Framework Fundamentality

(Based on joint work with Stephan Hartmann)

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Outline:

1. Models, theories, frameworks, and views
2. The closed and the open systems view
3. The fundamentality of the open systems view
4. Framework fundamentality

Models:

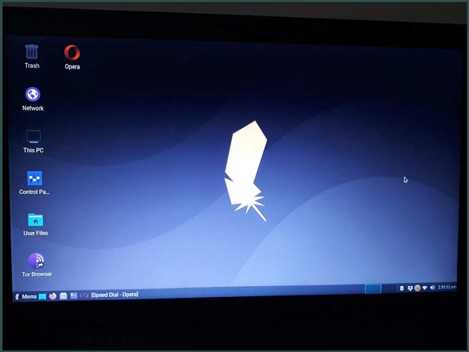
- These are the main representational tools used in science.
- Represent a specific system for a particular epistemic or practical purpose such as explanation, prediction or the planning of an intervention.
- E.g., The model of the hydrogen atom represents it in terms of a positively charged proton (=the atomic nucleus) with a certain mass m_p and a negatively charged electron with a certain mass m_e.
- Models are usually (but not always) formulated in the context of a specific scientific theory.

Theories:

- Specify laws for particular domains, which are then applied by models in concrete cases.
- E.g., the model of the hydrogen atom is usually modelled using non-relativistic quantum theory, which is sufficient for calculating the different discrete energy levels of the atom.
- Alternatively, one can model the hydrogen atom using relativistic quantum theory, which yields various relativistic corrections to the non-relativistic account.
- Non-relativistic QM and relativistic QM have much in common:
  - In both, the state of a system, $\mathcal{S}$, is represented by a state vector, or "wavefunction", $|\psi\rangle$.
  - The evolution of the state is (fundamentally) unitary: preserves "length" (conserves information).

Theoretical frameworks:

- Encapsulate what the theories formulated under them always assume (i.e., in all of their models).
- Analogy: Theoretical frameworks are to theories as computer operating systems are to the particular programs that run under them.



Views:

- A given theoretical framework is formulated in accordance with a particular view.
- Views combine both metaphysical and methodological commitments.

Metaphysics:

- Questions regarding ontology, or what exists.
- Questions regarding first principles, e.g., the principle of cause and effect.

Methodology:

- Questions regarding how to describe objects of interest.
- Questions regarding how to investigate objects of interest.

Views (continued)

W. V. O. Quine:

- “Ontology” (metaphysical) vs. “ideology” (methodology).

“Much in the way of the ideological study can be usefully pursued … within the theory of reference.” (Quine, 1951, p. 15).

We want to argue, on the contrary, that real insight into the objects of a science, how science is practiced, and in how scientific theories and frameworks develop and progress over time (cf. Kuhn) comes from considering the way that methodological and metaphysical commitments interact.

What is a view? (in more detail)

- Motivated by a particular metaphysical position concerning the nature of the objects one wants to describe.
  - Represents the reason for wanting to adopt a given framework, formulated in accordance with that view, in the first place.
- Associated with a set of methodological presuppositions in accordance with which we characterize the objects in a given domain.

Theoretical frameworks are generally formulated in accordance with a particular view in this sense.

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The closed systems view

(1) Metaphysical motivation: Isolated systems are the proper subject matter of science.

(2) Associated with the methodology that models all phenomena fundamentally in terms of closed systems.

"[T]he same force and vigor always remains in the world and only passes from one part to another in agreement with the laws of nature and the beautiful pre-established order."
(Leibniz & Clarke, 2000, Leibniz's first letter, sec. 4)

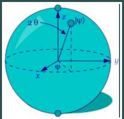
Standard quantum theory (**ST**)

- Formulated in accordance with the closed systems view.
    - I.e., a given system's dynamics is generated by its Hamiltonian (representing the system's total energy), which doesn't include any terms to reflect the system's interaction with something external.

- Physical state of a closed system, $\mathcal{S}$, is represented by a state vector, $|\psi\rangle$, in a Hilbert space (describing its possible states) for $\mathcal{S}$.

- Dynamics of $|\psi\rangle$ is unitary (given by rotations that preserve "length", or conserve information):

$$|\psi_t\rangle = U_t|\psi_0\rangle$$



Strictly speaking no system (except, perhaps, the whole universe) can really be isolated. How do we model open systems in **ST**?

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.

Examples of quantum theories of open systems formulated in the framework of **ST**:

- Weisskopf-Wigner theory of spontaneous emissions
- Laser theory
- Quantum information theory

The open systems view

(1) Metaphysical motivation: The proper subject matter of science is systems that are, in general, open.

(2) Associated with the methodology according to which one need not model phenomena in terms of closed systems. The influence of the environment on a system is represented fundamentally in terms the dynamical equations that we take to govern its evolution.

General Quantum Theory of Open Systems (**GT**)

- Formulated in accordance with the open systems view (but no change to the mathematical formalism per se).
  - The environment is not explicitly modelled as a separate system; its influence is represented in the dynamical equations that govern the evolution of $\mathcal{S}$.

- 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 necessarily on $\mathcal{S} + \mathcal{E}$) and can be non-unitary in general.
  - Non-unitarity $\rightarrow$ information loss over time.

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Some prima facie reasons to worry about the closed systems view

- Not clear that **ST** has ever actually succeeded at representing a closed system.
  - Every material object in the universe is at a minimum subject to the influence of the gravitational field (Zeh, 2007, p. 56).
  - Entangled correlations cannot be shielded either, and unlike gravity they do not decrease with distance (Herbst et al., 2015; Yin et al., 2017).
  - The universe as a whole, perhaps, is the lone target system that can be considered to be an isolated system in the absolute sense, but to date the various approaches to quantum gravity have achieved only partial success (see, e.g., Wuthrich, 2022).
- Of course, even when a system is not absolutely isolated we can sometimes successfully model it as isolated if the effects of the environment are negligible (Ladyman & Thébault, 2025, sec. 10.3).
- But all that means is that an open systems account of the same phenomenon will more accurately describe it in principle.

Deeper reasons to worry about the closed systems view:

Approaches to interpreting **ST** that take it to be complete (in some sense):

- "(neo-)Everettian" approaches: **ST** provides us with a complete description of physical reality.
- "(neo-)Bohrian" approaches: **ST** provides us with all of the resources one needs to model any given (probabilistic) physical phenomenon to whatever level of detail one would like.

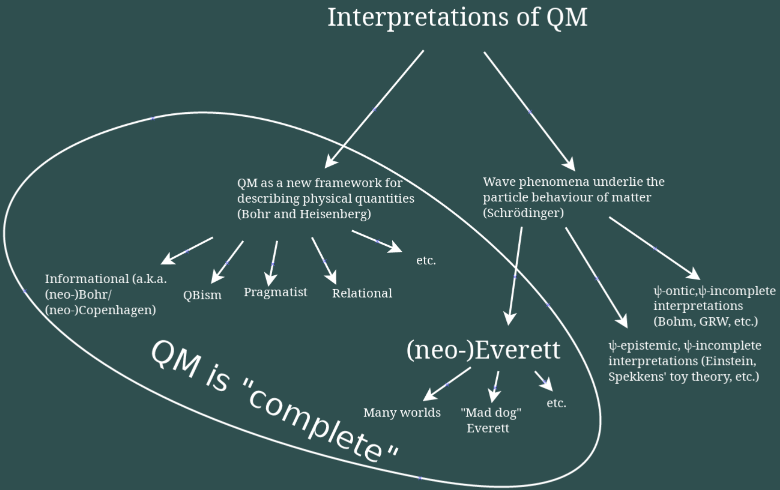
Both (neo-)Everettian and (neo-)Bohrian approaches are ontologically committed to open systems (or so we argue).

Recall that the closed systems view has two components:

(1) Metaphysical motivation: Isolated systems are the proper subject matter of science.

(2) Associated with the methodology that models all phenomena fundamentally in terms of closed systems.

Our claim is that in **ST** these come apart.


Interpretations of QM
QM as a new framework for describing physical quantities (Bohr and Heisenberg)
Wave phenomena underlie the particle behaviour of matter (Schrödinger)
Informational (a.k.a. (neo-)Bohr/ (neo-)Copenhagen)
QBism
Pragmatist
Relational
etc.
ψ-ontic,ψ-incomplete interpretations (Bohm, GRW, etc.)
(neo-)Everett
ψ-epistemic, ψ-incomplete interpretations (Einstein, Spekkens' toy theory, etc.)
QM is "complete"
Many worlds
"Mad dog" Everett
etc.

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What does a state vector, $|\psi\rangle$, actually signify for a Bohrian?

"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. Disregard of this point has sometimes led to confusion, and in particular the use of phrases like 'disturbance of phenomena by observation' or 'creation of physical attributes of objects by measurements' is hardly compatible with common language and practical definition." (Bohr, 1958, pp. 392–393).

The Bohrian approach:

- 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.
- The meaning of $|\psi\rangle$, for a Bohrian: 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 the measuring device as described with respect to a particular measurement basis.
- **ST** is about open systems, on a Bohrian approach, despite being formulated from the closed systems view.

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

The Everettian approach:

- The density operator, $\rho_{\mathcal{S}}$, representing an (open) subsystem, with in general non-unitary dynamics, of a larger system $\mathcal{S} + \mathcal{E}$, 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 a given eigenbasis, as the universal state vector $|\Psi\rangle_{\mathcal{S}+\mathcal{E}}$ (cf. Wallace & Timpson, 2010).
- Interestingly, quantum theory is unique in this regard (D'Ariano et al., 2017).
- Question: What about the universe as a whole? Could it be represented as a density operator with non-unitary dynamics?

The Everettian approach (continued):

Ultimately, what is the Everett interpretation committed to?

- Fundamental unitarity?
    - Not necessarily!
        - Taking the non-unitary dynamics of a density operator to be fundamental, even in the case where it represents the universe as a whole, is consistent with the Everett interpretation (see, e.g., Wallace 2012, sec. 10.5).
    - Ultimately the Everett interpretation is committed to quantum theory, not necessarily the closed systems view of quantum theory.

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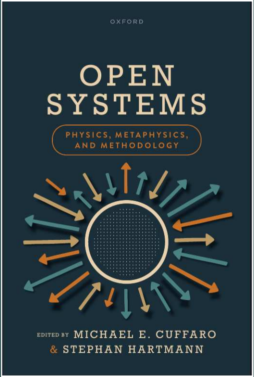
Although **ST** is formulated in accordance with the closed systems view, according to which all phenomena must ultimately be modelled in terms of isolated systems, the systems it represents are in general open.

In other words, the metaphysical motivation and methodological presuppositions of **ST** come apart.

Moreover the metaphysical position that it is, on reflection, committed to aligns with the metaphysical motivation for **GT**.

Thus there are good reasons, that stem from considering the structure and implications of **ST** itself, for wanting to move beyond it and to embrace **GT**.

This is the deepest sense in which **GT** can be considered to be a more fundamental theoretical framework than **ST**, and it expresses one important aspect of the internal dynamics of theoretical progress—how theoretical frameworks can change over time.



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