Models and Theories

A Philosophical Inquiry

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Introduction

The unknown captivates. Ever since antiquity, humans have devised methods and techniques to uncover what is hidden. In modern science, models and theories play an indispensable role in this endeavour. Many scientific disciplines develop theories that are used both to discover, explore, and control phenomena, and to systematise, organise, and summarise our knowledge about them. Mastering a field often requires understanding its theories. Quantum theory, relativity theory, electromagnetic theory, and evolutionary theory are examples of theories that are central in their respective domains. But theories are not the only means by which scientists push the boundaries of knowledge. Models play prominent roles in many disciplines. The billiard ball model of the gas, the Bohr model of the atom, the Lotka-Volterra model of predator-prey interaction, general circulation models of the atmosphere, and agent-based models of social systems are examples of models that are foundational in their fields.

What are theories? What are models? And how do models and theories relate to each other? These are the core questions that this book is concerned with. They are time-honoured questions. Since the beginning of the last century an impressive body of literature has emerged that is concerned with the nature of models and theories. Unsurprisingly, different schools of thought have given different answers to these questions, and, indeed, interpreted the questions themselves differently. Readers encounter a bewildering array of positions that are often difficult to pin down and map out.

This book aims to offer guidance in this unwieldy territory in three ways. First, it provides an introduction to the problems, issues, and challenges that have shaped the field, as well as an introduction to the philosophical positions that have driven the discussions about models and theories. Second, it presents a guide to the literature, documenting what has been said when and by whom, and locating individual contributions in the wider intellectual context. Third, it takes stock and assesses where the different debates stand. What has been achieved, what has fallen by the wayside, and what can we learn from failed attempts? Occasionally, the first and second aims are in tension with each other. On the one hand, points could be made without extensive referencing, and those who are primarily interested in the arguments themselves may find references distracting. On the other hand, those who are interested in how debates have unfolded, and, indeed, in further reading, may not be satisfied with a decontextualised abstract argument. I have tried to mitigate this conflict by using in-text references only for direct quotations and when I explicitly discuss a particular position. All other references are in the endnotes. These endnotes anchor arguments in debates, and they provide additional readings for those who wish to pursue a matter further.

Throughout the book, I illustrate arguments and positions with examples to add palpability to abstract points. There is a temptation to be original in the choice of examples and use one's own favourites in lieu of cases that have become standard points of reference. Wherever possible I have resisted this temptation and I have stuck with the well-known cases that are discussed in the literature. This is a deliberate choice rather than intellectual lethargy. First, in keeping with the aim of providing a guide to the literature, the book seeks to acquaint the reader with cases that have actually been discussed in the literature rather than with a collection of personal favourites. Second, standard cases serve as touchstones. Accounts and arguments need to make sense of, and be tested against, accepted paradigm cases. A discussion based on previously unseen (and possibly idiosyncratic) examples would rightly arouse suspicions of cherry-picking or shifting goal posts. Third, the more intriguing the examples, the more likely they are to divert attention away from the main problems and issues. Keeping cases within the boundaries of the expected is therefore also a means to focus attention on the conceptual issues. Once a point is clear, readers can replace the book's examples with their own.

In particular, in the first two parts of the book, the examples are largely taken from physics. This choice is primarily owed to the fact that the views discussed in these parts have been schooled and developed with examples from physics. This said, I admit to having done little to resist this concentration on physics, which aligns with own interests and, more importantly, competences. Had a philosopher of biology or economics written this book, they might have made different choices. The choices should, however, not present an obstacle to reading the book. The knowledge of physics required to understand the philosophical points rarely, if ever, goes beyond high school curriculum, and those who spent their formative years studying Homer's epics rather than Newton's axioms will be able to glean enough physics to follow the examples by spending a little time on a relevant Wikipedia page.

Goodman famously noted that "[f]ew terms are used in popular and scientific discourse more promiscuously than 'model'", and that "almost anything from a naked blonde to a quadratic equation" may be regarded as a model (1976, 171). Goodman is spot on. It is therefore worth briefly reviewing some of the meanings of "model" and setting aside those that are irrelevant in the current context. The word "model" derives from the Latin "modulus", which means "measure" or "standard". It reappears in the 16th century in Italian as "modello" and in English as "model", where it designates architectural plans or drawings representing the proportions of a building, or, more generally, a likeness that is made to scale. The notion of a model as a true-to-scale replica is still a possible usage of the term in modern-day science, although, as we shall see, it is by no means the only one. The same cannot be said about the many other usages of the term. We expressly exclude the following as intended uses of "model" in this book. First, occasionally "model" is used as a synonym for "theory", for instance when physicists call their best theory of elementary particles "the standard model", or when the Bohr model of the atom is also referred to as the "Bohr theory of the atom". It makes little sense to ask, as we do in this book, how models and theories relate to one another unless models and theories are considered to be different, and so we set aside a use of the term "model" that takes models to be theories. Second, phrases like "it's just a model" indicate either that scientists take a cautious attitude towards a certain proposition which they regard as speculative or provisional, or that something is known to be false and entertained only for heuristic purposes. To what extent a product of scientific thought is supported by fact is an important question. Indeed, this question is so important that it has its own subfield within the philosophy of science, namely confirmation theory. Our question is prior to the question of confirmation theory. We ask: what is the thing about which one can later ask whether, and if so to what degree, it is confirmed by evidence? For this reason, we do not use "model" as a qualifier of evidential support.

Other uses of "model" are so obviously out of line with the topic of this book that there should be no danger of confusion. "Model" can be used as a synonym for "notion" or "conception", for instance when we speak of the "the ancient model of the atom" or "the enlightenment model of free speech". A model can be something that serves as a template for the production of something else, for instance when we say that medieval guilds provided the model for the first universities in the 11th and 12th centuries. A model can also be a method or recipe for achieving something, for instance when we say that contractarianism is the justificatory model in social systems governed by social rules. The department's "model student" is an example to be emulated. Ford's *Model T* and the latest model of the *MacBook Air* are particular products. Little Jimmy's model railway is a toy. And then there are models who do not wake up for less than ten thousand dollars a day. Regimenting language is neither possible nor desirable, but it ought to be clear that "model" is not used in any of these meanings in this book.

"Theory" descends from the ancient Greek term *theōría*, which is closely related to *theōrós* (spectator). So *theōría* literally means something like *the spectator's view* or *watching* or *observing*. It has subsequently been used to mean *consideration* and *speculation*. In the 16th century "theory" came to refer to the conceptual basis of a subject area of study and the principles of a field. This is a workable first indication of the meaning of "theory" in the context of contemporary science, and we will develop this conception further in this book. However, like "model", "theory" has also acquired a number of divergent and, at least in the current context, unhelpful meanings, which we have to set aside. In a reversal of the tentative character supposedly expressed by "model", a theory is sometimes seen as something with a secure foundation, or as a true description of reality.[1] Usage, however, is not uniform and "theory" can also have the exact opposite meaning. Before making an MRI scan, doctors have a theory that a tumour is benign, but they will be able to confirm this only once they have the results; you can have a theory that your neighbour does not pay his taxes; and scientist urge caution by exclaiming "oh, well, that's just a theory!". Whichever way one wants to use "theory", as previously noted, degrees of confirmation are not our concern here and so we set these uses of "theory" aside.

Sometimes "theory" is contrasted with "practice". Something is said to be a "theory" if it belongs to the realm of unsullied contemplation and if it is antithetical to action. When confronted with an impractical suggestion an engineer might dismiss it as something that "works only in theory"; branding a claim as "correct in theory" is tantamount to saying that it is unworkable; and halfway through the exam period a student may become resigned to the view that there is now "only a theoretical possibility" of still getting a first class honours degree. While not infrequent in idiomatic expressions, the use of "theory" as a euphemism for the unachievable is irrelevant to our discussion. And, as an afterthought, we might add that it is often also unjustified – the history of many technical innovations (just think of radio transmission and GPS) testifies to the fact that there is nothing more practical than a good theory!

Now that we have identified the relevant senses of "model" and "theory", we are in a position to ask what models and theories are and how they operate. Our discussion of these questions begins with the movement of logical empiricism which gained prominence in the 1920s.[2] There is a degree of arbitrariness to every cut-off, and my own is no exception. One

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[1] This conception of "theory" can also be found in the philosophical literature. See, for instance, Achinstein's (1968, 215), Hesse's (1967, 355-6), Redhead's (1980, 147), and Wimsatt's (1987, 23).

[2] There is a question concerning labels. I here follow Creath (2017) in using "logical empiricism" as an umbrella term covering the entire movement, including the Vienna Circle. Sometimes the label "logical positivism" is used to refer to the philosophy of Vienna Circle, and distinguished from the "logical empiricism" of the Berlin Society for Scientific Philosophy (Salmon 2000, 233). Other times the line between the two is drawn along continental boundaries: "logical positivism" is taken to denote what happened in Europe before World War II and "logical empiricism" is taken to refer what became of that movement in North America after the war. However, as Creath (2017, Sec. 1) notes, fundamentally the term "logical empiricism" has no precise boundaries, and there is little to distinguish it from "logical positivism".

could have begun the discussion with Poincaré, Duhem and Mach, or with the great "philosophical physicists" or the late 19th century, Boltzmann, Hertz, Kelvin, and Maxwell. Or maybe with Mill and Hume, or … There is something to be said for each of these potential choices. However, while undoubtedly these authors made important contributions, the focus on theories and models as we know it from current debates only crystallised in the work of the logic empiricists. It is only through their work that "models and theories" became a recognisable subfield of the philosophy of science. This motivates my choice in taking logical empiricism as the starting point of the discussion.

The arrangement of the material in the book is broadly chronological, beginning with logical empiricism and ending with topics that have emerged only relatively recently. This could give the impression that this is a historical book. It is not. The focus of the discussion is systematic: it is concerned with the tenability of arguments and the cogency of accounts, rather than with historical figures and their intellectual trajectories. The broadly historical arrangement of the material is a ploy to make the arguments easier to follow because certain positions become intelligible only when contrasted with their predecessors and when discussed against certain backgrounds. The qualification "broadly" is essential. Throughout the book I make a conscious effort to emphasise how historical positions bear on contemporary problems. It is indeed one of the theses of this book that positions that have long been assigned to the dust bin of history turn out to be surprisingly relevant to contemporary concerns when given a fresh reading. Readers will be confronted with current problems and concerns from the outset, and they will not have to fight their way through long chapters dealing with material that is only of historical interest to finally get "back to the future" at the end of the book.

The book is divided into four parts, and every part has four chapters. I will now introduce the content and objectives of the four parts, and then give an overview of the individual chapters.

Part I is concerned with what I call the *Linguistic View of Theories* (the *Linguistic View*, for short), broadly the view that a scientific theory is a description of its subject matter in a formal language. The Linguistic View is better known as the "syntactic view of theories", but, as we will see, this is a misnomer and I prefer the descriptively more accurate label "Linguistic View of Theories". The view is closely associated with logical empiricism and is widely believed to have departed for good when logical empiricism perished in the 1960s. So some readers may wonder: why begin a book on models and theories with a discussion of a philosophical position that is long gone?

The answer is that reports of the death of the Linguistic View have been premature. Engaging in an extensive discussion of the Linguistic View is not an act of philosophical necrophilia; it is an expression of the conviction that there is much of contemporary interest to be learned from it. Specifically, it is one of the contentions of this book that the divide between linguistic and non-linguistic conceptions of theories is a false dichotomy, and that the anti-linguistic turn that happened in the philosophy of science around 1960 was a mistake.[3] Theories have both linguistic and non-linguistic elements, and the challenge for an analysis of theories is to show how they work together and how they can be integrated into a consistent whole. A reflection on the Linguistic View is a starting point for this project.

[3] Or, if one follows Rorty (1967) in seeing the *linguistic turn* as one of the major developments in early 20th century philosophy, then one might describe the events around 1960 as the anti-linguistic U-turn.

Readers who remain unconvinced that topics and positions associated with the Linguistic View have much life left in them should find these chapters useful for another reason. Love it or hate it, the modern discussion about the nature of models and theories has its origins in logical empiricism, and the positions and doctrines of the logical empiricists still provide the backdrop against which many debates unfold. Familiarity with these positions and doctrines is therefore a *sine qua non* for everybody who wishes to partake in contemporary discussions. Those who remain unconvinced of the systematic value of the Linguistic View may read these chapters as providing the necessary background for what is to follow.

The demise of the Linguistic View marks a branching point in the discussion. Those who shared the logical empiricists' emphasis on formal analysis but thought that this analysis had to proceed along different lines gathered under the umbrella of the *Model-Theoretical View of Theories* (*Model-Theoretical View*, for short), broadly the view that a scientific theory is a family of models. The proponents of this view usually self-identify as contributing to the "semantic view of theories", but, for reasons that will become clear later, "semantic view of theories" is no less misleading than "syntactic view of theories" and is therefore a label that is best avoided. We discuss the Model-Theoretical View in Part II.

Those who not only disagreed with how the logical empiricists put formal methods to use but also regarded the emphasis on formal methods as unhelpful to begin with took a different route. While sharing the Model-Theoretical View's emphasis on models, they intended to avoid the view's reliance on formal methods and aimed to develop a philosophical account of models through an analysis of scientific practice. We discuss this approach in Part IV. Philosophers working in that paradigm never formed a cohesive school of thought, and there is no umbrella notion under which they all could be subsumed. This is not accidental. Writers working in this tradition were committed to developing their views in close proximity to scientific practice and were generally wary of overarching programmes and rational reconstructions. A certain degree of disunity is the inevitable consequence of this philosophical outlook. Writing about a movement that is by its very nature dispersive is difficult, and so there is a temptation to group the ungroupable. Occasionally this is done by subsuming philosophers working in this intellectual tradition under the umbrella of the "models as mediators programme". This is not entirely fortunate. "Models as mediators" was the name of a particular research project on models carried out at LSE in the 1990s, as well as the title of an influential book that came out of the project. While the project is squarely within this intellectual tradition, the tradition itself goes back to the 1950s and has a longer and more diverse history than the "models as mediators" project. If one had to coin a label, then *Models in Scientific Practice Programme* would probably be a fitting option, and the models as mediators project would be a particular project falling under that label.

The discussions of the Model-Theoretical View of Theories in Part II and the Models in Scientific Practice Programme in Part IV are connected by a discussion of scientific representation, which is the focus of Part III. The reason for placing a discussion of scientific representation in-between the discussions of the two main approaches to models is that the question of how models represent their target systems has already become a focal point in various places in Part II, and important points of contention between the Model-Theoretical View of Theories and the Models in Scientific Practice Programme turn on how the relation between models and their targets is construed. So Part III both brings a discussion that started in Part II to a conclusion and lays the groundwork for the discussion of the Models in Scientific Practice Programme in Part IV. Beyond this strategic role, Part III deals with an important topic in its own right: how models relate to the parts or aspects of the world that they are about. This problem has a universal and a specific aspect. The universal aspect concerns a discussion of scientific representation in general, and we will discuss a number of different accounts of scientific representation. The specific aspect concerns particular model-world relations that play an important role in applications: analogy, idealisation, abstraction and approximation. Understanding these relations is crucial, and a large portion of Part III is dedicated to analysing them.

Now that we are clear on the content of, and the relations between, the four parts, let us have a look at the core arguments of the individual chapters.[4] The four chapters of Part I discuss different aspects of the Linguistic View. In Chapter 1 we articulate the Linguistic View and defend it against a number of criticisms which, if successful, would immediately undermine the view. We glean the basic tenets of the Linguistic View by looking at how Newton developed his mechanics in his *Philosophiae Naturalis Principia Mathematica*, and we then work our way toward a general formulation of the view, which has become known as the Received View of Theories. We then discuss four objections against the view: that it is committed to kind of logic that is too weak to capture any serious mathematics; that it regards theories as purely syntactical items; that it is committed to absurd identity criteria for theories; and that it fails to illuminate how theories operate in scientific practice. We will see that these objections miss their target. It is therefore justified to take the Linguistic View seriously and see how its various aspects can be developed.

In Chapter 2 we discuss what role models play in the Received View. We begin by distinguishing between two different types of models: representational models and logical models. The former are representations of a target system; the latter are items that make a formal sentence true if the sentence is interpreted as describing the model. The Received View employs the latter notion and sees models as alternative interpretations of a theory's formalism. This notion of a model provides the entry ticket to formal semantics, which plays an important role both in the discussion of the Received View and in the development of the Model-Theoretical View. We discuss the notion of a set-theoretical structure on which this semantics is based, along with the notion of two structures being isomorphic. This leads to a discussion of the expressive power of first-order logic, which also involves a discussion of two famous results in formal logic, the Löwenheim-Skolem theorem and Gödel's first incompleteness theorem. Insights gained in this discussion will also be important when assessing the Model-Theoretical View in Chapter 5.

After this discussion of the formal aspects of a theory, we turn to the relation between theory and observation. In Chapter 3 we see that understanding this relation led logical empiricists to bifurcate a theory's vocabulary into observation terms and theoretical terms. The former are terms like "red" that refer to observables, while the latter are terms like "electron" that (purportedly) refer to unobservables. This bifurcation faces three important objections: that the *epistemic* distinction between observables and unobservables fails to translate into a *linguistic* distinction between different terms; that there is no clear line between what is observable and what is unobservable; and that observation is always theory-laden. These are serious objections, and the most promising way to circumvent them is to bifurcate a theory's vocabulary differently, namely between antecedently understood and new terms. Observations are often made and recorded in the form of data, and the raw data gathered in

[4] What follows is not a complete synopsis of each chapter. I focus on the main line of argument of each chapter with the aim of making visible how the chapters hang together.

experiments are processed to form data models. We study how observations are distilled into data models, and we get clear on what this process involves.

As we have seen, the Received View relies on a bifurcation of a theory's vocabulary into observation terms and theoretical terms. While it seems, at least prima facie, clear what the meaning of observation terms is, the same cannot be said of theoretical terms. In Chapter 4 we address the question of how theoretical terms acquire meaning. We begin our discussion with verificationism, and then go through the important empiricist responses to the problem: explicit definitions, implicit definitions, reduction sentences, interpretative systems, meaning from models, elimination either through Craig's theorem or the Ramsey sentence, the Carnap sentence, Hilbert's ε-operator, and definite descriptions. We then turn to the alternative realist programme, which regards theoretical terms as being on par with observation terms: both refer to things in the world. We end the chapter with a discussion of the causal-historical theory of reference, which explains how exactly terms can do this.

As we have seen previously, the Linguistic View was followed by the Model-Theoretical View of Theories, which is the focus of the chapters in Part II. Chapter 5 begins with a detailed discussion of Suppes' structuralist version of the Model-Theoretical View, which regards a theory as a family models and models are taken to be set-theoretical structures. This helps structuring the discussion in this part of the book because other formulation of the view build on Suppes' account in various ways. One of the core issues in the Model-Theoretical View is the role of language. The view construes theories as non-linguistic entities, and by banning language from theories it aims to excise the issues we encountered in Chapters 2 to 4. The question of when two theories are identical provides a touchstone for this view, and through a discussion of this issue we will reach the conclusion that language is an important part of a theory that cannot be omitted. The challenge for a tenable account of theories is therefore to integrate linguistic and non-linguistic elements in a cogent way. In the last section of the chapter I sketch an account that tries to do this, which I call the "dual view" of theories.

In Chapter 6 we raise the question of how an account that regards a theory as a family of models, understood as set-theoretical structures, analyses the relation of a theory to its intended subject matter. This is the problem of scientific representation: how do the models of a theory represent their target systems? We start our discussion of this question with a reflection on the problem itself because on closer inspection it becomes clear that there is no such thing as "the" problem of scientific representation. We distinguish between five different questions that an account of representation must answer, and we formulated five conditions of adequacy that a successful answer to these questions must meet. This provides the lens through which we analyse the two accounts of representation that are implicit in the structuralist version of the Model-Theoretical View: the Data Matching Account and the Morphism Account. The former says that models must have substructures that are isomorphic to data models of the kind we encountered in Chapter 3; the latter says that target systems themselves have structures and models are isomorphic to them. We conclude that neither provides a satisfactory account of representation: the Data Matching Account conflates evidential support with representation, and the Morphism Account only provides incomplete answers to the problems of representation. So the issue of representation is left unresolved in the structuralist version of the Model-Theoretical View.

In Chapter 7 we look at the internal organisation of a theory. The basic posit of the Model-Theoretical View is that a theory is a family of models. But not any collection of models is theory, and so far little has been said about what binds this family together. What are the "family ties" between the models of a theory? The most detailed answer to this question has been given in a research programme known as *Munich Structuralism*. This programme offers a comprehensive answer to the question of what binds the models of a theory together. We articulate this view and introduce the programme's core notion of a theory net. As an added benefit, this analysis of the internal organisation of theories offers a new perspective on the problem of theory-ladenness of observation. We discuss what this perspective involves and relate it back to the discussion in Chapter 3.

The versions of the Model-Theoretical View discussed in Chapters 5 to 7 are structuralist versions because they regard the models of a theory as set-theoretical structures and analyse both how models represent and how models relate to one another in structural terms. In Chapter 8 we discuss two alternative accounts. The first regards models as abstract entities and analyses representation in terms of similarity: a model represents its target due to being similar to it. Using the five questions and five conditions for an account of representation from Chapter 6, we scrutinise the similarity account of representation and find it wanting in various ways. The second alternative account regards models as abstract replicas and explicates representation in terms of idealisation and abstraction. This proposal points in an interesting direction, but remains too skeletal to provide a tenable account of representation. So, again, the issue of representation is left unresolved.

An important conclusion that emerges from the discussion in Part II is that even though scientific representation is a core problem for any account of models and theories, no tenable account of representation has emerged from the Model-Theoretical View. The chapters in Part III focus on this problem. Chapter 9 is dedicated to an examination of alternative accounts of representation that have emerged in recent discussions. We introduce and discuss the positions that sail under the banners of General Griceanism, direct representation, inferentialism, representation-as, and DEKI. Some of these offer promising alternatives to the accounts we have discussed in Part II.

Many of the accounts of representation discussed in Chapter 9 are "overarching" accounts. They pin down the general structure of how representation works, but they require as inputs in various places analyses of specific model-world relationships. The three chapters to follow provide analyses of some of the most important relations of this kind. Chapter 10 discusses analogies and analogical models. We begin by offering a general characterisation of analogies and then discuss some important kinds of analogies, chief among them formal analogies, material analogies and functional analogies. We then turn to different uses of analogies and discuss first analogical models – models that relate to their target systems by analogy – and then turn to the heuristic use of analogies in theory construction. We end with a discussion of the relation between analogies and metaphors.

The next two chapters discuss idealisations. Chapter 11 begins by distinguishing between the closely related, but, as we will see, different concepts of idealisation, approximation, and abstraction. In doing so we provide analyses of abstraction and approximation. Idealisation turns out to be more difficult to circumscribe, and an extensive discussion of attempts to define idealisations leads us to the conclusion that there is no unified definition. As a result, a discussion of idealisation has to proceed in a piecemeal manner, introducing different kinds of idealisations and analysing them one by one. This is the project for Chapter 12, where we discuss two important types of idealisations: limit idealisations and factor exclusions. Limit idealisations push a certain property to an extreme, for instance by considering that a slippery surface is frictionless; a factor exclusion amounts to omitting a certain factor entirely, for instance by disregarding the collision of particles in a gas. After providing some mathematical background on limits, we present an analysis of limit idealisations and factor exclusions, and we discuss their consequences for our understanding of what information we can gain from idealised models about their target systems.

The chapters in Part IV of the book are concerned with models as they are used in scientific practice. Chapter 13 discusses the relation between models and theories. As we have seen, the Linguistic View and the Model-Theoretical View both see models as subordinate to theories, albeit in very different ways. For the Linguistic View, they are alternative interpretations of a theory's formalism; for the semantic view, they are the building blocks of theories. Neither of these visions does justice to the way models operate in practice, where they can stand in different and complex relations to theories. We discuss a number of model-theory relations ranging from total independence to close alliance, and we then ask whether, and how, the Model-Theoretical View could account for these relations.

If models are divorced from theory, the question of what models are appears in a new light. This is the topic of Chapter 14. We begin our discussion by distinguishing between an ontological and functional reading of the question. On the former, the question is what kind of things model objects are; on the latter, the question is what it means for something for function as a model. We discuss different answers and come to the sober conclusion that there is no definition of what a model is, neither ontologically nor functionally. Nevertheless, there is an interesting question about what kinds of things usually do serve as models. To put the question into focus, we formulate five desiderata that an account of model objects must satisfy. These desiderata are less pressing in the case of material models, physical objects like ship-shaped blocks of wood and systems of waterpipes and reservoirs. However, they become important in the context of non-material models. We discuss set-theoretical structures, abstract objects, descriptions, mathematical objects, equations, computational structures, fictional objects, and artefacts as potential model objects, and we conclude that upon closer analysis they can be reduced to two: mathematical models and fictional models. We then formulate an account of fictional models that meets the challenges.

In many contexts, scientific communities end up producing a multiplicity of models of the same target system. Nuclear physics and climate science are paradigmatic examples of disciplines where this happens. Prima facie this is puzzling: why do scientists do this and how to they handle these "multi-model situations"? In Chapter 15 we first discuss the motivations for constructing multiple models of the same target, and then discuss different ways of approaching the resulting "model ensembles": robustness analysis, perspectivism, and uncertainty management. We identify the situations in which they are appropriate and discuss their pros and cons.

Models proliferate. Those delving into the literature on scientific models will find a bewildering array of model types. A recent, but almost certainly incomplete, count returned over 120 different model types. This is disorientating and perplexing. Chapter 16 aims to impose some order on this "model muddle" by briefly introducing each model type, explaining how different model types relate to one another, and sorting the different types into broad groups. This will make the collection of models easier to understand and handle.

The book ends with an Envoi.

Space constraints rendered it impossible to make theory change, inter-theory relations, laws of nature, scientific explanation, scientific understanding, confirmation, thought experiments, measurement theory, mechanisms, computer simulations, and the roles of models in the special science themes of the book. I hope that the richness of the material covered in the book compensates for these, and indeed other, omissions.

There is nothing pleonastic about noting that the chapters of this book have been written as book chapters. They were not previously published as papers, and they are designed to build on each other and to contribute to an unfolding narrative. This said, I have tried to make the chapters self-contained and so they are also readable in isolation. Unfortunately, the linearity of writing does not always do justice to the winding paths of thought and to the complex interrelations of various topics. I have tried to mitigate the tension between the linear progression of a text and the complexity of the relations between ideas by adding ample signposts and cross references, indicting how the materials in different parts of the book are related.

Some sections in the book are technically more demanding than others in that they rely on results from formal logic or make extensive use of symbolic notation. Sections of this kind are marked with an asterisk. Readers with limited enthusiasm for logic and formal material can skip these sections without losing the thread because the book is written so that nothing in later parts builds on material in the asterisked sections. Finally, as is common in analytic philosophy, I use “iff” as a shorthand for “if and only if”, and “$:=$” indicates a definition (with the definiendum on the side of the colon).

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Every chapter of *Models and Theories* has its own bibliography. This is a comprehensive bibliography containing all works cited in the book. The references are from my own final version (October 2021), and changes and updates made at proof stage are not reflected in the below.

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