Reading List in Philosophy of Quantum Field Theory

David Wallace, September 2022

Introduction

This is a reasonably comprehensive reading list for contemporary topics in philosophy of quantum field theory (QFT), 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 make any attempt to discuss the history of QFT; I also ignore questions of the general epistemology of particle physics except where they clearly connect to QFT. I have also *mostly* confined this list to papers in the philosophy literature, and avoided extensive citations to physics review papers that I think are philosophically interesting (the main exceptions are in the effective field theory section).

To keep the task of compiling this list manageable, I've also had to make some fairly arbitrary calls about the boundaries of 'philosophy of QFT'. I ignore string theory despite its intimate connections with QFT; I include general relativity as a quantum field theory but ignore its applications to black hole statistical mechanics; I include the Unruh effect but not the Hawking effect; I ignore critical phenomena in the purely classical-statistical-mechanical context despite the very close ties between that topic and renormalization-group theory in QFT; I ignore gauge theory except in its specifically quantum-field-theoretic applications (so I leave out the Aharonov-Bohm effect, and discussion of the metaphysics of classical gauge theory).

Philosophy of QFT is a highly interconnected subject and some of my subdivisions involve fairly arbitrary choices. Under 'interconnections' in many sections, I try to give some indication of what connects to what. In most subsections I have marked on entry (or 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 inefficient.

A note on terminology

One central theme in the literature on QFT – both in philosophy of physics and in mathematics and physics proper – is the question of what formulation of QFT is appropriate. The substantial majority of physicists, including almost all those who are in the business of making empirical predictions, works with an approach to QFT based on a combination of canonical and path-integral methods, which takes a relatively relaxed attitude to mathematical rigor and often takes seriously the idea of a (usually underspecified) short-distance cutoff. A minority, mostly in mathematical physics and applied mathematics departments, have pursued an alternative approach that foregrounds mathematical rigor, though to date at the cost of much more limited interaction with experiment.

It is a somewhat vexed question what to *call* these two approaches. The former approach has sometimes been called 'heuristic' or 'perturbative' QFT, but these names are unnecessarily limiting – the theories in question are conceptually very deep, make astonishingly accurate predictions, and cannot simply be reduced to their perturbative expansions in specific contexts. In my own work I have sometimes referred to 'cutoff' or 'Lagrangian' QFT, but in both cases this makes substantive claims about the details of these QFTs which could be challenged without leaving the overall framework. One could refer to 'mainstream' or 'conventional' QFT and be on firm grounds at least sociologically, but that terminology might be unintentionally seen as derogatory to the alternative. As for the second approach, it is normally called `algebraic' QFT (or AQFT), but this conflates a (granted, dominant) tradition in that approach with the whole approach, and elides the presence of the axiomatic and constructive QFT programs. In the end I have chosen to name these approaches after their main disciplinary locations, and refer respectively to 'theoretical-physics' and 'mathematical-physics' approaches to QFT.

A note on electronic resources

Almost every article I cite here can be found online, albeit sometimes only in preprint form. Where I'm aware of a book chapter preprint on one of the major archives I have given a link, but I have not attempted to be exhaustive.

Learning quantum field theory: theoretical-physics style

There is a fairly sharp (and philosophically significant) divide between QFT in the form used by *theoretical* physicists, and QFT in the form used by *mathematical* physicists. Accordingly I have split this section into two parts. Sources in the first part are normally written in physicists' style, with a focus on calculational methods and on the connection to experiment and with a relatively casual attitude to mathematical rigor; sources in the second part are normally written in mathematicians' style, with an emphasis on proof over calculation or experiment and a generally-high level of rigor. This is *not* simply a matter of style: the two communities are largely discussing different theories, whose relationship with one another is philosophically and mathematically contested.

General introductions

There are dozens of textbooks on QFT; this list represents my own preferences, which may not be yours. They are listed in rough order of difficulty.

- David Griffiths, *Introduction to Elementary Particles* (Harper and Row, 1987). This isn't a QFT textbook, it's an introduction to particle physics that stops just short of formal QFT but gives a good overview of the Standard Model, along with heuristic explanations of various QFT topics like gauge theory, quark confinement, and symmetry breaking.
- Michael E.Peskin and Daniel V.Schroeder, *An introduction to Quantum Field Theory* (Addison-Wesley,1995). The nearest there is to a standard introductory text; I like it but my experience is that lots of philosophers find it confusingly organized.
- Mark Srednicki, *Quantum Field Theory* (Cambridge University Press, 2007). Covers fairly similar material to Peskin and Schroeder but in a quite different style (and order).
- Anthony Zee, *Quantum Field Theory in a Nutshell* (Princeton University Press, 2010). Organized around the path integral; less focus on calculational methods than Peskin and Schroeder; idiosyncratic but insightful.
- Ta-Pei Cheng and Ling-Fong Li, *Gauge Theory of Elementary Particle Physics* (Oxford University Press, 1984). You could probably use this as an introduction to general QFT, though its focus is on gauge theory in the standard model.
- Thomas Banks, *Modern Quantum Field Theory: A Concise Introduction* (Cambridge University Press, 2008). Dense but clear.

More advanced general books

These are books that I think would be difficult if you haven't already encountered QFT, but are good for going beyond the basics.

- Steven Weinberg, *The Quantum Theory of Fields,* volumes I and II (Cambridge University Press, 1995/1996). Volume II in particular is the best reference I know on modern QFT. The first part of Volume I is a good source for scattering theory and the representation theory of the Poincare group.
- Tony Duncan, *The Conceptual Framework of Quantum Field Theory* (Oxford University Press, 2012). A beautiful book and the closest I know to a really conceptually careful presentation of QFT, but again I think it would be difficult as a first introduction.
- Jean Zinn-Justin, *Quantum Field Theory and Critical Phenomena*, 4th edition (Oxford University Press, 2002). Advanced reference focused on the common aspects of QFT and critical phenomena; some discussion of finite-temperature field theory.

- Pierre Deligne *et al* (eds.), *Quantum Fields and Strings: A Course for Mathematicians,* volumes I and II (American Mathematical Society, 2000). Edited and revised proceedings of an intensive school aimed at getting mathematicians up to speed with modern QFT. Much is concerned with quite specialist topics, but the articles by Gross on the renormalization group and by Witten (x2) on perturbative QFT and on the dynamics of QFT are valuable. (Preliminary versions are online at https://www.math.ias.edu/QFT .)
- Sidney Coleman, *Aspects of Symmetry* (Cambridge University Press, 1985). Somewhat older but deeply insightful collection of lectures, covering symmetries in QFT broadly construed. Especially useful for anomalies, spontaneous symmetry breakdown, and instantons.
- John F. Donoghue, Eugene Golowich, and Barry R.Holstein, *Dynamics of the Standard Model*, 2nd edition (Cambridge University Press, 2014). The standard (so to speak) reference on the Standard Model; technically demanding.
- Joseph I. Kapusta and Charles Gale, *Finite-Temperature Field Theory Principles and Applications,* 2nd edition (Cambridge University Press, 2006). A standard reference on finite-temperature field theory, concentrated on high-energy physics applications.
- Alexander Altland and Ben Simons, *Condensed Matter Field Theory*, 2nd edition (Cambridge University Press, 2010). Standard text on QFT methods in condensed-matter physics; also discusses finite-temperature methods.

Learning quantum field theory: mathematical-physics style

I know this territory less well myself, so my choice of references is accordingly less informed.

Axiomatic QFT

The older 'axiomatic' approach to mathematically rigorous quantum field theory starts with the standard (Hilbert-space) formulation of quantum mechanics.

- Raymond F. Streater and Arthur S.Wightman, *PCT, Spin and Statistics, And All That* (W.A.Benjamin, 1964). A classic presentation; much of the book is concerned with the formal material to prove the PCT and spin-statistics theorems, but chapters 1 and 3 comprise a good introduction. (Chapter 1 is also a good run-down on Lorentz-covariant QM, applicable in both 'styles' of QFT.)
- Rudolf Haag, *Local Quantum Physics: Fields, Particles, Algebras*, 2nd edition (Springer, 1996), ch.2
- David Kazdhan, "Introduction to QFT", in Pierre Deligne *et al* (eds.), *Quantum Fields and Strings: A Course for Mathematicians,* volumes I and II (American Mathematical Society, 2000). Also available (in preliminary form) at https://www.math.ias.edu/QFT/fall/index.html .

Algebraic QFT: introductions

Axiomatic QFT has largely been superseded by algebraic QFT (AQFT), which replaces the Hilbert space foundation with a more abstract presentation associating C*-algebras with regions of spacetime.

- Laura Ruetsche, *Interpreting Quantum Theories* (Oxford University Press, 2011), chapters 3-5. A conceptually-focused introduction to AQFT aimed at philosophers.
- Detlev Buchholz, *Algebraic Quantum Field Theory: A Status Report,* arXiv:math-ph/0011044. A short introductory review.

Algebraic QFT: more detailed presentations

- Rudolf Haag, *Local Quantum Physics: Fields, Particles, Algebras*, 2nd edition (Springer, 1996). Although Haag discusses axiomatic QFT, his focus is very much on AQFT.
- Hans Halvorson and Michael Mueger, “Algebraic Quantum Field Theory”, arXiv:math-ph/0602036. A long (200-page) review article ‘with an orientation towards foundational topics’.

Constructive QFT

Constructive QFT aims (with only partial success thus far) to use mathematically rigorous methods to reconstruct modern renormalization-group methods of QFT construction.

- Arthur Jaffe, “Constructive Quantum Field Theory”, *Mathematical Physics* 2000, (2000) pp.111-127. Brief review.

Review articles and other general sources for philosophy of QFT

Philosophy of QFT has evolved quite rapidly, and so I separate sources here into three periods.

1980s/1990s philosophy of QFT

In this period philosophy of QFT had not really developed as a separate subject, and very few philosophers of physics were sufficiently familiar with QFT to consider its philosophy. The style of QFT studied in this period is primarily mainstream 'physics' QFT, though sometimes in a fairly simplistic form (and the lessons of the renormalization group and effective field theory were only beginning to spread through physics proper at the time, and so were not much picked up by philosophers). Much of the work done in this period can be found in three collections:

- Harvey Brown and Rom Harre (eds.), *Philosophical Foundations of Quantum Field Theory* (Oxford University Press, 1988). See in particular the articles by Michael Redhead, James Cushing, and Paul Teller.
- Simon Saunders and Harvey R. Brown (eds.), *The Philosophy of Vacuum* (Oxford University Press, 1991).
- Tian Yu Cao (ed.), *Conceptual Foundations of Quantum Field Theory* (Cambridge University Press, 1999).

An important early paper was:

- Michael Redhead, "Quantum Field Theory for Philosophers", *PSA Proceedings* 1982, vol.2, pp.57-99.

I think the first book-length single-authored treatment of philosophy of QFT is

- Paul Teller, *An Interpretive Introduction to Quantum Field Theory* (Princeton University Press, 1997).

2000s philosophy of QFT

The turn of the century saw a large increase in philosophical interest in QFT. The bulk of new work in this period was carried out in the framework of algebraic quantum field theory, and as such became somewhat less connected with QFT as understood by the physics mainstream. Reviews of work in this tradition include:

- Laura Ruetsche, "Philosophical Aspects of Quantum Field Theory: I/II", *Philosophy Compass 7* 2012) pp.559-570, 571-584.
- Hans Halvorson and Michael Mueger, "Algebraic Quantum Field Theory", arXiv:math-ph/0602036. A long (200-page) review article, covering QFT itself but 'with an orientation towards foundational topics' and referencing most of the extant philosophy literature on AQFT.

Ruetsche's influential book, *Interpreting Quantum Theories* (Oxford University Press, 2011) also reviews much of the work in the algebraic tradition up to that point.

2010s/2020s philosophy of QFT

More recently, research in QFT has broadened, with increased interest in the mainstream (theoretical physics) tradition in physics and in its relation to the algebraic approach alongside continued exploration of philosophical topics in AQFT. Two recent reviews are:

- David Baker, "The philosophy of quantum field theory", (2016), in *The Oxford Handbook of Topics in Philosophy,* https://doi.org/10.1093/oxfordhb/9780199935314.013.33. A review article mostly from the AQFT perspective but touching on its relation with theoretical-physics QFT.
- David Wallace, "The quantum theory of fields", in Eleanor Knox and Alastair Wilson (eds.), *The Routledge Companion to Philosophy of Physics* (Routledge, 2022), pp.275-295; online copy at http://philsci-archive.pitt.edu/15296/ . A review article mostly from the theoretical-physics perspective.

Field and Particle

A central question in the philosophy of QFT has been: to what extent is field theory (especially in 'particle' physics) really a theory of particles at all? A variety of technical and conceptual pathologies suggest that particles are unreal or at any rate non-fundamental in QFT.

Interconnections

- Another important class of objections to particles is based on considerations from *inequivalent representations.*
- If the ontology of QFT is not a particle ontology, what is it? This is discussed by some of the papers on *the ontology of quantum field theory.*
- The apparent pathologies caused by Haag's theorem are related to broader interpretative questions about how to formulate QFT, discussed under *choice of framework.*

Overview

- Laura Ruetsche, "Is Particle Physics Particle Physics?", in *Interpreting Quantum Theories* (Oxford University Press, 2011), ch.9,
- (*) Doreen Fraser, "Particles in Quantum Field Theory", in Eleanor Knox and Alastair Wilson (eds.), *The Routledge Companion to Philosophy of Physics* (Routledge, 2022), pp.323-336.

Particle localization

Various no-go theorems seem to suggest that *localized* particles, in particular, cannot be defined in a Lorentz-covariant theory.

- Simon Saunders, "Locality, Complex Numbers, and Relativistic Quantum Theory", *PSA Proceedings* 1992 (1), 365-380.
- David B. Malament, "In Defense of Dogma: Why There Cannot Be a Relativistic Quantum Mechanics of (Localizable) Particles", in R. Clifton (ed.), *Perspectives on Quantum Reality* (Kluwer, 1996), 1-110.
- David Wallace, "Emergence of Particles in Bosonic Quantum Field Theory", arXiv:quant-ph/0112149 .
- (*) Hans Halvorson and Rob Clifton, "No Place for Particles in Relativistic Quantum Theories?", *Philosophy of Science* 69 (2002) 1-28.
- Jonathan Bain, "Quantum field theories in classical spacetimes and particles", *Studies in History and Philosophy of Modern Physics* 42 (2011) 98-106.

The Reeh-Schlieder Theorem

The Reeh-Schlieder theorem, a formal result of algebraic quantum field theory (though reflecting facts about the entanglement of the vacuum reproducible from other perspectives) creates further difficulties for any attempt to make sense of localizability in QFT.

- (*) Michael Redhead, "More Ado about Nothing", *Foundations of Physics* 25 (1995), 123-137.
- Gordon Fleming, "Reeh-Schlieder meets Newton-Wigner", *Philosophy of Science* 67 (2000), S495-S515.
- Hans Halvorson, "Reeh-Schlieder defeats Newton-Wigner: On alternative localization schemes in relativistic quantum field theory", *Philosophy of Science* 68 (2001) 111-133.

- Giovanne Valente, “Does the Reeh-Schlieder theorem violate relativistic causality?”, *Studies in History and Philosophy of Modern Physics* 48 (2014) 147-155.
- Giovanne Valente, “Recovering particle phenomenology”, *Studies in History and Philosophy of Modern Physics* 51 (2015) 97-103.

Haag’s Theorem

Haag’s theorem seems to imply that there can be no well-defined multiparticle scattering theory in QFT.

- Against Particle/Field Duality: Asymptotic states and interpolating fields in interacting QFT (or: Who’s afraid of Haag’s theorem?)”, *Erkenntnis* 53 (2000) 375-406.
- John Earman and Doreen Fraser, “Haag’s Theorem and its Implications for the Foundations of Quantum Field Theory”, *Erkenntnis* 64 (2006) 305-344.
- (*) Doreen Fraser, “The Fate of ‘Particles’ in Quantum Field Theories with Interactions, *Studies in History and Philosophy of Modern Physics* 39 (2008) 147-155.
- Anthony Duncan, “How to stop worrying about Haag’s theorem”, in *The Conceptual Framework of Quantum Field Theory* (Oxford University Press, 2012) 359-370.
- Michael E. Miller, “Haag’s Theorem, Apparent Inconsistency, and the Empirical Adequacy of Quantum Field Theory”, *British Journal for the Philosophy of Science* 69 (2015) 801-820.

Unitary Inequivalence and its Implications

In quantum theories with infinitely many degrees of freedom, algebraic and Hilbert-space definitions of observables come apart (they are essentially equivalent in systems with finitely many degrees of freedom, like N-particle quantum mechanics). The philosophical implications of this have been a major locus of debate in philosophy of AQFT.

Interconnections

- The papers on inequivalent notions of particle overlap with the discussion under *field and particle.*
- Some of the questions on theory interpretation overlap with those in *choice of framework* and *effective field theories and the renormalization group.*
- *Spontaneous symmetry breaking* provides one of the clearest sources of inequivalent representations.

General introduction

- Laura Ruetsche, "Johnny's So Long at the Ferromagnet", *Philosophy of Science* 73 (2006) 473-486.

(See also the general references on AQFT above, since this is a major theme of the AQFT literature.)

Algebraic vs Hilbert-Space definitions of equivalence

- (*) Laura Ruetsche, "Interpreting QM∞: Some Options", in *Interpreting Quantum Theories* (Oxford University Press, 2011), ch.6.
- Ben Feintzeig, "On the Choice of Algebra for Quantization", *Philosophy of Science* 85 (2018) 102-125.
- Tracy Lupher, "The Limits of Physical Equivalence in Algebraic Quantum Field Theory", *British Journal for the Philosophy of Science* 69 (2018) 553-576.

Inequivalent notions of particle

QFT seems to imply that different observers will use unitarily inequivalent representations to describe the particle content of a theory.

- Rob Clifton and Hans Halvorson, "Are Rindler Quanta Real? Inequivalent Particle Concepts in Quantum Field Theory", *British Journal for the Philosophy of Science* 52 (2001) 417-470..
- (*) Aristidis Arageorgis, John Earman and Laura Ruetsche (2003) "Fulling Non-uniqueness and the Unruh Effect: A Primer on Some Aspects of Quantum Field Theory", *Philosophy of Science* 70 (2003) 164-202.

Broader implications for theory interpretation

- Laura Ruetsche, *Interpreting Quantum Theories* (Oxford University Press, 2011), especially ch.15.
- (*) Simon Friederich (2012) "Pristinism under Pressure – Ruetsche on the Interpretation of Quantum Theories", *Erkenntnis* 78 (2013) 1205-1212.
- Hans Halvorson, "Ruetsche on the pristine and adulterated in quantum field theory", *Metascience* 22 (2012) 1-7.

- Steven French, "Unitary Inequivalence as a Problem for Structural Realism", *Studies in History and Philosophy of Modern Physics* 43 (2012) 121-136.
- Caspar Jacobs, "The Coalescence Approach to Inequivalent Representation: Pre- QM∞ Parallels", *British Journal for the Philosophy of Science,* forthcoming, https://doi.org/10.1086/715108 .

Inequivalent representations from the theoretical-physics perspective

- David Wallace, "In Defence of Naivete: The Conceptual Status of Lagrangian QFT", *Synthese* 151 (2006) 33-80, section 4.

Choice of framework: theoretical-physics vs. mathematical-physics approaches

A major theme of recent philosophy of QFT has been the question of which formulation of the theory is (most) appropriate for foundational and philosophical study.

Interconnections

This topic overlaps with almost all those discussed, but the strongest overlaps are with *effective field theories and the renormalization group*.

Readings

- Ray F. Streater, "Why Should Anyone Want to Axiomatize Quantum Field Theory", in Harvey R. Brown and Rom Harre (eds.), *Philosophical Foundations of Quantum Field Theory* (Oxford University Press, 1998), 137-148.
- David Wallace, "In defence of naivete: The conceptual status of Lagrangian quantum field theory", *Synthese* 151 (2006) 33-80.
- Edward MacKinnon, "The Standard Model as a Philosophical Challenge", *Philosophy of Science* 75 (2008) 447-457.
- (*) Doreen Fraser, "Quantum Field Theory: Underdetermination, Inconsistency, and Idealization", *Philosophy of Science* 76 (2009), 536-567. (Partially a reply to Wallace 2006).
- (*) David Wallace, "Taking Particle Physics Seriously: A Critique of the Algebraic Approach to Quantum Field Theory", *Studies in the History and Philosophy of Modern Physics* 42 (2011), 116-125. (Partially a reply to Fraser 2009).
- Meinard Kuhlmann, "Why Conceptual Rigour Matters to Philosophy: on the Ontological Significance of Algebraic Quantum Field Theory", *Foundations of Physics* 40 (2010) 1625-1637.
- Doreen Fraser, "How to take particle physics seriously: A further defence of axiomatic quantum field theory", *Studies in the History and Philosophy of Modern Physics* 42 (2011), 126-135. (Partially a reply to Wallace 2010.)
- Jonathan Bain, "Pragmatists and Purists on CPT Invariance in Relativistic Quantum Field Theories", http://philsci-archive.pitt.edu/9909 (2013).
- Matthias Egg, Vincent Lam and Andrea Oldofredi, "Particles, Cutoffs and Inequivalent Representations. Fraser and Wallace on Quantum Field Theory", *Foundations of Physics* 47 (2017) 453-466.
- Leif Hancox-Li, "Solutions in Constructive Field Theory", *Philosophy of Science* 84 (2017), 335-358.
- James Fraser, "The Real Problem with Perturbative Quantum Field Theory", *British Journal for the Philosophy of Science* 71 (2020), 391-413.

Effective field theory and the renormalization group

"Effective field theory", a way of thinking about QFT that embraces its non-fundamental, energy-level-relative nature and that developed in the 1970s and 1980s, is widely seen by theoretical physicists as revolutionizing our understanding of QFT. Philosophical work has concentrated on explicating the concept of effective field theory and the related idea of the 'renormalization group', and on exploring its significance for broader questions of emergence and scientific realism.

Interconnections

- Effective field theory is intimately connected to the *choice of framework* for QFT.
- *Gravity as an effective field theory* deals with the application of the effective-field-theory framework to general relativity.
- The effective-field-theory program has implications for *the ontology of QFT,* and its challenges to scientific realism overlap with those advanced by Ruetsche in her discussions of *inequivalent representations.*
- One of the main applications of effective-field-theory methods in physics is to *spontaneous symmetry breaking.*

Overviews by physicists

This is one place where I have included quite a number of papers by physicists, since this is one place where eminent physicists have commented extensively on interpretational matters.

- (*) Joseph Polchinski, "Effective field theory and the Fermi surface", arXiv:hep-th/9210046 (1992).
- David Gross, "The Triumph and Limitations of Quantum Field Theory", in T.Cao (ed.), *The Conceptual Foundations of Quantum Field Theory* (Cambridge University Press, 1999), 56-67; preprint at arXiv:hep-th/9704139 (1997).
- (*) Steven Weinberg, "What is quantum field theory, and what did we think it was?" in T.Cao (ed.), *ibid*, preprint at arXiv:hep-th/9702027 (1997).
- Sean Carroll, "The Quantum Field Theory on Which the Everyday World Supervenes", arXiv:2101.07884 (2021).

Overviews by philosophers

- Tian Yu Cao and Silvan Schweber, "The conceptual foundations and the philosophical aspects of renormalization theory". *Synthese* 97 (1993), 33-108.
- Nick Huggett and Robert Weingard, "The Renormalisation Group and Effective Field Theories", *Synthese* 102 (1995), 171-194.
- (*)Sebastien Rivat and Alexei Grinbaum, "Philosophical Foundations of Effective Field Theories", *European Physical Journal A* 56 (2020), 90.

Effective field theories, reduction, and emergence

- (*) Elena Castellani, "Reductionism, Emergence, and Effective Field Theories", *Studies in History and Philosophy of Modern Physics* 33 (2000), 251-267.
- Stephan Hartmann, "Effective field theories, reductionism and scientific explanation", *Studies in History and Philosophy of Modern Physics* 32 (2001), 267-304.
- Jonathan Bain, "Emergence in Effective Field Theories", *European Journal for Philosophy of Science* 3 (2013), 257-273.

- Karen Crowther, “Decoupling Emergence and Reduction in Physics”, *European Journal for Philosophy of Science* 5 (2015), 419-445.
- Alexander Franklin, “Whence the effectiveness of effective field theories?”, *British Journal for the Philosophy of Science* 71 (2020), 1235-1239.

Effective field theories and scientific realism

- (*) Porter Williams, “Scientific Realism Made Effective”, *British Journal for the Philosophy of Science* 70 (2019), 209-237.
- James Fraser, “Towards a Realist View of Quantum Field Theory”, in S.French and J.Saatsi (eds.), *Scientific Realism and the Quantum* (Oxford University Press, 2020), 276-292.
- Laura Ruetsche, “Perturbing Realism”, in S.French and J.Saatsi, *ibid*, 293-304.
- Sebastien Rivat, “Effective Theories and Infinite Idealizations: a challenge for scientific realism”, *Synthese* 198 (2021), 12107-12136.

The renormalization group

The renormalization group is at the same time a key technical tool in understanding effective field theory, and a centerpiece of our modern methods for taming infinities in QFT. (The divide between this subsection and the subsection on effective field theories and emergence is somewhat arbitrary.)

- R. Batterman, “Reduction and renormalization”, in G. Ernst and A. Huttemann (eds.), Time, Chance and Reduction: Philosophical Aspects of Statistical Physics (Cambridge University Press, 2010), pp. 159-189. http://philsci-archive.pitt.edu/2852
- Jeremy Butterfield and Nazim Bouatta “Renormalization for Philosophers” (2014), arxiv:1406.4532.
- Bihui Li, “Coarse-Graining as a route to microscopic physics: the renormalization group in quantum field theory”, *Philosophy of Science* 82 (2015), 1211-1223.
- Adam Koberinski and Doreen Fraser, “Renormalization group methods and the epistemology of effective field theories” (2022), http://philsci-archive.pitt.edu/20975/.
- Sebastien Rivat, “Renormalization Scrutinized”, *Studies in History and Philosophy of Modern Physics* 68 (2019), 23-39.
- Doreen Fraser, “The development of renormalization group methods for particle physics: Formal analogies between classical statistical mechanics and quantum field theory”, *Synthese* 197 (2020), 30207-3063.
- (*) Porter Williams, “Renormalization Group Methods”, in E.Knox and A.Wilson (eds.), *The Routledge Companion to Philosophy of Physics* (Routledge, 2022), 296-310.
- Elena Castellani and Emilia Margoni, “Renormalization Group Methods: Which Kind of Explanation?”, *Studies in History and Philosophy of Science* 95 (2022), 158-166.

Naturalness

- Porter Williams, “Naturalness, the autonomy of scales, and the 125GeV Higgs”, *Studies in History and Philosophy of Modern Physics* 51 (2015), 82-96.
- (*) Porter Williams, “Two notions of naturalness”, *Foundations of Physics* 49 (2019), 1022-1050.
- David Wallace, “Naturalness and Emergence”, *The Monist* 102 (2019), 499-524.
- Jeremy Butterfield, “Lost in Math?” [essay review of S.Hossenfelder, *Lost in Math: How Beauty Leads Physics Astray*], arxiv:1902.03480 (2019), sections 5-7.

- Arianna Borrelli and Elena Castellani, “The Practice of Naturalness: A Historical-Philosophical Perspective”, *Foundations of Physics* 49 (2019), 860-878.
- Joshua Rosaler and Robert Harlander, “Naturalness, Wilsonian Renormalization, and ‘Fundamental Parameters’ in Quantum Field Theory”, *Studies in History and Philosophy of Modern Physics* 66 (2019), 118-134.
- Jonathan Bain, “Why be Natural?”, *Foundations of Physics* 49 (2019), 9.

The ontology of quantum field theory

If QFT is our best candidate for a fundamental theory, it presumably is our best bet to learn about fundamental ontology – and if we have to understand it as an emergent higher-level theory, still it ought to tell us something about *non*-fundamental ontology.

Interconnections

- One key ontological question is whether we can think of QFT as a theory of particles – and if not, what their ontological status is. This is discussed by readings in the *field and particle* section.
- *Effective field theories* challenge the conventional approach to interpretation and ontology for physical theories, as do some considerations arising from *inequivalent representations.*

Field-based ontologies

- David Wallace and Christopher Timpson, "Quantum Mechanics on Spacetime I: Spacetime State Realism", *British Journal for the Philosophy of Science* 61 (2010) pp. 697-727. (NB: Part II still does not exist.)
- David Baker, "Against Field Interpretations of Quantum Field Theory", *British Journal for the Philosophy of Science* 60 (2009), 585-609.
- Thomasz Bigaj, "Are field quanta real objects? Some remarks on the ontology of quantum field theory", *Studies in History and Philosophy of Modern Physics* 62 (2018), 145-157.
- (*) David Baker, "The philosophy of quantum field theory", (2016), in *The Oxford Handbook of Topics in Philosophy,* https://doi.org/10.1093/oxfordhb/9780199935314.013.33*,* section 4.
- Noel Swanson, "How to be a relativistic spacetime state realist", *British Journal for the Philosophy of Science* 71 (2020), 933-957.

Structural Realism and quantum field theory

- Vincent Lam, "The Entanglement Structure of Quantum Field Systems", *International Studies in the Philosophy of Science* 27 (2013), 59-72.
- (*) David Glick, "The ontology of quantum field theory: structural realism vindicated?", *Studies in History and Philosophy of Science* 59 (2016), 78-86.
- Philipp Berghofer, "Ontic structural realism and quantum field theory: are there intrinsic properties at the most fundamental level of reality?", *Studies in History and Philosophy of Science* 62 (2018), 176-188.

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Spontaneous symmetry breaking

Spontaneous symmetry breaking occurs (at least on the usual account; philosophers have challenged that account) when the ground state of a system is not invariant under a symmetry of that system. In QFT the spontaneous breaking of global symmetries leads to *Goldstone bosons* – massless scalar particles. The spontaneous breaking of local symmetries is said by physicists to underly the Higgs mechanism that gives mass to elementary particles, as well as the phenomenon of superconductivity in solid-state physics. Philosophical discussions have included whether spontaneous symmetry breaking is a dynamical process, whether we have a gauge-independent understanding of the Higgs mechanism, and the nature of the analogy between spontaneous symmetry breaking in condensed-matter and relativistic systems.

Interconnections

- Spontaneous symmetry breaking is a major source of *inequivalent representations*, and is one of the main use cases for *effective field theory* methods.

The general phenomenon

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The Higgs mechanism

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- Holger Lyre, "Does the Higgs mechanism exist?", *International Studies in the Philosophy of Science* 22 (2008), 119-133.
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Discrete symmetries

Discrete symmetries raise a collection of distinct philosophical issues, relatively disconnected(!) from other topics in the subject.

Interconnections

- The very different formal methods used to analyze the discrete symmetries in the papers in this section connect to the debate on the *choice of framework* for philosophy of QFT.

Antiunitary symmetries in general

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Time reversal

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- Bryan Roberts, "Three merry roads to T-violation", *Studies in History and Philosophy of Modern Physics* 52 (2015), 8-15.
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Antimatter

- David Baker and Hans Halvorson, "Antimatter", *British Journal for the Philosophy of Science* 61 (2010), 93-121.
- David Wallace, Wallace, "QFT, Antimatter, and Symmetry", *Studies in History and Philosophy of Modern Physics* 40 (2009), 209-222.

The CPT theorem

- Jonathan Bain, "Pragmatists and Purists on CPT Invariance in Relativistic Quantum Field Theories", http://philsci-archive.pitt.edu/9909 (2013).
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- David Baker, "The philosophy of quantum field theory", (2016), in *The Oxford Handbook of Topics in Philosophy,* https://doi.org/10.1093/oxfordhb/9780199935314.013.33, section 6.
- Jonathan Bain, *CPT Invariance and the Spin-Statistics Connection* (Oxford University Press, 2016).
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Gravity as an effective field theory

At least in the high-energy tradition in physics, general relativity is seen as an example of an effective field theory, valid at 'low' energies but breaking down around the Planck length. This approach to general relativity arguably underpins and unifies most of the astrophysical and cosmological situations in which gravitational and quantum-mechanical phenomena coexist; it is also the natural setting for the so-called 'cosmological constant problem', the problem of why QFT does not lead to a vast, observationally-ruled-out contribution to the cosmological constant.

Interconnections

This topic is a special case of the general discussion of *effective field theories*.

Overviews

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- Karen Crowther, "Emergent spacetime according to effective field theory: From top-down and bottom-up", *Studies in History and Philosophy of Modern Physics* 44 (2013), 321-8.
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The cosmological constant problem

- (*) Steven Weinberg, "The cosmological constant problem", *Reviews of Modern Physics* 61 (1989), 1-23.
- Svend Erik Rugh and Henrik Zinkernagel, "The quantum vacuum and the cosmological constant problem", *Studies in History and Philosophy of Modern Physics* 33 (2002), 663-705.
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- (*) Mike Schneider, "What's the problem with the cosmological constant?", *Philosophy of Science* 87 (2020), 1-20.
- Adam Koberinski, "Problems with the cosmological constant problem", in C.Wuthrich, B.Le Bihan and N.Huggett (eds.), *Philosophy Beyond Spacetime* (Oxford University Press, 2021).
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- Mike Schneider, "Betting on future physics", *British Journal for the Philosophy of Science* 73 (2022), 161-183.
- David Wallace, "Quantum Gravity at Low Energies", *Studies in History and Philosophy of Science* 94 (2022), 31-46. Section 11.

Miscellaneous topics

These don't easily fit into other categories. They are in no particular order.

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- John Dougherty, "I ain't afraid of no ghost", *Studies in History and Philosophy of Science* 88 (2021), 70-84.

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Infrared divergences

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