CHAPTER 2

Models as mediating instruments

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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 much from looking at a model – we learn more from building the model and from manipulating it. Just as one needs to use or observe the use of a hammer in order to really understand its function, similarly, models have to be used before they will give up their secrets. In this sense, they have the quality of a technology – the power of the model only becomes apparent in the context of its use. Models function not just as a means of intervention, but also as a means of representation. It is when we manipulate the model that these combined features enable us to learn how and why our interventions work.

Our goal then is to flesh out these categories by showing how the different essays in the volume can teach us something about each of the categories. Although we want to argue for some general claims about models – their autonomy and role as mediating instruments, we do not see ourselves as providing a 'theory' of models. The latter would provide well-defined criteria for identifying something as a model and differentiating models from theories. In some cases the distinction between models and theories is relatively straightforward; theories consist of general principles that govern the behaviour of large groups of phenomena; models are usually more circumscribed and very often several models will be required to apply these general principles to a number of different cases. But, before one can even begin to identify criteria for determining what comprises a model we need much more information about their place in practice. The framework we have provided will, we hope, help to yield that information.

2.1 CONSTRUCTION

2.1.1 Independence in construction

When we look for accounts of how to construct models in scientific texts we find very little on offer. There appear to be no general rules for model construction in the way that we can find detailed guidance on principles of experimental design or on methods of measurement. Some might argue that it is because modelling is a tacit skill, and has to be learnt not taught. Model building surely does involve a large amount of craft skill, but then so does designing experiments and any other part of scientific practice. This omission in scientific texts may also point to the creative element involved in model building, it is, some argue, not only a craft but also an art, and thus not susceptible to rules. We find a similar lack of advice available in philosophy of science texts. We are given definitions of models, but remarkably few accounts of how they are constructed. Two accounts which do pay attention to construction, and to which we refer in this part of our discussion, are the account of models as analogies by Mary Hesse (1966) and the simulacrum account of models by Nancy Cartwright (1983).

Given the lack of generally agreed upon rules for model building, let us begin with the accounts that emerge from this volume of essays. We have an explicit account of model construction by Marcel Boumans who argues that models are built by a process of choosing and integrating a set of items which are considered relevant for a particular task. In order to build a mathematical model of the business cycle, the economists that he studied typically began by bringing together some bits of theories, some bits of empirical evidence, a mathematical formalism and a metaphor which guided the way the model was conceived and put together. These disparate elements were integrated into a formal (mathematically expressed) system taken to provide the key relationships between a number of variables. The integration required not only the translation of the disparate elements into something of the same form (bits of mathematics), but also that they be fitted together in such a way that they could provide a solution equation which represents the path of the business cycle.

Boumans' account appears to be consistent with Cartwright's simulacrum account, although in her description, models involve a rather more straightforward marriage of theory and phenomena. She suggests that models are made by fitting together prepared descriptions from the empirical domain with a mathematical representation coming from the theory (Cartwright 1983). In Boumans' description of the messy, but probably normal, scientific work of model building, we find not only the presence of elements other than theory and phenomena, but also the more significant claim that theory does not even determine the model form. Hence, in his cases, the method of model construction is carried out in a way which is to a large extent independent of theory. A similar situation arises in Mauricio Suárez's discussion of the London brothers' model of superconductivity. They were able to construct an equation for the superconducting current that accounted for an effect that could not be accommodated in the existing theory. Most importantly, the London equation was not derived from electromagnetic theory, nor was it arrived at by simply adjusting parameters in the theory governing superconductors. Instead, the new equation emerged as a result of a completely new conceptualisation of superconductivity that was supplied by the model. So, not only was the model constructed without the aid of theory, but it became the impetus for a new theoretical understanding of the phenomena.

The lesson we want to draw from these accounts is that models, by virtue of their construction, embody an element of independence from both theory and data (or phenomena): it is because they are made up from a *mixture* of elements, including those from outside the original domain of investigation, that they maintain this partially independent status.

But such partial independence arises even in models which largely depend on and are derived from bits of theories – those with almost no empirical elements built in. In Stephan Hartmann's example of the MIT-Bag Model of quark confinement, the choice of bits which went into the model is motivated in part by a story of how quarks can exist in nature. The story begins from the empirical end: that free quarks were not observed experimentally. This led physicists to hypothesise that quarks were confined – but how, for confinement does not follow from (cannot be derived from) anything in the theory of quantum chromodynamics that supposedly governs the behaviour of quarks. Instead, various models, such as the MIT-Bag Model, were proposed to account for confinement. When we look at the way these models are constructed, it appears that the stories not only help to legitimise the model after its construction, but also play a role in both selecting and putting together the bits of physical theories involved. Modelling confinement in terms of the bag required modelling what happened inside the bag, outside the bag and, eventually, on the surface of the bag itself.

At first sight, the pendulum model used for measuring the gravitational force, described in Margaret Morrison's account, also seems to have been entirely derived from theory without other elements involved. It differs importantly from Hartmann's case because there is a very close relationship between one specific theory and the model. But there is also a strong empirical element. We want to use the pendulum to measure gravitational force and in that sense the process starts not with a theory, but with a real pendulum. But, we also need a highly detailed theoretical account of how it works in all its physical respects. Newtonian mechanics provides all the necessary pieces for describing the pendulum's motion but the laws of the theory cannot be applied directly to the object. The laws describe various kinds of motion in idealised circumstances, but we still need something separate that allows us to apply these laws to concrete objects. The model of the pendulum plays this role; it provides a more or less idealised context where theory is applied.[1] From an initially idealised model we can then build in the appropriate corrections so that the model becomes an increasingly realistic representation of the real pendulum.

It is equally the case that models which look at first sight to be constructed purely from data often involve several other elements. Adrienne van den Bogaard makes a compelling case for regarding the business barometer as a model, and it is easy to see that such a 'barometer' could not be constructed without imposing a particular structure onto the raw data. Cycles are not just there to be seen, even if the data are mapped into a simple graph with no other adjustments to them. Just as the bag story told MIT physicists what bits were needed and how to fit them together, so a particular conception of economic life (that it consists of certain overlapping, but different time-length, cycles of activity) was required to isolate, capture and then combine the cyclical elements necessary for the barometer model. The business barometer had to be constructed out of concepts and data, just as a real barometer requires some theories to interpret its operations, some hardware, and calibration from past measuring devices.

We claim that these examples are not the exception but the rule. In other words, as Marcel Boumans suggests, models are typically constructed by fitting together a set of bits which come from disparate sources. The examples of modelling we mentioned involve elements of theories and empirical evidence, as well as stories and objects which could form the basis for modelling decisions. Even in cases where it initially seemed that the models were derived purely from theory or were simply data models, it became clear that there were other elements involved in the models' construction. It is the presence of these other elements in their construction that establish scientific models as separate from, and partially independent of, both theory and data.

But even without the process of integrating disparate elements, models typically still display a degree of independence. For example, in cases where models supposedly remain true to their theories (and/or to the world) we often see a violation of basic theoretical assumptions.

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[1] Although the model pendulum is an example of a notional object, there are many cases where real objects have functioned as models. Everyone is familiar with the object models of atoms, balls connected with rods, which are widely used in chemistry, appearing both in the school room and in the hands of Nobel prize winners. Most people are also familiar with the early object models of the planetary system. Such object models have played an important role in scientific research from an early time, and were particularly important to nineteenth-century physicists as we shall see later.

Geert Reuten's account of Marx's Schema of Reproduction, found in volume II of *Capital*, shows how various modelling decisions created a structure which was partly independent of the general requirements laid down in Marx's verbal theories. On the one hand, Marx had to deliberately set aside key elements of his theory (the crisis, or cycle, element) in order to fix the model to demonstrate the transition process from one stable growth path to another. On the other hand, it seems that Marx became a prisoner to certain mathematical conditions implied by his early cases which he then carried through in constructing later versions of the model. Even Margaret Morrison's example of the pendulum model, one which is supposed to be derived entirely from theory and to accurately represent the real pendulum, turns out to rely on a series of modelling decisions which simplify both the mathematics and the physics of the pendulum.

In other words, theory does not provide us with an algorithm from which the model is constructed and by which all modelling decisions are determined. As a matter of practice, modelling always involves certain simplifications and approximations which have to be decided independently of the theoretical requirements[2] or of data conditions.

Another way of characterising the construction of models is through the use of analogies. For example, in the work of Mary Hesse (1966), we find a creative role for neutral analogical features in the construction of models. We can easily reinterpret her account by viewing the neutral features as the means by which something independent and separate is introduced into the model, something which was not derived from our existing knowledge or theoretical structure. This account too needs extending, for in practice it is not only the neutral features, but also the negative features which come in from outside. Mary Morgan (1997a, and this volume) provides two examples from the work of Irving Fisher in which these negative analogical features play a role in the construction of models. In one of the cases, she describes the use of the mechanical balance as an analogical model for the equation of exchange between money and goods in the economy. The balance provides not only neutral features, but also negative features, which are incorporated into the economic model, providing it with independent elements which certainly do not appear in the original equation of exchange. Her second example, a model of how

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[2] For a discussion of when modelling decisions are independent of theory, see M. Suárez's paper in this volume.

economic laws interact with the institutional arrangements for money in the economy, involves a set of 'vessels' supposed to contain the world stores of gold and silver bullion. These vessels constitute negative analogical features, being neither part of the monetary theories of the time nor the available knowledge in the economic world. Both models depend on the addition of these negative analogical features and enabled Fisher to develop theoretical results and explain empirical findings for the monetary system.

2.1.2 Independence and the power to mediate

There is no *logical* reason why models should be constructed to have these qualities of partial independence. But, in practice they are. And, if models are to play an autonomous role allowing them to mediate between our theories and the world, and allowing us to learn about one or the other, they *require* such partial independence. It has been conventional for philosophers of science to characterise scientific methodology in terms of theories and data. Full dependence of a theory on data (and vice versa) is regarded as unhelpful, for how can we legitimately use our data to test our theory if it is not independent? This is the basis of the requirement for independence of observation from theory. In practice however, theory ladenness of observation is allowed provided that the observations are at least neutral with respect to the theory under test.

We can easily extend this argument about theories and data to apply to models: we can only expect to use models to learn about our theories or our world if there is at least partial independence of the model from both. But models must also connect in some way with the theory or the data from the world otherwise we can say nothing about those domains. The situation seems not unlike the case of correlations. You learn little from a perfect correlation between two things, for the two sets of data must share the same variations. Similarly, you learn little from a correlation of zero, for the two data sets share nothing in common. But any correlation between these two end-values tell you both the degree of association and provides the starting point for learning more.

The crucial feature of partial independence is that models are *not* situated in the middle of an hierarchical structure between theory and the world. Because models typically include other elements, and model building proceeds in part independently of theory and data, we construe models as being outside the theory–world axis. It is this feature which enables them to mediate effectively between the two.

Before we can understand how it is that models help us to learn new things via this mediating role, we need to understand how it is that models function autonomously and more about how they are connected with theories and the world.

2.2 FUNCTION

Because model construction proceeds in part independently of theory and data, models can have a life of their own and occupy a unique place in the production of scientific knowledge. Part of what it means to situate models in this way involves giving an account of what they do – how it is that they can function autonomously and what advantages that autonomy provides in investigating both theories and the world. One of our principle claims is that the autonomy of models allows us to characterise them as instruments. And, just as there are many different kinds of instruments, models can function as instruments in a variety of ways.

2.2.1 Models in theory construction and exploration

One of the most obvious uses of models is to aid in theory construction.[3] Just as we use tools as instruments to build things, we use models as instruments to build theory. This point is nicely illustrated in Ursula Klein's discussion of how chemical formulas, functioning as models or paper tools, altered theory construction in organic chemistry. She shows how in 1835 Dumas used his formula equation to introduce the notion of substitution, something he would later develop into a new theory about the unitary structure of organic compounds. This notion of substitution is an example of the construction of a chemical conception that was constrained by formulas and formula equations. Acting as

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[3] This of course raises the sometimes problematic issue of distinguishing between a model and a theory; at what point does the model become subsumed by, or attain the status of, a theory. The rough and ready distinction followed by scientists is usually to reserve the word model for an account of a process that is less certain or incomplete in important respects. Then as the model is able to account for more phenomena and has survived extensive testing it evolves into a theory. A good example is the 'standard model' in elementary particle physics. It accounts for particle interactions and provides extremely accurate predictions for phenomena governed by the weak, strong and electromagnetic forces. Many physicists think of the standard model as a theory; even though it has several free parameters its remarkable success has alleviated doubts about its fundamental assumptions.

models, these chemical formulas were not only the referents of the new conception but also the tools for producing it. Through these models the conception of a substitution linked, for the first time, the theory of proportion to the notions of compound and reaction. We see then how the formulas (models) served as the basis for developing the concept of a substitution which in turn enabled nineteenth-century chemists to provide a theoretical representation for empirical knowledge of organic transformations.

What we want to draw attention to however is a much wider characterisation of the function of models in relation to theory. Models are often used as instruments for exploring or experimenting on a theory that is already in place. There are several ways in which this can occur; for instance, we can use a model to correct a theory. Sir George Francis FitzGerald, a nineteenth-century British physicist, built mechanical models of the aether out of pulleys and rubber bands and used these models to correct Maxwell's electromagnetic theory. The models were thought to represent particular mechanical processes that must occur in the aether in order for a field theoretic account of electrodynamics to be possible. When processes in the model were not found in the theory, the latter was used as the basis of correction for the former.

A slightly different use is found in Geert Reuten's analysis of how Marx used his model to explore certain characteristics of his theory of the capitalist economy. In particular, Marx's modelling enabled him to see which requirements for balanced growth in the economy had to hold and which (such as price changes) could be safely neglected. Marx then developed a sequence of such models to investigate the characteristics required for successful transition from simple reproduction (no growth) to expanded reproduction (growth). In doing so he revealed the now well-known 'knife-edge' feature of the growth path inherent in such models.

But we also need models as instruments for exploring processes for which our theories do not give good accounts. Stephan Hartmann's discussion of the MIT-Bag Model shows how the model provided an explanation of how quark confinement might be physically realised. Confinement seemed to be a necessary hypothesis given experimental results yet theory was unable to explain how it was possible.

In other cases, models are used to explore the implications of theories in concrete situations. This is one way to understand the role of the twentieth-century conception of 'rational economic man'. This idealised and highly simplified characterisation of real economic behaviour has been widely used in economists' microeconomic theories as a tool to explore the theoretical implications of the most single-minded economising behaviour (see Morgan 1997b). More recently this 'model man' has been used as a device for benchmarking the results from experimental economics. This led to an explosion of theories accounting for the divergence between the observed behaviour of real people in experimental situations and that predicted from the theory of such a model man in the same situation.

Yet another way of using models as instruments focuses not on exploring how theories work in specific contexts but rather on applying theories that are otherwise inapplicable. Nancy Cartwright's contribution to the volume provides an extended discussion of how interpretative models are used in the application of abstract concepts like force functions and the quantum Hamiltonian. She shows how the successful use of theory depends on being able to apply these abstract notions not to just any situation but only to those that can be made to fit the model. This fit is *carried out* via the bridge principles of the theory, they tell us what concrete form abstract concepts can take; but these concepts can only be applied when their interpretative models fit. It is in this sense that the models are crucial for applying theory – they limit the domain of abstract concepts. Her discussion of superconductivity illustrates the cooperative effort among models, fundamental theory, empirical knowledge and an element of guesswork.

In other cases, we can find a model functioning directly as an instrument for experiment. Such usage was prominent in nineteenth-century physics and chemistry. The mechanical aether models of Lord Kelvin and FitzGerald that we mentioned above were seen as replacements for actual experiments on the aether. The models provided a mechanical structure that embodied certain kinds of mechanical properties, connections and processes that were supposedly necessary for the propagation of electromagnetic waves. The successful manipulation of the models was seen as equivalent to experimental evidence for the existence of these properties in the aether. That is, manipulating the model was tantamount to manipulating the aether and, in that sense, the model functioned as both the instrument and object of experimentation.

Similarly, Ursula Klein shows us how chemical formulas were applied to represent and structure experiments – experiments that were paradigmatic in the emerging sub-discipline of organic chemistry. Using the formulas, Dumas could calculate how much chlorine was needed for the production of chloral and how much hydrochloric acid was simultaneously produced. Due to these calculational powers, the formulas became surrogates for the concrete measurement of substances involved in chemical transformations. They functioned as models capable of singling out pathways of reactions in new situations. Because the formulas could link symbols with numbers it was possible to balance the ingredients and products of a chemical transformation – a crucial feature of their role as instruments for experiments.

2.2.2 Models and measurement

An important, but overlooked function of models is the various but specific ways in which they relate to measurement.[4] Not only are models instruments that can both structure and display measuring practices but the models themselves can function directly as measuring instruments. What is involved in structuring or displaying a measurement and how does the model function as an instrument to perform such a task? Mary Morgan's analysis of Irving Fisher's work on models illustrates just how this works. The mechanical balance, as used by merchants for weighing and measuring exchange values of goods, provided Fisher with an illustration of the equation of exchange for the whole economy. What is interesting about Fisher's model is that he did not actually use the balance model directly as a measuring instrument, but he did use it as an instrument to display measurements that he had made and calibrated. He then used this calibrated display to draw inferences about the relative changes that had taken place in the trade and money supply in the American economy over the previous eighteen years. In a more subtle way, he also used the model of the mechanical balance to help him conceptualise certain thorny measurement problems in index number theory.

An example where it is considerably more difficult to disentangle the measurement functions from model development is the case of national income accounts and macroeconometric models discussed by Adrienne van den Bogaard. She shows how intimately the two were connected. The model was constructed from theories which involved a certain aggregate conception of the economy. This required the reconception of economic measurements away from business-cycle data and toward national income measures, thereby providing the

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[4] We do not include here examples of using models as calculation devices – these are discussed in section 2.3.2, when we consider simulations.

model with its empirical base. At the same time, the particular kinds of measurements which were taken imposed certain constraints on the way the model was built and used: for example, the accounting nature of national income data requires certain identities to hold in the model. Models could fulfil their primary measurement task – measuring the main *relationships* in the economy from the measurements on the *individual variables* – only because the model and the measurements had already been structured into a mutually compatible form.

As we mentioned above, models themselves can also function directly as measuring instruments. A good example of this is the Leontief input–output model. Based on the Marxian reproduction model (discussed by Reuten), the Leontief model can be used to measure the technical coefficients of conversion from inputs to outputs in the economy. This Leontief matrix provides a measurement device to get at the empirical structure of the economy, and can be applied either at a very fine-grained or a very coarse-grained level, depending on the number of sectors represented within the model. Another good example is provided in Margaret Morrison's discussion of the pendulum referred to above. It is possible using a plane pendulum to measure local gravitational acceleration to four significant figures of accuracy. This is done by beginning with an idealised pendulum model and adding corrections for the different forces acting on various parts of the real pendulum. Once all the corrections have been added, the pendulum model has become a reasonably good approximation to the real system. And, although the sophistication of the apparatus (the pendulum itself) is what determines the *precision* of the measurement, it is the analysis and addition of all the correction factors necessary for the model that determines the *accuracy* of the measurement of the gravitational acceleration. What this means is that the model functions as the source for the numerical calculation of G; hence, although we use the real pendulum to perform the measurement, that process is only possible given the corrections performed on the model. In that sense the model functions as the instrument that in turn enables us to use the pendulum to measure G.

Models can also serve as measuring instruments in cases where the model has less structure than either the pendulum or the input–output cases. One example is the use of multivariate structural time-series models in statistical economics. These are the direct descendants of the business barometer models discussed above and share their general assumption that certain economic time series consist of trends and cycles, but they do not specify the time length of these components in advance. When these models are run on a computer, they generate relatively precise measurements of whatever trend and cyclical components are present in the data and provide an analysis of the interrelationships between them.

2.2.3 Models for design and intervention

The final classification of models as instruments includes those that are used for design and the production of various technologies. The interesting feature of these kinds of models is that they are by no means limited to the sorts of scale models that we usually associate with design. That is, the power of the model as a design instrument comes not from the fact that it is a replica (in certain respects) of the object to be built; instead the capacity of mathematical/theoretical models to function as design instruments stems from the fact that they provide the kind of information that allows us to intervene in the world.

A paradigm case of this is the use of various kinds of optics models in areas that range from lens design to building lasers. Models from geometrical optics that involve no assumptions about the physical nature of light are used to calculate the path of a ray so that a lens can be produced that is free from aberration. A number of different kinds of geometrical models are available depending on the types of rays, image distance and focal lengths that need to be considered. However, technology that relies on light wave propagation requires models from physical optics and when we move to shorter wave lengths, where photon energies are large compared with the sensitivity of the equipment, we need to use models from quantum optics. For example, the design of lasers sometimes depends on quantum models and sometimes on a combination of quantum and classical. The interesting point is that theory plays a somewhat passive role; it is the model that serves as an independent guideline for dealing with different kinds of technological problems (see Morrison 1998).

A similar situation occurs in nuclear physics. Here there are several different models of nuclear structure, each of which describes the nucleus in a way different from and incompatible with the others. The liquid drop model is useful in the production of nuclear fission while the optical model serves as the basis for high energy scattering experiments. Although we know that each individual model fails to incorporate significant features of the nucleus, for example, the liquid drop ignores quantum statistics and treats the nucleus classically while others ignore different quantum mechanical properties, they nevertheless are able to map onto technologies in a way that makes them successful, independent sources of knowledge.

In economics, we can point to the way that central banks use economic models to provide a technology of intervention to control money and price movements in the economy. There is no one model that governs all situations – each bank develops a model appropriate for its own economy. This modelling activity usually involves tracking the growth in various economic entities and monitoring various relationships between them. More recently monetary condition indicators (MCIs) have been developed; these indicators are derived from models and function as measurement tools. With the help of their model(s) and MCIs, the central bank decides when and how much to intervene in the money market in order to prevent inflation. The model provides the technology of intervention by prompting the timing, and perhaps indicating the amount of intervention needed. Sometimes the model-based intervention is triggered almost automatically, sometimes a large amount of judgement is involved. (Of course some central banks are more successful than others at using this technology!) The more complex case of macroeconometric modelling and its use as a technology of intervention is discussed below (in section 2.4 on learning).

As we stressed above, part of the reason models can function as instruments is their partial independence from both theory and data. Yet, as we have seen in this section, models fulfil a wide range of functions in building, exploring and applying theories; in various measurement activities; and in the design and production of technologies for intervention in the world. These examples demonstrate the variety of ways in which models mediate between theories and the world by utilising their points of intersection with both domains. Indeed, these intersections are especially evident in cases like the optical models and nuclear models in physics and the monetary and macroeconomic models in economics. Although they draw on particular aspects of high level theory, they are by no means wholly dependent on theory for either their formulation or decisions to use a particular model in a specific context.

We want to caution, however, that our view of models as instruments is not one that entails a classical instrumentalist interpretation of models. To advocate instrumentalism would be to undermine the various ways in which models do teach us about both theories and the world by providing concrete information about real physical and economic systems. They can do this because, in addition to playing the role of instruments, they fulfil a representative function, the nature of which is sometimes not obvious from the structure of the model itself.

2.3 REPRESENTATION

The first question we need to ask is how an instrument can represent. We can think of a thermometer representing in a way that includes not simply the measurement of temperature but the representation of the rise and fall in temperature through the rise and fall of the mercury in the column. Although the thermometer is not a model, the model as an instrument can also incorporate a representational capacity. Again, this arises because of the model's relation to theory or through its relation to the world or to both.

2.3.1 Representing the world, representing theory

Above we saw the importance of maintaining a partial independence of the model from both theory and the world; but, just as partial independence is required to achieve a level of autonomy so too a *relation* to at least one domain is necessary for the model to have any representative function whatsoever. In some cases the model may, in the first instance, bear its closest or strongest relation to theory. For example, in Morrison's case the model of a pendulum functions specifically as a model of a theory – Newtonian mechanics – that describes a certain kind of motion. In other words, the pendulum model is an instance of harmonic motion. Recall that we need the model because Newton's force laws alone do not give us an adequate description of how a physical pendulum (an object in the world) behaves. The pendulum model represents certain kinds of motion that are both described by the theory and produced by the real pendulum. To that extent, it is also a model of the physical object. Fisher's mechanical balance model (discussed by Morgan) provided a representation of the theory of the monetary system. This model enabled him to explore theoretical aspects of the dynamic adjustment processes in the monetary economy and the phenomena of the business cycle in a way that the existing theoretical representation (the equation of exchange) did not allow.

Alternatively, the model-world representation may be the more prominent one. The early statistical business barometers, constructed to represent (in graphic form) the path of real-world economic activity through time, were used to help determine the empirical relationships between various elements in the economy and to forecast the turning points in that particular economy's cycle. In contrasting cases, such model-world representations may be used to explore theory by extending its basic structure or developing a new theoretical framework. Such was the case with the nineteenth-century mechanical aether models of Kelvin and FitzGerald discussed above. Recall that their function was to represent dynamical relations that occurred in the aether, and based on the workings of the model FitzGerald was able to make corrections to Maxwell's field equations. In the previous section we saw how manipulating these models had the status of experiment. This was possible only because the model itself was taken as a *representation* of the aether.

The more interesting examples are where the practice of model building provides representations of both theory and the world, enabling us to see the tremendous power that models can have as representative instruments. Margaret Morrison's discussion of Prandtl's hydrodynamic model of the boundary layer is a case in point. At the end of the nineteenth century the theory of fluid flow was in marked conflict with experiment; no account could be given of why the very small frictional forces present in the flow of water and air around a body created a no-slip condition at the solid boundary. What Prandtl did was build a small water tunnel that could replicate fluid flows past different kinds of bodies. In a manner similar to a wind tunnel, this mechanical model supplied a *representation* of different kinds of flows in different regions of the fluid, thereby allowing one to understand the nature of the conflict with experiment. That is, the water tunnel furnished a visualisation of different areas in the fluid, those close to the body and those more remote. The understanding of the various flow patterns produced by the tunnel then provided the elements necessary to construct a mathematical model that could represent certain kinds of theoretical structures applicable to the fluid.

But, the idea that a model can represent a theoretical structure is one that needs clarification. In the hydrodynamics case the two theories used to describe fluids, the classical theory and the Navier-Stokes equations were inapplicable to real fluid flow. The former could not account for frictional forces and the latter was mathematically intractable. The mathematical model, developed on the basis of the phenomena observed in the water tunnel, allowed Prandtl to apply theory in a specific way. The tunnel enabled him to see that, in certain areas of fluid flow, frictional forces were not important, thereby allowing the use of classical hydrodynamics. And, in areas where frictional forces were present the mathematical model provided a number of approximations to the Navier-Stokes equations that could apply in the boundary layer. The fluid flow was divided conceptually into two regions, one of which treated the fluid as ideal while the other required taking account of the boundary layer close to a solid body. The mathematical model of a fluid with a boundary layer functioned as a representation of both classical theory and the Navier-Stokes equations because each played a role in describing the fluid, yet neither was capable of such description taken on its own. In that sense the model was a representation of certain aspects of theoretical structure in addition to representing the actual phenomena involved in fluid flow past a solid body. In the first instance, however, the model-world representation was established by the water tunnel and it was this that formed the foundation for the model-theory representation as exemplified by the mathematical account of fluid flow.

Another case where the model bears a relation to both theory and the world is Fisher's hydraulic model of the monetary system discussed by Mary Morgan. The representative power of the model stems from both domains, with the structure of the model (its elements, their shapes and their relationships) coming from theory while the model could be manipulated to demonstrate certain empirical phenomena in the world. Because the model represented both certain well-accepted theories (e.g. the quantity theory of money) and could be shown to represent certain well-known empirical phenomena (e.g. Gresham's law that 'bad money drives out good'), the model could be used to explore both the contested theory and problematic phenomena of bimetallism.

As we can see from the examples above, the idea of representation used here is not the traditional one common in the philosophy of science; in other words, we have not used the notion of 'representing' to apply only to cases where there exists a kind of mirroring of a phenomenon, system or theory by a model.[5] Instead, a representation is seen as a kind of rendering – a partial representation that either abstracts from, or translates into another form, the real nature of the system or theory, or one that is capable of embodying only a portion of a system.

Morrison's example of the pendulum is about as close to the notion of 'mirroring' that we get. The more corrections that are added to the pendulum model the closer it approximates the real object and gives us accurate measurements. Many, perhaps most cases, are not like this. Even cases where we begin with data (rather than theory) do not produce reflecting models. For example, the business barometers of van den Bogaard's

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[5] See R. I. G. Hughes (1997) for a discussion of the notion of representation.

chapter are thought to reflect rather closely the time path of the economy. But they are by no means simple mirrors. Such a model involves both the abstraction of certain elements from a large body of data provided by the economy and their transformation and recombination to make a simple time-series graphic representation which forms the barometer.

Often, models are partial renderings and in such cases, we cannot always add corrections to a stable structure to increase the accuracy of the representation. For example, models of the nucleus are able to represent only a small part of its behaviour and sometimes represent nuclear structure in ways that we know are not accurate (e.g. by ignoring certain quantum mechanical properties). In this case, the addition of parameters results in a new model that presents a radically different account of the nucleus and its behaviour. Hence in describing nuclear processes, we are left with a number of models that are inconsistent with each other.

There are many ways that models can 'represent' economic or physical systems with different levels of abstraction appropriate in different contexts. In some cases abstract representations simply cannot be improved upon; but this in no way detracts from their value. When we want to understand nuclear fission we use the liquid drop model which gives us an account that is satisfactory for mapping the model's predictions onto a technological/experimental context. Yet we know this model cannot be an accurate representation of nuclear structure. Similarly we often use many different kinds of models to represent a single system. For example, we find a range of models being used for different purposes within the analytical/research departments at central banks. They are all designed to help understand and control the monetary and financial systems, but they range from theoretical small-scale micro-models representing individual behaviour, to empirical models which track financial markets, to large-scale macroeconometric models representing the whole economy. Sometimes they are used in conjunction, other times they are used separately. We do not assess each model based on its ability to accurately mirror the system, rather the legitimacy of each different representation is a function of the model's performance in specific contexts.

2.3.2 Simulation and representation

There is another and increasingly popular sense in which a model can provide representations, that is through the process of simulation. Sometimes simulations are used to investigate systems that are otherwise inaccessible (e.g. astrophysical phenomena) or to explore extensions and limitations to a model itself. A simulation, by definition, involves a similarity relation yet, as in the case of a model's predictions mapping onto the world, we may be able to simulate the behaviour of phenomena without necessarily knowing that the simulated behaviour was produced in the same way as it occurred in nature. Although simulation and modelling are closely associated it is important to isolate what it is about a model that enables it to 'represent' by producing simulations. This function is, at least in the first instance, due to certain structural features of the model, features that explain and constrain behaviour produced in simulations. In the same way that general theoretical principles can constrain the ways in which models are constructed, so too the structure of the model constrains the kinds of behaviour that can be simulated.

R. I. G. Hughes' discussion of the Ising model provides a wealth of information about just how important simulation is, as well as some interesting details about how it works. He deals with both computer simulations of the behaviour of the Ising model and with simulations of another type of theoretical model, the cellular automaton. The Ising model is especially intriguing because despite its very simple structure (an array of points in a geometrical space) it can be used to gain insight into a diverse group of physical systems especially those that exhibit critical point behaviour, as in the case of a transition from a liquid to a vapour. If one can generate pictures from the computer simulation of the model's behaviour (as in the case of the two-dimensional Ising model) it allows many features of critical behaviour to be instantly apprehended. As Hughes notes however, pictorial display is not a prerequisite for simulation but it helps.

His other example of simulation involves cellular automata models. These consist of a regular lattice of spatial cells, each of which is in one of a finite number of states. A specification of the state of each cell at a particular time gives the configuration of the cellular automata (CA) at that time. It is this discreteness that makes them especially suited to computer simulations because they can provide exactly computable models. Because there are structural similarities between the Ising model and the CA it should be possible to use the CA to simulate the behaviour of the Ising model. His discussion of why this strategy fails suggests some interesting points about how the structural constraints on these simple models are intimately connected to the ways in which simulations can provide knowledge of models and physical systems. Hughes' distinction between computer simulation of the model's behaviour and the use of computers for calculational purposes further illustrates the importance of regarding the model as an active agent in the production of scientific knowledge.

The early theoretical business-cycle models of Frisch (discussed by Boumans) were simulated to see to what extent they could replicate generic empirical cycles in the economy (rather than specific historical facts). This was in part taken as a test of the adequacy of the model, but the simulations also threw up other generic cycles which had empirical credibility, and provided a prediction of a new cycle which had not yet been observed in the data. In a different example, the first macroeconometric model, built by Tinbergen to represent the Dutch economy (discussed by van den Bogaard and more fully in Morgan 1990), was first estimated using empirical data, and then simulated to analyse the effects of six different possible interventions in the economy. The aim was to see how best to get the Dutch economy out of the Great Depression and the simulations enabled Tinbergen to compare the concrete effects of the different proposals within the world represented in the model. On this basis, he advocated that the Dutch withdraw from the gold standard system, a policy later adopted by the Dutch government.

Consequently we can say that simulations allow you to map the model predictions onto empirical level facts in a direct way. Not only are the simulations a way to apply models but they function as a kind of bridge principle from an abstract model with stylised facts to a technological context with concrete facts. In that sense we can see how models are capable of representing physical or economic systems at two distinct levels, one that includes the higher level structure that the model itself embodies in an abstract and idealised way and the other, the level of concrete detail through the kinds of simulations that the models enable us to produce. Hence, instead of being at odds with each other, the instrumental and representative functions of models are in fact complementary. The model represents systems via simulations, simulations that are possible because of the model's ability to function as the initial instrument of their production.

Because of the various representative and investigative roles that models play, it is possible to learn a great deal from them, not only about the model itself but about theory, the world and how to connect the two. In what follows we discuss some ways that this learning takes place.

2.4 LEARNING

2.4.1 Learning from construction

Modelling allows for the possibility of learning at two points in the process. The first is in constructing the model. As we have pointed out, there are no rules for model building and so the very activity of construction creates an opportunity to learn: what will fit together and how? Perhaps this is why modelling is considered in many circles an art or craft; it does not necessarily involve the most sophisticated mathematics or require extensive knowledge of every aspect of the system. It does seem to require acquired skills in choosing the parts and fitting them together, but it is wise to acknowledge that some people are good model builders, just as some people are good experimentalists.

Learning from construction is clearly involved in the hydrodynamics case described by Margaret Morrison. In this case, there was visual experimental evidence about the behaviour of fluids. There were also theoretical elements, particularly a set of intractable equations supposed to govern the behaviour of fluids, which could neither account for nor be applied directly to, the observed behaviour. Constructing a mathematical model of the observed behaviour involved a twofold process of conceptualising both evidence and the available theories into compatible terms. One involved interpreting the evidence into a form that could be modelled involved the 'conceptualisation' of the fluid into two areas. The other required developing a different set of simplifications and approximations to provide an adequate theoretical/mathematical model. It is this process of interpreting, conceptualising and integrating that goes on in model development which involves learning about the problem at hand. This case illustrates just how modelling enables you to learn things both about the world (the behaviour of fluids) and the theory (about the way the equations could be brought to apply).

A similar process of learning by construction is evident in the cases that Marcel Boumans and Stephan Hartmann describe. In Boumans' example of constructing the first generation of business-cycle models, economists had to learn by trial and error (and by pinching bits from other modelling attempts) how the bits of the business-cycle theory and evidence could be integrated together into a model. These were essentially theoretical models, models designed to construct adequate business-cycle theories. Thereafter, economists no longer had to learn how to construct such theoretical models. They inherited the basic recipe for the business-cycle, and could add their own particular variations. At a certain point, a new recipe was developed, and a new generation of models resulted. In Hartmann's examples, various alternative models were constructed to account for a particular phenomenon. But in the MIT-Bag Model and the NJL model, both of which he discusses in detail, we see that there is a certain process by which the model is gradually built up, new pieces added, and the model tweaked in response to perceived problems and omissions.

2.4.2 Models as technologies for investigation

The second stage where learning takes place is in using the model. Models can fulfil many functions as we have seen; but they generally perform these functions not by being built, but by being used. Models are not passive instruments, they must be put to work, used, or manipulated. So, we focus here on a second, more public, aspect of learning from models, and one which might be considered more generic. Because there are many more people who use models than who construct them we need some sense of how 'learning from using' takes place.

Models may be physical objects, mathematical structures, diagrams, computer programmes or whatever, but they all act as a form of instrument for investigating the world, our theories, or even other models. They combine three particular characteristics which enable us to talk of models as a technology, the features of which have been outlined in previous sections of this essay. To briefly recap: first, model construction involves a partial independence from theories and the world but also a partial dependence on them both. Secondly, models can function autonomously in a variety of ways to explore theories and the world. Thirdly, models represent either aspects of our theories, or aspects of our world, or more typically aspects of both at once. When we use or manipulate a model, its power as a technology becomes apparent: we make use of these characteristics of partial independence, functional autonomy and representation to learn something from the manipulation. To see how this works let us again consider again some of the examples we discussed already as well as some new ones.

We showed earlier (in section 2.2) how models function as a technology that allows us to explore, build and apply theories, to structure and make measurements, and to make things work in the world. It is in the process of using these technologies to interrogate the world or our theory that learning takes place. Again, the pendulum case is a classic example. The model represents, in its details, both the theory and a real world pendulum (yet is partially independent of both), and it functions as an autonomous instrument which allows us to make the correct calculations for measurements to find out a particular piece of information about the world.

The general way of characterising and understanding this second way of 'learning from using' a model is that models are manipulated to teach us things about themselves. When we build a model, we create a kind of representative structure. But, when we manipulate the model, or calculate things within the model, we learn, in the first instance, about the model world – the situation depicted by the model.

One well-known case where experimenting with a model enables us to derive or understand certain results is the 'balls in an urn' model in statistics. This provides a model of certain types of situations thought to exist in the world and for which statisticians have well-worked out theories. The model can be used as a sampling device that provides experimental data for calculations, and can be used as a device to conceptualise and demonstrate certain probability set ups. It is so widely used in statistics, that the model mostly exists now only as a written description for thought experiments. (We know so well how to learn from this model that we do not now even need the model itself: we imagine it!) In this case, our manipulations teach us about the world in the model – the behaviour of balls in an urn under certain probability laws.

The Ising model, discussed by Hughes, is another example of the importance of the learning that takes place within the world of the model. If we leave aside simulations and focus only on the information provided by the model itself, we can see that the model had tremendous theoretical significance for understanding critical point phenomena, regardless of whether elements in the model denote elements of any actual physical system. At first this seems an odd situation. But, what Hughes wants to claim is that a model may in fact provide a good explanation of the behaviour of the system without it being able to faithfully represent that system. The model functions as an epistemic resource; we must first understand what we can demonstrate in the model before we can ask questions about real systems. A physical process supplies the dynamic of the model, a dynamic that can be used to generate conclusions about the model's behaviour. The model functions as a 'representative' rather than a 'representation' of a physical system. Consequently, learning about and from the model's own internal structure provides the starting point for understanding actual, possible and physically impossible worlds.

Oftentimes the things we learn from manipulating the world in the model can be transferred to the theory or to the world which the model represents. Perhaps the most common example in economics of learning about theory from manipulation within a model, is the case of Edgeworth-Bowley boxes: simple diagrammatic models of exchange between two people. Generations of economics students have learnt exchange theory by manipulations within the box. This is done by tracing through the points of trade which follow from altering the starting points or the particular shape of the lines drawn according to certain assumptions about individual behaviour. But these models have also been used over the last century as an important technology for deriving new theoretical results not only in their original field of simple exchange, but also in the more complex cases of international economics. The original user, Edgeworth, derived his theoretical results by a series of diagrammatic experiments using the box. Since then, many problems have found solutions from manipulations inside Edgeworth-Bowley box diagrams, and the results learnt from these models are taken without question into the theoretical realm (see Humphrey 1996). The model shares those features of the technology that we have already noted: the box provides a representation of a simple world, the model is neither theory nor the world, but functions autonomously to provide new (and teach old) theoretical results via experiments within the box.

In a similar manner, the models of the equation of exchange described by Mary Morgan were used to demonstrate *formally* the nature of the theoretical relationship implied in the quantity theory of money: namely how the cause–effect relationship between money and prices was embedded in the equation of exchange, and that two other factors needed to remain constant for the quantity theory relation to be observable in the world. This was done by manipulating the models to show the effects of changes in each of the variables involved, constrained as they were by the equation. The manipulation of the alternative mechanical balance version of the model prompted the theoretical developments responsible for integrating the monetary theory of the economic cycle into the same structure as the quantity theory of money. It was because this analogical mechanical balance model represented the equation of exchange, but shared only part of the same structure with the theoretical equation of exchange, that it could function autonomously and be used to explore and build new theory.

The second model built by Fisher, the hydraulic model of the monetary system incorporated both institutional and economic features. It was manipulated to show how a variety of real world results might arise from the interaction of economic laws and government decisions and to ‘prove’ two contested theoretical results about bimetallism within the world of the model. But, these results remained contested: for although the model provided a qualitative 'explanation' of certain historically observed phenomena, it could not provide the kind of quantitative representation which would enable theoretically-based prediction or (despite Fisher's attempts) active intervention in the monetary system of the time.

These manipulations of the model contrast with those discussed by Adrienne van den Bogaard. She reports on the considerable arguments about the correct use of the models she discusses in her essay. Both the barometer and the econometric model could be manipulated to predict future values of the data, but was it legitimate to do so? Once the model had been built, it became routine to do so. This is part of the econometrics tradition: as noted above, Tinbergen had manipulated the first macroeconometric model ever built to calculate the effects of six different policy options and so see how best to intervene to get the Dutch economy out of the Great Depression of the 1930s. He had also run the model to forecast the future values for the economy assuming no change in policy. These econometric models explicitly (by design) are taken to represent both macroeconomic theory and the world: they are constructed that way (as we saw earlier). But their main purpose is not to explore theory, but to explore past and future conditions of the world and perhaps to change it. This is done by manipulating the model to predict and to simulate the outcomes which would result if the government were to intervene in particular ways, or if particular outside events were to happen. By manipulating the model in such ways, we can learn things about the economy the model represents.

2.5 CONCLUSION

We have argued in this opening essay that scientific models have certain features which enable us to treat them as a technology. They provide us with a tool for investigation, giving the user the potential to learn about the world or about theories or both. Because of their characteristics of autonomy and representational power, and their ability to effect a relation between scientific theories and the world, they can act as a powerful agent in the learning process. That is to say, models are both a means to and a source of knowledge. This accounts both for their broad applicability, and the extensive use of models in modern science.

Our account shows the range of functions and variety of ways in which models can be brought to bear in problem-solving situations. Indeed, our goal is to stress the significance of this point especially in light of the rather limited ways that models have, up to now, been characterised in the philosophical literature. They have been portrayed narrowly as a means for applying theory, and their construction was most often described either in terms of 'theory simplification' or derivation from an existing theoretical structure. These earlier views gave not only a limited, but in many cases an inaccurate, account of the role of models in scientific investigation. Our view of models as mediating instruments, together with the specific cases and detailed analyses given in these essays, go some way toward correcting the problem and filling a lacuna in the existing literature.

A virtue of our account is that it shows how and why models function as a separate tool amongst the arsenal of available scientific methods. The implication of our investigations is that models should no longer be treated as subordinate to theory and data in the production of knowledge. Models join with measuring instruments, experiments, theories and data as one of the essential ingredients in the practice of science. No longer should they be seen just as 'preliminary theories' in physics, nor as a sign of the impossibility of making economics a 'proper' science.

NOTE

Two earlier users of the term 'mediators' in accounts of science should be mentioned. Norton Wise has used the term in various different contexts in the history of science, and with slightly different connotations, the most relevant being his 1993 paper 'Mediations: Enlightenment Balancing Acts, or the Technologies of Rationalism'. His term 'technologies' is a broad notion which might easily include our 'models'; and they mediate by playing a connecting role to join theory/ideology with reality in constructing a rationalist culture in Enlightenment France. Our focus here is on using models as instruments of investigation about the two domains they connect. The second user is Adam Morton (1993) who discusses mediating models. On his account the models are mathematical and mediate between a governing theory and the phenomena produced by the model; that is, the mathematical descriptions generated by the modelling assumptions. Although our account of mediation would typically include such cases it is meant to encompass much more, both in terms of the kinds of models at issue and the ways in which the models themselves function as mediators.

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