A new indeterminacy-based quantum theory

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Abstract

I propose a novel (interpretation of) quantum theory, which I will call Environmental Determinacy-based or EnD Quantum Theory (EnDQT). In contrast to the well-known interpretations of quantum theory, EnDQT has the benefit of not adding hidden variables, is not in tension with relativity, and provides a local causal explanation of quantum correlations without measurement outcomes varying according to perspectives or worlds. It is conservative, and so unlike collapse theories, in principle, arbitrary systems can be placed in a superposition for an arbitrary amount of time, and no modifications of the fundamental equations of quantum theory are required. Furthermore, it provides a series of novel empirical posits that may distinguish it from other interpretations of quantum theory. According to EnDQT, some systems acquire determinate values at some point, and the capacity to give rise to determinate values through interactions propagates to other systems in spacetime via local interactions. This process can be represented via certain networks. When a system is isolated from the systems that belong to these networks, it will non-relationally have indeterminate values.

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1. Introduction

The measurement problem arises from interactions in quantum theory (QT), which, without introducing some extra assumptions, can lead the quantum state of the system to be in a superposition at macroscopic scales, where the latter doesn't correspond to a physical magnitude with determinate values. However, we know from classical physics and experimental evidence that this can't be the case at macroscopic scales.

In the search for a solution to this problem, as far as we know, a conservative approach should seek to fulfill the following desideratum:

i) A precise criterion for when determinate values arise that doesn't modify the fundamental equations of QT, like spontaneous collapse theories, or postulates a special force that causes such collapse, such as gravitational collapse theories.[2] This is because we have currently no evidence for that.

However, we have some evidence that decoherence[3] and interactions between quantum systems play some role in giving rise to determinate outcomes. On the other hand, so far, it's plausible to consider that systems that would decohere could, in principle, continue evolving unitarily. In the end, decoherence only gives rise to systems in a superposition. Similarly, it's plausible to consider that any other system could in principle evolve unitarily indefinitely. So, this conservative solution should also fulfill the desideratum of

ii) Allowing for any system to in principle be in a superposition of quantum states for an arbitrary amount of time.

Therefore, a conservative approach should fulfill the task of

UT) Not modifying the fundamental equations of QT or denying its universality. Furthermore, allowing for arbitrary systems can in principle be in a superposition of quantum states for an arbitrary amount of time.

[2] See, e.g., Ghirardi & Bassi (2020) and Diósi (1987).
[3] See, e.g., Schlosshauer (2007).

A strategy to fulfill UT) is to allow for any system to be placed in a superposition for an arbitrary amount of time, even very massive systems or large systems, but invoking interactions that can lead to observables with determinate values, where these interactions are described quantum mechanically via decoherence. Decoherence doesn't modify the basic equations of QT and thus allows for a conservative approach. Also, many approaches to QT have used decoherence to help them solve the measurement problem. But which interactions and systems? Again, we could be conservative and appeal to some other systems that are themselves decohered, where these systems were decohered thanks to some other systems, and so on. However, this idea seems to start giving rise to an infinite regress and some vagueness regarding the details of these interactions.

To deal with these issues, we could appeal to some special systems or events that establish when these interactions began, a more precise structure that represents such interactions, and simple and conservative rules that establish how determinate values arise from them. Environmental Determinacy-based Quantum Theory (EnDQT) will pursue this strategy by introducing a network structure whose edges represent *certain* interactions between systems represented via decoherence, and that establishes when these interactions give rise to them having determinate values, which I call stable differentiation chains (SDCs).[4] Furthermore, SDCs started *somewhere*. As I will argue, the first systems with determinate values arose in the past through some special systems, which I call initiators. These systems started chains of local interactions over time and space, which are the SDCs. By interacting with an initiator, a system acquires a determinate value of an observable during these interactions and the capacity to give rise to other systems having determinate values in interactions with them, which allows these later systems to lead other systems to have determinate values and to themselves have determinate values, and so on. So, these chains allow determinate values to propagate between systems and persist over spacetime, where it is indeterministic which value will arise among the possible ones. These interactions are modeled via decoherence; thus, they don't lead to any modification of the basic equations of QT. The systems that don't belong to this network or don't interact with it at some point can, in principle, unitarily evolve indefinitely.

[4] The reason for this name can be seen in the appendix B.

Furthermore, another important desideratum that a conservative approach to QT should achieve is

LC) Not being in tension with relativity because it doesn't favor a reference frame or not adding hidden variables that lead to retrocausality or superdeterminism.

For EnDQT to achieve LC), first, I will argue that it is able to deal with the Bell's theorem by providing a local explanation of quantum correlations via Quantum Causal Models.[5] (section 4).

Second, EnDQT will adopt a perspective on quantum states where they don't literally and directly represent some physical entity; instead, together with other elements of the theory, such as observables, they help to gain knowledge about and indirectly represent together with the networks representing SDCs, how systems evolve and affect each other, how SDCs evolve, when systems acquire or not determinate values. Also, how systems evolve outside interactions.

So, importantly, given that EnDQT doesn't reify the quantum state, in the Bell-type scenarios, the measurement of Alice doesn't non-locally affect Bob, and vice-versa. Contrary to collapse theories, there is no literal physical collapse of quantum states (which could be highly entangled and non-local) in a superposition during interactions. Instead, there is a local state update of the original state of the target system that can be implemented upon decoherence of this system by its environmental systems *that belong to SDCs*, under their local interactions. This leads to the view where decoherence shouldn't be interpreted as representing a process of branching of the wave-function/quantum states, but rather as a process in which, under *local interactions*, an environmental system that belongs to an SDC, gives rise to another system having determinate values. Note that, contrary to Everettian-like views, decoherence is a necessary but not sufficient criterium for determinate values to arise because it matters if the environmental systems belong to an SDC.

A common way to fulfill i) and ii) is by adopting a relationalist interpretation in which the outcomes of Alice or Bob are relative to, for example, worlds, private perspectives, environments, simultaneity hyperplanes, etc.[6] However, for EnDQT these outcomes and all physical states will be absolute/non-relationalist. So, EnDQT,

[5] See, e.g., Costa & Shrapnel (2016); Allen et al. (2017), and Barrett et al. (2019).
[6] See, e.g., Wallace (2012), Di Biagio & Rovelli (2021), Healey (2017), and Dieks (2019).

NR) Doesn't adopt a so-called relationalist interpretation of QT,

Given the well-known issue of probabilities in Everettian QT,[7] this might be deemed a desiderata and advantage of this view. Also, it's unclear if relationalism in a single-world is desirable.

So, EnDQT should be regarded as a conservative approach to QT that aims to fulfill mostly well-accepted desiderata. I will start by explaining the basics of EnDQT and argue that it provides UT) and start building the case that it provides LC) and NR) (section 2). In section 3, I will argue that EnDQT provides LC) and NR) by showing that it provides a non-relational, local, and non-superdeterministic/non-retrocausal explanation of quantum/Bell-type correlations. In section 4, I will suggest future developments. I will assume non-relativistic QT and the Schrödinger picture Hilbert space-based finite dimensional QT to simplify.

2. EnD Quantum Theory: the basics

I will start by presenting the main features of this view and show why it doesn't fall into UT). Also, I will start building the argument for why it allows for LC) and NR). Its main features, which will be presented in the following order, involve an account of systems and their properties, interactions, decoherence, and how having a determinate value and allowing other systems to have determinate values propagates via decohering interactions, where certain chains of interactions are formed. Afterwards, I will present certain hypotheses that support EnDQT, and certain empirical predictions that it provides. Then, I will argue that EnDQT achieves UT).

To simplify, throughout this paper, I will employ the familiar view that what exists are systems, systems are collections of observables, and observables of systems sometimes have a determinate value, where their eigenvalues represent the latter. This leads systems to "have a determinate value." Or observables sometimes *have indeterminate values*, leading systems to "have an indeterminate value." Interactions are represented via QT, and some of them (which are represented via decoherence) lead systems to have a determinate value of an observable.

[7] See, e.g., Albert (2010) and Price (2010).

Different ontologies can make the above view more precise and allow EnDQT to adopt a more robust realism. One may understand determinate values of systems as referring to flashes that arise or are produced under interactions, i.e., an ontology of local events in spacetime (but differently from collapse theories and with a different interpretation of the quantum state), but there are other ways.[8]

I will consider a (quantum) system as occupying local regions of spacetime and being represented at a moment in time by a certain (equivalence class of) quantum states and observables that act on the quantum states that belong to the Hilbert space of the system. Given the aim of not being in tension with relativistic causality, I will be interested in an ontology constituted fundamentally by local systems and their local interactions, and hence on systems whose observables act on quantum states concerning a single region of space.[9][10] I will be very liberal about what constitutes a system. For example, an atom's internal degrees of freedom could constitute one.

Concerning the observables of a system S, for the sake of parsimony and for the purposes of allowing for a local theory (more on this in section 3), I will assume that:

Any observable O of S, including the non-dynamical ones, outside of certain interactions of S involving O, cannot have determinate values but rather have indeterminate values.

More on this below.[11] Interactions leading to decoherence play a key role for EnDQT in leading to determinacy. I will start by presenting its features. First, how do we represent and establish that a system is interacting with another one? I will represent it in the following standard way,

[8] The flash ontology was first proposed by Bell (2004) and named by Tumulka (2006). We could also view observables as representing determinables and determinate values as representing determinates of those determinables like in Calosi & Wilson (2018). Quantum indeterminacy could arise when we have a state of affairs constituted by a system lacking a determinate of a determinable. Alternatively, we could have an ontology of quantum properties, and this is the one I favor (see appendix B).

[9] This assumption can be made more adequate under a quantum field theoretic treatment.

[10] A system localized in multiple regions of space would be for example the larger system that forms a Bell pair.

[11] The eigenstates of the non-dynamical observables, which are never observed in a superposition, are typically considered to be subject to superselection rules (see, e.g., Bartlett et al., 2007). These rules can be regarded as prohibiting the preparation of quantum states in a superposition, which are eigenstates of some observable and assume a coherent behavior. Rather than postulating these rules, decoherence in a widespread environment in spacetime might be used to explain this superselection (see, e.g., Earman, 2008; Giulini et al., 1995). This is the perspective taken here. However, one may object to this perspective, and EnDQT can be adapted to allow non-dynamical observables of systems always to have determinate values, even when they aren't interacting.

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

As mentioned, decoherence plays a key role in how EnDQT represents interactions that could lead to determinate values, so I will briefly explain it and some of the assumptions I will make. Let's consider a system S in the following state,

$$|\psi>_S = \sum_{i=1}^{N} \alpha_i |s_i>_S, \qquad (1)$$

and an environmental system E of S, constituted by many subsystems, interacting strongly with system S. For instance, $|\psi>_S$ could be a superposition of spin-z eigenstates, and S would be interacting strongly (i.e., the Hamiltonian of interaction dominates the system's evolution) with the many subsystems with a spin in a certain direction that constitute system E. For simplicity, throughout this article, I will assume this kind of strong interaction evolution of the system under interactions with its environment.[12] Now, let's assume that S locally interacts with E in the environment of S, where their interaction is represented via the standard von Neumann interaction,

$$(\sum_{i=1}^{N} \alpha_i |s_i>_S)|E_0>_E \rightarrow_{\hat{U}} \sum_{i=1}^{N} \alpha_i |s_i>_S |E_i(t)>_E = |\Psi>_{S+E}. \qquad (2)$$

The distinguishability between the different states of the environment concerning its interactions with the target system can be quantified via the overlap between quantum states $<E_i(t)|E_j(t)>_E$. The impact of this distinguishability of the states of E on the statistics for the observable of S whose eigenstates are $|s_i>_S$ can be analyzed via the reduced density operator of S, obtained from tracing over the degrees of freedom of E in $|\Psi>_{S+E}$.,

$$\hat{\rho}_S(t) = \sum_{i=1}^{N} |\alpha_i|^2 |s_i>_S<s_i| + \sum_{i,j=1,i\neq j}^{N} \alpha_i^* \alpha_j |s_i>_S<s_j| < E_i(t)|E_j(t)>_E + \alpha_j^* \alpha_i |s_j>_S<s_i| <E_j(t)|E_i(t)>_E. \qquad (3)$$

[12] So, the dynamics will be driven by the interaction Hamiltonian. More complex models of decoherence (see, e.g., Zurek, 2003, Zurek et al., 1993) where the system doesn't interact strongly with the environment, and self-Hamiltonian also has some weight in the evolution of the system, may give rise to different observables with determinate values depending on the initial quantum states. For simplicity I will not talk about these more complex cases here or analyze how in these cases SDCs could be formed.

Under an appropriate Hamiltonian (i.e., the Hamiltonian of interaction) describing the interactions between these two systems, and in fairly generic interactions, we get that $< E_j(t)|E_i(t) >_E$ exponentially decreases over time until $< E_j(t)|E_i(t) >_E \approx 0$. The recurrence time of this term (back to not being significantly small in comparison with the other terms) tends to be so large that it can exceed the universe's age, giving rise to a quasi-irreversible process. When states of the environment become extremely distinguishable under interactions between S and E over time, we have,

$$\hat{\rho}_S \approx \sum_{i=1}^{N} |\alpha_i|^2 |s_i >_S < s_i|. \quad (4)$$

I will say that *S was decohered by system E, or the states of S were decohered by the states* $|E_i(t) >_E$ *of E or by E*. The reduced density operator $\hat{\rho}_S$ can be used to predict the resultant statistics of this interaction and the timescale in which we can *update* the state of S to one of the $|s_i >_S$ under decoherence. Moreover, this model can account for the disappearance of interference effects due to S in situations where it interacts with E. From now on, I will call the states $|E_i(t) >_E$ and $|E_j(t) >_E$ for all i, j with $i \neq j$ when they are distinguishable, i.e., $< E_j(t)|E_i(t) >_E \approx 0$, approximate eigenstates (henceforward, eigenstates) of the observable O of E because the projectors onto these states will approximately commute with the observable O of E. Note that what decoherence ontologically is will be precisified soon.

Now, let's call the *determination capacity (DC),*

The capacity that a system S via interactions with a system S' to i) allow S' to have determinate values and ii) to provide the DC to S'.

The DC will be transmitted between systems via interactions, forming the Stable Differentiations Chains (SDCs). Decoherence plays a key role in representing this transmission and how systems come to have a determinate value,

A necessary and sufficient condition for a system X that has the DC interacting with system Y, and giving rise to Y having a determinate value v of an observable O of Y at *t*', *is for X to decohere Y at t*'. *In the situations that we will be concerned with here, observable O of Y that is monitored by X when they start interacting has to approximately commute with the reduced density operator of Y*, which is a *consequence of the decoherence of Y by X at t*', *and where the eigenvalues of O include v.*[13]

Note that

Times such as t' *above or time intervals around t*′ *from now on will be represented and inferred via the time that the overlap terms above go quasi-irreversibly to zero under decoherence, being used to infer the time decoherence takes.*

Furthermore, since we aim for a local non-relational theory (more on this below),

A determinate value of a system Y arises indeterministically in the above decohering interaction with a system X that has the DC with probabilities given by the Born rule, and where having such values is absolute/non-relational.

I will now turn to the *stability conditions*. The stability conditions establish what it takes for a system to have a determinate value and transmit the DC to others, and how the former and the later are related. These conditions are also the conditions to belong to or form an SDC. SDCs are represented by networks representing the propagation of the DC, which gives rise to systems that belong to it having determinate values. It's a chain because the DC propagates between systems via a chain of interactions, as we will see more clearly below.

I will essentially stipulate one possible condition, called the relativistic condition, which involves different sub-conditions. As I have explained in section 1, we want to use decohering interactions to establish when systems have determinate values, where the environment is constituted by systems that have themselves been subject to decoherence. However, there is the risk of an infinite regress and vagueness. Also, we want to achieve LC), which includes EnDQT to be local. So, the heuristic that aided the

[13] 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 it is considered that the decoherence of the momentum is indirect.

stipulation of these conditions was providing a precise, simple, local, empirically plausible, and infinite regress stopping criteria for when a system can have and transmit the DC, where having the DC depends on other systems of the network. An example at the end of the next section will make the conditions clearer.

I propose two kinds of systems that constitute an SDC, which are individuated by how they have the DC. The first kind consists of initiator systems or initiators, where

RC1) Initiators are systems that have the DC independently of the interactions with other systems (initiator condition).

So, the decoherence of some system S by an initiator is necessary and sufficient to allow that later system to have a determinate value of some observable O of S. Since they have the DC by default, they can start the SDCs. The second kind of system consists of non-initiator systems, which are all other systems in the SDCs, where

RC2) Non-initiator systems are systems where having the DC depends on having interacted with other systems that have the DC (non-initiator condition).

The SDCs are represented by Direct Acyclic Graphs (DAGs, i.e., directed graphs with no cycles) and represent the propagation of the DC. So, DAGs represent the interactions between systems that allow them to have determinate values and to provide the DC to other systems that might result in them having determinate values and transmitting the DC to other systems, and where this propagation starts with the initiators. The nodes represent the systems that are involved in these interactions and the edges represent these interactions. In some DAGs that aim to depict the whole situation, the systems with only directed arrows towards them represent systems that have the DC but won't end up transmitting it to other systems. An SDC ends when it reaches these systems. The nodes with no directed arrows towards them represent the initiators. Why do we have acyclic relations, represented by DAGs, and not cyclic ones in space and over time? Because a system Y that is receiving the DC from system X cannot transmit to X the DC. For simplicity, here I will mostly not care about the distinction between a token network, which represents concrete interactions between systems and type networks, which represent interactions between types of systems that exist in specific regions of spacetime.

So, according to the relativistic condition, SDCs, which start with initiators, propagate the DC *over time* by having systems that interacted with initiators and by other systems that interacted with the former systems and so on. To further explain this condition, let's consider the following DAG representing an SDC:

$$S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4 \rightarrow \cdots, \tag{5}$$

where S_1 is an initiator. Or

$$\ldots \rightarrow S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4 \rightarrow \cdots, \tag{6}$$

if S_1 is not an initiator but has the DC.

The following conditions pose a series of timing constraints,

RC3) A system S_2 can only end up transmitting to a system S_3 the DC, if S_3 interacts with S_2 while S_2 is interacting with a system S_1. So, if S_3 interacted with S_2 after S_2 had a determinate value due to S_1 (i.e., after their interaction has ended), S_2 could not end up transmitting the DC to S_3 (timing constraints on the propagation of the DC).

RC4) Assuming that a system S_1, which has the DC, gives rise to a system S_2 having a determinate value, S_2 can have other determinate values while interacting with other system even after the interactions with S_1 ends, if, while it interacts with S_1, a system S_3 interacts with S_2. These values will now be the ones that are influenced by the interactions with S_3, due to the decoherence of S_3 by S_2. A system S_2 can have a determinate value due to S_3 until the interaction with S_3 ends (timing constraints on having determinate values).

If it helps, think about the RC1) as analogous to the condition for transmitting a virus where the virus is analogous to the DC. Think about RC2) as analogous to the condition of continuing to have the virus. A person having a virus lasts (let's assume) for a particular amount of time. Similarly, S_2 being able to have a determinate value lasts until S_3 has a determinate value due to the decoherence of S_3 by S_2. The originators of the virus would be the initiators.

The relativistic subconditions above are still incomplete because they don't specify precisely the observables involved in transmitting the DC, or their relations with determinate values. To fulfill this gap, I will add the following condition, which involves two subconditions,

RC5) i) The observable O of a system S_2, which a system S_1 with the DC is monitoring when S_1 is transmitting the DC to S_2, should be involved in monitoring the observable O' of S_3, in order for S_2 to acquire the DC due to S_1 and transmit it to S_3. By "an observable O of S_2 being monitored by S_1 with the DC," I mean that the eigenstates of the observable O of S_2[14] are being in the process of being decohered by S_1. Furthermore, what I mean by "[t]he observable O of a system S_2 (...) should be involved in monitoring the observable O' of S_3, in order for S_2 to transmit the DC to S_3" is that the states that evolve from the eigenstates of O of S_2, under interactions between S_2 and S_3, should be the ones that are involved in the process of decoherence of the eigenstates of O' of S_3 in order for S_2 to transmit the DC to S_3. ii) Furthermore, given RC4), I will consider that when the interactions between S_3 and S_2 ends, S_2 will also have a determinate value. The possible determinate values of S_2 will be represented by the eigenvalues of the observables that act on the states that evolve from the eigenstates of O of S_2 (observables condition).

RC4) and RC5-ii) are based on the fact that is plausible to consider that distinguishability of a system by its environment in decohering processes involves the environment having a determinate value too, even if full distinguishability/decoherence isn't achieved.

RC1)-RC5) contain an ambiguity: can a system like S_2 give rise to S_3 having a determinate value and the DC *only when* S_2 has a determinate value due to S_1 or not? To address this ambiguity, the simplest option is to consider that transmitting the DC and having a determinate value is aligned. So, I will add the condition RC6),

RC6) Initiator systems don't need to have a determinate value to transmit the DC. Non-initiator systems need to have a determinate value due to a system to have the DC due to that system, and thus be able to transmit it to other systems. So, a system S_2

[14] Or, the states whose projectors onto them approximately commutes with O.

interacting with S_3 gives rise to system S_3 having the DC and a determinate value (given RC5), being S_3 capable of also having it afterwards in the interaction with S_4), only when S_2 interacted with S_1 and had a determinate value due to S_1, and so on for the systems that will interact with S_3, etc. More concretely, given RC5), in order for S_2 to have the DC due to S_3 — leading the states that evolve from the eigenstates of an observable O of S_2, which upon decohering (completely) certain states of S_3 at t, give rise to S_3 having a determinate value under their interaction — the eigenstates of O of S_2 should be decohered by S_1 at t' where $t' < t$, and where S_1 gives rise to S_2 having a determinate value (symptomatic spreading constraint).

So, condition RC6) requires that S_2 is decohered by S_1 when it decoheres S_3 in order for S_2 to allow S_3 to have determinate values and the DC.[15] If that doesn't happen, this SDC will disappear, and it had just two elements, S_1 and S_2. The condition RC6) is also plausible to impose because it makes sense to think that the environment has having a determinate value in order to decohere/distinguish the states of its target system. I will go back to the consequences of condition RC6) below.

For reasons of simplicity and due to their privileged status, we can consider that initiator systems don't need to have a determinate value to transmit the DC, not even during the interaction. However, another possibility is that they have determinate values just while interacting with other systems, where those values will be associated with the eigenstates of the initiators that decohere these systems. I think both options are empirically open, and it will depend on what kind of initiators we adopt. Perhaps, this question doesn't even matter (more on this below).[16]

RC1)-RC6) lead to the full statement of the relativistic condition and allow us to draw an analogy between the spreading of the DC via SDCs and the spreading of a virus without asymptomatic spreaders. Someone spreads this virus only when they have

[15] Another possibility is that a system can have the DC without having a determinate value. This can give rise to a system S having a determinate value, without first being decohered qua disentangled from other system S', having a determinate value due to S', where S' doesn't yet have a determinate in interactions with other system. The problem of this condition is that it will be troubling to use decoherence as a criterion for systems to have a determinate value. For instance, we could have a situation where A, B, and C are interacting, and we let A decohere B, and C be decohered by A where both could occur in an arbitrary order so that determinate values arise, since B could decohere C without having itself being decohered/disentangled from A. However, if we let that happen, we will face complications due to the entanglement monogamy (Coffman et al., 2000). This is because the *maximal* entanglement between two systems giving rise to decoherence, would constrain their entanglement with a third system, and thus they won't be able to decohere this third system (Dawson et al., 2005). So, we wouldn't be able to simply use decoherence on both ongoing interactions to determine if systems have a determinate value. This is unlike the simpler cases that RC1)-RC6) lead to. In these cases, A has to decohere first B and a determinate value has to arise, "disentangling both," in order for B to decohere C, and give rise to C having a determinate value.
[16] Initiators might not even exist as systems, but just as events that give rise to a system having a determinate value.

symptoms of it. Analogously, system S_2 gives rise to S_3 having determinate values only when it has determinate values due to S_1.

Let's understand better the relativistic condition by seeing how we could model the formation of an SDC obeying it. In the example I will provide, I will adopt the following conventions. When I place a subscript SDC in the quantum states of a system S, I will mean that the system has the DC, either because it's an initiator, or non-initiators that interacted with other systems that allowed it to have the DC. Systems S' with quantum states sharing an index or label (by convention) with the appropriate quantum states of S, will also have the DC. The same with the quantum states of the systems sharing an index or label with the above quantum states of S', and so on.

Let's consider a simple and idealized example where we can neglect the intrinsic evolution of the systems. This example will involve systems A, B, and C, where A is an initiator, in a toy mini universe where the SDC that will be formed has the following structure, $A \rightarrow B \rightarrow C$. Let's assume that C interacts with B while B is interacting with A, where the interactions between A and B started first.

However, for the sake of simplicity, let's assume that when B and C start interacting, the change of the quantum states of B due to C is negligible, while A and B are still interacting, in such a way that we can consider that the interaction of B and C starts when the one between A and B ends. Thus, we can just analyze the evolution of the quantum states of A while A and B are interacting, where this interaction ends approximately at t'. We have then the following interaction between A and B,

$$\begin{gathered} |E_{ready} >_{A\,SDC} \ (\alpha'|E_0' >_B + \beta'|E_1' >_B)\,(\alpha|\uparrow>_C + \beta|\downarrow>_C) \rightarrow_{t'} \\ (|E_0(t') >_{A\,SDC} \ |E_0' >_B + |E_1(t') >_{A\,SDC} |E_1' >_B)(\alpha|\uparrow>_C + \beta|\downarrow>_C). \end{gathered} \tag{7}$$

If $< E_0(t')|E_1(t') >_{A\,SDC} \approx 0$ and $< E_1(t')|E_0(t') >_{A\,SDC} \approx 0$ quasi-irreversibly when A and B end their interaction, B has a determinate value of the observable monitored by A at t'that arises from their interaction (i.e., 0 or 1), and acquires the DC. Let's assume that B has a determinate value 0. Now, let's consider the interaction between B and C, which (given our idealization) starts when the interaction between A and B ends. Let's assume that it ends at t'',

$$|E_0(t') >_{A\,SDC} \ |E_0'^{\uparrow}(t'') >_B |\uparrow>_C + \tag{8}$$

$$|E_0(t') >_{A\,SDC}\ \ |E_0'^{\downarrow}(t'') >_B |\downarrow>_C.$$

The evolution of the interaction between B and C could be analyzed via the reduced density operator $\rho_C(t)$. The interaction between B and C will allow C to have a determinate value (↑ or ↓) at t'' and the DC if $< E_0'^{\uparrow}(t'')|E_0'^{\downarrow}(t'') >_B \approx 0$ and $< E_0'^{\downarrow}(t'')|E_0'^{\uparrow}(t'') >_B \approx 0$ quasi-irreversibly when B and C end their interaction. Also (given RC4) and RC5-ii)), B will have a determinate value at t'' that arises from its interaction with C (where the possible values that it can have are represented via the eigenvalues of $|E_0'^{\uparrow}(t'') >_B$ and $|E_0'^{\downarrow}(t'') >_B$). Furthermore, C could transmit the DC to another system of that universe if it interacted with it before the interaction with B ends.

Note that since system A is an initiator, its ability to give rise to other systems having determinate values and provide the DC doesn't depend on the interactions with other systems. However, this example wouldn’t significantly change if A was a non-initiator. We would just assume that A has the DC thanks to other systems.

Three things to notice. First, we can see that EnDQT provides a new interpretation of Born probabilities. They allow us to predict how SDCs evolve.

Second, in decoherence models, the environment of a system is often composed of many subsystems. In that case, it’s more realistic to assume that

In order for systems to have the DC, transmitting it to other systems via local interactions, its subsystems involved in those interactions have to have the DC. So, in order for a system, such as S_2 composed of subsystems $S_2^1, S_2^2, \dots, S_2^n$, to have the DC, transmitting it to S_3, $S_2^1, S_2^2, \dots, S_2^n$ have to have the DC due to the local interactions with some other system S_1 or its subsystems. The states of $S_2^1, S_2^2, \dots, S_2^n$ that are decohered by S_1 compose in the usual way to, under their evolution, give rise to the states of S_2 that decohere S_3 (value-mereology assumption).

If we also assume this condition, we will have slightly different conditions that also take into account the existence of subsystems of systems having the DC. For instance, let’s consider that instead of S_2 above, we also have subsystems S_2^i for some i of S_2 where S_2^i is not able to decohere S_3 alone, but S_2 is. S_2 would just be able to give rise to S_3 having a determinate value, having the DC, if its subsystems S_2^i for all i

interacted with subsystems of S_1, acquiring the DC, where S_1 and its subsystems have the DC.

Subsystems of a system, such as S_2^i for all i, may be spacelike separated from each other and are considered to form a "cause" for the "common effect," which is a system having a determinate value of a particular observable, such as an observable of S_3. This forms a DAG with "colliders" (Figure 1)

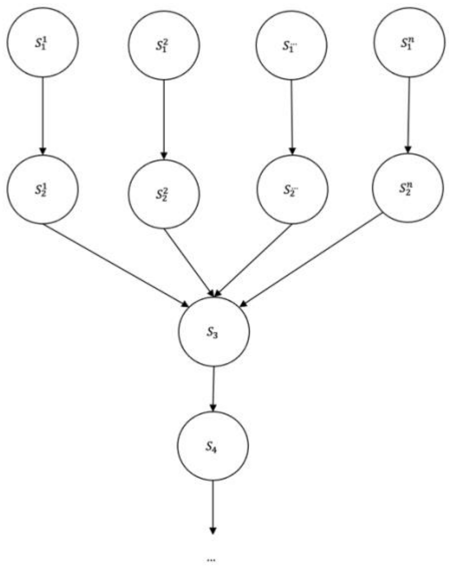

Figure 1: DAG that involves a common effect (i.e., a "collider").

We can also treat the structure of the following DAG as also involving a *common cause* if we treat S_1 as a whole, neglecting its subsystems (Figure 2).

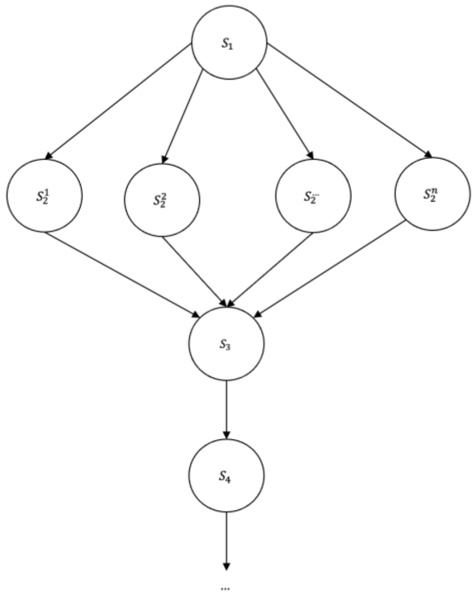

Figure 2: DAG that involves a common cause and a common effect.

From now on, I will presuppose the plausible value-mereology assumption. Although one might challenge it and bring other more sophisticated or realistic value-mereology-like assumptions, I don't think they can affect the core of EnDQT.

Third, given the above stability conditions, note that a system whose quantum state is in an eigenstate of some observable doesn't have a determinate value if it's not having a decohering interaction with systems that belong to an SDC. This assumption contradicts both directions of the famous Eigenstate-Eigenvalue 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.[17]

I have been relying on decoherence to give an account of how determinate values arise via SDCs, but something more needs to be said about their behavior. I will further postulate some natural hypotheses about the structure of SDCs to fulfill the goal of achieving UT), LC), and NR). The first hypothesis should explain the success of the models of irreversible process of decoherence in helping account for determinate values arising via SDCs.[18] Thus, I will pose that the SDCs are widespread in such a way that

[17] See appendix A for a response to an objection regarding EnDQT's denial of this link.

[18] The irreversible process of decoherence should be distinguished from the reversible/virtual one, which is not considered to be decoherence at all.

The irreversible process of decoherence tracks the interactions between systems that belong to SDCs (SDCs-decoherence-hypothesis).

Another important aspect is to specify when do we expect the SDCs to start. The heuristic to establish when SDCs start aims to fulfill the following desideratum: SDCs should help explain the widespread success of some aspects of classical physics in accounting for diverse phenomena in certain contexts, where classical physics is based on systems represented by variables that assume determinate values. According to our current best science, classical physics is accepted to apply in a specific domain, even at the beginning of the universe. Even models of inflationary cosmology appeal to classical physics. So, it's plausible to consider that SDCs started via initiators that are already present in the early universe,

SDCs started at least in the early universe (SDCs-starting-hypothesis).

It is also advantageous to consider that initiators and initiative events are in the early universe because, according to the standard view, special events are expected at this stage.

Finally, we need to specify what initiators are. This is important because there are conceivable universes with abundant initiators that would very likely lead us to lose the ability to unitarily control quantum systems, i.e., universes where we would very likely lose the ability to place arbitrary target systems in a superposition of states for an arbitrary time. These would be universes where we would very likely end up isolating our target systems with the initiators. This loss of control would arise because initiators don't depend on other systems in order to have the DC and give rise to determinate values, generating multiple chains inside an *isolated* region, and more stochastic processes. Also, if initiators were abundant, this gives rise to a mysterious dualism involving initiators and non-initiators.

Fortunately, the *SDCs-starting-hypothesis* already places initiators in a region where it's unlikely that they would be manipulated and isolated with other systems, and so those worries are diminished. But this doesn't solve the above dualistic worry, since initiators may still exist somewhere. In order to diminish this worry further, we may consider initiators as manifesting themselves rarely. However, initiators may also simply don't exist or manifest themselves anymore to start SDCs, for example, existing or interacting/manifesting themselves only in the past initial conditions. They might have been just systems involved in a fluctuation of a primordial quantum field, which gave rise to sufficient SDCs to spread determinacy throughout our universe, or something else. Let's call these special events, *initiative events*. The challenge of this option is explaining why initiators shouldn't reappear, or these events shouldn't occur again. Relatedly, they may just be a *useful fiction* that is used to represent the first system or systems with determinate values and the DC, and which are involved in the *initiative event(s)*. I will, therefore, pose the following hypotheses,

Initiators are either i) rare, ii) don't exist or manifest themselves anymore to start SDCs, or iii) they are a useful fiction that is used to represent the first events involving systems with determinate values and the DC (SDCs-initiators-hypothesis).

It's an empirical matter to know which one of these hypotheses is correct. I find them the most plausible, but I am not strongly committed to any of them, and other ones are possible. We are still in the early stages to say something very substantive about initiators, but we should start thinking about empirical signatures of their existence.

For instance, the existence of either one or much more than one initiator may have consequences. Suppose we have only one initiator, unless it's at the *center* of the universe, we may have an anisotropy in the distribution and evolution of determinate values in the universe (because determinate values will arise more likely in one region than the other).[19] More than one initiator may fix this asymmetry.

We can also develop heuristics to establish which systems are initiators or initiative events. A possible one is looking at the earliest systems that gave rise to the decoherence of other systems in the early universe. For instance, it is hypothesized that all structures in the universe can be traced back to primordial fluctuations during an accelerated (inflationary) phase of the very early universe. Certain models of decoherence were devised to account for the decoherence of these cosmological fluctuations.[20] The systems implicated in this decoherence may be the initiators, or the events underlying this process may be the initiative events. Furthermore, they may allow us to explain the transition from a symmetric quantum state to a (basically

[19] It would be interesting to explore this topic further.
[20] E.g., Kiefer & Polarski (2009).

classical) non-symmetric state, which can be used to explain the quantum origin of cosmic structure.[21]

I will end this section by mentioning two predictions of EnDQT. The first prediction is the following, as we can see via the above example, in order for a system (like C above) to continue having determinate values of an observable and giving rise to other systems having the DC and having determinate values, interactions of the above kind should proceed at other times, i.e., C has to interact with other systems while interacting with B. This leads EnDQT to predict a phenomenon that I will call the *dissolution of an SDC*. If, during the evolution of an SDC, no system interacts with the system like C that is leading the expansion of that SDC, that SDC will disappear, not being able to give rise to further determinate values.[22]

Second, as we have also seen with the example above, adopting the relativistic condition generates constraints on how SDCs are formed, and with these constraints, new predictions. Decoherence timescales roughly serve as an indicator for the timescale it takes for environments of a system to decohere that system, where that system ends up having specific determinate values (that are observed in the lab). Condition RC6) predicts that the decoherence timescale that we empirically observe of a kind of system Z by a kind of system Y should be superior or of the same order as the decoherence timescale of Y by a kind of system X, where Y is typically decohered by X before Y decoheres Z, and where the interaction between X and Y starts first. Otherwise, contrary to what is assumed by RC6), we can have situations where Z will have a determinate value first (due to Y), then Y will a determinate value due to X. Since the decoherence timescales are typically empirically determined, a further analysis of the current empirically determined decoherence timescales is needed to see if they agree with the predictions of condition RC6).

The predictions of this condition are empirically supported in the case Y are macrosystems (e.g., measurement devices), and Z are microsystems. This is because macroscopic systems have decoherence timescales much shorter than the microscopic systems that they can decohere.[23] Furthermore, the conditions for a quantum system to

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[21] See, e.g., Perez et al. (2006).

[22] Note that a system like C may also continue having determinate values if the eigenstates of O of C are decohered by other system that belongs to another SDC that is expanding.

[23] The cross section for larger systems is larger than the one for a smaller system. Moreover, the decoherence rate of a quantum system, which is the inverse of the decoherence timescale, is proportional to their cross-section, as well as the flux of systems of the environment. See the collisional models of decoherence in, e.g., Joos & Zeh (1985), Kiefer & Joos (1999), and references therein.

be considered a classical controller of another quantum system support condition RC6).[24] So, so far, the relativistic condition seems to be favored. It would be interesting if we find further evidence for or against it.

As we can see, EnDQT is able to achieve UT), not modifying the fundamental equations of QT. It only used decoherence to assign determinate values to a system and the SDCs, whose description appeals to such equations. Furthermore, arbitrary systems can be placed in a superposition for an arbitrary time duration as long as they don't interact with members of an SDC.

3. Why EnD Quantum Theory is local?

In this section, I will argue that EnDQT achieves LC) and NR) by showing how it provides a local common cause explanation of quantum/Bell-type correlations and without adopting the non-local/action at a distance, relational, or superdeterministic/retrocausal strategies.

First, like in standard QT, the Hamiltonians of interaction (should) represent local interactions. Second, EnDQT doesn't modify the equations of QT, and so it can be rendered Lorentz-invariant, and thus it can be rendered compatible with relativity in this sense. Third, EnDQT deals with the EPR-Bell scenarios without violating relativistic causality, i.e., without forcing us to assume that the causes of correlations travel at a speed faster than the speed of light (i.e., the causes of events are always in their past lightcone), and it does that also by providing a local common cause explanation of quantum correlations. Let's see how.[25]

A widely accepted version of Bell's theorem involves, together with the no-superdeterminism assumption[26], the factorizability condition,

$$P(AB|XY\Lambda) = P(A|X\Lambda)P(B|Y\Lambda). \tag{9}$$

The variables A, B, **Λ**, 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. **Λ**

[24] See Milburn (2012).
[25] Future work will enter into more details about this strategy (Pipa, forthcoming-b).
[26] This assumption states that any events on a space-like hypersurface SH can be considered to be uncorrelated with any set of interventions subsequent to SH.

represents some set of (classical) "hidden" variables in the past lightcone of A and B (see also Figure 3), representing the common causes of the correlations between X and Y.

This condition is seen as a consequence of two assumptions:[27]

-The causes of an event are in its past lightcone,

-The (what I will call) classical Reichenbach's 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 **Λ**, where conditioning **Λ**, A and B are decorrelated, i.e., $P(A, B|\, \boldsymbol{\Lambda}) = P(A|\, \boldsymbol{\Lambda})P(B|\, \boldsymbol{\Lambda})$. However, it's unclear that we should accept that these probabilistic relations and condition given by the CRCCP should in general represent a causal structure involving quantum systems, given the exotic features of the latter. The CRCCP can be seen as a consequence of Classical Markov Condition (CMC), assumed by classical causal models (CCMs).[28]

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 $\boldsymbol{V} = \{X_1, \dots, X_n\}$. A joint probability distribution $P(X_1, \dots, X_n)$ is *classical Markov* with respect to G if and only if it satisfies the following condition: for all distinct variables in $\boldsymbol{V}, P$ over these variables factorizes as $P(X_1, \dots, X_n) = \prod_j P\left(X_j \middle| Pa(X_j)\right)$, where $Pa(X_j)$ are the "parent nodes" of X_j, i.e., the nodes whose arrows from these nodes point to X_j.

[27] Bell (1976, 1981, 1990, 2004) See also, e.g., Myrvold et al. (2021) and references therein.
[28] We will not derive it here, but see Hitchcock & Rédei (2021).

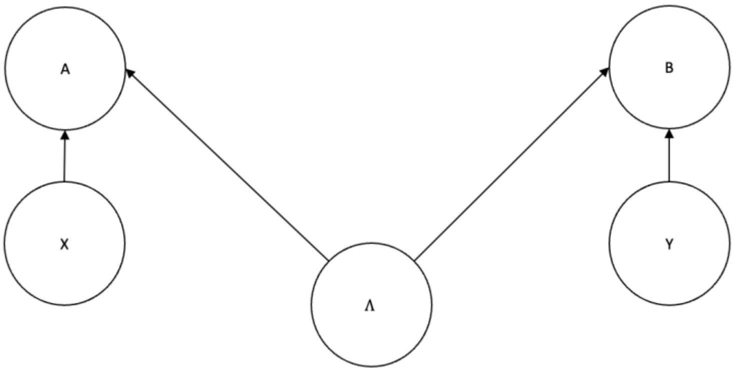

Figure 3: DAG of the common cause structure of Bell correlations, which respects relativity. This causal structure respects relativistic causality because X or A doesn't influence Y or B, and vice-versa, where these events may be spacelike separated. Moreover, no other variables influence the variables A, B, X, or Y, or they don't influence anything else. So, there are no retrocausal or superdeterministic causal relations.

The CMC for the above DAG, 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),

$$P(AB|XY) = \sum_{\Lambda} P(\Lambda)\mathrm{P}(\mathrm{A}|\mathrm{X}\Lambda)\mathrm{P}(\mathrm{B}|\mathrm{Y}\Lambda). \quad (10)$$

The acceptability of the CRCCP can be supported by the empirical success of the application of the CMC via CCMs (e.g., Pearl, 2009).[29] EnDQT responds to Bell's theorem by rejecting that the CMC can be applied in general to accurately represent causal relations between quantum systems, and hence it rejects the applicability of the CRCCP and the factorizability condition to make such accurate representation.[30]

There are at least two complementary ways of justifying the rejection of the CMC. One way is by looking at a precise justification of the CMC involving structural equations: they involve relationships between endogenous variables V_j (i.e., variables whose values are determined by other variables in the model) that depend on their endogenous parent variables $Pa(V_j)$ plus exogenous variables U_j (i.e., variables whose

[29] There is also a way of deriving the factorizability condition, as well as the non-superdeterminism condition directly from CCMs and the CMC. See Khanna et al. (2023).

[30] So, note that EnDQT also rejects outcome independence and parameter independence that can be used to derive factorizability condition (Jarrett, 1984) by rejecting their applicability to represent causal relations between quantum systems.

values are determined from outside the model) establishing a directed deterministic relationship $V_j = f(Pa(V_j), U_j)$. Pearl and Verma (1995) proved that if we have a DAG G' representing the causal structure on V_j , the probability distribution $P(V_j)$ that results from the marginalization of the noise sources, if U_i are probabilistically independent in P, $P(V_j)$ will respect the CMC concerning G'.[31]

The above justification invokes features rejected by EnDQT. First, the systems assumed by these equations have in general determinate values in the sense of not having indeterminate ones represented by QT such as via subsystems of entangled states. Second, the origin of the probabilities of the CMC is in the ignorance about some underlying determinate values. Furthermore, note that, according to EnDQT, these systems with quantum indeterminate values according to EnDQT that travel to each wing don't even have a probabilistic model independently of the measurements of Alice or Bob. So, we can't have a probability over the common causes independently of their interactions, as it's assumed by this proof. Third, the causal relations between systems aren't described QT. More precisely, they don't involve unitary evolutions, decoherence, and quantum indeterministic processes.

We could assign a determinate value to the whole state $|\Psi>$ of the entangled systems that would correspond to the eigenvalues of the observable that this state is an eigenstate of. However, Alice and Bob rather act on the subsystems of these systems. So, we should consider that it is not the whole state $|\Psi>$ that determines the outcomes, but its subsystems. Each subsystem of this entangled state influences locally the outcomes of Alice and Bob, and there is no way to assign a determinate value to each subsystem.

There are at least two possible objections to this justification of the rejection of the CMC. First, there could be some other justification to the CMC that doesn't assume determinate values, but quantum indeterminate ones, although it's difficult see which one that would be. Second, this justification makes unclear whether a causal explanation of quantum correlations can be provided, and this deficiency could press us to reject other assumptions instead of the CRCCP.

However, we can go further in terms of presenting evidence for why CCMs are inappropriate and justify the rejection of the CMC that improves over the above one. A way of finding the limitations of the domain of applicability of the CCMs is by

[31] See, e.g., Pearl (2009), Pearl & Verma (1995), and Hitchcock (2022).

examining the more general models that putatively represent causal relations in the quantum domain, i.e., quantum causal models (QCMs).[32] I will analyze how QCMs make certain assumptions that CCMs don't make, and that that these assumptions concern the quantum domain according to EnDQT. QCMs are in principle more general because they reduce to classical ones in a certain "classical limit." Like we found what is wrong with classical mechanics when we examine 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.

As I will explain, QCMs will have the role of showing how EnDQT provides a local causal explanation of Bell-type correlations. Note that QCMs currently are only formulated for finite dimensional Hilbert spaces. However, this isn't a fundamental limitation. I will thus pose the following argument,

P-1) QCMs, which assume the *quantum* Markov condition (QMC) that is a modification and generalization of the classical one, according to EnDQT, explain locally Bell-type/quantum correlations.

P-2) Quantum causal models interpreted by EnDQT explicitly consider that systems that participate in those causal relations i) can assume indeterminate values represented via QT, ii) only assuming determinate values when they interact with an SDC, and iii) where those relations are described via QT. i)-iii) are appropriate assumptions for EnDQT.

P-3) On the other hand, CCMs and the CMC, which arise in a certain limit from QCMs (Barrett et al., 2020), don't make in general the same EnDQT-appropriate assumptions as QCMs.

C) Hence, according to EnDQT, CCMs, with its CMC, are inappropriate to provide an account of quantum causal relations contrary to QCMs. The latter provides an appropriate causal explanation of Bell correlations, which is local.

Let's turn to the justification of P1). QCMs consider that each node in the causal DAG concerns a possible locus of interventions on the properties of a system. More concretely, each node is associated with a set of CP (completely positive) maps

[32] Costa & Shrapnel (2016), Allen et al. (2017), and Barrett et al. (2019).

$\tau_{A_1}^{k_{A_1}|x_{A_1}} \otimes ... \otimes \tau_{A_n}^{k_{A_n}|x_{A_n}}$,[33] also called quantum instruments, instead of random variables as in the CCMs case. This set gives the "possibility space" that can be associated with the different ways the properties of a system with its quantum state can change under local interventions x, which correspond to the preparation of quantum systems, transformations, measurements on them, etc., each leading to different outcomes k.

The QMC is defined through the causal DAG where the edges of the DAG are associated with quantum channels/completely positive trace-preserving (CPTP) maps.[34] Examples of a quantum channel are unitary maps, evolution of the system with noise, etc.[35] Both CP and CPTP maps are written as positive semi-definite operators via the Choi-Jamiolkowski (CJ)-isomorphism.[36]

The QMC representing a certain causal structure, held fixed, is written via the process operator σ, which is a CPTP map, and factorizes analogously to the CMC. More precisely, a process operator $\sigma_{A_1, ..., A_n}$ is compatible with a DAG G with nodes $A_1, ..., A_n$, if and only if it obeys the quantum Markov condition (QMC, Barrett et al., 2019) where this condition says for all i, l in the DAG G there are quantum channels such that $[\rho_{A_i|Pa(A_i)}, \rho_{A_l|Pa(A_l)}] = 0$, and

$$\sigma_{A_1, ..., A_n} = \prod_i \rho_{A_i|Pa(A_i)}. \quad (11)$$

We need to have $[\rho_{A_i|Pa(A_i)}, \rho_{A_l|Pa(A_l)}] = 0$ because the product of two positive operators is positive if and only if they commute. $\sigma_{A_1, ..., A_n}$ factorize analogously to conditional probabilities in the CMC.

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[33] A quantum channel is a linear map ε that is a completely positive trace preserving (CPTP) map. A map is a CPTP map if: a) it is trace preserving, i.e., $Tr(\rho) = Tr(\varepsilon(\rho))$ for all density operators ρ, b) positive, i.e., ε(ρ) ≥ 0 whenever the density operator ρ ≥ 0, and c) completely positive. When only b) and c) are fulfilled, we have a completely positive (CP) map rather than a CPTP map. A CP-map can be associated with a positive operator-valued measure (POVM). See Nielsen & Chuang (2011).

[34] See previous footnote.

[35] Each (quantum) node A_i is associated with an income Hilbert space $\mathcal{H}_{A_i^{input}}$, which I will write as A_i^{input}, and an output Hilbert space $\mathcal{H}_{A_i^{output}}$, corresponding to the incoming and outgoing system, which I will write as A_i^{output}, and each edge is associated with an output Hilbert space of one node and the input Hilbert space of another node. Note that the CPTP map are written as $\rho_{A_j|A_i} = \rho_{A_j^{input}|A_i^{output}}$ via the CJ isomorphism. When it is written $\rho_{B|DA}\, \rho_{C|AE}$, what is meant is that $\rho_{B|DA}\, \rho_{C|AE} = \rho_{B|DA} \otimes \rho_{C|AE} = (\rho_{B|DA} \otimes I_{E^{output}} \otimes I_{C^{input}})(\rho_{C|AE} \otimes I_{B^{input}} \otimes I_{D^{output}})$, where X^{input} and X^{output} is the inputs and outputs of node X. Moreover, $Tr_A \rho_{AB|C} = \rho_{B|C}$ and $Tr_B \rho_{AB|C} = \rho_{A|C}$.

[36] See, e.g., Barrett et al. (2019).

A version of the Born rule allow us to represent the overall causal structure, which also involves certain measurements on the nodes $A_1, \dots, A_n$ with outcomes $k_{A_1}, \dots, k_{A_n}$, given interventions $x_{A_1}, \dots, x_{A_n}$,

$$P\left(k_{A_1}, \dots, k_{A_n} | x_{A_1}, \dots, x_{A_n}\right) = Tr_{A_1,\dots,A_n}[\sigma_{A_1,\dots,A_n} \tau_{A_1}^{k_{A_1}|x_{A_1}\,SDC} \otimes \dots \otimes \tau_{A_n}^{k_{A_n}|x_{A_n}\,SDC}]. \quad (12)$$

One obstacle that QCMs have to provide a local causal explanation of Bell correlations is their operationalism. Causal influences are typically understood by the possibility of "signaling" from one node to another.[37] The causal structure represented by QCMs represents the constraints on these signaling relations. So, node X cannot signal to node Y if and only if node X doesn't precede node Y in the graph. Signaling between node X and node Y should be understood as occurring when a variation in the choice of certain instruments/interventions performed at node X can vary the probabilities of an outcome k concerning measurements performed at node Y.

One may worry that, like in other quantum theories such as Bohmian mechanics,[38] although there isn't signaling, we still have non-local influences, and QCMs are hiding such influences. If we adopt EnDQT, which doesn't consider that there are hidden non-local influences that cannot be used for signaling, we don't need to have this worry. This is because SDCs are necessarily involved in the influences that give rise to determinate values and they are local (see previous section). Furthermore, using the concept of signaling and an operationalist language is unnecessary, and we don't need to adopt an account where signaling or causation is irreducible. We can rather consider that systems in a region *influence* the determinate value of certain systems in another region, where such influences are modally described/governed by QT, and QCMs allow us to represent and infer those influences.

Let's see how adopting the point of view of EnDQT, QCMs provide a local causal (non-relationalist, non-retrocausal, and non-superdeterministic)[39] common cause explanation of quantum correlations. Now, A, B, and Λ, represent spacetime regions, instead of classical variables. Consider below how, via the QMC and a version of the Born rule, we can represent the local common cause structure that explains Bell correlations (Figure 4),

[37] When all the relevant systems participating in causal relations are included (Barrett et al., 2019).
[38] See, e.g., Goldstein (2021).
[39] See Wood & Spekkens (2015) for examples of non-local, superdeterministic, and retrocausal causal structures.

$$P(x,y|s,t) = Tr_{\Lambda AB}\left(\rho_\Lambda \rho_{A|\Lambda} \rho_{B|\Lambda} \tau_A^{x|s\,SDC} \otimes \tau_B^{y|t\,SDC}\right). \tag{13}$$

The systems prepared at the source act as common causes for Bell correlations, having indeterminate values until each system interacts with Alice and Bob's measurement devices, giving rise to the correlated outcomes. ρ_Λ via its subsystems represents the systems prepared at the source, which for example could be systems that have indeterminate values of spin-p (p ranges over all possible directions of spin). We use ρ_Λ to represent each system in the different regions *separately* by keeping track of the labels A and B and the channels $\rho_{B|\Lambda}$ and $\rho_{A|\Lambda}$. Each system evolves locally to region A/B, where Alice/Bob influences the outcomes that arise in A/B. This influence is represented via the quantum channel $\rho_{A|\Lambda}$ in the case of A, and $\rho_{B|\Lambda}$ in the case of B. $\rho_{A|\Lambda}$ and $\rho_{B|\Lambda}$ are identity channels that acting on the density operator ρ_Λ representing the systems in region Λ, *evolve* them to regions A and B, respectively. The influence on the outcomes is also represented via the POVMs $\tau_A^{x|s\,SDC}$ in the case of Alice, where s is her random measurement choice, and x is her outcome/the determinate value of S, and analogously via $\tau_B^{y|t\,SDC}$ in the case of Bob. The superscript SDC means that these are interventions that give rise to a determinate value, connecting systems with an SDC, and correspond to other kinds of edges in the DAG in the Figure 4. Alice and Bob due to their measurements will lead the systems to become part of an SDC because they also belong to SDCs.

So, with the above account EnDQT allows QCMs to be explicitly local and non-operational, where the local interactions at each wing are mediated by the SDCs, and these interactions plus the prepared systems at the source, provide a local non-relational common cause explanation of quantum correlations.

Note that by adopting EnDQT's view of quantum states, it isn't considered that the (local) measurement of Alice on the system affects the system of Bob and Bob, and vice-versa. We aren't reifying quantum states. We can represent this situation via the following *EnDQT-causal-DAG*, where in grey, we represent the systems that don't belong to an SDC and their evolution, and in black the systems that belong to an SDC and their evolution/interactions:

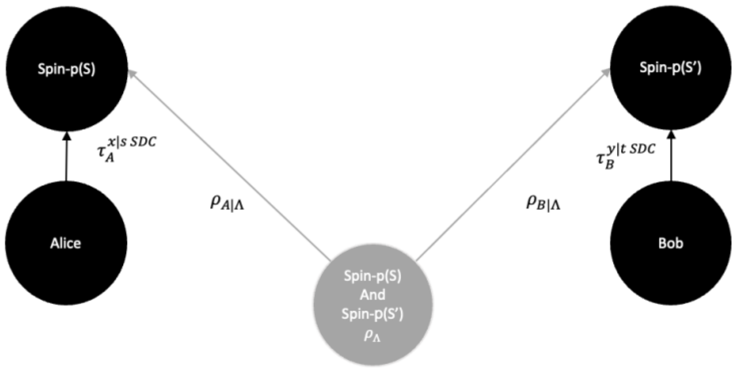

Figure 4: *EnDQT-causal-DAG* of the common cause structure of Bell correlations, which respects relativity being local, non-retrocausal, and non-superdeterministic, and is adopted by quantum causal models as interpreted by EnDQT. Furthermore, the outcomes are absolute/non-relative.

A QCM for the popular extended Wigner's friend-like scenarios[40] could be elaborated. Suppose we have two friends/agents in isolated space-like separated labs in each wing, and one Wigner/agents next to each lab, where the friends share an entangled pair prepared at the source like in the Bell scenario. The friends in their isolated labs allow the Wigners to unitarily manipulate the contents of the lab. We would then treat each friend and their target systems as being in an entangled superposition of states at each wing, as long as the friends and their systems don't interact with members of the SDCs. So, the evolution of each system of the entangled pair to each wing and the "measurements" of each friend would be treated via a unitary channel that entangles each friend and their target system, where these channels would also be used to represent the causal structure of this situation. Then, the Wigners in each wing can unitarily manipulate or measure these entangled states. We could then calculate the probabilities for these measurement outcomes for the different measurement settings of the Wigners, providing a local common cause explanation for this situation.[41] Note that, in this case, contrary to what is assumed by the theorems underlying these scenarios, there is no joint probability distribution for the outcomes of the friends and Wigner. This is because the friends inside their labs don't obtain any

[40] See, e.g., Bong et al. (2020); Brukner (2018), Frauchiger & Renner (2018), Ormrod et al. (2023), Myrvold (2002), and Schmid et al. (2023) for a review.
[41] More on this in Pipa (forthcoming-b).

outcomes since they don't interact with SDCs, which allows the Wigners to unitarily manipulate them.[42]

It doesn't seem that any current quantum theories can use QCMs in this local and non-operational way to give a local common cause explanation of quantum correlations like the Bell and extended Wigner's friend ones. So, EnDQT seems to be the first one to be able to do so. To see this, note that relationalist theories are, along with EnDQT, the only non-operational non-hidden variable theories that don't modify the fundamental equations of QT and consider it a universal theory. So, they are the only ones that could consider that QCMs provide the whole causal story. However, typically, in relationalist theories, the shared correlations of the friends only arise when they meet. So, there isn't a common cause explanation in the above sense, and therefore the causal structure will have to be different to take that into account. Moreover, QCMs in the single-world cases (at least) should be modified to account for these multiple varying perspectives, since they don't take into account that variation.[43] Adopting EnDQT, we don't need to adopt relationalism in order to not modify the basic equations of QT or don't deny its universality.

How to support P-2) and P-3)? QCMs consider that common causes can have indeterminate values represented via QT, i.e., via subsystems of an entangled state, and probabilities explicitly don't arise from the ignorance of underlying determinate values. Contrary to CCMs and in agreement with EnDQT, for QCMs, explicitly common causes, represented by the subsystems of the entangled state, don't have determinate values and a Born probabilistic model independently of the interactions with Alice or Bob. Contrary to CCMs, the relations of influence are explicitly represented via QT, i.e., via CPTP maps when systems don't interact with members of an SDC and by POVMs when systems interact with members of SDCs. Only in a limit where we can consider the systems has having determinate values, the QMC reduces to the CMC.[44]

[42] What does the friend experience when it is in a superposition? See appendix A for a response to an objection regarding EnDQT account of Wigner's friend scenarios and the friend's experiences.

[43] So, contrary to the suggestions of others (Cavalcanti & Wiseman, 2021, Schmid et al., 2023, and Yīng et al., 2023). EnDQT considers that QCMs don't need be modified and adapted to a relationalist approach in order for them to explain the correlations in extended Wigner's friend scenarios.

[44] The details about how to obtain this limit precisely are too evolved to be presented here. Basically, the classical limit should involve a process operator $\sigma_{A_1 \ldots A_n}$, where there is an orthonormal basis at each node (that is, an orthonormal basis for $\mathcal{H}_{A_i^{in}}$, along with the basis for $\mathcal{H}_{A_i^{out}}$), such that $\sigma_{A_1 \ldots A_n}$ is diagonal with respect to the product of these bases. This corresponds, for example, to the situation where the systems at the source are prepared in a product state.

So, according to EnDQT, CCMs with its CMC, are inappropriate to provide an account of quantum causal relations, contrary to QCMs.[45] The latter provides an appropriate causal explanation of Bell correlations, which is local. In this way, EnDQT deals with the Bell's theorem.

Sometimes the EPR criterion of reality is used as part of an argument to argue that QT is non-local, and that the EPR argument (Einstein et al., 1935) ruled out the existence of local indeterministic theories (e.g., Maudlin, 2014). This can't be right because EnDQT is a counterexample to that claim. I don't have space to enter into details but note that the EPR criterion of reality assumed in this argument can be precisely seen (Gömöri & Hofer-Szabó, 2021) as a consequence of the classical Reichenbach principle, which, as I have mentioned, is a special case of the more general CMC (Hitchcock & Rédei, 2021). However, EnDQT doesn't consider that the CMC can in general represent causal relations between quantum systems, and thus it rejects the EPR criterion as representing such causal relations.

4. Conclusion and future directions

I have proposed EnDQT and argued that, contrary to the other well-known quantum theories, it has the benefit of being a local, non-relational, and non-superdeterministic/non-retrocausal QT. Systems have determinate values only while interacting with other systems of SDCs. On top of that, EnDQT it has the benefit of being conservative, not modifying the fundamental equations of QT, and, in principle, arbitrary systems can be placed in a superposition for an arbitrary amount of time. Also, EnDQT is able to give a local causal explanation of quantum correlations. There are many future directions. For instance, one should develop more realistic models, seek to develop techniques to map SDCs, and test and extract further prediction from EnDQT, which might distinguish it empirically from other quantum theories.[46]

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[45] EnDQT could offer the possibility of a deterministic version not presented here, since it doesn't serve our purposes. In this version, SDCs evolve deterministically. Furthermore, it could be postulated a probabilistic process in the early universe that would select an initiator among many, each associated with certain hidden variables. Then, we would have a deterministic process that would evolve this initiator, and the interactions of this initiator, which would give rise to other systems having determinate values, and so on. We would be completely ignorant about which initiator was selected, and this would ground the quantum probabilities. The problem of this view is that we wouldn't be able to coherently reject the classical Markov condition (since initiators will have determinate values and the systems that interact with them, and so on) as representing causal relations between quantum systems, and we would have to deal with the Bell's theorem in such a way that it defeats our purposes.

[46] See appendix C for further discussion on future directions.

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Appendix A: Response to objection concerning the denial of the EEL and the Wigner's friend experiences

In this section, I will reply to two objections regarding EnDQT. First, one might object to EnDQT approach to indeterminacy because it's *odd* that a system whose quantum state is in an eigenstate of some observable doesn't have a determinate value if it's not interacting with systems that belong to an SDC. As it was mentioned, this assumption contradicts both directions of the famous Eigenstate-Eigenvalue 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.

For EnDQT, a system can have a determinate value of some observable O, but that doesn't imply that its state is in an eigenstate of O. It can be attributed to that system a particular reduced density operator or be a subsystem of a larger system in an entangled state like the ones attributed in the case of interactions involving decoherence, which aren't eigenstates of O. Moreover, a system can be in an eigenstate of O, but that doesn't per se imply that it has a determinate value of O since that system being connected with an SDC matters.

Although this seems odd, we saw in the main text how this indeterminacy allows us to deal with the Bell's theorem plausibly. Furthermore, note that in realistic situations, the systems of interest are never prepared in a pure state. When examined in more detail, this is instead an artifact of an idealization. Using standard unitary-only QT (no spontaneous collapses), what ultimately happens is that the system whose state is getting prepared gets entangled with the preparation device's degrees of freedom or some other relevant degrees of freedom. This gives rise to all the coefficients in the (reduced) density operator of this system (tracing out the degrees of freedom of the preparation device or the relevant environment) being approximately zero, except the coefficient that concerns the "pure state" being prepared (if the preparation procedure is a really good one).

Considering decoherence seriously and not assuming some spontaneous collapse view, the system is still in an entangled state with some other degrees of freedom of some other systems if the preparation doesn't involve any actual measurement. This prepared state doesn't correspond to what we can assign in general determinate values of some observable precisely.[47] Moreover, even upon a measurement of a system "in an eigenstate of some observable," the system shortly after evolves into a superposition.[48] Thus, EnDQT doesn't consider the idealization concerning the assignment of pure state to S as a sufficient criterion for S to have a determinate value associated with that state and considers that realistically at least local systems are never in a pure state. That is also why decoherence is used to model measurement-like interactions in general.

This view doesn't imply that we should consider that "larger non-local systems" constituted by subsystems, such as Bell pairs, cannot be in a pure state (I will be neutral about this) or that this cannot be useful as an idealization. However, I will consider that the local subsystems (which might be composed of further subsystems that interact locally with each other) of such larger non-local systems, which are the systems that I am considering here to exist more fundamentally, don't have determinate values independently of local interactions with elements of an SDC.

One might object that in some extended Wigner's friend theorems,[49] it's plausible to consider that the friend Alice inside the isolated lab sees a determinate outcome. In a sense, this theorem assumes that Wigner, without performing any operations on Alice and her lab and after her measurement, simply opens the door of her lab and asks her about what outcome she obtained. In the simple case discussed in the introduction, she will answer that she obtained spin-up or spin-down with 50% of probability each (i.e., if Wigner makes a projective measurement on the state of Alice after her measurement, without performing any other operation on the lab, he will obtain these outcomes). So, it seems that Alice sees a determinate outcome contrary to

[47] See Wessels (1997) for more details on this issue.
[48] Modulo quantum Zeno-like measurements, which increase the probability of the system being found in the same quantum state in repeated measurements.
[49] See Bong et al. (2020).

what is claimed by EnDQT. To put the objection more dramatically, the measurement problem can be casted as the problem of accounting for the experiences of determinate outcomes of experimentalists upon measurements, despite QT predicting that measurement-like interaction can yield indeterminate outcomes. The friend inside the isolated lab seems to experience a determinate outcome, but EnDQT gives no account of what this agent is experiencing. Hence, EnDQT doesn't solve the measurement problem and is an unsatisfactory QT.

First, note that, according to EnDQT, Wigner opening the lab triggers a physical process that leads to Alice obtaining determinate outcomes and reporting that to Wigner. It's not necessarily the case that Alice sees a determinate outcome inside her lab before opening the door. That process can arise over the interactions with the SDCs.

Second, we shouldn't worry that EnDQT leads to friend-like agents without experiences. We shouldn't follow our intuitions in the extreme (and quite possibly unrealistic) environments of a completely isolated agent and think that that agent will be exactly like us. One possible prediction is that a) the agent lacks mental/phenomenal/cognitive states: this is the *absent experience hypothesis*. This hypothesis is contrary to the *relationalist hypothesis* assumed by relationalists, where the later consider that the friend saw a determinate relative outcome.

However, EnDQT can even consider that the friend *experiences* something in the isolated lab via particular hypotheses, dissolving the above worry. We might consider that b) friend-like systems in isolated regions have some different kinds of mental/phenomenal/cognitive states that depend on indeterminate properties, which I will call the *quantum experience hypothesis*. For instance, they experience positions without experiencing the determinate value of position. Or c) we might adopt a new version of the extended mind hypothesis of Clark & Chalmers (1998), which I have called *quantum extended mind hypothesis*, and that accounts for the friend's experiences. The idea is that a friend could talk with Wigner from its isolated lab and have experiences within it, but the *bearers* of the determinate cognitive or phenomenal or mental states in these cases would be in the external environment of the friend in the interaction with the outputs of the friend to their environment (i.e., the interactions between the elements of the SDCs with the outputs of the friend). Like the most sophisticated technology is perhaps an extension of our mind, for an incredible agent like the friend, its outputs and interactions with the external environment are an extension of their mind.[50] So, Alice (or a realistic Alice, see below) could in fact have experiences in these situations, and EnDQT can account for them. There is much more to say about this. Future work will go into more detail on a), b), and c).

Note that if we consider realist Wigner's friend scenarios, the position adopted by EnDQT regarding the friend's experiences and the adoption of the above hypotheses shouldn't be seen as something restricted to EnDQT in realistic scenarios. If extended Wigner's friend scenarios become realizable one day, it will very likely be via quantum computers and *quantum agents* running on those quantum computers as friends instead of human friends.[51] Assuming that such quantum agents have experiences, many realist interpretations of QT will be pressed to assume that quantum agents don't have internally determinate experiences. This is because, typically, their experiences will depend on superpositions of qubits. As it is recognized by many MWI proponents,[52] we can have robust branching into worlds when there is decoherence, but inside some quantum computers, we shouldn't often have such branching because there isn't a lot of decoherence (at least ideally and in many architectures of a quantum computer). Many proponents of interpretations such as the MWI won't consider that in many situations there is enough robust branching inside the quantum computer so that we could have something like an agent with determinate experiences running on those circuits. Collapse theories won't also consider that there is such an agent because they don't consider that collapses happen (at least frequently) in situations like those within a quantum computer.

So, EnDQT in realistic circumstances leads to the same account of agent's experiences as (at least) these realist and consistent quantum theories. Thus, these views are on an equal footing when it comes to realistic scenarios in terms of accounting for the agent's experiences, and they could also adopt one of the above hypotheses concerning the friend's experiences along with EnDQT.

As a side note, although single-world relationalists can account for the *relative* friend's experiences and prima facie this is advantage of these views relative to EnDQT, there is a good case to be made that this is not *absolute*. A more careful inspection of

[50] Note that the extended quantum mind thesis differs from the traditional extended mind thesis by considering that even phenomenal states can have extended bearers. I don't see any problem with considering that. More concretely, the extended mind thesis might be justified via individuating mental states through its functional roles (Clark & Chalmers, 1998). However, some may reject the claim that phenomenal states can be individuated by their functional roles (e.g., Chalmers, 1996). It's unclear that my thesis requires a functionalist account of phenomenal states. I will leave the investigation of this topic for future work.
[51] See Wiseman et al. (2023) for a proposal.
[52] See most prominently, Wallace (2012, section 10.3).

single world relationalist views, such as Relational Quantum Mechanics,[53] shows that relative to some systems, other systems phenomenal states can be indeterminate, since relative to one system, the other system might be in a superposition of certain quantum states that phenomenal states depend on. So, it's unclear that the above-mentioned advantage of relationalist views is really an advantage.

Appendix B: The basics of an ontology of quantum properties

One might object that EnDQT doesn't offer a clear ontology since an ontology that views the world in terms of systems, observables, and determinate or indeterminate values is unclear and not so satisfactory when we compare it with the richer ontology where the wavefunction is reified. As I have mentioned, EnDQT offers the possibility of different ontologies that reject the view that quantum states are entities in the world. I prefer an ontology where the world is filled with matters of fact even when systems are not interacting, and not just observables and flashes, for example. This is an ontology of *quantum properties*, where systems are collections of quantum properties and these quantum properties come in terms of different *degrees of differentiation D*.*

So, for example, we have spin in a given direction, which comes in terms of different degrees of differentiation. These features of quantum properties are represented through observables concerning P and quantum states that are eigenstates of those observables. Plus, at least in the simple cases, the degree of differentiation is measured via the non-diagonal terms of the reduced density operator of the system subject to decoherence, when we trace out the degrees of freedom of the environmental system that are interacting or interacted with the system of interest. In the simple decoherence cases that we have been concerned here, the quantum state of some system S with $\alpha, \beta \neq 0$,

$$\alpha|\uparrow_z>_S + \beta|\downarrow_z>_S, \tag{14}$$

and the observable S_z that acts on the Hilbert space of S, represents the quantum property spin-z of S. This spin-z has a degree of differentiation D*=0 and we consider that the system has an undifferentiated spin-z, i.e., D*=0-spin-z.

[53] See, e.g., Rovelli (1996) and Di Biagio & Rovelli (2021).

If S *is not* interacting with any other system E belonging to an SDC, but interacted with E in the past, or if it's instead interacting with some E *that doesn't* belong to an SDC, we represent the quantum property spin-z via the observable S_z and

$$\alpha|\uparrow_z>_S |E_\uparrow >_E + \beta| \downarrow_z>_S |E_\downarrow >_E, \tag{15}$$

(adding a time dependence in the latter case). The degree of differentiation is calculated via the overlap terms qua distinguishability of the states of E concerning S, such as $< E_\uparrow(t)|E_\downarrow(t) >_E$ and $< E_\downarrow(t)|E_\uparrow(t) >_E$. We consider in this case that system S has a spin-z *unstably differentiated* to some degree D*. More generally, given

$$\rho(t) = \sum_{i=1}^{N} |\alpha_i|^2 |s_i >_S < s_i| + \sum_{i\neq j}^{N} \alpha_i \alpha_j^* |s_i >_S < s_i| < E_j(t)|E_i(t) >_E, \tag{16}$$

a measure of the degree of differentiation of the different D*-P of S in ST over time t for the simple scenarios that I am considering (where the evolution of the target system is dominated by the Hamiltonian of interaction with the environment) will be given by the von Neumann entropy[54] $S(\hat{\rho}_S(t))$ of $\hat{\rho}_S(t)$ over lnN, where N is the number of eigenvalues of $\hat{\rho}_S(t)$,

$$D^*(P, S, ST, t) = \frac{S(\hat{\rho}_S(t))}{lnN}. \tag{17}$$

Thus, we can measure and represent the degree of differentiation D*' of a quantum property D*'-P of S at a time t, how the differentiation of quantum properties of S change over t, and the differentiation timescale (which is equal to the decoherence timescale), with $0 \leq D^*(P, S, ST, t) \leq 1$, in *the possible set of spacetime regions* ST where they are differentiated via interactions with other systems E. Or after those interactions in other STs in the absence of further interactions with other systems.

So, unstable differentiation of a quantum property of a system S are changes in such quantum property by other systems S' that, if S' belonged to an SDC, they would

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

be stably differentiated. Typically, situations of virtual/reversible (as opposed to the irreversible one, see below) decoherence concern such unstable differentiation.

When the system E above belongs to an SDC and $D^*(P, S, ST, t)$ is relatively and quasi-irreversibly large (≈ 1), we consider that the system has a quantum property *stably differentiated* to some degree D*. We represent the spin-z of system S via

$$\alpha|\uparrow_z>_S |E_\uparrow(t)>_{E\,SDC} + \beta|\downarrow_z>_S |E_\downarrow(t)>_{E\,SDC}, \quad (18)$$

or we represent it via the appropriate reduced density operators of S.

To explain the dependence between the degree of determinacy of values of systems and the degree of differentiation of their quantum properties, I will adopt a functionalist account of indeterminacy. Very roughly, functionalism about property P* is the position that P* is the property of having some other property P in a certain situation or having specific features.[55] The functionalist position provides an account of the dependence relation between the so-called values properties (henceforward, values) v (or value intervals) that I have been talking about, which come in terms of different degrees of determinacy, and quantum properties.

To have a value v of P (where P could be energy, momentum, position, etc.) with a non-minimal degree of determinacy D is to have stably differentiated quantum 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 differentiation are related when the systems have a quantum property *unstably* differentiated to some degree D* or just undifferentiated (which is the lowest degree of differentiation). To have an indeterminate value of P is to have an undifferentiated or unstably differentiated quantum property D*-P to an arbitrary degree D*.

Forthcoming work (Pipa, forthcoming-a), will enter into further details about this ontology. The point is that we have here a more realist ontology. This different ontology may seem at first pedantic compared with the simpler ontology of flashes and observables. However, it captures more structure represented by quantum states (and decoherence) than the flashes. Systems don’t only have determinate values under interactions (which would be analogous to the flashes), they have quantum properties

[55] There is more to say about how to characterize the kind of functionalism I am appealing to. I will leave that for future work.

with different degrees of differentiation that change over time and, via interactions, change the degree of differentiation of one another.[56]

Appendix C: Future directions

Future work should seek to test and further develop EnDQT. As one can see, EnDQT has a series of distinct features when compared with other quantum theories. At first, it seems that it will be very hard to distinguish EnDQT empirically from the other unitary interpretations of QT because, in practice, like EnDQT all of them appeal to (irreversible) decoherence connected with some environments in one way or another.

However, since EnDQT is local, we can regard that as indirect evidence for this view, since so-far locality, as posed by relativity, hasn't been disconfirmed. Also, if we find clear evidence for initiators, it will confirm EnDQT and disconfirm the other current quantum theories because, currently, there isn't any theory that could generate the same predictions.

Furthermore. EnDQT offers a finer account of how determinacy propagates than other views since for EnDQT, certain interactions between systems become important. If this finer account ends up being further developed and empirically confirmed, it provides good support for EnDQT since the other interpretations of QT don't require it. It can also disconfirm it. If we cannot empirically find or it is even impossible to hypothesize coherently SDCs with some stability conditions (not necessarily the one proposed here), this could offer means to do it. So, we should find ways to further test the relativistic condition with its distinct predictions discussed in section 2.2 and propose and test new ones.

A simpler test for EnDQT is to see what the features of the SDCs in the case of the empirically well-supported decoherence models would be and see if we can get some predictions out of it with specific stability conditions.

A more challenging test would be to map the SDCs of our universe with their different structures and features that impact the determinacy of values and see which hypotheses underlying the structure of SDCs hold. This test would press us to make the

[56] This ontology has potentially the advantage of capturing what often happens in general measurements represented via positive operator-valued measures (POVMs). A sufficient way (Nielsen & Chuang, 2011) of implementing a general measurement is via a unitary interaction of the state of the target system S with an ancilla system followed by a projection onto the ancilla. We can interpret that what happens is that the ancilla unstably differentiates to some degree the quantum properties of the target system, S, then the ancilla is stably differentiated. Its value allows us to gain some information about the quantum properties of S.

hypotheses concerning the SDCs posed in the main text more precise. Given the widespread determinacy at the macroscopic scale, a possible heuristic to make the above hypotheses more precise would be to consider that the SDCs that exist in our universe are the most robust under perturbations to give rise to determinate values at a cosmological scale, given some stability conditions. Such robustness could perhaps be evaluated via redundancy measures of the SDC network since disruptions in the network could be compensated by redundant connections; centrality measures that allow SDCs to spread (roughly via nodes that have more connections than others), etc. Once these SDCs are identified, we could make experiments or do observations to find out if those structures exist. Additionally, new quantum systems could be hypothesized to explain such robust SDCs (perhaps suggesting new physics), or we could make sense of some already existing physical systems by the fact that they help the existence and spread of SDCs. To achieve the above end, future work should integrate the tools of causal modeling and network theory with EnDQT to map and understand SDCs better.

Another way to find confirmatory evidence for EnDQT is by searching for other phenomena that it can further explain. Firstly, future work should investigate how EnDQT could allow for explanations of the diverse temporal asymmetries. The initial conditions of the SDCs perhaps could be used further explain the past hypothesis[57] in its quantum form. Roughly, according to Wallace (2023), the latter is the special quantum state in the early universe that plus the laws explains the direction of time. This state could be the one where the initiators didn't interact with the other systems, or nothing else interacted to form SDCs.

Secondly, future work should seek to investigate SDCs associated with spacetime and gravity, in order to see if EnDQT could help achieving the integration of QT with gravity. Indeed, SDCs and gravity/spacetime have some aspects in common. Initiators like the origin of gravity may date back to the beginning of the universe, both SDCs and spacetime expand and they are widespread. This investigation could be done by investigating current programs that aim to achieve this integration or develop a new one.

[57] Albert (2000).

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