The Open Systems View

Michael E. Cuffaro* Stephan Hartmann†

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Abstract

There is a deeply entrenched view in philosophy and physics, the closed systems view, according to which isolated systems are conceived of as fundamental. On this view, when a system is under the influence of its environment this is always described in terms of a coupling between it and a separate system which taken together are isolated. There is an alternative, the open systems view, according to which systems interacting with their environment are conceived of as fundamental, and the environment's influence is represented via the dynamical equations that govern the system of interest's evolution. In this paper we propose (although the formalism is not original to us) a theoretical framework which we call the general quantum theory of open systems (**GT**), within which one can make sense of the dynamics of open quantum systems in fundamental terms, and we argue that the open systems view, as formalized in **GT**, is fundamental in quantum theory.

1 Introduction

There is a deeply entrenched view in philosophy and physics according to which closed or isolated systems are conceived of as fundamental. For Gottfried Wilhelm Leibniz, for instance, the cosmos as a whole is an example; God forms it and sets it in motion, but then stands outside of it and allows it to proceed ever after in accordance with its own internal principles (Leibniz, 2000, sec. 4). In the context of physics, a system is considered to be closed if it does not exchange energy, matter, heat, information or anything else with its environment,[1] and there are reasons stemming from physics to believe that the cosmos is the only closed system that truly exists. For instance, it is well-known that gravity (unlike the, in many respects structurally similar, electromagnetic field) cannot be shielded, thus every material object in the universe is subject to the influence of the gravitational field.[2] Further, entangled correlations between spatially separated systems, as described by quantum theory, also cannot be "shielded" and moreover do not decrease with distance (Herbst, 2015; Yin et al., 2017). Even in a near perfect vacuum like those that exist between galaxies, correctly describing a quantum system requires us to consider the vacuum fluctuations of the electromagnetic field (Zeh, 1970). Thus, if we are to take seriously the idea that closed systems are fundamental, it seems that we should conclude, with Jonathan Schaffer (2013), that "the cosmos is the one and only fundamental thing" (2013, p. 67).[3]

Of course, physics is not only concerned with the cosmos. But when the influence of the rest of the cosmos, i.e., of its environment, on a particular system of interest, $\mathcal{S}$, is negligible

*Munich Center for Mathematical Philosophy, LMU Munich, E-mail: Michael.Cuffaro.@lmu.de

†Munich Center for Mathematical Philosophy, LMU Munich, E-mail: S.Hartmann@lmu.de

in the context of a particular investigation, then it is legitimate and fruitful, for the purposes of that investigation, to treat S as closed (Wallace, 2022, p. 242). Further, in the case where the influence of the environment is not negligible, a more accurate characterization of a system's dynamics can be achieved by modeling it as one subsystem of a larger dynamically isolated composite system, such that its dynamics is determined on the basis of the contributions arising from its interactions with the other subsystems, as well as from the contributions intrinsic to it.[4] In this sense, what we will be calling the "closed systems view" has been highly successful in physics, and in theoretical frameworks formulated in accordance with the closed systems view such as Hamiltonian mechanics, results such as Noether's Theorem intimately relate the concept of a closed system to the existence of certain symmetries and corresponding conservation laws. The same can be said of classical electrodynamics (though see Frisch, 2005), and similarly for quantum theory in its standard formulation.

When we take a closer look at the way that the closed systems view is applied in physics, however, we encounter prima facie problems. For instance, the paradigmatic example of a model of a closed system is a model of the universe as a whole.[5] But although it is true that standard models of cosmology (based on the Friedman-Lemaître-Robertson-Walker solutions to the Einstein field equation) describe it as a closed system, they are in many cases based on strong idealizations introduced for little reason other than to simplify the associated mathematics (Smeenk and Ellis, 2017, sec. 1.1). Particularly noteworthy is the scale factor which, as Sloan (2021) points out, carries no physical significance in itself. The upshot is that although our best cosmological models describe the universe as closed, there are reasons to question whether such a description is really apt (see also Gryb and Sloan, 2021; Sloan, 2018).[6]

This is not a triviality. Taking the closed systems view dogmatically in physics may have the negative consequence of artificially limiting the alternatives one is willing to consider when one is deciding upon the appropriate dynamical model with which to characterize a given class of systems. Stephen Hawking's proposal, for instance, to model a black hole's dynamics as formally similar to that of an open system (Hawking, 1976) is, to be sure, controversial (for discussion, see Giddings, 2013; Page, 1983; Wallace, 2020). But although our goal here is not to defend Hawking's particular model per se, it is important to point out that at least part of the motivation for wanting to reject it seems to be nothing more than the (in our view, misguided) idea that it runs counter to quantum theory, formulated in accordance with the closed systems view, and the fundamental unitary dynamics described by it (see, e.g., Giddings, 2013, pp. 32–34; cf. Wallace, 2020, p. 219). The implicit premise here seems to be that, given that unitary quantum theory is arguably physics' most empirically successful theoretical framework, this should constitute a strong motivation to conform our picture of the fundamental dynamics of systems to the schema it provides.

We remark that it is not clear, first of all, what such a picture really amounts to. One of the more promising approaches to quantizing gravity, for instance, is the so-called quantum reference frames approach (see, e.g. Castro-Ruiz, Giacomini, Belenchia, and Brukner, 2020; Giacomini, Castro-Ruiz, and Brukner, 2019), where, rather than modeling time as an external parameter, one treats a reference clock as a quantum system like any other. But although relative to a given clock one can describe the evolution of a given system in unitary terms, no single such clock is preferred, so that the unitary evolution one describes will be different depending on the reference clock chosen. This is clearly *not* the simple picture of an isolated quantum system to which one objectively assigns a particular state vector unitarily evolving through time (see also Oriti, 2021, sec. 3).

More importantly, in any case, the objection wrongly represents what quantum theory's empirical success actually rests upon, namely, its applications to systems that are empirically accessible. These are, invariably, the subsystems of the universe. While it is of course true that in many cases one can effectively treat a given system of interest, $\mathcal{S}$, as isolated, and that even when one cannot do so one can still (as we will see) in many cases model the dynamics of $\mathcal{S}$ by first modeling the dynamics of the larger dynamically coupled closed system, $\mathcal{S} + \mathcal{E}$, and then abstracting away from $\mathcal{E}$'s degrees of freedom; one should not forget that it is the dynamics of $\mathcal{S}$, not the dynamics of $\mathcal{S} + \mathcal{E}$, that one has successfully described when one does this (as $\mathcal{E}$ will typically be highly idealized). The basis of quantum theory's empirical success, in other words, arguably lies in the way that it effectively describes the dynamics of open systems.[7]

And there are yet deeper reasons to worry about the closed systems view as it pertains to quantum theory. There are essentially two senses in which one can take any theory of physics to be complete. First, one can mean, by "complete", that such a theory provides us with, at least in principle, a complete description of reality. Alternately, and more pragmatically, one can take the completeness of a theory to mean that it provides us with all of the resources we need to describe any actual (in general probabilistic) given physical phenomenon to whatever level of detail we would like. Approaches to interpreting quantum theory that take it to be complete in the first sense principally include Hugh Everett III's, as well as its many modern descendants (Saunders, Barrett, Kent, and Wallace, 2010). Approaches that take it to be complete in the second sense (and which tend to focus on that sense) include those of Niels Bohr, Werner Heisenberg, Wolfgang Pauli, John von Neumann and others, and their modern descendants, and are popularly referred to using the label "Copenhagen" or "orthodox", although they do not constitute a unified view (see Howard, 2004). We have argued elsewhere (Cuffaro and Hartmann 2021, sec. 3; Cuffaro and Hartmann 2023; Cuffaro and Hartmann 2024; and Cuffaro 2023) that regardless of which of these senses of completeness one takes to be of primary interest,[8] quantum theory, in a way that other theoretical frameworks for physics like classical mechanics are not, is ontologically committed to open systems. What we want to emphasize here is that this is despite the fact that the formulation of quantum theory these approaches all focus on—what we will be calling standard quantum theory (**ST**)—is actually formulated in accordance with the closed systems view.

Since the dynamics of an open system, as formally described by **ST**, is in general non-unitary; there is, it seems to us, a clear motivation to consider adopting a theoretical framework in which it is possible to fundamentally describe the dynamics of a system in that way. In this paper we propose one: the general quantum theory of open systems (**GT**).[9] We will proceed as follows: After clarifying what we mean by the terms "theoretical framework," "theory," "model" and "view" in Section 2.1, in Section 2.2 we present the conceptual core of **ST**, and discuss through a few examples the way that closed and open systems phenomena are modeled in that framework. Then, as a prelude to our introduction of **GT**, we discuss, in Section 3.1, how to derive the Lindblad equation, governing the dynamics of an important class of (in general, open) systems, in **ST**. In Section 3.2 we introduce **GT**. We discuss the main assumptions involved in the derivation of the Lindblad equation in **GT** in Section 3.3, and show that **GT** is more general than **ST** by discussing (as an illustrative example) one of these, the principle of complete positivity, in some detail. In Section 4 we then explicate the concept of an object of a theoretical framework as that through which a framework's subject matter is represented, and we consider the relation of what we call relative ontic fundamentality as it obtains between frameworks. We argue, in turn, from the point of view of orthodox, Everettian, and hidden-variable interpretations of **ST** (though note that, unlike the first two, hidden-variable interpretations deny that **ST** is complete and thus reject it as a candidate fundamental framework) that **GT** is, ontologically speaking, a more fundamental framework than **ST**, along the way clarifying how the various aspects of the concept of a view (i.e., its motivating metaphysical principle and associated modeling assumptions) work together.

2 Setting the Stage

ST is a theoretical framework for quantum physics. In Section 2.1 we take up the question of what this means, and in Section 2.2 we discuss what its core concepts are.

2.1 Models, Theories, Frameworks and Views

In the philosophical literature on scientific theories one regularly encounters three terms which are too often not carefully distinguished from one another: "framework," "theory," and "model," here ordered according to their generality, i.e., with regard to how "far away" each is, conceptually, from the so-called target system in a given field of inquiry. Closest to the target system is the (theoretical) *model*, the main representational device used in science, which represents a specific system for a particular epistemic or practical purpose such as explanation, prediction or the planning of an intervention. The model of the hydrogen atom, for instance, represents it in terms of a positively charged proton (=the atomic nucleus) with a certain mass m_p and a negatively charged electron with a certain mass m_e.

Models are usually formulated in the context of a specific *scientific theory*.[10] The model of the hydrogen atom, for instance, is typically formulated in non-relativistic quantum theory which allows us to calculate the different discrete energy levels of the atom. As an alternative one could employ relativistic quantum theory, which would yield various relativistic corrections to the non-relativistic account.

We note that non-relativistic and relativistic quantum theory have much in common. In both, for instance, the state of a system is represented by a state vector and the time evolution of a state vector is unitary. This is because both are formulated within the same *theoretical framework*, **ST**, which accounts for what both theories always assume, i.e., in all of their models.[11] **ST** is not the only theoretical framework for describing the physics of quantum systems. In Section 3.2 we will introduce an alternative to **ST**, which we are calling **GT**, that is interestingly different in a sense that can be captured by the concept of what we will be calling a *view*, which has two components: (i) a set of methodological presuppositions in accordance with which we characterize the objects of a given domain, that is (ii) motivated by a particular metaphysical position concerning the nature of those objects.

The view in accordance with which **ST** is formulated is called the *closed systems view*, which we define here as: (i) motivated by the metaphysical position according to which isolated systems are thought of (a priori) as exclusively making up the subject matter of a given scientific domain; (ii) associated with the methodology that models all phenomena in terms of isolated systems; with the consequence that the dynamics of a given open system, $\mathcal{S}$, must always be modeled (whenever the influence of the environment cannot be neglected altogether) in terms of its being coupled to a further system $\mathcal{E}$ (representing its environment), such that $\mathcal{S} + \mathcal{E}$ form an isolated system.

By contrast, **GT**, which we will introduce in Section 3.2, is formulated in accordance with the *open systems view*, which we define here as: (i) motivated by the metaphysical position according to which the subject matter of a given scientific domain is thought of (a priori) to consist of systems that are in general open, i.e., in interaction with their environment; (ii) associated with the methodology such that, rather than modeling the dynamics of a given open system $\mathcal{S}$ in terms of an interaction between two systems that together comprise a single isolated composite system, we represent the influence of the environment on $\mathcal{S}$ in the dynamical equations that we take to govern its evolution from one moment to the next.

2.2 Standard Quantum Theory (ST)

In the form of quantum theory presented in most textbooks on the topic—what we are calling **ST**—the physical state of a system, $\mathcal{S}$, at a time t is represented by a normalized state vector, $|\psi(t)\rangle$; one element in a Hilbert space, $\mathcal{H}_S$, representing $\mathcal{S}$'s possible states. $\mathcal{S}$'s dynamical evolution is given, in general, by

$$|\psi(t)\rangle = U(t)\,|\psi(0)\rangle, \tag{2.1}$$

where the time evolution operator $U(t) = \exp(-\mathrm{i}\,H\,t)$, with H a Hermitian operator representing the system's Hamiltonian whose eigenvalues are the possible energy values of the system.

ST is a highly successful theoretical framework that has many applications. For example, it is applicable to atoms ("atomic physics"), atomic nuclei ("nuclear physics"), and solid state systems ("condensed matter physics"), each of which is characterized by a certain class of target systems, Hamiltonians and modeling strategies. Within atomic physics, constructing a model of an atom involves specifying a Hamiltonian which is the sum of the Hamiltonians of the various subsystems and of the terms that account for their interaction. In the case of the hydrogen atom, for instance, the Hamiltonian consists of three terms: a kinetic energy term representing the nucleus (i.e. the proton), a kinetic energy term representing the electron, and a term accounting for the Coulomb attraction of the electron and the proton. More sophisticated models are also possible, taking, for instance, the interaction between the magnetic field from the electron movement and the nuclear spin into account. Once the Hamiltonian is specified, one can solve the corresponding Schrödinger equation. Note that a system such as the hydrogen atom can also be analyzed using relativistic quantum theory. In this case, one solves the Dirac equation instead of the Schrödinger equation. Irrespective of the particular quantum theory that a given model has been formulated in, there are a number of things that can be said about every dynamical model of **ST**, of which we note the following two. (I) It follows from the above assumptions (i.e., those stated in the previous paragraph) that $U(t)$ is a unitary map on the state space of $\mathcal{S}$. (II) $\mathcal{S}$ is a closed system. This follows from the fact that H, which describes the possible energy values of the system, includes no terms representing its interaction with an environment.

Modeling the atoms, nuclei and condensed matter systems we mentioned above as closed systems seems physically plausible insofar as it has been experimentally confirmed that such systems can be effectively isolated at least to a large degree, and that factoring in the influence of their environment yields in most cases only a negligible contribution to whatever quantities are of interest. Other contributions, such as the effects of the interaction of the electron magnetic field with the nuclear spin in the case of the hydrogen atom, are much more important, but are still describable in terms of closed systems within **ST** in a natural way. Not all phenomena can be modeled in a simple way as closed systems, however. Some phenomena are decidedly "open systems phenomena" such that the dynamics of a given target system needs to be modeled as effectively determined to a considerable extent by the system's environment (Hartmann, 2016). Lasers are an example: A laser is pumped by an external energy source, and coherent laser radiation is emitted in turn. The spontaneous emission of a photon by an atom is another. In Section 3.1 we will go through a specific example, relating to an important class of systems, of how to derive the dynamics of an open system, given in the form of the Lindblad equation, in

ST. But in the rest of this section our concern will be to discuss in a more general way how open systems are represented in this framework.

We begin by noting that, since interacting systems are in general represented as being entangled in **ST**, it is not possible to represent the state of an open system, $\mathcal{S}$, using a state vector (Schrödinger, 1983, p. 160). Fortunately, there is a natural probabilistic generalization of the state vector—the so-called density operator—that can be used to represent $\mathcal{S}$'s probabilistic state. We will take the time to unpack this concept carefully as it will prove important for our analyses in the rest of this paper.

To begin with we consider a large number—usually called an *ensemble*—of similar quantum systems $\mathcal{S}_i$ which have all been prepared using an identical preparation procedure.[12] For instance one might specify that a given system, $\mathcal{S}_i$, is to be prepared in the state $|\psi_1\rangle$ with probability p and in the state $|\psi_2\rangle$ with probability $1 - p$, which will progressively generate an ensemble for which the relative frequencies of $|\psi_1\rangle$ and $|\psi_2\rangle$ tend, respectively, toward p and $1 - p$ as we prepare more and more systems. The so-called *properly mixed state* of such an ensemble is represented by a *density operator*, which can be expressed as follows:

$$\rho = p\,|\psi_1\rangle\langle\psi_1| \;+\; (1-p)\,|\psi_2\rangle\langle\psi_2|. \tag{2.2}$$

In addition to representing the state of the ensemble, we can also think of ρ as characterizing each of its members (indeed, the very idea of an ensemble can be regarded as a useful fiction to aid us in characterizing an individual system in this more general way), since each member of the ensemble has been identically prepared. When there are more than two alternatives, ρ is given more generally by

$$\rho = \sum_j p_j\,|\psi_j\rangle\langle\psi_j|, \tag{2.3}$$

where the p_j are non-negative real numbers summing to 1. Note, however, that the relation between preparation procedures and ensembles (and their corresponding ρ) is many-to-one: For a given ensemble whose state is represented by some density operator ρ, there are in general infinitely many preparation procedures that will give rise to it; i.e.,

$$\rho = \sum_j p_j\,|\psi_j\rangle\langle\psi_j| \tag{2.4}$$

$$= \sum_k p'_k\,|\phi_k\rangle\langle\phi_k| \tag{2.5}$$

whenever $\sum_j p_j\,|\psi_j\rangle\langle\psi_j|$ and $\sum_k p'_k\,|\phi_k\rangle\langle\phi_k|$ are related by a unitary transformation (Nielsen and Chuang, 2000) (p. 103). Despite this, the predictions yielded by the density operator ρ are the same regardless of how it is decomposed into state vectors; i.e., the right-hand sides of Eqs. (2.4) and (2.5) predict the same statistics for measurements. The one exception to the many-to-one rule is the case of an ensemble for which every system is prepared in the same state $|\phi\rangle$. In this case we characterize the ensemble using a *pure state* whose density operator takes the form:

$$\rho = |\phi\rangle\langle\phi|. \tag{2.6}$$

There are also more general ways to generate an ensemble. If one were to correlate pairs of quantum particles, for instance, and then ignore the right-hand particle from each pair, the ensemble of left-hand particles progressively generated would be in what is called an *improperly mixed state* (d'Espagnat, 1966, 1971). Because correlated quantum systems are generally entangled in quantum theory, an ensemble in an improperly mixed state, ρ, *cannot* be understood as having been generated using a probabilistic procedure like the ones given above; i.e., a system in such an ensemble cannot be understood to be in a state $|\psi_j\rangle$ with a certain probability. This is even though the statistics arising from a sequence of measurements on the members of an improperly mixed ensemble are indistinguishable from a sequence of those same measurements on a properly mixed ensemble whose state is also described by ρ. This is the kind of case one deals with in the quantum theory of open systems, where the improperly mixed state characterizing the system of interest $\mathcal{S}$, represented by the *reduced density operator* ρ_S, is derived by tracing over the degrees of freedom of the environment from the combined state $|\Psi\rangle_{\mathcal{S}+\mathcal{E}}$. This amounts to preparing an ensemble of systems $\mathcal{S}+\mathcal{E}$, all in the state $|\Psi\rangle_{\mathcal{S}+\mathcal{E}}$, and then selecting $\mathcal{S}$ from each pair (and ignoring $\mathcal{E}$) to form a new ensemble in an improperly mixed state represented by the reduced density operator ρ_S that, as we will see in more detail in Section 3.1, may in general evolve non-unitarily consistently with the unitary dynamics of $|\Psi\rangle_{\mathcal{S}+\mathcal{E}}$.

3 The Dynamics of Open Quantum Systems

3.1 Prelude: Deriving the Lindblad equation in ST

An important historical predecessor of the quantum theory of open systems (as formulated within **ST**) is the Weisskopf-Wigner theory of spontaneous emissions (Weisskopf and Wigner, 1930), which accounts for the observation that atoms prepared in an excited state will randomly emit photons over time, returning to their ground state while the emitted radiation disappears into the universe. The starting point of the theory is that while the exact time of emission is impossible to determine, it is experimentally well known that an excited state decays exponentially at a certain rate. Given this, questions such as how the decay rate depends on particular characteristics of the atoms, which characteristics are relevant, and what the decay mechanism is, arise. But giving a closed systems account of spontaneous emission is problematic since the radiation is sent into empty space and there are infinitely many modes and directions by which this can occur. Instead, in the Weisskopf-Wigner theory one models the decay as a stochastic process. Although Weisskopf and Wigner did not explicitly refer to this as a theory of open systems, theirs was the first contribution to what has since been further developed into the powerful, elegant, and more general theory which we now introduce. The basic strategy employed is to embed the open system of interest, $\mathcal{S}$, within a sufficiently large "box" representing its environment, $\mathcal{E}$, that guarantees that the composite system, $\mathcal{S}+\mathcal{E}$, can be treated as isolated.[13]

To focus our discussion, we will consider a single two-level atom (= $\mathcal{S}$) that is coupled to an environment $\mathcal{E}$, such that $\mathcal{S}+\mathcal{E}$ forms a closed system in the above sense. To account for its dynamics, we make the following assumptions:

1. The total Hamiltonian is given by $H = H_S + H_E + H_{SE}$.

2. $\mathcal{S}$ and $\mathcal{E}$ are initially uncorrelated and weakly coupled, i.e. $\mathcal{E}$ affects the state of $\mathcal{S}$ but not vice versa. This is sometimes called the *Born approximation*.

3. The future state of $\mathcal{S}$ only depends on its present state. Metaphorically put, $\mathcal{S}$ has a short memory and "forgets" its earlier states. This is the *Markov approximation*.

Here, H_S is the Hamiltonian of the two-level atom, H_E is the Hamiltonian of the environment which is modeled as an infinite collection of two-level atoms. Finally, H_{SE} accounts for the interaction between the system and the environment.

After calculating the evolution of $\mathcal{S}+\mathcal{E}$, one then takes the partial trace with respect to $\mathcal{E}$, yielding an equation for the evolution of the reduced density operator $\rho := \rho_S$ in the quasi-spin formalism:

$$\dot{\rho} = -\mathrm{i}\,[H_S, \rho] + A\ \left([\sigma_- \rho, \sigma_+] + [\sigma_-, \rho\, \sigma_+]\right). \tag{3.1}$$

Here the basis states are $|1\rangle := (1,0)^{\mathrm{T}}$ and $|0\rangle := (0,1)^{\mathrm{T}}$ and the Pauli matrices $\sigma_\pm$ represent the corresponding raising and lowering operators.[14] A is the decay rate of the target system.

It is interesting to note that the dynamics of ρ in Eq. (3.1) involves a unitary part and a non-unitary part. The unitary part is given by $\mathcal{L}_u \rho := -\mathrm{i}[H_S, \rho]$ where we have introduced the superoperator $\mathcal{L}_u$.[15] Abbreviating the non-unitary part by $\mathcal{L}_{n-u}\rho$, Eq. (3.1) can be written in the compact form,

$$\dot{\rho} = (\mathcal{L}_u + \mathcal{L}_{n-u})\,\rho. \tag{3.2}$$

In the absence of the non-unitary part, Eq. (3.2) is equivalent to the Liouville-von Neumann equation which reduces to the Schrödinger equation (or its relativistic counterpart) if the initial state of the system is a pure state. Note that the specific form of the non-unitary part in Eq. (3.1) depends on the particular system under consideration. If one were to consider a different system, e.g. a decaying photon mode, the non-unitary part would look different. It turns out, however, that it always has the general form

$$\mathcal{L}_{n-u}\,\rho = \frac{1}{2}\sum_i \left([L_i\,\rho, L_i^\dagger] + [L_i, \rho\, L_i^\dagger]\right), \tag{3.3}$$

where the L_i are bounded operators. Eq. (3.2), with the form of $\mathcal{L}_{n-u}$ given by Eq. (3.3), is known as the Lindblad equation. We note that it can be shown that if the non-unitary dynamics of a system has the form specified in Eq. (3.3), then probability is conserved.[16] Probability conservation therefore does not presuppose an underlying unitary dynamics.

To sum up: We have seen that there are a number of physical phenomena, such as spontaneous emission and lasers, that require us to model the dynamics of a target system as driven to a considerable degree by its environment. The key idea which allows one to account for such phenomena within **ST** is to embed the open system under consideration into a larger closed system that includes, as its subsystems, both the system and its environment. One can then derive equations of motion describing the effective dynamics of the system that are non-unitary in general. Interestingly, given the assumptions listed above, the non-unitary part of the dynamics reflected in these equations always has the same form—the Lindblad form given in Eq. (3.3)—which suggests that a more principled discussion is in order. This is the subject of the next subsection.

3.2 A General Theoretical Framework for Open Quantum Systems

The earliest work on characterizing the general form of the dynamics of a quantum system represented by a density operator—what we are here calling **GT**—is to be found in papers by Sudarshan, Mathews, and Rau (1961) and by Jordan and Sudarshan (1961), who characterize the possible dynamical evolutions of a density operator, $\rho_{\mathcal{S}}$, acting on the Hilbert space, $\mathcal{H}_{\mathcal{S}}$, of a given system of interest, $\mathcal{S}$, as most generally given in the form of a positive linear map. Unlike **ST**, according to which the dynamical evolution of $\mathcal{S}$ is obtained via a contraction (via the partial trace operation discussed in Section 3.1) of the dynamics of $\mathcal{S}+\mathcal{E}$ to the state space of $\mathcal{S}$; in **GT**, the dynamical equations that govern the evolution of $\mathcal{S}$ pertain directly to $\mathcal{S}$ itself. Systems are modeled as genuinely open in **GT**; i.e., **GT** is a framework formulated in accordance with the open systems view, according to which we generally do not describe the influence of the environment on $\mathcal{S}$ in terms of an interaction between two systems, but instead represent the environment's influence in the dynamical equations that we take to govern the evolution of $\mathcal{S}$.

Deriving the dynamics of a given class of systems in **GT** involves imposing a number of "principles" or conditions on the dynamics of a system in addition to the minimal conditions that we stated in the previous paragraph. In the next subsection we discuss the main assumptions involved in the derivation of the Lindblad equation in **GT**. **GT** is able to describe more than what can be described using the Lindblad equation, however. Indeed, as we will see, none of the main assumptions that are assumed in its derivation—the continuity, Markov, and complete positivity assumptions (we will discuss the latter in some detail)—need hold in general in **GT**.

3.3 Deriving the Lindblad Equation in GT

To begin with, we consider the evolution of a system $\mathcal{S}$ during a given period of interest as governed by a family of dynamical maps, such that a given map in the family, Λ_t, maps $\mathcal{S}$ from some initial state ρ_{t_i} to ρ_{t_f} where $t_f = t_i + t$. Arguably, for a particular Λ_t to serve its purpose as a dynamical map, it is reasonable to require that the state of $\mathcal{S}$ at t_f be completely determined given only a full specification of both Λ_t and of the system's state at time t_i. This is no different from, for instance, the situation in classical mechanics, where the state ω_{t_1} of a system at time t_1 can be fully determined through applying the classical dynamical laws to the full specification of its state, ω_{t_0}, at time t_0. In the case of classical mechanics, a system's dynamics is reversible in the sense that the dynamical laws will take the time-reverse of the system's state at time t_1, $-\omega_{t_1}$ (obtained by reversing the momenta but holding the positions of the system's constituents constant), to the time-reverse of the initial state, i.e. $-\omega_{t_0}$, at time t_2 with $t_2 := t_1 + t$. This is also true (putting aside the question of how to make sense of the dynamics of a measurement interaction) in **ST**, where reversibility follows from unitarity.

In **GT**, by contrast, the dynamics of a system can be non-unitary, and therefore irreversible, in general. Since reversibility is a feature of perfectly deterministic processes, the dynamics of systems in **GT** are not in general deterministic in that sense. If, however, every map Λ_t associated with $\mathcal{S}$ is such as to uniquely map each state in its state space to another state in the same space, then the dynamical evolution of $\mathcal{S}$ thus described is an example of a *Markov process* (cf. assumption 3 in Section 3.1), a generalization of a deterministic process for which the probabilistic state of a given system at time t_f is wholly determined, given Λ_t, by considering its probabilistic state at time $t_i := t_f - t$, though the reverse is not true in general. It follows from this that the dynamical maps describing a system's dynamics may be mathematically composed. That is, describing the evolution of the state of a system during a period $t + s$ is equivalent to describing, first, its evolution during the period s, followed by its evolution during the period, t:

$$\Lambda_{t+s}\rho = \Lambda_t\Lambda_s\rho. \tag{3.4}$$

In order to complete the derivation of the Lindblad equation we require two further general assumptions. The first is that the dynamics should at all times be "completely positive." This is a subtle requirement, which we can both motivate and explain through the following argument. Any dynamical map, Λ_t, on the state space of a system should be such as to map one valid physical state of the system into another. Formally, a density operator is a *positive semi-definite operator*, which effectively means that it assigns non-negative probabilities to the outcomes of measurements on a system. Further, since the probabilities of measurement outcomes must sum to 1, density operators must always be of unit trace: $\text{Tr}(\rho) = 1$. It follows from this that Λ_t must be a trace-preserving positive map; i.e., it must map one positive semi-definite operator of unit trace into another if it is to be physically meaningful.

In addition to describing the evolution of $\mathcal{S}$, it should also be possible to describe the evolution of $\mathcal{S}$ in the presence of further systems. Imagine, in particular, that $\mathcal{S}$ is evolving in the presence of its environment, $\mathcal{E}$, over a period of time, and that at the initial time, t_0, $\mathcal{S}$ and $\mathcal{E}$ are uncorrelated. Imagine, further, that there exists a "witness" system $\mathcal{W}_n$ (where n is the dimensionality of the witness's state space) that, let us assume, is inert and not evolving. We assume in addition that $\mathcal{S}$ and $\mathcal{W}_n$ are spatially separated and not interacting with one another presently. Then it suffices to describe the dynamics of $\mathcal{S}$ and $\mathcal{W}_n$, under these assumptions, if we trivially extend the dynamical map Λ_t for $\mathcal{S}$ via the identity transformation I_n on the state space of $\mathcal{W}_n$:

$$\Lambda_t \otimes I_n.$$

Requiring that Λ_t be *completely positive* means, not only that Λ_t should be a positive map; but also that $\Lambda_t \otimes I_n$ should be a positive map for all n. Not all positive Λ_t are completely positive in this sense, however.[17] Requiring complete positivity means that any such maps cannot be valid maps on $\mathcal{S}$. This is arguably (although we will question it shortly) a reasonable requirement on a dynamical map, for it seems reasonable to require that it should be possible to consider the action of Λ_t on $\mathcal{S}$ regardless of $\mathcal{S}$'s initial state; in particular that the effect of Λ_t on $\mathcal{S}$ should be the same, and should always be valid, regardless of the existence of some other system $\mathcal{W}_n$ with which $\mathcal{S}$ is not even (presently) interacting.

The last condition we will require of our family of dynamical maps is also the simplest to state: In order to derive the Lindblad equation in the framework of **GT**, we require that it describe the system $\mathcal{S}$ as evolving continuously in time. Intuitively, this means that Λ_t evolves ρ_0 so that, as t approaches zero, the resulting state of the system becomes "infinitesimally close" to ρ_0.

A family of dynamical maps that satisfies the Markov condition, complete positivity and continuity is called a *quantum dynamical semigroup* (QDS). For a given QDS there exists a densely defined superoperator $\mathcal{L}$ which "generates" the semigroup in the sense that by successively applying $\mathcal{L}$ to a given density operator ρ for a system at some initial time we can construct the dynamical map Λ_t on ρ for any t.[18] One can show (Gorini, Kossakowski, and Sudarshan, 1976; Lindblad, 1976) that for a system S characterized by a separable Hilbert space, the (bounded) generator $\mathcal{L}$ of a quantum dynamical semigroup describing its motion can always be expressed in the general form given by Eqs. (3.2)–(3.3), which we derived for the specific case of a single two-level atom in Section 3.1. To sum up: The Lindblad equation gives the general form of the (bounded) generator of a continuous, completely positive, one-parameter dynamical semigroup describing the evolution of an open quantum system, or at any rate the important class of such systems we have been discussing so far.

GT is more general than the Lindblad equation, however. The Markov (Barandes, 2023), continuity (Wolf and Cirac, 2008) and complete positivity assumptions (Jordan, Shaji, and Sudarshan, 2004) all may be relaxed. The latter, in particular, is especially illuminating as it provides a principled illustration of what follows from taking the open systems view of quantum theory. Recall that, according to the argument we gave above, the trouble with a positive but not completely positive map, Λ_t, on the state space of $\mathcal{S}$ is that extending Λ_t to include the (assumed) trivial dynamics of the witness generally results in negative probabilities for the outcomes of measurements on $\mathcal{S} + \mathcal{W}_n$. However, following Shaji and Sudarshan (2005), we note, first of all, that a prediction of negative probabilities is only possible if $\mathcal{S}$ is initially entangled with $\mathcal{W}_n$. But in that case, according to Shaji and Sudarshan (2005), $\mathcal{W}_n$ should really be thought of as part of the environment. This is important because it can be shown (Jordan et al., 2004, pp. 13–14) that the reduced dynamics of a system, $\mathcal{S}$, are describable by a completely positive map only if $\mathcal{S}$ is initially *not* entangled with its environment.[19] Thus, if we impose complete positivity as a fundamental principle, it would seem that no valid physical description of the dynamics of $\mathcal{S}$ can be given when it is initially entangled. It is precisely for setups like these that a "not completely positive" map will be useful. For when $\mathcal{S}$ and $\mathcal{E}$ are entangled, it follows that it is impossible for $\mathcal{S}$ to be (for instance) in a pure state, or in general in any state that is not a valid partial trace over the combined state of $\mathcal{S} + \mathcal{E}$. With this in mind one can then define a map that is completely positive *vis á vis* the states that are not ruled out by a given setup, while for states that are ruled out we allow that the map may not even be positive on $\mathcal{S}$, let alone its trivial extension positive on $\mathcal{S} + \mathcal{W}_n$ (for discussion, see Cuffaro and Myrvold (2013)).

In the context of **ST**, one can give a better argument for imposing complete positivity as a fundamental principle, namely that complete positivity is assumed in the derivation of Stinespring's dilation theorem (Stinespring, 1955), which asserts that corresponding to a given $\rho_{\mathcal{S}}$ there is a unique (up to unitary equivalence) pure state $|\Psi_{\mathcal{S}+\mathcal{A}}\rangle$ of a larger system $\mathcal{S} + \mathcal{A}$ (where $\mathcal{A}$ is called the "ancilla" subsystem), whose dynamics is unitary, and from which we can derive the in general non-unitary dynamics of $\mathcal{S}$. In other words the procedure for deriving the effective dynamics of an open system that we discussed in Section 3.1 is predicated upon the assumption of complete positivity. Since **ST** is formulated in accordance with the closed systems view, every system is modeled as part of some closed system by definition in that framework, from which it follows that complete positivity must be imposed as a fundamental physical principle. As Raggio and Primas (1982) put it:

> A system-theoretic description of an open system has to be considered as phenomenological; *the requirement that it should be derivable from the fundamental automorphic dynamics of a closed system* implies that the dynamical map of an open system has to be completely positive (p. 435, our emphasis).[20]

Models formulated in **GT** are under no such restriction. In a framework in which open systems dynamics are represented as fundamental, there is no need to be able to derive the dynamics of a system in this way. We can in principle describe the dynamics of any system, even in principle the universe as a whole, *as if* it were initially a subsystem of an entangled system.[21]

In the next section we will argue that **GT** is (ontologically) more fundamental than **ST**. But before we begin we remark that it might be thought that the greater expressive power of **GT** constitutes, all by itself, an argument for this conclusion. We disagree. Appealing to the greater expressive power of **GT** to argue for its relative fundamentality is, in our view, circular insofar as this is to appeal to the very dynamical possibilities that the advocate of the closed systems view (from which **ST** is formulated) finds objectionable. For this reason, in the remainder of this paper we will mainly be restricting our attention to the dynamical possibilities that can be made sense of in both frameworks.

4 The Fundamentality of the Open Systems View

We have now seen that there are two alternative ways to characterize the physics of quantum systems. The first way uses **ST**, a theoretical framework formulated in accordance with the closed systems view, and represents closed systems using state vectors that evolve unitarily. The second way uses **GT**, a theoretical framework formulated in accordance with the open systems view, and represents all systems using density operators that evolve, in general, non-unitarily. The question that we will be addressing in this section concerns which of these characterizations is the more fundamental one. We will argue that **GT** is more fundamental than **ST** *in the ontic sense*, which concerns what we will be calling the *objects of a theoretical framework*. But before we do so we need to be more clear about what we mean by this.

4.1 Framing the Question

In Section 2.1 we distinguished between models, theories, and theoretical frameworks. The question of ontic fundamentality is relevant to all three. In particle physics, for instance, one might say that a model of a phenomenon given in terms of quarks is more fundamental than one given in terms of protons, appealing to the fact that protons are "made up" of quarks (and gluons) according to our best theory. In arithmetic, to take a different example, one might claim that integers are more fundamental than rational numbers, given that a fraction is formed by relating two integers and made up of them in that sense (cf. Frege, 1980, p. II). The second example illustrates that the question of relative ontic fundamentality as it relates to two models of a target system in the context of a given theory can be a subtle one.[22] Every integer is the sum of two rationals, after all, thus one could (conceivably) argue on that basis that rationals, not integers, are more fundamental in arithmetic. Note that the above arguments all assume that if A is "made up of" B (whatever that means in a given context[23]), then B is more fundamental than A. That is only one way to flesh out ontic fundamentality in the context of a given theory, however. There may be others. But we will set this question aside for now. The important thing to take away from these examples, for our purposes, is that in each case what is being compared are particular models as described within a single theory.

The question of whether one theory or theoretical framework is more fundamental than another is not like the question of whether quarks are more fundamental than protons in particle physics, or whether integers are more fundamental than rationals in arithmetic. Answering the question of which of two given theories or theoretical frameworks is more fundamental, where each, within itself, supports its own relations of ontological fundamentality with respect to the objects it describes, can be a subtle and difficult exercise. As Kerry McKenzie (2019, §4) notes, some such questions will be easier to answer than others, at least prima facie. A compelling case, for instance, can be made that classical theory is less fundamental than quantum theory because certain aspects of the appearance of classicality can be seen to follow from the unitary dynamics of quantum-mechanical systems via the dynamical process of decoherence. How one interprets this dynamical account of the appearance of classicality is another matter, of course, but putting interpretive questions to one side for the moment, the reason this case is particularly compelling is that (as McKenzie notes) all one needs to do to get the appearance of classicality is to consider the effective dynamics of quantum systems entangled with their external environment.

The above example of the relation between quantum and classical theory seems to suggest that we can call one theoretical framework more fundamental than another if objects as described by the latter can always be seen to arise as a special case of some aspect of objects as described by the former.[24] The basic idea is to think of fundamentality comparisons between frameworks in terms of a kind of determination (or what Bennett (2017) calls a *building*) relation; i.e., it is to think of the more fundamental as somehow being responsible for, i.e., as a *sufficient condition* for bringing about the less fundamental (McKenzie, 2019, sec. 3).[25]

We are almost ready to propose our first candidate explication of the relation of ontic fundamentality between theoretical frameworks. But before this we need to informally explicate, and then elaborate on, the idea of an *object of a theoretical framework*:

> **(Object)** Let $\mathcal{F}$ be a theoretical framework. O is an Object ("capital-O") of $\mathcal{F}$ iff, in every model of every theory that can be formulated in $\mathcal{F}$, objects (in the "little-o", or "pre-theoretic" sense) are representable in terms of O.

Clearly this explication is very informal, but it is enough to convey the idea that the Objects of a theoretical framework are always available irrespective of any particular modeling assumptions one might employ in a given context (other than the minimal assumptions required by the framework). In other words, the Objects of a theoretical framework codify its methodological presuppositions; i.e., the ways in which (little-o) objects may be modeled in the framework.

Let us illustrate this in more concrete terms using the examples of **ST** and **GT**. Consider: (i) In every model of every theory that can be formulated in **ST**, the state of a closed system, $\mathcal{S}$, is given by a unitarily evolving normalized state vector, $|\psi\rangle$;[26] (ii) in every model of every theory that can be formulated in **GT**, the state of a system, $\mathcal{S}$, is given by an in general non-unitarily evolving density operator, ρ. Our little-o object is $\mathcal{S}$ in each case.[27] Our Objects are $|\psi\rangle$ and ρ, by which we do not mean any particular instantiation of $|\psi\rangle$ or any particular instantiation of ρ but the *abstract concepts* of a state vector and of a density operator in general, instances of which we draw upon to represent a given system in a given model. From here on, whenever we discuss the "objects of a theoretical framework" (or use a similar expression), what we mean are objects in the sense of Object, but we will generally not use (except when it makes sense to do this for emphasis) a capital-O.[28]

In the next subsection we will proceed to explicate the concept of ontic fundamentality as it relates, first, to the objects of a theoretical framework, and second, to theoretical frameworks themselves. In the latter case we will see that our first attempt at an explication (what we will call **OntFund-1**) is too abstract to decide the issue between **ST** and **GT** as it does not consider the little-o objects, i.e., the ontologies, that the objects of these frameworks actually represent. We then proceed to argue for the relative ontic fundamentality of **GT** in accordance with an understanding of that relation (whose formal explication will be left until end of the section) that does consider their underlying ontologies: **OntFund-2**.

4.2 Ontic fundamentality

Motivated by the idea, discussed above, that fundamentality comparisons between frameworks should be thought of in terms of a kind of determination or "building" relation; i.e., that the more fundamental should be thought of as a sufficient condition for bringing about the less fundamental, let us begin by considering the following explication of ontic fundamentality as it relates to two objects of a given theoretical framework. It is, of course, debatable whether a necessary condition (representing dependence) might be more suitable (McKenzie, 2019, sec. 3), but as we will see this will make no difference either to our diagnosis of why our first attempt to cash out the fundamentality relation between theoretical frameworks fails, or to the way that we will ultimately cash out the fundamentality relation between theoretical frameworks at the end of this section.

> **(OntFund-O)** Let O_F and O_P be any two objects of a given theoretical framework, $\mathcal{F}$. O_F is *ontologically more fundamental* than O_P with respect to $\mathcal{F}$ iff whenever an instance of O_P appears in any model of any theory that can be formulated in $\mathcal{F}$,

some instance of O_F can be understood to determine O_P in that model. Furthermore, O_F is *ontologically fundamental* in $\mathcal{F}$ iff nothing is more fundamental than O_F in $\mathcal{F}$.

We now use **OntFund-O** to define:

(OntFund-1) Let $\mathcal{F}_F$ and $\mathcal{F}_P$ be two theoretical frameworks. $\mathcal{F}_F$ is *ontologically more fundamental* than $\mathcal{F}_P$ iff: for all fundamental (in the sense of **OntFund-O**) objects, O_P, in $\mathcal{F}_P$, $\mathcal{F}_F$ always re-describes any instance of O_P as determined given an instance of some other object, O_F, that is more fundamental in $\mathcal{F}_F$. Furthermore, $\mathcal{F}_F$ is *ontologically fundamental* iff there is no theoretical framework more fundamental than $\mathcal{F}_F$.

Note that we have not explicated what it means, in general, to "re-describe" (an instance of) an object of one framework in some other framework. The reason is that we do not presuppose that it means the same thing irrespective of the nature of the two frameworks under consideration. We do know, however, what it means in the context of a comparison between **ST** and **GT**. As we have seen, any state vector $|\psi\rangle$ can alternately be described as a density operator by taking the projection onto $|\psi\rangle$, $\rho = |\psi\rangle\langle\psi|$. This density operator describing the "pure" state of a system is equally valid in both **ST** and **GT**, while the state vector $|\psi\rangle$ is exclusive to **ST**. Although **GT** and **ST** differ in the way that they describe the dynamics of systems in general, the density operator functions as a bridge-concept that allows us to compare the two frameworks with one another.

Unfortunately, it seems that **OntFund-1** cannot help us to determine whether **ST** or **GT** is more fundamental. On the one hand, the fundamental (unitary) dynamical evolution of a state vector, $|\psi\rangle$, as described in **ST**, is always re-describable in **GT** in terms of the fundamental (in general non-unitary) dynamical evolution of a density operator, ρ (in the sense that unitary dynamics is a special case of Eq. (3.2) in which the non-unitary term makes no contribution). On the other hand, given a completely positive trace-preserving map, Λ_t, on the state space of a system $\mathcal{S}$ initially in the state ρ, Stinespring's theorem (see Section 3.3) guarantees that we can uniquely derive the non-unitary dynamics of $\mathcal{S}$ from the unitary dynamics of a larger system $\mathcal{S} + \mathcal{E}$. Finally, confirming what we said earlier, since we can always translate **ST**'s picture of an evolving system into the language of **GT** and vice versa without loss of information, it should be clear that substituting dependence for determination will not help.

The trouble with an explication like **OntFund-1** is that it is too abstract. In particular we have not considered the little-o objects—the ontologies—that the capital-O objects of **ST** and **GT** represent. Let us then do so, beginning with **GT**. In this case the ontology of the framework is (comparatively) clear: In accordance with the open systems view, **GT** conceives of systems in general as being in interaction with an external environment. Note that this does not necessarily mean that all systems described by the framework must be conceived of as open in this sense; i.e., the open systems view does not, per se, deny that closed systems exist. It merely denies that one *must* exist, and represents all systems as, in general, open. As for **ST**, we have argued elsewhere (Cuffaro and Hartmann, 2021, sec. 3; Cuffaro and Hartmann, 2024) that characterizing its ontology is considerably more complicated, but that if one takes **ST** to be a candidate fundamental theoretical framework (i.e., if one takes it to be complete in some sense), there are broadly speaking only two interpretational options available: the Everettian and orthodox families of interpretations (as we characterized them in Section 1); and that whichever one is inclined towards, **ST** is ontologically committed to open systems, in a way that other theoretical frameworks for physics like classical mechanics are not, despite being formulated in accordance with the closed systems view, according to which all systems must be modeled in terms of closed systems. We will now argue that whether one favors an Everettian or an orthodox interpretation—or neither—there are good reasons to take **GT** to be ontologically more fundamental than **ST**, and we will schematically represent our argument, at the end of this section, in the form of our second and final explication of the relation of ontic fundamentality between theoretical frameworks, **OntFund-2**.

On an orthodox interpretation of **ST**, the closed system represented by a state vector is merely abstract; it codifies a collection of unitarily-related conditional probability distributions—our formal descriptions of the phenomena characteristic of a given open system in the context of its possible physical interactions (Cuffaro and Hartmann, 2021, p. 23; in Cuffaro, 2023, sec. 3.2 such a statement is given in the context of the informational interpretation). Open systems, which are most generally represented by density operators, are the stuff of the world for such interpretations. There is no room for closed systems, in an ontological sense, at all. But since **ST** is formulated in accordance with the closed systems view, expressing that $\mathcal{S}$ is an open system, regardless of whether $\mathcal{S}$'s state is given in terms of a density operator or a state vector, *always* involves introducing a hypothetical second system in interaction with the first, both of which are conceived of as open systems.

Thus the picture of a physical system that is presented to us by **GT**, which describes it as an in principle non-unitarily evolving open system, is a picture of a physical system that an orthodox interpreter is already ontologically committed to on the basis of her understanding of **ST**. **GT** differs from **ST** insofar as it eliminates, from our description of a system, the second system that we must introduce, in any theoretical framework formulated in accordance with the closed systems view, to account for its dynamics. But despite this an orthodox interpreter's underlying conception of a system as open need not change in the move from **ST** to **GT**. That is, although the degrees of freedom associated with the second system are stripped away from our description of a system in **GT**, the density operator characterizing the system may straightforwardly be interpreted in the same way as before; i.e., as encoding a probability distribution over the ways that the system will manifest itself to a user of the theory that is interacting with it in a particular way. Finally, **GT** makes fully explicit which conditions are required in general to recover the dynamical evolutions that are possible in **ST**. The orthodox interpreter thus has, we conclude, very good reasons to embrace **GT** as the more fundamental theoretical framework.

Let us now turn to Everettian interpretations. We begin by considering more carefully the ways in which **GT** and **ST** actually differ. We leave aside the difference in expressive power between these two frameworks that relates to the possibility of relaxing principles like the complete positivity, continuity and Markov assumptions, and restrict our attention to the dynamical descriptions that make sense in both frameworks (for the reasons we gave at the end of Section 3.3). With respect to this overlap area, **GT** and **ST** are, evidently, predictively equivalent. Predictive equivalence on a given domain does not imply empirical equivalence (let alone theoretical equivalence) on that domain, however. In particular, Curiel (2014) has shown how two predictively equivalent theoretical frameworks can evince empirically significant differences when we examine the global features of each. One of the global features of a theoretical framework consists in the way that it allows one to describe everything in its domain, which in this case (since these are frameworks for physical theories) comprises everything that physically exists. In the case of **GT**, the picture one draws of the physical universe's evolving state describes it as an in principle non-unitarily evolving density operator, while in the case of **ST** one depicts it in terms of a unitarily evolving state vector.

Let us then ask ourselves the question: *Must* the universe as a whole be described in terms of a unitarily evolving state vector for an Everettian? The answer is no, at least according to some Everettians.[29] David Wallace (2012, sec. 10.5), for instance, argues quite explicitly that there are no philosophical reasons (for an Everettian or otherwise) not to take seriously the possibility that the universe's dynamics is that of a non-unitarily evolving density operator (pp. 397–400), and further, that there is positive evidence for this possibility that comes from considering the physics of black holes (pp. 400–401). Wallace (see Wallace, 2020) no longer finds that particular evidence convincing. But regardless of what one makes of this and other evidence, the point we want to make here, to begin with, is that there is no a priori reason to think that describing the universe in terms of a non-unitarily evolving density operator is somehow inconsistent with the Everett interpretation.

As an illustration, consider the simple density operator below, expressed as a mixture of two pure states:

$$\rho = p\,|\psi_1\rangle\langle\psi_1| \;+\; (1-p)\,|\psi_2\rangle\langle\psi_2|. \tag{4.1}$$

The fact that the different terms, $|\psi_1\rangle\langle\psi_1|$ and $|\psi_2\rangle\langle\psi_2|$ are decoherent (i.e., the decomposition of ρ is diagonal in the given basis) makes it unproblematic, irrespective of whether or not ρ evolves unitarily, to identify them with independently evolving worlds. In other words, unlike the case of a unitarily evolving state vector, where we must appeal to environmental decoherence as well as to pragmatic considerations in order to argue that, *for all practical purposes*, the worlds that one identifies in the associated superposition are effectively independent from one another even though, strictly speaking, they are not (Wallace, 2003); in the case of a decoherent mixture like the one described in Eq. (4.1), the worlds represented by $|\psi_1\rangle\langle\psi_1|$ and $|\psi_2\rangle\langle\psi_2|$ are independent in a strict sense (i.e., there are no "interference terms") and not just independent for all practical purposes. Thus the motivation to think of the quantum description of the universe as consisting in a description of multiple independently evolving worlds is even more clear in **GT**, where a fundamental description of the universe may take the form of Eq. (4.1), than it is in **ST**.

Sean Carroll, in a paper entitled "Reality as a Vector in Hilbert Space" concedes that:

> Technically [the state of the universe] is more likely to be a mixed state described by a density operator, but that can always be purified by adding a finite-dimensional auxiliary factor to Hilbert space, so we won't worry about such details (Carroll, 2022, p. 5)

Carroll, unlike Wallace, does not comment on whether the mixed state of the universe should be understood as evolving non-unitarily or unitarily. For our part we see no reason to rule out the possibility that it could be evolving non-unitarily, for it is simply the case that density operators evolve, in general, non-unitarily in **ST**. If we are to take seriously the idea that the universal state is represented by a density operator (as Carroll plainly does), then we should take the possibility that it is represented by a non-unitarily evolving density operator just as seriously. And if we do so, then we should view **GT** as more fundamental than **ST**, since the former is the only framework that actually permits us to model the state of the universe fundamentally in terms of a non-unitarily evolving density operator.

Of course, as Carroll can be taken to be suggesting in the above quotation, one can always represent, within **ST**, the dynamics of the universe, even in such a case, using the techniques we discussed in Section 3.1. Given this one might argue that there is no need to abandon this representation, and therefore no need to abandon **ST**, as fundamental. One is tempted to object to this that such a representation of the universe is nothing more than a mathematical trick. It could be rightly rejoined, however, that it is not the job of a theoretical framework to provide an answer to the question of whether a particular purification of a particular density operator is physically significant. Questions like that, it could be argued, are best decided on a case by case basis in the context of a particular theory that can be formulated within the framework of **ST**. But the question at issue here concerns frameworks, not theories, and there is no reason that one can glean from the framework of **ST** per se to view either representation as any less physically significant than the other.

We do not disagree. But other things being equal we think that if we are willing to take seriously the idea that the universe might be in a non-unitarily evolving mixed state, then given the choice between: on the one hand, a framework that *requires* us to artificially inflate the number of degrees of freedom under consideration in order to model a given system's dynamics, irrespective of whether, in our heart of hearts, we take these extra degrees of freedom to hold real physical significance; and, on the other hand, a theoretical framework that does not, as a rule, require us to artificially inflate the degrees of freedom needed to model a given system's dynamics in this way; then we should choose the latter. We further remark that abandoning **ST** in the sense we are concerned with in this paper does not require that we deny that a representation of a non-unitarily evolving universe's dynamical state in terms of a state vector defined over a larger Hilbert space represents something real. It only requires that we abandon the idea that that state vector is fundamental. Finally, we remark that all of this assumes that it is even possible to represent the dynamics of the universe in terms of a state vector defined on a larger Hilbert space at all. As we explained in Section 3.3, **GT** is more expressive than this. Should *this* somehow be taken as a reason, for an Everettian, to reject **GT**? We think not. Ultimately the Everettian should consider herself to be committed to quantum theory, not necessarily the closed systems view of quantum theory.

Of course, nothing we have just said constitutes a reason for thinking that a description of the universe in terms of a non-unitarily evolving density operator is any more likely to be true than a description in terms of a unitarily evolving state vector. But it should be clear, we think, that both descriptions are perfectly consistent with Everett. Ultimately, for an Everettian, which of **GT** or **ST** one adopts should not be decided upon dogmatically. The answer should rather depend upon the physical evidence. Given the prima facie problems for the closed systems view that we discussed in Section 1 which stem from considering cosmology and black hole physics, given that issues such as (for instance) the arrow of time can be more easily resolved in a framework that allows for irreversible dynamics, and finally given that the success of **ST** is actually predicated upon the way that it describes the dynamics of open systems (as we pointed out in Section 1), we think there is every reason to take the idea that the universe's evolution takes the form of the evolution of an open system completely seriously in fundamental physics; i.e., as a live option that any theoretical framework should allow us to make fundamental sense of. And if we do this then there is every reason to embrace **GT**, rather than **ST**, as our preferred theoretical framework for quantum theory, given that the former is the only framework that actually permits us to model the dynamics of the universe fundamentally in these terms.

As far as interpretations of **ST** go, this leaves only hidden-variable theories, which will require only a brief discussion. Hidden-variable theories of **ST**, given that they are not competing interpretations of **ST** but different theoretical frameworks entirely, are not really relevant to our comparison between **GT** and **ST**. Moreover, since **GT** shares those features of **ST** which lead hidden-variable proponents to seek an alternative theoretical framework in the first place—measurement outcomes are still irreducibly probabilistic in **GT**, and the probability distributions over measurement outcomes for different experiments performable on a system are still in general incompatible—those who favor hidden-variable theories are unlikely to embrace **GT** as a fundamental theoretical framework for physics. There is nevertheless something that advocates of hidden-variable theories may take away from our comparison between **GT** and **ST**:

that, since there are good reasons to conclude that **GT** is ontologically more fundamental than **ST**, regardless of how one approaches the question of interpreting **ST** under the assumption that it is complete (in some sense), then the proponent of a hidden-variable interpretation would do better to focus her intellectual energies on **GT** rather than **ST** in her efforts to recover whatever she requires of a framework that it be able to do. For instance, it is possible (though it is by no means required in general) to formulate a dynamical collapse theory within the framework of **GT**: Collapse theories (Ghirardi, 2018) assume that state vector collapse occurs in position space, and the resulting dynamics can be derived from a suitable Lindblad equation. Such solutions to the measurement problem are of course controversial and they run into problems with a relativistic extension. However an advocate for **GT** is not obliged to accept collapse theories. It is merely possible to formulate them within this framework. We emphasize, again, that **GT** is a theoretical framework, not a particular theory.

Considering that, (i) as we have argued elsewhere (Cuffaro and Hartmann 2021, sec. 3; Cuffaro and Hartmann 2023; Cuffaro and Hartmann 2024; Cuffaro 2023),[30] **ST** is ontologically committed to open systems, regardless of how one interprets **ST** as a candidate fundamental theoretical framework; (ii) that, regardless of how one interprets **ST** *tout court*, one should conclude that **GT** is more fundamental than **ST** with respect to the dynamical descriptions that can be made sense of in both; this is enough to conclude that **GT** is ontologically more fundamental than **ST**, and thus enough to have fulfilled the goal that we set for ourselves in this section. What remains is to provide our proposal, finally, for an explication of ontic fundamentality as it relates to theoretical frameworks:

> **(OntFund-2)** Let $\mathcal{F}_F$ and $\mathcal{F}_P$ be two theoretical frameworks, and let $\{O_F\}$ and $\{O_p\}$ be their corresponding fundamental objects (in the sense, say, of **OntFund-O**). Furthermore let $\mathcal{F}_F$ and $\mathcal{F}_P$ be motivated by two distinct metaphysical positions, $\mathcal{M}_F$ and $\mathcal{M}_P$, respectively, in regard to their little-o objects. $\mathcal{F}_F$ is *ontologically more fundamental* than $\mathcal{F}_P$ iff the way that the $\{O_p\}$ actually represent their little-o objects corresponds not to $\mathcal{M}_P$ but to $\mathcal{M}_F$. Furthermore, $\mathcal{F}_F$ is *ontologically fundamental* iff there is no theoretical framework more fundamental than $\mathcal{F}_F$.

5 Discussion

Recall, from Section 2.1, that associated with a given view is (i) a set of methodological presuppositions in accordance with which we characterize the objects of a given domain, that is (ii) motivated by a particular metaphysical position concerning the nature of those objects (and objects in general). Frameworks are formulated in accordance with a given view insofar as they formalize that view's methodological presuppositions and apply them universally to all the phenomena describable in the framework. We have seen, however, that the subject matter of a theoretical framework—what a philosophical analysis of its objects leads us to conclude about the ontology they represent—does not necessarily conform to the metaphysical position that motivates us to formalize the framework in terms of those objects in the first place. In the case of **ST** we saw that the metaphysical position that motivates the use of the state vector to represent physical systems does not align with the way that physical systems are actually represented in the framework: Although **ST** is formulated in accordance with the closed systems view, the systems it represents are in general open.

The fact that the ontological implications of taking a view in a given domain might decouple from the metaphysical position that motivates the view in the first place might seem paradoxical, but we can begin to understand how this situation arises in quantum theory if we consider that the closed systems view from which it is formulated is essentially the view of the world that **ST** has inherited from classical physics. **ST** generalizes probabilistically (as compared with classical physics) the way in which one represents the state of a closed system while remaining consistent with the methodological presuppositions of the closed systems view. But the result of this generalization, as we have seen, is that what is actually represented by the objects of **ST** is a domain of little-o objects that includes open systems essentially. And since the dynamics of an open system, as formally described by **ST**, is in general non-unitary; there is a clear motivation to adopt a more general theoretical framework, which might in principle involve a change in corresponding view, in which it is possible to fundamentally describe the dynamics of systems in that way. That framework, we have argued, is **GT**, and the view in accordance with which **GT** is formulated is the open systems view.

The open systems view is less restrictive than the closed systems view insofar as it is consistent with the metaphysical position that motivates the former that closed systems can exist. The obvious candidate for a closed system in **GT**, given that (let us presume) everything is in interaction with everything else, is the cosmos as a whole. One of the possible ways in which the cosmos can evolve in **GT** is unitarily, in which case interpreting it to be a closed system would seem to be conceptually unproblematic. However, **GT** does not require us to model the dynamical evolution of the cosmos as unitary—unlike **ST**, it allows for the dynamical evolution of the cosmos to be non-unitary. But what can this really mean? Should we interpret the non-unitary evolution of the cosmos as the dynamical evolution of an open or of a closed system? Neither concept would seem to be adequate. On the one hand, it would seem to make little sense to describe a non-unitarily evolving system as described by **GT** as closed. The generator of the quantum dynamical semigroup for such a system, as we saw in Section 3.3, includes terms besides those associated with the system's Hamiltonian, and these extra terms are most naturally interpreted as due to the system's interaction with an external system. On the other hand, it also seems to make little intuitive sense to say that the universe as a whole is literally an open system, at least not in the sense that we usually mean by this term. After all, the universe just means everything that exists, does it not?

It would seem, then, that the ontological distinction between open and closed systems (at least when it pertains to the cosmos) breaks down in **GT**. This is a lesson which metaphysicians should take to heart. Ultimately, density operators, state vectors, and other formal concepts in physics are bits of mathematics that we use to describe the world.[31] We must not presume that every such concept that arises in a scientific theory will conform, when interpreted ontologically, to our pre-theoretic concepts or even to the concepts of our predecessor theories. Ultimately metaphysics and physics must work together: Physics provides the opportunity for metaphysics to re-conceptualize basic ontological distinctions such as that between an open and a closed system, while metaphysics, on the basis of this renewed understanding of the world, motivates new physics.

What, then, can it mean to represent the cosmos as a non-unitarily evolving density operator? We will leave it for another occasion to fully explore this question, but we will gesture at some possible answers here: Given that (a) the dynamics of a non-unitarily evolving universe as described by **GT** would appear to us *as if* it were the dynamics of a system interacting with an external system (i.e., it can be described as though it were the dynamics of a subsystem of an entangled system), one might be tempted to conceive of the cosmos in the way that Newton did, i.e., as occasionally subject to (and indeed requiring) interventions from some external entity (perhaps divine). While this option is perhaps always open, it is not entirely satisfactory as it seems to us that the main motivation for understanding the universe in this way (coming from physics, at any rate) stems from the closed systems view.

An alternative, which is arguably more fully in the spirit of the open systems view, is to think of the form taken by the dynamical evolution of the cosmos as just a brute fact, which we can describe in **GT**, but which, like the principle of inertia in Newtonian mechanics, is not subject to further explanation. But just like the brute fact of the principle of inertia in Newtonian mechanics, the brute fact of the form of the dynamics of the universe is one that may potentially lead the way to new physics. Could this new physics lead us back to a kind of closed systems view in the end? We think this is unlikely, and anyway it would require a re-conceptualization of what a "closed system" is. In any case, while it would be a mistake to rule this out as a logical impossibility, we can certainly say that from our current standpoint, the open systems view, as we have described it in this paper, is fundamental in quantum theory. Wherever (quantum) physics leads us in the future, we will have arrived there by following the path laid out by it, not the path laid out by the view it has superseded. Philosophers are best served, therefore, in their discussions of the nature of reality, in focusing on the description of it provided by the open systems view.

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Notes

[1]It may also be closed with respect to only one such quantity. For instance, a system is *chemically closed* if it does not exchange matter with the environment (though it might, for example, exchange heat with it).

[2]Zeh (2007, p. 56) discusses an interesting thought experiment originally due to Borel showing how the microstate of a gas in a vessel under normal conditions on Earth will be completely changed, within seconds, as a result of the displacement of a mass of a few grams at around the distance of Sirius.

[3]See also Primas (1990, pp. 234, 243–244).

[4]In the context of quantum theory, see, e.g., Migdal (2000).

[5]Another example of a conceptual puzzle that arises for the closed systems view is that of how to make sense of the so-called arrow of time (Callender, 2021; Roberts, 2022).

[6]Given that the universe refers to everything that exists, one might wonder how it is possible to think of it as anything other than closed. This will become clearer as we progress, but for now we simply remind the reader of Ladyman and Ross's (2007, sec. 2.3.4) distinction between what they call (following Carnap) the formal and material modes of speech. Our main (but not exclusive) concern in this paper is the former, i.e., with the question of whether a given system of interest is best conceptualized or *modeled* as a closed system.

[7]Thanks to Wayne Myrvold (personal communication) for suggesting this.

[8]Note that in Cuffaro (2023) the focus is exclusively on the informational approach to quantum interpretation.

[9]**GT**, which is our label for it, is our take on the formalism originally introduced in Sudarshan et al. (1961) and Jordan and Sudarshan (1961). **GT** is similar in some respects to the framework that Eddy Chen (e.g., Chen, 2021, 2020a,b) calls "density matrix realism," though the connection with open systems dynamics is not as central in Chen's framework as it is in **GT**.

[10]Exceptions are *phenomenological models* (see, e.g., Frigg and Hartmann, 2020), which account for a target system using a wide range of assumptions which do not necessarily arise from the same theory. Such models are an important part of science, and often pave the way to new theories (Hartmann, 1995, 1999; Kao, 2019, 2021), but for our purposes we need only be concerned with models formulated in the context of a single theory.

[11]Nielsen and Chuang (2000, p. 2) draw the analogy between a framework and the particular theories it subsumes, on the one hand, and an operating system on which particular computer applications are run, on the other. Note that making this distinction is not always a straightforward exercise. There is much to say about this and other related questions, as well as about the related issue of theoretical equivalence. For our purposes, however, we think the distinction (which is essentially the same as the one drawn by Wallace (2019)) between quantum theory as a framework and the particular theories it subsumes is relatively clear.

[12]Our use of the concept of an ensemble does not commit us to a frequentist interpretation of probability (cf. Myrvold, 2021, p. 151). It is only a particularly useful fiction for conveying the difference between pure, properly mixed, and improperly mixed states, and what it means for a properly and an improperly mixed state to be (locally) indistinguishable from one another.

[13]For two modern textbooks on the topic, see Alicki and Lendi (2007); Breuer and Petruccione (2007). Davies (1976) is a classic text.

[14]That is, $\sigma_+|0\rangle = |1\rangle$, $\sigma_+|1\rangle = 0$, $\sigma_-|0\rangle = 0$ and $\sigma_-|1\rangle = |0\rangle$.

[15]A superoperator is an operator that acts on other operators.

[16]Proof: We take the trace on both sides of Eq. (3.2) and obtain $\mathrm{Tr}\,\dot{\rho}(t) = \mathrm{Tr}\,(\mathcal{L}_u\,\rho) + \mathrm{Tr}\,(\mathcal{L}_{n-u}\,\rho)$. As both terms on the right hand side are (sums of) commutators (see Eq. (3.3)) and the trace of a commutator vanishes, we get that $\mathrm{Tr}\,\dot{\rho}(t) = 0$. This implies that $d/dt\,(\mathrm{Tr}\,\rho(t)) = 0$ and therefore $\mathrm{Tr}\,\rho(t) = \mathrm{Tr}\,\rho(0) = 1$. It is then easy to show that $\sum_m p_m(t) = \sum_m \mathrm{Tr}\left(\rho(t)\,M_m^\dagger M_m\right) = \mathrm{Tr}\left(\sum_m \rho(t)\,M_m^\dagger M_m\right) = \mathrm{Tr}\,\rho(t) = \mathrm{Tr}\,\rho(0) = 1$, where $p_m(t)$ is the probability of obtaining the outcome m given a measurement at time t, and M_m is the projective operator corresponding to m, such that $\sum_m M_m^\dagger M_m = I$ (i.e., such that the M_m satisfy the completeness relation; see Nielsen and Chuang, 2000, p. 85). Hence, $\sum_m p_m(t) = \sum_m p_m(0) = 1$. □

[17]One example of a positive but not completely positive map takes a density operator (expressed as a matrix) to its transpose (see Nielsen and Chuang, 2000, p. 369).

[18]The analogue of the generator of a QDS in **ST** is the system's Hamiltonian, which likewise can be used to generate a (unitary) map on the state space of the system for any t.

[19]Jordan et al.'s result generalizes an earlier result for two-dimensional systems proved by Pechukas (1994).

[20]Raggio and Primas were presumably not aware, when they wrote this, of Pechukas's and Jordan et al.'s results published decades later. Note that the use of a not completely positive map is not necessarily inconsistent with this statement if it is thought of as a mere mathematical tool (Cuffaro and Myrvold, 2013).

[21]For more on the properties of not completely positive maps, see Dominy, Shabani, and Lidar (2016) and Rohira, Sanduja, and Adhikari (2021).

[22]In this case we can think of the "target system" as the particular quantity described by the expressions "3", "1/3 + 8/3", "2/3 + 7/3", and so on.

[23]As Karen Bennett (2017, sec. 2.1) would put it, there are multiple "building relations" (which form a unified family) in virtue of which we can take one thing to be more fundamental than some other thing.

[24]In the rest of the section we will focus on comparisons between frameworks rather than theories.

[25]Bennett's particular characterization of building is as a directed relationship between fundamental and non-fundamental such that the former is understood as necessitating and generating the latter (2017, sec. 3.1). Both necessitation and generation express sufficient conditions insofar as a particular state of the non-fundamental is taken to be entailed (in one of those senses) by a particular state of the fundamental. Other philosophers who cash out fundamentality in terms of determination include Fine (2015) and Dasgupta (2015).

[26]The mere fact that a given system, $\mathcal{S}$, happens to be a subsystem of the entangled system, $\mathcal{S} + \mathcal{E}$, does not imply, of course, that it is *presently* interacting with $\mathcal{E}$; and one might argue, on these grounds, that $\mathcal{S}$ should (in the case where it is not presently interacting with $\mathcal{E}$) more properly be thought of as a closed rather than as an open system, even though its state cannot be represented by a state vector. We have elected, instead (see Section 1) to define a closed system as one whose degrees of freedom are not dynamically coupled to anything else, and an open system as one for which they are. We think this is appropriate given the highly general terms of our discussion. Whether $\mathcal{S}$ and $\mathcal{E}$ are presently interacting or have interacted in the past, the fact that they have interacted with one another at all (such that the resulting correlations between them can be made manifest given a measurement of the composite system) is encoded in the way that one represents their composite state, which is what we are concerned with here (cf. Clifton and Halvorson, 2001; Valente, 2013).

[27]Our understanding of a little-o object is similar to the way that Primas (1990) characterizes a system: "By a *system* we just mean the referent of a theoretical discussion" (p. 244). Note, however, that our understanding of an Object (capital-O) does not correspond (see note 26) to what Primas calls an object: "An object is defined to be an open quantum system, interacting with its environment, but which is not Einstein-Podolsky-Rosen-correlated with the environment" (ibid.).

[28]Note that our distinction between little-o and capital-O objects is similar to Ladyman and Ross's (2007, sec. 2.3.4) distinction between what they call (following Carnap) the formal and material modes of speech. We are also following Carnap insofar as we use the word "object" (in the capital-O sense) to refer to an abstract concept (Carnap, 2003).

[29]For an example of an Everettian who does require this, see Deutsch (1991).

[30]Note that in Cuffaro (2023) the focus is exclusively on the informational approach to quantum interpretation.

[31]This is a way of putting the point that we owe to Wayne Myrvold.

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