Beyond the Wigner's friend dilemma:
A new indeterminacy-based quantum theory

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Abstract

I propose a novel local, non-relational single-world, non-collapse, non-superdeterministic/non-retrocausal (interpretation of) quantum theory called Environmental Determinacy-based or EnD Quantum Theory (EnDQT). In contrast to some quantum theories, EnDQT is not in tension with relativity and provides a local causal explanation of Bell correlations. Additionally, unlike collapse theories, in principle, arbitrary systems can be placed in a superposition for an arbitrary amount of time. Furthermore, it provides a series of novel empirical posits that may distinguish it from other quantum theories. According to EnDQT, some systems acquire determinate values at some point in time, 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] in which relativistic considerations are taking into account, and a tension between unitary quantum theory and the Born rule is identified. This 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,

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

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 system in the z-direction.[6] QT leads to the prediction that he will obtain spin-z up with

[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 of different quantum theories.
[5] See, e.g., Zurek (2003).
[6] Let's assume that the interaction between Alice's measurement device and her system is modelled in the following way, $|\text{Alice}_0>_A (\alpha|\uparrow>_{S_A}|\downarrow>_{S_B} + \beta|\downarrow>_{S_A}|\uparrow>_{S_B} \rightarrow_{\hat{U}} \alpha|\text{Alice}_\uparrow>_A|\uparrow>_{S_A}|\downarrow>_{S_B} + \beta|\text{Alice}_\downarrow>_A|\downarrow>_{S_A}|\uparrow>_{S_B}$. This

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, QT, if not disambiguated, can yield two contradictory predictions. The predictive consequences of this ambiguity at the heart of QT can be magnified and precisified via different no-go theorems.[7] If we want to deal clearly 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;

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;

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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's theorems.

[8] See, e.g., Kent (2015).

C) 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;

D) 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;

E) 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)-E) 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 doesn't adopt any of the options A)-E), so it might not suffer from any of their issues. So, I will argue that EnDQT is a local, non-relationalist, no-collapse, non-

[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).

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 unitary evolve indefinitely.

The key novelty of EnDQT is a network structure that allows systems to give rise to 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 determinate values under interaction with other systems, where these later systems can lead to other systems 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 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 causal structure that explains locally Bell correlations is the one given by Quantum Causal Models,[15] as I will explain later (section 4). I will also mention that 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 only (unitary) QT that can use quantum causal models to give a local (non-relationalist) common cause account of the extended Wigner's friend scenarios and Bell correlations unproblematically, i.e., facing the Wigner's friend dilemma.[16] In relationalist theories, agents have to meet afterward for their (relative) outcomes to be shared between them, which has to be accounted for by a relationalist causal structure. Moreover, it's unclear how to use these models when outcomes vary according to the perspectives. So, EnDQT is the QT that fits better with quantum causal models. This is a great benefit of this view, given the growing literature in this area and the virtues of this tool.

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

[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.

interpretation of the quantum state).[17] Nevertheless, I will favor a more fundamental ontology of systems as collections of quantum properties that come in terms of different *degrees of differentiation* and 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 belong to SDCs.

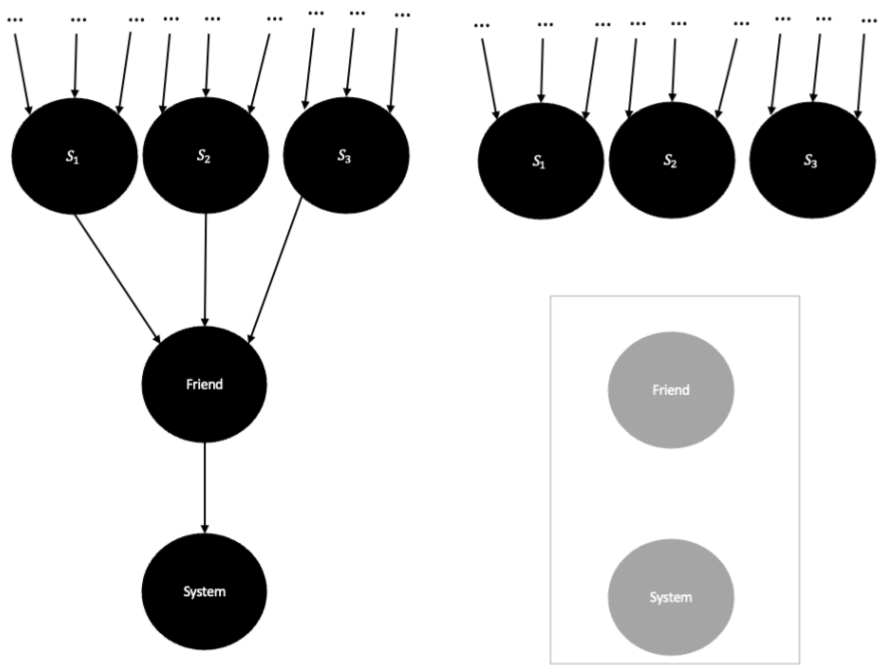

Figure 1

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 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).

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

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 in a way with elements of an SDC represented by 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 suggests that initiators are either inaccessible to direct manipulation, accessible but rarer, or do not exist anymore. The presence of initiators within isolated labs would not allow Wigner to unitary control the contents of the lab because initiators can give rise to other systems having determinate values, independently of their interactions with other systems. Given enough time, initiators, or SDCs formed through them, would likely destroy the superposition of the target system inside the lab. Considering the in-principle success of unitary quantum theory and the capacity of isolating systems of arbitrary sizes to have coherent control over their degrees of freedom, both of these hypotheses seem to hold. 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. To simplify, I will assume non-relativistic QT and the Schrödinger picture Hilbert space-based finite dimensional QT.

2. EnD Quantum Theory: the basics

I will start by giving a brief standard explanation of decoherence,[18] and some assumptions I will make. Let's consider a system S in the following states,

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

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 that constitute system E. For simplicity, throughout this article, I will assume this kind of evolution of the system under interactions.[19] 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,

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

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

[19] 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.

The distinguishability between the different states of the environment 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 $S + E$,

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

Under an appropriate Hamiltonian 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,

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

I will say that *S was decohered by system E, or the states of S were decohered by the states $|E_i(t) >$ of E or by system 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* 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.

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 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, we will be interested in an ontology constituted fundamentally by local systems and their local interactions, and hence on observables that act only on the states of a system localized in a single region of spacetime.[20] Systems have determinate values when the 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, 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.[21] How do we represent and establish that a system is interacting with another one? I will represent it in the following standard way:

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'.

Moreover, I will consider that a

A necessary condition (but not sufficient for all kinds of systems) for a system X interacting with system Y to give rise to Y having a determinate value v of an observable O at t is for X to decohere Y at t. In the situations that we will be concerned with here, observable O has to approximately commute with the reduced density operator of X, which is a *consequence of the decoherence of X by Y at t, where the eigenvalues of O include v.*

I propose that two kinds of systems constitute the network that gives rise to determinate values, which I have called the stable differentiation chain (SDC). The first kind consists of initiator systems, which are a kind of special systems that are at the

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

[21] The eigenstates of the non-dynamical observables, which are never observed in a superposition, are typically said 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.

basis of allowing all other systems to give rise to determinate values and thus start the SDCs. More concretely and generally,

Initiator systems or initiators X can give rise to other systems Y having an observable O with a determinate value v in interactions with them, independently of their interactions with other systems. In order to do that, it's necessary and sufficient that they decohere the eigenstates of O at t with eigenvalues that include v. So, the above condition is necessary and sufficient.

Note that

Times such as t above 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.

The second kind consists of non-initiator systems, which are all other systems in the network. Regarding non-initiators in broad terms,

Non-initiators X being able to give rise to other systems Y having an observable O with determinate values v in interactions with them necessarily depends on the interactions with systems that belong to an SDC and which will involve the decoherence of Y by X. However, the decoherence of Y by X is not a sufficient condition for X to give rise to Y having v.

Note also that determinate values arise indeterministically in the interactions, with probabilities given by the Born rule.

The SDC is represented by a Direct Acyclic Graph (DAG, i.e., a directed graph with no cycles). So, DAGs represent the interactions between systems that allow them to have determinate values and to give the capacity to other systems to have determinate values, and which start with the initiators. The nodes represent the systems that are involved in these interactions and the edges represent their interactions. In certain DAGs, the systems with only directed arrows towards them represent systems that have determinate values but won't be able to give rise to other systems with determinate values. An SDC ends when it reaches these systems. The nodes with no directed arrows towards them can represent the initiators.

For simplicity, here I will mostly not care about the distinction between 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. There are different possible additional necessary conditions for systems to give rise to and belong to an SDC, which allow systems to have and/or give rise to other systems having determinate values. I will call all these conditions, *stability conditions*. I will focus on one that I will call relativistic condition.

2.1. Stability conditions

According to the relativistic condition,[22] SDCs, which start with initiators, are constituted and propagate over time by having systems that have determinate values and the capacity to allow other systems to have determinate values and provide that same capacity to these systems.

To explain this condition, let's consider the following DAG representing an SDC:

$$S_1 \to S_2 \to S_3 \to S_4 \to \cdots.$$

I will start by assuming the following:

If a system S_3 has the capacity to provide another system S_4 the potential of having a determinate value then S_3 will have the potential of having a determinate value.

Also, I will assume that

[22] 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 of 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.

A system S_2 has the capacity to provide a system S_3 the capacity to provide another system S_4 the potential of having a determinate value if and only if system S_2 has the capacity to provide another system S_3 the potential of having a determinate value.

The above conditions become more intuitive if we draw an analogy with disease spreading. Consider the potential of having determinate values as analogous to having a particular disease and consider having determinate values as analogous to being sick (i.e., showing symptoms of that disease). Consider a person having the capacity to transmit to another person a particular disease as being analogous to system S_2 having the capacity to provide another system S_3 the potential of having a specific determinate value. Intuitively, having the capacity to give another person some disease implies having that disease, but not the other way around. Someone can have a disease and not be able to spread it. Also, person P having the capacity to give other person P' the capacity to give some other person P'' a specific disease implies that P has the capacity to give P' that disease. Moreover, P having the capacity to give P' a particular disease implies that P has the capacity to give another person P' the capacity to give some other person P'' that disease. Thus, they are equivalent.

I will now go over the conditions for system S_3 to have the *capacity* to provide another system S_4 with the potential of having a determinate value. They are the following,

-If system S_3 is an initiator (which is not the case according to the DAG above), it already has that capacity independently of its interactions with any other system.

Initiators are analogous to the systems that start the disease. Being the originator of the disease, it makes sense to consider that they can spread it.

-Or if system S_3 isn't an initiator, it has to be interacting with another system S_2 that has that capacity, and where the interactions with S_2 started before the end of the interaction between S_2 and system S_2, where S_1 also has that capacity. The criterion for an interaction between S_1 and S_2 to end is for S_2 to have a determinate value due to the interaction with S_1. In other words, eigenstates $|E_i' >$ of O of S_2 shouldn't be yet decohered by S_1 when S_3 starts interacting with S_2. I will consider that when a system

S_2 has a determinate value due to the decoherence that arose from S_1 that the interaction between S_1 and S_2 has ended because decoherence occurs after a "longer period of time." So, it's reasonable to assume that systems S_1 and S_2 aren't interacting anymore when S_2 has a determinate value due to S_1.

Given the above, S_3 can then provide this capacity to another system S_4 if the interaction with S_4 *started before* the end of the interaction between S_3 and S_2, i.e., before S_3 has a determinate value due to S_2, and so on. The analogy of this situation is with the time it takes for a disease to be contagious. A person can only spread a disease during a period of time. Similarly, S_2 can only provide another system S_3 the potential of having determinate values during a period of time, which is while it is interacting with S_1. The same with S_3 while it is interacting with S_2, and so on.

The above conditions are the conditions for a system S_3 to have the *capacity* to provide other system S_4 the potential of having determinate values, which implies that S_3 has the potential of having a determinate value (see above). However, it's still not the condition of S_3 (actually) having a determinate value. The above conditions are analogous to the conditions of being able to spread a particular disease ("the disease of determinate values") that imply having that disease but aren't analogous to the condition of being sick due to it. Someone may spread a disease and have that disease but still not be sick due to it, like asymptomatic people that are asymptomatic at least for some time. The next conditions are analogous to the conditions of showing symptoms of the disease, and it is the condition of having a determinate value.

Let's now turn to the necessary (but not sufficient) conditions for a system S_3 to have determinate values:

-In order for S_3 to have a determinate value v of observable O of S_3, it has to have the above capacity by interacting with system S_2 that already has that capacity, and be decohered by them, i.e., the eigenstates of O have to be decohered by S_2.

-In order for S_3 to still have determinate values after the interaction with S_2 above is finished, it has to be interacting with another system S_4 that doesn't yet have a determinate value and giving rise to S_4 having a determinate value. S_3 having determinate values lasts until S_4 has a determinate value due to the decoherence of S_4

by S_3. So, S_3 will have determinate values represented by either one of the eigenvalues of the observables O of S_3 acting on its eigenstates, where these eigenstates are the quantum states that participate in the process of decoherence of S_4 by S_3.

The relativistic condition contains an ambiguity: can S_2 give rise to S_3 having a determinate value only when S_2 has a determinate value due to S_1? To address this ambiguity, we may add one of the following additional conditions on having determinate values to the above conditions on having determinate values, which leads to necessary and sufficient conditions on having determinate values. Let's start with condition A):

A) A system S_2 interacting with S_3 gives rise to system S_3 having a determinate value only when S_2 is also interacting with S_1, having a determinate value due to S_1. More concretely, the eigenstates of observable O of S_2 decohere (completely) certain states of S_3 at t, giving rise to S_3 having a determinate value only if some states that evolved to those eigenstates were decohered by S_1 at t' where $t' < t$, giving rise to S_2 having a determinate value.

If we follow decoherence as a condition for systems having determinate values and assume condition A), S_1 should (fully) decohere S_2 before S_2 decoheres fully S_3. Otherwise, S_2 decohering S_3 becomes almost obsolete to give rise to S_3 having a determinate value because S_2 has to be decohered by S_1 first. So, I will assume that condition A) requires that S_2 is decohered when it decoheres S_3 in order for S_2 to allow S_3 to have a determinate value. If that doesn't happen, no determinate values will arise, and this SDC will disappear. I will go back to the consequences of condition A) below.

The condition A) allow us to draw an analogy between the spreading of determinate values and the spreading of a disease without asymptomatic spreaders. Someone spreads this disease only when they have symptoms of it. Analogously, system S_2 gives rise to S_3 having a determinate value only when it has a determinate value due to an appropriate S_1 that interacted with S_2. Moreover, a person being sick lasts 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. Condition A) together with the above conditions leads to the relativistic condition-A).

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

B) System S_2 interacting with S_3 gives rise to system S_3 having a determinate value, independently of S_2, which also interacts with S_1 besides S_3, having a specific determinate value due to S_1.

Condition B) allows us to draw an analogy between the spreading of determinate values and the spreading of a disease where asymptomatic spreaders may exist for a time. Someone can spread it even when they don't *yet* have symptoms. The symptoms may show up first in the person who contracted that disease 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. Condition B) together with the above conditions (except A)), leads to the relativistic condition-B).

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 a system S_2 composed of subsystems $S_2^1, S_2^2, \ldots, S_2^n$ to give rise to determinate values of another system S_3, $S_2^1, S_2^2, \ldots, S_2^n$ have to have a determinate value due to some other system S_1 or its subsystems.

I will call the above claim, the *value-mereology assumption*. If instead of S_2, we had for example some subsystem 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, we have slightly different conditions. The difference is that S_2 would just be able to give rise to S_3 having a determinate value if its subsystems S_2^i for all i interacted with subsystems of S_1, where S_1 are initiators or (in a slightly different case) systems that have the capacity of allowing subsystems S_2^i to have the potential to have determinate values. Besides that, conditions A) and B) and all the other conditions are similar, but instead of S_2, we have S_2^i.

Subsystems of a system, such as S_2^i for every 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 following the structure of the following DAG as involving also a common cause if we treat (for example) the S_1 as a whole, neglecting its subsystems (Figure 3).

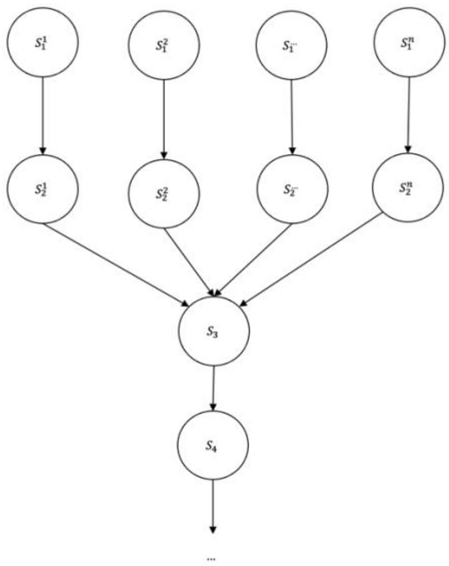

Figure 2: DAG that involves a common effect (i.e., a “collider”).

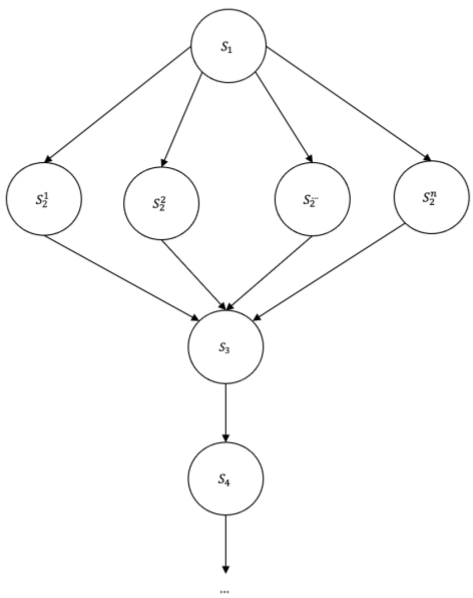

Figure 3: DAG that involves a common cause and a common effect.

From now on, I will presuppose the plausible value-mereology assumption. Although one might challenge it and bring other more sophisticated 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 system S, I will mean one of the following two things:

-If S is an initiator, S can give rise to an SDC or

-If S is not an initiator, S is connected with an SDC in different instants of time via the interactions between S and members of that SDC, and can give rise to an SDC.

Now, let's consider that system S' is decohered by S at t, where S belongs to an SDC at t, and perhaps those interactions continue at $t' > t$. In this case, the quantum states of S' decohered by S share an index i with the appropriate quantum states of S that decohered S'. I will consider that S' will start belonging to the SDC that S belongs to during a time instant or period of time, depending on the duration of the interactions.

So, let's consider an example that involves the interaction between systems A, B, and C in a mini universe obeying condition A), where the SDC that will be formed has the following structure, $A \rightarrow B \rightarrow C$. Let's consider the case where system B doesn't yet have an observable with a determinate value, but it's on its way to having one because of system A. Note that system A has determinate values in interactions with B. Being an initiator, its ability to give rise to them doesn't depend on the interactions with other systems. However, this example wouldn't change if A wasn't a non-initiator.[23] Let's consider the following states,

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

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

and so on for $\rho_{BC}^{\downarrow\downarrow}(t)$ and $\rho_{BC}^{\downarrow\uparrow}(t)$. We then have the reduced density operator, obtained from tracing out the degrees of freedom of A,

[23] If, instead, A wasn't an initiator, this would imply the assumption that the interaction of A with other systems that belong to an SDC and that allow it to give rise to B having a determinate value has ended.

$$\rho_{BC}(t) = \rho_{BC}^{\uparrow\uparrow}(t) + \rho_{BC}^{\downarrow\downarrow}(t) + \rho_{BC}^{\uparrow\downarrow}(t) + \rho_{BC}^{\downarrow\uparrow}(t) + Interference\ terms\ (< E_0(t)|E_1(t) >_{A\,SDC}, < E_1(t)|E_0(t) >_{A\,SDC}, \dots).$$

The interference terms are a function of the overlap terms $< E_0(t)|E_1(t) >_{A\,SDC}$ and $< E_1(t)|E_0(t) >_{A\,SDC}$. Now, assuming that this mini universe obeys condition A), only if $< E_0(t)|E_1(t) >_{A\,SDC} \approx 0$ and $< E_1(t)|E_0(t) >_{A\,SDC} \approx 0$ occurs before $< E_i'^{\uparrow}(t)|E_i'^{\downarrow}(t) >_B \approx 0$ and $< E_i'^{\downarrow}(t)|E_i'^{\uparrow}(t) >_B \approx 0$, B would be able to make C having a determinate value. The evolution of this later interaction between B and C could be further analyzed via $\rho_C(t)$ obtained by tracing out the degrees of freedom of B. On the other hand, if we had a mini-universe still obeying A) but where $< E_i'^{\uparrow}(t)|E_i'^{\downarrow}(t) >_B \approx 0$ and $< E_i'^{\downarrow}(t)|E_i'^{\uparrow}(t) >_B \approx 0$ occurs before $< E_0(t)|E_1(t) >_{A\,SDC} \approx 0$ and $< E_1(t)|E_0(t) >_{A\,SDC} \approx 0$, the interaction between B and C would not give rise to C having a determinate value. If we had a mini universe that obeyed B) instead, the above order wouldn't matter to determine if C would have a determinate value.

Note that in all the possibilities described above, B won't be able to allow other systems (such as C) to give rise to determinate values if it's fully decohered by A and it doesn't interact with any other system before that. So that SDC would disappear. 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) because of its interactions with elements of this SDC, more specifically with A. Moreover, (assuming A)) B only ends up allowing C to have determinate values in interactions with this system when it has certain determinate values. Furthermore, in the absence of further interactions between C and other systems, this SDC disappears. We can see by what I have been saying that the stability conditions have specific empirical consequences. I will go back to this point shortly.

As a side note, one might consider odd that a system in an eigenstate of some observable doesn't have a determinate value if it's not interacting with systems that belong to an SDC, where that interaction impacts that observable in a particular way. 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 system S is in eigenstate $|q>_S$ *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 it 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, note that in realistic situations, the systems of interest are never prepared in a pure state, and when examined in more detail, this is instead an artifact of an idealization. Using standard unitary-only quantum theory (no spontaneous collapses), what 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.[24] Moreover, even upon a measurement of an eigenstate of some observable, the system shortly after evolves into a superposition.[25] Thus, EnDQT doesn't consider the idealization concerning the assignment of pure state to S as a sufficient criterion for S to have a specific 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 of all kinds. This view doesn't imply that we should consider that "larger

[24] See Wessels (1997) for more details on this issue.
[25] Modulo quantum Zeno-like measurements, which increase the probability of the system being found in the same quantum state in repeated measurements.

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 an SDC.

We can see via this example an important role of Born probabilities, providing a new interpretation of these 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.

Why do we have acyclic relations, represented by DAGs, and not cyclic ones in space and over time? One reason is that decoherence tends to be an asymmetric process, and we are following it. Perhaps more clearly, another reason is that the process of giving rise to determinate values decorrelates the systems from other systems and gives rise to new correlations. So, any attempt to form cycles would *break* them by decorrelating certain systems from the other systems that they are interacting with.

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 to extended Wigner's friend scenarios to occur. If the friend is not interacting with these elements, she cannot give rise to her target system having an observable with a determinate value. Also, herself will not experience any determinate values if her lab was isolated or cut out from a relevant SDC for her experiences. This differs from what a supporter of the Many-Worlds Interpretation or a collapse theory, for example, would say for systems like human agents or measurement devices. Similarly, her measurement device, wouldn't detect the system if it was cut out from interacting with the SDC relevant for its detections. Thus, EnDQT, in my view, has the virtue of providing a series of new predictions and phenomena, as I have anticipated above. I would like to mention now other two. I will discuss further ones in section 4. Some additional natural conditions on the structure of SDCs need also to be imposed for EnDQT to work successfully. I will explain them in the next section.

The first prediction is the following, as we have seen above with the example, it's important to note that in order to O_i of a system like C to continue having determinate values and giving rise to other systems having determinate values, interactions of the above kind should proceed at other times, i.e., system C has to interact with other systems. 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 it to further expand that SDC, i.e., no system interacts with the system that is leading the expansion of an SDC at a particular time, that SDC will disappear and not give rise to determinate values.[26]

Second, as we have also seen with the example above, adopting A) generates constraints on how SDCs are formed, and with these constraints, new predictions. Decoherence timescales roughly serves 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 of a system Z by a system Y that we empirically observe, should be inferior or of the same order as the decoherence timescale of Y by X, where Y is typically decohered by X when it decoheres Z. 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. Note that the decoherence timescales are typically empirically determined. So, a further analysis of the current empirically determined 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 and Z are microsystems. This is because macroscopic systems have decoherence timescales much shorter than the microscopic systems that they can decohere.[27] In the case both Y and Z are macrosystems, this condition generates more surprising constraints on the structure of SDCs and new predictions since this would imply that system Y can only give rise to system Z having determinate values if Y has determinate values due to X.[28] Furthermore, the conditions for a quantum system to be considered as a classical controller of another quantum system support condition A).[29]

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

[27] 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) references therein.

[28] Similarly, in the case we treat Y as being constituted by a series of microsystems as subsystems. Only when X decoheres each subsystem of Y can Y give rise to a Z having a determinate value. Z could be a macrosystem or a microsystem. Assuming the value-mereology assumption, this later case should lead to the same predictions as the first case where we don't consider the subsystems of Y. However, we are talking about quantum systems here, we need to analyze this later case in more detail.

[29] Milburn (2012). Thanks to Gerard Milburn for pointing out this paper to me.

So far, relativistic condition-A) seems to be favored. Also, it fits well with the idea that determinate values propagate 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.

If one is unsatisfied with the relativistic condition and its subconditions, or if they turn out to be falsified, one can always search for other possibly more appropriate conditions. For instance, another possible and more demanding relativistic condition is what I will call *relativistic condition II*. Briefly, the difference from the one above is that in order for a non-initiator system X to give rise to a non-initiator system Y having a determinate value when interacting with X, the states of X that lead to the decoherence of Y at the beginning and end of their interaction have to be decohered by systems belonging to an SDC both at the beginning and at the end of the interaction with those systems. If that happens, when X decoheres Y, Y will have a determinate value in interaction with X. Only then Y can decohere other systems and help feeding this two-step process, allowing these other systems to have determinate values.

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. These conditions constrain the laws and systems in the actual universe. Let's call the SDCs that obey these conditions early universe robust SDCs (eurSDCs) for reasons that will become clear. 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"[30] is opposed to virtual or reversible decoherence (which is typically considered not to be decoherence at all), where the latter is tied to reversibility (like in the Winger's friend isolated lab case), and where the former 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 the 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

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

systems becoming inaccessible to Wigner in such a way that he cannot unitarily reverse the process via local operations.[31]

The natural conditions mentioned above hold that the structure of eurSDCs over time and space should be *robust, temporally pervasive, and be such that explains the success of unitary quantum theory.*[32] 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,[33] involves systems that are stably connected/interacting with eurSDCs.[34] 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 which 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 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 the SDC network spreads through spacetime mimics 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 is grounded in 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

[31] EnDQT also offers 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 reject the classical Markov condition (since initiators will have determinate values and the systems that interact with them, see below). We would 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 these initiators would serve as the hidden variables $\mathbf{\Lambda}$ that would give rise to the deterministic process.

[32] 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.

[33] 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.

[34] 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.

number of systems that don't belong to them, allowing them to evolve and persist over time without being influenced by SDCs and also allowing us to shield them from the SDCs at least to a certain extent. These later members account for the quantum phenomena in our universe. So, 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. Note that also that these conditions are implicitly assumed by other approaches of QT 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 wouldn't be able to see interference anymore. On the other hand, imagine a multiverse with no interactions, 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 assumed implicitly 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 best science, classical physics apparently (at least for now) 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, we should 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.[35]

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

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

The robustness of eurSDCs already explains the success of unitary QT to some extent, i.e., the ability to in unitarily control arbitrary systems for an arbitrary time. However, eurSDCs still has to have initiators that explains such success. There could exist possible universes with initiators that 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 possible universes where we would very likely end up isolating our target systems with the initiators. This loss of control is because these systems don't depend on other systems in order to give rise to determinate values. Also, they can generate multiple chains inside the lab, and more stochastic processes. Given this, there are at least five options regarding what kinds of initiators could exist in a universe: *abundant and strongly interacting*, *weakly interacting or rare and directly manipulable*, *rare and not directly manipulable*, *not rare and not directly manipulable*, *or not existent anymore*. Let's evaluate each one of the options, and see how well they could explain the success of unitary QT.

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. If they are weakly interacting or rare and directly manipulable, it seems more likely that we could place arbitrary systems in a superposition for an arbitrary amount of time because isolating these systems from the initiators is easier. However, there is a genuine possibility that they are inaccessible to being ever directly manipulated. The privileged position of initiators, which start acting at the beginning of the universe and continue acting in a privileged position, makes this hypothesis plausible.

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 more than one initiator 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 more in one region than the other). 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, and they existed only in the past initial conditions. They might have been just a fluctuation of a primordial quantum field, which gave rise to sufficient SDCs to spread determinacy throughout our universe, or something else. The challenge of this option is explaining why they shouldn't reappear, but phenomena in the early universe tends to be nevertheless special.

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 true. Due to their simplicity and explanatory power, my favorite options are the one where they are rare and not directly manipulable or the one where they don't exist anymore. 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 observed or manipulated. Nevertheless, if initiators are found or inferred, it would confirm EnDQT and disconfirm the other current quantum theories because, currently, there isn't any theory that could generate the same predictions. As we can see, these 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.

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.

3. Surpassing the Wigner's friend dilemma

We can now see in more detail that this view allows us to surpass the Wigner's friend dilemma. In order to have 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 the SDC. Given the above conditions and hypotheses, since decoherence in open environments is related to systems that are connected with an SDC, by shielding the systems from decoherence, we are actually shielding it from the SDC. 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.

Moreover, 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 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.[36]

As I will argue in more detail in future work, Pipa (in preparation-a, in preparation.-b) EnDQT is able also to provide a local explanation of Bell correlations. Bell's factorizability condition, assumed in popular derivation of the Bell's theorem,

[36] Note that, since EnDQT doesn't modify the equations of QT or has a preferred basis of QT, in principle it can be extended to quantum field theory to make QT further compatible with relativity.

can be derived via classical causal models.[37] Given the success of these models in inferring causal relations from correlations, I will consider that this is the most adequate tool to derive empirically significant Bell inequalities[38] and its assumptions that pertain to represent causal relations (and not just correlations),[39] allowing us to rigorously representing probabilistic causal relations (which are the empirically relevant relations that we capture). Of course, we might disagree with the assumptions of these models, but we need to justify why. I will turn to that now.

Besides assuming that all the common causes of the variables have been measured, causal models assume the Classical Markov Condition (CMC) and faithfulness, which some of quantum theories reject (but not EnDQT, 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 $\boldsymbol{V} = \{X_1, \ldots, X_n\}$. A joint probability distribution $P(X_1, \ldots, X_n)$ is classical Markov with respect to G if and only if it satisfies the following condition: For all distinct variables in $V = \{X_1, \ldots, X_n\}$, P over these variables factorizes as $P(X_1, \ldots, X_n) = \prod_j P\left(X_j \middle| Pa(X_j)\right)$, where $Pa(X_j)$ are the "parent nodes" of X_j, i.e., the nodes whose arrows point to the "child nodes," i.e., X_j.

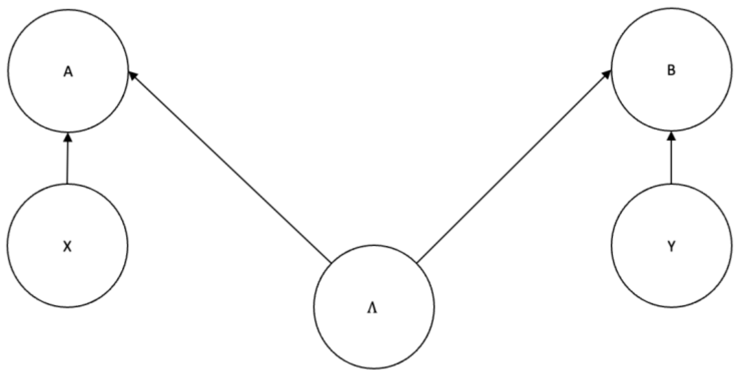

Figure 4: DAG of the common cause structure of Bell correlations, which respects relativity and is represented by classical causal models. The variables A, B, **Λ**, X, and Y

[37] This derivation is done via the d-separation algorithm, which assumes the CMC (see Theorem 5 in Khanna et al., 2023). The factorizability condition is the following: $P(AB|XY\Lambda) = P(A|X\Lambda)P(B|Y\Lambda)$ (see Figure 4). We can derive all the assumptions of the above-mentioned Bell's theorem via this algorithm, including the statistical independence assumption. See Pipa (in preparation-a, in preparation.-b) for more details.

[38] So, this disqualifies inequalities (and Bell-like theorems) where we have perfect correlations. There doesn't seem to exist a non-idealized way to perfectly align measurement devices or to not get some experimental noise. Note that EnDQT can still deal with these other theorems.

[39] Pearl (2009).

concern events embedded in a Minkowski spacetime. A and B are the (observed) variables that represent the different measurement results of Alice and Bob, X and Y are the (observed) variables that represent the different possible choices of measurement settings for Alice and Bob. $\mathbf{\Lambda}$ represents some set of (classical) "hidden"/latent variables[40] in the past lightcone of A and B, representing the information about the pair of quantum systems, and like the other variables, it assumes determinate values. The variables $\mathbf{\Lambda}$ represent complete common causes of the correlations between X and Y. 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, not favoring a preferred reference frame. 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 independence relations in the probability distribution over $\boldsymbol{V}$ have to be a consequence of the CMC. The CMC for the above DAG, which respects relativity, allows us to derive the following equation together with the assumption of faithfulness,[41]

$$P(AB|XY) = \sum_{\Lambda} P(\Lambda)\mathrm{P}(\mathrm{A}|\mathrm{X}\Lambda)\mathrm{P}(\mathrm{B}|\mathrm{Y}\Lambda).$$ [42]

The CMC is based on the assumption that common causes of systems have determinate values independently of the interactions of members of an SDC.[43] However, EnDQT rejects that and therefore rejects the CMC, and thus rejects (*altogether*) the factorizability condition.[44] Quantum Causal Models (QCMs)[45] consider that common causes can have indeterminate values.

[40] Contrary to the observed variables, these are variables that are inferred via the observed ones in the mathematical model.
[41] Theories such as Bohmian mechanics and retrocausal theories reject this assumption (Evans, 2018; Wood & Spekkens, 2015).
[42] The form of this condition can be derived in the following way: from faithfulness and the CMC applied to the above DAG, we arrive at the following expression $P(ABXY\Lambda) = P(A|X\Lambda)P(B|Y\Lambda)\mathrm{P}(\mathrm{X})\mathrm{P}(\mathrm{Y})\mathrm{P}(\Lambda)$. Then, assuming that the choices of measurement settings by Alice and Bob are independent P(XY)=P(X)P(Y), we arrive at the condition $P(AB|XY) = \sum_{\Lambda} P(\Lambda)\mathrm{P}(\mathrm{A}|\mathrm{X}\Lambda)\mathrm{P}(\mathrm{B}|\mathrm{Y}\Lambda)$.
[43] See Pearl & Verma (1995) for a rigorous derivation of the CMC based on structural equations. These equations assume that causes have determinate values in general. EnDQT rejects the justification of the CMC and the CMC, as well as Bell's factorizability condition which is one of its consequences.
[44] 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.
[45] Costa & Shrapnel (2016), Allen et al. (2017), Barrett et al. (2019).

In more detail, QCMs consider that each node concerns a possible locus of interventions on the properties of a system, and it is associated with specific input and output quantum states. More formally, each node is associated with a set of CP maps (complete positive maps),[46] also called quantum instruments, instead of random variables as in the classical causal models' 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 or interactions, which correspond to the preparation of quantum systems, transformations, measurements on them, etc. Each edge can be seen as evolving the systems between notes and is an associated with a quantum channel (such as unitary channels, associated with unitary evolutions, etc.).

Instead of appealing to the CMC, QCMs[47] appeal to a Quantum Markov Condition (QMC). The QMC is defined through a DAG where the edges of the DAG are associated with quantum channels, which factorize analogously to conditional probabilities in the CMC, and the nodes are associated with input quantum system in a given state/with a determinate or indeterminate value, serving as causes that aren't manipulated but are kept fixed.

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,[48] and a version of the Born rule, we can give a causal explanation of Bell correlations,

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

We can see that the above expression is analogous to the CMC above. Let's interpret it, assuming that ρ_Λ is, for example, a singlet state assigned to systems S and to S'. It represents, together with the appropriate observables of S and S' prepared at the source with a spin-p (where p is a specific axis, i.e., x, y, z, in a θ angle to z, etc.) systems with certain indeterminate values. The system of Alice evolves locally to the

[46] Nielsen & Chuang (2011).

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

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

region A, where Alice is, via the unitary evolution (or more precisely quantum channel[49]) $\rho_{A|\Lambda}$, and the same in the case of Bob via $\rho_{B|\Lambda}$. Then, each system represented via the quantum state ρ_{Λ} is measured by Alice and Bob.[50] 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. Both the measurement devices of Alice and Bob are connected with SDCs. The superscript SDC means that the systems measured by either Alice or Bob will become part of an SDC, even if for a brief moment in time, due to other systems that also belong to SDCs (i.e., the measurement devices of Alice and Bob).

So, (cutting a long story short[51]) the expression above represents the above common cause local structure. It tells us that in the EPR-Bell scenario case, we have systems S and S' with indeterminate values at the source at time t plus some other systems (i.e., Alice's and Bob's measurement devices with their different settings) that have a complete influence in S and S' having certain determinate values in regions A and B at some future times, increasing the probabilities that these determinate values will arise.

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:

[49] This is completely positive trace-preserving map (CPTP) written in CJ- form, i.e., using the Choi-Jamiolkowski (CJ) isomorphism.

[50] The CPTP maps in the EPR-Bell scenario are identity channels that transport systems from the source to regions A and B.

[51] Pipa (in preparation-a, in preparation.-b).

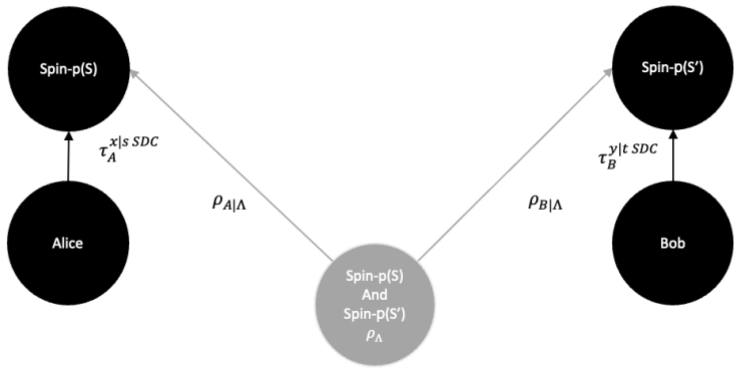

Figure 5: DAG of the common cause structure of Bell correlations, which respects relativity and is local, being represented by quantum causal models as interpreted by EnDQT.

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/dynamics 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).[52] Furthermore, note that EnDQT doesn't essentially deviate from standard decoherence-based quantum theory, and so it can be rendered Lorentz-invariant.

A QCM for the extended Wigner's friend-like scenarios could be elaborated. Suppose we have two friends in isolated labs in each wing. The evolution of the systems to each wing and the "measurements" of each friend would be treated via unitary channels. Then, we would treat the friend and their systems as being in an entangled superposition of states, and Wigners would perform interventions on these states.[53]

It's unclear whether any current quantum theories, including relationalist ones, can use QCM in this local way. Typically, in relationalist theories, the shared correlations of the friends only arise when they meet. The causal structure will therefore be different and should take into account their meeting. Moreover, QCM should in the single-world cases (at least) be modified to account for these multiple varying perspectives. Allowing QCM to provide a local explanation of Bell correlations, in a

[52] In the limit where local operations are diagonal in a fixed based, we recover CCM. Regarding the case above, this is interpreted as concerning the case where the common causes belong to an SDC.
[53] Pipa (in preparation-a, in preparation.-b).

realist simple way (with no necessary modifications) and that clearly faces the Wigner's friend dilemma, is another advantage of adopting 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 ontologically. EnDQT offers the possibility of different ontologies that reject the view that quantum states are entities in the world. We could think of determinate values as "flashes" occurring under particular interactions in spacetime with nothing happening in between the preparation and the 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. The features of quantum properties are inferred and represented through observables concerning P and quantum states, where 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. So, for example, in the simple decoherence cases that we have been concerned here, the quantum state of some system S

$$\alpha|\uparrow_z>_S + \beta|\downarrow_z>_S,$$

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 say 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 some other system that doesn't belong to an SDC; we represent the quantum property spin-z via the observable S_z and

$$\alpha|\uparrow_z>_S |E_\uparrow>_E + \beta|\downarrow_z>_S |E_\downarrow>_E.$$

Or if it's instead interacting with some system E *that doesn't* belong to an SDC,

$$\alpha|\uparrow_z>_S\ |E_\uparrow(t)>_E + \beta|\downarrow_z>_S\ |E_\downarrow(t)>_E.$$

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

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

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

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

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.

When the system belongs to an SDC, we say that the system has a quantum property *stably differentiated* in some degree D*. We represent the spin-z of system S via

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

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

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 a property P* is the property of having some other property P that plays a role or function R.[55] The functionalist position provides an account of the dependence relation between the so-called values properties (henceforward, values) v (or value intervals) that I have been talking about, which come in terms of different degrees of determinacy, and quantum properties:

A non-minimally determinate value property, i.e., D-v-P where $0 < D \leq 1$*, instantiated by system S at time t, is the property of having a quantum property D*'-P with D*'=D*$\neq 0$*, when S is interacting at time t with systems in a way obeying particular stability conditions, which makes it belong to an SDC.*

The indeterminate value property, i.e., D-v-P where $D = 0$*, instantiated by system S at time t is the property of having a quantum property D*'-P with an arbitrary degree of differentiation when S is not interacting with certain systems at time t in a way obeying particular stability conditions, which makes it belong to an SDC.*

Adopting this view, we can look at the representations of quantum properties (via decoherence, etc.) and see what theoretical roles they have in terms of accounting for such interactions. Through them, they will represent values with some degree of determinacy.

More could be said about this ontology. Quantum properties of systems have different roles represented via the laws, which allow systems to increase or decrease the degree of differentiation of quantum properties of other systems under interactions. For instance, the quantum properties that play a role in measurement-like interactions, increase the degree of differentiation of quantum properties of other systems. However, let's save these complications for forthcoming work. 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 the

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

quantum state (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.[56]

I will end this section by replying to an objection. One might object that in some extended Wigner's friend theorems,[57] it's plausible to consider that the friend Alice inside the isolated lab sees a determinate outcome. In a sense, this theorem assumes that Wigner, without performing any operations on Alice and her lab and after her measurement, simply opens the door of her lab and asks her about what outcome she obtained. In the simple case discussed in the introduction, she will answer that she obtained spin-up or spin-down with 50% of probability each (i.e., if Wigner makes a projective measurement on the state of Alice after her measurement, without performing any other operation on the lab, he will obtain these outcomes). So, it seems that Alice sees a determinate outcome contrary to 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 quantum theory 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 the physical process of stable differentiation 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

[56] This ontology has 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.

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

mental/phenomenal/cognitive states: this is the *absent experience hypothesis* and is contrary to the *relationalist hypothesis* assumed by relationalists at least superficially (more on this below).

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 have some different kinds of mental/phenomenal/cognitive states that depend on indeterminate properties, which I will call the *quantum experience hypothesis*. For instance, 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.[58] 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.[59] 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

[58] 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. 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.

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

by many MWI proponents,[60] 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 the quantum computer). Many proponents of interpretations such as the Many-Worlds 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.

Furthermore, although relationalists can account for the *relative* friend's experiences, 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 what are the advantages of assuming the relationalist hypothesis in general to not also suffer from the above objection.

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 an SDC. I thus have shown that we can have a coherent non-relationalist, non-hidden variable unitary universal quantum theory. I also 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 an arbitrary superposition of quantum states.

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

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 (i.e., very roughly, the assumption regarding lower entropy initial conditions of the universe). The low entropy state of the universe would be just the state where the initiators didn't interact with the other systems, and nothing else interacted to form SDCs. Moreover, the evolution of SDCs gives rise to a temporally asymmetric process. These potential explanatory resources can provide further support to EnDQT and set it apart from other quantum theories that don't have similar explanatory resources.

In order to further develop EnDQT, the elements and structure of SDCs need to be further specified. 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 "simple" test is to see what the features of the SDCs in the case of the empirically well-supported decoherence models (to a certain spatiotemporal extent) 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, as well as testing and proposing new ones.

A more challenging test would be to map the SDCs in 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 to give rise to determinate values at a cosmological scale level, given some stability conditions. Such robustness could 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.

As one can see, EnDQT has a series of distinct features when compared with other quantum theories. It will be very hard to definitely distinguish EnDQT empirically from the other unitary interpretations of QT because, in practice, all of them appeal to (irreversible) decoherence connected with some environments in one way or another. Despite all this, EnDQT offers a finer account of how determinacy propagates than other views since for EnDQT, connections 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. Furthermore, 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.

Finally, in this article, I have been conservative and 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 regime. However, it's plausible that we need to be more radical and consider other kinds of SDCs and initiators, represented via some other theory in order to solve issues in other areas of physics, such as the integration of quantum theory with gravity. Perhaps we should seek SDCs associated with "classical" gravity (related in some ways but not necessarily the same as gravity causes collapse theories). Indeed, this is a plausible 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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