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SCIENTIFIC MODELS

Models are of central importance in many scientific contexts. Cases in point are the roles played in their respective domains by the MIT bag model of the nucleon, the billiard ball model of a gas, the Bohr model of the atom, the Pauling model of chemical bonds, the Gaussian-chain model of a polymer, the Lorenz model of the atmosphere, the Lotka-Volterra model of predator/prey interaction, agent-based and evolutionary models of social interaction, and general equilibrium models of markets.

This importance has been increasingly recognized by philosophers. As a result, the philosophical literature on models has been growing rapidly over the last decades, and with it the number of different types of models that philosophers recognize. Some of the notions used as categories have created phenomenological models, computational models, developmental models, explanatory models, impoverished models, testing models, idealized models, theoretical models, scale models, heuristic models, caricature models, didactic models, fantasy models, toy models, imaginary models, mathematical models, substitute models, iconic models, formal models, analog models, and instrumental models. The key to coming to terms with this variety is to realize that these different categories pertain to these different issues that arise in connection with models:

1. Semantics: What is the representational function that models perform?
2. Ontology: What kind of things are models?
3. Epistemology: How does one learn with models?
4. Models and theory: How do models relate to theory?
5. Models and other debates in the philosophy of science:
    - (a) Models and the realism versus antirealism debate
    - (b) Models and reductionism
    - (c) Models and laws of nature
    - (d) Models and scientific explanation

Semantics: The Representational Functions of Models

Models can perform two fundamentally different representational functions. On the one hand, a model can be a representation of a selected part of the world (the "target system"). Depending on the nature of the target, such models are either models of phenomena or models of data. On the other hand, a model can represent a theory in the sense that it interprets the laws and axioms of that theory. These two notions are not mutually exclusive and scientific models can at once be representations in both senses.

Representational Models I: Models of Phenomena

Many scientific models represent a phenomenon, where 'phenomenon' is used as an umbrella term covering all relatively stable and general features of the world that are interesting from a scientific point of view. Well-known examples of models of this kind include the billiard ball model of a gas, the Bohr model of the atom, the double helix model of DNA, the scale model of a bridge, the Mundell-Fleming model of an open economy, and the Lorenz model of the atmosphere. The representational function of these models is widely acknowledged among philosophers; but despite the ubiquity of representation talk in the literature on models, the issue of scientific representation as regards models has barely been recognized, much less seriously discussed.

A first step toward a discussion of this issue is to realize that there is no such thing as the problem of scientific representation. Rather, there are different but related problems. It is not yet clear what the specific set of questions is that a theory of representation should come to terms with, but two problems in particular seem to occupy center stage in tackling the issue (Frigg 2003, chap. 1). The first problem is to explain in virtue of what a model is a representation of something else; or more formally: What fills the blank in '*M* represents *T* if and only if ______,' where *M* is a model and *T* a target system? Somewhat surprisingly, this question did not attract much attention in twentieth-century philosophy of science.

The second problem is concerned with representational styles (see Scientific Style). It is a commonplace that one can represent the same subject matter in different ways. Weizsäcker's liquid-drop model represents the nucleus of an atom in a manner very different from the shell model, and a scale model of the wing of an airplane represents the shape of the wing differently from how a mathematical model does. What representational styles are there in the sciences?

Although this question is not explicitly addressed in the literature on the so-called semantic view of theories (see Theories), two answers seem to emerge from its understanding of models. One version of the semantic view posits that a model and its target have to be isomorphic (Suppes 2002) or partially isomorphic (da Costa and French 2003) to each other. Another version drops isomorphism in favor of similarity (Giere 1988). This approach enjoys the advantage over the isomorphic view that it is less restrictive and also can account for cases of inexact and simplifying models.

Furthermore, one can understand the discussions about certain types of models as contributions to an investigation into representational styles.

Iconic Models An iconic model is supposed to be a naturalistic replica or a truthful mirror image of the target. Paradigm cases of iconic models are scale models such as wooden cars or model bridges, which are either enlarged or downsized copies of the original. More elaborate examples of iconic models can be found in the life sciences, where one particular organism (or group thereof) is investigated in order to find out something about the species to which it belongs. In a clinical trial, for instance, a certain number of patients are administered a drug, their reaction(s) to this drug is monitored, and the result is supposed to show how humans in general react to this drug.

What criteria does a model have to satisfy in order to qualify as an icon? Although there seem to be strong intuitions about how to answer this question in particular cases, no theory of iconicity for models has been formulated yet.

Idealized Models An idealization is a deliberate simplification of something complicated with the objective of making it more tractable. Most idealizations fall into either of two classes.

One class consists of cases in which idealization amounts to "stripping away" all properties from a concrete object that are believed not to be relevant to the problem at hand. This allows one to focus on a limited set of properties in isolation. An example from economics is the Philips curve, which specifies a relationship between inflation and unemployment, disregarding all other economic factors. This process of stripping away is often referred to as 'Aristotelian abstraction,' 'method of isolation,' or 'use of negligibility assumptions.'

The other class comprises idealizations that involve deliberate distortions. Physicists build models consisting of point masses moving on frictionless planes; economists assume that agents are perfectly rational; biologists study isolated populations, and so on. It was characteristic of Galileo's approach to science to use simplifications of this sort whenever a situation was too complicated to tackle. For this reason one can refer to this process as 'Galilean idealization' (cf. McMullin 1985).

Galilean idealizations are beset with riddles. What does a model involving distortions of this kind say about the world? How does one test its accuracy? In reply to these questions, Laymon (1991) has put forward a theory that understands idealizations as ideal limits: Imagine a series of experimental refinements of an actual situation that approach the postulated limit and then require that the closer the properties of a system come to the ideal limit, the closer its behavior has to come to the behavior of the ideal limit (monotonicity). But these conditions need not always hold, and it is not clear how to understand situations in which no ideal limit exists.

Galilean and Aristotelian idealizations are not mutually exclusive. On the contrary, they often come together. For instance, this happens in what is sometimes called 'caricature models,' which isolate a small number of main characteristics of a system and distort them into an extreme case.

Analogical Models Stock examples of analogical models include the hydraulic model of an economic system, the billiard ball model of a gas, the computer model of the mind, and the liquid-drop model of the nucleus. At the most basic level, two things are *analogous* if there are certain relevant similarities between them. Hesse (1963) distinguishes different types of analogies according to the kinds of similarity relations in which two objects enter. A simple type of analogy is based on shared properties. There is an analogy between the Earth and the moon based on the fact that both are large, solid, opaque, spherical bodies, receiving heat and light from the sun, revolving around their axes, and gravitating toward other bodies. But sameness of properties is not a necessary condition. An analogy between two objects can also be based on relevant similarities between their properties. In this more liberal sense, one can say that there is an analogy between sound and light because echoes are similar to reflections, loudness to brightness, pitch to color, detectability by the ear to detectability by the eye, and so forth.

Analogies can also be based on the sameness or resemblance of relations between parts of two systems rather than on their monadic properties. It is in this sense that some politicians assert that the relation of a parent to children is analogous to the relation of the state to citizens. The analogies mentioned so far have been what Hesse calls 'material analogies.' A more formal notion of analogy can be obtained by abstracting from the concrete features the systems possess and focusing only on their formal setup. What the analog model then shares with its target is not a set of features, but the same pattern of abstract relationships. This notion of analogy is closely related to what Hesse calls 'formal analogy.' Two items are related by formal analogy if they are both interpretations of the same formal calculus. For instance, there is a formal analogy between a swinging pendulum and an oscillating electric circuit because they are both described by the same mathematical equation.

A further distinction due to Hesse is among positive, negative, and neutral analogies. In comparing properties or relations between two items, positive analogies consist in those they share (both gas molecules and billiard balls have mass), while negative analogies consist in those they do not (billiard balls are colored, gas molecules are not). The *neutral analogy* comprises the properties not yet known to belong to either the positive or the negative analogy (do gas molecules obey Newton's laws of collision?). Neutral analogies play an important role in scientific research because they give rise to questions and suggest new hypotheses.

Phenomenological Models Phenomenological models have been defined in different, though related, ways. A standard definition takes them to be models that represent only observable properties of their targets and refrain from postulating hidden mechanisms and the like. Alternatively one can define phenomenological models as being independent of general theories. These two definitions, though not equivalent, often coincide in practice because hidden mechanisms or theoretical entities are commonly brought into a model via a general theory.

Each of these notions has its internal problems. But more pressing is the question of how the different notions relate to each other. Are analogies fundamentally different from idealizations, or do they occupy different areas on a continuous scale? How do icons differ from idealizations and analogies? At the present stage the answers to these questions are not known. What one needs is a systematic account of the different ways in which models can relate to the world and of how these ways compare with each other.

Representational Models II: Models of Data

Another kind of representational model is the *model of data* (Suppes 2002). A model of data is a corrected, rectified, regimented, and in many instances idealized version of the data gained from immediate observation, the so-called raw data. Characteristically, one first eliminates errors (e.g., removes points from the record that are due to faulty observation) and then presents the data in a "neat" way—for instance, by drawing a smooth curve through a set of points. These two steps are commonly referred to as data reduction and curve fitting. When investigating the trajectory of a certain planet, for instance, one first eliminates erroneous points from the observation records and then fits a smooth curve to the remaining ones. Models of data play a crucial role in confirming theories because it is the model and not the often messy and complex raw data that is compared with a theoretical prediction.

Both steps in the construction of a data model raise serious questions. How does one decide which points on the record need to be removed? And given a clean set of data, what curve can be fitted to it? The first question has been dealt with mainly within the context of the philosophy of experiment (see Experiment). At the heart of the latter question lies the so-called *curve fitting problem*, which is that the data themselves do not indicate what form the fitted curve should take. Traditional discussions of theory choice suggest that this issue is settled by background theory, considerations of simplicity, prior probabilities, or a combination of these. Forster and Sober (1994) point out that this formulation of the curve fitting problem is a slight overstatement because there is a theorem in statistics due to Akaike that shows (given certain assumptions) that the data themselves underwrite (though do not determine) an inference concerning the curve's shape if it is assumed that the fitted curve has to be chosen so that it strikes a balance between simplicity and goodness of fit in a way that maximizes predictive accuracy.

Models as the Thing Represented: Models of Theory

In modern logic, a model is a structure that makes all sentences of a theory true, where a *theory* is taken to be a set of sentences in a formal language, and a *structure* a set of objects along with the relations in which they enter. The structure represents the abstract theory in the sense that it interprets it and provides an object that embodies its essential features. As a simple example, consider Euclidean geometry, which consists of axioms (e.g., Any two points can be joined by a straight line) and the theorems that can be derived therefrom. Any structure of which all these statements are true is a model of Euclidean geometry.

Many models in science carry over from logic the idea of interpreting an abstract calculus. This is particularly pertinent in physics, where general laws—such as Newton's equation of motion—lie at the heart of a theory. These laws are applied to a particular system (e.g., a pendulum) by choosing a special force function, making assumptions about the mass distribution of the pendulum, etc. The resulting model, then, is an interpretation (or realization) of the general law.

Ontology: What Are Models?

Physical Objects

Some models are straightforward physical objects. These are commonly referred to as material models. The class of material models comprises anything that is a physical entity and that serves as a scientific representation of something else. Among the members of this class are wooden models of bridges, planes, and ships; analog models of neural systems resembling electric circuits or of an economy resembling lengths of pipe; and Watson and Crick's model of DNA. But material models also lend themselves to more cutting-edge cases, especially from the life sciences, where certain organisms are studied as stand-ins for others.

Material models do not give rise to any ontological difficulties over and above the well-known quibbles in connection with objects, which metaphysicians deal with (e.g., the nature of properties, the identity of objects, parts and wholes, and so on).

Fictional Objects

Many models are not material models. The Bohr model of the atom, a frictionless pendulum, or isolated populations are in the scientist's mind rather than in the laboratory, and they do not have to be physically realized and experimented upon to perform their representational function.

It seems natural to view them as fictional entities. This position can be traced back to the German neo-Kantian Vaihinger and has been advocated more recently by Giere (1988, Ch. 3), who calls them 'abstract entities.' The drawback of this suggestion is that fictional entities are notoriously beset with ontological riddles. This has led many philosophers, most prominently Quine, to argue that there are no such things as fictional entities and that apparent ontological commitments to them must be renounced (see Quine, Willard Van). This has resulted in a glaring neglect of fictional entities, in particular among philosophers of science.

Set-Theoretic Structures

An influential point of view takes models to be set-theoretic structures. This position can be traced back to Suppes' work in the 1960s and is now, with slight variants, held by most proponents of the semantic view of theories (see Theories).

This view of models has been criticized on different grounds. One pervasive criticism is that many types of models that play an important role in science are not structures and cannot be accommodated within the structuralist view of models, which can account neither for how these models are constructed nor for how they work in the context of investigation (Cartwright 1999; Morgan and Morrison 1999). Another charge held against the set-theoretic approach is that it is not possible to explain how structures represent a target system that forms part of the physical world without making assumptions that go beyond what the approach can afford (Frigg 2003, Chs. 2 and 3; Suárez 2003).

Descriptions

A time-honored position has it that what scientists display in scientific papers and textbooks when they present a model are more or less stylized descriptions of the relevant target systems.

This view has not been subject to explicit criticism. However, some of the criticisms that have been marshaled against the syntactic view of theories equally threaten a linguistic understanding of models. First, it is a commonplace that one can describe the same thing in different ways. But if one identifies a model with its description, then each new description yields a new model, which seems to be counterintuitive. Second, models have different properties than descriptions. On the one hand, one can say that the model of the solar system consists of spheres orbiting around a big mass or that the population in the model is isolated from its environment, but it does not seem to make sense to say this about a description. On the other hand, descriptions have properties that models do not have. A description can be written in English, consist of 517 words, be printed in red ink, and so on. None of this makes sense when said about a model.

Equations

Another group of things that are habitually referred to as models, in particular in economics, consists of equations (which are then termed 'mathematical models')—for instance, the Black-Scholes model of the stock market and the Mundell-Fleming model of an open economy.

The problem with this suggestion is that equations are syntactic items, and as such they face objections similar to the ones put forward against descriptions. First, one can describe the same situation using different coordinates and as a result obtain different equations; but one does not seem to obtain a different model. Second, the model has properties different from the equation. An oscillator is three-dimensional, but the equation describing its motion is not. Equally, an equation may be inhomogenous while the system it describes is not.

Gerrymandered Ontologies

The proposals discussed so far have tacitly assumed that a model belongs to one particular class of objects. But this assumption is not necessary. It might be the case that models are a mixture of elements belonging to different ontological categories.

Epistemology: Learning with Models

Models are vehicles for learning about the world. By studying a model one can discover features of the system the model stands for. This cognitive function of models has been widely acknowledged in the literature, and some even suggest that models give rise to a new style of reasoning, called 'model-based reasoning' (Magnani and Nersessian 2002). This leaves one with the question of how learning with a model is possible.

Hughes (1997) provides a general framework for discussing this question. According to his "DDI" account of modeling, learning takes place in three stages: *d*enotation, *d*emonstration, and *i*nterpretation. One begins by establishing a representation relation (denotation) between the model and the target. Then one investigates the features of the model in order to demonstrate certain theoretical claims about its internal constitution or mechanism; i.e., one learns about the model (demonstration). Finally, these findings have to be converted into claims about the target system; Hughes refers to this step as 'interpretation.' It is the latter two notions that are at stake here.

Learning About the Model: Experiments, Thought Experiments, and Simulation

Learning about a model happens at two places, in the construction and the manipulation of the model (Morgan and Morrison 1999). There are no fixed rules for model building, and so the very activity of figuring out what and how a model fits together affords an opportunity to learn about the model. Once the model is built, one learns about its properties not by looking at it, but by using and manipulating it to elicit its secrets.

Depending on what kind of model one is dealing with, building and manipulating a model employs different activities demanding a different methodology. Material models seem to be unproblematic, as they are commonly used in the kind of experimental contexts that have been discussed extensively by philosophers of science (the model of a car is put in the wind tunnel to measure its air resistance). This is not the case with fictional models. What constraints are there to the construction of fictional models, and how does one manipulate them? The natural response seems to obtain an answer to these questions by performing a thought experiment. Different authors have explored this line of argument but they have reached very different and often conflicting conclusions as to how thought experiments are performed and what the status of their outcomes is (Hitchcock 2004, Chs. 1 and 2).

An important class consists of mathematical models. In some cases it is possible to derive results or solve equations analytically. But quite often this is not the case. It is on this point that the invention of the computer has had a great impact, as it allows one to solve equations that are otherwise intractable by making a computer simulation. Many parts of current research in both the natural and social sciences rely on computer simulations. To mention only a few examples, computer simulations are used to explore the formation and development of stars and galaxies, the detailed dynamics of high-energy heavy-ion reactions, aspects of the intricate process of the evolution of life, and factors determining the outbreak of wars, the progression of an economy, decision procedures in an organization, and moral behavior.

What is a simulation? Simulations characteristically are used in connection with dynamic models, i.e., which involve time. The aim of a simulation is to solve the equations of motion of such a model, which is designed to represent the time evolution of its target system. So, one can say that a simulation represents one process by another process (Hartmann 1996; Humphreys 2004).

It has been claimed that computer simulations constitute a genuinely new methodology of science, or even a new scientific paradigm (Humphreys 2004). Although this contention may not meet with univocal consent, there is no doubt about the practical significance of computer simulations. In situations in which the underlying model is well confirmed and understood, computer experiments may even replace real experiments, which has economic advantages and minimizes risk (as, for example, in the case of the simulation of atomic explosions). Computer simulations are also heuristically important. They may suggest new theories, models, and hypotheses, for example, based on a systematic exploration of a model's parameter space.

But computer simulations also bear methodological perils, as they may provide misleading results. In many cases the relevant variables are continuous. But due to the discrete nature of the calculations carried out on a computer, they do not allow for an exploration of the full range of the variables, and therefore may not reveal certain important features of the model.

Converting Knowledge About the Model into Knowledge About the Target

Once knowledge about the model is available, it has to be "translated" into knowledge about the target system. It is at this point that the representational function of models becomes important again. Models can provide information about the nature of their target systems only if one assumes that (at least some of) the model's aspects have counterparts in the world. But if learning is tied to representation and if there are different kinds of representation (analogies, idealizations, etc.), then there are also different kinds of learning. If, for instance, one has a model that is taken to be a realistic depiction, the transfer of knowledge from the model to the target is accomplished in a different manner than when one deals with an analog model or a model that involves idealizing assumptions.

What are these different ways of learning? Although numerous case studies have been made of how certain specific models work, there do not seem to be any general accounts of how the transfer of knowledge from a model to its target is achieved (with the possible exception of theories of analogical reasoning; see references above). This is a difficult question, but it is one that deserves more attention than it has received so far.

Models and Theory

One of the most perplexing questions in connection with models is how they relate to theories. The separation between models and theory is a very hazy one, and in the jargon of many scientists it is often difficult, if not impossible, to draw a line. So the question is: Is there a distinction between models and theories, and if so, how do they relate to one another?

In common parlance, the 'model' and 'theory' are sometimes used to express someone's attitude toward a particular piece of science. The phrase "It's just a model" indicates that the hypothesis at stake is asserted only tentatively, while something is awarded the labeled 'theory' if it has acquired some degree of general acceptance. However, this way of drawing a line between models and theories is of no use to a systematic understanding of models.

The Two Extremes: The Syntactic and the Semantic View of Theories

The syntactic view of theories, which is an integral part of the logical empiricist picture of science, construes a theory as a set of sentences in an axiomatized system of first-order logic (see Theories). Within this approach, the 'model' is used in both a wider and a narrower sense. In the wider sense, a model is just a system of semantic rules that interpret the abstract calculus, and the study of a model amounts to scrutinizing the semantics of a scientific language. In the narrower sense, a model is an alternative interpretation of a certain calculus. If, for instance, one takes the mathematics used in the kinetic theory of gases and reinterprets the terms of this calculus so that they refer to billiard balls, the billiard balls are a model of the kinetic theory of gases. Proponents of the syntactic view believe such models to be irrelevant to science. Models, they hold, are superfluous additions that are at best of pedagogical, aesthetical, or psychological value (cf. Bailer-Jones 1999).

The semantic view of theories reverses this standpoint and declares that one should dispense with a formal calculus altogether and view a theory as a family of models (see Theories). Although different versions of the semantic view assume a different notion of model, they all agree that models are the central unit of scientific theorizing.

Models as Independent of Theories

One of the most perspicuous criticisms of the semantic view is that it mislocates the place of models in the scientific edifice. Models are relatively independent from theory, rather than being constitutive of them; or to use Morrison's (1998) phrase, they are "autonomous agents." This independence has two aspects: construction and functioning (Morgan and Morrison 1999).

A look at how models are constructed in actual science shows that they can be derived entirely from neither data nor theory. Theories do not provide algorithms for the construction of a model; model building is an art and not a mechanical procedure. The London model of superconductivity is a good example: The model's principal equation has no theoretical justification and is motivated solely on the basis of phenomenological considerations (Cartwright 1999).

The second aspect of the independence of models is that they perform functions that they could not perform if they were a part of, or strongly dependent on, theories.

Models as Complements of Theories A theory may be incompletely specified in the sense that it imposes only certain general constraints but remains silent about the details of concrete situations, which are provided by a model (Redhead 1980). A special case of this situation is if a qualitative theory is known and the model introduces quantitative measures. Redhead's example for a theory that is underdetermined in this way is axiomatic quantum field theory, which imposes only certain general constraints on quantum fields but does not provide an account of particular fields.

While Redhead and others seem to think of cases of this sort as somehow special, Cartwright (1983) has argued that they are the rule rather than the exception. In her view, fundamental theories such as classical mechanics and quantum mechanics do not represent anything at all, as they do not describe any real-world situation. Laws in such theories are schemata that need to be concretized and filled with the details of a specific situation, which is a task that is accomplished by a model.

Models Stepping in When Theories Are Too Complex to Handle Theories may be too complicated to handle. In such a case a simplified model may be employed that allows for a solution (Redhead 1980). Quantum chromodynamics, for instance, cannot easily be used to study the hadron structure of a nucleus, although it is the fundamental theory for this problem. To get around this difficulty, physicists construct a tractable phenomenological model (e.g., the MIT bag model) that effectively describes the relevant degrees of freedom of the system under consideration (Hartmann 1999). A more extreme case is the use of a model when there are no theories available at all—take Bohr's model of the atom at the time he proposed it. The models scientist then construct to tackle this situation are sometimes referred to as "substitute models."

Models as Preliminary Theories The notion of models as substitutes for theories is closely related to "developmental models," which consist of cases in which models are some sort of a preliminary exercise to theory. A closely related notion is that of probing models (also known as 'study models' or 'toy models'). These are models that do not perform a representational function and that are not expected to provide information about anything beyond the model itself. The purpose of these models is to test new theoretical tools that are used later to build representational models (cf. Wimsatt 1987).

Models and Other Debates in the Philosophy of Science

The debate about scientific models has important repercussions for other debates in the philosophy of science. The reason for this is that traditionally the debates about realism, reductionism, explanation, and laws were couched in terms of theories, because only theories were acknowledged as carriers of scientific knowledge. So the question is whether, and if so how, discussions of these matters change when shifting the focus from theories to models. Up to now, no comprehensive model-based accounts of any of these issues have been developed, but models did leave some traces in the discussions of these topics, and it is these traces that will be dealt with in this section.

Models and the Realism Versus Antirealism Debate

It has been claimed that the practice of model building favors antirealism over realism (see Instrumentalism; Realism). Antirealists point out that truth is not the main goal of scientific modeling. Cartwright (1983), for instance, presents several case studies illustrating that good models are often false. Realists reply that a good model, though not literally true, is usually at least approximately true. In this vein, it has been argued that by relaxing idealizations (de-idealization) the predictions of the model typically become better, which is taken to be evidence for realism (cf. McMullin 1985; Nowak 1979).

Apart from the usual complaints about the elusiveness of the notion of approximate truth, antirealists have criticized this reply as flawed for two related reasons. First, there is no in-principle reason to assume that one can always improve the model by adding de-idealizing corrections. Second, it seems that the outlined procedure is not in accordance with scientific practice, in which it is unusual for scientists to try to repeatedly de-idealize an existing model. Rather, they shift to a completely different modeling framework once the needed adjustments get too complicated. A further difficulty with de-idealization is that most idealizations are not "controlled." For example, it is not clear in which way one has to de-idealize the MIT bag model to eventually arrive at quantum chromodynamics, the supposedly correct underlying theory.

The antirealist "incompatible models argument" takes as its starting point the observation that scientists often use several incompatible models of one and the same target system for predictive purposes. There are, for example, numerous models of a gas or the atomic nucleus. These models seemingly contradict each other as they ascribe different properties to the target system. This seems to cause problems for realists, as they typically hold that there is a close connection between the predictive success of a model and its being at least approximately true. But if several theories of the same system are predictively successful, and if these theories are mutually inconsistent, they cannot all be true.

Realists can react to this argument in three ways—first, by challenging the claim that the models in question are indeed predictively successful; second, by defending a version of perspectival realism, according to which each model reveals one aspect of the phenomenon in question; and, finally, by denying that there is a problem in the first place, because scientific models, which strictly speaking are always false, are just the wrong vehicles to make a point about realism.

Models and Reductionism

The existence of a multiplicity of models raises the question of how different models are related. A simple picture of the organization of science along the lines of Nagel's model of reduction or Oppenheim and Putnam's pyramid picture does not seem to be compatible with the practice of modeling (see also Reductionism). But which picture of science is?

Cartwright (1999) and others have suggested a picture of science according to which there are no systematic relations between different theories and models. All theories and models are tightened together only because they apply to the same domain of phenomena but do not enter into any further relations (deductive or otherwise). One is confronted with a patchwork of theories and models, all of which hold, *ceteris paribus*, in their specific domains of applicability. Some argue that this picture is at least partially incorrect because there are various types of interesting relations that hold between different models or theories. These relations range from those of controlled approximations over a singular limit to rather loose relations. Some have even argued that, at least within the context of biology, models play an essential role in a reductionist enterprise (Sarkar 1998). These suggestions have been made on the basis of case studies, and it remains to be seen whether a more general account of these relations can be given and a deeper justification for them provided (e.g., in a Bayesian framework) (see Bayesianism).

Models and Laws of Nature

It is widely held that science aims at discovering laws of nature. Philosophers, in turn, have been faced with the challenge of explicating what laws of nature are (see Laws of Nature). According to the two currently dominant accounts—the best-systems approach and the universals approach—laws of nature are understood to be universal in scope, meaning that they apply to everything that there is in the world. This take on laws does not seem to square with a view that assigns models a center stage in scientific theorizing. What role do general laws play in science if models are what represent what is happening in the world?

One possible response is to argue that laws of nature govern entities and processes in a model rather than in the world. Fundamental laws, in this approach, do not state facts about the world but hold true of entities and processes in the model (cf. Cartwright 1983).

Models and Scientific Explanation

Laws of nature play an important role in many accounts of explanation, most prominently in the deductive-nomological model and the unification approach (see Explanation). Unfortunately, these accounts inherit the problems that beset the relationship between models and laws. This leaves two options. Either one can argue that laws can be dispensed with in explanations, an idea employed both in van Fraassen's pragmatic theory of explanation and in certain causal accounts of explanation. Or one can shift the explanatory burden on models. A positive suggestion along these lines is Cartwright's (1983) "simulacrum account of explanation," which suggests that one explains a phenomenon by constructing a model that fits the phenomenon into the basic framework of a grand theory (chap. 8). In this account, the model itself is the explanation that is sought. This squares well with basic scientific intuitions but leaves the question of what notion of explanation is at work. Other accounts of explanation do not seem to be more hospitable to models. Causal or mechanistic accounts of explanation (see Explanation, Mechanism) do not assign models an explanatory function and, at best, regard them as tools to find out about the causal relations that hold between certain parts of the world.

Conclusion

Models play an important role in science. But despite the fact that they have generated considerable interest among philosophers, there remain significant lacunae in the philosophical understanding of what models are and of how they work.

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