PHILOSOPHY OF PHYSICS

Mario Bacelar Valente
Department of Philosophy, Logic and Philosophy of Science, University of Seville, Spain

Keywords: Physics, Physics Education, Foundations of Physics, Philosophy of Physics, Philosophy of Science

Contents

Summary

Philosophy of Physics has emerged recently as a scholarly important sub-field of philosophy of science. However outside the small community of experts it is not a well-known field. It is not clear even to experts the exact nature of the field: how much philosophical is it? What is its relation to physics? In this work it is presented an overview of philosophy of physics that tries to answer these and other questions.

1. Introduction

This work will try to provide an account of philosophy of physics that is accessible to a wide audience besides actual practitioners of philosophy of physics. For this purpose philosophy of physics will be considered from different perspectives, so that it is possible to present different aspects of the field. The work is structured in a way that is informative both to the expert as to experts in related areas, and also to the educated non-specialist. Some examples of the 'state-of-the-art' in this field will be presented; however the main *motif* of the work will be to provide a broad account of philosophy of physics by taking into account its relation to: (1) physics; (2) physics education; (3) history of physics; (4) other sub-fields of philosophy of science, like philosophy of mathematics, philosophy of cognitive sciences, and philosophy of biology, (5) philosophy of science; (6) philosophy in general. Doing this will enable me to provide a positive characterization of: (1) what is unique to philosophy of physics; (2) in practical terms, what is it good for; (3) where are we today regarding this field; (4) what might be relevant features to take into account for the future development of the field.

In order to accommodate these different objectives in the work, Section 2.1 starts with a brief presentation of the historical development of philosophy of physics from within philosophy of science. Then, in Section 2.2, it is given a first account of philosophy of physics today. In Section 2.3 an example of an area/sub-field of philosophy of physics will be considered: philosophy of quantum field theory. In Section 3 it is considered the relation of philosophy of physics and physics. In Section 3.1 it is addressed the question about to what point is philosophy of physics autonomous with respect to physics. In Section 3.2 it is presented the idea that in part philosophy of physics can be seen as a continuation of physics by other means. Finally in Section 3.3 it is addressed the possible relevance of philosophy of physics in physics education. Section 4 is devoted to the relation of philosophy of physics and history of physics. Here it will be defended the importance of historically oriented works in philosophy of physics. In Section 5 it is given an account of the contemporary relation of philosophy of physics and philosophy. In Section 5.1 it is considered the current relation of philosophy of physics and philosophy of science. This will make possible a characterization of philosophy of physics revealing its specificity, i.e. what makes it unique. In Section 5.2 it is considered the importance of taking into account other sub-fields of philosophy of science for the development of philosophy of physics, in this way broadening the philosophical scope beyond what has become traditional in philosophy of physics. Then in Section 5.3 the philosophical *horizon* will be open even more by calling the attention to the importance of metaphysical presuppositions in physics, and the possible importance of alternative philosophical inputs, that go beyond the philosophical traditional in which philosophy of physics develops.

2. Philosophy of Physics as an Autonomous Discipline

Nowadays it is normal to find philosophers of physics in philosophy of science departments; also there are journals almost exclusively dedicated to philosophy of physics, and it is quite common to find highly specialized works on philosophy of physics in journals of philosophy of science. There is in fact an academic community of philosophers of physics, i.e. we face the fact that there is an academic discipline named philosophy of physics. It is possible to offer a sociological characterization of this discipline. However, here one is more interested in coming to terms with philosophy of physics in its own terms, i.e. by understanding the differentiating aspects of the discipline, its 'identity'. In order to do so Section 2.1 will start by considering the historical differentiation of philosophy of physics from philosophy of science. It will be shown that what we call today philosophy of physics was already part of philosophy of science, sometimes to the point that philosophers were actually doing philosophy of physics more than philosophy of science proper. In Section 2.2 it will be offered a first characterization of the current state of affairs: what is that branch of philosophy of science we call philosophy of physics? philosophy of physics will be characterized by calling the attention to its specialization, i.e. its limited 'domain of application'. In Section 2.3, as an example, one will look in detail at a particular instantiation of philosophy of physics, the one that is called philosophy of quantum field theory.

2.1. Philosophy of Physics within Philosophy of Science: Early Specialized Works.

Looking into the history of philosophy of science it is clear that with the advent of modern physics came a corresponding philosophy of science centered in physics. There is a continuity with previous developments, for example in the discussion of the so-called scientific method, i.e. there is no discontinuity in the philosophical inquiry; however issues related to mathematical sciences (physics and astronomy) progressively took the central stage of the philosophical debate, examples of that being the works of William Whewell and John Herschel in the first half of the nineteenth century (see, e.g., Losee 1993).

The development and differentiation of the modern disciplines of theoretical physics and experimental physics (see, e.g., Jungnickel and McCormmach 1986), was accompanied by more specific philosophical works. We find a clear example of this, in the late nineteenth and early twentieth century, in the work of Henry Poincaré. Considering just one of his books, *La Science et l'Hypothèse (1902)*, we find very specialized work that is a current trend of the 'self-identity' of philosophy of physics and other sub-fields of philosophy of science, like philosophy of cognitive sciences and philosophy of mathematics. For example Poincaré develops the view that the axioms of geometry are conventions. Nowadays one could put this line of ideas as a subject of philosophy of mathematics. Another interesting view is Poincaré's distinguish between a representative space and the mathematical geometric space. The first one is prior to a conceptual notion of space (and because of this prior to the geometric space) it is 'built' from our visual, tactile, and in particular motor 'sensations'. It is our bodily motion in correlation to solid bodies that enables the development of the notion of space. Poincaré (possibly, following Hermann von Helmholtz; see, e.g. Torretti 1984; Darrigol 2008) is making an anticipation of (similar) views later put forward by Maurice Merleau-Ponty in his *Phénoménologie de la Perception* (1945), like the idea of a lived space that is previous to the objective space (i.e. mathematical space), and the importance of the body-scheme to perception. This is a current research topic in cognitive sciences, which is motive of considerable debate in philosophy of cognitive sciences (see, .e.g., Noë 2004). Regarding philosophy of physics we find several examples of it in Poincaré's book: a conceptual analysis of the concept of force in classical mechanics, and of the principle of conservation of energy; or a critical analysis of Lorentz's electron theory.

Another example, that if published today would be regarded as a book of philosophy of physics, is Hans Reichenbach's *The philosophy of space and time (1928)*. Already the name is truly contemporary. In what regards the content, we find a treatment of the concepts of space and time based in the theory of relativity and in Einstein's theory of gravity, i.e. a detailed conceptual treatment of the concepts of space and time made by resort to a technically sophisticated knowledge of advanced physical theories. This is a clear anticipation of a 'concentration area' of philosophy of physics called, like the book, philosophy of space and time. We find in this book relevant features of contemporary philosophy of physics: (1) a concentration in particular concepts, fields/areas, or theories of physics; (2) a detailed technical analysis; (3) a lack of more metaphysical approaches/aspects/considerations.

Throughout the twentieth century we find works classified as philosophy of science that nowadays would be classified as philosophy of physics. let us consider just a few more examples:

- In *Quantum mechanics without the observer* (1964) Karl Popper makes a critical analysis of the standard interpretation of quantum mechanics, presenting in the form of thirteen theses and a summary what he calls a realistic interpretation. One example of Popper propositions is his reinterpretation of the Heisenberg uncertainty relations in terms of the frequency interpretation (already presented by Popper in 1934; see Popper 1934), and in terms of his later propensity interpretation. We see in this work a clear example of another concentration area of contemporary philosophy of physics centered in quantum mechanics.

- In *Virtual Processes and Virtual Particles: Real or Fictitious?* (1970) Mario Bunge addresses the question of the status of the so-called virtual quanta that arises in the quantum field theory description of physical processes, like for example the electron-electron scattering (the quantum 'equivalent' of a collision between billiard balls). According to Bunge, virtual quanta are conceptually irrelevant (fictions), since they are associated with terms of a perturbative expansion. At best they should be seen as a computational intermediary. This work is a clear example of what we call today philosophy of quantum field theory, another sub-field (concentration area) of philosophy of physics.

- In *Leçons sur la genèse des théories physiques (1974)*, Jacques Merleau-Ponty provides an analysis of contributions by Galileo, Ampère and Einstein, centered in the distinction between three elements of physical theories: conceptual, mathematical, and experimental. The difference between the conceptual and mathematical elements are particularly clear in Galileo that had a new conceptual scheme to address the motion of bodies but had to resort to imperfect mathematics to implement it (in particular Galileo lacks a mathematical notion of instantaneous velocity).

All these examples show that what we regard today as philosophy of physics was being done for quite some time under the label of philosophy of science; and that we must regard philosophy of physics as emerging from philosophy of science.

2.2. Philosophy of Physics on Its Own

Since there was philosophy of physics inside philosophy of science it seems difficult to define it in its own terms by an intrinsic characterization that provides a differentiating *motif*. In the end we know that there are social factors involved, and the question is if it is possible to avoid them when coming to terms with philosophy of physics as an autonomous discipline. As a sub-field of philosophy of science it simply emerged from it due to the coming-to-be of a specialized community that promoted a self-identity as philosophers of physics, when in the end the new discipline seems to be already very old. In its definition as a discipline we assist at a consolidation of topics that were already present, and, which in part, have already been mentioned in this review: a specialization, following a very technical approach, in physical theories or fields, like e.g. quantum mechanics; a concentration in conceptual foundational issues, e.g. related to the theory of relativity; a very focused treatment of more philosophical aspects, like e.g. the ontology of space and time. In their affirmation as an autonomous group it is particularly important the relation of the self-defined philosophers of physics with the, by now separated, philosophy of science and with physics. These are issues that will be addressed below. It will be defended the view that it is possible to give an 'intrinsic' non-sociological characterization of philosophy of physics by considering these relations. For the moment let us consider in more detail an example of contemporary philosophy of physics.

2.3. One Example: Philosophy of Quantum Field Theory

As philosophy of physics emerged as an autonomous discipline in relation both to physics and philosophy of science an important aspect of its consolidation was the specialization on particular issues. One example already felt with strength in the seventies of last century was the philosophy of space and time (see, e.g., Earman 1970; Fine 1973; Friedman 1973; Sklar 1974; Glymour 1977; Malament 1977). Regarding quantum field theory we can consider it birth decade to be the eighties. The works of Michael Redhead and Paul Teller were particularly important in putting forward a consistent and more systematic philosophical approach to quantum field theory (see, e.g., Redhead 1983, 1988; Teller 1990a, 1990b, 1995). When looking into these works one is already facing a possible identity problem of philosophy of physics. What is there in these works that makes them philosophical? What differentiates them from works in foundations of physics made by physicists? For example in *A philosopher looks at quantum field theory* (1988) Michael Redhead presents a list of eight questions that he considers to be of a more or less metaphysical character. Examples of these semi-metaphysical questions are: Q. 3. What is the nature of the vacuum in quantum field theory; Q. 4. What is the status of so-called virtual particles? (This is the issue addressed in the above mentioned work by Bunge).

Only in a very 'decaff' metaphysics can these questions be considered metaphysical at all. These are typical foundational problems addressed by the (usually) anti-metaphysical theoretical physicists. Looking now at Paul Teller's work one is again confronted by the difficulty of grabbing the philosophical content of his approach. In his *An interpretive introduction to quantum field theory* (1995) Teller tries to provide an interpretation of quantum field theory. This comes out to be a proposal for substituting an idea of particles as hard material 'real' stuff (substances) by associating to quantum fields the idea of a propensity for detecting a number of quanta (particles) of a particular type. Again it is difficult to make precise what is the distinctive philosophical aspect of this work. The view defended here is that this possible identity problem is not a feature of the early days of philosophy of quantum field theory (or even of philosophy of physics in general) but something that we still face today. This situation is even clearer in the present time with more and more very specialized works and a consolidation of philosophical-like standard issues addressed within philosophy of quantum field theory (see, e.g., Rugh and Zinkernagel 2002; Huggett 2002; Lyre 2004; Wallace 2006; Falkenburg 2010, Baker and Halvorson 2010; Bacelar Valente 2011a, 2011b); one example of a 'philosophical question' is: what is the right ontology for quantum fields, one in terms of particles, fields, or something else? (See, e.g., Kuhlmann, Lyre, and Wayne 2002)

In reality there is no hard-and-fast way to address the possible identity problem of philosophy of physics in general and philosophy of quantum field theory in particular. The view defended here is that a work to be considered as a philosophical work on a specific subject like quantum field theory, it is necessary that it attains the right balance between broad philosophical aspects, more specific issues related to philosophy of science, and a detailed (usually very technical) treatment of, in this case, quantum field theory. One example where the right balance is achieved is in the book *Particle metaphysics* (2007) by Brigitte Falkenburg. In this work Falkenburg defends a moderate form of realism based on a properties realism strongly dependent on the practical unity of physics (that she calls semantic unity) due to the operational and theoretical layered structure of physics. The operational aspect of physics unity results from physics defining methodology in terms of the construction of scales of physical quantities and associated measurement theories and practices. There is a theoretical aspect to this unity due to the theory-ladenness of experimental data.

From the quantum electrodynamical description of quantum phenomena associated to a metaphysical idea of particle, Falkenburg develops an anti anti-realist argumentation. This enables her to develop an operational concept of particle based on the measurement of defined dynamic properties. In this work Falkenburg calls the attention to the fact that it is not possible to separate what might be considered the empirical elements of the theory from metaphysical presuppositions. This is an important issue to which one will return in Section 5.3.

3. Philosophy of Physics and Physics

As we have seen there might be some overlap between the work of a physicist doing foundations of physics and of a philosopher doing philosophy of physics, and there is a good reason for that. Being highly specialized, as an autonomous field, philosophy of physics was born as a field for the specialist, and the ones that have the technical know-how are in this case physicists, i.e. the majority of the members of the community of philosophers of physics have had formal academic formation in physics. This social aspect has consequences on the type of intellectual output of the members of the community. In simple terms we might have too much physics and too little philosophy.

3.1. Studies in Foundations Of Physics: Is Philosophy of Physics Autonomous in Regard to Physics?

Since there is a bias towards physics one faces the problem of a possible lack of autonomy of philosophy of physics in relation to physics. It is already a common situation to have both theoretical physicists and philosophers of physics in workshops and conferences dedicated to foundations of physics. One example of this can be seen in the book *Conceptual foundations of quantum field theory* (1999); here we find the contributions of the participants at a conference on foundations of quantum field theory. Looking at the list of contributors we see that twenty or so participants were from departments of physics or related, and around seven from departments of philosophy. So, is philosophy of physics autonomous in regard to physics?

One should avoid generalizations; however there is a clear overlap between physics and philosophy of physics. In the next section it will be explored the positive possibilities opened by this. Right now it is sufficient to mention that this overlap does not have to create an identity problem to philosophy of physics if, besides the common-ground of issues of physics, philosophy of physics addresses clearly specific 'philosophical' issues that go beyond conceptual and foundational issues. Regarding this last point the view defended here is that it is not enough to have a few metaphysical-like standard academic issues around to justify philosophy of physics as an autonomous and creative discipline. There must be more. This point will be considered again when addressing the question of the contemporary relation of philosophy of physics with philosophy of science and with philosophy in general.

3.2. Philosophy of Physics as Continuation of Physics by Other Means

In *Inventing Temperature: measurement and scientific progress* (2004) Hasok Chang advocates the view of philosophy of physics (and also history of physics) has having a possible complementary function in relation to physics. According to Chang, philosophy of physics addresses foundational questions and explores possible alternative conceptual elements of physical theories. The importance of this philosophy of physics 'mode of inquire' is that it enables literally the creation of knowledge. As it was already mentioned, this particular aspect of philosophy of physics is also found in foundational and conceptual studies made from within physics itself. It is this overlapping of domains that enables this productive *facet* of philosophy of physics. In this way, with Chang, one can consider that philosophy of physics can be a continuation of physics by other means, but only because even if starting from a different point there is a *locus* of encounter between physics and philosophy of physics. This implies that the type of knowledge that can be provided by philosophy of physics is limited in a way that physics is not, which is not something we would not expect. Philosophy of physics in its physics-like mode is centered in particular in the conceptual elements of physical theories, or in some rare cases on the mathematical formulation of existing theories. This clearly limits the new knowledge that philosophy of physics can provide. However the contribution can potentially be quite important. Returning to Jacques Merleau-Ponty's 'philosophy of physics', he presents the case of Einstein's 1905 theory of relativity as a clear example where the change occurs manly in the conceptual element. In fact the mathematical structure of Einstein's theory of relativity was basically all in Lorentz's electron theory (the main contributions being made by Lorentz and Poincaré; see, e.g., Darrigol 2005). Einstein's contribution was at a conceptual level; he created a new conceptual system that transformed the experimental and mathematical elements of Lorentz's electron theory into what we now know as the theory of relativity.

3.3. Philosophy of Physics in Physics Education, an Example: Einstein's Theory of Gravity

In our schools and universities the education of physics is usually made without an accompanying account of its history or of philosophical issues. History is usually relegated to a secondary role of promoting particular idealized views on science, and philosophy of physics or science are usually considered not very relevant in (what is seen as) a technical scientific formation. According to Michael R. Matthews

If students do not learn and appreciate something about science, its history, its interrelations with culture, religion, worldviews, and commerce, its philosophical and metaphysical assumptions, its epistemology and methodology, then the opportunity for science to enrich culture and human lives is correspondingly minimized. (Matthews 2001, 3)

Even if one considers that a humanistic approach is not necessary in physics education, it can still be made a case for the need of philosophy (and history) of physics at a very pragmatic level: philosophy of physics (like history of physics) is very useful for the students learning and understanding of physics. In this review it will be considered one 'case-study', that of the learning of Einstein's theory of gravity.

To study Einstein's theory of gravity one needs first to learn advanced mathematics. This can be done in separate from physics education or in many cases as an all-in-one discipline where the students are taught on the run the differential geometry needed to cope with Einstein's theory of gravity. In the end it is unavoidable that a large amount of time is devoted to the learning of mathematics. That the study of Einstein's theory of gravity is inevitably loaded with mathematics can easily be seen in textbooks on the subject. As an example let us consider a few textbooks that we may consider as belonging to an introductory or intermediate level:

-
-
-

Bibliography

Adam, J. A. (2002). The mathematical physics of rainbows and glories. *Physical Reports*, 356, 229- 365. [A good review of the physical description of rainbows]

Bacelar Valente, M. (2011a). The relation between classical and quantum electrodynamics. *Theoria*, 26, 51-68. [A philosophy of quantum field theory paper addressing the question of the intertheoretical relation between classical and quantum electrodynamics]

Bacelar Valente, M. (2011b). Are virtual quanta nothing but formal tools? *International Studies in the Philosophy of Science*, 25, 39-53. [A paper addressing a classical issue of philosophy of quantum field theory]

Baker, D., and Halvorson, H. (2010). Antimater. *British Journal for the Philosophy of Science*, 61, 93-121. [A paper on philosophy of quantum field theory]

Batterman, R. W. (2002). *The devil in the details: asymptotic reasoning in explanation, reduction, and emergence*. Oxford: Oxford University Press. [Presents, among other things, Batterman's views on intertheoretical relations using the description of the rainbow as a case-study]

Berry, M. (1994). Asymptotics singularities and the reduction of theories. In, D. Prawitz et al. (eds.), *Logic, methodology, and philosophy of science*, vol. IX (pp. 597-607). New York: Elsevier. [Presents Berry's views on intertheoretical relations]

Berry, M., and Upstill, C. (1980). Catastrophe optics: morphologies of caustics and their diffraction patterns. In, E. Wolf (ed.), *Progress in optics, XVIII*, (pp. 257-346). Amsterdam: North Holland. [Contains a catastrophe theory application to the description of rainbows]

Bunge, M. (1970). Virtual processes and virtual particles: real or fictitious? *International Journal of Theoretical Physics*, 3, 507-508. [This paper is an example of an anticipation of works on philosophy of quantum field theory]

Burtt, E. A. ([1924] 1954). *The metaphysical foundations of modern science*. New York: Doubleday Anchor Books. [A classical about the metaphysical substructure of physics]

Callahan, J. J. (2000). *The geometry of spacetime: an introduction to special and general relativity.* New York: Springer-Verlag. [A good introduction to Einstein's theory of gravity]

Cao, T. L. (1999). *Conceptual foundations of quantum field theory*. Cambridge: Cambridge University Press. [Contains several interesting papers on foundations of quantum field theory]

Chang, H. (2004). *Inventing temperature. Measurement and scientific progress*. Oxford: Oxford University Press. [Presents a simultaneous an interrelated historico-philosophical study of thermometry]

Darrigol, O. (2005). The genesis of the theory of relativity. In T. Damour, O. Darrigol, B. Duplantier, and V. Rivasseau (Eds.), *Einstein, 1905-2005: Poincare Seminar 2005*. Berlin: Birkhauser Verlag. [Presents a good account of the history of the coming to be of the theory of relativity]

Darrigol, O. (2007). A Helmholtzian approach to space and time. *Studies in History and Philosophy of Science*, 38, 528-542. [A good historically motivated philosophy of space and time paper]

Darrigol, O. (2008). The modular structure of physical theories. *Synthese*, 162, 195-223. [A new view on physical theories in terms of a modular structure that changes the way of addressing intertheoretical relations]

Duhem, P. ([1906] 2007). *La théorie physique: son object et sa structure*. Paris: Librairie Philosophique J. Vrin. [A classical on philosophy of physics]

Earman, J. (1970). Who's afraid of absolute space. *Australasian Journal of Philosophy*, 48, 287-319. [A paper on philosophy of space and time]

Earman, J. (1989). *World enough and space-time*. Cambridge: MIT Press. [A modern classical on philosophy of space and time]

Falkenburg, B. (2007). *Particle metaphysics. A critical account of subatomic reality*. Berlin: Springer. [A philosophy of quantum field theory book taking into account experiments on microphysics]

Falkenburg, B. (2010). Wave-particle duality in quantum optics. In, M. Suárez, M. Dorato., and M. Rédei (eds.), *EPSA Philosophical issues in the sciences*. Berlin: Springer. [A paper on philosophy of quantum field theory taking into account the so-called which-way experiments of quantum optics]

Ferreirós, J. (2001). *Riemanniana selecta*. Madrid: Consejo Superior de Investigaciones Científicas. [Selection of important writings by Riemann with a detailed introduction by José Ferreirós]

Ferreirós, J. (2004). The motives behind Cantor's set theory: physical, biological and philosophical questions. *Science in Context*, 17, 1-35. [A detailed account of the diverse motivations underlying Cantor's work]

Ferreirós, J. (2007). *Labyrinth of thought: a history of set theory and its role in modern mathematics.* Basel: Birkhäuser Verlag. [A historical account of the origin of set theory]

Ferreirós, J., and Gray, J. (2006). *The architecture of modern mathematics*. Oxford: Oxford University Press. [Contains papers on history and philosophy of mathematics]

Friedman, M. (1973). Grünbaum on the conventionality of geometry. In, P. Suppes (ed.), *Space, time and geometry*. Dordrecht: Reinel. [A paper on philosophy of space and time]

Friedman, M. (1983). *Foundations of space-time theories*. Princeton: Princeton University Press. [A modern classical on philosophy of space and time]

Fine, A. (1973). Reflections on a relational theory of space. In, P. Suppes (ed.), *Space, time and geometry*. Dordrecht: Reinel. [A paper on philosophy of space and time]

Glymour, C. (1977). Indistinguishable space-time and the fundamental group. In, J. Earman, J. Glymour, and J. Staechel (eds.), *Minnesota studies in the philosophy of science*, vol 8. Minneapolis, Minnesota University Press. [A paper on philosophy of space and time]

Gibbs, R. W. (2004). *Embodiment and cognitive science*. Cambridge: Cambridge University Press. [A good account of cognitive science developments around the idea of embodied mind]

Gooding, D. (2003). Varying the cognitive span: experimentation, visualization, and computation. In, H. Radder (ed.), *The philosophy of scientific experimentation*. Pittsburgh: University of Pittsburgh Press. [A philosophy of experimentation paper]

Hacking, I. (1983). *Representing and intervening: introductory topics in the philosophy of natural science*. Cambridge: Cambridge University Press. [A modern classic of philosophy of science stressing aspects of experimentation]

Hawley, K. (2006). Science as a guide to metaphysics. *Synthese*, 149, 451-470. [A paper on the subject of the possible relevance of physics to metaphysics]

Heidelberger, M. (2003). Theory-ladenness and scientific instruments in experimentation. In, H. Radder (ed.), The philosophy of scientific experimentation. Pittsburgh: University of Pittsburgh Press. [A philosophy of experimentation paper]

Huggett, N. (2002). Renormalization and the disunity of science. In, M. Kuhlmann, H. Lyre, and A. Wayne (Eds.), *Ontological aspects of quantum field theory*, pp. 255-277. Singapore: World Scientific. [A paper on philosophy of quantum field theory]

Isham, C. J. (1999). *Modern differential geometry for physicists*. Singapore: World Scientific. [A good introduction to differential geometry]

Jammer, M. (1999). *Concepts of force*. New York: Dover Publications. [A historically oriented study of the concept of force]

Jungnickel, C., and McCormmach, R. (1986). *Intellectual mastery of nature: theoretical physics from Ohm to Einstein*. Chicago: University of Chicago Press. [A historical account of the arising of the discipline of theoretical physics in 19th century German universities]

Koyré, A. (1966). *Études d'histoire de la pensée scientifique*. Paris: Éditions Gallimard. [Presents Koyré's views regarding the metaphysical substructure of physics]

Kuhlmann, M., Lyre, H., and Wayne, A. (2002). *Ontological aspects of quantum field theory*. Singapore: World Scientific. [Contains several interesting papers on philosophy of quantum field theory]

Kuhn, T. S. (1961). The function of measurement in modern physical science. *Isis*, 52, 162-76. [A paper stressing the importance of experimentation]

Kuhn, T. S. (1962). Historical structure of scientific discovery. *Science*, 136, 760-764. [A paper revealing subtleties regarding experimentation and its interpretation]

Ladyman, J. (2007). Does physics answer metaphysical questions. In, A. O'Hear (ed.), *Philosophy of science: royal institute of philosophy supplement 61*. Cambridge: Cambridge University Press. [A paper on the subject of the possible relevance of physics to metaphysics]

Lakatos, I. (1978). *The methodology of scientific research programmes.* Cambridge: Cambridge University Press. [Contains diverse writings by Lakatos]

Lyre, H. (2004). Holism and structuralism in U(1) gauge theory. *Studies in History and Philosophy of Modern Physics*, 35, 643-670. [A paper on philosophy of quantum field theory]

Losee, J. A. (1993). *Historical introduction to the philosophy of science*. Oxford: Oxford University Press. [A concise history of philosophy of science]

Ludvigsen, M. (1999). *General relativity, a geometric approach*. Cambridge: Cambridge University Press. [A good introduction to Einstein's theory of gravity]

Malament, D. (1977). Observationally indistinguishable space-times. In, J. Earman, J. Glymour, and J. Staechel (eds.), *Minnesota studies in the philosophy of science*, vol 8. Minneapolis, Minnesota University Press. [A paper on philosophy of space and time]

Mancosu, P. (2008). *The philosophy of mathematical practice*. Oxford: Oxford University Press. [Contains philosophical papers on the actual practice of mathematics]

Matthews, M. R. (2001). Science teaching: the role of history and philosophy of science. In, G. Nagarjuna (ed.), *History and philosophy of science: implications for science education* (pp. 3-20). Mumbai, India: Homi Bhabha Centre for Science Education. [A paper by an expert on physics education]

Merleau-Ponty, J. (1974). *Leçons sur la genèse des théories physiques*. Paris: Librairie Philosophique J. Vrin. [A good work on philosophy of physics]

Merleau-Ponty, M. ([1945] 2006). *Phénoménologie de la perception*. Paris: Éditions Gallimard. [A very influential work to current approaches of cognitive sciences]

Nagel, E. (1961). *The structure of science: problems in scientific explanation*. London: Routledge. [A twentieth century classical of philosophy of science]

Noë, A. (2004). *Action in perception*. Cambridge: MIT Press. [A philosophy of cognitive sciences book centering on the entanglement of human mobility and perception]

Norton, J. D. (1993). General covariance and the foundations of general relativity: eight decades of dispute. *Reports on Progress in Physics*, 56, 791-858. [A historically oriented review on the subject of covariance in Einstein's theory of gravity]

Panza. M. (2011). From velocities to fluxions. In, A. Janiak, and E. Schliesser (eds.), *Interpreting Newton*. Cambridge: Cambridge University Press. [A paper on Newton's development of the mathematical theory of fluxions from his physical description of motion]

Paty, M. (1993). *Einstein philosophe*. Paris: Presses Universitaires de France. [A detailed account of the evolution of Einstein's ideas in relation to space and time]

Pincock, C. (2011). Mathematical explanations of the rainbow. *Studies in History and Philosophy of Modern Physics*, 42, 13-22. [A recent paper on intertheoretical relations centering on a debate with Batterman]

Poincaré, H ([1902] 2009). *La science et l'hipothèse*. Paris: Éditions Flammarion. [A classical of philosophy of science]

Popper, K. R. ([1934] 1959). *The logic of scientific discovery*. London: Hutchinson. [A classical of philosophy of science]

Popper, K. (1967). Quantum mechanics without "the observer". In, M. Bunge (ed.), *Quantum theory and reality*. Berlin: Springer. [A detailed presentation of Popper's criticism to the standard interpretation of the quantum theory]

Radder, H. (2003). *The philosophy of scientific experimentation*. Pittsburgh: University of Pittsburgh Press. [Contains philosophical papers on experimentation]

Redhead, M. (1983). Quantum field theory for philosophers. In, Asquith, P. D. and Nickles, T. (eds.), *Proceedings of the 1982 biennial meeting of the Philosophy of Science Association*. East Lansing:

Philosophy of Science Association. [A paper on philosophy of quantum field theory]

Redhead, M. (1988). A philosopher looks at quantum field theory. In, H. R. Brown and R. Harré (eds.), *Philosophical foundations of quantum field theory* (pp. 9-23). New York: Oxford University Press. [A paper on philosophy of quantum field theory]

Reichenbach, H. ([1928] 1957). *The philosophy of space and time*. New York: Dover Publications. [A classical on philosophy of space and time]

Rosenberg, A., and Mcshea, D. W. (2008). *Philosophy of biology: a contemporary introduction*. New York: Routledge. [A good introduction to philosophy of Biology]

Rugh, S. E., and Zinkernagel, H. (2002). The quantum vacuum and the cosmological constant problem. *Studies in History and Philosophy of Modern Physics,* 33, 663-705. [A philosophy of physics paper that blends issues related to cosmology and quantum field theory]

Schutz, B. F. (1985). *A first course in general relativity*. Cambridge: Cambridge University Press. [A good introduction to Einstein's theory of gravity]

Shapin, S. (1996). *The scientific revolution*. Chicago: University of Chicago Press. [A historical account of the so-called scientific revolution]

Sklar, L. (1974). *Space, time and spacetime*. Berkeley: California University Press. [A book on philosophy of geometry and philosophy of space and time]

Sterelny, K., and Griffiths, P. (1999). *Sex and death: an introduction to philosophy of biology.* Chicago: University of Chicago Press. [A good introduction to philosophy of Biology]

Teller, P. (1990a). Three problems of renormalization. In, H. R. Brown and R. Harre (eds.), *Philosophical foundations of quantum field theory*. Oxford: Clarendon Press. [A paper on philosophy of quantum field theory]

Teller, P. (1990b). A prolegomenon to the proper interpretation of quantum field theory. *Philosophy of Science,* 57, 594-618. [A paper on philosophy of quantum field theory]

Teller, P. (1995). *An interpretative introduction to quantum field theory*. Princeton: Princeton University Press. [A book on philosophy of quantum field theory]

Thompson, E. (1995). *Colour vision: a study in cognitive science and the philosophy of perception*. New York: Routledge. [A book on philosophy of cognitive science centering on the perception of color]

Torretti, R. (1984). *Philosophy of geometry, from Riemann to Poincaré*. Dordrecht: Reidel. [A book of philosophy of mathematics]

van Fraassen, B. C. (1980). *The scientific image*. Oxford: Oxford University Press. [A late twentieth century classic on philosophy of science presenting an anti-realist view]

Wald, R. M. (1984). *General relativity*. Chicago: University of Chicago Press. [A good advanced book on Einstein's theory of gravity]

Wallace, D. (2006). In defence of naiveté: the conceptual status of Lagrangian quantum field theory. *Synthese*, 151, 33-80. [A paper on philosophy of quantum field theory]

Wheaton, B. R. (1983). *The tiger and the shark: empirical roots of wave-particle dualism*. Cambridge: Cambridge University Press. [A historical account of the experimental work related to the wave-particle duality]

Biographical Sketch

Mario Bacelar Valente, teaches philosophy of science at the University of Seville and is a member of the research projects "Filosofía de las prácticas matemáticas: agencia humana, conocimiento y contextos" (reference: FFI2009-10024) and "El legado de la física clásica en la física cuántica y la cosmología" (reference: FFI2008-06418-C03-02).