Models in Physics

Roman Frigg, LSE

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Abstract

In its most common use, the term ‘model’ refers to a simplified and stylised version of the so-called target system, the part or aspect of the world that we are interested in. For instance, in order to determine the orbit of a planet moving around the sun we model the planet and the sun as perfect homogenous spheres that gravitationally interact with each other but nothing else in the universe, and then apply Newtonian mechanics to this system, which reveals that the planet moves on an elliptical orbit. Views diverge about what sort of entity such a model is. Those focussing on the formal aspects of models regard them either as equations or set-theoretical structures, while those opposed to such an approach take them to be descriptions or abstract (yet non-mathematical) entities. A further question concerns the relation of models and theories. In some cases models can be derived from theory simply by specifying the relevant determinables in a theory’s general equations. But many models cannot be obtained from theory in this straightforward way, and some even involve assumptions that contradict the fundamental theory. The relation of models to their respective target systems is equally complex and fraught with controversy. Two influential proposals take the relation between a model and its target to be isomorphism or similarity, respectively. This, however, has been criticised as too restrictive as many models do not seem to fit this mould.

1. Introducing Models

In physics ‘model’ is used in different ways. Phrases like ‘it is just a model’ indicate either that physicists take a cautious attitude towards a particular piece of physics which they regard as particularly speculative and provisional, or that the piece of physics is known to be false and is entertained only for heuristic reasons. On some occasions theories are referred to as ‘models’, for instance in particle physics where the best and currently widely accepted theory of elementary particles is called ‘the standard model’. However, in the most common use of the term, ‘model’ refers to a simplified and stylised version of the part or aspect of the world that we are interested in (the so-called ‘target system’).

This usage of the term as well as the many philosophical questions to which it gives rise are best introduced with a well-known example from classical mechanics. To determine the orbit of a planet moving around the sun we posit that the force acting between the sun and a planet is gravity and that its magnitude is given by Newton’s law of gravity, $F_g = Gm_p m_s / r^2$, where m_p and m_s are the masses of the planet and the sun respectively, r the distance between the two, and G the constant of gravitation. We then make the idealising assumption that this is the only force relevant to the planet’s motion and we neglect all other forces, most notably the gravitational interaction with the other planets in the solar system. We furthermore assume that both the sun and the planet are perfect spheres with a homogenous mass distribution (i.e. the mass is evenly distributed over the sphere), which allows us treat their gravitational interaction as if all the mass of each object was concentrated in its centre. The sun’s mass is vastly larger than the planet’s and so we can assume that the sun is at rest and the planet orbits around it. Now we turn to classical mechanics and use Newton’s equation of motion, $\vec{F} = m\vec{a}$, where $\vec{a}$ is the acceleration of a particle, m its mass and $\vec{F}$ the force acting on it. Placing the sun at the origin of the coordinate system and plugging in the above force law we obtain $\ddot{\vec{x}} = -Gm_s \vec{x} / |\vec{x}|^3$, the differential equation describing the planet’s trajectory (where we have, of course, used $\vec{a} = \ddot{\vec{x}}$, i.e. that the acceleration is equal to the second derivative of the position). This equation can be solved and we find that the planet moves on an elliptic orbit around the sun.

This example illustrates the problems that surround modelling in physics. First, which among the many things that occur in this account of the determination of the planet’s orbit form part of ‘the model’? That is, when asked to identify the model of the sun-planet system, do we point to an imaginary system consisting of two gravitationally interacting homogenous ideal spheres, to a particular description of the target system, to the equation describing the planet’s orbit, or to something else? Second, theory plays a crucial role because it is classical mechanics that eventually allows us to determine the planet’s orbit. But what exactly is the role that theory plays in modelling and how do models relate to theory? Third, what is the relationship between the model and the target system? We have made all kinds of idealisations and simplifications. How can these be understood and justified? In what follows these three issues are addressed one at a time.

2. The Ontology of Models

One of the essential features of modern physics is its mathematisation. Theories are based on a particular formalism and progress is made by putting to use or extending the formalism. From this point of view it seems natural to focus on the mathematical aspects of modelling and regard the equation describing the planet's motion as the model. This usage of the term, although common among scientists, is problematic. We can describe a situation using different coordinates (for instance spherical rather then Cartesian ones), which results in different equations. Yet we do not seem to obtain a different model of the planet-sun system simply by expressing the relation between the sun and the planet in different coordinates.

A different account in the same spirit regards models as set-theoretic structures (Da Costa and French 2003). A set-theoretic structure $S = \langle U, O, R \rangle$ is a composite entity consisting of a non-empty set U of individuals, an indexed set O (i.e. an ordered list) of operations on U, and an indexed set R of relations on U. *Per se*, such a structure is purely formal in the sense that it is not specified what the individuals are, and both relations and functions are specified purely extensionally (that is, *n*-place relations are defined as classes of *n*-tuples, and functions taking *n* arguments are defined as classes of (*n*+1)-tuples). This conception of models avoids the problem of the previous account because structures are objects of which equations are true or false, and as such they themselves are independent of a particular description.

The set-theoretic approach to models in physics has been criticized as being overly formal and unable to account for how models are constructed, investigated, and put to use in scientific practice (Cartwright 1999, Morrison 1999). A view that can avoid this charge is that models are descriptions: what scientists display in papers and textbooks when they present a model is a description, in many ways simplified and stylised, of the target system. The problem is that on this account models are, again, dependent on a particular mode of description and different, albeit equivalent, descriptions (e.g. one in French rather than English) would count as a different model.

This problem can be circumvented by regarding models as abstract entities (Giere 1988). On this view, the model of the planet-sun system is an abstract object consisting of exactly those entities that are specified in the description of the model, namely two gravitationally interacting homogenous ideal spheres. This is in line with common scientific parlance, in which models are often talked about as if they were objects, albeit not physical ones. However, this view needs to explain how models, thus understood, relate to a mathematical formalism, and it suffers from the problem that the ontological status of these objects is problematic (see FICTIONAL ENTITIES).

3. Models and Theory

Most of the time, models in physics involve a theory, in the above example Newtonian mechanics. What is the relationship between model and theory? The answer to this question depends both on one's view of what theories are and on the particular case at hand.

In some cases the equations that form part of the model can be obtained from a general theory simply by specifying the relevant determinables in the general equations of the theory; in the above example by plugging the law of gravity into Newton's equation of motion and choosing x and m to be the planet's position and mass respectively. Hence the relation between theory and model is that between the general and the particular. The so-called semantic view of theories (see SCIENTIFIC THEORIES) gives this notion a special gloss. This view regards theories are families of models, where the models of a family are non-linguistic entities (on most versions, set-theoretic structures) that satisfy a particular equation. A model then involves theory by belonging to a particular family of models, which constitutes a theory.

This picture of the relation of models and theories captures well what happens in some domains, for instance classical mechanics and space time theories, but it fares poorly in other areas, where there is no straightforward 'downward path' from general equations to models (see Cartwright 1983 and the contributions to Morgan and Morrison 1999). An example for the independence of models from theories is the London model of superconductivity, whose principal equation is motivated solely on the basis of phenomenological considerations rather than being derivable from the relevant theory, classical electromagnetism. In this sense models are said to be 'autonomous agents' that 'mediate' between theory and the world (Suárez 1999).

Sometimes theories are too complex to handle, in which case a simplified model, which can be solved, is employed to bridge this 'computation gap' (Redhead 1980). For instance, the hadron structure of a nucleus is in principle correctly described by quantum chromodynamics, and yet this theory cannot easily be used because we cannot solve its equations. To get around this problem physicists construct simplified but tractable models, the MIT bag model being a well-known example (Hartmann 1999). These models, also referred to as 'phenomenological models' often not only fail to be motivated from a theoretical point of view; they may, strictly speaking, even contradict fundamental theory.

Models are also constructed where there are no theories available. Bohr's model of the atom was formulated in the early twentieth century without a worked-out quantum theory in the background, and then turned out to play a crucial role in the development of such a theory (Leplin 1980).

4. Models and Target Systems

Many models are representations of their target systems (see MODELS). What does it mean for a model to be a representation of something else? Those who take models to be set-theoretic structures of some sort or other explain representation in terms of there being an isomorphism, or some other formal mapping, between the model and the target (Da Costa and French 2003, Swoyer 1991, van Fraassen 1980). This view has been criticised on the grounds that isomorphism seems to be too stringent a relation to be able to capture how most models relate to their targets, and that isomorphism, even where it obtains, is only a part of what is needed to explain how representation works (Frigg 2006, Suárez 2003).

Giere (1988) suggests that a model represents its target due to there being scientists who put forward a so-called 'theoretical hypothesis', specifying that the model and the target are similar in relevant respects and to relevant degrees. The most important kind of similarity in physics is idealisation: a model is similar to its target if it is an idealisation of the target. In the most general terms, an idealization is a deliberate simplification of something complex in order to make it more tractable. Planets are not spherical, do not have a homogenous mass distribution, and interact not only with the sun but also with all other planets: yet this fictional scenario can be seen as in idealisation of the real solar system.

These idealisations belong to what has become known as Galilean idealisations (McMullin 1985), which is the most prominent kind of idealisation in physics. Intuitively speaking, Galilean idealisations are ones that involve a deliberate distortion of certain relevant properties, aimed at eliminating unnecessary computational complexities in order to be able to focus on those factors that are deemed salient in the production of the effect under investigation. Point masses, frictionless planes, massless strings, isolated systems, infinitely extended planes are some well-known examples. The philosophical problem is how to comprehend these idealisations, and to discuss what relevance results obtained in an idealised model have for our understanding of the target system in which the idealising assumptions are false (see IDEALISATIONS).

Some models in physics do not have a target system at all, and their sole purpose is to serve as a 'laboratory' to test theoretical tools that can later-on be used to build either theories or representational models. Such models are often referred to as 'tinker-toy models' or 'probing models'. A case in point is the so-called '$\varphi^4 -$model' in quantum field theory, which is known not to represent anything in the world, but which nevertheless has been studied extensively because it allows physicists to develop a sense for what certain types of models are like, to try out complicated techniques such are renormalisation in a simple setting, and to get acquainted with certain mechanisms – here symmetry breaking – that turn out to be important in other contexts (Hartmann 1995).

References and Further Readings

Cartwright, Nancy (1983), *How the Laws of Physics Lie*. Oxford: Oxford University Press. (Argues that there is no simple connection between models and theories.)

—— (1999), *The Dappled World. A Study of the Boundaries of Science*. Cambridge: Cambridge University Press, Ch. 8. (A sustained critique of the semantic view of theories.)

Da Costa, Newton, and Steven French (2003), *Science and Partial Truth: A Unitary Approach to Models and Scientific Reasoning*. Oxford: Oxford University Press. (Develops an approach to models and theories based on set-theoretic structures.)

Frigg, Roman (2006), "Scientific Representation and the Semantic View of Theories", *Theoria* 55: 37-53. (Critically discusses the isomorphism view of representation.)

Giere, Ronald (1988), *Explaining Science: A Cognitive Approach*. Chicago: University of Chicago Press, Ch. 3. (Presents a version of the semantic view of theories taking models to be abstract entities which represent due to similarity with their target systems.)

Hartmann, Stephan (1995), "Models as a Tool for Theory Construction: Some Strategies of Preliminary Physics", in William Herfel, *et al.* (eds.), *Theories and Models in Scientific Process*. (Poznan Studies in the Philosophy of Science and the Humanities 44.) Amsterdam: Rodopi, 49-67. (Discusses the heuristic function of non-representational models.)

—— (1999), "Models and Stories in Hadron Physics", in Morgan and Morrison (1999), 326-346. (Examines cases in which models step in when theories are intractable.)

Leplin, Jarrett (1980), "The Role of Models in Theory Construction", in: T. Nickles (ed.), *Scientific Discovery, Logic, and Rationality*. Reidel: Dordrecht: 267-284. (Investigates the heuristic role models played in the construction of early quantum theory.)

McMullin, Ernan (1985), "Galilean Idealization", *Studies in the History and Philosophy of Science* 16: 247-73. (Discusses Galileo's views on idealisation and their relevance to contemporary physics.)

Morgan, Mary and Margaret Morrison (1999), *Models as Mediators. Perspectives on Natural and Social Science*. Cambridge: Cambridge University Press. (A collection of essays revolving around the theme that models are independent both from theories and from data.)

Morrison, Margaret (1999): "Models as Autonomous Agents", in Morgan and Morrison (1999), 38-65. (Argues with various examples that although models in physics involve theory, they are not in any simple way derivable from it.)

Redhead, Michael (1980), "Models in Physics", *British Journal for the Philosophy of Science* 31: 145-163. (Discusses different uses of models in physics, with a particular emphasis on their heuristic role.)

Suárez, Mauricio (1999): 'The Role of Models in the Application of Scientific Theories: Epistemological Implications', in Morgan and Morrison (1999), 168-196. (Discusses early models of superconductivity and argues that they are motivated by phenomena and not by theory.)

—— (2003), “Scientific Representation: Against Similarity and Isomorphism.” *International Studies in the Philosophy of Science* 17: 225-244. (Argues against isomorphism and similarity accounts of representation.)

Swoyer, Chris (1991), “Structural Representation and Surrogative Reasoning”, *Synthese* 87: 449-508. (Discusses different formal relations between model and target.)

van Fraassen, Bas C. (1980), *The Scientific Image*. Oxford: Oxford University Press. (Presents a version of the semantic view of theories based on the notion that models are isomorphic to their target systems.)