suggestions.