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## AUSZUG - EXTRAIT

### Progress in Physics (67)

Philosophy of physics – what is it and why is it worthwhile to study it?

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# Progress in Physics (67)

## Philosophy of physics – what is it and why is it worthwhile to study it?

Claus Beisbart, Uni Bern

These days, philosophy seems to be ubiquitous. In bookstores, we find popular books on philosophy, business companies pretend to have their philosophy, and universities offer degrees of advanced studies in, e.g., philosophy and medicine. It should not come as a surprise then that there is also a philosophy of physics. The latter is a growing field of scholarly research, as is evident from handbooks [1, 2, 3] and textbooks [4, 5, 6] as well as from conferences and summer schools. For the next few years, it is planned that the section “History of Physics” in the SPS features more philosophy of physics. But what exactly is philosophy of physics? Is the term more than a catchword, and why should it be worthwhile to study philosophy of physics?

### 1. A historical route to philosophy of physics

Historically speaking, it is no accident that physics and philosophy combine within philosophy of physics. For ages, physics and philosophy have been close friends as they share a common origin. At the dawn of Western thought in Ancient Greece, physics and philosophy were indeed difficult to disentangle. For instance, when Thales of Miletus (ca. 624 – ca. 546 BC) claimed that the ‘arche’ (the origin, basic principle) of everything was water, or when the so-called atomists suggested that the material world consisted of little indivisible particles, they put forward what we today take to be physical hypotheses. But although the content of their views is reminiscent of physics, their method was not physical in our sense of the term; they did not run controlled experiments but instead engaged in what we may call philosophical speculation. What we can call philosophical too is their aspiration to move beyond the appearances and to understand what the world really is.

The close alliance between physics and philosophy survived until the Scientific Revolution in the 18<sup>th</sup> century. It is interesting to note in this respect that, according to its title, Isaac Newton’s (1642 – 1726/27) main work on mechanics is part of natural philosophy. But further development

of modern physics required increasing experimental skills and mathematical sophistication, which, in turn, effected a specialization that eventually pushed philosophers out of physics. At the same time, technological innovation and the systematic use of the method of experiment provided

an increasing amount of data, which meant that less “philosophical” speculation was needed to learn about matter, its composition and the principles of its motion. But this did not mean that no task was left for more philosophically minded people. Some philosophers, notably Immanuel Kant (1724 – 1804), shifted the focus from the world to our knowledge of the world. They tried to explain how the spectacular success of modern science became possible and offered critical reflections on what they took to be the limits of science. Works such

as Kant’s *Critique of Pure Reason* thus paved the way to what is now called epistemology of science, which is a philosophical sub-discipline that tries to understand how science works (see, e.g., [7], pp. 1, 8). Another option for philosophers was to focus on questions that do concern the world and its structure, but to which physics does not offer conclusive answers. In this spirit, philosophers may ask, e.g., what space and time are. While, e.g., Samuel Clarke (1675 – 1729), a follower of Newton, took space to be absolute, i.e., something that exists independently of any matter, Gottfried Wilhelm Leibniz (1646 – 1716) countered that space is no more than the relationships between material beings. The discussion on this topic was constrained by the best physical knowledge of space and its structure at that time, but philosophers had to move beyond physical theories to answer the question of what space is. The challenge was to find out what the theories (at those times, Newtonian mechanics) implied for space and how this squared with our pre-theoretical understanding of space. Today, inquiries of this sort fall in the realm of what is called the *metaphysics of science*. Metaphysics is the study of the basic structure of the world. Metaphysics of science answers metaphysical questions by drawing on our best theories from the natural sciences.

While, in the 19<sup>th</sup> century, to some extent, physics and philosophy parted company, and some physicists became hostile towards any metaphysics, things changed dramatically during the first half of the 20<sup>th</sup> century. According to historian and philosopher Erhard Scheibe, physicists turned philosophical (again) at that time [8]. The reason was that Albert Einstein’s theories of relativity and quantum mechan-



Fig 2: Immanuel Kant, in his „*Critique of Pure Reason*“, tried to explain how it was possible to obtain the physical knowledge of his time.

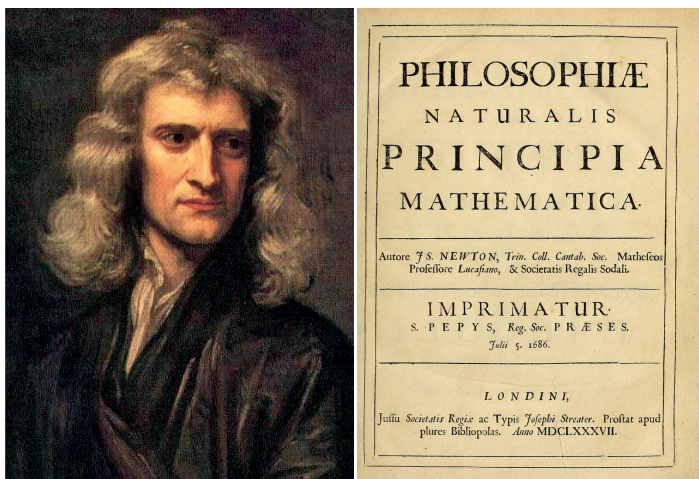


Fig 1: Isaac Newton (left panel) published his theory of motion and gravitation in his „*Principia*“ (right panel), a work that is supposed to contribute to philosophy.

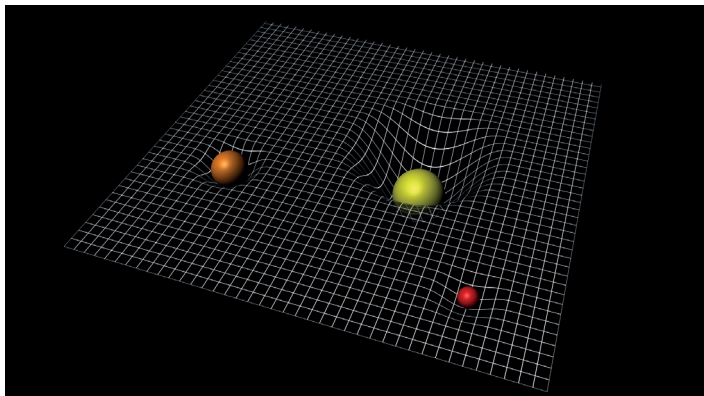


Fig 3: According to Albert Einstein's General Theory of Relativity, space-time can be curved, as illustrated in the viewgraph. This challenged Immanuel Kant's view that space can be known to be Euclidean independently of experience.

ics challenged not just popular philosophical views about science and its findings, but also shattered common sense about objects, space and time. For instance, if simultaneity is relative to observers, as famously argued by Einstein, how can we talk about the present ("the now") that is common to several people? Or how can light be a wave, while still being composed of particles (photons)? Physical theories provided "food for thought" and physicists themselves such as Werner Heisenberg (1901 – 1976), but also philosophers, e.g., Hans Reichenbach (1891 – 1953), immediately began to address such questions.



Fig 4: Hans Reichenbach was among the first philosophers who discussed Einstein's theories of relativity from a philosophical perspective.

The questions raised by the new theories proved difficult to answer, and most of them are still on the research agenda. But these days, they do not much occupy physicists anymore. Rather, the questions are addressed in a field that is now called *philosophy of physics*. The advent of philosophy of physics marks a new wave of specialization with its own division of labor. Very roughly, physicists concentrate on the application and further development of their theories, while philosophers of physics try to make sense of the puzzling features of those theories.

## 2. Philosophy of physics today

Philosophy of physics may be defined as a philosophical reflection about physics and its theories. It is one of the philosophies of the special sciences, and thus parallel to, e.g., philosophy of biology. The philosophies of the special sciences have partly been formed because it was increasingly realized that general philosophy of science is under threat of over-generalization.

As any philosophy of a particular science, philosophy of physics can be split in an epistemological and a metaphysical part, as indicated above. But today, philosophy of phys-

ics is mainly metaphysics of physics. The most important reason for this is the puzzling nature of many physical theories.

Methodologically, philosophy of physics (in what follows in the sense of metaphysics of physics) relies upon physics, because it draws on its theories. The focus is on well-established theories because only these theories promise insight into how our world is like deep down. But occasionally, less well-established theories, e.g., of quantum gravity are investigated to arrive at hypothetical results about how the world would look like if a certain theory was true. The challenge for philosophers is in any case to make sense of a specific theory or to show how several theories that seem incompatible fit together. To this purpose, it is essential to clarify what the basic concepts in which the theories are cast mean. But it is maybe easiest to introduce research in philosophy of physics using an example.

## 3. An example: the interpretation of quantum mechanics

Well-known axiomatic representations of non-relativistic quantum mechanics (QM) contain not just the Schrödinger equation for the wave function, but also a distinct postulate about measurements (which is often called collapse postulate). It is baffling that a physical theory that is supposed to be fundamental treats measurements in a separate manner. This puzzle is at the center of the so-called measurement problem. In its modern formulation [9], it arises because three well-established principles clash with each other:

- The linear Schrödinger equation fully governs the dynamical evolution of non-relativistic quantum systems.
- The outcomes of measurements on such quantum systems are fully determinate and unique.
- QM is a fundamental theory in that there are no degrees of freedom not implicit in the wave function.

The principles lead to a contradiction: Since the Schrödinger equation is linear, superpositions of two solutions to it solve the equation too. For instance, the eigenstate of the spin of an electron in the z-direction is a symmetric superposition of the two eigenstates of spin in the y-direction. Each of these eigenstates would lead to a measurement outcome of spin up or down in the y-direction, respectively. Thus, if (a) is true, then, during a measurement of spin in the y-direction on the z-eigenstate, the wave function representing the electron and the measurement apparatus is in a superposition of two states that correspond to a measurement of spin up and one of spin down. But following (b), the measurement result is not a superposition of spin up and spin down; instead, the measurement yields either spin up or spin down in the y-direction. This means that, either, the Schrödinger evolution is interrupted to yield a determinate outcome or that degrees of freedom not implicit in the wave function fix the outcome. Thus, we obtain a contradiction with either (a) or (c).

To avoid the contradiction, a resolution of the problem has to deny at least one of the three principles. In the last two decades, detailed proposals have been put forward in this respect. Typically, they do not just reject one of the principles, but rather provide a more comprehensive picture of the quantum world and its ontology (e.g., the kinds of things that exist at the quantum level). The so-called Ghi-

rardi-Rimini-Weber theory (GRW), for instance, denies (a), the idea being that the Schrödinger evolution is interrupted by so-called hittings (random events) which lead to what is considered the collapse of the wave function during measurement. The deviations from the Schrödinger evolution that ensue are so minimal that they cannot be observed with our present means, but they may become observable in the future. The many-worlds interpretation, in turn, denies that there are unique determinate outcomes of measurements. Instead, when a measurement occurs, a branching takes place, and different versions of an observer witness different outcomes depending on their branch. So what is characterized by the wave function is actually a tree of branching worlds, which each lack the puzzling features of QM. The so-called Bohmian version of quantum mechanics, in turn, denies (c) and holds that quantum mechanics is ultimately about classical particles with determinate locations and momenta, which form degrees of freedom not captured by the wave function. This function is only used to determine their dynamics by providing a guiding field for them.

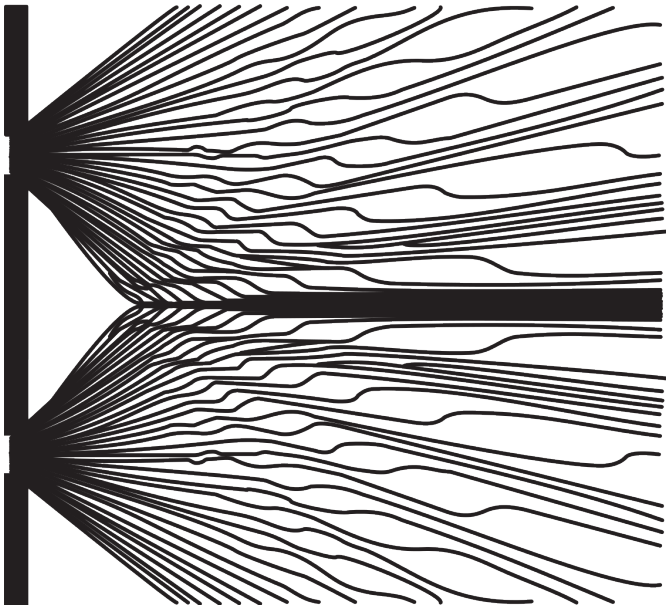


Fig 5: According to Bohmian mechanics, the wave function is used to trace the dynamics of particles with fully determinate trajectories in space. This viewgraph shows the trajectories of electrons for the double-slit experiment.

What we obtain in this way are various interpretations of quantum mechanics: They give competing accounts of what the quantum world is like according to standard non-relativistic quantum dynamics or a slight variation of it (GRW). There is no doubt that the various views come with their problems: Bohmian mechanics, for instance, is difficult to generalize to non-relativistic QM. The many-worlds theory, in turn, seems barely intelligible. It is no surprise then that philosophers have looked for alternatives. One prominent strategy to do so is to qualify QM as less important and to claim that crucial parts of the formalism of standard QM do not specify features of the real world. Rather, e.g., the wave function is supposed to only serve as a bookkeeping device that helps physicists to forecast the outcomes of measurements. This, then, is a task for philosophers of physics too: They need to decide to what extent physical theories deserve a realist treatment, i.e., to what extent they deliver true descriptions of reality rather than being mere instruments that do not represent how the world is.

In any case, the last two decades have seen tremendous efforts to render the various accounts of QM palatable, and there are lively debates between the proponents of the various theories. Of course, the controversies cannot be decided on the basis of data alone; instead, appeal to theoretical virtues such as simplicity, parsimony or consistency with other knowledge about the world is necessary to compare the theories. This, maybe, is characteristic of philosophical theorizing, but it is arguable that the theoretical virtues appealed to by philosophers are no different from those used in physics. It is further obvious that we do not really understand what quantum mechanics tells us about the real world if we do not engage with the various interpretations.

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#### Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in

quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Fig 6: In a famous paper from 1935, Albert Einstein, Boris Podolsky and Nathan Rosen raised the question of whether quantum mechanics delivers a complete description of physical reality.

#### 4. Other topics in the philosophy of physics

Of course, modern physics offers more food for thought than does quantum mechanics, and there are various other topics in the philosophy of physics. To begin, consider statistical mechanics as a prominent example. What is puzzling here is that the material macro-world features many processes that are irreversible, i.e., that only occur in one direction, although the relevant microphysics seems time-reversal invariant. Thus, coffee with milk is never observed to unmix spontaneously or to heat up at the expense of the temperature of the environment, although the fundamental laws of physics allow for this. One much-discussed answer to this puzzle holds that a special initial state of the Universe explains the existence of irreversible processes [10]. What is a matter of controversy here too (as it is in quantum mechanics) is the understanding of the probabilities used in statistical mechanics. Can we be realists about them and claim that they describe chances in the real world or are they merely devices to express our uncertainty about degrees of freedom we do not know much about?

Another focus of philosophy of physics is space and time. As indicated, the nature of space-time was already a matter of debate in the 18<sup>th</sup> century. Today, the question of whether space-time is independent of matter continues, but now under the auspices of general relativity (GR). The impact of GR on the status of space-time is mixed: On the one hand, as the name suggests, GR is a clear departure from absolutist conceptions of space, as defended by Clarke. On the other hand, according to GR, space-time is the bearer of highly non-trivial properties, e.g., curvature, and GR has non-trivial vacuum solutions, which indicate that space-time structure is independent of matter. Theories of quantum gravity, which are not yet well established though, suggest that time, and, maybe, even space emerge from more fundamental structures.

There are more physical theories, notably classical mechanics and electrodynamics, not to mention quantum field theory, that raise philosophical puzzles and that are investigated by philosophers. Physical cosmology also raises interesting issues. But we cannot further delve into them here.

## 5. Conclusion

Richard P. Feynman is sometimes said to have commented that philosophy of science is as useful to scientists as is ornithology to birds. There is indeed a type of philosophy of science that is not particularly useful or interesting to scientists, viz. an epistemology of science that is mainly about science and scientists. This type of philosophy is not concerned with the type of questions that scientists themselves address. Present-day philosophy of physics is different. It shares with physics a deep interest in the structure of the material world. It is based on physical theories and tries to understand what those theories imply for our understanding of the world. It uses the same sorts of concepts that are employed by physicists and can thus help physicists to better grasp and further develop them. In the 20<sup>th</sup> century, it was physics itself with its puzzling theories that has necessitated a philosophical inquiry into their meaning. We can thus hope that more philosophy of physics in the SPS will not just engage a small group of philosophers, but also physicists from various branches of the discipline.

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