Introduction

Imagine you want to determine the orbit of a planet moving around the sun. You know that gravity pulls the planet and the sun towards each other and that their motion is governed by Newton's equation. To put this knowledge to use, you first have to construct a model of the system. You make the idealising assumption that the gravitational interaction between the sun and the planet is the only force relevant to the planet's motion, and you neglect all other forces, most notably the gravitational interaction between the planet and other objects in the universe. You furthermore assume that both the sun and the planet are perfect spheres with a homogenous mass distribution (meaning that the mass is evenly distributed within each sphere). This allows you to pretend that the gravitational interaction between the planet and the sun behaves as if the entire mass of each object were concentrated in its centre. Since the sun's mass is vastly larger than the mass of the planet, you assume that the sun is at rest and the planet orbits around it. With this model in place, you now turn to mechanics. Newton's equation of motion is $\vec{F} = m\vec{a}$, where $\vec{a}$ is the acceleration of a particle, m its mass, and $\vec{F}$ the force acting on it, and the law of gravity says that the magnitude of the force acting between the planet and the sun is $F_g = G\, m_p\, m_s/r^2$, where m_p and m_s are the masses of the planet and the sun, respectively, r is the distance between the two, and G is the gravitational constant. Placing the sun at the origin of the coordinate system and plugging F_g into the equation, you obtain $\ddot{\vec{x}} = -Gm_s\,\vec{x}\,/\,|\vec{x}|^3$, where the double dots indicate the second derivative with respect to time. This is the differential equation describing the planet's trajectory, where you have, of course, used $\vec{a} = \ddot{\vec{x}}$, i.e. you utilised that acceleration is equal to the second derivative of position.

Constructing a model of the system has been crucial to deriving the desired result. In fact, without a model of the planet and the sun, you would not have been able to determine the planet's orbit. This example is not an exception. Models play a central role in science. Scientists construct models of atoms, elementary particles, polymers, populations, genetic trees, economies, rational decisions, aeroplanes, earthquakes, forest fires, irrigation systems, and the world's climate – there is hardly a domain of inquiry without models. Models are essential for the acquisition and organisation of scientific knowledge. So how do models work? How can it be the case that by studying a model, we can come to discover features of the thing that the model stands for? In this book we explore the idea that models work this way because they *represent* the selected parts or aspects of the world that we investigate. If we want to understand how models allow us to learn about the world, we have to come to understand how they represent.

Why is this important? Given the centrality of models in the scientific endeavour, the question of how models provide us with insight into the way the world is should concern anybody who is interested in understanding how science works. And given how central science is for understanding how we are situated in the world as epistemic agents – as agents who know things, who understand things, who categorise things, and so on – it should concern anybody who is interested in human cognitive endeavours. Furthermore, the question of how models represent is also conceptually prior to other debates concerning metaphysical, epistemological, and methodological questions in connection with science, and appropriate framings of these questions presuppose an understanding of how models represent.

The realism debate is a case in point. What does it mean to be a *scientific realist* about a model-based science? The usual way of characterising scientific realism is that mature scientific theories must be taken literally and be regarded as (approximately) true, both in what they say about observables and in what they say about unobservables (Psillos 1999). Despite many of the participants in this discussion rejecting a linguistic understanding of theories (associated with the so-called syntactic view of theories), the scientific realism debate is framed mostly in linguistic terms, focussing on the reference of theoretical terms and the (approximate) truth of theoretical statements. There is, at least on the face of it, a mismatch between an understanding of scientific theorising as an essentially model-based activity, which, as we will see, is not obviously linguistic in a straightforward sense, and the framing of the realism debate in linguistic terms (Chakravartty 2001). A reflection on how models represent can help us resolve this tension because it can help us understand what it means for models, or parts of models, to refer and to make truth-evaluable claims.[1]

The realism problem is often seen as particularly pressing in the context of model-based science because many models involve idealisations and approximations, or they are analogies of their targets. This has got enshrined in the categorisation of models, where it is common to classify models as idealised models, approximate models, or analogue models. This is salient in the current context because these classifications do not pertain to intrinsic features of models but to the ways in which models relate to their target systems. As such, idealisation, approximation, and analogy can be seen as being specific modes of representation, and a

[1] For recent discussions of scientific realism with a focus on models, see Reiss' (2012b) and Saatsi's (2016). For a general overview of models in science, see Bailer-Jones' (2002a) and Frigg and Hartmann's (2020). For a historical discussion of models in philosophy of science, see Bailer-Jones' (1999), and for a discussion of how physicists view their models, see her (2002b).

discussion of these modes might benefit from being situated in the wider context of a general theory of representation.[2]

Relatedly, how are we to understand scientific *pluralism*, or *perspectivism*, the idea that scientific practice provides us with multiple models of the same target system, either diachronically or synchronically? Are we to understand these multiple models as conflicting or complementary?[3] Again, this turns on how we understand their representational content.

Or consider the question of what it means for a model to *explain*. One popular way of analysing model-based explanation is to appeal to the idea that a model accurately captures the counterfactual profile of the target system because it either accurately represents how the target system would behave under various different conditions, or captures the difference makers of the phenomenon in question.[4] But this approach relies on us understanding how models can represent counterfactual behaviour, which requires an account of scientific representation. Further consider the notion that science provides us with *understanding* of features of the world.[5] This understanding is, at least in part, delivered by scientific models. But in order to know what it means for a model to provide understanding of a feature of the world, we have to have some grasp of the relationship between the model and the feature. And again, this relationship should be understood as a representational one.

So the question of scientific representation is foundational for various questions in the philosophy of science. This book is intended to provide those working on these questions, as well as those who are simply interested in the relationship between models and the world, with an introduction to the problem of scientific representation. Moreover, we hope that our discussion will be useful to scientists who are concerned with the relationship between their models and the aspects of the world that they are ultimately interested in. Beyond that, we hope that the book will be relevant for researchers in science studies interested in conceptual issues

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[2] Recent discussions of idealisation and approximation with an angle on models can be found in Batterman's (2009), Jebeile and Kennedy's (2015), Nguyen's (2020), Norton's (2012), Portides' (2007), Potochnik's (2017), Saatsi's (2011a), and Vickers' (2016). For a recent discussion of analogue models, see Dardashti et al. (2017, 2019).

[3] There is a fast-growing literature on pluralism and perspectivism. For useful discussions, see Chakravartty's (2010), Chang's (2012), Giere's (2006), Massimi's (2017, 2018), Mitchell's (2002), Morrison's (2011), Rueger's (2005), Taylor and Vickers' (2017), and Teller's (2018), as well as the contributions to Massimi and McCoy's (2019).

[4] See, for instance, Bokulich's (2011) and Strevens' (2008). Again, the relationship between models and explanation is a significant issue in its own right. For more on the relationship between representation and explanation, see Lawler and Sullivan's (2020), Reiss' (2012a), and Woody's (2004).

[5] The question of scientific understanding, and the role models play in scientists' quest for understanding, has received increasing discussion in recent years. See, for instance, De Regt's (2017), Doyle et al. (2019), Elgin's (2004, 2017), Illari's (2019), Khalifa's (2017), Kostić's (2019), Le Bihan's (2019), Reutlinger et al. (2018), Sullivan and Khalifa's (2019), and Verreault-Julien's (2019), as well as the papers collected in Grimm et al. (2017).

concerning model-based science, philosophers working on topics related to representation, and policy-makers taking decisions based on model outputs.

Before delving into the details, two caveats are in order. Approaching scientific modelling by investigating representation is not an imperialist endeavour: our discussion is neither premised on the claim that *all* models are representational, nor does it assume that representation is the *only* function of models. It has been emphasised variously that models perform a number of functions other than representation. Knuuttila (2005, 2011) submits that the epistemic value of models is not limited to their representational function and develops an account that views models as epistemic artefacts that allow us to gather knowledge in diverse ways; Morgan and Morrison (1999) emphasise the role models play in the mediation between theories and the world; Hartmann (1995) and Leplin (1980) discuss models as tools for theory construction; Luczak (2017) talks about the non-representational roles played by toy models; Peschard (2011) investigates the way in which models may be used to construct other models and generate new target systems; Bokulich (2009) and Kennedy (2012) formulate non-representational accounts of model explanation;[6] and Isaac (2013) discusses nonexplanatory uses of models which do not rely on their representational capacities. Not only do we not see projects like these as being in conflict with a view that sees some models as representational; we think that the approaches are in fact complementary. Our point of departure is that *some* models represent and that therefore representation is *one of* the functions that these models perform. We believe that this is an important function and that it is therefore a worthy endeavour to enquire into how models manage to represent something beyond themselves.

The second caveat is that we are not presupposing that models are the *sole* unit of scientific representation, or that all scientific representation is model-based. Various types of images have their place in science, and so do graphs, diagrams, and drawings.[7] In some contexts, scientists also use what Warmbrōd (1992) calls "natural forms of representation" and what Peirce would have classified as indices, namely, signs that have a "direct physical connection" to what they signify (Hartshorne and Weiss 1931–1935, CP 1.372, cf. CP 2.92): tree rings, fingerprints, and disease symptoms. These are related to thermometer readings and litmus paper indications, which are commonly classified as measurements. Measurements also provide representations of processes in nature, sometimes together with the subsequent condensation of measurement results in the form of charts, curves, tables, and the like.[8] And, last, but not least, many would hold that theories represent too. At

6 The issue of non-representational model explanations has also received attention phrased in terms of what Batterman and Rice (2014) call "minimal models". It is worth nothing, however, that the term is used in various ways in the literature. See, for instance, Fumagalli's (2015, 2016), Grüne-Yanoff's (2009, 2013), Jhun et al. (2018), and Weisberg's (2007).

7 Downes (2012), Elkins (1999), and Perini (2005a, b, 2010) provide discussions of visual representation in science.

8 Díez (1997a, b) and Tal (2017) offer general discussions of measurement. For a discussion of measurement in physics, in particular temperature, see Chang's (2004), and for a discussion of measurement in economics, see Reiss' (2001).

this point, the vexing problem of the nature of theories and the relation between theories and models rears its head again, and we refer the reader to Portides' (2017) for a discussion of this issue.

There is no question that these forms of "non-model representation" exist – they do and they play important roles in various branches of science. The question is whether these other kinds of representation function in ways that are fundamentally different from the way in which models function. Do, say, graphs represent in the same way that models do? The answer to this question will depend on what one has to say about models and hence depends on one's account of representation. What all accounts of scientific representation have in common is that they must address the issue. An account of scientific representation remains incomplete as long as it does not specify how it deals with alternative forms of representation.

The book is organised as follows. In Chap. 1 we reflect on the tasks ahead and present a list with five problems that every account of representation must answer, along with five conditions of adequacy that every viable answer must meet. These questions and conditions provide the analytical lens through which we look at the different accounts of representation in subsequent chapters.[9] In Chap. 2 we discuss Griceanism and representation by stipulation: the claim that models represent their targets because we intend them to, and that's all there is to say about the matter. In Chap. 3 we look at the time-honoured similarity approach, and in Chap. 4 we examine its modern-day cousin, the structuralist approach. Both, in relevantly different ways, take similarities, structural or otherwise, between models and their targets to be constitutive of scientific representation. In Chap. 5 we turn to inferentialism, a more recent family of conceptions which emphasise the role that models play in generating hypotheses about their targets. In Chap. 6 we discuss the fiction view of models and distinguish between different versions of the view. In Chap. 7 we consider accounts based on the notion of "representation-as", which identify the fact that models represent their subject matter as being thus or so as the core of a theory of representation.

While this book is an introduction to the literature, and while we have endeavoured to provide a balanced treatment of the positions we discuss, the book is also, as indicated in its title, an *opinionated* introduction. The conclusion we reach at the end of Chap. 7 is that all currently available positions are beset with problems and that a novel approach is required. This is our project in the final two chapters of the book. In Chap. 8 we develop what we call the DEKI account of representation and explain how it works in the context of material models. In Chap. 9 we generalise the DEKI account to ensure it applies to non-material models, and reflect on the relation between representation in art and science.

[9] A historical introduction to the issue of scientific representation can be found in Boniolo's (2007).

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