Reading list on philosophy of quantum mechanics

David Wallace, June 2018

A note on electronic resources

When I include a book chapter or similar as a reference, and there is a preprint of that chapter on one of the permanent archives (arxiv.org or philsci-archive.pitt.edu), I have included a link to the preprint; be aware that there are sometimes small changes, and that citations and page references should be to the published version. I have not bothered to put preprint links for journal papers; however, for any paper published in the last 20 years or so it is likely that a preprint is online somewhere.

1. Introduction

This is a reasonably comprehensive reading list for contemporary topics in philosophy of quantum theory, aimed at researchers and graduate students specializing in philosophy of physics, at colleagues putting together readings for seminars and classes, at academics in related areas interested in the debate, and at ambitious upper-level undergraduates looking for thesis ideas.

Any such list betrays the prejudices, and displays the limitations, of the author. Where I have intentionally been selective, it represents my judgements as to what areas are interesting and what work in those areas is likely to stand the test of time, and which current debates are worth continuing attention, but I will also have been selective accidentally, through ignorance of work in one area or another of this very large field. (I am research-active in the field, but not in every area of it.) The only real way to work around these sorts of limitations is to look at multiple such lists by different people.

I'll call out some explicit limitations. I don't attempt to cover history of physics, beyond a few sources on the Copenhagen interpretation and the origins of the Everett interpretation, the de Broglie-Bohm theory, and the GRW theory. I don't discuss quantum information except insofar as it relates to the interpretation of quantum theory (though C. Timpson, *Quantum Information Theory and the Foundations of Quantum Mechanics* (Oxford, 2013) is the place to start). I discuss metaphysical issues only insofar as they seem to connect to the interpretation of quantum mechanics, avoiding broader discussions of questions about separability, holism and causation that are influenced by quantum mechanics. Most notably, I do not cover quantum field theory.

In addition, this is a reading list for philosophy of quantum mechanics, not foundations of quantum mechanics, and I don't discuss more technical results except where they are clearly of direct importance to the interpretation of quantum mechanics. I have kept to a rule of not discussing proposed modifications of the quantum formalism except where those modifications have (a) demonstrated the ability to reproduce at least nonrelativistic quantum mechanics, and (b) generated some substantial literature discussing their conceptual features. (I stretch a point slightly on (a) to include a few readings on the retrocausal approach.)

Within philosophy of quantum mechanics, though, I have tried to be quite broad, covering topics from the metaphysics of Bohmian mechanics to the physics-is-information interpretative strategies. I am sure that many experts will regard some of the topics I cover as obviously nonsensical, but I am equally sure that different experts will have very different assessments of what is and isn't nonsense. (My own choice of topics is based on a mixture of (a) what I think may turn out to be right; (b) what I suspect will turn out to be wrong, but interestingly and instructively so; (c) what I think is probably silly, but seems influential enough that someone in the field ought to know something about it; no, I won't tell you which is which.)

Philosophy of quantum mechanics falls apart *reasonably* naturally into subsections, but I still had to make some arbitrary choices: notably, I separate decoherence off from the Everett interpretation, present questions of quantum-mechanical ontology collectively rather than under the headings of particular solutions to the measurement problem, and give primitive ontology its own section. Under "interconnections" in many sections, I try to give some indication of what connects to what. Also, in (pretty much) every subsection of the list I have marked one entry (very occasionally, two) with a star (*), which means: if you only read one thing in this subsection, read this. The starred entry is not necessarily the most important or interesting item, but it's the item that in my judgment will give you the best idea of what the overall topic is about. Where I have starred one of my own articles (which, I will admit, is fairly frequently) I have (almost always) also starred another.

I list items in a rough reading order, which is usually approximately-chronological. It doesn't indicate an order of importance: it means "if you read A and B, read A first", not "read A in preference to B". If you want to work out what to prioritize (beyond my starring of a few entries, above) then there isn't really a substitute for looking at the abstracts and seeing what's of interest. And don't be afraid to skim papers, and/or to skip over the mathematical bits. Of course you'll need to read those if you ever engage closely with the debate, but if you just want an overview, it can be overkill.

2. Introductory and general readings in philosophy of quantum theory

Two accessible introductions are:

- (*)D. Albert, *Quantum Mechanics and Experience* (Harvard University Press, 1994)
  No technical prerequisites; aimed at philosophers
- A.Rae, *Quantum Mechanics: Illusion or Reality?* (Cambridge, 2004)
  No technical prerequisites; aimed at a general audience

At a somewhat higher level (and in increasing order of difficulty):

- R. Penrose, *Shadows of the Mind* (Oxford University Press, 1994), chapters 5-6
  Self-contained but reasonably demanding introduction to conceptual problems in QM.
- R.I.G.Hughes, *The Structure and Interpretation of Quantum Mechanics* (Harvard University Press, 1989).
- D. Wallace, "Philosophy of Quantum Mechanics", in D. Rickles (ed.), *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008), http://arxiv.org/abs/0712.0149
  Review article; presupposes you have studied quantum mechanics.

Some important recent collections:

- J. Bell, *Speakable and Unspeakable in Quantum Mechanics* 2nd edition (Cambridge University Press, 2004).
  Okay, this one isn't that recent, but Bell is one of the central figures in the subject and any serious student of philosophy of quantum mechanics should read him. The second edition has two papers not found in the first (1987) edition.
- A. Ney and D. Albert (ed.) *The Wave Function: Essays on the Metaphysics of Quantum Mechanics* (Oxford University Press, 2013).
  Metaphysics of the quantum wavefunction; assumes little or no technical knowledge.
- S. Saunders *et al, Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010).
  The case for and against the Everett interpretation, touching on many other interpretative issues in the process.
- M. Bell and S. Gao (eds.), *Quantum Nonlocality and Reality – 50 years of Bell's Theorem* (Cambridge University Press, 2016).
  Looks at much of contemporary foundations of quantum theory through the lens of non-locality.

3. Physics and math resources

There are literally hundreds of textbooks on quantum mechanics; this list shouldn't be taken as more than one person's preferences, and different people learn in different ways, so look at a few books and see which ones work for you.

Be aware that while quantum physics *can* be presented in a mathematically rigorous way, it often is *not* so presented. (Things like position and momentum eigenstates, for instance, are ultimately dispensable, but are so useful that most physics texts use them anyway.)

Sources that don't presume any physics experience

- R. Penrose, *Shadows of the Mind* (Oxford University Press, 1994), chapter 5
- K.Hannabuss, *An Introduction to Quantum Theory* (Clarendon Press, 1997).
  Aimed at undergraduate mathematicians, so assumes a reasonably strong pure-maths background.
- R.I.G.Hughes, *The Structure and Interpretation of Quantum Mechanics* (Harvard University Press, 1989), first few chapters.
- A. Rae and J. Napolitano, *Quantum Mechanics*, 6^{th} edition (Taylor and Francis, 2016).
  Classic introduction aimed at first-year undergraduates.

Physics textbooks at an introductory level

- J. Binney and D. Skinner, *The Physics of Quantum Mechanics* (OUP, 2013).
- C. Cohen-Tannoudji et al, *Quantum Mechanics* (Wiley, 1977).
  A bit dry, but more technically careful than some.
- P.A.M. Dirac, *The Principles of Quantum Mechanics*, 4th edition (Clarendon Press, 1958).
  A classic; still relevant and readable.
- S. Gasiorowicz, Quantum Physics (3rd edition). Wiley, 2003.

More advanced texts, useful for specialist material

- L.E.Ballentine, *Quantum Mechanics* (Prentice Hall, 1990)
- D. Home, *Conceptual Foundations of Quantum Physics* (Plenum, 1997)
- C.J.Isham, *Lectures on Quantum Theory: mathematical and structural foundations* (Imperial College Press, 1995)
- A. Peres, *Quantum Theory: Concepts and Methods* (Kluwer, 1995)
- J. von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton, 1955).
  ***The** classic mathematically-rigorous presentation of QM – but not for the faint hearted.*

Quantum Information

- V. Vedral, *Introduction to Quantum Information Science* (Oxford University Press, 2006)
- M.A.Nielsen and I.L.Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, 2000)
  The standard reference.
- G. Benenti, G. Casati and G. Strini, *Principles of Quantum Computation and Information* (World Scientific)

Mathematical background

- R. Clifton, "Introductory Notes on the Mathematics Needed for Quantum Theory", http://philsci-archive.pitt.edu/390/
- P. Halmos, *Finite-Dimensional Vector Spaces* (Springer, 1958).
  For vector spaces and linear algebra.
- N.Young, *An Introduction to Hilbert Space* (Cambridge, 1988).
- W. Rudin, *Functional Analysis,* second edition (McGraw-Hill, 1991).
  Classic graduate text in functional analysis; a good reference if you want to see linear operators and spectral theory done rigorously.

4. The quantum measurement problem

The measurement problem is at the heart of philosophy of quantum mechanics. Do not assume consensus even on what the problem is: different ways of setting up, or thinking about, the measurement problem lead to different ways of assessing its potential solutions. Read several different accounts and form your own conclusions.

Interconnections

- In this section I consider only the measurement *problem* in isolation, but most of the rest of this list is concerned with proposed *solutions* to the problem.
- The transition between quantum and classical – the domain, in modern physics, of *decoherence theory* – is closely connected to the measurement problem.

Presentations by physicists

J. Bell, "Quantum Mechanics for Cosmologists", in *Speakable and Unspeakable in Quantum Mechanics,* (Cambridge University Press, 1987/2004). Sections 1-3.

(*) J. Bell, "Against 'Measurement'", *Physics World* 3 (1990) pp. 33-40. Reprinted in J. Bell, *Speakable and Unspeakable in Quantum Mechanics,* 2nd edition (Cambridge, 2004).

D. Home, *Conceptual Foundations of Quantum Physics: an overview from modern perspectives* (Plenum, 1997), chapter 2.

R. Penrose, *Shadows of the Mind* (Oxford University Press, 1994), chapter 6.

Presentations by philosophers

(*) D. Albert, *Quantum Mechanics and Experience* (Harvard University Press, 1992), Chapter 4 (pp. 73-79) and part of chapter 5 (pp. 80-92).

T. Maudlin, "Three Measurement Problems", *Topoi* 14 (1995) pp.7-15.

M.Redhead, *Incompleteness, Nonlocality and Realism: a Prolegomenon to the Philosophy of Quantum Mechanics* (Clarendon Press, 1989), chapter 2.

S. Saunders, "What is the problem of measurement?", *Harvard Review of Philosophy,* Spring 1994, pp. 4-22; online at http://www.harvardphilosophy.com/issues/1994/Saunders.pdf.

(*) D. Wallace, "What is orthodox quantum mechanics?"[1], forthcoming in *Ontology Studies – Outstanding Papers from the San Sebastian International Congresses of Ontology*. https://arxiv.org/abs/1604.05973

[1] But see also M. Gilton, "Whence the eigenstate-eigenvalue link?" *(Studies in History and Philosophy of Modern Physics* 55 (2016) pp. 92-100), which corrects one overreach in this paper.

4. Non-locality in quantum theory

Is quantum theory non-local? If so, in what way(s)?

The EPR thought experiment

"EPR" famously argued that if physics was local, the quantum-mechanical description of reality was incomplete; or, turning it around, that if quantum mechanics is a complete theory, it is nonlocal.

Einstein, B. Podolsky and N. Rosen, "Can Quantum-Mechanical Description of Reality be Considered Complete?", *Physical Review* 47 (1935), pp. 777-80. Reprinted in J. A. Wheeler and W. H. Zurek (eds.), Quantum Theory and Measurement (Princeton, 1983), pp. 138-41.
The famous "EPR paper".

N. Bohr, "Can Quantum-Mechanical Description of Reality be Considered Complete?", *Physical Review* 48 (1936), pp. 696-702. Reprinted in J. A. Wheeler and W. H. Zurek (eds.), Quantum Theory and Measurement (Princeton, 1983), pp. 145-51.
Bohr's reply to EPR.

(*) N. Harrigan and R.Spekkens, "Einstein, incompleteness, and the epistemic view of quantum states", *Foundations of Physics* 40 (2012), p.125.

M. Redhead, *Incompleteness, Nonlocality and Realism: A prolegomenon to the philosophy of quantum mechanics* (Clarendon Press, 1987), ch. 3 (pp.71-81).

The Bell inequality – presentations and initial discussion

John Bell demonstrated that any theory that violated a certain inequality – and which obeyed other, apparently-innocuous, conditions – would be non-local. Quantum mechanics violates that inequality; more importantly, that inequality has been empirically violated.

(*) J. S. Bell "Bertlmann's socks and the nature of reality", in J.S.Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge, 1987/204), pp. 139-158.

T. Maudlin, *Quantum non-locality and relativity: metaphysical intimations of modern physics*. (Blackwell, 1994), ch. 1 (pp.6-28), 5 (pp. 125-161), 7 (pp.189-222).

S. Aaronson, *Quantum Computing Since Democritus* (Cambridge University Press, 2013) pp. 176-8.
A fast (and irreverent!) account of the Bell Inequality as a cooperative game.

M. Redhead, *Incompleteness, nonlocality and realism: a prolegomenon to the philosophy of quantum mechanics* (Clarendon Press, 1987). Chapter 4 (pp. 82-118), esp. sections 4.1, 4.5, 4.6.

The Bell inequality – further discussion

Fifty years after Bell's paper, it remains controversial exactly what it establishes, especially for indeterministic theories, theories which lack a third-person description, or many-worlds theories.

J. N. Butterfield, "Bell's Theorem: What it takes", *British Journal for the Philosophy of Science* 43 (1992), pp. 41-83.

(*) T.Maudlin, "What Bell Did", *J. Phys. A: Math. Theor.47* (2014) 424010; http://arxiv.org/abs/1408.1826

T. Norsen, “Local Causality and Completeness: Bell vs. Jarrett”, *Foundations of Physics* 39 (2009) pp. 273-294.

W. Myrvold, “Lessons of Bell’s Theorem: Nonlocality, yes; Action at a distance, not necessarily.” In S. Gao and M. Bell (eds.), *Quantum Nonlocality and Reality – 50 years of Bell’s Theorem* (Cambridge University Press, 2016). http://philsci-archive.pitt.edu/11654

(*) H.Brown and C. Timpson, “Bell on Bell's theorem: The changing face of nonlocality”. In M .Bell and S. Gao (eds.), *Quantum Nonlocality and Reality – 50 years of Bell’s Theorem* (Cambridge University Press, 2016). http://arxiv.org/abs/1501.03521 .

D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation* (Oxford University Press, 2012), ch.8, esp. pp.308-312.
Bell’s inequality in the Everett interpretation.

C. Fuchs, N. Mermin and R. Schack, “An introduction to QBism with an application to the locality of quantum mechanics”, *American Journal of Physics* 82 (2014) pp. 749-754.

5. State-eliminativist hidden variable theories (aka Psi-epistemic theories)

Can we regard the quantum state rather like the probability distributions of classical statistical mechanics, so that the true physics is given by some underlying "hidden-variable" theory? (Approaches like this are often called "psi-epistemic" in the literature; I find that term misleading, as it conflates the general idea that the quantum state can be thought of as a probability distribution over hidden variables, with the more specific idea that those probabilities should be thought of as epistemic rather than, say, as relative frequencies or similar.)

Interconnections

- This class of interpretations tends to downplay the role of the observer, as opposed to *the Copenhagen interpretation and its descendants,* but the boundary between them is blurry
- A very different class of theories are also called "hidden-variable theories"; in this class, which includes the *de Broglie-Bohm theory* and the *modal interpretation,* the state is not analysed as a probability distribution but is a part of the theory alongside the hidden variables.

General discussions

(*) R. Spekkens, "In defense of the epistemic view of quantum states: a toy theory", *Physical Review A* 75 (2007) 032110.

S. Bartlett, T. Rudolph, and R.Spekkens, "Reconstruction of Gaussian quantum mechanics from Liouville mechanics with an epistemic restriction", *Physical Review A* 86 (2012) 012103.

N. Harrigan and R.Spekkens, "Einstein, incompleteness, and the epistemic view of quantum states", *Foundations of Physics* 40 (2012), p.125.

M. Liefer, http://mattleifer.info/2011/11/20/can-the-quantum-state-be-interpreted-statistically/ (2011).

D. Wallace, "Inferential vs. Dynamical Conceptions of Physics", in O. Lombardi *et al* (eds.), *What is Quantum Information?* (Cambridge University Press, 2017). http://arxiv.org/abs/1306.4907.

H. Brown, "The reality of the wavefunction: old arguments and new". Forthcoming in *Ontology Studies – Outstanding Papers from the San Sebastian International Congresses of Ontology*.
http://philsci-archive.pitt.edu/12978/

Non-contextuality and the (Bell)-Kochen-Specker theorem

The so-called "Kochen-Specker theorem" (a very similar result was previously proved by Bell) rules out a large class of otherwise-natural hidden-variable theories.

(*) J.S.Bell, "On the problem of hidden variables in quantum mechanics", in J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge, 1987/2004).

H. Brown, 'Bell's other theorem and its connection with nonlocality. Part I' in Bell's Theorem and the Foundations of Modern Physics, A. van der Merwe, F. Selleri and G. Tarozzi (eds.), (World Scientific Publishing Company, 1992) pp. 104-116.

N. Harrigan and T.Rudolph, "Ontological models and the interpretation of contextuality", http://arxiv.org/abs/0709.4266 .

N.D.Mermin, “Hidden variables and the two theorems of John Bell”, *Reviews of Modern Physics* 65 (1993) p.803.

(*)A. Peres, *Quantum theory: concepts and methods* (Kluwer, 1993). Chapter 7, esp. pp.187-191.

M. Redhead, *Incompleteness, nonlocality and realism: a prolegomenon to the philosophy of quantum mechanics.* (Clarendon, 1987). Chapter 5 (pp. 119-138).

The PBR theorem and related no-go results

The celebrated “PBR theorem” establishes, from apparently-innocuous assumptions, that the quantum state cannot be eliminated from the formalism without violating the predictions of the theory; similar results proved since seem to put very tight constraints on any viable eliminativist hidden-variable theory.

M.Pusey, J.Barrett and T.Rudolph, “On the reality of the quantum state”, *Nature Physics* 8 (2012), 475; http://arxiv.org/abs/1111.3328 .

(*) M. Leifer, “Is the quantum state real?” *Quanta* 3 (2014) pp. 67-155.

J. Barrett, E. Cavalcanti, R. Lal and O. Maroney, “No ψ-epistemic model can fully explain the indistinguishability of quantum states”, *Physical Review Letters* 112 (2014) 250403.

P.G.Lewis, D.Jennings, J.Barrett, and T.Rudolph, “Distinct quantum states can be compatible with a single state of reality”, *Physical Review Letters* 109 (2012) 150404

6. The Copenhagen interpretation and its descendants

"The Copenhagen interpretation" is officially the "standard interpretation" of quantum mechanics, but the term is used in a wide variety of ways, of which three important ones are "what Bohr thought" (which relies on the philosophically subtle notion of 'complementarity', "what Heisenberg thought" (which seems to have been a fairly straightforward operationalism), and "the wavefunction represents the physical system and undergoes a dynamical process of collapse caused by observation" (which is what Dirac and von Neumann advocated, and is often taught in textbooks, but which essentially no-one really accepts any more). In recent foundational work, variants of the Copenhagen interpretation based on ideas in quantum information have found favor with many physicists and a few philosophers.

Interconnections

- The Copenhagen interpretation shares with *state-eliminativist hidden-variable theories* the idea that the quantum state does not represent the physical state of any system.
- The consistent-histories formalism, used by Griffiths, Omnes et al to formulate an interpretation closely related to Bohr's, finds a conceptually rather different use in the study of *decoherence* and in the *Everett interpretation.*

The Copenhagen interpretation – historical sources

J. Wheeler and W. Zurek (eds.), *Quantum Theory and Measurement* (Princeton University Press, 1983).

G. Bacciagaluppi and A. Valentini, *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference* (Cambridge University Press, 2009).

The Copenhagen interpretation – subsequent analysis

What did Bohr (and, to a lesser extent, his contemporaries) actually have in mind?

(*) S. Saunders, "Complementarity and Scientific Rationality", *Foundations of Physics* 35 (2005) pp. 417-447.

D. Howard, "Who invented the 'Copenhagen Interpretation'? A study in mythology". *Philosophy of Science* 71 (2004) pp. 669-682.

J. Cushing, *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony* (University of Chicago Press, 1994), chapters 3,5,6.

J. Bub, *Interpreting the Quantum World* (Cambridge University Press, 1997), chapter 7 (esp. section 7.1).

R. Peierls, "Interview", in P. Davies and J. Brown (ed.), *The Ghost in the Atom* (Cambridge, 1986) pp. 70-82.

D. Howard, "What makes a classical concept classical? Toward a reconstruction of Niels Bohr's philosophy of physics", in J. Faye and H. Folse (eds.), *Niels Bohr and Contemporary Philosophy* (Kluwer, 1994).

E. Scheibe, *Logical Analysis of Quantum Mechanics* (Pergamon Press, 1970), ch.1

Operationalism and Pragmatism

Can we understand the quantum formalism simply as an operational calculus or pragmatic tool, with no pretensions towards describing physical reality?

(*) C. Fuchs and A. Peres, "Quantum Theory Needs No 'Interpretation', *Physics Today* 53 (2000) pp. 70-71. See also the letters to the editor, and Fuchs and Peres' reply, also in *Physics Today* 53.

A. Peres, *Quantum Theory: Concepts and Methods* (Kluwer, 1993) pp. 353-357.

(*) R. Healey, "Quantum Theory: a Pragmatist Approach", *British Journal for the Philosophy of Science* 63 (2012) pp. 729-771.

R. Healey, *The Quantum Revolution in Philosophy* (Oxford University Press, 2017).

R. Healey, "Quantum-Bayesian and Pragmatist Views of Quantum Theory", in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Spring 2017 edition).
https://plato.stanford.edu/archives/spr2017/entries/quantum-bayesian/

S. Friederich, "In defence of non-ontic accounts of quantum states", *Studies in History and Philosophy of Modern Physics* 44 (2013) pp. 77-92.

P. Lewis, "Quantum Mechanics and its (Dis)contents", manuscript. http://philsci-archive.pitt.edu/14420/

D. Wallace, "On the plurality of quantum theories", to appear in S. French and J. Saatsi (eds.), *Scientific Realism and the Quantum* (Oxford University Press, forthcoming). Section 5.

D. Wallace, "Interpreting the quantum mechanics of cosmology", to appear in A. Ijjas and B. Loewer (eds.), *Philosophy of Cosmology* (forthcoming).

Physics-is-information approaches

In the light of quantum information, should we regard quantum theory itself as a theory of information, knowledge or beliefs, rather than as a dynamical theory?

(*) C. Fuchs, "Quantum mechanics as quantum information (and only a little more)". http://arxiv.org/abs/quant-ph/0205039.

C. Fuchs, N. Mermin and R. Schack, "An introduction to QBism with an application to the locality of quantum mechanics", *American Journal of Physics* 82 (2014) pp. 749-754.

C. Caves, C. Fuchs, and R. Schack, "Subjective probability and quantum certainty", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 255-274.

(*) C. Timpson, "Quantum Bayesianism: a Study", *Studies in History and Philosophy of Modern Physics* 39 (2008) pp. 579-609.

A. Zeilinger, "The message of the quantum", *Nature* 438 (2005) p.743.

M. Daumer, D. Durr. S. Goldstein, T. Maudlin, R. Tumulka, and N. Zanghi, "The message of the quantum?", *AIP Conference Proceedings* 844 (2006) 129.
Reply to Zeilinger.

A. Hagar, "A philosopher looks at quantum information theory", *Philosophy of Science* 70 (2003) pp. 752-775.

C. Timpson, *Quantum Information Theory and the Foundations of Quantum Mechanics* (Oxford University Press, 2013)

R. Healey, "Quantum-Bayesian and Pragmatist Views of Quantum Theory", in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Spring 2017 edition).
https://plato.stanford.edu/archives/spr2017/entries/quantum-bayesian/

Consistent histories

Does the consistent-histories formalism – a mathematical framework to describe when a series of questions about a system can consistently be answered – provide a way to sharpen up something like Bohr's complementarity?

R. Griffiths, "Consistent histories and the interpretation of quantum mechanics", *Journal of Statistical Physics* 36 (1984) pp. 219-272.

(*) R. Griffiths, "A consistent quantum ontology", *Studies in History and Philosophy of Modern Physics* 44 (2013) pp. 93-114.

Omnes, R., "Logical reformulation of quantum mechanics, I. Foundations", *Journal of Statistical Physics* 53 (1988) pp. 893-932.

A. Bassi and G. Ghirardi, "Decoherent histories and realism", *Journal of Statistical Physics* 98 (2000) pp. 457-494.

E. Okon and D. Sudarsky, "Measurements according to consistent histories", *Studies in History and Philosophy of Modern Physics* 48 (2014) pp. 7-12.

R. Griffiths, "Consistent quantum measurements", *Studies in History and Philosophy of Modern Physics* 52 (2015) pp. 188-197.
Reply to Okon and Sudarsky.

E. Okon and D. Sudarsky, "The consistent histories formalism and the measurement problem", *Studies in History and Philosophy of Modern Physics* 52 (2015) pp. 217-222.
Reply to Griffiths.

D. Wallace, "Philosophy of Quantum Mechanics", in D. Rickles (ed.), *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008), http://arxiv.org/abs/0712.0149 . Section 3.3.

Relational quantum mechanics

M. Brown, "Relational Quantum Mechanics and the Determinacy Problem", *British Journal for the Philosophy of Science* 60 (2009) p.679.

(*) C. Rovelli, "Space is blue and birds fly through it", *Philosophical Transactions of the Royal Society of London A,* forthcoming; https://arxiv.org/abs/1712.02894 .

C. Rovelli, "Relational Quantum Mechanics", *International Journal of Theoretical Physics* 35 (1996) p.1637.

B. van Fraassen, "Rovelli's World", *Foundations of Physics* 40 (2010) pp. 390-417.

7. Decoherence

"Decoherence", loosely, is the study of how the collective degrees of freedom of sufficiently large systems evolve so as to suppress quantum interference. Formally this induces a transition from a quantum description to a classical (though probabilistic) description. Decoherence has been claimed to solve the measurement problem, but the claim is hotly contested.

Interconnections

- Insofar as decoherence solves the measurement problem, it does so (it is generally agreed) only by underwriting the process of branching in the *Everett interpretation.*
- In the *de Broglie-Bohm theory,* decoherence explains why the wavefunction undergoes effective collapse.
- Decoherence makes it extremely hard to test *dynamical-collapse theories*, as decoherence and dynamical collapse are for practical purposes indistinguishable (indeed, sometimes "decoherence" is used interchangeably for both, and 'intrinsic decoherence' (i.e. collapse) is distinguished from 'environment-induced decoherence").
- The framework of "decoherent histories" is also used in the consistent-histories interpretation, arguably a close relative of the *Copenhagen interpretation.*

Core concepts in the environment-induced decoherence program

There are two main schools in decoherence (which should be thought of as complementary ways to study the same physical phenomenon, not as incompatible). The best-known is environment-induced decoherence, where the goal is to write down closed-form dynamics for a system interacting with an environment.

H.D.Zeh, "There are no quantum jumps, nor are there particles!", *Physics Letters A* 172 (1993) pp. 189-192.

(*) W.H.Zurek, "Decoherence and the Transition from Quantum to Classical – Revisited" (2003), http://arxiv.org/abs/quant-ph/0306072

J. Paz and W. Zurek, "Environment-Induced Decoherence and the Transition from Quantum to Classical", https://arxiv.org/abs/quant-ph/0010011

Core concepts in the decoherent-histories program

The other main school is decoherent histories, which makes various conceptual features of decoherence (its irreversibility in time, its applicability to closed systems) more explicit, to some extent at the cost of calculational tractability.

J.Halliwell, "Macroscopic Superpositions, Decoherent Histories, and the Emergence of Hydrodynamic Behaviour", in S.Saunders *et al* (ed.), *Many Worlds? Everett, Quantum Theory and Reality* (Oxford University press, 2010).

M. Gell-Mann and J. Hartle, "Classical Equations for Quantum Systems", *Physical Review D* 47 (1993) pp. 3345-3382.

(*) J. Hartle, "Quasiclassical Realms", in S.Saunders *et al* (ed.), *Many Worlds? Everett, Quantum Theory and Reality* (Oxford University press, 2010).

References

E. Joos *et al*, *Decoherence and the Appearance of a Classical World in Quantum Theory, 2nd ed.* (Springer, 2003)

M. Schlosshauer, *Decoherence and the Quantum-to-Classical Transition* (Springer, 2007).

Conceptual discussion

How does decoherence relate to the measurement problem?

W. Zurek, "Decoherence, einselection, and the quantum origins of the classical", *Reviews of Modern Physics 75* (2003), p. 715-775.

F. Dowker and A. Kent, "On the consistent histories approach to quantum mechanics", *Journal of Statistical Physics* 82 (1996) pp. 1575-1646.

G. Bacciagaluppi, "The Role of Decoherence in Quantum Mechanics", *The Stanford Encyclopedia of Philosophy (Winter 2003 Edition)*, Edward N. Zalta (ed.), available at http://plato.stanford.edu/archives/win2003/entries/qm-decoherence/.

D. Wallace, *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation* (Oxford University Press, 2012), ch.3

P. Stamp, "The decoherence puzzle", *Studies in History and Philosophy of Modern Physics* 37 (2006) pp. 467-497.

Decoherence and time asymmetry

Is decoherence time-asymmetric? If so, why? Can it be reformulated to eliminate the time asymmetry?

M. Gell-Mann and J. Hartle, "Time symmetry and asymmetry in quantum mechanics and quantum cosmology", in J. J. Halliwell, J. Perez-Mercarder, and W. Zurek (eds.), *Physical Origins of Time Asymmetry* (Cambirdge University Press, 1994), pp. 311-345.

(*) G. Bacciagaluppi, "Probability, Arrow of Time and Decoherence", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 439-456.

D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation* (Oxford University Press, 2012), chapter 9.

8. The Everett interpretation (aka the Many-Worlds Theory)

According to the Everett interpretation, quantum mechanics can (must?) be understood as a theory where the world is constantly branching into copies. It is claimed (!) that this is actually a very conservative approach, requiring no modification of the underlying quantum formalism.

Interconnections

- The Everett interpretation, in its modern forms, makes essential use of *decoherence*.
- Bell's theorem (arguably) does not apply to the Everett interpretation, meaning that considerations of *non-locality in quantum theory* are radically different.
- In the Everett interpretation, the quantum state is supposed to offer a complete representation of the physical system being studied; it is contentious how to understand the *ontology of quantum mechanics* in the light of this.
- Along the same lines, the Everett interpretation clearly lacks a *primitive ontology,* which is a problem insofar as this is a requirement for a theory to be empirically valid.

Overviews

S. Saunders, "Many Worlds: an Introduction", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010). http://philsci-archive.pitt.edu/12408/

D. Wallace, "The Everett Interpretation", in R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics* (Oxford University Press, 2013). http://philsci-archive.pitt.edu/8888/

Decoherence-based solutions to the preferred basis problem

In modern approaches to the Everett interpretation, the "many worlds" arise emergently, and are a by-product of decoherence.

S. Saunders, "Time, quantum mechanics and decoherence", *Synthese* 114 (1998) pp. 404-444.

(*) D. Wallace, "Decoherence and Ontology, or: how I learned to stop worrying and love FAPP", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010). https://arxiv.org/abs/1111.2189

D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation* (Oxford University Press, 2012), chapters 2-3 and First Interlude.

(*) T. Maudlin, "Can the world be only wavefunction?", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010).

D. Baker, "Measurement outcomes and probability in Everettian quantum mechanics", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 153-169.

R. Bousso and L. Susskind, "The multiverse interpretation of quantum mechanics", *Physical Review D* 85 (2011) 045007.

Other solutions to the preferred basis problem

Everett intended his interpretation to require no modification of quantum theory, and modern versions likewise attempt to be modification-free, but there is a substantial tradition of attempts to modify the *formalism in one way or another in order to explicitly introduce "worlds" or similar into the theory. (Though NB: these approaches, for the most part, have few contemporary supporters.)*

D. Deutsch, "Quantum Theory as a Universal Physical Theory", *International Journal of Theoretical Physics* 24 (1985) pp. 1-41.

M. Lockwood, "'Many Minds' Interpretation of Quantum Mechanics", *British Journal for the Philosophy of Science* 47 (1996) pp. 159-188.

D. Albert and B. Loewer, "Interpreting the Many Worlds Interpretation", *Synthese* 77 (1998) pp. 195-213.

J. Barrett, *The quantum mechanics of minds and worlds* (Oxford University Press, 1999), chs.6-7.

V. Allori, S. Goldstein, R. Tumulka and N. Zanghi, "Many Worlds and Schrodinger's First Quantum Theory", *British Journal for the Philosophy of Science* 62 (2011) pp. 1-27.

Probability in Everett: general considerations

The 'probability problem' – how we are to understand probabilities in a deterministic, branching, theory – is generally agreed to be the most severe difficulty for the Everett interpretation (albeit some advocates claim that this is just a general problem of how to understand probability, in a new context).

S. Saunders, "Chance in the Everett interpretation", https://arxiv.org/abs/1609.04720. Lightly revised version of article of the same title in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory and Reality* (Oxford University Press, 2010).

(*) D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation* (Oxford University Press, 2012), chapter 4.

(*) D. Albert, "Probability in the Everett picture", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010).

D. Papineau, "A fair deal for Everettians", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010). (An earlier version of the arguments can be found in D. Papineau, "Many worlds are no worse than one", *British Journal for the Philosophy of Science* 47 (1996) pp. 233-241.

A. Rae, "Everett and the Born rule", *Studies in History and Philosophy of Modern Physics* 40 (2009) pp. 243-250.

H. Brown, "Curious and sublime: the connection between uncertainty and probability in physics". *Philosophical Transactions of the Royal Society of London* A369 (2011) pp. 1-15.

E. Adlam, "The problem of confirmation in the Everett interpretation", *Studies in History and Philosophy of Modern Physics* 47 (2014) pp. 21-32.

Probability in Everett: Decision-theoretic arguments

David Deutsch tried to derive probabilities in Everettian quantum mechanics by considering the rational strategies for an agent; I developed these strategies in the 2000s and they have been widely discussed.

D. Deutsch, "Quantum Theory of Probability and Decisions", *Proceedings of the Royal Society of London* A455 (1999) pp. 3129-3137.

H. Barnum, C. Caves, J. Finkelstein, C. Fuchs, and R. Schack, "Quantum Probability from Decision Theory?", *Proceedings of the Royal Society of London* A456 (2000) pp. 1175-1182.

D. Wallace, "Everettian Rationality: defending Deutsch's approach to probability in the Everett interpretation", *Studies in History and Philosophy of Modern Physics* 34 (2003) pp. 415-439.
This is an exegesis of the two papers above, and a defence of Deutsch (properly understood) against Barnum et al's criticisms.

(*) H. Greaves, "Probability in the Everett interpretation", *Philosophy Compass* 2 (2006).
A very clear exegesis of the state of play in 2006 (but, NB, lots has changed since then).

(*) D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation* (Oxford University Press, 2012), chapter 5. https://arxiv.org/abs/0906.2718

H. Price, "Decisions, Decisions, Decisions: can Savage Salvage Everettian Probability?", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010). https://arxiv.org/abs/0802.1390

A. Kent, "One world versus many: the inadequacy of Everettian accounts of evolution, probability, and scientific confirmation", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010). https://arxiv.org/abs/0905.0624

F. Dizadji-Bahmani, "The probability problem in Everettian quantum mechanics persists", *British Journal for the Philosophy of Science* 66 (2015) pp. 257-283.

Probability in Everett: other approaches

There are other strategies to understand Everettian probability, beyond the decision-theoretic ones.

(*) E. Farhi, J. Goldstone and S. Gutman, "How probability arises in quantum mechanics", *Annals of Physics* 192 (1989) pp. 368-382.

W. Zurek, "Probabilities from Entanglement, Born's Rule from Invariance", *Physical Review A* 71 (2005) 052105.

S. Carroll and C. Sebens, "Many Worlds, the Born Rule, and Self-Locating Uncertainty", https://arxiv.org/abs/1405.7907

A. Aguirre and M. Tegmark, "Born in an infinite universe: a cosmological interpretation of quantum mechanics", *Physical Review D* 84 (2011) 105002.

L. Vaidman, "Probability in the Many-Worlds Interpretation of Quantum Mechanics", in Y. Ben-Menahem and M. Hemmo (eds.), *Probability in Physics* (Springer, 2012).
http://philsci-archive.pitt.edu/8558/

Probability in Everett: the epistemic problem

It was recognized in the early 2000s[2] *that solving the probability problem requires us to understand not just how we should act in the future, given information about the quantum state (the 'practical problem') but also, and more importantly, why (for Everettians) the data ordinarily thought of as confirming quantum theory actually does confirm it (the 'epistemic problem' or 'evidential problem').*

H. Greaves, "On the Everettian epistemic problem", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 120-152.

(*) H. Greaves and W. Myrvold, "Everett and evidence", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010). http://philsci-archive.pitt.edu/4222/

(*) D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett Interpretation* (Oxford University Press, 2012), chapter 6. https://arxiv.org/abs/0906.2718

R. Dawid and K. Thebault, "Against the empirical viability of the Deutsch-Wallace-Everett approach to quantum mechanics", *Studies in History and Philosophy of Modern Physics* 47 (2014) pp. 55-61.

J. Read, "In defence of Everettian decision theory", *Studies in History and Philosophy of Modern Physics,* forthcoming.

Uncertainty and the metaphysics of Everettian branching

Can branching be understood as a process of genuine uncertainty for the branched agent? Do we really have branching, or just divergence of initially-identical branches?

S. Saunders, "Time, quantum mechanics and probability", *Synthese* 114 (1998) pp. 373-404.

(*) D. Wallace, *The Emergent Multiverse* (Oxford University Press, 2012), chapter 7.

P. Lewis, "Uncertainty and probability for branching selves", *Studies in History and Philosophy of Modern Physics* 38 (2007) pp. 1-14.

S. Saunders and D. Wallace, "Branching and Uncertainty", *British Journal for the Philosophy of Science* 59 (2008) pp. 293-305. See also response by Paul Tappenden, and reply to that response, in the same issue.

N. Belnap and T. Muller, "Branching with uncertain semantics: discussion note on Saunders and Wallace, 'Branching and Uncertainty'", *British Journal for the Philosophy of Science* 61 (2010) pp. 681-696.

A. Wilson, "Macroscopic ontology in Everettian quantum mechanics", *Philosophical Quarterly* 61 (2011) pp. 363-382.

(*) A. Wilson, "Everettian quantum mechanics without branching time", *Synthese* 188 (2012) pp. 67-84.

Historical sources

H. Everett III, "Relative-state formulation of quantum mechanics", *Review of Modern Physics* 29 (1957) pp. 454-462.

[2] I *believe* the first statement in print is in a now-historical preprint of mine, https://arxiv.org/pdf/quant-ph/0211104.pdf (section 3), but in any case the idea clearly came independently to several others (Greaves, Myrvold, Albert in particular).

B. DeWitt and N. Graham (eds.), *The Many Worlds Interpretation of Quantum Mechanics* (Princeton University Press, 1973). Recently reprinted.

J. Barrett and P. Byrne (eds.), *The Everett Interpretation of Quantum Mechanics: Collected Works 1955-1980 with Commentary* (Princeton University Press, 2012).

Philosophical consideration of the historical Everett's views

B. Bevers, "Everett's 'Many-Worlds' proposal", *Studies in History and Philosophy of Modern Physics* 42 (2011) pp. 3-12.

(*) J. Barrett, "Everett's pure wave mechanics and the notion of worlds", *European Journal of Philosophy of Science* 1 (2011) pp. 277-302.

A. Cunningham, "Branches in the Everett Interpretation", *Studies in History and Philosophy of Modern Physics* 46 (2014) pp. 247-262.

9. The de Broglie-Bohm theory

The "de Broglie-Bohm theory" – also known as "Bohmian mechanics" and as the "pilot-wave theory" – was developed by de Broglie in 1927, rediscovered by Bohm in 1952, and provides a hidden-variable theory for position measurements in non-relativistic quantum mechanics: it has been vigorously defended – notably by John Bell – as a fully satisfactory solution to the measurement problem in the non-relativistic domain and as a template for a properly intelligible approach to quantum mechanics.

Interconnections

- It is often said that Bell's theorem tells us that de Broglie-Bohm theory is non-local. This is confused: Bohmian mechanics is transparently non-local. Bell's theorem (arguably) tells us instead that any empirically-adequate physical theory is non-local, so that the non-locality of de Broglie-Bohm theory is innocuous. In any case, the theory is extensively discussed in the literature on *non-locality in quantum theory.*
- Bohmian mechanics is the main inspiration for the program of *primitive ontology.* In particular, the "Everett-in-denial" objection to Bohm's theory (readings in this section) is closely connected to the question of the right ontology for the theory.

Presentations of the theory

D. Albert, *Quantum Mechanics and Experience* (Harvard University Press, 1992), chapter 7.

(*) D. Durr, S. Goldstein and N. Zanghi, "Bohmian mechanics as the foundation of quantum mechanics", in J. Cushing, A. Fine and S. Goldstein (eds.), *Bohmian Mechanics and Quantum Theory: An Appraisal* (Springer, 1996). https://arxiv.org/abs/quant-ph/9511016

S. Goldstein, "Bohmian Mechanics", in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Summer 2017 edition). https://plato.stanford.edu/archives/sum2017/entries/qm-bohm/

J. S. Bell, "Quantum Mechanics for Cosmologists", in C. Isham, R. Penrose and D. Sciama (eds.), *Quantum Gravity 2* (Oxford University Press, 1981) pp. 611-637. Reprinted in J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, 1987/2004). Section 4.

J.S. Bell, "On the impossible pilot wave", *Foundations of Physics* 12 (1982) pp. 989-999. Reprinted in J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, 1987/2004).

P. Holland, *The Quantum Theory of Motion* (Cambridge University Press, 1993).

J. Bricmont, *Making Sense of Quantum Mechanics* (Springer, 2016).

Effective collapse and the quantum/classical transition

It is sometimes argued that the quantum/classical transition is especially natural in de Broglie-Bohm theory.

(*) V. Allori, D. Durr, S. Goldstein and N. Zanghi, "Seven steps towards the classical world", *Journal of Optics B* 4 (2002) pp. 482-488.

D. Durr, S. Goldstein, and N. Zanghi, "Bohmian mechanics and the Meaning of the Wave Function", in R. Cohen, M. Horne and J. Stachel (eds.), *Experimental Metaphysics – Quantum Mechanical Studies for Abner Shimony.* https://arxiv.org/quant-ph/9512031

J. Rosaler, "Is de Broglie-Bohm Theory Specially Equipped to Recover Classical Behavior?", *Philosophy of Science* 82 (2015) pp. 1175-1187.

Probability

Probabilities arise in de Broglie-Bohm theory from an initial probability distribution over the space of particle configurations; how is this to be understood?

(*) A. Valentini and H. Westman, "Dynamical origin of quantum probabilities", *Proceedings of the Royal Society of London* A 461 (2005) pp. 253-272.

D. Durr, S. Goldstein and N. Zanghi, "Quantum Equilibrium and the Origin of Absolute Uncertainty", *Journal of Statistical Physics* 67 (1992) pp. 843-907.

S. Goldstein and W. Struyve, "On the uniqueness of quantum equilibrium in Bohmian mechanics", *Journal of Statistical Physics* 128 (2007) pp. 1197-1209.

Fooled detectors

In some experiments, the de Broglie-Bohm particles are not to be at the location where they were (apparently) detected; should this concern us?

H. Brown, C. Dewdney and G. Horton, "Bohm particles and their detection in the light of neutron interferometry", *Foundations of Physics* 25 (1995) pp. 329-347.

J. Barrett, "The persistence of memory: surreal trajectories in Bohm's theory", *Philosophy of Science* 67 (2000) pp. 680-703.

L. Vaidman, "The reality in Bohmian quantum mechanics or can you kill with an empty wave bullet?", *Foundations of Physics*

B. Hiley and R. Callaghan, "Delayed choice experiments and the Bohm approach", *Physica Scripta* 74 (2006) pp. 336-348.

A. Sole, "Surrealistic Bohmian trajectories appraised", *European Journal for Philosophy of Science* 7 (2017) pp. 467-492.

The 'Everett-in-denial' objection

Since de Broglie-Bohm theory keeps the unitarily-evolving wavefunction and just adds extra particles, it has been claimed that it is just the Everett interpretation plus some epiphenomenal fluff. (See also the section on "Primitive ontology".)

D. Deutsch, "Comment on Lockwood", *British Journal for the Philosophy of Science* 47 (1996) pp. 222-8.

H. Brown and D. Wallace, "Solving the measurement problem: de Broglie-Bohm loses out to Everett", *Foundations of Physics* 35 (2005) pp. 517-540.

P. Lewis, "How Bohm's Theory Solves the Measurement Problem", *Philosophy of Science* 74 (2007) pp. 749-760.

A. Valentini, "Pilot wave theory: many worlds in denial?", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory and Reality* (Oxford University Press, 2010). https://arxiv.org/abs/0811.0810

H. Brown, "Commentary: Reply to Valentini", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory and Reality* (Oxford University Press, 2010). https://arxiv.org/abs/0901.1278

Locality and relativistic covariance

The de Broglie-Bohm theory has explicitly non-Lorentz-covariant dynamics; how are we to understand this and how is it undetectable?

(*) A. Valentini, "Signal-locality in hidden-variables theories", *Physics Letters A* 297 (2002) pp. 273-278.

D. Durr, S. Goldstein, T. Norsen, W. Struyve and N. Zanghi, "Can Bohmian mechanics be made relativistic?", *Proceedings of the Royal Society of London A* 470 (2014) 20130699.

Identical particles

de Broglie-Bohm theory seems to offer a particularly natural way to think about identical particles; it also raises the question of how particles can have different dynamical properties given how minimal they are in the theory.

(*) S. Goldstein, J. Taylor, R. Tumulka and N. Zanghi, "Are all particles identical?", *Journal of Physics A* 38 (2005) 1567.

H. Brown, E. Sjoqvist and G. Bacciagaluppi, "Remarks on identical particles in de Broglie-Bohm theory", *Physics Letters A*

Extensions to quantum field theory

What are the prospects for developing a quantum-field-theoretic version of the theory?

J. Bell, "Beables for Quantum Field Theory", in B. Hiley and F.D.Peat (eds.), *Quantum Implications: Essays in Honour of David Bohm* (Routledge, 1987). Reprinted in J. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, 1987/2004).

D. Durr, S. Goldstein, R. Tumulka and N. Zanghi, "Bohmian Mechanics and Quantum Field Theory", *Physical Review Letters* 93 (2004) pp. 1-4.

(*) W. Struyve, "Pilot-Wave Theory and Quantum Fields", *Reports on Progress in Physics* 73 (2010) 106001.

(*) D. Wallace, "On the Plurality of Quantum Theories: Quantum theory as a framework, and its implications for the quantum measurement problem", S. French and J. Saatsi (eds.), *Scientific Realism and the Quantum* (Oxford University Press, forthcoming).

Historical sources and discussion

G. Bacciagaluppi and A. Valentini, *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference* (Cambridge University Press, 2009).

D. Bohm, "A suggested interpretation of the quantum theory in terms of 'hidden' variables, I and II", *Physical Review* 85 (1952) pp. 166-193.

J. Cushing, "Bohm's causal interpretation of quantum mechanics", in J. T. Cushing, A. Fine and S. Goldstein (eds.), *Bohmian Mechanics and Quantum Theory: An Appraisal* (Springer, 1996).

10. Dynamical-collapse theories

In a "dynamical collapse" theory, the wavefunction undergoes a physical collapse according to well-defined dynamical laws which are chosen so as to reproduce quantum phenomena on the micro level while recovering a macroscopically definite world. Concrete models where developed comparatively recently (the 1980s and later). The most carefully studied, and philosophically important, are the GRW model and the related CSL model; the Diosi-Penrose proposal that wavefunctions collapse when the gravitational field would otherwise enter a superposition has also received a lot of attention.

Interconnections

- It has been somewhat contentious to establish in what sense the *non-locality* of collapse models implies action at a distance, and/or violation of relativistic covariance.
- Dynamical collapse models – the GRW model in particular – have been test-beds for discussions of *quantum ontology* and of the *primitive-ontology* program.

The Ghirardi-Rimini-Weber (GRW) and Continuous-State-Localisation (CSL) models: introductions

G. Ghirardi, A. Rimini and T. Weber, "Unified Dynamics for Micro and Macro Systems", *Physical Review D* 34 (1986) pp. 470-491.

(*) J. Bell, "Are there quantum jumps?", in C. Kilmister (ed.), *Schrodinger: centenary celebration of a polymath* (Cambridge University Press, 1987). Reprinted in J. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, 1987/2004).

A. Bassi, "Dynamical reduction models: present status and future developments", *Journal of Physics Conference Series* 67 (2007) 012013.

P. Pearle, "Combining stochastic dynamical state-vector reduction with spontaneous localization", *Physical Review A* 39 (1989) pp. 2277-2289.

The GRW and CSL models: more detailed accounts

(*) G. Ghirardi, "Collapse theories", in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Spring 2016 edition). https://plato.stanford.edu/archives/spr2016/entries/qm-collapse/

A. Bassi and G. Ghirardi, "Dynamical reduction models", *Physics Reports* 379 (2003) p.257.

D. Home, *Conceptual Foundations of Quantum Physics: an overview from modern perspectives* (Plenum, 1997), pp. 97-118.

Gravitationally-induced wavefunction collapse

L. Diosi, "Gravitation and the quantum-mechanical localization of macro-objects", *Physics Letters A* 105 (1984) pp. 199-202.

R. Penrose, "On gravity's role in state vector reduction", *General Relativity and Gravitation* 28 (1996) p.581.

(*) A. Bassi, A. Grossardt, and H. Ulbricht, "Gravitational Decoherence", *Classical and Quantum Gravity* 34 (2017) 193002.

Prospects for empirical testing

How constrained are dynamical-collapse theories by the data?

(*) W. Feldmann and R. Tumulka, "Parameter diagrams of the GRW and CSL theories of wavefunction collapse", *Journal of Physics A* 45 (2012) 065304.

A. Leggett, "Testing the limits of quantum mechanics: motivation, state of play, prospects", *Journal of Physics: Condensed Matter* 14 (2002) pp.R415-R451.

M. Schlosshauer, "Experimental motivation and empirical consistency in minimal no-collapse quantum mechanics", *Annals of Physics* 321 (2006) pp. 112-149.

The problem of tails

Dynamical collapse never leads to exactly-localised systems; does it matter?

D. Albert and B. Loewer, "Tails of Schrodinger's Cat", in R. Clifton (ed.), *Perspectives on Quantum Reality: Non-Relativistic, Relativistic, Field-Theoretic* (Kluwer, 1996).

A. Cordero, "Are GRW tails as bad as they say?", *Philosophy of Science* 66 (1999) pp. 59-71.

P. Lewis, "GRW: A case study in quantum ontology", *Philosophy Compass* 1 (2006) pp. 224-244.

(*) K. McQueen, "Four tails problems for dynamical collapse theories", *Studies in History and Philosophy of Modern Physics* 49 (2015) pp. 10-18.

D. Wallace, "Philosophy of Quantum Mechanics", in D. Rickles (ed.), *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008). Sections 5.2-5.4. https://arxiv.org/abs/0712.0149

D. Wallace, "Life and death in the tails of the wave function", preprint. https://arxiv.org/abs/1407.4746

The flash ontology

An alternative reading of GRW (and related theories) where the entire macroworld supervenes on the spacetime points at which collapse occurs.

F. Dowker and I. Herbauts, "The status of the wave function in dynamical collapse models", *Foundations of Physics Letters* 18 (2005) pp. 499-518.

V. Allori, S. Goldstein, R. Tumulka, and N. Zanghi, "On the common structure of Bohmian mechanics and the Ghirardi-Rimini-Weber theory: Dedicated to GianCarlo Ghirardi on the occasion of his 70th birthday", *British Journal for the Philosophy of Science* 59 (2008) pp. 353-389. Sections 3, 6, 7.

(*) M. Esfeld and N. Gisin, "The GRW Flash Theory: a relativistic quantum ontology of matter in space-time?", *Philosophy of Science* 81 (2014) pp. 248-264.

F. Arntzenius, *Space, Time, and Stuff* (Oxford Unviersity Press, 2012), section 3.15.

Relativistic covariance and the extension to quantum field theory

What are the prospects?

(*) W. Myrvold, "On peaceful co-existence: is the collapse postulate incompatible with relativity?", *Studies in History and Philosophy of Modern Physics* 33 (2002) pp. 435-466.

R. Tumulka, "A relativistic version of the Ghirardi-Rimini-Weber model", *Journal of Statistical Physics* 125 (2006) p.821.

D. Bedingham, D. Durr, G. Ghirardi, S. Goldstein, R. Tumulka, and N. Zanghi, "Matter density and relativistic models of wave function collapse", *Journal of Statistical Physics* 154 (2014) pp. 623.

D. Wallace, "On the Plurality of Quantum Theories: Quantum theory as a framework, and its implications for the quantum measurement problem", S. French and J. Saatsi (eds.), *Scientific Realism and the Quantum* (Oxford University Press, forthcoming).

11. Other proposed solutions to the measurement problem

Quantum logic

Does quantum mechanics tell us that classical logic is empirically wrong?

H. Putnam, "Is logic empirical?", *Boston Studies in the Philosophy of Science* 5 (1969) pp. 216-241. Reprinted in H. Putnam, *Mathematics, Matter and Method: Philosophical Papers vol. 1* (Cambridge University Press, 1979).

M. Dummett, "Is logic empirical?" in H. D. Lewis (ed.), *Contemporary British Philosophy* (Allen and Unwin, 1976) pp. 45-68. Reprinted in M. Dummett, *Truth and Other Enigmas* (Duckworth, 1978).

M. Redhead, *Incompleteness, Nonlocality and Realism: a prolegomenon to the philosophy of quantum mechanics* (Clarendon Press, 1987). Chapter 7.

(*) M. Dickson, "Quantum Logic is Alive ^ (It Is True ᵛ It Is False)", *Philosophy of Science* 68 (2001) pp. S274-S287.

Retrocausality

"Retrocausal" approaches to quantum theory – that is, approaches where causal influences can propagate backwards in time – offer a potential end run around many difficulties, in particular with Bell's inequalities. But at present there is no really well-worked out model even in the non-relativistic domain.

H. Price, "Does time-symmetry imply retrocausality? How the quantum world says 'Maybe'", *Studies in History and Philosophy of Modern Physics* 43 (2012) pp. 75-83.

J. Cramer, "The transactional interpretation of quantum mechanics", *Reviews of Modern Physics* 58 (1986) pp. 647-687.

(*) P. Evans, H. Price and K. Wharton, "New slant on the EPR-Bell experiment", *British Journal for the Philosophy of Science* 64 (2013) pp. 297-324.

M. Leifer and M. Pusey, "Is a time symmetric interpretation of quantum theory possible without retrocausality?", *Proceedings of the Royal Society of London A* 473 (2017) 20160607.

The modal interpretation

Modal interpretations (there are several variants) are hidden-variable theories where the hidden variables are determined dynamically rather than fixed all at once (as in the de Broglie-Bohm theory). Severe technical and conceptual problems identified in the 1990s have caused them to decline in popularity, but they still have some advocates.

(*) O. Lombardi and D. Dieks, "Modal Interpretations of Quantum Mechanics", in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Spring 2017 edition).
https://plato.stanford.edu/archives/spr2017/entries/qm-modal/

(*) D. Wallace, "Philosophy of quantum mechanics", in D. Rickles (ed.), *The Ashgate Companion to Contemporary Philosophy of Physics* (Ashgate, 2008), sections 6.1-6.4.

G. Bacciagaluppi, "Delocalized properties in the modal interpretation of quantum mechanics", *Foundations of Physics* 30 (2000) pp. 1431-1444.

F. Arntzenius, “Curioser and Curioser: A personal evaluation of modal interpretations”, in D. Dieks and P. Vermaas (eds.), *The Modal Interpretation of Quantum Mechanics* (Kluwer, 1998).

12. Ontology of quantum mechanics

What is the ontology of "quantum theory"? The question is usually asked in the context of dynamical-collapse theories or the de Broglie-Bohm theory (and sometimes in the context of the Everett interpretation), and answers to some extent transfer between them.

Interconnections

- In the last 20 years (and for de Broglie-Bohm theory in particular, and GRW to a lesser extent) there has been a lot of attention paid to so-called "*primitive ontology"* theories of quantum ontology, so much so that I have given them their own section.
- Wavefunction realism has been formulated with *the Everett interpretation* and *dynamical-collapse theories* in mind, though it has been discussed in the context of the *de Broglie-Bohm theory* too.
- Spacetime state realism and the Heisenberg approach fairly explicitly assume *the Everett interpretation.*

Wave function realism

Should the wavefunction – as originally proposed by David Albert – be interpreted as some kind of field on a physically-realized, very-high-dimensional space?

D. Albert, "Wave function realism", in A. Ney and D. Albert (eds.), *The Wave Function: Essays on the Metaphysics of Quantum Mechanics* (Oxford University Press, 2013). Reprised and updated version of D. Albert, "Elementary Quantum Metaphysics", in J. Cushing, A. Fine and S. Goldstein (eds.), *Bohmian Mechanics and Quantum Theryo: An Appraisal* (Kluwer, 1996).

T. Maudlin, "Can the world be only wavefunction?", in S. Saunders *et al* (eds.), *Many Worlds? Everett, Quantum Theory, and Reality* (Oxford University Press, 2010).

B. Monton, "Against 3N-dimensional space", in A. Ney and D. Albert (eds.), *The Wave Function: Essays on the Metaphysics of Quantum Mechanics* (Oxford University Press, 2013).

P. Lewis, "Dimension and Illusion", in A. Ney and D. Albert (eds.), *The Wave Function: Essays on the Metaphysics of Quantum Mechanics* (Oxford University Press, 2013). http://philsci-archive.pitt.edu/8841/

(*) A. Ney, "Fundamental physical ontologies and the constraint of empirical coherence: a defense of wave function realism", *Synthese* 192 (2015) pp. 3105-3124.

(*) D. Wallace, "Against wavefunction realism", to appear in S. Dasgupta and B. Weslake, *Current Controversies in Philosophy of Science* (Routledge, forthcoming).

W. Myrvold, "What is a Wavefunction", *Synthese* 192 (2015) pp. 3247-3274.
http://philsci-archive.pitt.edu/11117/

Spacetime state realism

Can we instead understand quantum theories (or, at least, spacetime theories) as living on ordinary three-dimensional space but with a very high level of holism?

(*) D. Wallace and C. Timpson, "Quantum Mechanics on Spacetime I: Spacetime State Realism", *British Journal for the Philosophy of Science* 61 (2010) pp. 697-727.

NB: the sequel still doesn't exist.

D. Wallace, *The Emergent Multiverse: Quantum Theory according to the Everett interpretation* (Oxford University Press, 2012), chapter 8.

(*) F. Arntzenius, *Space, Time, and Stuff* (Oxford Unviersity Press, 2012), section 3.13.

N. Swanson, "How to be a relativistic spacetime state realist", preprint. http://philsci-archive.pitt.edu/14412/

J. Ismael and J. Schaffer, "Quantum holism: nonseparability as common ground", *Synthese,* forthcoming.

D. Baker, "The philosophy of quantum field theory", *Oxford Handbooks Online* (2015). http://philsci-archive.pitt.edu/11375/. Section 4.

The Heisenberg picture as ontology

Deutsch and Hayden suggest a way of understanding (Everettian) quantum theory that is completely local; does it work?

(*) D. Deutsch and P. Hayden, "Information flow in entangled quantum systems", *Proceedings of the Royal Society of London* A 456 (1999) pp. 1759-1774.

D. Wallace and C. Timpson, "Non-locality and gauge freedom in Deutsch and Hayden's formulation of quantum mechanics", *Foundations of Physics* 37 (2007) pp. 951-955.

D. Deutsch, "Vindication of Quantum Locality", *Proceedings of the Royal Society of London* A 468 (2012) pp. 531-544.

D. Baker, "The philosophy of quantum field theory", *Oxford Handbooks Online* (2015). http://philsci-archive.pitt.edu/11375/. Section 4.

F. Arntzenius, *Space, Time, and Stuff* (Oxford Unviersity Press, 2012), section 3.14.

General concerns

Are there dubious hidden assumptions in the way discussions of quantum ontology are conducted?

(*) D. Wallace, "Lessons from realistic physics for the metaphysics of quantum theory", *Synthese,* forthcoming.

H. Halvorson, "To be a realist about quantum theory", preprint. http://philsci-archive.pitt.edu/14310/.

L. Ruetsche, *Interpreting Quantum Theories* (Oxford University Press, 2012), chapters 1, 12-14.

13. Primitive ontology

An influential (but contentious) recent approach to the ontology of physical theories requires them to include a "primitive ontology", which must consist of localized particles (or, sometimes, fields) and which is the sole basis by which the theory makes contact with experiment.

Interconnections

- Primitive ontology was developed primarily in the context of *the de Broglie-Bohm theory,* though it has been extended to some *dynamical-collapse theories* (notably GRW).
- The Everett interpretation cannot naturally be given a primitive ontology (at least, not on most versions) so questions of the coherence, or requirement, for a primitive ontology are related to questions of the empirical coherence of Everettian quantum mechanics.
- Conversely, the primitive-ontology framework offers advocates of the *de Broglie-Bohm theory* a potential reply to the Everett-in-denial objection.
- The primitive-ontology approach is a rival to other approaches to the *ontology of quantum theory.*

The general approach

V. Allori, S. Goldstein, R. Tumulka, and N. Zanghi, "On the common structure of Bohmian mechanics and the Ghirardi-Rimini-Weber theory: Dedicated to GianCarlo Ghirardi on the occasion of his 70th birthday", *British Journal for the Philosophy of Science* 59 (2008) pp. 353-389.

(*) V. Allori, S. Goldstein, R. Tumulka, and N. Zanghi, "Predictions and Primitive Ontology in Quantum Foundations: a Study of Examples", *British Journal for the Philosophy of Science* 65 (2014) pp. 323-352.

V. Allori, "Primitive Ontology in a Nutshell", *International Journal of Quantum Foundations* 1 (2015) pp. 107-122.

M. Esfeld, D. Lazarovici, V. Lam, and M. Hubert, "The physics and metaphysics of primitive stuff", *British Journal for the Philosophy of Science* 68 (2017) pp. 133-161.

Criticisms

P. Lewis, "On the Status of Primitive Ontology", to appear in S. Gao (ed.), *Collapse of the Wave Function* (Cambridge University Press, 2018). http://philsci-archive.pitt.edu/14421/

A. Ney and K. Phillips, "Does an adequate physical theory demand a primitive ontology?", *Philosophy of Science* 80 (2013) pp. 454-474.

M. Egg, "The physical salience of non-fundamental local beables", *Studies in History and Philosophy of Modern Physics* 57 (2017) pp. 104-110.

D. Wallace, "On the Plurality of Quantum Theories: Quantum theory as a framework, and its implications for the quantum measurement problem", S. French and J. Saatsi (eds.), *Scientific Realism and the Quantum* (Oxford University Press, forthcoming). Section 6.

The status of the quantum wavefunction in primitive-ontology approaches

The wavefunction is not mathematically eliminable from theories with primitive ontology; how are we to think of it?

T. Maudlin, "The nature of the quantum state", in A. Ney and D. Albert (eds.), *The Wave Function: Essays on the Metaphysics of Quantum Mechanics* (Oxford University Press, 2013).

S. Goldstein and N. Zanghi, "Reality and the Role of the Wavefunction in Quantum Theory", in A. Ney and D. Albert (eds.), *The Wave Function: Essays on the Metaphysics of Quantum Mechanics* (Oxford University Press, 2013). https://arxiv.org/abs/1101.4575

G. Belot, "Quantum states for primitive ontologies: a case study" *European Journal for Philosophy of Science* 2 (2012) pp. 67-83.

Humean approaches to the quantum wavefunction

Although the wavefunction cannot be mathematically eliminated, perhaps it can be eliminated from our metaphysics via a Humean conception of laws?

C. Callender, "One World, One Beable", *Synthese* 192 (2015) pp. 3153-3177.

H. Bhogal and Z. Perry, "What the Humean should say about entanglement", *Nous* 51 (2015) pp. 74-94.

M. Esfeld, "Quantum Humeanism, or: physicalism without properties", *Philosophical Quarterly* 64 (2014) p.256.

(*) N. Dewar, "La Bohume", *Synthese,* forthcoming. http://philsci-archive.pitt.edu/13235/