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GRW as an ontology of dispositions ☆

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ABSTRACT

The paper argues that the formulation of quantum mechanics proposed by Ghirardi, Rimini and Weber (GRW) is a serious candidate for being a fundamental physical theory and explores its ontological commitments from this perspective. In particular, we propose to conceive of spatial superpositions of non-massless microsystems as dispositions or powers, more precisely propensities, to generate spontaneous localizations. We set out five reasons for this view, namely that (1) it provides for a clear sense in which quantum systems in entangled states possess properties even in the absence of definite values; (2) it vindicates objective, single-case probabilities; (3) it yields a clear transition from quantum to classical properties; (4) it enables to draw a clear distinction between purely *mathematical* and *physical* structures, and (5) it grounds the arrow of time in the time-irreversible manifestation of the propensities to localize.

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1. Introduction

The interpretation of quantum theory proposed by Ghirardi, Rimini, and Weber (1986) (GRW) is realist with respect both to the quantum domain and to the classical domain. That is to say, it acknowledges that in the physical world there are both quantum superpositions, including entanglement, as well as classical properties. The aim of GRW is to put forward a coherent and unifying dynamics that covers both these domains and thus includes a precisely described transition from quantum superpositions to classical, well-defined properties (the so-called state reduction). Such an aim is achieved via a non-linear modification of Schrödinger's equation. The goal is therefore to improve on the standard textbook version of quantum mechanics, with its pernicious dualism between Schrödinger's linear, deterministic and reversible evolution for undisturbed systems on the one hand, and a completely different—non-linear, indeterministic and irreversible but in any case unspecified—evolution when it comes to measurement on the other, whereby no clear definition is ever given as to which processes in nature should count as *measurements* (cf. the case of Schrödinger's infamous cat).

Following the original presentation, GRW is typically received as a purely *phenomenological* theory. However, in a recent paper, Allori, Goldstein, Tumulka, and Zanghì (AGTZ, 2008) follow Bell (1987) and Ghirardi, Grassi, and Benatti (1995) in treating GRW as a theory requiring "beables", or, as they put it, a *primitive ontology*, involving the distribution of matter in three-dimensional space.[1] While we fully agree with AGTZ that, in order to be a satisfactory physical theory and therefore solve the measurement problem, an interpretation of the formalism of GRW needs to go beyond the abstract setting of configuration space and wave function's change of shape, we believe that the kind of primitive ontology postulated by AGTZ and by the previous authors still does not do full justice to GRW's implicit ontological presuppositions. In our view, in fact, this theory commits us to regarding spatially superposed states as something that *underlies* those events that manifest themselves as the distribution of matter in space-time. We shall argue that (i) it is in this sense that GRW can be regarded as a serious candidate for a *fundamental physical theory* and (ii) the framework proposed here can contribute to a deeper understanding of the nature of dynamical reduction models as well as of the meaning of the so-called "wave function collapse".

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[1] Bell (1987) introduced the so-called "flash ontology", later repudiated in favor of a wave function ontology, while Ghirardi et al. (1995) introduced the so-called "density of stuff" ontology.

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To start with, we briefly compare GRW with the other two serious interpretations of quantum theory that are locatable in a realist framework, namely the one going back to Everett and the one proposed by Bohm and his followers (next section). We then argue that GRW can be regarded as a theory that essentially subscribes to an ontology of dispositions or powers or, more precisely, *propensities* (Section 3). By elaborating on five important advantages that speak in its favour, we defend this claim against well-known reservations about introducing dispositions in physics and its philosophy (Section 4).

2. The state of the art

The discussion on the interpretation of quantum theory both in physics and in philosophy in the last decades has made it clear that quantum theory as such need not lend support to anti-realism or instrumentalism. After the advent of quantum theory, what has to be abandoned is not the hypothesis that physics tells us something about the world, but rather *some* presuppositions of our "manifest image" (Sellars, 1962). Nevertheless, a methodological attitude consisting in trying to save as much of the manifest image as is allowed by the ontology suggested by the scientific image seems to us so eminently reasonable as to require no further justification. For this reason, this attitude will be adopted in what follows.

Since the 1950s, coherent realist interpretations of quantum theory have been worked out in detail, and since the development of quantum cosmology in particular, it has become clear that an interpretation of quantum theory is called for that is not centred on the notion of *measurement* or *observer*. In order to illustrate the main options for a realist approach to quantum theory, here we will have space to focus briefly just on *three* main candidates, namely the theories of Everett, Bohm and GRW.

On the interpretation going back to Everett (1957), there are no state reductions or collapse postulates, and consequently no genuine evolution from quantum superpositions to classical properties: all systems in the world, including the macroscopic ones, are subject to superpositions and entanglement. Decoherence can account for the *appearance* of classical properties to local observers, but it does *not* change anything as regards to the fact that there can be no genuinely classical properties; superpositions persist, they are simply not accessible to local observers (see e.g. Adler, 2003). Consequently, if Everett's interpretation is to account for our observation of classical properties by invoking decoherence, it has to subscribe to the ontological commitment of there being infinitely many branches of the universe running parallel to each other both toward the future *and toward the past*,[2] including infinitely many consciousness states of each observer (that latter point is stressed in particular by the so-called many minds interpretation; see Albert & Loewer, 1988; Lockwood, 1989, chaps. 12 and 13). Taking into account the above methodological constraint of conserving as much as possible of the manifest image, such a munificent ontological commitment can be regarded as a central objection to this interpretation.[3]

The other realistic approach to quantum theory known since the 1950s requires a modification of the formalism of standard quantum theory. The theory of Bohm (first publication Bohm, 1952, last one by Bohm himself Bohm & Hiley, 1993) is based on the assumption that quantum systems are essentially constituted by individual particles, each possessing a definite value of position. The motion of the quantum particles in space-time *is determined by a quantum potential*—or, in more recent formulations, *guided by a velocity field*—that acts non-locally on the particles without being acted upon by them (see Goldstein, 2006, for a recent review). On this ontological basis, Bohmian mechanics reproduces the predictions for measurement outcomes of standard quantum mechanics. Whereas Everett's interpretation departs very much from the ontology of classical physics, Bohm's theory is to a certain extent closer to this ontology and therefore to the manifest image of the world, at least insofar as it conceives quantum systems as composed by individual particles with well-defined trajectories in space-time. These particles' velocities, however, non-classically and highly non-locally depend on the positions of all the other particles. The drawback of this proximity to the manifest image, as well as to the ontology of classical mechanics, is that it invites a number of objections, notably concerning the commitments both to (i) the reality or causal efficacy of a guiding field living in an abstract configuration space and (ii) an ontology of individual particles also in a context in which, as in quantum field theory, it is the notion of *field* that is fundamental.[4]

This situation is the rationale for trying to develop a third approach that does justice to both sides, the quantum as well as the classical one. The idea roughly is to take the Schrödinger dynamics to describe the development of undisturbed microscopic quantum systems and to amend it non-linearly in order to include a transition to genuinely existing classical properties when it comes to macroscopic systems. The aim is to forbid macroscopic superpositions by suggesting a *unified* dynamics for microscopic and macroscopic systems, thus overcoming the incoherent dualism of the two unrelated and conflicting evolutions in standard textbook quantum mechanics.

GRW achieves this result by supplementing the linear Schrödinger dynamics with a stochastic factor. For an isolated, non-massless microscopic quantum system whose wave function has a certain spatial spread—corresponding to one of the theories' new constants—such a factor yields a very low probability for spontaneous localization (that is, for a spontaneous adoption of a rather definite numerical value of position): it will *on average* take 10^{16} s for such an isolated system to undergo a spontaneous localization. By contrast, when one considers a huge ensemble of microscopic quantum systems (a macroscopic system), there will be a spontaneous localization of the macrosystem in an extremely short time, since the collapse rate of the macro-object as a whole, e.g. its centre of mass, increases with the number of constituents. Thus, a macro-object made of 10^{23} microscopic, non-massless quantum constituents will localize in 10^{-7} s. Any spontaneous localization of one of these systems implies in fact the spontaneous localization of all the others: in force of the correlations between the entities comprising a very large system, when one entity is "hit", it is as if all the others were also hit, and therefore it is *as if* the whole entangled system collapsed (Clifton & Monton, 1999, p. 701). Macroscopic systems that are composed of microscopic quantum systems endowed with mass will therefore undergo a definite localization in an extremely short time, and on that basis will acquire definite numerical values of all their macroscopic properties (see Ghirardi et al., 1986 and Ghirardi,

[2] This point about the symmetric character of the "branching" was reminded to one of us by Carlo Rovelli, and it is obviously implied by the time-symmetric character of the Schrödinger equation.

[3] The other well-known problem, that of making sense of *quantum probabilities*, is the subject of current discussion since a seminal paper advocating a decision theoretic approach (Deutsch, 1999). For an interesting objection against the possibility of accounting for probabilities within an Everettian approach, see Putnam (2005).

[4] Relativistic generalizations of bohmian mechanics have been attempted, and are discussed by Bell (1987, pp. 173–180) and by Bohm & Hiley (1993, Chapters 11 and 12).

2005, chaps. 16.8 and 17, in particular pp. 417–418). *The theory thereby ensures that linear superpositions of states corresponding to macroscopic differences in the presupposed "beables" are forbidden.* However, how should we understand such beables?

Bell (1987) elaborates on GRW in conceiving the spontaneous localizations as *flashes* occurring at space-time points. He regards macroscopic objects as "galaxies of such flashes" (see Bell, 1987, in particular p. 45/p. 204 in the reprint). Our framework is better adapted to this particular formulation of GRW, even though the same conclusion would hold for the "density of stuff" version of the theory, originally due to Ghirardi et al. (1995, to be described in more details in 3). An important advantage of flash-GRW is that, as Tumulka (2006) has shown, a relativistic version of this theory *can* be developed, without a commitment to a privileged reference frame or coordinate system (see the discussion of this proposal by Maudlin, 2008). By contrast, the density-of-stuff version of GRW needs a privileged reference frame.

There are of course further concerns with GRW beyond its consistency with relativity, the main one being that the amendment of Schrödinger's equation is done so to speak "by hand", or in an *ad hoc* way. One could suspect, for instance, that if spatial superpositions of non-zero rest mass microsystems were observed, say, at a scale that is beyond that required by the new constant of nature (10^{-7} m) envisaged by GRW's original model, the theory could be elastically modified accordingly, *so as to avoid any possible refutation by experience*. This latter objection, however, is not fair. GRW and its further improvements since 1986 may of course not be the last word on the matter of a unified dynamics for microscopic and macroscopic systems, but the project of developing such a dynamics is a well-motivated one, given on the one hand the enormous empirical success of quantum physics, and on the other the above mentioned drawbacks entailed by Everett's or Bohm's approaches. When it comes to the transition to macroscopic systems, a unified dynamics of the microscopic and the macroscopic world can only be achieved by a correction of the Schrödinger equation that has to be guided by our knowledge of classical physical properties, in their still imprecisely known separation from the quantum ones. Any physically precise, exact, and elaborate result of such a way of thinking deserves to be taken seriously as being on the right track towards a fundamental equation, where the adjective "fundamental" is motivated by the *unifying explanatory power* of a theory that purports to bring together the dynamics of the micro- and the macro-world in a single equation. Furthermore, despite concerns about the possibility of testing the theory due to the quickness of the decoherence processes, the theory is in principle falsifiable, in particular in those cases in which GRW predicts collapse but the system is shielded from decoherence (or the two pull in different directions) (see Bacciagaluppi, 2007 and Bassi & Ghirardi, 2003, Section V).

3. GRW's commitment to dispositions as the most plausible ontological option

In a nutshell, we think that GRW makes two fundamental ontological assumptions: (1) spatial superpositions of non-massless microsystems whose wave function has a spatial spread that is significantly greater than the new constant 10^{-7} m evolve into well-localized states in an observer-independent way, and independently of interactions with other physical entities, by means of processes of spontaneous localization. (2) Since these processes are irreducibly probabilistic, GRW is the only realistic interpretation of quantum theory that is indeterministic. What do these assumptions amount to? And how are we to understand these irreducible probabilities? These two questions will be the subject of, respectively, this section and the next one.

It is well-known that the fundamental characteristic of quantum mechanics, distinguishing it from classical physics, is the existence of superposed states (see Dirac, 1958). Whereas on the Everett interpretation superposed states always evolve into further superposed states, GRW admits events of spontaneous localization (the so-called tail problem will be discussed below). One way to read these events is to claim that in GRW, in contrast to the Everett interpretation, non-massless microsystems possess a *disposition for spontaneous localization* (see Dorato, 2006, 2007; Suárez, 2007). In the current state of our knowledge, this disposition is irreducible: it is *not* grounded on non-dispositional, categorical properties. It belongs to the ontological ground floor, so to speak, and it is a real and actual property, not a purely possible property. It is therefore appropriate to talk in terms of a *power* for spontaneous localization: while this modal language is not explicitly present in GRW's original papers, it is not only compatible with them, but also recommended for reasons that will become clear in the last section.

The peculiar character of a GRW disposition to localize is that for its manifestation it does *not* need outside triggering conditions involving other microsystems: that is the point of calling the localization "spontaneous". *Qua* spontaneous, the disposition in question is independent of any interactions, including any interactions with measurement devices or environmental conditions, and it therefore does not presuppose any cause, although, *qua* property, in our view it *is* a type of cause, namely a probabilistic cause of the localization.

In the philosophical literature on the metaphysics of properties, a position known as the causal theory of properties has become a strong contender since the 1980s (see notably Shoemaker, 1980; Bird, 2007), standing in opposition to the view known today as "Humean metaphysics", according to which all properties are categorical, that is, pure *qualities*. According to this position, *all* properties, including the fundamental physical ones, are dispositions or powers to produce certain specific effects. Dispositions are thus *not* properties of properties: on the causal theory of properties, by contrast, properties just *are* dispositions.

In a nutshell, dispositions regarded as powers are real properties whose nature or essence consists just in that power. One can therefore characterize this position by saying that *insofar as properties are certain qualities, they are powers to produce certain specific effects* (cf. also the way in which Heil, 2009, p. 178, presents the last position of C. B. Martin, one that conceives properties as "powerful qualities"). Take charge for example. Insofar as elementary charge is a qualitative, fundamental physical property, distinct from e.g. mass, it is the power to build up an electromagnetic field, thus repulsing like-charged and attracting opposite-charged objects. In other words, the very qualitative character of charge consists in its being and exercising the power to build up an electromagnetic field. Since the qualitative nature of properties thus is a *causal* nature, we can in principle gain knowledge of that qualitative nature via its effects. To the extent that laws of nature are nothing but the abstract codification of such causal relationships—a view that here will be taken for granted—we can also add that laws, *qua* descriptions of the properties of physical systems, are also essentially descriptions of their causal powers or dispositions (for arguments for this view of laws, see, among others, Cartwright, 1989; Harré, 1993; Hüttemann, 1998; Dorato, 2005; Bird, 2007).

In any case, we submit that this way of conceiving properties is the ontology appropriate for GRW. As already mentioned, in our view GRW distinguishes itself from Everett by attributing quantum system endowed with mass a disposition for spontaneous localization. However, it would be wrong-headed to conceive GRW's dispositions to localize as properties *in addition* to the properties characterizing an isolated quantum system. From a physical point of view, such a separation would clearly be on the wrong track. Consider superpositions of systems whose Ψ function's spatial spread is significantly greater than 10^{-7} m: within the GRW interpretation, the disposition for spontaneous localization, and thus state reduction, is the *essence* of such spatially superposed states, since the latter, according to GRW, are to be regarded as intrinsically unstable. Using Bell's expression (1987, p. 204), we can say that Schrödinger's cat *is both dead and alive* (i.e. in a macroscopic superposed state) "for no more than a split second" (that is, 10^{-7} s). Thus, the superposed states described as above *are* themselves dispositions or powers to localize spontaneously,[5] thanks to the particular powers that GRW attributes to non-massless quantum systems.

Of course, as it happens with all the other dispositions, also the GRW disposition to localize will *manifest* only in the right conditions, which in our case involve the new constant of nature (although, as mentioned above, there are no *external* triggering conditions needed, since the disposition is one for *spontaneous* localization). If the wave function of, say, an individual proton is well-localized (the spread is much less than the new constant 10^{-7} m), then the particle in question will *not* manifest its disposition to localize.[6] If instead the spread of the spatial superposition of the proton is significantly greater than the above constant, then it will eventually localize with the given frequency. But this does *not* mean that the disposition in question is not *essential to the proton*: according to GRW, in fact, a universe composed just by an isolated proton would still have an *intrinsic* disposition to localize once in 100 millions years, independently of the existence of other particles, even if it does not manifest this disposition because its spatial spread is small. This fact has interesting metaphysical consequences that have not been noted before.

We now have four different ontological readings of GRW: (i) a wave function ontology, in which configuration space is primary and space-time emergent (Albert, 1996; Clifton & Monton, 1999), (ii) Bell's flashes around a centre of reduction located in physical space, (iii) continuous fields, and, as we claim, (iv) dispositions, which in our view are more fundamental than flashes and at least as fundamental as the continuous fields. Therefore, leaving (i) by side (we will come to it in the fourth point of the next section), GRW's beables are to be regarded either (ii) as constellations of flashes, or (iii) as fields, or, if we are correct, (iv) *as intrinsically constituted by powers to localize*.[7]

Summing up, the metaphysics of causal properties applied to the GRW interpretation entails two ontological commitments:

(1) Dispositions or causal powers to localize, constituting non-massless quantum systems, do not need outside triggering or manifestation conditions, but manifest themselves spontaneously in the right condition of spatial superposition—in other words, they exercise spontaneously the power that they are. This holds for other fundamental physical properties as well. For instance, an elementary charge also builds up an electromagnetic field spontaneously, not needing outside triggering conditions (such triggering conditions are of course required for the manifestation of the field in the form of the attraction and repulsion of objects, but not for building up the field itself from elementary field sources). Apart from these physical considerations, conceiving the fundamental physical properties as powers that manifest themselves spontaneously avoids the infinite regress objection against the causal theory of properties (see e.g. Armstrong, 1999, Section 4): if properties are powers and if powers always need external triggering conditions, then it seems that the triggering condition *b* for power *a* is itself a power that needs a triggering condition *c* for exercising its triggering, etc. Thus, our claim is that the *fundamental* physical properties are powers (dispositions) that manifest themselves spontaneously, without depending on outside triggering conditions. Nonetheless, an analogy with dispositions that need triggering conditions still remains also in the case of GRW. Since the *typical* conditions for the manifestation of GRW dispositions are interactions between microsystems and macrosystems—an isolated quantum entity can be in a superposed state for 100 millions years—with the necessary provisos we can regard such interactions as the triggering stimuli for the manifestation of the disposition to localize.

(2) Powers or dispositions for spontaneous localization constituting non-massless quantum systems are dispositions that admit of degrees: the more microentities there are, the greater is the strength of that disposition. The disposition to localize can be measured, as Cartwright (1989) has it, in terms of the GRW probabilities. More precisely, therefore, the powers or dispositions for spontaneous localization are *propensities*.

Having set out our view, in the following we shall defend it against some widespread reservations, thereby developing five arguments that speak in its favour.

4. Five arguments for the commitment to dispositions

There is a widespread reservation against dispositions in general, claiming that a commitment to dispositions or powers is completely unmotivated in the context of physics and quantum mechanics in particular, since it relies on an outdated, scholastic and wordy metaphysics. As a consequence, not only would our move of introducing dispositions in GRW be totally external to the physical theory itself, but it would also be irrelevant for a deeper understanding of the implications of dynamical reduction models for our overall physical knowledge. More generally, given that powers or dispositions notoriously do not seem to explain anything (recall the famous *virtus dormitiva* explanation of the reason why opium induces sleep given by Molière), shouldn't we always *dispense with dispositions*? In order to rebut this important objection in our context, it is worthwhile to spell out in more detail what a dispositional reading of GRW adds to our understanding of dynamical reduction models.

There are at least five reasons why the above stated objection is not conclusive. The first reason involves the peculiar role that the principle of superposition and the notion of property enjoy in quantum mechanics. The second reason concerns the possibility of grounding a satisfactory interpretation of the irreducible probabilities required by GRW in terms of *probabilistic dispositions*, that is, *propensities*, in opposition to the brilliant "Humean Best System" (HBS) analysis suggested by Frigg and Hoefer (2007). The third reason expresses our dissatisfaction with looking at macroscopic objects as mere "galaxies of flashes" or fields (Bell, 1987; AGTZ, 2008): endowing quantum systems with dispositions is a more promising ontological commitment in order to account for classical properties, including our experience of macroscopic objects. This point will also entail a discussion of a well-known difficulty of GRW, the so-called "tail problem", which could pose a

[5] Here we use the terms 'disposition' and 'power' interchangeably.

[6] We owe this point to one of the two anonymous referees.

[7] Of course, considered from the viewpoint of other physical theories, GRW beables have further properties.

threat to the framework defended here. The fourth reason concerns the need to be able to distinguish between purely mathematical and real physical structures: we submit that the causal conception of the latter defended here can account for this distinction, and can thus avoid some counterintuitive consequences of the wave function ontology.[8] The fifth reason is centred on the possibility to ground the time-asymmetric character of the GRW theory in the time-asymmetric nature of dispositions in general. Let us discuss these reasons in turn.

(1) It is well-known and uncontroversial that one of the ways to characterize the central difference between classical and quantum physics is given by the peculiar role that the principle of superposition plays in the latter theory (see e.g. Dirac, 1958, p. 12). It is also well-known and uncontroversial that the superposition of non-factorizable states, that is, entanglement, entails or is equivalent to the fact that there are no properties with definite numerical values upon which the entangled state supervenes. Let us therefore grant that *the lack of properties with definite numerical values (implied by superposed or entangled states) is the litmus test for the presence of quantum mechanical phenomena*. In some sense, and in comparison with classical mechanics, this is *the* philosophical lesson to be brought home after the discovery of quantum mechanics.

For this reason, some scholars have even gone so far as saying that in quantum mechanics one should not even talk of properties. This claim would hold both for superposed or entangled states and for those observables whose values contextually depend on the measurement setting (as spin in Bohmian mechanics).[9] We can now express the objection in the following way: if *no property talk* is appropriate in a quantum mechanical experiment—possibly except for non-contextually possessed properties—why introduce dispositions, which *are* a kind of properties, to clarify what superposed states are?

First of all, by introducing dispositions in order to characterize the nature of superposed states, we are not guilty of ''naïve realism about operators'' (Daumer, Dürr, Goldstein, & Zanghì, 1996): on the contrary, in our view, conceiving the spatially superposed states described as above as propensities to localize is a direct consequence of recognizing the lack of definite, state-dependent properties for most of the time for most microscopic systems. ''Lack of property'' in our view simply means ''lack of some definite state-dependent properties'' or ''lack of some state-dependent properties corresponding to definite magnitudes'', but not lack of any kind of properties whatsoever, which would be entirely absurd! That is why the view of properties as dispositions in the sense of causal powers fits extremely well with quantum mechanics: this view provides for a clear sense in which quantum systems in superposed (including entangled) states possess state-dependent properties without possessing properties with definite numerical values. Recalling that here we take for granted the view that laws of nature are about dispositions, the dynamics expressed by the causal powers constituting the quantum systems is captured and described by the unified law of evolution proposed by GRW.

Furthermore, if we are careful to distinguish the possession of a definite property from the disposition to manifest one, we avoid any paradox of the Kochen-Specker kind, roughly consisting in attributing *too many* definite properties to quantum systems (see Suárez, 2004b). In a word, according to GRW, the state-dependent properties of non-massless quantum systems are objectively indefinite, but they are mind-independently and probabilistically disposed to become definite.

In brief, our first reason for a commitment to dispositions, therefore, is that this commitment takes into account the fact that in superposed or entangled quantum states there might be no properties with definite numerical values, while avoiding the absurd consequence of claiming that in such cases there are no state-dependent properties at all. Spatial superpositions of non-massless microsystems, if regarded as possessing, among other things, a disposition (causal power) to localize, *are both* lack of any definite spatial property on which the disposition could supervene *and* a propensity to lose that indefiniteness by becoming definite through events of spontaneous localizations.

(2) In the philosophy of quantum mechanics, the *propensity* interpretation of quantum probabilities has been around for a long time (for a historical sketch and a survey, see Suárez, 2007; Dorato, 2007; and for a criticism of some untenable approaches, see Suárez, 2004a). We believe that it has finally found a clear and defensible version in the GRW dynamical reduction model. In fact, an important advantage of the propensity interpretation of probabilities is the possibility to attribute *single-case probabilities*. It is well-known that quantum mechanical probabilities must refer also to single systems, at least if the theory is indeterministic and if the ignorance interpretation of superpositions is, as it should be, out of question. In order to talk about an objective, mind-independent probability, as GRW requires, a propensity theorist has the advantage of not having to refer to ensembles of particles, or to actual or idealized frequencies. Frequencies are simply supervenient on, and a manifestation of, those propensities to localize that are the essence of spatially superposed quantum particles.

Frigg and Hoefer (2007), in contrast, have claimed that a so-called *Humean Best System* (HBS) interpretation of the GRW probabilities is more convincing than the dispositionalist reading defended here. According to them, in order to make room for the view that the probabilities introduced by GRW are objective (in the sense of being *non-epistemic*), single case propensities are *not* needed, since HBS *chances* suffice. HBS chances are supervenient on all the local facts in the whole history of the world, and are therefore not to be identified with subjective degrees of belief as in the Bayesian approach to probability. It is this realist grounding in the occurrent, local facts of the world history that, in Frigg and Hoefer's view, guarantees the *objectivity* of GRW probabilities. According to them, however, such local facts in the history of the universe are to be conceived *non-dispositionally and non-modally*. Probabilities, consequently, do not have any modal character, and need not be conceived of as propensities or powers.

In our view, the weakness of a HBS analysis of GRW probabilities derives from the weakness of Lewis' approach to laws of nature, to which a HBS account of probabilities seems to be committed. Coherently with such an account, also the Lewisian approach to laws refuses to recognize any sort of modal property in nature, and must explain nomicity in terms of matters of local facts: laws in HBS accounts denote nothing but lists or histories of events or occurrent facts. In Frigg and Hoefer's proposal, what propensity theorists call ''disposition to collapse'' really refers to the *whole* mosaic of local states of affairs, on which GRW laws supervene as axioms or theorems of the theory that achieves the best combination of *simplicity*

[8] See the first option (i) of the previous section.

[9] ''In a general experiment no system property is being measured, even if the experiment happens to be measurement-like. (Position measurements are of course an important exception.)'' (Dürr, Goldstein, & Zanghì, 2003, pp. 18–19).

and *strength*. The real trouble here, however, is not only that simplicity and strength are language-dependent virtues, but also that they are *merely epistemic virtues*, albeit intersubjectively shared ones. We submit that the epistemic character of these virtues infects also Frigg's and Hoefer's account of probabilities with subjectivity.[10]

Lewis is quite aware that an appeal to simplicity, strength and their balance—given that these virtues are relative to our current, socially shared, standards—make his account of laws *relative to us* (Lewis, 1986, p. 123). However, he thinks that this relativity yields some stability: if in other possible worlds people had different standards, their laws would not count as laws *if our standards are fixed across different possible worlds*. Also this defense, however, is unconvincing: if it is an appeal to the standards of our *present* culture that makes a proposition a law, Lewis' account is non-objectivistic nevertheless, in the sense of being culture-relative, and mind-dependent: why should the standards of our particular culture matter? (see also Carroll, 2004, p. 54).

On the contrary, given our commitment to the claim—which here cannot be defended—that law statements are made true by dispositions or causal powers possessed by physical systems, we rely on the view that it is capacities rather than laws that are basic (see e.g. Cartwright, 1997; Bird, 2007). Consequently, it seems to us that an *objectivist* view of the GRW probabilities can be more naturally defended by committing oneself to mind-independent properties or relations that microsystems have, and by conceiving these properties or relations in a modal way, that is, as dispositions or causal powers.

The HBS position, on the contrary, seems to oscillate between frequentism, with all its known problems, and *epistemic* views of probability, introduced by the criteria of simplicity and strength of laws, pushing one's position toward subjectivism or Bayesianism. For example, in HBS accounts it is not clear how, without relying on "actual frequencies" of events in actual histories, one is going to distinguish between "stochastic histories" governed by probabilistic laws and "deterministic histories" governed by deterministic laws. As a consequence, Frigg and Hoefer have to accept the claim that frequencies *are* part of the Humean mosaic, and hence ground objective probability claims. The difference between HBS and frequentism is that the former position does not assign probabilities *solely* on the basis of frequencies but also takes epistemic virtues into account (simplicity, strength, etc).[11] However, such virtues are at best a heuristic guide to discover mind-independent facts, since, as noted above, they are *epistemic* and *language-dependent*. It then follows that if probabilities are chosen on the basis of the overall simplicity of the accepted theoretical framework, they become epistemic and language-dependent, and therefore mind-dependent too, contrary to the GRW requirements. Furthermore, if we accept Frigg's and Hoefer's (correct) claim that an appeal *just* to frequentism is a non-starter for GRW probabilities, it seems that in order to make sense of objectivist chances, there is no other choice but to commit oneself to probabilistic dispositions, that is, propensities. Since Frigg and Hoefer recognize that propensities have many advantages, but end up preferring the HBS account, we conclude that they simply ought to reverse their judgment: HBS have nice features, but to ground objective chance in GRW, propensities are better.

One final complication for the propensity interpretation of the GRW probabilities might arise via the Principal Principle (a rule that commands to adapt our subjective degrees of beliefs to objective chance). Lewis and others have thought that propensity theorists cannot avail themselves of the Principal Principle, without which they cannot give epistemic warrant to the propensities. Why believe in the fact that a quantum system *s* has a propensity *P* to collapse, say in 10 min, if *s* could collapse much later or much earlier? (The Poisson distribution for times of collapse of course works as an average for the number of systems that collapse in the unit time). Our response is that we can learn about the strength of the propensities that need to be postulated (and therefore about the laws) only after having observed very many localization processes. The way the propensities to collapse in time are distributed implies that it is rational to expect that most of the systems collapse in the average time prescribed by the law, but this makes the link between credence and objective propensity *analytic*: if the propensity of localization is *P*, then our credence in the manifestation of the propensity should be *P*.

(3) Our claim is that GRW is a fundamental theory, because it regards propensities for localization as ontologically primitive, thereby explaining the measurement results. Before spelling out what this explanation amounts to, it is important to dispel an objection that may jeopardize our view that dispositions to localize always manifest as well-defined localizations. In virtue of Heisenberg's indeterminacy relations in fact, the post-hit wave function describing the system in configuration space cannot be attributed too sharp a peak, lest the momentum of the system be indefinitely large: in this case the system would heat up with observable consequences. Furthermore, the wave function of a closed system of particles cannot have a bounded support, because it is known since the late twenties that Schrödinger's "wave" tends to spread: as a consequence, except in isolated moments of time, the system's wave function must always possess tails going to infinity. If this is the case, not only would each particle in the system not be localized, but the end result of the "localization" would just be another superposed state, closer to a product state, but still superposed. The dispositions strictly speaking would not be dispositions to localize, but rather dispositions to enter a state that can only be described by a more sharply peaked wave function centred on a given point. There are various and controversial ways out from this difficulty, but independently of the path taken, the "tails objection" does not pose any real threat to the approach suggested here. The first way out is to remind ourselves that the configuration space and the wave function are useful tools to represent physical systems, but are not themselves, as EPR would put it, "elements of reality". Here, we definitely side with AGTZ (2008) in holding that the role of the wave function is simply to provide an algorithm that guides the evolution of the physical system: the "hit" of the wave function, however, that is, its multiplication with a Gaussian, is itself not a physical event, but *is merely a mathematical representation of the spontaneous manifestation of the propensity to localize*. In the same spirit, the existence of tails, corresponding to the fact that mutually alternative measurement outcomes are not correlated to perfectly orthogonal states, *qua mathematical fact*, does not necessarily pose threats to the definiteness of localization of macroscopic objects, *until a reasonable physical interpretation of this fact is provided*.

One possible interpretation of this fact has been given by Ghirardi and Bassi: "the problem [...] raised by the appearance of the tails in theories of the GRW-type has very little to do with the so-called 'measurement problem of Standard QM',

[10] These authors seem to be aware of some difficulties of the Lewisian approach to laws (Frigg & Hoefer, 2007, p. 381).

[11] In this way the HBS theorist may drop the notion of a *Kollektiv*, which causes well-known troubles to the von Mises type frequentist.

but instead is strictly related to another relevant problem, i.e., the one of describing, within a genuine Hilbert space formalism (without resorting to some kind of hidden variables), a physical system having a definite location." (Ghirardi & Bassi, 1999, p. 56). But even if one is not satisfied with Ghirardi and Bassi's claim that any *realistic* measurement in our laboratory, and therefore any solution of the measurement problem, *must* end up with non-exactly mutually orthogonal outcomes, another way out is available to show that the tails do not jeopardize the approach defended in this paper.

This second way out has been advocated by Albert and Loewer (1996, p. 87), and then defended by Clifton and Monton (1999). It consists in weakening the eigenstates-eigenvalue link by claiming that a particle is located in *some region* of space if and only if its wave function is *almost* in an eigenstate of being there. "Some region" is liberal enough as to make room for the wave function not being too sharply peaked and thereby avoid unobservable consequences. At the same time, it assumes that *a very high probability* for a quantum system to be in a certain region is sufficient to assert that the system just *is* located in that region, despite the fact that the tails extend everywhere in configuration space. Notice that even if this second solution were to imply, strictly speaking, that the end result of the localization process is yet another superposed state, closer to a product state than the previous one (a "quasi-product state"), we would not find this terribly upsetting, as long as the approximation in question is capable of explaining our experience of a cat being definitely alive or dead. And GRW is capable of achieving this result.

Finally, against the background of the causal theory of properties, which we take to be the appropriate metaphysics of properties for GRW, it might be wrong-headed to expect the manifestation of a disposition—in other words, the exercise of the power that a property is—to result in a categorical property. On the contrary, there might be in the world no categorical properties at all: insofar as properties are certain qualities, they are powers to produce certain effects. Thus, any effect that a power (disposition) produces again is a power (disposition)—and nevertheless an actual property. Consequently, if superposed states are powers for spontaneous localization, exercising that power results again in a power, as described by the GRW modification of Schrödinger's equation. In a nutshell, against the background of the causal theory of properties, it would be quite inappropriate to expect that a disposition disappears in favour of purely categorical properties. Rather than constituting an objection, the "tails objection" confirms the appropriateness of the causal theory of properties for GRW.

We can now move to the comparison of our view with the approach of AGTZ (2008). AGTZ base themselves on the following presupposition: ruling out (correctly) the idea that GRW is a theory about the wave function suffering "hits" and living in a 3N configuration space (Albert, 1996; Clifton & Monton, 1999), there are only two remaining versions of the GRW ontology: the so-called event-like Bell ontology of flashes (the centres of the localization processes) (GRWf), and the ontology of a field advocated by Ghirardi et al. (1995), corresponding to the "density of stuff" in Newtonian space-time (GRWm). However, we insist that this presupposition is *not* correct, or is at least incomplete: GRW is not only an ontology of the results of localization processes, but is *also committed to a realist attitude toward the superposed states themselves*. AGTZ claim: "A parallel with BM [Bohmian mechanics] begins to emerge: GRWm and BM both essentially involve more than the wave function. In one the matter is spread out continuously, while in the other it is concentrated in finitely many particles; however, both theories are concerned with matter in three-dimensional space, and in some regions of space there is more than in others" (AGTZ, 2008, pp. 359–360). By contrast, we maintain that the superposed states represented by the wave function of the systems are not only part of the ontology, but are also more fundamental than flashes and at least as fundamental as the continuous fields spread in space-time.

They are more fundamental than the flashes because flashes are the *manifestations* of the dispositions to collapse. These dispositions are at least as fundamental as the continuous fields because the localization of the latter (the breaking of superposed or entangled states) is due to the fact that such fields *are*, *among other things*, propensities to localize. The localized nature of those fields at the classical level is thus due to their being dispositions, requiring a hypersurface of simultaneity along which their manifestation occurs (recall that the field interpretation of GRW, unlike the flash one, requires a privileged reference frame for the collapse to occur). Finally, the assignment of a mass or flashes distribution prior to a certain time—if these are conceived as purely categorical, *local* properties—is by no means sufficient to make predictions concerning mass or flashes distributions at later times, since only the complete distribution of flashes of fields across the whole of space-time would suffice.[12]

We thus claim that the wave function is a mathematical symbol essentially referring to such propensities. One may maintain that *classical* space-time just *is* constituted by the set of flashes (in GRWf) or by the density of "stuff" (in GRWm). However, given the reality of superposed states in GRW's theory, one has to set out an ontology that is explanatorily prior, and we propose to do so in terms of dispositions to localize possessed by each non-zero rest mass micro-entity.

The intention of GRW is to *answer* the following crucial question (instead of just accepting an answer to that question as given): how is it that spatially superposed microsystems that are not sufficiently localized *generate* the classical world of definite properties, where everything is exclusively either here or there? We assume that propensities to localize are primitive and that the spatially superposed states denote, among other things, just such propensities. An important argument for this view is that it provides a clear theory unifying quantum properties and classical properties, without presupposing observers or measurement devices. It therefore is a candidate for a fundamental theory, being applicable to cosmology as well.

According to our view, there is a causal relation between the superposed or entangled state at a certain time and the localization at a later time, since the superposed or entangled state *is* the power to produce the localization. Nonetheless, there is no deterministic cause, but only a probabilistic one, consisting in a propensity that manifests itself spontaneously, thus spontaneously producing the localization event. The explanatory character of dispositions (powers, propensities) in this case is given by the fact that they *unify* the microscopic world with the classical world, much along the direction of those theories of scientific explanations that point toward unification as the main criterion for explanations (Friedman, 1974; Kitcher, 1976). However, there can of course be no explanation of the fact that elementary, non-massless micro-entities that are spatially superposed as the new constant of nature indicates are powers for spontaneous localization—in

[12] We owe this point to one of the referees.

the same sense in which there can be no explanation of the fact that elementary charges are powers to build up an electromagnetic field. In view of our current knowledge of the physical world, this is just what they are. In describing the character of the fundamental physical properties, we've reached the ontological ground floor.

(4) In contrast to what AGTZ claim, it is possible to spell out a realist attitude towards propensities to localize *without subscribing to any form of realism as regards mathematical entities such as configuration space*. On the contrary, conceiving the entangled states described by the wave function as causal powers just avoids Albert's (1996) counterintuitive, realistic commitment to the configuration space.[13] It provides for a clear distinction between mathematical entities such as configuration space and physical entities (this advantage has been first stressed by Suárez, 2004b, 2007). While mathematical structures, whatever they may be, do not cause anything, it is the litmus test for something to be a real physical (in contrast to a mere mathematical) entity that it is causally efficacious. We submit that the commitment to causal properties in the domain of fundamental physics is necessary to be able to distinguish mere mathematical from real physical entities. Maintaining that real physical entities, in contrast to mathematical ones, are localized in space-time is clearly *not* sufficient for this purpose, since spatially superposed microsystems are physically real and yet they do *not* possess a localization in space-time.

(5) Finally, interpreting GRW in terms of a commitment to superposed states being causal powers (dispositions, propensities) for localization is a candidate for a fundamental theory also because it might yield a clear grounding for the direction of time. Let us come back to the comparison between a propensity and a HBS interpretation of the GRW probabilities. A further reason why the propensity interpretation fares better than its HBS rival is that one of the well-known difficulties of the former—the asymmetry of the propensity *vis à vis* the symmetry of probabilistic dependence exemplified in Bayes' theorem (Humphreys, 1985)—in our case turns actually into a surprising advantage: the asymmetric character of propensities fits in well with the asymmetric character of the GRW localizations. Typically, the time-asymmetric nature of propensities has been contrasted with the time-symmetric character of the physical laws and therefore criticized on the basis of this very reason. However, as Frigg and Hoefer (2007) correctly note, Born-like probabilities are "forward-looking" anyway, and if one is committed to the existence of physical processes in which systems in superposed states localize in accordance with those Born probabilities, then there exist physical processes governed by a physical law such as the one proposed by GRW that are *not* time-reversal invariant. The time-asymmetric propensities to localize are therefore the truth-maker of the GRW fundamental law of evolution, unifying micro- and macrodynamics, *but failing to be time-reversal invariant*: the process of localization can in principle not be reversed, and the reason for this fact is that a disposition or power is intrinsically directed to the effects in which its manifestation consists. On the currently still speculative hypothesis that the GRW localizations can be conceived as the basis for all time-asymmetric phenomena (Albert, 2000, chap. 7), the ontology of fundamental physical propensities for localization grounds the direction of time.

[13] However, for a conception of scientific realism inviting us to live with the abstract, see Psillos (forthcoming).

In conclusion, against the background of these five arguments, we claim that, far from belonging to an outdated, scholastic metaphysics, the commitment to dispositions (causal properties in the sense of propensities) is the clue for a comprehensive and coherent understanding of the world as described by contemporary science, from fundamental physics to classical physics.

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