Scientific Models

1. Introduction: Systematic Questions Concerning Models

Models are of central importance in many scientific contexts. The roles the MIT bag model of the nucleon, the billiard ball model of a gas, the Bohr model of the atom, 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, or general equilibrium models of markets play in their respective domains are cases in point.

This importance has met with increasing recognition by philosophers. As a result the literature on models has been growing rapidly over the last decades, and with it the number of different types of models that philosophers recognize. Probing models, 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, analogue models and instrumental models are but some of the notions that are used to categorize models. The key to come to terms with this abundance is to realize that these notions pertain to different problems that arise in connection with models:

- Semantics – what is the representational function that models perform?
- Ontology – what kind of things are models?
- Epistemology – how do we learn with models?
- Models and theory – how do models relate to theory?
- Models and other philosophical debates:
    - Models and the realism versus antirealism debate
    - Models and reductionism
    - Models and explanation
    - Models and laws

2. 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.

2.1 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 which are interesting from a scientific point of view (empiricists like van Fraassen (1980) only allow for observables to qualify as such, while realists like Bogen and Woodward (1988) do not impose any such restrictions). 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 and an open economy, or the Lorenz model of the atmosphere are well-known examples for models of this kind. 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 has barely been recognized, much less seriously discussed.

A first step towards 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 has to come to terms with, but two problems in particular seem to occupy center stage in tackling the issue (Frigg 2003, Ch. 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* iff ___', where '*M*' stand for 'model' and '*T*' for 'target system'? Somewhat surprisingly, this question has not attracted much attention in twentieth century philosophy of science.

The second problem is concerned with representational styles. 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 air plane represents the wing in a way that is different from how a mathematical model of its shape 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 versions of the semantic view posits that a model and its target have to be isomorphic (van Fraassen 1980; Suppes 2002) or paritially isomorphic (da Costa and French 2003) to each other. Another version drops isomorphism in favor of similarity (Giere 1988, Teller 2001). This approach enjoys the advantage over the isomorphism 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 a naturalistic replica or a truthful mirror image of the target. For this reason icons are sometimes also referred to as 'true models' (Achinstein 1968, Ch. 7). Paradigm cases of iconic models are scale models such as wooden cars or model bridges, which are either enlarged or down-sized copies of the original (Black 1962). More elaborate examples of iconic models can be found in the life sciences, where we investigate one particular organism (or group thereof) in order to find out something about the species to which they belong. In a clinical trial, for instance, a certain number of patients are administered a certain drug and their reaction to this drug is monitored and the result is supposed to tell us how humans in general react to this drug.

What criteria does a model have to satisfy in order to qualify as an icon? Although we seem to have 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.

The first class consists of cases in which idealization amounts to 'stripping away', in our imagination, all properties from a concrete object that we believe are not relevant to the problem at hand. This allows us 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'; other labels include 'negligibility assumptions' (Musgrave 1981) and 'method of isolation' (Mäki 1994).

The second class comprises idealizations which involve deliberate distortions. Physicist 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 sort of idealizations as 'Galilean idealizations' (McMullin 1985, though McMullin uses the term in a way that also involves a component of Aristotelian abstraction).

Galilean idealizations are beset with riddles. What does a model involving distortions of this kind tell us about reality? How can we test its accuracy? In reply to these questions Laymon (1991) has put forward a theory which understands idealizations as ideal limits: imagine a series of experimental refinements of the actual situation which 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. This happens for instance in what Gibbard and Varian (1978) call 'caricatures'. Caricature models 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 or 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 one that 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 towards 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 we 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 this sense that some politicians assert that the relation of a father to his children is analogous to the relation of the state to the citizens. The analogies mentioned so far have been what Hesse calls 'material analogies'. We obtain a more formal notion of analogy when we abstract from the concrete features the systems possess and only focus on their formal set-up. What the analogue 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 the one between positive, negative and neutral analogies. The positive analogy between two items consists in the properties or relations they share (both gas molecules and billiard balls have mass), the negative analogy in the ones they do not share (billiard balls are colored, gas molecules are not). The neutral analogy comprises the properties of which it is not known yet whether they belong to 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.

Analogies have been widely discussed in the literature and various authors have emphasized the heuristic role that analogies play in theory construction and in creative thought (Bailer-Jones and Bailer-Jones 2002; Hesse 1974, Holyoak and Thagard 1995, Kroes 1989, Psillos 1995, and the essays collected in Hellman 1988).

Phenomenological models. Phenomenological models have been defined in different, though related, ways. A standard definition takes them to be models that only represent observable properties of their targets and refrain from postulating hidden mechanisms and the like. Another approach, due to McMullin (1968), defines phenomenological models as models that are 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.

Concluding remarks. Each of these notions has its internal problems. But more pressing than these 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 we do not know how to answer these questions. What we are in need of is a systematic account of the different ways in which models can relate to reality and of how these ways compare to each other.

2.2 Representational models II: models of data

Another kind of representational models are so-called ‘models of data’ (Suppes 1962). A model of data is a corrected, rectified, regimented, and in many instances idealized version of the data we gain 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 present 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 we investigate the trajectory of a certain planet, for instance, we first eliminate points that are fallacious from the observation records and then fit a smooth curve to the remaining ones. Models of data play a crucial role in confirming theories because it is the model of data and not the often messy and complex raw data that we compare to a theoretical prediction.

Both steps in the construction of a data model raise serious questions. How do we decide which points on the record need to be removed? And given a clean set of data, what curve do we fit to it? The first question has been dealt with mainly within the context of the philosophy of experiment (see for instance Galison 1997 and Staley 2004). 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 which shows that the data themselves underwrite (though not determine) an inference concerning the curve's shape if we assume that the fitted curve has to be chosen such that it strikes a balance between simplicity and goodness of fit in a way that maximises predictive accuracy. (Further discussions of data models can be found in Harris 2003 and Mayo 1996).

2.3 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 (see Bell and Machover 1977 or Hodges 1997 for details). The structure represents the theory in the sense that it interprets the abstract theory and gives us an object which embodies the essential features of the theory. 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 from these axioms. 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 being the interpretation of 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.

3. Ontology: What Are Models?

3.1 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 we find stock examples like wooden models of bridges, planes, or ships, analogue models like electric circuit models of neural systems or pipe models of an economy, or Watson and Crick's model of DNA. But also more cutting edge cases, especially from the life sciences, where certain organisms are studied as stand-ins for others, belong to this category.

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 object, parts and wholes, and so on).

3.2 Fictional objects

Many models are not material models. The Bohr model of the atom, a frictionless pendulum, or isolated populations, for instance, are in the scientist's mind rather than in the laboratory and they do not have to be physically realised 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', as well as by Achinstein (1968) and Black (1962) who refer to models involving fictional entities as 'theoretical models'. The drawback of this suggestion is that fictional entities are notoriously beset with ontological riddles. This has led many philosophers, most prominently Quine (1953), to argue that there are no such things as fictional entities and that apparent ontological commitments to them must be renounced. This has resulted in a glaring neglect of fictional entities, in particular among philosophers of science. Fine (1993), in a programmatic essay, draws attention to this neglect but does not offer a systematic account of how fictions are put to use in science.

3.3 Set-theoretic structures

An influential point of view takes models to be set-theoretic structures. This position can be traced back to Suppes (1960) 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 science are not structures and cannot be accommodated within the structuralist view of models, which can neither account for how these models are constructed nor for how they work in context of investigation (Cartwright 1999, Downes 1992, Morrison 1999). Another charge held against the set-theoretic approach is that it is not possible to explain how structures represent a target system which 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).

3.4 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 (Achinstein 1968, Black 1962).

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 we can describe the same thing in different ways. But if we identify 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, we 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 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 any sense when said about a model.

3.5 Equations

Another group of things that are habitually referred to as 'models', in particular in economics, is equations (which are then termed 'mathematical models'). The Black-Scholes model of the stock market or the Mundell-Fleming model of an open economy are cases in point.

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 co-ordinates and as a result obtain different equations; but we do 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, the system it describes is not.

3.6 Gerrymandered ontologies

The proposals discussed so far have tacitly assumed that a model belongs to one partivcular 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. In this vein Morgan (2001) suggests that models involve structural as well as narrative elements ('stories', as she calls them).

4. Epistemology: Learning with Models

Models are vehicles for learning about the world. By studying a model we 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, so-called 'model based reasoning' (Magnani and Nersessian 2002, Magnani, Nersessian and Thagard 1999). This leaves us with the question of how learning with a model is possible.

Hughes (1997) provides a general framework for discussing this question. According to his so-called DDI account of modeling, learning takes place in three stages: denotation, demonstration, and interpretation. We begin by establishing a representation relation ('denotation') between the model and the target. Then we investigate the features of the model in order to demonstrate certain theoretical claims about its internal constitution or mechanism; i.e. we learn 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.

4.1 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 1999). There are no fixed rules or recipes for model building and so the very activity of figuring out what fits together and how affords an opportunity to learn about the model. Once the model is built, we do not learn about its properties by looking at it; we have to use and manipulate the model in order to elicit its secrets.

Depending on what kind of model we are dealing with, building and manipulating a model amounts to different activities demanding a different methodology. Material models seem to be unproblematic as they are commonly used in the kind of experimental contexts which have been discussed extensively by philosophers of science (we put the model of a car in the wind tunnel and measure its air resistance).

Not so with fictional models. What constraints are there to the construction of fictional models and how do we manipulate them? The natural response seems to be that we answer these questions by performing a thought experiment. Different authors (e.g. Brown 1991, Gendler 2000, Norton 1991, Reiss 2003, Sorensen 1992) 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.

An important class of models are 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 at this point where the invention of the computer had a great impact, as it allows us to solve equations which are otherwise intractable by making a computer simulation. Many parts of current research in both the natural and social sciences rely on computer simulations. 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 as well as the outbreak of wars, the progression of an economy, decision procedures in an organization and moral behavior are explored with computer simulations, to mention only a few examples (Hegselmann et al. 1996, Skyrms 1996).

What is a simulation? Simulations characteristically are used in connection with dynamic models, i.e. models that involve time. The aim of a simulation is to solve the equations of motion of a 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, Rohrlich 1991, Winsberg 2001, and various contributions to Sismondo and Gissis 1999). 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. Due to the discrete nature of the calculations carried out on a digital computer they only allow for the exploration of a part of the full parameter space and this subspace may not reveal certain important features of the model.

4.2 Converting knowledge about the model into knowledge about the target

Once we have knowledge about the model, this knowledge 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 instruct us about the nature of reality only if we assume 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, we have a model we take to be a realistic depiction, the transfer of knowledge from the model to the target is accomplished in a different manner than when we deal with an analogue, 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 (this 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 that it has gotten so far.

5. 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 terms ‘model’ and ‘theory’ are sometimes used to express someone’s attitude towards 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.

5.1 The two extremes: the syntactic and the semantic view of theories

The syntactic view of theories, which is an integral part of the logical positivist 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 term model is used in a wider and in 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 (Braithwaite 1953, Nagel 1961, Spector 1965). If, for instance, we take the mathematics used in the kinetic theory of gases and reinterpret the terms of this calculus in a way 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 (Carnap 1938, Hempel 1965).

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

5.2 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 slogan, they are 'autonomous agents' (1998). 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 neither from data nor from theory. Theories do not provide us with algorithms for the construction a model; they are not 'vending machines' into which one can insert a problem and a models pops out (Cartwright 1999, Ch. 8) – model building is an art and not a mechanical procedure. The London model of superconductivity affords us with a good example for this. The model's principal equation has no theoretical justification and is motivated solely on the basis of phenomenological considerations (Cartwright et al. 1995).

The second aspect of the independence of models is that they perform functions which 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 only imposes 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 (Apostel 1961). Redhead's example for a theory that is underdetermined in this way is axiomatic quantum field theory, which only imposes 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. On 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 (Apostel 1961, 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. The models scientist then construct to tackle this situation are sometimes referred to as 'substitute models' (Groenewold 1961).

Models as preliminary theories. The notion of models as substitutes for theories is closely related to the notion of a developmental model. This term has been coined by

Leplin (1980), who pointed out how useful models were in the development of early quantum theory and is now used as an umbrella notion covering cases in which models are some sort of a preliminary exercises to theory.

A closely related notion is the one of probing models (also ‘study models’ or ‘toy models’). These are models which do not perform a representational function and which are not expected to instruct us about anything beyond the model itself. The purpose of these models is to test new theoretical tools that are used later on to build representational models. In field theory, for instance, the so-called _^{4}-model has been studied extensively not because it represents anything real (it is well-known that it doesn’t) but because it allows physicist to ‘get a feeling’ for what quantum field theories are like and to extract some general features that this simple model shares with more complicated ones (Hartmann 1995). Probing models are also used in other disciplines such as biology (Wimsatt 1987) and economics (Hausman 1992).

6. 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 we shift the focus from theories to models. Up to now, no comprehensive model-based accounts of any of these issues has been developed; but models did leave some traces in the discussions of these topics, and it is these traces that we will be dealing with in this section.

6.1 Models and the realism versus antirealism debate

It has been claimed that the practice of model building favors antirealism over realism (see REALISM and INSTRUMENTALISM). 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, thought not literally true, is usually at least approximately true. In this vein, Laymon (1985) argues that by relaxing idealizations (de-idealization) the predictions of the model typically become better, which he takes to be evidence for realism (see also Brzezinski and Nowak 1992, McMullin 1985, and Nowak 1979), and Teller (2001) develops a similarity-based account of approximate truth for models.

Apart from the usual complaints about the elusiveness of the notion of approximate truth, antirealist have criticized this reply as flawed for two related reasons. First, as Cartwright (1989) points out, 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 (Suárez 1999) where it is unusual that scientist try to repeatedly de-idealizing an existing model. Rather, they shift to a completely different modeling framework once the adjustments to be made get too complicated. A further difficulty with de-idealization is that most idealizations are not ‘controlled’. It is, for example, 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.

A further antirealist argument, the so-called ‘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 (Morrison 2000). 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 various ways. First, they can challenge the claim that the models in question are indeed predictively successful. Second, they can defend a version of perspectival realism (Giere 1999). According to this view, each model reveals one aspect of the phenomenon in question. And finally, realists can deny that there is a problem in the first place because scientific models, which are always strictly speaking false, are just the wrong vehicle to make a point about realism.

6.2 Models and reductionism

The existence of a multiplicity of models raises the question how different models are related. A simple picture of the organization of science along the lines of Nagel’s (1961) model of reduction or Oppenheim and Putnam’s (1958) pyramid picture does not seem to be compatible with the practice of modeling (see also REDUCTIONISM). But which picture of science is?

Some have suggested (Cartwright 1999, Hacking 1983, see also the papers in Falkenburg and Muschik (1998)) a picture of science according to which there are no systematic relations between different theories and models. All of our theories and models are tightened together only because they apply to the same empirical reality but do not enter into any further relations (deductive or otherwise). We are 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 controlled approximations over singular limit relations (Batterman 2002) to rather loose relations called stories (Hartmann 1999; see also Bokulich 2003). These suggestions have been made on the basis of cases studies and it remains to be seen whether a more general account of these relations can be given and whether a deeper justification for them can be provided (e.g. in a Bayesian framework). See Gähde (1997) for a structuralist account.

6.3 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 it is models that 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, on this approach, do not state facts about the world but hold true of entities and processes in the model. Different variants of this view have been advocated by Cartwright (1983, 1999), Giere (1999), and van Fraassen (1989).

6.4 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 us with two options. Either one can argue that laws can be dispensed with in explanations, an idea which is employed in both van Fraassen's (1980) pragmatic theory of explanation and Woodward's (2003) approach to causal explanation. Or one can shift the explanatory burden on models. A positive suggestion along these lines is Cartwright's so-called 'simulacrum account of explanation', which suggests that we explain a phenomenon by constructing a model that fits the phenomenon into the basic framework of a grand theory (1983, Ch. 8). On this account, the model itself is the explanation we seek. This squares well with basic scientific intuitions but leaves us with the question of what notion of explanation is at work (see also Elgin and Sober 2002). Other accounts of explanation do not seem to be more hospitable to models. Causal or mechanistic accounts of explanation (see EXPLANATION, MECHANISTIC) 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.

7. Conclusion

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

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