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 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.

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