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Models in Science and Engineering

Imagining, Designing and Evaluating Representations

Michael Poznic

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Models in Science and Engineering

Models in Science and Engineering

Imagining, Designing and Evaluating Representations

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1 In fact, as it turned out, I now have two promoters as Rafaela has been offered a professorship at the Karlsruhe Institute of Technology. In German one used to call the adviser of the thesis either mother or father of the thesis, 'Doktormutter' or 'Doktorvater.' So, I can say that with both of them I have a perfect pair of parents of the thesis.

work, together with Rafaela, on an earlier version of the paper that grew into Chapter 4 of this thesis. Besides, Maarten, Peter, Rafaela and myself used to discuss also papers by other scholars that were relevant for my dissertation. For very special occasions even Sjoerd Zwart joined in. Because Sjoerd works not only for the university in Delft but also for Eindhoven University of Technology, he is quite busy and I am very grateful that he was the first one to accept the invitation to join the committee for the dissertation. The other members of the committee need to be thanked: I'm also indebted to Mieke Boon, Igor Douven, Stephan Hartmann and Herman Russchenberg. Special thanks go to Ibo van de Poel who spontaneously accepted the invitation to become reserve member of the committee. To continue with thanking my former Delft colleagues: Pieter Vermaas offered many valuable tips for strategic decisions concerning submissions and other matters. I especially remember the trip to a conference at Virginia Tech in Blacksburg (US) that I undertook together with Peter and Pieter. There, we had many conversations over lunches and dinners on philosophical and mundane topics. Another impressive trip during my time in Delft was the one to the West coast of the US, to UC Berkeley, to attend a workshop on engineering ethics, which was organized by our colleague Behnam Taebi as well as some other US scholars. Together with my PhD colleagues Jan Bergen, Christine Boshuijzen-van Burken, Zoë Robaey and Shannon Spruit, I spent a wonderful week in San Francisco. I learnt not only about the trendy culture of microbreweries, but also heard for the first time about organs on chips (the topic of Chapter 4). On top of that, also a robust scholarly output was generated by this event. My first English publication came out of it: a commentary on a paper by the organizers of the workshop, which, however, was not included in this dissertation. Sabine Roeser as the head of the section supported me with help on formal issues in the last phase of the dissertation. Veronica Alfano and Taylor Stone were helpful in offering their advices as English native speakers in proofreading some papers. Filippo Santoni di Sio and Phil Robichaud offered moral support at get togethers in our favorite café, the Huszár near Delft's train station. Last but not least, I want to acknowledge three very charming ladies: Diana Droog, Monique Pijls and Anneke van Veen were always helpful and offered constructive advices for any organizational problem that I came across. To all of you go my sincere thanks.

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1 Introduction

Contents

Science and technology are shaping our culture now more than ever. We use smart phones and other electronic devices, we travel easily around the globe with the help of airplanes and we can access any kind of information faster than ever with the help of the Internet. These innovations (among many others) have been made possible by advancements in science and technology and so they can be seen as resulting partly from epistemic practices in science. Much of the scientific knowledge is obtained by the practice of modeling, which occupies a great deal of scientists' time. Scientists explore the world by using models.[2] According to Ron Giere one may say that in contrast to other institutions such as commerce, military, arts, politics or religion, science works in a specific way. "[S]cientists are engaged in exploring how the world works. [...] They engage in careful and deliberate interactions with the world. They do experiments and make observations" (Giere 1997, p.19). In the following pages, the term 'understanding' is used in a narrow sense to express the aim of learning how the world works in this specific scientific manner. Of course, scientists are not the only ones to seek an understanding of the world in a broader sense, but scientists use fairly specific methods in contrast to, e.g., artists and literary or religious writers.

[2] The term 'modeling' refers to the activity of using or building models, whereas 'model' refers to the product of scientific inquiries. A model can embody the knowledge that results from epistemic practices in science.

Often these methods used in the sciences are simply called *the* scientific method although it is questionable whether all the various disciplines in fact share a single and identical method (cf. Andersen & Hepburn 2015). Furthermore, scientists study particular phenomena and usually do not reflect on how the world works globally. For this purpose of studying particular phenomena scientists use models to represent these phenomena. But what is the nature of these models? This question is the starting point of the present dissertation.

The focus of interest is, however, not occupied with metaphysical questions on models such as questions about the ontological status of models. For example, models are classified as abstract objects, hypothetical objects, concrete objects or linguistic objects in the academic literature (cf. Giere 1988; Frigg 2010a; Weisberg 2013; Toon 2012). Irrespective of the exact ontological status of models, I assume that there are models beside descriptions of models.[3] Rather than discussing metaphysical questions about models, this thesis focuses on pragmatic and epistemological questions. *How can one learn about particular phenomena by using models?* This is the central question of the current dissertation. One brief answer is that one can learn about phenomena by using particular models if these models *represent* the phenomena. A longer answer will be presented in the following chapters. Answering this question involves not only (partially) explaining what representation is, but also how the notions of representation and evaluation are connected in the context of modeling. The thesis includes a fresh look at so-called similarity views on representation and a discussion of fictionalist accounts of modeling, while expanding on the general framework of indirect representation that is discussed below (see 1.1.2).

In addition to the scientific uses of models this thesis also examines how technological uses of models can be conceptualized. One reason that engineers are interested in models is because models can be used as tools for designing technical artifacts. The study of the connection between modeling and design, however, has often been neglected in philosophy.[4] This thesis proposes a first step toward a more substantive study by addressing key questions in this issue of

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3 In the terminology of an indirect view of representation, to be discussed below (see 1.1.2), there are model descriptions *and* model systems. Examples for model descriptions are mathematical equations; corresponding examples for model systems are set-theoretic structures that satisfy those equations.

4 Some notable exceptions are Wynn & Clarkson (2005), Sterrett (2014) and Eckert & Hillerbrand (forthcoming).

modeling and design. The overall aim is to illuminate epistemic uses of models in science and engineering.

In this introductory chapter, I first give an overview of scholarly discussions of models in science and engineering to the extent that they are relevant for this thesis (see 1.1). The topics covered are i) models and representation, ii) indirect representation, iii) relation of representation, iv) resemblance and representation, v) fictionalism about models and vi) modeling and design. I will then introduce the particular chapters of the thesis (see 1.2). Finally, this introduction will conclude with a short discussion of potential routes for future research (see 1.3).

1.1. Models in Science and Engineering

The term 'model' has often appeared in scientific discourse as well as in engineering or philosophical discourse for the last thirty years or so. It is widely acknowledged that scientists and engineers are engaged in modeling. There are mathematical models, scale models of buildings or cars, climate models and animal models. Some examples of models are the double helix model of DNA, the Bohr model of the atom, the Schelling model of segregation, the Lotka-Volterra model of predator-prey interaction and the billiard ball model of a gas, to name just a few. This thesis begins with the basic question of what these models in science and engineering are.

One thing is certain: scientists and engineers use models. Yet it remains an open question whether it is possible to say anything about models that is at the same time general and informative. According to Roman Frigg and Stephan Hartmann (2012), this issue may not allow a uniform answer because there are so many different uses of models in science. In addition, there seem to be different uses of models in science and engineering. For example, it is often claimed that scientists primarily aim at understanding the world whereas engineers are primarily interested in changing the world (cf. Franssen et al. 2015). Thus, an intuitive idea might be that scientists use models for understanding and engineers use models for changing the world. However, it is questionable whether such a sharp line can be drawn between science and engineering.

Giving a general account of what models are seems to present a particular difficulty. This thesis seeks to provide an account of models that goes beyond the generic level to look at particular applications of models. The strategy here is to focus first on models that are used for representational purposes. The concept of representation is strongly connected to the practice of modeling because the function of many models is to represent something. I therefore first distinguish two alternative approaches to the task of explicating representation. One approach begins with the question of what a representation simpliciter is. The other approach focuses on the question of what a correct, faithful, or adequate[5] representation is.

1.1.1. Models and Representation

In philosophy of science, scholars agree that most models are representations. If most models are representations then one might learn what models in science (and perhaps also in engineering) have in common by examining the question of what representations are. The present thesis follows this shift from the problem of explaining what models are to the problem of explaining what representations are. Scholars often mention the *problem of scientific representation* (cf. Callender & Cohen 2006; Frigg 2006; Toon 2012; Boesch forthcoming). It is not entirely clear, however, what exactly that problem is. A majority of philosophers thinks that the problem consists of at least two questions: First, what makes a model, as a representational vehicle, a representation of something else, often called a target system?[6] Second, what makes a model, as a representational vehicle, an adequate representation of a target system?[7] This division of the problem into two distinct questions is currently the standard approach to representation in philosophy of science (cf. Callender & Cohen 2006; Frigg 2006; Contessa 2013; Nguyen 2016). The first question asks what representation simpliciter is and the second addresses the issue of adequate representation. Those who hold of a view of representation that focuses on the descriptive aspect of the concept of representation approach the first question before they deal with the second question. Some do not even address the second question (cf. Toon 2012). By contrast, a

5 In the scholarly literature one can find these adjectives or even other terms used to express a positive evaluation of a representational vehicle.

6 I follow common scholarly usage in referring to the things that are to be represented by models as *targets* or *target systems*. Target systems are systems in the world that can be studied with the help of scientific methods.

7 As already noticed one could also speak of a correct or faithful representation. In the following I will mainly use the term 'adequate.'

view that is concerned with the normative aspect of the concept of representation focuses on answering the question of what makes a representational vehicle an adequate representation of something else. According to a view that focuses on the normative aspect, answering this question is the main problem of understanding representation. Further, such a view argues that representational modeling requires evaluations of models by model users, rather than a purely descriptive perspective on models. This is because representational vehicles such as models are used for epistemic purposes. Representational models have an epistemic function. Models are instruments that are used as "investigative devices for learning something" (Morrison & Morgan 1999, p. 11). The central question of a normative account of representation might then be formulated as: by virtue of what do models adequately represent target systems in order to foster knowledge about these target systems?

In this thesis, I distinguish between models identified as attempted representations and models identified as adequate representations. The term 'representation' as predicated of a model can mean at least two things. I thus propose the following terminological distinction: (i) A *representational* model is a model that is used with the intention of adequately representing a particular target system. Thus, a representational model is first of all a relatum in a relation of attempted adequate representation. (ii) A *representative* model is a representational model that does adequately represent a target system and, so, it is a relatum in a relation of adequate representation (cf. Poznic 2017).

The issue of these opposing approaches to accounts of representation is taken up in Chapter 2. There, it is argued that the main problem of understanding representation is answering the question of what makes a representational vehicle a representative one, that is, an adequate representation of something else.

1.1.2. Indirect Representation

The general framework that I use in this thesis is the view of indirect representation first proposed by Ron Giere (1988), which was explicitly named with that term by Michael Weisberg (2007). According to the view of indirect representation, modeling is a procedure that consists of two steps. First, model users specify 'model systems' with the help of 'model descriptions.' These model descriptions can be mathematical equations or sentences in a technical, scientific language or ordinary language sentences. These model descriptions characterize model systems, which can be various types of entities. Model systems may be concrete entities such as scale models; they may be abstract, mathematical entities such as set-theoretic structures; or they may be computational structures, like those that lie at the heart of computer simulation models (cf. Weisberg 2013). Model systems aim at representing target systems, with a relation of adequate representation to be established between model system and target system (cf. Poznic 2016b).

One influential perspective on the indirect view of representation is Frigg's fictionalist account of modeling and representation. Frigg (2010a) calls the relation between model descriptions and model systems 'p-representation.' Model descriptions prescribe how particular propositions are to be imagined. These propositions constitute the 'world of the model,' which characterizes the model system. Frigg refers to the relation between model systems and target systems as 't-representation.' The relation of t-representation partially forms the foundation for knowledge about the target systems. Because models systems t-represent particular target systems, facts about the model systems can be translated into claims about the target systems (cf. Frigg 2010a, 2010b).[8]

The framework of indirect representation presupposes that representation is a relation between, at the very least, a model system and a target system. This relation can also be conceptualized as involving additional relata alongside these two relata. This is discussed further in the following section.

1.1.3. Relation of Representation

In the scholarly literature, representation is primarily regarded as a relation that, at minimum, involves models and targets. There are, however, scholars who object to an approach that understands representation as a relation. One motivation for this strategy is that models with no existing targets, such as models of the ether, are then conceptually excluded from being regarded as representations. Tarja Knuuttila (2011), Adam Toon (2012), and Mauricio Suárez (2015), for example, discuss whether representation is a relation at all. This is a point worth considering, but one may instead simply declare that it is not the case that all models are representations. With the introduced terminology of representative and representational models in subsection 1.1.1 one can distinguish between

8 Frigg's fictionalist view of modeling is discussed in more detail in Chapters 5 and 6.

models that are representations and models that are not. Some models may be representational models without being representative models, i. e., they are not representations but only *attempted* representations.[9]

Because models are used with a particular intention, the aims of the model users shape the relation of representation. Therefore several scholars agree that representation is at least a triadic relation between models, targets, and users (Knuuttila 2011; Contessa 2013). Giere (2004) argues that representation should be regarded as a four-term relation between models, targets, users and purposes.[10]

Users and purposes are also central to the approach defended in this thesis. Yet in some cases, the users and purposes remain implicit. The picture of indirect representation that I have presented in the previous section, for example, did not explicitly involve users and purposes. If the relata of users and purposes are understood to be fixed elements throughout various contexts, then it might be feasible to speak as if representation were a dyadic relation between vehicles and targets.[11] To use my terminology, we may say that a representative model is one relatum in the relation of representation, which adequately represents a particular target for certain users according to a particular purpose.[12] A representative model does not adequately represent the corresponding target in any respect for all possible users or purposes. One lesson to be taken from the debates on representation is that representations are almost always partial and incomplete (cf. Teller 2001).

This thesis is intended to expand on the work of Giere, Weisberg and other scholars following an indirect view of representation. Furthermore, I also regard representation as primarily a relation. Since models are not in themselves relations, but rather the corresponding model system is only one relatum in a

9 A further point is that not all models are used exclusively for representing targets. Some models may be used for designing targets and some may be used for representing targets (see Chapter 4).

10 Some scholars even discuss other additional candidate relata for the relation of representation such as audiences or commentaries (Mäki 2009).

11 In a scientific community the use of a particular model may have the common purpose of representing a particular target and in such a case this shared purpose in the community may be implicitly presupposed while talking of the model representing the target.

12 The term ‘model’ that I introduce in Chapter 4 denotes a representative model in the explicated sense. In this chapter one may understand the term ‘models’ as referring to representative model systems.

potential relation of representation, I refer to models as 'representations' only in a derivative sense. I therefore differentiate the notions 'model' and 'representation' because not all models are representations, given that the understanding of representation as a relation is fundamental and representation is understood as a success term. For example, models of the solid, elastic ether are not representations of the ether because the ether does not exist. If one relatum of the alleged relation between model and ether does not exist, then there is no relation and the model is not a representative model.[13] Furthermore, there are toy models or probing models that are constructed solely to investigate specific theoretical tools without the aim of representing target systems. An example is the so-called φ^4-model that is used for such a purpose in quantum field theory (cf. Frigg & Hartmann 2012). There are also other scholars who stress that models are used for many different purposes other than representing real-world targets (Giere 2004; Peschard 2011; Knuuttila & Boon 2011; Morgan 2012; Gelfert 2016). It is true, of course, that there are other purposes for models, and there are relations between vehicles and targets other than representation, but the most common purpose of using models is to represent something over and above the models themselves.

As mentioned above, representations are almost always partial and incomplete. One way of dealing with the fact that no model system is perfect is to invoke the notion of similarity. No model system is a perfect copy of a target, but a model system can at least be similar to a target in specific respects and to certain degrees of similarity.

1.1.4. Resemblances between Model Systems and Target Systems

The similarity view of modeling and representation argues that it is reasonable to assume that if one wants to learn about a target system from using a model, then its model system has to resemble the target system in a specific way.[14] It

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13 One may think of the ether as a hypothetical entity and with this understanding there might be a relation between the model and the hypothetical entity. In this thesis, however, I presuppose that there is no ether and no hypothetical entity of the ether and from this it follows that there cannot be a relation between model and ether.

14 I use the notions of resemblance and similarity interchangeably. Two things are similar if and only if they share some of their features. Similarity is a reflexive and symmetric relation.

seems to be necessary that the model system and the target share some relevant features in order for valid claims to be made about the target based on the model system.

There are many positions on modeling and resemblance in philosophy of science: Early similarity views of models employ the notion of analogy (Hesse 1963; Leatherdale 1974). According to Mary Hesse, the 'positive analogy' consists of properties that a model and target share, the 'negative analogy' consists of properties of the model that the target does not have, and the 'neutral analogy' consists of properties of the model for which it is not yet known whether they are shared by the target. The most prominent proponent of a similarity view is Giere (1988, 2006), who uses this notion explicitly. Weisberg (2013) develops a similarity view that draws primarily on psychological studies of similarity judgments. In addition, he allows for the possibility that similarity may not be symmetric. Alongside these approaches, there are various structuralist views that can be interpreted as similarity views as well. Many structuralist views give a precise mathematical definition of structural similarity that utilizes the notion of a mapping relation between set-theoretic structures, employing notions of homomorphism (Bartels 2006), isomorphism (French 2003), or partial isomorphism (da Costa & French 2003). Christopher Pincock (2012) defends a structuralist view of representation that is not committed to a specific mapping relation between structures. Another structuralist view is defended by Bas van Fraassen (2008). According to this view, the embedding of data models in substructures of theoretical models is an achievement of model users that can be explicated with the notion of a morphism. Van Fraassen further acknowledges selective resemblance as a representation criterion for the outcome of a measurement. He does not explicitly endorse a similarity view. In fact, he endorses a use account of representation and argues against naive similarity views of representation.[15] However, one can interpret his insistence on selective resemblance as a defense of a weak form of a similarity view.

The issue of similarity and representation is taken up again in Chapter 3, where serious objections against similarity views of representation are discussed and ultimately rebutted (see also Poznic 2016a).

A subclass of similarity relations is the relation of isomorphism. This relation between two structures is reflexive, symmetric, and transitive.

15 A naive similarity view involves the claim that a model represents a target if and only if the model resembles the target.

1.1.5. Fictionalism about Models

Many descriptions of systems in the sciences are not literal descriptions of existing physical or social systems. Some examples are descriptions of ideal gases, of frictionless planes, and of the actions of perfect rational agents, among many others. A fictionalist account of modeling seeks to provide an answer to the question of what these descriptions are about if they have no correlate in the physical or social world. The general answer of Waltonian fictionalist accounts of modeling is that the aforementioned descriptions are not genuine descriptive statements but rather prescriptions for *imagining* certain propositions.[16] One specific answer is that such 'descriptions' are prescriptions for imagining propositions about hypothetical systems that do not exist in our world. This is the position of Frigg's indirect view (cf. Frigg 2010a). Another specific answer is that these 'descriptions' are prescriptions for imagining particular propositions that are concerned, not with hypothetical systems, but rather with existing target systems. Toon's (2012) direct view takes this position.

The practice of talking and thinking about such non-existent hypothetical systems as if they existed in our world is often called *face-value practice*.[17] I follow this use of the term as a label for the motivation of fictionalism: scientists participate in the face-value practice when they speak and think about hypothetical systems as if they exist. The motivation for fictionalist accounts of modeling is that they can offer an explanation for the face-value practice (cf. Poznic 2016c).

According to Waltonian fictionalism the acts of imagination must follow certain rules in particular contexts. These contexts are regarded as games, referred to as 'games of make-believe.' These games involve tools, or 'props,' and principles that together with the props prescribe the imagining of certain propositions. If the principles are widely shared and there are stable rules then these imaginings are not just subjective and contingent ones. The propositions that are to be imagined receive a certain status that is intersubjectively recognizable by participants of the game of make-believe.[18] Because of this status of objective

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16 The term 'Waltonian fictionalism' is borrowed from Weisberg (2013), who uses it to label Frigg's (2010a) account, which draws on ideas from Kendall Walton (1990). Likewise, I refer to Toon's (2012) fictionalist account with this term.

17 This name for the practice originates in Thomson-Jones (2010); the practice is also discussed by Peter Godfrey-Smith (2009), Michael Weisberg (2013), as well as Toon (2012).

18 Whether scientific activities should be compared to or even regarded as involving games of make-believe is heatedly debated. There are also many opponents of fictionalism with regard to

imaginings, the proponents of fictionalism are able to explain why imaginary model systems can have a central role in epistemic practices in science without compromising the objectivity of science.

Waltonian fictionalism is thoroughly discussed in Chapter 5. This chapter consists of a detailed criticism of two particular fictionalist views defended by Frigg and Toon. The criticism is put forward primarily from an epistemological point of view.

1.1.6. Modeling and Design

One of the claims of analytic philosophy of technology is that the practice of engineering is aimed at designing technical artifacts (cf. Franssen et al. 2015).[19] This practice involves means-end reasoning and the considerations of the functional requirements of the products that are to be designed and built (cf. Meijers 2009, part III). However, the connection to modeling and representation has not received so much attention in this branch of philosophy. There are only a few scholars who work at the intersection of philosophy of science and philosophy of technology (cf. Sterrett 2014; Knuuttila & Boon 2011). And, although there is a literature on modeling in the engineering sciences (cf. Zwart 2009; Boon & Knuuttila 2009; Eckert & Hillerbrand forthcoming), the debates in philosophy of science and philosophy of technology are often isolated. It is not clear how the practice of representational modeling in the sciences is linked to or to be contrasted with modeling for the purpose of designing artifacts in engineering. It is also not evident whether the models used by engineers represent targets in the same way as the models used by scientists. On the other hand, means-end reasoning is rarely discussed in philosophy of science. Furthermore, discussions in philosophy of technology about technical functions have no counterpart in the philosophy of science. It is an open question how epistemic functions of scientific models should be conceptualized. Some scholars identify models as 'epistemic tools' (cf. Knuuttila 2011), but there is no consensus as to what this perspective on models as epistemic tools implies.

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modeling, who argue that the practices of science should be sharply contrasted with games of make-believe.

19 The focus here is on design in a technical context that may include the sense of aesthetical design but does not necessarily have to include it.

The topic of modeling and design is taken up in Chapter 4. As in the rest of this thesis the discussion there begins from the background of an indirect view of representation (see Poznic 2016b).

1.2. Overview of Thesis

The central question of this thesis is how one can learn about particular targets by using models. The epistemic use of models is based on the assumption that models must be representative models in order to foster knowledge about targets. Thus the thesis begins by examining the concept of representation from an epistemic point of view and supports an account of representation that does not distinguish between representation simpliciter and adequate representation. Representation understood here in the sense of a representative model, is regarded as a success term. That is, a representative model is one relatum in a relation of *adequate* representation (Chapter 2). When a representative model represents a target, it allows users of this model to learn something about the target. I argue that a representative model has this epistemic function because it shares relevant features with the target. This presupposes a similarity view of representation. Similarity views of representation face serious objections, which I will rebut (Chapter 3). One way that some scholars articulate a similarity view of representation is to defend an indirect view of representation. In this thesis, while I do not explicitly argue for an indirect view, I assume that the indirect view is a good option, if not the best, for articulating the similarity view. I demonstrate how such an indirect view can be expanded to account for cases of technological modeling. A case study in bioengineering is used to show that the indirect view of representation must acknowledge a distinction between two directions of fit in relations between vehicles and targets. In this context, I apply the notion of design to a relation between vehicle and target, thereby connecting ideas from philosophy of science with ideas from philosophy of technology (Chapter 4). Fictionalist accounts of models are intended to tackle the issue of the ontology of models.[20] In this thesis, however, I discuss two prominent fictionalist accounts from an epistemological point of view in light of my central

[20] Some fictionalist accounts claim that they are able to explain ontological commitments to models as objects away (Frigg 2010a; Toon 2012). However, fictionalists also make epistemological claims about modeling; for example Frigg (2010a) states that one requirement of a fictionalist account is to explain how it is possible to learn with the help of models.

question regarding how one can learn about targets by using models.[21] This question is addressed from the standpoint of Waltonian fictionalism. The result of my discussion is that the two Waltonian fictionalist accounts cannot sufficiently answer the question. I therefore criticize these accounts for their inability to deliver a satisfactory epistemology of representation (Chapter 5). Although I criticize Waltonian fictionalism, I also show that the foundational theory of Waltonian fictionalism, the theory of make-believe, can nevertheless be used to account for the distinction between projections and predictions that is made by the Intergovernmental Panel on Climate Change, henceforth 'IPCC' (Chapter 6).

In giving a more detailed summary of the chapters of this thesis, the following paragraphs will cover what each chapter achieves individually, as well as what chapters 2 and 3 deliver in combination. The thesis proposes a novel perspective on representation, arguing an evaluative stance of model users towards models is necessary. This perspective gives rise to the contention that representation is a *thick* epistemic concept. The term 'thick concept' is more frequently used in ethical debates to refer to concepts that fundamentally involve evaluative and descriptive aspects. In this thesis it is argued that *representation* likewise fundamentally involves evaluative and descriptive aspects, and that these two aspects of representation are strongly intertwined. Just as nonseparationist positions in metaethics argue for the strong connection of evaluative and descriptive aspects of thick *ethical* concepts, this thesis argues for the strong connection of evaluative and descriptive aspects in representation as a thick *epistemic* concept. Accordingly, *Chapter 2* of the thesis argues for a 'thick account' of representation. Moreover, it argues that representation is a success term. In philosophy of science, many scholars claim that the nature of representation should be explained only with descriptive notions. I refer to this answer to the question on representation as the *thin* answer. Some thin theorists admit that there are unconnected evaluative questions about representation: for instance, what is an adequate or successful representation? Or conversely, what is a misrepresentation? All thin views agree on the methodological rule that these evaluative questions, if they are addressed at all, should be addressed independently of the question of what a representation is. *Thick* accounts, by contrast, claim that descriptive and evaluative questions about representation can only be answered in conjunction. The thick views, in acknowledging the evaluative

21 This chapter specifically asks how fictionalists can explain knowledge about targets.

aspect of the concept of representation, reject the separation of descriptive and evaluative aspects. In this chapter, I make two arguments in favor of a thick account, and discuss possible objections to such an account. My conclusion is that the arguments on balance support a thick account.

Chapter 3 deals with arguments against similarity views of scientific representation. This chapter argues that a sophisticated similarity account is still a viable option despite these objections. By refuting the arguments against similarity views of representation, the chapter argues indirectly for similarity as a necessary condition of representation.

The major epistemic virtue of successful models is their capacity to adequately represent specific phenomena or target systems. According to similarity views of representation, models must be similar to their corresponding targets in order to represent them. This chapter scrutinizes Mauricio Suárez's (2003) arguments against similarity views of representation, concluding that the intuition that representation involves similarity is not refuted by Suárez's arguments. The arguments do not make the case for the strong claim that similarity between vehicles and targets is neither necessary nor sufficient for representation. In particular, one claim can still be defended: a vehicle is a representation of a target only if the vehicle is similar to the target in relevant respects and to a specific degree of similarity.

Suárez's arguments against similarity views of representation are often cited (for example, Godfrey-Smith 2009; Knuuttila 2011; Knuuttila & Boon 2011; Toon 2012; Bolinska 2015; Levy 2015) but rarely dealt with in detail (cf. Bueno & French 2011 for a notable exception). This chapter thoroughly discusses and evaluates these arguments. By rebutting these arguments the chapter shows that a sophisticated similarity view is still a reasonable option. The chapter opens the possibility for a broad similarity view on representation that is compatible with structuralist views on representation but also connects with similarity views such as Giere's or Weisberg's views.

Thus far I have presented the contents of Chapter 2 and Chapter 3 separately. Let me now point out what these two chapters deliver together. Mainstream approaches to representation distinguish between i) representation simpliciter and ii) adequate representation. It is argued that similarity views or structuralist views do not provide answers to the primary question of what representation simpliciter is, but only to the secondary question of what adequate representation is. In view of my argument for the thick account of representation, chapters 2 and 3 jointly show that a similarity view can address the question of what representation is, without detaching the issue of the adequacy of representation. In the epistemic context of modeling, the goal of adequately representing a target system is the central motivation for researchers. A thick account of representation accounts for this goal and addresses the meaning of representation as a success term in a weak sense.

The next chapter broadens the perspective on representation in science and touches on an example from the gray area between science and engineering. *Chapter 4* involves a case study of an organ on chip model in bioengineering. The notion of design is used to apply an indirect view of representation to this engineering context. It is shown that the notions of representation and design can be used to open up a novel perspective on models that might lead to a unified account of models in science and engineering. These two notions are interpreted as referring to modeling relations between vehicles and targets that differ in their respective directions of fit: The relation of representation has a vehicle-to-target direction of fit and the relation of design has a target-to-vehicle direction of fit. The case study of an organ on chip model illustrates that the technical device does participate in both design and representation relations. The two relations share the same relatum of the organ on chip but they have different directions of fit. In the design relation the chip is adjusted to conform to a design plan, in which case we are dealing with a target-to-vehicle direction of fit. In the representation relation the chip is adjusted to conform to a human organ, in which case we are dealing with a vehicle-to-target direction of fit. This example shows that a conception of modeling as involving only relations with a vehicle-to-target direction of fit is too narrow to account for all models in science and engineering. With this distinction between design and representation relations, the chapter shows that the aims of understanding and changing the world are both involved in the practice of modeling organs with organs on chips. This chapter is intended as an expansion on the existing accounts of indirect representation. In addidtion, the chapter argues that accounts of representation miss a crucial modeling relation when they only focus on modeling relations with a vehicle-to-target direction of fit. Finally, the proposal of interpreting design as a modeling relation may allow for other uses of models beside the sole purpose of representation.

The last two chapters discuss fictionalism about models. Fictionalism is first criticized from an epistemological point of view, before fictionalist ideas are then constructively applied to the example of a model in climate science. *Chapter 5* criticizes Waltonian fictionalist accounts of modeling and representation for not providing a satisfactory epistemology of modeling. In particular, this chapter focuses on the views put forth in the works of Frigg and Toon. A fundamental thesis of their views is that scientists are participating in games of make-believe when they study models in order to learn about the models themselves and about target systems represented by the models. In discussing the epistemology of Waltonian fictionalism, I argue that the views of Frigg and Toon can explain how scientists learn about models they are studying. However, Waltonina fictionalism does not sufficiently account for how the use of models can foster an understanding of target systems.

Chapter 6 applies the Waltonian theory of make-believe to a case study in climate modeling. Scenarios are interpreted as props in games of make-believe and it is argued that the attitude one must take toward scenario-based model results is to make-believe and not to believe. The background of the chapter is that climatologists of the IPCC recently introduced a distinction between *projections* understood as scenario-based model results, and *predictions*, or model results to which certain probabilities can be ascribed. This chapter explores the difference between the two and suggests that projections can be interpreted as propositions towards which the appropriate attitude is to make-believe rather than to believe. By applying pretense theory, the chapter contends that scenarios function as props in authorized games of make-believe and that results of models that employ scenarios are to be interpreted as implied fictional truths. This interpretation enables an explanation of the difference between projections that should be make-believed and other model results that should be believed.

1.3. Outlook

This thesis addresses some important issues on models in science and engineering, yet there are still plenty of questions that are open for future examination. In this final section I point out some possible routes for future research.

Agnes Bolinska (2015) argues that the central feature of an epistemic representation is its 'informativeness.' In addition, she claims that the aim of faithfully representing a target is central to the practice of representational modeling. For this reason she reverses the order in which the questions involved in the problem of representation are considered. She claims that the issue of adequate representation is to be dealt with before the issue of representation simpliciter can be addressed. One general question this thesis raises is how her arguments relate to the thick account proposed in Chapter 2. Is Bolinska's strategy able to solve the problem of representation without adopting a normative attitude towards representation? A more specific question that might be asked is: Do model users choose a representational model without evaluating the model prior to making their choice? Furthermore: Can the aim of faithfully representing a target be accounted for without considering a normative perspective on modeling?

Chapter 4 distinguishes between the relation of representation that has a vehicle-to-target direction of fit and the relation of design that has a target-to-vehicle direction of fit. Can this distinction be applied to architectural scale models? Architects use scale models in presentations in order to persuade customers to accept their bids of planning and building projects that involve artifacts such as bridges, shopping malls, houses or other buildings. Such scale models are *prima facie* concerned with these target buildings. However, do the models represent the buildings and, if so, how do they do this? A potential reply to the question of whether an architectural scale model represents a building may be that the model stands in a representation relation to a design plan and that the design plan stands in a design relation to the building. Are there alternative answers to the question and, if so, what reasons support these answers?

In Chapter 5, I argue against two particular fictionalist accounts of modeling, and the primary criticism is that these accounts do not deliver a satisfactory epistemology of modeling. One question this raises is whether, for example, Frigg's Waltonian fictionalism could evade my criticism by acknowledging a structuralist perspective on modeling. To be more precise, in order to justify the knowledge about a target that a particular model delivers, one could point to the structural similarity between model system and target system. Because both the target system and the model system instantiate the same structure, claims about the model could be translated into claims about the target. It remains to be examined in what way a hypothetical model system can be said to instantiate a structure. A further question is then how this translation of claims about the model system into claims about the target system can be understood.

To conclude this introductory chapter let me turn to the category of computational models. Weisberg (2013) distinguishes concrete models, mathematical models, and computational models. The bulk of this thesis is concerned with the first two types of models. Only the last chapter deals with a case study of computational models, namely climate models. However, the case study focuses on the input of these models and not on the models themselves. One question that is not addressed in this dissertation is whether climate models can represent targets in the sense of being similar to targets as argued in chapters 3 and 4. Are the targets of climate models possible objects, as opposed to actual objects? Does an account of representation need to differentiate between actual targets and possible targets?

The topic of modeling, design, and representation is a lively and interesting research area; the questions sketched here as well as other issues concerning models in science and engineering will need to be examined in future studies.

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2 Thin versus Thick Accounts of Scientific Representation

Abstract

This chapter proposes a novel distinction between accounts of scientific representation: it distinguishes thin accounts from thick accounts. Thin accounts focus on the descriptive aspect of representation whereas thick accounts acknowledge the evaluative aspect of representation. Thin accounts focus on the question of what a representation as such is. Thick accounts start from the question of what an adequate representation is. In this chapter, I give two arguments in favor of a thick account, the Argument of the Epistemic Aims of Modeling and the Argument of the Normativity of the Practice of Modeling. I also discuss possible objections to a thick account: the Argument from Misrepresentation and the Objections from Model Testing. The conclusion will be that the arguments on balance support a thick account of representation.

Contents

2.1. Introduction

A common diagnosis in philosophy of science is that there is a problem of representation.[22] However, there is no consensus about what exactly the problem is and how it should be addressed. According to the received view on the situation of the debate, deflationary or pragmatic accounts of representation oppose substantive accounts of representation. The former stress the uses of representational vehicles such as models, and the latter focus on objective relations between representational vehicles on the one hand and target systems on the other hand (Suárez 2010). Some scholars claim that these two sets of accounts do not contradict each other; they may instead be complementary (Chakravartty 2010). In fact, some accounts can be associated with both pragmatic and substantive approaches to representation (Giere 1988; Hughes 1997; Contessa 2013). There is an ongoing debate about whether representation is a relation at all (Knuuttila 2011; Suárez 2015), but I will use the language of relation in the following pages, since the question I address does not hinge on this debate. Of course, there may be other relata involved in representation beside representational vehicles and target systems. Candidates for other relata are users, purposes, audiences, and commentaries (cf. Giere 1988, 2004; Mäki 2009; Parker 2010).

In this chapter, I propose a novel distinction between accounts of representation: thin versus thick accounts. I suggest dividing accounts of representation into, on the one hand, thin accounts that focus on the descriptive aspect of representation and, on the other hand, thick accounts that acknowledge the evaluative aspect as well as the descriptive one. This chapter argues for a *thick* account of representation, in contrast to accounts that focus only on its descriptive aspects and that either do not acknowledge the evaluative aspect at all or try to explain what adequate representation or misrepresentation is only after providing an account of the descriptive aspect of the notion of representation.

The chapter presupposes that representation is a relation and that considerations involving users and purposes are needed in order to give a satisfactory account of it. Representation is taken to be a pragmatic notion and it is regarded as a relation between model, target, users, and purposes. The central question of this chapter is whether the evaluative aspect of representation has to be ac-

22 Throughout this chapter and the rest of the thesis, 'representation' will mainly refer to representation in the sciences; I am particularly interested in model-based representation.

counted for in an explanation of this concept. The main thesis is that representing with the help of a model involves a positive evaluation of the fit between the particular model and the target of the representation. The practice of representing essentially involves some form of evaluation of the fit between representational vehicle and target. It is, so I will argue, a mistake to think that there is such thing as a purely descriptive concept of representation and that this concept can help to illuminate epistemic practices in science.

The structure of the chapter is as follows: first, Section 2.2 gives a motivation for the terminology of thin and thick accounts of representation by looking at debates in meataethics about thin and thick ethical concepts. Section 2.3 introduces the distinction between thin and thick accounts of representation. In Section 2.4, I will present arguments in favor of a thick account of representation. The first argument for a thick account is the *Argument of the Epistemic Aims of Modeling*. The second argument for a thick account is the *Argument of the Normativity of the Practice of Modeling*. After that, I will examine possible objections to a thick account in Section 2.5. First, I will discuss an argument for a thin account of representation. This *Argument from Misrepresentation* points to the sheer abundance of shortcomings in scientific models, and derives from that a negative result for a thick account of representation. Second, the *Objections from Model Testing* raised against a thick account will be discussed. I rebut these objections. Finally, Section 2.6 summarizes and concludes.

2.2. Motivation

My approach in this chapter is inspired by the debate surrounding thin and thick ethical concepts in moral philosophy, particularly in metaethics, and it applies a lesson from this field to the conversation about representation within philosophy of science. In metaethics, the nature of the distinction between thin and thick ethical concepts has been debated extensively (cf. Williams 2006; Elstein & Hurka 2009; Eklund 2011; Kirchin 2013). According to the standard view, thin ethical concepts such as 'good' or 'bad' mainly contain evaluative content, whereas thick concepts such as 'just' or 'courageous' have a descriptive or factual content in addition to the evaluative content. The use of a thin concept expresses a positive or negative evaluation of a certain object, event or state of affairs.[23] A thick notion, on the other hand, is both descriptive and evaluative because speakers using it not only provide an evaluation but also offer a description that can be appropriate or not.

According to a separationist view on thick ethical concepts, the content of thick concepts can be separated into an evaluative and a descriptive element. Examples for such a separation may be the distinction between a descriptive aspect and an evaluative aspect of derogatory notions for members of a nation or an ethnic group. The descriptive aspect of a term such as 'Krauts' or 'Boches' denotes Germans whereas the evaluative aspect is a strongly negative appraisal of the denoted persons. Restricted to these kinds of terms separationism seems to be plausible. Nonseparationists, however, deny the possibility of splitting off the evaluative from the descriptive content of all thick concepts by pointing to examples of thick concepts that constitute difficult cases for a separationist project. Because the problem of disentangling the descriptive and the evaluative content of some thick ethical concepts is a challenge for separationists, this chapter starts from the assumption that nonseparationism regarding certain concepts is plausible. If you predicate, e.g., of a particular distribution of goods that it is just then you evaluate and describe the distribution simultaneously. You cannot separate the descriptive aspect of the predication and regard the original predication as to be compounded of a descriptive predication to which an evaluative predication is just added because there is no value-free characterization of the alleged descriptive meaning of the predicate 'just.' Any characterization of what amounts to be a just distribution involves already an evaluation. The same goes for representation, as this chapter will argue.

The lesson from metaethics is that descriptive and evaluative aspects may be inseparably intertwined in thick concepts. I contend that representation is a thick epistemic concept in the sense of having an evaluative and a descriptive aspect. Furthermore, I claim that the concept of representation essentially has an evaluative content that is not detachable from the concept as such. As the use of

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23 I will not distinguish between prescriptive and evaluative aspects of concepts, or concepts themselves. It may be that, in addition to evaluative and descriptive aspects, there is a prescriptive aspect that may or may not be separable from the evaluative aspect. In what follows, I mainly use the language of evaluation in order to talk about these notions or aspects of notions. The term 'evaluative' therefore means normative, in a broad sense that encompasses both a deontic and an axiological meaning.

a thick ethical notion such as just or courageous involves a description and an evaluation of a particular state of affaires or person, likewise the use of the term 'representation' involves a description and an evaluation of a particular representational vehicle in light of certain users and purposes.

In my analysis of accounts of representation, I employ the modifiers thin and thick in a way different from the ethical case. I use *thin* to refer to a descriptive account of representation, and I use *thick* to refer to an account that acknowledges the evaluative aspect of representation in addition to the descriptive aspect. If the concept of representation in the sciences is normative – and I argue that it is – then one could call it a thick *epistemic* concept of representation. So the use of the notions of thin and thick that I propose for philosophy of science creates a mirror image of the distinction between thin and thick concepts in ethics. Thin and thick ethical concepts both have an evaluative aspect; thick ethical concepts are thought to involve a descriptive aspect as well. In contrast, a thick account of representation stresses the evaluative aspect that a thin account denies or downplays. Thus the move from a thin to a thick perspective on representation means adding evaluative content, while the move from a thin to a thick ethical concept means adding descriptive content.

One might say that because of this mirroring the two cases of thick epistemic and ethical concepts are disanalogous. Yet, what the current chapter claims is that the use of the concept of representation just as the use of the concepts of justice, for instance, involves evaluation that is not detachable from the descriptive aspects of the predications 'model *X* is a representation' and 'distribution *Y* is just.' To call a model a representation or to call a distribution of goods just is to essentially evaluate the respective subject under discussion.

2.3. Thin and Thick Accounts of Representation

There are many formulations of the problem of representation. I will briefly mention three different ways of addressing it. Understood in one way, the problem lies in explicating the notion of representation. Roman Frigg, for example, divides the problem of representation into parts; one part is the "the enigma of representation," and an answer to this enigma should explain "in virtue of what is a model a representation of something else" (2006, p. 50). This can be interpreted as a search for an explication of the concept of representation.

Frigg differentiates the "problem of style" from the enigma of representation (ibid.). This problem of style has a descriptive aspect and an evaluative aspect.[24] For our purpose, only the latter is relevant. Frigg believes that the evaluative aspect addresses the question of "whether there is a distinction between scientifically acceptable or unacceptable styles" of representation (2006, p. 50). Craig Callender and Jonathan Cohen, who provide a second way of understanding the problem of representation, distinguish three relevant questions: the "constitution question," the "normative issue" and the "demarcation problem" (2006, p. 69). The constitution question asks "what constitutes the representational relation between a model and the world," and the normative issue asks "what it is for a representation to be correct" (ibid.). The demarcation problem involves distinguishing "scientific from other sorts of representation" (p. 68). So Callender and Cohen acknowledge, just as Frigg does, an evaluative question among the issues surrounding representation. However, they also stress that the question of what constitutes the representation relation is the most important issue to resolve. Their account is aimed at reducing representation to the allegedly more fundamental category of mental representation, and they therefore deny that there is a *special* problem of scientific representation. Understood in a third way, the problem of representation involves accounting for the activity of using models in order to learn about certain targets. This formulation demands an answer to the problem of representation that not only incorporates pragmatic considerations but also takes the epistemic function of representational models seriously. Because certain models represent phenomena, they can be used to shed new light on these phenomena. The fact that a model is a representation of a target seems to allow a user of the model to learn something about the target. According to the third way of addressing the problem, this is the central issue an account of representation has to explain (cf. Suárez 2004, 2015; Contessa 2007, 2013; Bolinska 2013, 2016).[25]

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24 According to Frigg, there is "a factual and a normative variant" of that problem of style (2006, p. 50).

25 Many scholars try to address the problem of representation in related but non-identical ways (cf. Giere 1988, 2004; Hughes 1997; Bailor-Jones 2003; van Fraassen 2008; Chakravartty 2010; Bueno & French 2011; Toon 2012; Weisberg 2013; Boesch forthcoming). However, it is not always clear whether these scholars belong to what I call here the thin or the thick camp of accounts of representation.

2.3.1. Thin Accounts and the Descriptive Aspect of Representation

Thin accounts of representation focus on its descriptive aspect. This is not always explicitly stated, and some accounts do not recognize this as a core feature of their views; nevertheless, there are certain telltale indications of the descriptive focus. One such indication is that some views attempt to distinguish between the problem of defining a representation simpliciter and the problem of defining an adequate representation. In this vein, Gabriele Contessa (2013) addresses the problem of representation in two steps. First he defines 'epistemic representation,' and then he defines 'faithful epistemic representation' as an extension of the first notion. Contessa and others claim that the question of what makes a representation adequate is to be answered only subsequently to the so-called constitution question (that is, the question of what makes a certain vehicle a representation in the first place). As mentioned above, Callender and Cohen distinguish the constitution question from the normative question; they argue that these topics should be carefully separated. "Our feeling is that many authors writing on models don't contrast these questions as sharply as they should. […] In our view, running these issues together is conducive to confusion" (2006, p. 69). In contrast, this chapter contends that the separation of these questions about representation may cause us to lose sight of the epistemic aims of modeling.[26] One could question whether there really is such a danger. In principle, someone aiming for a descriptive understanding of the constitution question is thereby not committed to neglecting epistemic aims of modeling. Callender and Cohen, for example, grant that there are pragmatic constraints on the use of representational vehicles in science. These constraints may be related to the epistemic aims of representational vehicles.

Other scholars also express their acknowledging stance towards separating the questions. Adam Toon and Mauricio Suárez claim explicitly that the question of the adequacy of representations should be distinguished from the problem of representation as such.

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26 There are alternative analyses of the situation of the debate. For example, Agnes Bolinska calls the focus on representation simpliciter the "Mere-Representation Priority (MRP) approach" (2015, p. 67). Her position concerning representation simpliciter and adequate representation is in plain contrast to Contessa and others: she argues that an account of successful epistemic representation should be developed *before* an account of representation simpliciter.

> It is important to distinguish the problem of representation for scientific models from a closely related question. That is the question of what makes a model accurate (or, perhaps, correct or realistic). (Toon 2012, p. 23)

> [A] good theory may provide us with insight into some of the features that are normally associated with scientific representations such as accuracy, reliability, truth, empirical adequacy, explanatory power; but again we shall not assume that this is a requirement. In other words, we shall not require a theory of scientific representation to mark or explain the distinction between accurate and inaccurate, or between a reliable and unreliable one, but merely between something that is a representation and something that is not. This presupposes a distinction between the conditions for x to be a representation of y, and the conditions for x to be an *accurate* or *true* representation of y. Both are important issues, but they must be addressed and resolved separately. (Suárez 2003, p. 226, emphasis in original)

The strategic advice proposed in the passages above is that you should first explicate what representation is. Only afterward may you ask what constitutes adequate representation or misrepresentation – if you ever raise this question at all. The danger of losing sight of epistemic aims is also not conclusively entailed by these quotes; yet, it is way much easier to overlook the aims of modeling in case one focuses on the descriptive aspect of representation if one regards the constitution question as *the* problem of representation in science like Toon does.

In contrast, the thick account that I am defending here does not address the constitution question and the adequacy question separately. I believe that the question of what makes a representation an adequate representation or a misrepresentation must be addressed in order to produce a satisfactory explanation of representation. The main reason for this, as I will argue in detail below, is that representation essentially incorporates an evaluative aspect that is due to the inherent epistemic function of models and to the normativity of the practice of modeling.

2.3.2. Thick Accounts and the Evaluative Aspect of Representation

Thick accounts of representation stress the importance of its evaluative aspect. They leave room for a notion of adequate representation or misrepresentation; in fact, they assume that a sound explanation of representation should address the question of what makes a representation adequate, as well as the question of what misrepresentation is.[27] Let me first introduce some terminology. A *representational* model is used with the intention of standing for a particular target in order to learn about the target. A *representative* model is a representational model that represents a certain target adequately in some respects, and so stands for the target as a representative in these respects. Such a model is one relatum of the relation of *adequate* representation. In general, the use of representational models as epistemic tools is related to the goals of model users. The purpose of using models is, in most cases, to learn something about the targets that are to be represented by the models; thus the goal of adequately representing a particular target is derived from the epistemic considerations that drive the activity of modeling. This epistemic context provides the background for the first argument in Section 2.4.

Another feature of the evaluative aspect of representation that thick accounts try to capture is connected to the normativity of the practice of modeling. This is related to the aims of science and to the epistemic context of modeling. Modeling, just like other practices, is a rule-based activity. Its rules and norms ensure that the agents pursuing the activity are able to come as close as possible to the epistemic aim of science, namely to learn about certain targets.[28] I will say more about this normativity in the second part of Section 2.4.

A further point to be noted is that the thick account of representation proposed by this chapter distinguishes between the two notions of model and representation. Representation is regarded as a relation between model, target, users, and purposes. Because a model is one relatum of the relation of representation it is not wise to equate models and representations. One model may be part of many different relations of representation. So, the concepts of model and representation must be kept as distinct concepts. It is not an arbitrary terminological issue to declare that representations are not to be equated with models. Any pragmatic account of representation is well-advised to make this distinction because, e.g., any change in purpose leads to there being a different relation of

27 Here, the question is not only what distinguishes adequate representation from misrepresentation but also whether there are different types of misrepresentation. A more specific question, relevant to the argument in Section 2.5, is whether any misrepresentation is in fact a representation. One might think that there are at least two classes of misrepresentations: misrepresentations that are inadequate representations in some respects and misrepresentations that are not representations at all.

28 Modeling also requires creativity and knowing-how. Of course, it is not enough to just follow certain pre-defined rules in order to reach neat results of particular modeling tasks.

representation. This dependence on purposes of users of representational vehicles is also a relevant feature of scientific representation that is missing in many cases of linguistic representation. The purpose of a user of a sentence of a scientific text does not influence the meaning of that sentence. A sentence that is used in the speech act of assertion such as a sentence about the lethal dose of a certain toxic substance is either correct or incorrect independent of the purpose of the sentence's user. The adequacy of representation in science, in contrast, is dependent on the purpose of model users.

Let me illustrate the difference between thin and thick accounts with the help of an example. The harmonic oscillator is an established model in physics, and it has many applications. I will focus on applications in the context of classical physics. The simple harmonic oscillator is derived from the central law in classical mechanics stating that force equals mass times acceleration. Together with a particular force function, the mathematical equation of the model can be deduced. For example, Hooke's law provides an equation that can be used for representing a bouncing spring. Here, a linear oscillation and a linear restoring force characterize the model, which is understood as an idealized system of a massless spring and a bouncing bob that is not subject to frictional forces (cf. Toon 2012). Another application of the harmonic oscillator is the task of representing a simple pendulum. With some simplifying assumptions in place, the same mathematical equation can be used to characterize a model of the pendulum. If the angle of swing is relatively small so that the cosine of that angle roughly equals one, the simple harmonic oscillator is also an appropriate model of the simple pendulum. Ron Giere (1988), for example, asks whether the harmonic oscillator is well-suited for representing the pendulum in an antique grandfather clock. So there are at least two potential targets that may be represented with the harmonic oscillator: a bouncing spring and a pendulum. Here we have at least two different representations with the help of one model.[29]

A thin account of representation claims that it is possible to decide whether the harmonic oscillator is a representation of the pendulum without addressing the issue of the adequacy of the harmonic oscillator as a model of the pendulum. In contrast, a thick account of representation claims that, in order for a user to decide whether the harmonic oscillator represents the pendulum, she has to ask

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29 There are other possible applications of this model. An electric circuit is a further target that may be represented with the help of the harmonic oscillator.

whether the model is good enough for the purpose at hand. If the user designates the model as a representation of the target, she is thereby evaluating the model as a good model for this particular purpose. In my terminology, such a model – that is, a good model for a particular purpose – is a representational model and a representative model of the target for the user. Note that the distinction between the notions of model and representation is crucial. The harmonic oscillator model can be used to represent many different targets. The model is one relatum of different relations of representation. In one instance the model may represent a pendulum and in another instance the model may represent a bouncing spring. Because representation is a pragmatic notion, the purposes of users are shaping the particular practices of representational modeling. The model is the tool and representation is the relation between model, target, users, and purposes (cf. Giere 2004).

The question of whether representation essentially encompasses an evaluative aspect is related to the question of whether representation is a success term.[30] Yet if representation is a thick concept, then this does not necessarily imply that representation is a success term in the *strong* sense, as I will call it. This strong sense of a success term means that any representation is completely accurate in all respects. If representation is taken to be a success term, then this can also mean that any representation involves partial success in some respects, but not necessarily complete success in all respects. I will call this sense of the notion of success term *weak*. My account of representation as a thick epistemic concept relies on and illuminates this weak sense of 'success term.' I will give arguments in favor of a thick account that deal especially with the question of the adequacy of representation. In the context of these arguments, it is natural to regard representation as a success term, at least in the weak sense. According to a thick account of representation, to call a model a representation implies that the model is positively evaluated as an adequate representation in at least some respects.

Instead of using the notions of description and evaluation in order to talk about thick concepts, one can follow Bernard Williams and speak of world-guidedness and action-guiding. Describing the idea of action-guiding, Williams stresses the prescriptive aspect of ethical concepts.

30 Other scholars also discuss the question of whether representation is a success term (cf. Chakravartty 2010, p. 209f.; Knuuttila 2011, p. 264f.; Contessa 2013, p. 12).

> Any such [thick] concept [...] can be analyzed into a descriptive and a prescriptive element: it is guided round the world by its descriptive content, but has a prescriptive flag attached to it. It is the first feature that allows it to be world-guided, while the second makes it action-guiding. (2006, p. 141)

Williams uses the notion of world-guidedness to refer to the descriptive aspect of thick ethical concepts. I will apply this notion to representation in the sciences and will argue that, in the context of scientific modeling, world-guidedness not only supports a descriptive view of representation but also allows one to take the evaluative aspect of representation seriously.

With regard to scientific representation, world-guidedness means that representations cannot be established merely by fiat and that features of a model must correspond to features of a target in order for the model to represent the target adequately. As Anjan Chakravartty notes, the phenomenon of representation in the sciences is not a purely conventional matter:

> [I]n many contexts, [...] representation is something that is often established merely by *fiat*. [...] In the sciences, something more than merely wishing it were so, or deciding it is so, is involved in making things such as these [models] into representations of their target systems. In debates concerning accounts of scientific representation, it is these latter kinds of things that are intended. (2010, p. 200f., emphasis in original)

Model-based representation is guided by the world. Adequate representation is the goal of the activity of modeling – and is at the same time a prerequisite for a model to deliver knowledge about a target. Because of that representation involves evaluation as will be argued in detail below.

Outside the sciences, representations may function differently. For example, certain linguistic representations, such as convenient definitions or literary representations, come into being through a creative act; they do not have to relate to facts in the world. These representations are less – or maybe even not at all – world-guided.[31] Representations that relate to certain facts are world-guided. In those cases the vehicle can be used to gain understanding about the target only if vehicle and target stand in a relation of fit to each other.

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31 Of course, the sentence about the lethal dose of the toxic substance mentioned in the previous section is an example of a sentence that is world-guided. The point that I am stressing here is that linguistic representation per se does not involve world-guidedness.

Let me now turn to my arguments for a thick account of representation. First, I will consider the epistemic aims of modeling and the connection of these aims to evaluations made by model users. Second, I will consider the normativity of the practice of modeling.

2.4. Arguments for a Thick Account

2.4.1. The Epistemic Aims of Modeling

The line of argument of this subsection is in a nutshell the following. First, there are epistemic aims in science. By representing, model users attempt to learn about targets. Second, representation is world-guided. One only can learn from using models about targets if there is a relation of fit between models and targets. Third, evaluations are conditional on the attempt to learn. A model user that attempts to learn from a model about a target has to evaluate the fit between model and target. Thus, only if the model user positively evaluates the fit, it is reasonable for her to take the model as an epistemic tool for learning about the target – that is – as representative of the target. Let me elaborate.

Scientific modeling is driven by epistemic considerations. We model certain phenomena in order to learn something about the world. This general purpose of modeling defines the epistemic function of representational models. More in particular, model users may try to achieve various specific goals. For instance, representational models are used to gain understanding about particular targets. For example, the harmonic oscillator can be used to determine the period of oscillation of a particular bouncing spring. According to the model, this period of oscillation is equal to 2π times the square root of the quotient of the mass and the spring constant of the spring in question. The harmonic oscillator is only chosen to represent a particular spring if the model user deems it a good model for this specific purpose. Given that the user approves of it, that means that the model is considered by the user to adequately represent the target; the model is a representative model for this user, given her purposes.

Models, such as model organisms and scale models, also have experimental uses involving the manipulation of systems. Instead of experimenting with a target directly, one can make the model the object of study. This is done for several reasons. The target may not be accessible, or there may be ethical reasons for preferring the model. In some cases, it is simply much cheaper to experiment on the model than to investigate the target directly. In any case, the choice to use a model involves an evaluation. You only choose a model if you think that it is appropriate for your particular purpose. This choice involves the assumption that the model is representative of the target of interest. When a scientist experiments on a model, the results of her experiments can be translated into claims about a target, only if the model is an adequate representation of the target.

Even in pedagogical contexts, the epistemic function of models is relevant. As a paradigmatic situation, imagine a chemistry teacher instructing a student with the help of a model of a particular type of molecule. The student is able to learn something about the target during her engagement with the model. For example, she can easily see how many hydrogen bridge linkages a certain organic molecule allows. But she can learn something about the target only if the model adequately represents it.[32]

In general, then, users are interested in any given model because they have an underlying interest in a target that is to be represented by that model. The various practices of representational modeling are bound together by the epistemic function of models – that is, by the idea that a user can learn something about a target by using a model. Again, this is only possible if there is a certain relation of fit between model and target. To use terminology from the previous section, the world-guidedness of representation requires this relation of fit. Therefore, the user has to evaluate the model; this is especially true if she has to choose between different models. The evaluation of fit between model and target is an essential component of the practice of representation. Only if there is a relation of fit can reasoning about the model be translated into reasoning about the target. Because modelers want to learn about the target from studying the model, they have to evaluate the fit between model and target. The condition of fit can be spelled out in the following way: models have to be representatives of targets in order to license inferences about those targets. When models represent targets adequately, in relation to epistemic aims and to particular purposes, knowledge about the targets can be gained by studying the models. This close connection between epistemic aims, evaluation of models and the adequacy of representation speaks in favor of a thick account of representation. Representation is a pragmatic notion and the purposes of model users are crucial for the

32 There are also many pedagogical uses of models that do not straightforwardly aim at representing particular targets. Often, the teacher will be satisfied if the student learns something about the model itself.

individuation of particular representations that are carried out with the help of models. Because there is a particular purpose for any representation, a model user has to evaluate the fit between model and target according to the purpose. Only when a model user evaluates a model positively, the model can rightly be called a representation, i.e., representative of a particular target.

To conclude this subsection, because the representational use of a scientific model has the inherent goal of adequately representing a certain target,[33] model users, for this reason, evaluate their models according to standards determined by their particular purposes. This means that representation, in addition to its descriptive aspect, has an evaluative aspect that is tied to the function of models as epistemic tools. The practice of modeling involves an evaluation that is related to the necessary world-guidedness of representation. Like the ethical concepts of courage and justice, this concept of representation is thick. The epistemic evaluation that accompanies modeling can be expressed with the term 'representative' – an adjective that characterizes models or other vehicles that are successfully used to represent a corresponding target.

2.4.2. The Normativity of the Practice of Modeling

A related argument for a thick account of representation focuses on the normativity of science, and of modeling in particular. Science is a rule-based normative practice per se, and the following definition of practice exemplifies some of its relevant properties.

> By a 'practice' I am going to mean any coherent and complex form of socially established cooperative human activity through which goods internal to that form of activity are realised in the course of trying to achieve those standards of excellence which are appropriate to, and partially definitive of, that form of activity. (MacIntyre 2007, p. 187)

Modeling is a rule-based activity that has standards of excellence. The practice is therefore endowed with an inherent normativity, and the source of this normativity lies in the agents of the practice of particular sciences. These agents

33 In its focus on the goal of representation, my view echoes that of Bolinska (2013). She claims that the aim of faithfully representing a target is a necessary and sufficient condition for the 'informativeness' of a representational vehicle. Such informativeness is an essential property of epistemic representation. However, Bolinska explicitly states that epistemic representation is not a success term, in either a strong or a weak sense.

evaluate the outcomes of their practices with comparison to the standards of excellence. One specific set of rules in science is constituted by the binding methodological norms in the disciplines; additionally, there exist established systems of criticism among peers. In such contexts, you cannot establish a representation by fiat. As argued in Section 2.3.2, then, representation in science is not a purely conventional matter along the lines of stipulative definitions of certain terms or symbols. When asking whether your model does or does not represent a phenomenon, you cannot simply declare that it does. When submitting a paper on a model that you propose as representing a phenomenon, for example, you have to convince your colleagues to get it published. You have to provide evidence that is based on the model and on salient facts relating to the world around you. A presupposition of these attempts to convince your colleagues is that you evaluate your model. Your model will only convince a colleague if she also sees it as good enough according to a certain standard. A relation of fit between model and target is the gold standard of any successful modeling. Using the terminology we borrowed from ethics, representational modeling is world-guided. The upshot is that not every representational model counts as a representative model, because not every model is one relatum of a relation of adequate representation. The goal of adequately representing a target lies at the heart of the practice of modeling. Without that goal, the representational use of models would make no sense at all. Every representational use aims at that goal – and so the thick notion of representation is not just an optional surplus feature that may or may not be added to the alleged descriptive core of representation. In fact, the thick notion of representation guides the practice of modeling. The norms that are codified in methodological rules motivate scientists in their activities. Their goal is to come as close as possible to the epistemic aim of science, namely to learn about certain targets. So the understanding of representation as encompassing evaluative and descriptive aspects, and especially the primary importance of the evaluative aspect, is strongly supported by the practice of science.

In the following section I will discuss potential objections to a thick account. I will start with the Argument from Misrepresentation. This argument presupposes a genus-species model of the relation between representation and misrepresentation. At first, I will present the argument and, afterwards, I will give several answers to the argument that a defender of a thick account might endorse.

2.5. Objections to a Thick Account

2.5.1. The Case for a Thin Account: The Argument from Misrepresentation

This argument for a thin account of representation focuses on misrepresentation rather than adequate representation. It starts with the idea that if the job of an account of representation is to study models that are actually used, many of which have shortcomings, then a focus on the adequacy of representation appears to be insufficient. Instead, an account of representation should also encompass misrepresentation. What adequate representation and misrepresentation have in common is a descriptive element – the genus of representation; because this descriptive element is at the core of a thin notion of representation, goes the argument, the thin account is the correct one.

To summarize the Argument from Misrepresentation: its premises are that i) most scientific models are misrepresentations and that ii) every misrepresentation is nonetheless a representation. Therefore, if you want to study all kinds of models in scientific practice, then it is not wise to focus on the adequate representations; doing so will only give you access to one species of the genus of representation. This genus is a thin descriptive concept that is contained in both misrepresentation and adequate representation.[34]

In order to argue for the first premise, some proponents of thin accounts of representation stress that most or even all models misrepresent their targets in one way or another. “Most models are inaccurate (or incorrect or unrealistic) in some way” (Toon 2012, p. 23). Indeed, no model seems to be the “perfect model” (cf. Teller 2001). Modeling involves idealization, approximation, simplification and other techniques that could yield incorrect inferences about targets. So

[34] This genus-species model of representation and misrepresentation is mirrored in debates about thick ethical concepts. Thick ethical concepts are more specific than thin ethical concepts. And, conversely, thin concepts are more general than thick concepts in their applicability. Under separationist assumptions about thick concepts, this may generate a genus-species model of the distinction: a thick concept might be a species of a certain thin concept (which functions as a genus). ‘Good’ could be seen as a genus for various species such as ‘courageous’ or ‘brave’ (cf. Tappolet 2004). According to a separationist view, a thick concept consists of an evaluative element and a descriptive element; the descriptive element can be interpreted as the distinguishing feature of a species concept, the so-called *differentia*. So the thin concept and the descriptive element become the genus and the differentia of the thick concept that is treated as a species concept (cf. Kirchin n.d., Ch. 3).

scholars often stress that it is “a fact that all models contain significant falsehoods” (Reiss 2012, p. 44). Even these misrepresenting models might represent the targets adequately in some respect; yet in this reasoning the focus is on the ways in which models fall short, and the conclusion is that most scientific models are misrepresentations. The second premise of the argument is that every misrepresentation is nonetheless a representation. As Bas van Fraassen and Agnes Bolinska independently claim, “Misrepresentation is a *species* of representation” (cf. van Fraassen 2008, p. 15; Bolinska 2013, p. 222, my emphasis). Their use of the notion of species to describe the relation between representation and misrepresentation stresses one aspect of the picture of representation as a genus concept. Here the genus of representation is an alleged descriptive concept, and the species concept is misrepresentation. A second implied species concept is the concept of adequate representation.

What can the supporter of a thick account of representation answer to this argument? An initial response might be that the notion of misrepresentation is as evaluative as the notion of adequate representation. Both ideas presuppose that a user has to evaluate a model before she can declare it to be either a misrepresentation or an adequate representation. However, the thin theorist might answer that she is focusing on the genus concept of these two species concepts of misrepresentation and adequate representation. Thus, if she regards misrepresentation as a species of a descriptive genus concept and she acknowledges that the differentia of the species concept of misrepresentation involves an evaluation, she may even consent that misrepresentation is evaluative.

Let me try a second reaction to the Argument from Misrepresentation, one that is initially directed against the first premise. Briefly, it goes like this: the fact that a model may be a misrepresentation in one respect does not mean that it is a misrepresentation in all relevant respects. A more detailed answer is the following one. The ability to say something illuminating about misrepresentation is an important virtue of any account of the problem of representation, and it is often mentioned as a requirement for dealing with this problem (see, e.g., Frigg 2006; Knuuttila 2011; Frigg & Nguyen 2016). According to many scholars, representation is at least a triadic relation among models, targets, and users. And perhaps there are further relata to be added to this relation; candidates for other relata are purposes, commentaries and audiences. If models are called either representations or misrepresentations, then this has to be conditionalized on at least one further relatum. Wendy Parker stresses this point when she observes that speaking of the adequacy of models is a rather ambiguous mode of description. Where representations are concerned, Parker proposes using the notion of adequacy-for-purpose instead of the more general notion of adequacy (cf. Parker 2010; see also Bolinska 2016). This requirement of adding the condition of purpose to adequate representation is just as relevant for misrepresentation. No model is an adequate representation or a misrepresentation in itself, as these terms only make sense in the context of a specific purpose. So the first premise of the argument has to be revised as follows: most models misrepresent their targets given the various purposes involved. This leads to a relativization of the first premise. Models can be misrepresentations and adequate representations of the same target at the same time. According to one purpose, model *X* is an adequate representation of *T*; according to another purpose, *X* is a misrepresentation of *T*. So it does not follow that models that have shortcomings cannot represent their targets adequately relative to a purpose. A misrepresenting model in one respect is in many cases simultaneously an adequate representation in another respect. Even if the first premise is true, the conclusion that it is wrong to focus on the adequacy of representation does not follow.

A third line of argumentation is directed against the second premise, which states that a misrepresenting model of a target is nonetheless a representation of that target. There are two related considerations that are used in the following reply to the second premise. First, a misrepresenting model is a scientific representation not because it is a misrepresentation in one respect but because it is an adequate representation in another or even some other respects. This is part of a thick account of representation and in the following response this first point derives from the preferred thick view. Second, if a model were misrepresenting a target in all relevant respects, then it might not be considered a representation at all. The first point weighs against a certain interpretation of the premise, which seems to imply that misrepresentations are representations because they are misrepresentations. If one assumes that the set of representations is divided into misrepresentations and adequate representations, and if one further assumes a purely descriptive perspective, then this might be correct. However, a model is not a representation solely in virtue of being a misrepresentation. A model is a representation because it is used with a certain epistemic goal and because a model user attempts to establish a relation of fit between a representational vehicle and a particular target system. This attempt involves an evaluation of the fit between model and target. A misrepresenting model that is still assessed as a scientific representation may on the one hand misrepresent the target in one respect but on the other hand may still adequately represent the target in another respect. To invoke the second point, a completely negative evaluation of the fit between model and target may lead to the insight that the attempted representation is in fact not a representation at all. A model can only be rightly called a representation of a target if that model is at least in some respect an adequate representation of that target. Identifying the different types of misrepresentation is relevant for the correctness of the second premise. If there is a type of misrepresentation that is a complete failure, and if this type of misrepresentation is not regarded as a representation at all, then the second premise is refuted. An example of a model that is a complete failure is hard to give. Examples from the history of science that are nowadays regarded as failures may come to mind. For example, the phlogiston model of combustion or the model of the ether may be mentioned. Let us look at the phlogiston model, first. According to this model of combustion, materials that are burnt release a particular substance, namely phlogiston. As such a substance does not exist the model seems to be a failure. In this example of the model of phlogiston one might try to find certain representative aspects, though. If one reinterprets the model as a model that, first of all, captures a nomological structure and one neglects the commitment to a substance of phlogiston then it might be adequate to a certain extent (cf. Ladyman 2011). So, one could invoke the first point again, namely the point about a misrepresentation being in one aspect a failure and in another aspect an adequate representation. The ether model may be a more viable candidate for a model that is a complete failure. Chakravartty (2010) discusses the case of a model of the ether, in which he stresses the importance of the distinction between a model and a representation. To him the model is not a representation. If Chakravartty is right then the model of the ether is an example for a model that is a failure and that is not a representative model.

> We discover that a concrete model of the elastic solid ether, for example, while no doubt a scientific model, is not a representation after all, upon discovering that there is no such thing as the ether. One of the two relata of the intended representational relation is absent in this case. (Chakravartty 2010, p. 209)

The model of the ether is not a representation of the ether, given that the purpose of the model is to learn about the medium of particular wave phenomena. Thus the concepts of model and representation can be distinguished. Chakravartty gives a further indirect argument:

> [I]f all merely intended scientific representation is genuine representation, then the term 'scientific representation' connotes nothing distinctive, for 'representation of

> the ether' would seem to mean nothing more nor less than 'model of the ether' [...]. One might plausibly maintain, however, that the term 'scientific representation' should connote something other than the mere acknowledgement that something is a model. (2010, p. 210f.)

The surplus of the term 'scientific representation' over the acknowledgement that something is a model is the positive evaluation that the first term contains. Because of that there is a difference between calling *X* a model of *T* and calling *X* a representation of *T*. If the foregoing reasoning is correct, the concrete model of the elastic solid ether is not a representation of the ether. The thick theorist is able to account for the distinction between a model of *T* and a representation of *T*. To call a certain vehicle a representation is to evaluate the vehicle, whereas to call it a model does not involve such an evaluation.

The conclusion of this section is that the Argument from Misrepresentation does not substantiate a thin account of representation. A defender of a thick account may still claim that representation essentially has an evaluative aspect and that the concept of representation is not a purely descriptive one.

2.5.2. Objections from Model Testing

The Argument of the Epistemic Aims involves the claim that a model user has to approve of a model in order to declare it a representation. One might object to this claim. There are cases where scientists do not have to approve of models but still use them as representations. An example is the case of two conflicting models that are tested for which of the two has the better fit to a target. This is the objection from suspended judgment.

There is another claim contained in the Argument of the Epistemic Aims, namely that it is only possible to learn about a target from using a model in case that there is a certain relation of fit between model and target. One might object that testing models themselves might produce knowledge, even when the models display a poor fit to the targets. To use the terminology introduced in Section 2.3.2, the question is whether one can learn from using a model even when the model is not a representative model. This is the objection from learning.

i) Suspended judgment. A scientist testing two conflicting models may suspend judgment about which is the better model of the two. It is true that, in principle, the scientist does not have to approve of the models. However, the choice of selecting these two models as candidates for testing can be accounted for with a preceding evaluation of these models by the scientist. There may have been many other models that could have been chosen as candidates but the choice to test just these two models needs a reason. If a preceding evaluation is needed for the choice, then the choice of the two models already presupposes an evaluation of the models in comparison to other models. The two models are attempted representations in the sense of being representational models but it is not yet decided which of the two is the favored model. So, neither of the two models is a representative model for the scientist pursuing the test. One could object to the use of the term 'representational' here, since it was introduced as meaning 'used with the intention to adequately represent.' The scientist doing the test only intents to test the models, she does not aim at representing a target adequately, one may say. In this case a proponent of a thick view may reply that if the scientist testing the models does not aim at representing a target adequately, then the models do not function as representational models.

ii) Learning. One might learn something from using a model even if the model does not adequately represent a target. Here, it is crucial to distinguish between knowledge about models and knowledge about targets. Of course, one can learn a lot about a model by testing the model itself. For example, one might test the model for consistency or one might test whether a certain inference does follow from the model. In the first case, one might learn whether the model is consistent or not. In the second case, one might learn whether the inference from the model is valid or not. These two points speak only for knowledge about models, though. Knowledge about targets is hardly to come by in case that the models do not have a sufficient fit to the targets. Assuming that knowledge about targets requires inferring justified claims about targets, one can question whether a model user is able to infer justified claims about a target from using a model, which does not adequately represent this target. If the model user cannot derive justified claims about the target, she cannot reach knowledge about the target. At best, the model user can reach justified claims about the model itself. However, the translation of these claims about the model into justified claims about the target requires a sufficient fit between model and target.[35] As the thick account of representation requires, facts about a target can only be learned from using a model in case that the model adequately represents the target.

35 I elaborated on the distinction between knowledge about models and knowledge about targets in more detail at another place (cf. Poznic 2016; see also Chapter 5).

2.6. Conclusion

Taking inspiration from the debate about thick ethical concepts in metaethics, I explained the difference between thin accounts and thick accounts of representation. The former focus on the descriptive aspect of representation, whereas the latter underscore the importance of its descriptive and evaluative aspects. I made a case for a thick account of representation, presenting two linked arguments for such an account. The first relates to the epistemic aims of modeling; the second relates to the normativity of the practice of science. These arguments support the preferred thick account of representation that treats its evaluative aspect as inseparable from its descriptive aspect. According to these arguments, the representational use of a scientific model has the inherent goal of adequately representing a certain target, and this goal is established by the epistemic function of representational models. For this reason, model users have to evaluate the fit between models and targets according to the goal of adequately representing targets. It would be impossible to explain what representation is without taking the goal and the evaluation into account. I discussed possible objections to a thick account. First, an argument that supports an opposing view: the Argument from Misrepresentation favors a thin account of representation. My refutation of this argument showed that scientific practice supports a distinction between model and representation, and that the thick account has more resources than the thin account to explain this distinction. Second, I answered the Objections from Model Testing.

The conclusion of this chapter is that the Argument from Misrepresentation fails to conclusively establish a thin account of representation. In fact, the epistemic aims of modeling and the normativity of the practice of science support a thick account of representation. Representation has, in addition to its descriptive aspect, a straightforward evaluative aspect. Therefore, the question of adequacy and the issue of misrepresentation cannot be avoided. They are fundamental to any account of representation.

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3 Representation and Similarity: Suárez on Necessary and Sufficient Conditions of Scientific Representation

Abstract

The notion of scientific representation plays a central role in current debates on modeling in the sciences. One or maybe *the* major epistemic virtue of successful models is their capacity to adequately represent specific phenomena or target systems. According to similarity views of scientific representation, models should be similar to their corresponding targets in order to represent them. In this chapter, Suárez's arguments against similarity views of representation will be scrutinized. The upshot is that the intuition that scientific representation involves similarity is not refuted by the arguments. The arguments do not make the case for the strong claim that similarity between vehicles and targets is neither necessary nor sufficient for scientific representation. Especially, one claim that a similarity view wants to uphold, still, is the following thesis: only if a vehicle is similar to a target in relevant respects and to a specific degree of similarity then the vehicle is a scientific representation of that target.

Contents

3.1. Introduction

The activity of modeling primarily aims at representing certain target systems. It seems to be obvious to some philosophers and to many scientists that models have to be similar to their corresponding targets in order to represent them. Although the notion of similarity has its defenders and quiet friends there are a great number of opponents. In philosophy of science's debates on representation and modeling, Mauricio Suárez's arguments against similarity views of scientific representation are frequently mentioned. In detail, these arguments are put forward in Suárez (2003). Although they are often cited, they are but rarely discussed extensively.[36] Are they really knockdown arguments against any similarity account of representation in the sciences? In particular, one question raised in this chapter is whether the arguments show that it is impossible to establish an account of scientific representation that comprises similarity as a necessary condition for a vehicle to represent a target. In the following, I will first give a concise survey of the background of these debates (Section 3.2). Secondly, Suárez's own position will be characterized briefly and I will discuss a distinction made by Suárez between two different kinds of relations, namely the distinction between *means* and *constituents* of representation (Section 3.3). Afterwards, I will introduce Suárez's reductionist and non-reductionist opponents and I will also discuss his arguments against similarity as a sufficient condition for representation (Section 3.4). Finally, I will analyze his arguments against similarity as a necessary condition for scientific representation (Section 3.5) and the last paragraph contains a concluding discussion (Section 3.6).

3.2. Theories of Scientific Representation

The overall aim of using models in the sciences is to gain epistemic benefits. The activity of modeling has an epistemic function and this function seems only to be fulfilled by models that are in some appropriate way connected to reality. It almost seems inevitable to ask: how can scientists gain knowledge of the natural

36 One exception is Bueno & French (2011) and, there, the authors deal with Suarez's arguments as challenges to their own formal account of representation. In Contessa (2007) it is argued that Suárez's arguments should be interpreted as only opposing conceptions of faithful epistemic representation in contrast to conceptions of epistemic representation. I assume that the notion of scientific representation that I am elaborating on is neither equivalent to epistemic representation nor to faithful epistemic representation in Contessa's sense.

world by studying models if these models do not share certain features with their target systems? Notions of resemblance or similarity appear relevant when explaining why scientific models can be used to foster knowledge of certain phenomena.[37]

In this vein, several accounts of representation have emerged in the last years. They focus on the information a representational vehicle is able to convey. These 'informational' views try to explain what representation is by pointing to similarity relations between vehicles and targets, at least in one way or the other (cf. Chakravartty 2010). There are different variants of this position; some use the formal notions of isomorphism, partial isomorphism, homomorphism[38], or other mathematical mappings. Others speak of analogies, similes, or resemblances. Either way, the relation between vehicles and targets comprises structural similarities in most cases.

In seeming contrast to these informational views, other approaches focus on the activity of representing. These approaches specifically start their study of representation with the *use* of representational vehicles. According to these views, the intended uses of scientific models or other representational vehicles by scientists are prior to any established relation of representation. These views are labeled differently. 'Pragmatic,' 'deflationary' or 'functional' are all adjectives that are used to name these particular views. They set the task of studying the use of a model in specific contexts of application. A recent defense of such a deflationary view is put forward by Bas van Fraassen and his main contention is a so-called 'Hauptsatz' of representation: "There is no representation except in the sense that some things are used, made, or taken, to represent some things as thus or so" (van Fraassen 2008, p. 23). Although some see a conflict between the two perspectives on representation they can be regarded as complementary rather than as excluding each other (cf. Chakravartty 2010). One reason is that only if there is a certain informational connection between target and vehicle then the preferred use of one model over another in order to learn about the

37 I use 'similarity' and 'resemblance' as synonymous and I will follow Suárez's characterization of similarity. A vehicle and a target are similar if and only if they share some of their properties (cf. Suárez 2003, p. 227).

38 There is a debate on whether homomorphisms are instances of similarity. Because similarity is reflexive and symmetric and homomorphism is not, as Bartels (2006) argues, his homomorphism account of representation evades problems that a similarity account faces. Chakravartty (2010), on the other hand, subsumes homomorphism accounts to the informational camp and claims that homomorphism can be described in terms of structural similarity.

target could be justified. In order to answer questions of why one model is a better representational vehicle than another one an informational standpoint is needed. And on the other hand, the question of whether a certain model is a good representation as such is ambiguous. A representational vehicle like, e.g., the harmonic oscillator can be used to model different kinds of phenomena for different purposes. Here, a standpoint, which incorporates the study of specific uses, is needed in order to individuate a specific representation that is achieved with the help of a model.

3.3. Suárez's Inferential View and the Means of Representation

Suárez endorses a so-called 'inferential' account of scientific representation that is devoted to the practice of model building. He notices a "diverse range of models and modeling techniques employed in the sciences" (Suárez 2010, p. 92). In order to understand the activity of scientists it is vital for this account to study actual uses of models in specific contexts of application. Furthermore, the purposes of scientists that use and develop models are of highest relevance according to this position. Simultaneously the study of general properties of representational vehicles or general relations between these vehicles and their respective targets is shifted to concrete relations that scientists actually employ when modeling a phenomenon. The inferential conception is characterized by two conditions for a vehicle to represent a target. These conditions are meant to provide only 'surface features' instead of universal necessary and sufficient conditions that are present in every instance of scientific representation (cf. Suárez 2004, p. 771). These two features are (a) the *representational force*, and (b) the capacity of the vehicles to allow inferences about the respective target systems, the *inferential capacity*. The first condition is grounded in the scientists' practice of using representational tools like models or other vehicles. In the course of this practice scientists establish an asymmetry in the relation between models and targets. Beyond that, the norms of the respective community ensure that there is a restricted determination of targets of these representational models. Suárez calls the asymmetry in the relation the 'essential directionality' of representation (Suárez 2004, p. 767). This directionality assures that the force consists in the models pointing to the targets and not vice versa (cf. Suárez 2010, 98). The second condition of inferential capacity should assure that via studying representational models scientists are able to learn something about the respective target systems. Vehicles should allow inferences about these target systems.

Suárez agrees with Chris Swoyer that successful models should allow *surrogative reasoning* (cf. Swoyer 1991). Besides, this phenomenon of representational vehicles, to allow inferences about their targets, is a feature stressed by other accounts of representation, that could be subsumed either under the label of informational or under a label of a use account (cf. Contessa 2007; Hughes 1997).

A related value of representational vehicles that Suárez stresses is the cognitive value of 'objectivity.' According to Suárez, scientific representations are cognitively valuable because they "provide us with specific information regarding their targets" (Suárez 2004, p. 772). The representations possess this property of objectivity, which means that they enable understanding of certain phenomena or targets. The objectivity of representation guarantees that one can learn something about the world via studying representational vehicles. Because of that feature, scientific representation cannot be established through mere stipulation as, for example is possible in cases of linguistic representations (cf. Suárez 2003, 227). Beyond that, representational vehicles must possess an internal structure and their parts and relations must be interpretable in terms of the target's parts and relations.[39] Furthermore, there has to be a standard for correctness of inferences from the vehicles to the targets that is grounded in the practice of a certain scientific community (cf. Suárez 2010, p. 98).

Suárez makes a distinction between *means* and *constituents* of representation and this distinction underlies at least four of his arguments against similarity views of representation. He is looking for an account of the means of representation whereas he portrays some or maybe all of his opponents as trying to explicate the constituents of representation. This distinction is unfortunately not well explicated. Very roughly the difference seems to be one between a constituent as a general relation and a means as a specific relation. Looking for a more precise characterization of the contrast leaves one with puzzling hints only. Suárez gives the following definitions of these two kinds of relations.

> At any time, the relation R between A and B is the means of the representation of B by A if and only if, at that time, R is actively considered in an inquiry into the properties of B by reasoning about A. [...] The relation R between A and B is the

39 This feature is also stressed by Contessa. In his *interpretational* account of representation an interpretation of a model in terms of a target is the defining constituent of the notion of epistemic representation (cf. Contessa 2007).

> constituents of the representation of B by A if and only if R's obtaining is necessary and sufficient for A to represent B. (Suárez 2003, p. 230)

The means may be interpreted as a concrete token of a representational relation, because Suárez characterizes it as the relation between a vehicle *A* and a target *B* that is actively considered in an inquiry. The constituent as a general relation between vehicle and target may be interpreted as a relation type in contrast to a token. Or perhaps the constituent may be seen as a universal in contrast to a means as a particular. It is not clear whether the first contrast, between type and token, the second one, between universal and particular, or even a further contrast is aimed at. There is another quote that makes it even more difficult to understand what Suárez means by 'means':

> [T]here may be a great variety of means by which representation does its work: isomorphism and similarity are just two common ones, but there are others, such as exemplification, instantiation, convention, truth. (Suárez 2003, p. 229)

Here, Suárez lists examples for other means. As Suárez defines means as relations between vehicles and targets this raises the question in which ways instantiation and convention are relations between these two relata. Furthermore, he points out that "an object *A* [...] may hold more than one type of relation to another *B*, but at any one time only one of these will be the means of representation" (Suárez 2003, p. 229). From this follows that even if one examines a single pair of model and corresponding target it is possible that different scientists may actively consider different relations between these two relata. Therefore one model can yield various means of representation depending on the scientists using that model. Even a single scientist is able to consider different relations after each other. These relations are then means that must be taken with an index of time and in order to differentiate them from other scientists' means there must be a second index for users as well.

Suárez uses the notion of means in his first argument against informational views of scientific representation. The *Argument from Variety* should reveal that there are many different means of representation that cannot be accounted for by similarity or structural views of representation. Suárez uses different examples of apparently successful scientific representations in order to show that the means of representation are not captured by a similarity or a structural view in each case. For example, he claims that the case of a scale model of a bridge shows the inadequacy of structural views. Here, the means is a similarity relation and therefore a structural view cannot account for this means.

> It is by reasoning on the basis of these similarities that the source [the vehicle, in my terminology] does its representational work. […] By contrast isomorphism, which is well-defined only as a relation between mathematical structures, does not apply directly to the relation between two physical objects described in case 1 [The case of scale model and bridge]. But it does apply to some abstract structures that are exemplified by these two objects, such as their geometric shape. […] The means of the relation of representation are not in this case captured by the [structural] conception because this conception misidentifies its relata, which are the physical objects themselves, and not the structures exemplified. (Suárez 2003, p. 231)

In contrast to the scale model, another case, a graph of a bridge, can be accounted for by the structural view because here isomorphism is the means of representation.

> [A] piece of paper containing the graph of a bridge is only similar to the bridge it represents with respect to the geometric shape and proportions between the different points; nothing else is interestingly similar. This "similarity of structure" is better captured by the alternative [structural] conception […]. Maps, plans and graphs are typical cases where isomorphism is the means of scientific representation. (Suárez 2003, p. 231)

So in one case a similarity view is the appropriate account and in the other case a structural view is the better account. None of the two is the better account for both examples. Beyond that, Suárez also gives two more examples, the Billiard Ball Model of a gas as a representation of a system of molecules and the representation of a quantum system by a quantum state diffusion equation. Also these cases purport to show that none of the accounts can explain all instances of representation.

> Although similarity and isomorphism are among the most common means of representation in science neither one, on its own, covers even nearly the whole range. (Suárez 2003, p. 231)

The conclusion of the argument is that no single view is capable of explicating the variety of means of representation. "[I]t follows that neither [the structural] nor [the similarity view], on their own, can account for the means of scientific representation" (Suárez 2003, p. 229). There is the problem of interpreting the distinction between means and constituents and the missing proper understanding of means. It is difficult to evaluate Suárez's argument and its conclusion. Nevertheless, the following comments may be made. Why are the exemplified structures in the case of the scale model and bridge not possible relata of the representation relation? At first sight, it seems that both views could say something meaningful about this case of representation. The second case seems to point in the same direction. Here, also similarity and structural views may both be applicable. Suárez himself diagnoses a similarity between points on paper and the geometric shape of the bridge. Because the similarity is a structural similarity and it is only limited to a geometrical shape the structural view is assessed as 'better' as the similarity view. However, this is not reason enough to exclude the similarity view.

Consider again the first case of the scale model of a bridge. If one takes a means as a relation that is relative to a user then it could be the case that one user *X* really considers a structural relation between a structure that is exemplified by the scale model and a structure that is exemplified by the bridge. Another user *Y* might consider a property that the model and the bridge share, say the ratio of the height to its length. Does this really show that there are different relations that are used in the activity of representation in case of user *X* and in case of user *Y*? If the question is answered in the affirmative then we need at least two theories of means of representation, namely a theory of the means of user *X* and a theory of the means of user *Y*. If there are different moments in time to take into account and other user dependent means, as well, then the number of theories might be multiplied even more. This reasoning shows that such an understanding of means leads to the difficulty of finding a single or even a small number of theories of the means of representation. There is no reason to show that a similarity view and a structural view of representation are not capable of explaining both these successful representations of a bridge with the help of various vehicles. Beyond that, if one asks what unites these phenomena then a similarity view might provide a good answer. According to a sophisticated similarity view these two means of user *X* and *Y* could be seen both as forms of similarity. The best explanation of scale model and bridge is then that it is a case of representation because model and bridge stand in the relation of similarity to each other. *Prima facie*, the Argument from Variety is not convincing.

3.4. Substantive Reductionist Views and Arguments Against Sufficiency

3.4.1. Reductionist and Other Similarity Views

The major group of opponents that Suárez faces is constituted by adherents of reductionist views on representation. These views focus on the relation of representation and they "aim to radically naturalize the notion of representation" (Suárez 2003, p. 225). To naturalize a concept in this context amounts to reducing it to facts. In order to do that, the reductionist has to show that the concept does not depend upon purposes or value judgments of agents. Furthermore, Suárez characterizes the reductionist views as 'substantive.' A substantive view tries to formulate a single necessary and sufficient condition of scientific representation. The substantive view poses a constitutional question regarding representation, namely: what is the relation between a vehicle and a target that constitutes representation? (cf. Suárez 2010, p. 92).

Suárez strongly argues against the explication of representation with the help of 'similarity' or related notions. He attacks a position that can be regarded as an *ideal type* of a similarity view. According to this position a vehicle *A* represents a target *B* if and only if *A* is similar to *B*. In fact, he faces two opposing positions, the position using the aforementioned slogan and another one that uses 'isomorphism' instead of 'similarity.' He labels these positions as *Sim* and *Iso*, respectively, and they read as follows:

> *Sim*: A vehicle represents a target iff the vehicle is similar to the target.
>
> *Iso*: A vehicle represents a target iff the structure exemplified by the vehicle is isomorphic to the structure exemplified by the target. (cf. Suárez 2003, p. 227)

As I reconstruct Suárez, he delivers six arguments against these two positions of *Sim* and *Iso*: the Logical Argument (1), the Argument from Mistargeting (2), the Non-Sufficiency Argument (3), the Argument from Quantitative Inexactness (4), the Non-Necessity Argument (5) and the Argument from Variety (6). I divide the arguments into three groups. One group is constituted by arguments directed at similarity as a sufficient condition for representation. The second group encompasses arguments against similarity as a necessary condition. And the third one consists of the Argument from Variety already discussed in the foregoing section. Suárez refers to the arguments as touchstones for a theory of representation. He claims for example that a "satisfactory theory of representation must defeat these [...] arguments" (Suárez 2004, p. 768).[40] The arguments are in the

40 In this quote and in the original paper he speaks of five arguments. I count them as six because I divide his originally called *Argument from Misrepresentation* into two, namely *Argument from Mistargeting* and *Argument from Quantitative Inexactness*. This is motivated by

first place meant to counter naturalistic reductions of representation. However, Suárez does not use the arguments for this purpose only. In the 2003 paper and in later papers, as well, he applies the arguments to other positions besides the reductionist approaches. For example, he tries to amend the two attacked positions of *Sim* and *Iso* and in the course of that amendment he discusses non-reductionist positions that he labels as *Sim*' and *Iso'* respectively. Proponents of these positions do not follow the aim of naturalizing representation (cf. Suárez 2003, p. 238).[41]

In the following, I will subsume the positions of *Sim* and *Iso* under the single heading of 'similarity views,' when possible. This is justified because isomorphism can be regarded as a special form of similarity. The reason for this classification is that the relation of similarity is reflexive and symmetric and the isomorphic relation between two structures is reflexive, symmetric and transitive. So, the isomorphic relations are a subclass of the class of similarity relations. Occasionally, Suárez himself concedes that. "It is possible in general to understand isomorphism as a form of similarity" (Suárez 2003, p. 228) and he even states that "isomorphism is a case of similarity" (Suárez 2003, p. 232). In other contexts, however, he stresses that similarity and isomorphism are different means that are exploited in particular instances of representation.

Suárez's reason for attacking the very thin looking positions of *Sim* and *Iso* seems to rest also on the distinction between means and constituents. According to Suárez, discovering the constituent of representation is the aim of a substantive account of representation. Thus, philosophers endorsing a substantive view are looking for a relation that is both necessary and sufficient for a vehicle to represent a target. So as to face the simplest forms of such a substantive view

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them aiming at different conditions of representation, at a sufficient and at a necessary condition respectively.

41 The positions of *Sim'* and *Iso'* involve an additional clause and by that deliver sufficient conditions of representation. This has the consequence that "the non-sufficiency argument no longer applies" and, beyond that Suárez ponders whether "the logical argument might also lose its force" (Suárez 2003, p. 238). He stresses that the other arguments are applicable to these non-naturalistic positions, nonetheless. "But the other arguments still apply. The non-necessity argument is, if anything, strengthened, as the necessary conditions on representation are now stronger. The argument from variety shows that neither [*Iso'*] nor [*Sim'*] can describe all the means of representation; while the misrepresentation and non-necessity arguments show that they do not provide a substantial theory of the constituents of representation" (ibid.).

Suárez draws the picture of his opponents above that might be regarded as a naive view on representation.[42]

It appears that similarity views like *Sim* or *Iso* are not very widespread. Particularly the claim that similarity is sufficient for representation seems to be hardly convincing at first sight.[43] And in this ideal form, these theses lack a single proponent. However, recently, Adam Toon (2012) reconstructed Ron Giere's similarity view of representation as providing a sufficient condition of that notion that has similarity as one conjunct. Beyond that, there are scholars who claim that certain formal interpretations of similarity are sufficient for representation. Andreas Bartels (2006) argues that a homomorphism is sufficient for a potential representation and Steven French (2003) questions the claim that isomorphism is not sufficient for representation.

Especially the requirement of similarity as a necessary condition for representation is intuitively compelling. In Section 3.5, the underlying question that will be asked is whether it is possible to establish an account of scientific representation that comprises similarity as a necessary condition in the sense of left-to-right reading of the biconditional of *Sim*. First, let us examine Suárez's arguments against similarity as a sufficient condition. There are three arguments against similarity as a sufficient condition for representation that Suárez gives. They are the Logical Argument (1), the Argument from Mistargeting (2) and the Non-Sufficiency Argument (3).

3.4.2. Arguments Against Similarity as a Sufficient Condition

(1) The Logical Argument. Suárez assumes that there is a general class of representations of which scientific representation is a subclass. Beyond that, Suárez speaks of 'ordinary' representations but he does not explicitly state what the ordinary representations are. It seems that he regards primarily paintings as prototypical examples of ordinary representations and that scientific representations are a subclass of ordinary representations. Suárez claims that

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42 This is the name Goodman (1968) gives to a closely related position concerning pictorial representation. In fact, he even dubs it the *most naive* view.

43 Consider a pair of twins. If similarity were sufficient for representation then one twin would represent the other. This is an unwelcome consequence of similarity being sufficient for representation and this example can be used in a reductio argument against the claim of *Sim* (cf. Goodman 1968, p. 4).

representational relations in general are not reflexive, not symmetric, and not transitive. Scientific representation therefore possesses these properties of not being reflexive, not being symmetric, and not being transitive.

> A substantive theory must make clear that scientific representation is indeed a type of representation; i.e. that it shares the properties of ordinary representation. Representation in general is an essentially non-symmetric phenomenon. [...] Representation is also non-transitive and non-reflexive. (Suárez 2003, p. 232.)

Furthermore, he suggests that representation might be irreflexive, asymmetric, and intransitive. But he does not want to argue for that (cf. ibid.). Although Suárez distances himself from developing a substantive theory, he does not renounce the demand mentioned in the first sentence in the preceding quote. In line with this he uses examples from the fine arts to exemplify the logical properties of representation. Diego Velázquez‘s painting of Pope Innocent X is a representational vehicle that has the Pope as its target. The painting represents the Pope. This representational relation is not reflexive because the painting does not represent itself. Neither is it symmetric because the Pope does not represent the painting. And finally another painting is used to indicate that representation is not transitive. This is shown by Francis Bacon‘s variation on Velázquez‘s painting that represents the original painting but not the Pope. In using these examples Suárez is able to show that these paintings and maybe paintings in general have the requested properties of ordinary representations.

The argument can be summarized as follows: because *Sim* and *Iso* cannot account for the logical properties of ordinary representation, both views are inadequate. In fact, according to the two accounts, representation is at least reflexive and symmetric. And this in turn contradicts the claim that representation possesses the logical properties of not being reflexive and not being symmetric. This is at first sight a convincing argument and because of that it seems to be indeed effective against the right-to-left reading of the biconditional of *Sim*. Granted that works of art are paradigmatic representations and that scientific representations and these representations share the same logical properties it is compelling. The take home message of this argument is: similarity is not sufficient for representation.

Although I introduced similarity in the sense of a symmetric and reflexive relation there are other approaches that use it in a way that it is open for similarity to be not symmetric (e.g. Weisberg 2013). Empirical reasons for this decision are psychological studies of similarity judgments. A non-symmetric similarity relation that was empirically investigated is for example the estimated similarity between China and North Korea (cf. Tversky 2004, Ch. 1 & 3). Participants in psychological studies endorsed the claim that North Korea is more similar to China than China is to North Korea. If you think that this allows inferring the conclusion that China really is less similar to North Korea than North Korea is to China you may find the following argument interesting and not a purely sophistic afterthought.

To employ an example from a movie by Roman Polanski: the similarity relation between the baby of Rosemary, which she conceived by the devil, and the father of the baby could be assessed as not symmetric. A possible reductio argument goes as follows. If Rosemary‘s baby is similar to its father and if similarity is symmetric then the father must be similar to his child. Yet, there is a strong intuition that a father is not as similar to his baby as the baby is similar to him and moreover there is an even stronger intuition that the devil is not similar to a baby. Hence, the reductio argument may lead to similarity being not symmetric. A possible reply could be to point out that this particular asymmetry is grounded in a further relation, maybe a causal one. Or another reply could be that literally similarity is symmetric but there are special uses of the notion that suggest an understanding of it with an asymmetry built into that relation (cf. van Fraassen 2008, p. 18).

(2) The Argument from Mistargeting. In this argument, Suárez treats a problem of misrepresentation that leads to considering the wrong target. He again illustrates the argument by invoking a situation using Velazquez‘s painting as a vehicle of representation. Suppose that a person looks roughly similar to Pope Innocent X as depicted in the painting. To think of the painting as a representation of that person is a mistake. Suárez calls it ‘mistargeting’ and he concludes that the similarity view of representation cannot explain why this situation involves a misrepresentation. According to *Sim*, the painting should be regarded as a representation of the person because it is similar to him. The similarity view yields that this apparent misrepresentation is not a misrepresentation at all. And this looks like an absurd consequence of this view. In particular, what this example shows is that *Sim* cannot distinguish between accidental and other forms of similarity. The view is not able to assure that the vehicle refers to the target. Furthermore, like in the preceding argument, the stress is only on the right-to-left direction of the biconditional of *Sim*. There may be similarity between two relata without reference. This is the lesson that can be learned from

the Argument from Mistargeting. The take home message is the same as the one from the Logical Argument: similarity is not sufficient for representation.

This reasoning presupposes that this particular misrepresentation is not a representation at all. And certainly common sense would agree. The painting is not a representation of the person. However, the question is what that means for scientific cases. In debates over scientific representation most scholars assume that misrepresentation is a form of representation. Here a difference pointed out by Andreas Bartels and Robert Cummins may help. According to these authors, successful representation involves representational content and reference that provides the respective target (cf. Bartels 2006; Cummins 1996). In this case, the mistake is that the vehicle does not refer to the target. In most scientific cases of misrepresentation, the vehicles refer to their targets while the content is not in order.[44]

(3) The Non-Sufficiency Argument. Actually the two other arguments already revealed that there are severe problems for a naive similarity view that aims at accounting for a sufficient condition of representation. In order to be thorough let us quickly go through these next points.

First, Suárez stresses that the two accounts have nothing to say about the representational force. The feature of essential directionality "lies at the heart of the phenomenological non-symmetry of the representational relation" (Suárez 2003, p. 236). Because neither *Sim* nor *Iso* can capture this directionality they do not provide sufficient conditions for representation. Neither *Sim* nor *Iso* can explain why the vehicle points to the target and not vice versa.

In a second line of reasoning especially *Iso* is under concern. Suárez assumes that it is solely possible for an object to exemplify a structure if the object stands in a particular relation to the structure. Now according to *Iso*, if two objects stand in a representational relation there has to be an isomorphic mapping from one structure to another structure. A second assumption is that the objects themselves cannot stand in this isomorphic relation to each other. Each object needs to exemplify a structure to do so. The relation between the object exemplifying a structure and the structure itself is a problem for *Iso* because this particular account only covers the relation between structures and it cannot explain this

44 This kind of misrepresentation is used in the *Argument from Quantitative Inexactness* (see Section 3.5.1). Aside from that there are misrepresentations in science that are mistaken because of failures in reference. These cases like e.g. ether or phlogiston are lacking any referent at all.

additional relation. Van Fraassen displays an analogous argument, which he calls the 'Loss of Reality' objection (cf. van Fraassen 2008, p. 258).

> What we need to ask ourselves now, though, is [...] how an abstract entity can represent something physical, so as to make sense of it in this concrete context. [...] How can we answer the question of how a theory or model relates to the phenomena by pointing to a relation between theoretical and data models, both of them abstract entities? The answer has to be that the data model[s] represent the phenomena. (van Fraassen 2008, p. 252f.)

Structural accounts want to explain the relation between on the one hand a theory or model and on the other hand a phenomenon or target with the help of certain mapping relations between structures. There may be an isomorphism between a theoretical model and a data model if these models are understood as structures. The relation that one originally wants to cover is the relation between model and target. One wants to explain how the model represents the target. However, a structural account cannot claim that the data model represents the target because representation is a mapping relation between structures and the target is not a structure. So, according to the structural similarity view of representation the relation between data model and target cannot be called a representation relation.

Both arguments point to a specific problem for structural accounts like *Iso*. The relation between objects and structures is something that such formal accounts cannot cover. For example, the chain of isomorphisms between different models in a hierarchy of models does not reach to the target. The route from theoretical models to data models cannot bridge the gap to the target itself. One possible answer to that challenge is that the relation between data model and target does not have to be called a representation relation. Maybe it is enough to speak here of exemplification. The target exemplifies a structure and the data model is just such a structure that may be exemplified by the target. The theory or model represents the target via the structural relation between theoretical model and data model and the additional relation of exemplification between target and data model. A slight variant to that answer could be that the theoretical model is similar to the target by way of the morphism between theoretical model and data model and the exemplified structure of the target that is accounted for by the data model.[45]

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45 Thanks to an anonymous reviewer for pressing me on that issue.

In summary, most of the arguments seem to be correct conditional on generally accepted assumptions. The arguments may indeed show that similarity is not sufficient for representation. But, even if similarity would be not sufficient for scientific representation that did not rule out the relation to constitute a necessary condition for scientific representation. Let us turn now to the arguments regarding necessary condition.

3.5. Arguments Against Similarity as a Necessary Condition

Two of the six arguments are directed at similarity as a necessary condition for representation. These two are the Argument from Quantitative Inexactness and the Non-Necessity Argument (see Section 3.5.2). Let's start with the Argument from Quantitative Inexactness

3.5.1. The Argument from Quantitative Inexactness

This argument touches on the problem of misrepresentation in modeling. Suárez acknowledges two forms of misrepresentation. One form is the phenomenon of mistargeting that was already discussed in the previous section. The other form is the phenomenon of inaccuracy, or 'inexactness' as I want to call it.

> The second form of misrepresentation is the even more ubiquitous, perhaps universal, phenomenon of inaccuracy. Most representations are to some degree inaccurate in some or other respects. [...][*Sim*] requires that the target and the source must share some although not necessarily all their properties. Hence [*Sim*] can account for the type of inaccuracy that arises in an incomplete or idealised representation of a phenomenon, i.e. one that leaves out particularly salient features such as the highly idealised representation of classical motion on a frictionless plane. But this will not always help to understand inaccurate representation in science, where the inaccuracy is much more often quantitative than qualitative. (Suárez 2003, p. 234f.)

In some cases of misrepresentation similarity accounts can explain why an inaccurate model is a representation of a target. For example, incomplete or idealized representations leave out certain properties that are not important. Yet, the models and the targets share important properties. And so the models and targets are similar to each other. Suárez calls this type of inaccuracy 'qualitative.' He concedes that similarity views can account for this qualitative inaccuracy. In contrast, *quantitative* inaccuracy poses a problem. In science, most cases of inaccuracies involve these quantitative inaccuracies. The conclusion of the argument is that similarity views cannot explain quantitative inaccuracies in scientific modeling. The example of Newtonian mechanics without relativistic corrections providing a representation of the solar system is a case in point. There is a variance between predictions and observations of planetary motions.

> The interesting question is not what properties fail to obtain, but rather how far is the divergence between the predictions and the observations regarding the values of the properties that do obtain. [*Sim*] offers no guide on this issue. (Suárez 2003, p. 235)

The guidance that Suárez seems to be missing can be interpreted as a quest to *degrees* of similarity. Let's see whether a similarity view can give an answer to that.

In the following discussion of the argument I am going to use a distinction that was first put forward by Paul Teller (2008) in order to make sense of the fact that modeling involves idealizations and abstractions and, still, can lead to representations that are accurate enough depending on certain purposes. Teller distinguishes precise or imprecise claims from accurate or inaccurate claims (cf. Teller 2008, p. 436). He furthermore uses a more general predicate, namely the term 'inexact.' Claims that are inexact may either be imprecise or inaccurate (or both). With this distinction, he tries to justify the use of certain inexact claims in order to state something that may be imprecise but still accurate enough. Teller takes ordinary language claims about the height of people as an example. If one claims that a person's height is 6 feet then this claim could be interpreted as meaning either that the height is 6 feet precisely or that it is 6 feet close enough. Given that no human being is precisely 6 feet tall, this claim is unsuccessful in the way that it is either false because no one is precisely 6 feet tall or that in a certain context a more accurate information is needed than just 6 feet close enough. So, the claim may be false because it is imprecise or false because it is inaccurate (cf. Teller 2008, p. 438). However, in another context this second vague interpretation of the claim may be accurate enough although it is not precise. So, interpreted as 6 feet close enough and used in a context where one only wants to distinguish between, say heights around 5 feet and heights around 6 feet, the claim may be imprecise yet accurate enough.

Let us now apply these notions to the Newtonian modeling. A Newtonian model allows inferring certain descriptions of planetary motions. These descriptions that Suárez calls 'inaccurate' are in the terminology introduced above first of all inexact descriptions. Yet, although these descriptions are inexact still the models built from the Newtonian theory represent the planetary motions accurately enough for certain purposes. Suárez himself concedes that Newtonian mechanics can "provide an approximately correct representation of the solar system" (Suárez 2003, p. 235). So, while this modeling does not allow a precise description of the planetary motions, it nevertheless can lead to a description that is accurate enough, at least for certain purposes.

Precisely because similarity is a notion that admits to degrees it is well suited to cover this case of inexactness. The characterization of sharing a property could be used to talk about this divergence between prediction and observation. Given that some value *X* is the calculated value of the prediction one could add an error term Δ. This leads to a quantitative property *X* +/− Δ. With the help of this further variable margins of error around the value *X* can be defined. Ronald Giere notices the use of these margins of error as one strategy to deal with the problem that strictly speaking mathematical equations are often false when they are used as descriptions of empirical facts.

> The margins of error rarely appear in the descriptions or calculations until one gets to the point of comparing theoretical predictions with actual measurements. When it comes time to compare the abstract model with reality, the deltas may then be understood as specifying the degree of similarity [...] between the abstract model and the real system. (Giere 1999, p. 50)

These margins of error can then be seen as established degrees of similarity in specific contexts like, e.g., the context of evaluating measurement outcomes. Of course, it is not written into *Sim* directly how small this error term should be. The definite interval cannot be fixed beforehand. What counts as accurate enough depends on concrete cases. Notice that this is a move that reductionist accounts might not support. This move seems to involve at least some implicit or explicit value judgments that determine what is accurate enough.

A reductionist may try to give a stricter definition of the different forms of inexactness. Let us go back to Teller's example of height and try to sharpen the notion of accuracy. I propose to shift the scale of feet to the scale of meters and to reason with decimals. Suppose, we are again talking about the height of a person, we may say that she is 1.80 m tall. First of all this is probably inexact because the person's exact height is most likely different from 1.80 m. The number of the height will have more non-zero digits. Say our person is precisely 1.81523 m tall. In that case our claim would be not that precise but could still be accurate enough depending on how many correct digits the claim contains. For example in a context in which the first two digits are required to be correct the above claim is accurate enough. If we require three correct digits and we follow the standard rule of rounding then we should better say that she is 1.82 m tall. In that context of the three required correct digits our above sentence is false. The person is not 1.80 but 1.82 m tall. Yet, one could claim that it is less inaccurate than say that she is 1.90 m tall. Can a reductionist be satisfied with this solution? Still, there is the notion of required number of correct digits and this requirement has to be based on a normative claim. A view that does not allow an explication of representation that involves value judgments cannot tolerate such a move. So, the hard reductionist has to find another answer to the argument.

A non-reductionist similarity view, in contrast, can answer the challenge of the quantitative inexactness. In fact the apparent weakness of similarity views turns out to be a virtue. Although some models like the Newtonian models mentioned above might be inexact representations, they still do not have to be regarded as inaccurate. These representations can be seen as accurate enough. It is a virtue of similarity that it can be used to make sense of the claim that Newtonian mechanics can represent planetary motions accurately enough. Although the theory delivers no descriptions that are perfectly precise it nevertheless represents the planetary motions because its models are similar to the phenomenon. This case can be made efficient for the non-reductionist opponent's point of view, contrary to Suárez. Thus, in order to state that similarity is a necessary condition for scientific representation there need to be established degrees of similarity. Margins of error that are used, for example, to evaluate measurement outcomes can be regarded as established degrees in scientific practice. Similarity may be not sufficient for representation. Yet, it may still be tenable to defend the claim that similarity is necessary, given specific degrees of similarity.

3.5.2. The Non-Necessity Argument

Given that similarity is simply constituted by two things sharing any property it is trite to state that everything is similar to everything. This is the starting point of the Non-Necessity Argument.

> It is trivial that any object is in principle similar to any other object. In fact the point is often made that if all logically possible properties are permitted, then any object is similar to any other object in an infinite number of ways, i.e. there is an infinite number of properties that we can concoct that will be shared between the objects.

> [...] If so, similarity would be necessary for representation but in a completely trivial way. For it would not only be a necessary condition on representation but also on non-representation. (Suárez 2003, p. 235)

If any object is similar to any object similarity is not only a necessary condition for representation but also for non-representation, this is indeed a trivial result. In response to that, Suárez assesses a possible reply for an advocate of a similarity view. This reply consists in stressing the aspect of relevance. Only the relevant similarities are matters of concern.

> A restriction is needed here to only those properties or aspects of the source and the target that are "relevant" to the representational relation: A represents B if and only if A and B are similar in the relevant respects. It is not the case that any source is in principle trivially similar in the relevant aspects to what it represents. (ibid.)

In fact, the similarity theorist only needs to claim that the relevant similarity is a necessary condition and not a necessary and sufficient one. So, the claim that she can endorse is: a vehicle represents a target *only if* vehicle and target are similar in the relevant respects. However Suárez does not want to stop here. He presses the similarity theorist on the notion of relevance. A further attack against the similarity account is to ask what the criterion of relevance actually is. Suárez assumes that this criterion must establish a link between relevance and the representational relation and he imagines a possible explication of that link. His 'improved' similarity slogan is: "A represents B if and only if A and B are similar in those respects in which A represents B" (Suárez 2003, p. 235). This is obviously circular. If the similarity theorist subscribed to this view she might be in trouble.

Yet, a similarity theorist does not have to agree to this slogan. She only needs to endorse the above claim about the necessary condition of relevant similarity. The crucial question at this point is whether the endorser of a similarity view must provide a general criterion of relevance. Here, a specific stance to relevance that acknowledges the practice of science might be enough. The relevant respect in which two things such as models and targets are similar to each other is a contextual issue. Research questions define relevant properties that are studied in scientific practice. The relevant respects are given before modeling starts and because of that no further analysis of the notion is required.

Suárez comes to a parallel conclusion but again he besets the similarity theorist once more. He presents an example from the fine arts in order to show that relevant similarity is not necessary for representation.

> The defender of similarity might retort that 'relevance' is a fully intuitive notion of straightforward application in practice; a primitive notion in no need of further analysis. That this is not so is made most vivid in the analogy with art, and to illustrate this point I like to invoke *Guernica*, the well-known painting by Picasso. [...] The point is that none of the targets of *Guernica* can be easily placed in the relevant similarity relation with the painting, and *mutatis mutandis* for isomorphism. (Suárez 2003, p. 235f.)

A second point in the argument is the relation between mathematical equations and the targets the equations describe. According to Suárez, this is not a relation of similarity. "An equation – i.e. the actual physical signs on the paper – is as dissimilar as it could be from the phenomenon that it represents" (Suárez 2003, p. 236). So, there are two counterexamples against the claim of relevant similarity as a necessary condition of scientific representation. The first is a work of art and the second is a mathematical equation. Both do represent corresponding targets but they are not similar to their targets.

In order to evaluate this argument, a short notice is in order. The first example is not a representation in the sciences. It may be that it is a counterexample to a broad similarity view of representation. My short reply to it is that if you are interested in *scientific* representation then this is not a legitimate example. Linguistic entities do also represent but hardly anyone would claim that a term is similar to what it refers to, e.g., the term 'cats' is clearly not similar to certain animals (cf. Chakravartty 2010, p. 200).[46] The second counterexample may be a representation in the sciences. If the equation is used in order to represent a specific phenomenon in the context of a modeling task then it is a representational vehicle. Besides, it may indeed also be regarded as a linguistic entity.[47] Granted, as a syntactical unit an equation is not similar to a target. However, to claim that it is even seems to be a category mistake. No defender of similarity would claim that this is the required relation in modeling. Yet, an equation is not simply regarded as a syntactic entity. In the wake of the semantic view of theo-

46 Chakravartty discusses the case of linguistic representation and the example of the term 'cats' and the corresponding animals. He ponders over the interpretation of this representation as involving a form of similarity, too. Specifically, he reflects about the relation between the semantic content of linguistic expressions and corresponding targets in the world.

47 The question whether mathematical representation counts as linguistic or not is usually answered in the affirmative by scholars following the syntactic view of scientific theories. Followers of the semantic view take the other direction. A recent handbook entry on representation in science follows this second route (Teller 2008).

ries a shift from uninterpreted calculi to mathematical structures is made. The objects of study of philosophers of science following the semantic view are not primarily linguistic entities. If an equation is used in a scientific context then this equation specifies a mathematical structure. In this context, the structure can be regarded as the model of the target system. And such a structure might indeed be similar to the target if the equation under scrutiny is used to adequately represent the phenomena. Maybe there is even an isomorphic mapping from the structure to a data model of the target. Yet, other mappings could be more adequate. Someone who endorses a similarity account is not committed to *Iso* or related views that declare isomorphism to be a necessary condition for representation.

This argument does not show that similarity cannot be conceptualized as a necessary condition of scientific representation, either. Especially if relevant respects are conceded, the similarity theorist is not in trouble.

3.6. Conclusion and Discussion

Suárez's rejection of an explication of scientific representation with the help of similarity seems to be based on his belief that, in order to explicate the notion this way, similarity has either to be the means or the constituent of representation. If similarity is the constituent then it must be necessary and sufficient for representation. The first three arguments are used to show that similarity is not sufficient. According to these arguments, similarity cannot be the constituent of representation. The Argument from Variety is used to show that similarity is not in all cases of representation a means of representation. According to that argument, similarity is not *the* means of representation. I have argued that the Argument from Variety is not decisive for the question whether similarity is or is not the means of representation.

Suárez's arguments against similarity as a necessary condition for scientific representation could be satisfactorily answered especially from a non-reductionist point of view. So, similarity may be conceptualized as a necessary condition for scientific representation granted that relevant respects and degrees of similarity are conceded. While similarity may not be necessary and sufficient for representation it might be defended that it is necessary, still. Similarity may not be the constituent of representation but nevertheless it is a relation that may be used to explicate scientific representation. The arguments did not show the following thesis false: only if a vehicle is similar to a target in relevant respects and to a certain degree of similarity then the vehicle is a scientific representation of that target.

The question as to whether there are other necessary conditions for a vehicle to represent a target remains open. Likewise, the study whether there are several necessary conditions that are jointly sufficient is a task for further research.

As a prospect of a positive account of similarity being a necessary condition I would like to end with mentioning how the considered condition can be compared to other proposed conditions. Besides similarity scholars discuss other conditions for representation in the sciences like interpretation (Hughes 1997; Contessa 2007) or inferential capacity (Contessa 2007; Suárez 2004). If one compares the different proposed conditions for scientific representation similarity, inferential capacity and interpretation then similarity looks as the best option to take because it can give a ground for the other conditions. Especially, similarity is more fundamental than the condition of inferential capacity. Similarity can be used in order to explain why representational models could have an inferential capacity in the first place. In a nutshell, only because there is a similarity between vehicle and target, it is justified to derive certain surrogative inferences from the vehicle to the target. Similarity between models and targets is a reason for models to have the capacity to lead to correct inferences about the targets. Without the similarity relation, the inferences from models to target systems can hardly be justified. It may be true that an interpretation of a model in terms of a target can also explain why a model can lead to inferences about the target. Yet, that is not sufficient to ground the correctness of the inferences. It would be a miracle to reach correct claims about a target with the help of a model if the model were not similar to the target.

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4 Modeling Organs with Organs on Chips: Scientific Representation and Engineering Design as Modeling Relations

Abstract

On the basis of a case study in bioengineering this chapter proposes a novel perspective on models in science and engineering. This is done with the help of two notions: representation and design. These two notions are interpreted as referring to modeling relations between vehicles and targets that differ in their respective directions of fit. The representation relation has a vehicle-to-target direction of fit and the design relation has a target-to-vehicle direction of fit. The case study of an organ on chip model illustrates that the technical device can participate in both design and representation relations. The two relations share the same relatum of the organ on chip but they have different directions of fit. In the design relation the chip is adjusted to a design plan, in which case we are dealing with a target-to-vehicle direction of fit. In the representation relation the chip is adjusted to a human organ, in which case we are dealing with a vehicle-to-target direction of fit. The example shows that a conception of modeling as involving only relations with a vehicle-to-target direction of fit is too narrow to account for models in science and engineering.

Contents

4.1. Introduction

Modeling is one of the core activities of contemporary scientific practice: Research at universities, private institutes, and industry often centers on building and using models for a variety of purposes. These purposes include the utilization of mathematical models in order to predict or explain phenomena, the use of concrete models such as scale models or animal models to perform experiments, or the application of computational models to conduct simulation studies (cf. Weisberg 2013). These different aims of prediction, explanation, or simulation are united by the epistemic aim to learn something about the world. From an epistemic point of view, it is apparent that a model can be used to reach an understanding of a target system only if it adequately represents that system (cf. Chakravartty 2010; Bueno & French 2011; Bolinska 2013; Shech 2015). According to this view of representation, models are required to adequately represent certain targets in order to be used to infer justified claims about these parts of the world. This is reflected in debates that take representation to be the main function of epistemic vehicles such as scientific models.

Many scholars stress that there are other functions of models. Models may have exploratory functions (Gelfert 2016), or they may be 'epistemic tools' that deliver knowledge in other ways than by representing real-world targets (Knuuttila 2011). Some models, such as economic models, may be special in the way that they do not represent actual targets, but instead deliver narratives that enable the study of model worlds (Morgan 2012). Thus models may be used beyond representational purposes. This chapter, however, takes as its starting point a discussion of a particular view of models and representation that focuses on the representational function of models. According to this indirect view of representation, the function of models is to represent target systems. The models do not represent in a direct way but through model systems; these model systems are to represent target systems (cf. Giere 1988; Godfrey-Smith 2006; Weisberg 2007; Frigg 2010). Starting from this particular view of modeling, I will show that insights from philosophy of technology can help to broaden this perspective on models by applying it to the design of objects such as technical artifacts. Further, a case study from bioengineering is used to make the case for design and representation as being two functions of modeling. I will illustrate and clarify the different roles of models and model systems in a research and a design context.

In addition to the fields mentioned above, models are also widely used in engineering, including the engineering sciences. In technological modeling, however, there are other aims at play besides the purely epistemic ones. A frequently cited conviction is that engineers want to change the world rather than understand it.[48] Take the case of an engineering model of a building and a realization of that building, for example a particular house or bridge. This case involves a modeling relation between a model and an object that is to be modified, or between a model and an object that does not exist yet. In such a case, as I will argue, the notion of design is at least equally suitable for characterizing the relation between model and target as the notion of representation. Indeed, design is often regarded as the defining characteristic of engineering and, in the philosophy of technology, it is claimed that the main goal of the practice of engineering is to come up with effective and efficient designs. Engineers aim to deliver designs and produce artifacts as realizations of these designs (cf. Meijers 2009, part III).

However, the epistemic aims that are central to the natural and social sciences are not absent in engineering. Practical as well as epistemic aims guide the professional activities of engineers, and this is related to the importance of the notions of design and representation in science and engineering. To demonstrate, I will discuss a case study that lies at the intersection of science and engineering, and argue that the practice of modeling organs with so-called 'organ on chip'[49] models involves two different kinds of relation between vehicles and targets, which differ in their directions of fit.[50] The representation relation has a vehicle-to-target direction of fit, whereas the design relation has a target-to-vehicle direction of fit. With this proposal, both of the aims pursued in the use of models – namely, understanding as well as changing the world – can be accounted for in a philosophical analysis of the example in bioengineering. Furthermore, I suggest that the relations between vehicle and target may be interpreted as grounded in relations of similarity, which supports a unified perspective on models in science and engineering.

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48 This is a conviction that is often found in the literature, see for example the beginning of the quote by Peter Kroes cited in Section 4.4 that can be interpreted in that way.

49 To avoid potential misunderstanding let me stress the following. The organ on chip is not a computer chip. Organ on chip models consist of human tissues and of microchips that function as platforms for these tissues. See Section 4.3 for a detailed description of these artifacts.

50 For the term 'direction of fit' see Searle (1983) and further discussion below.

This contrasts with the standard view of modeling in science, which involves only relations between models as vehicles and certain phenomena as targets with a vehicle-to-target direction of fit. The inverse direction of fit is not explicitly discussed in recent accounts of modeling (cf. Giere 2006; Godfrey-Smith 2006; Contessa 2007; van Fraassen 2008; Bueno & French 2011; Knuuttila 2011; Morgan 2012; Pincock 2012; Toon 2012; Weisberg 2013; Gelfert 2016).[51] The case study discussed below will show that a conception of modeling as involving only relations with a vehicle-to-target direction of fit is too narrow to account for models in science and engineering.

The structure of the chapter is as follows. Following this introduction, Section 4.2 presents a perspective on models and representations that is based on an indirect approach to representation. Here, a distinction between *model descriptions* and *model systems* is crucial. A common account is that model descriptions stand in a *specification* relation to model systems and that model systems as vehicles for representation aim at representing target systems. I follow this terminology, but in the remainder of the chapter I will interpret the specification relation as a design relation. Section 4.3 introduces the case study from bioengineering, where the discussion primarily takes the perspective of philosophy of science and the indirect view of representation is applied to the example. In Section 4.4, I discuss the consideration of vehicles and targets in reference to the activities of designing and representing in order to enable a unified treatment of models in science and engineering: I will conceptualize the notions of representation and design as modeling relations between vehicles and targets. The concept of *direction of fit* is then applied to the modeling relations between vehicles and targets. In Section 4.5, the bioengineering example is presented from the perspective of philosophy of technology. The relation between the plan of the chip and the constructed chip is interpreted as a design relation with a target-to-vehicle direction of fit. Section 4.6 considers resemblance as a foundation for the relations of representation and design. Finally, Section 4.7 concludes the chapter with a brief summary of the argument.

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51 An exception is Suárez (2015) in which the construction of a bridge with the help of an engineering model is discussed. The notions of representation and design are used in the account of the construction of the bridge but the connection between the two notions is not analyzed.

4.2. Indirect Representation

The core of the indirect view of representation is that first, model descriptions specify model systems and, second, model systems represent target systems.

One variant of an indirect view on models and representation has recently been put forward by Michael Weisberg (2013), who proposes that the great variety of scientific models can be captured with the help of the following distinctions. There are three types of models according to Weisberg: i) concrete models, ii) mathematical models and iii) computational models. Examples for these types are i) laboratory animals that are used in preclinical trials, or the San Francisco Bay-Delta model made of water, concrete and metals that was used to represent the salinity of water in the San Francisco Bay; ii) the mathematical Lotka-Volterra model of predator-prey interaction, or Newtonian models of planetary motions; and iii) Schelling's model of segregation, or global climate models such as general circulation models. These three categories are not mutually exclusive. Thus a given model may be at the same time a concrete and a computational model (the Bay-Delta model), or at the same time a mathematical and a computational one (a general circulation model). Further, all types of models involve *model descriptions* and *model systems*. Model descriptions and model systems are conceived as clearly distinct; in the case of mathematical models, equations can be regarded as the model descriptions and certain objects satisfying these equations can be regarded as the model systems. Weisberg and many others speak of these objects as structures. There are other options for construing these model systems. Ronald Giere, for example, terms model systems as 'abstract objects' (1988), and for Roman Frigg they are hypothetical systems that are best understood in comparison to literary fictions (2010).[52] The debate on models and representations often focuses on mathematical models. However, most accounts of models and representations do not exclude concrete model systems as vehicles for representation. In the case of a concrete model the model description can be regarded as a plan for the construction of the model system. To construct a concrete model system is often a task that is analogous to the activity of designing a technical artifact. One could say that the model is also an artifact, but it is an *epistemic* artifact. Here, the notion of design may be

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52 An alternative fictionalist view on models is defended by Adam Toom (2012). His view, however, denies that there are model systems. Toon's view is a *direct* view of representation, as opposed to an *indirect* view.

applied quite intuitively to characterize the relation between model description and model system. The model system is a concrete object that is to be built according to the model description, which is comparable to a plan or a blueprint of the model system.[53]

Scholars account for the relation between model descriptions and model systems in various ways. According to Giere (1988), it is a relation of definition, whereas Frigg (2010) uses the notion of make-believe in order to make sense of the relation between model descriptions and model systems. Other scholars speak of *specification* in this context, but it is not clear how the relation of specification is to be interpreted for various types of models (cf. Godfrey-Smith 2006; Weisberg 2007, 2013). I will also use the notion of specification, and will provide an interpretation for the relation between model description and model system that utilizes the concept of direction of fit.

All scholars who follow the framework of indirect representation regard the further relation between *model systems* and *target systems* as the core relation of representation (Giere 1988; Godfrey-Smith 2006; Frigg 2010; Weisberg 2007, 2013). I will follow this usage and refer to the relation between model systems and target systems as the representation relation. Some scholars also want to call the specification relation a representation relation (Frigg 2010; Weisberg 2013); others stress the difference between specification and representation by claiming that the model descriptions are special descriptions insofar as they cannot misrepresent the model system. The model descriptions are considered to be necessarily true of the model systems (cf. Giere 1988). One consequence of this is that these two relations, the specification and the representation relation, differ. The representation relation can be unsuccessful in the sense of not displaying a 'fit' between the two relata. The specification relation, in contrast, is always successful if Giere is correct that model descriptions are necessarily true of model systems. My result will be that, in the end, the specification relation is a special kind of modeling relation. Thus I agree with those who regard specification as a form of representation in one aspect. Yet I want to stress the important point that these two relations, the specification relation and the representation relation, differ. With a terminology to be established in the following sections, the thesis of this chapter is that the representation relation is a relation with a

[53] In the remainder of the chapter, I will argue that this relation between model description and model system can indeed be interpreted as a design relation.

vehicle-to-target direction of fit, while the specification relation is a relation with an inverse direction of fit, namely a target-to-vehicle direction of fit.[54]

4.3. Modeling Organs with Organs on Chips

Let us know turn to an example that is taken from the borderland between science and engineering. The device to be discussed in this section is a so-called *organ on chip model*, which was developed by a group of researchers in a department of bioengineering. This model, which presents a case of both a representation and a design, is located at the intersection of science and engineering, and it is related to the area known as emerging technologies. I will begin by giving some background on the field of organ on chip modeling (4.3.1) before discussing the *Three Chamber Chip*, which I use to refer to the basic device for constructing two particular organ on chip models (4.3.2).

4.3.1. Organs on Chips

The following case study is an analysis of organ on chip models in the field of tissue engineering. This field of engineering has a great overlap with cell research in biology and particularly with medical research. The models are used to represent human organs in order to study *inter alia* the toxicity or efficacy of certain drugs. This practice is driven by epistemic goals such as predicting risks and benefits of treatments with a specific drug or learning about certain diseases. However, this practice is also driven by practical goals. The engineers aspire to develop certain technical artifacts during the modeling of the organs and systems of tissues with the help of the techniques they explore through modeling. Organs on chip models are specific devices that aim to model core functions of human organs. These models consist of cultured living cells and microchips that host the extracellular matrix of those cells. Part of the in vitro environment of the cells is a specific architecture built on a platform, which is the size of the micrometer scale. Because insights from microchip technology are applied while designing these devices they are called *organs on chips* (cf. Huh

54 The case study shows this to be correct about concrete models. The second claim may have to be qualified as being valid for concrete models, only. Whether the specification relation of mathematical models also has this target-to-vehicle direction of fit will be left open in this chapter.

et al. 2012a; Capulli et al. 2014; van der Meer & van den Berg 2012). In general, organs on chips are intended to constitute in vitro surrogates for human organs. The chips are meant to be similar to the organs with respect to microstructure, dynamic mechanical properties, and biochemical functionalities (Huh et al. 2013). Because of this similarity there is a potential that these devices could support drug discovery and drug development studies in the future. Beyond that, there is even the hope that they will at some point replace experiments with animals that are costly, time-consuming, and problematic from an ethical point of view. Currently, most of these organs on chips exist only as prototypes. Some of these prototypes have been used to show results such as the replication of certain diseases and corresponding drug treatments, as well as the mimicking of in vivo responses of organs to certain induced toxic particles (cf. Huh et al. 2012b). In order to discuss one example in more detail, I will now look at an organ on chip that was created by a group of researchers at University of Pennsylvania. The researchers call their device an 'organ-on-chip model' or a 'lung-on-a-chip model.' I will use the term 'Three Chamber Chip' in order to talk about the basic device that is used for modeling the two human organs of lung and intestine. The Three Chamber Chip can be regarded as a prototype for an industrially produced epistemic tool for drug research. It is at a developmental stage because it is not yet established as a mass product in the chemical or pharmaceutical industry.

4.3.2. The Three Chamber Chip

The Three Chamber Chip was developed by Dan Huh and his research group at University of Pennsylvania (Huh et al. 2010, 2012b, 2013). Together with an artificially built environment, living human cells are cultivated on a special microchip. The chip is composed of three separate chambers, which are positioned parallel to one another. In the central chamber human tissues are placed on both sides of a permeable and elastic membrane that constitutes the environment for the respective cells. The elastic membrane divides the chamber into two parallel microchannels. The membrane is coated with extracellular matrix material and living cells are cultured on the two opposite sides of the membrane.

The human lung is the representational target in one application of the Three Chamber Chip. Lung cells such as alveolar epithelial and microvascular endothelial cells are placed around the membrane. With these two kinds of tissue, two different channels are created in the central chamber of the chip: first, there is an alveolar channel that is filled with air and, second, there is a vascular channel that is filled with a liquid. The first channel is meant to model the air sacs of the lung and the second channel is meant to model the blood vessels. Mechanical and biochemical influences can be applied to these tissues. The mechanical force on the tissues is used to mimic the breathing motion in lungs. The membrane that divides the two channels can be stretched and released in a periodic movement. This movement is induced by applying a vacuum to the outer chambers of the chip, which affects the two tissue layers simultaneously. By applying these mechanical forces to the tissue layers it is possible to model the contraction of the air sacs in the lung. With regard to biochemical influences, one can introduce, for example, nutrients, drugs, and other fluids into the vascular channel and thus affect the endothelial cells. Or, one can introduce particles in the alveolar channel and thus affect the epithelial cells (cf. Huh et al. 2010, 2012b).

In addition to its use for modeling the human lung, the Three Chamber Chip can also be employed as a 'gut chip.' The research group has shown the viability of using intestine cells on the chip in order to model the human intestine (Huh et al. 2013). Here, the same mechanical forces as in the lung on chip can be applied to the tissues. By applying a vacuum to the outer chambers of the microchip the peristalsis of the intestine can be modeled. So, the first variant of the Three Chamber Chip is a lung chip and the second variant is a gut chip. When modeling the lung and the intestine, the same two kinds of cells are used, since epithelial and endothelial cells are both central to the function of the respective organs. The chip is thus a device with a variable target of modeling because, at the outset, it is not determined whether it is a device for modeling the lung or the intestine.[55]

While building the Three Chamber Chip, the researchers use a basic protocol for building the core chip. Subsequently, they turn to additional protocols that can be used to turn it into either the lung chip or the gut chip (Huh et al. 2013). To use the terminology of the indirect view of representation introduced in the foregoing section, these protocols can be understood as model descriptions that specify a model system. The Three Chamber Chip is a model system that can be

55 Other scholars also discuss this phenomenon of variable targets: Susan Sterrett stresses that model users consider not only the suitability of models but also the suitability of targets (cf. 2014, p. 36). Axel Gelfert (2016) claims that exploration is one of the core functions of models and he discusses four exploratory uses. One particular exploratory function of models is that they are used to explore the suitability of different targets (cf. Gelfert 2016, p. 93).

used to represent human organs, and during that activity a relation between chip – as vehicle – and human organ – as target – with a vehicle-to-target direction of fit is sought. In this respect, the chip can be regarded as a model system that is used to represent a certain target system. For example, the lung chip is used to represent pulmonary edema, fluid accumulation in the lung, and the treatment of pulmonary edema with a certain drug (Huh et al. 2012b). Pulmonary edema is the target of the modeling and the lung chip as a model system is the vehicle of representation that is adjusted in order to adequately represent the target. In the future, the lung chip may be used in preclinical research to represent other syndromes and the effects of respective drug treatments. The Three Chamber Chip can also be used to model the intestine. When the researchers use endothelial and epithelial cell from the intestine they can construct a gut chip. This gut chip is then a model system that can be used to represent different targets than the lung chip. The built lung and gut chips are constructed model systems that are used to represent particular target systems.

The above discussion has shown that the example of bioengineering can be reconstructed using the theoretical notions of model descriptions, models systems, and target systems introduced above. In the remainder of the chapter I will present an alternative perspective on organ on chip models that involves the notion of design.

4.4. Modeling Relations and Directions of Fit

In my description of the organ on chip model I have regarded representation as a relation between a model system and a target system. The main reason for preferring the relation interpretation of representation is that the use of models to infer claims about target systems can be justified only if there is an established relation of representation between model systems and target systems (cf. Suárez 2004). The notion of a *model* will henceforth be used in order to specifically refer to the product of representation. It encompasses a model system that stands in a representation relation to a target system. In that sense, the model is an epistemic tool because it can be used in order to learn about a target system. The model of pulmonary edema that can be realized with the help of the Three Chamber Chip is an example in which the lung chip is used to represent this vascular leakage syndrome in the human lung.

In parallel to my approach to representation, I propose to regard design as a relation as well.[56] The notion of *design plan* will henceforth be used to name one relatum of the relation of design. I understand the design plan as a vehicle that stands in a modeling relation to a target. For example, there is a relation between the plan of an artifact and a realization of that artifact, or the relation between a conceptual design and a technical device that is to be built in the future. This relation can be seen as a specific kind of modeling relation. It is a modeling relation between a vehicle and an object that is to be modified or between a vehicle and an object that does not exist yet. The activity of designing – largely like representing – involves a certain vehicle. However, that vehicle does not represent certain actual facts in the world. Rather, the vehicle prescribes desired or intended facts. The goal of designing is to modify an object or to create something that did not exist beforehand. That is, designing, involves either a modification of an existing object – usually a physical thing – or the creation of something new. Thus the relation of design is concerned with how certain matters should be in contrast to how they in fact are. Here, the condition for the success of the relation differs from the condition for the success of representation. In the case of designing, the target must be adjusted to the vehicle in order for the technical functions to be fulfilled. In the case of representing, the vehicle, that is a model system, must be adjusted in order to adequately represent a corresponding target. One can apply the notion of a direction of fit in order to distinguish between the relations of design and representation:

56 The notions of representation and design can be understand as standing for either a process or a product. On the one hand, the respective terms can denote a process or activity. Representation can mean the practice of representing, i.e., the activity of using scientific models for particular purposes. For example, models can be used in order to infer relevant claims about target systems that are represented by model systems (cf. Suárez 2004). Design can mean the activity of designing, i.e., the practice of building a concrete or perhaps a non-concrete object that effectively and efficiently fulfills a technical function (cf. Vermaas et al. 2011; Kroes 2012; Houkes & Vermaas 2010, 2014). On the other hand, representation can mean the product that is the outcome of the process of representation. In the philosophy of science, models are called 'representations' and with this choice of terminology the aspect of representation as product is stressed. Similarly, design can mean the outcome of the activity of designing. This outcome can be characterized as a plan of an artifact. The design can be used to produce technical artifacts such as mass products, e.g., airplanes and tools for the handyman or architectural artifacts that are singular products, e.g., official buildings or residential houses.

> Instead of taking the world for what it is (as in science) engineering design seeks to change the world to meet given needs, desires or goals. Whereas in science our ideas and beliefs are adjusted to how things are in the world, the engineering attitude is precisely the opposite, namely to adapt the world to our ideas, desires and needs. This difference in attitude between science and engineering may be expressed by the difference between a "mind-to-world fit" and a "world-to-mind fit." (Kroes 2012, p. 135)

Although the directions of fit can be associated with attitudes – as in the foregoing quote – I am applying them to the relations between vehicles and targets specifically.

The usage of these notions of mind-to-world and world-to-mind directions of fit goes back to John Searle's *Intentionality* (1983). In earlier writings, Searle distinguished between a word-to-world direction of fit and the inverse direction of world-to-word. With a shift in focus from the philosophy of language to the philosophy of mind, he changed the terminology to mind-to-world and world-to-mind directions of fit.

Applying Searle's concept of direction of fit to vehicles and targets, there can be two directions in which vehicles can fit to a thing that is to be modeled. The fit can go from the vehicle to the target or vice versa. The idea of directions of fit was first introduced in a publication by Elizabeth Anscombe (1957). She invites the reader to imagine a customer in a supermarket with a shopping list and a detective spying on that customer and writing down a list of the things the customer collects in the shopping basket. The lists can be regarded as the vehicle and the shopping basket with the items can be regarded as the target. The customer adjusts the items in the shopping basket to the list and the detective adjusts the list to the items in the shopping basket.

> It is precisely this: if the list and the things that the man actually buys do not agree, and if this and this alone constitutes a mistake, then the mistake is not in the list but in the man's performance [...] whereas if the detective's record and what the man actually buys do not agree, then the mistake is in the record. (Anscombe 1957, p. 56)

Using language of mental states, there are two different kinds of direction of fit between mental states as vehicles and things in the world as targets. One can have different attitudes towards a state of affairs. First, one can *believe* that something is the case, like the detective who writes down what is in the shopping basket. This kind of propositional attitude has a mind-to-world direction of fit. Or, secondly, one can *wish* that something else would be the case, like the customer who wants to buy the things that are written down on the shopping list and has a wish to carry these items home. In general, this means that in order to be successful in the attitude of believing one must adjust one's beliefs from time to time in order to be able to make correct claims about certain things. On the other hand, in the case of wishes one cannot simply adjust one's mental state and so fulfill the desire that something is the case. That would be wishful thinking. Because a wish has a world-to-mind direction of fit one can only satisfy a wish by changing the world accordingly.

In order to incorporate not only mental and linguistic representation but also scientific representation and even engineering design, I propose to speak of directions of fit between vehicles and targets. The relation between a model system as a paradigmatic vehicle for representation and a corresponding target system has a *vehicle-to-target* direction of fit. The vehicle has to be adjusted in order to represent the target well enough. The corresponding relation that points in the opposite direction is thus the *target-to-vehicle* direction of fit. The relation between the plan of an artifact (a vehicle) and the artifact that is to be built (a target) involves such a target-to-vehicle direction of fit. In the following section, I will apply this terminology to the case study of the Three Chamber Chip. The built chip and the plan of the Three Chamber Chip stand in a target-to-vehicle direction of fit.

4.5. The Design of Organ on Chip Models

In Section 4.3, I showed that a particular organ on chip model could be analyzed as a model system standing in a representation relation to a target system. In this section, I will show that the Three Chamber Chip can be regarded not only as a representational model but also as a constructed artifact. I will present a complementary perspective on the Three Chamber Chip that focuses on the notion of design and uses the terminology introduced in the preceding section. In parallel to regarding the Three Chamber Chip as a representational model, the chip – understood as a target – can also be seen as standing in a design relation to a plan of the artifact, which is a vehicle of design. Because the chip is adjusted to this design plan during the construction of the chip, the relation between the chip and the design plan is a modeling relation with a target-to-vehicle direction of fit. The end goal of the construction of the chip is to produce a device that performs the functions of a specific organ. And, in fact, the correct designing of the chip is a prerequisite for the proper use of the chip as a model system with a representational function. So, the design is a first step that enables, in a second step, the representation of a particular target. As discussed in Section 4.3, the plan of the chip can also be regarded as a model description of a corresponding model system. Using that language, the organ on chip is then a model system that stands in a specification relation to the plan of the chip that can be regarded as the model description. The model description is the vehicle and the model system is the target that is adjusted to the model description. This suggests a new way of understanding the specification relation. The specification relation between model descriptions and model systems is a design relation. That is, the model system as a target is adjusted to a model description as a vehicle.

During the activity of constructing a chip a design relation is to be established: the relation between the plan of the microchip and the built microchip. For example, in Huh et al. (2013), a procedure for building an organ on chip is described in detail. In fact, the procedure is divided into several protocols that can be used to build at least two different kinds of chips, a lung chip and a gut chip. Once built, the chips are concrete devices that stand in a design relation to the plan of a device that is defined by the particular protocols that are used for the construction of the chips. The plans of the organs on chips are examples of products of an engineering practice of core designing. At the current stage, the devices are still prototypes. The goal is that the chips will eventually be built as industrial products in mass production and then used, for example, in the pharmaceutical industry to test certain drugs in a preclinical test phase.

The future outlook of the development of organs on chips will be the application of these fabricated organs in an industrial setting. At present, in the pharmaceutical industry cell and disease processes are analyzed primarily with the help of animal models. For various reasons it is preferable to find an alternative to these models. There is hope that the organs on chip will become real alternatives to animal models.

In the context of a broader perspective on tissue engineering, some scholars aspire to build so-called ‘biological machines.’ These machines are artificial devices that may exhibit functions that do not exist in nature but might be useful in the future. The goal is “to form a tissue or an organ or even an integrated cellular system that does not even exist in nature” (Nerem 2014, p. 894). However, what these machines and functions are remains somewhat speculative. The machines might be developed in interplay with modeling human organs and systems of tissues with the help of organs on chips. The relation between the description of the useful functions – the vehicle – and the yet to be built biological machines – the target – would also be a relation with a target-to-vehicle direction of fit. During the construction, the biological machines have to be adjusted to the description of the functions, whatever these functions actually turn out to be.

4.6. Resemblances between Vehicles and Targets

In this section I will discuss a plausible interpretation of the relations between vehicle and target with the concept of similarity, which will strengthen the novel perspective on models in science and engineering proposed in this chapter.

There are ongoing debates about the connection between representation and similarity. The arguments for or against similarity need not be repeated here (see, e.g., Suárez 2003; Frigg 2006; Chakravartty 2010; Elgin 2010). Elsewhere I have argued for the tenability of similarity views of scientific representation (cf. Poznic 2016) and here I will assume that it is possible to explicate representation with the help of similarity. There may be different types of similarity involved in modeling. For example, Susan Sterrett (2014) discusses the use of particular engineering models and the connection to dynamic and kinematic similarities. For our present purposes, however, I am interested in a general notion of similarity and, will not consider these different types of similarity here.

The researchers engaged in organ on chip modeling aim at representing human organs. Their explicit goal is to create devices that are similar to the corresponding organs. The scholars use terms like 'replicate,' 'recapitulate,' 'mimic,' 'recreate' or 'reconstitute' to describe the goal of establishing these similarities (cf. Chung et al. 2012; Fisher et al. 2014; Huh et al. 2010, 2012a; Capulli et al. 2014; van der Meer & van den Berg 2012). One example of such an established similarity is the replication of the breathing motion of microvascular endothelial cells and of alveolar epithelial cells with the help of the Three Chamber Chip discussed in Section 4.3.2.

The case study of the Three Chamber Chip illustrates that researchers try to adjust a technical device to a plan of the device in order to realize the functions of a human organ. The design relation between the plan of the Three Chamber Chip and the constructed chip is based on a similarity between the chip and the plan. The device should imitate the described functions of the organ by resembling the plan of the chip. The functions of human organs are quite well understood. Thus the organs and their functions can be described in detail.

These descriptions form the basis for proposing a vehicle, that is, a design plan of the device that is intended to mimic the organs. The descriptions lead to protocols that define the design plan. This plan is used to realize the intended device. The device is adapted to the plan of the device, namely the protocols. The plan of the device functions as the vehicle for the design relation to the device as the target. Thus like representation, design can also be interpreted as being based on similarity or resemblance.

Although the directions of fit differ for the relations of design and representation, in both cases, the relata stand in a certain relation to each other. The proposed candidate for this relation is resemblance or similarity. A vehicle and a target are similar if and only if they share some of their properties. The relation of resemblance is usually not understood as an overall similarity but the resemblance is relativized to certain respects that are relevant for the research focus in question. Beyond that, resemblance is a notion that admits of degrees and is therefore not a categorical matter: Two things are more or less similar to each other. Although there are discussions about whether or not similarity is symmetric, it is largely presupposed that similarity is a symmetric relation. According to a similarity view of representation, a model system adequately represents a target only if the former resembles the latter in relevant respects and to a sufficient degree. In the debates of scientific representation, this resemblance is for the most part understood as a structural similarity between model systems and target systems.

There are many positions on modeling and resemblance in the philosophy of science (cf. Hesse 1963; Leatherdale 1974; Giere 1988, 2006; French 2003; da Costa & French 2003; Bartels 2006; van Fraassen 2008; Pincock 2012; Weisberg 2013; Sterrett 2014). I assume that most of these positions are compatible with my interpretation of representation and design as contributing to an account of models in science and engineering. This is indeed only a hypothesis that requires further research in order to be shown as correct or incorrect.

The researchers in the field of organ on chip modeling use terms like replicate, reconstitute, mimic, etc. in order to describe the goal of building a device that stands in a certain relation to a human organ. One can reasonably assume that this language can best be captured with the notion of similarity. The goal of the researchers is to build a device that is similar to a human organ. This similarity between device and human organ may be the foundation for a representation relation. Given that the design relation may also be based on similarity this interpretation of the relations between vehicle and target strengthens the unified perspective on models in science and engineering proposed in this chapter. The basic relation of similarity then grounds both the relation of representation and the relation of design.

4.7. Conclusion

The case study in bioengineering illustrates that there are two kinds of modeling relation that are relevant for current practices in science and engineering. These two kinds of modeling relation between vehicles and targets differ in their respective directions of fit. The representation relation has a vehicle-to-target direction of fit, while the design relation has a target-to-vehicle direction of fit. The case study has shown that a conception of modeling as involving only relations with a vehicle-to-target direction of fit is too narrow to account for models in science and engineering. As indicated above, the standard view on modeling in science involves only relations between model systems as vehicles and target systems with a vehicle-to-target direction of fit. The inverse direction of fit is not addressed at all in recent accounts of modeling in science. Beyond that, scholars account for the relation between model descriptions and model systems in various ways. The discussion above suggests that the relation between concrete model systems and model descriptions is a design relation. Further, I have proposed that the notion of similarity can be used to interpret the relations between vehicle and target. Both the representation and the design relation may involve the same basic relation, namely the similarity relation, which opens up the possibility of a unified account of models in science and engineering.

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5 Make-Believe and Model-Based Representation in Science: The Epistemology of Frigg's and Toon's Fictionalist Views of Modeling

Abstract

Roman Frigg and Adam Toon, both, defend a fictionalist view of scientific modeling. One fundamental thesis of their view is that scientists are participating in games of make-believe when they study models in order to learn about the models themselves and about target systems represented by the models. In this chapter, the epistemology of these two fictionalist views is critically discussed. I will argue that both views can give an explanation of how scientists learn about models they are studying. However, how the use of models can foster an understanding of target systems is not sufficiently accounted for by Frigg and Toon.

Contents

5.1. Introduction

The comparison of scientific modeling with the creation or appreciation of fiction has become a popular topic in philosophy of science (see, e.g., Godfrey-Smith 2009; Suárez 2009; Woods 2010; Frigg and Hunter 2010; Levy 2015). In this chapter, I will critically discuss two particular fictionalist accounts of modeling: Roman Frigg (2010a, 2010b, 2010c) and Adam Toon (2010a, 2010b, 2012) compare models to works of fiction. Frigg's and Toon's fictionalist views build upon Kendall Walton's (1990) theory of make-believe and they transfer the insights from Walton's theory about fictional arts such as literature and painting to the sciences. Because of that their views can be called *Waltonian fictionalist* views.[57] In line with Walton's theory of make-believe, both views argue that the practice of modeling can be analyzed as the engagement of scientists in games of make-believe. Yet the two views differ: Frigg defends an *indirect* view of modeling and Toon defends a *direct* view. According to Frigg's indirect view of modeling, model descriptions specify hypothetical model systems and these model systems represent target systems. According to Toon's direct view, model descriptions are imaginative descriptions of target systems and there are no hypothetical model systems.

An important motivation for a fictionalist account of modeling is that many descriptions in the sciences do not seem to be literal descriptions of existing physical or social systems. Examples are descriptions of ideal gases, descriptions of frictionless planes and descriptions of actions of perfect rational agents, among many others. What are these descriptions about if they have no correlate in the physical or social world? One possible answer is that the descriptions are about hypothetical systems that do not exist in our world. This is Frigg's answer. Toon claims that these descriptions are prescriptions to imagine particular propositions and that the propositions are not about hypothetical systems but about existing target systems. Toon (2012) and others call the practice of talking and thinking of such non-existing hypothetical systems as if they existed in our world the *face-value practice*.[58] I will follow these scholars in using this term as a label for the motivation of fictionalism: scientists are participating in the face-value practice when they are speaking and thinking as if there are hypothetical systems. The answer of the two Waltonian fictionalist views to the question of how to interpret the face-value practice is that these descriptions are not genuine statements but prescriptions to *imagine* certain propositions. Frigg and Toon

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57 The term 'Waltonian fictionalism' is borrowed from Michael Weisberg (2013) who uses it to label Frigg's account.

58 This name of the practice originates in Thomson-Jones (2010 and the practice is discussed also by Peter Godfrey-Smith (2009) and Michael Weisberg (2013). On top of that, Martin Thomson Jones calls the hypothetical systems 'missing systems.' This notion of a missing system can be used to identify fictional model systems, as well as, fictional elements in modeling practices.

differ in their interpretation of these propositions as such. According to Frigg, the propositions are about hypothetical systems, whereas Toon claims that they are about existing target systems.

The goal of studying models is to pursue an epistemic purpose: modelers want to learn something. At least, they are eager to learn about the models themselves and, at best, they gain insights into target systems that are represented by the models. The main question of this chapter is whether Waltonian fictionalism is able to explain how modelers can learn from using epistemic tools such as scientific models. More in particular I will focus on the question how the two fictionalist views may account for the practice of using models in order to learn about target systems.

The structure of the chapter is as follows. First, I will discuss the two Waltonian fictionalist accounts of models in Section 5.2. Part of this section will be an introduction to the notion of a game of make-believe, the discussion of a particular example of such a game and the application of the theory of make-believe to scientific modeling. In Section 5.3, the epistemology of Waltonian fictionalism will be scrutinized in detail and the chapter will be concluded in Section 5.4.

5.2. Waltonian Fictionalism

The notion of a game of make-believe is the fundamental concept of the two fictionalist accounts (and of Walton's theory of make-believe, likewise). It is drawn from practices and experiences that almost every human being engages in already as a child. To give a very rough first idea of what games of make-believe are, think of games that children play if they pretend that a broomstick is a horse or if they pretend that they are feeding a baby when they are playing with a doll. The engagement in games of make-believe related to literature and science is claimed to be continuous with these children's games. Nevertheless there are differences: Some games are merely private games and others are practices in a community that are widely shared and stable over time. In the first case a game leads to imaginings that may be merely subjective but in the second case the imaginings have a certain status that grounds objective imaginings. This status of imaginings in so-called 'authorized' games of make-believe will be elaborated on, later on, as this 'objectivity' may ground the knowledge that models are supposed to deliver.

i) Games of make-believe. A game of make-believe is constituted by participants who use objects, so-called 'props,' in order to imagine particular propositions according to certain rules. These rules are called 'principles of generation' (Walton 1990, p. 38). A principle of generation is a conditional rule that prescribes the imagining of a particular proposition.

Props and principles prescribe the imagining of certain propositions; they 'generate' these propositions. A proposition that is in that way prescribed by a prop and a principle of generation is called a 'fictional proposition' (cf. Walton 1990, p. 35). Frigg defines a fictional proposition with the help of the further notion of a work *w*. In the case of literary fictions, the work *w* may be a novel or a story, which contains or at least supports the propositions that should be imagined; the *w*-prop and the *w*-principles are ingredients of the game of make-believe belonging to the particular work. Frigg's definition of a fictional proposition *p* reads: "*p* is fictional in work *w* iff the *w*-prop together with the *w*-principles of generation prescribes *p* to be imagined" (Frigg 2010c, p. 270). In the following subsection, a game of make-believe will be discussed that involves the use of tree stumps as props. In general, props can be ordinary objects such as broomsticks or tree stumps that have concrete features such as length or width, but the props also can be linguistic entities that have abstract features such as semantic content.

ii) *Hunting bears*. In order to make the theory of make-believe more comprehensible the following example of a game with concrete props may help. The example is a children's game in which children pretend to hunt bears in a wood. According to the game, the children treat every tree stump that they come across in the wood as a bear. The principle of generation of the children's game is the rule to treat a stump as a bear or, to be more precise, to imagine the proposition that there is a bear if one sees a stump. The essential ingredients of this game are the tree stumps and the rule to imagine the particular proposition when one sees a stump. The convention that every tree stump counts as a bear leads to there being a fact about how many bears there are in the wood according to the game. The proposition that there are say five bears in the wood is fictional in the game if and only if there are five tree stumps in the wood. A fictional proposition is also called a 'fictional truth' (Walton 1990, p. 40). However, theorists of make-believe stress that the notions of fictional truth or truth in a fiction must be distinguished from truth *simpliciter* (cf. Walton 1990, p. 41; Frigg 2010b, p. 117). Although "truth in fiction is not a species of truth" (Frigg 2010b, p. 117) the fictional truths have a certain status that grounds objective imaginings:

> An oddly shaped stump might prompt a child to imagine a wolf and not a bear, but the proposition that there is a wolf before them is only imagined, not fictional. Fic-

> tional truths therefore possess a certain kind of 'objectivity'; participants can be unaware of fictional truths and mistaken about them. (Toon 2010a, p. 304)

The acts of imagination according to a particular game are not arbitrary and they are not only subjective imaginings. Because the imagined propositions are prescribed by the principles they have the status of objective imaginings. This status is grounded in a shared practice of people engaging in the same game. On top of that, the status of some fictional truths is related to facts in the world. The fictional truths in the game of hunting bears depend on facts about the tree stumps. If a proposition is fictional then everyone engaged in the game ought to imagine the proposition. There may even be certain fictional truths that are not yet discovered. So, it is common to truths and fictional truths that they both can be discovered. Frigg and Toon give the example of the hidden tree stump that generates the fictional truth that there is a hidden bear in the children's game (cf. Frigg 2010c, p. 271; Toon 2010b, p. 80). Thus one can even make mistakes in a game of make-believe. Frigg mentions the case of a player taking a mole heap for a stump in the children's game (cf. Frigg 2010c, p. 265f.). In the case of taking a mole heap for a stump a player would be mistaken if she would claim that there fictionally is a bear. The state of the world together with the principles of generation determines what is fictional in the game. If there is a stump then it is fictional that there is a bear. If there is only a mole heap then it is not fictional that there is a bear.

iii) *Authorized games of make-believe.* Props can be ordinary objects such as the tree stumps in the children's game but they can also be linguistic entities such as literary descriptions in novels[59] or – as we will see shortly – descriptions in science. What is common to all of them is the capacity to make propositions fictional. The principles can be either constituted by ad hoc rules or they can be widely shared rules in a community that are relatively stable. The principle of the children's game of hunting bears is constituted by an ad hoc rule because the principle of that game is not widely shared and it is not stable. In contrast, the principles that govern the use of props in games that are 'authorized' are stable. Games that involve well-known works of literature have principles that are

59 Walton and the fictionalists regard the whole work of fiction as a prop in a game of make-believe.

widely shared and stable.[60] For example, the rule to imagine certain propositions about Sherlock Holmes, a character in the stories by Arthur Conan Doyle, is a stable rule of an authorized game. An example of a fictional proposition of this authorized game is that a detective lives in Baker Street 212B in Victorian London. So, there are unauthorized games with ad hoc rules such as the children's game and there are authorized games with stable rules that are publicly agreed upon (cf. Frigg 2010a, p. 259; Walton 1990, p. 60). Frigg gives the example of Hamlet, the play written by Shakespeare, as a prop in an authorized game of make-believe. A prop of an authorized game is called a 'representation' (Walton 1990, p.51; Frigg 2010c, p. 266). Tree stumps are not representations but works of literature, such as Hamlet, are representations. Representations do not only have the capacity to stimulate the imagination and to generate fictional propositions but it is their function to prescribe certain imaginings and so it is their function to generate fictional truths (cf. Walton 1990, p.52f.; Toon 2010a, p. 304). Representations have this function due to their belonging to an authorized game of make-believe.[61]

Fictionalists make a distinction between 'primary' fictional truths and 'implied' fictional truths. The primary fictional truths follow 'immediately' from the props. For example, the proposition that there are five bears might be a primary fictional truth in the children's game. Besides these primary fictional truths there are also implied fictional truths. An example for an implied fictional truth is the proposition that the five bears are dangerous (cf. Frigg 2010b, p. 115). Corresponding to these two kinds of fictional truths, there are two kinds of principles of generation. 'Direct' principles generate primary fictional truths and

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60 It is often the case that people in a community agree on certain issues about a fictional character, which are not told explicitly in the work itself. Readers or friends of theater agree for example that according to Shakespeare's play it is very likely that Hamlet's uncle killed Hamlet's father. However, the same persons do likely not agree on the question of whether Hamlet's refusal to kill his uncle is due to an unresolved Oedipus complex. It seems to be a fictional truth in Shakespeare's play that Hamlet's uncle killed Hamlet's father. It is at least debatable whether certain statements supported by a psychoanalytic interpretation of the play also express fictional truths (cf. Walton 1990, p. 138).

61 With regard to representation, a crucial difference between Frigg's and Toon's fictionalist accounts of models in science shows up. For Toon, Walton's notion of representation is to be equated with the notion of model-based representation in science whereas Frigg distinguishes between *p-representation*, representation of a model system with the help of a prop, and *t-representation*, representation of a target system with the help of a model system. I will elaborate on these two notions of p-representation and t-representation in the next subsection.

'indirect' principles together with the primary fictional truths generate implied fictional truths (cf. Frigg 2010b, p. 115). Let me now discuss the application of the theory of make-believe to the practice of modeling in the sciences. First, an application in the context of Frigg's indirect view will be discussed, and, later on, another example in the context of Toon's direct view.

iv) *The model of Sun and Earth*. Frigg gives examples of descriptions in various disciplines that he interprets as props in games of make-believe. For example, he cites models from physics, biology, and economics as involving props that are used to make-believe particular propositions (cf. Frigg 2010c, p. 261). One model that he analyzes in detail is the Newtonian model of the Earth orbiting around the Sun. According to that model, the two celestial bodies of Earth and Sun can be compared to an isolated system of two bodies with gravitation as the acting force. Beyond that, the bodies are regarded as perfect spheres with an even distribution of mass and it is assumed that the model sun is at rest.[62] These assumptions are the starting point of the modeling. Frigg calls the assumptions 'model descriptions' and he interprets the model descriptions as props of a game of make-believe (cf. Frigg 2010c, p. 267f.). Frigg claims that these descriptions are not descriptions of the Sun and the Earth. Rather they are tools to imagine a hypothetical system containing two ideal bodies. This hypothetical system is called the 'model system.' Participants of the game use the model descriptions in order to imagine propositions about the hypothetical model system.[63] The model system is in certain respects similar to a character in a work of fiction. Frigg compares the model system to a fictional character such as Madame Bovary or Sherlock Holmes and he names three common features of model system and character: 1. Model systems and characters can be subject of thought and debate. 2. One can make claims about them that are judged as correct or incorrect. 3. They are only imaginary and not real things (Frigg 2010c, p. 256f.).[64]

62 Note that when I refer to the Earth and Sun of our solar system I use capitals to indicate that we are using proper names. When I refer to model sun and model earth I use lowercases.

63 In this respect there is striking difference between Frigg's account and Toon's account. Toon claims that the postulation of hypothetical model systems is not necessary. According to his view, the model descriptions prescribe imaginings about the targets themselves and not about model systems. See also footnote 61.

64 The third claim about characters in fictions hinges on a particular position concerning fictional entities that is not shared among all scholars. If you are a fictional realist then you believe that

Frigg terms the relation between the model description and the model system 'p-representation.' As discussed in the previous subsection, a prop in an authorized game of make-believe is called a representation. Thus, p-representation is a relation between the prop and the model system that should be imagined. The model system is conceptualized by Frigg to be equivalent to a set of propositions. The model system is characterized by the 'world of the model' and the world of the model is equivalent to the set of propositions that are fictional according to the model descriptions and the respective principles of generation (Frigg 2010b, p. 118).[65]

By using the assumptions in order to imagine a model system it is possible to derive several inferences. One particular inference is that the model earth moves around the model sun in an elliptical orbit. Frigg points out that the determination of the orbit of the model earth around the model sun is an implied fictional truth of the modeling interpreted as a game of make-believe. Props and principles of direct generation generate the primary fictional truths of the modeling. For example, it is generated that the model earth is spherical. The implied fictional truths follow from the primary fictional truths and from principles of indirect generation, in this case the laws of classical mechanics. In this way Frigg reconstructs the activity of modeling as an act of imagination in a game of make-believe. The assumptions of the modeling are the props. Linguistic conventions are the direct principles of the game. The theory of classical mechanics, i.e., the laws and general principles of classical physics, provides the indirect principles of generation of that game. The proposition that the orbit of the perfectly spherical model planet around the model sun is an ellipsis is an implied fictional truth of the game of make-believe (cf. Frigg 2010c, p. 268).

The target of the modeling is the Earth and especially the movement of the Earth around the Sun. The relation between the model system and the target is called 't-representation.' Frigg defines t-representation as a relation between two relata, the model system and the target system. Two conditions have to be fulfilled in order for the model system to t-represent the target system: First, the model system has to denote the target system and, second, there has to be a 'key'

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characters are part of our world and that they do exist. For example, characters may be regarded as cultural artifacts (cf. Thomasson 1999).

65 Although Toon does not use the notion of a model system he nevertheless uses the notion of the world of a model. Toon also takes the world of a model to be constituted by the fictional propositions of the particular game of make-believe (cf. Toon 2012, p. 45).

that specifies how facts about the model system are to be translated into claims about the target system.[66] The first condition establishes the aboutness of the model system. The second guarantees that there is cognitive relevance of the model system for the target system (cf. Frigg 2010c, p. 275f.). The fictional truth that the model earth moves in an elliptical orbit around the model sun can be translated into the claim that the Earth's trajectory around the Sun is almost a perfect ellipsis (cf. Frigg 2010b, p. 135).

v) The model of the bouncing spring. According to Toon, modelers do not consider hypothetical model systems. Model descriptions prescribe the imagining of propositions about the targets directly. Toon discusses the example of modeling a bouncing spring with the help of the harmonic oscillator:

> When we model the bob bouncing on the end of a spring as a simple harmonic oscillator, we take the bob to be a point mass *m* subject only to a uniform gravitational field and a linear restoring force exerted by a massless, frictionless spring with spring constant *k* attached to a rigid surface. (Toon 2012, p. 38)

> [T]hese are not straightforward descriptions of the bouncing spring. Nevertheless, I believe, they do represent the spring, in Walton's sense: they represent the spring by prescribing imaginings about it. (p. 39)

These model descriptions prescribe the imagining of propositions about the spring that should be modeled. The descriptions generate – together with principles of generation – fictional propositions about the spring. The world of the model contains primary and implied fictional propositions. There are primary fictional propositions, for example, it is fictional that the spring exerts a linear restoring force. The primary fictional propositions lead to implied fictional propositions such as the proposition that the oscillation of the bob is sinus-shaped.

Because of this direct approach, Toon does not need to postulate further notions such as 't-representation' or 'key' like Frigg does. However, this parsimonious approach has problems with accounting for the knowledge about targets a model can deliver, which will elaborated on in the next section.

66 The notion of a key is not sufficiently accounted for by Frigg and this will be the topic of my criticism in Section 5.3.

5.3. The Epistemology of Waltonian Fictionalism

The two fictionalist views give an elaborate account of how games of make-believe are involved in the practice of modeling. The question is whether they are able to explain how modelers may learn from using epistemic tools such as scientific models. In the following two subsections, I will discuss this question in detail.

According to a particular game of make-believe, model descriptions generate fictional propositions. Model descriptions are comparable to works of fiction because both can generate fictional propositions. The fictional propositions of a particular model constitute the world of that model. One aspect of learning from models is to learn about the models themselves. Frigg and Toon agree on this point. Modelers can learn about models by finding out which propositions are indeed fictional propositions that belong to the world of the model (see 5.3.1). The more important aspect of learning from models is to find out about target systems. On this second aspect Frigg's and Toon's answers diverge. According to Toon, some fictional propositions are not only to be imagined but also to be asserted about target systems. The fictional propositions that are true of target systems can foster the knowledge about the targets (see the first part of 5.3.2). According to Frigg, fictional propositions have to be translated into claims about target systems. This translation is achieved with the help of a so-called key, a notion that is not based on Walton's theory (see the second part of 5.3.2). Let us first address the issue of learning about models.

5.3.1. Learning about Models

Both views stress that the world of a model is an important aspect of the object of study of modelers. The world of the model consists of all propositions that are fictional in the particular game of make-believe. Primary fictional propositions and implied fictional propositions belong to the world of a particular model. The practice of learning about a particular model is mainly about examining which propositions follow from the primary fictional propositions. These implied fictional propositions constitute the important knowledge about the models that modelers strive for. The implied fictional propositions are generated with the help of the indirect principles of generation of the particular modeling task and in case that these principles are explicit principles the modelers have indeed a justification for knowing these propositions. The primary fictional propositions and the principles together imply these propositions. And modelers can point to the principles as reasons of how they know that a certain implied proposition is indeed fictional.

Hence one can say that both fictionalist views account for knowledge about the models themselves given the appropriate principles of generation. Nevertheless, the notion of a principle of generation remains somewhat opaque. Both views don't define the notion. They distinguish between, on the one hand, principles of direct generation and, on the other hand, principles of indirect generation or principles of implication:

> Thus, we may divide the principles by which fictional truths are generated into two kinds: principles of direct generation and principles of implication. The former are conditional upon the features of the representation. They say for example, that if a novel contains certain words then certain fictional truths are generated. Principles of implication tell us what further fictional truths are implied by primary fictional truths. (Toon 2012, p. 46)

Frigg gives some examples of principles of generation. He mentions, e.g., linguistic conventions as an example of direct principles and the laws of classical mechanics as an example of the indirect ones (cf. Frigg 2010c, p. 268). Toon admits that it is difficult to state the principles of implication:

> I believe that principles of implication are more difficult to specify explicitly and will vary from case to case. [...] Even without an explicit statement of the various principles of generation, however, this account provides us with a way of understanding learning about a theoretical model. This is not a matter of learning facts about any object. Instead, it is a matter of discovering what is fictional in the world of the model. (Toon 2012, p. 47)

Granted that the practice of science can deliver evidence for the existence of principles of implication on a case-by-case basis both accounts do give an account of how modelers learn about the world of a model. But what about learning about the targets of models?

5.3.2. Learning about Targets

First, I will scrutinize Toon's answer to how a fictionalist view can account for learning about targets (*i*) and thereafter Frigg's answer (*ii*).

i) *Toon' account*. The point of discussion will be how modelers learn about a bouncing spring from using the model of the bouncing spring. There are several propositions in the world of the model of the bouncing spring. Some of the fictional propositions are false about the actual bob and spring. For example, the proposition that the bob is a point mass is false as is the proposition that the spring in fact exerts a linear force (cf. Toon 2012, p. 42). Nevertheless these propositions belong to the world of the model and they are fictional propositions. In contrast, other fictional propositions about the bob are true or at least approximately true.[67] For example, the fictional proposition that the bob's period of oscillation is roughly equal to 2π times the square root of the quotient of the mass and the spring constant is true (cf. Toon 2012, p. 67). Toon's view needs to distinguish fictional propositions that are true about targets from propositions that are not true about targets if it is to explain how modelers may learn about targets. It seems that Toon cannot appeal to the principles of generation and the model descriptions; they simply generate a set of fictional propositions and they are not able to distinguish between those propositions that are true of the target and those that are not. Toon can only defer the problem of detecting the true propositions among the fictional propositions to other principles. However at some point, where he speaks about the principles of generation, he seems to load the principles of generation with that further task too:

> Principles of generation often link properties of models to properties of the systems they represent in a rather direct way. If the model has a certain property then we are to imagine that the system does too. If the model is accurate, then the model and system will be similar in this respect. (Toon 2012, p. 68f.)

Here, the principles of generation seem to ensure that model and target share certain features. This is however conditionalized on the model being *accurate* which is a condition that itself is not further spelled out.

In my opinion, Toon's view cannot distinguish between fictional propositions that are true and fictional propositions that are not true. One needs to discern fictional propositions that are true from fictional propositions that are not true in order to learn something from a model about a target. Since Toon's view is not able to deliver a criterion for which propositions from the set of fictional propositions are also true propositions about the targets, I conclude that Toon's view does not give a satisfactory epistemology of modeling.[68]

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67 In the following I will omit the disclaimer but I will mean *true or approximately true* proposition when I write that a proposition is true.

68 In a recent publication, Arnon Levy (2015) elaborates on a direct view of modeling. He explicitly claims that his position is in agreement with Toon's one. Levy mentions that Toon

A possible reply that Toon might give is that only the implied fictional propositions are the propositions that are to be asserted about the targets, whereas the primary fictional propositions are the ones that are not true about the targets. There are two problems with this reply. First, it is not clear why the combination of *untrue* primary fictional propositions with the principles of implication would generate implied fictional propositions that are *true* about the targets. Second, there is the problem of distinguishing primary from implied fictional propositions. The distinction between primary and implied fictional propositions hinges on the distinction between principles of direct generation and principles of implication. This distinction itself is not clearly explicated. If Toon's answer to the question of the missing criterion is indeed based on this distinction then he faces a similar problem as Frigg, which brings me to the next subsection.

ii) *Frigg's account*. According to Frigg's view, modelers first learn about hypothetical model systems. There are facts about models that can be inquired about by studying the worlds of the models. In a second step, facts about models can be translated into claims about targets. A so-called key allows for the translation of a fictional proposition into a claim about a target. Unlike Toon, Frigg does not have the problem of distinguishing fictional propositions that are true from fictional propositions that are not true because fictional propositions are not about targets according to his account. However, a question is whether all fictional propositions are candidates for a translation into true claims about targets. Frigg does not say much about this but a reasonable assumption is that only some propositions are candidates. One might guess that only the implied fictional propositions are candidates for a translation into claims about the targets. In this case the already mentioned problem of distinguishing primary from implied fictional propositions and distinguishing the two sorts of principles of generation is as relevant for Frigg as it is for Toon.[69]

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largely is concerned with the content of models and not with how knowledge about targets is possible. He gives an account of modeling that utilizes the notion of partial truth to explain how modelers learn about targets. It may be that this strategy can solve the problems of Toon's view that I discussed. Levy, however, very briefly touches on his view of make-believe, only, and from these few remarks it is not clear whether he really is perfectly in line with Toon's approach. For example, Levy seems to regard the real-world phenomena as the props and not the model descriptions like Toon and Frigg have it (cf. Levy 2015, p. 791).

69 An anonymous reviewer pointed out that Frigg is not committed to the claim that only implied fictional truths are candidates for a translation. The primary fictional truth that the model sun

Granted that there is a definite set of propositions that are candidates for a translation, a second problem is how to account for this translation. Frigg's view postulates a key that allows translating a fictional proposition into a claim about a target. Frigg gives no explication of the notion of a key, but he gives the analogue of a map of London, which has a "key of translation" that helps to infer "facts about the city […] from facts about the map" (2010b, p. 126). The keys of models differ from keys of maps, though.

> However, unlike for maps where we know the key by construction (we have used a certain projection method, certain symbols, etc. when drawing the map), in the case of models the key has the character of a hypothesis. (Frigg 2010b, p. 129)

The key of a map is a legend but the key of a model is only a hypothesis. Therefore the key of the model does not translate facts about the model system, i.e. fictional propositions, into facts about the target system like the key of the map. The key of the model translates fictional propositions into claims about targets. Frigg is explicit about this difference and he writes, "keys [of models] are often implicit and determined by context" (Frigg 2010b, p. 128). Therefore a philosophical analysis is required "to make hidden assumptions explicit, and present a clear statement of them" (ibid.). However, Frigg's account does not deliver an explication of the notion of key. The only thing that he delivers is that he discusses the ideal limit as an example for a key of models.[70]

One may argue that the absence of a clear explication is a problem only if essential questions are left unanswered, and if the account contains fundamental ambiguities.[71] This is fair enough but usually this kind of answer is given when concepts are used that are well established in philosophy. The concept of a key is not an established one in philosophy and the few remarks that Frigg gives to characterize it are not supporting an explanation of how the key can foster knowledge about a target.

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and the model earth have mass and attract each other gravitationally can be translated into a claim about the target. If this is the case then the problem still is how to distinguish the fictional truths that *can* be translated from the fictional truths that *cannot*.

70 The discussed model of Sun and Earth appears to use the key of ideal limit. For this special case of a mathematical model in classical physics Frigg gives at least examples for the basic notions of his theory but there are no explications of the notions. Nevertheless, Frigg can point out that there is at least one instance for each of the mentioned tools of *direct principle*, *indirect principle* and *key*.

71 Thanks to an anonymous reviewer for raising this objection and the following one.

Given that a key only has the character of a hypothesis it is not clear how the study of model systems really can deliver knowledge about the target systems. The key functions as the important tool in order to translate a fictional proposition into a claim about the target. Hence, the translation inherits the character of a hypothesis and it is questionable whether any claim about the target generated by a hypothetical key is true and so could instantiate knowledge about the target.

One may further object that a model cannot establish by itself that a claim is also true and that only experimental test can establish that a claim is true. This objection may be answered with the help of a distinction that is not spelled out in Frigg's account, namely the distinction between models that are used in an early phase of research and models that are developed in the context of an established body of knowledge. The context of the discussed model by Frigg is classical mechanics and this part of physics is not in an early phase anymore. For example, one may want to use an expanded model of the celestial bodies that also incorporates the moon to predict the next solar eclipse. If the model allows for the translation of a fictional truth into a claim that the next eclipse will be in September 2016 then this is more than just a hypothesis.[72] This claim can be regarded as a reliable prediction. One might regard this claim as a justified claim that constitutes knowledge and one might even regard this claim as a true claim.[73]

5.4. Conclusion

Both, Toon and Frigg as Waltonian fictionalists give an account of how modelers learn *about models*. According to them, the modelers use principles of generation in order to learn about the models: model descriptions and principles generate the fictional propositions of the particular games of make-believe. The worlds of the models are characterized by the set of fictional propositions of the games. To know the fictional propositions is to know facts about the models.

In *Toon's* case the fictional propositions are propositions about the targets. Some of these propositions may be true about the targets and therefore they may

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72 The paper on which this chapter is based already was written in 2015.

73 This issue touches upon deep and longstanding philosophical problems, namely the question of statements about the future and the nature of truth. Are claims about future events true or false? Is truth an epistemic concept or not? A discussion of these problems falls outside the scope of this chapter.

ground knowledge about the targets. However, Toon's account cannot distinguish between fictional propositions that are true and fictional propositions that are not true about the targets and therefore the account cannot give a criterion for knowledge about targets. One solution to this problem of distinguishing fictional propositions that are true about the targets from propositions that are not true could be that the principles of implication may generate the true propositions about the targets. That solution, however, presupposes a clear distinction between direct principles and principles of implication, a distinction which Toon's account does not sufficiently spell out.

In *Frigg's* case, the knowledge about the targets is dependent on fictional propositions and on the keys that support translating the fictional propositions into claims about the targets. So, for Frigg there are three different kinds of tools that are needed in order to reach claims that may constitute knowledge about targets: props, principles and keys. On top of that, the principles are separated into direct and indirect principles of generation. However, this distinction is – just as in Toon's account – also missing a proper explication in Frigg's account. That is why to interpret the indirect principles as functioning to detect the fictional propositions that are candidates for a translation into claims about the targets is problematic. The third tools, the keys, are not given an explicit definition but they are characterized as hypotheses. It is not clear how hypothetical keys could translate fictional propositions into true claims about targets. Because of that it is questionable whether Frigg can explain how a justification for true claims about the targets can be given. Therefore the epistemology of Frigg's fictionalism stands on a rather weak footing.

Let me finally add a brief constructive remark to this rather negative result of the chapter. Although I criticize both views for not giving a sufficient epistemology of modeling, it might be feasible to combine Frigg's view with a structuralist account of representation. In the case of the model of Sun and Earth, it seems that the model system and the target system share a common structure. Because of this shared structure, claims about the target that are inferences of the modeling can be justified. There are many structuralist accounts in the literature and these accounts may help to formulate a solution to the problem of how one may learn from models about targets in the context of an indirect fictionalist view.

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6 Imagination in Climate Modeling: Scenarios as Props in Games of Make-Believe

Abstract

Climatologists recently introduced a distinction between projections as scenario-based model results on the one hand and predictions on the other hand. This chapter explores the difference between the two. We suggest interpreting projections as propositions to which one should have the attitude of make-belief instead of the attitude of belief. By applying pretense theory, we contend that scenarios function as props in authorized games of make-believe and that results of models that depend on scenarios are to be interpreted as implied fictional truths. With this interpretation, we explain the difference between projections that should be make-believed and other model results that should be believed.

Contents

6.1. Introduction

Scenario-based reasoning plays a central role in many fields of applied science. Starting with the first Report to the Club of Rome in the 1970s (Meadows et al. 1972), scenario-based reasoning took center stage in models that are used to inform decision-makers in the area of environmental policy. Via technology assessment, scenario-based thinking has also entered the engineering sciences (e.g. Carroll 1995). Today, particularly in the field of sustainability and energy supply, scenarios provide the basis for strategic decisions both in companies and on the level of policy.

Scenarios often provide the input for computational models.[74] Sophisticated examples include the scenarios for climate models that are used by the Intergovernmental Panel on Climate Change, henceforth 'IPCC.' Intuitively, there seems to be an epistemic difference between scenario-based modeling and modeling that does not involve scenarios; in fact, scientists themselves suggest this. For example, the IPCC calls the output of climate simulations that involve scenarios 'projections,' and not 'predictions' or 'prognoses' (cf. Nakicenovic et al. 2000). Focusing on quantitative methods, 'prediction' and 'prognosis' have precise meanings. In medicine, for example, predictions refer to the likely course of a disease in an individual, while prognoses identify subpopulations of people that most likely develop a certain disease or react to a certain treatment (cf. Brünner 2009). But what exactly distinguishes projections, besides the involvement of scenarios, remains an open question.

Dennis Bray and Hans von Storch express their worry about 'projection' and 'prediction':

> Both terms, prediction and projections, [...] are subject to different interpretations and connotations. Thus, the use, if not explicitly specified, has the potential to cause problems not only in the communication of climate science in the broader scientific realm but also in the understanding by the public at large, potentially influencing policy decisions, policy design, and policy implementation and public perceptions of climate change. (2009, pp. 534f.)

Bray and von Storch assume that the difference between projections and predictions is that the former are descriptions of *possible* outcomes whereas the latter are descriptions of *probable* outcomes and we will start from this characterization. Given that projections as scenario-based results are descriptions of possible results, to use the notion of possibility may be a first step in explaining what scenarios and scenario-based model results are. An intuitively appealing ap-

74 While in this chapter we focus on scenarios as the input to climate models, the literature also refers to model output as consisting of scenarios. Thus it is important to distinguish between input and output scenarios. In the following pages, we apply the term 'scenarios' solely to input scenarios.

proach might be to invoke the language of possible worlds. However, the metaphysical extravagance of the possible worlds framework is undesirable. We will take an alternative route in this chapter.[75] The theory of make-believe, in contrast, is ontologically parsimonious and only rests on the activity of imagining and corresponding attitudes of those who participate in games of make-believe. In offering an interpretation of the notion of projection we build on the work of scientific fictionalists and on the theory of make-believe. With this interpretation we aim to supplement certain views on climate models in philosophy of science that focus on 'serious' or 'real' possibilities (cf. Katzav 2014; Betz 2015). Joel Katzav, for example, discusses a possibilist view of climate models according to which "useful climate model assessment does not primarily aim to teach us something about how the climate system actually is but, rather, primarily aims to teach us something about how it might be" (2014, p. 229). Despite the burgeoning study of climate models within philosophy of science (e.g. Winsberg 2012; Parker 2014; Katzav 2014; Betz 2015; Frigg et al. 2015; Frisch 2015) and the dependence of most climate models on scenarios, so far scenario-based reasoning in the sciences has rarely been discussed in philosophy of science.[76] Following the views of climate scientists who see scenarios as characterized either by 'storylines' or 'narratives,' and following debates in philosophy of science that compare models to 'fictions,' we study the role of make-believe and the imagination in scenario-based reasoning. We are thus in dialogue with scholars such as Peter Godfrey-Smith (2009), Roman Frigg (2010a, 2010b, 2010c), and Adam Toon (2012), who defend a position of scientific fictionalism. We will focus on Frigg's account in particular. Like Toon, Frigg holds a Waltonian fictionalist[77] view, but unlike Toon, he holds an indirect view of representation that explicitly allows imagined model systems to take on a central role in the sciences. We argue that scenario-based modeling results can be interpreted as propositions to which one should have the attitude of make-belief

75 There are also other approaches that want to apply the notion of a 'credible world' to climate modeling. Betz (2015), for example argues that climate models can be interpreted as credible worlds. This approach might be fruitful but we want to focus on scenarios, here, and we do not want to presuppose a particular conception of models except for the framework of indirect representation to be discussed in Section 6.3.

76 For notable exceptions see, for example, Betz (2009) and Lloyd and Schweizer (2014).

77 Waltonian fictionalist views build on Kendall Walton's (1990) theory of make-believe and imagination.

instead of the attitude of belief.[78] Borrowing the terminology from Walton and Frigg that we outline in Sections 6.2 and 6.3, scenario-based modeling generates model results that we interpret as implied fictional truths because scenarios function as props in authorized games of make-believe. While for Frigg only the specification of model systems involves a form of make-believe, we contend that the scenario-based representation of target systems (such as the evolution of the Earth's climate with the help of specific models) also involves a form of make-believe. Moreover, in contrast to Frigg and Toon, we argue that the 'scientific fictions' of the modeling are the scenarios and not the models as such because scenarios function as props in games of make-believe. Whether or not the models themselves – understood as model descriptions or model systems or both – are to be interpreted as fictions in the sense of props, and whether or not the models do contain fictional elements, our analysis leaves open.

The chapter is structured as follows. Section 6.2 discusses the theory of make-believe that underlies the notion of fiction in the arts. This theory provides the basis for Frigg's so-called 'fiction view' of models, which is the subject of Section 6.3. With the help of Walton's vocabulary and Frigg's fictionalism, we look into scientists' uses of scenarios and offer an interpretation of the notion of projection. As a case study, we take a closer look at the so-called 'emissions scenarios' that provide the input for climate models. We describe these scenarios in Section 6.4 and give our philosophical interpretation of them in Section 6.5. The chapter concludes with a discussion in Section 6.6.

Before we begin our analysis, let us issue a caveat. Generally speaking, while proponents of scientific fictionalism do use the notion of fiction, they usually do not want to downplay scientific findings as material that is simply made up. When models are compared to fictions, this is not meant to denigrate them as stories that are arbitrarily invented. No fictionalists' claim should be interpreted as a postmodernist claim that equates fiction and science as a whole enterprise (cf. Frigg 2010c, p. 247). Comparing models to fictions is sometimes criticized as grist for the mills of anti-scientists. For example, Ron Giere points to the danger of playing into the hands of the followers of 'creation science,' who try to argue against evolutionary theory (cf. 2009, p. 257). Relatedly, one might fear that interpreting the scenario-based results of climate simulations as fictional

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78 We use the term 'belief' to refer to an attitude toward propositions that takes them to be true simpliciter, probably true, or empirically adequate.

truths will encourage climate skeptics. This fear, however, is not justified and misses the point that climate modeling obeys certain scientific standards, e.g., it is partly derived from corroborated, well-tested theories such as thermodynamics. Rather, we believe that our analysis helps to produce adequate interpretations of scenario-based modeling results and explains how they differ from model results that do not use scenarios as an input.[79] Frigg makes a distinction that is very helpful in this context: he draws a line between fiction as falsity or non-existence and fiction as imagination (cf. 2010c, pp. 248f.). Waltonian fictionalists primarily use the latter notion of fiction, and the theory of make-believe grounds their interpretation of fiction as imagination. In particular, they build on the work of Kendall Walton (1990), which also provides the starting point for our analysis of scenario-based reasoning. Thus, we begin with a discussion of Walton's theory in the following section.

6.2. Objective Imagination and Make-believe

According to Walton, studying games of make-believe is the first step toward understanding any kind of fictional art, such as literature, film, theater, or painting. Games of make-believe are fundamentally about imaginings that are constrained by certain rules. Such games vary widely. They range from games with linguistic material such as novels, to games with concrete objects such as playing 'house' with dolls, to games with works of program music and to games with works of cinema such as Hollywood films. The notion of make-believe, on which Walton's theory is founded, springs from observation of the universal phenomenon that children play games, in which they imagine things that do not have to be real. Human beings at the youngest age can and regularly do engage in such games, which involve pretense without the intention of deceiving other players.[80] Children playing in a wood who agree to imagine that tree stumps are

79 One may argue that the dependence on scenarios is not a specific property that distinguishes climate models from other models. The objection may go like this: Any model needs external input from variables that are not modeled internally. For example, even initial or boundary conditions are external input to most models. We will discuss in more detail as to how initial conditions and scenarios differ in subsection 6.4.1.

80 Accordingly, the theory of make-believe is often referred to as 'pretense theory.' We will use 'make-believe' and 'pretense' as synonyms. Walton himself, however, is ambivalent about the use of the latter term (cf. 1990, p. 81f., p. 391f., pp. 400-405).

bears illustrate a simple form of a game of make-believe. Suppose that in the game there is a prescription that all participants should imagine a bear when they notice a tree stump. The stumps are 'props' in this game of make-believe (cf. Walton 1990, p. 37). In general, in any game of make-believe, a prop acts as a crucial aid to the required imagining. Together with certain rules, in this case the above-mentioned prescription plus further principles of inference, the props prescribe propositions that the players are supposed to imagine. These propositions that ought to be imagined are called 'fictional propositions.' A fundamental statement of the theory is that props 'generate' fictional propositions. For example, five tree stumps in a part of the wood generate the fictional proposition that in this part of the wood there are five bears. Fictionally there are five bears, while actually there are only five tree stumps. The rules of the game are called 'principles of generation' (cf. Walton 1990, p. 38). The rule to imagine that there is a bear when one sees a tree stump is a principle of 'direct' generation. Besides direct principles, there are other principles of 'indirect' generation. For example, one might introduce the principle that the tree stumps should be imagined to have the properties of panda bears. This would lead to a less interesting game than one in which participants are to imagine dangerous grizzlies. Direct principles, indirect principles, and props generate fictional propositions such as the proposition that there are five dangerous bears in the wood (cf. Frigg 2010b, p. 115).

Fictional propositions can be regarded as 'fictional truths'; in other words, the fact that a certain proposition is fictional constitutes a fictional truth. This should not be conflated with truth *simpliciter*, because in the example it is not true that there are five bears in the wood; it is true that there are five tree stumps. The prop and the direct principle generate the 'primary fictional truth' that there are five bears. The primary fictional truth and the indirect principle generate the 'implied fictional truth' that there are five dangerous bears (cf. Frigg 2010a, p. 259; Walton 1990, p. 140).

To say that it is fictional that there are five dangerous bears means that there is a prescription for imagining this proposition. From this it follows that what participants should imagine in this game is not arbitrary. In general, the props and principles of generation ensure that there are accepted standards for what is fictionally the case in such a game. If a participant were to imagine that there were only four bears in the wood if there are in fact five tree stumps, she could be corrected and told that fictionally there are five bears. So participants can make mistakes in games of make-believe. Props and principles guarantee that there is something to discover in games of make-believe, because these props and principles deliver criteria for appropriate imaginings within such games.

Walton develops the theory of make-believe by applying it to representational arts more generally. Works of fiction such as novels or paintings are props in games of make-believe, much like the tree stumps in the children's game. Novels, paintings, and other props generate fictional truths; engagement with art is therefore continuous with games such as the one the children play in the wood. Appreciators of art should, according to specific rules, imagine certain propositions in order to understand a given artwork correctly. However, the status of the principles of generation in the children's game is different from the status of those principles in most games involving works of art. The rules in the children's game are ad hoc. They are not stable and are not widely shared in a community beyond the few players in that particular game. The rules of games involving works of art, however, are mostly stable and widely shared. These games are 'authorized' games (cf. Walton 1990, p. 51; Frigg 2010a, p. 264). Unlike the tree stumps that only happen to be used by children as props for the game of hunting bears, the props in authorized games are designed to be used as props; moreover, there is agreement regarding the use of these props because of stable and widely-shared principles of generation. In the Middle Ages, for example, everyone in Europe knew that the colors of the Virgin Mary in paintings were blue and white. The game of make-believe involving paintings in the Middle Ages included the principle that one should imagine the Virgin Mary when seeing a woman dressed in blue and white clothes in a painting. Arthur Conan Doyle's Sherlock Homes stories provide another example. These stories make it fictional that there is a detective living at 221B Baker Street in Victorian London. Such paintings and works of literature are not ad hoc props. It is their function to serve as props, and they are specifically made for this purpose. For this reason, most games of make-believe that require participants to engage with representational artworks are authorized games. In most cases, members of a society therefore agree in judging certain statements about works of art to be correct or incorrect. For example, every knowledgeable person will agree that it is correct that Sherlock Holmes lives at 221B Baker Street. This is a fictional truth, while the proposition that Holmes lives at 221B Paddington Street is not. Importantly, one should have the attitude of make-belief toward the proposition about Holmes living at 221B Baker Street, rather than the attitude of belief.

Appreciators of artworks, then, are invited to imagine fictional propositions that are constrained by the works as props and by stable and shared principles of generation.

6.3. Modeling and the Imagination

Philosophers of science have recently transferred pretense theory from the fine arts to the sciences (cf. Frigg 2010a, 2010b, 2010c; Toon 2012). Scientific modeling often involves descriptions that seem to refer to hypothetical entities rather than actual entities. Examples include point particles, the frictionless movements of a solid body along a slope, perfectly homogenous mass distributions, perfectly rational agents, and instantaneous access to information. Indeed, such 'hypothetical systems' (Frigg 2010a) or 'missing systems' (Thomson-Jones 2010) are part and parcel of many scientific models.[81] According to Waltonian fictionalists, modelers do not believe that these hypothetical entities exist, but they have the attitude of make-belief toward propositions about these entities.

Walton's theory, which originated with children's games, applies insights from these games to the appreciation of arts in general. In this section, we will apply the theory of make-believe to modeling in science by elaborating on Frigg's Waltonian fictionalist account. In Sections 6.4 and 6.5, we address the peculiarities of scenario-based modeling from a Waltonian fictionalist perspective.

The theory of make-believe is used to understand the practice of scientific modeling, which involves the formulation of model descriptions. These descriptions can come in different forms, such as ordinary language sentences, sentences in a technical vocabulary, or even mathematical equations. Frigg's position is distinguished by the way in which it focuses on model descriptions as sentences in a natural language. It is not clear whether model descriptions can include mathematical equations according to Frigg (cf. 2010a). In one reading, mathematical equations do not necessarily belong to the set of model descriptions. According to another reading of Frigg's position, and according to other fictionalist views, model descriptions comprise both linguistic statements and mathematical equations (cf. Cartwright 1983; Toon 2012).

81 Peter Godfrey-Smith characterizes such missing systems as entities that do not exist but that might have existed, and that in such a case "would have been concrete, physical things, located in space and time and engaging in causal relations" (2009, p. 101).

Most scientific models are used with the intention of representing target systems. Thus the model descriptions seem *prima facie* to be descriptions of certain target systems. Whether or not they represent target systems directly, however, is an issue of debate. According to Frigg, who follows a framework of indirect representation, model descriptions do not directly represent target systems: instead, they specify model systems that may stand in a representational relation to target systems (see also Godfrey-Smith 2006; Weisberg 2007).[82]

So in Frigg's indirect view of model-based representation, model descriptions specify model systems. The latter instantiate a certain structure, the model structure, and this structure may satisfy model equations. Frigg's account of make-believe in modeling seeks to explain how model descriptions specify model systems; this account is inspired by Walton's theory of make-believe.

As mentioned at the beginning of this section, scientific models often involve descriptions that do not seem to refer to any actual entity. Although it is clear that perfectly homogenous mass distributions are not part of our world, scientists speak of such things as if they were. Consider as an example the two-body model of the Earth's motion around the Sun. Here scientists undeniably model the world in terms of non-existing entities; two perfectly spherical bodies that have a homogenous mass-distribution are used as 'stand-ins' for the Earth and the Sun of our solar system.

Frigg uses this example of the model of Sun and Earth to apply the theory of make-believe to the sciences. Modelers consider model descriptions, i.e. sentences such as 'There are two gravitationally interacting bodies of homogeneous mass distribution, located from each other at a certain distance and interacting only gravitationally,' in order to imagine a hypothetical model system. In this case, we have the system of two hypothetical bodies governed by Newton's theory of gravitation. As discussed in the previous section, a prop in an authorized game of pretense generates fictional propositions. Frigg interprets the model description as just such a prop. According to Frigg's theory, model descriptions should be used to imagine propositions that characterize a hypothetical object, the 'model system,' which Frigg sees as equivalent to a set of propositions. The

82 According to an account of direct representation, in contrast, model systems as intermediate objects do not have to be postulated. Toon (2012), for example, defends such a direct account: he argues that model descriptions can represent target systems directly. Another direct view is defended by Arnon Levy (2015).

models system is characterized by the set of propositions that are fictional according to the model descriptions and the respective principles of generation (cf. Frigg 2010c, p. 271).

Using a model description to imagine a corresponding model system, it is possible to make several inferences. For a fixed position of the model sun, one particular inference is that the model earth moves around the model sun in an elliptical orbit with certain properties. Frigg points out that the exact determination of the orbit of the model earth around the model sun is an implied fictional truth if the modeling is interpreted as a game of make-believe. First, the props and principles of direct generation produce the primary fictional truths of the modeling; for example, it is generated that the model earth and the model sun are spherical bodies. Second, the implied fictional truths follow from the primary fictional truths and from principles of indirect generation. These principles are much more complex than in the example of the children's game, as they are in this case the laws of classical mechanics.

Frigg reconstructs the activity of modeling as an act of imagination in a game of make-believe. The model description of the model sun and the model earth functions as the prop in this game. The background theory, including laws and general principles, aligns with linguistic conventions to constitute the game's principles of generation. And the proposition that the orbit of the perfectly spherical planet around the model sun is an ellipsis is an implied fictional truth in the game (cf. Frigg 2010c, p. 268).

The target of the modeling is our Earth's movement around the Sun. Following Frigg, two conditions have to be fulfilled in order for the model system to represent the target. First, the model system has to denote the target; second, there has to be a 'key' that specifies how facts about the model system are to be translated into claims about the target. These two conditions establish the intentionality and the cognitive relevance of the model (cf. Frigg 2010c, p. 276). The fictional truth that the model earth moves in an elliptical orbit around the model sun can be translated into the claim that our Earth moves in an elliptical orbit around our Sun, at least to a certain degree of approximation.[83]

The theory of make-believe offers an explanation for the 'face value practice' (Thomson-Jones 2010) of speaking of apparently non-actual things as if they

83 The translation of fictional truths into claims about the target occurs via what Frigg calls the key of the modeling. In the case of the model of Sun and Earth, the key is the ideal limit, and therefore the orbit is almost an ellipsis.

were part of our world: scientists engage in games of make-believe when they use model descriptions in order to imagine model systems. So model descriptions can be regarded as props in games of make-believe. Unlike the tree stumps in the children's game, but like artworks in authorized games, the props are meant as props. And, as in the children's game, what the scientists are to imagine is not arbitrary. It is constrained by principles of generation. In Frigg's case of the model of the Earth's movement around the Sun, these principles are Newton's laws. In general, there are shared and stable principles in science that are missing in the children's game. Each discipline has its own principles of generation that allow only restricted inferences from model descriptions of specific modeling tasks. The principles of generation, together with the props, constrain what should be imagined. With the help of principles and props, then, one can derive the fictional truths of a particular modeling.

In the following sections, we will apply pretense theory to scenario-based modeling. We will argue that not only model descriptions but also scenarios may act as props in games of make-believe. In order to produce model results, the modeler has to imagine certain propositions that are constrained by different scenarios and by the principles of the model in question.

6.4. Scenarios in Climate Modeling

Today decision-makers in various areas, from policymakers to CEOs, rely on scenario-based reasoning. The increasing importance that scenarios play in decision-making and in contemporary applied sciences can be traced back to the 1960s, when Herman Kahn's studies on thermonuclear war not only impacted strategic military thinking and decision-making on the level of policy, but also shaped public discourse in the United States during the Cold War period of the 60s and 70s (Ghamari-Tabrizi 2005). Scenario-based modeling results currently play a particularly important role in the social, health, and environmental sectors. In the latter category, the energy realm made headlines with early scenario-based analysis published in the *Limits to Growth* Report to the Club of Rome (Meadows et al. 1972). This study focused mainly on energy-related issues. Today more than ever, the energy realm and its impact on the environment are examined with the help of scenarios.

Recently, debates surrounding models as fiction have focused mainly on the natural sciences, particularly physics. In these fields, scientific fictions coincide with the models or with contested entities that some authors have termed missing systems. In the following pages, we turn to the applied sciences. Our case study is climate modeling that seeks to estimate changes in global mean temperature, precipitation, or sea level. We will argue that in scenario-based models, scenarios act as props in games of make-believe; due to the involvement of scenarios, irrespective of the status of the models themselves, the proper attitude toward the scenario-based model *output* is that of make-belief.

First, we will discuss an objection to our approach to scenario-based modeling. According to this objection there is no significant difference between scenarios and initial conditions (6.4.1). Second, we introduce emission scenarios of climate models used by the IPCC (6.4.2).

6.4.1. Scenarios and Initial Conditions

An issue until now unexplored is the question of whether scenarios are simply sophisticated initial conditions. We will show in this chapter that scenarios can be seen as props. If scenarios were simply sophisticated initial conditions, then a question that could be raised is whether we are committed to transferring the interpretation of scenario-based model results as fictional truths to other model results as well. This would contradict the realistic intuition that model results should ideally be not fictional truths but propositions that are to be believed. Scenarios and initial conditions both deliver input to climate models. However, their function and use differ as we will outline hereafter.

Both scenarios and initial conditions deliver input to climate models. (Quantitative) scenarios and initial conditions both encompass a set of valued parameters. Climatologists distinguish between scenario input and initial conditions, though. In the case of the IPCC climate models the scenarios provide the height of future climate forcing, i.e., the evolution of greenhouse gas concentration in the atmosphere. They relate to energy demand and the economic growth of a society which both are related to the growth of the population of the society. The first difference is while initial conditions in climate models describe the state of the atmo-, hydro- or kryosphere at the present or some past point in time, scenarios determine the *evolution* of the climate forcing throughout the time period to be modeled, often the course of a century.

A second difference is that initial conditions are mostly factual. Scenarios on the other hand are about the future and are mostly hypothetical; they are not about factual states of affaires, but about potential ones.

Another difference between scenarios and initial conditions is that climatologists deal with the uncertainties arising from initial conditions and uncertainties arising from scenario input in very different ways. While initial conditions such as the present state of the atmosphere are taken from measurements with rather specific uncertainties associated to them, scenarios are very sophisticated estimates about the future course of events when it comes to climate variables such as greenhouse gas emissions. The quantitative scenario input for climate models comes from rather complex, though much less formalized mathematical models themselves (cf. Hillerbrand 2014). While the initial state is known within some bounds, the scenario can be associated with high uncertainties that are hard to quantify; scenarios as possible future emission pathways are not assigned a specific likelihood or probability of occurrence (cf. Bray & van Storch 2009; Hillerbrand 2014). This is the central reason as to why the IPCC suggests the differentiation between predictions and projections as introduced in section 6.1 of this chapter. "Essentially, a projection of climate change differs from a prediction in that a scenario of future emissions is assumed without giving it any specific likelihood of occurrence" (Giorgi 2005, p. 252f.). Despite the high uncertainties associated with scenario input, it needs to be kept in mind that complex model-based reasoning underlies the scenarios. Scenarios are not simple guesses about the possible future world we live in with respect to climatic relevant parameters. Rather scenarios derive from sophisticated estimates about possible emission futures and the underlying economic, ecological and political changes.

The last difference between scenarios and initial conditions is that while there is often only one set of initial conditions, there is usually a multitude of many scenarios. Scenarios operate in a holistic way in the sense that their function can only be understood in comparison to other scenarios of one group of scenarios, often called a family of scenarios. Someone working with scenarios needs many of them to compare model runs with respect to these different scenarios.[84]

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84 Important for the purposes of this chapter is that the scenarios are most often associated with climate futures that are described in narratives (RCP scenarios) or storylines (SRE scenarios). These narratives and storylines 'regulate' the way input from a scenario can be used as a special tool in climate modeling. In Section 6.5 we will apply the Waltonian concept of a prop in order to explain this special functioning of scenarios in climate models.

In the following, we take a detailed look at the scenarios used by the IPCC for modeling the climate.

6.4.2. Scenarios and Families of Scenarios

Particularly when analyzing large-scale environmental issues such as those associated with global warming and greenhouse gas emissions, scenarios provide the input for complex simulation models. Because of their dependence on scenarios, physical climate models are particularly well-suited for our analysis. We therefore focus in the following pages on scenarios as used in physical climate modeling. Here, the IPCC provides standard sets of scenarios for climatologists. As climate modeling consumes time and money and it is very complex, standardized scenarios are helpful tools: Sets of standardized scenarios provide a database for the models; they enable climatologists to compare different climate model runs.

So-called 'emissions scenarios' help to estimate climate-relevant factors that are needed as input in climate models. The scenarios parameterize assumptions about the future development of energy demand and supply over the course of the twenty-first century, such as those regarding the growth of the global population or economic growth. These parameters determine the temporal evolution of greenhouse gas concentrations, as well as other climate-relevant factors such as aerosol concentration and changes in albedo, over the course of the century (van Vuuren et al. 2011). The IPCC defines scenarios as "alternative images of how the future might unfold" (Nakicenovic et al. 2000, p. 3). Emissions scenarios are special socio-economic images, understood as a synthesis of quantitative statements and qualitative information – such as 'narratives' that characterize a plausible future (cf. Kriegler et al. 2012, p. 808).

The third and the fourth IPCC reports consider as many as 40 individual scenarios. These scenarios were first published in the *Special Report on Emissions Scenarios* in 2000 (Nakicenovic et al. 2000). Accordingly, they are labeled 'SRE' scenarios. In every SRE scenario, different assumptions are made about technological and economic development. Some scenarios consider a more environmentally friendly future than others; however, none of them consider deliberate political measures to limit greenhouse gas emissions (such as, for example, the Kyoto Protocol).[85]

The fourth assessment report classifies the 40 SRE scenarios into four families, with different outlooks on socio-economic development. The descriptions of these different socio-economic developments are called 'storylines.' The four families that are labeled *A1*, *A2*, *B1*, and *B2* can be characterized with the following storylines:

- The *A1* scenario family assumes quick economic growth and a world population that peaks at 9 billion in 2050, gradually declining afterwards. New and efficient energy technologies spread quickly all over the globe, and income and wealth disparities among various regions begin to even out. Different scenarios in this family emphasize the use and development of different technologies: one scenario is fossil-intensive, while another focuses on non-fossil fuels.
- *A2* scenarios share with those from the *A1* family the assumption that economic growth correlates with more energy demand; however, the world is now imagined as less integrated, as economic growth differs from region to region. Moreover, the world population continuously increases even after 2050.
- *B1* scenarios, like *A1*, consider a more integrated world with the same population dynamics – but one in which economic growth yields less greenhouse gas emission due to the introduction of green and efficient technologies.
- The *B2* scenario family resembles the less integrated world in *A2*, in which economic and technological development is very fragmented. Like *B1*, it is more ecologically friendly than *A2*. But in contrast to *B1*, environmentally friendly solutions are local rather than global (cf. Solomon et al. 2007, p. 18).

As regards future greenhouse gas emissions, the projected atmospheric concentration in the four scenario families ranges from 490 to 1260 ppm. The significance of the predicted range become clear when one compares it to the pre-industrial level of about 280 ppm in 1750 and to the concentration of 368 ppm in 2000. Of course, though this spans a wide range of emission futures,

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85 Implemented around the time of the third and fourth IPCC reports, the Kyoto Protocol was the United Nations' international treaty regarding greenhouse gas emissions. It was adopted in December of 1997 and was signed by many states – with the U.S. and China as notable exceptions.

the real course of events may well be very different, and real emissions may be well outside the predicted range (cf. Hillerbrand 2014).[86]

The information provided by these scenarios is extremely complex. Climate models have different resolutions: the scenarios offer high-resolution input data for numerical climate models that divide the world into grids.[87] Moreover, all climate scenarios incorporate knowledge from very different fields: from physical climate models, impact models, ecosystem models, and others. They are not dreamt up in the lab or constructed out of thin air; they are gauged against scientific background knowledge. Consequently, new research delivers an update to these scenarios from time to time, as detailed in the supporting materials prepared in anticipation of the fifth IPCC assessment report:

> New sets of scenarios for climate change research are needed periodically to take into account scientific advances in understanding of the climate system as well as to incorporate updated data on recent historical emissions, climate change mitigation, and impacts, adaption and vulnerability.[88]

Hence, the fifth IPCC report considers new scenarios. Instead of clustering a large group of scenarios into families as in the fourth report, now only four so-called representative scenarios are considered. The four scenarios are characterized as

> alternative pathways (trajectories over time) of radiative forcing levels (or CO2-equivalent concentrations) that are both representative of the emissions scenario literature and span a wide space of resulting greenhouse gas concentrations that lead to clearly distinguishable climate futures.[89]

These radiative forcing trajectories are termed 'Representative Emission Pathways' or 'RCP' scenarios. The four representative scenarios are called *RCP8.5*,

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86 This is related to the mentioned point of the difference between scenarios and initial conditions. The scenarios are not descriptions of an actual future. They are first of all about potential futures.

87 For example, the scenarios in the recent fifth IPCC report provide the input data for a spatial grid with cells measuring half a degree of latitude and longitude, resulting in 518,400 cells in total.

88 http://sedac.ipcc-data.org/ddc/ar5_scenario_process/scenario_overview.html

89 See previous footnote.

RCP6, *RCP4.5*, and *RCP2.6*, where the numbers refer to radiative forcings (measured in watts per square meter) by the year 2100.[90]

Each of the RCP scenarios was developed by a different research group. These research teams reviewed the existing literature and synthesized values for a wide range of scientific and socio-economic data such as population growth, GDP, air pollution, land use, and energy sources. But unlike the SRE scenarios, this database contains climate-relevant parameters only and does not include socio-economic data. Researchers can instead test various social, technical, and economic circumstances that are compatible with the various RCP scenarios. The descriptions of these circumstances are called narratives, and are in a sense equivalent to the storylines of the SRE scenarios. These narratives are provided by so-called "shared socio-economic reference pathways," which are defined as "parsimonious narrative[s] capturing the key dimensions of the underlying global scale socio-economic development" (Kriegler et al. 2012, p. 808). However, the new scenarios also differ from the SRE scenarios in other respects. For example, the RCP scenarios can incorporate political measures to counterbalance climate change, such as the two-degree goal or possibly geo-engineering. Though these scenarios span a broad range of potential futures, it is conceivable – i.e. in accordance with the laws of nature – that the actual future lies outside the range spanned by the RCP scenarios used in the fifth report.

Like the SRE scenarios, the latest IPCC scenarios consider fairly different climate futures. Because the real course of events may well be outside the range spanned by the representative pathways, scientists do not believe that all the outputs of climate models will be realized. Policymakers, however, often conflate them with adequate representations of an actual future. In fact, scientists frequently assert that the outputs of the climate models are highly uncertain. They rarely quantify this uncertainty in terms of probabilities (cf. Hillerbrand 2010). Rather, the import is that scenarios are used in situations where we face high uncertainty. This is true for scenario analysis more generally, and is also highlighted in the supporting materials for the fifth IPCC assessment report: "The goal of working with scenarios is not to predict the future but to better under-

90 The last scenario is also referred to as *RCP3PD*, where 'PD' stands for Peak and Decline – meaning that the radiative forcing peaks in the twenty-first century and then declines to the level of 2.6 watts per square meter.

stand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures."[91]

The IPCC purposely introduced the novel term 'projection' in order to distinguish scenario-based model results from prognoses or predictions. We will provide an interpretation of this term in which we contend that the expected attitude toward the scenario-based output of a climate model is not belief but make-belief. However, this claim does not mean that the output is arbitrary. Predicated on a scenario that contains information about factors such as future greenhouse gas concentration, the projection of a particular model run is an outcome that is scientifically constrained. As shown in the previous sections, the make-believe in a game is constrained by props and principles of generation.

6.5. Scenarios as Props in Games of Make-Believe

In order to stress their reliance on input from scenarios, the IPCC uses the term 'projections' for scenario-dependent climate model outputs; this term distinguishes them from prognoses and predictions. We follow the IPCC's practice, and we use the language of pretense theory to make sense of this practice. In particular, we contend in the following pages that both prognoses and predictions can be regarded as quantitative claims to which one should have the attitude of belief. In contrast, we argue, the proper attitude toward projections based on scenario-based models is make-belief.

The scenarios that the IPCC considers yield quantitative information about climate-relevant parameters such as greenhouse gas and aerosol concentration in the atmosphere. For us it is important that both quantitative and qualitative model results generated with the help of scenarios can be characterized by propositions. Let us consider some model results generated by climate models. Take this quotation from the Summary for Policymakers of the Working Group I Contribution to the recent IPCC report:

> Relative to the average from year 1850 to 1900, global surface temperature change by the end of the 21st century is projected to *likely* exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*). Warming is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), *more likely than not* to exceed 2°C for RCP4.5 (*high confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). Warming is

91 http://sedac.ipcc-data.org/ddc/ar5_scenario_process/

> *unlikely* to exceed 4°C for RCP2.6, RCP4.5 and RCP6.0 (*high confidence*) and is *about as likely as not* to exceed 4°C for RCP8.5 (*medium confidence*). (Stocker et al. 2013, p. 20; emphasis in original)

From this we extract the proposition that warming is more likely than not to exceed 2°C. This is, however, not a claim that a scientist believes; instead it has to be conditionalized on a specific scenario, here the scenario RCP4.5. We propose to regard such an apparent claim as a fictional proposition that is generated by the specific scenario. The climate scientist does not believe the proposition that warming is more likely than not to exceed 2°C. Rather, the scientist make-believes the proposition that warming is more likely than not to exceed 2°C given a specific emissions scenario. Conditional on the RCP4.5 scenario, the content of the proposition is something that it is appropriate to imagine. Using the terminology of Waltonian fictionalism, the scenario RCP4.5 generates the fictional proposition that warming is more likely than not to exceed 2°C.

This passage also contains the statement that warming is unlikely to exceed 4°C. Like the statement that warming is more likely than not to exceed 2°C, this statement is to be conditionalized on particular scenarios, here the three scenarios RCP2.6, RCP4.5 and RCP6.0. The scenario RCP4.5 generates both the proposition that warming is more likely than not to exceed 2°C and the proposition that warming is unlikely to exceed 4°C. This second proposition is also something that one should not *believe*. This is because, if there are no measures to mitigate the emissions of greenhouse gasses in the near future, then warming may easily exceed 4°C. Thus the proposition that warming is unlikely to exceed 4°C might be false, and so one should not believe it. The proper attitude toward this proposition is make-belief as well. What is more, both propositions are constrained by the same scenario. Given the RCP4.5 scenario, the respective climate model mandates that we should imagine that warming is more likely than not to exceed 2°C and that warming is unlikely to exceed 4°C.

Take a look at a quotation from another Summary for Policymakers:

> The evidence for human influence on the climate system has grown since the IPCC Fourth Assessment Report (AR4). It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together. (Pachauri et al. 2014, p. 5)

The statement in the last sentence of the quotation is not conditionalized on one or more emissions scenarios. It is a claim about the cause of warming over the last sixty years. The reader, like the scientists, should have the attitude of belief toward this statement. In contrast, the first IPCC quotation provides typical examples of projections; these results should be make-believed. Hence we argue that projections as model results can be interpreted as fictional propositions toward which one should have the attitude of make-belief rather than the attitude of belief. But other propositions, such as the cited causal claim, are instead to be interpreted as claims that express beliefs. Likewise, claims that express predictions or prognoses require the attitude of belief.

Make-belief is not aimed at true beliefs; make-belief involves imagining something according to specific rules. The content of certain propositions to be imagined may be true, yet it is often not literally true. In an authorized game of make-believe, there are shared and stable rules or principles. For this reason, an authorized game of make-believe is not a freely floating form of imagining, like dreaming up which figures one can see in a cloud. Although propositions that should be make-believed are not always true, they nevertheless have certain correctness conditions; fictional truths therefore have the status of objective imagination. The propositions generated by scenario-based models can be regarded as forms of fictional truth. As detailed in Section 6.2, such truth is not to be conflated with propositions that are to be believed because one should not unconditionally believe that global warming is unlikely to exceed 4°C; rather this proposition should be make-believed. It is true that, under certain assumptions detailed in a specific scenario, the model projections imply that this is unlikely. The scenario acts as a prop. Together with the principles, the scenario generates the *fictional* truth that the warming is unlikely to exceed 4°C. Like the modeling discussed in Section 6.3, the principles of generation encompass physical laws. In the case of climate modeling, these are most notably the laws of thermodynamics and fluid dynamics. Beyond that, a whole range of (explicit as well as tacit) knowledge is part of the required competence of a climate modeler. It ranges from knowledge of atmospheric chemistry, to knowledge of modeling cloud formations and their interaction in the atmosphere, to knowledge of how to model and parameterize subgrid processes that are too small to be modeled directly on the numerical grids used to implement the climate models (Hillerbrand 2014). The incorporation of this and other knowledge that is both empirically testable and tested makes climate projections a part of scientific inquiry to be distinguished from 'mere fiction.'[92] The theory of make-believe offers an account of the difference between propositions that are mandated by props and principles and propositions that are not mandated.

6.6. Concluding Discussion

According to Waltonian fictionalism, the theory of make-believe can explain the face value practice of talking and thinking about hypothetical entities. For Waltonian fictionalists, model descriptions are props in games of make-believe. In this chapter, we showed that the theory of make-believe can shed new light on the use of scenarios in climate modeling. We used emissions scenarios to demonstrate that in climate modeling, scenarios can be reconstructed as props in games of make-believe. We argued that the scenarios and not the model descriptions comprise such props. Along with this reconstruction, we offered an interpretation of the notion of projection as used by the IPCC; our interpretation explained the difference between projections and both predictions and prognoses by scrutinizing the required attitude toward these different model results. Just as props generate propositions that are to be imagined according to certain games of make-believe, so the scenarios of climate models generate projections as model results that are to be imagined by users of these models. The appropriate attitude toward model results that are generated by scenarios is therefore not belief but make-belief.

As noted above, however, using Walton's theory of make-believe to analyze scientific modeling does not undermine the trustworthiness and reliability of scientific modeling in the slightest. According to pretense theory, the scientifically justified methodology of modeling is part of the principles of generation. The virtue of Waltonian fictionalism applied to scenario-based models is that it helps to differentiate the specific attitude toward model-based results that rely on scenarios. Moreover, we hope that our interpretation will help the users of scenario-based model results, scientists as well as laypeople and policymakers, to better understand these results and to integrate them into their knowledge systems.

92 Here we use the term 'fiction' in the dismissive way that a climate skeptic might employ it.

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Summary

The central question of this thesis is how one can learn about particular targets by using models of those targets. A widespread assumption is that models have to be representative models in order to foster knowledge about targets. Thus the thesis begins by examining the concept of representation from an epistemic point of view and supports an account of representation that does not distinguish between representation simpliciter and adequate representation. Representation, understood in the sense of a representative model, is regarded as a success term. That is, a representative model is one relatum in a relation of *adequate* representation (Chapter 2). When a representative model represents a target, it allows users of this model to learn something about the target. It is argued that a representative model can have this epistemic function because it shares relevant features with the target. This presupposes a similarity view of representation. Similarity views of representation face serious objections, which will be rebutted (Chapter 3). One way of spelling out a similarity view of representation is to defend an indirect view of representation. In this thesis, which does not argue for an indirect view, it is assumed that the indirect view is a good option, if not the best, for articulating the similarity view. It is demonstrated how such an indirect view can be expanded to account for cases of technological modeling. A case study in bioengineering is used to show that the indirect view of representation must acknowledge a distinction between two directions of fit in relations between vehicles and targets. In this context the notion of design is interpreted as a relation between a vehicle and a target, thereby connecting ideas from philosophy of science with ideas from philosophy of technology (Chapter 4). Fictionalist accounts of models are intended to tackle the issue of the ontology of models. In this thesis, however, two prominent fictionalist accounts are discussed from an epistemological point of view in light of the central question regarding how one can learn about targets by using models. This question is addressed from the standpoint of Waltonian fictionalism. The result of the discussion is that the two discussed Waltonian fictionalist accounts cannot sufficiently answer the question. These accounts are criticized for their inability to deliver a satisfactory epistemology of representation (Chapter 5). Although Waltonian fictionalism is criticized, the present thesis also shows that the foundational theory of Waltonian fictionalism, the theory of make-believe can

nevertheless be used to account for the distinction between projections and predictions that is made by the Intergovernmental Panel on Climate Change (Chapter 6).

After this bird's eye view of the thesis, the following paragraphs will introduce the contents of each chapter in more detail. This thesis proposes a novel perspective on scientific representation, arguing that an evaluative stance of model users towards models is necessary. Further, it is argued that representation essentially encompasses evaluative and descriptive aspects and that these two aspects of representation are strongly intertwined. Just as nonseparationist positions in metaethics argue for the strong connection of evaluative and descriptive aspects of thick *ethical* concepts, this thesis argues for the strong connection of evaluative and descriptive aspects in representation as a thick *epistemic* concept. Accordingly, *Chapter 2* of the thesis argues for a 'thick account' of representation. Moreover, it argues that representation is a success term. In philosophy of science, many scholars claim that the nature of representation should be explained only with descriptive notions. This answer to the question on representation is called the *thin* answer in this thesis. Some thin theorists admit that there are unconnected evaluative questions about representation: for instance, what is an adequate or successful representation? Or conversely, what is a misrepresentation? All thin views agree on the methodological rule that these evaluative questions, if they are addressed at all, should be addressed independently of the question of what a representation is. *Thick* accounts, by contrast, claim that descriptive and evaluative questions about representation can only be answered in conjunction. The thick views, in acknowledging the evaluative aspect of the concept of representation, reject the separation of descriptive and evaluative aspects. Two arguments in favor of a thick account are given, and possible objections to such an account are discussed. The conclusion is that the arguments on balance support a thick account.

Chapter 3 deals with arguments against similarity views of scientific representation. This chapter argues that a sophisticated similarity account is still a viable option despite these objections. By refuting the arguments against similarity views of representation, the chapter argues indirectly for similarity as a necessary condition of representation.

The major epistemic virtue of successful models is their capacity to adequately represent specific phenomena or target systems. According to similarity views of representation, models must be similar to their corresponding targets in order to represent them. In this chapter, Mauricio Suárez's arguments against similarity views of representation are scrutinized, concluding that the intuition that representation involves similarity is not refuted by Suárez's arguments. The arguments do not make the case for the strong claim that similarity between vehicles and targets is neither necessary nor sufficient for representation. In particular, one claim can still be defended: a vehicle is a representation of a target only if the vehicle is similar to the target in relevant respects and to a specific degree of similarity.

Suárez's arguments against similarity views of representation are often cited but rarely dealt with in detail. This chapter thoroughly discusses and evaluates these arguments. By rebutting these arguments the chapter shows that a sophisticated similarity view is still a reasonable option. The chapter opens the possibility for a broad similarity view on representation that is compatible with structuralist views on representation but also connects with similarity views such as Ron Giere's or Michael Weisberg's views.

Mainstream approaches to representation distinguish between i) representation simpliciter and ii) adequate representation. It is argued that similarity views or structuralist views do not provide answers to the first question of what representation simpliciter is, but only to the second question of what adequate representation is. In view of the argument for the thick account of representation, chapters 2 and 3 jointly show that a similarity view can address the question of what representation is, without detaching the issue of the adequacy of representation. In the epistemic context of modeling, the goal of adequately representing a target system is the central motivation for researchers. A thick account of representation accounts for this goal and addresses the meaning of representation as a success term.

Chapter 4 involves a case study of an organ on chip model in bioengineering. The notion of design is used to apply an indirect view of representation to this engineering context. It is shown that the notions of representation and design can be used to open up a novel perspective on models that might lead to a unified account of models in science and engineering. These two notions are interpreted as referring to modeling relations between vehicles and targets that differ in their respective directions of fit: The relation of representation has a vehicle-to-target direction of fit and the relation of design has a target-to-vehicle direction of fit. The case study of an organ on chip model illustrates that the technical device does participate in both design and representation relations. The two relations share the same relatum of the organ on chip but they have different directions of fit. In the design relation the chip is adjusted to conform to a design plan in which case we are dealing with a target-to-vehicle direction of fit. In the representation relation the chip is adjusted to conform to a human organ in which case we are dealing with a vehicle-to-target direction of fit. This example shows that a conception of modeling as involving only relations with a vehicle-to-target direction of fit is too narrow to account for all models in science and engineering. This chapter is intended as an expansion on the existing accounts of indirect representation. In addition, the chapter argues that accounts of representation miss a crucial modeling relation when they only focus on modeling relations with a vehicle-to-target direction of fit. Finally, the proposal of interpreting design as a modeling relation may allow for other uses of models beside the sole purpose of representation.

The last two chapters discuss fictionalism about models. Fictionalism is first criticized from an epistemological point of view, but fictionalist ideas are also constructively applied to the example of a model in climate science. *Chapter 5* criticizes Waltonian fictionalist accounts of modeling and representation for not providing a satisfactory epistemology of modeling. In particular, this chapter focuses on the views put forth in the works of Roman Frigg and Adam Toon. A fundamental thesis of their views is that scientists are participating in games of make-believe when they study models in order to learn about the models themselves and about target systems represented by the models. In discussing the epistemology of Waltonian fictionalism, it is argued that the views of Frigg and Toon can explain how scientists learn about the models they are studying. However, Waltonian fictionalism does not sufficiently account for how the use of models can foster an understanding of target systems.

Chapter 6 applies the Waltonian theory of make-believe to a case study in climate modeling. Scenarios are interpreted as props in games of make-believe and it is argued that the attitude one must take toward scenario-based model results is to make-believe and not to believe. The background of the chapter is that climatologists of the Intergovernmental Panel on Climate Change recently introduced a distinction between *projections* understood as scenario-based model results, and *predictions*, or model results to which certain probabilities can be ascribed. This chapter explores the difference between the two and suggests that projections can be interpreted as propositions towards which the appropriate attitude is to make-believe rather than to believe. By applying pretense theory, the chapter contends that scenarios function as props in authorized games of make-believe and that results of models that employ scenarios are to be interpreted as implied fictional truths. This interpretation enables an explanation of the difference between projections that should be make-believed and other model results that should be believed.

Samenvatting

De centrale vraag van dit proefschrift is hoe men kan leren over specifieke onderzoeksobjecten, in het vervolg aangeduid als ‘doelen,’ door modellen van doelen (onderzoeksobjecten) te gebruiken. Een wijdverbreide aanname is dat modellen representatief moeten zijn voor doelen om kennis over die doelen te kunnen opleveren. Daarom begint het proefschrift met een onderzoek naar het concept van representatie vanuit epistemologisch oogpunt en ondersteunt het een opvatting van representatie waarin geen onderscheid wordt gemaakt tussen representatie simpliciter en *adequate* representatie. Representatie, in de zin van een representatief model, wordt beschouwd als een succesterm. Dat wil zeggen dat een representatief model een relatum is in een relatie van adequate representatie (hoofdstuk 2). Wanneer een representatief model een doel representeert, kunnen gebruikers van het model iets leren over het doel. We beargumenteren dat een representatief model deze epistemologische functie kan hebben omdat het relevante kenmerken deelt met het doel. Dit veronderstelt een gelijkenisvisie op representatie. Tegen gelijkenisvisies op representatie worden serieuze bezwaren ingebracht, maar die zullen worden weerlegd (hoofdstuk 3). Een van de manieren om een gelijkenisvisie op representatie te presenteren is door een indirecte visie op representatie te verdedigen. In dit proefschrift, waarin een indirecte visie niet wordt verdedigd, wordt aangenomen dat de indirecte visie een goede optie is, zo niet de beste, om de gelijkenisvisie te formuleren. We laten zien hoe een indirecte visie kan worden uitgebreid voor gevallen van technologische modellering. Met behulp van een casestudy in de biotechnologie laten we zien dat in een indirecte visie op representatie rekening moet worden gehouden met twee verschillende aanpassingsrichtingen (‘directions of fit’) tussen representatiemiddelen (waaronder modellen) en doelen. In deze context wordt het concept ‘ontwerp’ geïnterpreteerd als relatie tussen een representatiemiddel en een doel. Zo worden ideeën uit de wetenschapsfilosofie gecombineerd met ideeën uit de techniekfilosofie (hoofdstuk 4). Fictionalistische benaderingen van modellen zijn bedoeld om de kwestie van de ontologie van modellen te behandelen. In dit proefschrift worden twee prominente fictionalistische benaderingen echter vanuit epistemologisch gezichtspunt besproken in het licht van de centrale vraag hoe we iets over doelen kunnen leren door modellen te gebruiken. Deze kwestie wordt benaderd vanuit het Waltoniaans fictionalisme. De twee besproken Waltoniaans-fictionalistische benaderingen blijken niet in staat te zijn om de centrale vraag afdoende te beantwoorden. De kritiek is dat ze geen bevredigende epistemologie van representatie kunnen verschaffen (hoofdstuk 5). Hoewel het Waltoniaans fictionalisme wordt bekritiseerd, laat dit proefschrift ook zien dat de basistheorie van het Waltoniaans fictionalisme, de theorie van doen-alsof, wel kan worden gebruikt om het onderscheid tussen projecties en voorspellingen te duiden dat door het Intergovernmental Panel on Climate Change wordt gemaakt (hoofdstuk 6).

Na dit korte overzicht bespreken we in de volgende alinea's de inhoud van het proefschrift in meer detail voor elk hoofdstuk. Met dit proefschrift stellen we een nieuw perspectief voor met betrekking tot wetenschappelijke representatie, waarbij we beargumenteren dat het noodzakelijk is dat gebruikers van modellen een evaluatieve houding aannemen ten opzichte van modellen. Verder stellen we dat representatie in haar kern evaluatieve en descriptieve aspecten bevat en dat deze twee aspecten van representatie sterk met elkaar verstrengeld zijn. Zoals in niet-separationistische opvattingen binnen de meta-ethiek wordt gesteld dat er een sterk verband is tussen evaluatieve en descriptieve aspecten van 'thick' *ethische* concepten, zo stelt dit proefschrift dat er een sterk verband is tussen evaluatieve en descriptieve aspecten van representatie als 'thick' *epistemologisch* concept. In verband hiermee wordt in *hoofdstuk 2* van het proefschrift een 'thick' benadering van representatie verdedigd. Bovendien wordt beargumenteerd dat representatie een succesterm is. In de wetenschapsfilosofie wordt vaak gesteld dat de aard van representatie alleen moet worden uitgelegd met descriptieve begrippen. Dit antwoord op de vraag over representatie wordt in dit proefschrift 'thin' genoemd. Sommige aanhangers van deze zienswijze geven toe dat er afzonderlijke evaluatieve vragen over representatie bestaan, bijvoorbeeld: wat is een adequate of een succesvolle representatie? Of andersom, wat is een misrepresentatie? In alle 'thin' visies is men het eens over de methodologische regel dat deze evaluatieve vragen, zo ze al worden beantwoord, onafhankelijk moeten worden beantwoord van de vraag wat een representatie is. In 'thick' benaderingen wordt juist beweerd dat descriptieve en evaluatieve vragen over representatie alleen in samenhang met elkaar kunnen worden beantwoord. In deze visies wordt het evaluatieve aspect van het concept 'representatie' erkend en daarmee de scheiding tussen descriptieve en evaluatieve aspecten verworpen. We geven twee argumenten voor een 'thick' benadering en bespreken mogelijke bezwaren tegen een dergelijke benadering. De conclusie is dat de argumenten sterk genoeg zijn om de 'thick' benadering te ondersteunen.

Hoofdstuk 3 behandelt argumenten tegen gelijkenisvisies op wetenschappelijke representatie. In dit hoofdstuk stellen we dat een verfijnde gelijkenisbenadering ondanks deze bezwaren een bruikbare optie is. In dit hoofdstuk weerleggen we de argumenten tegen gelijkenisvisies op representatie en ondersteunen daarmee indirect gelijkenis als noodzakelijke voorwaarde voor representatie.

Het grote epistemologische voordeel van succesvolle modellen is hun vermogen om specifieke verschijnselen of doelsystemen adequaat te representeren. Volgens gelijkenisvisies op representatie moeten modellen lijken op hun overeenkomstige doelen om deze te kunnen representeren. In dit hoofdstuk worden de argumenten van Mauricio Suárez tegen gelijkenisvisies op representatie nauwkeurig bekeken, waarna we concluderen dat de intuïtie dat representatie gelijkenis met zich meebrengt, niet wordt weerlegd door de argumenten van Suárez. Zijn argumenten zijn geen bewijs voor de sterke bewering dat gelijkenis tussen representatiemiddelen en doelen noch noodzakelijk noch voldoende is voor representatie. In het bijzonder blijft de bewering verdedigbaar dat een representatiemiddel dan en slechts dan een representatie van een doel is als het middel gelijkenis vertoont met het doel in relevante opzichten en in een specifieke sterkte van gelijkenis.

De argumenten van Suárez tegen gelijkenisvisies op representatie worden vaak genoemd, maar zelden in detail behandeld. In dit hoofdstuk worden deze argumenten besproken en beoordeeld. Door deze argumenten te weerleggen laten we in dit hoofdstuk zien dat een meer verfijnde gelijkenisvisie nog steeds een redelijke optie is. Het hoofdstuk opent de mogelijkheid voor een brede gelijkenisvisie op representatie die compatibel is met structuralistische visies op representatie, maar ook kan worden gelieerd aan gelijkenisvisies zoals die van Ron Giere of Michael Weisberg.

In gangbare benaderingen van representatie wordt onderscheid gemaakt tussen (i) representatie simpliciter en (ii) adequate representatie. Vaak wordt beweerd dat gelijkenisvisies of structuralistische visies geen antwoord geven op de eerste vraag wat representatie simpliciter is, maar alleen op de tweede vraag wat adequate representatie is. Op basis van het argument voor de 'thick' benadering van representatie laten hoofdstukken 2 en 3 samen zien dat met een gelijkenisvisie de vraag kan worden behandeld wat representatie is, zonder de kwestie van de adequaatheid van representatie hiervan los te koppelen. In de epistemologische context van modellering vormt de doelstelling om een doelsysteem adequaat te representeren de centrale motivatie voor onderzoekers. Een 'thick' benadering van representatie beantwoordt aan deze doelstelling en gaat in op de betekenis van representatie als succesterm.

Hoofdstuk 4 behandelt een casestudy uit de biotechnologie van een model voor een orgaan op een chip. Het begrip 'ontwerp' wordt gebruikt om een indirecte visie op representatie toe te passen op deze technische context. We laten zien dat de begrippen 'representatie' en 'ontwerp' kunnen worden gebruikt om een nieuw perspectief op modellen te openen dat kan leiden tot een geünificeerde benadering van modellen in wetenschap en techniek. Deze twee begrippen worden geïnterpreteerd als verwijzend naar modelleringsrelaties tussen representatiemiddelen en doelen die verschillen in hun desbetreffende aanpassingsrichtingen: De aanpassingsrichting van de representatierelatie is van representatiemiddel naar doel en die van de ontwerprelatie is van doel naar representatiemiddel (het 'ontwerp'). De casestudy van een model voor een orgaan op een chip illustreert dat het technische apparaat (het orgaan op een chip) deel uitmaakt van zowel de ontwerp- als de representatierelatie. Het relatum, het orgaan op een chip, is voor de twee relaties hetzelfde, maar ze hebben verschillende correspondentierichtingen. In de ontwerprelatie wordt het orgaan op de chip aangepast aan een ontwerpplan, in welk geval de aanpassingsrichting dus van doel naar representatiemiddel is. In de representatierelatie wordt het orgaan op de chip aangepast aan een menselijk orgaan, in welk geval de aanpassingsrichting dus representatiemiddel naar doel is. Uit dit voorbeeld blijkt dat een opvatting van modellering waarin alleen relaties met een representatiemiddel-naar-doel richting een plaats hebben, te beperkt is om van toepassing te zijn op alle modellen in wetenschap en techniek. Dit hoofdstuk is bedoeld als uitbreiding op de bestaande benaderingen van indirecte representatie. Bovendien wordt in dit hoofdstuk beargumenteerd dat benaderingen die alleen gericht zijn op de modelleringsrelaties met een representatiemiddel-naar-doel-aanpassingsrichting van representatie, voorbijgaan aan een cruciale modelleringsrelatie. Ten slotte betekent het voorstel om ontwerp te interpreteren als modelleringsrelatie dat modellen andere doelen kunnen dienen dan alleen representatie.

In de laatste twee hoofdstukken wordt fictionalisme met betrekking tot modellen besproken. Fictionalisme wordt eerst vanuit epistemologisch standpunt bekritiseerd, maar fictionalistische ideeën worden ook constructief toegepast op het voorbeeld van een model in de klimaatwetenschap. In *hoofdstuk 5* worden Waltoniaans-fictionalistische benaderingen van modellering en representatie bekritiseerd omdat ze geen bevredigende epistemologie van modellering bieden. In het bijzonder richt dit hoofdstuk zich op de visies in de werken van Roman Frigg en Adam Toon. Een fundamentele these van hun visies is dat wetenschappers die modellen bestuderen om iets te leren over de modellen zelf en over de doelsystemen die door de modellen worden gerepresenteerd, zich bezighouden met doen-alsof-spelen. Wanneer we de epistemologie van Waltoniaans fictionalisme bespreken, stellen we dat de visies van Frigg en Toon kunnen verklaren hoe wetenschappers iets leren over de modellen die ze bestuderen. Het Waltoniaans fictionalisme verklaart echter niet voldoende hoe het gebruik van modellen tot het begrijpen van doelsystemen leidt.

In *hoofdstuk 6* wordt Waltons theorie van doen-alsof toegepast op een case-study in klimaatmodellering. Scenario's worden geïnterpreteerd als rekwisieten in doen-alsof-spelen en we beargumenteren dat de gewenste houding ten opzichte van resultaten van op scenario's gebaseerde modellen 'doen-alsof' is (*make-believe*) en niet 'geloven' (*believe*). De achtergrond van het hoofdstuk is dat klimatologen van het Intergovernmental Panel on Climate Change onlangs een onderscheid hebben geïntroduceerd tussen *projecties*, dat wil zeggen op scenario's gebaseerde resultaten van modellen, en *voorspellingen*, ofwel resultaten van modellen waaraan een bepaalde waarschijnlijkheid kan worden toegekend. In dit hoofdstuk gaan we in op het verschil tussen deze twee begrippen en opperen we dat projecties kunnen worden geïnterpreteerd als stellingen waartegenover de juiste houding er een is van 'doen-alsof' en niet van 'geloven.' Door de theorie van doen-alsof toe te passen betogen we in dit hoofdstuk dat scenario's fungeren als rekwisieten in geautoriseerde doen-alsof-spelen en dat resultaten van modellen die gebruikmaken van scenario's, moeten worden geïnterpreteerd als impliciet fictionele waarheden. Met behulp van deze interpretatie kunnen we het verschil duiden tussen projecties die we moeten behandelen als doen-alsof-beweringen (*make-believe*) en resultaten van andere modellen die kunnen worden geloofd (*believe*).

About the author

Michael Poznic was born on July 13th in 1973 in Aachen, near the Three-Country Point where Belgium, Germany and the Netherlands meet. He is married to Xiubo Li and lives in Karlsruhe. Before he became a philosopher he worked as a musician and guitar teacher from the 90s to the new millennium. As a guitar player he performed many concerts with various pop and jazz bands and as a teacher he showed students of all ages how to play pop, jazz and classical music on the guitar. After some years in music business he decided to do something completely different and enrolled at an institution of higher education to study philosophy. However, he worked for a registered association of musicians on a voluntary basis. Until 2016 he was chairperson of the management board of the Musikbunker Aachen e.V. In parallel to his musical life, he succeeded in his academic life. He received the degree of Magister Artium from RWTH Aachen University with a thesis on semantics and ontology of fiction in 2009. Beside philosophy he graduated in psychology and sociology as minors. He started to work on the current PhD dissertation at RWTH Aachen University and, in 2013, he moved to the Netherlands to join the philosophy section at Delft University of Technology. He finished the thesis in Delft and, after that, he moved to Karlsruhe to join the Institute for Technology Assessment and Systems Analysis (ITAS) at Karlsruhe Institute of Technology (KIT) to work as a postdoc researcher in philosophy. As service to the profession he fulfills the role of Managing Editor for the journal *Techné: Research in Philosophy and Technology*.

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Simon Stevin (1548-1620)

'Wonder en is gheen Wonder'

This series in the philosophy and ethics of technology is named after the Dutch / Flemish natural philosopher, scientist and engineer Simon Stevin. He was an extraordinary versatile person. He published, among other things, on arithmetic, accounting, geometry, mechanics, hydrostatics, astronomy, theory of measurement, civil engineering, the theory of music, and civil citizenship. He wrote the very first treatise on logic in Dutch, which he considered to be a superior language for scientific purposes. The relation between theory and practice is a main topic in his work. In addition to his theoretical publications, he held a large number of patents, and was actively involved as an engineer in the building of windmills, harbours, and fortifications for the Dutch prince Maurits. He is famous for having constructed large sailing carriages.

Little is known about his personal life. He was probably born in 1548 in Bruges (Flanders) and went to Leiden in 1581, where he took up his studies at the university two years later. His work was published between 1581 and 1617. He was an early defender of the Copernican worldview, which did not make him popular in religious circles. He died in 1620, but the exact date and the place of his burial are unknown. Philosophically he was a pragmatic rationalist for whom every phenomenon, however mysterious, ultimately had a scientific explanation. Hence his dictum 'Wonder is no Wonder,' which he used on the cover of several of his own books.

How can one learn about particular phenomena by using models? This is the central question of the present book. One brief answer is that one can learn about phenomena by using models if these models represent the phenomena. A longer answer will be presented in the individual chapters. Answering this question involves not only (partially) explaining what representation is, but also how the notions of representation and evaluation are connected in the context of modeling. The thesis includes a fresh look at so-called similarity views on representation and a discussion of fictionalist accounts of modeling, while expanding on the general framework of indirect representation. A case study in bioengineering is used to show that the indirect view of representation must acknowledge a distinction between two directions of fit in relations between vehicles and targets. In this context the notion of design is interpreted as a relation between a vehicle and a target, thereby connecting ideas from philosophy of science with ideas from philosophy of technology. In the concluding chapters fictionalist accounts of modeling are discussed. These accounts are criticized from an epistemological point of view but the accounts' foundational theory of make-believe is constructively applied to a case study in climate modeling.

'Wonder en is

gheen wonder'

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