C.R.AIPS 3

Proceedings of the Académie Internationale de Philosophie des Sciences

Comptes Rendus de l'Académie Internationale de Philosophie des Sciences

Tome III

Models and Representations in Science

Éditeur

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Scientific worldviews and models in Hermann von Helmholtz and Werner Heisenberg

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By scientific worldviews I mean conceptions that contain assumptions about and descriptions of the world. They are based on scientific knowledge and aim to increase this knowledge. They also serve in part to make scientific findings popular in society, and in part they take up non-scientific ideas. Their content need not be limited to theoretical discussions, but can include ethical principles, practical instructions for action, or also aesthetic evaluations. Scientific worldviews have accompanied modern science since its inception and continue to play an important role in the development of knowledge and the self-understanding of science.

Scientific worldviews and models may be related to each other in a variety of ways. I make a basic distinction between two relations, and I will discuss an example of each of them. On the one hand, models were and still are developed within the framework of scientific worldviews. For example, worldviews are the starting point for formulating models for phenomena that these conceptions do not as yet sufficiently capture. On the other hand, however, scientific worldviews can themselves take the form of a model. For example, worldviews must make simplifications in order to grasp the complexity of the world even approximately. Presumably, the two relations need not be mutually exclusive. In the two examples I discuss, however, the two relations are contrasted.

Hermann von Helmholtz, from whose work I take the first example, played an active role in the increase in use of models in natural science during the nineteenth century. This growing relevance, which paved the way for the current position of models, still unfolded essentially within the framework of the mechanistic worldview that can be traced back to the early modern transformation of science. Helmholtz was considered the leading exponent of this view. I will discuss one of the last of his mechanical models, that of so-called monocyclic systems. His aim in developing this model was to establish the similarity between the structures and representations of mechanical and thermodynamic phenomena in order to contribute to the understanding of the latter. Helmholtz's approach, which from our present-day perspective was misguided, led him to the limits of mechanistic model construction. Olivier Darrigol has proposed a Wittgensteinian image to capture this: Helmholtz climbed the ladder of model construction to the

Models and Representations in Science, edited by Hans-Peter Grosshans.
Comptes Rendus de l'Académie Internationale de Philosophie des Sciences 3 (2025).
G. Schiemann, Scientific worldviews and models in von Helmholtz and Heisenberg, pp. 199–208.

highest rung and then threw it away, in order, on the level thus reached, to make the transition to a description of the world from general principles.[1]

The collapse of the mechanistic worldview, the foundation of modern physics and further advances in science provided starting points for the second example, the one developed by Werner Heisenberg. Heisenberg took up a conception whose origins go back to antiquity—namely, that reality is organised in levels in accordance with superior principles. He formulated his approach as a model that systematically related scientific knowledge and his own life experience to phenomena of the respective levels. The application of mechanics is assigned to just one level in his model. Whereas Helmholtz had still mistakenly assumed that his worldview was true, but gave his model at best hypothetical validity, Heisenberg presented his worldview as a whole only as a hypothesis. For Heisenberg, it was not the only possible conception of the world and it was potentially subject to historical change that could affect all components of the model. However, the change that has occurred since then has not undermined the plausibility of the model.

In what follows, I will discuss the two models and conclude with a comparison and evaluation. Beforehand, I would like to note that neither Helmholtz nor Heisenberg described the representations that I have selected as models. This may be due to linguistic conventions of the time or to systematic reasons that still apply today. I assume a broad conception of models that covers both examples and understands by a model an interpretative representation of an object or system. Applying this conception to Helmholtz's monocyclic systems seems to me to be unproblematic, but there are alternative ways of characterising Heisenberg's conception of levels, as I will explain.

1 Hermann von Helmholtz's monocyclic systems

Hermann von Helmholtz's mechanism was based on the successful application of physical mechanics and was limited to natural phenomena, which he contrasted with mental phenomena. I situate him in a mechanistic tradition that considered matter and motion to be the only causes of all natural phenomena and claimed that it could grasp the forms of motion completely through the concepts and laws of physical mechanics. Within this tradition, Helmholtz defended a conception that placed the mechanical concept of force on an equal footing with that of matter. Helmholtz regarded his own mathematical formulation of the law of conservation of energy as the most successful application of mechanics and the most important confirmation of mechanism. He took the fact that mechanical energy could be converted into other forms of energy as proof that all natural phenomena have a mechanical foundation.[2] Analogies subsequently contributed to the mechanistic

[1] Cf. Darrigol 1994: 237.
[2] Cf. Schiemann 2009: 90–98 and Caneva 2021: 141–152.

understanding of electromagnetic phenomena. Thermodynamic phenomena represented one of the last unsolved problems of the mechanistic account of nature in the second half of the nineteenth century. How could it be explained that the whole energy of a thermal engine could not be transformed into mechanical work? What mechanical natural processes could be responsible for the inexorable increase in this no longer usable portion of heat in closed systems?

To improve the understanding of reversible processes, Helmholtz created the so-called monocyclic systems in the mid-1880s.[3] These were mechanical models whose internal structure was known entirely and whose concrete form did not necessarily have anything to do with the submicroscopic processes that mechanism regarded as the basis of thermal phenomena. The models applied concepts and laws of the physical theory of mechanics, so that only conservative—i.e., location-dependent—forces acted within the system, while the additional external forces did not necessarily have to be conservative. The coordinates of the moving or moved parts fell into two kinds. The one kind affected the physical state of the system only by its velocity. Helmholtz conceived of its motion as cyclic, i.e., each of the moving elements returned to the same place after a certain time. Systems in which the cyclical motions only depended on one parameter were called 'monocyclic'. With the second kind of coordinates, only the position had an effect on the state of the system, and the changes in position were thought to be negligibly slow.

With this division of coordinates, Helmholtz wanted to draw an analogy to the difference between the amount of heat in a system and the work done in it. The coordinates that produced effects through velocity were supposed to determine the thermodynamic properties, whereas those that produced effects through position determine the work done in the system. As examples of realisations of his monocyclic systems he offered technical constructions, such as a frictionlessly spinning top on which external forces act. That natural systems corresponding to the monocyclic constructions actually exist in nature would only be demonstrated later (by Boltzmann). Insofar as Helmholtz's intention in developing his models did not depend on realisations, they can also be described as fictional. Moreover, they did not contain any information about the material properties of the moving elements.

Helmholtz's model did not aim at a material but instead at a formal analogy between mechanics and thermodynamics, although the formal analogy was not free from material presuppositions. In formal terms, the mathematical representation of changes in the energy of the monocyclic system had the same structure as the change in the quantity of heat of a thermodynamic

[3]Cf. Helmholtz 1884. For the following compare Schiemann 2009: 388–397 and Bierhalter 1994.

system. Here, temperature corresponded to kinetic energy and entropy to a function of the mechanical impulses. The entropy equation for reversible systems was thus formally identical to the energy equation of a mechanical system. Helmholtz used the term ‘analogy’ in a way that corresponds to how it is understood today. Accordingly, analogies contain structural similarities between two different object domains.

Alisa Bokulich has pointed out that, in the context of nineteenth-century mechanism, formal analogies can also be understood in terms of a conception of levels.[4] Taking this as a starting point, the pure mathematical equations employed by Helmholtz can be interpreted as an upper level, beneath which is a level in which these equations are applied with different variables. The phenomena represented by these equations are then situated a further level down. Helmholtz’s mechanical analogy thus included two types of relations of representation: the just mentioned representation of the real phenomena by the equations of the middle level and, within this level, the representation of the thermodynamic equation by the mechanical equation of the model. Finally, mechanism still assumed the fundamental level of mechanically moved matter, which was supposed to generate the phenomena—in this case, those of the heat. This layer was beyond the testimony of direct perception and, as Helmholtz believed, was at best accessible to science.

Helmholtz explicitly did not claim that his analogy could explain mathematical relations of thermodynamics. His purpose in constructing the model only becomes clear against the background of his mechanistic worldview: within the framework of this worldview, the motion of heat appears—I quote Helmholtz—‘as a motion of an unknown kind’. He continues:

> Under such circumstances it seems to me entirely rational to investigate under which most general conditions the [. . .] distinctive features of the motion of heat might occur in other well-known classes of motions.[5]

The monocyclic systems fell under the ‘well-known classes’ and thus served to elucidate what is unknown in terms of what is known. They mediated between the theory of mechanics and a domain of phenomena which could not yet be clearly situated among the objects of mechanics. This procedure for extending knowledge is typical of models involving analogical relations. They are not equipped to produce knowledge of something new that cannot be explained in terms of what is already known.

Helmholtz’s attempt must be judged a failure because he started from false presuppositions. He could only establish the formal analogy based on arbitrary assumptions that satisfied his mechanism. Instead of using the statistical velocity distributions considered indispensable today, he calculated with

[4] Cf. Bokulich 2015.
[5] Helmholtz 1884: 176. Translation by Ciaran Cronin.

average values of the velocities. Moreover, his analogy permitted processes whose existence was excluded within the framework of the phenomenological laws of thermodynamics.[6] The most serious shortcoming, however, was that his analogy did not cover irreversible processes, as Helmholtz himself realised.

In an effort to integrate irreversibility into his worldview, Helmholtz shifted the focus of his reflections in his later years from mechanical models to general mechanical principles. In deriving the mechanical equations for monocyclic systems, he had already assumed the principle of least action as universally valid. His work in connection with the application of the principle to several physical phenomena also failed to capture irreversible processes, but made an essential contribution to the spread of variational principles in physics.[7]

2 Werner Heisenberg's order of reality

This brings me to the second example, Heisenberg's model of a scientific worldview. While Helmholtz's entire scientific work can be situated in the context of his mechanism, no particular worldview seems to have consistently influenced Heisenberg's work in a comparable way. It fits with this abstinence that the thoughts he nevertheless formulated concerning a worldview are to be found in a separate manuscript that was presumably written in 1943, but was only published posthumously in 1984. In a handful of public lectures from the 1940s one can find hints of this worldview. However, they provide no indication of the differentiated presentation in his substantial text, comprising around 150 book pages. The editors gave the book the fitting german title 'Ordnung der Wirklichkeit' (Order of Reality).[8] Since 2019, it has also been available in an English translation.[9]

Heisenberg's model of levels divides the world into six superimposed 'domains of reality', which are labelled in part according to the scientific disciplines that deal with them, in part according to the concepts that characterise them. In ascending order, these are the physical domain, the chemical domain, the domain of life, the domain of consciousness, the domain of symbols, and finally the domain of the so-called creative forces. According to Heisenberg, the physical domain includes the objects of classical physics and those of the two theories of relativity; the chemical domain, in his opinion, is formed by the objects of thermodynamics and quantum mechanics. While he describes these areas using the concepts and law-governed regularities of the associated theories, he does not assign the domains above them to

[6] See Franz Richarz's critique, discussed by Bierhalter 1994: 440 f.
[7] Cf. Schiemann 2024.
[8] Heisenberg 1942. Cf. Schiemann 2008: 84–113.
[9] Heisenberg 2019.

particular theories or disciplines and confines himself to characterising them in terms of their distinctive concepts. He relies on scientific knowledge as far as it seems possible to him and, in addition, sometimes brings in his own life experience. Presumably, the latter also enters into the uppermost level, which results from influences acting on beliefs and cognitive processes of individuals or groups. As phenomena to which this level refers, Heisenberg discusses religious myth and intellectual enlightenment, to which he attributes excellence in science and art.[10]

Heisenberg derives the basic determinants of the relationship between the concepts constitutive of the model and the areas of reality assigned to them from the child's acquisition of language in the lifeworld.[11] The concepts do not summarise sensory impressions, but instead represent states of affairs or thoughts. The more specifically they are determined and the better they have proved, the more precise their representational function becomes. Scientific language, to which Heisenberg attributed a partly static, partly dynamic character, is more precise than everyday language. Concepts of static language, as they are typically used by the mathematical sciences and jurisprudence, clearly refer to particular realities; the concepts of dynamic languages, which are found primarily in the humanities, are less concerned with representing phenomena than with the relationship to other concepts, with creating new concepts and with producing conceptual networks which, in their complexity, stand in interpretive relations to reality.

According to Heisenberg, static and dynamic languages each contain objective and subjective elements of representation. A fact is objective if it can be 'detached from ... its representation', subjective if 'in a complete description ... it may perhaps not be possible to ignore that we ourselves are interwoven in that web of connections'.[12] Objective and subjective aspects are found in every level, but in specifically different relations. Heisenberg arranges his levels between the ideal poles of the purely objective and the purely subjective. The lowest level, that of classical physics, is closest to the objective pole. Its idealisation can refrain to the largest extent from subjective aspects. The uppermost level is closest to the subjective pole. Although the knowledge acquired on this level is objective in character, it owes its existence to individual subjects. The model prescribes an ascent of the levels from the lowest to the highest, with a gradual increase in the subjective element. Heisenberg sees the scientific character of his model in its departure from objectivity. In addition, he justifies the systematic arrangement of his levels through the sequence of the ratios of objective and subjective elements.

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[10] Loc. cit. 53ff.
[11] Loc. cit. 20ff.
[12] Loc. cit. 33 and 46.

Finally, he intimates that this level structure is proposed as a solution to the problem of overcoming the separation between objective nature and subjective mind that goes back to René Descartes. He wants to replace this simplification of the world, which he considers far too crude, through a successive transformation of the relationship between objective and subjective aspects.[13] The question, however, is whether the separation between object and subject or between nature and mind can be sublated if we uphold the associated concepts. Won't the separation then be imported into each layer?

Despite the affinity between the levels achieved by successively lowering or raising the ratio of objective and subjective elements, there remain sharp conceptual distinctions between the levels. Separate boundary case relationships are defined for exceptional transitions that nevertheless exist between the levels. There are no relationships of reduction between the levels. The concepts of one level cannot be explained in terms of those of another level. Each neighbouring level exhibits something new that Heisenberg describes, but without clarifying its origin. The demarcation between the levels give the model a plural character. The model is only formally unified. But, the fact that the levels are separated from one another and transitions between them are only possible in exceptional cases does not mean that the phenomena assigned to them cannot occur together. In the lower area, the levels are completely contained within the neighbouring upper levels. The physical concepts are also valid in the context of their application in the domain assigned to chemistry, and the chemical terms are also valid in the context of their application in the domain assigned to biology.

Heisenberg's model of the order of reality does not raise any claim to exclusive validity. One of the characteristic features of his order is that the possibility of alternative worldviews is already built into it, both systematically and historically. A remarkable feature of his model is that it can also be read in reverse, leading to a quasi reverse order.[14] If one started from the uppermost level of the creative forces, the worldview would not have a scientific, but potentially a religious character. On Heisenberg's conception, the question of the meaning of life, which is excluded by science, would thus stand at the beginning and continue to serve as a guide in the gradual descent to objectivity. Presumably, the determinations of the layers and, consequently the phenomena represented by them, would change fundamentally. In particular, objectivity would appear, in Heisenberg's words, as an 'infinitely remote singularity that even though it is indeed decisive for order in the finite sphere ... can never be reached'.[15]

[13] Loc. cit. 34.
[14] Cf. Schiemann 2008: 91 f.
[15] Heisenberg 2019: 33.

Historically speaking, Heisenberg points to the transformation of worldviews in human history.[16] He situates the order he drafted in the series of these transformations, which is open towards the future. Heisenberg's order uses new natural scientific findings and relies on the knowledge of other disciplines, which has in part been known for some time. Although it does not explicitly distance itself from the mechanistic worldview, it can be understood as an alternative successor worldview that assigns mechanics only to a limited level. According to Heisenberg, not only the representations, but reality is also subject to change. In this way, social upheavals can also influence how the levels are represented. Heisenberg saw National Socialist rule and the beginning of the Second World War as a profound cultural break that could affect the scientific worldview.[17]

Heisenberg's order of reality can also be called a theory. There is little consensus on the concepts of model and theory. Moreover, often they are not sharply distinguished. In favour of the use of certain meanings of the notion of theory would be that Heisenberg's reflections employ independent structural principles and aim to unify various descriptions. However, Heisenberg himself seems to have believed that he was still far away from a theory. At times he speaks not so much of an existing order as of the search for an order. His remarks are fractured, incomplete and are not systematic in their structure. For example, he does not justify differences between the conceptual definitions of the levels and sometimes fails to provide adequate clarification of relationships between neighbouring levels. Against this background, the use of the expression 'model' can also be understood as designating a pragmatic substitute for a theory that is perhaps yet to be formulated.

A similar world model was developed around the same time by the philosopher Nicolai Hartmann, but Heisenberg was probably unaware of it. Although Hartman's outline is conceptually and systemically more elaborate, it contains a problematic critique of modern physics.[18] '[A]s a model for the order modern science is searching for', Heisenberg refers to a brief remark in the supplements to Johann Wolfgang von Goethe's theory of colours, where a comparable division of the world can also be found.[19]

3 Concluding remarks

Helmholtz's model is located between scientific worldview and reality. The scientific worldview claims that physical mechanics is applicable to all natural phenomena. The example discussed concerns a structural analogy between

[16] Loc. cit. 29ff.
[17] Loc. cit. 20 and 118f.
[18] Cf. Schiemann 2019.
[19] Heisenberg 2019: 35, cf. Goethe 1989: 788.

the mathematical representations of a model derived from physical mechanics and a natural phenomenon that has not yet been explained, namely, heat. The model has a descriptive character and is completely intelligible. It is supposed to demonstrate that thermal phenomena could be produced by mechanical motions. It becomes apparent, however, that these would have to be motions whose natural appearance is difficult to imagine, since the mechanical model is a tricky technical construct. Moreover, the model does not correspond to mathematical descriptions of other heat phenomena.

Even the assumptions of the mechanistic conception of the world have proven to be wrong, elements of the conception of levels it advocated have retained their importance for scientific research to the present day. Among them is the assumption of a level of processes that generate the phenomena, as this has become established in contemporary philosophy of biology under the heading of a 'mechanical philosophy', as well as the assumption of a layer of mathematical relations detached from the phenomena and their representations.

The notion of a model as an interpretative representation of an object or system I presuppose can be applied to Helmholtz's monocyclic systems, but not to his mechanism. The monocyclic systems represent an object of 'an unknown kind' and have interpretative content in their descriptive and analogical properties. His mechanism, however, is not intended to be a representation, but as the true mirror of natural phenomena. In contrast, Heisenberg stresses the interpretative and representational character of his worldview in different respects. The elements that enter into the representation of the world as subjective parts of the levels are to be mentioned as interpretive. Moreover, the possibility of alternative representations of the world gives his order an interpretative quality.

Conceptions of levels have been formulated since antiquity and remain relevant in contemporary science, as exemplified by emergence theory and the critiques of reductionism. They are scientific worldviews and share with them the good reasons for being called models. Scientific conceptions of the world will probably remain interpretative representations for at least as long as we lack a scientific theory that encompasses the world as a whole. As models, they can confine themselves to generating unity through formal structural elements, examples of which are provided by Heisenberg's model.

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