Philosophy of Physics

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1 Introduction

Physicists face an array of different kinds of challenges. Some involve research—measuring a key parameter, elaborating a theory, or solving some other research puzzle. Other challenges have to do with securing equipment, materials or funding. Yet a third set of problems stems from questions that no amount of physics expertise or resources can make go away. Examples include the following: Why is doing string theory scientific despite its lack of empirical predictions? How to interpret quantum mechanics? What is the nature of time and space? What constitutes fundamental physics? Controversies about these and similar issues have recently riled not only physics but also affect how outsiders view the discipline.

These kinds of controversies arise because physics is a highly complex activity made possible by inherited concepts and convictions that sometimes collide with each other or with developments or discoveries in a way that cannot be resolved by more laboratory research. These clashes can often be handled in a rough and ready practical way by scientists, but the issues behind them also can often be significantly clarified by critical reflection. Because philosophy is the systematic process of critical reflection, this kind of controversy is a place where physics and philosophy overlap, so we can call this third category of issues 'philosophical challenges'. Examining a few such philosophical challenges is a good way to illustrate what philosophy of physics is about, and its value for physicists.

To get an idea of how this overlap can happen, think of the realm of physics as like a giant workshop, a specialized and regulated environment where it is possible to create and study things and events—Higgs bosons, rare isotopes, superfluids—that do not appear, or appear crudely and rarely, in the surrounding world. Inside the workshop, we can be in near-complete control of the things and events we stage to try to understand 'the complicated array of moving things', as Richard Feynman says at the beginning of his lectures on physics. Inside the workshop, we can make sure that the results are general and do not depend on features of the world outside.

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Inside the workshop, researchers can put questions to nature, in Galileo's words, or question it like a court witness, in Immanuel Kant's. Nature is silent to those who would understand it unless it is probed. But there are no blank or formless questions; questions are always 'from somewhere', given specific form by the particular inherited concepts and practices that make meaningful both the questions and the responses. This inheritance consists of certain fundamental and generally unquestioned assumptions about matters taken for granted in the scientific quest for knowledge. Questions arise when mismatches occur between what is found in the world and physicists' expectations, and the answers may call into doubt aspects of the inheritance. Physics grows by answers that modify the workshop traditions—by the introduction of new concepts, such as the Higgs field, that change the tradition—or by seeking out and discovering some piece of evidence that the tradition says should be there: the Higgs field itself.

Philosophers of physics—and to some degree, all philosophers of science, though I will focus here only on philosophers of physics—are interested in the interactive activity of the workshop. But philosophers pay attention to this process differently than physicists do. I'll ignore the ignorant and half-witted remarks about philosophy that I've encountered by physicists who should have known better, and get right to it: philosophers seek to understand, not what physicists know, but how they know it. They study the back-and-forth cycle of interpretation and inquiry, which they call 'the hermeneutic circle', in a technical way. Philosophers investigate matters taken for granted in the workshop, such as the role of the tradition, different manners of questioning, the changing practices and assumptions of those who question, the nature of inquiry, and the way of life that finds it important to inquire into nature. This makes for enormous differences between physics and philosophy, and means that physics and philosophy of physics have different concepts, methods, standards, interests and literature. It also ensures that philosophy of physics is as alive, relevant and as full of active questions as physics itself.

There is a danger that philosophers may try to make the workshop interactions fit a single image or model. They may fall victim to the temptation, for instance, to try to capture what is happening in the workshop in terms of a characterization like 'realism' or 'instrumentalism' or 'nominalism' or 'idealism', and then try to shoehorn what they see of workshop activity into it. This is not only a bad way to inquire into something, but can lead physicists to suspect the wrong-headedness or irrelevance of philosophy. The first duty of a philosopher, like that of any scientist, is to look and describe rather than judge and prescribe. When this happens, it can help resolve the philosophical challenges mentioned above.

2 Background: Three traditions

Several philosophical traditions exist whose pronouncements about science are a function of how their tradition already understands the nature and importance of science. From the outside, their differences may erroneously resemble squabbling political parties with different ideological commitments, but that would be a misperception. Rather, it's that these philosophical traditions have different perspectives on science in somewhat the way physicists, chemists and engineers have different perspectives on atoms; different features are put centre-stage, and analyzed in different vocabularies for different ends.

Three philosophical traditions that have paid particular attention to physics are the analytic (or Anglo-American, so-called because it was developed by British and American philosophers out of logical empiricism), pragmatic, and continental (or hermeneutical) traditions. They are stylistically and methodologically different, though ingredients of each are blended together (with history of science) in what has become known as science studies, which approaches science from the start as a cultural product. The language of analytic philosophy, however, tends to dominate discussions of philosophy of physics.

Analytic

Analytic philosophers, the founding figures of whose tradition included logicians, physicists and mathematicians such as Rudolf Carnap, Hans Reichenbach and Bertrand Russell, tend to be primarily interested in the logic of science and the meaning of its basic concepts. The table of contents of its textbooks are typically divided into chapters on specialized topics: explanation, causality, theories, method and so forth. Analytic philosophers of science, as it were, position themselves as observers inside the workshop. They start with the language of scientific theorizing, and try to figure out the logical conditions for its successes. Analytic philosophers tend to share the view that concepts and theories are what is to be known about the world, and that these are to be judged by testing models against observations. They treat experimentation as the activity that precedes the emergence of theories, and subjects them to evaluation. Analytic philosophers tend to focus on the epistemology of science—on its conceptual and methodological difficulties, on how evidence is produced and evaluated, on the logic of scientific inquiry, and on the conceptual structure of its findings. Analytic philosophers of physics may be said to regard physicists as logicians of the world.

Pragmatic

Pragmatic philosophers, whose founding figures include Charles Peirce (a physicist and metrologist who participated in international surveying projects), William James and John Dewey, tend to be interested in how scientists approach and solve puzzles, and what the consequences are. Pragmatic philosophers of science tend to position themselves outside the workshop, while respecting its process of inquiry. They are aware that humans do not spring into being as scientists, but apprentice to become them. Pragmatic philosophers of science also notice that objects appear in the workshop not independently of the surrounding world but as products of a particular kind of engagement with nature. They also assume, however, that the puzzle-solving process that takes place in the workshop is essentially the same activity that drives everyday life—and they are interested in the puzzle-solving activity of the workshop insofar as the solutions make a difference in the world, and a difference to science as well. True ideas, pragmatists say, are those that make a difference: 'the truth is what works' is a pragmatist slogan. Pragmatically oriented philosophers tend to share the views that inquiry involves doing rather than just cognition, that theories are descriptions of entities found in scientific practice, and that scientific work is to be judged by how well it explains, predicts and gives us power over—rather than merely describes—the world. Pragmatic philosophers of physics may be said to view physicists as puzzle-solvers of the world.

Continental

Continental or hermeneutic philosophers, whose founding figures include Edmund Husserl, Martin Heidegger and Maurice Merleau-Ponty, tend to be interested in the workshop activity as one mode in which human beings can exist among others, and scientific knowledge as one way among others in which human beings are bound up with the world. Like pragmatic philosophers, they are aware that the workshop is its own world, and did not spring into being but arises from a particular way of framing what one experiences. Continental philosophers not only stand outside the workshop and see scientists as caught up in an ongoing dialogue with the world, but also aim to be reflective about where they, the philosophers, stand with respect to the process they are examining—what assumptions they are bringing to bear on it, and how these affect what they see. Continental philosophers tend to agree that workshop activity gives a primacy to things that appear in a certain (framed) way—to things that can be measured and manipulated—and tends to ignore things that do not, such as the powerful prescientific metaphors, images, and deeply embedded habits of thought that shape our thinking. Continental philosophers also agree that it is a mistake to assume that the original human encounter with the world is cognitive, for all ways of being, workshop activity included, spring from a pre-scientific engagement with the world. Humans must be trained—technically and interpretatively—to approach the world scientifically. Continental philosophers see a grave danger, indeed, in forgetting the origins of physics and science in general in the pre-scientific world, a broader milieu called the lifeworld. Continental philosophers may be said loosely to view physicists as disclosers of the world insofar as it is knowable and can be manipulated.

Many contemporary philosophers of physics and practitioners of science studies combine elements of one or more of these three approaches. But these remain the key ingredients, and it is important to understand the basic positions. I will not pause to describe how and why they emerged, or how they relate to each other. It may be frustrating to outsiders to discover that philosophers do not have a unified approach to studying science; it must, indeed, at times seem as pointless as sports analysts arguing over TV replays about the right things that should be done by players on the pitch. But these different approaches are valuable in that they bring different kinds of expertise to their analyses and scrutinize in detail different features of what is taking place: the logic, the puzzle-solving, and the interpretative and self-interpretative activity. Their value is best appreciated by seeing how they approach specific controversies that erupt within physics.

3 Current Directions

Many controversies involving science, such as those concerning creationism and evolutionary theory, have little or no deep philosophical dimensions. Controversies have recently arisen, however, that are created by ambiguous, unclear, unsatisfactory or conflicting background assumptions that physicists have about their own workshop practices. These assumptions do not explicitly appear as objects of investigation in the workshop, and so the controversies cannot be settled by carrying out more physics research. This, I said, creates an area of overlap for physics and philosophy, for these controversies can be handled informally and practically as well as studied systematically and reflectively.

I will therefore discuss four examples of ongoing or new controversies within physics that have attracted philosophical inquiry. These four controversies involve fundamental physics, the nature of space and time, quantum mechanics, and method.

In each of these cases, philosophers of physics approach the topic (time, let's say) as not just a physics topic, but as an issue that must be understood against a broader background of thinking about that topic (time in general). Philosophy of physics is thus not a separate domain in philosophy of science but full of issues that overlap with other discussions.

What is fundamental physics?

In practice, physics does not develop on a planned and unified landscape but in clusters. Groups of practitioners work together sharing interests, methods, problems and literature. Some of these groups overlap with others. Occasionally one cluster will absorb another, as nuclear physics did the science of radiation in the early 20th century, or a new group will develop between two others, as the melding of nuclear and particle physics produced heavy-ion physics in the late 20th century. Sometimes, however, the border between groups is unclear and it is uncertain how fields will evolve, grow and develop. In cases like this, it may be important to distinguish between fields that are fundamental and those that are governed by overarching laws of more basic fields. Does thermodynamics reduce to statistical mechanics? Is condensed-matter physics fundamental, or ultimately just an amalgam of physics and chemistry? The answers to such questions can shape a field by influencing available positions and resources, and its attractiveness for newcomers. Philosophers generally refer to this as the problem of reduction, and see it as posing the issue of what to call fundamental.

Philosophers from the three traditions I mentioned tend to approach this issue differently. Analytic philosophers generally focus on issues of conceptual logic. In his classic 1961 book *The Structure of Science: Problems in the Logic of Scientific Explanation*, for instance, Ernest Nagel devotes an entire chapter to reduction and its formal conditions. He distinguishes two kinds of reduction. One is an unproblematic and 'homogeneous' kind, in which laws created for one entities in one domain—Galileo's laws of falling bodies, say, or radioactive atoms—turn out to apply to another domain of essentially similar things—celestial bodies, or atoms in general. The other is a more problematic or 'heterogeneous' kind, where laws developed at one level of complexity come to absorb another with entities of quite dissimilar traits. A key concept here is 'emergence', or the appearance of properties at a high level of complexity that are not predictable from lower levels. A more detailed account of reduction can be found in *Concepts of Reduction in Physical Science* (1978), by Marshall Spector. In 'Reducing Thermodynamics to Statistical Mechanics: The Case of Entropy' (1999 *Journal of Philosophy* **96** 348), Craig Callendar points out that two commonly used frameworks for statistical mechanics, the Gibbsian and the Boltzmannian, have entirely different implications for the possibility of reducing thermodynamics to statistical mechanics.

Philosophers of a more pragmatic bent would examine these questions in a more social and historical context. The article 'Fundamental Disputations: The Philosophical Debates that Governed American Physics, 1939–1993' (2015 *Historical Studies in the Natural Sciences* **45** 703), by the philosopher and historian of science Joseph Martin, analyzes the reciprocal relation between philosophical arguments and professional pressures as these shaped American physics, including its resources, funding, political standing, and public acceptance, from just before the Second World War to the cancellation of the Superconducting Supercollider in 1993. A key argument turned on the question of reduction. Was fundamentality restricted to particle physics and research into laws governing the smallest bits of matter and energy, as influential reductionists like the physicist Viktor Weisskopf argued? Or was it also present in solid-state physics? Alvin Weinberg, for instance, argued that solid-state physics could be fundamental due to its interconnectedness and fecundity—it's fundamental to other sciences, technologies, and social issues. Philip Anderson, on the other hand, argued for an emergentist position in which solid-state physics could be fundamental; that is, solid-state physics could be fundamental because of the conceptual independence of higher level concepts. Martin examines the differences that these philosophical arguments helped to make in the pragmatically shaped outcome. The argument, he concludes, left an impact on the organization of every level of American physics. '[P]hilosophical outlooks, as elements of scientific discourse, shaped the American physics community's internal politics and external interactions'.

As for the approach of Continental philosophers, the issue of reductionism and emergence tends not to attract their interest. They tend to be interested less in specific problems encountered by physicists inside the physics workshop and more in the practice, thinking and place of that workshop in the larger world before any of its work begins—and how the practice, thinking and place of that workshop might guide the kinds of problems and issues that arise, and how physicists go about solving them. Continental philosophers are therefore more concerned to look at what appears and doesn't appear inside the physics workshop as a clue to illuminating the nature of scientific engagement with the world and its difference from other sorts of engagement.

What are time and space?

Time and space are understood quite differently inside and outside the scientific workshop, creating another arena where the difference between philosophical and physical approaches can be highlighted, as well as the differences between the interests and approaches of the different philosophical traditions.

Time

The difference with respect to time is largely the subject of the historian of science Jimena Canales's 2015 book *The Physicist and the Philosopher: Einstein, Bergson, and the Debate That Changed Our Understanding of Time*. That book is built around an episode that took place in 1922 in which an encounter between Henri Bergson and Albert Einstein set off a heated controversy about time.

Einstein was the world's most famous physicist, Bergson was Europe's most famous living philosopher. Einstein's work bore on profound issues about space and time. Was there an absolute space and time in which there were real lengths and time intervals, which contracted and dilated only apparently but not really—as Lorentz and Fitzgerald thought—or was there no absolute space and time, as Einstein maintained, so that lengths and time actually dilated? These issues were resolved in Einstein's favour.

Bergson saw another set of issues in play. He thought philosophy's mission was to bring to light aspects of reality not captured by scientific representations, or the abstract likenesses of reality like the model situations common in physics textbooks. Such representations are useful if you want to make predictions about and transformations of the world, but Bergson criticized the goal of 'embrac[ing] the totality of things in simple formulas'. Philosophy respects the density and richness of reality, and unearths and describes more aspects than are scientifically representable. Such aspects are found in our experience of time, he thought. Each of us lives through time, Bergson wrote, as a moving continuity that incorporates and allows surprise, novelty and transformation. 'Scientific time,' on the other hand, 'has no duration'. It's been homogenized, turned into abstract clock time that differs from moment to moment only by measurable distance from another point like way a point in space differs from others; all time, all space is the same as all others. But for Bergson, while scientific time is useful for building models and making predictions, that's not the full story of how humans live time. Time is not just for physicists.

At a meeting of the Société Française de Philosophie in April 1922, however, Einstein curtly dismissed Bergson with a devastating sentence: 'There is no such thing as the time of the philosophers'. For Einstein, there's objective, physical time, there's subjective, psychological time, and that's it. The lack of understanding between the two thinkers had many sources; one, no doubt, was the scorn that Bergson had heaped on quantified time in his books. But the dispute also reflected a division between the approach of physicists, for whom time is a measurement tool, and philosophers, who describe experienced time as a flow. The dispute was a symbol of the stark difference and mutual incomprehension of the two fields, and revealed some of the obstacles in the way of a dialogue. The difference between philosophical and physical views of time persists today, with many physicists dismissing the reality of experiential time, maintaining that real time is an abstract, durationless, precisely measurable quantity—the time of the clock.

Analytic philosophers are not much concerned with the difference between workshop time and ordinary time, and tend to focus on the logic and concept of the former. In an article in the *Journal of Philosophy* (1967 **64** 241), for instance, the American philosopher Hilary Putnam denied that there are 'any *philosophical* problems about Time; there is only the physical problem of determining the exact physical geometry of the four-dimensional continuum that we inhabit.' Other analytic philosophers have addressed the question of what kind of theory of time scientists hold—characterizing it as idealism, realism, or relationism, for instance—the nature of the distinction between past, present, and future, and issues including the nature of tense and the relevance of empirical linguistics. Pragmatists are less interested in these issues, seeing time as a dimension of inquiry itself. For Dewey, for instance, clocks and other measures used to characterize events in science are of less importance than the purposes and plans of the inquiries into those events, which rely on a different kind of time.

Continental philosophers concerned with time—who include Bergson—are on the other hand interested in just this difference between time inside and outside the workshop. For Kant, Husserl, Heidegger and others, perceiving the 'now' is only possible if we experience time, not as one instantaneous moment after another, but as a flow in which we retain phases of past perceptions and anticipate future ones. Only by such temporalizing, as it is called, can we experience both continuity and surprise in the present. Temporalizing is therefore a condition of the possibility of having a world in the first place; it's what it means to live through the present. This process is so close to us that it is impossible to see directly and difficult to interpret. Time, then, is not the result of some inquiry, some measurement, nor a tool of some project. Inquiring, measuring and having projects, in fact, are activities that we can plan and carry out and evaluate thanks to the fact that we temporalize, that we live *through* time. It is the pre-given horizon for all human activities. It even allows us to do such things such as create theories about time. The time of the clock depends on the time of the clockmaker. Continental philosophers thus tend to see clock time as part of the framing practice of the workshop, and the things and events that appear in that frame have a priority in our research. Clocks are used, not because workshops demand them, but because the way of life that workshops respond to demand them. Clocks, that is, measure time as we have already come to understand it as researchers into moving things. It then becomes a key part of the appearing of objects in the workshop.

Space

A similar gap also exists in notions of space, even if that divergence has never crystallized into a specific encounter as it did between Einstein and Bergson over time. Physicists are apt to explain the everyday experience of space as a smooth, 3D arena in which things always have definite positions as an illusion—a by-product of the limited sensory faculties of humans. As the German mathematician Hermann

Minkowski proclaimed in 1908, 'space by itself, and time by itself, are doomed to fade away into mere shadows', for only 4D spacetime can preserve 'an independent reality'. In quantum mechanics, moreover, the uncertainty principle forbids things from having definite locations.

In more speculative theories, space is more complicated. Some versions of quantum-field theory picture a fluctuating space–time foam. In loop quantum gravity, space is quantized, with its patches unable to become infinitely small. String theorists insist on 10, 11 or 26 dimensions, with the extra ones closed or 'compactified' so they are unseen even in current scientific experiments. The Columbia University theorist Brian Greene's 2011 book *The Hidden Reality: Parallel Universes and the Deep Laws of the Cosmos* discusses no less than nine types of alternate universes. Physicists, it seems, can't agree on what space is.

Philosophers, by contrast, tend not to consider the ordinary experience of space illusory. They are more interested in features that make such experience possible—features that are not incidental or subjective but belong to the full reality of spatial experience. As the French philosopher Maurice Merleau-Ponty wrote in his 1945 book *Phenomenology of Perception*, these aspects are like 'the darkness needed in the theatre to show up the performance'.

Philosophers, for instance, distinguish between 'allocentric', 'perceptual' and 'bodily' space. Allocentric space is an objective space in which locations and orientations can be defined—with a GPS, say—without reference to an observer's location. Perceptual or 'egocentric' space was identified in the 18th century by Kant. It is based on the spatial orientation provided by an observer's body—up and down, right and left, front and back—without which it would be impossible to locate something in allocentric space even with a compass or GPS device.

Bodily or 'proprioceptive' space was described by 20th-century philosophers (including Merleau-Ponty) as an awareness of the presence of your own body and its ability to move. It is the sense you have of your head and hands as you scroll through this ebook. Bodily space is the non-mathematical sense called upon in walking, playing and operating things such as a GPS or a compass. Bodily space is thus parallel to lived time. Historically minded philosophers of physics, meanwhile, like to point out that the assumption of what Kant called 'simple location'—the idea that everything is always at a particular place at a particular time—is a historically contingent idea, one that the English philosopher Alfred North Whitehead, in his 1925 book *Science and the Modern World* called 'the very foundation of the seventeenth century scheme of nature.' Space, in short, is not just for physicists.

Given the gap between the physical and philosophical approaches to time and space, you might wonder why we don't just assume that physicists and philosophers investigate different things: time and space versus duration and place, say, or Time and Space versus time and space.

That will not work, for physics and philosophy are both ambitious disciplines; each aims to describe *the* world, not just a particular slice of it. As the physicist John Bell wrote: 'To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation will not exclude the big world outside the laboratory.' That big world includes human experiences. Husserl, meanwhile, denounced the 'scientific fanaticism' of those who think they are studying the world when they rely on only what shows up in laboratories. Philosophy's task, as Husserl saw it, is to investigate the basic features of all human activities, including science, and the experiences that make them possible. Both physicists and philosophers, then, insist that they are the ones talking about 'Time' and 'Space' rather than 'time' and 'space'. One of the tasks of philosophy of physics is to come up with a framework which accommodates these seemingly conflicting ambitions.

How to interpret quantum mechanics?

Physicists who were in at the beginning of quantum mechanics, and in particular Niels Bohr and Werner Heisenberg, realized that it collided with long-standing concepts and assumptions about the theory and practice of physics and even nature itself—that it, in short, raised philosophical issues in the sense I have been describing. Noting, for instance, that orbital trajectories and frequencies had no measurable consequences, Heisenberg was led to a reinterpretation (*Umdeutung*) of kinematical and mechanical relations in quantum theory in his famous paper launching quantum mechanics (1925 *Zeitschrift für Physik* **33** 879). New kinematical concepts, he thought, were required to understand the quantum realm and describe its ontology (the kind of existence that it has). Bohr adopted a different approach. New kinematic concepts were not required, and in fact were impossible. While Heisenberg thought that quantum mechanics forced scientists to develop and adopt a new, non-classical descriptive framework, much as relativity had, Bohr thought that such a new framework was not necessary and that one need only use the old classical concepts while accepting their restricted domains of applicability. At the Como conference in September 1927, Bohr labelled his solution to the philosophical difficulties 'complementarity', which since then has been considered a principal feature of what eventually would be called the 'Copenhagen Interpretation'. Bohr managed to get Heisenberg, who was interested in philosophy, to subscribe to the idea at least for a time. It was not a true philosophical solution, however, for it swept philosophical difficulties under the rug. It left vague many concepts crying for greater philosophical specification, including measurement, observation, ontology, objectivity, and the ontology of the wave function. The resulting perplexities have not vanished in the ensuing decades.

Guido Bacciagaluppi and Antony Valentini's book *Quantum Theory at the Crossroads: Reconsidering the* 1927 *Solvay Conference* examines some of the early philosophical discussions of quantum mechanics. Patrick Heelan's books *Quantum Mechanics and Objectivity: A Study of the Physical Philosophy of Werner Heisenberg* and *The Observable: Heisenberg's Philosophy of Quantum Mechanics* examine the trajectory of Heisenberg's philosophical interpretations of quantum mechanics. It is the argument of David Kaiser's book *How the Hippies Saved Physics: Science, Counterculture, and the Quantum Revival*, which argues that thoughtful discussion of interpretations of quantum mechanics declined after the Second World War, and that the absence of a robust philosophical account of quantum mechanics played a role in wacky developments such as popular culture associations of it with Eastern mysticism.

Quantum mechanics is indeed difficult to interpret. It describes the world as the product of two ingredients: an information function (wave equation) that overlays possibilities, and something that dispels this function and turns one of its possibilities into reality. The strangeness of this non-classical account has inspired attempts to restore the conventional concepts. One way is to deny the significance of the first ingredient (the wave equation) by saying that the eventual discovery of hidden variables will restore the classical framework; the other way is to deny the significance of the second ingredient by claiming that the other possibilities do not go away but all continue to exist in parallel (the 'many-worlds' interpretation). The first way seems to have been experimentally disproven, while the second generates no testable predictions and makes a hash of the philosophical notion of reality. Serious interpretations therefore focus on the role of the wave function.

The epistemology of quantum mechanics—its implications for what can be known—is the principal theme for the analytic approach. One key issue, for instance, involves questions that quantum mechanics poses for the logic and nature of indeterminacy—the condition in which it is impossible to ascertain the values of variables except within limits—and what this implies for the completeness or incompleteness of the theory. This, for instance, is the context in which Nagel discusses quantum mechanics in *The Structure of Science*. In *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective*, Max Jammer provides a thorough analysis of the half-century or so of interpretations. More recently, other kinds of interpretations have appeared within the analytic tradition. One example is 'Qbism', or quantum Bayesianism, which treats epistemological issues as concerning beliefs within a broad Bayesian perspective—effectively transforming knowledge into probabilities.

In the pragmatic perspective, Dewey saw the development of quantum mechanics not as a puzzle or challenge but as a confirmation of his view that knowledge is not a spectacle—a view which he called the 'spectator theory of knowledge'—but an artefact, the product of an interaction with the world. Pragmatism, he thought, had effectively already anticipated Bohr. In quantum mechanics, Dewey wrote in *The Quest for Certainty: A Study of the Relation of Knowledge and Action* (1929) 'What is known is seen to be a product in which the act of observation plays a necessary role. Knowing is seen to be a participant in what is finally known.' Dewey continued, 'The principle of indeterminacy thus presents itself as the final step in the dislodgment of the old spectator theory of knowledge. It marks the acknowledgment, within scientific procedure itself, of the fact that knowing is one kind of interaction which goes on within the world.'

The continental approach is to take a strictly phenomenological approach to quantum mechanics. Phenomenology, a movement within continental philosophy initiated by Husserl begins by questioning the 'natural attitude'—the perspective in which we ordinarily experience the world. The natural attitude takes for granted the being of the things we encounter: sticks and stones, people, scientific entities, and so forth. Phenomenologists seek to set aside the assumptions of this attitude to examine the raw data, so to speak, of how these things appear to us. It turns out that how an object is grasped depends on how the grasper is 'positioned' with respect to it. When we apprehend a cup, for instance, it never shows all of itself to us at once but only in profiles depending on how we are positioned. This is nothing subjective, but simply the way that things in the world appear. Phenomenologists are therefore able to describe the being, the ontology, of things that are only revealed piecemeal in the world via profiles to embodied observers. What, then, is the ontology of quantum phenomena? These, too, show themselves differently depending on how the observation is made. There are two differences between quantum phenomena and the classical phenomena traditionally studied by phenomenologists. First, quantum phenomena are not observed by naked perception but mediated through instruments; second, while classical phenomena can be returned to as 'the same'—I can move to see the backside of the cup and then return to see the same front again—this is not the case with quantum phenomena. Quantum phenomena are path dependent, meaning that the order of the decisions that take place in the environment affecting the appearance of the phenomena can affect the way it appears not only at that moment but also in the future.

In the two books on Heisenberg's interpretations of quantum mechanics mentioned above, Heelan has made the most ambitious attempt to interpret quantum mechanics by a continental philosopher. Our Newtonian instincts—our natural attitude as scientists—assumes that atomic phenomena such as electrons have, as Heelan says, a 'kinematic place and motion in the space and time of the laboratory', but our physics says otherwise. This is due to the fact that such phenomena, when measured, are not simply present but made present by experimental contexts in which they turn up in vastly different and even apparently incompatible ways. Thus arises what Heisenberg considered the 'central issue about quantum mechanics', according to Heelan: 'Can a quantum entity that is 'non-intuitable' but nevertheless 'observed' in a laboratory measurement be 'real' in the 'ontological' sense?' Heelan proceeds to apply phenomenological approaches to describe in what sense it can. Despite this and other philosophical work, physicists themselves do not agree on how to interpret quantum mechanics, meaning that there is still lots of work to keep both philosophers and physicists busy on this topic.

Is there a scientific method?

Is string theory scientific? How is that even a legitimate question? While many physicists consciously accept that string theory is scientific, other physicists have labelled it an unscientific sham for methodological reasons, inasmuch as it has no experimentally testable predictions and, barring a miracle, will have none for decades. Because it cannot be experimentally 'tested' as per the traditional logical empiricist/analytic requirement for scientific method, some physicists have even pointed to apparent similarities between the scientific status of string theory and intelligent design (see, for example, Robert Ehrlich 2006 *Physics in Perspective* **8** 83, though Ehrlich ultimately considers string theory scientific and intelligent design not). Surely a description of the scientific method ought to be able to lay this nonsense to rest!

Here, again, the philosophical traditions I have mentioned approach the issue differently.

The background to the controversy was generated by the logical empiricist/analytic tradition, which outlined criteria for the scientific method that were too rigid, setting the bar for what counts as 'science' too high. Scientific method was described as a process that started with data obtained from observations, moving to a theoretical level able to make calculable predictions with logical rigour, and then looking for these predictions in the world, delivering facts to start anew. To state it concisely, the logical empiricist/analytic approach to scientific method saw it as an abstract and formalistic process that conceived science as comprised of a system of syntactic rules and a set of meanings for its terms, as well as an experimental infrastructure whose aim was to determine the outcome of predictions, with the overall goal objectification and explanation. This simple picture is often called the deductive-nomological or DN model. John Kemeny, in his 1959 book *A Philosopher Looks at Science* diagrammed it to resemble an inverted U or a football goal. Induction (turning data points into generalizations) is a post that rises from the field (or 'world of facts'), connects with a crossbar or theoretical realm that leads to a prediction, whose verification returns via the other goalpost to the ground. Science's strength depends on its regular earthly contact. As science is endless, Kemeny says, 'we may expect this cyclic process to continue indefinitely'. Analytic philosophers often invoke cherry-picked stories about discoveries in an attempt to show that this is the way it must be. Kemeny, for instance, proceeds to illustrate the inverted U model of scientific method with a canned story about the discovery of the planet Neptune whose discovery was predicted on the basis of calculations drawn from irregularities in Uranus's orbit.

The analytic tradition has sometimes sought to modify the rigid picture of scientific method that it inherited from logical empiricism, but it still shares the focus on method, confirmation, and theorizing rather than experimentation and practice, and screens out other aspects, such as conjecturing, imagination and discernment, relegating these to psychology and sociology. To use another sporting analogy, it views science as about scoring; it focuses on scoring strategies and not on such things as how the game evolves, the attitude of its players, its social role, or indeed the actual game-playing. To be scientific is to adopt optimal scoring strategies; the aim of traditional logical empiricist/analytic philosophy of physics is to describe the optimal strategies in terms of evidence and justification.

String theory does not meet the rigid criteria for scientific method—a serious problem given how thoroughly the language of logical empiricist/analytic philosophy permeates philosophy of science. In *String Theory and the Scientific Method*, Richard Dawid—a physicist and philosopher from the University of Vienna—confronts this problem head-on. Dawid seeks to amend the traditional logical empiricist/analytic philosophy of science, arguing that physicists can be on solid ground when drawn to a theory for reasons other than testability, and proposes criteria. He makes three arguments, and in the style of analytic philosophy gives them acronyms: there may be No Alternatives to the theory (NAA, for No Alternatives Argument), the theory may bring Unexpected Coherence or clarity (UCA), and its research programme may be analogous to others that have succeeded (the Meta-Inductive Argument or MIA). His analytic approach disposes him to try to formulate a revised form of 'the scientific method' that's similar to the old one, but with amendments. We might call his approach a 'Modified Analytic Response' (MAR) that does whatever tinkering is needed to keep the analytic account from getting too out of touch with actual scientific practice. It amounts to an admission that the 'Neptune discovery' example of scientific activity is canned and extremely rare, and to make it a model for scientific method disenfranchises vast amounts of clearly scientific activity.

Dawid's book is unusual within analytic philosophy of physics, informed as it is by the seasoned sense of a scientific practitioner. He knows that the physics game he's playing is going on just fine—even though it is missing a goalpost and has a *very* long crossbar that vanishes off the horizon. He's disturbed enough by the mismatch between the physics he knows and what the analytic tradition tells him to challenge the latter. Dawid wants to amend the scoring strategies of physics by adapting the rules to what he as a player knows to be happening on the field. This, however, may be received in the analytic community as a Trojan Horse, for downplaying testing and admitting a role for the experiences of a practising physicist amounts to repudiation of a core feature of logical empiricist/analytic philosophy of science.

Dawid's willingness to start with his practice as a scientist and challenge what has been said about that practice shares much with pragmatism. Pragmatic approaches to scientific method are much more inclusive than analytic approaches, and not only respect but mesh better with actual scientific practice. In the case of string theory, for instance, they would focus less on whether or not string theory followed the right rules and more on whether it furthered the relevant process of inquiry. One of the founders of the pragmatist movement was Charles S Peirce, who was trained in astronomy, physics, and metrology and participated in international surveying projects. Peirce's views on scientific method reveal the influence of his scientific work and his metrological experiences in particular, which allowed him to appreciate features of science that eluded—and still elude—those with a more formalistic outlook. In conducting inquiry, Peirce continues, scientists inherit the often defective tools, hypotheses and experiences of predecessors. But it doesn't matter if these are defective or imperfect, because science does not proceed like mathematical demonstration, but is a fallible process in which a community of inquirers corrects errors in ongoing revision. Knowledge grows, not in a staccato-like way in which one representation replaces another, nor even in which one paradigm replaces another, but in a continuously expanding process in which a concept's meaning is not an abstraction or picture, but the totality of its effects on the world. Peirce also appreciated that scientists' education and experience was valuable, for it gave them an educated taste for important problems and the means to tackle them. In contrast to his friend and fellow pragmatist William James, Peirce—thanks to his metrological experiences—saw science as not built of individuals confronting puzzles in private, but of networks of competent individuals working in a network of labs in an inherently public enterprise. Peirce, too, appreciated the 'economy of research'; that an important part of science is maximizing the resources of available 'money, time, thought, and energy' when deciding what to work on and how to express one's results.

Peirce thus rejected the abstract and formalistic picture of scientific method. Instead, he described inquiry of all sorts—science included—in terms of a more sophisticated and historically evolving process with three intertwined dimensions. One dimension, which he called 'firstness' or abduction, involves paradigm-breaking creativity; an analogue in physics might be the appearance of novel ideas for measurement techniques. Another, 'secondness' or induction, involves the systematic implementing of ideas in a manner that respects the play of causes and effects—such as in the design and execution of measurement techniques. The final dimension, 'thirdness' or analogical deduction, involves the operation of a distributed, open ended, evolving social matrix, such as the role of the international surveying project to which Peirce belonged, in which a community acquires and retransmits new habits. Peirce viewed previous philosophy as suffering from the neglect or over-emphasis of the role of one or more of these elements, and his philosophy as pointing to their proper balance.

String theory, in this pragmatic light, is eminently scientific, not because of any set of predictions and confirmations, but for other reasons. These include the insights it yields about existing physics (field theory, for instance), the way it carries forward the concerns and aims of theoretical physics, and the way it is conducted by a community of physics researchers. While analytic philosophy is not well poised to illuminate actual scientific practice in an important way, pragmatism helps highlight the way theory-change is motivated by the needs of practice, and sometimes a motivating source for that practice. String theory is scientific, in short, because it is having a transformative impact on—making a difference to—the scientific community.

If one can speak of method for a continental philosopher it means seeking a way to get a phenomenon to show itself to an inquirer as what it is. A continental approach to method would not seek to dictate procedures to scientific activity, but to understand the interpretations driving it. Like other theories, string theory reflects an attempt by scientists to revise and transform the concepts they've inherited in the light of something that does not fit. A continental philosopher of physics thus would approach string theory with less interest in evaluating its scientific character using a set of criteria, and more interested in the way it is thought to make sense of the world. Developing a new theory is not like picking and choosing a wallpaper, but an interpretive process. Physics is less a matter of testing lucky theoretical guesses than a continual reinterpretation that makes explicit what scientists already understand, partly but imperfectly, in the light of new discoveries. A continental approach would ask such questions as: Who is the community that is interested in string theory, what are its interests, why does that community consider string theory to address those interests? It would seek to bring to light in a systematic and reflective way what the practitioners understand experientially about physics that gives them the sense that string theory (say) is (or is not) scientific. A continental approach, in short, would be interested in how pursuing string theory reflects the way of life of those carrying it out.

The case of Yang–Mills

A dramatic illustration of the flaw of relying on an inverted 'U', Neptune-discovery-like model of scientific practice concerns the history of Yang–Mills theories. In 1954, when the future Nobel-prize-winning physicist Chen Ning Yang and Robert Mills first proposed their mathematical scheme for treating the strong interaction, it was a non-starter according to the rules of traditional analytic philosophy of science. As Wolfgang Pauli pointed out to Yang in a blunt exchange during a seminar, Yang's theory had a show-stopping defect: in such theories, the mass of such a field had to be zero. In quantum electrodynamics, which is a so-called 'Abelian' theory, it is fine that the force-carrying particle (the photon) is massless; but extending field theory to hadrons required a 'non-Abelian' theory, in which nature requires that the force-carrying particles be massive. When Pauli asked Yang how the force-carrying particles in his field would acquire mass, Yang was unable to respond, and in a hostile manner Pauli therefore dismissed the theory as wrong. Pauli was only channelling the voice of the quantum field theory of the day. The Yang–Mills theory involved massless force-carrying particles, and nature said that this was not true in the domain where its authors were trying to apply it. The 'Pauli snag' meant that, by the standards of traditional analytic philosophy, the Yang–Mills theory was clearly wrong from the outset. Yet he and Mills published their idea anyway (1954 *Physical Review* **96** 191–5). Years later, in his *Selected Papers*, trying to express their rationale for publishing the idea despite the obvious defect, Yang wrote simply: 'The idea was *beautiful* and should be published.' As it turned out, the theory went on to become an integral part of modern theoretical high-energy physics, the framework on which modern field theory is built.

This transformation happened in a complicated, 20-year saga with unexpected twists, dramatic moments, and tangled plots and sub-plots, which I have sketched out in 'Yang–Mills for Historians and Philosophers' (2016 *Modern Physics Letters A* **31** 7). Spontaneous symmetry breaking and quarks (discovered in the 1960s), as well as the asymptotically free field theories of quantum chromodynamics (developed in the 1970s) showed that the relevant physical states are not quarks and gluons but colour singlets. A gauge theory of the sort that Yang and Mills were aiming to build therefore turned out to apply to entities different from the neutrons and protons and pions that had inspired their effort. The moment when Yang–Mills went from an 'unscientific' (according to traditional analytic criteria) theory that did not apply to the world to a 'scientific' one that did cannot be pinned to any specific date between 1954 and, say, 1975. It required a gradual shift in ideas about the world to which the Yang–Mills proposal itself contributed and even made possible. (I know that last sentence is vague, and would need to be fleshed out by discussion of the actual experimental practices and evolving theories, and interactions within the scientific community in which the impetus for these shifts is to be found.)

The traditional analytic framework, then, forces one to say that, in 1954, the Yang–Mills theory was *not yet* true of the world, or that the theory was developed for the *wrong* world. But this is silly; Yang and Mills developed the theory precisely because they *were* responding to their world. The lesson for philosophy of science is that one cannot understand the change in attitude towards Yang–Mills by looking from the outside and judging the theories it accepts by some imposed criteria. If you want to understand scientific theorizing, you need to know about the experimental context and the communal world in which such theories are developed and modified.

A pragmatist, for instance, would be impressed by the impact that Yang–Mills theory had on high-energy theory. It established field theory as the dominant theoretical language. It had longer-term structural effects; its development made possible the beginning of the era when you were confident that looking at constraints at low energies could allow you to make predictions at extremely high energies. Over time, the landscape of high-energy or short-distance physics has been dramatically reshaped by Yang–Mills theory, in a way likely to remain a key part of future developments. Yang–Mills theory made a difference.

A continental philosopher would be interested in Yang–Mills theory for the way it shows that theory-making is not always a matter of seeking something provable and applicable to the world, but can involve articulating a sense of the world that has not yet taken shape, yet nevertheless resonates with current practice in a way that ends up furthering it. This is something neither analytic philosophy (with its focus on method) nor pragmatism (with its focus on puzzle-solving) is poised to appreciate, for it requires an account of the experience of scientists, perhaps articulated in part by someone who seeks to understand this practice as it is experienced. A continental philosopher of science would want to sit down with Yang and explore what he was intuitively trying to express by the word 'beautiful'. What did he know that made him confident enough to publish despite what 'one said' about force-carrying bosons and theories requiring experimental confirmation? In some cases, it seems, theory-making involves summarizing and organizing some pre-existing sense of the world that is not yet explicitly stated, before any proof or evidence (afterwards, of course, we can say it was this way all along). The 1954 Yang–Mills theory laid out what would make it possible for the resources of quantum field theory to apply.

Other issues

The three philosophical approaches to physics that I mentioned reveal their differences when they have actual work to do. Many more issues could be cited that analysts, pragmatists, and phenomenologists approach with different aims and results. Allan Franklin, for instance, examines the epistemology of experiment, or as he puts it in 'Experiment in physics'—an article from the web-based Stanford Encyclopedia of Philosophy—the 'set of strategies that provides reasonable belief in experimental results'. Pragmatists are interested less in epistemological issues within experimentation than in its broader role within inquiry, while continental thinkers focus on the character of the experimental approach to nature and on its relation to other kinds of performed events. Aesthetics is another issue that highlights differences between the philosophical approaches to physics. The mathematician and philosopher Gottlob Frege counselled abandoning ‘aesthetic delight for an attitude of scientific investigation’; Dewey thought that aesthetic issues could not be separated from inquiry; while continental philosophers see aesthetic issues as part of the experimental way of life.

4 Outlook

Aside from continuing work on these and other issues, several kinds of challenges lay ahead.

One is to make clear the value of the work of these three philosophical approaches to those who understand and practise physics. These approaches bring different kinds of expertise to their analyses and scrutinize in detail different features of what is taking place: the logic, the puzzle-solving, and the interpretative and self-interpretative activity of physics. These three groups of philosophers, who look at different dimensions of scientific practice with different aims and audiences in mind, tend to include people with expertise in fields that lie beyond physics. Their research, in other words, may well help physicists themselves to think about their work in ways they ordinarily do not, and to ward off misconceptions about the nature of scientific activity. Pointing out misconceptions is indeed something that philosophers are extremely good at. One contribution of philosophers might be to underscore the insight that physics is a practice, not a method that’s learned and applied mechanically. Another might be to help physicists to beware of becoming vulnerable to ‘Pauli snags’—to hesitating when an intuitively appealing theory collides with firm convictions.

A second challenge is for philosophers of physics to be on the lookout for ‘Yang moments’, or places where physics appears to become ‘stuck’ because long-standing convictions or practices are clashing with new developments or discoveries or experiences in a way that cannot be reconciled by doing more physics. Such moments are prone to reveal deep and still undisclosed features of physics. What, for instance, *did* Yang mean by ‘beautiful’? He knew something of critical importance to theory-making, but was unable to say it to Pauli. This is the kind of thing that fascinates phenomenologists, who explore physics as it is lived and practised, and who are especially interested in collisions between the experiences of practitioners and what one is able to say about those experiences. Whatever Yang was onto at that moment is important for philosophers of physics to study—and any philosophy of physics that neglects it or tries to define it out of physics is not serious.

For philosophers of physics should not take their most important problems from textbooks but from the practice of physics itself.

Additional resources

General

Batterman R (ed) 2013 *The Oxford Handbook of Philosophy of Physics* (New York: Oxford University Press)

A general, wide-ranging introduction to issues in philosophy of physics within the analytic tradition.

Bitbol M 2008 Is consciousness primary? *NeuroQuantology* **6** 53

Explores how answers to the question posed in the title frame differences between philosophy and the sciences.

Bunge M 1973 *Philosophy of Physics* (Dordrecht: Reidel)
A discussion of some issues in the methodology and foundations of physics from an analytic perspective. Contains the notable sentence, 'Philosophy, methodology and foundations, like rose bushes, are enjoyable when cultivated but become ugly and thorny when neglected.'

Crease R P 2012 Phenomenology and natural science *Internet Encyclopedia of Philosophy* http://www.iep.utm.edu/phenomsc/
A general introduction to issues in philosophy of science within the continental tradition.

Crease R P 2003 Inquiry and performance: Analogies and identities between the arts and the sciences *Interdisciplinary Sci. Rev.* **28** 266
Uses the concept of performance, or the conception, production, and interpretation of events to illuminate aspects of experimental inquiry.

Rescher N 1979 *Peirce's Philosophy of Science* (Notre Dame: University of Notre Dame Press)
A study of the philosophy of science of Charles S Peirce, a noted physicist and pragmatist philosopher.

Renn J *et al* (ed) 2007 *The Genesis of General Relativity: Sources and Interpretations.* Boston Studies in the Philosophy of Science 2504 vols (Berlin: Springer)
Includes discussions of some of the philosophical issues in the development of relativity.

Ryckman T 2005 *The Reign of Relativity: Philosophy in Physics 1915–1923* (New York: Oxford)
The early impact of general relativity on philosophy, which among other things illuminates the differences between analytic and continental philosophy.

Ströker E 1997 *The Husserlian Foundations of Science* (Boston, MA: Kluwer)
Describes the approach to natural science of Edmund Husserl, founder of phenomenology.

Zammito J H 2004 *A Nice Derangement of Epistemes: Post-Positivism in the Study of Science from Quine to Latour* (Chicago, IL: University of Chicago Press)
A survey of the past half-century of science studies.

Reductionism and the fundamental

Martin J D (forthcoming). *Solid State Insurrection* (Pittsburgh, PA: University of Pittsburgh Press)
Contains a description of the debate between particle and solid state physicists over the nature of fundamental research exhibiting the reciprocal impact of philosophical views and professional pressures.

Sklar L 1993 *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge: Cambridge University Press)
An accessible account of the philosophical foundations of statistical mechanics that covers a range of topics.

Spector M 1978 *Concepts of Reduction in Physical Science* (Philadelphia, PA: Temple University Press)
A detailed analysis of the conceptual issues of reduction in the physical sciences by an analytic philosopher.

Time and space

Casey E S 1998 *The Fate of Place* (Berkeley, CA: University of California Press)
A history of the conceptualization of space/place in Western thought by a continental philosopher.

Earman J 1989 *World Enough and Space-Time: Absolute Versus Relational Theories of Space and Time* (Cambridge, MA: MIT Bradford)
A history of concepts of time, framed by the extended clash between Newtonian absolutist and Leibnizian relativist notions, in a way that sheds light on contemporary debates in physics.

Sklar L 1974 *Space, Time and Spacetime* (Berkeley, CA: University of California Press)
A study of issues in understanding space and time that require the tools of both physics and philosophy.

Quantum mechanics

Albert D Z 1994 *Quantum Mechanics and Experience* (Cambridge, MA: Harvard University Press)
An exploration of measurement issues in physics from an analytic perspective.

Barad K 2007 *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Durham, NC: Duke University Press)
An ambitious phenomenology-like interpretation of quantum mechanics.

Bub J 1999 *Interpreting the Quantum World* (Cambridge: Cambridge University Press)
A study of interpretive issues involving measurement, with a particular focus on 'no-collapse' interpretations.

Heelan P A 1995 *Quantum Mechanics and Objectivity: A Study of the Physical Philosophy of Werner Heisenberg* (The Hague: Nijhoff)
Heelan P A 1965 *The Observable: Heisenberg's Philosophy of Quantum Mechanics* (Lang).
These two books trace and develop the evolution of Heisenberg's philosophical thinking within a phenomenological perspective. Bitbol's introduction to the latter work provides a valuable introduction to continental philosophy of physics for physicists.

Jammer M 1974 *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective* (New York: Wiley)
A study of the first half-century of evolving interpretation of quantum mechanics and its logical foundations

Spector M 1990 Mind, matter, and quantum mechanics ed P Grim *Philosophy of Science and the Occult* 2nd ed (Albany, NY: State University of New York Press) pp 326–49
A sober analysis by an analytic philosopher of the implications of quantum mechanics on metaphysical issues of mind and matter.

Von Baeyer H C 2016 *QBism: The Future of Quantum Physics* (Cambridge, MA: Harvard University Press)
An interpretation of quantum mechanics in terms of Bayesian probability theory.

Method

Crease R P 2015 Two paths for continental philosophy of science *J. Dialect. Nat.* **37** 111
Continental perspectives on issues in philosophy of science, including method.

Dawid R 2014 *String Theory and the Scientific Method* (Cambridge: Cambridge University Press)
A philosopher and string theorist demonstrates the necessity of alterations to the account of method in conventional analytic philosophy of science.