Beyond the Wigner's friend dilemma:
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 doesn't modify its equations or add 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. Unlike collapse theories, in principle, arbitrary systems can be placed in a superposition for an arbitrary amount of time, and no modifications of the 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 there is isolation from the rest of the systems that belong to these networks, such as inside the friend's isolated lab in the extended Wigner's friend scenarios, indeterminate values non-relationally arise inside.

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1. Introduction

The extended Wigner's friend theorems[2] present a version of the measurement problem[3] that identifies a tension between relativity, some natural assumptions regarding when measurement outcomes should arise, and the predictions of standard quantum theory. More concretely, this version of the problem can be regarded as a dilemma involving different options that different quantum theories adopt to escape this tension. Let's analyze a simplified version of the scenarios underlying these theorems to illustrate how the theories involved in this dilemma are motivated.[4]

Consider the following EPR-Bell-like scenario. We have Alice in an isolated laboratory so that "no information leakage" arises from the interaction between the lab and the open environment.[5] Then, the contents of the lab can be coherently manipulated by performing arbitrary quantum operations on them, treating these contents as pure states. Space-like separated from Alice, there is Bob, who shares with Alice a pair of systems in the following singlet state,

$$|\Psi(t)>_{A+B}= \frac{1}{\sqrt{2}}(|\uparrow_z>_A|\downarrow_z>_B-|\downarrow_z>_A|\uparrow_z>_B). \tag{1}$$

Next to Alice's laboratory is Wigner, also space-like separated from Bob. After Alice measures her system, Wigner, who can treat the interactions between Alice and her system as evolving unitarily, performs operations on Alice plus Alice's system that reverse their quantum states to the previous ones before her measurement.

Let's look at this situation from the perspective where Alice measures her system in a spin-z direction in two relativistic inertial reference frames, which establish different hyperplanes of simultaneity, i.e., different slices of spacetime in which all events in a slice occur simultaneously. Let's consider frame 1 (lab frame). The quantum framework predicts that Alice will obtain spin-z up with probability ½ and spin-z down with probability ½. Then, Alice's result is reversed by Wigner, and Bob measures his

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[2] See, e.g., Bong et al. (2020), Brukner (2018), Frauchiger & Renner (2018), and Myrvold (2002).

[3] See, e.g., Maudlin (1995) and Myrvold (2018).

[4] The following scenario was proposed by Gao (2018). Here I don't mean to support what Gao's claim his theorem proves, which has been disputed (see, e.g., Healey, 2021). Rather, I use his scenario to briefly provide the intuition behind contemporary motivations for different quantum theories.

[5] See, e.g., Zurek (2003).

system in the z-direction.[6] QT leads to the prediction that he will obtain spin-z up with probability ½ and spin-z down with probability ½, conditioning on the state of Alice. Let's call Alice and Bob "friends."

Because the friends are space-like separated, according to relativity, we can choose another inertial reference frame, frame 2. In this frame, Alice measures the spin-z of her system, then (contrary to the frame 1 case) Bob measures his system, and then Alice's measurement is undone by Wigner. In this situation, if Alice obtains, for example, spin-z up, the quantum framework predicts that Bob, conditioning on the outcome of Alice, will obtain spin-z down with 100% probability if he measures it on the same basis as Alice. However, in frame 1, according to the predictions of standard QT, Bob's result doesn't need to be spin-z down.

So, if QT isn't disambiguated, it can yield two contradictory predictions. The predictive consequences of this ambiguity at the heart of QT can be magnified and precisified via different extended Wigner's friend no-go theorems.[7] If we want to deal with this ambiguity and these theorems, the following dilemma that involves a (perhaps non-exhaustive) list of options arises:

> A) deny unitary QT by modifying the dynamical equations of QT like collapse theories, which localize particles at random times. A modification of the dynamical equations can lead to the collapse of the state of Alice inside her isolated lab and Wigner not being able to manipulate the superposition of Alice plus her system unitarily. Relatedly, deny that QT is universal, i.e., that it applies in principle to any physical system, which, for example, can lead to a collapse due to the coupling with non-quantum systems;

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[6] Let's assume that the interaction between Alice's measurement device and her system is modelled in the following way, $|\mathrm{Alice}_0>_A (\alpha|\uparrow>_{S_A}|\downarrow>_{S_B} + \beta|\downarrow>_{S_A}|\uparrow>_{S_B} \to_{\hat{U}} \alpha|\mathrm{Alice}_\uparrow>_A|\uparrow>_{S_A}|\downarrow>_{S_B} + \beta|\mathrm{Alice}_\downarrow>_A|\downarrow>_{S_A}|\uparrow>_{S_B}$. This interaction can be reversed locally by acting only on Alice's system and her lab. The reversal by Wigner of Alice's interaction with her system lead us again to the following state, $|\mathrm{Alice}_0>_A (\alpha|\uparrow>_{S_A}|\downarrow>_{S_B} + \beta|\downarrow>_{S_A}|\uparrow>_{S_B})$.

[7] In the simplest theorem (Bong et al., 2020) there is instead two Wigners and two friends and systems measured by the friends. The Wigners can coherently/unitarily manipulate the friends together with their systems. The random measurements by the Wigners and their friends, as well as the choices of their settings, give rise to certain correlations and conditional probabilities. Specific locality and no-superdeterminism/free-choice assumptions are postulated. Important to my purposes, it is also assumed that "observed events" exist absolutely and not relative to a perspective, and that sometimes randomly Wigner doesn't perform any operations, just opens the lab, and sets his outcomes equal to the friend's outcomes ("the absoluteness of observed events"). I will come back to this later assumption in section 3. These assumptions constrain those probabilities and bounds generated by the correlations derived from these probabilities. Probabilities given by the Born rule violate those bounds. No hidden variables are explicitly invoked in these theorems, contrary to the Bell-like theorems.

B) add specific kinds of "hidden" variables, such as the ones involved in future boundary/teleological conditions,[8] retrocausal or superdeterministic interpretations, that could solve the above contradiction;

C) violate relativistic causality/locality by choosing a preferred frame, which can solve this contradiction by allowing Alice to influence the outcome of Bob or vice-versa;

D) adopt a so-called relationalist interpretation of QT, in which the outcomes of Alice or Bob are relative to, for example, a multiplicity of worlds, private perspectives or environments, simultaneity hyperplanes, etc. Therefore, Alice cannot condition her (single) measurement results in the absolute outcomes of Bob since they aren't absolute. Relationalist interpretations involve options where the dynamics are always deterministic, which includes Everett's relative-state formulation of QT[9] and the Many-Worlds Interpretation (MWI).[10] Also, there are indeterministic single-world options, such as relational quantum mechanics,[11] QBism,[12] Diek's perspectival modal interpretation,[13] and Healey's pragmatism.[14]

Let's call this dilemma the Wigner's Friend dilemma. The received view in foundations and philosophy of physics typically accepts this dilemma, as one can see by inspecting the Extended Wigner's Friend Theorems and prominent literature about those theorems. For instance, Brukner (2022) writes,

"The startling conclusion [of the extended Wigner's friend scenarios] is that the existence of 'objective facts' shared by Wigner and his friend is incompatible with the predictions of quantum theory as long as assumptions of 'locality' and 'freedom of choice' are respected."

Options A)-D) lead to mostly well-known and often undesirable consequences, which I will not explore here. In this article, I will propose a new quantum theory called Environmental Determinacy-based Quantum Theory (EnDQT), which goes beyond the received view by not adopting any of the options A)-D), and so it might not suffer from

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[8] See, e.g., Kent (2015).
[9] See, e.g., Barrett (2018) and references therein.
[10] See, e.g., Wallace (2012).
[11] See, e.g., Wallace (2012), Di Biagio & Rovelli (2021) and Adlam & Rovelli (2022).
[12] See, e.g., Fuchs & Stacey (2019).
[13] See Dieks (2019) and references therein.
[14] See, e.g., Healey (2017) and Healey (2022).

any of their issues. I will argue that EnDQT is a local, non-relationalist, no-collapse, non-retrocausal/superdeterministic/teleological quantum theory. Thus, importantly, contrary to many quantum theories (such as Bohmian mechanics), EnDQT has the benefit of not being in tension with relativity and in a non-relational way (i.e., outcomes don't vary with measurers/systems), which can allow it to circumvent the issues that arise when making outcomes relative to systems, worlds, agents. etc. Also, in principle, it allows for arbitrary systems of arbitrary size to be placed into a superposition indefinitely, contrary to collapse theories. So, any system, in principle, can unitarily evolve indefinitely.

The key novelty of EnDQT is a network structure that represents interactions between systems, which establishes when these interactions give rise to them having determinate values. As I will argue, the first systems with determinate values arose in the past through some special systems (which I call initiators). Moreover, these systems started chains of local interactions over time and space, which I will call stable differentiation chains (SDCs; the reason for this name will become clearer at the end of the paper). By interacting with an initiator, a system acquires a determinate value during these interactions and can give rise to other systems having determinate values in interactions with them, which allows these later systems to lead other systems to having determinate values, and so on via an indeterministic process. So, these chains allow determinate values to propagate and persist over spacetime, giving rise to other systems having determinate values. They can be represented by certain networks where they will represent how systems relate in terms of interactions over spacetime. The interactions are modeled via decoherence; thus, they don't fundamentally favor any observable. They just involve entanglement between systems via their local interactions. The systems that don't belong to this network or don't interact with it at some point can, in principle, unitarily evolve indefinitely.

So, contrary to collapse theories, according to this view, systems of any scale can be placed in arbitrary superpositions for an arbitrary amount of time and evolve deterministically as long as they don't interact with elements of an SDC. Thus, Extended Wigner's friend scenarios, in which the friend plus her system are maintained in a superposition and Wigner can manipulate their state, are only possible when we isolate the contents of the lab from the systems belonging to SDCs.

The perspective adopted here is that quantum states don't literally and directly represent some physical entity; instead, they help predict, gain knowledge about, and indirectly represent together with the networks representing SDCs, how systems evolve and affect each other, how SDCs evolve, and how systems evolve outside interactions. So, in the Bell-type scenarios, the measurement of Alice doesn't non-locally affect Bob, and vice-versa, and locality is preserved as we will see in more detail. Moreover, 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. There is instead 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 under their local interactions. Furthermore, decoherence shouldn't be interpreted as representing a process of branching of the wave-function/quantum states or something related, but rather as a process in which (when specific conditions are fulfilled) an environmental system gives rise to another system having determinate values during interactions and in a single-world.

The local causal explanation of Bell correlations is provided via Quantum Causal Models,[15] as I will explain later (section 4). I will also explain that the extended Wigner's friend scenario can be dealt with via these models by considering that the friend and their system are in a superposition in these situations, being subject to Wigner's interventions and not obtaining determinate outcomes.

As I will argue, to my knowledge, EnDQT is the first and only local non-relational quantum theory. More concretely, it's the first and only (unitary) QT that (via quantum causal models) gives a local (non-relationalist and non-operational) local common cause account of the extended Wigner's friend scenarios and Bell correlations.[16] This is a great benefit of this view, given the growing literature in this area and the virtues of this tool. Contrary to the suggestions of others,[17] EnDQT considers that quantum causal models don't need be modified to adapt them to a relationalist approach to those models. We don't need to adopt relationalism in order to not modify the basic equations of QT or don't deny its universality.

To simplify, throughout most of the paper, I will employ the familiar language of systems, observables of systems as having determinate values, where the later corresponds to their eigenvalues, and systems having determinate or indeterminate values. Note that I will (at least but not only) consider isolated systems whose quantum state is in a superposition of the eigenstates of a certain observable as having

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[15] See, e.g., Costa & Shrapnel (2016); Allen et al. (2017), and Barrett et al. (2019).

[16] See section 4 for the causal graph of the local account in the case of Bell correlations.

[17] Cavalcanti & Wiseman (2021), Schmid et al. (2023), and Yīng et al. (2023).

indeterminate values of that observable. Different ontologies can precisify what the above language means and allow EnDQT to adopt a more robust realism. One may understand determinate values of systems as referring to flashes, i.e., an ontology of local events in spacetime (but differently from collapse theories and with a different interpretation of the quantum state).[18] Nevertheless, I will favor a more fundamental ontology of systems as collections of quantum properties that have values with different degrees of determinacy in interactions with particular systems (see section 3). Quantum states will also represent those properties, together with helping represent the SDCs. Events arise when systems have determinate values, where systems have those values when they belong to SDCs.

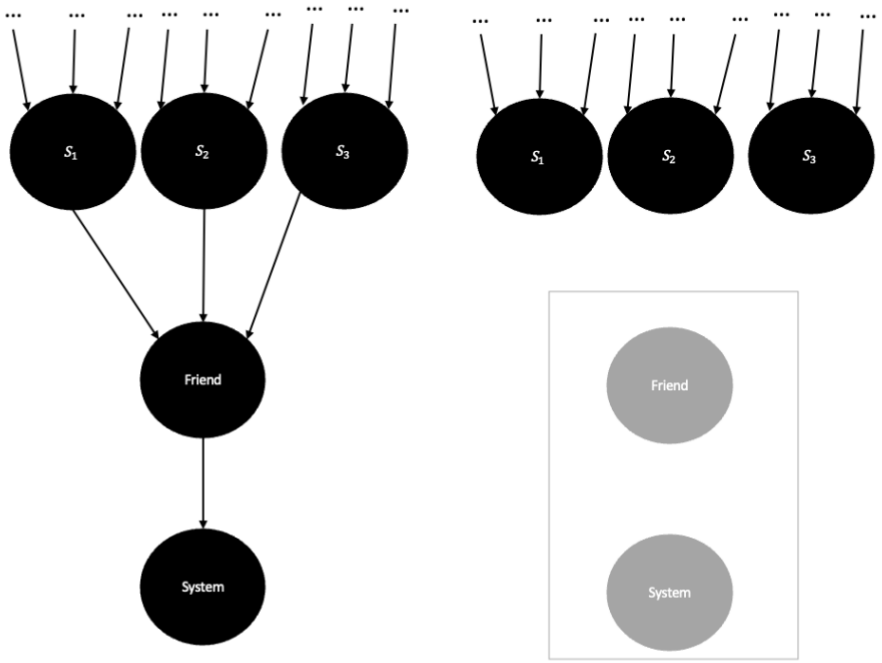

Figure 1

To see how EnDQT works in more detail, let’s look at Figure 1. We can see local interactions over a two-dimensional spatial region in a Wigner’s friend scenario at different times (where time runs from the top to the bottom). X → Y → Z→… represents a system X interacting with system Y, giving rise to Y having determinate values, which allows Y to give rise to Z having determinate values under interactions with Z and so on over spacetime (where these interactions can be represented via decoherence plus specific constraints). We can see a sample of a network representing

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[18] The flash ontology was first proposed by Bell (2004) and named by Tumulka (2006).

an SDC that started in the past and is expanding over spacetime. Dark nodes are systems that belong to this SDC with respect to specific quantum properties. Grey nodes are systems that don't belong to this or any SDC (in the case of total isolation, like in the Wigner's friend case).

On the left, we have the situation where the Friend is connected to this network via interactions that allow her to give rise to determinate values under interactions with her system. On the right, we have the situation where the lab is isolated, isolating the friend from this network of interactions before she measures her system. Since she is detached from the SDCs, the friend/measurement device doesn't have determinate values of any (or at least any dynamical) observable and cannot give rise to determinate values in interaction with other systems. So, Alice in her isolated lab doesn't obtain determinate values of any observable in her interactions, and Bob should not condition his outcomes on the outcomes of Alice because they are indeterminate.

Hence, according to EnDQT, the assumption that we can collect statistics or assign probabilities (which are based on determinate outcomes) or quantum states representing systems with determinate values or elaborate frequencies based on the state of affairs of Alice/friend in her sealed lab is denied at any scale. No relative outcomes exist for the friends because there are no determinate outcomes at all, and this fact is *non-relative*. Thus, everyone will assign the friend and her system the same state and agree on the state of affairs inside the lab. This strategy applies to any extended Wigner's friend scenario since they all make these assumptions.

So, EnDQT considers that the criterion for a system having a property "with a determinate value" involves the system interacting with elements of an SDC represented via decoherence. However, decoherence can only be used to establish the criteria for determinacy when the interactions between systems that give rise to decoherence belong to these chains. It cannot be used as a criterion when the friend's lab is isolated.

The above isolation doesn't require anything besides the isolation from systems that give rise to the irreversible (*open environment*) decoherence process. This is because, as I will argue, EnDQT relies roughly on two plausible hypotheses. The first one is that systems that give to the decoherence process in the typical open-environment situations are connected to SDCs. The second hypothesis is the existence of initiators or events that give rise to SDCs. As I will discuss later, the postulation of these hypotheses and the dynamics of SDCs shouldn't be seen as problematic but rather as a virtue because they predict new physical phenomena and may allow EnDQT to be tested one day, differentiating it from other quantum theories.

I will start by explaining the basics of EnDQT (section 2). Section 3 explains how EnDQT goes beyond the Wigner's friend dilemma and how it can provide a local explanation of Bell 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

Let's turn to the explanation of the theory. From now on, I will consider a (quantum) system as occupying local regions of spacetime and as being represented at a moment in time by a collection of observables and certain quantum states (or equivalent classes of quantum states) that belong to the Hilbert space of the system and that these observables act upon. 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 observables of systems localized in a single region of space.[19][20] Systems have determinate values when their observables have those values. I will be very liberal about what constitutes a system. For example, an atom's internal degrees of freedom could constitute a quantum system.

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 the section 3 where I discuss the Bell's theorem), I will assume that any observable O of S, including the non-dynamical ones, outside of interactions of S involving O, cannot have determinate values but rather have indeterminate values (more on this below, see also the following footnote).[21]

Interactions 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:

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

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

[21] 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'.

Decoherence plays a key role on how EnDQT represents interactions, and so I will briefly explain it and some of the assumption that I will make.[22] Let's consider a system S in the following states,

$$|\psi>_S = \sum_{i=1}^{N} \alpha_i |s_i>_S, \tag{2}$$

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 specific spin in a certain direction that constitute system E. For simplicity, throughout this article, I will assume this kind of evolution of the system under interactions.[23] 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,

$$(\sum_{i=1}^{N} \alpha_i |s_i>_S)|E_0>_E \rightarrow_{\hat{U}} \sum_{i=1}^{N} \alpha_i |s_i>_S |E_i(t)>_E = |\Psi>_{S+E}. \tag{3}$$

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 by analyzing the reduced density operator of S, obtained from tracing over the degrees of freedom of E in the density operator of $S+E$,

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[22] See, e.g., Schlosshauer (2007) for further details.

[23] 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.

$$\hat{\rho}_S(t) = \sum_{i=1}^{N} |\alpha_i|^2 |s_i>_S< s_i| + \sum_{i,j=1, i\neq j}^{N} \alpha_i^* \alpha_j |s_i>_S< s_j| < E_i(t)|E_j(t)>_E + \alpha_j^* \alpha_i |s_j>_S< s_i| < E_j(t)|E_i(t)>_E. \quad (4)$$

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 different from zero) 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,

$$\hat{\rho}_S \approx \sum_{i=1}^{N} |\alpha_i|^2 |s_i>_S< s_i|. \quad (5)$$

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 be used to 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 in section 3.

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

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

Given decoherence, I will consider that a

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, where the eigenvalues of O include v.*[24]

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 and are used to infer the time decoherence takes.

Also,

The criterion for an interaction between interacting systems X and Y to end is for Y to have a determinate value due to the interaction with X. So, I will consider that when a system Y has a determinate value due to the decoherence that arose from X that the interaction between X and Y has ended because decoherence occurs after a "longer period of time." So, it's reasonable to assume that systems X and *Y aren't interacting anymore when Y has a determinate value due to X.*

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

A determinate value of a system Y arises indeterministically in the above interaction with a system X that has the DC with probabilities given by the Born rule.

Given the DC, I propose that two kinds of systems that constitute a stable differentiation chain (SDC), which is represented by a network that propagates the DC giving 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. The first kind consists of initiator systems or initiators, where

Initiators are systems that have the DC independently of other systems.

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[24] 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.

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. The second kind of systems consists of non-initiator systems, which are all other systems in the SDCs, where

Non-initiator systems having the DC depends on their interactions with other systems that have the DC.

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.

In the next section I will explain the *stability conditions*. The stability conditions will precisify 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 an SDC. I will essentially stipulate one possible condition, called the relativistic condition involving different subconditions. The heuristic that aided the stipulation of these conditions was providing a clear, simple, local, empirically plausible, non-circular, and non-problematic criteria, i.e., some criteria that appeals to initiators and that respect relativity (see next footnote), for when a system can have and transmit the DC, where having the DC depends on other systems of the network and their local interactions depend at least on their Hamiltonian of interaction (and not solely on entangled quantum states since EnDQT is not reifying them). If I postulated some criteria that doesn't depend on an SDC network, and that aims to not modify the basic equations of QT, it would likely lead me to some traditional hidden variable accounts or to adopt a relationalist view, which we know to have problems of their own. An example at the end of the next section will make the conditions clearer.

2.1. Stability conditions

According to the relativistic condition, SDCs, which start with initiators, are constituted and propagate *over time*[25] by having systems that interacted with initiators and by other systems that interacted with them and so on. To postulate and explain these conditions, let's consider the following DAG representing an SDC:

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

where S_1 is an initiator. Or

$$\ldots \rightarrow S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4 \rightarrow \cdots, \tag{7}$$

if S_1 is not an initiator but has the DC.

According to this condition,

RC1) 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.

RC2) Assuming that a system S_1 that has the DC gives rise to a system S_2 having a determinate value, S_2 will continue having other determinate values even after the

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[25] An unsatisfactory alternative is the so-called non-relativistic condition. According to this condition in order for a system S_2 to give rise to system S_3 having a determinate value at a time t, system S_1 (which is a initiator or a system that belong to an SDC) has to be interacting with S_2 and giving rise to S_2 having a determinate value *at the same time t*. This condition is unsatisfactory because the events of systems giving rise to other systems having a determinate value would be space-like separated if they occur in different regions of space (as they should). We could therefore choose a reference frame when one occurs after the other (and not at the same time). Thus, the non-relativistic condition needs a preferred choice of reference frame to work properly, and this is in tension with relativity.

interactions with S_1 *ends, if, while it interacts with* S_1*, a system* S_3 *interacts with it. 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 *having determinate values due to* S_3 *lasts until the interaction with* S_3 *ends.*

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 having determinate values 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 conditions above are still vague because they don't specify the observables involved in the transmission of the DC. I will add the following condition,

RC3) The observable O of a system S_2 *that 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 transmit the DC to* S_3*. By an observable O being monitored by* S_1*, I mean that the eigenstates of the observable O of* S_2 *are decohered by* S_1 *in order for* S_2 *to have a determinate value of O due to* S_1*.*[26] *Furthermore, what I mean is that the states that evolve from the eigenstates of O of* S_2 *should be the ones that can decohere the eigenstates of O' of* S_3*. Thus, they are involved in monitoring the latter observable.*

RC1)-RC3) contain an ambiguity: can a system like S_2 give rise to S_3 having determinate values *only when* S_2 has a determinate value due to S_1 or not? To address this ambiguity, we may add one of the following conditions to the above ones, making the relation between having/transmitting the DC and having determinate values due to having the DC more precise. Let's start with condition A):

> *A) In the case of non-initiator systems, they need to have a determinate value to have the DC and thus transmit it to other systems. So, a system* S_2 *interacting with* S_3 *gives rise to system* S_3 *having the DC and determinate values (being* S_3 *capable of also having them afterwards in the interaction with* S_4*), only when* S_2 *interacted*

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[26] Or that the projector onto these states approximately commute with O.

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, in order for* S_2 *to have and thus transmit the DC to* S_3 *—leading the states that evolve from the eigenstates of an observable O of* S_2*, which decohere (completely) certain states of* S_3 *at t, to give rise to* S_3 *having determinate values under their interaction — the eigenstates of O of* S_2 *should be decohered by* S_1 *at t' where* $t' < t$*. The latter gives rise to* S_2 *having determinate values.*

So, condition A) 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. If that doesn't happen, this SDC will disappear, and it had just two elements, S_1 and S_2. Conditions RC3) and A) are plausible to impose because it makes sense to think that the environment has determinate values in order to decohere/distinguish the states of the target system. I will go back to the consequences of condition A) below.

For reasons of simplicity and due to their privileged status, I have opted for considering that initiator systems don't need to have a determinate value to transmit the DC. However, another possibility is that they have determinate values 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).[27]

Condition A) together with RC1)-RC3) leads to the relativistic condition-A). The relativistic condition-A) 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 particular virus only when they have 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. We will soon see an example that will make this clearer.

Instead of A), another possible alternative condition is the following:

B) Systems don't need to have a determinate value to have and spread the DC, although they may eventually have it. What is necessary to have the DC is that their interactions form an SDC, i.e., a chain of interactions that ultimately traces its

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[27] Initiators might not even exist as systems, but just as events that give rise to a system having a determinate value.

> *origin to the initiators. So, system S_2 interacting with system S_3 can have and transmit the DC, and (perhaps if complete decoherence ends up happening) give rise to S_3 having determinate values, independently of S_2 having a determinate value due to S_1, where the latter has the DC. What is necessary is that S_1 and S_2 interact.*[28]

Condition B) together with RC1)-RC3) (except A)), leads to the relativistic condition-B). The relativistic condition-B) allows us to draw an analogy between the spreading of determinate values and the spreading of a virus where asymptomatic spreaders may exist for a time. Someone can spread a virus even when they don't (at least yet) have symptoms. The symptoms may show up first in the person who contracted that virus and only then in the person who has transmitted it to that person. Analogously, system S_3 can have a determinate value due to S_2, even if S_2 doesn't yet have a determinate value due to S_1 or won't have a determinate value.

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 the DC 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 under local interactions, $S_2^1, S_2^2, \dots, S_2^n$ 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.

I will call the above claim the *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

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[28] *and where (given RC1)) S_2 is interacting with S_1 when S_3 starts interacting with S_2, and so on for the rest of the systems that will interact with S_3, etc.*

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 space-like 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 2) We can also treat the structure of the following DAG as also involving a *common cause* if we treat (for example) S_1 as a whole, neglecting its subsystems (Figure 3).

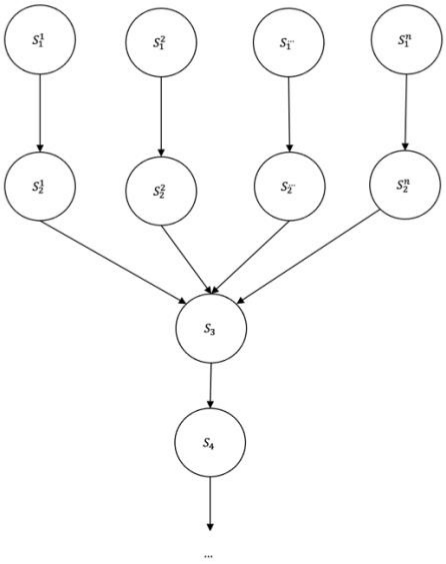

Figure 2: DAG that involves a common effect (i.e., a "collider").

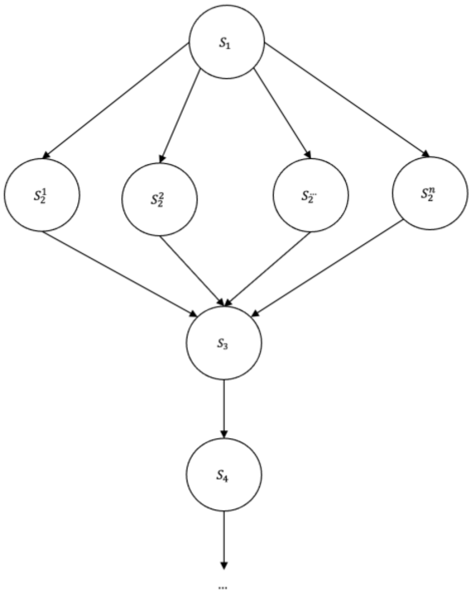

Figure 3: DAG that involves a common cause and a common effect.

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

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 one of the following two things:

-If S is an initiator, S has the DC and can give rise to an SDC or

-If S is not an initiator, S has the DC, being connected with an SDC via its interactions with other systems, and can propagate that SDC.

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. Let's focus on the case where system B doesn't yet have an observable with a determinate value and the DC, where this observable is monitored by A, but (likely) it's on its way to having one because of system A that has the DC. Furthermore, for the sake of simplicity, let's assume that when B and C start interacting, the evolution of the quantum states of B are 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 of 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 $t' < t$.

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.[29] Let's consider the following states,

$$\rho_{BC}^{\uparrow\uparrow}(t) = \sum\nolimits_{i=1,0} \alpha_i^{\uparrow\uparrow} |E_i'^{\uparrow}(t) >_B < E_i'^{\uparrow}(t)| | \uparrow>_C<\uparrow |, \tag{8}$$

$$\rho_{BC}^{\uparrow\downarrow}(t) = \sum\nolimits_{i=1,0} \alpha_i^{\uparrow\downarrow} |E_i'^{\uparrow}(t) >_B < E_i'^{\downarrow}(t)| | \uparrow>_C<\downarrow |, \tag{9}$$

and so on for $\rho_{BC}^{\downarrow\downarrow}(t)$ and $\rho_{BC}^{\downarrow\uparrow}(t)$. We then have the reduced density operator, obtained for example (and ideally) from tracing out the degrees of freedom of A from the pure state that represents the interaction between A, B, and C,

$$\begin{gathered}\rho_{BC}(t) = \rho_{BC}^{\uparrow\uparrow}(t) + \rho_{BC}^{\downarrow\downarrow}(t) + \rho_{BC}^{\uparrow\downarrow}(t) + \rho_{BC}^{\downarrow\uparrow}(t) + Interference\ terms\ (< \\ E_0(t')|E_1(t') >_{A\,SDC}, < E_1(t')|E_0(t') >_{A\,SDC}).\end{gathered} \tag{10}$$

The interference terms are a function of the overlap terms $< E_0(t')|E_1(t') >_{A\,SDC}$ and $< E_1(t')|E_0(t') >_{A\,SDC}$. If $< E_0(t')|E_1(t') >_{A\,SDC} \approx 0$ and $< E_1(t')|E_0(t') >_{A\,SDC} \approx 0$, B has a determinate value of the observable monitored by A that arises from their interaction (i.e., 0 or 1), has the DC, and also (given *RC2)*) continues having determinate values that arise from its interaction with C (i.e., predicted from the eigenvalues of $|E_i'^{\uparrow}(t) >_B$ or $|E_i'^{\downarrow}(t) >_B$ for some i).

The interaction between B and C, will allow C to have a determinate value and the DC if $< E_i'^{\uparrow}(t)|E_i'^{\downarrow}(t) >_B \approx 0$ and $< E_i'^{\downarrow}(t)|E_i'^{\uparrow}(t) >_B \approx 0$ quasi-irreversibly over

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[29] Furthermore, the interaction of A with other systems that belong to an SDC and that allow it to have the DC has ended or nearly ended in such a way that we can neglect their influence.

time while B and C are interacting. Furthermore, C can transmit the DC to other systems of that universe if it interacts with these systems before the interaction with B ends and acquires the DC because of B. The evolution of the interaction between B and C could be further analyzed via the reduced density operator $\rho_C(t)$.[30]

Now, if the above universe obeys A), and instead B decohered C before A decohered B (even if A was just a system with the DC and not an initiator) the interaction between B and C would not give rise to C having determinate values and the DC. On the other hand, if we had a mini universe that obeyed B), the above order wouldn't matter to determine if C obtains the DC from B.

So, the interpretation of what happens during these interactions is the following, system B can both give rise to C having determinate values and allow C to give rise to further systems having determinate values (or to allow C to form a larger system that allows the latter to give rise to other systems having determinate values), having and transmitting the DC to C, because of its interactions with elements of this SDC, more specifically with A, that transmit to B the DC. Moreover, (assuming A)) B only ends up allowing C to have determinate values in interactions with it and others, transmitting the DC to C when B has a determinate value due to A.

Note that B won't be able to allow other systems (such as C) to have the DC if it's fully decohered by A and it doesn't interact with any other system before that. In this case, that SDC would disappear, not propagating to C. Similarly, in the absence of further interactions between C and other systems while interacting with B, this SDC disappears. Given their constraints, we can start seeing that the stability conditions have specific empirical consequences. I will go back to this point shortly.

We can also see that EnDQT provides a new interpretation of Born probabilities. They allow us to predict how SDCs evolve, giving rise to determinate values under the interactions that constitute an SDC. This account of how determinate values arise gives us a way of interpreting the probabilities mentioned in the Born rule.

One might object that the relativistic conditions consider as an idealization the widely used von Neuman interactions in which the environment has both a determinate value, at least initially, that corresponds to an eigenstate $|E_{ready}>$ of a certain

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[30] Note that these multiple states that allow us to infer the determinate values of a system such as B don't necessarily imply that the system B will have multiple different determinate values at the same time (and so on for other systems), i.e., the ones that correspond to the observable that A monitored and the ones that the states of B represent. Rather, we are representing different determinate values of B over time. After A makes those values determinate, we represent the other values of B forward in time via its quantum states. Quantum states are just predictors to infer quantum properties and determinate values. We shouldn't see them as offering literal representations.

observable of the environment and it's uncorrelated with the target system. However, this is not problematic because this interaction is an idealization anyways.

Relatedly, 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. 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 will see below 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 quantum theory (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).

So, considering decoherence and entanglement 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.[31] Moreover, even upon a measurement of a system "in an eigenstate of some observable," the system shortly after evolves into a superposition.[32] 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 I use decoherence 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.

Note that if the mathematical models of decoherence and the mapping of SDCs seem approximate or too flexible and idealized, this should be regarded as a virtue rather than an issue. It instead reflects the fact that the physical world is complex. Decoherence, for example, has been proven very useful, as well as using DAGs to represent different complex relations between systems via tools such as causal modeling.

As we can see with the relativistic conditions, EnDQT seems to be able to surpass the Wigner's friend dilemma because it requires that the friend is not interacting with the elements of SDCs in order for the extended Wigner's friend scenarios to occur. More concretely, for example, Wigner won't be able to reverse the state of the friend plus her system via the application of an intervention represented by the adjoint to the unitary evolution that entangles Alice and her system.

However, Wigner can perform such reversal if the friend is not interacting with elements of an SDC since she cannot give rise to her target system having an observable with a determinate value. Furthermore, it's plausible to consider that she will not experience any determinate values if her lab is isolated or cut out from relevant SDCs that determine her experiences (more on this below). Similarly, her measurement device wouldn't detect the system if it is cut out from interacting with the SDCs relevant for its

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[31] See Wessels (1997) for more details on this issue.

[32] Modulo quantum Zeno-like measurements, which increase the probability of the system being found in the same quantum state in repeated measurements.

detections. This differs from, for example, what a supporter of the Many-Worlds Interpretation (MWI) or a collapse theory would consider in the case of systems like human agents or measurement devices. On top of that, contrary to collapse theories, systems not interacting with SDCs can in principle be in a superposition for an arbitrary amount of time, and no modification of the basic equations of QT is needed.

As I have anticipated above, I would like to end this section by mentioning two predictions of EnDQT. I will discuss further ones in section 4. In the next section, I will explain some additional natural conditions on the structure of SDCs that also need to be imposed for EnDQT to work successfully.

The first prediction is the following, as we have seen above with the example, it’s important to note that in order for a system like C continuing 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., system 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 that is leading the expansion of that SDC at a particular time like C, that SDC will disappear, not being able to give rise to further determinate values.[33]

Second, as we have also seen with the example above, adopting the relativistic conditions-A) generates stricter constraints than the relativistic conditions-B) 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). If we adopt condition A), this condition 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 when Y decoheres Z, where the interaction between X and Y starts first. Otherwise, contrary to what is assumed by A), 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

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[33] 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.

decoherence timescales is needed to see if they agree with the predictions of condition A).

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.[34] Furthermore, the conditions for a quantum system to be considered as a classical controller of another quantum system support condition A).[35]

So far, relativistic condition-A) seems to be favored. Also, it fits well with the order of interaction between systems accompanying the order in which determinate values arise, and with the idea that determinate values and the DC propagate together over interactions over time. It would be interesting if we find further evidence for or even against it, favoring relativistic condition-B) instead, or some other alternative. So, these conditions don’t exhaust the possibilities EnDQT allows for.[36]

2.2. Conditions on the structure of SDCs

We have been relying on decoherence to give an account of how determinate values come about. However, we need to impose further natural conditions on the structure of SDCs to fulfill the goal of surpassing the Wigner’s friend dilemma. Let’s call the SDCs that obey these conditions, early universe robust SDCs (eurSDCs) for reasons that will become clearer. These SDCs should satisfy the following desideratum, which follows from EnDQT’s use of decoherence: the SDCs should explain the success of (real) decoherence in helping account for determinate values. The so-called “real decoherence”[37] is opposed to virtual or reversible decoherence (which is typically considered not to be decoherence at all), where the latter is tied to the reversibility of quantum states (like in the Winger’s friend isolated lab case), and where the former

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[34] 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.

[35] See Milburn (2012).

[36] For instance, another possible and more demanding relativistic condition is what I will call *relativistic condition II*. Briefly and roughly, the difference to the one above is that in order for a non-initiator system X to have the DC, giving rise to a non-initiator system Y having a determinate value when interacting with X and to transmit to Y the DC, the states of X that lead to the decoherence of Y have to be decohered both at the beginning and at the end of the interaction with Y by systems belonging to SDCs, having the DC. If that happens, when X decoheres Y, Y will have the DC and a determinate value in interaction with X. So, only then Y will have the DC, being able to decohere other systems and help feeding this two-step process, allowing other systems to have determinate values.

[37] See, e.g., Zeh (2003) for the distinction between virtual and real decoherence.

occurs in open systems and leads at least to effective irreversibility. For instance, when the lab is open, “the information encoded via quantum states” about the initial state of the friend and/or her system or their interaction quickly and uncontrollably becomes “delocalized” due to the constant “interactions and entanglement” of the system and the friend with *many* other systems becoming inaccessible to Wigner in such a way that he cannot unitarily reverse the process via local operations.

The natural conditions mentioned above hold that the structure of eurSDCs over time and space should be *robust, temporally pervasive, and be such that it justifies the success of unitary quantum theory.*[38] These conditions give rise to a series of hypotheses that need to be precisified in future work.

The structure of eurSDCs should be *robust* in the sense that the elements belonging to them should be distributed throughout our universe in such a way that what is represented via the irreversible decoherence models mentioned above,[39] involves systems that are connected/interacting with eurSDCs.[40] This allows EnDQT to use open-environment decoherence as a tool because the environments that give rise to decoherence will be connected with eurSDCs. This condition is plausible since an environmental system that is large or has many subsystems and is typically behind (what we usually call) the irreversible decoherence processes will be more likely connected with SDCs. Since they are many or the system is large, they are an easier target for systems belonging to SDCs. Also, these subsystems will be more easily propagators of SDCs because they are more likely to develop interactions between each other and other systems. Similarly, in the case of a large system with other systems (disregarding the subsystems of the former). On top of this, the way SDCs through spacetime mimic how entanglement and decoherence with its local interactions spreads. So, it’s plausible to consider that whatever happens in the process of irreversible decoherence that gives rise to determinate values across spacetime (plus the assumption of indeterminism) is grounded on the SDCs.

Note that, like the events that give rise to decoherence, eurSDCs should be distributed such that they leave space for the independent existence of a sufficient number of systems that don’t belong to them, allowing them to evolve and persist over

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[38] One weaker hypothesis would just consider that these conditions hold in our region of the universe. This possibility deserves further exploration. I have adopted the one above because it is the simplest.

[39] When the system is in an eigenstate of the measured observable, its state formally is at least locally reversible, but as mentioned above, those situations should be seen as idealized.

[40] Seeing what could happen if this hypothesis doesn’t hold and what sort of predictions arrive from it deserves future exploration. See also section 4.

time without being influenced by SDCs and also allowing us to shield them from the SDCs at least to a certain extent. More concretely, SDCs shouldn't be completely robust and pervasive; otherwise, we wouldn't explain why we see interference and other quantum effects throughout the universe and why we manage to isolate (with some success) quantum systems.

It might be objected that the above conditions show that EnDQT is adding too much on top of standard QT. However, note that other approaches of QT implicitly assume these conditions and should be rather seen as natural. Imagine that every system was decohered in a MWI multiverse all the time, given some initial conditions and laws. We thus could end up not being able to see interference anymore or rarely. On the other hand, imagine a MWI multiverse with no interactions between systems, or no interactions between us and our measurement devices. In these multiverses there wouldn't exist measurement outcomes or we wouldn't be able to know about the measurement outcomes, respectively. In a sense, with the robustness condition, I am rendering explicit what is implicitly assumed by many quantum theories.

The *temporal pervasiveness* aims to satisfy the following desideratum: like decoherence, eurSDCs should help explain the widespread success of some aspects of classical physics in accounting for diverse phenomena in certain contexts, where importantly, classical physics is based on systems represented by variables that assume determinate values. According to our current best science, classical physics apparently 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 eurSDCs started via initiators that are already present in the early universe. Then, eurSDCs expanded over spacetime to explain why determinate values and classical physics continued to be successful in a specific domain. eurSDCs draw an interesting parallel with modern cosmology. Like the origin of matter or spacetime at the *big bang*, there was also the origin of determinacy in the early universe. Furthermore, like the expansion of the universe, there is also the expansion of determinacy.[41]

SDCs should *justify the success of unitary quantum theory* by explaining why we can (at least in principle) unitarily manipulate any isolated quantum systems. In

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[41] If these analogies are physically related or are just analogies deserves further research. See also below and section 4.

other words, why, in principle, arbitrary systems could be placed in a superposition for an arbitrary amount of time.

The robustness of eurSDCs already helps justifying the success of unitary QT to some extent, i.e., the (at least so far well confirmed) ability to in unitarily control arbitrary systems for an arbitrary time. However, eurSDCs still have to have certain kind of initiators that explain such success. There are conceivable universes with 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 the lab, and more stochastic processes.

So, let's examine what kinds of initiators could explain the success of unitary QT in the above sense. There are at least six options regarding what kinds of initiators could exist in a universe: *abundant and strongly interacting*, *weakly interacting or rare and manipulable*, *rare and not directly manipulable, not rare and not directly manipulable*, *not existent anymore, or be a useful fiction*. Let's roughly evaluate each one of the options.

If initiators were *abundant and strongly interacted* with other systems in general, it would likely challenge the claim that arbitrary systems can be placed in practice in a superposition for an arbitrary amount of time. They would likely give rise to abundant SDCs, and it's hard to see how we could shield the rest of the systems from the influence of SDCs. If unitary QT is correct, it doesn't seem that initiators are abundant and strongly interact with other systems. Suppose they are *weakly interacting or rare and manipulable*. In that case, it seems more likely that we could place arbitrary systems in a superposition for an arbitrary amount of time because isolating systems from the initiators is easier.

However, there is a genuine possibility that they are inaccessible to being ever manipulated. The privileged position of initiators, which start acting at the beginning of the universe and continue acting, makes this hypothesis plausible. So, they may not be manipulable and rare. There might even just exist a single initiator in the universe. The challenge of assuming, for example, only one initiator is that it's harder to establish how this single initiator can spread determinate values widely throughout the universe.

However, this challenge may be dealt with if we have SDCs well-connected with this initiator.

The existence of either one or many more than one initiators may have consequences. If we have only one initiator, unless this initiator is 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).[42] More than one initiator may fix this asymmetry, but the initiators wouldn't be so rare in this case. If we have many initiators, it's harder (but not impossible) to argue that these initiators are inaccessible.

Initiators may also simply *don't exist anymore,* for example, existing 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).

It's an empirical question which one of these hypotheses is correct. Here, I will not definitely opt for one or the other picture, except that I think it's unlikely that the hypothesis that initiators are abundant and strongly interacting is the right one. Due to their simplicity and explanatory power, my favorite options are the one where they are rare and not directly manipulable, the one where they don't exist anymore, or just a useful fiction, being perhaps just initiative events. It would show why we don't need to worry about the existence of two kinds of systems, where the initiator ones might never be directly observable or manipulable. Furthermore, being initiators or initiative events special is not problematic because we expect that the early universe will have some special physical phenomena.

How to find who are the early universe initiators or initiative events? A heuristic to establish the initiators or initiative events is by looking at the earliest systems that gave rise to decoherence of other systems in the early universe. For instance, it is hypothesized that all structure in the universe can be traced back to primordial fluctuations during an accelerated (inflationary) phase of the very early Universe.

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[42] It would be interesting to explore this further. Note that this hypothesis is compatible with of other kinds of initiators.

Certain models of decoherence were devised to account for the decoherence of these cosmological fluctuations.[43] 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 an (basically classical) non-symmetric state, which can be used to explain the quantum origin of cosmic structure.[44]

As we can see, these different possible hypotheses don't challenge the claim that, if we adopt EnDQT, we can place in principle arbitrary systems in a superposition for an arbitrary amount of time and, more generally, that we can surpass the Wigner's friend dilemma.

Now that we have seen what conditions in the structure of the SDCs that we may assume, let's see in more detail how EnDQT surpasses the Wigner's friend dilemma.

3. Surpassing the Wigner's friend dilemma

In order to realize an extended Wigner's friend scenario, i.e., a scenario where Wigner is capable of reversing the state of the friend plus her system, the isolation per se is insufficient. It needs to be disconnected from SDCs. Given the above conditions and hypotheses, since decoherence in open environments is related to systems that are connected with SDCs, by shielding the systems from decoherence, we are actually shielding it from SDCs. In this way, the friend cannot give rise to the system having determinate values, and we can deal with the Wigner's friend scenario without assuming relationalism and other approaches to QT.

Moreover, as I have mentioned, we can do so without any spontaneous collapse process. In principle, we can place arbitrary systems in superpositions during arbitrary times as long as we manage to shield them from the members of the SDCs. This might be a challenge for larger systems if not impossible in practice. However, it's not impossible in principle. Given the conditions on the SDCs, it is as difficult as shielding systems from the effects of decoherence. Note that there is an indeterministic process going on during interactions. Still, such an indeterministic process is not *a collapse* like in collapse theories, given EnDQT's non-representationalist stance towards quantum states. An indeterministic process of this kind is also assumed by relationalist theories, except the many-world interpretation, although in the case of EnDQT, determinate

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[43] E.g., Kiefer & Polarski (2009).

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

values of systems are absolute. On the other hand, in relationalist theories, they are always relative to something.

Furthermore, EnDQT does not conflict with relativistic causality and doesn't involve retrocausality or superdeterminism. First, like in standard QT, the Hamiltonians of interaction (should) represent local interactions. Second, 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) or that there is some preferred reference frame. EnDQT doesn't modify the equations of QT, and so it can be rendered Lorentz-invariant, and thus it can be a local theory in this related latter sense.

As I will argue in more detail in upcoming work,[45] EnDQT is able to provide a local explanation of Bell correlations. A widely accepted version of Bell's theorem involves the factorizability condition:[46]

$$P(AB|XY\Lambda) = P(A|X\Lambda)P(B|Y\Lambda). \tag{11}$$

The variables A, B, $\boldsymbol{\Lambda}$, X, and Y concern events embedded in a Minkowski spacetime. A and B are the variables that represent the different measurement results of Alice and Bob, X and Y are the different possible choices of measurement settings for Alice and Bob. $\boldsymbol{\Lambda}$ represents some set of (classical) "hidden" variables in the past lightcone of A and B (see also Figure 4), representing the information about the pair of quantum systems, contributing to the representation of the common causes of the correlations between X and Y.

This condition is seen by Bell as a consequence of three assumptions:[47]

-The cause of a certain event is in its temporal past (no-retrocausality),

-The relation of temporal order is invariant under Lorentz boosts (locality),

-The (what I will call) classical Reichenbach's Common Cause Principle (CRCCP).

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[45] Pipa (forthcoming-b).

[46] Bell (2004b).

[47] See Myrvold et al. (2021) and references therein.

Briefly, the CRCCP states the following: let's suppose that events A and B are correlated, then either A causes B, or B causes A, or both A and B have common causes $\boldsymbol{\Lambda}$, where conditioning $\boldsymbol{\Lambda}$, 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 latter. The CRCCP can be seen as a consequence of the classical causal models (CCMs).[48] As we will see, these models allow us to see *why and when* we should use that the CRCCP and the factorizability condition to represent relations of influence between entities with a causal structure that respects relativistic causality.

Besides assuming that all the common causes of the variables are included in the model, causal models assume the (what I will call) Classical Markov Condition (CMC) and faithfulness (more on this below). Roughly, the CMC connects the causal structure provided by some theory represented by a DAG with conditional probabilistic statements. The CMC is the following,

let's assume we have a DAG G, representing a specific 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.

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[48] Such derivation uses the d-separation theorem. We will not derive it here, but see Hitchcock & Rédei (2021).

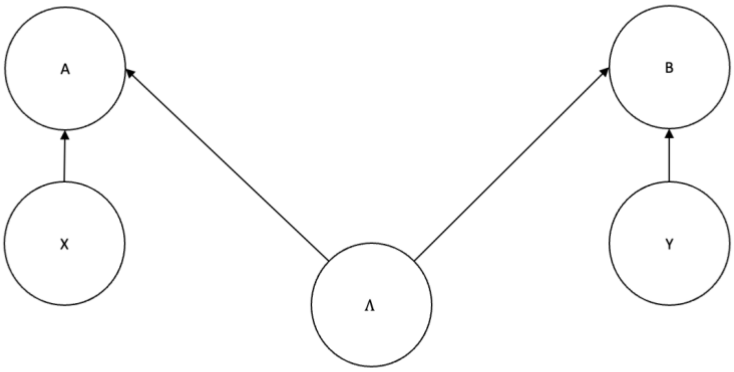

Figure 4: DAG of the common cause structure of Bell correlations, which respects relativity and tries to be correctly represented via classical causal models. This causal structure respects relativistic causality because X or A doesn't influence Y or B, and vice-versa, where these events may be spacelike separated. Moreover, no other variables influence the variables A, B, X, or Y, or they don't influence anything else. So, there are no so-called retrocausal or superdeterministic causal relations.

Consider faithfulness as the assumption that all the probabilistic independence relations among the variables in $\boldsymbol{V}$ have to be a consequence of the CMC.[49] The CMC for the above DAG, which respects relativity, allows us to derive the following equation together with the assumption of faithfulness (I will denote certain regions of spacetime, the related nodes, and variables whose values may be instantiated in those regions using the same letters),

$$P(AB|XY) = \sum_{\Lambda} P(\Lambda)\mathrm{P}(\mathrm{A}|\mathrm{X}\Lambda)\mathrm{P}(\mathrm{B}|\mathrm{Y}\Lambda). \qquad (12)$$

I will consider that we should accept the CRCCP and the factorizability condition to represent causal relations if we accept CCMs and their assumptions to represent those relations, since the former is a consequence of the later, and the latter has been shown to have fruitful empirical applications.

EnDQT responds to Bell's theorem *by rejecting the applicability* of the CMC to represent causal relations between quantum systems, and hence the CRCCP and the factorizability condition to represent those relations. More concretely, the CMC and CCMs like all models, have a certain domain of applicability.[50] This domain is different

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[49] See Hitchcock (2022) for more details.

[50] 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).

from the domain that involves relations of influence between quantum systems according to EnDQT, and so the scope of CMC should be limited to the domain of those entities. How to find this domain in order to see the limits of the CMC?

One way is by examining a plausible and precise justification for the CMC, which offers us a way to understand the commitments of these models. Pearl and Verma (1995) have provided a precise justification of the CMC structural equations that allows us to understand these commitments and provides evidence for its domain of applicability. Structural equations concerns directed deterministic relationships between variables.[51] Roughly, in acyclic structural equations, we have a set of endogenous variables V_j (i.e., variables whose values are determined by other variables in the model) that depend on their endogenous parent variables $Pa(V_j)$ (which correspond to parent nodes in the DAGs and also assume determinate values), plus a probability distribution P' over exogenous variables U_j (i.e., variables whose values are determined from outside the model), establishing a deterministic relationship between them $V_j = f(Pa(V_j), U_j)$. Importantly, the way $f(Pa(V_j), U_j)$ determines V_j is not represented via QT. Pearl and Verma (1995) proved that if we have a DAG G' representing the causal structure on V_j , the probability distribution P on V_j that results from the marginalization of the noise sources if the error variables U_i are probabilistically independent in P, will respect the CMC with respect to the DAG G'.

As we can see, this justification doesn't consider the existence of systems with indeterminate values *represented via QT* that participate in causal relations, and which give rise indeterministically to determinate values. 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.

We could hypothetically assign a determinate value to the whole state $|\Psi>$ of 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

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This can't be right because EnDQT is a counterexample to such claims. 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 (what I will call) classical Reichenbach principle (by contrast with the quantum one that is a consequence of quantum Markov condition, see below). This principle 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.

[51] Pearl (2009); Pearl & Verma (1995), Hitchcock (2022).

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.

Also, like we can see through the structural equations, those relations of influence are not described by standard QT as viewed by EnDQT, i.e., unitary evolution, decoherence, and determinates values arising indeterministically when we have interactions with members of an SDC. So, given these assumptions underlying the justification for the CMC, EnDQT finds CCMs inappropriate to represent or infer causal relations between quantum systems.[52] It seems difficult to see to see how to precisely justify the CMC without the above assumptions that EnDQT denies.

However, we can go further in terms of presenting evidence for why CCMs are inappropriate. A complementary way of finding the limitations of the domain of applicability of the CCMs is by examining the more general models that putatively represent causal relations in the quantum domain, i.e., quantum causal models (QCMs).[53] I will analyze how QCMs makes certain assumptions that CCMs don't make, and that that these assumptions concern the quantum domain according to EnDQT. QCMs are putatively more general because they reduce to classical ones in a certain 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 quantum causal models interpreted via EnDQT.

Furthermore, QCMs will also have the role of showing how EnDQT provides a local causal explanation of Bell-type correlations. Rather than accepting the CMC to help representing causal relations between quantum systems, EnDQT accepts instead

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[52] So, note that EnDQT also rejects outcome independence and parameter independence associated to the factorizability condition (Jarrett, 1984) by rejecting their applicability to represent causal relations between quantum systems. So, we shouldn't infer any causal relations from those conditional independencies.

[53] EnDQT could offer the possibility of a deterministic version not presented here, where the SDCs evolve deterministically. In this case, there would exist a chancy process in the early universe that would select an initiator among many. Then, we would have a unitary process that would evolve this initiator, and the interactions of this initiator, which would deterministically 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, see below) as representing causal relations between quantum systems (see above). Relatedly, we would also violate parameter independence ($P(A|X,Y,\mathbf{\Lambda}) = P(A|X,\mathbf{\Lambda})$ and $P(B|X,Y,\mathbf{\Lambda}) = P(B|Y,\mathbf{\Lambda})$), since initiators would serve as the hidden variables $\mathbf{\Lambda}$ that would give rise to the deterministic process.

the *quantum Markov condition* (QMC) provided by QCMs to help representing those relations.[54]

QCMs consider that each node in the causal DAG concerns a possible locus of interventions on the properties of a system, and it is associated with specific input and output quantum states. More concretely, each node is associated with a set of CP (completely positive) maps,[55] 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 associated quantum state can change under local interventions, which correspond to the preparation of quantum systems, transformations, measurements on them, etc.

The QMC[56] is defined through the causal DAG where the edges of the DAG are associated with quantum channels or completely positive trace-preserving (CPTP) maps,[57] which factorize analogously to conditional probabilities in the CMC, and the nodes are associated with input quantum system in a given state serving as causes that aren't manipulated but are kept fixed (more on this and an example below, see eq. 13).

Causal influences are typically understood by the possibility of "signaling" from one node to another when all the relevant systems participating in causal relations are included.[58] Signaling between node X and node Y should be understood as occurring when a variation on the choice of certain instruments/interventions performed at node X can vary the probabilities of an outcome k concerning measurements performed at node Y.[59] The causal structure represented by QCMs is typically understood as representing 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.[60]

It's reasonable to worry that, like in other quantum theories such as Bohmian mechanics, 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

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

[55] 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., $\varepsilon(\rho) \geq 0$ whenever the density operator $\rho \geq 0$, and c) completely positive. When only b) and c) are fulfilled, we have a completely positive (CP) map rather than a CPTP. A CP-map can be associated with a positive operator-valued measure (POVM). See Nielsen & Chuang (2011).

[56] Note that QCMs currently are only formulated for finite dimensional Hilbert spaces. However, this isn't in principle a fundamental limitation.

[57] See previous footnote.

[58] The reason causal influence is not simply defined as the possibility of signaling, unless all causal relations are taken into account, is because there could exist unobserved variables in such a way that there is influence, but there doesn't seem to exist signaling (Barrett et al., 2019).

[59] See the Born rule in the footnotes further below to see how this can be expressed more precisely.

[60] See footnote below for a complete statement of the QMC.

hidden non-local influences that cannot be used for signaling, we don't need to have this worry. Furthermore, using the concept of signaling and an operationalist language is unnecessary. Relatedly, we don't need to adopt an account where the possibility of signaling, or causation is irreducible. We can rather consider that systems in a region *possibly 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 in more detail how adopting the point of view of EnDQT, QCMs provide a local causal (non-relationalist) explanation of Bell correlations. 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. Consider below how, via the QMC, faithfulness,[61] and a version of the Born rule, we can represent the local common cause structure that explains Bell correlations (Figure 5),

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

We can see that the above expression is analogous to the CMC (eq. 12) applied to the Bell scenario. Let's then interpret and explain it (see also Figure 5).[62] Let's assume that ρ_Λ is, for example, a singlet state assigned to systems at the source. It represents, together with the appropriate observables, the systems prepared at the source with indeterminate values of spin-p (for all p, where p ranges over all possible directions of spin). Each system represented *via* the quantum state ρ_Λ is measured by Alice and Bob. These measurements are represented via the Positive Operator-Valued Measurement (POVM) $\tau_A^{x|s\,SDC}$ in the case of Alice, where s is her random measurement choice, and x is her outcome/the determinate value of S, and via $\tau_B^{y|t\,SDC}$ in the case of Bob that represents the parallel situation. The system of Alice evolves locally to region A, where Alice also influences the outcomes that arise in A. This possible influence is represented via the unitary evolution (or more precisely quantum channel[63]) $\rho_{A|\Lambda}$, and the analogous thing happens in the case of B, where this is

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[61] We also get an analogous definition of faithfulness but associated with the factorization of quantum channels.

[62] See also the footnotes further below.

[63] This is completely positive trace-preserving map (CPTP) written in CJ-form, i.e., using the Choi-Jamiolkowski (CJ) isomorphism, which allow us to write this map as positive semi-definite operator.

represented via $\rho_{B|\Lambda}$. More concretely, $\rho_{A|\Lambda}$ and $\rho_{B|\Lambda}$ are identity channels that acting on the density operator ρ_{Λ} of the systems in region Λ *transport* them to regions A and B, respectively, representing the possible influence between these regions. So, each copy of that quantum state will represent the system that is in region A or B, where each system will be measured locally by Alice and Bob, which belong to local SDCs. The superscript SDC means that the systems measured by Alice and Bob will become part of an SDC due to the measurement devices of Alice and Bob that also belong to SDCs.[64]

Note that by adopting EnDQT's view of quantum states, we don't consider that the (local) measurement of Alice on the system represented by ρ_{Λ} affects the system of Bob and Bob, and vice-versa. We aren't reifying quantum states. Moreover, the channels $\rho_{A|\Lambda}$ and $\rho_{B|\Lambda}$ allow us to represent the local unitary evolution of systems between spacetime regions, which Alice and Bob subsequently measure, and how systems with some indeterminate values prepared at the source (locally) influence some determinate values arising in the future (e.g., s and t above). We can use ρ_{Λ} in the different regions 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 $\rho_{A|\Lambda}$.

So, (cutting a longer story short[65]) the expression above represents the above common cause local structure that gives rise to Bell correlations. It tells us that in the EPR-Bell scenario case, we have systems S and S' at some time with quantum indeterminate values at the source plus some other systems (i.e., Alice's and Bob's measurement devices with their different settings) that have a complete influence in S

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[64] The QMC representing a certain causal structure is written via the process operator σ, which is a CPTP map written in the CJ-form (see the previous footnote). It is stated in the following way: a probability distribution P is compatible with a DAG G if and only if it satisfies the classical Markov condition. Analogously, a process operator $\sigma_{A_1,\ldots,A_n}$ is compatible with a DAG G with nodes $A_1, \ldots, A_n$, 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 $\sigma_{A_1,\ldots,A_n} = \prod_i \rho_{A_i|Pa(A_i)}$. The requirement that CPTP maps in the CJ-form must commute can be understood via the quantum theoretical/probabilistic constraints of having positive operators because the product of two positive operators is positive if and only if they commute. Note that $\rho_{A_j|A_i} = \rho_{A_j^{input}|A_i^{output}}$ through 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. Note that each (quantum) node A_i is associated with an income Hilbert space $\mathcal{H}_{A_i^{input}}$ and an output Hilbert space $\mathcal{H}_{A_i^{output}}$, corresponding to the incoming and outgoing system, and each edge is associated with an output Hilbert space of one node and the input Hilbert space of another node. Moreover, $Tr_A \rho_{AB|C} = \rho_{B|C}$ and $Tr_B \rho_{AB|C} = \rho_{A|C}$. The process operator respecting the QMC and the operators representing certain measurements can then serve as input to a specific Born rule (see eq. 13) to yield the predictions of certain outcomes k, given certain interventions s, $P(k_{A_1}, \ldots, k_{A_n} | x_{A_1}, \ldots, x_{A_n}) = Tr_{A_1,\ldots,A_n}[\sigma_{A_1,\ldots,A_n} \tau_{A_1}^{k_{A_1}|x_{A_1}\ SDC} \otimes \ldots \otimes \tau_{A_n}^{k_{A_n}|x_{A_n}\ SDC}]$. In the case of the DAG in Fig. 4, $\sigma_{AB\Lambda} = \rho_{\Lambda} \rho_{A|\Lambda} \rho_{B|\Lambda}$.

[65] Pipa (forthcoming-b).

and S’ having certain determinate values in regions A and B at some later times, influencing the probabilities that these determinate values arise. So, 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 explanation of quantum correlations.

We can represent this situation via the following 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 relations:

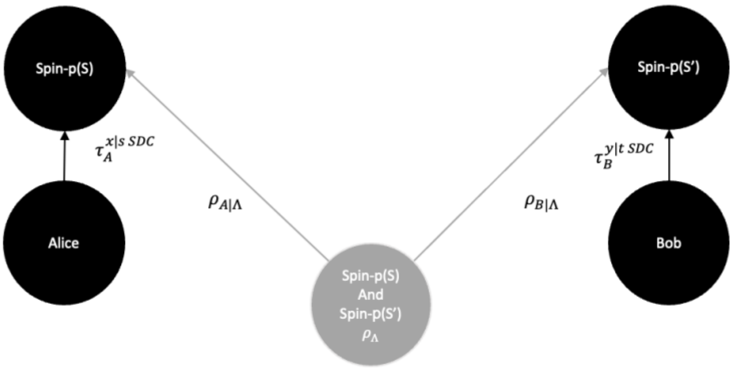

Figure 5: DAG of the common cause structure of Bell correlations, which respects relativity and is local, being represented by quantum causal models as interpreted by EnDQT.

As we can see, QCMs consider that common causes can have *indeterminate values represented via QT*. Importantly, contrary to CCMs and in agreement with EnDQT, for QCMs explicitly common causes don’t have a probabilistic model independently of the interactions with Alice or Bob. Furthermore, the relations of influence are 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. So, it shows that QCMs have the right domain of applicability to represent quantum causation according to EnDQT,[66] and that the domain of applicability of CCMs is limited according to this theory to account for such causal relations.

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[66] There is a way of further justifying the QCMs and the QMC based on unitary evolutions via quantum structural models, and which doesn’t make the above assumptions behind CCMs. See Barrett et al. (2019) and Suresh et al. (2023). More on this in Pipa (forthcoming-b).

A QCM for the extended Wigner's friend-like scenarios could be elaborated. Suppose we have two friends in isolated labs in each wing, and one Wigner next to each lab. The evolution of the systems to each wing and the "measurements" of each friend would be treated via a unitary channel that entangles each friend and their target system (with no collapse happening), where these channels would also be used to represent the causal structure of this situation. So, we would treat each friend and their target system as being in an entangled superposition of states at each wing. Then, the Wigners in each wing can measure these states. We could then calculate the probabilities for these measurement outcomes for the different measurement settings, given a certain common cause causal structure.[67]

It doesn't seem that any current (unitary) quantum theories, including relationalist ones, can use QCMs in this local and non-operational way to give a local causal explanation of Bell-type correlations like in Figure 3. So, EnDQT seems to be the first one to 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 basic 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. Moreover, QCMs in the single-world cases (at least) should be modified to account for these multiple varying perspectives. QCMs don't take into account that variation. The causal structure will therefore be different and should take into account their meeting or at least its variation.

So, to my knowledge, EnDQT is the first and only local non-relational quantum theory. Allowing QCMs to provide a local explanation of Bell correlations and extended Wigner's friend scenario correlations (with no necessary modifications), being the first approach to unitary QT that does that while clearly facing the Wigner's friend dilemma, is another advantage of EnDQT.

One might object that the EnDQT provided here doesn't offer a clear ontology since talking about systems and determinate or indeterminate values makes it unclear what we are talking about in the world. EnDQT offers the possibility of different ontologies that reject the view that quantum states are entities in the world. We could think of systems with determinate values as "flashes" occurring under particular interactions in spacetime with nothing happening in between the preparation and the

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[67] More on this in Pipa (forthcoming-b).

measurement of the system. However, I prefer a more *realist* ontology where flashes are less fundamental and something happens in between those flashes, and where the world is filled with matters of fact even when systems are not interacting. 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.

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[68] $S(\hat{\rho}_S(t))$ of $\hat{\rho}_S(t)$ over lnN, where N is the number of eigenvalues of $\hat{\rho}_S(t)$,

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

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, unstably 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 be stably differentiated. These properties would quickly become stably differentiated if the appropriate quantum properties of S' became stably differentiated while S' appropriately interacts with S. 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

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

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 is the position that

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[68] 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.

a property P* is the property of having some other property P in a certain situation or having specific features.[69] 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 *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 unstably differentiated quantum property D*-P to an arbitrary degree D*.

Forthcoming work,[70] 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. 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 with different degrees of differentiation that change over time and, via interactions, change the degree of differentiation of one another.[71]

I will end this section by replying to an objection. One might object that in some extended Wigner's friend theorems,[72] 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

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

[70] Pipa (forthcoming-a).

[71] 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.

[72] See Bong et al. (2020).

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 what is claimed by EnDQT. Perhaps 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 quantum theory.

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.[73] 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 adoptions 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.[74] Assuming that such quantum agents have experiences, many realist interpretations of quantum theory 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,[75] 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.

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[73] 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.

[74] See Wiseman et al. (2023) for a proposal.

[75] See most prominently, Wallace (2012, section 10.3).

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 single world relationalist views, such as Relational Quantum Mechanics, 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.

4. Conclusion and other future directions

I have proposed EnDQT and argued how it surpasses the Wigner’s friend dilemma by considering that systems absolutely have determinate values only while interacting with other systems of SDCs. I have argued that it’s not in tension with relativistic causality, contrary to other quantum theories, and without being a relationalist view. On top of that, EnDQT doesn’t modify the dynamical equations of quantum theory, and thus, in principle, arbitrary systems can be placed in a superposition for an arbitrary amount of time. Also, EnDQT is the only (unitary and non-relational) QT that is able to give a local causal explanation of Bell correlations and the extended Wigner’s friend scenario correlations. I thus have shown that we can have a coherent (interpretation of) quantum theory that doesn’t modify its equations or add hidden variables, is not in tension with relativity, and provides a local causal explanation of Bell-type correlations without measurement outcomes varying according to perspectives or worlds.

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 definitely 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. 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. Relatedly, EnDQT might be disconfirmed. If we cannot empirically find or it is even impossible to hypothesize coherently such eurSDCs with some stability conditions (not necessarily the one proposed here), this could offer means to disconfirm EnDQT.

In order to achieve such confirmation or disconfirmation, we need to further develop EnDQT, by further specifying the elements and structure of SDCs, and building more concrete models. Furthermore, since EnDQT relies on particular hypotheses, future work should develop them further so that we can test get more concrete predictions out of it. I will elaborate on various tests below.

A simpler test 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. Relatedly, another development would be finding ways to further test the relativistic condition-A) with its distinct predictions discussed in section 2.2, as well as testing and proposing new ones.

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 eurSDCs hold. As a reminder, the hypotheses concern the robustness of eurSDCs, their temporal pervasiveness, and their structure, which is such that it explains the success of unitary quantum theory. This test would press us to make the hypotheses concerning the eurSDCs 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 ends, 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. 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[76] 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 would be the one where the initiators didn't interact with the other systems, or nothing else interacted to form SDCs. Future work should investigate that.

In this article, I have made some simplifications. I have assumed that SDCs and initiators are represented via (non-relativistic) quantum theory, and that we just need to use decoherence and DAGs to account for how determinate values arise. In principle, we could extend EnDQT to the relativistic quantum theoretic regime. However, perhaps we need to be more radical and consider other kinds of SDCs and initiators in order to solve issues in other areas of physics, such as the integration of quantum theory with gravity. So, perhaps we should seek SDCs associated with spacetime and gravity.[77] Indeed, this is a possibility given that (at least the first) initiators like the origin of gravity may date back to the beginning of the universe, given the common expanding nature of spacetime and SDCs, and given the widespread nature of gravity. Future work should investigate that.

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[76] Albert (2000).

[77] Perhaps these SDCs should be directly related with "classical" gravity (related in some ways but not necessarily the same as gravity causes collapse theories).

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