On the merits of modeling quantum mechanics via reconstruction

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Prospects & Introduction

I introduce a specific kind of modeling – called reconstruction , after Alexei Grinbaum[1]– that gives great progress in the foundations of Quantum Mechanics.

The practise I am considering is not about giving models of the theory in question (quantum mechanics) but about models that are used for *complete* or *intentionally incomplete* reconstruction (terminology by Grinbaum) of the theory in question.

I will show how the models provide novel understanding: they resolve issues by the deductive method that is part of reconstructing.

This shows an interesting new way in which modeling practises can assist in further understanding of scientific theories.

[1] A.Grinbaum, Br. J. Philos. Sci., Vol. 58: 387-408 (2007)

Outline

Background: Interpretations of Quantum Mechanics

Wheeler famously asked: “**Why the quantum?**”: How should we interpret quantum mechanics (QM)?

- Why is an interpretation needed: to solve the so-called measurement problem, to deal with the nonlocality of quantum correlations, or its alledged non-classicality.

- Methodology used: ‘study quantum physics from the inside’: The practise of giving the theory a clear meaning using the formalism of the theory and nothing more.

A plethora of interpretations have been provided in the last 80 years.

To name a few popular interpretations:

- Many worlds interpretation
- Modal Interpretation
- Kopenhagen interpretation
- Bohmian mechanics
- Statistical interpretation
- FAPP (decoherence) interpretation
- ....(pick your own)

I can be brief: This interpretation program has failed: There is no consensus on what *the* meaning of QM is.

- Why did this program fail? That would be a talk in itself.

However, I believe we *lack* enough understanding of the theory to provide a conclusive interpretation. What is needed is *more* understanding; for we do not know what 'the quantum' is.

$\Longrightarrow$ I propose a new question: "What is the quantum?"

Better even: "What is essentially and uniquely quantum?"

This we do not know. To novel attempts at answering this question using a modeling practise, I will turn next.

Reconstructing Quantum Mechanics

- Methodology: 'study quantum physics from the outside' (and not solely from the inside): From a larger theoretical point of view.

- It uses a particular type of modeling which has shown much foundational progress in the last decade or so.

- It is a result of the recent marriage between quantum foundations and quantum information theory.

- Early precursors: David Bohm, John Bell: on (local) hidden variable models.

Models of reconstruction:

Method: Theorems and major results are formally derived from simpler mathematical assumptions, whereby the assumptions, or axioms appear in the formal language as representations of a set of physical principles. (Grinbaum[2])

1. Give a set of physical principles that constrain the law-like behaviour of physical systems.
2. Formulate their mathematical representation as axioms of the theory.
3. Rigourously derive the formalism of the theory.

$\Longrightarrow$ Start from a general family of theories and try to constrain it using physical principles so as to arrive at QM.

[2] A.Grinbaum, Br. J. Philos. Sci., Vol. 58: 387-408 (2007)

Features of reconstruction

- Analytic, not synthetic.

- Great persuasive power:

  " Why is it so? Because we derived it", (Grinbaum).

- The quest is: how to identify QM uniquely, what makes QM quantum, what set of axioms in the model is to be used. Which are necessary and sufficient?

- The question of meaning, previously asked of the formalism, is removed and bears, if at all, on the selection and justification of the first principles.

First principles[3]

- They are physical statements that are supposed to be fundamental, and which are posited as axioms.
- They must be physical, i.e. their meaning must be immediately clear; they must tell us something directly and intuitively comprehensible about the world.

  Example:

  The principle of the impossibility of superluminal signalling.

  NOT: "The partially ordered set of all questions in QM is isomorphic to the partially ordered set of all closed subspaces of a separable Hilbert space."
  (one of Mackey's axioms in his axiomatisation of 1957).

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[3] A.Grinbaum, Br. J. Philos. Sci., Vol. 58: 387-408 (2007)

First principles

- They must allow for a clear unambiguous translation of their content into mathematically formulated axioms.
- They must be independent of a particular mathematical formalism employed to derive quantum mechanics.
- They have solely an epistemic status. The personal motives for adopting certain first principles should be bracketed. One should be ontologically agnostic. The principles should be free of ontological commitment.
- They need *not* be ultimate truths about nature.

Further features of reconstruction models

- Reconstruction becomes meaningful due to the content of the first principles on which it relies.

- The sole philosophical problem that is left after the construction is the *justification* of the first principles.

But this task is external to the reconstruction program. Again, the principles need not have philosophical justification, nor be confirmed truths about nature.

Let us for comparison look at thermodynamics: ‘Why is it that perpetuum mobile of the first and second kind are impossible?’
$\Longrightarrow$ As far as the *understanding* of the theory goes, this physical principle needs no justification.

Complete and incomplete reconstructions

Two types of reconstruction (Grinbaum):

A) Complete reconstructions

B) Intentionally incomplete reconstructions

A) Complete reconstruction

- *The ultimate goal*: to view QM as a theory reflecting the constraints imposed by the fundamental physical principles on theoretical representations of physical processes.

Example: Clifton, Bub and Halverson (2003): quantum information constraints used to derive quantum theory.

1. No superluminal information transfer via measurement.
2. No broadcasting
3. No secure bit commitment

CBH show using the C^*algebraic framework, that these three principles constrain the framework to be quantum theory.

Clifton–Bub–Halverson reconstruction

CBH argue: quantum theory is a theory of information constrained by information theoretic principles.

The three axioms are neutral towards philosophical positions: they can be adopted by a realist, instrumentalist, or subjectivist.

We gain understanding of the theory irrespective of the justification of the principles; for this it is irrelevant.

Other complete reconstructions:

- Hardy's derivation from 'five reasonable axioms'.
- Rovelli's derivation using two information-theoretic principles.

However, all these three reconstructions fail.

Hardy's: not all his axioms can be given *physical* meaning. Especially the one that gives quantum theory rather than a classical theory.

CBH's and Rovelli's: the formalism used assumes implicitly too much.

- CBH: use a C^*-algebra.
- Rovelli: uses a complete atomic orthocomplemented lattice taken from quantum logic.

CBH and Rovelli use too much implicit substantive mathematical axioms. The formalism should not be already close to QM. One should adopt a more general framework.

The important lesson to be learned: The (mathematical) framework used must be narrow enough to allow the axioms to be succinctly expressed mathematically, but broad enough that the main substantive assumptions will be contained in the axioms rather than in the framework itself.

B) Intentionally incomplete reconstructions

Intentionally incomplete reconstructions take this last lesson serious: No substantive assumptions should be hidden in the formalism.

Motto: In order to understand quantum mechanics it is useful to demarcate those phenomena that are essentially quantum, from those that are more generically non-classical.

Investigate theories that are neither classical nor quantum; explore the space of possible theories.

“Is quantum mechanics an island in theory space?” (Aaronson, 2004). If indeed so, where is it?

Intentionally incomplete reconstructions

Methodology of intentionally incomplete reconstructions:

- Start with a general reconstruction model with a very weak formalism.
- Gradually see what (quantum) features are consequences of what added physical principles,
- as well as see which features go connected and which features are a consequence of adding which principle.
- Thereby one learns which principle is responsible for which element in the (quantum) theoretical structure.

This modeling shows that many ‘essential’ quantum features are not special to quantum theory (any non-classical theory might have them).

Comparison to the practise of modifying QM

Consider modifications of QM such as non-linear extensions of the Schrödinger equation. (e.g. GRW theory).

These non-linear models take standard QM to be incomplete, and purport to replace it by a more complete version.

However, reconstruction models see themselves as incomplete, do not question the validity of QM or compete as a rival theory for explaining empirical phenomena (Grinbaum). They recover solely some aspects of QM.

Are ‘quantum’ features uniquely quantum?

- Does the model forbid superluminal signalling?
- Does the model allow nonlocality, and to what extent?
- Is the model contextual?
- Does the model allow teleportation, dense coding, remote steering?
- Does the model posses a continuum of states, and transformations of states?
- Does model solve NP-complete problems in polynomial time?

Answer is ‘yes’ or ‘no’, depending on the model. Some features are strongly connected, others are unconnected.

Case study: the feature of non-locality

The feature of *non-locality* is an example of where the modeling shows that a quantum feature (perhaps thought to be capturing 'the essence' of quantum theory) is not special to quantum theory.

All local realistic models must obey the Bell-inequality. QM correlations can violate it, though not maximally. These so-called 'non-local correlations' are essential to QM.

However, models with general non-signalling correlations can be correlated even stronger: they are more non-local.

"Why are QM correlations not more non-local?", a question asked only as recent as 1996 by Popescu and Rohrlich.

Case study: the feature of non-locality

Recently, through the type of modeling discussed here, some possible answers have been suggested:

- Stronger correlations would result in a world where communication complexity becomes trivial.
- Or a world where the possible dynamics on the states is very much constrained.

Furthermore: A set of properties is found in common to **all** theories that are no-signalling and which are nonlocal:

Intrinsic randomness, monogamy of correlations, a no-cloning theorem holds, privacy of correlations, and uncertainty relations for measurement outcomes.

$\Longrightarrow$ QM is NOT the unique theory having these features.

How to obtain a complete reconstruction of QM?

This is still an open question, although some conjectures:

- Quantum theory is optimal for computation (Barrett).

If indeed true, how to identify QM uniquely? Ask for the theory that allows for optimal computation.

- The possibility of teleportation seems to be quite restricting too, moving one closer to QM.

The merits of intentionally incomplete models

Traditionally, QM is compared with classical physics which is a more restrictive theory.

$\Longrightarrow$ New paradigm: ‘study QM from the outside’: Compare QM with a more general family of theories.

It is found that many properties that are attributed to QM are generic within the larger family of physical theories.

Thus rather than regard quantum theory special for having the generic ’quantum’ properties, a better attitude may be to regard classical theories as special for *not* having them.

Example: Many theories will likely have a measurement problem, when interpreted beyond the purely operational. Classical physics is perhaps special for *not* having it (Barrett).

Discussion and outlook

In order to make foundational progress one should move away from the traditional business of providing interpretations, and instead adopt a strategy of reconstruction: using general models that allow for incorporating physical principles.

One should adopt: ‘the view from outside, not from the inside’. Implement this via models of reconstruction, i.e., Grinbaum’s view.

If it succeeds: one is able to characterize a theory uniquely by deducing its formalism exactly from physical principles. We then understand the theory, although we perhaps can not answer: ’why these principles?’.

Discussion and outlook

Again the merits:

- Reconstruction uses deduction, thus it is clear where things come from.
- Great conceptual transparency
- The question of meaning bears, if at all, on the selection and justification of the principles.
- Largely independent of ontological prejudices.
- The principles and the formalism used are clearly distinghuishable.

Prospect: this type of modeling may provide understanding of other physical theories, and could be fruitful elsewhere (e.g., theories of cognition, theories of mind, theories of language and possibly even further).