Do we have any viable solution to the measurement problem?

June 3, 2026

Plan

- Single-world realist approaches and QFT
- The Everett interpretation
- Relational approaches
- Other Ways Forward

Unitary-Only vs Single-World Realist

- **Single-World Realist (SWR):** there exists a unique observable reality which different observers by and large agree on.
  de Broglie-Bohm and spontaneous collapse approaches
- **Unitary-Only:** interpretations which do not add anything to the standard formalism of unitary quantum mechanics

  Everett interpretation, various relational and neo-Copenhagen interpretation
- A third category of 'non-realist' approaches - I will not discuss these in detail.

SWR approaches

- Typically add to the unitary quantum formalism either hidden variables or collapses in order to extract a single real world out of it.
- SWR approaches are relatively intuitive and appealing from a common-sense point of view.
- But unfortunately, they don't (currently) work for quantum field theory.

SWR approaches

- There exist generalizations of SWR approaches which work for some regimes of QFT.
- Relativistic generalizations of de Broglie-Bohm replace 'particles' with another quasi-classical variable, e.g:
  - A variable encoding both the number of particles and the positions of those particles[1] (different from standard Bohmian particles since the number can change)
  - The electromagnetic field[2]
  - Grassman fields[3]
- But none of these things can reproduce all of QFT because they rely on features of a specific regime.
- e.g. in QFT, particles appear only at certain scales. So 'particle number and position' can't work for all regimes.

[1] Detlef Dürr et al. "Bohmian Mechanics and Quantum Field Theory". In: *Physical Review Letters* 93.9 (2004). ISSN: 1079-7114. DOI: 10.1103/physrevlett.93.090402. URL: http://dx.doi.org/10.1103/PhysRevLett.93.090402.

[2] W Struyve and H Westman. "A minimalist pilot-wave model for quantum electrodynamics". In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 463.2088 (2007), pp. 3115–3129. DOI: 10.1098/rspa.2007.0144.

[3] Antony Valentini. "On the pilot-wave theory of classical, quantum and subquantum physics". PhD thesis. SISSA, Trieste, 1992.

SWR approaches

- Maybe we'll eventually figure out how to make them work for QFT.
- But Wallace offers a general argument suggesting that this is unlikely to happen[a].

[a] David Wallace. *The sky is blue, and other reasons quantum mechanics is not underdetermined by evidence*. 2022. URL: http://philsci-archive.pitt.edu/20537/.

SWR approaches: Wallace's Argument

- From a reductionist point of view, whatever you add to unitary quantum mechanics should presumably be added at the smallest possible scales.
- You want it to scale up in such a way as to produce the relevant quasi-classical ontology at larger scales - i.e. particles with positions in the Bohmian case, or collapses in the position basis in the spontaneous collapse case.

SWR approaches: Wallace's Argument

- But in QFT, the relationship between fundamental scales and ordinary scales is very complicated and indirect.
- We use scale transformations involving renormalization where the values of parameters change across different scales
- The features of the theory look different at different scales - for example, there may be phenomena which look like 'particles' at some scales, and no particles at other scales.
- So it's unlikely that any simply-defined thing at fundamental scales will turn into a simple thing at ordinary scales.

SWR approaches: Wallace's Argument

- Worry: we know that all sorts of things emerge from the fundamental quantum fields (tables, chairs, etc).
- Indeed, we know that the de Broglie-Bohm particles do, in some sense, emerge from the fundamental quantum fields as a 'real pattern.'
- So if they can emerge from fundamental quantum fields, then surely we must be able to add something similar to fundamental quantum fields at the relevant scales and get particles, collapses etc to emerge.

SWR approaches: Wallace's Argument

- But the things that emerge naturally from the fundamental quantum fields do so in all or many branches of the wavefunction.
- In order to give us a SWR approach, Bohmian and collapse approaches need a structure to emerge which picks out just one branch of the wavefunction, otherwise they haven't solved the measurement problem.
- It's challenging to imagine how to make this work, given that the branching structure isn't available at the fundamental scales.

Unitary-Only Approaches

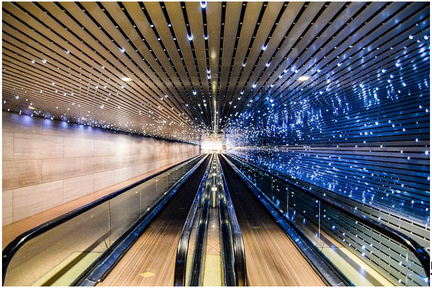
- Unitary-only approaches do not posit a single real world shared by everyone
- Thus they face significant problems around *epistemology* - it seems difficult to understand how measurements could give us meaningful information about the things the theory describes
- If this can't be done, these approaches would undermine the reasons we have for believing in quantum mechanics in the first place

Example: the Everett interpretation

- The Everett interpretation says that when we perform a measurement, all the possible outcomes occur
- This leads to the *probability problem*: how can we make sense of any probabilities other than 1 when all of the outcomes definitely occur?
- This is a problem of epistemology, because nearly all of the evidence for quantum mechanics is based on observed relative frequencies.
- If we can't solve the probability problem, we can't connect the theory to the observed frequencies, so we can't understand how measurements could give us meaningful information about the things the theory describes
- So the Everett interpretation seems to be self-undermining

Example: the Everett interpretation

- Many solutions to the probability problem have been proposed.
- Some of them may work if you just care about probabilities with respect to predictions about your own personal future.
- But relating probabilities to past observed relative frequencies is a very different kind of problem.
- The probability problem needs to be solved in a way that makes sense of the role of probabilities in the evidence for quantum mechanics[4].


[5]

[4] Emily Adlam. "The Problem of Confirmation in the Everett Interpretation". In: *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 47 (2014), pp. 21 –32. ISSN: 1355-2198. DOI: http://dx.doi.org/10.1016/j.shpsb.2014.03.004. URL:

Example: Observer-Dependent Interpretations

- Observer-Dependent interpretations aim to maintain both of the following precepts:
  - Unitary quantum mechanics is complete.
  - Quantum measurements have only one outcome for a given observer, i.e. observers do not branch.
- They do this by positing that quantum mechanics is *inherently relational*: quantum states and measurement outcomes can only be stated relative to an observer/system/reference frame, etc. They do not hold absolutely.
- In light of the phenomenon of 'observer-dependent state update' etc in QFT, this may be a tempting route

The 'subjective' approach: QBism

- QBism adopts a 'purely subjective' relational approach. Quantum states are relative to observers because they represent nothing other than beliefs and knowledge.
- QBism maintains that quantum states and the quantum formalism are nothing other than normative recommendations about how agents ought to set their degrees of belief.
- An important corollary is that two different agents can assign different quantum states to the same quantum system, and neither of them can ever be right or wrong.
- There is no restriction on this: even if they assign mutually orthogonal states, neither of them can ever be right or wrong.

The 'subjective' approach: QBism

- This seems puzzling: couldn't we just measure it and thus find out who is right and who is wrong?
- There are two options here:
  - Deny intersubjectivity: we can't share our measurement outcomes.
  - Deny that quantum states actually predict or describe measurement outcomes.

    This means one cannot use measurement outcomes to learn anything about which quantum states would have been right or wrong to assign. But then measurement outcomes can't be used to empirically confirm the theory at all.

The Objective Approach: Relational Approaches

- Relational approaches adopt a more 'objective' approach to the relationality of quantum states.
- The state of a system S relative to R encodes predictions for the results that R will obtain if they 'measure' S. The predictions might be different for different observers so we have different relative states.
- These states are not purely subjective. They may have some subjective aspects relating to the subject's limited information, but at least partially they encode objective facts about what the results of measurements will really be.

The Objective Approach: Relational Approaches

All relational approaches must have two parts:

- Quantum descriptions relative to systems.
- Actual measurement outcomes, or some generalization.

Relational quantum mechanics is one example[6]:

When two systems interact, a 'quantum event' occurs in which the value of a variable of one system becomes definite relative to the other.

[6] Carlo Rovelli. "Relational quantum mechanics". In: *International Journal of Theoretical Physics* 35.8 (1996), 1637–1678. ISSN: 1572-9575. DOI: 10.1007/bf02302261. URL: http://dx.doi.org/10.1007/BF02302261.

Example: Observer-Dependent Interpretations

- For example, the Wigner's friend scenario.
- When the Friend does a measurement on S, there is a 'quantum event' corresponding to the Friend obtaining an outcome, so the state of the system 'collapses' relative to the Friend.
- But this quantum event is irrelevant for external observers - it doesn't exist at all relative to Wigner.
- So the state relative to Wigner is different - he can still describe the Friend and S unitarily.
- Note that it is essential to this story that the quantum event does *not* feature in the description relative to external observers.

The Objective Approach: Relational Approaches

- These approaches are committed to the claims that *everything is quantum* and *all quantum descriptions are relational*.
- If we take this seriously it is hard to avoid the conclusion that all facts are relative - there are no absolute facts.
- In particular, even relations between different observers are themselves only true relative to some external system.

Objections to Observer-Relative Approaches

- Suppose I tell you my measurement result. Does what you hear match what I thought I said?
- The observer-relative interpretations maintain that there can't be any absolute fact about this: there can only be a match relative to some additional external system.
- Communication can never be said to succeed in an absolute way.
- Each observer is stuck within their own relative description and can't ever learn about facts relative to anyone else.

Relational Quantum Mechanics

- This surely undermines the social aspects of scientific practice.
- Also, the whole point of these approaches is that they aim to preserve the correctness of unitary QM for everyone, even in the face of the Wigner's Friend experiement.
- But they also say nobody can ever know anything about what other observers have seen.
- So we can never have any reasons to *believe* that QM is correct for other observers.
- This makes them self-undermining.

Relational Quantum Mechanics

- It's possible to propose an alteration to fix this.
- **Cross-Perspective Links**[7]: In a scenario where some observer Alice measures a variable V of a system S, then provided that Alice does not undergo any interactions which destroy the information about V stored in Alice's physical variables, if Bob subsequently measures the physical variable representing Alice's information about the variable V, then Bob's measurement result will match Alice's measurement result.
- This makes RQM into something more like a SWR approach.
- However, note that this means RQM is no longer unitary-only. Something must be added to the quantum formalism.

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[7] Emily Adlam and Carlo Rovelli. "Information is Physical: Cross-Perspective Links in Relational Quantum Mechanics". In: *Philosophy of Physics* (2023). DOI: 10.31389/pop.8.

Relational Quantum Mechanics and QFT

- How do we define the quantum events?
- Recent criticism of RQM[8] has focused on the imprecision of this notion.
- ‘Interaction’ is not precisely defined or instantaneous. It comes in degrees. A given pair of systems will almost always be undergoing some kind of (perhaps very weak) interaction.
- All attempts to make this notion precise run into problems.

[8] James Ladyman and Anthony Thompson. “The Problem of Interactions in Relational Quantum Mechanics”. In: *Philosophy of Physics* 4 (Mar. 2026). DOI: 10.31389/pop.206, Paolo Faglia. “Relational Quantum Mechanics does not Resolve the Problem of Measurement”. In: *Philosophy of Physics* (2025). DOI: 10.31389/pop.209.

Relational Quantum Mechanics and QFT

- The precision issue seems to get significantly worse in QFT.
- In QFT, individual systems such as 'particles' arise only in certain regimes.
- It's unlikely that there exists anything that can be straightforwardly identified as a 'system' at the most fundamental scales of QFT.
- But in order to define RQM (or any similar relational view) we need to have systems relative to which events and states can be defined.
- If we can't even define the systems precisely, there's no hope of defining quantum events precisely.

Proposed solution: spacetime regions

- Rovelli[9] has suggested replacing 'systems' with regions of spacetime.
- But this makes it even harder to understand how to define a quantum event - what does it mean to say that two regions of spacetime are 'interacting'?
- It seems potentially worrying in the context of diffeomorphism-invariance.
- And, given the possibility that spacetime itself is not fundamental, this may seem like just kicking the can down the road.

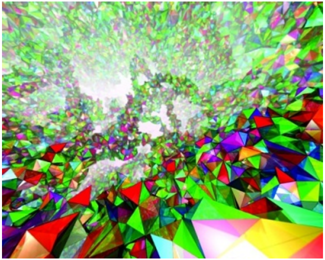
[9] Private communication

Proposed solution: in media res

- The observer-dependent approaches says that all meaningful descriptions are relative to something.
- So we don't have to start from a perspective-neutral picture, identify a system, then write down a description relative to it. We just start from a given system and write down the description relative to it.
- The description relative to a system doesn't usually include a description of that system at all and hence we don't even have to consider the question of whether the reference itself is precisely defined.

Proposed solution: in media res

- But we are still going to face problems with defining 'quantum events,' since these surely cannot be defined precisely if there is no way to define the systems involved precisely.
- This won't work for the RQM+CPL version.



Proposed solution: Self-reference

- In general RQM is formulated such that a system is not assigned a quantum state relative to itself.
- This seems important because it avoids paradoxes[10].
- Also, the main purpose of the quantum state of S relative to R is to predict the outcome of measurements/interactions between S and R. It's unclear what the state of R relative to R could mean.
- And this follows the general practice where the reference system is not a dynamical degree of freedom - e.g. setting a system as the origin of your coordinate system.

[10] Ruth E. Kastner. "Conventional Quantum Theory Does Not Support a Coherent Relational Account". In: *Philosophy of Physics* (2024). DOI: 10.31389/pop.158.

Proposed solution: self-reference

Argument that we should not be able to define an $S - R$ quantum event within standard quantum mechanics:

- The observer-dependent approaches tell us that quantum mechanics is inherently relational, so if we are using the quantum formalism to derive an $S - R$ quantum event we must do so relative to some reference system.
- Since systems are not assigned quantum states relative to themselves, we cannot describe an interaction between S and R or a joint state of S and R relative to either S or R, and thus there is no possible way of giving a precise derivation of the $S - R$ quantum event relative to either S or R.
- Since the $S - R$ quantum event does not appear in the quantum description relative to systems other than S and R, it does not make sense to try to derive this event from the quantum description relative to some system other than S or R.
- So the $S - R$ quantum event cannot be derived in a precise way using the quantum formalism at all.

Proposed solution: self-reference

- In light of this argument, there is an easy way of understanding both systems and quantum events if we do *not* insist that quantum mechanics is complete.
- What happens if we are describing S relative to R and S and R interact?
- Clearly we cannot describe this interaction relative to R because we can't describe R relative to R.
- In the description relative to R we must see some kind of discontinuity - something like a 'wavefunction collapse' or 'quantum event.'
- Thus relational approaches tell us what is so special about 'measurement' - it simply refers to a scenario where a system interacts with the reference relative to which we are currently describing it.

Proposed solution: self-reference

- But interactions are not discrete binary events. S and R are probably always interacting to a very small degree. How then can we ever describe S relative to R?
- The quantum description of S relative to R should be understood as an *approximation* which is suitable in the case where the interaction between S and R is sufficiently weak.
- So if quantum mechanics is inherently relational, we are led naturally to a view in which the quantum formalism is a relational approximation applying in the limit of weak interaction.
- Then there is no reason to expect that 'quantum events' can be described or derived in an exact way. They correspond to the breakdown of an approximation and this is not sharp.
- Likewise, the systems do not have to be precisely defined. The relational description is an approximation so the systems can be too.

Proposed solution: self-reference

- So we probably have to deny the completeness of quantum mechanics.
- However, this does not amount to simply adding a ‘hidden variable’ in the traditional dynamical reductionist sense.
- It looks like some kind of non-reductionist story.

Proposed solution: self-reference

- Quantum mechanics is to be understood as a relational approximation - presumably what it approximates is a high-level holistic description encoding relative facts.
- Quantum mechanics might describe something like ‘partial observables’ as an approximation to a higher-level theory in terms of ‘complete observables.’
- This would not amount to adding something at very small scales and then scaling up via renormalization. Rather it would amount to starting from a global, holistic description and deriving both QM and QFT out of it as relational approximations.
- So plausibly this escapes the Wallace-style worries that affect other SWR approaches.

Other approaches?

Wallace: SWR approaches need a '*microphysically-stateable, precisely-defined dynamical variable*' to ground our actual world.

Can we relax one of these demands?

- 'Microphysically-stateable' $\rightarrow$ a non-reductionist approach with ontology that is not defined at fundamental scales.
  e.g. RQM, or some version of consistent histories
- 'Precisely-defined' $\rightarrow$ an approach which allows that what counts as '*the* real world' is only vaguely-defined.
- 'Dynamical' $\rightarrow$ an approach which is not based on time evolution.
  e.g. Kent's Lorentzian solution to the quantum reality problem