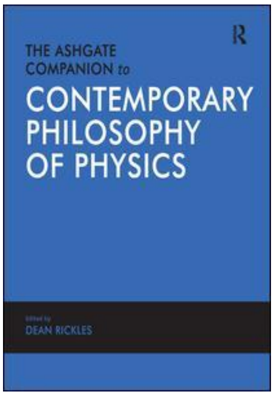

The Ashgate Companion to Contemporary Philosophy of Physics

Dean Rickles

Advancing the Philosophy of Physics

Publication details
https://www.routledgehandbooks.com/doi/10.4324/9781315612676.ch1
Dean Rickles
Published online on: 16 Oct 2008

1

ADVANCING THE PHILOSOPHY OF PHYSICS

DEAN RICKLES

There are several (general) philosophy of physics textbooks on the market.[1] An obvious question to ask at the outset then is: Why another one? In his "Some Philosophical Aspects of Particle Physics", Michael Redhead bemoans the common practice of philosophers of science of dealing with examples "which are no longer of current research interest in science" ((1980), p. 279). This practice is still common even among many philosophers of physics, and, for the most part, the available textbooks continue to engage in this practice. Generally, one finds a little spacetime, a little statistical mechanics, and a little quantum theory. Now, these are of course the 'pillars' of modern physics, so it is what we should expect to be covered in any textbook on the philosophy of physics worth its salt (and, indeed, they are well represented in this book). However, the issues that are dealt with are usually very old fashioned and very limited in scope: 'spacetime' means 'the twins paradox' (and possibly conventionalism); 'statistical mechanics' means 'time asymmetry'; and 'quantum theory' means 'the measurement problem'. Redhead is surely right that this leads physicists to "regard philosophy of science as somewhat irrelevant". Rightly so, too, if this were *in fact* representative of much of what actually goes on in philosophy of physics. However, the state of play as represented in philosophy of physics and (some) philosophy of science journals shows a very different level of engagement, with philosophers of physics investigating the frontiers of scientific research. This disparity (or the impression of such) is the *raison d'être* for the book you are now reading. The result is an introductory textbook covering those portions of philosophy of physics research that other textbooks fail to cover, or cover only very briefly or very simplistically. The three pillars of modern physics—relativity, quantum theory and statistical mechanics—are still represented, then, but from a more advanced and contemporary perspective.

1.1 What is Philosophy of Physics?

A pretty good characterization of a philosopher of physics is 'one who is shunned by philosophers and physicists in near equal measure'! Philosophers often view

[1] For example, (d'Espagnat, 2000; Kosso, 1997; Lange, 2002; Sklar, 1992; Torretti, 1999; Cushing, 1998). These are very different books, all excellent, several of which the reader ought to be acquainted with before tackling this book. Torretti's book is especially interesting since it covers the development of philosophy of physics as a discipline in its own right, with its origins in the natural philosophy of the seventeenth century.

philosophers of physics as focusing on too restricted a field and as mere lapdogs to physicists. Physicists often view philosophers of physics either as simply incapable of understanding their work or else as tackling issues that are incapable of being resolved or that are not really in need of being resolved (i.e. irrelevant), and hence that are no aid to progress. This is, I hope you will agree, unfair to both physicists and philosophers of physics for a variety of reasons:

- Philosophers of physics don't just *accept* what physicists tell them; a large part of their job is to *interpret* the constructions of physicists (and thus go beyond the ability of such constructions to yield accurate predictions). Another large part of the philosopher of physics' job is to assess the epistemic status of the claims made by physicists (in the context of their theories or otherwise). This part is often highly critical, involving the denial of physicists' claims. For example, it may be taken for granted by physicists that their theory comes with a particular unique ontology, a single way that the world would be if the theory were true. This is almost always false.[2] If there are multiple pictures then it is assumed that evidence or internal, rational principles can settle the matter in favour of one or the other. Failing this, physicists might simply say they are not in the business of offering ontologies, only with making the right predictions. This might be true for many, but it conflicts with the intuitions of most physicists' views of what they see themselves as doing, namely uncovering the (objective) secrets of Nature—Steven Weinberg, for example, staunchly defends such a view (see (Weinberg, 1987)). Philosophers of physics probe the assumptions that underlie such intuitions, and often expose erroneous ones.
- Philosophers of physics have also been known to occupy more *constructive* rôles too, contributing work on, e.g. quantum information theory, that is virtually indistinguishable from 'normal' physics—of course, many philosophers of physics began life as professional physicists, and in some cases led very distinguished careers in physics. One can often find philosophers contributing to physicists' journals, books, conferences, and workshops—indeed, one frequently finds that the philosophers' contributions are the most technical (possibly as a result of some need to prove themselves amongst the group of physicists).
- Physicists aren't just concerned with describing the *actual world*: they often work on circumscribing what is physically possible, and often on what is possible according to various notions of physical necessity (i.e. involving different laws of physics). However, more importantly, physicists often employ (albeit often implicitly) a great many philosophical principles—a belief

[2] The problem amounts to the 'underdetermination' of the ontology by the theoretical framework. David Wallace discusses this problem in the context of the quantum measurement problem: see §2.6.5. Another example is the underdetermination that arises in the interpretation of generally relativistic spacetimes: both the view that spacetime points are substances and that spacetime points are material constructs are compatible with the generally covariant formalism—Rickles touches upon this issue in §5.7.2.

> in the unity of Nature being one example; a belief in the simplicity of Nature being another. Moreover, as an examination of the history of physics quickly shows, philosophical scruples are never far away in revolutionary research: Newton, Bohr, Schrödinger, Heisenberg were all unashamedly 'philosophical physicists'. Also, though they quite vocally said otherwise, the views of Dirac and Feynman were laced with philosophical presumptions. And let's not forget Einstein; for him, philosophical thinking freed the mind leading to better physics:
>
> I fully agree with you about the significance and educational value of methodology as well as history and philosophy of science. So many people today—and even professional scientists—seem to me like someone who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is—in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth. (Einstein, from a letter to R. A. Thornton—taken from (Howard, 2005), p. 34)
>
> The links between philosophy and physics are, then, tight and old. There have been clear instances in the past where aspects of one have influenced aspects of the other. Results in physics have directly contributed to the demise (or at least severe weakening) of positions in philosophy, especially in metaphysics. Kant's views on the necessity of certain concepts in experience—Euclidean space and time for example—foundered in the light of developments in physics. The reasons for the tight connections are obvious: both involve a desire to understand the fundamental nature of things. The categories investigated intersect: matter, space, time, causality, etc. If a philosophical theory concerning these categories does not accord with the world as described by physics, then it perishes. In this way physics acts as a judge presiding over cases of metaphysics.

In other words, physics and philosophy of physics are not really so different (at least if we are talking about *theoretical* physics). This is a curious and, I think, almost *unique* case in which the 'philosophy of $\mathcal{X}$' is very close to $\mathcal{X}$ itself.[3] A browse through the pages of the *International Journal of Theoretical Physics*, *Foundations of Physics*, *Studies in the History and Philosophy of Modern Physics*, makes it hard to tell what is physics and what is philosophy of physics. Indeed, one can often find collaborations between philosophers and physicists on both 'philosophical products' and 'physics products'. The chapters in this book respect this blurry distinction: the contemporary landscape of physics, treated here, involves considerable philosophical reflection from both

[3] Think of the cases where $\mathcal{X}$ is 'music', 'art', 'religion', or even 'mathematics'; here the meta-study of these subjects is a long way from the subjects themselves. (Perhaps the relationship between (certain areas of) philosophy of cognitive science and its 'scientific' study comes close to the intimate relationship between philosophy of physics and physics.)

camps and, likewise, contemporary philosophy of physics involves considerably more technical sophistication than previously required. The available textbooks on philosophy of physics simply fail to reflect the present situation—note that I do not say that they *should*; they have different aims from those of this book.[4]

1.2 The Job of the Philosopher of Physics

There are many 'philosophy of ...' subjects, as mentioned above. Indeed, most work in philosophy is of such a sort: the application to some specific field of enquiry or subject matter of the concepts, tools and methods of philosophy. Then there are *central* ways—the 'pillars of philosophy'—of investigating such things, i.e. ontological (metaphysical), logical, axiological, linguistic, epistemological, and methodological. The philosophy of physics is no different from, say, the philosophy of mind in this respect. One can apply all of the standard resources of philosophy to the subject matter of physics just as one can apply them to the mind.

1.2.1 *The Interpretation Game*

Arthur Fine once pondered what it is that philosophers of science do that scientists don't do (1988, p. 4): Why are there philosophers of science at all? His answer, one that I agree with, boiled down to *interpretation*. This does not mean that scientists are not perfectly capable in such activities; Fine also rightly points out that they *do* engage in such debate. But they also sometimes engage in discussions of the ethics and politics or science, and venture into many areas that are deemed to lie outside of the proper practice of science. The point is, there are also people whose primary areas of expertise are those subjects just mentioned. Philosophers of physics, to a very large extent, *devote* themselves to the interpretation of physical theory. Likewise, that does not mean they are not perfectly capable of doing computational work in physics; many of them do too. Fine goes further: he would like to see philosophers of science doing empirical science. However, I don't agree with Fine that "[w]ith very few exceptions ... this divides philosophers from scientists pretty well" (ibid., p. 6). A vast number of physicists don't 'get their hands dirty' at all with empirical science. Fine's main point, however, is that there isn't really much of a difference between 'the scientific understanding of science' and 'the philosophical understanding of science'. That matches what was previously argued.

What does it mean to *interpret* a theory? Bas van Fraassen puts it best; the interpreter will ask: "Under what conditions is this theory true?" and "What

[4]Here I am exluding the magnificent recent *Handbook on the Philosophy of Physics* (Butterfield and Earman, 2007), which pushes the line taken here, only even more so. However, this book is not (to my mind, at least) feasibly usable as a textbook, even at the post-graduate level. Rather, it is, as I'm sure the editors would be the first to admit, a book intended to aid researchers already at the top of their game in terms of physics and philosophy of physics. However, that book would make excellent, and hopefully not nearly so forbidding reading once the contents of the present book have been assimilated.

does it say the world is like?" (1991, p. 242). The interpreter will then answer by specifying the class of worlds that make the theory true.[5] What we end up with, then, is a set of worlds that make the theory true; or, a set of possible worlds according to the theory. Thus, interpretation, according to Gordon Belot, "consists of a set of stipulations which pick out a putative ontology for the possible worlds correctly described by the theory" (1998, p. 533).

Now, there are differing degrees of complexity which interpretation has to deal with. In some cases, interpreting a theory is a simple matter: the formalism seemingly maps one-to-one on to physically possible worlds. Or, there might be multiple types of possible worlds that constitute models of the theory, but that are compatible. The kinds of interpretive problems philosophers of physics are interested in happen when there are multiple *incompatible* possible worlds. We see this, for example, in the interpretation of quantum mechanics, where we have possible worlds (each satisfying the formal demands of quantum mechanics) with collapse and without collapse, with world-splitting and without world-splitting, and so on. Or quantum field theory with particles and without particles. Electromagnetism as a theory of fields versus potentials versus loops; as a local theory versus an action-at-a-distance theory. General relativity as a theory with fundamental spacetime points and without fundamental spacetime points. These are empirically equivalent and they satisfy the basic postulates of the theories (van Fraassen's syntactic part), but they are not equivalent *simpliciter*: they differ at the level of interpretation. This is, of course, the problem of underdetermination again: the representation relation between formalism (the syntactic structure of a theory) and worlds is one-to-many. We find similar underdetermination problems in all of the main pillars of physics. The basic problem is that there is an apparent ontological difference with no empirically discernible difference: even assuming one of the worlds really did describe the actual world, there is no way we could come to know, empirically, *which* world that was.[6] The negative energy solutions of Dirac's equation make a fine case in point here. The solutions appeared as part of the formal structure in Dirac's theory, but they weren't included in the semantics: no interpretation was given to them, and they were deemed 'surplus structure', to borrow a phrase of Michael Redhead's. However, this is a rather large amount of surplus to be carrying around, and there is no apparent reason for its existence (*qua* surplus) that would explain it—that is, there is no symmetry responsible for generating it, or any other noticeable mechanism. Dirac *reinterpreted* the negative energy solutions (or just interpreted them in our sense) so that they left 'the realm of surplus' and entered 'the realm of the

[5]Van Fraassen argues that there are two parts to this specification: (1) a *syntactic* part, in which the purely formal structures are specified; and (2) a *semantic* part, in which the 'worlds' are specified (where the worlds are models of the formal structure outlined in the first part).

[6]The stage is set, at this point, for a rehearsal of the various positions in philosophy of science: instrumentalism; constructive empiricism; structural realism, etc. However, these issues will not, on the whole, play any part in this book, though the material covered will no doubt have consequences for these more traditional philosophy of science type debates.

physical': they were taken to have a counterpart in the worlds that are models of the theory (i.e. that satisfy the equation). This new interpretation involved viewing the negative energy states as 'holes' that are positive (anti-electrons). These holes are 'filled' by electrons.

Of course, interpretation demands there be *something to interpret*. However, one of the issues faced in the chapters by Frigg (on statistical mechanics) and by Rickles (on quantum gravity) is that there is no unique, agreed upon formal framework. We don't quite know what the theory *is*! Quantum mechanics too has numerous formulations, but they are equivalent.[7] Not so in the cases of statistical mechanics and quantum gravity, though the reasons are different: in the case of quantum gravity there is simply a problem concerning experimental evidence. The problem for statistical mechanics is more *normative*: we aren't entirely sure what it ought to be a theory of. For this, and other reasons, these chapters follow a slightly different route to the others: the class of interpretations is multiplied by the number of formal frameworks. However, the issues involved are the same once we target a specific formalism.

1.2.2 *Experimental Philosophy*

The interpretation game seeks to work out what a theory is telling us about the world. Related to the interpretation game is the second major job of the philosopher of physics: seeing what impact this has on our conceptual scheme. The results of interpretation are often incompatible with widely-held beliefs about the world, especially where space, time, and matter are concerned.[8] When the theory has a firm experimental basis, this can lead to revisions. Even without experiment it suggests contingency in that conceptual scheme, the possibility that it might be wrong.

Abner Shimony coined the term 'experimental metaphysics' to describe cases where some metaphysical assumptions are rendered untenable (or less likely) or supported by 'real world' experiments (see Cohen et al., 1997 and Shimony, 1993). The case he had in mind was the metaphysical and experimental status of Bell's theorem: Bell's inequality is violated by experiments, which demonstrate quantum correlations—or, at least, provide virtually incontrovertible evidence. However, Bell's theorem is loaded with weighty metaphysical assumptions having to do with determinism, realism, and locality. These back-react on a host of philosophical positions. This general methodology can be readily generalized to other cases. For example, recent work in the philosophy of spacetime physics aims to show how metaphysical positions having to do with the reality of time and change are impacted upon by particular approaches to quantum gravity (see

[7]Wallace, in this book, argues that though quantum mechanics provides a reliable algorithm for generating accurate predictions of macroscopic phenomena, it does not constitute a satisfactory physical theory: it is unable to explain why it is so successful.

[8]For example, even very basic courses on the philosophy of space and time now have to take into account special relativistic considerations. The Newtonian idea of a unique 'now line' partitioning the events of the universe into past and future is simply no longer tenable, and this is so for experimental reasons—cf. (Saunders, 2002).

Belot and Earman, 2001; Rickles, 2006). Classical general relativity too—with its exotic solutions involving wormholes and rotating, cylindrical universes permitting time travel—has greatly modified philosophical debate over time, change, and causation. Even the higher reaches of modal metaphysics are not immune from the impact of physics: something of a cottage industry of work has sprung up charting the connections between theories of possibility and interpretations of symmetries (see (Rickles, 2007) for a review. Along different lines, (Butterfield, 2004) shows how analytical mechanics is heavily laden with modal involvement.

Given the basis in physics, one could argue that this experimental brand of metaphysics offers a justification (or a concrete implementation) of Strawson's (1990) 'revisionary metaphysics', which he had argued against in favour of so-called 'descriptive metaphysics'. For Strawson, our conceptual scheme—as elucidated by metaphysics—is not the kind of thing that changes over time. At the very least, there is a constant core based on the subject-predicate distinction. However, even this distinction is placed under pressure by discoveries in physics. Whether Strawson would have seen matters in this way as quite another thing, of course. Also, whether, and to what extent one can really do experimental metaphysics is not something we need discuss here—certainly the cases are not always as straightforward as appears at first sight (the quantum gravity example is a case in point and the case of Bell's theorem too is hardly settled beyond all doubt). Part of the problem here is the underdetermination of interpretive pictures by the formalism and the experiments. However, it cannot be denied that much of contemporary philosophy of physics is engaged in experimental metaphysics in some way, and the contributions to this book are no exception.

1.3 What Parts of Physics are Amenable to Philosophical Investigation?

My preferred answer would be: any and all! Answers that say otherwise confuse the distinction between what philosophers of physics do and what philosophers of science (in general) do. Philosophy of physics is concerned with the products of physics, the theories and models. Given the relatively uniform structure of these theories and models (i.e. they use, roughly, the same mathematical structures) it is reasonable to assume that they will all submit to the probing of their implications. For once we have such a structure to hand, we can look at its possible interpretations. This is the case even when there is no experimental evidence in favour of some theory. This is precisely what we find in quantum gravity research: theories with zero experimental support, but that can be interpreted in just the same way as if there was such support. In this sense, doing philosophy of physics (*qua* interpretation of physics) and doing theoretical physics are very similar indeed: both construct and examine possible worlds. It is up to the Nature and the experimentalists (and the philosophers of science) to tell us whether we're on to something! Taking this liberal view on board, this book is about applying philosophy to very recent advances in physics, or at least recent enough not to be included in most other philosophy of physics textbooks. Inasmuch as traditional issues are covered, and they are, they are dealt with in the context of the contemporary debate.

1.4 Preview of the Chapters

As mentioned in the introduction, the three pillars of modern physics are represented in this book: quantum theory is covered by David Wallace and Chris Timpson, statistical mechanics by Roman Frigg, and relativity by Dean Rickles. There are points of overlap between the chapters, as should be expected given that these theories are intended to describe one and the same world. A nutshell preview of the chapters follows.

1.4.1 *Quantum Mechanics*

Quantum mechanics generates by far the most work within philosophy of physics. It is responsible for *the* philosophical problem of physics: the measurement problem. Given the seriousness of this problem, and its habit of infecting numerous *prima facie* distinct issues, Wallace focuses his chapter squarely on it. His (very careful and finely nuanced) review concentrates on very recent work, involving decoherence, consistent histories, dynamical-collapse interpretations, hidden-variables (modal) interpretations, and neo-Everettian views. Wallace finishes by considering the state of the interpretative issues in the context of quantum field theory, where the merger with special relativity means that Lorentz invariance has to be satisfied. Overall, Wallace paints a very bleak picture of the situation in quantum mechanics, one that warrants immediate and serious attention from both physicists and philosophers. This should be seen as a *challenge* rather than a criticism.

1.4.2 *Statistical Mechanics*

Statistical mechanics, and thermal physics more generally, began with foundational issues, and these remain today. This is not surprising given the central rôle probability plays. As Roman Frigg points out in his chapter, there is still no unique formal framework of statistical mechanics to speak of; instead, there are many competing approaches. Indeed, Jos Uffink describes the foundations of statistical physics as “a battlefield between a dozen or so different schools, each firmly dug into their own trenches” (2004, p. 6). However, the overarching aim is the same: to provide an account of how macrophysical phenomena (the properties and behaviour of ‘unit complex systems’) are related to microphysical phenomena (the properties and behaviour of individual subunits contained in the unit). The statistical element arises since there are enormous numbers of subunits per unit. A central problem is trying to make sense of the connection given the apparently very different laws obeyed by units and subunits respectively. Frigg critically examines the details of the various approaches, highlighting those assumptions and implications of philosophical significance, especially those linked to the notion of equilibrium and non-equilibrium.

1.4.3 *Quantum Information Theory*

Quantum information theory does not break radically new ground conceptually speaking. However, what it does do is provide a new window onto the conceptual problems of quantum theory. Moreover, it forces us to better understand the nature of *classical* theory and the ways in which classical and quantum differ. This question is not pursued purely for philosophical interest; rather, it is pushed in a bid to *exploit* the quantum world. An underlying hope, however, is that in getting greater physical insight into the quantum mysteries, one might thereby be able to resolve the philosophical problems facing quantum mechanics. Timpson discusses these issues, giving a sober assessment of many grandiose claims that have been drawn so far, preferring to draw inferences about the *structure* of quantum theory from quantum information theory, rather than about metaphysical interpretive issues.

1.4.4 *Quantum Gravity*

Quantum gravity does not yet denote a specific theory or approach; instead there are many competing research programmes battling it out to earn that title. An utter lack of experimental evidence is at the root of this proliferation, itself due to the miniscule distances at which quantum gravity is expected to make itself manifest. Given that quantum gravity ought minimally to include general relativity and quantum theory (in the appropriate limits) we face the problems with these 'ingredient' theories, and then some. There are many novel conceptual problems brought about by the merger between quantum and gravity, including, not surprisingly, problems having to do with the nature of space, time, and change. Rickles introduces the basic ideas of quantum gravity, the various research programmes, and exposes a number of these problems.

These chapters make it clear that there is plenty of work to be done in philosophy of physics. Recent developments in physics have not resolved the conceptual problems that plagued the theories in their earliest days. We do have new ways to make sense of the problems, and the problems themselves are more narrowly circumscribed; however, in many ways we face now the same set of problems that faced earlier generations. It is hoped that this book will spark a new generation of philosophers of physics who might one day resolve the problems raised in these pages once and for all.

***

As Roberto Torretti's book (1999) makes wonderfully clear, the philosophy of physics is an evolving discipline. It was once, in Newton's day, so tightly woven into the fabric of physics as to be virtually one and the same thing. At the beginning of the twentieth century the ties that bind closed again, with little to distinguish philosophical discussion of physics from physics itself. These periods of proximity were sparked off by revolutionary episodes in physics, causing the foundations to feel not quite so sturdy.[9] Though many physicists try to ignore it, the foundations of physics never quite recovered from these blows. As Carlo Rovelli puts it, the revolution was "incomplete" (2000). Philosophers are left with the mess of trying to piece together the various fragments of the theoretical edifice. But we are left with many puzzles and, given the conceptual nature of many of these, it will take the efforts of both physicists and philosophers of physics to solve them.

[9]For example, Kuhn wrote that "It is no accident that the emergence of Newtonian physics in the seventeenth century and of relativity and quantum mechanics in the twentieth should have been both preceded and accompanied by fundamental philosophical analyses of the contemporary research tradition." (Kuhn, 1970, p. 88). A little further on, he writes: "Confronted with anomaly or with crisis, scientists take a different attitude toward existing paradigms, and the nature of their research changes accordingly. The proliferation of competing articulations, the willingness to try anything, the expression of explicit discontent, the recourse to philosophy and the debate over fundamentals, all these are symptoms of a transition from normal to extraordinary research." (Kuhn, 1970, pp. 90–1)

REFERENCES

Belot, G. (1998). Understanding electromagnetism. *The British Journal for the Philosophy of Science*, 49: 531–55.

——— and J. Earman. (2001). PreSocratic quantum gravity. In C. Callender and N. Huggett, eds, *Physics Meets Philosophy at the Planck Scale*, pp. 213–55. Cambridge: Cambridge University Press.

Butterfield, J. and J. Earman eds (2007). *Philosophy of Physics*, Vol. 2 of *Handbook of the Philosophy of Science*. Elsevier Science Publishing Co..

——— (2004). Some aspects of modality in analytical mechanics. P. Weingartner and M. Stoeltzner eds, *Formale Teleologie und Kausalitat in der Physik*, pp. 160–98. Mentis.

Cohen, R.S., M. Horne and J. S. Stachel eds (1997). *Experimental Metaphysics: Quantum Mechanical Studies for Abner Shimony, Vol. 1.* Springer.

Cushing, J. T. (1998). *Philosophical Concepts in Physics: The Historical Relation between Philosophy and Scientific Theories*. Cambridge: Cambridge University Press.

——— (1988). Foundational problems in and methodological lessons from quantum field theory. In H. Brown and R. Harré eds *Philosophical Foundations of Quantum Field Theory*, pp. 25–39. Oxford: Clarendon Press.

d'Espagnat, B. (2000). *On Physics and Philosophy*. Princeton University Press, 2000.

Fine, A. (1988). Interpreting science. *Philosophy of Science (Proceedings)*, 2, Symposia and Invited Papers: 3–11.

Howard, D. (2005). Albert Einstein as a philosopher of science. *Physics Today*, December: 34–40.

Kosso, P. (1997). *Appearance and Reality: An Introduction to the Philosophy of Physics*. Oxford: Oxford University Press.

Lange, M. (2002). *An Introduction to the Philosophy of Physics: Locality, Fields, Energy and Mass*. Oxford: Basil Blackwell.

Redhead, M. L. G. (1980). Some philosophical aspects of particle physics. *Studies in the History and Philosophy of Science*, 11(4): 279–304.

Rickles, D. (2006). Time and structure in canonical gravity. In D. Rickles, S. French, and J. Saatsi, eds, *The Structural Foundations of Quantum Gravity*, pp. 152–95. Oxford: Oxford University Press.

——— (2007). *Symmetry, Structure and Spacetime*. Philosophy and Foundations of Physics. Elsevier.

Rovelli, C. (2000). The century of the incomplete revolution: Searching for general relativistic quantum field theory. *Journal of Mathematical Physics*, 41(6): 3776–800.

Saunders, S. (2002). How relativity contradicts presentism. In C. Callender, ed, *Time, Reality & Experience*, pp. 277–92. Cambridge: Cambridge University Press.

Shimony, A. (1993). Experimental test of local hidden-variables theories. In A. Shimony, ed, *Search for a Naturalistic World View, Vol. II*, pp. 77–89. Cambridge: Cambridge University Press.

Sklar, L. (1992). *Philosophy of Physics*. HarperCollins Canada / Westview S/Dis.

Strawson, P.F. (1990). *Individuals: An Essay in Descriptive Metaphysics*. London: Routledge.

Torretti, R. (1999). *The Philosophy of Physics*. Cambridge: Cambridge University Press.

Uffink, J. (2004). Boltzmann's work in statistical physics. *Stanford Encyclopedia of Philosophy*, E. N. Zalta ed, http://plato.stanford.edu/entries/statphys-Boltzmann.

van Fraassen, B. (1991). *Quantum Mechanics: An Empiricist View*. Oxford: Oxford University Press.

Weinberg, S. (1987). Towards the final laws of physics. In *Elementary Particles and the Laws of Physics: The 1986 Dirac Memorial Lectures*. Cambridge: Cambridge University Press.