Philosophy of Physics, 2021-22

Two courses, this term and next, on
Philosophical aspects of QFT.
Roughly: flat spacetime is this term, while curved spacetime is next term.

Both courses are taught by:
Jeremy Butterfield (Trinity College); and
Bryan Roberts (Philosophy LSE);
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We aim to be in person in Meeting Room 5, but also recorded and so on Moodle soon after: NB Moodle also has videos of last year's ancestor course.

Bryan built the course website which is at:

https://personal.lse.ac.uk/robert49/teaching/partiii/

You can already download from there, cf. the button 'Introducing philosophy of physics':

1) a general reading list;
2) links to archive sources, e.g. *Pittsburgh*
and as background to 12 and 19 October sessions:
3) pdfs of 3 "quantum philosophy" classic papers by Schroedinger and Bell;
and
4) a pdf of superb 2019 paper by Landsman on functional analysis in quantum theory.

Office hours with me start at Thursday 14 October, 3.30; on Zoom, via the green button at the website.

Meet and greet: Wednesday 13 October 14.30 to 15.15 (so after first lecture); in marquee.

If you choose to do a Part III essay, it could be in Philosophy of Physics. Two or three will be offered ...
As an appetizer, details of previous essays follow ....

For discussion, Wednesday 6 October 2021:
Previous Years' Part III Essays for Philosophy of Physics:
with links to many essays, now uploaded to the Pittsburgh philosophy of science archive

This list comprises:
(i) last year's two essays, which relate to this year's course; then
(ii) four essays about quantum field theory, also relating to this year's course; then
(iii) three essays about the measurement problem (Kent, Landsman, decoherence); then
(iv) three essays about quantum foundations (Kochen-Specker, Everett, information); then
(v) two essays about spacetime (the hole argument, "matter vs. geometry")

1. Limits on relativistic quantum measurement . . . .

This essay lies at the interface of algebraic quantum theory and the description of quantum measurement, focussing on how they each describe measurement in the setting of Minkowski spacetime. Traditionally, the algebraic approach to quantum theory has an operational flavour, with description of measurement being mostly confined to the words, and not expressed in the formalism. In particular, algebraic quantum field theory traditionally associates to each bounded region of Minkowski spacetime an algebra of operators, whose self-adjoint elements are interpreted as the physical quantities that can be measured by an operation confined to the region in question. There was some, but not much, formal analysis of this operation, e.g. in the work of Hellwig and Kraus, and of Davies and Lewis. But recently, Fewster and Verch have given a detailed analysis along these lines, which includes a theorem expressing no-signalling, i.e. "good causal behaviour"—that spacelike correlations involve no superluminal causation. For this literature, one can begin with Fewster and Verch, in [1].
On the other hand: in 1993, Sorkin argued that assuming that arbitrary field-theoretic quantities could be measured would imply superluminal signalling; (which he took as a sign that the path-integral framework was fundamental). These ideas were developed by Beckman, Gottesmann, Preskill and co-authors: at first using ideas from quantum information theory; and then applying these ideas to the measurement of Wilson loop operators in

a gauge theory. A later analysis, again focussing on quantum information processing, is by Benincasa and co-authors. This literature is in [2].
Recently, two papers have addressed anew the topic of measurements that are "impossible" because they imply superluminal signalling—their results being apparently at loggerheads, even contradictory. Borsten and co-authors give a criterion for a measurement to be no-signalling, that implies strong limitations on what can be measured. Bostelmann and co-authors argue Sorkin's argument, i.e. his protocol for signalling, does not hold good in the Fewster-Verch framework. These papers are in [3].
The aim of the essay is to adjudicate—indeed, resolve!—this debate.

Relevant Courses

Essential: None
Useful: Quantum Field Theory, Philosophical Aspects of Quantum Field Theory, Quantum information theory

References

[1]: C. Fewster and R. Verch (2020), Quantum fields and local measurements, *Communications in Mathematical Physics* **378**, 851-889; available at https://arxiv.org/abs/1810.06512. This framework is summarized in: C. Fewster (2020), A generally covariant measurement scheme for quantum field theory in curved spacetimes, in F. Finster et al. (eds.) *Progress and Visions in Quantum Theory in View of Gravity*; available at https://arxiv.org/abs/1904.06944
[2]: R. Sorkin (1993), 'Impossible measurements on quantum fields', in B. Hu and T. Jacobson (eds.) *Directions in General Relativity*, volume II, p. 293-305; gr-qc:/9302018. D. Beckmann, D. Gottesmann, M. Nielsen and J. Preskill (2001), 'Causal and localizable quantum operations' *Physical Review* **A64** 052309, available at https://arxiv.org/abs/quant-ph/0102043. D. Beckmann, D. Gottesmann, A. Kitaev and J. Preskill (2002), 'Measurability of Wilson loop operators' *Physical Review* **D65** 065022, hep-th:/0110205. D. Benincasa, L. Borsten, M. Buck and F. Dowker (2014), 'Quantum information processing and relativistic quantum fields' *Classical and Quantum Gravity* **31** 075007, available at https://arxiv.org/abs/1206.5205
[3]: L. Borsten, I. Jubb and G. Kells (2019), Impossible measurements revisited, available at https://arxiv.org/abs/1912.06141. H. Bostelmann, C. Fewster and M. Ruep (2020), Impossible measurements require impossible apparatus, available at https://arxiv.org/abs/2003.04660

Done by J. Fuksa, R. King and T. van der Lugt; available at (respectively): http://philsci-archive.pitt.edu/19551/ ; http://philsci-archive.pitt.edu/19549/ ; http://philsci-archive.pitt.edu/19427/

2. Symmetry and symplectic reduction ....

Symplectic reduction is a large subject in both classical and quantum mechanics. One starts from Noether's theorem in a classical Hamiltonian framework, and thereby the ideas of: Lie group actions; the co-adjoint representation of a Lie group G on the dual $\mathfrak{g}^*$ of its Lie algebra $\mathfrak{g}$; Poisson manifolds (a mild generalization of symplectic manifolds that arise when one quotients under a symmetry); conserved quantities as momentum maps. With these ideas one can state the main theorems about symplectic reduction. Main texts for this material include [1].

The flavour of these theorems is well illustrated by the *Lie-Poisson* reduction theorem. It concerns the case where the natural configuration space for a system is itself a Lie group G. This occurs both for the pivoted rigid body and for ideal fluids. For example, take the rigid body to be pivoted, so as to set aside translational motion. This will mean that the group G of symmetries defining the quotienting procedure will be the rotation group SO(3). But it will also mean that the body's configuration space is given by $G = \mathrm{SO}(3)$, since any configuration can be labelled by the rotation that obtains it from some reference-configuration. So in this example of symplectic reduction, the symmetry group acts on itself as the configuration space. Then the theorem says: the quotient of the natural phase space (the cotangent bundle on G) is a Poisson manifold isomorphic to the dual $\mathfrak{g}^*$ of G's Lie algebra. That is: $T^*G/G \cong \mathfrak{g}^*$. There are several 'cousin' theorems, such as the *Marsden-Weinstein-Meyer* theorem. For a philosopher's exposition of the Lie-Poisson reduction theorem, cf. [2].

The essay should, starting from this basis, expound one or other of the following two topics. (Taking on both would be too much.)

(A): The first topic is technical and concerns the application of these classical ideas to quantum theory: more specifically, the interplay between reduction and canonical quantization. Physically, this is a large and important subject, since it applies directly to some of our fundamental theories, such as electromagnetism and Yang-Mills theories. The essay can confine itself to the more general aspects: which are well introduced and discussed by Landsman and Belot; [3].

(B): The second topic is more philosophical. It concerns the general question under what circumstances should we take a state and its symmetry-transform to represent the same state of affairs—so that quotienting under the action of the symmetry group gives a non-redundant representation of physical possibilities? This question can be (and has been) discussed in a wholly classical setting. Indeed, the prototype example is undoubtedly the question debated between Newton (through his *ammanuensis* Clarke) and Leibniz: namely—in modern parlance—whether one should take a solution of, say, Newtonian gravitation for N point-particles and its transform under a Galilean transformation to represent the same state of affairs. This topic is introduced by the papers in [4]. In particular, Dewar discusses how, even when we are sure that a state and its symmetry-transform represent the same state of affairs, quotienting can have various disadvantages.

Relevant Courses

Essential: None
Useful: Symmetries, Fields and Particles; Philosophical Aspects of Quantum Field Theory.

References

[1]: R. Abraham and J. Marsden (1978), *Foundations of Mechanics*, second edition: Addison-Wesley; V. Arnold (1989), *Mathematical Methods of Classical Mechanics*, Springer, (second edition); J. Marsden and T. Ratiu (1999), *Introduction to Mechanics and Symmetry*, second edition: Springer-Verlag.
[2]: J. Butterfield (2006) On Symmetries and Conserved Quantities in Classical Mechanics, in W. Demopoulos and I. Pitowsky (eds.), *Physical Theory and its Interpretation*, Springer; 43 - 99; Available at: http://arxiv.org/abs/physics/0507192; J. Butterfield (2006). On Symplectic Reduction in Classical Mechanics, in J. Earman and J. Butterfield (eds.) *The Handbook of Philosophy of Physics*, North Holland; 1 - 131. Available at: http://arxiv.org/abs/physics/0507194.
[3]: G. Belot (1998), 'Understanding electromagnetism', *British Journal for the Philosophy of Science* **49**, p. 531-555; G. Belot (2003), 'Symmetry and gauge freedom', *Studies in History and Philosophy of Modern Physics* **34** 189-225;
N. Landsman (2006), 'Between Classical and Quantum', Section 4. in J. Earman and J. Butterfield (eds.) *The Handbook of Philosophy of Physics*, North Holland; 1 - 131. Available at: http://arxiv.org/abs/physics/0507194.
N. Landsman (2017). *Foundations of Quantum Theory*: Sections 5.6-5.12. Springer. Open access: downloadable at: https://link.springer.com/book/10.1007/978-3-319-51777-3
[4]: Four papers by G. Belot: (2000), 'Geometry and motion', *British Journal for the Philosophy of Science* **51**, p. 561-596; (2001), 'The principle of sufficient reason', *Journal of Philosophy* **98**, p. 55-74; (2003), 'Notes on symmetries', in Brading and Castellani (ed.s) (2003), pp. 393-412. (2013), 'Symmetry and equivalence', in R. Batterman (ed.), *Oxford Handbook of Philosophy of Physics* Oxford University Press, 2013. All Belot papers are available at:

https://sites.google.com/site/gordonbelot/home/papers-etc
Caulton, A. (2015). 'The Role of Symmetry in the Interpretation of Physical Theories'. *Studies in History and Philosophy of Modern Physics*, **52**, pp. 153-162. N. Dewar (2017) 'Sophistication about symmetries', *British Journal for the Philosophy of Science*: available at: https://academic.oup.com/bjps/advance-article-abstract/doi/10.1093/bjps/axx021/4111183

Done by M. O'Callaghan; available at: http://philsci-archive.pitt.edu//19515/

3. Bell correlations in quantum field theory ....

'Bell correlations' means the violation of Bell-type inequalities, which is the hallmark of quantum non-locality. A rich context for analysing non-locality is provided by the algebraic approach to quantum field theory (AQFT: [1], Chapters 1, 2 and 4; [2] Part III, pp. 105-148): for the basic idea is to associate with each bounded region $\mathcal{O}$ of Minkowski spacetime an algebra $\mathcal{A}(\mathcal{O})$ of operators, of which a self-adjoint element $A \in \mathcal{A}(\mathcal{O})$ represents a physical quantity pertaining to that part of the field system lying in $\mathcal{O}$, that is measurable by a procedure confined to $\mathcal{O}$. In fact, the violation of Bell inequalities in AQFT is now known to be "generic", as regards the choices of regions $\mathcal{O}$, and of quantities A, and of states. Results up to 1990 (by authors such as Landau, Summers and Werner) are reviewed in [3]. Clifton and Halvorson give further results in [4]; and in [5], they discuss the prospects for "peaceful coexistence" between quantum non-locality and relativity theory's requirement of no action-at-a-distance. These prospects are further explored in [6]. The purpose of the essay will be to review these developments.

Relevant Courses

Essential: None
Useful: Quantum Field Theory, Philosophy of Physics

References

[1] H. Araki, *Mathematical Theory of Quantum Fields*, Oxford University Press, 1999.

[2] R. Haag, *Local Quantum Physics: Fields, Particles, Algebras*, Springer, 1992.

[3] S. Summers, On the independence of local algebras in quantum field theory, *Reviews in Mathematical Physics* **2** (1990), pp. 20-247.

[4] R. Clifton and H. Halvorson, 'Generic Bell correlation between arbitrary local algebras in quantum field theory', *Journal of Mathematical Physics*, **41**, (2000), 1711-1717; available at: http://uk.arxiv.org/abs/math-ph/9909013.

[5] R. Clifton and H. Halvorson, 'Entanglement and Open Systems in Algebraic Quantum Field Theory', *Studies in History and Philosophy of Modern Physics*, **32**, (2001), 1-31; available at: http://uk.arxiv.org/abs/quant-ph/0001107.

[6] J. Butterfield, 'Stochastic Einstein Locality Revisited', *British Journal for the Philosophy of Science*, **58**, 2007, 805-867; available at: http://uk.arxiv.org/abs/0708.2192; and at: http://philsci-archive.pitt.edu/archive/00003468/

Done by T. Leung and G. Thiang; latter available at: http://philsci-archive.pitt.edu/8689

4. Localization in relativistic quantum theories . . . .

Ever since the work of Newton and Wigner [1], it has seemed impossible to identify localized statevectors or position operators in Lorentz-invariant quantum theories that were not counter-intuitive in some way: the most striking feature being superluminal propagation of the localized states. The topic remains controversial. On the one hand, there are no-go theorems forbidding localization in certain senses, e.g. [2]. On the other hand, other authors argue that denying these theorems' assumptions allows coherent, and even physically significant, notions of localization [3,4]. The purpose of the essay will be to review these developments.

Relevant Courses

Essential: None
Useful: Quantum Field Theory, Philosophy of Physics

References

[1] T. Newton and E. Wigner, Localized states for elementary systems, *Reviews of Modern Physics* **21**, 400-406.

[2] R. Clifton and H. Halvorson, No place for particles in relativistic quantum theories?, *Philosophy of Science* **69**, 2002, 1-28; reprinted in J. Butterfield and H. Halvorson (eds.) *Quantum Entanglements: Selected papers of Rob Clifton* O.U.P., 2004, pp.225-262.

[3] G. Fleming and J. Butterfield, Strange Positions, in J. Butterfield and C. Pagonis (eds.) *From Physics to Philosophy*, C.U.P., 1999, pp. 108-165; (especially pp. 108-131, and 153 et seq.)

[4] G. Fleming, Observations on Hyperplanes: II. Dynamical Variables and Localization Observables, available on the Pittsburgh Philosophy of Science e-archive:http://philsci-archive.pitt.edu/archive/00002085/

Done by: V. Assassi, D. Schroeren, and L Herrmann; the latter is available at: http://philsci-archive.pitt.edu/5427/

5. Philosophical aspects of spontaneous symmetry breaking.

Spontaneous symmetry breaking (SSB) within quantum field theory (QFT) has been central to our understanding of many phenomena in condensed matter physics, elementary particle physics and cosmology. Masterly introductions to the physics include [1,2]. A fine introduction to the philosophical issues is [3, 4]. The philosophical literature on SSB has emphasized the rigorous, algebraic approach to quantum field theory, as against more heuristic formalisms; for example [5,6,7]. Accordingly, the purpose of this essay is to conceptually examine SSB in QFT.

Relevant Courses

Essential: None
Useful: Quantum Field Theory, Advanced Quantum Field Theory, Philosophical Foundations of Quantum Field Theory

References

[1] E. Witten, From Superconductors and four-manifolds to weak interactions, *Bulletin-American Mathematical Society* **44** (2007), pp. 361391.

[2] S. Weinberg. *The Quantum Theory of Fields*, Vol II. Cambridge University Press 1996. Chapters 19, 21.

[3] J. Earman. Laws, symmetry, and symmetry breaking: Invariance, conservation principles, and objectivity. *Philosophy of Science*, **71** (2004), pp. 1227-1241.

[4] J. Earman. Rough guide to spontaneous symmetry breaking, in K. Brading and E. Castellani (eds.) *Symmetries in Physics: Philosophical Reflections*, Cambridge University Press, 2003.

[5] L. Ruetsche. *Interpreting Quantum Theories.* Oxford University Press, 2011. Chapters 12, 13 and 14.

[6] C. Liu and G. Emch. Explaining quantum spontaneous symmetry breaking. *Studies in History and Philosophy of Modern Physics*, **36** (2005), pp. 137-163.

[7] D. Baker and H. Halvorson. How is spontaneous symmetry breaking possible? Available online at: http://philsci-archive.pitt.edu/8517/

Done by: S. van Dam, S. Rivat, and G. Schwarz. They are available at, respectively: http://philsci-archive.pitt.edu/9295/ ;
http://philsci-archive.pitt.edu/9161/ ; http://philsci-archive.pitt.edu/9303/

6. Pilot-wave theory and quantum fields ....

One approach to solving the measurement problem in quantum theory proposes that a certain quantity Q is 'preferred' in that a quantum system always has a definite value for it. So Q needs to be chosen so that:
(i) its definite values appropriately explain the definiteness of the macro-realm, and this will presumably involve equations of motion fo rthe values that mesh suitably with the quantum state's unitary evolution;
(ii) its definite values do not violate various no-go theorems such as the Kochen-Specker theorem.

The best-developed example is the pilot-wave approach of de Broglie and Bohm [1, 2]. This approach can be adapted to field theories: indeed, Bohm's original paper [3] gave a pilot-wave model of the electromagnetic field. In general, the approach faces difficulties in constructing models that are relativistic in a more than phenomenological sense. But recently there has been considerable progress, and clarification of the various options: both for particle ontologies [4] and for field ontologies [5].

The purpose of the essay will be to review these developments.

Relevant Courses

Essential: None
Useful: Quantum Field Theory, Philosophy of Physics

References

[1] P. Holland, *The Quantum Theory of Motion*, C.U.P. 1993.

[2] D. Bohm and B. Hiley, *The Undivided Universe*, Routledge 1992.

[3] D. Bohm (1952), A hidden variable interpretation ..., Part II, *Physical Review* **85**, 180.

[4] S. Colin and W. Struyve (2007), A Dirac sea pilot-wave model for quantum field theory, *Journal of Physics A*, **A40** 7309-7342; arXiv: quant-ph:0701085.

[4] W. Struyve (2010), Pilot-wave theory and quantum fields, *Reports on Progress* , 7309-7342; arXiv: quant-ph:0707.3685.

Done by M. Lienert and available at: http://philsci-archive.pitt.edu/8710/

Now I turn to: some previous Essays in Philosophy/Foundations of Quantum Theory

7. Kent's relativistic solution to the quantum measurement problem . . . .

Kent has proposed, in three recent papers [1], a philosophically realist solution to the quantum measurement problem, that is distinctive in being: (i) relativistic, unlike the pilot-wave theory and dynamical reduction models (in most versions), yet (ii) 'one-world' (unlike the Everett interpretation). The key idea is to choose as a preferred quantity (or 'beable' in John Bell's terminology) the electromagnetic stress-energy distribution on a late-time hypersurface: which one thinks of as registering the arrival on the hypersurface of photons that have scattered off macroscopic bodies at earlier times, so that the stress-energy distribution records the positions of those bodies (including in particular, the positions of pointers on measurement apparatuses). Thus Kent proposes that the actual values of this late-time beable make definite: (i) the values of stress-energy at appropriate earlier spacetime points (by orthodox quantum correlations between the two regions); and thus also (ii) the values of quantities like the position of the centre-of-mass of macroscopic bodies. The aim of the essay is to assess, and if possible develop, this proposal.

There are three natural topics to be addressed:

(A): *Development*: Kent describes various alternative versions of the proposal. He also gives, especially in his second and third papers, toy-models which illustrate how the proposal works. Some of these models use the formalism of photon wave mechanics, as developed by Bialynicki-Birula, Sipe and others. So it is natural to investigate these alternatives, and to develop these models.

(B): *Comparison*: It is natural to compare Kent's proposal with other programmes for solving the measurement problem. The most obvious comparison is with the pilot-wave theory (e.g. [2]), since it also selects a preferred quantity (in most versions, the positions of point-particles) and retains orthodox quantum theory's unitary evolution.

(C): *Non-locality*: It is natural to ask how Kent's framework describes quantum nonlocality: in particular, to ask what are its verdicts for the various locality conditions that are distinguished in the foundational literature. Two well-known conditions are Outcome Independence and Parameter Independence (in Shimony's terminology [3]). Butterfield argues that Kent's proposal violates Outcome Independence (a verdict that agrees with orthodox quantum theory; cf. [3]). But he also argues that the verdict about Parameter Independence remains open: and that settling the matter, for example by giving a toy-model of a Bell experiment, would give an interesting application of two important recent theorems: one by Colbeck, Renner and Landsman [4], and one by Leegwater [5].

Relevant Courses

Essential: None

Useful: Philosophical aspects of quantum field theory.

References

[1]: A. Kent: (1): Solution to the Lorentzian quantum reality problem, *Physical Review A* **90**, 012107; arxiv: 1311.0249; (2014). (2): Lorentzian quantum reality: postulates and toy models, *Philosophical Transactions of the Royal Society A* **373**, 20140241; arxiv: 1411.2957; (2015). (3): Kent, A.: Quantum reality via late time photodetection; arxiv: 1608.04805 (2016).

[2]: P. Holland: *The Quantum Theory of Motion*, C.U.P. 1993; D. Bohm and B. Hiley, *The Undivided Universe*, Routledge 1992.
[3] A. Shimony: (1) Controllable and uncontrollable nonlocality. In: Kamefuchi , S. et al. (eds) *Foundations of Quantum Mechanics in the Light of New Technology*, Tokyo: Physical Society of Japan (1984). (2): Bell's theorem, in *The Stanford Encyclopedia of Philosophy.* Available at: https://plato.stanford.edu/entries/bell-theorem/ (2009).
J. Butterfield: Peaceful Coexistence: examining Kent's relativistic solution to the quantum measurement problem; http://arxiv.org/abs/1710.07844; http://philsci-archive.pitt.edu/14040; forthcoming in *Proceedings of the Nagoya 2015 Conference on Foundations of Quantum Theory*, ed. M.Ozawa et al., Springer.
[4] R. Colbeck and R. Renner: (1) No extension of quantum theory can have improved predictive power, *Nature Communications* **2**, 411. http://dx.doi.org/10.1038/ncomms1416 (2011). (2) The completeness of quantum theory for predicting measurement outcomes, arxiv:1208.4123 (2012).
N. Landsman: (1) The Colbeck-Renner theorem, *Journal of Mathematical Physics* **56**, 122103; (2015). (2): *Foundations of Quantum Theory*, (Chapter 6.6) Springer 2017: freely downloadable anywhere, as a whole, or Chapter by Chapter, from https://link.springer.com/book/10.1007/978-3-319-51777-3
[5]: G. Leegwater: An impossibility theorem for parameter independent hidden variable theories, *Studies in the History and Philosophy of Modern Physics*, **54** 18-34; http://philsci-archive.pitt.edu/12067/; (2016).

Done by: B. Marsh and S. Crawford: available on request from JNB.

8. Spontaneous symmetry breaking and quantum measurement . . . .

Spontaneous symmetry breaking (SSB)—roughly speaking, a system's ground state (or equilibrium state at a low enough temperature) not being invariant under a symmetry of the laws—is a very large subject, with many aspects. The foundational and philosophical literature tends to discuss SSB using algebraic formulations of quantum theory, which are well adapted to treating rigorously quantum systems with infinitely many degrees of freedom (such as in quantum field theory and quantum statistical mechanics). In this framework, SSB is a matter of unitarily inequivalent representations of the relevant algebra: cf. e.g. [1].
Recently, Landsman (and coauthors) has used such formulations to analyse spontaneous symmetry breaking in quantum measurement processes. This

work represents the quantum measurement problem as an example of the impossibility of SSB in a finite quantum system, i.e. one with finitely many degrees of freedom: such as the systems of interest in a measurement process. Landsman describes how the appropriate limit (as $\hbar \to 0$, or the number N of degrees of freedom goes to infinity) of the ground state (or equilibrium state at a low enough temperature) of such a system is mixed—and does not display the SSB we actually see. He proposes a solution based on the idea that perturbations prevent the bad limiting behaviour, and yield SSB of the appropriate kind in a finite system. The first paper takes a toy model of measurement using a double-well potential [2]; the second considers spin-chains (Ising and Curie-Weisz) [3]. These analyses also show how a classical system, i.e. a commutative algebra of observables, can be a rigorous limit of a sequence of quantum systems (non-commutative algebras): a large theme that is dubbed *asymptotic Bohrification* in Landsman's review [4], and book [5]. The overall view is well summarized in Chapter 11 of [5].

There are various natural questions about this proposal that can be pursued. There are 'external' questions, e.g. about its conception of what the measurement problem really is, and about comparison with other models of measurement (Landsman favours that of Spehner and Haake, e.g. [6]). There are also 'internal' questions. These tend to focus on how best to couple the perturbation that yields the appropriate 'collapsed' state in the apparatus to the measured quantity on the measured system—and how to make the statistics of the perturbation sensitive to the amplitudes, in the system's state, for the various eigenvalues of that quantity. Such questions have been pursued by van Heugten and Wolters [7]. So the aim of the essay is to assess this framework for understanding SSB, and-or for understanding quantum measurement.

Relevant Courses

Essential: None
Useful: Quantum field theory, Statistical field theory, Philosophical aspects of quantum field theory.

References

[1]: F. Strocchi. *Symmetry Breaking*, Lecture Notes on Physics 643 (Springer Berlin Heidelberg 2008); L. Ruetsche *Interpreting Quantum Theories* O.U.P. (2011), Chapters 12-14; D. Baker and H. Halvorson, How is spontaneous symmetry breaking possible? Understanding Wigner's theorem in light of unitary inequivalence, *Studies in the History and Philosophy of Modern Physics* **44**, 464-469 (2013).
[2] N. Landsman and R. Reuvers, A flea on Schrödinger's Cat, *Foundations of Physics* **43** 373407 (2013)

[3] N. Landsman, Spontaneous symmetry breaking in quantum systems: Emergence or reduction? *Studies in History and Philosophy of Modern Physics* **44**, 379394 (2013).
[4] N. Landsman, Bohrification: From classical concepts to commutative algebras. To appear in Faye, J. and Folse, J. (eds.) *Niels Bohr and Philosophy of Physics: Twenty-First Century Perspectives*, London: Bloomsbury; (2017) arXiv:1601.02794.
[5] N. Landsman, *Foundations of Quantum Theory*, Springer 2017: freely downloadable anywhere, as a whole, or Chapter by Chapter, from https://link.springer.com/book/10.1
3-319-51777-3
[6] D. Spehner and F. Haake, Quantum measurements without macroscopic superpositions. *Physical Review A* **77**, 052114 (2008).
[7] J. van Heugten and S. Wolters, Obituary for a flea, *Proceedings of the Nagoya Winter Workshop 2015: Reality and Measurement in Algebraic Quantum Theory*, to appear. Ozawa, M., et al. (ed.) arXiv:1610.06093.

Done by: L. Den Daas: available at: http://philsci-archive.pitt.edu/15056/

9. Decoherence and the Quantum Measurement Problem . . .

The physics of decoherence is a well-established and multi-faceted subject. Joos et al, and Schlosshauer [1, 2] give fine reviews. But there remains controversy about whether it solves the problem (or better: all the problems!) of quantum measurement [3,4]. In particular: what further interpretative postulate is needed to give a unique outcome to a quantum measurement? The purpose of the essay will be to review these developments.

Relevant Courses

Essential: None
Useful: Quantum Information, Entanglement and Nonlocality, Philosophy of Physics

References

[1] E. Joos et al., *Decoherence and the appearance of the classical world in quantum theory*; Springer 2003.

[2] M. Schlosshauer, *Decoherence and the quantum to classical transition*, Springer 2008.

[3] N. Landsman, 'Between Classical and Quantum', in J. Earman and J. Butterfield eds., *Handbook of the philosophy of science; volume II, philosophy of physics*, Elsevier Available online at http://philsci-archive.pitt.edu/archive/00002328/.

[4] H. Janssen, 'Reconstructing reality', Available online at http://philsci-archive.pitt.edu/archive/00004224

Done by: B. Hensen: available at: http://philsci-archive.pitt.edu/5439/

10. The Kochen-Specker and Conway-Kochen theorems..... Dr. Jeremy Butterfield

The Kochen-Specker theorem [1] gives tight constraints on how one could supplement orthodox quantum theory's assignment of values to physical quantities. In foundations of quantum theory, it has had a large legacy. This essay considers just three strands. In approximate historical order, they are as follows.

(1): Bell's own proof [2] of a version of the theorem motivated his famous non-locality proof [3], which of course led to countless studies of how locality constrained such supplementations of orthodox quantum theory. For Bell's purpose in [3] was to ascertain whether any such supplementation, in order to replicate quantum mechanical statistics, must be Ônon-localÕ like the pilot-wave theory is. This went along with his advocacy [4] of the pilot-wave theory: which escapes the Kochen-Specker theorem, simply by not obeying its mathematical assumptions.
(2): Conway and Kochen [5] adapted some early 1980s theorems, which consider a spatially separated pair of spin 1 systems (not just one, as in the original Kochen-Specker theorem), to argue that these quantum mechanical systems showed a form of free will (!). This led to some rebuttals (unsurprisingly): but the recent analyses by Landsman et al. [6, 7] seem definitive.
(3): The Kochen-Specker theorem has various mathematical facets which have long been explored. For example, (A): one can ask what is the minimal number of quantities (specifically, projections) for which a proof can be given? And what about analogous theorems for multiple systems, or theorems where the argument depends on a choice of state? And (B): the theorem leads in to the general study of quantum contextuality, which can be cast in various general settings, for example topos theory (the initial paper being [8]). An up-to-date introduction to both (A) and (B), mostly via Mermin's 1990 proof of the Kochen-Specker theorem, is [9].

The aim of the essay is to review these developments. Though all three strands could be pursued, it is probably wise to restrict yourself to combining two strands, the natural pairs being: (1) and (2); or (1) and (3).

Relevant Courses

Essential: None
Useful: Philosophical aspects of quantum field theory

References

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Done by: C. Lu, A. Barbar and E. Jones-Healey

11. Probability in the Everett Interpretation . . . .

Many have believed that the Everett interpretation [1] of quantum theory has an insuperable problem about probability. Indeed, two problems!
(i) Probability makes no qualitative sense, since according to the Everett interpretation, *every* outcome of an [apparently indeterministic] quantum measurement (or other interaction that increases the number of components in the preferred basis) happens.
(ii) Probability makes no quantitative sense, since the interpretation's determinism prevents the Born-rule probabilities of the components of the final state having any significance.

Deutsch [2] argued that one could solve (i) and (ii) by adapting traditional ideas from rational decision theory. He showed that a rational agent in an Everettian world, subject to appropriate bets on measurement outcomes, would have to set her degrees of belief (which fixes her betting behaviour) equal to the Born-rule probabilities, on pain of being forced to lose money by a clever arrangement of bets. The theorem has since been developed and discussed, especially by Wallace [3,4,5].

But questions remain. In particular, for a person who is not yet an Everettian, the question arises: why should the requirements of rationality for an agent who knows she is in an Everettian world, have any bearing on my degrees of belief in measurement oucomes? Or on my degree of belief in the Everett interpretation? The purpose of the essay will be to review these developments.

Relevant Courses

Essential: None
Useful: Quantum Information, Entanglement and Nonlocality, Philosophy of Physics

References

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Done by: S. Dooley, G. Mikelsons and S. Nielsen; the last is available at http://philsci-archive.pitt.edu/5501/

12. Information-theoretic aspects of quantum foundations . .

The rise of quantum information theory has had an enormous impact on the way people address foundational and philosophical questions about quantum theory. As regards philosophy, at least three main developments can be discerned. One is the philosophical assessment [1, 2: Section 4.1.4] of recently discovered phenomena and protocols, such as teleportation [3]. A second is that interpretations of the quantum state as subjective [4, 5] or epistemic [6] have been re-invigorated; and there has of course been philosophical assessment of this [7, 8, 9]. A third development is the philosophical assessment [2: Section 4.4.2, 9] of axiomatic formulations that invoke information-theoretic principles, such as no-cloning, at their base [10, 11].

These three developments are of course inter-related. So the purpose of the essay will be to review one or two of them (i.e. according to whether the candidate wants to focus on their inter-relations).

Relevant Courses

Essential: None
Useful: Quantum Information Theory, Philosophy of Physics

References

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Essays about the first and second areas (but not the third) were done by J. Perczel, and by J. Lee respectively. Available on request.

Now I turn to: two previous Essays in philosophy of space and time

13. Einstein's hole argument and its legacy . . . .

Einstein devised his famous 'hole argument' in late 1913, as an argument against general covariance: namely, that any generally covariant theory would be radically indeterministic. Late in 1915, after he had found the field equations of general relativity, which are generally covariant, he re-assessed the argument as showing only that we should not think of spacetime points as objects, on pain of a radical indeterminism [4]. In physics, the legacy of this episode has been to recognize 'gauge-freedom' about 'which spacetime point is which' in formulations of general relativity, especially in its initial-value problem, much studied since the 1960s [1]. In philosophy, the legacy has been more recent: only since the late 1980s has the hole argument been centre-stage in discussions of 'absolute' vs. 'relational' aspects of general relativity [2, 3]. The purpose of the essay will be to review these developments.

Relevant Courses

Essential: None
Useful: General Relativity, Philosophy of Physics

References

[1] R. Wald: *General Relativity*, Chap.10, University of Chicago Press, 1984.

[2] J. Norton, Stanford Encyclopedia of Philosophy (on internet) article on Einstein's Hole Argument: http://www.seop.leeds.ac.uk/entries/spacetime-holearg/ ; which cites [3] and [4].

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Done by H. Goetzke and available at: http://philsci-archive.pitt.edu/8719/

14. Matter or geometry as fundamental in relativity theory

The relation between the dynamics of matter and radiation, and the geometric structure of space or spacetime, remains a controversial issue, even in well-established and well-understood theories such as relativity, both special and general. The broad central question is whether: (i) space or spacetime has an intrinsic geometric structure independent of matter and radiation (so that, for example, a wholly empty spacetime would have geometric structure) or (ii) geometric structure depends on the presence of matter and radiation, and is even perhaps determined by it. Of course, there are various ways to make these options precise, especially by different definitions of 'depends'.
Although the broad question goes back a long way (even to the debate between Newton and Leibniz), in recent decades the discussion of it—for familiar theories—has focused on three topics. The second and third concern special relativity. (a): The proposal for a relationist/Machian foundation for mechanics, and even field theory; even relativistic versions of these; and even for general relativity; [1, 2], discussed by e.g. [3]. (b) The proposal that in special relativity, spacetime structure is entirely a corollary of the dynamics of matter and radiation; [4, 5], criticized by [6, 7, 8]. (c) The proposal that simultaneity in special relativity is a matter of convention, despite its being uniquely definable from the causal structure; [9, 10].
The aim of the essay is to review at least two of these three developments.

Relevant Courses

Essential: None
Useful: General Relativity, Philosophy of classical and quantum mechanics

References

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Essays on topics (a) and (b) were done by K. O'Donnell and D. Hoving: the latter is available at: http://philsci-archive.pitt.edu/9737/