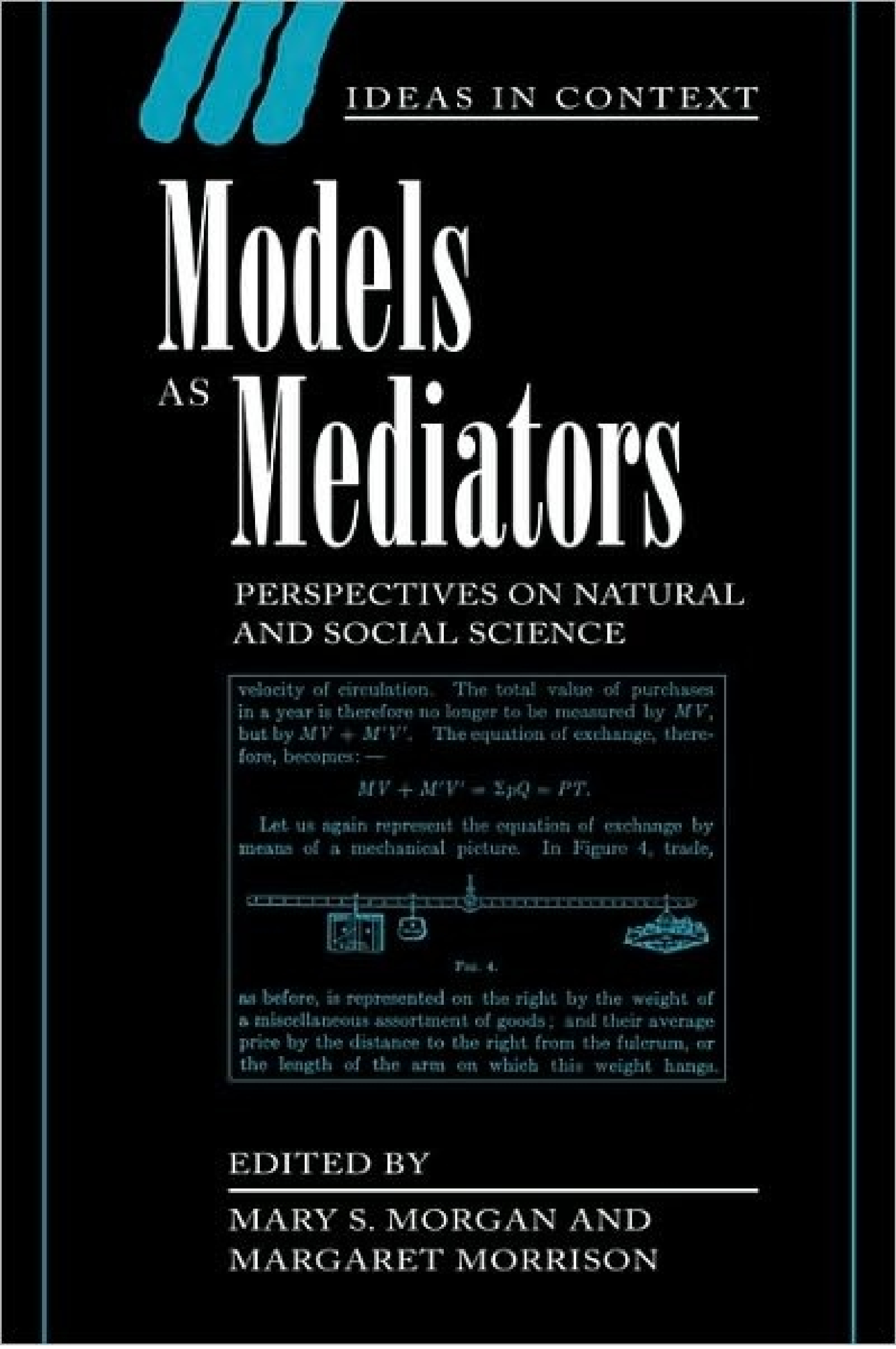
IDEAS IN CONTEXT
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velocity of circulation. The total value of purchases in a year is therefore no longer to be measured by MV, but by $MV + M'V'$. The equation of exchange, therefore, becomes: —
$$MV + M'V' = \Sigma pQ = PT.$$
Let us again represent the equation of exchange by means of a mechanical picture. In Figure 4, trade,
FIG. 4.
as before, is represented on the right by the weight of a miscellaneous assortment of goods; and their average price by the distance to the right from the fulcrum, or the length of the arm on which this weight hangs.
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MODELS AS MEDIATORS

Models as Mediators discusses the ways in which models function in modern science, particularly in the fields of physics and economics. Models play a variety of roles in the sciences: they are used in the development, exploration and application of theories and in measurement methods. They also provide instruments for using scientific concepts and principles to intervene in the world. The editors provide a framework which covers the construction and function of scientific models, and explore the ways in which they enable us to learn about both theories and the world. The contributors to the volume offer their own individual theoretical perspectives to cover a wide range of examples of modelling from physics, economics and chemistry. These papers provide ideal case-study material for understanding both the concepts and typical elements of modelling, using analytical approaches from the philosophy and history of science.

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Edited by Quentin Skinner (*General Editor*)
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The books in this series will discuss the emergence of intellectual traditions and of related new disciplines. The procedures, aims and vocabularies that were generated will be set in the context of the alternatives available within the contemporary frameworks of ideas and institutions. Through detailed studies of the evolution of such traditions, and their modification by different audiences, it is hoped that a new picture will form of the development of ideas in their concrete contexts. By this means, artificial distinctions between the history of philosophy, of the various sciences, of society and politics, and of literature may be seen to dissolve.

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MODELS AS MEDIATORS

Perspectives on Natural and Social Science

EDITED BY

MARY S. MORGAN and MARGARET MORRISON

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Preface

This project has a long and varied history, both intellectually and geographically. Our interest in models arose in the context of independent work done by Morrison in the history and philosophy of physics and by Morgan in the historical and philosophical aspects of econometrics. Our first conversation about models occurred at the History of Science meeting in Seattle in Fall 1990 and lively discussions comparing modelling in our two fields continued through the early 1990s. Thereafter, from 1993–1996, through the generous support of Nancy Cartwright and the Centre for the Philosophy of the Natural and the Social Sciences (CPNSS) at the London School of Economics, we organised a working research group focusing on issues relevant to modelling in physics and economics. The goal of the project was not to find or construct general principles that these two disciplines shared; instead, our initial focus was empirical – to examine the ways in which modelling works in each field and then move on to investigate how the presuppositions behind those practices influenced the way working scientists looked on models as a source of knowledge. The project at the LSE was directed by Cartwright, Morgan and Morrison and consisted of a group of graduate students who attended regularly, as well as a constant stream of European and American visitors and faculty from various LSE departments such as economics, statistics and philosophy. The CPNSS not only provided support for graduate students working on the project but enabled us to organise seminars and workshop meetings on the topic of modelling.

While the LSE group work was primarily focused on physics, another group, concentrating mainly on economics, was organised by Morgan at the University of Amsterdam from 1993 onwards. Though the meetings of this group were less eclectic in subject coverage, their membership and approach spanned from the history and philosophy of economics over to social studies of science. The group involved, as core members, Geert Reuten and Marcel Boumans (from the Faculty of Economics and Econometrics) and Adrienne van den Bogaard (from Science Dynamics). The research work of the group was supported by the Tinbergen Institute and by the Faculty of Economics and Econometrics at the University of Amsterdam. Joint meetings (both formal and informal) between members of the two groups took place on a regular basis thereby enhancing the cooperative nature of the project and extending our 'data base' of studies on various aspects of modelling.

The year 1995–96 was a critical year for the project in two respects. First, Morgan and Morrison were fellows at the Wissenschaftskolleg zu Berlin. It was there that we felt our ideas finally began to take shape during a period of intense reading and discussion. Much to our delight a number of the other fellows were also interested in modelling and we benefited enormously from conversations about philosophical and practical issues concerning the construction and function of models in fields as diverse as biology, architecture and civic planning. Our time at the Wissenschaftskolleg was invaluable for solidifying the project, giving us the time to think through together the issues of why and how models can act as mediators in science. We are extremely grateful to the director Professor Wolf Lepenies and the entire staff of the Kolleg for their generous support of our work.

The year was also crucial for the genesis of this volume. During the year we organised two small-scale workshop meetings on modelling. The first took place in Amsterdam through the generous financial support of the Royal Dutch Academy of Sciences (KNAW) and the Tinbergen Institute. This three-day meeting involved the main researchers from the LSE and the University of Amsterdam together with some other international speakers, all expert on the topic of models in science. The present volume was conceived in the enthusiastic discussions amongst members of the two research groups that followed that workshop. The year culminated with a second small two-day conference at the Wissenschaftskolleg in Berlin, supported by the Otto and Martha Fischbeck Stiftung, where once again LSE, Amsterdam and now Berlin interests were represented. These two workshops together saw early presentations of most of the essays contained in this volume.

There are many scholars who made a significant contribution to the project but whose work is not represented in the volume. Three of the LSE research students come immediately to mind – Marco Del Seta, Towfic Shomar and George Zouros. Mike Williams (from De Montfort University) contributed to our Amsterdam discussions. Special symposia

resulting from our work on modelling have been presented at the Joint British and North American History of Science Society Meeting in Edinburgh in July 1996; the Philosophy of Science Meeting in Cleveland in October 1996 and the History of Science Society Meeting in San Diego in November 1997. Many papers have been given at specialist (subject-based) conferences and individual seminars and lectures. We would like to thank the audiences for their enthusiasm, questions and criticisms. We also thank many unnamed individuals who have taken the trouble to comment on individual papers, Cambridge University Press's anonymous referees who helped us improve the structure of the volume and our editors at Cambridge University Press: Patrick McCartan, Richard Fisher and Vicky Cuthill as well as Adam Swallow who saw the book through production. Our thanks go also to Linda Sampson and Kate Workman at the LSE, the secretariat at the University of Amsterdam, and Elfie Bonke at the Tinbergen Institute for their help with the research projects and with the volume. Margaret Morrison would like to thank the Social Sciences and Humanities Research Council of Canada for its continued and generous support of her research as well as the Philosophy Department at the University of Toronto who allowed her periods of time away to pursue the research. Mary Morgan would like to thank the Tinbergen Institute, the Department of Economic History at the London School of Economics, the LSE Staff Research Fund, and the British Academy for their support in terms of research time and expenses. Finally we thank Professor George Fisher for permission to use a figure from his grandfather, Irving Fisher's, work on the front cover of this book.

MARGARET MORRISON AND MARY S. MORGAN

CHAPTER 1

Introduction

Margaret Morrison and Mary S. Morgan

Typically, the purpose of an introduction for an edited volume is to give the reader some idea of the main themes that will be explored in the various papers. We have chosen, instead, to take up that task in chapter 2. Here we want to simply provide a brief overview of the literature on models in the philosophy of science and economics, and to provide the audience with a sense of how issues relevant to modelling have been treated in that literature. By specifying a context and point of departure it becomes easier to see how our approach differs, both in its goals and methods, from its predecessors.

The use of models in scientific practice has a rich and varied history with their advantages and disadvantages discussed by philosophically minded scientists such as James Clerk Maxwell and his contemporaries Lord Kelvin and Sir George Francis FitzGerald. In fact, it was the use of mechanical models by British field theorists that became the focus of severe criticism by the French scientist and philosopher Pierre Duhem (1954). In Duhem's view models served only to confuse things, a theory was properly presented when cast in an orderly and logical manner using algebraic form. By contrast, mechanical models introduced disorder, allowing for diverse representations of the same phenomena. This emphasis on logical structure as a way of clarifying the nature of theories was also echoed in the early twentieth century by proponents of logical empiricism. This is not to suggest that their project was the same as Duhem's; we draw the comparison only as a way of highlighting the importance of logical form in philosophical appraisals of theories. The emphasis on logic is also significant because it was in this context that models came to be seen as an essential part of theory structure in twentieth-century philosophy of science.

It is perhaps not surprising that much of the early literature on theory structure and models in philosophy of science takes physics as its starting point. Physical theories are not only highly mathematical but they are certainly more easily cast into an axiomatic form than theories in other sciences. According to the logical empiricist account of theories, sometimes referred to as the received view or the syntactic view, the proper characterisation of a scientific theory consists of an axiomatisation in first-order logic. The axioms were formulations of laws that specified relationships between theoretical terms such as electron, charge, etc. The language of the theory was divided into two parts, the observation terms that described observable macroscopic objects or processes and theoretical terms whose meaning was given in terms of their observational consequences. In other words, the meaning of 'electron' could be explicated by the observational terms 'track in a cloud chamber'. Any theoretical terms for which there were no corresponding observational consequences were considered meaningless. The theoretical terms were identified with their observational counterparts by means of correspondence rules, rules that specified admissible experimental procedures for applying theories to phenomena. For example, mass could be defined as the result of performing certain kinds of measurements. One can see then why this account of theory structure was termed the syntactic view; the theory itself was explicated in terms of its logical form with the meanings or semantics given by an additional set of definitions, the correspondence rules. That is to say, although the theory consisted of a set of sentences expressed in a particular language, the axioms were syntactically describable. Hence, without correspondence rules one could think of the theory itself as uninterpreted.

An obvious difficulty with this method was that one could usually specify more than one procedure or operation for attributing meaning to a theoretical term. Moreover, in some cases the meanings could not be fully captured by correspondence rules; hence the rules were considered only partial interpretations for these terms.[1] A possible solution to these problems was to provide a semantics for a theory (T) by specifying a model (M) for the theory, that is, an interpretation on which all the axioms of the theory are true. As noted above, this notion of a model comes from the field of mathematical logic and, some argue, has little to do with the way working scientists use models. Recall, however, that the goal of the logical empiricist programme was a clarification of the nature of theories; and to the extent that that remains a project worthy of pursuit, one might want to retain the emphasis on logic as a means to that end.

[1] A number of other problems, such as how to define dispositional theoretical terms, also plagued this approach. For an extensive account of the growth, problems with, and decline of the received view, see Suppe (1977).

But the significance of the move to models as a way of characterising theories involves replacing the syntactic formulation of the theory with the theory's models. Instead of formalising the theory in first-order logic, one defines the intended class of models for a particular theory. This view still allows for axiomatisation provided one can state a set of axioms such that the models of these axioms are exactly the models in the defined class. One could still formulate the axioms in a first-order language (predicate calculus) in the manner of the syntactic view; the difference however is that it is the models (rather than correspondence rules) that provide the interpretation for the axioms (or theory). Presenting a theory by identifying a class of structures as its models means that the language in which the theory is expressed is no longer of primary concern. One can describe the models in a variety of different languages, none of which is the basic or unique expression of the theory. This approach became known as the semantic view of theories (see Suppes (1961) and (1967); Suppe (1977); van Fraassen (1980) and Giere (1988)) where 'semantic' refers to the fact that the model provides a realisation in which the theory is satisfied. That is, the notion of a model is defined in terms of truth. In other words the claims made by the theory are true in the model and in order for M to be a model this condition must hold.

But what exactly are these models on the semantic view? According to Alfred Tarski (1936), a famous twentieth-century logician, a model is a non-linguistic entity. It could, for example, be a set theoretical entity consisting of an ordered tuple of objects, relations and operations on these objects (see Suppes (1961)). On this account we can define a model for the axioms of classical particle mechanics as an ordered quintuple containing the following primitives $\mathscr{P} = <P, T, s, m, f>$ where P is a set of particles, T is an interval or real numbers corresponding to elapsed times, s is a position function defined on the Cartesian product of the set of particles and the time interval, m is a mass function and f is a force function defined on the Cartesian product of the set of particles, the time interval and the positive integers (the latter enter as a way of naming the forces). Suppes claims that this set theoretical model can be related to what we normally take to be a physical model by simply interpreting the set of particles to be, for instance, the set of planetary bodies. The idea is that the abstract set-theoretical model will contain a basic set consisting of objects ordinarily thought to constitute a physical model. The advantage of the logicians' sense of model is that it supposedly renders a more precise and clear account of theory structure, experimental design and data analysis (see Suppes (1962)).

Other proponents of the semantic view including van Fraassen and Giere have slightly different formulations yet both subscribe to the idea that models are non-linguistic entities. Van Fraassen's version incorporates the notion of a state space. If we think of a system consisting of physical entities developing in time, each of which has a space of possible states, then we can define a model as representing one of these possibilities. The models of the system will be united by a common state space with each model having a domain of objects plus a history function that assigns to each object a trajectory in that space. A physical theory will have a number of state spaces each of which contains a cluster of models. For example, the laws of motion in classical particle mechanics are laws of succession. These laws select the physically possible trajectories in the state space; in other words only the trajectories in the state space that satisfy the equations describing the laws of motion will be physically possible. Each of these physical possibilities is represented by a model.[2] We assess a theory as being empirically adequate if the empirical structures in the world (those that are actual and observable) can be embedded in some model of the theory, where the relationship between the model and a real system is one of isomorphism.

Giere's account also emphasises the non-linguistic character of models but construes them in slightly less abstract terms. On his account, the idealised systems described in mechanics texts, like the simple harmonic oscillator, is a model. As such the model perfectly satisfies the equations of motion for the oscillator in the way that the logicians' model satisfies the axioms of a theory. Models come in varying degrees of abstraction, for example, the simple harmonic oscillator has only a linear restoring force while the damped oscillator incorporates both a restoring and a damping force. These models function as representations in 'one of the more general senses now current in cognitive psychology' (Giere 1988, 80). The relationship between the model and real systems is fleshed out in terms of similarity relations expressed by theoretical hypotheses of the form: 'model M is similar to system S in certain respects and degrees'. On this view a theory is not a well-defined entity since there are no necessary nor sufficient conditions determining which models or hypotheses belong to a particular theory. For example, the models for classical mechanics do not comprise a well-defined group because there are no specific conditions for what constitutes an admissible force function. Instead we classify the models on the basis of their

[2] Suppe (1977) has also developed an account of the semantic view that is similar to van Fraassen's.

family resemblance to models already in the theory: a judgement made in a pragmatic way by the scientists using the models.

Two of the things that distance Giere from van Fraassen and Suppes respectively are (1) his reluctance to accept isomorphism as the way to characterise the relation between the model and a real system, and (2) his criticism of the axiomatic approach to theory structure. Not only does Giere deny that most theories have the kind of tightly knit structure that allows models to be generated in an axiomatic way, but he also maintains that the axiomatic account fails even to capture the correct structure of classical mechanics. General laws of physics like Newton's laws and the Schrodinger equation are not descriptions of real systems but rather part of the characterisation of models, which can in turn represent different kinds of real systems. But a law such as $F = ma$ does not by itself define a model of anything; in addition we need specific force functions, boundary conditions, approximations etc. Only when these conditions are added can a model be compared with a real system.

We can see then how Giere's account of the semantic view focuses on what many would call 'physical models' as opposed to the more abstract presentation characteristic of the set theoretic approach. But this desire to link philosophical accounts of models with more straightforward scientific usage is not new; it can be traced to the work of N. R. Campbell (1920) but was perhaps most widely discussed by Mary Hesse (1966).[3] The physical model is taken to represent, in some way, the behaviour and structure of a physical system; that is, the model is structurally similar to what it models. If we think of the Bohr atom as modelled by a system of billiard balls moving in orbits around one ball, with some balls jumping into different orbits at different times, then as Hesse puts it, we can think of the relation between the model and the real system as displaying different kinds of analogies. There is a positive analogy where the atom is known to be analogous to the system of billiard balls, a negative analogy where they are disanalogous and neutral where the similarity relation is not known. The kinds of models that fulfil this characterisation can be scale models like a model airplane or a mathematical model of a theory's formalism. An example of the latter is the use of the Langevin equations to model quantum statistical relations in the behaviour of certain kinds of laser phenomena. In this case we model the Schrodinger equation in a specific kind

[3] There are also other noteworthy accounts of models such as those of Max Black (1962) and R. B. Braithwaite (1953, 1954).

of way depending on the type of phenomena we are interested in. The point is, these physical models can be constructed in a variety of ways; some may be visualisable, either in terms of their mathematical structure or by virtue of their descriptive detail. In all cases they are thought to be integral components of theories; they suggest hypotheses, aid in the construction of theories and are a source of both explanatory and predictive power.

The tradition of philosophical commentary on models in economic science is relatively more recent, for despite isolated examples in previous centuries, economic modelling emerged in the 1930s and only became a standard method in the post-1950 period. In practical terms, economists recognise two domains of modelling: one associated with building mathematical models and the activity of theorising; the other concerned with statistical modelling and empirical work.

Given that mathematical economists tend to portray their modelling activity within the domain of economic theory, it is perhaps no surprise that philosophical commentaries about mathematical models in economics have followed the traditional thinking about models described above. For example, Koopmans' (1957) account can be associated with the axiomatic tradition, while Hausman's (1992) position is in many ways close to Giere's semantic account, and McCloskey's (1990) view of models as metaphors can surely be related to Hesse's analogical account. Of these, both Koopmans and Hausman suggest that models have a particular role to play in economic science. Koopmans sees economics beginning from abstract theory (as for example the formulation of consumer choice theory within a utility maximising framework) and 'progressing' through a sequence of ever more realistic mathematical models;[4] whereas for Hausman, models are a tool to help form and explore theoretical concepts.

In contrast to these mathematical concerns, discussions about empirical models in economics have drawn on the foundations of statistics and probability theory. The most important treatment in this tradition is the classic thesis by Haavelmo (1944) in which econometric models are defined in terms of the probability approach, and their function is to act as the bridge between economic theories and empirical economics. Given that economists typically face a situation where data are not generated from controlled experiments, Haavelmo proposed using models

[4] Recent literature on idealisation by philosophers of economics has also supposed that models might be thought of as the key device by which abstract theories are applied to real systems and the real world simplified for theoretical description. See Hamminga and De Marchi (1994).

in econometrics as the best means to formulate and to solve a series of correspondence problems between the domains of mathematical theory and statistical data.

The account of Gibbard and Varian (1978) also sees models as bridging a gap, but this time between mathematical theory and the evidence obtained from casual observation of the economy. They view models as caricatures of real systems, in as much as the descriptions provided by mathematical models in economics often do not seek to approximate, but rather to distort the features of the real world (as for example in the case of the overlapping generations model). Whereas approximation models aim to capture the main characteristics of the problem being considered and omit minor details, caricature models take one (or perhaps more) of those main characteristics and distorts that feature into an extreme case. They claim that this distortion, though clearly false as a description, may illuminate certain relevant aspects of the world. Thus even small mathematical models which are manifestly unrealistic can help us to understand the world. Although they present their account within the tradition of logical positivism described above, it is better viewed as a practise-based account of economic modelling in the more modern philosophy of science tradition seen in the work of Cartwright (1983), Hacking (1983) and others. Their treatments, emphasising the physical characteristics of models (in the sense noted above), attempt to address questions concerning the interplay among theories, models, mathematical structures and aspects of creative imagination that has come to constitute the practice we call modelling.

Despite this rather rich heritage there remains a significant lacuna in the understanding of exactly how models in fact function to give us information about the world. The semantic view claims that models, rather than theory, occupy centre stage, yet most if not all of the models discussed within that framework fall under the category 'models of theory' or 'theoretical models' as in Giere's harmonic oscillator or Hausman's account of the overlapping generations model. Even data models are seen to be determined, in part, by theories of data analysis (as in Haavelmo's account) in the same way that models of an experiment are linked to theories of experimental design. In that sense, literature on scientific practice still characterises the model as a subsidiary to some background theory that is explicated or applied via the model. Other examples of the tendency to downplay models in favour of theory include the more mundane references to models as tentative hypotheses; we have all heard the phrase 'it's just a model at this stage', implying that the hypothesis has not yet acquired the level of consensus reserved for theory. The result is that we have very little sense of what a model is in itself and how it is able to function in an autonomous way.

Yet clearly, autonomy is an important feature of models; they provide the foundation for a variety of decision making across contexts as diverse as economics, technological design and architecture. Viewing models strictly in terms of their relationship to theory draws our attention away from the processes of constructing models and manipulating them, both of which are crucial in gaining information about the world, theories and the model itself. However, in addition to emphasising the autonomy of models as entities distinct from theory we must also be mindful of the ways that models and theory do interact. It is the attempt to understand the dynamics of modelling and its impact on the broader context of scientific practice that motivates much of the work presented in this volume. In our next chapter, we provide a general framework for understanding how models can act as mediators and illustrate the elements of our framework by drawing on the contributions to this volume and on many other examples of modelling. Our goal is to clarify at least some of the ways in which models can act as autonomous mediators in the sciences and to uncover the means by which they function as a source of knowledge.

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CHAPTER 2

Models as mediating instruments

Margaret Morrison and Mary S. Morgan

Models are one of the critical instruments of modern science. We know that models function in a variety of different ways within the sciences to help us to learn not only about theories but also about the world. So far, however, there seems to be no systematic account of *how* they operate in both of these domains. The semantic view as discussed in the previous chapter does provide some analysis of the relationship between models and theories and the importance of models in scientific practice; but, we feel there is much more to be said concerning the dynamics involved in model construction, function and use. One of the points we want to stress is that when one looks at examples of the different ways that models function, we see that they occupy an autonomous role in scientific work. In this chapter we want to outline, using examples from both the chapters in this volume and elsewhere, an account of models as *autonomous agents*, and to show how they function as *instruments* of investigation. We believe there is a significant connection between the autonomy of models and their ability to function as instruments. It is precisely because models are partially independent of both theories and the world that they have this autonomous component and so can be used as instruments of exploration in both domains.

In order to make good our claim, we need to raise and answer a number of questions about models. We outline the important questions here before going on to provide detailed answers. These questions cover four basic elements in our account of models, namely how they are constructed, how they function, what they represent and how we learn from them.

CONSTRUCTION What gives models their autonomy? Part of the answer lies in their construction. It is common to think that models can be derived entirely from theory or from data. However, if we look closely at the way models are constructed we can begin to see the sources of their independence. It is because they are neither one thing nor the other, neither just theory nor data, but typically involve some of both (and often additional 'outside' elements), that they can mediate between theory and the world. In addressing these issues we need to isolate the nature of this partial independence and determine why it is more useful than full independence or full dependence.

FUNCTIONING What does it mean for a model to function autonomously? Here we explore the various tasks for which models can be used. We claim that what it means for a model to function autonomously is to function like a tool or instrument. Instruments come in a variety of forms and fulfil many different functions. By its nature, an instrument or tool is independent of the thing it operates on, but it connects with it in some way. Although a hammer is separate from both the nail and the wall, it is designed to fulfil the task of connecting the nail to the wall. So too with models. They function as tools or instruments and are independent of, but mediate between things; and like tools, can often be used for many different tasks.

REPRESENTING Why can we learn about the world and about theories from using models as instruments? To answer this we need to know what a model consists of. More specifically, we must distinguish between instruments which can be used in a purely instrumental way to effect something and instruments which can also be used as investigative devices for learning something. We do not learn much from the hammer. But other sorts of tools (perhaps just more sophisticated ones) can help us learn things. The thermometer is an instrument of investigation: it is physically independent of a saucepan of jam, but it can be placed into the boiling jam to tell us its temperature. Scientific models work like these kinds of investigative instruments – but how? The critical difference between a simple tool, and a tool of investigation is that the latter involves some form of representation: models typically represent either some aspect of the world, or some aspect of our theories about the world, or both at once. Hence the model's representative power allows it to function not just instrumentally, but to teach us something about the thing it represents.

LEARNING Although we have isolated representation as the mechanism that enables us to learn from models we still need to know *how* this learning takes place and we need to know what else is involved in a model functioning as a mediating instrument. Part of the answer comes from seeing how models are used in scientific practice. We do not learn