

Theoretical Model in Teaching Physics: Perspective "Discipline Culture"

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1. Introduction

Peierls (1980) introduced typology of models as used in physics. We suggest modification which reflects the nature of model as a special theoretical construct. Our approach draws on the idea that model mediates between the represented object (phenomenon) and certain system of basic principles (theory). This *first* possible function of model, mediation, follows from the difficulty of any theory to describe real objects.

Moreover, we suggest that relationship between physical theory, model and object is not linear but rather can be represented by means of a semantic triangle: object-sign-concept (Frege 1890). The interrelation object-model-theory is similar (Fig. 1).



Figure 1. (a) Semantic triangle of Frege; (b) Similar triangle: object-model-theory.

The semantic triad of Fig. 1b is silent regarding the sequence of unfolding. This may lead us to another function that model can play when the theory is not known. In this case, a model serves as a device of construction of a new theory. In such a case, the model is heuristic and presents a hybrid of elements from the old and new theories. Such a model anticipates the new theory, guessing regarding its essential features. This is the *second* possible function of a model: a mediator between the new and old theories. The latter function is in fact an important cultural function facilitating the progress of physics. Awareness of the two functions of models suggests implications to physics teaching and broadens the common approach to using models in physics education (Hestenes 1992).

2. Critic of Peierls' typology

The suggested by Peierls (1980) typology of models encloses seven types:

1. *Hypothesis*. 2. *Phenomenological model*. 3. *Approximation*. 4. *Simplification*. 5. *Heuristic model*. 6. *Analogy*. 7. *Thought Experiment*.

Considering the examples brought by Peierls, we see that models of Rutherford and Bohr are identified as the same type 1. Bohr's model is stated by Peierls to be "a more quantitative version of Rutherford's including the quantum conditions for selecting possible orbits and the rules for frequencies of emission and absorption lines. This is still type 1 model..." (*ibid.*)

It is difficult to agree with this identification since Rutherford's model was totally classical, whereas Bohr's one included quantum postulates: conceptually innovative elements. This fact essentially distinguishes between the two models, suggesting separation in their theoretical affiliation.

It is indeed difficult to distinguish between the types *hypothesis* and *phenomenological model*. For example, in the 19th century several distinguished physicists developed the kinetic theory of gases. Some of them (e.g. Van der Waals) believed that gas (and liquids) presented a system of moving atoms. Others (e.g. Maxwell) considered such a model to be merely a convenient representation. It was unclear, then, which type of model had to adopt atomism. Either classification of this model appeared as subjective.

Furthermore, with regard to *approximation* (type 3) and *simplification* (type 4), Peierls seemingly addressed mathematical procedure in the former and a disregarding of details in the latter. This separation is, however, not strict. In fact, disregarding of details expressed as a mathematical step, presents approximation. This is what happens when we neglect terms in

any expansion in a small parameter. Evidently, approximation is not always justified, but always brings simplification.

Similarly, the separation between *heuristic* model (type 5) and *analogy* (type 6) could be fuzzy as well. Faraday's and Maxwell's models of ethereal media used in the development of electromagnetism had both features. Similarly unclear affiliation may have the model of Drude for electron gas in the old theory of conductivity in metals.

Summarizing, the typology of Peierls is valuable in its representing the variety of functions that models play in physics. The spectrum is broad and deserves reflection in physics curriculum, important for constructing an adequate image of physics.

3. The nature of model

We suggest another typology basing on the nature of model as a mediator between theory (basic principles) and the considered by it objects/phenomena (e.g. Morrison, 1999). In practice, an object (O) can be treated by theory (t), a specific theory which is deduced from the fundamental theory – Theory (T). This mediating relationship might be presented symbolically (Fig. 2a).

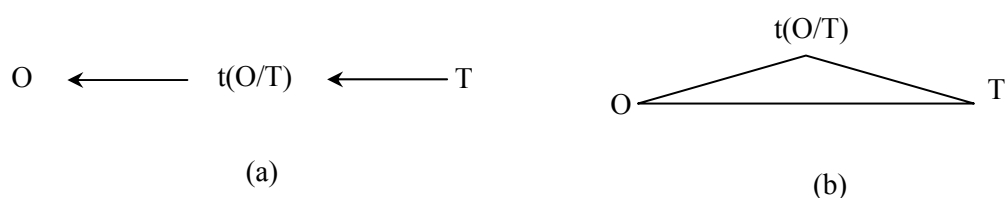


Figure 2. (a) Mediating relationship: object-theory-Theory; (b) Semantic relationship: object-theory-Theory.

Such presentation, however, masks the direct relation between Theory and the considered by it objects/phenomena. Therefore, the semantic representation (Fig. 2b) is more adequate. The latter presents a semantic triangle of the type considered in Tseitlin and Galili (2006). In a sense, specific theory represents the object and such a theory is determined by the Theory that provides general conceptualization. We can illustrate specific theory by the electromagnetic theory of light (while the fundamental theory is electromagnetism), or by celestial mechanics (while the fundamental theory is Newtonian mechanics). Specific theories address certain subject domains: light or cosmic objects and should not be confused with models.

Models enter the play when a theory, a subset of the Theory, is not sufficient and one needs additional assumptions, features not included in the theory thus facilitating an account for the object, mediating it to the Theory (Fig. 3). If the case where such a Theory is lacking, we appeal to some theoretical hypothesis.

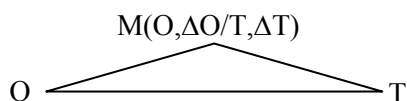


Figure 3. Model as a mediator between Object and Theory.

Model replaces the original object by another (ΔO stands for variation) and might introduce additional theoretical features (ΔT). The need for additional theoretical features destroys the idea of semantic triangle in the sense of Frege (1892), which presumes the *whole* concept to be located in the concept vertex T.

Comparing the triangles Fig. 2b and Fig. 3, we can infer the relationship between model and theory:

$$M(O, \Delta O/T, \Delta T)_{\Delta O=0, \Delta T=0} = t(O/T) \quad (1)$$

This result means that model coincides with theory (a subset of Theory) when the deviations (ΔO , ΔT) are nullified.

This representation allows understanding of the nature of models and helps to follow up the dynamics of creation of a new theory as Einstein conceived it (Heisenberg 1971):

... although we are about to formulate new natural laws that do not agree with the old ones, we nevertheless assume that the existing laws—covering the whole path from the phenomenon to our consciousness—function in such a way that we can rely upon them and hence speak of "observation".

In our terms, this statement means that despite the innovation of the theory ΔT we introduce, we generally remain within the same Theory T (vertex T in the semantic triangle). This representation visualizes the process when modeling facilitates creation of a New Theory, often starting with making changes in the Old Theory (e.g. quantum Ansatz of Plank to classical theory of radiation). This point seemingly represents the genus of modeling, its conceptual role in physics research.

4. New typology

To construct a new typology of models we start with Peierls' typology and its critique provided above. Thus we suggest three pairs: (1) *Hypothesis* and *Phenomenological* model, (2) *Approximation* and *Simplification*, and (3) *Heuristic* model and *Analogy* to identify as three types: (1) Representative-Ontological, (2) Simplifying and (3) Heuristic-Epistemological models, correspondently.

Furthermore, in accord with the introduced interpretation (Fig. 3), we will distinguish between the models M_O modifying the Object from M_T , those modifying the Theory:

$$M_O(O/T) = M(O^*/T) = M(O, \Delta O / T) \quad (2)$$

$$M_T(O/T) = M(O/T^*) = M(O / T, \Delta T) \quad (3)$$

O^* and T^* stand for the modified Object and Theory. We thus obtain:

- a. *Representative-Ontological* models of two types: M_O^R and M_T^R ;
- b. *Simplifying* models of two types: M_O^S and M_T^S ;
- c. *Heuristic-Epistemological* models of two types: M_O^H and M_T^H .

For example:

- a. M_O^R models: Copernicus' model of solar system, Maxwell's ether, Rutherford's atom.

M_T^R models: Bohr's atom, Lorentz-Fitzgerald contraction. These models usually anticipate new theory. Often forgotten after the revolution, they possess bricolage nature.

- b. M_O^S models: Newton's models for movement of planets, van der Waals equation for gases.

M_T^S models: Ohm's and Hooke's laws, Bernoulli's equation (hydrodynamics).

- c. M_O^H models: specific heat model of Einstein, gas as billiard balls. It is important not to confuse these models with M_O^R models.

M_T^H models: Ising model for phase transition, Faraday's and Maxwell's etherical models for electromagnetism.

Although a particular model may combine several affiliations this does not diminish the importance of clarification of the nature of a particular model.

5. Theories and models in discipline culture

Recently we have introduced the concept of discipline-culture (Tseitlin and Galili 2005). This approach reflected the idea that several scientific disciplines together perform a dialogue regarding the Nature. New disciplines are produced by this reality and there are many interdisciplinary problems. Thus mechanics and thermodynamics together treat hydrodynamic problems; astrophysics unites almost all physical disciplines. This reality makes the simple view of normal science (an activity within a single paradigm, one basic Theory) problematic. Separate isolated *research programs* (Lacatos 1978) may serve only as an approximation. It is more representative to speak about physics research within what we call discipline-culture framework.

As a *research program*, discipline has a nucleus (major principles, concepts) and normal part (applications of the nucleus - body). In addition to these two a *discipline-culture* includes periphery that incorporates alternative conceptions, contradicting the nucleus with regard to the same subject (Fig. 4).

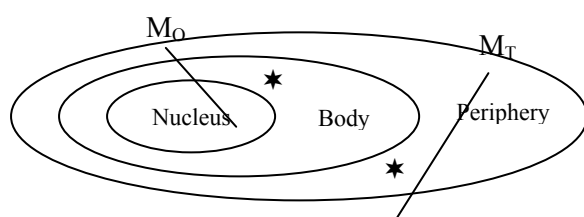


Figure 4. Discipline-culture structure. Models of the type M_O are located in the body of the discipline and models of the type M_T are located in the periphery.

The framework of discipline-culture may help to represent different types of models. Thus, the more a model emphasizes variation of the *object* than a *theory* (M_O), the closer such a model is to the nucleus and is located in the body. Such is Landau's free electron in a magnetic field, which is close to the nucleus of quantum physics. Lakatos interpreted M_O models as *protecting belts* of the nucleus, demonstrating their power in predicting and accounting for experimental results. We can add that these models provide *stability* to the discipline-culture against its changes (breakthrough between the periphery and nucleus in creation a new discipline-culture).

However, models are used in physics also as a device for producing new physics. These are M_T models. Plank's model of quanta to account for thermal radiation, Einstein's model of photons to account for photo-effect, Bohr's model for atom to account for atomic spectra, all were models that did not fit any nucleus at the time they were produced. Their place was in the periphery of classical disciplines (Newtonian mechanics, Maxwell's electromagnetism).

In short, M_O models are mainly useful in application of the known theory. In many cases models of M_T become the major tool of physics. They may stand against the renowned nucleus or with still unclear, for the moment, relationship to them. It is between the two roles of models that demarcation line runs between fundamental and applied sciences. Heuristic-epistemological and representative-ontological models present the working area producing new physics. These models serve an important cultural role of mediators between new and old theories, facilitating heredity in science. Models of M_T types can also serve a shortcut in cases when applying Theory, even if possible, is extremely difficult (e.g. random phase approximation in solid state physics). It is clear that this role is of much practical importance.

6. Implication: teaching physics as a culture

Culture has no internal area; it is all located at boarders, which cross it all over in its every part. Every atom of culture essentially exists at the boarders, which provide it with importance and meaning; isolated from the boarders, it loses the ground, becomes empty, arrogant, and dies. (Bakhtin 1975: 25)

Teaching physics as a culture presumes presenting models in the variety of types and so roles, nature and meanings. The important aspect of such teaching is the fact that models introduce additional features and assumptions not included in the Theory and/or objects/phenomena. These new elements should be emphasized and discussed, facilitating students' meaningful learning of physics.

The important cultural detail is the "boarder location" of M_T type models. In this aspect student attains the perception of physics as a *culture*, that is, as knowledge construct inherently incorporating different views (conceptions, paradigms). There, at the boarder, much (and perhaps the major) activity occurs. This perception holds equally in physics and humanities (Bakhtin 1975).

In the reality of physics teaching we often take the strategy emphasizing rigid structure, not its non-homogeneity. For instance, in our survey of physics textbooks we did not find stating the fact that Lorentz force is not Newtonian. This very fact may stand at the beginning of a different instruction of electromagnetism (Galili & Kaplan 1997), introducing students into the world of relativistic theory. This approach followed Einstein and Infeld (1938) review of physics in which they considered the model of Lorentz force as a construct breaking

with the Newtonian paradigm. This book can serve an example of treating physics as a culture, incorporating models as a language and tools. Discipline-culture approach to teaching physics keeps with this tradition and develops it (Galili & Hazan 2004).

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