The Open Systems View of Quantum Theory

(based on joint work with Stephan Hartmann)

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Interpretational debates in quantum theory

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However there are (prima facie) reasons to question this focus. For instance,

> *Gleason's theorem (Gleason, 1957): quantum theory's assignment of probabilities is complete in the sense that every probability measure over yes-or-no questions concerning the observable quantities associated with a system is representable by means of a density operator acting on the system's Hilbert space.*

This isn't true for state vectors (unless you appeal to a larger Hilbert space).

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- Even if you argue, as Everettians do, that probability assignments aren't fundamental, it makes sense to focus your interpretational energy on the density operator.

Probability assignments aside, density operators are generally used to represent open systems.

- These evolve in more general ways than the closed systems represented by state vectors.

Cuffaro & Hartmann:
The Open Systems View (arXiv:2112.11095)

- Open systems, represented by density operators, are fundamental in quantum theory.

Cf. Chen (2018).

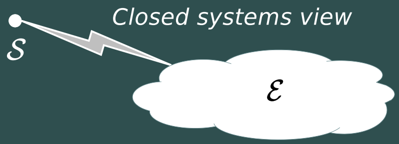
General Quantum Theory of Open Systems (GT)

- Physical state of $\mathcal{S}$ represented by a density operator, ρ
- Time-evolution of ρ is governed by a dynamical map, Λ_t:

$$\Lambda_t \rho_0 = \rho_t$$

  - Λ_t acts on the state space of $\mathcal{S}$ (not on $\mathcal{S} + \mathcal{E}$).
  - Non-unitary in general

In standard quantum theory (ST), open systems dynamics must always be viewed as a contraction (via the partial trace operation) of the dynamics of $\mathcal{S}+\mathcal{E}$, which is represented in terms of a unitarily evolving state vector, $|\Psi_{\mathcal{S}+\mathcal{E}}\rangle$.



- This forces the dynamical map on an open system to be completely positive (i.e., this is implicit in Stinespring's theorem).

  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 (Raggio & Primas, 1982, 435).

In GT, however, open systems are taken to be fundamental.

- No need to understand open system dynamics in terms of a contraction of the dynamics of a larger closed system.
- It follows that the dynamical maps governing an open system do not, in general, need to be completely positive.
- This makes it possible to describe the evolution of the universe as a whole as if it were initially a subsystem of an entangled system.

So GT, unlike ST, allows for fundamental non-unitary evolution, and is, in this sense, a more general dynamical framework than ST (despite not really adding anything to the Hilbert space formalism).

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- Our response (our take on a suggestion of W. Myrvold's):
  - On the contrary, in practice we strictly speaking only ever apply quantum theory to open systems.
  - Although this typically involves the methodological assumptions associated with the closed systems view,
  - It's not the dynamics of of $\mathcal{S} + \mathcal{E}$ but the dynamics of $\mathcal{S}$ that we take ourselves to have successfully described when we do this.
  - There is a clear empirical motivation to extrapolate from the dynamics of open systems rather than from the dynamics of closed systems.

Further motivations (from other areas of physics):

- No general principle of energy-momentum conservation in general relativity (see Curiel 2019; Hoefer 2000; Maudlin et al. 2020).
- Standard models of cosmology describe the universe as closed but are often based on strong idealizations introduced only to simplify the mathematics (Smeenk & Ellis, 2017, Sec. 1.1).
  - Thus, although our best cosmological models describe our universe as a closed system, this does not necessarily mean that our universe actually is a closed system (see also Gryb & Sloan, 2021; Sloan, 2018).
- Black hole physics gives us (prima facie) reasons to motivate describing the evolution of the cosmos as formally similar to the evolution of an open system (Hawking, 1976).
- Global unitary evolution is hard to square with some of the more important approaches to quantum gravity (Oriti, 2021, sec. 3.1).

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  - Both take (vanilla) quantum mechanics as providing the resources with which to completely describe reality.
  - But in terms of their a priori commitments, these two interpretations couldn't be more different.
  - Yet, we argue, both have very good reasons to endorse the open systems view of quantum theory.

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- This is simultaneously true of all observables. The state determines the answers to all questions concerning all observable quantities in advance.

In ST, states fail to be truthmakers in two senses (Janas et al., 2022; Pitowsky, 2006):

1. The "big" measurement problem: Specifying $|\psi\rangle$ yields, in general, only the probability that the answer to a given experimental question will take on a given value.
   - Not as much of a departure from classicality as one might think. Conditional on the selection of an observable, observed statistics are describable by a classical probability distribution.

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2. The "small" measurement problem: The classical probability distributions associated with individual observables cannot be embedded into a global classical probability distribution over all observables.
   - In ST one can only say that conditional upon inquiring about A, there is a particular probability distribution that one can use to characterise the possible answers to that question.
   - ST's unitary description of a measurement interaction does not, by itself, prefer any one of these (a.k.a. the preferred basis problem).

The MWI:

- Subscribes to the "traditional metaphysical picture"
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  - But, since the values of observable (dynamical) quantities cannot actually be consistently interpreted (because of the big and small measurement problems) as representing determinate properties of a single classically describable physical system,
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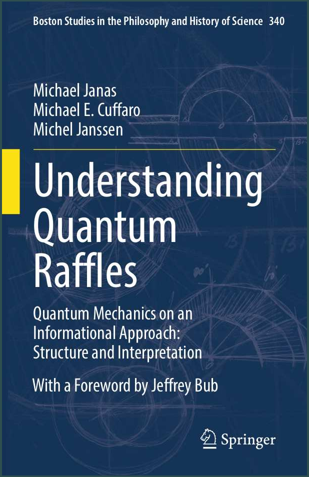
  - and since physical reality is completely described by the quantum-mechanical state vector,
  - the most natural thing to say is that, at least in principle, all of the (approximately) classical possibilities described by the state vector are physically realised.

Informational (a.k.a. neo-Bohrian / neo-Copenhagen) interpretation:



See also: Pitowsky (1989); Brukner & Zeilinger (2005); Bub & Pitowsky (2010); Bub (2016); Brukner (2017); Demopoulos (2022).

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- Isn't opposed to the traditional metaphysical picture per se.
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  - How we carve nature at the joints is something that should be motivated by physical theory.
- Not anti-realist. The question is not whether, but how to assign physical properties to what we take to be the external world (cf. Perović, 2021, 118).
  - In other words what's taken as primary is not the traditional metaphysical picture.
  - Rather: the empiricist methodology through which we reason from the values revealed in experiments, carried out under precisely specified experimental conditions, to a picture of the world that does not transcend, but is anchored in, the contextual models one gives of phenomena under the dynamical assumptions characterising each of them.

In other words, probabilities are essentially conditional probabilities for an informational interpreter; and the picture our theories build up of the world is in this sense essentially a contextual picture (which of course can admit of special cases, of which classical theory is one).

- (i.e., in classical theory, conditional probability assignments can, in a very natural way, be abstracted away from so that we can think of probability assignments as absolute).

That is,

- Because the probability distributions over the values of every classical observable are determined independently of whether a physical interaction through which one can assess those values is actually made, we are invited to think of them as originating in the properties of an underlying physical system that exists in a particular way irrespective of anything external.

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- What is exhibited by the quantum state is not a collection of observer-independent properties, but the structure of and interdependencies among the (unitarily related) possible ways that one can effectively characterise a system in the context of a physical interaction (cf. Curiel, 2014, sec. 3).

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  (a) Non-dynamical quantities (mass, spin, charge, etc.): valid regardless of experimental context.
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- Does (b) depend, physically or metaphysically, on the existence of conscious observers?
  - No. All that is happening here is that a schematic representation of what (relevantly) constitutes an observer—a classical conditional probability distribution (a.k.a. "Boolean frame")—is being used as a formal tool with which to describe how the various possibilities that are implicit in the world are necessarily related to one another.

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- Physics is in the business of describing, in accordance with this methodology, the true empirical relations that obtain in the world.

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|\psi\rangle_{\mathcal{S}} &= \alpha|b_1^+\rangle + \beta|b_1^-\rangle \\
&= \alpha'|b_2^+\rangle + \beta'|b_2^-\rangle.
\end{aligned}
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What does this mean on the informational interpretation?

- Coupling the degrees of freedom of $\mathcal{S}$ to those of a further system $\mathcal{M}$ will yield a collection of unitarily-related conditional probability distributions over the possible outcomes of an assessment of $\mathcal{M}$ as described with respect to a particular basis b_m.

"In the treatment of atomic problems, actual calculations are most conveniently carried out with the help of a Schrödinger state function, from which the statistical laws governing observations obtainable under specified conditions can be deduced by definite mathematical operations. It must be recognized, however, that we are here dealing with a purely symbolic procedure, the unambiguous physical interpretation of which in the last resort requires a reference to a complete experimental arrangement." (Bohr, 1958, pp. 392–393, our emphasis).

Informational interpretation:

- Notice that $\mathcal{S}$ is conceived of here as an open system (even when its state is described by a state vector), but since open systems dynamics are not fundamental in ST, we require a larger Hilbert space (including the degrees of freedom of both $\mathcal{S}$ and $\mathcal{M}$) to represent it as such.

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- ST is about open systems, on the informational interpretation, despite being formulated from the closed systems view (which it inherits from classical mechanics).
- The motivation for adopting GT, which takes open systems to be fundamental, as our theoretical framework for describing quantum reality is very clear.

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- To solve the "small" (a.k.a. preferred basis) problem, we appeal to decoherence: When $\mathcal{S}$ interacts with another system $\mathcal{M}$ (which might include the degrees of freedom of a human agent), the terms in the above superposition for $\mathcal{S}$ begin to decohere with respect to a given basis for the density operator characterising $\mathcal{M}$.

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- An agent included in $\mathcal{M}$ observes a particular statistical distribution over the outcomes (say $|b_1^+\rangle$ and $|b_1^-\rangle$) in agreement with the predictions given by the density operator corresponding to $\mathcal{S}$.
- All of this is determined by the universal state vector, $|\Psi\rangle_{\mathcal{S}+\mathcal{M}}$.

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- In more general terms,
    - Corresponding to any given probability distribution over pure states of $\mathcal{B}$ (i.e., to any given density operator for $\mathcal{B}$), one can always find a pure state of some larger system $\mathcal{A}+\mathcal{B}$ from which that probability distribution can be derived.
    - All such purifications are "essentially the same" (D'Ariano et al., 2017, p. 171).
    - $\rho_{\mathcal{S}}$, expressed as a decoherent mixture of various states corresponding to the elements of an eigenbasis of $\rho_{\mathcal{M}}$ is just as objective a description of everything there is, relative to the degrees of freedom included in our representation of $\mathcal{S}$ and to the given eigenbasis, as the universal state vector $|\Psi\rangle_{\mathcal{S}+\mathcal{M}}$.

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- What about the universe as a whole? Mustn't it, for the MWI, necessarily be described in terms of a unitarily evolving pure state (thus entailing that we privilege ST over GT)? Apparently not (at least not on all versions of the mWI).
    - David Wallace (2012): not inconsistent with the MWI to represent the universe in terms of a non-unitarily evolving density operator. (Whether we do so or not depends on the available evidence.)
    - Sean Carroll (2021): "Technically [the state of the universe] is more likely to be a mixed state described by a density operator" (p. 5).

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Upshot:

- There are good reasons, we think, for an advocate of the MWI to at least be open to the idea that the universe is describable in terms of an in-principle non-unitarily evolving density operator.
- Since this is how one, in general, describes the dynamics of open systems, there are good reasons to view the dynamics of open systems to be fundamental in quantum theory.

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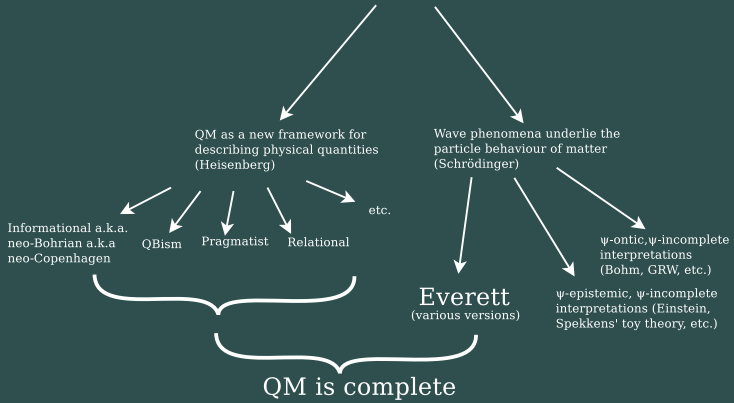
We think both the MWI and the informational interpretation have a clear motivation to embrace GT as our theoretical framework for quantum theory.

Interpretations of ST

(Janas, Cuffaro, & Janssen, 2022)



- Much of what I said about the informational interpretation could also have been said about QBism, Pragmatist, and Relational views.
- What about hidden-variable theories (HVTs)? GT is unlikely to satisfy those who advocate for them. Nevertheless, since we can consider GT to be preferred over ST for anyone who interprets the latter as complete, it would seem to follow that advocates of HVTs should focus on providing an underlying ontology for GT, not ST.

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