IPP-QM-16: Wavefunction realism

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MT24

The course

1. Basic quantum formalism
2. Density operators and entanglement
3. Decoherence
4. The measurement problem
5. Dynamical collapse theories
6. Bohmian mechanics
7. Everettian structure
8. Everettian probability
9. EPR and Bell's theorem
10. The Bell-CHSH inequalities and possible responses
11. Contextuality
12. The PBR theorem
13. Quantum logic
14. Pragmatism and QBism
15. Relational quantum mechanics
16. Wavefunction realism

Richard Healey, ‘How to be a single-world quantum relativist’

Thursday 5 December 15.00-17.00 (GMT/UTC), Lecture Room, Radcliffe Humanities Building.

Abstract: As Timotheus Riedel notes in a recent paper, over the past few years, a flurry of related no-go results in extended Wigner’s friend scenarios has been taken to place strong constraints on the possibility of absolute facts about the outcomes of quantum measurements. In my pragmatist view a system’s quantum state, and the outcome of a measurement on it, are each relative—not to “the observer” but to something physical. I shall explain what this means, how my view differs from Rovelli’s relational quantum mechanics, and why this perspective on quantum theory is not refuted by arguments based on extended Wigner’s friend scenarios, including Riedel’s.

Today

Quantum state ontology

Wavefunction realism

State vector realism

Spacetime state realism

Wrapping up

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Wavefunction ontology and spacetime structure

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These questions are (broadly) *distinct* from solutions to the measurement problem. E.g., all of the three major realist approaches to quantum mechanics (dynamical collapse, Bohmian mechanics, Everett) will have to contend with them.

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2. Hilbert space realism.
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(There are others, e.g. that of Deutsch & Hayden (2000), which I won't consider here.)

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  2. the name of the view is somewhat confusing since *all* the views we'll look at are realist about the quantum state.

Ney on wavefunction realism

According to wave function realism, [...] although we may seem to occupy a three-dimensional space of the kind described by classical physics, the more fundamental spatial framework of quantum worlds like ours is instead quite different, one of very many dimensions, with no three of these dimensions corresponding to the heights, widths, and depths of our ordinary experience. (Ney 2020, pp. ix–x)

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Ney claims that wavefunction realism offers a clear ontology which is both *local* and *separable*.

The separability claim

> *It [the wave function, according to wavefunction realism] is separable because all states of the wave function, including the entangled states we have been considering, are completely determined by localized assignments of amplitude and phase to each point in the higher-dimensional space of the wave function.* (Ney 2020, p. 87)

The locality claim

That wavefunction realism affords an ontology satisfying the principle of locality again appears to be immediate, since there indeed appears to be ‘no action at a distance’ on *configuration space*.

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- But to what extent should we place importance upon these desiderata?
  - Different notions of simplicity and associated virtues.
  - Significance of intuitions in physical theorising?

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- But this equivocates between (i) non-relativistic quantum mechanics (where wavefunction realism indeed privileges the position basis), and (ii) relativistic QFT (where wavefunction realists have to do something else).
- And in any case, even granting this, Ney must contend with the apparent basis-dependence of wavefunction realism *in general*: *some* basis always has to be preferred.

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- ...but then why stress so much configuration space in the presentation of the view?

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Answer: If it's suppose to be offering a fundamental metaphysics of the world, it seems inadequate to restrict attention to non-relativistic quantum mechanics.

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But, on the contrary, *overwhelmingly* more empirical results require recourse to QFT for their explanation than to non-relativistic QM alone—see (Wallace 2022).

Problems from relativistic QFT

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1. The problem of fermions.
2. The problem of particle non-conservation.

The problem of fermions

[O]nly bosonic field theories can be represented as wavefunctions on configuration space. Others—the 'fermionic' field theories that represent electrons and quarks (and so are central to our quantum-mechanical descriptions of ordinary matter)—possess no such representation. (Wallace 2021, p. 6)

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Question: Do you find this convincing? (Why would it not change the points that follow?)

The problem of particle non-conservation

Since in relativistic QFT particle number is not conserved,

> *the wave function realist should instead postulate an infinite number of (non-normalized) wave functions: a single-particle wave function living on a three-dimensional space; a two-particle wave function living on a six-dimensional space, and so on. However, [...] the wave function realist will not prefer to adopt such an ontologically profligate metaphysics'.* (Ney 2020, pp. 135–6)

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(This objection is raised by, for example, Wallace & Timpson (2010).)

Ney on this problem

> *[A]ssuming that the spacetime representation from which we began is continuous, the higher-dimensional space will be continuously infinite-dimensional with each point corresponding to an assignment of field operators to all spacetime points or, assuming discreteness, to the smallest regions in the low-dimensional representation.*
>
> *At this stage, we may note that we are no longer considering wave functions on a space with the structure of a classical configuration space as the central elements in the wave function realist's basic ontology. What we have instead is a field defined on another kind of high-dimensional space, one for which locations are correlated with assignments of field operators to regions in a four-dimensional ontology.* (Ney 2020, p. 149)

Wallace in response

> *My immediate feeling about this move is: if what is really intended is a wavefunction on field configuration space, shouldn't we be discussing that metaphysics rather than being distracted by the red herring of wavefunctions on N-particle configuration space? Granted, the latter has the virtue of being simpler to talk about, but it has the vice of being inconsistent with our current best quantum theories, which seems more serious.* (Wallace 2021, pp. 4–5)

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...and might the wavefunction-on-field-configuration-space view be too much ontology to swallow?

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2. It is difficult to extend this to quantum field theory, where no single basis seems to have the preferred status which the position basis might arguably be said to have in non-relativistic quantum mechanics.
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- This, indeed, is in line with the functionalism invoked by Albert (2013):

> *[I]f we can characterize* what it is for there to be *a three-dimensional object in terms of the playing of some functional role, and the wave function plays that role, then the wave function will* ipso facto *be capable of constituting three-dimensional objects.* (Ney 2020, p. 211)

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- **Question:** What do you make of this invocation of functionalism?

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Let's now move on to consider—briefly—a possible alternative to wavefunction realism: *state vector realism*.

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- This position would avoid the basis-relativity charge; however, it's not clear that it would avoid (some of) the other issues with QFT (e.g., rebarbatively infinite-dimensional spaces).
- Ney (2022) also has a couple of objections to state vector realism which are worth looking at...

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- But all of the structure encoded in the wave function is still present in the ray-in-Hilbert-space approach: indeed, it *must* be, since one can move from the latter to the former by simply choosing a basis.

Summarising again

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- So state vector realism avoids the basis-relativity charge, but still faces some of the other worries which were a problem for wavefunction realism.
- Moreover, it's not obvious that Ney's critiques of state vector realism find their mark.
- Let's now look at a third very different option for cashing out wavefunction ontology: *spacetime state realism* (Wallace & Timpson 2010).

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Wrapping up

Our heroes

Spacetime state realism

According to spacetime state realism (SSR), the fundamental ontology of a quantum mechanical world consists of a state-valued field evolving in four-dimensional spacetime. Each spacetime region is associated with a local Hilbert space whose density operators represent the possible values of the field in that region. Much as in classical field theories, these field values are interpreted as characterizing the intrinsic, local properties of the region. (Swanson 2020, p. 934)

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2. Wavefunction realism has a *simple* (complex scalar valued) field on a *complicated* (3N-D) spacetime.

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Let's now see how spacetime state realism works in a little more detail...

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- Cf. the fact that the field values associated to each spacetime point in electromagnetism represent the intrinsic (electromagnetic) properties of that point.

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- Cf. the fact that the field values associated to each spacetime point in electromagnetism represent the intrinsic (electromagnetic) properties of that point.
- (Of course, the properties here won't be scalars or vectors, but in general more complicated things.)

Illustration from Wallace

To provide a simple model, imagine a Universe consisting of a great many interacting qubits whose spacetime trajectories we approximate as classical [...] The qubits each bear the property or properties represented by their two-dimensional density operator; pairings of qubits bear properties represented by a four-dimensional operator; and so on. There need be no reason to blanch at an ontology merely because the basic properties are represented by such objects: we know of no rule of segregation which states that, for example, only those mathematical items to which one is introduced sufficiently early on in the schoolroom get to count as possible representatives of physical quantities! (Wallace 2012, p. 299)

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Features of spacetime state realism

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- Ney does not like this non-separability which is baked into spacetime state realism.
- However, one can ask: (a) what is so bad about this? (b) isn't this a price worth paying for compatibility with QFT? Etc.
- Swanson (2020) has a number of technical worries about spacetime state realism (not for the faint hearted!), but tries to shore them up.

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- Wavefunction realism seems to have the advantage of offering an ontology which is local and separable.
- However, it has both technical and conceptual issues, which might sway one to prefer something else, e.g. spacetime state realism.

Today

Quantum state ontology

Wavefunction realism

State vector realism

Spacetime state realism

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Question: On the basis of everything you've seen, which response to the measurement problem do *you* prefer?

References

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