

Models in physics teaching: arguing a broader view

Michael Tseitlin and Igal Galili
The Hebrew University of Jerusalem

"Physicists tend to use models to aid their understanding of complicated physical situations. ... different types of model serve as aids in thinking more clearly about physical problems, ... as steps towards rational understanding of the actual situation."
(Peierls 1980)

1. Introduction

Two major trends of the philosophy of science, rationalism and empiricism, coincide regarding the physics knowledge as two folded. Firstly physicists develop knowledge constructs, *principles/theories*, and secondly they *apply* them to account for various phenomena and situations (Einstein 1918, Losee 1989). This was the way of physics, the way of Aristotle, Newton, Einstein, Bohr, among many others. Physics curricula in schools often present physics mainly in the second aspect of this program: application. This misbalance often causes inadequate image of the nature of physics, emphasizing training of application and remaining silent (or being highly naïve) regarding the genesis of knowledge (research activity and scientific literacy in epistemology). One can imagine, however, physics curriculum representing both aspects and using *models* for this purpose. This is because models are used by physicists in both types of activity, application of old as well as constructing of new principles and theories. We will try to present this problem and suggest its solution.

2. Models in normal science and in normal curriculum

Kuhn (1962) described "normal science" as an elaboration of a certain conceptual framework (paradigm) in a sophisticated research activity: "Bringing a normal research program to a conclusion... requires the solution of all sorts of complex instrumental, conceptual, and mathematical puzzles." To a great extent this activity is interwoven with constructing models allowing solving complex problems. Thus, it was the model of gas as particles that allowed to Daniel Bernoulli to apply Newtonian theory to gases anticipating statistical physics of later times. It was Lord Kelvin, who constructed his "innumerable and disparate models" to apply the all-inclusive mechanical explanation of matter (Duhem 1914/1954). We teach mathematical pendulum as the simplest model demonstrating oscillations (Matthews 2000). Faraday's and Maxwell's mechanical models of electromagnetism tried to reduce electromagnetism to a mechanical model of perturbations in the medium of ether (Whittaker 1960).

We see that models served as a way by which physics applied certain known paradigm to solve complex, often very difficult, "puzzles", requiring much effort. "Normal science", as defined by Kuhn, is by far not a simple application of procedures and models, even when the theory is known. Models mediate between the theory and concrete questions regarding reality.

In education, however, we are often pushed to the shortest way to reach easily measurable progress in learning, and represent physics as a collection of models, ready to use procedures. Trying to help students, we are doing our best to represent physics as well organized procedures of algorithmic solving of *standard problems* and accordingly evaluate the result of learning. This is an intention of a regular, "normal", curriculum, and in this it is not similar even to the "normal science" (leave alone the "revolutionary science"), exactly like "puzzles resolving" is not similar to applying algorithm, although both use modeling.

Modeling is sometimes represented in education as a reduction to special cases: uniform rectilinear motion, accelerated rectilinear motion, circular motion, harmonic oscillator (Halloun 2004). The role of theory is reduced to "Laws of change" (Newton's laws) and "Law of interaction" (the Law of Universal Gravitation) *within* a model (Hestenes 1995). Thus theory plays the role of useful rules, normally taking a little, if any, conceptual attention of the student. Although such an instruction may help in coping with problems of regular

tests, it is clear that it changes the Gestalt of physics: emphasizing the instrumental arsenal of physics, “the trees”, it forgets the general picture of the Nature – “the forest”. Whether this could be considered satisfying depends on the adopted values and goals of the curriculum. The message of such an instruction is that "normal physics" is a tool to solve problems and this craft can be mastered through a careful application of some prescription.

Among other teaching modes are elaborations of physics as a history of ideas about Nature, individual projects, laboratory of guided exploration, physics Olympics, which are closer to Kuhnian idea of "normal science". Modeling in these activities appears as a process of heuristic accounts for a situation. One can get a flavor of such use from Polya's approach to problem solving in mathematics (1945/1973). Polya wrote about heuristic strategies of going to the extreme, changing the symmetry of the problem, replacing the given problem with a similar more familiar one, etc. All these are modeling strategies, since are based on a replacement of one object with another. We may add from physics the simplifying approximations and qualitative thought experiments. Such trends of exploration in physics use modeling as an invention, discovery of an artificial construct apt to replace certain real object or situation. Guiding the analysis seeking such a representative replacement Polya emphasized the encouraging of holistic and inventive thinking about the problem of concern. He wrote: “Think of the man who cannot see the forest for the trees”.

In the context of physics teaching, models appear as a means of physics account of the Nature, together with concepts, principles (ontological and epistemological), objects, rules of logic, mathematical apparatus. All these separately present “trees” telling about the “forest” – fundamental theories. Such items as the principle of relativity, the concept of inertia, operational definition of weight (or any other physical concept) enter curriculum being interwoven with modeling. Theory becomes an intricate organism, "a picture of the world", rather than "a collection of models".

3. Taxonomy of models in physics research

Peierls (1980) presented a typology of models in physics including a variety of types. We present them all here, replacing some of Peierls' examples with those more relevant to school physics.

1. *Hypothesis* ('Could be true'). [e.g. Different models of atoms, models of solar system, atom-vacuum conception.]
2. *Phenomenological* model ('Behaves as if...'). [e.g. Phlogiston, caloric, Maxwell's ether, water and gas models of electricity current.]
3. *Approximation* ('Something is very small or very large'). [e.g. The laws of linear response: Hooke, Ohm, Newton; perfect gas, mathematical pendulum.]
4. *Simplification* ('Omit some features for clarity'). [e.g. Van der Waals' equation for gas, various models of solar system and planets, Drude's model for conductivity.]
5. *Heuristic* model ('No quantitative justification, but gives insight'). [e.g. Einstein model for specific heat, simple model for ocean tides.]
6. *Analogy* ('Only some features in common'). [e.g. Water and gas analogies for electrical current, analogy between pendulum and LC circuit.]
7. *Thought experiment* ('to disprove hypothesis'). [e.g. Carno cycle, Maxwell's demon, Einstein-Podolsky-Rosen experiment.]

Although this classification can be debated (we made it in the second paper), the list is rich in approaches to complex systems, interpreting them in terms of simpler ones, in order to reveal the features of the former. The list presents variety of functions models play in physics. For example, heuristic models seek a different goal from making approximation; heuristic model may not even pretend being hypothetical: Einstein's model for specific heat did not suggest calculation, but provided a mechanism of decreasing of specific heat at low temperatures. Similarly, Van der Waals' equation was suggested for numerical account of gas and as a heuristic tool, rather than gas depiction (hypothetical function). The fact that the same model can be ascribed, using Peierls' classification, to more than one type suggests that it rather displays possible functions of models than their classification.

Modeling in "normal" physics could be often arranged in a sequence of rising degree of complexity. For example, the models of solar system could start from the sun and point planets, not interacting and moving in circular orbits. Subsequent models include elliptical orbits, mutual attraction of planets, their spherical shape, satellites and comets. Despite of the

rising accuracy, the models remain, however, within the same *theory* of Newton's gravitation. The choice of a model depends on the particular objective faced by the researcher: prediction of eclipse, traveling to the Moon, or else. Importantly, many models quoted by Peierls were different from the latter type. Rather than being logically deduced from the known theory Pierels' models presented the "revolutionary science" (now or in the past), an account of the unknown reality by means of heuristic constructs imitating it. The question is, then, whether we see implications of this list to physics education.

4. Status sensitive teaching

Models massively penetrate to all domains of physics and therefore inevitably present in physics curricula. However, the question remains regarding the way of presentation, whether teaching distinguishes modeling and, if it does, whether the functional type of the particular model is specified. For this purpose, Peierls' classification can be very useful. Models presenting, for example, the special cases of movement, are traditionally considered in the common teaching of motion. This use, however, should not exhaust the image of models constructed by the students. Reduction to the merits of one type would mean to abandon the tradition of using models in a variety of functions in the real science.

In our survey of the popular physics textbooks (we checked about twenty textbooks of introductory course published in English in the past decade), we found that although models are widely presented, there is a general lack of addressing the status of models; the authors are silent on their nature and functions in the particular context. Models often create a perception that they are the theory, or that they are photographic image of reality, which models are not.

We did not see mentioning that Hooke's and Ohm's laws present models of certain type. Different models of atoms are rarely explained with regard to their relationship to reality (beyond the critique of correctness). For example, such presentation of Van der Waals' model may cause a false conception that it presents a literal depiction of gas (balls of a finite size), whereas the author suggested it as a heuristic model and a means of numerical account to replace the model of point masses. No difference is normally made whether the introduced model is deduced from the known theory (such as a uniformly accelerated motion) or serves as a heuristic device in the absence of such a theory (for instance original introduction of photons or matter waves).

Discussion and Conclusion

Much work of physics educators is needed to provide physics teachers with the information regarding the nature and function of models. Currently such information is often not available and not included in the training of prospective teachers. Physics education discourse on modeling is extremely important in this regard, providing a better understanding of physics to the learners. Teaching models with their status and function could improve physics curriculum since it can reveal the nature of physics as a method of knowing. Understanding the role of modeling brings the student closer to both "normal" and "revolutionary" physics. A serious effort of conceptual clarification is required to explain students the relationship between models and theory (principles, laws, concepts). This step could change the image of physics as a discipline, attracting students who are naturally curious regarding the way the Nature is organized. Such an image includes the models which anticipated scientific revolutions.

In a sense, almost all physical statements regarding natural phenomena could be considered as models, being conceptual representations of reality. However, physicists do not do this. They distinguish between *theories*, *models*, *principles*, concepts and so on. The core of physics is its theory, which presents the most general and inclusive construct. This picture is differently interpreted by constructivist-empiricists and realists-empiricists, implying different research programs (e.g. Hacking 1983). However, making modeling a sole focus of physics curriculum, moving theory to the shade, neglecting its status as approaching to the Truth about Nature, may change the fundamental values of learning science and hence may reduce students' motivation to learn physics, as something worth to devote the whole life.

References

- Einstein, A. (1914/1965). 'Principles of Theoretical Physics.' Speech at Prussian Academy of Sciences. In A. Einstein, *Fizika i real'nost* (Physics and Reality), Nauka Moscow, pp. 5-7. http://www.e-scoala.ro/biblioteca/albert_einstein1.html.
- Hacking, I. (1983). *Representing and Intervening*. Cambridge University Press, Cambridge.
- Halloun, I. A. (1996). 'Schematic Modeling for Meaningful Learning of Physics.' *Journal of Research in Science Teaching*, 33(9), 1019-1041.
- Halloun, I. A. (2004). *Modeling theory in science education*. Kluwer Academic Dordrecht
- Hestenes, D. (1986). *New Foundations for Classical Mechanics*,
- Hestenes, D. (1995). 'Modeling software for learning and doing physics.' In C. Bernardini, C. Tarsitani, and M. Vicentini (eds.) *Thinking physics for teaching*. Plenum, New York, pp.25-65.
- Kuhn, T. (1962). *The Structure of Scientific Revolutions*. The University of Chicago Press, Chicago.
- Losee, J. (1993). *The Historical Introduction to the Philosophy of Science*. Oxford University Press, Oxford.
- Peierls, R. (1980). 'Model-Making in Physics.' *Contemporary Physics*, 21, 3-17.
- Polya, G. (1945/1973). *How to solve it*. Princeton University Press, Princeton.
- Whittaker, E. (1960). *A History of the Theories of Aether & Electricity*. Harper, New York