

Models and analogies in science

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Abstract: Science makes extensive use of models, *i.e.* simplified or idealized representations of the systems found in the physical world. Models fall into at least two categories: mathematical and physical models. In this paper, we focus attention mainly on the latter, trying to show that they are essential tools not only of the scientific description of the world ‘out there’, but of man’s cognition of things, especially things not directly accessible to the senses. The spring-and-ball (SB) model of chemistry is a most instructive example of a physical model. In other disciplines, from cosmology to physiology, models are used that are of the same kind or play the same role. It is concluded that physical models are objects which belong to the world accessible to man’s direct experience, often constructed *ad hoc* and possibly idealized. They serve as referents for analogies, which appear to be indispensable in most aspects of scientific theorizing, especially for the understanding of the submicroscopic levels of reality.

Keywords: *models, analogies, idealization, truth, molecular spring-and-ball models.*

1. Models in chemistry and in other sciences

1.1 A concrete case: the spring-and-ball model

Let us briefly examine, first of all, the nature and meaning of the stick-and-ball model of a molecule, or its improved form, the spring-and-ball (SB) model. This is an extension of the sphere model of the atom and of the mass-point model of elementary particles. As discussed in a previous paper,[\[1\]](#) the basic explanatory concept of chemistry, molecular structure, is defined in terms of the SB model, developed from an idea of Kekulé going back to 1858. The question "does a molecule have a structure?" should be answered as follows: "a molecule has a structure in the sense that it has a property analogous to the structure of its SB model." The explanation of the observed spectroscopic bands as due to transitions between vibrational states, and the Born-Oppenheimer proof[\[2\]](#) that quantum mechanics is compatible with the SB model proves the validity of statements on molecules based on the assumption that the latter behave essentially – *i.e.* with respect to their geometrical and mechanical properties – as if the SB model a chemist has on his desk were a faithful magnification (roughly a hundred million times) of a molecule. This analogy is the origin and justification of the introduction of structure and shape as characteristic molecular properties.

Chemistry, therefore, shows how far analogical thinking is entrenched in science. Analogy in general is not a simple notion; in this case, however, its meaning is clear: the geometrical and mechanical properties of the macroscopic model are assumed to match closely (though not completely) the properties of the corresponding real molecule.[\[3\]](#) The SB model of chemistry thus provides a concrete example of thinking by analogy in science, and hence a good starting point in a general study of models.

1.2 The role of models in science

It is not an overstatement that a sapient use of models is the essential trait of Galilean science. Galileo himself used what three centuries later Einstein called *Gedankenexperimente* to establish the foundations of mechanics;^[4] and those idealized experiments may be treated as taking place in a world that closely matches those features of reality which science can study. It seems legitimate to say that the name ‘physical models’ applies to the objects of which this ideal world is made. The objects in question were originally just limiting cases of objects and processes in the world which we perceive directly in typical *Gedankenexperimente*; but in contemporary science they can be representations, such as our five senses can perceive or our imagination can shape in our minds, of those real entities that are too small or too big or too complex for direct observation. In these cases they are not referents for a critical analysis of the laws governing concrete situations and processes; they are as it were the representatives of the objects of study before the court of human reason.

In this perspective, a reflection on models in science is a chapter of any study on the relation between sensible reality and the procedures by which science derives knowledge about it. Let us admit that models are the tools of scientific thinking: physical models are tools of *descriptive* analogical thinking, mathematical models at large are the tools of *argumentative* analogical thinking.^[5] But what exactly does the term ‘tool’ mean in this case? This is no easy question, because, as the SB model shows, at least physical models have different functions depending on whether one is studying the world of our ordinary experience or the submicroscopic world. To find an answer we have to examine the nature of scientific truth taking the ontological structure of sensible reality into account. In plain words: if the statements of science concern models, how can they be expected to disclose the truth about what lies ‘out there’, *i.e.* what appears to be independent of the observer’s will and wishes?^[6]

2. True statements in science

2.1 Examples, images, and truth judgments

The current, largely intuitive view is that a scientific statement is true, in principle at least, either because it is logically derived from the fundamental laws of nature or because it matches observed facts. However, if use is made of analogies, both physical and logical, what justifies the belief that scientific statements concern reality? A schematic answer is that one should distinguish between different degrees of truth. This has been well known since antiquity, but the rise of empiricism and analytical philosophy has impaired the philosophical memory of our culture. The famous (and infamous) classification of things into genera, species, etc. implies the use of limited truths. The statement that a diatom is a microscopic unicellular animal can be qualified as true provided, (a), the meanings of the terms used, e.g. what is an animal, are clearly known; (b), it is implied that all there is to know about a diatom is contained in those terms. Similarly, the statement that a gas in a container with a mobile wall responds to increases in external pressure by reducing its volume does not describe entirely the behavior of a real system, but it is true under the agreement that there are no other perturbations, that friction can be neglected, and so on.

Let us thus grant that, in order to be true, a statement need not match reality in all its aspects, relations, and/or details, but has to match it only as far as it goes. This consideration applies both to scientific concepts and to relations between them.

The difficulties begin at this point. When a zoologist thinks of the term ‘animal’, does that evoke any picture in his imagination? This question should be turned to the psychologists, but it will suffice here to answer that when thinking of an animal at least some people do imagine a lion, a bee, an amoeba, so as to visualize those properties which make them animals, ignoring at the same time those which are specific of their class, order or minor subdivisions. The ‘ignoring’ here can be an extremely fast and subconscious process, but even ordinary people know by observation on their children that this combination of a concrete image with an abstraction process is learned in tender age.

The fact that physical models provide images is a reasonable explanation for the extensive use of models in science. If this is granted, why should we waste more time in working towards a precise definition of models, in contrast with the current opinion that definitions are not necessary? Why not try to understand what models are just by means of examples, in accordance with the practice of modern education? The answer can be given in two points.

First, ‘understanding by examples’ can only be considered sufficient by people not familiar with introductory mathematics, where that view is shown to be limited to negative assertions.

Secondly, there has been a decline of the belief that science is the only way to knowledge of a reliable kind. This trend is good in itself, but it is liable to go too far, and make scientists lose confidence in their work. It would seem that the only defensive measure is to bring to light the scope and limits of scientific ‘truths’, by making explicit a number of tacit beliefs till now implicit in scientific thought. Now, an important unexpressed belief is that models are ‘tricks’ used during the preliminary stages of research, and that science should reach beyond them. If this belief is mistaken, and models are indispensable tools, or indeed built-in features of the scientific enterprise, then it becomes indispensable that we should know how to use them.

It thus appears that a clearer understanding of models is worthwhile. In order to proceed in this direction, we must consider how science arrives at ‘truth’, and in what sense the scientists qualify their statements as true.

2.2 Truth and understanding

The paradigms of science are paths towards the intellection of facts. As a metaphor for this, Galileo spoke of "reading the Book of Nature". This metaphor – although suggested to Galileo by the custom of relying on real books by honored Masters[7] – was well chosen, for ‘intellection’ comes from Latin *inter-legere*, ‘to pick among’. Now, *legere* also means ‘to read’, and reading a message so as to be able to communicate its content is an excellent illustration of the process of understanding. The output of a scientific study, in fact, consists in judgments constructed in terms of appropriate concepts from the analysis of data. The judgments and the concepts are said to be formalized, meaning that at the conscious level they are expressed in a language, and they become ‘propositions’ or ‘statements’ which must then be tested for their truth value: if they are false, they are rejected as not being knowledge.[8]

In practice – though seldom at a philosophical level – the statements falling within the realm of science are said to be true if they are:

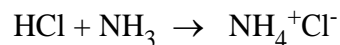
(a) correctly derived from (or at least consistent with) principles and other premises;

(b) faithful to reality.

Condition (a) is necessary (*cf.* end of this section) for the statements of science to be true, but it is not sufficient, unless the premises are true in sense (b). Those premises, however, are the ‘laws of nature’, which are hypotheses so satisfactory that scientists treat them as unquestionable, but are generalizations, and hence cannot be proven experimentally. Even such a fundamental principle as the conservation of energy is all the time *sub judice*. [9] Therefore, strictly speaking, the only sufficient condition for a truly scientific statement is (b), whereas (a) is only a necessary condition. Then two questions arise:

- Is science a set of statements true in sense (a)?
- Are the statements of science susceptible of tests for truth in sense (b)?

It would seem that in either case the answer is negative, unless the terms ‘true’ and ‘truth’ are carefully qualified, essentially because the statements of science are the output of a special information processing. This processing is guided by two simplifications: (i), it selects patterns of events by ignoring details and fluctuations; (ii), it treats as identical real entities which differ only by ‘accidental’ details. An example is the statement that ammonia and hydrochloric acid react to give ammonium chloride:



The meaning and validity of this equation are easily tested experimentally; for example, if an open bottle of household ammonia is placed close to an open bottle of household hydrochloric acid, fumes of ammonium chloride will be seen to form above the bottles. Therefore, it should be considered scientifically true. In fact, however, it is subject to three limitations at least:

- it refers to pure substances, and the substances actually used are not pure;
- it does not contain information on the time evolution of the process;
- it does not describe the details of the actual experiment.

The equation under consideration thus applies to a ‘model world’, and only in that world do questions 1 and 2 above under

consideration apply. The example of ammonia and hydrochloric acid thus provides an illustration of the claim that scientific knowledge obtained depends on models in two ways – in the processing of factual information and in the assessment of the truth-value of the resulting statements. The entities and processes referred to in science are not entities and processes as such, but suitable idealizations, which may be called ‘models’ and ‘model processes’, respectively. Therefore, in point (a) above, which concerns the logical status of scientific statements, the expression ‘other premises’ should include in particular the criteria and limits of validity of the analogies on which the statements of science rest; in point (b), faithfulness to reality, the proviso should be added that faithfulness is required within the limits imposed by the models used.

3. Reality according to science

3.1 Ontological structure of sensible reality

Let us say it again: the physical world according to science is not the real world; it is a world that matches faithfully those features of reality which science can study, but lacks the variable details which make each instance of our experience of reality unique; a world in which all surfaces are perfectly smooth, all horses of a type or sort are identical to one another, all pure benzene bottles contain but molecules of benzene, and so on. It would seem that science works with a ‘a world of shadow types’, a copy of the world of sensible experience in which only standard objects (types) are admitted, and those types are as it were shadows of the individual objects or beings which they represent.[10] It is nevertheless quite a rich world, because several types are often assigned to a particular object of the real world – just think of horses from the points of view of a race-horse breeder and a zoologist –; but in it, for example, there is no type for *my* horse Thaumasio. As mentioned, it seems that one acceptance of the term ‘model’ in science applies to the shadow types under consideration.

Horses and other objects or beings of the same size belong to the world accessible to our direct experience. However, science is also concerned with objects and processes that are not directly perceived by our senses. In what sense, if any, are they reduced by science to models or phantoms of what they really are? We have already an idea of the answer from the SB model (Sect. 1.1). To make that idea more explicit we have to examine briefly the ‘ontological structure of sensible reality’. This rather formal expression applies to the result of an attempt to describe reality as an ordered collection of objects and beings – entities – of different sizes, degrees of complexity, accessibility to observation.

Let us consider an example discussed by Heidegger[11]: a tree in full bloom standing before us on a meadow. Is the tree real? Or is it only a collection of nuclei and electrons suspended as it was in emptiness? The latter question is answered positively by physicalistic reductionism, but on further reflection, it appears to be untenable. As we have tried to show in a previous paper,[12] a tree is a collection of particles, but it is not just that; because it is the actualization of one system out of the huge number of systems those particles can make up. The tree is also a collection of cells and dead material; it is a collection of leaves and branches and roots, and it is a tree, indeed a blooming tree, with its colors and its pleasant smell.

Examples of this sort suggest a general view of what ‘to exist’ means that is unconceivable in a physicalistic frame of mind. According to this view, the physical world consists of objects (physical systems) more or less independent but clearly distinguishable from one another. Concrete examples of those objects, roughly in descending size order, are:

- an intergalactic gas cloud, the Sombrero galaxy;
- the red giant star Betelgeuse, the planet Mars;
- the Pacific ocean, the Himalaya mountains range;
- the ecosystem of Easter Island, the Schwarzwald, a whale;
- *an oak, a human being, the heart of a lion, a bee;*
- a microscopic mite, a diatom, a cell of an anatomical tissue;
- a DNA molecule, a carbon dioxide molecule, a hydrogen atom;
- a photon, a neutron.

These objects belong to different fields of inquiry in Bunge’s sense,[13] and are therefore studied by different disciplines. Those in italics belong to the DA (direct access) level of reality, because man can see, touch, smell, hear (and sometimes taste) them in their entirety; they are perceived by man as such.[14]

Careful examination of the list above will give the reader a feeling for the nature of the ‘size ladder’ of material reality; that ladder, which seems at first sight to extend from infinity to infinity, was the object of Pascal’s famous reflection on ‘the two infinities’.[15]

Before the DA objects, large objects are listed whose entire reality cannot be perceived by all our senses, if at all. Even in the case of a familiar object such as a mountain one can easily realize that for us to see it as a whole it must be so remote that we cannot touch it, and vice versa. A star is only perceived as a shining point, or not at all.

As to the objects listed after those which belong to the DA level, a mite or a cell can only be examined visually with a microscope, and cannot be detected by touch. A molecule cannot even be seen by simple magnification, because it is smaller than the wavelength of visible light; so that what we call an ‘image’ obtained, say, by scanning tunnel microscopy is a theoretical construction based on the formal similarity between matter waves and light waves. Even when an image can be obtained with light, it is actually based on an analogy, albeit a very close one. The varying theory-dependence of our knowledge of material entities too large or too small for man’s direct access – and the resulting problems with the nature of our ‘perception’ of them – suggest that we should attribute to material reality a layer structure from the point of view of intelligibility. This level structure may or may not have an ontological import, but it is essential for the ‘existence judgments’ which science is expected to pronounce.

The size levels (or layers) should not be confused with another aspect of the structure of reality, namely complexity. Each object or being in the universe only belongs to one size level, whereas different complexity levels are simultaneously present in any given object. Moreover, objects such as a microscopic mite and a whale belong to the same level of reality on the complexity scale and are by far more complex than a star: despite their difference in size they are studied by the same discipline – zoology. In short, complexity is another feature of reality according to which entities should be classified and disciplines distinguished. We have discussed it elsewhere in connection with chemistry,[16] and shall not pause on it here, because all that is needed about levels of reality in connection with models has been said above. The major inference to be drawn is that, since man has no direct perception of a large majority of the objects which science has detected in the physical universe, his knowledge is based on analogies with *ad hoc* objects, possibly artificial, as is the case with the SB model of molecules.

3.2 About analogies and metaphors

In support of the above remarks, we recall the points raised in Sect. 2.1, namely that, in the vast realm of perception and thought, analogies with direct sensible experience are much more important than people usually think. They lie at the very roots of the terms used to express abstract concepts and processes, for those terms were created by ‘metaphors’, *i.e.* analogies with physical operations.[17] For example, when we say that ‘we grasp an idea’ we unwittingly use two metaphors. First, we imagine that our mind is like a man stretching out his hand and closing his fingers on an object that is the idea; second, we treat the idea as a shape which we see with our inner eyes (‘idea’ in Greek means primarily ‘shape’, ‘outer aspect’). Similarly, when we say that we ‘express’ something, we use a metaphor, for the Latin verb ‘*exprimere*’, from which ‘to express’ comes, means ‘to squeeze out.’

These examples show, if need be, that, although the etymological roots of words are seldom present in our minds, even speculative thinking has its roots in the everyday sensible experience.

According to historians, even mathematics began with concrete, visualizable problems; and there are grounds for believing that formulas are visualized by the mathematicians for their minds to work on, even in transfinite mathematics. However that may be, in the sciences of nature visualization (and sometimes association with other sensations, like sounds) plays a fundamental role, not only as regards creativity but as regards understanding.

If – and to the extent to which – this is so, it implies that the categories of our direct-access level of reality are those which we use for understanding objects and processes belonging to size and (perhaps) complexity levels far remote from that level. This is why those models which are representations at man’s DA level of material objects not directly accessible are indispensable tools of science.

3.3 Analogical models

We can now restate what we already saw about the fundamental model of chemistry. Atoms and molecules belong to a size level of reality whose objects cannot be perceived by our senses. Man’s familiarity with wheat, sand, flour, and his ability to imagine a

succession of smaller and smaller sizes even beyond what he actually observes suggest the conjecture that matter is made of tiny indivisible particles which we call ‘atoms’ (Greek for ‘objects that cannot be cut into smaller pieces’). The chemists make that conjecture into the fundamental hypothesis that molecules have a specific property called structure. From that hypothesis, they start the enterprise of disentangling observations and partial inferences about chemical transformations.

Let us denote by R the real size level of an object, by DA man’s direct-access level, by M-DA a physical model belonging to the DA level. The procedure under consideration can then be schematized as follows:

- atoms are assumed to exist (R);
- they are visualized as tiny spheres (M-DA);
- the elements are assumed to be made of identical atoms (DA);
- pure substances are defined in terms of the elements (DA);
- molecules are introduced (R);
- they are assumed to be groups of atoms (R);
- they are visualized as clusters of spheres (M-DA);
- isomers are discovered (DA);
- the clusters are replaced by edifices of spheres (M-DA);
- molecular structure is defined by analogy (R).

Molecular structure, as defined, is then used to explain chemical transformations, with the help of further guesses and tests, observations and inferences.

4. Conclusion

The above scheme completes our argument about physical models in science. Let me conclude with a brief recapitulation.

We recalled at the beginning that the word ‘model’ can be used for a mathematical model, already discussed by other authors, and for a physical model, which appeared to require further reflection. A brief examination of the SB model of molecules confirmed the claim that science studies an idealized copy of reality, and suggested that we should therefore explore the role of idealizations and analogies in our endeavor to apprehend and comprehend reality. Idealizations (reduction to standard types) provide analogies used in science to cope with difficulties arising from those details which make each perceived object unique. Reality beyond the thresholds of direct perception is apprehended by means of analogies constructed *ad hoc*, namely with very special, often artificial systems, real or imaginary, belonging to our direct access level of reality. This led us to focus our attention on these physical or ‘analogical’ models and their relation to reality.

Physical models thus serve a double purpose: they allow scientists to ignore inessential details of entities belonging to the ordinary environment of man without dismissing their collocation on space and time; and they provide counterparts in that same ordinary environment of entities not immediately accessible to the five senses of man. To grasp the ontological significance of models of objects lying beyond our direct perception, from galaxies to electrons, layers or ‘levels’ of reality corresponding to size and to complexity should be considered. There is a size level of reality which can be perceived by man with his five senses; it may be called ‘man’s direct-access’ (DA) level. It turns out that our knowledge, including abstract thinking, is based on analogies with material objects or processes at the DA level. *Ad hoc* objects (‘models’) at the DA level supporting analogies for objects not directly accessible to our senses are essential tools of scientific thinking.

Notes

[1] G. Del Re: ‘The Ontological Status of Molecular Structure’, *Hyle – International Journal for Philosophy of Chemistry*, **4** (1998), 81-103.

[2] M. Born, J. R. Oppenheimer: ‘Zur Quantentheorie der Moleküle’, *Annalen der Physik*, **84** (1927), 457-84.

[3] Of course, the results of a calculation of the vibrational properties of a molecule will usually match the observed vibrational frequencies only if the parameters are chosen in the proper way. This is consistent with the fact that the theory is based on an analogy.

[4] For example, when he established Galilean relativity, by considering flies in a ship in perfect uniform motion.

[5] For mathematical models, cf. the survey by Salvo D'Agostino, Sandro Petruccioli (eds.): *Mathematical Models and Physical Theories*, published as a reprint from: *Rendiconti dell'Accademia Nazionale delle Scienze detta dei XL (Rome)*, serie V, vol. IX, parte II, 1985, pp. 65-198. The general question of mathematics vs. description in terms of visualizations was treated by Henri Poincaré: *La science et l'hypothèse (1902)*, Paris, Champs-Flammarion, 1968; cf. G. Del Re: 'Poincaré et le mécanisme', *Philosophia Scientiae (Nancy)*, **1** (1996), spec. issue 1, 55-69.

[6] Although for our present purposes this intuitive description of realism is sufficient, there would be much to add in the frame of a general theory of thought and perception. The Kantian critique to essentialism and the difficulties which it raised in connection with realism is well known to everybody since secondary school.

[7] *Il Saggiatore* (1623), Ed. Naz. Op. Galileo, Firenze, Barbèra, 1896, vol. VI, p. 235.

[8] This is a cursory mention of the view on science adopted for this study, and is not intended to dispose of the numberless studies on scientific knowledge published in this century.

[9] Henri Poincaré, *op.cit.*, p. 148f.

[10] A. S. Eddington, *The Nature of the Physical World (1935)*, London, J.M. Dent & Sons, Everyman's Library, 1947, pp. 5-10 and *passim*. Note that Eddington was writing when science was assumed to coincide with physics.

[11] Martin Heidegger, *Was heißt Denken? – Vorlesungen des Wintersemesters 1951-52*, Stuttgart, Reclam, 1992, pp. 25-29. Cf. A. S. Eddington, *loc.cit.*

[12] Del Re, 'On the ontological status ... ', *op.cit.*

[13] Mario Bunge: 'Is Chemistry a Branch of Physics?', *Zeitschrift für Allgemeine Wissenschaftstheorie*, **13** (1982), 209-223.

[14] Strictly speaking, only the objects that man can *handle* belong to the DA level; but the separation we are trying to establish has a somewhat fuzzy border, and, as the reader certainly sees, it is not worthwhile to try to be more precise.

[15] Blaise Pascal, *Pensées* (ca. 1660), ed. by Louis Lafuma, Paris, Éd. du Seuil 1963, pp. 199-72.

[16] G. Del Re: 'Chemistry and Complexity', in: G. Costa, G. Calucci, M. Giorgi (eds.), *Proceedings of the Third International Symposium on Conceptual Tools for Understanding Nature*, Singapore, World Scientific 1997, pp. 153-164; cf. also works by the same author already cited. The complexity levels are very close to what N. Hartmann called *Seinsschichten* (layers of reality). This was pointed out in connection with chemistry by J. Schummer: *Realismus und Chemie*, Würzburg, Königshausen & Neumann, 1996. Independently from Hartmann (and perhaps in a less systematic form), also S. Alexander proposed around 1920 a layer structure of reality.

[17] A great merit of Heidegger was precisely that he brought this point to the forefront of philosophical thought. It is unfortunate that the recent dramatic decline of classical studies has caused a loss of feeling for the original values of most philosophical words, which is slowly but steadily spreading from the Anglo-Saxon world to the Latin and the German countries.

