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Modelling Nature: An Opinionated Introduction to Scientific Representation

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Preface

Models matter. Scientists spend much effort on constructing, improving, and testing models, and countless pages in scientific journals are filled with descriptions of models and their behaviours. Models owe much of their importance in the scientific process to the fact that many of them are representations, which allows scientists to study a model to discover features of reality. And the importance of representation is not limited to science. We look at photographs, contemplate paintings, study diagrams, read novels, watch movies, appreciate statues, are perplexed by kinematic installations, and watch the lights when crossing the road. There is hardly an aspect of our lives that is not permeated by representations. But what does it mean for something to represent something else? This is the question we discuss in this book. We focus on scientific representation, but, as we shall see, the boundaries between scientific representation and other kinds of representation are porous, if not spurious, and attempts to seperate scientific representation and analyse it in blissful isolation are doomed to failure.

The problem of scientific representation has by now generated a sizable literature, which has been growing particularly fast over the last decade. However, even a cursory look at this literature will leave the reader with the impression that the discussion about scientific representation is still in its infancy: there is no stable terminology, no shared understanding of what the central problems are, and no agreement on what might count as an acceptable solution. The aim of this book is threefold. Our first task is to get clear on what the problems are that we ought to come to grips with, how these problems should be formulated, and what criteria an acceptable solution has to satisfy. We then review the extant literature on the topic and assess the strengths and weaknesses of different proposals in the light of our conceptualisation of the problems and our criteria for adequate solutions. Finally, we offer our own answers to the quandaries of scientific representation and formulate what we call the DEKI account of representation.

Parts of the book build on previous publications. Chaps. 1, 2, 3, 4, and 5, and Sects. 7.1 and 7.2 are improved and expanded versions of our (2017a). We included new material in many places and updated the arguments in the light of criticisms and comments we received. Sect. 4.5 includes parts of our (2017); Sects. 7.3, 7.4, 7.5, and 7.6 are based on material from our (2017b); Chap. 8 includes material from our (2018); and Sects. 9.4 and 9.5 include material from our (2019a).

The book is intended to be intelligible to advanced undergraduate students, and it should also be useful for graduate seminars. We hope, however, that it will be of equal interest to professional philosophers and researchers in science studies, as well as to scientists and policy-makers who care about how, and what, models tell them about the world.

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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).

Contents

Chapter 1
Problems Concerning Scientific Representation

What questions does a philosophical account of scientific representation have to answer and what conditions do these answers have to satisfy? Different authors have focussed on different issues and framed the problem in different ways. As we noted in the Preface, there is neither a shared understanding of the problems that an account of scientific representation has to address; nor is there agreement on what an acceptable solution to these problems would look like. In fact, there is not even a stable and standard terminology in which problems can be formulated. The aim of this chapter is to develop such a terminology, to state what we take to be the core problems that every account of representation must solve, and to formulate conditions of adequacy that acceptable solutions to these problems have to meet.[1] This leads us to identify five problems and five conditions. These will be used to structure the discussion throughout the book and to evaluate views and positions. It is a coincidence that the number of conditions is equal to the number of questions. The conditions of adequacy are not "paired up" with the questions (so that, for instance, the first condition would concern the first question, and so on). The conditions are independent of particular questions.

We begin our discussion by looking at a representation's "aboutness", its ability to support surrogative reasoning, and the problem of demarcating different sorts of representation (Sect. 1.1). Not all representations are of the same kind and the same target can be represented in different styles (Sect. 1.2). Some representations are accurate while others are misrepresentations, and some models have no target system at all despite being representations (Sect. 1.3). Many representations are mathematised, which raises the question of how mathematics hooks onto something in the physical world (Sect. 1.4). The last question concerns the nature of the objects

[1] To frame the issue of representation in terms of five problems is not to say that these are separate and unrelated issues that can be dealt with one after the other in roughly the same way in which we first buy a ticket, then walk to the platform, and finally take a train. The division is analytical, not factual.

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that do the representing: what kind of objects are models and how are they handled in scientific practice (Sect. 1.5)?

The discussion in these sections is dense, and it is easy to lose track of the various points. For this reason we end the chapter with a summary (Sect. 1.6). The summary serves two purposes. The first, and obvious, purpose is to recapitulate, in concise form, the different problems and conditions that will guide our discussion, and thereby provide an easily accessible point of reference for later debates. The second, and less obvious, purpose is to offer the hurried reader a convenient way forward. We realise that the discussions in Sect. 1.1 through to Sect. 1.5 go into more detail than some readers may care to engage with. The summary in Sect. 1.6 is self-contained and understandable even when read in isolation. Those who prefer to bypass lengthy philosophical reflections concerning the nature of a theory of representation and wish to get into a discussion of the different accounts of representation straightaway can now fast-forward to Sect. 1.6 *without* first reading the other sections in this chapter.

1.1 Aboutness, Surrogative Reasoning, and Demarcation

The selected part or aspect of the world that is represented by a representation is the representation's *target system* (or *target*, for short). The target of a portrait of Newton is Sir Issac Newton; the target of his model is the solar system. The object that is doing the representing is the *carrier*.[2] A canvas covered with pigments is the carrier of Newton's portrait, and the object described at the beginning of the Introduction is the carrier of the model of the solar system. Representation, then, is the relation between a carrier and a target. We follow common usage and speak of "a representation" when we refer to the carrier *as related to* its target. In this sense Newton's portrait is a representation, and the model of the solar system is a representation. An *account of representation* offers answers to questions that arise in connection with representation, and *conditions of adequacy* state requirements that a satisfactory account of representation must satisfy.

Models have "aboutness": they are representations *of* a target system. The first and most fundamental question concerning scientific representation therefore is: in virtue of what is a model a scientific representation of something else?[3] To appreciate the thrust of this question it is instructive to briefly consider the parallel problem in the context of pictorial representation. When seeing, say, van Gough's *Self-Portrait with Bandaged Ear* we immediately realise that it depicts a man wearing a green jacket and a blue hat. Why is this? Symbolist painter Maurice Denis issued

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[2] Contessa speaks of the "vehicle" of a representation (2007, p. 51) to cover all objects that are used by someone to represent something else, and Suárez prefers the term "source" (2004, p. 768). While both are workable suggestions, "vehicle" and "source" are now too closely associated with their respective accounts of representation to serve as a neutral term to state our problem.

[3] Explicit attention has been drawn to this question by Frigg (2002, p. 2, 17; 2006, p. 50), Morrison (2008, p. 70), Stachowiak (1973, p. 131), and Suárez (2003, p. 230).

the by now notorious warning to his fellow artists that "[w]e should remember that a picture – before being a war horse, a nude woman, or telling some other story – is essentially a flat surface covered with colours arranged in a particular pattern" (Denis 2008, p. 863). This gets right to the point: how does an arrangement of pigments on a surface represent something outside the picture frame?

There is nothing peculiar about pictures and the same question arises for every representation: what turns something into a representation of something else? We call this the *Representation Problem*. This problem comes in different versions, and, as we will see, which version one choses to address will depend on one's views concerning different kinds of representations. An obvious kind of representation to investigate, at least in the current context, is scientific representation (we come to other kinds soon). Echoing Denis' remark about pictures we can then say that before being a representation of an atom, a population, or an economy, a model is an equation, a structure, a fictional scenario, or a mannerly physical object. What turns mathematical equations or structures, or fictional scenarios or physical objects, into representations of something beyond themselves? It has become customary to phrase this problem in terms of necessary and sufficient conditions. The question then is: what fills the blank in "*X* is a scientific representation of *T* iff ___", where "*X*" stands for the carrier, and "*T*" the target system? We call this the *Scientific Representation Problem* (*SR-Problem*, for short), and the biconditional the *SR-Scheme*. So one can say that the SR-Problem is to fill the blank in the SR-Scheme.

A central feature of representation is its directionality. A portrait represents its subject, but the subject does not represent the portrait. Likewise, a model is about its target, but the target is not about the model. An account of representation has to identify the root of this directionality, and this means that the SR-Problem has to be solved in way that accounts for it. We call this the *Condition of Directionality*, which is our first condition of adequacy for an account of representation.

To spare ourselves difficulties further down the line, our formulation of the Representation Problem needs to be qualified in the light of a second condition of adequacy that any account of scientific representation has to meet. The condition is that models represent in a way that allows scientists to form hypotheses about the models' target systems: they can generate claims about target systems by investigating models that represent them. As we have seen in the Introduction, students of mechanics can generate claims about the trajectory of a planet by studying the properties of the Newtonian model. This is no exception. Many investigations are carried out on models rather than on reality itself, and this is done with the aim of discovering features of the things that models stand for. Every acceptable theory of scientific representation has to account for how reasoning conducted on models can yield claims about their target systems, and there seems to be widespread agreement on this point.[4] Following Swoyer (1991, p. 449) we call this the *Surrogative Reasoning Condition*.

[4] Bailer-Jones (2003, p. 59, origional emphasis) notes that models "*tell us* something about certain features of the world"; Bolinska (2013) and Contessa (2007) both call models "epistemic representations"; Frigg (2003, p. 104; 2006, p. 51) sees the potential for learning as an essential explanan-

This gives rise to a potential problem for the SR-Scheme. The problem is that any account of representation that fills the blank in that scheme in a way that satisfies the Surrogative Reasoning Condition will almost invariably end up covering kinds of representation that one may not want to qualify as scientific representations. Pictures, photographs, maps, diagrams, charts, and drawings, among others, often provide epistemic access to features of the things they represent, and hence they may fall under an account of representation that explains surrogative reasoning. However, at least some of them are not scientific representations. While the photograph of a cell taken with a microscope and a chart of the temperature in the test reactor can be regarded as scientific representations in a broader sense, the portrait of the leader of an expedition, a photograph of the Houses of Parliament, and a drawing of a ballet scene are not scientific representations and yet they provide epistemic access to their subject matter in one way or another. This is a problem for an analysis of scientific representation in terms of necessary and sufficient conditions because if a representation that is not prima facie a scientific representation (for instance a portrait) satisfies the conditions of an account of scientific representation, then one either has to conclude that the account fails because it does not provide sufficient conditions,[5] or that first impressions are wrong and that the representation actually is a scientific representation.

Neither of these options is appealing. To avoid this problem one can follow a suggestion of Contessa's (2007) and broaden the scope of the investigation. Rather than analysing the category of scientific representation, one can analyse the broader category of *epistemic representation*. This category comprises models, but it also includes all other kinds of representation that allow for surrogative reasoning such as maps, photographs, and diagrams. The task then becomes to fill the blank in "*X* is an epistemic representation of *T* iff ___", where, again, "*X*" stands for the carrier and "*T*" for the target system. For brevity we use "*R*(*X, T*)" as a stand-in for "*X* is an epistemic representation of *T*", and so the biconditional becomes "*R*(*X, T*) iff ___". We call the general problem of figuring out in virtue of what something is an epistemic representation of something else the *Epistemic Representation Problem* (*ER-Problem*, for short), and the biconditional "*R*(*X, T*) iff ___" the *ER-Scheme*. The ER-Problem then is to fill the blank in the ER-Scheme.[6]

dum for any theory of representation; Liu (2013, p. 93) emphasises that the main role for models in science and technology is epistemic; Morgan and Morrison regard models as "investigative tools" (1999, p 11); Poznic says that "studying models is to pursue an epistemic purpose: modelers want to learn something" and thereby "gain insight into target systems that are represented by the models" (2016a, p. 202); Suárez (2003, p. 229; 2004, p. 772) submits that models licence specific inferences about their targets; and Weisberg (2013, p. 150) observes that the "model-world relation is the relationship in virtue of which studying a model can tell us something about the nature of a target system".

[5] We nuance this in Sect. 1.2, where we qualify the role of necessary and sufficient conditions.

[6] Frigg (2006, p. 50) calls this the "enigma of representation" and in Suárez's (2003, p. 230) terminology this amounts to identifying the "constituents" of a representation. In his (2004) Suárez explicitly offers only necessary but insufficient conditions on *M* representing *T*. Although it seems

The question of whether one should address the SR-Problem or the ER-Problem gives rise to the *Scientific Representational Demarcation Problem*: do scientific representations differ from other kinds of epistemic representations, and, if so, wherein does the difference lie?[7] It is important to note that the Scientific Representational Demarcation Problem concerns the question whether there is a difference between scientific representations and other kinds of epistemic representations *as regards their representational characteristics*. There may be any number of other differences. Scientific representations characteristically are produced by people who call themselves scientists, are published in scientific journals, are discussed at scientific conferences, and so on; non-scientific epistemic representations typically do not have these features. However, considerations pertaining to the history of production and social function of representations are irrelevant to the Scientific Representational Demarcation Problem (or at least are only relevant to the extent that they are relevant to their representational characteristics).

Those who give a positive answer to the Scientific Representational Demarcation Problem and therefore maintain that scientific representations have to be demarcated will, in the first instance, have to offer a solution to the SR-Problem. They may then address the ER-problem and show what sets scientific representations apart from other epistemic representations. Those who give a negative answer believe that scientific representations are not fundamentally different from other epistemic representations and can therefore turn to the ER-problem right away.

At this point a second demarcation problem arises. As noted in the Introduction, science employs representations that are not usually deemed models: theories, scientific images, graphs, diagrams, and so on. And the variety of types of representation would seem to be even larger in artistic contexts, where one finds paintings, drawings, etchings, sculptures, video installations, and many more. This gives rise to the *Taxonomic Representational Demarcation Problem*: are there different types of representations, and, if so, what are these types and wherein do the differences between them lie? As in the case of the Scientific Representational Demarcation Problem, the Taxonomic Representational Demarcation Problem only concerns the question whether there is a difference between different types of representations *as regards their representational characteristics*. Hence, even those who give a negative answer to the question are not forced to say that all representations are the same, or that all scientific representations are models. They are only committed to saying that there is no difference between different types of representations in the *way in which they represent*, and that any differences that one may identify are external to issues of representation.

As their names suggest, we understand the *Scientific Representational Demarcation Problem* and the *Taxonomic Representational Demarcation Problem* as two subproblems of the same overarching problem, the *Representational Demarcation Problem*,

like the ER-Scheme rules out his account from the offset, in Chap. 5 we argue that a plausible reading of the inferential conception fits neatly into the ER-scheme.

[7] Callender and Cohen discuss what they call "a kind of demarcation problem for scientific representation" (2006, pp. 68–69), which is effectively this problem.

the question whether there are different types of representations and, if so, what the types are.

The two demarcation problems are independent of each other in that it is possible to give a negative answer to one while giving a positive answer to the other. We call someone who gives negative answers to both a *universalist* because this denial amounts to believing that all epistemic representations function in the same way (representationally speaking), and that they are therefore covered by the same account. A universalist will address the ER-Problem.

Someone who denies taxonomic demarcation while upholding scientific demarcation believes that there is a difference between scientific and non-scientific representations but that otherwise representations, both scientific and non-scientific are the same (again, as far as their representational function is concerned). Someone who holds this view will address the SR-Problem.

Those who buy into taxonomical demarcation will have to say what types of representation they recognise, and each type *Y* will then require its own analysis with the aim of filling the blank in "*X* is a scientific/epistemic representation type *Y* of *T* iff ___", where "*X*" and "*T*" are as above. Either "scientific" or "epistemic" is chosen depending on whether they also buy into scientific demarcation: someone who does will choose "scientific", while someone who rejects scientific demarcation will choose "epistemic". We call this the *Type Representation Problem* (*TR-Problem*, for short), and the corresponding biconditional is the *TR-Scheme*. Addressing the TR-Problem then amounts to first making a list of all types of representation that one recognises and then completing the TR-Scheme for each type.

What would a taxonomic demarcation look like? Since models are of central importance in our context, one would expect that they would be among the recognised representational types, and that there would be a philosophical discussion around a "model representation problem". This problem would consist in filling the blank in the TR-Scheme for models, namely "*X* is a scientific/epistemic model representation of *T* iff ___". Interestingly, this is not the turn that the discussion has taken. In fact, models do not seem to get recognised as representational types sui generis in the sense that those who discuss "how models represent", by and large, discuss models in tandem with other kinds of epistemic representations. As we will see in Chap. 3, the taxonomic demarcation that has taken hold in the discussion is the distinction between direct and indirect representations. It so happens that proponents of this distinction reject scientific demarcation, and so they will aim to fill the blank in two TR-Schemes for epistemic representation, namely "*X* is a direct epistemic representation of *T* iff ___" and "*X* is an indirect epistemic representation of *T* iff ___".

The different versions of the Representation Problem and their dependence on the answers to the two demarcation problems are summarised in the matrix in Fig. 1.1. It is worth spelling out these options in a more detail. Someone who denies scientific demarcation while upholding taxonomic demarcation believes that there are different kinds of epistemic representations and that these require separate analyses, but at the same time believes that these kinds cut across the science versus

Scientific Representational Demarcation Problem	Taxonomic Representational Demarcation Problem: Yes	Taxonomic Representational Demarcation Problem: No
Yes	Address the Type Representation Problem for “scientific representation”	Address the Scientific Representation Problem
No	Address the Type Representation Problem for “epistemic representation”	Address the Epistemic Representation Problem

Fig. 1.1 Matrix showing how different answers to the Scientific Representational Demarcation Problem and the Taxonomic Representational Demarcation Problem determine which version of the Representation Problem one is going to address

non-science divide in that scientific and non-scientific uses of these types are covered by the same philosophical analysis. On such a view there are, say, scientific as well as non-scientific photographs, and scientific as well as non-scientific models, but these are covered by the same analysis.[8] Proponents will therefore address the TR-Problem for “epistemic representation”.

Someone who responds positively to both demarcation problems has to distinguish between different kinds of representation both within the class of scientific representations and the class of non-scientific representations. A theorist of this sort has two options. She might think that even though there is a difference between scientific and non-scientific representations, the internal division of both groups are the same. On such a view there could, for instance, be scientific and non-scientific photographs, scientific and non-scientific diagrams, scientific and non-scientific models, and so on, but the scientific version of a type would have to be covered by a different analysis than its non-scientific cousin. Another option is to think that subdivisions of scientific and non-scientific representations are different to begin with, which means that each group requires its own taxonomical scheme.

The original demarcation problem – to distinguish between science and non-science, and in particular pseudo-science – is not as active a research problem as it once was. For this reason, those interested in representation may also have little

[8] The notion of a non-scientific model is not an artefact of our classification. That the use of models need not be confined to science becomes clear from the recent debate about the use of models within philosophy. For a discussion of models in various parts of philosophy see, for instance, Colyvan’s (2013), Godfrey-Smith’s (2012), Hartmann’s (2008), Sprenger and Hartmann’s (2019, Chap. 1), and Williamson’s (2018).

enthusiasm to get involved in questions of demarcation. Accordingly, with the exception of Callender and Cohen, who note their lack of optimism about solving this problem (2006, p. 83), the Scientific Representational Demarcation Problem seems to have received little, if any, explicit attention in the recent literature on scientific representation. This can be seen as suggesting that authors favour a negative answer. Indeed, such an answer seems to be implicit in approaches that discuss scientific representation alongside other forms of epistemic representation such as pictorial representation. Elgin's (2010), French's (2003), Frigg's (2006), Suárez's (2004), and van Fraassen's (2008) are examples of approaches of this kind.

However, the two representational demarcation problems are of systematic importance even if one ends up not demarcating at all. This is because, as have just seen, they have implications for how we address the problem of representation and what examples we use. Those who give negative answers to both problems can address the ER-problem directly and do not have to draw other distinctions. Those who give positive answers to at least one of the demarcation problems will have to address different representation problems and face different possible counterexamples. So one's stance on demarcation has clear methodological implications, and even those who are not inclined to engage with the problem at any level of detail will have to make their choices explicit to avoid causing difficulties downstream.

Our study of the issues concerning representation is not yet complete, and having put a tripartite distinction between the ER-Problem, the SR-Problem, and the different TR-Problems into place does, strictly speaking, require us to address all further issues that we encounter with respect to all three problems. We refrain from doing so and focus on the ER-Problem for three reasons. First, carrying all problems with us would lead to meandering strings of distinctions that would be hard to keep track of even for veterans in matters of representation. Second, it would fill pages with redundancies because the points we make about the ER-scheme carry over the other schemes mutatis mutandis. Third, while it is important for our analysis that we are clear on what problems there are and which of the problems we address, most positions in the current debate are either universalist, or nearly universalist in that they uphold only few demarcations. Even though discussions have focussed on models, this seems to be a pragmatic decision based on the fact that models are important. But for universalists (who reject the demarcation), at bottom all instances of epistemic representation function in the same way and the question whether the analysis starts with models, pictures, or yet something else, loses its teeth because any starting point will lead to the same result. A universalist studies models as *samples* of epistemic representation and claims that the result of the study generalises. We adopt this strategy in what follows and discuss models as instances of epistemic representation. Those who disagree with this classification can retrace the previous steps and re-introduce the distinctions we now suppress.

1.2 The ER-Scheme and Representational Styles

Even someone who accepts both representational demarcation problems and distinguishes between different types of representation will grant that not all representations of the same type work in the same way.[9] Consider the example of (non-scientific) painting, where the point is so obvious that it hardly needs mention: an Egyptian mural, a two-point perspective aquarelle, and a pointillist oil painting represent their respective targets in different ways. This pluralism is not limited to visual representations. As we have previously seen, there seem to be various types of scientific representation. And even if we restrict our focus to models, they don't all function in the same way. For example, Woody (2000) argues that chemistry as a discipline has its own ways to represent molecules. But differences in style can even appear in models from the same discipline. Weizsäcker's liquid drop model represents the nucleus of an atom in a manner that seems to be different from the one of the shell model. A scale model of the wing of a plane represents the wing in a way that is different from how a mathematical model of its cross section does. Or Phillips and Newlyn's famous hydraulic machine and Hicks' mathematical equations both represent a Keynesian economy but they seem to do so in different ways. In other words: they employ different *styles*. This gives rise to the question: what styles are there and how can they be characterised? This is the *Problem of Style* (Frigg 2006, p. 50). There is no expectation that a *complete* list of styles be provided in response to this problem. Indeed, it is unlikely that such a list can ever be drawn up, and new styles will be invented as science progresses. A response to the problem of style will always be open-ended, providing a taxonomy of what is currently available while leaving room for new additions.

How can different styles be accommodated in the ER-Scheme? One might worry that the scheme seems to assume that epistemic representation is a monolithic concept and thereby make it impossible to distinguish between different kinds of representation. This impression is engendered by the fact the scheme asks us to fill a blank, and blank is filled only once. But if there are different styles of representation, we should be able to fill the blank in different ways on different occasions. The answer to this problem lies in the realisation that the ER-Scheme is more flexible than appears at first sight. In fact, there are at least three different ways in which different styles of representations can be accommodated in the ER-Scheme. To pinpoint the locus of flexibility let us replace the blank with variable for a condition on representation and rewrite the ER-Scheme as "$R(X, T)$ iff C", where C denotes a condition (and, as we have seen in the previous section, $R(X, T)$ is a stand-in for "X is an epistemic representation of T"). The scheme then says that X is an epistemic representation of T iff C obtains. The condition will usually involve a relation between X and T (although, as we will see shortly, there can also be other relata). For this reason we call C the *grounding relation* of an epistemic representation. The ER-Problem now is to identify C.

[9] For someone who does not demarcate, or only demarcates along one dimension but not the other, the observation that there are different representational styles is even more obvious.

To see how the introduction of a grounding relation helps us to deal with styles, let us assume, for the sake of illustration, that we have identified two styles: analogue representation and idealised representation. The result of an analysis of these relations is the identification of their respective grounding relations, C_A and C_I. The first way of accommodating them in the ER-Scheme is to fill the blank with the disjunction of the two: "$R(X, T)$ iff C_A or C_I". In plain English: X is an epistemic representation of T if and only if X is an analogue representation of T or X is an idealised representation of T. This move is possible because, first appearances notwithstanding, nothing hangs on the grounding relation being homogeneous. The relation can be as complicated as we like and there is no prohibition against disjunctions. In the above case we have $C = [C_A$ or $C_I]$. The grounding relation could even be an open disjunction. This would help accommodate the observation that a list of styles is potentially open-ended. In that case there would be a grounding relation for each style and the scheme could be written as "$R(X, T)$ iff C_1 or C_2 or C_3 or …", where the C_i are the grounding relations for different styles. This is not a new scheme; it's the same old scheme where $C = [C_1$ or C_2 or C_3 or …] is spelled out.

Alternatively, one could formulate a different scheme for every kind of representation. This would amount to changing the scheme slightly in that one would then no longer analyse epistemic representation per se. Instead one would analyse different styles of epistemic representations. Consider the above example again. The response to the ER-Problem then consists in presenting the two biconditionals "$R_A(X, T)$ iff C_A" and "$R_I(X, T)$ iff C_I", where $R_A(X, T)$ stands for "X is an analogical epistemic representation of T" and $R_I(X, T)$ for "X is an idealised epistemic representation of T". This generalises straightforwardly to the case of any number of styles, and the open-endedness of the list of styles can be reflected in the fact that an open-ended list of conditionals of the form "$R_i(X, T)$ iff C_i" can be given, where the index ranges over styles.

In contrast with the second option, which pulls in the direction of more heterogeneity, the third option aims for more unity. The crucial observation here is that the grounding relation can in principle be an abstract relation that can be concretised in different ways, or a determinable that can have different determinates. On the third view, then, the concept of epistemic representation is like the concept of force (which is abstract in that in a concrete situation the acting force is gravity, or electromagnetic attraction, or some other specific force), or like colour (where a coloured object must be blue, or green, or …). This view would leave "$R(X, T)$ iff C" unchanged and take it as understood that C is an abstract relation.

At this point we do not adjudicate between these options. Each has its pros and cons, and which is the most convenient to work with depends on one's other philosophical commitments. What matters is that the ER-scheme does have the flexibility to accommodate different representational styles, and that it can accommodate them in at least three different ways.[10]

[10] In passing we note that these accommodations can be done at all levels of analysis and hence can also be used to clarify the issues of demarcation discussed previously. The scheme's flexibility allows for the option of demarcating between scientific and non-scientific epistemic representa-