Complexity and Analogy in Science
Pontifical Academy of Sciences, *Acta* 22, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/acta22/acta22-mittelstrass.pdf

Complexity, Reductionism, and Holism in Science and Philosophy of Science

Jürgen Mittelstrass

There are concepts that belong to the basic terminology of science but which are not used in everyday scientific work – such as the concepts of natural law and causality. Such concepts touch on the epistemological foundations of science, and thus transcend individual disciplines and presuppose a particular interest, the interest in foundational questions of science, and presumably also special skills and competence. Not everything that belongs to these foundations is self-evident and not everything that is said about them in philosophy of science is universally accepted – which in turn lies in the fact that we are dealing with different theoretical approaches. Theory meets theory, and this does not always go without conflict.

In the following, as an introduction to considerations of a theoretical, methodological and epistemological nature, which especially deal with aspects of complex structures, I offer some brief explications of a conceptual nature oriented towards the concepts of complexity, reduction and holism.

1. In a comprehensive presentation of the role that the concept of complexity plays in the development of modern science we read: "Complexity determines the spirit of twenty-first century science. The expansion of the universe, the evolution of life, and the globalization of human economies and societies all involve phase transitions of complex dynamical systems".[1] And further: "The theory of nonlinear complex systems has become a successful problem solving approach in the natural sciences – from laser physics, quantum chaos, and meteorology to molecular modelling in chemistry and computer-assisted simulations of cellular growth in biology. On the other hand, the social sciences are recognizing that the main problems of mankind are global, complex, nonlinear, and often random, too. Local changes in the ecological, economic, or political system can cause a global crisis. Linear thinking and the belief that the whole is only the sum of its parts are evidently obsolete".[2] In

[1] K. Mainzer, *Thinking in Complexity: The Computational Dynamics of Matter, Mind and Mankind*, 5th edition, Berlin and Heidelberg: Springer 2007, p. VII.

[2] *Ibid.*, p. 1.

fact, complexity has become not only an important topic but also the key to scientific explanations in all areas of science.

This does not necessarily mean that conceptual clarity has been achieved in questions of complexity. For the concept of complexity displays different (scientific) meanings depending on the area to which it is applied, even while its basic meaning remains constant. Are the concepts used in different disciplines similar, or may a phenomenon be, for instance, biologically complex but physically not? Does the fact that some problems are in principle unsolvable for reasons of complexity (due to limited time and computational power) pose a problem for scientific practice? Shall our practice just ignore problems we cannot currently handle – or can science render apparently complex systems in simple underlying theories? Furthermore, is there a difference between the complex and the complicated such that some complex systems are not actually complicated even though all complicated systems are indeed complex. In general, again, complexity has become an important area of research in many disciplines in the last decades. For instance, the complexity and the ensuing unpredictability of weather systems has been known for a long time. And theoretical tools to master complexity have been developed in biology, where the apparent complexity of organisms has been used to argue against evolutionary theory, as well as in economics and social theory, where so-called "complexity theory" aims to help us understand systems which appear unsystematic.

As to the distinction between complexity and complicatedness:[3] The greater the number of objects and relations of a system, the greater its complexity. Complicatedness depends on the inhomogeneity of the object area. There can thus be systems of high complexity but small complicatedness (for example: organic molecules composed of numerous elements of few different kinds) whereas high complicatedness as a rule leads to complexity (for example: organisms). No wonder that the theory of complex dynamic systems, in which cause-and-effect connections are non-linear (for instance in the motion of more than two bodies under the influence of gravity), is currently becoming ever more influential, especially because of its many applications (another example is the prediction of developments in the weather). This discipline closely joins newer mathematical methods such as chaos theory to older methods from statistics and probability theory.

[3] The following is taken from K. Lorenz, "komplex/Komplex", in: J. Mittelstrass (Ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. IV, 2nd edition, Stuttgart and Weimar: Metzler 2010, pp. 277-279.

In so far as the reduction of complexity is done in explanatory intent, this is achieved especially by model building. Models serve to simplify complex structures and to visualize abstract structures. Thus, astronomical models (for instance, in the form of orreries) were viewed in the sense of the first purpose (simplifying structures), and physical models (for instance in the form of the atomic model) were viewed in the sense of the second purpose (visualizing abstract, non-intuitive structures) and mechanical models (for instance, in the form of corpuscular models) generally in the sense of both purposes (describing visualizable situations that were nonetheless in need of explanation by the basic concepts of space, time, mass and force). As a rule, we should differentiate between scale models, analogue models and theoretical models. Scale models are enlarged or miniature replicas of real or imaginary objects, for instance, in the three-dimensional representation of the DNA-molecule ("double helix"). Analogue models represent an object in a structurally similar (homomorphic) other object, for instance, in the form of the planetary model of the atom (in physics) or computer-models of the brain in the philosophy of mind. Theoretical models consist of a set of assumptions and equations with which the essential properties of an object or system are to be grasped, for instance (in the intuitive case) in the form of Niels Bohr's atom-model or of billiard-ball models in the kinetic theory of gases.

As a rule a complex state of affairs cannot be completely grasped, even when models are applied. This is for instance the case where chance plays a role. The Copenhagen interpretation of quantum mechanics, that is, the theory of microphysical phenomena, assumes an irreducible, ontological contingency, that is, the existence of absolute chance in the physical world. The assumption is not uncontroversial. For instance, David Bohm's interpretation of quantum mechanics suggests that the quantum world can in fact be grasped with causal-deterministic vocabulary. From this, and from the fact that Bohm's interpretation and the Copenhagen interpretation of quantum mechanics are empirically indistinguishable,[4] it follows that it may not be possible to find out whether there is really absolute chance in the world or not. All arguments for and against seem here to be relative to a physical theory and its interpretation. How are we supposed to know whether – remembering Albert Einstein's admonition that God does not play dice – there is not the possibility of a deeper deterministic description

[4] See J. Mittelstrass, *Konstruktion und Deutung: Ueber Wissenschaft in einer Leonardo- und Leibniz-Welt*, Berlin: Humboldt University 2001, p. 18.

that excludes accident while coping with complexity. Not only philosophy, but natural science as well has its difficulties with chance and necessity.

Nothing is changed by the circumstance that complex relations cannot be completely grasped. This can in turn be elucidated under the concept of predictability: Even in a deterministic world there are limits to predictability.[5] Two reasons can be given in support of this. First, *deterministic chaos*. This refers to the strong dependence of a system's states on the magnitude of defined parameters. Since the magnitude of these parameters can never been known, the prediction of system's states is bound by uncertainty, which translates into a range of different developments in chaotic systems. Unpredictability as a result of chaos is not limited to complex systems, rather, it can also occur in simple systems that only consist of a few elements. For example, two coupled pendulums constitute a simple system, the relevant laws of which have been known for centuries. But it has only recently become clear that, within such an arrangement, a distinct range of initial conditions – namely system stimulations of medium strength – there can be chaotic and unpredictable oscillations. Second, the problem of a Laplace's demon. This label (credited to Emil Du Bois-Reymond)[6] refers to a fictitious superhuman intelligence, which – under the assumption of a stable, closed and all-determined system typical for a mechanistic worldview – knows of all initial conditions of all possible movements and thus can predict the location of any particle for every point in time. Now, quantum mechanical systems – in contrast to relativistic physics, where differential equations describe deterministic systems with regards to their state variables – are non-deterministic with regard to conjugate variables such as position and momentum. Rather, they are statistical, i.e. incalculable even by Laplace's demon – an implication confirmed by recent developments in physics. But whatever holds for a deterministic world also holds for a complex world and its reductions.

2. With the concept of *reduction* or reductionism philosophy of science denotes, on the one hand, an essential aspect of scientific theory formation and, on the other, a procedure that describes the successful reduction of

[5] See, in more detail, J. Mittelstrass, "Predictability, Determinism, and Emergence", in: W. Arber *et al.* (Eds.), *Predictability in Science: Accuracy and Limitations*, Vatican City: The Pontifical Academy of Sciences 2008 (Pontificiae Academiae Scientiarum Acta 19), pp. 162-172.

[6] "Ueber die Grenzen des Naturerkennens" (1872), in: E. Du Bois-Reymond, *Vortraege ueber Philosophie und Gesellschaft* (ed. S. Wollgast), Hamburg: Meiner 1974, pp. 56-57.

one theory to another. In general the concept of reduction involves tracing back entities, concepts or theories to others. Reductions serve the goal of unifying the scientific world picture through the use of a conceptual system – and consequently ontology – as uniform as can be and the elimination or replacement of philosophically or methodologically problematical concepts (or the entities they refer to) by unproblematic concepts (ontological reduction). Examples are the reduction of phenomenological thermodynamics to statistical dynamics, the reduction of Mendelian genetics to molecular genetics and the ontological reduction of psychological processes to physical processes via a theory reduction of psychology to neurophysiology.

One expression of a reductionistic programme is so-called *physicalism*, that is, the programme to express all (non-logical) expressions of a unified scientific language in the language of physics. There are two versions: "The strictest version of physicalism restricts all scientific theories to the terms of currently accepted physics. This view demands, for example, that all processes or objects can be assigned a particular quantum of energy. A weaker variant of physicalism demands the completeness of the physics of the time. This conception accordingly takes the historical change of physics explicitly into account. This view of physicalism makes a comprehensive claim for the validity of the theory of inorganic phenomena and asserts that all entities (i.e., including biological and psychological ones) are physical. A further weakening of the concept of physicalism results if only the natural sciences of the time taken as a whole are set to be comprehensive and complete. In particular, this includes the possibility that biology is not reducible to the theory of inorganic phenomena, but must have recourse to special regularities. In this form of physicalism (...) emergent terms and laws are admissible in principle".[7]

Now, a claim for derivability of the reduced theory from the reducing theory presupposes that both are compatible with one another. But since the reducing theory is designed to correct and improve the reduced theory, this in turn presupposes that both are incompatible. That is, the formal and informal conditions of reduction cannot be satisfied simultaneously; the correction of T_1's laws by T_2 precisely excludes their derivation.[8] This, again, is the reason why Karl Popper rejects the idea of reducibility of theories to

[7] M. Carrier and J. Mittelstrass, *Mind, Brain, Behavior: The Mind-Body Problem and the Philosophy of Psychology*, Berlin and New York: Walter de Gruyter 1991, p. 172.

[8] See again M. Carrier and J. Mittelstrass, *op. cit.*, p. 43. Here too the proof that this difficulty has been solved by applying Tarski's concept of interpretability to the reduction

one another and defends the incompatibility of successive theories. The principle of a critical examination characterizing a logic of scientific discovery requires, according to Popper's concept of falsifiability and the asymmetry of verification and falsification, a pluralism of theories so as to be able to select a "successful" one. Progress among theories is due to the ongoing process of critical revision of existing theories from the perspective of truth or at least verisimilitude.

3. Compared to the approaches represented in the programme of reduction, *analogies* display a weak form of relationship between entities, concepts or theories. Here the point is that this connection can be materially different but formally the same. We should distinguish between *structural* and *functional analogies*: "If the correspondence of particular relationships among the elements of a system with one another is reversibly unique to those among elements of another system (without there needing to be a correspondence between the elements themselves), we say that both systems agree partially in their structure or that a 'structural analogy' holds between them. If one grasps similarity as agreement of two systems in certain (not all) 'characters' in the sense of properties of their elements or element groups, then similar systems agree also in the relationships between the corresponding elements or element groups and are thus structurally analogous".[9] An example would be again Bohr's planetary model of the atom. A "functional analogy" between two systems on the other hand occurs if these are equally suited for a particular purpose, that is, interchangeable for achieving that purpose. An example here: the concept of force in physics and everyday life. Epistemologically speaking, both cases are forms of *similarity*, that is, agreement of two systems in some, but not necessarily all, characteristics. Analogue models accordingly represent a system or an object in a structurally similar (homomorphic) or in a functionally similar system or object.

4. The line of thought pursued here in the case of the concepts complexity, reduction and analogy lead in the philosophy of science to a position that on the one hand turns against the reductionist programme and on the other hand represents the attempt to do justice to the actual complexity of scientific objects, concepts or theories in a different manner as well, namely

problem (A. Tarski, "A General Method in Proofs of Undecidability", in: A. Tarski *et al.*, *Undecidable Theories*, Amsterdam: North-Holland 1971, pp. 1-35).

[9] Chr. Thiel, "Analogie", in J. Mittelstrass (Ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. I, 2nd edition, Stuttgart and Weimar: Metzler 2005, pp. 117-118.

in the sense of a unity to be regained, a *holistic* unity of disciplinary and transdisciplinary explanations.[10] Under the designation *holism* are to be understood methodological approaches to the explanation of conceptual or empirical phenomena, that take their point of departure from a "holistic" point of view. Conceptually or methodologically, the issue is in particular the distinction between the part-whole relation and the element relation, since wholes are understood as compositions of parts but not merely as the sum of their parts. This is the case because the relations determining the composition make the whole an independent unity, whose qualities cannot be completely traced back to the qualities of the parts. The concept holism was introduced in 1926 in a biological context.[11] It also plays a role in the interpretation of quantum theory, in social-scientific theory formation and in the theory of confirmation.

In biology the concept of holism designates the attempt, in opposition to the particular positions of mechanism and vitalism, to derive all phenomena of life from a holistic "metabiological principle". According to this view biological processes can be adequately explained only if organisms are not grasped as isolated natural bodies (as in physics), but are rather seen in structure and function as standing in inseparable interaction with their own subsystems and the environment. Depending on how this abstract principle is conceptualized, it has either found general recognition in biology or been dismissed as incompatible with the biological facts. For the paleontologist Edgar Dacqué, for instance, holism was a methodological part of a teleological conception of evolution in which humankind, as the primeval form of life, included all the developmental possibilities of the animal kingdom (the animal species appear in this conception as dead ends in biological development).[12] In physics the appearance of so-called entangled states in quantum theory is often viewed as a violation of the principle of separation and as the basis for an *ontological holism*. This principle states that every physical system possesses its fundamental properties independent of other systems distinct from it. The exhibition of these properties, but not their presence, can be influenced by their interactions with other systems. In composite systems the state of the aggregate system results from the states of the subsystems and their interactions.

In entangled states, such as described in the so-called Einstein-Podol-

[10] I follow closely here my article "Holismus" in the *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. III, 2nd edition, Stuttgart and Weimar: Metzler 2008, pp. 427-430.

[11] J.C. Smuts, *Holism and Evolution*, London: Macmillan 1926, 3rd edition 1936.

[12] E. Dacqué, *Leben als Symbol: Metaphysik einer Entwicklungslehre*, Munich and Berlin: Oldenbourg 1928.

sky-Rosen paradox, an aggregate system consisting, for instance, of two initially coupled and later separated particles, has constant properties – it is in a pure state – although this does not hold for the subsystems. The aggregate system exists in a well-defined state, whereas the subsystems do not possess the correlated properties (such as spin and polarization) independently of one another. The probability distribution for the appearance of particular property values of the aggregate system cannot be calculated as the product of such probability distributions for the subsystems. Accordingly the state of the aggregate system does not supervene on the states of the sub-systems. The holism of quantum theory is expressed in the violation of the principle of separation, through which the whole is ascribed primacy before the parts.

In the philosophy of the social sciences *methodological holism* is the view that social relations can only be interpreted and explained in terms of social wholes. This holism is methodological insofar as it primarily refers to the conditions of understanding. The counter-position is so-called methodological individualism, as advocated, for instance by Popper among others. According to this individualism all social relations can be explained out of the actions of individual persons and their interactions, which in turn can be traced back to motives and beliefs and thus need not necessarily refer to social wholes. Opposed to this position, advocates of holism such as Karl Marx and Émile Durkheim postulate the impossibility of abstracting from the influence of social institutions on the behaviour of individuals. According to Marx social conditions and their development can only be interpreted in categories of social "totalities" such as relations of production or classes; for Durkheim institutions such as family or religious communities act as social facts upon the individual.

While biological, quantum-physical and social-scientific elaborations of holistic notions are supposed to serve the particular interpretative and explanatory needs of partial areas of investigation, the so-called *confirmation holism* of philosophy of science deals with the over-arching thesis that theories can only be empirically evaluated as wholes. This form of holism arises in the framework of a hypothetical-deductive conception of empirical testing and confirmation, according to which the investigation of the tenability of a hypothesis, not comprehensively testable by immediate observation, is carried out by deriving empirically accessible consequences. If the consequences turn out to be true, the hypothesis is taken to be empirically confirmed. However, Pierre Duhem pointed out that the derivation of empirical consequences must have recourse to numerous other hypotheses, for instance, those taken from background knowledge or those about the function of the measuring instruments applied. Every successful test confirms not only the hypothesis under consideration, but also the entire group of hypotheses used in the testing process.

Similar arguments are made in philosophy of science in the framework of so-called *meaning holism* or *semantic holism*. Here, the meaning of individual concepts or propositions results from their interactions with other linguistic structures. They do not have meaning in isolation but only in the context of comprehensive language systems. This holism arises out of confirmation holism when it is joined to the verificationist premise that the conditions of empirical testing provide information on meaning. A further ground is the realization that the meaning of scientific concepts is understood only in the context of the corresponding scientific theory and cannot be acquired by knowledge of the appropriate definitions alone. The meaning of a concept like that of force can be clarified only by the role that it plays in the system of the laws of mechanics. According to this context theory of meaning a scientific concept acquires its specific content only through its integration in theory.

As an aside let me remark that holistic approaches of this kind lead to the concept of *emergence* insofar as, both in the sense of the confirmation holism and also in the sense of semantic holism, it is the system-properties that give us information about the behaviour of the system. These properties are in turn *emergent*. Emergence says again that it is impossible to use characteristics of elements and the interrelations between these to describe characteristics of ensembles or make predictions about them. The core element of a *strong* emergence thesis is a 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 in turn is essentially a phenomenon of complexity.

Here, too, our considerations return us to the concept of complexity, which is, from the perspective of philosophy of science as well, the key concept of the modern development of science and points to the future, possibly also to the limits, of scientific progress.