CHAPTER FIFTEEN

Three-Dimensional Models in Philosophical Perspective

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The essays in this book on three-dimensional models in wax, wood, wire, plaster, and plastic challenge the approaches that philosophers have taken towards scientific knowledge. Model-based approaches to science have become a popular way around philosophical difficulties with a purely linguistic account of the theories and explanations that codify knowledge. On the model-based view, words are means of comparing models—abstract or concrete, symbolic or physical—with worldly phenomena, but knowledge is produced in the contact between models and world. Connections between representations and the concrete world cannot themselves be exclusively abstract if science is to yield empirical knowledge. Yet, while the approach is open in principle to a wide variety of models, philosophers of science have tended to cleave to familiar shores—mainly mathematical models and 2-D visual representations—with only occasional nods to 3-D physical models. Study of 3-D models may thus provide a fresh philosophical purchase on the relations between representations and knowledge.

A history of the philosophy of scientific representations since the 1940s would reveal movement towards higher dimensionality: from 1-D linguistic or symbolic expressions in the work of most logical empiricists, towards 2-D, non-linguistic, pictorial, diagrammatic, and graphical displays post-Kuhn. Instead of reconstructing theories, the new work aims to interpret a variety of representational practices in parallel with increased attention in cognitive psychology to mental maps and 'visual thinking', and in sociology to scientific practice.

Consideration of 2-D representations served well to criticise the logical empiricist philosophy of scientific theories, but replacing linguistic analysis with a semantic view of theories helped only a little in understanding the history and variety of representational practices in the sciences. The movement showed how non-linguistic tools such as set theory could be useful, yet switching formal tools was only one step; wood, wire, plaster, and wax remain to be accommodated.

The studies of 3-D models in this book cast doubt on the utility of critiques from two-dimensionality for illuminating representations in more dimensions. Rather, the philosophy of scientific representations needs rethinking, perhaps from a (4-D?) perspective on science as a process, or from cognitive theories that distinguish among representational contents, targets, and attitudes (Cummins 1995). 3-D models have more to contribute than evidence against linguistic accounts of science-as-theory and knowledge-as-fully-inscribable. Their making and uses challenge the possibility of comprehending scientific knowledge through articulation of word–world representation relations alone.

Knowledge has a tacit (Polanyi 1962), gestural (Sibum 1995), even muscular side (Cat 2001), which is as important as word–world relations for understanding science. Scientists have often been clearer about this than philosophers. James Clerk Maxwell, for example, wrote, "There are . . . some minds which can go on contemplating with satisfaction pure quantities presented to the eye by symbols, and to the mind in a form which none but mathematicians can conceive. There are others who feel more enjoyment in following geometrical forms, which they draw on paper, or build in the empty space before them" (Maxwell 1890, 220, quoted in Cat 2001, 407).

Since *models*—not just words—must be made and compared to produce knowledge (Teller, 2001; Giere 1988; 1997), knowing how models are made and deployed is as important to the philosophy of scientific representation as knowing that models are linguistically connected with phenomena by hypotheses in specified respects and degrees. Moreover, knowledge acquired through performance (Sibum 1995, 28) can by its nature be put into words only imperfectly and even then requires conventional notations that themselves can be understood only in terms of their associated performances (Goodman 1976). Often in science, for reasons of commerce, priority, protocol, or tact, it has proved undesirable to express the connections in words anyway.

If ideas cannot be comprehended without a history of the gestural knowledge and the objects through which they came to be expressed, and to which the terms of their expression most directly refer, then history of scientific ideas is a poor history indeed. A philosophy of representation that takes account only of texts is similarly inauspicious. But how is one to understand scientific practice if our tools for understanding are built solely out of logics of representation? The problem remains even if logic could be extended beyond words and mathematical symbols to handle pictures and diagrams. These essays show that there is a world of models and representations beyond descriptions and inscriptions. If philosophy of science is to contribute seriously to multi-disciplinary investigation of scientific representations, it must consider gestural as well as symbolic knowledge and the variety of means and modes of making, experiencing, and using models.

Evelyn Fox Keller characterises models as tools *for* various kinds of scientific activities, such as material intervention or concept and theory development, in addition to their role in representing objects (or phenomena) already in existence—models *of* things (Keller 2000; see also Sismondo 1999). Malcolm Baker, in his chapter on models in eighteenth-century England, draws a similar distinction between models *for* the construction of objects such as vehicles, and models of—taking *after*—objects already constructed. Models do more than simply 'stand for' something else.

The histories in this book show how 3-D models can be both models *of*—objects that stand for others that are worthy of inclusion in epistemologies of science—and models *for*—objects that facilitate various scientific activities. Although recent philosophical literature on models as mediators of word–world or theory–phenomenon relationships has usefully complicated naïve correspondence views of scientific knowledge (van Fraassen 1980; Cartwright 1983; Lloyd 1988; Giere 1988; 1997; Morrison and Morgan 1999), it has not really come to grips with the dual origins of philosophical talk about models, arising on the one hand from philosophies of language, truth, and logic (particularly model theory), and on the other from scientists' shop talk and use of models as guides for action (Wimsatt 1987).

One move took theories of theories away from formal, syntactic analysis towards semantics and pragmatics, opening up for philosophers terrain explored in parallel ways by sociologists who rejected functionalism. The syntactic view focused on theory structure and logic of explanation at the cost of attention to meanings, modes, and purposes of representation. The new emphasis on models brought to the fore problems with formalist accounts, but without seriously questioning the representational and other aims of modelling.

The second move rode a Kuhnian wave of historical contextualisation of scientific knowledge, raising history to the status of constraint on philosophising: science ought to be accurately described rather than whiggishly normed. Model-based views of mediation between words and world seemed closer to ways scientists talked and worked than did the 'received view' of scientific theories (van Fraassen 1980; Wimsatt 1980; Lloyd 1988; Morrison and Morgan 1999).

Philosophers tried to patch up or replace received views of scientific theories and explanation while tending, ironically, to perpetuate the legacy of logical empiricism by expanding the search among representations for analytical routes to word–world relations; on this view models are clearly in the middle. However, a model-based view of science must be incomplete if it offers only a model-based view of scientific theories without a model-based view of scientific practice.

Nelson Goodman's *Languages of Art* outlined a broader philosophy of representations. His nearly forgotten but still useful observations on diagrams, maps, and models appeared as part of a general exploration of a theory of notation applicable to both science and art. He wrote,

> While scientists and philosophers have on the whole taken diagrams for granted, they have been forced to fret at some length about the nature and function of models. Few terms are used in popular and scientific discourse more promiscuously than 'model'. A model is something to be admired or emulated, a pattern, a case in point, a type, a prototype, a specimen, a mock-up, a mathematical description—almost anything from a naked blonde to a quadratic equation—and may bear to what it models almost any relation of symbolization. In many cases, a model is an exemplar or instance of what it models: the model citizen is a fine example of citizenship, the sculptor's model a sample of the human body, the fashion model a wearer, the model house a sample of the developer's offerings, and the model of a set of axioms is a compliant universe. In other cases, the roles are reversed: the model denotes, or has as an instance, what it models: the car of a certain model belongs to a certain class. And a mathematical model is a formula that applies to the process or state or object modelled. What is modelled is the particular case that fits the description (Goodman 1976, 171–72).

Attention to 3-D models should help philosophers confront the full scope of this promiscuity. Models demand as much attention from philosophers as do the phenomena from the scientists who wish to describe, represent, intervene in, manipulate, construct, or control them. The essays in this book begin to give 3-D models the sustained, varied, and nuanced attention that pictures have received (Jones and Galison 1998).

In the remainder of this commentary, I shall address two ways in which taking seriously the implications of the present book might challenge philosophical talk about models, and hence the role of models in philosophies of scientific knowledge: (1) the concept of a model is historical, and (2) we can appreciate the significance of 3-D models only in making and use.

'MODEL' IS A HISTORICAL CONCEPT

Like objectivity (Daston and Galison 1992) and experiment (Hacking 1983), the concept of a model and its representational powers should be historicised. This would challenge the application of univocal, ahistorical standards to models in science and help philosophers who aim to understand science as a process rather than a 'body' of knowledge. Reading the chapters in this book, I detect two major shifts in meaning of the word 'model', the first in the late eighteenth and early nineteenth centuries, and the second in the late twentieth century.

In the eighteenth century, 'model' meant primarily an original, such as an ancient church, that served as a pattern for a modern copy (Baker, this volume). It played dual roles as a representation *of* an antiquity and *for* the construction of a new work. 3-D figures *of* agricultural machines as well as cathedrals paved the way for a shift of emphasis to objects that represent ideas to be realised and therefore serve as representational tools in discussions with patrons, fabricators, users, and eventually wider publics. In the transition between ideas and realisations, models took on a political role also, in establishing rights over works of art and nature (Schaffer). A key innovation may thus have been the fruitful running together of political and scientific notions of one thing 'standing for' another.

In the nineteenth century, 'model' came to mean primarily, not a subject worthy of representation, but the representation itself. Along the way, models variously stood for the scientific work of representation (Evans), the relation of representation in shows of force (Schaffer) and, finally, those bits of reality worth understanding, explaining, or controlling. Meinel's chapter on chemical models shows that, rather than representations of an external reality, up to mid-century chemical moulds were used as tools of construction and aids to thought that drew on formal notations of chemical composition that were emphatically not to be taken as corresponding to reality.

'Model', as the representation itself, replaced neither the ancient meaning (model as subject of imitation) nor the transitional eighteenth-century one (model as tool for presentation of projects). The chapters on nineteenth- and twentieth-century anatomical waxes (Hopwood), moulages (Schnalke), and economic machines (Morgan and Boumans) point to ways in which the new meaning enhanced rather than replaced old conceptions of mediation. In the twentieth century, a 3-D molecular model functioned *both* as a representation of worldly molecules and as a subject worthy of contemplation, a tool of engineering and patronage, and an instrument of pedagogy and entertainment (de Chadarevian). These models not only mediate between words and worlds (Morrison and Morgan 1999) but also between patrons, producers, and publics (Secord, Nyhart). How, though, did mediation among audiences and allies come to depend on the representational functions of models? Many of these essays hint that this was linked to the nineteenth-century emergence of cultures of construction. If so, the philosophical claim that models mediate must be historicised too.

A second shift of meaning has occurred recently as computer simulation began to overtake material 3-D practices. In this shift, '3-D' changed reference from physical, space-filling objects to 2-D visual displays of 3-D information, especially in interactive graphic displays on computer screens (Francoeur and Segal). The use of 3-D language to describe literally 2-D images and the varieties of associated visual and tactile experience raise additional philosophical challenges. Interactive graphic displays fall conceptually between the static 2-D displays of traditional graphics and the dynamic interactivity of 3-D physical models. Interactive computer graphics free users from the contraints of a single, imposed visual perspective by allowing user-controlled rotation and manipulation of images. They couple tactile and visual experience through control of the screen image via user-input devices such as the 'globe' in a 1960s molecular graphics project at MIT (Francoeur and Segal) and the now ubiquitous 'mouse'. Although interactive graphics extended the tradition of physical modelling, they also constituted a new

mode of interaction with numerical data, allowing users to intervene kinaesthetically in the simulation process. This is terra incognita for conventional philosophies of scientific knowledge.

3-D MODELS IN MAKING AND USE

Understanding scientific models of any dimensionality requires study of how they are made and used in addition to analysis of their formal representational properties. We want to know, for example, how 2-D drawings at the laboratory bench guide theory and channel experiment and hypothesis testing (Griesemer 2000a).

A less well-known tradition in philosophy of science has focused on heuristic processes of 1-D and 2-D model-building as a way of classifying and understanding processes and products of this activity (Wimsatt 1980; 1981a; 1981b; 1987; Griesemer 2000b). This approach aims to ensure that represented phenomena are robust to the idealising and falsifying assumptions of models by requiring a variety of models making different idealising assumptions. "[O]ur truth is the intersection of independent lies" (Levins 1966) because, as Nancy Cartwright has argued, to be explanatory, our representations of phenomena must falsify (simplify, idealise), but the truth "doesn't explain much" (Cartwright 1983, 44; see also Wimsatt 1987).

3-D models present challenges even to the heuristic perspective because knowledge depends not only on the robustness of representations to falsifying assumptions but also on the robustness of our workings of models in varying and generally uncontrolled conditions of use. Gestural heuristics that govern swinging hammers, gluing plastics, cutting waxes, and writing software are needed, not only to build 3-D models but also to use them. These have not been targets of heuristic accounts in philosophy of science. No doubt gestural heuristics are required for making and using models of any dimensionality, but the demand for tactility and multiple perspectives in making and using 3-D models pushes this need to prominence.

The importance of 3-D models to a philosophy of gestural heuristics is particularly evident in the work of Morgan and Boumans on the Phillips machine. To understand the Phillips machine as a hydraulic model of the dynamic macroeconomy is to use it, to set the machine into activity, to see and hear the liquid flow around the machine, and to witness its leaks and failures. To describe the machine, Morgan and Boumans had to set it into figurative motion by narrating the flow through the articulated parts of 2-D cartoons and photographs. Merely describing or looking at the machine (or a photograph of it) is hardly heuristic or fruitful at all.

The argument from gestural knowledge is explicit also in the chapters on anatomical models. Mazzolini writes of Felice Fontana's 'artificial anatomy' in wax and wood. Fontana wrote of the artists he employed as instruments of his anatomical work and later in his career of the virtues of wood over wax models: because the former could be disassembled and reassembled, the body of the model could be physically entered. Fontana's contemporary, Condillac, offered a theory of sensation that justified this conception of anatomy as learning by doing: the origin of ideas lies in the coordination of the senses, particularly sight and touch. Hopwood's chapter on embryological waxes appeals to similar forms of knowledge in explaining how anatomists coped with the introduction of serial sectioning in the last third of the nineteenth century. This technique revealed structural details never before seen, but threatened to deprive microscopists of the physical engagement with bodily form that dissection under a magnifying glass had provided. Eventually, research in embryological anatomy produced composites of wax-plate models constructed from sectioned specimens plus books that included pictures of the models. By the end of the century, leading anatomists argued that the models, which could be seen from all sides and even 'dissected' with hot wires, were more important publications than printed works.

But why would scientists find gestural knowledge valuable and how would a philosophy of this kind of knowledge differ from a purely representational one? What does working in wax, or wire, or wood add? One view is that working with models is concrete, so the problem of representation cannot be solved from the side of abstraction alone because it is in the nature of representations to connect the abstract and the concrete (Cat 2001). The tactile, muscular, kinaesthetic experience of working with a model brings experience to mind in more and different ways than the merely visual. In other words, the gestural heuristics for using 3-D models may differ from those for representations in 2-D, and philosophy should take account of these differences.

A philosophy of scientific knowledge that includes an account of gestural heuristics requires comprehension of the variety of scientific experiences of models of different dimensionalities as well as analysis of models of any particular dimensionality. If tacit gestural knowledge brings experiences to mind, the question remains how those experiences can be translated into marks on paper, images, publishable plastic models, or reports by historians of science. Who or what mediates and is mediated in the production of scientific models? Because representation is itself an aim of science, these problems of representation have no philosophical end points. There are no knowledge products that can be fully described and analysed in abstraction from the processes of idealisation and abstraction that produced them. Thus, it would be wrong to take 3-D models out of their historical and social contexts of making and use to attempt philosophical closure. So rather than sum up, I invite the reader to engage with these essays and, indeed, with the models themselves.

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CHAPTER SIXTEEN

Material Models as Visual Culture

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Models have long been an important issue in the history of science, medicine, and technology, thanks particularly to the concern of philosophers and sociologists with models as heuristic devices for scientific thinking. Nevertheless, for historians to problematise models, as this volume does, is to do something original. Despite the long-standing interest in scientific and medical *thinking*, strikingly little attention has been paid to the *physicality* of models as distinct from their role as bearers of concepts. *Models: The Third Dimension of Science* both brings into prominence a distinctive type of cognition in science, medicine, and technology through a focus on material models, and provides a wealth of historical examples to suggest how they worked in practice. As a result it offers fresh insights to those in other fields who are concerned with visual and material culture and whose assumptions about aesthetic values and productive interpretations are likely to be somewhat different.

We might want to consider the extent to which the distinction between conceptual and material models reflects academic practice in the humanities and social sciences. Professional scholars place great, if generally unconscious, emphasis on two-dimensional items. Words, pieces of paper, computer screens, and, to a lesser extent, images are our bread and butter. I would suggest that virtually every person who has received a humanistic education feels more comfortable working in two dimensions than in three. Aspects of some disciplines, archaeology and anthropology for example, proceed differently, but they are exceptions. So working with three dimensions, which is commonplace in most sciences, could be seen as the province of some specialists, while most other academics operate with two.