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How to Do Science with Models

A Philosophical Primer

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"This is a truly excellent book. Not only does it provide insightful analysis of contemporary philosophical accounts of modelling, but it draws our attention to important yet unexplored questions related to the exploratory function of models and their connection to issues in the philosophy of technology. By focusing our attention on a broad range of examples it provides the best systematic treatment of scientific modelling to appear in many years. Highly recommended!" **Margaret Morrison**, *University of Toronto*.

Preface

After volcanic ash from the eruption of the Icelandic volcano Eyjafjallajökull in 2010 had shut down air traffic across the Atlantic Ocean for several days in a row, an angry airline CEO appeared in a television interview with the BBC and blamed civil aviation authorities for basing their decision to close the transatlantic airspace on 'mere models.' While the CEO's frustration may have been understandable from a business point of view, from the viewpoint of science it was a rather disingenuous way of reacting: After all, modern aircraft, too, are designed on the basis of models of flow, turbulence, atmospheric motion, and material behavior, which embody basically the same fundamental theoretical principles, whether one is dealing with the distribution of volcanic ash or its effects on jet engines. Modern science and technology are saturated with models—so much so that it is difficult to imagine what the modern scientific world would look like without the use of models. The ubiquity of models in contemporary science and technology is hardly news to any working scientist or engineer, but the realization that scientific inquiry and technological innovation are inextricably intertwined with scientific models has not yet sunk in with the general public and its representatives. Consider the case of climate change: Even today, it is not uncommon to come across pundits and politicians who dismiss the carefully cross-checked predictions of climate scientists on the grounds that they are 'just based on models'—yet the very same people then happily go on to make policy on the basis of (model-based) forecasts of economic growth. Models, then, are all around us, whether in the natural or social sciences, and any attempt to understand how science works had better account for, and make sense of, this basic fact about scientific practice.

This book is an attempt to come to philosophical terms with the ubiquity and indispensability of models in contemporary science and technology. As such, it is a contribution to a growing body of work by scholars in the history and philosophy of science. Historians and sociologists of science, over the past twenty-odd years or so, have amassed a vast number of case studies that describe and analyze specific scientific models in great detail. At the same time, a lively philosophical debate has developed, which focuses on general questions concerning the nature of models and the possibility of model-based representation. Yet, too often, these two projects—the in-depth study of specific cases of scientific models and the abstract concern for model-based representation—have stood side by side with one another, without entering into a true dialogue. By contrast, one of the guiding methodological assumptions of this book is that descriptive adequacy and normative–theoretical ambition need not be mutually exclusive: As I hope to show, careful attention to scientific modeling as a practice may itself be a source of insight about what gives model-based science its cohesion and makes it successful—and about what its limitations are. At the heart of this approach is the thought that the key to answering any of the more general philosophical questions about scientific models lies in the diversity of their varied uses and functions.

The structure of this book is as follows. The first two chapters provide a concise survey of the existing philosophical debate about scientific models, first from an ontological angle, by tackling the question 'What are Scientific Models?' (Chap. 1), and then by addressing the problem of scientific representation in relation to scientific models and theories (Chap. 2). While the main focus is on systematic questions, both chapters also retrace some of the historical trajectory of the debate, for example by showing how our current notion of 'scientific model' is indebted to the nineteenth-century notion of 'mechanical analogy' (Chap. 1, Sect. 1.2), or how philosophers in the twentieth century—especially in the wake of Nelson Goodman's philosophy of art—have reconsidered the notion of (scientific) representation (Chap. 2, Sect. 2.2). Chapter 3 looks in detail at a number of case studies from across the natural sciences in order to identify recurring strategies of model building. Examples discussed range from population biology (Lotka–Volterra model) to condensed matter physics (BCS and Ginzburg–Landau models of superconductivity); special attention is given to the question of whether modeling necessarily involves trade-offs between different theoretical desiderata (such as generality and precision) and whether the existence of trade-offs can serve as a demarcation criterion between different scientific disciplines, notably biology and physics. The final two chapters advance the philosophical debate in distinct ways, by identifying a number of previously overlooked functions and uses of scientific models. Thus, Chap. 4 discusses exploratory uses of scientific models and seeks to establish exploration as one of the core functions of scientific modeling, alongside the more traditional goals of explanation and prediction. Chapter 5, finally, links the debate about scientific models to questions in the philosophy of technology, in particular the question of how artifacts simultaneously enable and constrain certain actions and how we, as users of such artifacts, engage with them at a phenomenological level. Models, I conclude, are not simply neutral tools that we use at will to represent aspects of the world around us; rather, they contribute new elements—which are neither to be found in the underlying 'fundamental theory' nor to be found in the empirical data—to the process of scientific inquiry and, by mediating between different types of user–model–world relations, enable the generation of new scientific knowledge.

My philosophical interest in scientific models began when, as a physics student studying quantum many-body models, I first realized that the very same models could be used to describe radically different target systems and were sometimes invoked by different researchers in support of incompatible research agendas. Yet, in spite of this diversity of uses and functions of models, there is also a palpable sense in which model-based science is marked by great cohesion and has vastly improved our scientific understanding of the world around us. After a dozen or so years of thinking and writing about scientific models, I am now more convinced than ever that the strength of models as tools of inquiry lies precisely in their diversity and flexibility. While the choice of examples in this book—notably, the prominence given to models from many-body physics—no doubt reflects the early origins of my interest in models, special care has been taken to also include examples from disciplines such as biology, chemistry, and sociodynamics. While all the material in this book has been thoroughly rewritten, several of the chapters draw on previously published (or, in some cases, forthcoming) work. Thus, Chaps. 1 and 2 draw on material from my chapter 'The Ontology of Scientific Models' in the forthcoming *Springer Handbook of Model-Based Science* (eds. Lorenzo Magnani and Tommaso Bertolotti). Chapter 3 (esp. Sects. 3.6 and 3.7) overlaps with my paper 'Strategies of Model-Building in Condensed Matter Physics: Trade-Offs as a Demarcation Criterion Between Physics and Biology?', *Synthese*, Vol. 190, No. 2, 2013, pp. 252–273. Section 5.2 of Chap. 5 is based on my discussion note 'Symbol Systems as Collective Representational Resources: Mary Hesse, Nelson Goodman, and the Problem of Scientific Representation,' *Social Epistemology Review and Reply Collective*, Vol. 4, No. 6, 2015, pp. 52–61, while Sect. 5.3 of the same chapter (along with Chap. 3, Sect. 3.3) is heavily indebted to my chapter 'Between Rigor and Reality: Many-Body Models in Condensed Matter Physics' in Brigitte Falkenburg's and Margaret Morrison's jointly edited volume *Why More is Different: Philosophical Issues in Condensed Matter Physics and Complex Systems*, Heidelberg: Springer 2015, pp. 201–226.

Over the years, I have had the good fortune to encounter many sympathetic and supportive colleagues and scholars from whom I have learnt a great deal about the philosophy of scientific models. While it would be impossible to name all of them and acknowledge every single influence on my thinking about models, I do wish to acknowledge the following individuals, all of whom in one way or another have personally left their mark on the work presented here—whether by sending me written comments, by participating in joint workshops, or by simply making time to discuss my work on models during a coffee break at a conference: Anna Alexandrova, Sorin Bangu, Ann-Sophie Barwich, Robert Batterman, Justin Biddle, Agnes Bolinska, Marcel Boumans, Alex Broadbent, Anjan Chakravartty, Hasok Chang, Chuanfei Chin, Jeremy Chong, Tamás Demeter, Paul Dicken, Steffen Ducheyne, Kevin Elliott, Brigitte Falkenburg, Uljana Feest, Stephan Hartmann, Michael Heidelberger, Mary Hesse, Paul Humphreys, Cyrille Imbert, Stephen John, Jaakko Kuorikoski, Martin Kusch, Sabina Leonelli, Lorenzo Magnani, Simone Mahrenholz, Uskali Mäki, John Matthewson, Cornelis Menke, Boaz Miller, Teru Miyake, Jacob Mok, Mary Morgan, Robert Nola, Alfred Nordmann, Wendy Parker, Chris Pincock, Demetris Portides, Hans-Jörg Rheinberger, Mauricio Suárez, Adam Toon, Marion Vorms, and Jeff White. I am especially grateful to Gabriele

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I have profited enormously from a reading group which convened four times over the course of two weeks in July 2015 and during which an almost complete draft of the book was discussed. I am especially grateful to Grant Fisher, Lina Jansson, Eric Kerr, Joel Chow, Bernadette Chin, and Will Zhang for taking the time to engage closely with my arguments and for offering a host of useful suggestions (along with several important corrections). Thanks are due to the Office of the Deputy President (Research and Technology), Humanities and Social Sciences Division, National University of Singapore, for providing funding for this reading group ('The Epistemology of Technology and Technoscience,' WBS: R-106-000-040-646). Chapter 4 ('Exploratory Uses of Scientific Models') was conceived and written while on sabbatical leave in Berlin during the first half of 2015; early versions of the argument were presented at the philosophy departments of Leibniz Universität Hannover, Technische Universität Darmstadt, and Freie Universität Berlin. I am grateful to audiences on all three occasions for their valuable feedback and to Sybille Krämer for hosting me in her research group during the Berlin portion of my sabbatical. Funding for research assistance and artwork was provided by the Faculty of Arts and Social Sciences, National University of Singapore, in the form of a book grant (WBS: R-106-000-048-133), for which I am grateful. This has allowed me to hire a research assistant, Bernadette Chin, who has done a superb job proofreading and indexing the manuscript, and also to commission illustrations from Jerry Teo with whom it was a pleasure to work. I am grateful to Anatomisches Museum Basel for granting me permission to use an image of one of their wax models and to Nick Hopwood for providing me with a high-quality reproduction of that image.

I hope that this book will prove useful to various audiences. While its main target audience is professional philosophers of science, it should also be accessible enough for classroom use at the graduate and advanced undergraduate levels. Working scientists, too, I hope, will find fresh insights in the following five chapters; while this book will not teach them how to construct models for specific scientific problems, it may alert them to some of the broader desiderata of model building as a scientific practice. So, with a bit of luck, readers may not only learn about how science is done with models, but may also develop an appreciation of why models are essential to good science.

Singapore
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Axel Gelfert

Contents

Chapter 1
Between Theory and Phenomena: What are Scientific Models?

1.1 Introduction

Models can be found across a wide range of scientific contexts and disciplines. Examples include the Bohr model of the atom (still used today in the context of science education), the billiard ball model of gases, the DNA double helix model, scale models in engineering, the Lotka-Volterra model of predator–prey dynamics in population biology, agent-based models in economics, the Mississippi River Basin model (a 200-acre hydraulic model of the waterways in the entire Mississippi River basin!), and general circulation models (GCM) which allow scientists to run simulations of the Earth's climate system. The list could be continued indefinitely, with the number of models across the natural and social sciences growing day by day. Indeed, the deployment of models has not only become central to the scientific enterprise at large, but also to the very image scientists have of themselves. As John von Neumann put it, with some hyperbole: 'The sciences do not try to explain, they hardly even try to interpret, they mainly make models' [1, p. 492]. Whatever shape and form the scientific enterprise might have taken in the absence of models, given their de facto pervasiveness across many disciplines and subdisciplines, it seems safe to say that science without models would not look anything like science as we presently know it.

Philosophical discussions of scientific models likewise distinguish between a bewildering array of different kinds of models. The *Stanford Encyclopedia of Philosophy* gives the following list of model-types that have been discussed by philosophers of science: 'Probing models, phenomenological models, computational models, developmental models, explanatory models, impoverished models, testing models, idealized models, theoretical models, scale models, heuristic models, caricature models, didactic models, fantasy models, toy models, imaginary models, mathematical models, substitute models, iconic models, formal models, analogue models and instrumental models' [2]. As early as 1968, the proliferation of models and model-types, in the sciences as well as in the philosophical literature,

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led Nelson Goodman to lament in his book *Languages of Art:* 'Few terms are used in popular and scientific discourse more promiscuously than "model"' [3, p. 171]. If this was true of science and popular discourse in the late 1960s, it is all the more true of twenty-first century philosophy of science.

As an example of a mathematical model in physics, consider the *Ising model*, proposed in 1925 by the German physicist Ernst Ising as a model of ferromagnetism in certain metals. The model starts from the idea that a macroscopic magnet can be thought of as a collection of elementary magnets, whose orientation determines the overall magnetization. If all the elementary magnets are aligned along the same axis, then the system will be perfectly ordered and will display a maximum value of the magnetization. In the simplest one-dimensional case, such a state can be visualized as a chain of 'elementary magnets', all pointing the same way:

$$\cdots \uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow \cdots$$

The alignment of elementary magnets can be brought about either by a sufficiently strong external magnetic field or it can occur spontaneously, as will happen below a critical temperature, when certain substances (such as iron and nickel) undergo a ferromagnetic phase transition. Whether or not a system will undergo a phase transition, according to thermodynamics, depends on its energy function which, in turn, is determined by the interactions between the component parts of the system. For example, if neighbouring 'elementary magnets' interact in such a way as to favour alignment, there is a good chance that a spontaneous phase transition may occur below a certain temperature. The energy function, then, is crucial to the model and, in the case of the Ising model, is defined as

$$E = -\sum_{i,j} J_{ij} S_i S_j$$

with the variable S_i representing the orientation (+1 or −1) of an elementary magnet at site i in the crystal lattice and J_{ij} representing the strength of interaction between two such elementary magnets at different lattice sites i, j.

Contrast this with *model organisms* in biology, the most famous example of which is the fruit fly *Drosophila melanogaster*. Model organisms are real organisms —actual plants and animals that are alive and reproduce—yet they are used as representations either of another organism (for example when rats are used in place of humans in medical research) or of a biological phenomenon that is more universal (e.g., when fruit flies are used to study the effects of crossover between homologous chromosomes). Model organisms are often bred for specific purposes and are subject to artificial selection pressures, so as to purify and 'standardize' certain features (e.g., genetic defects or variants) that would not normally occur or would occur only occasionally in populations in the wild. As Rachel Ankeny and Sabina Leonelli put it, in their ideal form 'model organisms are thought to be a relatively simplified form of the class of organism of interest' [4, p. 318]; yet it often takes considerable effort to work out the actual relationships between the model organism and its target system (whether it be a certain biological phenomenon or a specific class of target organisms). Tractability and various experimental desiderata—e.g., a short life cycle (to allow for quick breeding) and a relatively small and compact genome (to allow for the quick identification of variants)—take precedence over theoretical questions in the choice of model organisms; unlike for the Ising model, there is no simple mathematical formula that one can rely on to study how one's model behaves, only the messy world of real, living systems.

The Ising model of ferromagnetism and model organisms such as *Drosophila melanogaster* may be at opposite ends of the spectrum of scientific models. Yet the diversity of models that occupy the middle ground between theoretical description and experimental system is no less perplexing. How, one might wonder, can a philosophical account of scientific models aspire to any degree of unity or generality in the light of such variety? One obvious strategy is to begin by drawing distinctions between different overarching types of models. Thus, Max Black [5] distinguishes between four such types: scale models, analogue models, mathematical models, and theoretical models. The basic idea of scale and analogue models is straightforward: a scale model increases or decreases certain (e.g., spatial) features of the target system, so as to render them more manageable in the model; an analogue model also involves a change of medium (as in the Phillips machine, a once-popular hydraulic model of the economy, where the flow of money was represented by the flow of liquids through a system of pumps and valves). Mathematical models are constructed by first identifying a number of relevant variables and then developing empirical hypotheses concerning the relations that may hold between the variables; through (often drastic) simplification, a set of mathematical equations is derived, which may then be evaluated analytically or numerically and tested against novel observations. Theoretical models, finally, begin usually by extrapolating imaginatively from a set of observed facts and regularities, positing new entities and mechanisms, which may be integrated into a possible theoretical account of a phenomenon; comparison with empirical data usually comes only at a later stage, once the model has been formulated in a coherent way. Peter Achinstein [6] includes mathematical models in his definition of 'theoretical model', and proposes an analysis in terms of sets of assumptions about a model's target system. This allows him to include Bohr's model of the atom, the DNA double helix model—considered as a set of structural hypotheses rather than as a physical ball-and-stick model—the Ising model, and the Lotka-Volterra model among the class of theoretical systems.

When a scientist constructs a theoretical model, she may help herself to certain established principles of a more fundamental theory to which she is committed. These may then be adapted or modified, notably by introducing various new assumptions specific to the case at hand. Often, an inner structure or mechanism is posited which is thought to explain features of the target system. The great variety of models that may thus be generated makes vivid just how central the use of models is to the scientific enterprise. At the same time, it might make one wonder whether it is at all reasonable to look for a unitary philosophical account of models.

This has led some commentators to abandon the search for an account of the nature of models and further to the conclusion that, as Bernd Mahr puts it, modeling can only 'be understood if one stops looking for an answer to the question *of the nature of the model* and starts asking instead *what justifies conceiving of something as a model*' [7, p. 305]. In the absence of any widely accepted unified account of models, it may be natural to assume, as indeed many contributors to the debate have done, that 'if all scientific models have something in common, this is not their *nature* but their *function*' [8, p. 194]. Furthermore, 'if we accept that models are functional entities, it should come as no surprise that when we deal with scientific models ontologically, we cannot remain silent on how such models function as carriers of scientific knowledge' [9, p. 120]. Two broad classes of functional characterizations of models can be distinguished, according to which it is either *instantiation* or *representation* that lie at the heart of how models function.

As Ronald Giere [10] sees it, on the *instantial view*, models instantiate the axioms of a theory, where the latter is understood as being composed of linguistic statements, including mathematical statements and equations. By contrast, on the *representational view*, 'language connects not directly with the world, but rather with a model, whose characteristics may be precisely defined'; the model then connects with the world 'by way of similarity between a model and designated parts of the world' [10, p. 56]. Other proponents of the representational view have de-emphasized the role of similarity, while still endorsing representation as one of the key functions of scientific models. Within the class of representational views, one can further distinguish between views that emphasize the *informational* aspects of models and those that take their *pragmatic* aspects to be more central. Anjan Chakravartty nicely characterizes the informational variety of the representational view as follows: 'The idea here is that a scientific representation is something that bears an objective relation to the thing it represents, on the basis of which it contains information regarding that aspect of the world' [11, p. 198]. The term 'objective' here simply means that the requisite relation obtains independently of the model user's beliefs or intentions as well as independently of the specific representational conventions he or she might be employing. By contrast, the *pragmatic* variety of the representational view of models posits that models function as representations of their targets in virtue of the cognitive uses to which human reasoners put them. The basic idea is that a scientific model facilitates certain cognitive activities—such as the drawing of inferences about a target system, the derivation of predictions, or perhaps a deepening of the scientific understanding—on the part of its user and, therefore, necessarily involves the latter's cognitive interests, beliefs, or intentions.

These examples and classifications are necessarily rough sketches, and much of the rest of this book is devoted to giving more depth to our philosophical picture of scientific models. This will involve giving detailed discussions of various cases from across the sciences and exploring their implications for how we should best understand scientific models. The central assumption of this approach is that the key to answering any of the more fundamental questions about scientific models lies in the diversity of their varied uses and functions. While this will require careful attention to the actual uses and applications of scientific models, it would be quite misguided to think that a descriptive approach to scientific modeling could, by itself, tell us what makes something a model, let alone a *good* model. For this, we will need to look beyond the level of case studies and identify possible vantage points from which to judge the success or fruitfulness of a model. A number of philosophical theories have, of course, attempted just that, for example by thinking of models in the same terms as scientific theories. However, one should remain open to the possibility that careful attention to scientific modeling as a practice may itself turn up a 'middle range' of factors which, though strictly speaking not universal, nonetheless help us explain both the success of model-based science and certain recurring patterns of how models are deployed across different disciplines. As I shall argue in later parts of the book, some of the uses and functions of scientific models—e.g., their exploratory role in inquiry—are more akin to certain types of experimentation than to the traditional goals of scientific theories. Furthermore, models often contribute new elements to the theoretical description and empirical investigation of their target systems—elements which are neither part of the fundamental theory nor can be easily 'read off' from the data. Before turning to these questions in more depth, however, it will be instructive to first look more closely at the history of the term 'model' in science, so as to gain a better understanding of what motivates the use of models in scientific inquiry in the first place.

1.2 Models, Analogies, and Metaphor

Given their centrality to contemporary science, it should come as no surprise that scientific models have enjoyed a long and varied history. With our current concepts in hand, it may seem easy to identify past instances of models being employed in science. However, the term 'model' has itself undergone a number of changes throughout the history of science. Indeed, it was not until the nineteenth century that scientists began to engage in systematic self-reflection on the uses and limitations of models. Philosophers of science took even longer to pay attention to models in science, focusing instead on the role and significance of scientific theories. Only from the middle of the twentieth century onwards did models begin to attract significant philosophical interest in their own right. Yet in both science and philosophy, the term 'model' underwent important transformations. In this section, one such transformation—from a narrow focus on mechanical models to our much broader contemporary understanding of the term 'scientific model'—will be traced.

Take, for example, Pierre Duhem's dismissal, in 1914, of what he takes to be the excessive use of models in Maxwell's theory of electromagnetism, as presented in an English textbook published at the end of the nineteenth century:

> Here is a book intended to expound the modern theories of electricity and to expound a new theory. In it there are nothing but strings which move round pulleys which roll around drums, which go through pearl beads, which carry weights; and tubes which pump water

while others swell and contract; toothed wheels which are geared to one another and engage hooks. We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory. [12, p. 7]

What Duhem is mocking in this passage, which is taken from a chapter titled 'Abstract Theories and Mechanical Models', is a style of reasoning that is dominated by the desire to *visualize* physical processes in purely mechanical terms. His hostility is thus directed at *mechanical* models only—as the implied contrast in the chapter title makes clear—and does not extend to the more liberal understanding of the term 'scientific model' in philosophy of science today.

Indeed, when it comes to the use of *analogy* in science, Duhem is much more forgiving. The term 'analogy', which derives from the Greek expression for 'proportion', itself has multiple uses, depending on whether one considers its use as a rhetorical device or as a tool for scientific understanding. Its general form is that of 'pointing to a resemblance between relations in two different domains, i.e. *A* is related to *B* like *C* is related to *D*' [13, p. 110]. An analogy may be considered merely *formal*, when only the relations (but not the relata) resemble one another, or it may be *material*, when the relata from the two domains (i.e., *A* and *B* on one side, *C* and *D* on the other) have certain attributes or characteristics in common. Duhem's understanding of 'analogy' is more specific, in that he conceives of analogy as being a relation between two sets of statements, such as between one theory and another:

Analogies consist in bringing together two abstract systems; either one of them already known serves to help us guess the form of the other not yet known, or both being formulated, they clarify the other. There is nothing here that can astonish the most rigorous logician, but there is nothing either that recalls the procedures dear to ample but shallow minds. [12, p. 97]

Consider the following example: When Christiaan Huygens (1629–1695) proposed his theory of light, he did so on the basis of *analogy* with the theory of sound waves: the relations between the various attributes and characteristics of light are similar to those described by acoustic theory for the rather different domain of sound. Thus understood, analogy becomes a legitimate instrument for learning about one domain on the basis of what we know about another. In modern parlance, we might want to say that sound waves provided Huygens with a good *theoretical model*—at least given what was known at the time—for the behaviour of light.

There is, however, a risk of ambiguity in that last sentence—an ambiguity which, as D.H. Mellor [14, p. 283] has argued, it would be wrong to consider harmless. Saying that 'sound waves provide a good model for the theory of light' appears to equate the model *with the sound waves*—as though one physical object (sound waves) could be identified with the model. At first sight this might seem unproblematic, given that, as far as wave-like behaviour is concerned, we do take light and sound to be relevantly analogous. However, while it is indeed the case that 'some of the constructs called "analogy" in the nineteenth century would today be routinely referred to as "models"' [15, p. 46], it is important to distinguish between, on the one hand, 'analogy' as the similarity relation that exists between a theory and