An Indeterminacy-based Ontology for Quantum Theory

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Abstract

I present and defend a new ontology for quantum theories (or "interpretations" of quantum theory) called Generative Quantum Theory (GQT). GQT postulates different sets of features, and the combination of these different features can help generate different quantum theories. Furthermore, this ontology makes quantum indeterminacy and determinacy play an important explanatory role in accounting for when quantum systems whose values of their properties are indeterminate become determinate. The process via which determinate values arise varies between the different quantum theories. Moreover, quantum states represent quantum properties and structures that give rise to determinacy, and each quantum theory specifies a structure with certain features. I will focus on the following quantum theories: GRW, the Many-Worlds Interpretation, single-world relationalist theories such as Relational Quantum Mechanics, Bohmian Mechanics, hybrid Classical-Quantum theories, and Environmental Determinacy-based (EnD) Quantum Theory. I will argue that GQT should be taken seriously because it provides a series of important benefits that current widely discussed ontologies lack, namely, wave function realism and primitive ontology, without some of their costs. For instance, it helps generate quantum theories that are compatible with relativistic causality, such as EnD Quantum Theory. Also, GQT has the benefit of providing new ways to compare and evaluate quantum theories, which may lead to philosophical and scientific progress.

1 Introduction

What exists at the fundamental level according to our best scientific theories? Or, more concretely, what is the right ontology behind the puzzling phenomena represented by quantum theory (QT), arguably our most widely applicable fundamental theory? It is unclear how to understand and answer satisfactorily

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these questions. There are several interpretations of QT, or more accurately, different quantum theories (QTs). Also, there are longstanding foundational and philosophical issues surrounding the elements of the theory, such as the wave function or quantum state. To address these questions, there are diverse, what I will call ontological frameworks that provide clear ontologies applicable to various quantum theories.

A widely debated framework is Wave function Realism,[1] which considers that what fundamentally exists is a wave function living in a large multidimensional configuration space.[2] Another widely debated framework called primitive ontology,[3] typically considers that quantum states/wave functions/density operators have a nomological character. Moreover, the primitive ontology that these objects describe/govern concerns entities with determinate features that live in a determinate location of the three-dimensional space. Other alternatives consider that the density operator is a property of spacetime points,[4] etc. Since we currently don't know what the right QT is, a plausible strategy to investigate its ontology is to formulate and analyze ontological frameworks, which, given their generality and clarity, will likely provide that information.

What the current major ontological frameworks have in common is that they consider that there are determinate properties or features or laws or fields (e.g., wave function, primitive ontology, etc.) that are fundamental and play a key explanatory role. Indeterminate properties, in a sense that will be clarified, arise from them and have a secondary explanatory role. For instance, according to wave function realism, indeterminate properties arise from a multidimensional field, and what plays a key explanatory role is this field.[5] However, historically, the so-called Eigenstate-Eigenvalue Link (EEL) played an important role in interpreting QT, especially within the more "orthodox" interpretations.[6] According to this link:

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[1] See, e.g., Albert (1996, 2023) and Ney (2021).

[2] The wave function that represents this field mathematically concerns quantum states expressed in a basis. Disregarding the spin, in non-relativistic QT, the wave function is typically considered a *square-integrable* and smooth function whose domain is the $\mathbb{R}^{3N}$ configuration space where N is the number of particles, and the range is complex numbers. More concretely, in the non-relativistic case, the wave function in the configuration space is obtained by projecting the quantum state onto the position basis of the particles under analysis. For a single particle, the wave function $\psi(\mathbf{r}, t)$ is given by $\Psi(\mathbf{r}, t) = \langle\langle\mathbf{r}|\Psi(t)\rangle\rangle$. This projection gives the probability amplitude for finding the particle at position $\mathbf{r}$ at time t. For a system of N particles, the wave function $\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N, t)$ is obtained by projecting the quantum state onto the combined position basis of all particles: $\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N, t) = \langle\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N|\Psi(t)\rangle$. $\mathbf{r}_i$ represents the position of the i-th particle. Thus, in this non-relativistic case, for the wave function realist, if we have a universe with just one particle, we consider that that universe just has 3 dimensions. If we have a universe with N particles, for the wave function realist, the space of that universe has literally 3N dimensions, each dimension corresponding to one possible configuration of the particles. Even if particles are far apart in the three-dimensional space, such as in the Bell scenario, they are near each other in the configuration space. This "locality" in the configuration space makes this view attractive to some. The wave function is a field because it assigns complex amplitudes to the regions of this multidimensional space.

[3] See, e.g., Allori (2013), Dürr et al. (1992), and Goldstein and Zanghì (2013).

[4] Wallace and Timpson (2010). See also, e.g., Myrvold (2022) and references therein.

[5] See also Glick (2017).

[6] See Gilton (2016) for a historical overview of the importance of this link.

A system S has a determinate value q of an observable O if and only if the quantum state of S is in an eigenstate of O with an eigenvalue q.

This link often leads to the assumption that if the quantum state of S is in a quantum state that is not an eigenstate of some observable, the system has, in a sense, an *indeterminate value* of that observable. It also has led to the view that QT presents a new kind of indeterminacy, an ontological indeterminacy.[7] The source of this indeterminacy is not in our knowledge or the semantics of our language[8] but in the world itself. However, despite this link's importance, an ontological framework applicable to the major QTs, and where quantum indeterminacy plays an important explanatory role, hasn't been proposed and defended.

I propose and defend an alternative ontological framework called generative quantum theory (GQT). In this framework, quantum indeterminacy plays an important explanatory role rather than the opposite, reversing the arrow of explanation from what is typically proposed by the ontological frameworks of QT. I will compare GQT to the most widely discussed ontological frameworks, wave function realism and primitive ontology, and explain that it doesn't suffer from some of their notorious costs while proving some important benefits.

The rough idea of GQT is that the world is constituted by default by entities with so-called *indeterminate (value) properties*, which give rise to entities with *determinate (value) properties*, which are considered to be objective features of the world. GQT will also offer the possibility of giving rise to QTs where entities with determinate value properties also exist by default, along with entities with indeterminate value properties.[9] Via a relation between determinate and indeterminate value properties and other features of systems, I will also provide a new analysis of quantum indeterminacy and determinacy. Furthermore, contrary to the previous ontological frameworks, this framework postulates different new sets of features. In this article, I will propose seven different but interrelated features. The combination of these different sets can help generate different QTs, which, as I will argue, will provide several benefits.

Often associated with Wave function Realism and Primitive Ontology is a reificatory view of the wave function or a literalist reading of it either as a law or an object. GQT will adopt a different view of quantum states/wave functions and density operators,[10] assigning them various roles. They will allow for inferences about and representation of the different possibilities of determinate values arising. Also, they help represent the so-called *quantum properties* of systems that are related to value properties, "giving rise to them." However, this representation won't be a literalist or *self-standing* one. Quantum states have the support of values, observables and other tools, such as directed graphs, DAGs (directed acyclic graphs, i.e., directed graphs with no cycles), and

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[7] See, e.g., Barnes and Williams (2011), Lewis (2016), and Calosi and Wilson (2019).

[8] See, e.g., Fine (1975) and Williamson (1994).

[9] Such as Bohmian mechanics, as we shall see.

[10] Note that I will often refer to density operators as quantum states.

Quantum Causal Models, to make inferences and represent the various features mentioned above. Importantly, and this is a key innovation, these tools will support inferences and representations about structures of interactions that give rise to determinacy.[11] Different QTs will appeal to different structures of this kind. Given their epistemic role, quantum states of a system won't collapse in a physical sense during interactions. There is instead a state update of the original state of a system that can be implemented, for example, upon its decoherence, specific interactions, under collapse, branching, etc. I will argue that this view on the nature of quantum states is less problematic than the one adopted by WR and PO.

I will start by presenting the basics of GQT via the Ghirardi-Rimini-Weber (GRW) theory (Section 2.1). Then, in the rest of section 3, I will present the Many-Worlds Interpretation (MWI), relationalist single-world, and Bohmian Mechanics versions of GQT.[12] Finally (Section 2.4), I will show how GQT helps moving beyond the standard interpretations by helping generating Environmental Determinacy-based Quantum Theory (EnDQT). I have presented EnDQT in Pipa (2023), but GQT shows how the idea for EnDQT arose and how it connects with other QTs. I will also show how GQT applies to Hybrid Classical-Quantum theories.[13] I will then compare GQT with wave function realism and the primitive ontology framework and argue that it provides important benefits that these views don't provide, and without some of their costs (section 2.4). Also, I will argue that it allows us to make a new comparison between QTs and argue that EnDQT should be preferred in a certain sense.

According to GQT, systems can occupy spatiotemporal regions (ST version) or give rise to spacetime (non-ST version) using, for example, an appropriate theory of quantum gravity. I will focus on the ST version for simplicity, but spacetime regions aren't necessarily fundamental in this view. To simplify, I will mainly assume non-relativistic QT and the Schrödinger picture Hilbert space-based finite-dimensional QT in the presentation of the theories. However, I will have something to say about the quantum field theoretic case in Section 2.4. Furthermore, note that given the non-reificatory approach to quantum states, viewing it as only as an auxiliary tool, GQT doesn't rely on a particular mathematical formulation of QT, and it can be expressed in terms of other formulations.[14]

2 Some generative quantum theories based on quantum properties

I will start presenting a generative version of GRW, which I will call generative-GRW. This theory will serve to explain in the following order the basic features

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[11] See Section 2.4.

[12] See, e.g., Wallace (2012), Goldstein (2021), Ghirardi and Bassi (2020) and references therein.

[13] E.g., Diósi (1995) and Oppenheim (2023).

[14] Such as the Heisenberg picture, interaction picture, and the Lagrangian formulation.

assumed by GQT: generators, generative properties, the kinds of determinate values that generators generate, the ontology of properties adopted, the conditions that establish how generators account for determinacy, and two structural features that help explain how determinacy arises via interactions.

2.1 A generative collapse theory and introduction to GQT

We can characterize the role of any "interpretation" of QT or QT as giving an account of how systems end up having determinate values, although, given the EEL, unitary interactions leave such values indeterminate.

To give a general account of how systems come to have determinate values, GQT introduces generator systems of determinacy or *generators*. Note that the word "generate" will be used in two different senses. It will be used to designate how GQT helps build new QTs, and how some elements of GQT give rise to determinacy. Generators are systems that have the capacity to give rise to other systems having determinate values. *Non-generator systems* don't have the capacity to give rise to other systems having determinate values. Also, we have *generative properties*, which are the properties that generators have via which they influence other systems to have determinate values. A key claim of GQT is that each QT introduces different generators and generative properties, which generate different kinds of determinate values. Generators and generative properties are two interrelated features that help generate QTs. As it will become clearer, in the case of generative-GRW, the generators are the systems that have positions, and some of their positions are generative properties.

The kind of determinate values that each generator generates is another feature that helps generate QTs. The determinate values generated by generators can be absolute (i.e., don't vary according to systems), relative to a system (for system X, system Y has a determinate value v, but for system Z, Y has a value v' or an indeterminate value), relative to multiple copies of systems (multiple copies of the same interacting systems arise, each with different possible determinate values like in the MWI), etc. Unless stated otherwise, I will consider the determinate values generated as absolute, although in the next section, we will see other possibilities. GQT, in principle, allows for multiple ontologies of properties, and this is another one of the features that help generate QTs (see section 4). In this article, I will propose and focus on an ontology of properties where it's manifest when systems S', interacting with other system S, have the properties that give rise to S having a determinate value, i.e., it becomes manifest when systems S' have generative properties.

According to this ontology, for GRW and GQT in general, systems are collections of quantum properties, and value properties (henceforward, values) are related to quantum properties (more on this below). To explain what quantum properties are, first note that I will assume that GRW considers that there are fundamental quantum systems called particles. I will consider that particles are systems that have different subsystems, each a collection of certain quantum properties. Only one of the systems has position quantum properties (alongside momentum and energy), and the other systems have other quantum properties, such as spin and energy. The former system, as I have mentioned above, is a generator because it has the capacity to give rise to other systems having determinate values (having generative quantum properties). This contrasts with the subsystem of the particle that has spin quantum properties, which isn't a generator. Quantum properties of subsystems of particles are represented via quantum states belonging to different Hilbert spaces and self-adjoint operators (which I will call observables) that act on those spaces.

Quantum properties have a feature called *differentiation*, which impacts the determinacy of the values that systems having those properties give rise to. Interactions with generators change the degree of differentiation of a quantum property that a target system and the generators have (we will see further below why differentiation comes in degrees). More concretely, the differentiation of a quantum property that a target system S might end up with due to an interaction with generators can be inferred and measured via the distinguishability of certain quantum states of the generators concerning the quantum states of S (hence the use of the term differentiation). Furthermore, the quantum states of S are eigenstates of an observable that also represents that property.[15] When such differentiation is *maximal* and *stable* (in a certain sense to be defined soon), I consider that we end up having S with that quantum property *stably differentiated*, and S will have a determinate value related to that quantum property. Crucially, generators under interactions with S will also have a quantum property stably differentiated, and thus a determinate value, when they give to S having a stably differentiated quantum property (again, to some degree at least, as we shall see). This quantum property of the generators is a *generative quantum property*. So, for GQT,

All generative quantum properties of a generator system are fully stably differentiated.

Note that not all stably differentiated quantum properties are generative. Spin quantum properties in different directions in GRW are never generative. It is the subsystem of the particle that has certain positions that gives rise to other systems having a determinate value, not the subsystem that has spin.

As we will see, the use of the term *stable* is because the process that allows us to infer if there is determinacy will often involve, via decoherence, the analysis of a certain quantity that should assume a stable value over time to license those inferences, i.e., the distinguishability/differentiation of the quantum states of an "environmental system" interacting with a target system. So, I will consider that the stabilization of the differentiation of a quantum property of a target system S in most QTs arises via a *stable quasi-irreversible* or *irreversible process* that gives rise to and fixes the determinacy of the value in some degree proportional to the degree of differentiation of the quantum property that S has at some time t. More concretely, this process leads S to have a quantum property D*-P with a degree of differentiation D* to give rise to a value of P (e.g., spin in different

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[15] Or improper eigenstates in the non-idealized case of systems whose quantum properties are represented via infinite-dimensional Hilbert spaces, such as position quantum properties. See, e.g., Wallace (2019).

directions, position, etc.) with a degree of determinacy D=D* at t. I will call the process in which a generator system S', having a generative quantum property, gives rise to other systems S having a stably differentiated quantum property, a *process of stable differentiation* or the stable differentiation of quantum properties of S by S'.

In generative-GRW, this process is the process of collapse or spontaneous localization. It leads systems to have a stably differentiated quantum property and, thus, a determinate value. In the MWI and EnDQT this process is a quasi-irreversible and irreversible process, respectively, represented via decoherence. In the former case, it is called the process of branching into different worlds.

Let's turn to further details of this view. I will consider that

Unless stated otherwise, in the absence of interactions or other processes that lead to a process of stable differentiation, quantum properties of systems will be undifferentiated, which means having the lowest degree of differentiation. So, some interactions or processes change the differentiation of the quantum properties that systems have.

Thus, indeterminate values/undifferentiated quantum properties are the default features of systems. Only under certain processes and interactions do systems having determinate values arise. It is in this sense that for GQT, quantum indeterminacy plays an important explanatory role, being an important tool to interpret QTs: it establishes when determinacy doesn't arise, being a default feature of systems. The exceptions in this article are Bohmian mechanics, where some systems have always determinate values of position, and hybrid classical-quantum theories, which will have, for example, the metric and its conjugate momentum always stably differentiated. In the case of these two theories, having determinate values or indeterminate values are both default features of systems. Note that, perhaps, one may consider the (typically regarded) non-dynamical quantum properties (e.g., electric charge, mass) to be also stably differentiated by default. However, the QTs investigated here can assume that "non-dynamical" observables represent undifferentiated quantum properties that become stably differentiated under interactions with the typical appropriate environments. Although this is not mandatory when adopting GQT, for simplicity, I will assume this in this article.[16]

Stability conditions are the conditions under which a system comes to have a stably differentiated quantum property or (more generally) a determinate value, and they are another feature that helps generate QTs. Stability conditions for generative and non-generative quantum properties may differ in the case of the theories explained in this section, and to summarize, they are the following,

A system S has a stably differentiated quantum property, giving rise to S having a determinate value associated with that property when,

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[16] Decoherence was proposed to account for such so-called superselection rules (see, e.g., Earman (2008) and Giulini et al. (1995)) So decoherence by an appropriate environment could be used by at least by some QTs to represent and infer such interaction.

i) if that quantum property is a generative one (which only generators have), S has that stably differentiated quantum property due to a spontaneous chancy collapse process (GRW), due to or in certain interactions (MWI, single-world relationalist views, and EnDQT), or S has by default that quantum property stably differentiated (Bohmian mechanics and hybrid classical-quantum theories); or

ii) if that quantum property isn't a generative one, S is interacting with generators that have a generative quantum property, which gives rise to S having that stably differentiated quantum property.

Regarding i), for example, Bohmian mechanics considers that the position quantum properties of systems are always stably differentiated by default, and those are the generative quantum properties. GRW considers that generators can be subject to collapse, which gives rise to systems having stably differentiated position quantum properties independently of the interactions they have with other systems, going from having an undifferentiated position to a stably differentiated one. More concretely, systems in GRW often evolve unitarily; however, they have the probability per unit time λ of indeterministically being localized, *collapsing,* and having at least a stably differentiated and determinate value of position. Note that I don't mean that collapse refers to the wave function but the stable differentiation process involving systems since the wave function here is not considered a real entity.

The collapse of a system S_i in a spacetime region is represented via the multiplication of the total wave function written in the position basis by a narrow Gaussian wave packet in the position basis whose width is σ, which represents the localization accuracy. Moreover, the probability of the wavepacket being centered in region C is given by the Born rule. The stably differentiated quantum property of the generator system S_i affected by collapse is represented by the post-collapse wave function[17] plus the observable position that acts on the Hilbert space of system S_i. The possible determinate values of S_i are represented by the eigenvalues of the observable that the position quantum states of S_i are eigenstates of.[18]

Regarding ii), generative-GRW also considers that when a generator or non-generator target system S interacts with a certain generator system or systems S', so that they get *entangled*[19] and a collapse happens, this leads to the stable differentiation of the quantum properties of S by S'. More precisely, we can infer that there is an interaction that involves generators S' having a generative

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[17] Given that the quantum state has an inferential role, I will accept the standard assumption that we can ignore the global phases of the quantum state to make inferences about and represent properties.

[18] Due to the continuous spectrum of the position observable, it brings some extra complications. However, given our finite-dimensional Hilbert space idealization, I will neglect them. See, e.g., Wallace (2019) for ways of dealing with it. Also, the wave function leaves some "tails" upon collapse, assuming the representational and inferential role of the quantum states assumed by GQT, the approximate ways of representing determinate values aren't a problem for this view (more on this below).

[19] I will make precise below the interactions represented via entanglement.

quantum property, which leads the target system S to have a determinate value. The stably differentiated quantum property of the target system will be represented by the eigenstates of the observable concerning a property (spin in different directions, etc.) that are correlated with the position states of the generator or generators upon collapse plus that observable. As I have said above, the full distinguishability of the quantum states in a superposition of the generator or a collection of generators constituting system S' concerning the quantum states of the target system S (which could be a generator or not) *just before* collapse (or another process of stable differentiation in the case of other QTs) allows us to infer which stably differentiated quantum property S will have due to S' after a certain time. These quantum properties often go beyond position and can be energy, spin in a direction, etc.

In the case of generative-GRW, the stable differentiation of a quantum property of a target system (i.e., a system under analysis by a model) can be inferred via the quasi-irreversible process of decoherence of the target system by its environment composed of many generators, and which occurs just before collapse. This is because quasi-irreversible decoherence will typically require many environmental systems having a position (which is correlated with the position of the others) to be stably entangled over time with the target system. So, very likely, some will collapse, triggering a collapse process that leads the others within that environment to have a determinate value due to their correlations, as well as the target system. More on this process below.

Relatedly, it is plausible to consider that at least some quantum properties can be stably differentiated in terms of different degrees, and this impacts the subsequent *degree of determinacy* that arises from those quantum properties. For example, in the double-slit experiment, if the detectors at the slits interact with a quantum system weakly, in such a way that we can't fully distinguish in which slit it passed, we get some disappearance of interference. These interactions will give rise to a low entanglement between the position and the degrees of freedom of the detector. Furthermore, the more the interactions between the target system and the detector distinguish the path of the system, the more entanglement we have between the position of the target system and the degrees of freedom of the detector, and the more the interference tends to disappear until it disappears completely under maximal entanglement. So, I will consider that quantum properties come in terms of different *degrees of (stable) differentiation*, as well as the determinacy of the resultant values.

For example, a system can have different quantum properties spin-x with different degrees of differentiation over time. Values come in terms of degrees of determinacy D and depend on the degree of differentiation D* of quantum properties. A quantum property is undifferentiated when it has the lowest degree of differentiation and differentiated when it has the highest one. A value with the maximum degree of determinacy is a determinate value, and with a minimum degree of determinacy is an indeterminate value.[20]

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[20] Remember that this assumption is not mandatory when adopting since GQT allows for different property ontologies.

I will now show more concretely how we can infer the degree of differentiation of the quantum property that a system, after interactions, ends up with via the degree of entanglement of its quantum states with its environment and decoherence.

The degree of differentiation of a quantum property of a system can be measured via the non-diagonal terms of the reduced density matrix of the system subject to decoherence when we trace out the degrees of freedom of the environmental systems that are interacting or interacted with the system of interest. Let's consider a toy scenario with system E, which is a generator, constituted by many subsystems that interacted or are interacting with system S. For instance, suppose S has quantum properties spin in different directions that are interacting strongly (i.e., the Hamiltonian of interaction dominates the system's evolution in the timescales of interest) with many systems with positions, which constitute E.[21][22] For simplicity, throughout this article, I will assume this kind of evolution of the system under the interactions that lead to decoherence.[23] Let's assume some situations where S initially has an undifferentiated spin-z quantum property. S then interacts with E, and their interaction is represented via the standard von Neumann interaction at least approximately as $|\uparrow_z\rangle_S|E_0\,(t)\rangle_{\text{E DS}} \rightarrow |\uparrow_z\rangle_S|E_\uparrow\,(t)\rangle_{\text{E DS}}$, $|\downarrow_z\rangle_S|E_0\,(t)\rangle_{\text{E DS}} \rightarrow |\uparrow_z\rangle_S|E_\downarrow\,(t)\rangle_{\text{E DS}}$, or as

$$(|\uparrow_z\rangle_S + |\downarrow_z\rangle_S)|E_0(t)\rangle_{\text{E DS}} \rightarrow \alpha|\uparrow_z\rangle_S|E_\uparrow(t)\rangle_{\text{E DS}} + \beta|\downarrow_z\rangle_S|E_\downarrow(t)\rangle_{\text{E DS}} \qquad (1)$$

The change in the degree of differentiation of the quantum property spin-z of S upon this interaction can be inferred and calculated through the reduced density operator $\hat{\rho}_S\,(t)$, which is obtained by doing the partial trace of the degrees of freedom of the environment. More concretely, this analysis is done through the overlap terms that concern the distinguishability of the states of E with respect to the spin-z of S, i.e., $\langle E_\uparrow(t)|E_\downarrow\,(t)\rangle_{\text{E DS}}$ and $\langle E_\downarrow(t)|E_\uparrow\,(t)\rangle_{\text{E DS}}$. More generally, consider a system S that initially has an initially undifferentiated quantum property D*-P, where the observable that concerns P has eigenstates $|s_i\rangle_S$. Given the interaction between S and environmental system E, after tracing out the degrees of freedom of E, we obtain that

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[21] Alternatively, in other QTs that don't privilege position, we could consider instead an environment with systems with spin in multiple directions. See, e.g., Cucchietti et al. (2005).

[22] Realist decoherence models involving environments with position quantum properties include, for example, collisional models of decoherence and models of quantum Brownian motion. See, e.g., Joos and Zeh (1985), Kiefer and Joos (1999), and Schlosshauer (2007) and references therein.

[23] More complex models of decoherence (see, e.g., Zurek (2003) where the systems don't interact strongly with the environment, which involves the self-Hamiltonian having more weight on their evolution, may give rise to different observables with determinate values depending on the initial quantum states. More on this below.

$$\hat{\rho}_S(t) = \sum_{i=1}^{N} |\alpha_i|^2 |s_i\rangle_S \langle s_i| + \sum_{\substack{i,l=1 \\ i\neq l}}^{N} \Big(\alpha_i^* \alpha_l |s_i\rangle_S \langle s_l| \langle E_i(t)|E_l(t)\rangle_{\mathrm{E\ DS}} \\ + \alpha_l^* \alpha_i |s_l\rangle_S \langle s_i| \langle E_l(t)|E_i(t)\rangle_{\mathrm{E\ DS}} \Big) \tag{2}$$

Then, a measure of the degree of differentiation of the quantum property D*-P of S in the spatiotemporal region ST for the simple scenarios that we are considering will be given by the von Neumann entropy[24] $S\left(\hat{\rho}_S(t)\right)$ of $\hat{\rho}_S\left(t\right)$ over lnN, where N is the number of eigenvalues of $\hat{\rho}_S\left(t\right)$,

$$D^*(P, S, ST, t) = \frac{S(\hat{\rho}_S(t))}{\ln N} \tag{3}$$

If $D^*(P, S, ST, t)$ via the above overlap terms goes quasi-irreversibly, *i.e., stably,* to one over time (in the sense that the recurrence of this term back to not being significantly different from zero is astronomically large), and these interactions involve many environmental systems that make this process hard to reverse, it is considered that S is decohered by E. In the QTs that appeal crucially to decoherence to infer when systems have determinate value, such as the MWI (Section 2.2) and EnDQT (Section 2.4), it is inferred that when decoherence occurs, S has a *stably* differentiated quantum property, having a determinate value due to E (but with some caveats in the case of EnDQT). More precisely, we can infer from this process that E also has a stably differentiated quantum property/generative quantum property, which leads S to also have a stably differentiated quantum property.

Upon knowing the actual result, we update the state of S to one of the $|s_i\rangle_S$, and consider that the system has a determinate value, which is an eigenvalue of the observable that $|s_i\rangle_S$ is an eigenstate of. Similarly, for E, where its possible determinate values will be the eigenvalues of the observable that $|E_i\rangle_E$ are eigenstates of. In the language typically employed by decoherence theorists, $|s_i\rangle_S$ for each i are pointer states, and the observable that these states are eigenstates of is the pointer observable "selected" by the environment E.[25] In GRW, also taking into account the account the collapse laws, we can infer there will be a collapse to when this occurs with an environment constituted by systems with the quantum property position. However, the collapse timescale is typically longer than the decoherence timescale.[26]

More generally, we can measure and represent the degree of differentiation D* of the quantum property D*-P that S will end up with at the end of the interaction with E at t, with $0 \leq D^*(P, S, ST, t) \leq 1$, in the possible elements

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[24] Given a density operator ρ_S for quantum system S, the von Neumann entropy is $S(\rho_S) = -tr(\rho_S \ln \rho_S)$. $S(\hat{\rho}_{\mathrm{S}}\ )$ is zero for pure states and equal to ln N for maximally mixed states in this finite-dimensional case.

[25] Note that pointer states here don't necessarily refer to the quantum states of a measurement device, but whatever is the target system.

[26] See Bacciagaluppi (2020) and references therein for the relation between collapse theories, decoherence, and their timescales.

of the set of spacetime regions ST where S is differentiated by E. At least in the case of the MWI and EnDQT, we can also infer the differentiation timescale, which is equal to the decoherence timescale. This is done by analyzing the value in which $D^*(P, S, ST, t)$ stably converges over time.

Thus, note that, as I have mentioned, a quantum property of S might not be fully stably differentiated and just be *stably differentiated* to some degree D* by E, and thus, it gives rise to a value with a degree of determinacy D = D*. This happens if the above quantum states of the environment have a certain *stable* non-zero overlap over time (notice how stability plays a role in these inferences). So, it is considered that in order for generators to have a generative quantum property and hence give rise to this process, they need to give rise to a quasi-irreversible process, which involves many degrees of freedom of the environment, in such a way that they decohere the target system *to some degree*.

The decoherence in these scenarios gives rise to the following criterion: in order for system S to have a determinate value v of O_S, the observable O_S of S that is monitored by system E, and whose eigenstates are decohered by E in the sense above, has to at least approximately commute with the Hamiltonian of interaction H_{SE} representing the interaction between S and E, i.e., $[H_{\mathrm{SE}}, O_S] \approx 0$. This is the so-called commutativity criterion.[27] The value v is among the possible eigenvalues of O_S.

We can use decoherence to represent quantum properties. The generative (stably differentiated) quantum property of the target system is represented by the quantum states in the superposition that are decohered by (or entangled with) the generator plus the observable that these quantum states are eigenstates of. The generative (stably differentiated) quantum property of the generator is represented by the quantum states that decohere the quantum states of the target system to some degree and the observables that such quantum states are eigenstates of.

However, not all interactions with generators[28] give rise to systems having a determinate value, although there is something that changes in the quantum properties of the systems under these interactions. Consider the spin of a particle in different directions in a series of Stern-Gerlach devices without letting the particles hit a screen between each device. This leads the system S^* with a spin in a certain direction to interact with the generator $S^{'}$, leading to their entanglement. Assuming the GRW theory, there is something that changes in the spin direction of the quantum systems when they go from one magnet to the other, but (very likely) there is no collapse/stable differentiation. If there

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[27] See Schlosshauer (2007) and references therein. This criterion implies that all terms in a Hamiltonian of interaction will individually satisfy this criterion. In more complex models of decoherence where the Hamiltonian of interaction doesn't dominate the evolution of the systems, note that this monitoring may be indirect, such as the decoherence of momentum in more complex models of decoherence than the ones mentioned here (Zurek et al., 1993), where there is direct monitoring of the position. The latter is contained in the Hamiltonian of interaction of the system (but not the former), and that's why the decoherence of the momentum is indirect.

[28] Or, at least in the case of EnDQT and MWI, with systems that could end up being generators.

were, we would have an irreversible process, and thus, we wouldn't be able to reverse the result of the operations by having a Stern-Gerlach interferometer that reverses the state of the particle to its previous state. So, it's plausible to consider that the spin of the system that interacts with the generator has an indeterminate value, although there is something that changes in the quantum property that corresponds to that indeterminate value.

In most QTs presented here, the interactions that don't lead to stable differentiation, such as the one above, can be *inferred* and represented simply by the quantum states and observables in the models where we have entanglement between the degrees of freedom of interacting quantum systems,[29] or relatedly where we have the so-called virtual/*reversible* decoherence. This decoherence involves "entangling" interactions that are reversible, not giving rise to an irreversible or quasi-irreversible physical process, because often they don't involve enough environmental systems that make such process hard to reverse unitarily, and thus, it's not typically considered real/irreversible decoherence. In the case of GRW, this reversible process involves the entanglement between the quantum states of a small number of generator or generators $S^{'}$ in the position basis (the environment) and the generator or non-generator target system S^*.[30] Taking into account the collapse laws, since it doesn't involve sufficient systems to very likely collapse occurs, it allows us to infer that stable differentiation likely won't occur. In the Stern-Gerlach case above, we obtain that both systems, after interacting, are represented by

$$|\Psi(t')\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow_z\rangle_{S^*} |\text{up}\rangle_{S'} + |\downarrow_z\rangle_{S^*} |\text{down}\rangle_{S'} \right) \tag{4}$$

and the self-adjoint operators spin-z and position that act on the position and spin Hilbert spaces of S. So, via entanglement and reversible decoherence, we represent and infer those systems that have an undifferentiated quantum property in interactions with other systems, and thus, when generators don't have generative quantum properties.[31] So, GQT considers decoherence as an epistemic tool that can be used to infer which systems have undifferentiated or stably differentiated quantum properties and to infer if they will give rise or not to stable differentiation and, therefore, determinacy through interactions. Equivalently, it serves as a tool to infer if generators will have a generative quantum property under interactions. Furthermore, for some QTs (such as in the MWI) decoherence also allows us to infer which systems are generators and have generative quantum properties. Some factors will need to be taken into account in the use of decoherence as an inferential tool, some of them already mentioned above, but I want to emphasize them. To infer if we have systems with undifferentiated or stably differentiated quantum properties, we need to

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[29] QTs will often postulate different structures that establish when systems are interacting or not. I will come to that soon.

[30] See, e.g., de Oliveira and Caldeira (2006).

[31] Note that, if we had collapse, the quantum property of the non-generator system would be represented either by $|\uparrow_z>_{S^*}$ or $|\downarrow_z>_{S^*}$ plus the spin-z observable. The determinate values that arise from the spin-z quantum property are represented by $\uparrow_z$ or $\downarrow_z$.

find if we have a reversible or an irreversible process of decoherence, respectively. This analysis largely appeals to pragmatic factors, such as the number of systems that interact with the target system. It is also necessary to analyze the quantum properties of the systems of the whole environment that interact with the target system during different times since specific environmental systems may contribute more to determining the degree of differentiation of the quantum property that the system under analysis might end up with. For example, at least in the case of GRW, in the Stern-Gerlach apparatus, the (reversible decohering) interaction between the spin and the position degrees of freedom of the particle crucially contributes to measuring the degree of differentiation of spin-z, *but not* the stability of that quantum property and the determinacy that it arises. Afterward, the degrees of freedom of the particles that constitute the screen detector can be regarded (let's assume that there is a collapse at the screen) as contributing to the particle having a stably differentiated position, which ends up leading it to also have a stably differentiated spin. So, the degree of the stably differentiated spin that the particle ends up with depends on the interaction that started previously with the subsystem of the particle that has the quantum property position. Nevertheless, depending on the context, note that both reversible and irreversible decoherence allow us to measure the degree of differentiation of a quantum property via the degree of entanglement/distinguishability of the quantum states of the environment that are correlated with the quantum states concerning that quantum property. I will make this idea more precise below by distinguishing different kinds of interactions.

Finally, for some QTs, it's necessary to analyze whether decoherence involves generators that very likely will have generative quantum properties, giving rise to the target system having a quantum property stably differentiated to some degree. As we saw in the GRW case, this should be an environment that collapses the target system in such a way that *it distinguishes* its different quantum states that were previously in a superposition.

As mentioned before, differentiation and determinacy are related, and this allows for an analysis of quantum indeterminacy and determinacy. This relation will establish that a property P*, in this case, a value property, is the property of having some other property P** having specific features. So, I will consider that

For a system to have a value v of P (where P could be energy, position, etc.) with a non-minimal degree of determinacy D is to have stably differentiated quantum property D-P to a non-minimal degree D* where D=D*. A system with a quantum property (fully) stably differentiated will have a determinate value of P.*

On the other hand, indeterminacy and undifferentiation are related,

For a system to have an indeterminate value of P is to have an undifferentiated quantum property.

Note that according to this relation, we have *multiple* quantum properties concerning P, represented by quantum states and observables, that correspond to a non-maximally determinate value of P.[32] Just think about the variety of eigenstates of an observable concerning P that we can superpose and/or entangle with the quantum states of other systems to get quantum states that allow us to represent an indeterminate value of P.

Now that I have presented the ontology of properties that GQT will adopt in this article, I will turn to two structural features, which will help to give rise to different QTs. Certain structures, which include different kinds of interactions, account for how determinacy arises or not. Importantly, *what constitutes an interaction* how to infer it, and the different interactions that belong to the structure of interactions, varies according to the QT. Kinds of interactions between systems with undifferentiated quantum properties form structural features called Indetermination Structures (ISs), where these interactions don't involve or give rise to any system having a determinate value. ISs are one of the structural features assumed by GQT. In the case of GRW, what I will call *collapse-ISs* are represented and inferred via equations such as 1. Systems that don't belong to ISs belong to Determination Structures (DSs), which also involve different kinds of interactions between systems. I will call them *structural generators* since they give rise to determinacy. I will call the DSs for generative-GRW, collapse-DSs. DSs is the last feature considered by GQT that I will present in this article. As will become clearer, each QT may adopt different DSs, ISs, property ontologies, generators, stability conditions, generative properties, and kinds of determinate values that generators generate. Also, as it can be seen, these seven features are related to each other.

DSs and ISs can have a structure that may sometimes be represented by directed graphs, undirected graphs, or a hybrid (thus being structures). Nodes represent systems, and edges between nodes represent certain kinds of interactions. One of them is *Stable Differentiation Interactions* (*SDIs*), which involves an arrow that goes from the generator or generators to the target system, leading them to have determinate values. On the other hand, we have Unstable Differentiation Interactions (UDIs), which are a sub-kind of ISs. UDIs are interactions between systems S' and S'' in which *if* some generator S stably differentiated a quantum property of S'/S", it would also stably differentiate a quantum property of S''/S' to a degree inferred from how much the quantum states of S'/S" distinguish the quantum states of S"/S' (or in other words, how much the quantum states of S'/S" are distinguishable). For instance, in the Stern-Gerlach case above, if some environment E in the screen stably differentiates the position quantum property of system S'' (which is a subsystem of the particle S), the spin-z of S' (another subsystem of S) is stably differentiated to a degree D* that is quantified by the overlap of the quantum states in the position basis of S'' that are entangled with the states of S'. Also, we have UDIs where one or both systems are generators, and if a quantum property of S'/S" became stably differentiated, a quantum property of S"/S' would also become stably differentiated, where such degree of differentiation would be measured like in the above case. As I will explain, UDIs

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[32] Note also that this relation doesn't imply that undifferentiated quantum properties are more fundamental than indeterminate value properties.

might have a direction.

UDIs can be inferred via reversible decoherence with no collapse like the one we have seen above, or simply when we have entangled systems. So, as we can see, unstable differentiation interactions don't give rise to an irreversible qua stable process, but instead to a *reversible qua unstable process*. Therefore, they don't change the stable differentiation of quantum properties that systems have although they could end up leading to processes that change it as I have explained above.

I will now introduce other interactions between systems that belong to ISs with an example that shows how generative-GRW accounts for interference phenomena. I will also demonstrate some extra explanatory resources that GQT allows for in accounting for interference phenomena, although builders of generative quantum theories might not wish to assume them.[33]

I will consider that systems can occupy multiple "locations," allowing us to represent the relations of influence behind interference phenomena, but without appealing to the wave function. The trick is to use the interactions that DSs and ISs allow for. When systems have an indeterminate position value, they are associated with multiple locations, and we can call each system-location pair a "part" of the system, and these parts in these multiple locations interact via *potential destruction interactions*. So, the latter are self-interactions that systems develop between the different parts of themselves that occupy different regions of spacetime. These interactions also belong to collapse-ISs, being reversible.

Relatedly, collapse-DSs also involve self-interactions called (*actual) destruction interactions*, and they arise from the potential ones. This interaction arises when one part of the system has a quantum property stably differentiated, leading the system in the other locations to not exist anymore (irreversibly). So, it occurs when a system goes from having an indeterminate position to a determinate one Note that when a potential destruction interaction turns into actual destruction interaction, we have the phenomenon typically called *collapse of the wave function* in ontologies that reify it. Let's see how this works by considering a system that goes through a Stern-Gerlach interferometer with a detector placed in one of the arms. Let's, for example, assume that we have a neutron S constituted by system $S^{'}$ having, among others, the quantum property position and system S* having, among others, the quantum property spin-x, which initially are stably differentiated when the electron is prepared. When it reaches the first beam splitter, the system is split into two locations, having an undifferentiated position and spin-z. So, between the two locations, it's indeterminate where $S^{'}$ is. Undirected potential destruction interactions are developed between the parts of the system at these locations. They are undirected interactions because they don't have any direction of influence. Also, $S^{'}$ and S^{*} develop a directed UDI, since $S^{'}$ could end up stably differentiating S^{*}, but not vice-versa. The particle's quantum state is the one of eq. 1.

When the system interacts with a detector placed in one arm of the interfer-

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[33] They may wish to not introduce the interactions that I will introduce below and "systems having different locations." However, this will likely diminish their explanatory resources.

ometer, the energy of the particle is stably differentiated by this detector, where the quantum state just before collapse is

$$|\Psi(t'')\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow_z\rangle_{S^*}|up\rangle_{S'}|E_{\text{detected D1}}\rangle + |\downarrow_z\rangle_{S^*}|down\rangle_{S'}|E_{\text{Not detected D1}}\rangle\big). \tag{5}$$

So, just before the collapse, the detector has for very brief moments an indeterminate location of its pointer. Let's suppose that system S is stably differentiated by D1. S' in the other branch of the interferometer will "destroyed." We would obtain $|\Psi' > \approx |\uparrow_z>_{S^*}$ $|\text{up} >_{S'}$ $|E_{detected\ D1}$ $>$, with S having determinate value $\uparrow_z$ and up, and the rest of the systems that constitute the detector having determinate values correlated with these ones.

Note that the structure of the destruction relations is not directly represented via the quantum state, but rather inferred from it and represented via the directed graphs (more on this below). Note also that although the state of the whole system after the collapse is not an eigenstate of position, this is unproblematic because of the non-literalistic representational role quantum states have for GQT. The system being close to being in a quantum state associated with these properties is enough to represent them.

Let's now consider an EPR-Bell scenario,[34] where space-like separated Alice and Bob perform random measurement on systems in a singlet-state, giving rise to correlations. To account for EPR-Bell-like correlations, we can also use DSs and ISs. Consider the state below, representing particles S_A and S_B before either Alice or Bob measuring them,

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow_z\rangle_A|\downarrow_z\rangle_B + |\downarrow_z\rangle_A|\uparrow_z\rangle_B\big) |R\rangle_{E_A}|R'\rangle_{E_B}|R''\rangle_{L_A}|R''\rangle_{L_B} \tag{6}$$

Above we have two systems, E_A and E_B, with position R and R', respectively, and two systems A and B, each with an undifferentiated spin in all directions. L_A and L_B are the measurement devices of Alice and Bob before interacting with their target systems. Taking into account the above entangled state, it is considered that the structure of the IS is composed by systems A and B connected by an undirected (non-local) UDI. It is undirected because it can go both ways when one of the systems' spin in a direction becomes stably differentiated.

Afterward, it can happen (for example) that, in a certain reference frame, L_B and E_B interact first with B, and we obtain the following quantum state just before collapse,

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[34] Bell (1964).

$$\begin{aligned}|\Psi(t)\rangle = \frac{1}{\sqrt{2}}\big(&|\uparrow_z\rangle_A|\downarrow_z\rangle_B|down'\rangle_{E_B}|down''\rangle_{L_B}\\ &+|\downarrow_z\rangle_A|\uparrow_z\rangle_B|up'\rangle_{E_B}|up''\rangle_{L_B}\big)\\ &|R\rangle_{E_A}|R'''\rangle_{L_A}.\end{aligned} \tag{7}$$

L_B will very likely have a stably differentiated position and trigger a collapse process, which stably differentiates the quantum properties of E_B, B, and A, and leads the potential destruction relations that arose to become destruction relations. Below (Figure 1), we can see a directed graph representing the structure of the DS that is formed.

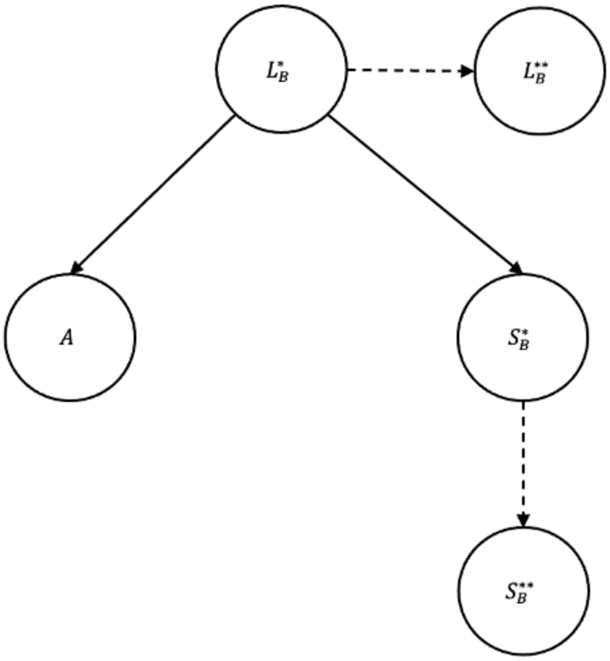

Figure 1: Directed graph representing a collapse-DS. Dashed arrows are destruction relations with a possible direction. The system arising in a determinate location (I have represented the part of the system at this location with a star) leads to the disappearance of the system being in the other location represented via a double star. The rest of the arrows are stable differentiation interactions.

To summarize, in this section, we have seen seven interrelated features postulated by GQT: a property ontology, generators, generative properties, the kinds of determinate values that generators generate, stability conditions, DSs, and ISs. As it will become clear, the combination of different sets of these features helps generate different QTs.

2.2 The generative-MWI and generative-single-world-relationalism

Let's turn to different versions of the generative-Many-Worlds Interpretation (MWI), and single-world relationalist views. Unlike generative-GRW and, as we will see, generative-Bohmian mechanics, these views don't necessarily consider that particles play a fundamental role. Like in generative-GRW, all systems have indeterminate values by default. Now, certain interactions give rise deterministically to multiple copies of systems, each with the different possible stably differentiated quantum properties and determinate values, giving rise to what is typically called different worlds corresponding to different sets of determinate values. Each world is represented by one of the terms in a given superposition. Unlike generative-GRW, in principle, systems with diverse quantum properties are generators, not just systems with positions. So, many kinds of systems have the capacity to give rise to determinate values individually or at least collectively.

In this case, the process of branching into different worlds is the process of stable differentiation. The pattern explained in the previous section is repeated here: when generators have generative quantum properties, they can stably differentiate the quantum properties of the other systems and thus lead them to have determinate values. However, generative-MWI adopts stability conditions (Section 2.1.) that postulate that, in order for the target system to have a stably differentiated quantum property, it has to suffer a quasi-irreversible process due to its interactions with generators having a generative quantum property. This process is represented and inferred via the irreversible process of decoherence, where generators decohere the target system. Relatedly, like I have explained in the previous sections, decoherence is used to represent and infer which systems are generators, and the properties of generators that are generative and hence stably differentiated, giving rise to this process. On the other hand, as I also have explained in the previous section, via entanglement and reversible decoherence, we represent and infer those systems that have an undifferentiated quantum property in interactions with other systems, and thus, when systems don't have generative quantum properties.

I will present the different generative-MWI views via examples in which we have a Bell scenario where Alice (Lab A) and Bob (Lab B) can measure their systems in only two possible directions. I will start with a version of MWI where there is "local" branching,[35] calling it *generative-quasi-local-MWI* for reasons that I will soon explain. For heuristic reasons, I will put a subscript DS in the quantum states of systems that are generators and will have a generative quantum property in the interactions under analysis, and thus give rise to interactions belonging to a DS, stably differentiating other systems' quantum properties. Furthermore, systems with different subscripts will belong to different *quasi-local-MWI-DSs*.

So, consider the following state,

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[35] See Sebens and Carroll (2018) for the distinction between local and global branching.

$$
\begin{aligned}
|\Psi(t)\rangle_{A+B} = \frac{1}{\sqrt{2}}\big(|\uparrow_z\rangle_A|\downarrow_z\rangle_B - |\downarrow_z\rangle_A|\uparrow_z\rangle_B\big) \\
|E_{\text{ready}}\rangle_{\text{Lab A DS}'}|E'_{\text{ready}}\rangle_{\text{Lab B DS}''}
\end{aligned}
\tag{8}
$$

Like in generative-GRW, we have UDIs involving A and B. When Bob interacts with his system, he stably differentiates the spin-z quantum property of system B, which also leads to the non-local stable differentiation of the spin-z of A. Such determinate values result in two worlds or more precisely, two new quasi-local-MWI-DSs,

$$
\begin{aligned}
|\Psi(t')\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow_z\rangle_A|\downarrow_z\rangle_B|E'_{\downarrow_z}\rangle_{\text{Lab B DS}'} \\
- |\downarrow_z\rangle_A|\uparrow_z\rangle_B|E'_{\uparrow_z}\rangle_{\text{Lab B DS}'}\big) \\
|E_{\text{ready}}\rangle_{\text{Lab A DS}''}
\end{aligned}
\tag{9}
$$

Note that Bob doesn't affect the branching of Alice. Only when Alice interacts with A will she branch into two other worlds, obtaining two determinate values. Those values are only shared between the different versions of Alice and Bob if they meet. Since there is some non-locality in this version of the MWI, I have called it quasi-local.

Note also that, before the above interaction, Lab B can have a stably differentiated quantum property (being represented by $|E^{'}{}_{\text{ready}}\rangle_{\text{Lab B }DS''}$ plus the observable that this state is an eigenstate of) due to interactions that Lab B is developing with other systems not included in the model. So, systems that start having stably differentiated quantum properties may persist in having stably differentiated quantum properties through interactions, forming different worlds. The same in the case of Lab A.

As I have mentioned, GQT allows us to play around with the kinds of determinate values that are generated. Instead of giving rise to multiple determinate values deterministically, we could have a theory like the above one, but generators give rise indeterministically to single relative determinate values, which are relative to the different generator systems,[36] and A would not be connected with B via a UDI. So, the stable differentiation of properties of A would not affect the one of B, and vice-versa. Furthermore, for Alice (if they don't interact), Bob and his system would have indeterminate values, and vice-versa. This *generative-single-world-relationalism* resembles in some ways other relationalist theories, such as Relational Quantum Mechanics and Healey's pragmatism.[37]

Furthermore, briefly, if we wanted a generative-single-world-relationalist theory that resembles more Relational Quantum Mechanics (RQM), we would consider that any system is a generator and gives rise to/generates relative determinate values upon *any* interaction. So, all quantum properties assumed by systems under interactions are generative. However, when not interacting, it is considered that systems have indeterminate values relative to each other.

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[36] See also the beginning of the previous section.

[37] Di Biagio and Rovelli (2021), Healey (2017), and Rovelli (1996).

Then, we would consider that the role of decoherence is to infer when relative determinate values of a target system S and records of those values are inevitably shared between (environmental) larger systems S', S'', S''', S'''', etc. that also interact, where S' locally interacts first with S, decohering it. Then S'' interacts with S', gets entangled with S and S', and obtains a record of the determinate value of S, and so on for S''' that interacts with S'', etc. In other words, decoherence is used to infer when systems inevitably stably differentiate the quantum properties of each other, giving rise to shared relative determinate values concerning the systems they interact with, or records of determinate values. The above chains of local interactions would be the DSs for *generative-RQM*.

GQT also allows us to play around with the structure of DSs and ISs and generate other generative-MWIs. For instance, in one generative-MWI we could have an IS where when Bob interacts with his system, he leads B to have a stably differentiated spin-z quantum property, *but this doesn't* lead A to have a stably differentiated spin-z, and vice-versa, and so we wouldn't have the above UDIs. This renders the MWI local in the sense that there is no influence between Alice and Bob in so far that they can be considered space-like separated.[38] Let's call this version generative-local-MWI because it doesn't have the non-locality that I have identified above in the quasi-local version. Another generative-MWI would consider that instead of preexistent non-local UDIs, we have a theory with SDIs leading to non-local interactions between systems having different stably differentiated quantum properties over time. These SDIs would establish which systems belong to the same world. Let's call it *generative-global-MWI*. Bob and Alice would be connected via an SDI, and the splitting into branches of Bob when he measures his system would non-locally split Alice into multiple worlds even before she does her measurement or vice-versa. The resultant worlds of this branching would each contain different systems connected by SDIs that establish if they belong to the same world.

2.3 The generative-Bohmian mechanics

Like generative-GRW, *generative-Bohmian mechanics* considers systems with quantum properties position as generators. The positions and velocities will be generative quantum properties,[39] being, by default, stably differentiated. The rest of the quantum properties will lead to a behavior similar to GRW, but without irreversibility since the theory is deterministic. Like in generative-GRW, we have fundamental particle quantum systems. The guiding equation represents the velocity of the particles with a stably differentiated position and how the latter changes over time, where this equation depends on the quantum states of systems.

The degree of decoherence or entanglement between the quantum states of the target system and the wave function of the particles in the position basis

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[38] There are issues here regarding how we can determine space-like separation if Alice and Bob don't share the same world. I will discuss a related issue in Section 3

[39] Why assume that these are the ones? We can point to, for example, to these being the only ones present in all interactions that give rise to determinate values, having an important explanatory role in the theory.

allows for a measure of the degree of stable differentiation of a quantum property of the target system upon interactions with these later systems. For instance, in the case of spin in a certain direction, the stable differentiation is measured via the overlap of the wave function in the position basis, where such wave functions distinguish the eigenstates of spin in that direction. The stable differentiation of other quantum properties, such as the energy of the particle, can be measured via the decoherence of the particle wave function by its environment constituted by systems that have the position quantum property.

To present generative-Bohmian mechanics in more detail, I will go over examples. Bohmian mechanics, being a hidden variable theory, also leads to the interpretation of quantum states as concerning our ignorance about which quantum properties of the particle are stably differentiated. Let's consider the one-particle case in a certain Stern-Gerlach interferometer experiment. In the beginning, we have a particle constituted by two subsystems, one subsystem A with an undifferentiated spin-z and a subsystem E_A with a stably differentiated position within a larger region R ,

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow_z\rangle + |\downarrow_z\rangle \right) |R\rangle_{E_A} \tag{10}$$

The eigenstate of the position of E_A, $|R\rangle_{E_A}$, concerns our ignorance about the current value of the position of a particle within that larger region R. Like in collapse theories I will proceed in a different way to account more satisfactorily for interference. This version of generative-Bohmian mechanics considers that it is associated to each particle a so-called *partner particle*. Partner particles are systems with the quantum property position and behave like those systems in GRW, having different "parts" in different spatiotemporal locations, but now we don't have irreversible destruction relations.

Partner particles will play the role of the branches of the wave function (including the empty branches, i.e., the branches that don't have particles) and account for interference without reifying the wave function, although they are inferred via it. Instead of having a particle "carried by a wave," we rather have a particle interacting with its partner particle. Like other quantum properties in generative-Bohmian mechanics, the position of a partner particle can be undifferentiated or stably differentiated to a degree where the degree of differentiation is measured via the amount of irreversible decoherence that the wave function associated with the particle and the partner particle suffers caused by the interaction with an environment. Also, when the wave function of the partner particle is in an eigenstate of the position operator, it has a determinate value of position, which will coincide with the one of its associated particle.

Let's then continue with our Stern-Gerlach interferometer example. Let's consider a system that passes by a Stern-Gerlach device, giving rise to a particle in the arms of the interferometer that has a stably differentiated position and spin-z as subsystems, and a partner particle with an undifferentiated position (no irreversible decoherence is involved). We are ignorant about the determinate value of the spin-z of the particle because we are ignorant about the initial conditions/position of the particle that entered the interferometer. Like in collapse theories, the two locations of the parts of the partner particle are interacting via potential destruction interactions when its position is indeterminate. We represent the state of this particle and its partner particle via

$$|\Psi(t')\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow_z\rangle_B |up\rangle_{E_{\mathrm{B\ DS}}} + |\downarrow_z\rangle_B |down\rangle_{E_{\mathrm{B\ DS}}}\right) \tag{11}$$

This interaction turns into a destruction interaction when one of the parts of the partner particle has a stably differentiated position due to, for example, a larger system such as a measurement device. However, contrary to collapse theories, the destruction interaction can be reversed (after a long time) to a potential one.

If the interferometer is set in the appropriate way, the particle and its partner can give rise to interference.[40] The degree of differentiation of the rest of the quantum properties (beyond position and spin) depends on how differentiated they are by systems with the quantum property position. If in the above situation, we measure the system by placing a detector at one of the arms of the interferometer, the interaction between the system and the detector gives rise to (for example) the particle having a stably differentiated energy. Also, as I have said it will stably differentiate the position of the partner particle, and the other part of the partner particle that also goes through the other side will disappear. Thus, we can update the wave function of the systems to an (effective) wave function of the system, which represents the particle and its partner particle with determinate values.

Let's see what the SDIs and ISs are for two particles with a stably differentiated position and undifferentiated spin in any direction. To do that, let's consider the again the EPR-Bell scenario with the quantum systems prepared at the source in the state of eq. 5, but let's ignore the measurement devices of Alice and Bob. We have two systems, E_A and E_B, with stably differentiated position, which together with systems A and B, each with an undifferentiated spin in any direction, constitute two particles S_A and S_B, respectively.

The non-local structure of ISs is at least represented and inferred via the entangled states between systems and other equations of Bohmian mechanics. Subsystems of the particle with undifferentiated quantum properties form non-local UDIs like in generative-GRW and in the generative-quasi-local-MWI. More concretely, local interactions between the generators and A/B lead A/B to have a stably differentiated quantum property (e.g., spin in a certain direction) and lead to a non-local stable differentiation of a quantum property of B/A. This changes the position determinate value of E_B/E_A when it interacts with B/A. Let's suppose that a magnetic field acts on particle S_A in such a way that E_A interacts with A where this interaction ends up stably differentiating the spin-z of A, changing the determinate value of E_A. Then, this also leads to the non-local stable differentiation of the spin-z of B. Furthermore, when E_B and B interact, E_B will have a determinate value of position influenced by the determinate value

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[40] Note that the stable differentiation of the spin quantum property here is more easily reversible.

of B. Updating the state to the one that resulted from the interactions, we end up, for example, with the following quantum state,

$$|\Psi(t')\rangle = |\uparrow_z\rangle_A |\downarrow_z\rangle_B |\text{up}\rangle_{E_A \text{ DS}} |\text{down}\rangle_{E_{\text{B}} \text{ DS}} \tag{12}$$

Note that, like in other generative quantum theories, particles with indeterminate value properties play the role of the wave function in generative Bohmian mechanics. Generative Bohmian mechanics needs this dual ontology because, on any understanding, Bohmian mechanics has a dual ontology. So, this version of Bohmian mechanics is no more “unnatural" than any other alternative version of this view.

2.4 The generative-EnDQT and generative-hybrid-classical-quantum-theories

GQT was inspired by Environmental Determinacy-based Quantum Theory (EnDQT) presented in Pipa (2023). EnDQT is a local non-relationalist non-superdeterministic/non-retrocausal quantum theory that makes indeterminacy basic. Besides being local (more on what I mean by local below), another benefit of EnDQT is that it's a conservative view since it doesn't modify the fundamental equations of QT. In this section, I will show how GQT helps generate EnDQT and how EnDQT provides a way to move beyond the MWI/GRW/Bohm orthodoxy altogether. In doing that, it also allows us to formulate a local interpretation of QT in the domain where we know where to apply QT. I will also briefly go over hybrid classical-quantum theories, expressed via the lens of GQT, and explain some of their similarities with EnDQT.

Like the MWI and other relationalist views, for generative-EnDQT (henceforward, EnDQT) particles don't play a fundamental role. The stability conditions, i.e., the conditions under which a system comes to have a determinate value/stably differentiated quantum property, can be understood via four conditions that form the core of EnDQT. Plus, EnDQT involves two hypotheses. Viewing EnDQT via GQT, we see that a key innovation of EnDQT is the determination capacity (DC), which is the capacity that systems have to give rise to other systems having their quantum properties stably differentiated and to transmit the DC to other systems under interactions. No other QT introduces this capacity, which is transmitted between systems under certain rules. As we will see, another innovation is the possible introduction of a new kind of generator.

I will now go over the conservative determination conditions (CDCs), which are the stability conditions for EnDQT in the non-relativistic domain.[41] They are called this way because I think that they are the most conservative conditions for the DC to spread in this domain:

CDC1) The determination capacity (DC) of system X concerning system Y (DC-Y) is the capacity that X has while interacting with Y,

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[41] More on this in Pipa (2023) and further below.

i) to allow Y to have a determinate value under the interaction with X that also leads X to have a determinate value, where X and Y have a determinate value in the same spacetime region,

ii) to provide the DC to Y concerning another system Z (DC-Z) if and only if a) Z starts interacting locally with Y while Y is already interacting with X, and b) Y has a determinate value due to X and Z doesn't disturb this process.

So, the DC propagates between systems via interactions because Z can then have the DC concerning a system K (DC-K), if and only a) K starts interacting with Z while Z is already interacting with Y, and b) Z has a determinate value due to Y, and so on for a system L that interacts with K while K interacts with Z, etc. Note that X having a determinate value and Y having a determinate value in the interaction in i) is the same event (i.e., it occurs in the same spacetime region). This is why, for EnDQT interactions give rise to determinate values.

As we have seen, the DC propagates between systems via local interactions over spacetime, so interactions only concern the regions where the systems are, where following the standard way,

For a system X to interact with system Y from time t to t', the quantum states of X and Y must at least evolve from t to t' under the Hamiltonian of interaction representing the local interaction between X and Y.

The chains of interactions that give rise to systems having determinate values and may propagate the DC are the so-called Stable Determination Chains (SDCs). They are the DSs of EnDQT. All systems that don't belong to SDCs belong to ISs. Furthermore, contrary to some other QTs, there aren't interactions at a distance between systems that compose the DSs or the ISs. Also, in agreement with GQT we have that

CDC2) Interactions between system X and a set of systems that form a system Y that may be larger, which has the DC, lead system X to have a certain determinate value, which corresponds to a certain quantum property stably differentiated, where the distinguishability of the physical state of Y concerning the possible determinate values of X allows us to infer if X will have a determinate value among the possible ones and when that happens. Such distinguishability is inferred via the decoherence of X by Y, and where it's indeterministic, the values that will arise among the possible ones.

Now, we can use CDC2) to spell out CDC1) in terms of decoherence (more on how to understand decoherence according to EnDQT below).

CDC1*) The DC-Y of X is the capacity that X has while interacting with Y, i*) to decohere Y, which leads both systems to have a determinate value. Let's suppose that system S in eq. (1) is an instance of X, and system E is an instance Y. The possible values of X are represented by $\uparrow_z$ and $\downarrow_z$. The possible values of Y are represented by $E_\uparrow$ and $E_\downarrow$.

ii*) to provide the DC-Z to Y if and only if ii*-a) Z starts interacting with Y while Y is already interacting with X and ii*-b) Y is decohered by X, and Z doesn't disturb this process, i.e., driving away to other states, the states of Y that are being decohered by X.

CDC3) I will consider that two kinds of systems constitute an SDC:

-Initiator systems or initiators, which are systems that either a) have the DC concerning any system by default (i.e., they always have the DC-X for any system X), i.e., independently of their interactions with other systems. Or b) they are the first systems that have the DC concerning some system that they are interacting with or the ones that we initially assign in our models the DC concerning some system that they are interacting with. Because of this, initiators are the systems that start SDCs.

-Non-initiator systems are systems that don't have the DC concerning a system by default but have it due to their interactions with other systems that have the DC.

So, for EnDQT, like in some other generative quantum theories, the world is fundamentally constituted by systems with indeterminate values/undifferentiated quantum properties, which include initiators. The latter *may* have the DC concerning any system by default, not having to have their quantum properties stably differentiated in a previous interaction to stably differentiate the quantum properties of other systems and transmit the DC. On the other hand, non-initiators have to have certain quantum properties stably differentiated due to some previous interactions to have the DC. The DSs for EnDQT are called SDCs because the process that gives rise to them can be seen as a process that, in order to occur, needs to be stable in the sense that it stably obeys CDC1*). More concretely, in order to infer that systems have determinate values, it is necessary that the overlap terms of the quantum states of the environment go *stably* to zero. Also, given CDC1*) again, it's also necessary that systems that interact with systems that are going over this process, are *stably* not disturbed from going over this process.

Since systems are typically composed of many systems, EnDQT also assumes that

CDC4) For a system S to have the DC concerning some system S', its subsystems must have the DC concerning S' or its subsystems.

Let's review the simple and idealized example.[42] I will soon make this example more concrete further below. I will again assume that systems interact quickly compared with how quickly they intrinsically evolve, so that, once again, we can neglect the systems' intrinsic evolution. This example will involve systems S_0, S_1, and S_2, where S_0 is an initiator, in a toy mini universe where the SDC that will be formed has the following structure: $S_0 \rightarrow S_1 \rightarrow S_2$. The arrows represent the stable differentiation of a quantum property of S_1 by S_0, which allows S_1 to stably differentiate a quantum property of S_2 and have the DC-S_2.

Let's suppose that S_0 is an initiator of the kind a), and thus it has the DC concerning any system. Let's assume that S_2 starts interacting with S_1 while S_1 is already interacting with S_0 so that S_1 has the DC-S_2, and S_1 can end up transmitting the DC to S_2 concerning some other system that S_2 might end up interacting with. However, in order to fulfill CDC1-ii) and to simplify, let's assume that when S_1 and S_2 begin interacting, the changes of the states of S_1 that the interaction with S_2 leads to is negligible in such a way that we can neglect the evolution of the quantum states of S_1 while S_0 and S_1 interact. Then, we can idealize that S_1 and S_2 start interacting only when the interaction between S_0 and S_1 ends.[43] Thus, we can just analyze the evolution of the quantum states of S_0 while S_0 and S_1 are interacting, where this interaction ends approximately at t', and these systems have a determinate value at t'.

Let's then put a subscript SDC on the quantum states of a system if that system is an initiator or has the DC relative to some system. We then have the following interaction between S_0 and S_1,

$$\begin{gathered} |E_{\text{ready}}\rangle_{S_0\ \mathrm{SDC}}(\alpha'|E'_0\rangle_{S_1} + \beta'|E'_1\rangle_{S_1}) \rightarrow_{t'} \\ |E_0(t')\rangle_{S_0\ \mathrm{SDC}}|E'_0\rangle_{S_1} + |E_1(t')\rangle_{S_0\ \mathrm{SDC}}|E'_1\rangle_{S_1} \end{gathered} \tag{13}$$

So, if $\langle E_0(t')|E_1(t')\rangle_{S_0\ \mathrm{SDC}} \approx 0$ and $\langle E_1(t')|E_0(t')\rangle_{S_0\ \mathrm{SDC}} \approx 0$ quasi-irreversibly when S_0 and S_1 end their interaction, S_1 will have a quantum property stably differentiated by S_0 and a determinate value of the associated quantum property (let's suppose that is either 0 or 1) that arises from its interaction with S_0, and acquires the DC-S_2 (given our idealization). I am assuming that occurs at $t^{'}$. Let's further assume that S_1 has a determinate value 0. Then, the stably differentiated quantum property will be represented by $|E_0^{'}\rangle_{S_1}$ and the observable that $|E_0^{'}\rangle_{S_1}$ is an eigenstate of. Now, let's consider the interaction between S_1 and S_2, which (assuming our idealization) starts when the interaction between S_0 and S_1 ends. Let's assume that it ends at $t^{''}$,[44]

$$\begin{gathered} |E'_0\rangle_{S_1\ \mathrm{SDC}}\,(\alpha|\uparrow\rangle_{S_2} + \beta|\downarrow\rangle_{S_2}) \rightarrow_{t''} \\ |E_0^{'\uparrow}(t'')\rangle_{S_1\ \mathrm{SDC}}|\uparrow\rangle_{S_2} + |E_0^{'\downarrow}(t'')\rangle_{S_1\ \mathrm{SDC}}|\downarrow\rangle_{S_2} \end{gathered} \tag{14}$$

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[42] See Appendix A in Pipa (2023) for a toy model.

[43] We could similarly consider that while S_0 interacts with S_1, S_2 starts interacting with S_1 in such a way that it doesn't drive the states of S_1 out of being states that S_0 decoheres in the following sense: the Hamiltonian of interaction of S_0 and S_1 would still at least approximately commute with the (pointer) observable that these states are eigenstates of.

[44] Note that the quantum states of S_1 and S_2 absorbed their quantum amplitudes.

The evolution of the interaction between S_1 and S_2 can be analyzed via the reduced density operator $\rho_{S_2}(t)$. This interaction will lead to the stable differentiation of a quantum property of S_2 and allow it to have a determinate value ($\uparrow$ or $\downarrow$) if $\langle E_0^{'\uparrow}(t)|E_0^{'\downarrow}(t)\rangle_{S_1} \approx 0$ and $\langle E_0^{'\downarrow}(t)|E_0^{'\uparrow}(t)\rangle_{S_1} \approx 0$ quasi-irreversibly when S_1 and S_2 end their interaction. Let's assume that this interaction ends at t'', and these systems will have a determinate value at $t^{''}$. So, S_1 will have indeterministically another stably differentiated quantum property and a determinate value at t'' that arises from its interaction with S_2, where the possible values that it can have are represented via the eigenvalues of the observable that $|E_0^{'\uparrow}(t'')\rangle_{S_2}$ and $|E_0^{'\downarrow}(t'')\rangle_{S_2}$ are eigenstates of. Furthermore, S_2 could have the DC concerning some other system S_3 if it interacted with it before its interaction with S_2 ends. In Appendix A in Pipa (2023), I have presented a more detailed toy model.

In the example above, S_1 could be a system well approximated by a large set of quantum harmonic oscillators[45] or a set of spin-1/2 systems or two-level systems that can be approximated as spin-1/2 systems. Each set of quantum systems interacts with a single spin-1/2 system. The collection of these systems constitutes system S_2. Then, system C could be another two-level system that will interact with S_2.[46]

As we can see, for EnDQT, irreversible decoherence is viewed as an inferential tool that represents how the systems that are part of the nodes of SDCs interact, and like generative-MWI and generative-Bohmian mechanics, to infer the time it takes for stable differentiation to occur. However, EnDQT is an indeterministic theory, contrary to these theories. Also, it's important to emphasize that now it is required that the systems that belong to the environment have the DC, in order for determinate values to arise. So, when there are interactions, but the systems involved don't belong to an SDC, not having the DC, their relevant quantum properties will remain undifferentiated. Thus, no determinate value arises, and we don't update the quantum state to the new state.

Let's now review two hypotheses assumed by EnDQT, starting with the one regarding decoherence. EnDQT has a subtler view of decoherence than other QTs. Let's call the models of decoherence that represent the interactions between systems having the DC, starting with the initiators, *fundamental decoherence models*. These models don't involve extra considerations, such as if the environment is inaccessible or open. The systems in CDC1-CDC4), and in the example above are represented via these models.

On the other hand, the so-called *pragmatic decoherence models* don't necessarily track the interactions with systems that have the DC. These models come in two kinds. We have seen them in the previous sections, but I will distinguish them here again to precisify some of their aspects and distinguish them from other processes. *Irreversible pragmatic decoherence models* are models

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[45] Or more precisely, bosonic modes. These interactions can be represented via the spin-boson mode. See, e.g., Leggett et al. (1987) and Schlosshauer (2007).

[46] The interactions between the systems that constitute S_2 and system S_3 would be modeled via the so-called spin-spin decoherence models developed in Zurek (1982) and Cucchietti et al. (2005).

that represent situations where it's considered that is impossible to reverse the process represented by them because they involve many systems, and where these situations may involve an environment that is open. These are the models typically associated with decoherence, which is a quasi-irreversible process. We also have what I will call *reversible pragmatic decoherence models.* These are models that represent a process that apparently involves decoherence in the sense that it is modeled by the overlap terms of the environment going quasi-irreversibly to zero. However, someone in some privileged position could reverse this process via operations on the systems or (to put it less pragmatically) they don't involve enough degrees of freedom to be considered irreversible. So, these models aren't what we associate with decoherence.

Given the distinctions above, EnDQT also postulates the following hypothesis regarding the structure of the SDCs:

The SDCs in our world are widespread in such a way that the empirically successful and local pragmatic irreversible decoherence models in open environments track the interactions between systems that belong to SDCs that serve as an environment for a target system that doesn't belong to an SDC, but ends up belonging to it. However, the SDCs in our world are such that there can also exist processes represented via local empirically successful reversible decoherence pragmatic models, where the latter are tracking the interactions between systems that don't belong to SDCs (*SDCs-decoherence hypothesis*).

Via this hypothesis, EnDQT grounds the success of these pragmatic decoherence models in representing processes that give rise to determinate values. It is important to notice that depending on one's ingenuity, *in principle,* it's possible to isolate macroscopic systems from the influence of SDCs, and so for EnDQT, in principle, arbitrary systems can be in a coherent superposition for an arbitrary amount of time. Thus, if this isolation is done properly in such a way that we can unitarily manipulate the contents of that region, we might have a process of reversible decoherence inside that region instead of an irreversible one. So, given the above hypothesis, if some situation, even involving interactions between macroscopic systems, is appropriately modeled by reversible pragmatic decoherence models, we can infer that we have managed to isolate the systems from the influence of SDCs. Of course, also given this hypothesis, in principle, doesn't mean in practice because our pragmatic models of decoherence tell us that it's very difficult to place large macroscopic systems in a superposition.

This view held by EnDQT contrasts with the one often assumed by MWI-like views, which would consider that determinacy arises within a large enough isolated spatiotemporal region with systems decohering each other inside of it. In the case of the MWI, the DC doesn't exist and matter. Note again that, contrary to most of the previous QTs, for EnDQT there aren't any non-local ISs or DSs connecting systems. Those structures arise and are maintained locally via their interactions. SDCs for EnDQT can be represented by directed graphs like the one in the example above, where the arrows represent the stable differentiation interactions arising between systems.

Now, we are in a better position to further clarify how EnDQT relates to some of the other features of GQT. Contrary to the other QTs explained here (more on this in the next section), EnDQT has the benefit of explaining in a unificatory and parsimonious way[47] via the initiators and the laws that describe/govern the interactions of systems that belong to the SDCs they give rise to, which systems can be generators and the generative quantum properties that they have. More concretely, initiators are a special kind of generators that have the capacity of allowing other systems to become generators when they interact with them. The generative quantum properties of generators are the properties that they have when they interact with other systems, giving rise to the latter having determinate values. Above, $|E_0(t')\rangle_{S_0\mathrm{SD}C}$ or $|E_1(t')\rangle_{S_0\mathrm{SD}C}$ and the respective observable that these quantum states are eigenstates of, represent those generative quantum properties. Systems that they interact with will be able to have determinate values and certain generative quantum properties, becoming generators. The possible generative quantum properties of S_1 are represented by $|E_0^{'\uparrow}(t'')\rangle_{S_1}$ or $|E_0^{'\downarrow}(t'')\rangle_{S_1}$, and the observable that these quantum states are eigenstates of, which gives rise to S_2 having a determinate value. So, we can trace the capacity of systems having generative quantum properties and being generators to interactions that ultimately originated with initiators.

The second hypothesis aims to address the question of what kind of systems initiators are. The inflaton is one possible candidate for an initiator because of its privileged and influential role in the history of the universe, which accounts for our belief that systems with determinate values are widespread (i.e., classicality is widespread). So, the inflaton field, with its quantum properties occupying regions of spacetime, would be the initiator.[48] The inflaton field is the initiator, but it transmits the DC via local interactions.

If we adopt initiators of the kind a), one of the reasons to consider the inflaton field (and the quantum systems that arise from this field) as a plausible candidate for an initiator is that it allows us to explain why we can sometimes maintain the

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[47] Note that initiators of the kind a) don't lead so much to a parsimonious theory, but the ones of the kind b) because they are identical to non-initiators.

[48] To clarify, notice that ultimately, the description of the inflaton field and the rest of the fields interacting with it would need to be quantum field theoretic. I haven't shown how GQT can be understood in the context of quantum field theory, but in principle, such an extension won't be problematic. Briefly, in one possible approach, the fundamental systems that transmit the DC are quantum fields in a finite spacetime region developing local interactions. More concretely, we associate to quantum fields in a finite spacetime region, such as the inflaton field ϕ in the spatial region x at t (whose observable is $\hat{\phi}\,(x,\ t)$), collections of quantum properties represented via the wave functional $\Psi[\phi,\ t]$ (see, e.g., Kuhlmann (2018) for an introduction to quantum fields). The wave functional assigns a complex amplitude to each possible configuration of classical fields in that spacetime region, yielding a superposition of these configurations. The quantum properties of the quantum system (which concerns that region) will also be represented by the observables that act on the wave functional in that region. So, although quantum fields, in general, can be associated with unbounded spacetime regions, the DC is transmitted between localized quantum fields via local interactions since the observables (including the field observables such as $\hat{\phi}\,(x,\ t)$) representing quantum systems and quantum properties concerns bounded spacetime regions developing local interactions. Thus, it's expected that quantum fields in certain regions will have stably differentiated quantum properties and spread the DC in local regions of spacetime.

coherence of quantum systems in quasi-isolated spatiotemporal regions. If there were initiators that could start SDCs in any region, it would be very difficult or impossible to maintain such coherence because they would destroy superpositions. We can allow for initiators that only manifested themselves at the beginning of the universe by observing that it's standardly considered that, at least in our universe, the inflaton field reached the absolute minimum of its potential and has been staying there.[49] Then, for example, if we consider the condition that this minimum corresponds to the point where the field is zero and if we consider that the coupling of the inflaton field to all other fields in the Lagrangian density that describes/governs our universe depends on the value of the inflaton field in such a way that the interaction terms representing these interactions are zero when the field zero, we can consider that the inflaton field in the stages of the evolution of the universe after the reheating phase will at least rarely interact with other fields/systems.[50] So, it will (at least) rarely give rise to SDCs after the reheating phase, which is our current phase. Let's represent the Lagrangian of our universe obeying these conditions as $\mathcal{L}_{\text{SDC}}$. So, the second hypothesis is that

> at least most current SDCs started in the early universe, and initiators had a privileged role in this stage, giving rise to these SDCs, and where the initiators are the inflaton field described via $\mathcal{L}_{\text{SDC}}$ (inflationary-starting hypothesis).

This is one possible concrete hypothesis for what initiators are, being an instance of the more abstract *SDCs-starting hypothesis*, which establishes when SDCs started. I regard this latter hypothesis as a placeholder for current and future cosmology. Given the current evidence for inflation, this is the initiator adopted. As I have argued in Pipa (2023), the possible specialness of initiators is, in principle, unproblematic because our evidence points toward early universe events involving some special physical phenomena and can provide other scientific and philosophical advantages (more on this in the next section).

An important benefit of EnDQT is that it deals with Bell's theorem and scenarios in the sense of not leading to the violation of relativistic causality, i.e., without forcing us to assume that the causes of the events involved in those correlations aren't in their past lightcone and without invoking superdeterministic or retrocausal explanations, being "local".[51] First of all, note that EnDQT doesn't modify the fundamental equations of QT, and so, in principle, it can be rendered Lorentz and generally covariant, and thus, it can be compatible with relativity in this sense as long as QT is.[52] However, future work will provide a model of EnDQT where this is shown explicitly. Second, let's see how it deals with the

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[49] See, e.g., Liddle and Lyth (2009).

[50] See, e.g., Kiefer and Polarski (2009) for models of decoherence involving the decoherence of the inflaton field, and a discussion of the various possible kinds of environmental systems. See also Pipa (2023).

[51] When I say that the causes are in the "past lightcone," I am implicitly assuming that this influence is non-instantaneous.

[52] Within the domain where we know where to apply QT. See Pipa (2023).

EPR-Bell scenarios and Bell's theorem.

A widely accepted version of Bell's theorem involves, together with the statistical independence or no-superdeterminism assumption,[53] the factorizability condition,

$$P(AB|XY\mathbf{\Lambda}) = P(A|X\Lambda)P(B|Y\mathbf{\Lambda}) \tag{15}$$

The variables A, B, $\mathbf{\Lambda}$, X, and Y concern events embedded in a Minkowski spacetime. A and B represent the different measurement results of Alice and Bob, X and Y are the different possible choices of measurement settings for Alice and Bob. $\mathbf{\Lambda}$ represents some set of (classical) "hidden" variables in the past lightcone of A and B (see also Figure 2), representing the common causes of the correlations between X and Y. This condition is seen as a consequence of two assumptions:[54] the causes of an event are in its past lightcone, and the classical Reichenbach Common Cause Principle (CRCCP).

Briefly, the CRCCP states that if events A and B are correlated, then either A causes B, or B causes A, or both A and B have common causes $\mathbf{\Lambda}$, where conditioning on the members of the set of variables $\mathbf{\Lambda}$, A and B are decorrelated, i.e., $P(A,\ B|\ \mathbf{\Lambda}) =\ P(A|\ \mathbf{\Lambda})P(B|\ \mathbf{\Lambda})$. However, it's unclear whether we should accept that the probabilistic relations and conditions given by the CRCCP should, in general, represent a causal structure involving quantum systems, given their quantum indeterminate values, and how they evolve. The CRCCP. However, why should we trust the CRCCP as a general statement about causal relations? The CRCCP as a general statement is better seen as a consequence of the more widely applicable Classical Markov Condition (CMC), assumed by the widely applicable Classical Causal Models (CCMs).[55]

The CMC connects the causal structure provided by some theory represented by a DAG with probabilistic statements. The CMC is the following,

Let's assume we have a DAG G, representing a causal structure over the variables $\mathbf{V} = \{X_1,\ \ldots,\ X_n\}$. A joint probability distribution $P\left(X_1,\ \ldots,\ X_n\right)$ is *classical Markov* with respect to G if and only if it satisfies the following condition: for all distinct variables in $\mathbf{V}$, P over these variables factorizes as $P\left(X_1,\ \ldots,\ X_n\right) = \prod_j P\left(X_j|\mathrm{Pa}\left(X_j\right)\right)$, where $\mathrm{Pa}\left(X_j\right)$ are the "parent nodes" of X_j, i.e., the nodes whose arrows from these nodes point to X_j.

The CMC for the DAG in Figure 2, which respects relativity, allows us to derive the following equation (I will denote certain regions of spacetime, the related nodes, and variables whose values may be instantiated in those regions using the same letters),

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[53] This assumption states that any events on a space-like hypersurface are uncorrelated with any set of interventions subsequent to it.

[54] Bell (1976, 2004). See also, e.g., Myrvold et al. (2021) and references therein.

[55] I will not derive it here, but see Hitchcock and Rédei (2021). See Pipa (2023) for some subtelities regarding this relation.

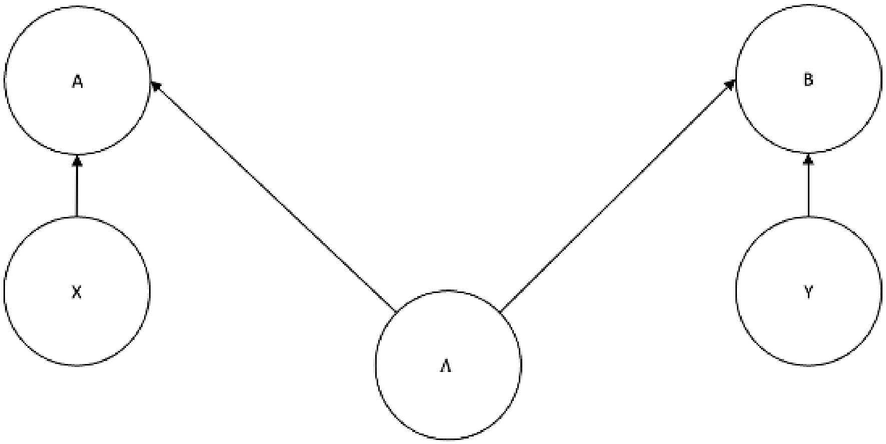

Figure 2: DAG of the common cause structure of Bell correlations, which respects relativity. This causal structure respects relativistic causality because X or A doesn't influence Y or B, and vice-versa, where these events may be spacelike separated. Moreover, no other variables influence the variables A, B, X, or Y, or they don't influence anything else. So, there are no retrocausal or superdeterministic causal relations.

$$P(AB|XY) = \sum_{\Lambda} P(\Lambda)P(A|X\Lambda)P(B|Y\Lambda). \tag{16}$$

The acceptability of the CRCCP can be supported by the empirical success of the application of the CMC via CCMs (e.g., Pearl, 2009). EnDQT responds to Bell's theorem by rejecting that the CMC can be applied in general to accurately represent causal relations between quantum systems, understood here simply as relations of influence. Hence, it rejects the applicability of the CRCCP and the factorizability condition to make such an accurate representation.

In Pipa (2023), I have provided various reasons why EnDQT rejects that the CMC and CCMs accurately represent causal relations between quantum systems.

One of the reasons comes from noticing that a clear and precise way of justifying the CMC is via Pearl & Verma's proof (Pearl and Verma, 1995) of the CMC. This proof roughly assumes that the Markov condition arises from the ignorance of some absolutely defined "hidden variables" Λ that are the common causes of correlations, where the latter represents some determinate values that determine these correlations. However, EnDQT rejects that common causes of the correlations are given by such determinate values that we are ignorant about. As we shall see, they are appropriately given by quantum states representing quantum indeterminate values.[56] Note that even if we specify some Λ via the

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[56] The argument in Pipa (2023) is more subtle, but I will simplify it here.

eigenvalues of the observable that some quantum state in the past is an eigenstate of, given that EnDQT is an indeterministic theory, such Λ can't work to specify a local common cause of Bell correlations. So, such specification wouldn't be appropriate anyway to infer the relations of influence behind Bell correlations. Thus, the CMC and the CCMs are inappropriate to accurately represent causal relations between quantum systems.[57]

Further below, I will provide other related reasons why EnDQT rejects that the CMC and CCMs accurately represent causal relations between quantum systems.

Instead of the CMC, EnDQT uses a generalization of the CMC, the quantum Markov condition (QMC), and Quantum Causal Models (QCMs)[58] that adopt a quantum version of the CMC as a more appropriate tool to accurately represent causal relations between quantum systems. As we will also see, QCMs provide a local common cause explanation of Bell correlations. This will show how a kind of DSs (i.e., the SDCs) and ISs help provide that explanation (more on this in the next section).

This explanation is done via the quantum Markov condition and a version of the Born rule (Figure 1),

$$P\left(x,y|s,t\right)=\mathrm{Tr}_{\Lambda\mathrm{AB}}\left(\rho_{\Lambda}\rho_{A|\Lambda}\rho_{B|\Lambda}\tau_{A}^{x|s\ \mathrm{SDC}}\otimes\tau_{B}^{y|t\ \mathrm{SDC}}\right). \tag{17}$$

Now, A, B, and Λ represent spacetime regions instead of classical variables. The systems that are prepared at the source are acting as common causes for Bell correlations. They have indeterminate values, until non-instantaneously reaching the measurement devices of Alice and Bob, which gives rise to the correlated outcomes. The entangled state ρ_{Λ}, through its subsystems, represents these systems that are prepared at a source, which, for instance, can be systems having indeterminate values of spin-p, where p is ranging over all possible directions of spin. ρ_{Λ} and the quantum channels $\rho_{B|\Lambda}$ and $\rho_{A|\Lambda}$ are used to separately represent each system prepared at the source that travels non-instantaneously to different regions, and this is done by keeping track of the labels A and B.[59] So, each one of the systems evolves locally to region A/B, where Alice/Bob will influence the outcomes arising in those regions. When it comes to A, this influence is represented via the quantum channel $\rho_{A|\Lambda}$, and when it comes B, by $\rho_{B|\Lambda}$. More concretely, $\rho_{B|\Lambda}$ and $\rho_{A|\Lambda}$ are identity channels that via their action on the density operator ρ_{Λ} , also represent the systems in region Λ that evolve to regions A and B, respectively. The influence that gives rise to the outcomes is also represented via the POVMs $\tau_{A}^{x|s\ SDC}$ in Alice's case, where s is her random measurement choice, and x is her outcome, and via $\tau_{B}^{y|t\ SDC}$ in Bob's case.

The superscript SDC placed in the POVMs means that these are interventions/interactions that give rise to a determinate value, involving systems that are part of a local SDC, making others also part of an SDC. These interactions are represented by other types of edges in the DAG in Figure 3. In this case,

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[57] I reflect further on this argument in Pipa (2023).

[58] Allen et al. (2017) and Costa and Shrapnel (2016).

[59] See Nielsen and Chuang (2011).

Alice and Bob, due to their measurements, will lead the target systems to be part of an SDC because they also belong to SDCs giving rise to the systems having a determinate value of spin in a specific direction, for example. So, via the above account, EnDQT uses QCMs to give a local common cause explanation of quantum correlations, which respects relativistic causality. It is important to notice that, by assuming GQT's perspective on quantum states, which doesn't reify them, and by assuming local DSs (the SDCs), we shouldn't consider that the measurement of Alice on her system influences Bob's system and vice-versa.

This scenario can be represented using a DAG, which I have called *EnDQT-causal-DAG*. The diagram shows in grey the evolution of systems that are not part of an SDC but rather an IS concerning the quantum properties of the model. The evolution and interactions of systems that belong to an SDC are in black:[60]

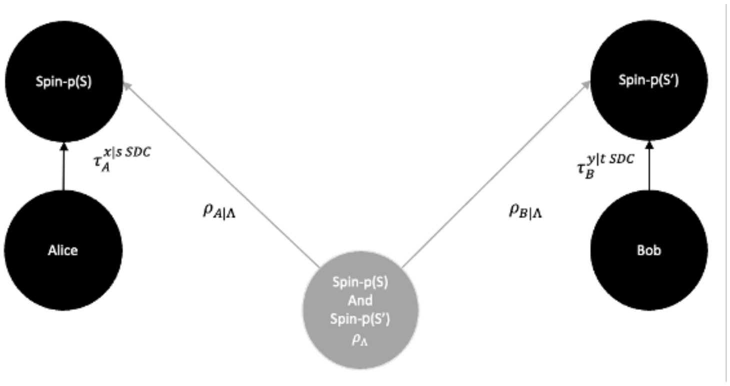

Figure 3: *EnDQT-causal-DAG* proposed by EnDQT, which allows for a non-relational local common cause explanation of Bell correlations.

We see above the role of structural generators in giving a local common cause explanation of Bell correlations.

In Pipa (2023), I have provided other reasons why EnDQT rejects that the CMC and CCMs accurately represent causal relations between quantum systems (see above some other related reasons). This argument, which is called the *argument for locality*, is based on finding the domain of applicability of the CCMs by examining the more general models that putatively represent causal relations in the quantum domain, i.e., QCMs, which reduce classical ones in a "classical limit." Like we found what is wrong with classical mechanics when we examined the more general theory, QT, which reduces to classical mechanics in some limit, we find what is wrong with the CCMs when we adopt QCMs interpreted via EnDQT. This argument is necessarily theory-dependent because it relies on an interpretation of CCMs and QCMs. Like all frameworks, these models always require an interpretation. The idea is that contrary to QCMs, CCMs with their CMC for EnDQT don't accurately represent relations of influence between

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[60] See Pipa (2023) to see how EnDQT can account for interference locally.

quantum systems. This is because, contrary to CCMs, QCMs, as interpreted by EnDQT, explicitly consider that systems that are common causes for Bell correlations,

i) only assume determinate values with a certain probability given by the Born rule when they interact with systems that belong to SDCs. Therefore, they don't consider that there are certain hidden variables, which represent those determinate values and determine those outcomes. Furthermore,

ii) the relations of influence for QCMs that give rise to quantum correlations are described via QT but without reifying the quantum states in the sense of EnDQT.

Thus, given i) and ii), for EnDQT QCMs don't lead to inferences that consider that Alice affects the space-like separated Bob and vice-versa in EPR-Bell scenarios; Alice and Bob, in EPR-Bell scenarios, interact locally with their target systems via local SDCs (where each system is represented via $\rho_{A|\Lambda}$), not influencing each other non-locally. Furthermore, no non-local ISs are assumed (or needed) like in the QTs above. i) and ii) allow EnDQT to interpret QCMs non-instrumentally and as clearly representing local features of the world, i.e., as not hiding non-local influences *behind* quantum states and interventions on systems.

Therefore, contrary to QCMs, given that CCMs interpreted by EnDQT don't explicitly assume i) and ii), CCMs with their CMC for EnDQT don't accurately represent relations of influence between quantum systems behind quantum correlations.

It is sometimes seen in the literature the argument that QT is non-local based on the claim that the EPR argument (Einstein et al., 1935) ruled out the existence of local indeterministic theories (e.g., Maudlin, 2014). So, one might worry that there is something wrong with my argument above. However, this argument concerning the non-locality of QT shouldn't be right because EnDQT, as an indeterministic local theory, is a counterexample to that claim. Note that the so-called EPR criterion of reality[61] assumed in this argument can precisely be seen as a consequence of the classical Reichenbach common cause principle (see Gömöri and Hofer-Szabó (2021), which, as I have mentioned, is a special case of the more general CMC Hitchcock and Rédei (2021)). However, as I have argued in more detail in Pipa (2023), EnDQT doesn't consider that the CMC can, in general, represent causal relations between quantum systems. Thus, it rejects the EPR criterion as representing such causal relations and, therefore, one of the basic premises of the above argument for non-locality.

Another generative quantum theory leads to a version of hybrid classical-quantum theories,[62] which I will call generative-hybrid. Due to reasons of

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[61] "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to that quantity." Einstein et al. (1935)

[62] See Oppenheim (2023) and, e.g., Diósi (1995).

space, here I will go over it briefly. In the case of this theory, we have a kind of gravity-causes collapse theory, where there are classical systems that evolve fundamentally stochastically,[63] and quantum systems. The evolution of both is described/governed by a hybrid classical-quantum dynamics. Quantum systems, by default, belong to an IS and have undifferentiated quantum properties like EnDQT, and like EnDQT, there aren't any non-local ISs. Furthermore, classical systems are a collection of quantum properties that are always stably differentiated, e.g., the metric and its conjugate in the hybrid theory that aims to describe gravity, and occupy spatiotemporal regions.[64] Note that the metric as a field will have values throughout all spacetime, and like in the case of quantum systems when we have quantum fields,[65] classical systems will pertain to certain spacetime regions. The stochastic behavior of the metric is represented via a positive density operator. A classical-quantum state is the tensor product between these operators and quantum states/density operators. A classical-quantum system is a collection of the quantum properties of both, concerning certain regions of spacetime. Classical systems are generators and stably differentiate the quantum properties of quantum systems, and the latter also backreacts on the classical systems, affecting their evolution. DSs concern the local evolution of these classical systems and their interactions with quantum ones. Generative-hybrid is local and can also provide a local causal explanation of Bell correlations like EnDQT (more on this below),[66] but gravity is necessarily the sole responsible for determinate values arising.

3 GQT vs. Wave Function Realism and Primitive Ontology and new generative quantum theories

Let's now compare GQT with Wave function Realism (WR) and Primitive Ontology (PO). I will argue that GQT has important benefits that these frameworks don't offer and without some of their notorious costs.

First, GQT offers a better way of making sense of the nature of the wave function or quantum state or density operators or matrices than WR and PO (I will refer to density operators also as quantum states from now on).[67] WR is an ontology that considers that the fundamental entity represented by QT is

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[63] So that the gravitational field doesn't "reveal" the location of the quantum systems in its interactions with them, *collapsing* their quantum states, in certain situations in agreement with experiments. However, the greater the rate of *decoherence* induced by classical systems on quantum systems, the lower the amount of diffusion/stochasticity induced by the quantum systems on the metric and their conjugate momenta of the classical system (Oppenheim et al., 2023).

[64] I don't regard calling these properties quantum or not as a substantive issue in a fundamental theory. Like in GRW, a quantum property doesn't need to be represented via standard QT.

[65] See footnote 48.

[66] This is why hybrid classical-quantum theories shouldn't reify the quantum state because this doesn't lead to inferences about non-local causal relations, adopting GQT point of view.

[67] I am also assuming that PO proponents can assume that density operators have a nomological character.

a wave function living in a $3N$ configuration space where N is the number of existing particles.[68] As it's well-known, the main challenge of WR is to give a plausible account of how to derive and make sense of the spatial three-dimensional manifest image from this more fundamental space. This is problematic, given the evidence that we have that, at least in the classical regime, systems occupy regions of spacetime. This brings me to the PO. According to this view, what is fundamental are entities with determinate locations in spacetime, having determinate features, like flashes, mass densities, etc., also known as local beables. This contrasts with the GQT since, in the latter case, fundamental entities can have indeterminate locations. Another feature of the PO framework is their view of wave functions/quantum states, which are to be considered fundamental but it's typically considered not to represent matter. It typically rather has a nomological character, governing or describing the behavior of the PO. Although PO advocates may also allow the wave function to be a physical wave in a high-dimensional space, I will specialize my discussion on the former case since it sets it more apart from GQT and WR. PO endorses a revisionist attitude towards the laws of nature by considering that a complicated object, such as a wave function/quantum state, which is also allowed to change over time, is a law.[69]

GQT doesn't suffer from the issues associated with considering the wave function as an entity in a 3N dimensional space or a law. The quantum state is more like a distribution over a set of possibilities, and possibilities, unlike laws, change over time. Furthermore, although systems may have certain indeterminate locations, they can still occupy regions of spacetime. Thus, GQT offers a better way of making sense of the nature of quantum states or the wave function than WR and PO.

Second, contrary to these other frameworks, GQT is built in such a way that helps formulate new QTs, which may lead to scientific and philosophical progress. For example, GQT, in principle, can help generate new QTs (and associated ontologies) that adopt a strategy compatible with relativistic causality, i.e., that are local in the sense of not requiring us to assume that the causes of the events involved in those correlations are not within their past lightcone, and without invoking superdeterministic or retrocausal explanations. Given the importance of relativistic causality, this should be regarded as a benefit. As I will argue, PO and WR lack this benefit.

We have seen EnDQT and a local version of the MWI above as examples of theories that GQT helped generate. Furthermore, by changing some of the features that EnDQT adopts, GQT can, in principle, help generate theories that are a hybrid of EnDQT and other QTs. As I will argue, these hybrids lead to other theories that allow for the compatibility between QT and relativistic causality,

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[68] See Section 1 for further information on WR.

[69] One strategy tries to address this worry by arguing that the fundamental wave function of the universe behaves more like a law and may be simpler because it doesn't change over time (Goldstein and Zanghì, 2013). This is supported by the Wheeler-DeWitt equation assumed by some theories of quantum gravity. However, this strategy is highly speculative because it relies on an assumption that not all quantum gravity programs make.

plus have some other benefits. Note that here I am not interested in locality in the sense that these theories are compatible with relativistic symmetries. This is an open question.[70] I will sketch three examples of these theories here and leave their development for future work.

Regarding what I will call *EnDQT-collapse*, it adopts a different kind of generators and, more specifically, initiators than the ones adopted by EnDQT. Systems with a specific quantum property (e.g., the position quantum property) can become indeterministically initiators with a probability per unit time and start an SDC like in EnDQT. Regarding what I will call *EnDQT-MWI*, it arises from considering a theory like EnDQT, but where the generators of EnDQT don't give rise to determinate values indeterministically in a single world but instead give rise to multiple systems with determinate values deterministically, where each corresponds to a world. We could perhaps also have an *EnDQT-Hybrid* that arises from modifying the generative-Hybrid by introducing initiators in them. In EnDQT-Hybrid, for example, initiators give rise to stochastically evolving classical systems with certain quantum properties always stably differentiated. Or, we wouldn't have initiators as systems but as the events that are behind the decoupling between the classical properties (i.e., always stably differentiated quantum properties that evolve stochastically in a certain way) and the quantum ones. So, EnDQT-Hybrid would have the advantage of giving a unifying explanation for why we have both classical and quantum systems.[71]

GQT helps generate versions of "consciousness causes collapse theories,"[72] without the need to modify the equations of QT. Consciousness here is understood as phenomenal consciousness. A system is considered conscious when there is something that is like to be that system from within the system.[73] Maintaining the (non-mandatory) ontology of quantum properties, there are multiple versions of this idea. For instance, in one version, only generators with stably differentiated quantum properties are conscious systems. In another version, not only the generator but also its target system of an interaction has a stably differentiated quantum property. Furthermore, systems with stably differentiated quantum properties would be determinately conscious. Since stable differentiation comes in degrees, one can formulate a version where being conscious comes in degrees, where the degree of stable differentiation of a quantum property of a system tracks the degree to which a system is conscious (conscious of what? more on this below). When a system has an undifferentiated quantum property, it is indeterminately conscious (in one subversion), or it has no consciousness (in another subversion).

However, let's focus on the first version that was mentioned, which is the most straightforward one. As I have mentioned, in this version, only generators

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[70] Note that, however, in the case of EnDQT-MWI and other theories that don't modify the fundamental equations of QT that we will see below, in principle, they allow for general covariance like EnDQT in principle allows. This is because they don't modify the fundamental equation of QT, and if QT allows for it (which is a conjecture), they also should allow for it. See Section 2.4.

[71] A mechanism to describe these kinds of initiators should be explored in future work.

[72] See, e.g., Chalmers and McQueen (2022), Stapp (1993), and Wigner (1961).

[73] Chalmers and McQueen (2022).

with stably differentiated quantum properties are conscious systems. There are at least two generative versions of this view. In the generative consciousness version, generators are systems that have the capacity to be conscious, and an indeterministic process gives rise to a generator being conscious. The Born rule gives the probabilities for this chancy process to occur. Decoherence would be an epistemic and inferential tool that helps investigate when we have generators that become conscious, having stably differentiated quantum properties. This is when they *decohere* other systems. In virtue of being conscious, systems give rise to others having stably differentiated quantum properties, where the values concerning these properties are absolute. Furthermore, they have experiences concerning such quantum properties. For instance, having the consciousness of energy would arise upon decoherence of some target system S in the energy basis (stably differentiating this quantum property of S), having consciousness of momentum would arise upon decoherence of some system in the momentum basis, and so on for other quantum properties.[74]

The problem with this view is that it inherits all the vagueness associated with decoherence. As I have explained in the previous sections, some processes apparently involve decoherence, but such decoherence is reversible and is not really considered decoherence. How to make that distinction? Unfortunately, for most quantum systems, we can't ask them whether they are conscious or not. One may argue that via the conditions for irreversible decoherence to occur, we would simultaneously investigate the conditions when consciousness arises, and we have multiple ways of finding what those conditions are. This often occurs when we have a large number of systems in an open environment. However, those conditions are still unclear because even what counts as an environment is still vague. The proponent of this view can appeal to a set of adequate theories of consciousness to inform them of what are the favorable conditions. This option would mean that generative consciousness is incomplete because it needs to appeal to other theories that very likely won't be physical theories. I think that this incompleteness renders this view less attractive.

One way of possibly surpassing this limitation is via an alternative version that I will call generative EnDQT-consciousness. This version is just like EnDQT (it has initiators, the DC, etc.), but it's considered that only systems with the DC are capable of being conscious. They become conscious when they have a stably differentiated quantum property and the DC. The capacity for a system to be conscious is transmitted via interactions. However, it's hard to see what this version adds to the original version of EnDQT. It rather seems to complicate it because now we have introduced consciousness at the fundamental level. Besides that, given our current science of consciousness, it's unclear whether stable differentiation of quantum properties of certain systems (or some analogous feature if we adopt some other ontology of properties) has anything to do with consciousness. Thus, it seems that we have introduced an unnecessary speculative assumption, and we might as well not assume it.

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[74] Here, we could adopt the view that it's the environment as a whole that is the generator, and it's the whole that is conscious, and none of its parts are. Or we could adopt the view that all the subsystems of the environment are generators, and all of them are conscious.

All theories mentioned above could use QCMs to provide a local common explanation of Bell correlations. Also, like EnDQT, they could formulate a version of the argument for locality explained in section 2.4 and in more detail in Pipa (2023) to deal with the Bell's theorem in a local way, as well as other similar strategies to EnDQT to deal with this theorem mentioned in section 2.4. This is because, similarly to EnDQT, in principle, they consider that systems that are common causes for Bell scenarios i) only assume determinate values with a certain probability given by the Born rule when they interact (locally) with generators, where these local interactions are guaranteed by their local DSs, and ii) where those relations are described via QT but without reifying the quantum states like EnDQT assumes. Thus, given i) and ii), these theories don't reify the quantum states, which doesn't lead to inferences that consider that Alice affects the space-like separated Bob and vice-versa in EPR-Bell scenarios; Alice and Bob, in EPR-Bell scenarios, interact locally with their target systems via local DSs, not influencing each other non-locally; and no non-local ISs are assumed or needed like in the QTs above. So, i) and ii) allow these theories to interpret QCMs non-instrumentally and as clearly representing local features of the world, i.e., as not hiding non-local influences *behind* quantum states and interventions on systems. Also, as I have mentioned above, all of them could, in principle, a version of the argument for locality, which uses i) and ii), to deal with Bell's theorem (see Section 2.4 and Pipa (2023)), arguing that what it shows is that the Classical Markov Condition and the Classical Causal Models don't accurately represent causal relations between quantum systems. So, they can use quantum causal models to provide a common cause explanation of quantum correlations like EnDQT. Rather, Quantum Causal Models adequately represent such relations. However, I want to emphasize that instead of providing the argument for locality via SDCs, the argument would be given in terms of their own local DSs and the ISs represented via QCMs and other tools such as directed graphs.

Furthermore, like EnDQT they can also reject the applicability of the Classical Markov Condition as accuratelly representing causal relations between quantum systems by rejecting Pearl and Verma justification of it. However, one from EnDQT that one should keep in mind is that local-MWI and EnDQT-MWI are deterministic and not indeterministic like EnDQT and the other views. Besides, they assume that there aren't single outcomes. So, these theories deal with Pearl and Verma's proof of the Causal Markov Condition (Pearl and Verma, 1995) by also rejecting that there are single outcomes of interactions, which is another assumption of that proof.

So, if quantum states concern systems with indeterminate values and the possible determinate values, as well as DSs and ISs, whether a theory obeys relativistic causality depends on the details of how the indeterminate values become determinate via ISs and DSs. Thus, by allowing for fundamental systems to have indeterminate value properties and not reifying the wave function or seeing it only as nomic, we gain the benefit of being able to add instead a different structure, which allows for locality in certain QTs. For instance, we saw that EnDQT appeals to ISs without non-local interactions and local SDCs that start with initiators as its structural generators, and above, I have mentioned other possible structural generators of this kind through the hybrid EnDQT versions. Let's call the strategy that appeals to i) and ii), assuming these kinds of structural generators, the local structural generative strategy since it can allow these theories to respect relativistic causality. They can also deal in a similar way to EnDQT with the argument from Maudlin (2014). See Pipa (2023) for more details.

On the other hand, WR and PO lack this benefit. If the wave function is a real field, then non-local causation in spacetime seems built into its structure. The fact that PO proponents regard the wave function/quantum states as a law rather than just helping to represent and infer features of systems and local DSs and ISs (like EnDQT assumes), presses one to consider that the regularities at a distance in Bell-like scenarios lead to non-local influences between events.

Thus, via the local structural generative strategy, GQT opens new and interesting possibilities and strategies compatible with relativistic causality. Hence, GQT, in principle, provides ways of helping construct QTs compatible with relativistic causality. Given the importance of relativistic causality, should be regarded as an important benefit, and it's one that these views lack.

Third, notice that not all QTs reify the wave function, and adopt WR, such as EnDQT, single-world relationalist theories mentioned above, such as Relational Quantum Mechanics, and hybrid classical-quantum theories. Furthermore, not all QTs see the wave function as a law, such as at least Relational Quantum Mechanics, other single-world relationalist views, and EnDQT. Since facts are relative to some entity in single-world relationalist views, there is not plausible to view a wave function as governing or describing in general all those facts.[75] Furthermore, unlike the case of the PO, some QTs tend to take systems with indeterminate values/undifferentiated quantum properties either absolutely or relationally as playing an important explanatory role, such as EnDQT or Relational Quantum Mechanics, respectively. Thus, GQT has the benefit of, in principle, being an ontological framework that has a wider application, which can facilitate the comparison between QTs because we can use the same ontological framework to better compare the different QTs (more on this below).

Fourth, by not reifying wave functions or considering them as laws, and by allowing for certain new kinds of entities, GQT provides new and interesting ways of comparing different QTs and finding their advantages and disadvantages, and which ones we should prefer. I regard this as another benefit of GQT since it might help us find the best QT, and as we will see, this way of comparing QTs cannot be done via the other ontological frameworks.

One type of new comparison that GQT allows for is at the level of generators and generative quantum properties. Despite our world being fundamentally quantum or at least mostly quantum, certain determinate values seem to arise, preferably due to certain generators, and generative quantum properties. What selects the elements of this subset of determinate values, generators, and generative quantum properties? As I have argued in Section 2.4, EnDQT via initiators

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[75] See the paragraphs above for the reasons why EnDQT doesn't adopt the nomological view.

and interactions between systems that belong to SDCs can, in principle, explain this selection in a unificatory and simple way.[76] It is simple because only one generator is, in principle, initially and fundamentally postulated (modulo future developments in cosmology), the inflaton, and simple CDCs. It is unificatory because all generative quantum properties and generators trace back to this system, as well as the determinate values that the systems having them favor.

On the other hand, generative-GRW, generative-Bohmian mechanics, and generative-hybrid favor only a subset of all quantum properties as generative, and it's a brute fact why only some quantum properties among the many existing ones are generative.[77] Also, they postulate many systems as generators (all the systems with position quantum properties). Generative-MWI and generative-relationalist-single-world theories don't postulate fundamental generators, except generative-RQM, which considers that all systems are generators. However, contrary to EnDQT, they need to provide a special role to many dynamical laws in order to provide a unificatory explanation for why, in a wide range of interactions, specific systems are generators and others aren't and why certain quantum properties are generative ones and others aren't. More concretely, what explains these features are the dynamical laws concerning the quasi-classical domain, which involves Hamiltonians or Lagrangians. However, this makes these views reliant on many laws to explain these features, which are all the laws that account for decoherence (which includes the various laws that describe emergent features and the diverse terms in the Lagrangians and Hamiltonians). This reliance on many laws might be considered problematic to some who want simpler and more straightforwardly concrete facts to explain generators and generative properties.

On the other hand, EnDQT explains why certain systems are generators and have generative quantum properties without necessarily relying on many laws. Rather, fundamentally, it appeals to more concrete entities, i.e., quantum systems. Generators and generative quantum properties are explained through chains of interactions that start with the initiators. This general, straightforwardly concrete, and simple facts, seems to me that it renders EnDQT more parsimonious than these views.

A MWI proponent might attempt to explain generators and generative quantum properties in a more unified way by appealing to the features of the environments that monitor a target system S.[78] These environments, via interactions, select a pointer observable that represents a quantum property of S that, in later interactions between S and other systems, will give rise to S having generative quantum property and S being a generator. However, then one would need to explain why the environment has those features that give rise to such selection, i.e., those generative quantum properties and this gives rise to circularity.

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[76] See Pipa (2023) for more formal details.

[77] One might argue that there is something special about position, but I am not sure that's right. We can also argue that energy and momentum are also very special.

[78] For example, one could be tempted to adopt the quantum Darwinist strategy Zurek (2009) and consider generative quantum properties as those that tend to proliferate in an environment.

One might object that EnDQT may move the brute facts concerning generators and generative quantum properties to the early universe where initiators manifested themselves. However, this is at least an explanation for them (versus a brute fact) or arguably a more parsimonious one since, as I have mentioned above, fundamentally, we may just need one special generator if we adopt initiators of the kind a) (i.e., the ones that have the DC regarding any system). Every other fact regarding generators and generative quantum properties should be explained through chains of interactions that started with the initiators. Furthermore, any QT already needs to invoke the initial conditions as a brute fact for various explanatory purposes (e.g., explain the arrow of time, solve the problems that inflation pertains to solve, etc.). EnDQT at least has the advantage of being able to ground the different already appealed brute facts in a more fundamental one, which concerns the initial state of initiators. However, note that there is a sense that this can be an explanation for the initial conditions of the universe because non-fundamental *special* facts about the initial conditions of the universe can be grounded on the more fundamental *special* facts about QT. This is because initiators as special entities, and the phenomena that they give rise to are fundamental for QT, according to EnDQT.[79]

Another type of new comparison that GQT allows for is at the level of the determination and indetermination structures appealed by each QT. EnDQT, via initiators and local interactions between systems, explains the local structure of SDCs in a unified and non-relational way. The ISs and/or DSs of other QTs, except generative-single-world-relationalist theories and generative-local-MWI, have a more complicated non-local structure (e.g., they postulate UDIs, destruction interactions, etc.), potentially conflicting with relativity. Furthermore, generative-single-world-relationalist theories and the generative-local-MWI offer us DSs that don't causally connect "distantly separated" systems or worlds (if a notion of distance even makes sense for these views) in the sense of worlds or systems that don't share the same environment. This threatens the power of their explanatory resources since some local phenomena are more plausible to explain if they are due to some "distant" systems or worlds. I am not just referring to phenomena involved in Bell correlations here, but whatever is happening with systems that are *not* connected with some DSs, although it's plausible and simpler to consider that they end up influencing the systems that belong to them. For example, it's plausible to consider that the values of the sun or even the moon are determinate before they influence systems on Earth. However, for generative-single-world-relationalists (such as RQM), the systems that belong to the sun or moon at least don't immediately interact with the measurement devices or inhabitants of Earth, and thus their values are indeterminate relative to us. This is at odds with the way we seem to successfully causally explain various phenomena via our scientific theories.

In the case of generative-local-MWI, the threat comes from the events that are happening in some worlds that seem to influence other worlds (e.g., the different branches concerning whatever is possibly happening to my family in

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[79] See Pipa (2023) for more details on these virtues.

the other continent that seem to end up influencing my branches). However, unlike generative-global-MWI, which connects different systems within a world via DSs, due to the ever-present unconnected branching, we don't have a way to track or even make sense of how different branches causally connect. This is again at odds with the way we seem to successfully causally explain various phenomena via our scientific theories.[80] We also have seen above the problems with the consciousness causes collapse theories that were proposed here.

Let's consider that if theory T1 is more parsimonious, less problematic, and more explanatory than theories T2, then theory T1 should be preferred to T2. Assuming this, I think that if we consider the above reasons of locality, parsimony, and explanatory power, we should prefer EnDQT to the above theories. GQT makes those reasons more manifest.[81]

Thus, by not reifying wave functions or considering them as laws and by allowing for new entities, GQT provides new and interesting ways of comparing different QTs, finding their advantages and disadvantages, and deciding which ones to prefer. I regard this as another benefit of GQT since it might help us find the correct QT. Relatedly, it provides arguments in favor of EnDQT.

However, we might not take the above comparison seriously and object that the preference for EnDQT regarding the above features when we compare it with other QTs, disappears when we adopt an ontology that views the wave function like WR or PO. These QTs can postulate the existence of the wave function of the universe either as a fundamental law or field, which provides a simpler and unificatory explanation for why certain systems are generators and others not, why certain quantum properties are generative and others aren't, and why certain structures exist. On top of that, one may even dismiss GQT because it's an ontological framework that gives, in a sense, an uncharitable treatment of some QTs that were built under the assumption that we should reify the wave function in some sense. However, I think the above comparison should be taken seriously, as well as GQT as a good ontological framework for QT.

First, I think that multiple issues regarding the different QTs manifest in similar ways when they adopt WR or the PO. The appeal to brute facts about primitive ontologies or the reliance on many laws are still there when these QTs

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[80] A tension is found in the MWI theories between allowing for more explanatory power via a generative-global-MWI view and allowing for more locality via a generative-local-MWI or arguably a generative-quasi-local-MWI view.

[81] What about if we compare EnDQT with the hybrid views presented above, and whose comparison hasn't been made yet? We would have to examine other costs of these theories. In the case of EnDQT-MWI, contrary to EnDQT, it will have an additional problem of probabilities plaguing the MWI, which can still make it an undesirable view, and it will have the same explanatory power deficits identified above that the local-MWI has. Note that due to its determinism and reversibility of quantum states, EnDQT-MWI is a theory different from EnDQT. In the case of EnDQT-collapse, in so far it would be empirically satisfactory, contrary to EnDQT, it will still involve the cost of modifying the fundamental equations of QT to account for the postulated probability per unit time of a system becoming an initiator. Also, it's unclear if this version is really local because the probability per unit time of a system becoming an initiator would be specified relative to a preferred reference frame. In the case of EnDQT-Hybrid, it's still unclear what would constitute its initiators or events mentioned above and whether gravity should be treated as a separate field that shouldn't be quantized.

adopt these ontological frameworks. The non-locality at the level of spacetime too, as well as the above issues with single-world-relationalist theories and the local-MWI. GQT just makes these features more manifest.

Furthermore, as I also mentioned, GQT, in principle, facilitates and improves the comparison between QTs because it can be applied more widely while using the same kind of ontology. So, it's plausible to consider that GQT can provide a more charitable treatment of QTs in general than these other two frameworks. Furthermore, given the current state of the foundations of physics, where we are still trying to unify QT with general relativity and solve the measurement problem, I think that we should consider that the general applicability and comparison between QTs that GQT allows for is epistemically more valuable than the restricted applicability that PO and WR tend to lead to. This is because it might allow for progress by offering new means to evaluate in general different QTs.

Even if one insists on the simplicity of the wave function/quantum states, these objects aren't necessarily simpler than DSs and ISs by many measures of simplicity. For instance, the relations of influence that they permit, which these ontologies take seriously, are very diverse and subject to multiple precisifications, not necessarily simplifying them. Just look at the different QTs, as well as subversions of them. For instance, just within the MWI, Sebens and Carroll (2018) make the distinction between local and global branching as one way of precisifying what these objects represent and the relations of influence that they allow for. There are likely various other ways of precisifying the relations permitted by the wave function just within the MWI. Also, these objects per se permit complicated nomic relations, actions at a distance, and/or evolutions within spaces of many dimensions. Furthermore, since we have a redundancy in the global phase,[82] many different wave functions/quantum states seem to be able to give rise to/govern/describe the *same* physical state of the systems, and so in this aspect, these ontologies seem to complexify even more the description of these relations of influence because there are too many possibilities. So, given the above reasons, DSs and ISs don't necessarily give rise to more complicated relations of influence than the wave function/quantum states.

On top of this complexity, PO and WR have epistemic issues that GQT doesn't have. Let's suppose we attempt to answer the question regarding how we know and why we have *this* wave function of the universe and not another, where this wave function accounts for the behavior of quantum systems. The answer to this question will hardly be satisfactory because wave functions aren't directly observable and do not easily connect with our familiar world or nomic standards. On the other hand, GQT appeals to, in principle, at least more familiar or standard entities: systems and their interactions; and a more familiar and standard view of quantum states to physicists, i.e., mostly as predictors and inferential tools. Also, many physicists are used to thinking about indeterminacy via the EEL (Section 1). These standard and familiar assumptions will likely

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[82] As said in Section 2.1, given the inferential role of quantum states assumed by GQT, we can ignore the global phases of quantum states to make inferences about and represent properties of systems.

lead GQT to be considered overall more satisfactory than PO and WR.

Furthermore, as I have mentioned, unlike GQT, these ontologies give rise to potentially problematic unexplained non-local influences (PO with its nomic view),[83] a revisionist attitude towards laws (PO), or the problem of making sense of the three-dimensional space manifest image (WR), which gives rise to further issues when comparing the different views. So, given this reason and the ones explained in the two previous paragraphs, I think that the above unificatory explanation based on the wave function is more problematic and not necessarily simpler.

Thus, since GQT provides benefits that these influential frameworks don't offer, including having wider applicability without the costs mentioned above, which include getting rid of what can be seen as problematic distractions associated with reifying the wave function or viewing it as nomic, I think it's a good ontology to compare different QTs and for QT. Moreover, I also think that GQT and the above comparison between QTs should be taken seriously.

4 Conclusion and future directions

I have presented Generative Quantum Theory as a new ontology for quantum theories and have shown how it can be implemented via GRW, the MWI and single-world relationalist views, Bohmian Mechanics, hybrid classical-quantum theories, and EnDQT. I have also distinguished it from the most discussed ontologies for QTs, namely, wave function realism and primitive ontology, and argued that it has certain benefits that they lack without some of their costs, such as non-locality.

I have presented generative quantum theories that adopt a property ontology based on quantum properties, which also allowed for a new analysis of quantum indeterminacy and determinacy. However, other generative theories are possible for other kinds of property ontologies. Future work should explore whether it's beneficial to build generative theories that use another account of properties, such as determinable-determinates,[84] etc.

Also, it should explore applying this framework to other QTs, such as superdeterministic, retrocausal,[85] and other relationalist theories, as well as to different pictures of QT. Relatedly, it should analyze other possible generators (structural and non-structural) and initiators. This could allow us to generate further new QTs. Also, it should extend this view to Quantum Field Theory.[86]

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[83] Whereas WR and GQT appeal to certain entities.

[84] In this property ontology, we would view observables as representing determinables (e.g., position, momentum, energy, etc.) and determinate values as representing determinates of those determinables. Interactions give rise to a determinable with a determinate. Systems would be considered as collections of determinables, which at different moments of time, have determinates or not (e.g., having a spin-x with or without a determinate of spin-x) depending on their interactions like in the gappy version of quantum indeterminacy presented in Calosi and Wilson (2019). Quantum indeterminacy arises when we have state of affairs constituted by a system lacking a determinate of a determinable.

[85] See, e.g., Hossenfelder and Palmer (2020) and Friederich and Evans (2019).

[86] However, see Section 2.4.

Furthermore, it should compare GQT with other ontological frameworks that weren't discussed here. I suspect that GQT will provide many benefits that they don't have without their costs, given the distinctiveness of GQT and since, in different ways, most of the other ontological frameworks reify the wave function or the quantum state or see it as a law.

References

Albert, D. Z. (1996). Elementary Quantum Metaphysics. In J. T. Cushing, A. Fine, & S. Goldstein (Eds.), *Bohmian mechanics and quantum theory: An appraisal* (pp. 277–284). Springer Netherlands. https://doi.org/10.1007/978-94-015-8715-0{_}19

Albert, D. Z. (2023). *A guess at the riddle: essays on the physical underpinnings of quantum mechanics*. Harvard University Press.

Allen, J.-M. A., Barrett, J., Horsman, D. C., Lee, C. M., & Spekkens, R. W. (2017). Quantum Common Causes and Quantum Causal Models. *Physical Review X*, *7*(3), 31021. https://doi.org/10.1103/PhysRevX.7.031021

Allori, V. (2013). Primitive Ontology and the Structure of Fundamental Physical Theories (A. Ney & D. Z. Albert, Eds.). https://doi.org/10.1093/acprof:oso/9780199790807.003.0002

Bacciagaluppi, G. (2020). The Role of Decoherence in Quantum Mechanics. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Fall 2020). Metaphysics Research Lab, Stanford University.

Barnes, E., & Williams, J. R. G. (2011). A Theory of Metaphysical Indeterminacy. In K. Bennett & D. W. Zimmerman (Eds.), *Oxford studies in metaphysics volume 6*. Oxford University Press.

Bell, J. S. (1964). On the Einstein Podolsky Rosen paradox. *Physics Physique Fizika*. https://doi.org/10.1103/physicsphysiquefizika.1.195

Bell, J. S. (1976). The Theory of Local Beables. *Epistemological Letters*, (March 1976).

Bell, J. S. (2004). La Nouvelle Cuisine. In *Speakable and unspeakable in quantum mechanics: Collected papers on quantum philosophy* (2nd ed., pp. 232–248). Cambridge University Press. https://doi.org/DOI:10.1017/CBO9780511815676

Calosi, C., & Wilson, J. (2019). Quantum Metaphysical Indeterminacy. *Philosophical Studies*, *176*(10).

Chalmers, D. J., & McQueen, K. J. (2022). Consciousness and the Collapse of the Wave Function. In S. Gao (Ed.), *Consciousness and quantum mechanics*. Oxford University Press, Usa.

Costa, F., & Shrapnel, S. (2016). Quantum causal modelling. *New Journal of Physics*, *18*(6), 63032. https://doi.org/10.1088/1367-2630/18/6/063032

Cucchietti, F. M., Paz, J. P., & Zurek, W. H. (2005). Decoherence from spin environments. *Physical Review A*, *72*(5), 52113. https://doi.org/10.1103/PhysRevA.72.052113 de Oliveira, T. R., & Caldeira, A. O. (2006). Coherence and Entanglement in a Stern-Gerlach experiment. *arXiv: Quantum Physics*. https://api.semanticscholar.org/CorpusID:118968673

Di Biagio, A., & Rovelli, C. (2021). Stable Facts, Relative Facts. *Foundations of Physics*, *51*(1), 30. https://doi.org/10.1007/s10701-021-00429-w

Diósi, L. (1995). Quantum dynamics with two Planck constants and the semiclassical limit. *arXiv preprint quant-ph/9503023*.

Dürr, D., Goldstein, S., & Zanghí, N. (1992). Quantum equilibrium and the origin of absolute uncertainty. *Journal of Statistical Physics*, *67*(5), 843–907. https://doi.org/10.1007/BF01049004

Earman, J. (2008). Superselection Rules for Philosophers. *Erkenntnis*, *69*(3).

Einstein, A., Podolsky, B., & Rosen, N. (1935). Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? *Physical Review*, *47*(10), 777–780. https://doi.org/10.1103/PhysRev.47.777

Fine, K. (1975). Vagueness, truth and logic. *Synthese*, *30*(3-4).

Friederich, S., & Evans, P. W. (2019). Retrocausality in Quantum Mechanics. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Summer 2019). Metaphysics Research Lab, Stanford University.

Ghirardi, G., & Bassi, A. (2020). Collapse Theories. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Summer 2020). Metaphysics Research Lab, Stanford University.

Gilton, M. J. R. (2016). Whence the eigenstate-eigenvalue link? *Studies in the History and Philosophy of Modern Physics*, *55*, 92–100. https://doi.org/10.1016/j.shpsb.2016.08.005

Giulini, D., Kiefer, C., & Zeh, H. D. (1995). Symmetries, superselection rules, and decoherence. *Physics Letters A*, *199*(5), 291–298. https://doi.org/https://doi.org/10.1016/0375-9601(95)00128-P

Glick, D. (2017). Against Quantum Indeterminacy. *Thought: A Journal of Philosophy*, *6*(3), 204–213. https://doi.org/https://doi.org/10.1002/tht3.250

Goldstein, S. (2021). Bohmian Mechanics. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Fall 2021). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/fall2021/entries/qm-bohm/

Goldstein, S., & Zanghì, N. (2013, April). 91Reality and the Role of the Wave Function in Quantum Theory (A. Ney & D. Z. Albert, Eds.). https://doi.org/10.1093/acprof:oso/9780199790807.003.0004

Gömöri, M., & Hofer-Szabó, G. (2021). On the meaning of EPR's Reality Criterion. *Synthese*, *199*(5), 13441–13469. https://doi.org/10.1007/s11229-021-03382-3

Healey, R. (2017). *The Quantum Revolution in Philosophy*. Oxford University Press.

Hitchcock, C., & Rédei, M. (2021). Reichenbach's Common Cause Principle. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Summer 2021). Metaphysics Research Lab, Stanford University.

Hossenfelder, S., & Palmer, T. (2020). Rethinking Superdeterminism. https://www.frontiersin.org/article/10.3389/fphy.2020.00139

Joos, E., & Zeh, H. D. (1985). The emergence of classical properties through interaction with the environment. *Zeitschrift für Physik B Condensed Matter*, *59*(2), 223–243. https://doi.org/10.1007/BF01725541

Kiefer, C., & Joos, E. (1999). Decoherence: Concepts and examples BT - Quantum Future From Volta and Como to the Present and Beyond. In P. Blanchard & A. Jadczyk (Eds.). Springer Berlin Heidelberg.

Kiefer, C., & Polarski, D. (2009). Why do cosmological perturbations look classical to us? *Adv. Sci. Lett.*, *2*, 164–173. https://doi.org/10.1166/asl.2009.1023

Kuhlmann, M. (2018). Quantum Field Theory. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Winter 2018). Metaphysics Research Lab, Stanford University.

Leggett, A. J., Chakravarty, S., Dorsey, A. T., Fisher, M. P. A., Garg, A., & Zwerger, W. (1987). Dynamics of the dissipative two-state system. *Reviews of Modern Physics*, *59*(1), 1–85. https://doi.org/10.1103/RevModPhys.59.1

Lewis, P. J. (2016). *Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780190469825.001.0001

Liddle, A. R., & Lyth, D. H. (2009). *The Primordial Density Perturbation: Cosmology, Inflation and the Origin of Structure*. Cambridge University Press. https://doi.org/DOI:10.1017/CBO9780511819209

Maudlin, T. (2014). What Bell did. *Journal of Physics A: Mathematical and Theoretical*, *47*(42), 424010. https://doi.org/10.1088/1751-8113/47/42/424010

Myrvold, W. C. (2022). Philosophical Issues in Quantum Theory (E. N. Zalta & U. Nodelman, Eds.; Fall 2022).

Myrvold, W. C., Genovese, M., & Shimony, A. (2021). Bell's Theorem. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Fall 2021). Metaphysics Research Lab, Stanford University.

Ney, A. (2021). *The World in the Wave Function: A Metaphysics for Quantum Physics*. Oxford University Press.

Nielsen, M. A., & Chuang, I. L. (2011). *Quantum Computation and Quantum Information: 10th Anniversary Edition* (10th). Cambridge University Press.

Oppenheim, J. (2023). A postquantum theory of classical gravity? *Physical Review X*, *13*(4), 41040.

Oppenheim, J., Sparaciari, C., Šoda, B., & Weller-Davies, Z. (2023). Gravitationally induced decoherence vs space-time diffusion: testing the quantum nature of gravity. *Nature Communications*, *14*(1), 7910. https://doi.org/10.1038/s41467-023-43348-2

Pearl, J. (2009). *Causality* (2nd ed.). Cambridge University Press. https://doi.org/DOI:10.1017/CBO9780511803161

Pearl, J., & Verma, T. S. (1995). A theory of inferred causation. In D. Prawitz, B. Skyrms, D. B. T. .-. S. i. L. Westerståhl, & the Foundations of Mathematics (Eds.), *Logic, methodology and philosophy of science ix* (pp. 789–811, Vol. 134). Elsevier. https://doi.org/https://doi.org/10.1016/S0049-237X(06)80074-1

Pipa, F. (2023). A new indeterminacy-based quantum theory. https://doi.org/https://doi.org/10.48550/arXiv.2310.04002

Rovelli, C. (1996). Relational quantum mechanics. *International Journal of Theoretical Physics*. https://doi.org/10.1007/BF02302261

Schlosshauer, M. A. (2007). *Decoherence and the quantum-to-classical transition*. Springer.

Sebens, C. T., & Carroll, S. M. (2018). Self-locating Uncertainty and the Origin of Probability in Everettian Quantum Mechanics. *The British Journal for the Philosophy of Science*, *69*(1), 25–74. https://doi.org/10.1093/bjps/axw004

Stapp, H. P. (1993). *Mind, Matter and Quantum Mechanics* (Vol. 12). Springer Verlag.

Wallace, D. (2012). *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199546961.001.0001

Wallace, D. (2019). What is Orthodox Quantum Mechanics? In *Philosophers look at quantum mechanics*. https://doi.org/10.1007/978-3-030-15659-6{_}17

Wallace, D., & Timpson, C. G. (2010). Quantum Mechanics on Spacetime I: Spacetime State Realism. *The British Journal for the Philosophy of Science*, *61*(4), 697–727. http://www.jstor.org/stable/40981311

Wigner, E. P. (1961). Remarks on the mind-body question. In I. J. Good (Ed.), *The scientist speculates*. Heineman.

Zurek, W. H. (1982). Environment-induced superselection rules. *Physical Review D*, *26*(8), 1862–1880. https://doi.org/10.1103/PhysRevD.26.1862

Zurek, W. H., Habib, S., & Paz, J. P. (1993). Coherent states via decoherence. *Physical Review Letters*, *70*(9), 1187–1190. https://doi.org/10.1103/PhysRevLett.70.1187

Zurek, W. H. (2003). Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics*, *75*(3), 715–775. https://doi.org/10.1103/RevModPhys.75.715

Zurek, W. H. (2009). Quantum Darwinism. *Nature Physics*, *5*(3), 181–188. https://doi.org/10.1038/nphys1202