The Principle of Complete Positivity and the Open Systems View

(based on joint work with Stephan Hartmann)

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Our claim:

- Complete positivity is an expression of what we call the "closed systems view of quantum theory."
- We should reject the closed systems view (in favour of the "open systems view") and deny complete positivity the status of a fundamental physical principle.

Outline:

1. The principle of complete positivity
2. The closed systems view vs. the open systems view
3. Making sense of fundamental open systems dynamics in Everettian and informational interpretations of QM
4. Conclusion

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- State change of $\mathcal{S}$ in the presence of $\mathcal{E}$: $\rho_{\mathcal{S}} \mapsto \mathrm{tr}_{\mathcal{E}}(U\rho_{\mathcal{S}} \otimes \rho_{\mathcal{E}}U^\dagger) = \rho'_{\mathcal{S}} = \Lambda\rho_{\mathcal{S}}$

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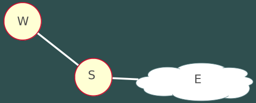

Consider the system $\mathcal{S} + \mathcal{W}_n$ evolving in the presence of $\mathcal{E}$, such that:

- $\mathcal{W}_n$: A system of dimensionality n not currently interacting with $\mathcal{S}$, but which may have interacted with it in the past.
- $\mathcal{W}_n$ evolves trivially.

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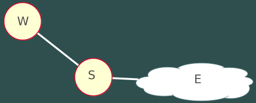

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Problem: Requiring that Λ be positive on $\mathcal{S}$ does not guarantee that $\Lambda \otimes I_n$ is positive on $\mathcal{S} + \mathcal{W}_n$.

- I.e., $\Lambda \otimes I_n$ will map some of the states in $\mathcal{H}_{\mathcal{S}+\mathcal{W}_n}$ to unphysical states (i.e., that yield negative probabilities for the results of measurements on $\mathcal{S} + \mathcal{W}_n$).

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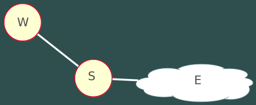

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Solution: Require that $\Lambda \otimes I_n$ be positive for all $\mathcal{W}_n$.

"One may reasonably doubt this argument. It is very powerful magic: $\mathcal{W}$ sits apart from $\mathcal{S}+\mathcal{E}$ and does absolutely nothing; by doing so, it forces the motion of $\mathcal{S}$ to be completely positive with dramatic physical consequences ..." (Pechukas, 1994).

More concrete reasons to be skeptical (Shaji & Sudarshan, 2005):

Suppose, on the one hand, that $\mathcal{S}$ and $\mathcal{W}_n$ are not entangled:

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- If we enforce complete positivity then it would seem to follow that no valid physical description of the dynamics of $\mathcal{S}$ can be given when it is initially entangled with $\mathcal{E}$.

Not completely positive (NCP) maps:

It is precisely for setups like these that an NCP map will make sense.

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- Such states that are outside of the 'compatibility domain' of an NCP map will be ill-described by it.
- But as long as such a map is completely positive in relation to all of the actually possible states of $\mathcal{S}$ in a given setup, it seems that there is no reason not to use it to describe the dynamics of $\mathcal{S}$ (Cuffaro & Myrvold, 2013, sec. 5).

A better argument for imposing complete positivity as a fundamental physical principle:

> 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, p. 435, our emphasis).

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Standard quantum theory (ST)

- Physical state of a closed system, $\mathcal{S}$, is represented by a state vector, $|\psi\rangle$, in a Hilbert space for $\mathcal{S}$.
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Strictly speaking no system (except, perhaps, the whole universe) can really be isolated. How do we model open systems in **ST**?

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Closed systems view of an open system:

- $\mathcal{S}$'s interaction with its environment is described in terms of its being coupled with a separate system $\mathcal{E}$ such that $\mathcal{S}+\mathcal{E}$ form an isolated system.

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

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  where the L_i are (bounded) operators.
- Guaranteed by Stinespring's dilation theorem (Stinespring, 1955), which assumes complete positivity.

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- 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 important recent approaches to quantum gravity (Oriti, 2021, sec. 3.1).

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- It isn't 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.[1]
- Thus there is a clear empirical motivation to extrapolate from the dynamics of open systems rather than from the dynamics of closed systems.

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

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

Cf. Chen (2018).

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

- Formulated in accordance with the open systems view
  - The environment is not represented as a separate system; its influence is represented in the dynamical equations that govern the evolution of $\mathcal{S}$.

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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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  - 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.

$$
\begin{aligned}
|\psi\rangle_{\mathcal{S}} &= \alpha|b_1^+\rangle + \beta|b_1^-\rangle \\
&= \alpha'|b_2^+\rangle + \beta'|b_2^-\rangle.
\end{aligned}
$$

What does this mean on the informational (neo-Bohrian) 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 (neo-Bohrian) 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).

Informational (neo-Bohrian) 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.
- 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 reality is very clear.

What about the universe as a whole?

- Note that it isn't essential that a particular system represented by $\mathcal{M}$ actually exists.
- What's important is the dynamical context that $\mathcal{M}$ represents. It's always possible to imagine a dynamical physical interaction with the empirically accessible degrees of freedom of any physical system—because, conceptually, that is just what we mean when we say that a physical system is empirically accessible—regardless of that system's size (Janas, Cuffaro, & Janssen, 2022, p. 216).
- The further question of whether it "really" makes sense to talk about the empirical accessibility of the universe as a whole is a philosophical question. But as far as physics is concerned, the idea of empirical accessibility is given a clear meaning, in the framework of QM, that can in principle be applied to *any* physical system.

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- Fundamental unitarity?
  - Not necessarily! (see, e.g., Wallace 2012, sec. 10.5).
  - Ultimately the Everett interpretation is committed to quantum theory.
  - But GT makes no changes to the quantum formalism. Rather, it takes a different view of that formalism—one that allows for fundamental non-unitary evolution.

Many worlds:

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

- The fact that the different terms, $|\psi_1\rangle\langle\psi_1|$ and $|\psi_2\rangle\langle\psi_2|$ are by definition decoherent makes it unproblematic, irrespective of whether ρ evolves unitarily, to identify them with independently evolving worlds.
- This is even clearer than the FAPP story one needs to give in the pure state, unitary, case.

Upshot:

- Fundamental open systems dynamics can be physically motivated.
- There is as munch empirical support, if not more, for GT as there is for ST.
- GT is as much in the spirit of Everett as ST is.

There seems to be little reason for an Everettian not to embrace GT as the proper dynamical framework with which to engage in foundational and philosophical investigations (and speculations) regarding the quantum world.

Interpretations of ST

(Janas et al, 2022)

ST as a new framework for describing physical quantities (Heisenberg).

Wave phenomena underlie the particle behaviour of matter (Schrödinger).

Informational (neo-Bohrian)

QBism

Pragmatist

Relational

etc.

Orthodox

Everett

(various versions)

ψ-ontic,ψ-incomplete interpretations (Bohm, GRW, etc.)

ψ-epistemic, ψ-incomplete interpretations (Einstein, Spekkens' toy theory, etc.)

ST is "complete"

Outline:

1. The principle of complete positivity
2. The closed systems view vs. the open systems view
3. Making sense of fundamental open systems dynamics in Everettian and informational interpretations of QM
4. Conclusion

~~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, p. 435).

Conclusion: We should reject complete positivity as a fundamental physical principle.

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