The Scientific Legacy of the 20th Century
Pontifical Academy of Sciences, Acta 21, Vatican City 2011
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Philosophical Foundations of Science in the 20th Century

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The 20th century was an important century in the history of the sciences. It deserves to be called a *scientific century*. It generated entirely novel insights in foundational issues and established a previously unknown intimate connection between science and technology. Whereas physicists at the end of the 19th century had thought of themselves as having reached the end of basic research and had believed the principles of physics to have been discovered in their entirety, in the first third of the 20th century we witness revolutionary changes, comparable to the scientific revolution of the 17th century.

With the development of the Special and the General Theory of Relativity as well as quantum theory, the central theoretical frameworks of modern, non-classical physics were introduced. Theoretical investigations into the statistical interpretation of thermodynamics and infrared radiation lead to the development of quantum mechanics, which in turn prompted modifications of the atomic model and allowed an explanation of the photoelectric effect. The development of the Special Theory of Relativity as a theory of the spatio-temporal relationships between inertial systems moving relative to each other, which yields an explanation of the properties of transformations of the Maxwell-Hertz equations, and of the General Theory of Relativity as theory of the classical (non-quantised) gravitational field, leads to entirely new conceptions of space, time and gravity. Essential steps in the development of quantum mechanics are the development of quantum statistics and of the uncertainty principle, which sets limits on the measurement of atomic processes. In contrast to classical physics, natural laws preclude determinate measurements of the system's state. At the same time, essential clarifications and specifications are made to fundamental concepts of epistemology (or natural philosophy) such as the concepts of space and time in the Theory of Relativity, of causality and locality in quantum theory, of matter and field in the physics of elementary particles.

Besides physics, the discipline of biology, especially molecular biology and biophysics, which, together with biochemistry, conceives of itself as a molecular research programme, as well as evolutionary theory, become a leading science. Within biology, due to the discovery of the chemical structure of the DNA and the deciphering of the genetic code, the 20th century has been called the century of the gene.[1] Developments in other parts of the natural sciences, such as astrophysics, chemistry, in the earth and environmental sciences as well as in the neurosciences are of comparable significance. In addition, there is an ever-closer connection between science and technology. Scientific research has reached a point where idealisations may be overcome and the controlled laboratory may be left behind. Rather, science is now in the position to do justice to the complexity of the real world.

These developments are accompanied by *epistemological* reflections. On the one hand, these are directly connected to the scientific developments and, as in the case of the concepts of space and time, are part of scientific theory construction; on the other hand, general philosophy of science experiences an increase in importance and influence within that part of philosophy which is close to science. Science does not just yield important discoveries, it also becomes reflexive – in the sense of making its own procedures, theoretical, methodic and empirical, the subject of critical scrutiny. This is especially true concerning the foundations of science.

In what follows, I present a few brief remarks on the topic of philosophical foundations. I want to address three different epistemological approaches: one that is scientific in the narrow sense, emerging out of scientific theorising itself, one that is both scientific and philosophical (mediating, in a sense, between science and philosophy), and one that is of a general philosophical nature (general in the sense of *general philosophy of science*). They are all representative of the connection between science and epistemology, and they all illustrate the high standard of scientific thought in the 20th century. To conclude, a few remarks on developments relating to new forms of organising research and a revised concept of research follow.

1. An approach that is scientific in the narrow sense is connected to epistemological problems which are primarily of scientific importance. Questions raised by quantum mechanics belong to this area. In the so-called Copenhagen Interpretation, a correspondence principle bridges the gulf between classic and quantum-theoretic explanations of the structure of matter. At the same time, the differences between quantum mechanics and classical physics lead to different epistemological interpretations, for instance an *instrumentalist* reading, according to which quantum mechanics is not about the physical reality as such, but about a world as perceived by the epistemological view of the physicist, or a *realist* interpretation, for instance

[1] E.F. Keller, *The Century of the Gene*, Cambridge Mass. and London 2000.

that advocated by Albert Einstein, according to which the physical objects exist independently of each other and the context of measurement.

An instrumentalist approach also implies the view that there are principled epistemological limits to knowledge or human cognition, whereas a realist approach implies the (problematic) view of the incompleteness of quantum mechanics, which might be overcome by assuming hidden parameters. Other examples might be the issue of the conventional nature of simultaneity within Special Relativity and the debate in the foundations of mathematics, in which formalist, Platonist and constructivist conceptions were competing as the bases of mathematics.

2. Connected to epistemological problems of this kind, resulting directly from scientific research, are ones of scientific as well as of philosophical significance. Among these are, for instance, the topics of determinism, emergence, and (again) realism. Everything we know about the world, in science and philosophy, seems to depend on the question whether we live in a *deterministic world*. A well-known example for this is chance in quantum mechanics.[2] Quantum mechanics imposes serious limitations on the predictability of events. The central principle of the theory is 'Schroedinger's equation', which serves to determine the 'state function' or 'wave function' of a quantum system. The state function is generally taken to provide a complete description of quantum systems; no properties can be attributed to such a system beyond the ones expressed in terms of the state function. Schroedinger's equation determines the time development of the state function unambiguously. In this sense, quantum mechanics is a *deterministic* theory.

However, apparently irreducible chance elements enter when it comes to predicting the values of observable quantities. The measurement process in quantum mechanics is described as the coupling of the quantum system to a particular measuring apparatus. Schroedinger's equation yields, then, a range of possible measuring values of the quantity in question, each of these values being labelled with a probability estimate. That is, Schroedinger's equation only provides a probability distribution and does not anticipate particular observable events. Heisenberg's so-called indeterminacy relations

[2] On this and the following point on 'emergence', compare the more extensive treatment in J. Mittelstrass, 'Predictability, Determinism, and Emergence: Epistemological Remarks', in: W. Arber *et al.* (eds.), *Predictability in Science: Accuracy and Limitations (The Proceedings of the Plenary Session 3-6 November 2006)*, Vatican City (The Pontifical Academy of Sciences) 2008 (*Pontificia Academia Scientiarum Acta* 19), pp. 162-172.

are a consequence of Schroedinger's equation, although historically they were formulated independently of this equation and prior to its enunciation. The Heisenberg relations place severe limitations on the simultaneous measurement of what are called 'incompatible' or 'incommensurable' quantities such as position or momentum or spin values in different directions. The more precisely one of the quantities is evaluated, the more room is left for the other one. Like the constraints mentioned before, the limitations set by the Heisenberg relations have nothing to do with practical impediments to increasing measurement accuracy that might be overcome by improved techniques. Rather, the relations express limitations set by the laws of nature themselves. This element of genuine, irreducible chance troubled Albert Einstein very much. It challenges the thesis of a deterministic world.

Concerning the concept of *emergence*, what is at issue is the relationship of properties of wholes to properties of its component parts, equally relevant in science and philosophy. Originally, it made reference to the conceptual contrast, in a biological context, between 'mechanicism' (as a particular variant of materialism) and 'vitalism.' Systematically, it says that it is insufficient to use characteristics of elements and their interrelations to describe characteristics of ensembles or make predictions about them[3] (the whole is more than its parts[4]). According to the *emergence thesis*, the world is a levelled structure of hierarchically organised systems, where the characteristics of higher-level systems are by and large fixed by the characteristics of their respective subsystems, yet at the same time essentially different. Different characteristics and processes occur in the respective levels. Furthermore, weak and strong emergence theses can be distinguished.

The core element of the strong emergence thesis is the non-derivability or non-explainability hypothesis of the system characteristics shaped from the characteristics of the system components. An emergent characteristic is non-derivable; its occurrence is in this sense unexpected and unpredictable. Weak emergence is limited to the difference of the characteristics of systems and system components and is compatible with the theoretical explainability of the system characteristics. Weak emergence is essentially a phenomenon of complexity. Of scientific interest is particularly the *temporal* aspect

[3] For the following see M. Carrier, 'emergent/Emergenz', in: J. Mittelstrass (ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. 2, 2nd ed., Stuttgart and Weimar 2005, pp. 313-314.

[4] See K. Lorenz, 'Teil und Ganzes', in: J. Mittelstrass (Ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. 4, Stuttgart and Weimar 1996, pp. 225-228.

of the emergence thesis, i.e. for ensemble characteristics that occur in developments. Limits of reducibility (of the whole to its parts) figure here as limits of explanation and predictability, which is an important criterion of a justified theory and thus its achievement. This temporal novelty is described by the concept of *creative advance of nature*.

All these epistemological reflections, in science as well as in philosophy, are related to the already-mentioned *realism* debate. In philosophy, one distinguishes between two kinds of realism. *Ontological realism* is the position that the world of objects exists independently of human perception, knowledge and thought; *epistemological realism* – in contrast to idealism, which thinks of the world as being a construction of the self or a representation of the world, respectively – is the position that in the process of discovery, the objects of discovery play an independent role. So epistemological realism assumes essential elements of ontological realism, put simply, the existence of an 'external world'. To the extent that in (philosophical or scientific) theories a realist stand is taken, these are called *empiricist* when they make reference to the relation of the object of discovery and the subject of discovery, or *Platonist* when they make reference to the status of general concepts, so-called *universals*. Accordingly, a distinction may be made between empiricist and Platonist positions on scientific theory formation.

The status of a theory furthermore depends, also from the epistemological point of view, on the interpretation chosen, also concerning determinism and realism. An example would be the interpretation of the electromagnetic field as a state of a mechanical ether in the mechanistic tradition of the 19th century. Departing from this interpretation, Albert Einstein conceived of this field as an independent magnitude. Both are different (possible) interpretations of the same Maxwellian theory of electrodynamics. Furthermore, it is disputable whether a relational theory of space, according to which space represents merely a relation among objects and does not itself exist beside the objects or outside them, is really adequate to the General Theory of Relativity – as Einstein himself believed. Depending on how one translates classical relationalism into the concepts of relativity theory, one receives different answers to the question. At the moment at least, it is impossible definitely to privilege a particular one of these translations. In other words: One and the same theoretical approach can be differently interpreted; interpretations in these scientific cases, too, are not unequivocal. On the contrary, they display characteristic uncertainties that cannot be completely removed even by a rational reconstruction of the basic principles underlying a theory. The interpretation of quantum theory is not essentially different in this regard from an interpretation (say) of Kant's theory of space and time.

In all of these cases we are dealing with questions and areas of research whose results are not clearly attributed to physics or philosophy. This is well illustrated by physicist-philosophers such as Albert Einstein, who first endorsed an operationalist and later a realist epistemology, or Werner Heisenberg, who pursued the project of finding a theory of everything, believing in homogeneous mathematical symmetry, or Stephen Hawking, who writes on quantum cosmology from a general epistemological perspective, endorsing a falsificationist position in the sense of Karl Popper.

3. A properly philosophical status may be attributed to epistemological reflections which in the 20th century gained significance as a discipline entitled *philosophy of science*. These in general deal with problems of structure and development of science, starting from a distinction between *research form* and *theory form* of science. In its research form science is trying to discover what is the case, in its theory form it represents what it has discovered. Science in the research form is an expression of object rationality (including questions regarding the constitution of objects), science in the theory form is an expression of rationality in justification. Epistemology in the domain of science essentially refers to the theory aspect, namely to questions regarding the *structure*, *dynamics* and *explication* of theories. Under the heading 'theory structure' it analyses the structures of the language of science and of scientific explanations and the formation of theories. Under the heading 'theory dynamics' it deals with the developmental structures of scientific theories and with questions concerning the criteria of comparative theory assessment. The heading 'theory explication' applies to questions such as 'is there a physical basis for the direction of time?' or 'does the wave function of quantum mechanics refer to individual particles or an ensemble of particles?' (the Copenhagen versus the statistical interpretation). As examples for such forms of thinking about science the influential approaches of Logical Empiricism (Rudolf Carnap being the main representative) and that of Karl Popper may be mentioned.

Logical Empiricism, which epistemologically may be characterised by its appeal to the conventionalism of Henri Poincaré and its criticism of the thesis of the *synthetic a priori* of Immanuel Kant, conceives of theory development as a continual progress of discovery in which earlier theories are reduced into later ones. Epistemologically speaking, it endorses a two-level view of the conceptual structure of scientific theories, according to which in the structure of science all true propositions are either logically or analytically true propositions, or alternatively empirically or synthetically true propositions.

On this basis, it at the same time pursues the project of the *unity of science*:[5] all states of affairs can be expressed in a physicalist language and by introducing *theoretical concepts*, i.e. concepts which refer to entities not directly observable and which cannot be defined in terms of observational concepts. They are introduced by the postulates of a theory and their function and role is explicated accordingly by the appropriate theoretical context. While theoretical concepts are generally coordinated with observational indicators by correspondence rules, nonetheless, these concepts cannot be translated into such empirical indicators. The reason for their introduction is that they help to order and unify experimental laws successfully. Concepts such as electromagnetic field or the quantum-mechanical wave function, to which empirical characteristics can be assigned only indirectly, partially, and in a manner mediated by theory, are considered legitimate, because with their help the explanatory power of the theories can be increased. Theoretical concepts are thus legitimate explanatory constructs. The conceptional structure of scientific theories according to this position is shaped accordingly.

Karl Popper's approach was very different. Opposing the idea of how the reducibility of theories into each other leads to scientific progress in Logical Empiricism, Popper defends the incompatibility of successive theories. In his methodology of empirical science or *logic of scientific discovery*, entitled 'falsificationist', the term 'corroboration' takes the place of the concept of justification, in particular, empirical justification, as Popper – again, in opposition to Logical Empiricism – appeals to the asymmetry of verification and falsification: general propositions, mostly natural laws, may only be refuted (falsified), but not verified, relative to an empirical basis. Basic propositions, which according to this conception figure as premises of an empirical falsification, are interpreted as corroborating a falsifiable hypothesis. The degree of corroboration of a theory in turn depends on its degree of testability, expressed by the concept of falsifiability. The principle of a critical examination characterising a logic of scientific discovery accordingly requires a pluralism of theories so as to be able to select a 'successful' one, which later (against Popper) was extended by a pluralism of methods by Paul Feyerabend. Progress among theories is due to the ongoing process of critical revision of existing theories from the perspective of truth or at least verisimilitude.

[5] See M. Carrier and J. Mittelstrass, 'The Unity of Science', *International Studies in the Philosophy of Science* 4 (1990), pp. 17-31.

In his later works, Popper tried to describe the formation of theories as an evolutionary process, as the expansion of knowledge in problem-solving contexts, the components of which are creative guesswork and the rational elimination of error. This process is supposed to be based on a 'third world of objective contents of thought', existing alongside the 'first world' of physical objects and the 'second world' of mental states. Opposing this we find *historicist* approaches (Thomas Kuhn), *reconstructivist* approaches (Imre Lakatos), *structuralist* approaches (Joseph Sneed, Wolfgang Stegmüller) and *constructivist* approaches (Paul Lorenzen, Jürgen Mittelstrass), which mostly differ in the degree of emphasis they give to the descriptive or normative perspectives. In all these approaches, the aspect of theory dynamics is dominant.

4. Philosophy, orienting itself on the task of a philosophy of science, stays close to science, and increasingly so even as science is entering in ever closer union with technology and finding new forms of organisation. A new approach towards *technology*, as it emerged in the 20th century, is displayed, for instance, in medicine, microelectronics, and laser technology – science is leaving its academic home and is relating its knowledge to the problems of this world more and more often[6] –, a change towards new *organisational forms* through strengthening the extra-university research in the area of basic as well as in the area of applied research – with big centres of sciences such as CERN, EMBL, the Weizmann Institute and the love of large science groups (centres, clusters, networks, alliances).

With these institutional developments, not only has the organisational structure of science changed, but also the *concept of research*. Originally, this concept was closely linked to the researching subject – researchers and not institutions researched – but now the link between research the verb and research the noun is pulling apart. The community of researchers has become Research with a capital 'R'; the (re)search for truth, central to the idea of science and at the very bottom of any scientist's self-image of what makes him or her a researcher, has become research as a business operation, an organisable and organised process in which individual scientists, thought

[6] See J. Mittelstrass, *Leonardo-Welt: Über Wissenschaft, Forschung und Verantwortung*, Frankfurt am Main (Suhrkamp), pp. 47-73 ('Zukunft Forschung: Perspektiven der Hochschulforschung in einer Leonardo-Welt' [1990]); H. Nowotny and P. Scott and H. Gibbons, *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty*, Cambridge etc. (Polity Press) 2001, 2007; P. Weingart and M. Carrier and W. Krohn, *Nachrichten aus der Wissensgesellschaft: Analysen zur Veraenderung der Wissenschaft*, Weilerswist (Velbruck Wissenschaft) 2007.

to be as interchangeable as individuals in the business world, disappear. The mentioned predilection for core areas, centres, clusters, alliances and networks in research is the embodiment of this change. The change is reinforcing the industrialization of science, but is also weakening science's ability to self-reflect. Self-reflection is a distinctive mark of enlightened science. It is characterised by the right ratio of proximity and distance. This is just as true in institutional terms and, when it is achieved, it constitutes the rationality of institutions, in this case scientific institutions. It is also true where scientific self-reflection is paired with social reflection (in the form of advising politics and society), a link in which modern society can find its true 'scientific' character.

There is also a *normative* aspect connected to the idea of self-reflection. Not just epistemological questions, but also aims and objectives are at issue here, and thus questions of orientation, both theoretical and practical. The ethical consequences of an increasing scientification of the world, for instance, belong to these. Philosophical foundations – these are not just epistemological, but also practical and ethically relevant foundations, through which science is normatively reconciling itself with itself and society. The fact that also foundational questions such as these have been addressed in the 20th century, together with the significant theoretical breakthroughs and the epistemological debates accompanying them, characterise it as a truly scientific century. At the same time, this character epitomises demanding requirements which science and philosophy have to satisfy today and in the future.