The Nature Of Scientific Models In Physics - A Philosophical Perspective

Lemmer, T.N
North-West University (Potchefstroom campus), Potchefstroom, South Africa, nwtml@puk.ac.za

Abstract
Although scientific models are mentioned and used all the time in physics education, there is very little reflection on what these models really are, and how they relate to reality. For instance, our formal concept of the electron is taught as if it is really as mundane as a grain of sand, while it is in reality a summation of deductions from experimental observations. Furthermore, there is often inconsistency in the terminology, with the terms 'model' and 'theory' used as synonyms by many authors for the same body of knowledge, e.g. 'Bohr's atom model' and 'Bohr's theory of the atom'. This presentation is an attempt at a fundamental philosophical analysis of scientific models in physics and its implications for science education.

Motivation

A few years ago a student asked me exactly what the difference between a model and a theory is. To my surprise, I couldn't give an answer that was satisfactory to myself. When I started to consult literature, I found that very little is actually written about this, and some of what is written is inconsistent. For example, some textbooks refer to Bohr's model of the atom, others to his theory. It is assumed that the terms are so common and familiar that they are rarely even included in textbooks' indices of terms. But is it really obvious and common knowledge?

The question "What is a scientific model" can be approached from two perspectives: The pragmatic (what are models used for?), and the ontological (what is the inherent nature of models?). The following analysis is primarily ontological, with relevant pragmatic aspects also noted. We must first know what a scientific model and theory is before we can state what the difference between them is.

Another comment bears making: As physicists, we use mathematics as our ideal for science. We insist on clear, precise and unambiguous definitions of terminology. This makes it even stranger that we do not really have a consensus on the meaning of such basic epistemological terms as model, theory, law and principle. On the other hand, such exact definition could be limiting. Stafleu (2001) argued that the positivist demand for exact definitions is often unnecessary and too restrictive. It can be more productive to work with a good characterization, which leaves room for extension of a concept, e.g. when new knowledge become available. Over time, the meanings of words change through a process of extending their usage. Words also acquire different meanings to people using them in different contexts in their working environments.

Literature survey

It is by no means obvious and common knowledge what "model" means in the context of science. A variety of appropriate sources to the study, *viz*. dictionaries in various languages, textbooks on philosophy of science and introductory physics textbooks (1st year tertiary level) were consulted.

The dictionaries did not help much. For example, the Oxford English Dictionary (Oxford, 1978) has more than a page of examples of uses of the word. However there is no description of the use of the word in the scientific sense of an abstract conceptual representation, except for the following interesting example:

c. A description of structure. *Obs.*

1578 T. Digges in L. Digges *Progn. Everlasting* To Rdr. M, I founde a description or Modill of the world and situation of Spheres Coelestial and Elementare according to the doctrine of Ptolome. *Ibid.*, But in this our age one rare witte.. hath by long studie,..deliured a new Theoricke, or model of the world, shewing that the earth resteth not in the Center of the whole world, but only in the Center of thys our mortal world.

The usage of the word in common English, as described in the dictionaries, does not really include the way it is normally used in the context of the physical sciences. The meanings given for the word fall into four broad classes:

- A physical representation of something else;
- a new type (e.g. a model of car);
- a role model to be followed; and

- a person modelling clothing.

In science the first sense is the only one used, but the use is not limited to a physical representation. It has been stretched by usage to that of an abstract representation. A first distinction should thus be made between the general uses and the scientific use of the word.

In order to find authoritative references for the latter, some readily available books on the philosophy of science were consulted (Kemeny, 1959; Stoker, 1969; Beerling *et al.,*1975 and Geertsema *et al.,* 1997). Surprisingly, none of them contained even a brief note on it, much less a discussion on its meaning(s) in the scientific context and language. They all simply use the word, implying that the meaning is understood. Two books by Bertels and Nauta (1970, 1974) had models as their sole subject. The second book also contains a list of definitions or descriptions from sixteen other authors. According to them, a model can be defined as follows:

There exists a system B
There exists a system O
B is independent of O
If B provides information about O by analogy
Then B is a model of O

Beerling *et al.* (1975) make a distinction between *deductive theories* and *deductive-hypothetical models*. A deductive theory is a formal logical construction (of theorems), based on symbols, axioms and postulates. A typical example is the postulates and theorems of abstract algebra. The process of theory construction must be entirely independent of physical meaning – it depends only on logic. A deductive-hypothetical model on the other hand, is the 'normal' scientific theory of a phenomenon.

Most textbooks consulted did not even have the term model in the indices - at most they had an entry for Bohr's model of the atom. Only one book (Knight, 2004) had a three quarter page discussion as part of the introduction. He writes "A model is a simplified description of reality – much as a model airplane is a simplified version of a real airplane – that is used to reduce the complexity of a problem to the point where it can be analyzed and understood."

And also:

"Learning how to simplify a situation is the essence of successful modeling."

In his book on the history of science Gribbin (2002) states that "Models are important, and helpful; but they are not the truth; in so far as there is scientific truth, it resides in the equations."

Science teachers at all levels (primary to tertiary) make use of models to teach. This has led to research about the educational aspects related to models. Smit (1995) compiled the following list of the general views held by the scientific community on the nature and functions of models in physics from a literature survey:

- Models are constructions of the human mind and are temporary by nature.
- The models used in physics are not pictures of the underlying reality but are viewed as representations of real entities.
- An important role is played by models in the acquisition of knowledge about nature and the comprehension of nature.
- A clear distinction is made between a model and a physical theory. Ideally, a theory should contain the description of a plausible model, modelled on some thing, material or process that is already well understood.
- Models help the physicist to predict, describe and explain natural phenomena, particles and structures. The descriptions are never complete. They simplify phenomena or make them easier to deal with. Different models can be used to describe the same entity.

Kuipers (1969) as quoted by Smit (1992) also distinguishes between two broad classes of models in science and technology, based on their purpose, being *knowledge* models and *manufacture* models. *Knowledge* models are the scientists' models – they supply knowledge of reality. Their primary function is to provide a better understanding of nature. Secondary functions are description, prediction and explanation of natural objects, processes or phenomena. *Manufacture* models are the engineers' models, which help them to manufacture real appliances. The models are used to experiment on and serve as plans for construction.

Du Toit (2000) discusses models for engineering applications and distinguishes between four levels of modelling used in numerical modelling of physical processes and configurations. This discussion demonstrates an advanced development of the term, implying not only familiarity, but also general acceptance and usage.

From the sources, the purpose of a scientific-technological model can be summarized as being to:

- imitate, demonstrate, illustrate or simulate; or
- highlight, i.e. emphasise or concentrate (focus on a particular aspect).

Models and reality

From the beginning of systematic philosophy a key question was what really exists, what really *is*, *i.e.* the ontological question. This leads directly to the question of if and how we can know this existing reality, *i.e.* the epistemological question. Since Descartes made his famous statement: *"Cogito, ergo sum"*, it has been generally accepted that the world/nature/universe does exist, but that it is neither completely known, nor completely knowable. The questions of ontology and epistemology have occupied great minds for millennia and we shall not presume to speak the final words here. Nevertheless, they are fundamental to the process of doing, learning and teaching science. Despite this, scrutiny of Physics handbooks shows that they are mentioned only very rarely, although answers to them are assumed implicitly. A prominent example is the concept of models as used in Physics.

Do we believe our scientific models and theories to be statements of reality (truth), or are they merely intellectual constructs with which to analyse nature? During the last two centuries two opposite views of science (and therefore also of the tools of science, like models) have developed, viz. determinism and instrumentalism. The deterministic view is that we learn to know reality (i.e. “the world”) in science through a process similar to Soduko. The universe/nature exists, it gives us some clues about itself. Through science we unravel the mystery, getting to know it better and more completely all the time. In this view science consists of a body of facts. For the early modernists and rationalists like Descartes and Newton, these fact were true; they were considered as descriptions of actual reality.

The development of modern physics in the twentieth century caused the second view, called instrumentalism to become predominant. Instrumentalists refer to Popper's view that the logical positivists' idea of the verification of theories is unattainable. Theories cannot be verified, only falsified, because we do not know the absolute truth against which it can be verified. However, we can falsify a theory by demonstrating its failure in one single aspect of what we do know of reality. Science can be reliable, but not true. Furthermore, scientific disciplines are practised within paradigms, which can and do change as science itself develops (Kuhn, 1973). All scientific knowledge is preliminary in nature and models and theories are only instruments i.e. useful tools used to study reality with no inherent truth. They do not make statements about reality.

Ontological view

The underlying ontological view that forms the basis for a characterisation of scientific-technological models is stated as follows:

- *There is a reality, a universe with all its objects and processes that exists and which we are studying.*
- *We do not and cannot know this reality in its totality.*
- *In order to study, understand and describe it, we make use of models. These models are therefore representations of aspects of reality. As such they do not describe the whole of that reality, but merely the part that we now know and understand in terms of the model itself.*

The model is thus a cognisant reflection of reality. This is not the same as the instrumentalist approach, i.e. it does not consider the models to be devoid of all inherent reality (*i.e.* truth) and merely as useful tools. It does accept that the models are approximations of reality within the context of cognisance, albeit limited in both content and scope.

Characterisation of a scientific model

On the basis of the analysis given, a scientific model (hereafter referred to as a model for brevity) is characterised as follows:

A scientific model is a simplified and limited representation of reality, used to obtain understanding and formalise theoretical knowledge.

It must be noted that this characterisation does not claim to be either inclusive of everything that could be considered as a scientific model, nor exclusive of everything that cannot. It is based on the assumption that the reader has a concept of the meaning of the term, due to experience and education. It is intended to be useful as educational terminology and as a guideline for epistemological analysis.

Functions of scientific models

By stating that a model could be a physical as well as a conceptual representation of an object or a process, the meaning of the word in the scientific context has already been extended from that given in the dictionaries. A conceptual representation can be an intellectual construction, such as a mathematical formulation, or a computer programme that provides an animation. Representing a process rather than an object is also an extension of the common usage, but is general practice in natural science.

A model can also be a representation of a concept. A good example is the representation of force. Newton conceived it as something that can cause action at a distance. Faraday thought in terms of field lines. In modern physics it is described in terms of an exchange of carrier particles. In all three cases we are dealing neither with material objects, nor with physical processes, but with intellectual creations introduced in scientific theory. These concepts have become so familiar that we have come to believe in their physical existence, while they find their validity basically in the models of them used in science.

Classification and hierarchy of models

A classification of types of models as used in science and technology can be posed. One benefit of this classification is that it gives a transition from the concrete (demonstrative physical scale models) to the abstract (illustrative, conceptual, theoretical). Thus there is a hierarchy of abstraction in the representation:

- Physical, static (typically scale) model
- Physical, dynamic model
- CAD-type or wire frame drawing
- Animated computer demonstration
- Conceptual (analogy) model (e.g. comparison of the atom with the solar system)
- A descriptive set of mathematical equations
- A scientific-mathematical law (e.g. Newton's universal law of gravity)
- A scientific theory.

Models and theories

Do the last two classes given in the previous paragraph really constitute models? The development from classical mechanics to general relativity has given us two alternative ways in which to view or comprehend gravity; the future may provide even more. In the sense that these theoretical constructions are representations of reality, they are actually formalised conceptual models, albeit very advanced or developed ones. Like other models, they provide us with an insight or demonstration of some important aspects of that part of reality they show us, but not everything about it. For example, Newton's universal law of gravity provides us with

- the concept of an attractive gravitational force;
- an algorithm to calculate the gravitational attraction between two bodies with mass, separated by a distance; and
- an analogy to apply to the electrostatic force between two charged particles, separated by a distance (for which it becomes a model itself).

It also leads us to some fundamental questions, but does not provide any answer to them, *e.g.*

- What is the nature and cause of the attractive force?
- Does the force exist, even if there is only one body with mass?

The question of whether a theory is a type of model is one of interpretation. The difference is one of degree and lies in tradition, not semantics. To distinguish between them is not incorrect, but such a distinction is inherently fuzzy. In my opinion it is epistemologically more useful to distinguish theories as a class of model, rather than wholly separate entities.

Models and realism: deterministic versus realistic models

There is another epistemological issue: are the laws of science deterministic and are the models based on them deterministic? This means that the model should, at least in principle, predict or describe exactly what is occurring in the physical object or process. Any deviation from reality by a deterministic model must only be ascribable to errors caused by simplifications in the model, to accuracy of measurement or to rounding errors in calculation. These deviations are intrinsic to the whole process of modelling. Consider for example a type of model that is being use increasingly in scientific research, *viz.* numerical models for computer simulations.

A typical numerical simulation consists of a combination of other models. Firstly, there are the theories of the physics involved in the problem. Secondly, there is the mathematical formulation of the problem. Thirdly, there is the discretization of the mathematical formulation in order to use an iterative algorithm to solve it on a computer. Lastly, there is the representation of the results of the model. The mathematical formulation of the model is in itself hierarchical and contains various levels of simplification and abstraction (Du Toit, 2000). All of these submodels can be sources of inaccuracy due to conceptual errors, numerical rounding or inappropriate scaling. The modeller must optimise between two conflicting requirements. In the first place, the numerical discretization must be fine and detailed enough to give sufficient resolution, both to obtain accurate solutions and to get a good representation. On the other hand, the finer and more detailed the discretization, the greater the computational load, which rapidly becomes too much.

It is not possible to have a deterministic numerical model. This is due to more than simplification and rounding error. It is also inherent to the physics on which a model is based. Not only does quantum and statistical physics preclude this on the microscopic scale, some very common and simple large-scale phenomena have been shown to display extreme dependence on initial conditions and non-linear behaviour in dynamics. Examples are the Duffing oscillator and turbulence in the convective flow of super-cooled helium (Addison, 1997). The study of these phenomena has popularly become known as chaos theory (more formally called non-linear dynamics). This makes it impossible not only in practice, but also in principle, to make exact deterministic calculations that demonstrate exactly and precisely what happens in reality.

Being prevented from constructing deterministic models by the realities of chaos, simplification and numerical rounding, we can still aspire to *realistic* models as a goal. These are models which, although not deterministic, mimic nature in such a way that the behaviour of the models cannot be distinguished from that of the physical systems they are representing. Such models can therefore be used to investigate the characteristics and behaviour of these physical systems, including the effects of changes in or to them.

Limitations of models

The first limitation of any model lies in the fact that it is a representation of reality. Reality itself is incompletely known at present, and probably not completely knowable in principle. This is why scientists use models – to enable conceptualisation of the unknown or unfamiliar. It follows that a model is intrinsically limited in its representation of reality.

The second limitation is that practice limits us in the detail that can be included in any model. We are constrained by a variety of factors from constructing a model in too fine detail. A model is therefore practically limited in its representation.

Thirdly, because we use models to enable us to conceptualise something, we cannot make the model so detailed as to become incomprehensible. This comprises a cognitive or intellectual limit.

Lastly, models are of temporary nature. With time, our insights change, or our designs do, or we change the models in the process of experimentation and development (Smit, 1995).

Conclusions

The general assumption that learners, and even all scientists, know what models are, is not valid. There is no explicit or even implicit consensus. It is imperative that a proper epistemological debate be conducted on this issue, as well as on the meaning of other related terms. It is also necessary that textbooks and educators should explicitly teach learners about it.

List of references

Addison, P.S. 1997. Fractals and chaos. An illustrated course. Bristol: Institute of Physics Publishing.

Beerling, R.F., Kwee, S.L., Mooij, J.J.A.. & Van Peursen, C.A. 1975. Inleiding tot de wetenschapsleer. Utrecht: Bijleveldt

Bertels, K. & Nauta, D. (eds.) 1970. Modelbegrip in wetenschap en techniek. Utrecht: Stichting televisie academie teleac.

Bertels, K. & Nauta, D. 1974. Inleiding tot het modelbegrip. Amsterdam: Wetenschappelijke Uitgevereij.

Du Toit, C.G. 2000 Die numeriese laboratorium en ingenieurswese. Inaugural lecture at Potchefstroom University for Christian Higher Education, Potchefstroom, South Africa.

Geertsema, J.C., Reinecke, C.J., & Ouweneel, W.J. 1997. Wetenskapsleer vir Natuurwetenskap, Farmasie en Ingenieurswese. Course notes for WNR 211, Potchefstroom University for Christian Higher Education, Potchefstroom.

Gribbin, J. 2002. Science – A history. London: Penguin Press.

Kemeny, J.G. 1959. A philosopher looks at science. New York: D. Van Nostrand Company.

Knight RP. 2004. Physics for scientists and engineers. With modern physics. A strategic approach. San Francisco: Addison Wesley.

Kuhn, T.S. 1973. The structure of scientific revolutions. 2nd ed. Chicago: University of Chicago Press..

OXFORD. 1978. The Oxford English dictionary. Oxford: Oxford University Press.

Shaw, C.T. 1992. Using computational fluid dynamics. Hertfordshire: Prentice Hall International (UK) Ltd.

Smit, J.J.A. 1992. Modelle in die onderrig van Fisika op tersiêre vlak. Potchefstroom: National Research Foundation report.

Smit, J.J.A. 1995. Models in physics: perceptions held by final-year prospective physical science teachers studying at South African universities. *International journal of science education*, 17(5):621-634.

Stafleu, M.D. 2001. Hoe belangrijk is de vakfilosofie voor natuurwetenschappers? Lecture presented to the Faculty of Natural Sciences at the Potchefstroom University for Christian Higher Education on 25 April 2001. Unpublished (lecture notes available from Sentrum vir Geloof en Wetenskap, PU for CHE, South Africa).

Stoker, H.G. 1969. Beginsels en metodes in die wetenskap. Johannesburg: Boekhandel De Jong.