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Model and Analogy in Science and in Teaching Physics

Model i analogia w poznaniu naukowym i nauczaniu fizyki

Модель и аналогия в научном познании и обучении по физике

I dedicate the present paper to the memory of Professor Włodzimierz Żuk, who always showed great concern about the problems of teaching pupils and students, and promoted any undertaking which aimed at improving the methods of teaching.

The term model is derived from the Latin word modus, modulus, which means an image, presentation, mode. The original meaning of this word was connected with art where it was used to denote the original, the prototype. It was probably in mathematics that the term appeared first in science. In the first half of the seventeenth century, the age of Rene Descartes and Pierre Fermat, the term 'model' came to be used to denote a theory which showed structural similarities to another theory. The former theory functioned as a model for the latter (both were isomorphic). It does not mean, however, that models in the present sense of the word had not been created earlier. Notional constructions (mental models) were created in the antiquity, for example Anaximander's model of the Earth, the geocentric model of the Ptolemeic planetary system, the model of the atom described by Democritus and Epicurus, or the two-dimensional model of Archimedes' lever. Yet these intellectual constructions were not called 'models.'

In modern times both the functions and the methods of creating models developed and increased their range. In the sixteenth century William Gilbert constructed a material model of the Earth, which he called 'terrella', in the form of a magnetized steel sphere. He also made an experiment which could be called a model experiment nowadays. He passed the magnetic needle around his 'terrestial magnet' and thus explained the phenomena, described previously in Arabic manuscripts, of magnetic inclination, magnetization of rods, demagnetization of magnets.

The development of mechanics in XVII, XVIII and XIX centuries produced the idea that all phenomena could be brought down to mechanical motion and be explained by means of visual mechanical models. J. C. Maxwell claimed that the need of models resulted from the necessity of physical interpretation of mathematical formalism. He pointed out to the didactic function of models.

In his work, "La Theorie physique", published in Paris in 1906, Peter Duhem, a French physicist and methodologist, speaks of models as visual means used by physicist while constructing theories. According to Duhem, a model is an aid invented by those physicists who must constantly appeal to their sensory imagination while studying the reality. Scientists of this type prevailed among English physicists. W. Thomson said: "... I can't understand anything unless I build up a model". He made an interesting attempt to reconcile the continuity of the matter with its atomic structure. He proposed a model of vortex atoms stating that atoms are vortex rings in a perfect continuous medium filling the Universe. J. Maxwell pointed out to a contradiction in Thomson's model. It consists in the fact that the universal ether is a weightless substance while vortex rings (atoms) have mass, whereas, according to Newton's mechanics, mass is the property of matter, and not of the states of its motion.

Peter Duhem claimed that in physics introducing models in the sense of geometric, mechanical patterns visualising certain structures was in fact unnecessary in relation to the theory itself. P. Duhem had a wider conception of a model. He identified for instance, Maxwell's theory with a system of equations which he called an algebraic model [3].

The appearance of the quantum theory has introduced limitation in the use of visual, mechanical models. Symbolic (mathematical) models have assumed primary importance. According to G. Frey and R. Ackoff, patterns of signs, symbols (mathematical equations) can be treated as models if the signs and symbols appearing in the equations have been clearly, unequivocally determined.

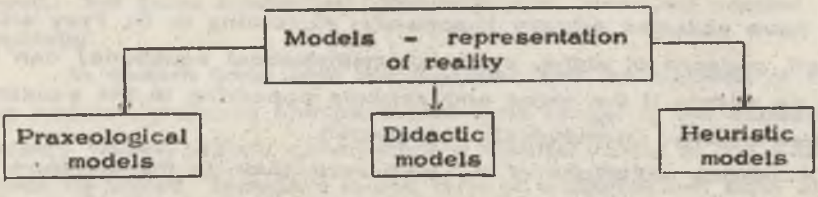
Numerous definitions of the model are given in the literature. The two definitons of the model in the sense of a representation of reality which are quoted below seem to be most suitable for the purposes of physics and technology [1,8].

In his work "Modelling and Philosophy" W. A. Sztoff defines the model in the following way: "A model is a system one can think of or realize materially, which, while representing or reproducing the examined object, can stand for it so that its examination gives us new information about the object."

In his book "Optimal Decisions in Applied Research" R.L. Ackoff states: "Models are representations of states, objects, events. They are idealized in that they are less complex than the reality and hence easier to use for research purposes. The simplicity of the models in compa_ison with the reality results from their including only those properties of reality which are relevant in a given case." This definition includes praxeological models used in research aiming at technological improvement, e.g. aeroplane models, cars in a wind tunnel, as well as mathematical models resulting from the application of the idealization method (e.g. a free fall model), which are constructed with the introduction of a number of idealizing assumptions. The model is the effect of abstracting (e.g. from the whole) and distinguishing those parts of the object which are particularly interesting for practical or theoretical reasons. The process of abstraction characteristic of model construction is called idealization.

There are several different classifications of models in the literature, which take the mode of constructing models as the criterion of division. On the basis of this criterion, models are usually divided into material and mental [8]. Classification according to function, however, seems to be more relevant, since it is chiefly its usefulness from the point of view of the purp-se for which the model has been constructed which determines its value.

Models which serve to represent reality can be divided into three basic groups with respect to the function they perform. The following scheme presents this type of division:



One and the same model may be used either as, for instance, a didactic or a heuristic one (it can fulfil one of these functions better), but in a given situation the purpose for which it has been used determines its function. For example, an electric system serving as a model of a mechanical system and used in order to obtain optimal technological solutions for the mechanical system performs the function of a praxeological model. Due to formal analogy, conclusions concerning the parameters of the mechanical system can be drawn on the basis of experiments and modifications of the electric system constituting what is generally called a model experiment. Models "in a scale" can also serve as didactic models; they substitute less accessible objects of more complex structure, and keep the same geometric characteristics, dynamic and physical similarity of phenomena. These models are used to explain the structure and the principles of operation of mechanisms.

This group of models also includes graphical representations: drawings, diagrams, schemes, structural patterns, used in order to visualize physical laws and phenomena. The group of didactic models also includes mechanical models visualizing a theory, as well as theories formulated in everyday language we are familiar with, as models of more formalized theories.

Heuristic models are representations of fragments of reality in a simplified form, in which the simplifications have been introduced in order to facilitate theoretical or experimental investigations. "Conceived" experiments making use of mental models and leading to new knowledge also fall under this heading.

While constructing and examining a model we use inference by analogy. In methodology an analogy is the compatibility of relations occurring between the features of events (objects, phenomena). These events are usually physically different (e.g. mechanical models of electric effects or mechanical models of atomic systems). Developed inference by analogy consists of two premises and a conclusion.

The following scheme presents one of the types of inference by analogy:

$$Z\ (a,b,c \overset{R}{\longleftrightarrow} P) \qquad\qquad Z'\ (a', b', c' \overset{R}{\longleftrightarrow} P')$$

premise ↓ p, q, r — premise ↓ p', q', r' conclusion

Event Z includes features a,b,c and feature P. A certain relation (R) exists between features a,b,c and feature P. Relation R has consequences p,q,r. Event Z' includes features a', b', c' and feature P'. We state the existence of the same relation R between features a', b', c' and feature P'. We can infer by the analogy on the occurrence of consequences p', q', r'. [2].

An analogy may concern objects or phenomena; this type of analogy can be called ontological analogy. An analogy including parallel relations between the effects of cognition and reality is called a notional-ontological analogy. This type of analogy includes the analogy between a model of reality and the reality itself. Notional analogy is an analogy between two conceptual structures. Inference by analogy is always reasoning from a detail about a detail. Both the conclusion and the premises have the same degree of generalization. Binary relations and coupled features are characteristic of analogy. Conclusions drawn by analogy are probable but they are never certain. Therefore, every conclusion drawn by analogy must be verified in an experimental way. If the experiment does not confirm the conclusion drawn by analogy between e.g. a fragment of reality and a model of that reality, the model must be modified or rejected.

Inference by analogy is used for research in physics mainly in order to formulate hypotheses. A certain number of loose facts result from observation. These new facts evoke memories of facts encountered earlier. Comparing those facts is done by way of inference by analogy. J. C. Maxwell defined analogy in the following way: "By physical analogy I understand partial similarity between the laws of two ranges of phenomena. A similarity which makes one illustrate the other".

Analogy can be used in order to illustrate one effect by another, well-known phenomenon. This new effect can be thus better understood and remembered. Analogy performs here the function of a didactic means. From the methodological point of view the use of analogy for the formulation of new laws and new notions is much more important.

Inference by analogy while constructing and examining models is rather seldom used for the purposes of teaching physics in schools. This fact has been indicated by the results of an inquiry carried out among secondary school pupils. In order to find out the most frequent associations of the term "model" among school children, as well as the function they ascribe to models, I carried out an inquiry including 590 pupils. These investigations had the form of a diagnostic test. The questions were:

1. What is a model?
2. For what purpose are models used in science?

The analysis of the answers leads to the conclusion that the term "model" is most frequently used in the meaning of a prototype, a pattern or a teaching aid. The heuristic function of models was pointed out by a very small proportion of pupils (0.5 per cent). The results of the inquiry are justifiable in the light of an analysis of school handbooks. In most handbooks I have had access to, the term "model", when it appears there, is used in the context of its didactic function. The role of models and the model method, of reasoning by analogy in developing imagination, abstract thinking and creative abilities is very small in the existing teaching practice. The point here is not only to have the pupil acquainted with the model method as a research method, but also to make him apply it in particular situations. Active participation of the pupils in the construction of models and their practical and theoretical examination would allow to accomplish the educational aims of the school which consist in developing creative abilities and intellectual flexibility of the pupils.

Three aspects of the problem can be distinguished in the teaching practice:

1. Directing the teaching process so as to encourage the pupils to seek analogies even between very remote phenomena also from outside the domain of physics. A method called "synectic", consisting in activating the teaching process by the use of analogies and metaphors, has been applied with very good results in the United States.

2. Creating models inaccessible to direct observation of reality on the basis of experimental data from indirect studies, trying to find

corresponding rules connecting extralogical categories of the models with notions which have observational meaning. What is meant here is the construction of microcosm models in science, and the use of "black boxes" for teaching purposes in schools. The pupils are already acquainted with the phenomena which take place in the "black box". They have also learnt the information necessary for their description. Yet the pupils cannot directly watch the course of the phenomena. They can only study the variation of certain parameters characterizing the phenomenon. The most essential parameters for the course of a given process are selected. On the basis of the variety of particular parameters and their functional relations the pupil creates a model of the phenomenon and the internal structure of the "black box".

3. The use of the idealization method in order to omit the complexity of phenomena. This method involves the following cognitive steps:

a) selecting a group of factors significant for the examined phenomenon,

b) setting up a hierarchy within that group, creating a model - a simplified representation of reality,

c) finding the relations determining the effect of the main factors on the examined one, with respect to the assumptions of idealization,

d) eliminating the idealizing assumptions one by one, and modification of the initial law by including additional factors (specification of the law leading to an approximation law) [7].

The idealization method can be illustrated when discussing e.g. the free fall of bodies, oblique throw, or projecting model and real experiments. A real experiment must be worked out so as to minimize the influence of additional factors.

The present article has presented some of the problems connected with including the model method, reasoning by analogy into the didactic process as its integral part. The model method is generally used in science, particularly in economy, biology or technology. If the pupils get acquainted with this method, if they are allowed to take active part in constructing and examining models, reasoning by analogy, they will make better graduates not only with respect to the methodology of physics, but also other empirical sciences.

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РЕЗЮМЕ

В работе представлено определение модели, классификация моделей а также дана характеристика логической операции "вывода по аналогии ". Эта операция служить для конструирования и исследований моделей. По исполнению анкеты среди учеников средних школ, представлено предложение включения метода моделей в практическое обучение по физике.

STRESZCZENIE

W artykule przedstawiono definicję modelu oraz klasyfikację modeli, scharakteryzowano wnioskowanie z analogii, którym posługujemy się przy konstruowaniu i badaniu modeli. Przechodząc do praktyki szkolnej omówiono wyniki badań ankietowych dotyczących rozumienia przez młodzież szkolną pojęcia "model", a następnie przedstawiono propozycję integralnego włączenia metody modelowej do procesu nauczania.

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