

Imagination Extended and Embedded: Artifactual vs. Fictional Accounts of Models

Tarja Knuuttila

Abstract

This paper presents an artifactual approach to models that also addresses their fictional features. It discusses first the imaginary accounts of models and fiction that set model descriptions apart from imagined-objects, concentrating on the latter (e.g. Frigg 2010; Frigg and Nguyen 2016, 2017; Godfrey-Smith 2006, 2009). While the imaginary approaches accommodate surrogative reasoning as an important characteristic of scientific modeling, they simultaneously raise difficult questions concerning how the imagined entities are related to actual representational tools, and coordinated among different scientists, and with real-world phenomena. The artifactual account focuses, in contrast, on the culturally established external representational tools that enable, embody and extend scientific imagination and reasoning. While there are commonalities between models and fictions, it is argued that the focus should be on the fictional uses of models rather than considering models as fictions.

1. Introduction: Modeling and Fiction

The theme of fiction has been revived in the current philosophical discussion on modeling. While models have conventionally been considered as models of some real-world target systems, several philosophers have observed that often such a determinable relationship between models and the real world cannot be found (e.g. Godfrey-Smith 2006, Weisberg 2007). Scientists frequently talk about their model systems in terms of them being imaginary, artificial, or toy models at best. A case can be made that a big part of the contemporary modeling practice, especially in its mathematical guise, deals with hypothetical systems instead of real ones. The question is how to understand such practice of reasoning proceeding

on the basis of surrogate systems. The notion of fiction has seemed to fit the bill, leading to a variety of accounts approaching models as fictions (e.g. Barberousse and Ludwig 2009; Knuuttila 2009; Suárez 2009; Frigg 2010; Toon 2011, 2012; Levy 2015; Frigg and Nguyen 2016, 2017; Bokulich 2016).

Despite the appeal of the idea of models as fictions, such understanding has not gained common currency. The attitude of philosophers of science towards fiction resembles the situation in many other fields of philosophy. Writing about fictional characters, Amie L. Thomasson notes that they are often conceived of as “freakish entities” that would be “too unruly to accommodate in a theory” (1999, p. xi). Fictional entities have seemed suspect things due to their merely possible, non-existent, mental or otherwise imaginary nature. This worry seems even to be heightened in the case of science. What kind of epistemic value could the positing of such vague imaginary objects have?

Any account approaching scientific models as fictions faces at least the two following challenges. First, if scientific models are considered as fictions rather than representations of real-world target systems, how are scientists supposed to gain knowledge by constructing and using them? And, second, how should the ontological status of models be understood? In an attempt to answer these questions philosophers of science have appealed to philosophy of art and literature. Kendall Walton’s (1990) theory of fiction has been especially popular, partly due to the plasticity of its central notions of make-believe and pretense. While it tackles the problem of the ontology of fictional systems, it simultaneously can be used to understand the indirect, surrogate nature of model-based reasoning. Adopting this latter line of applying Walton to scientific modeling Roman Frigg and James Nguyen (Frigg 2010; Frigg and Nguyen 2016, 2017) explicate how scientists’ “imaginings”, or “imagined-objects”, result from the process of employing “props” and “principles of generation” (Frigg 2010, Frigg and Nguyen 2016). In what follows, I will call their account, and any other account of modeling relying on imagined entities, imaginary accounts. Interestingly, Walton’s notion of make-believe has also been used to contest such positing of imagined entities. Toon (2011, 2012)

and Levy (2012, 2015) argue in favor of a “direct view” that bypasses any intermediaries such as imagined-objects and proceeds to project the imaginative description on real things themselves. Instead of imagined or abstract hypothetical systems, the actual systems are subject to make-believe. The rationale for this move, as Levy puts it, is that “there are no visible, tangible, audible things corresponding to the statements and beliefs of modelers” (782), and so the corresponding things are to be found from the real-world target systems themselves.

This move by Toon and Levy, I suggest, locates the visible, tangible things modelers are engaged with in the wrong place. I agree with Frigg and Nguyen, and others (Frigg and Nguyen 2016, 2017; Godfrey-Smith 2006; Weisberg 2007; Suárez 2009; Mäki 2011) that one pivotal feature of model-based reasoning lies precisely in its surrogative nature. Toon’s and Levy’s proposals abolish the distance between models and real-world systems that is crucial for how scientists use models and evaluate them. Yet, Toon’s and Levy’s accounts are motivated by a legitimate worry concerning what immaterial imagined-objects, basically mental phenomena within individual scientists’ minds, are able to accomplish in science. The basic problem of the imaginary accounts, I propose, derives from their separation of the imagined-object from the so-called model descriptions. According to the imaginary accounts, model descriptions are used to specify, or generate, imagined (i.e. fictional) entities that then become the locus of scientific representation. This raises difficult questions concerning how imagined entities are related to actual representational tools, and coordinated among different scientists, and with the real-world phenomena. I will argue that such accounts of fiction in science that make a clear distinction between imagined entities and the model descriptions conveying them, tend to face the aforementioned coordination problems, especially if they prioritize the former as being the vehicles of representation scientists are dealing with.

As an alternative, I will put forward an artifactual account of models that preserves the important insight of fictional accounts concerning the relative independence of model systems from real-world systems. The artifactual account treats models as purposefully created

artifacts that are constructed for the study of certain scientific problems. Approaching models as concretely constructed artifacts addresses the actual representational tools that are used in model construction. These representational tools— mathematical, diagrammatic, pictorial, 3-D etc. – form an ineliminable part of the model itself, and not just a “model description” that is separate from and secondary to imagined entities. Such an artifactual turn has some important implications concerning the process of modeling and scientific imagination. The imaginary accounts focusing on imagined-objects are bound to approach modeling as a primarily mental activity, and the activity of using external representational means as that of merely (partially) describing the mental content of scientists. In contrast, the artifactual account renders visible how the characteristics of the various representational tools used in model construction enable and shape scientific imagination, also delimiting what can be thought of.

In what follows, I will first examine what I call the imaginary accounts of models and fiction through Peter Godfrey-Smith’s discussion of models as imaginary concreta (2.1). His account provides a useful introduction to Frigg and Nguyen’s recent account of scientific representation (Frigg and Nguyen 2016) (2.2.). Next, I turn to Toon’s and Levy’s criticisms of the aforementioned imaginary accounts (2.3). In response to their criticism I argue that fictional entities do not appear so problematical if we treat them as man-made things, thereby introducing the artifactual account of models. In Section 3, I take a closer look at the artifactual character of models, and their abstract and concrete dimensions. Section 4 concludes.

2. Imaginary Accounts of Fiction in Science

2.1 Model-based Theoretical Strategy According to Godfrey-Smith

Godfrey-Smith (2006) puts forth an account of model-based science that knits modeling tightly together with fiction. He portrays in broad strokes the “deliberate detour” through

fiction that he sees as the defining characteristic of the strategy of contemporary model-based science. In proceeding this roundabout way modelers seek to “gain understanding of a complex real world system via an understanding of simpler, hypothetical system that resembles it in relevant respects.” (p. 726). This strategy involves constructing idealized models not even meant to be de-idealized, and employing sophisticated mathematical and computational methods. The recourse to a simpler, hypothetical model implies that the strategy is indirect. According to Godfrey-Smith such strategy is comprised of two steps: First, a simpler system is *specified* by a model description and then, second, the resulting model system is *compared* to the target system to see whether it resembles it.¹ In other words, the imagined model system is distinguished from the model description that specifies it, and moreover, it is the imagined model system that represents real-world phenomena. Godfrey-Smith finds a justification for this distinction from the modeling practice. He notices how scientists oscillate “between thinking of a model system in very concrete terms, and moving to a description of purely mathematical structure” (p. 736). This oscillation seems to capture something important on how modelers think about and use their models, also underlining the concreteness of scientists’ imaginings. Model systems are for Godfrey-Smith *imagined concreta*: “‘imagined concrete things’ – things that are imaginary or hypothetical but would be concrete if they were real” (2006, pp. 734–735). In other words, “they do not exist, but at least many of them might have existed and if they had, they would have been concrete, physical things, located in space and time [...]” (2009, p. 101).

Even though these imagined entities may seem puzzling, they nevertheless allow for inferences and comparisons concerning the real entities, according to Godfrey-Smith. In explaining how this is possible he refers to understanding and interpreting literature:

¹ Godfrey-Smith’s conceptualization of the strategy of model-based science is adapted from Giere’s (1988) treatment of models as abstract objects (although Giere himself does not want to cast this idea in terms of fiction, see Giere 2009).

We often assess similarities between two imagined systems (Middle Earth and Narnia), and between imagined and real-world systems (Middle Earth and Medieval Europe). Whatever the foundational status of these objects is, we are all able to trade in these complex assessments of resemblance with little effort and with considerable consensus much of the time. (2006, p. 738)

While it may be possible to think of the situations depicted in realistic novels in terms of their existence in the real world, it seems less plausible in the case of highly idealized models – the kinds of things that the model-based science primarily deals with. Godfrey-Smith acknowledges this, likening analytic models to sparse and schematic fictions, such as parables. However, he thinks that elaborate computer models could be more like realistic fictions. Looking at many computational models used in science this claim seems difficult to sustain. For example, structural multi-equation macroeconomic models consist of highly simplified, and theoretically embedded, aggregative representations of sectors of a model economy (including equations for consumption, investment, government expenditure, the monetary sector, etc.). Yet, it is difficult to see how they could be thought of as concrete spatio-temporal systems. Macroeconomists themselves have often explicitly warned against interpreting them too literally (e.g., Lucas 1980, Tobin 1970).

Another example is provided by agent, or individual, based models. They simulate the actions and interactions of individuals – yet being at the same time far removed from anything realizable. The Schelling model of racial segregation provides a representative example. Although it may be tempting to interpret the black and white checkers in the checkerboard as racially different inhabitants of a neighborhood, the model is simply too bare boned to be thought of as a concrete real-world system.² It is difficult if not impossible to envisage

² A model can be an entirely artificial/hypothetical/fictional construction even if it denoted some features of the real world: it would be impossible to understand such models, or any fictions, if they were not, at some points, hooked to the real-life entities, systems and processes.

checkers on the checkerboard or a computational algorithm simulating their moves to the neighboring grids in terms of actual racially segregated neighborhoods, the gap is just too wide. Instead of representing a non-existent but concretely realizable system, it presents an entirely hypothetical system that can be used to examine some theoretically interesting outcomes. The Schelling model showed that only a small preference for one's neighbors to be of the same color could lead to strongly racially segregated areas. As such it comes closer to a demonstration than a depiction of any fullblown imaginary world.

The idea that imagined model systems could be thought of as more concrete or otherwise richer in properties than their actual representations is crucial for the imaginary approaches. According to them there is more to the imagined-object than any model description can deliver, yet thinking of models as imagined candidates for concrete existence is not the only alternative. Roman Frigg and James Nguyen (Frigg 2010; Frigg and Nguyen 2016, 2017) construe these richer imaginary worlds through the notions of pretense and make-believe

2.2. Frigg and Nguyen's Waltonian Approach to Fiction in Science

In line with Godfrey-Smith, Roman Frigg and James Nguyen claim that the comparison of models to literary fiction provides “the core of the fiction view” (2017, p. 108). But their notion of fiction also covers “models that are not at all like things in the world” (p. 112) that presumably cannot so easily be understood as imagined concreta. To make sense of the richer imaginary worlds that models as fictions are invoking, Frigg and Nguyen utilize Kendall Walton's theory of make-believe. While Frigg (2010) considers models as fictions along Waltonian lines, Frigg and Nguyen (2016, 2017) construe an elaborate account of models and representation relating the Waltonian framework to their DEKI account of representation, inspired Nelson Goodman's (1976) and Catherine Elgin's (e.g. 2004) theory of pictorial representation. They reverse the conventional order of first inquiring into the nature of models,

and then asking how they represent by starting from representation instead. It shows, and Frigg and Nguyen are careful to point this out, that they are not primarily engaged in solving the ontological problem of what models or fictional entities amount to. They are more interested in the representational dimension of scientific modeling.

Frigg and Nguyen start developing the DEKI-account from a concrete vehicle with some material properties. In line with philosophical tradition, their prototypical model is a three-dimensional model. Such a thing can readily be thought of as an object with some distinct properties. Frigg and Nguyen call this object a “base”, or more specifically, an “O-object”, where “O” specifies what kind of a thing an object is. As Frigg and Nguyen ascribe to the pragmatic view of representation, an object becomes a representation first by introducing an agent into the picture. An agent *uses* an object to represent something. In particular, following Goodman and Elgin, this object may be used to represent something as something else, thereby becoming a Z-representation (e.g. Elgin 2010). An oft-used example of such *representation-as* is a famous caricature representing Winston Churchill as a bulldog. In this case, an O-object, a picture of Churchill, is interpreted as a Z-representation (a bulldog-representation). An O-object interpreted as a Z-representation is a vehicle of representation, or a model. Notice that not all models need to represent some target system: “some Z models are also representations of Z, others aren’t” (Frigg and Nguyen 2016, p. 227). Here Frigg and Nguyen refer, for example, to Maxwell’s aether model that is not a representation of aether, since there is no such thing as aether. Following Goodman, they call it an aether-representation (see above). Obviously, the possibility of fiction is lurking already here.

Central for the DEKI-account of representation is the combination of the notions of *exemplification* and *denotation*. In order to represent, a vehicle has to both denote a target system and exemplify some properties, *imputing* those properties or related ones to a target system (ibid.). Two complications are in order. Firstly, the properties exemplified by a model cannot usually be directly imputed to some target. After all, the model and the target are very different kinds of things. Because of this a *key* is needed that translates the exemplified

properties to properties that can be imputed to the target. The notion of the key is motivated, Frigg and Nguyen note, by the study of maps. The key tells how the properties exemplified by a vehicle can be turned into properties of a target system. DEKI account of representation gets its name from these four crucial elements of representation: denotation, exemplification, keying-up and imputation. The second complication concerns the properties a vehicle/ model is supposed to exemplify. Namely, in order to exemplify a property an item needs to both instantiate it and refer to it (like a sample that both instantiates a property, e.g. a color, and simultaneously refers to it). But instantiation can also be metaphorical, a “pretend instantiation”, something that becomes clearer in the case of fictional models. How, then, are fictional models understood according to the DEKI-account?

Fiction enters the scene when the ontologically less problematic realm of concrete material models is left behind. Nonconcrete models, such as mathematical models, are likened to literary fictions:

Nonconcrete models are typically presented through descriptions, portraying things like spherical planets and immortal rabbits. We call these descriptions *model descriptions*. This gives us the essential clue: model descriptions are like the text of a novel: they are props in the game of make-believe. (Frigg and Nguyen 2016, p. 237)

The notion of a prop and make-believe are taken from Kendall Walton’s theory of mimesis as make-believe (Walton 1990). One of the most attractive features of Walton’s account is how it solves the problem concerning the ontological status of fictional entities by not positing any such things. The contrary claims concerning fictional entities such as “Sherlock Holmes is a detective” and “Sherlock Holmes is a fictional character” are accounted for in taking at least some parts of our discussion concerning fictional characters as involving pretense or make-believe. From this perspective, the authors writing realistic novels, for example, merely *pretend* to assert something about real people and places. The fictional characters, and the

literary works they inhabit, are just props in the game of make-believe. And there is nothing inherently special about literature, for that matter. Anything that is able to affect our senses and is subject to a rule or “principle of generation” can function as a prop in a game of make-believe (Walton 1990, 38). For example, a toy, or even a stump can take the role of, for instance, an animal in children’s games of make-believe.

Applied to scientific modeling, model descriptions as props prompt scientists to imagine a model system. Such a model system is an imagined-object that due to the principles of generation “can have properties that have not been written into the original model description” (Frigg and Nguyen, 14). The model description combined with principles of generation creates a fictional system, an imagined-object, and it can be pretended that it has some properties, i.e. it is fictional in the model that the imagined-object has such properties. The game of make-believe constrains imagination due to facts about the props and the rules and interpretations imposed by principles of generation. Not much is said about either model descriptions or principles of generation, however. Frigg and Nguyen (2016) only mention that principles of generation involve background theories (2016, 11) and “mathematics can enter models in two places: in the model description and in the rules of generation” (15).

The relative neglect of model descriptions and principles of generation by Frigg and Nguyen seems understandable given that their focus is on the imagined-object. It is the vehicle of representation with associated set of properties, although an imagined one: “By mandating those involved in a certain game to imagine certain things, the model description generates the imagined-object that serves as the vehicle X of a representation as.” (2016, 13). But critics have been puzzled by how modeling and representation in scientific practice is supposed to proceed on the basis of imagined-objects (e.g. Toon 2011, Weisberg 2013, Levy 2015).

2.3. Imagined Entities and Problems of Coordination

Godfrey-Smith's and Frigg and Nguyen's approaches share the same core ideas concerning the role of imagination and fiction in modeling. These approaches that I call the imaginary accounts, share three features:

- (i) Fiction is approached in terms of imagined entities.
- (ii) Imagined entities are specified, or generated by model descriptions, taking into account background knowledge.
- (iii) A relation of representation or resemblance, is needed to relate the imagined entities to real-world targets.

The imaginary accounts aim to capture the indirect nature of modeling, whereby modelers proceed to study phenomena by constructing various kinds of model systems, often quite apart from considering their representational ties to real-world systems (Godfrey-Smith 2006, Weisberg 2007, Frigg 2010).³ It is precisely this combination of indirect representation and imagined (or abstract) systems as the focal point of modeling that has awakened criticism. Toon (2011) launches his critique of the imaginary approaches from the distinction between “direct” and “indirect approaches”. In indirect approaches a model description defines a fictional entity that then is supposed to represent a physical system. Toon finds such an intermediary step unnecessary, and fictional entities superfluous. Levy (2015) agrees, and claims that “if models are concrete hypothetical objects, then by virtue of their non-actuality, they are not the kinds of things we can observe and come into contact with” (784-785). He levels the same kind of critique also against the approaches that take models to be abstract objects (Weisberg 2013, Giere 1988) that by virtue of their abstractness “cannot be seen,

³ To argue for the indirect nature of modeling one does not need to invoke fiction, see Weisberg (2013).

touched or heard” (ibid.). In comparison to abstract approaches, fictional approaches fare better, according to Levy, since they are able to make a better sense of non-mathematical modeling, and visual and other sensory qualities. Yet neither Levy nor Toon sees any need to posit intermediate systems to which we do not have a sensible access. Instead, they prefer the direct approaches, and, perhaps surprisingly, are also making use of Kendall Walton’s notion of make-believe.

According to the direct make-believe construal, models are “imaginative descriptions of real-world phenomena” (Levy 2015, 797); they “prescribe us to imagine things about the actual system” (Toon 2011, 308). This comes with a cost, though. Toon’s and Levy’s direct make-believe accounts have problems in accounting for models that do not have real world-targets, or models whose targets are generalized (see e.g. Frigg and Nguyen 2017, 109-112). Perhaps the biggest loss is the inability of the direct make-believe account to explain how models enable surrogative reasoning. To be sure, the direct accounts do not even aim to accommodate surrogative reasoning. Yet the epistemic functioning of models does seem to require some distance to the real-world targets making the questions concerning how well a model fits a particular target meaningful. Eschewing surrogative reasoning seems too big a sacrifice in view of many theoretical modeling practices – and also an unnecessary one. The problem Toon and Levy have with imaginary accounts does not lie in their indirectness per se, but rather in how they posit a fictional entity that then acts as a possible vehicle of representation. It seems fair to ask how such imagined-objects could be used as means for surrogative reasoning that seems to be the point Levy is making by pointing towards their lack of sensuous qualities. The problem is how the imaginings of scientists, which are mental phenomena, and as such not intersubjectively available, can be coordinated with other dimensions of modeling practice. At least three sorts of coordination issues seem to appear.

First, if fictions are analyzed in terms of the pretense theory then *how are these imagined-objects to be compared to the real-world objects and systems?* The problem is that since an imagined-object is strictly speaking non-existent, the features of it are uninstantiated,

making the comparison difficult. It is far from clear why the uninstantiated properties of imagined-objects are less problematical than those objects themselves (whose ontological status the pretense account was designed to circumvent)? (See Godfrey-Smith 2009 for a discussion.) It is difficult enough to account for how some external representations are able to stand for and bring knowledge about real-world systems, and to ask the same question concerning imagined-objects seems even harder. Frigg and Nguyen do not even try to solve this problem, pointing out that the DEKI account of representation does not “require comparative claims” and referring to Salis’ (2016) proposal for how such comparisons could be made.

The second problem of coordination, that *between model descriptions and imagined entities* is no less vexing. The problem boils down to that of access, and the meaningfulness of discussing imagined-objects apart from their representations. What epistemic access do scientists have, as a collective, to imagined objects apart from them already having been represented somehow? Even if the object of investigation were entirely theoretical, the scientists would need to make use of established mathematical tools and theoretical notions to study these hypothetical objects. The fact that scientists can trade with hypothetical, abstract or fictional systems is not in doubt. The question is how they do so. Models do not amount to their external representations, in modeling these tools are interpreted, yet such interpretations are closely coupled with the specific external representations used. This coupling becomes especially palpable when one considers how changes in the mathematical representation frequently alter many epistemically relevant properties of a model. An illustrative example is provided by Weisberg and Reisman’s (2008) reconstruction of the Lotka–Volterra model in an individual-based framework. The model was originally formulated as a population-level model making use of ordinary differential equations. Weisberg and Reisman show how the change of a representational mode has important epistemic consequences: population level models are simple and more tractable, but they do not provide the means to study local-level interactions between individual organisms. A fictionalist positing imagined-objects would

presumably assume that the two different mathematical representations describe the same imagined system, as one of the benefits of the fictional approach is precisely to maintain the identity of the model system under different descriptions (e.g. Frigg 2010, p. 256, Frigg and Nguyen 2016, p. 237). Yet, if it is the fictional system that is supposed to represent the target system, as both Frigg and Godfrey-Smith would have it, the epistemic consequences of using different, often alternative mathematical, or computational modeling methods are left without explicit recognition.

Finally, there is the problem of *coordinating the imaginings of different scientists*. Weisberg (2013) raises the question of the variation in the imaginings of individual scientists: even if we were able to compare the features of imagined systems to the real-world systems, what assures us that we are dealing with the features of the same imagined systems? Frigg does not find this problematic since “[a]s long as the rules [of a particular game of make-believe] are respected, everybody involved in the game has the same imaginings” (2010, p. 264). What this solution tends to mask, is the fact that what *is* intersubjectively available to scientists are the representational means with which models are constructed and which provide the access to the properties and behavior of the model system. Moreover, these properties and behaviors also depend on the representational means used, as the example of the Lotka-Volterra model in its two different configurations shows. Moreover, the rules and norms concern the use and interpretation of these external representations in particular scientific contexts that provide the background knowledge for their interpretation.

The question is what kind of rules of generation are, over and above the ones concerning the use of culturally shared external representational means in some specific contexts, needed to understand modeling practices. What is the added epistemic value of invoking imagined-objects, and what is it that the focus on them tends to set aside? Modelers pay a lot of attention to the particular mathematical abstractions they are using, and to the modeling choices due to approximations and tractability. How are these choices going to be taken into account if we concentrate on pretend properties of imagined-objects? Or how are

we to ascribe fictional features to computational models, whose computational processes are quite opaque to human mind? For example, it is difficult (if not impossible) to mentally simulate the interactions of non-linear complex systems, or imagine probabilistic or high-dimensional models. This is precisely the reason why these models are so indispensable tools for scientific practice.

The important defect of imaginary accounts leading to different kinds of coordination issues at the level of scientific practice is due to the way they set apart model descriptions and imagined entities locating the most important epistemic role to the latter. As a result, imaginary accounts do not pay enough attention to the particularities of actual representational means with which scientists work and whose innovative use and application to new problems often leads to novel insights. Inasmuch as representational tools are merely ascribed the task of describing imagined-objects, the imaginary approaches largely ignore the way humans as cognitive agents are able to creatively use different kinds of representational means. Such tools are crucial for theoretical inferences and demonstrations but the imaginary account does not possess resources to address this aspect of scientific practice, concerning, for instance, the cognitive enablings of different mathematical representations and modeling methods. For example, using examples of classical mechanics and Feynman diagrams, Vorms (2011) shows that even in cases where the theoretical representations were identical from the formal and empirical point of view, they might still facilitate different kinds of inferences. Cognitive sciences have generated abundant evidence on this: Among one of the best know experimental studies Zhang (1997) shows that the same abstract structures conveyed by different representational tools have different affordances as to how humans are able to understand them.

In the light of these criticisms, the question is whether an alternative account could be formulated that would preserve the important insight of the imaginary accounts that models often depict hypothetical or fictional systems and license surrogate reasoning—yet avoiding the aforementioned coordination issues raising from the focus on imagined entities. I suggest

that an artifactual account presents a viable alternative, an alternative that under suitable adjustments to the imaginary accounts, could even complement them. The artifactual approach takes a departure from the imaginary accounts in two interrelated respects. First, it gives up the intuition that fictions are imagined, non-existent entities that are only due to the imaginings of scientist and their games of make-believe. In doing so this account takes seriously the fact that in scientific practice even mathematical models are treated as concretely manipulable objects, although the representational media used plays a different role in mathematical and scale modeling, for example. Secondly, in emphasizing the importance of considering models as intersubjectively available objects, the proposed account does not separate the so-called model descriptions from fictional model systems as the imaginary accounts do. The philosophical gist of the artifactual account is to consider the actual representational means with which a model is constructed and through which it is manipulated as irreducible parts of the model. It is these representational means and the cultural norms and rules governing their use and interpretation, in particular contexts, that draw together the various aspects of modeling: the imaginings of scientists, the abstract and other structures defined by different kinds of models, and, finally, various kinds of scientific targets.

4. Artifactual Account of Models

From the artifactual perspective models are like any other artifacts in that they are human-made objects *intentionally produced* for some *purposes* within the sphere of particular human activities. Hence, the artifactual character of models is twofold, providing two intertwined perspectives to modeling. On the one hand, artifacts are classified according to their intended purposes or functions (e.g. Simon 1996, Kornblith 1980), on the other hand they can be assorted according to their production methods. Consequently, the artifactual nature of a model can be approached, first, from the perspective of the purposes it is constructed for, and how well this purpose is served by its design. Second, the actual design of a model directs

attention to the representational means and materials that are used as constituents for its construction. Let me first discuss this second dimension of models, as it most clearly pinpoints the difference between artifactual and imaginary accounts.

4.1 Model construction: modes and media of representation

In constructing models, scientists are making use of external representational means, and the products of such activities are variously materialized objects. A material embodiment is needed for a model to function as a vehicle for communication and intervention within an intersubjective cultural activity such as science. Scientists do not read the minds of each other, and neither are they able process even modestly complicated relations or interactions without a recourse to external representational tools. There is a lot of evidence and theoretical discussion on the importance external representational tools for human cognition in cognitive science, typically addressed under such headings as extended, embodied and distributed cognition (e.g. Clark 2008, Hutchins 1995).

The focus of the artifactual approach on the epistemic value of external representational tools marks a departure from the imaginary approach to models and fiction. As discussed above, the imaginary approach distinguishes model descriptions from imagined-objects, prioritizing the latter as the vehicles of representation. The artifactual account, in contrast, considers model descriptions as irreducible parts of any representational vehicle, such as a model. In fact, calling a particular configuration of the representational means with which a model is constructed a model description is even misleading since it implies that a model as an object is separate from its representational embodiment.

Considering representational means as integral parts of models has direct consequences regarding different types of models. In agreement with the imaginary approach, as formulated by Frigg and Nguyen, the artifactual account considers models as objects. It does not, however, make a sharp distinction between concrete models such as scale models and

“nonconcrete” ones specified by e.g. mathematical representations. There is no need for it: the artifactual view offers a unified account of modeling covering both abstract/nonconcrete and “concrete” models. All models have both abstract and concrete dimensions because as external artifacts constructed and used in scientific practices they have a material, sensuously perceptible dimension that functions as a springboard for interpretation, and theoretical or other inferences. This material embodiment of models can play different epistemic roles, however, depending on the representational means in question. The huge variation in the material embodiment of different kinds of models, and the way abstract and concrete intersect in scientific representation becomes clearer once representational mode and medium are distinguished from each other (Kress and Leeuwen 2001).

In constructing models, scientists employ a multitude of *representational modes* (e.g., various symbolic, mathematical, diagrammatic, pictorial, and 3-D/geometric devices) and *representational media* (e.g. ink on paper, electric signals in computers, various materials of physical artifacts or even biological organisms and their parts). The representational mode provides the abstract dimension of a model, as different representational modes rely on different kinds of symbolic and semiotic organization. The representational media, in turn, furnishes the material embodiment of a model. There is no necessary correspondence between representational mode and media, one can write equations, for example, by making use of different media, e.g. using a pen and paper, or erasable markers and whiteboard. From the artifactual perspective, the difference between a mathematical and a physical three-dimensional model, then, is not due to the other being abstract (or nonconcrete) and the other concrete. Rather, the difference between the two lies in the different epistemic roles the representational mode and media play in their scientific uses.

In mathematical modeling, the focus is on the representational mode. For instance, in the mathematical modeling of genetic networks one can use different methods such as coupled ordinary differential equations (ODE), Boolean networks, and stochastic methods, all referring to different mathematical representational modes. In mathematical modeling, the use of

representational media functions primarily as an external scaffolding for memorizing, reasoning, communication, computing or demonstration. Yet, as mathematical models are often not analytically solvable, they need to be turned into simulation models that make many of their features dependent on a physical device. When it comes to simulation, several philosophers are willing to grant an important epistemic role to the medium, the digital computer (see e.g. Humphreys 2009, Lenhard 2006).

In the case of physical three-dimensional models, concrete media plays a more direct epistemic role. The material dimension of physical models does not merely function as an external scaffolding for cognitive and communicative functions. It also allows scientists to draw inferences that are based on the material features of the model. But the material features of the model also embody a symbolic, conceptual dimension. For example, the Phillips-Newlyn hydraulic model as a physical three-dimensional object embodies and renders visible economic ideas such as the principle of effective demand and the conceptualization of economy in terms of stocks and flows. The way water pools and flows in the containers and the tubes of the model takes upon a symbolic significance. The material and symbolic aspects have become coupled as a result of an intricate process of model design and construction (Morgan and Boumans 2004).

The artifactual approach urges also philosophers to study more in detail how the various kinds of representational modes and media enable scientific inferences and reasoning. The amazing variability of the actual representational tools used by modelers has frequently been noticed, but it has yet to be addressed by the philosophical discussion. There is certain irony about this situation given the blossoming interest in scientific representation. Philosophers have been engaged in studying the representational relation between models and their supposed target systems without paying too much attention to the representational artifacts used to accomplish such representational work. Representation is always an accomplishment, but the representational work involved cannot even be perceived unless its tools are acknowledged.

4.2. Purposeful construction: Constraints as affordances and limitations

Models serve a multitude of purposes in science. They can be fabricated in view of theory development, conceptual articulation, experimental design or science education, for example. These purposes may change, or co-exist – models in scientific practice are evolving entities, being reconstructed and repurposed by different groups and stakeholders. The bulk of philosophical literature on scientific modeling has concentrated on theoretical models and their epistemic uses. The question has been “in virtue of what do models give us knowledge”, and the answer has, more often than not, invoked the notion of representation. However, if we allow for the artifactual and surrogative nature of scientific modeling, any abstract analysis of the supposed representational relation between a scientific model and its target will not do. The question is *how models as artificial constructions, often without any fixed or determinable ties to the real world-systems, are able give us knowledge*. The artifactual approach seeks for an answer from the constrained constitution of models. As epistemic artifacts, scientific models can be seen as objects that are purposefully “constrained by their design in such a way that they enable the study of certain scientific questions” (Knuuttila 2011, 262)⁴. Models as epistemic artifacts are erotetic devices, designed to answer theoretical or empirical questions often in situations where many, if not most features of the real systems of interest remain unknown.

How do models fulfill this erotetic function? Morrison and Morgan’s (1999) appeal to learning provides a cue: scientists learn from models by constructing and manipulating them. From the perspective of learning, the epistemic value of modeling can be attributed to their manipulability instead of (a more or less) accurate representation. To be sure, something is represented in the model – the model is designed on the basis of previous knowledge – but that does not yet make a model a representation of any particular real-world target system. In this

⁴ The notion of a constraint has also been central in the work of Nancy J. Nersessian, see e.g. Nersessian 2002.

the artifactual account agrees with fictional ones, and those analyses of models that emphasize their surrogate or indirect nature. However, the model as an artifactual erotetic device is not as unconnected to the natural and social realities as it first may seem, since previous scientific knowledge and open scientific questions are built into the construction of a model.

Already a summary look at models in scientific practice, and the philosophical theorizing of them, testifies to their constrained design. Scientific models have, more often than not, been characterized precisely by their simplified nature—idealization being one of the stock problems when it comes to modeling. From the artifactual perspective idealizations, simplifications and approximations used in modeling have two primary aims. On the one hand, they constrain the model in such a way that it enables modelers to articulate and address a scientific problem in a systematic manner (Knuuttila 2005, 2011). On the other hand, they are used to make the model tractable and epistemically accessible. The latter aim is closely linked to the representational modes and media used, which often necessitate some assumptions or simplifications made.

As the design of scientific models is purposefully constrained, idealizations, simplifications and approximations characteristic of modeling should not be considered mainly as shortcomings of models as the representational approach would usually have it. Certainly, the philosophical tradition has also given a positive reading to the simplified nature of models through the notion of isolation. The idea is that models would be able to, through idealization and simplification, isolate some causal difference makers (Strevens 2008), or more modestly, study the workings of some causal factors in isolation from other factors (Cartwright 1999, Mäki 2011). The artifactual approach, in contrast, recognizes that models are not just transparent representations of some selected aspects of reality, the construction of a model is partly dictated by the representational modes and media used. This artificiality of models explains many of their unintended features, too. The actual model is often much richer than its intended character, but this does not boil down to scientists pretending it to be richer.

Importantly, the artifactual account is modest in that it is not committed to the idea that modelers would be able to single out effective causal factors and their interactions from the messy empirical phenomena – often much less is known of the causal structure of the world that is precisely the basic motivation of modeling in the first place. Indeed, a big part of especially mathematical and computational modeling consists of the study of various kinds of theoretical possibilities that are either hypothetical or so far removed from the real-world natural and social systems that it is difficult, if not impossible, to consider them as simplified, isolating versions of them. This feature of modeling may be one of the strongest reasons for considering many scientific models as fictions. Before discussing how the artifactual account can accommodate fictional features of modeling, let me still briefly guard against one possible misunderstanding: the artifactual account does not consider models as particulars. Some models like the San Francisco Bay model (see Weisberg 2013) are particular things, but usually when talking about models we refer to artifact kinds (Petroski 1992, Hilpinen 2011). When talking about ordinary objects we usually refer to artifact kinds, too – just think about the variety of things falling within the category of chairs. An artifact kind such as chair can be realized by various concrete media; e.g. wood, plastic and metal providing material for particular instantiations.

5. The fictionality of modeling: ontological and epistemological considerations

5.1. Ontological dependency

Fictions, like models, are cultural artifacts, and envisaging them as such gives a fresh outlook into fictions and their ontological status. Philosophers of science – Godfrey-Smith, Frigg and Nguyen providing illustrative examples – have tended to consider fictions as something primarily imaginary, mental or non-existent thus raising a question concerning their ontology.

One of the attractions of Kendall Walton's pretense theory lies precisely in its solution to the ontological problem of fiction by denying that fictional discourse would genuinely refer to fictional entities. The artifactual theory does not need to invoke pretension – that sits more uncomfortably with science than literature – reviving instead an older tradition already inherent in the etymology of the word “fiction”. It is derived from the Latin *fingere* , meaning “to form”. Building on the idea of fictions as man-made things, Amie L. Thomasson (e.g. 1999, 2009) presents an artifactual theory of fiction emphasizing that fictional worlds are constructed, and depend for their existence on their authors. In the earlier literature, the idea of relating the notion of an artifact to that of authorship has been elaborated by Hilpinen (1993). Thomasson considers fictional entities, such as Sherlock Holmes, as artifacts created by authors' activities of writing or telling stories, and dependent for their ongoing existence on these activities and their products. According to Thomasson, “[f]ictional objects [...] are not the inhabitants of a disjoint ontological realm but instead are closely connected to ordinary entities by their dependencies on both concrete, spatiotemporal objects and intentionality. Moreover, they are not a strange and unique type of entity: Similar dependencies are shared with objects from tables and chairs to social institutions and works of art” (1999, p. 12). Although, in Thomasson's view, fictional objects rigidly depend on the author(s) who create them, their identity is nevertheless flexible; once created, they can appear in different works. We are entitled to talk about the same fictional object if the author of the second work is competently acquainted with the fictional character in question in the previous work and intends to import the character to the second work (ibid., 67).

Much of what Thomasson says about fictional entities in literature applies to models as well. They have their origin in the work of individual scientists, their “authors”, whose names many models still carry, like the Ising model, the Schelling model, and the Lotka-Volterra model, just to mention a few well-known models extensively discussed also within philosophy of science. Like fictional characters in literature, these models are being circulated across various scientific domains, being reformulated and repurposed in their application to different

kinds of problems. Now, one might want to claim that this cross-disciplinary applicability of these models shows that they are in fact abstract entities. As objects of scientific work, however, they already appear embodied in certain (mathematical or computational) representational modes, and their manipulation presumes special material media, frequently, and in the present-day context nearly exclusively, the digital computer.

Although Thomasson considers fictional entities as abstract artifacts, she also notices that they simultaneously depend for their continued existence on concrete individual copies of texts and a capable audience willing to perpetuate the imaginaries of such objects.⁵ In developing on this insight one can consider the copies of the books by Conan Doyle and other artifacts, such as the BBC series “Sherlock”, as the material interface mediating between various authors and users – and enabling the further development of the character in the guise of other characters such as Dr. House in the Fox medical drama series. What is important to add here, moreover, is that when literary scholars or critics interpret literary works, they always back up their claims by referring back to the actual texts. And finally, the materiality of text is presently an intensively discussed topic among literary and media theorists (e.g. Hayles 2002, Drucker 2014), and studied by such literary genres as visual and concrete poetry. It is, I conclude, almost impossible to talk about Sherlock Holmes as an artifact without a reference to the concrete cultural artifacts where it features.

As we have seen, many of the points made above apply also to other cultural artifacts, ranging from ordinary things such as furniture and tools to institutional facts, such as contracts and money, all of them relying on human purposeful activities and their variously materialized productions. This being the case why is it that several philosophers of science have found it telling to draw parallels especially between models and literary fiction?

⁵ Thomasson is not very clear concerning the distinction between literary works and literary characters (Voltolini 2003). Literary characters like Sherlock Holmes are more akin to postulated fictional entities *within* models, than such models themselves.

5.2. *Functional self-containment*

Why does the comparison of models to literary fictions appear so pertinent? We have seen that for Frigg and Nguyen fiction provides a way to understand mathematical and other “nonconcrete” models analogously to physical models. In the case of physical models, the concrete objects themselves function as representations, whereas in the case of mathematical models the imagined-objects perform the same task. And Walton’s pretense theory provides a convenient way to tackle any resulting ontological quandaries concerning the imagined-objects. I suggest that there is another reason for considering models as fictions, more in line with the artifactual approach. In order to see what is at stake, let us consider how models differ from other representational artifacts in science. Scientific representation is replete with all kinds of visual and other renderings, often produced by sophisticated observational and imaging technologies: photographs, audiographs, charts, tables, computer generated displays of various kinds, and so on. What distinguishes models from many other kinds of representations is often their systemic, autonomous nature. In modelling scientists are studying purposefully constructed, and consequently artifactual, model systems in order to understand their internal relations and dynamic behavior. This is the feature of modeling that makes models akin to fictions: literary fictions as well as models are understood as fabricated “small worlds” of characters/entities and their relationships (e.g., Eco 1990, Morgan 2012).

The autonomy of fictions and models is based on the way they posit self-contained – and therefore also constrained – systems through which scientists, or novelists, can study certain situations. Understood in this way, fictions as well as models possess a “sufficient self-enclosure and internal complexity to constitute a situation whose relevant features can be identified by their mutual interrelations” (Rouse 2009, 45). This self-contained character is perhaps most evident in the case of highly idealized mathematical models that are typically hypothetical systems constructed for the study of some interdependencies between chosen components and the dynamic resulting from them. Such models exhibit possible mechanisms

that could answer to some theoretical questions or account for some empirical findings, or general patterns of phenomena. This orientation of theoretical modeling towards the general and the possible explains what Godfrey-Smith has aptly called the “modal ‘reach’” of models (2006, 732).

Although mathematical models have so far gotten most of the attention in the discussion of the fictional aspects of modeling, also many computational models provide striking examples of fictional self-contained “worlds”. For example, individual/agent-based models simulate the local interactions between distinct individuals generated from very simple behavioral rules. The point of this kind of modeling is often to study the surprising global consequences of such seemingly simple interactions. And even material three-dimensional physical models and biological model systems can be considered as self-contained systems that enable scientists to manipulate and study their internal complex interrelationships.

The artifactual account provides a fresh approach to the fictional side of modeling in not seeing fictions as imaginary, non-existent, or false, but rather as purposefully constructed entities. These entities exhibit their artificial reality created through the use of external representational tools, in their various modes and media. In envisaging the fictionality of models in terms of their self-containment, the artifactual account resists a truth-conditional understanding of fiction⁶. When a model functions as a fiction in scientific research, its truth (or falsity) is bracketed away from consideration. Of course, in some other uses, the very same model can be regarded as a representation of some specific target system and employed to generate empirically testable inferences concerning it. But then it is not treated as a fiction anymore. No model is a fiction in and of itself, it gains a fictional status in those uses in which the primary interest of scientists is to study the model system apart from any determinable representational ties to external target systems.

Finally, the self-contained, autonomous nature of models and fiction does not mean that they would not need to refer to relevant background knowledge in various ways. Quite the

⁶ For a discussion on the truth-conditional view on fiction, see Mauricio Suárez (2009b).

contrary. Without such knowledge, any literary fictions, models or other cultural representations would not even be understood. Although fictions put together autonomous self-contained situations, literary theorists also approach them in terms of their incompleteness in comparison to the real world. The expression “small world” covers both of these dimensions. While the word “world” refers to the self-contained and systemic nature of models and fictions, the word “small” implies that models and fictions are often sparse in that they only contain selected features. Consequently, “only some conceivable statements about some fictional entities are decidable, while some are not” (Dolezel 1998, 22). We may not know, for instance, how the fictional characters look like. In a film adaptation of a book, say *Anna Karenina*, the actors may not at all correspond to how we imagined them to be but that does not necessarily have any bearing on the faithfulness of the film to its literary original. The same applies to models. Scientists may have rich imaginings prompted by a model, but only those statements that are derivable from the actual model as an external artifact, taking into account the relevant theoretical and empirical background knowledge, are subject to scientific discussion.

5. Conclusion: Imagination Extended and Embedded

I have discussed the fictional side of modeling presenting an artifactual account that approaches models as artifacts that are constructed with various kinds of representational means in view of some epistemic purposes. This artifactual perspective pays heed to the specific representational modes and media that models employ, emphasizing their abstract-cum-concrete nature. With regard to the imaginary approaches to fiction in science, the artifactual account has some definite virtues. It tackles the worries concerning the supposedly vague ontological status of fictional entities in not ascribing fiction primarily to scientists’ imaginings and consequently ending up into problems concerning the coordination of imagined-objects with one another, with “model descriptions”, and, ultimately, the real world.

In contrast, the artifactual account does not separate model systems and their actual representations from each other – a feature that provides the artifactual approach unifying power. Models are not divided into abstract and concrete models, instead, the epistemic affordances of different kinds of external representational tools are addressed. These external artifacts, and not imagined-objects, provide the actual locus of scientific representation even in the case of fictional modeling. The external representational means in their various modes and media embody model systems thereby extending scientific imagination and reasoning into the artifactual realm. The question is whether or not scientific imagination should properly be considered as distributed between the scientists and their tools.

Bibliography

- Barberousse, A., & Ludwig, P. (2009). Models as fictions. In M. Suárez (Ed.), *Fictions in science: Philosophical essays in modeling and idealizations* (pp. 56-73). New York, NY: Routledge.
- Bokulich, A. (2016). Fiction as a vehicle for truth: Moving beyond the ontic conception. *The Monist* 99(3), 260-279.
- Cartwright, N. (1999). *The vanity of rigour in economics: Theoretical models and Galilean experiments*. (Centre for Philosophy of Natural and Social Science. Discussion paper series 43/99.)
- Clark, A. (2008). *Supersizing the mind: Embodiment, action, and cognitive Extension*. Oxford and New York: Oxford University Press.
- Dolezel, L. (1998). Possible worlds of fiction and history. *New Literary History*, 29(4), 785-809.
- Drucker, J. (2014). *Graphesis: Visual forms of knowledge production*. Cambridge, MA: Harvard University Press.

- Eco, U. (1990). *The limits of interpretation*. Bloomington, IN: Indiana University Press.
- Elgin, C. Z. (2004). True Enough. *Philosophical Issues* 14, 113–31.
- Elgin, C. Z. (2010). Telling Instances. In R. Frigg, & M. Hunter (Eds.), *Beyond Mimesis and Convention: Representation in Art and Science* (pp. 1–18). Dordrecht: Springer.
- Frigg, R. (2010). Models and fiction. *Synthese*, 172(2), 251–268.
- Frigg, R., & Nguyen, J. (2016). The fiction view of models reloaded. *The Monist*, 99(3), 225–242.
- Frigg, R., & Nguyen, J. (2017). Models and Representation. In M. Magnani, & T. Bertolotti (Eds.), *Springer Handbook of Model-Based Science* (pp. 73–126). Berlin and Heidelberg: Springer.
- Giere, R. N. (1988). *Explaining science: A cognitive approach*. Chicago and London: The University of Chicago Press.
- Giere, R. N. (2009). Why scientific models should not be regarded as works of fiction. In M. Suárez (Ed.), *Fictions in science: Philosophical essays on modeling and idealization* (pp. 248–258). New York, NY: Routledge.
- Godfrey-Smith, P. (2006). The strategy of model-based science. *Biology and Philosophy*, 21(5), 725–740.
- Godfrey-Smith, P. (2009). Models and fictions in science. *Philosophical Studies*, 143(1), 101–116.
- Goodman, N. (1976). *Languages of Art*. Indianapolis and Cambridge: Hackett.
- Hayles, K. N. (2002). *Writing machines*. Cambridge, MA: MIT Press.
- Hilpinen, R. (1993). Authors and artifacts. *Proceedings of the Aristotelian Society*, 93. pp. 155–178.

- Hilpinen, R. (2011). Artifact. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Winter 2011 ed.) Metaphysics Research Lab, Stanford University.
- Humphreys, P. (2009). The philosophical novelty of computer simulation methods. *Synthese*, 169(3), 615-626.
- Hutchins, E. (1995). *Cognition in the Wild*. Cambridge, MA: MIT Press.
- Knuuttila, T. (2005). Models, representation, and mediation. *Philosophy of Science* 72(5), 1260–1271.
- Knuuttila, T. (2009). Representation, idealization, and fiction in economics: From the assumptions issue to the epistemology of modelling. In Mauricio Suárez (Ed.), *Fictions in Science: Philosophical Essays on Modeling and Idealization* (pp. 205–231). New York & London: Routledge.
- Knuuttila, T. (2011). Modelling and representing: An artefactual approach to model-based representation. *Studies in History and Philosophy of Science Part A*, 42(2), 262-271.
- Kornblith, H. (1980). Referring to artifacts. *The Philosophical Review*, 89(1), 109-114.
- Kress, G., & van Leeuwen, T. (2001). *Multimodal discourse: The modes and media of contemporary communication*. London, UK: Arnold.
- Lenhard, J. (2006). Surprised by a nanowire: Simulation, control, and understanding. *Philosophy of Science*, 73(5), 605-616.
- Levy, A. (2015). Modeling without models. *Philosophical Studies*, 172(3), 781-798.
- Lucas, R. E. J. (1980). Methods and problems in business cycle theory. *Journal of Money, Credit and Banking*, 12(4), 696-715.
- Mäki, U. (2011). Models and the locus of their truth. *Synthese* 180:47–63.

- Morgan, M. S. (2012). *The world in the model: How economists work and think*. Cambridge, MA: Cambridge University Press.
- Morgan, M. S., & Boumans, M. J. (2004). Secrets hidden by two-dimensionality: The economy as a hydraulic machine. In S. Chadarevian, & N. Hopwood (Eds.), *Model: The third dimension of science* (pp. 369-401). Stanford, CA: Stanford University Press.
- Morrison, M., & Morgan, M. S. (1999). Models as mediating instruments. In M. S. Morgan, & M. Morrison (Eds.), *Models as mediators. Perspectives on natural and social science* (pp. 10-37). Cambridge, MA: Cambridge University Press.
- Nersessian, N. J. (2002). Maxwell and "the method of physical analogy": Model-based reasoning, generic abstraction, and conceptual change. In D. Malament (Ed.), *Essays in the History and Philosophy of Science and Mathematics*. LaSalle, IL: Open Court.
- Petroski, H. (1992). Engineering: The evolution of artifacts. *American Scientist*, 80(5), 416-420.
- Rouse, J. (2009). Laboratory fictions. In M. Suárez (Ed.), *Fictions in science: Philosophical essays in modeling and idealizations* (pp. 37-55). New York, NY: Routledge.
- Salis, F. (2016). "The Nature of Model-World Comparisons," *The Monist*, 99(3), 243-259.
- Simon, H. A. (1996). *The sciences of the artificial* (Third ed.). Cambridge and London: MIT Press.
- Strevens, M. (2008). *Depth: An account of scientific explanation*. Cambridge, MA: Harvard University Press.
- Suárez, M. (2009a). *Fictions in science: Philosophical essays on modeling and idealization*. New York, NY: Routledge.
- Suárez, M. (2009b). Fictions in scientific practice. In M. Suárez (Ed.), *Fictions in science: Philosophical essays in modeling and idealizations* (pp. 3-11). New York, NY: Routledge.

- Thomasson, A. L. (1999). *Fiction and metaphysics*. Cambridge, MA: Cambridge University Press.
- Thomasson, A. L. (2009). Fictional entities. In J. Kim, & G. Rosenkrantz (Eds.), *A companion to metaphysics* (Second ed., pp. 10-18). New York, NY: Routledge.
- Thomson-Jones, M. (2010). Missing systems and the face value practice. *Synthese*, 172(2), 283-299.
- Tobin, J. (1970). Money and income: Post hoc ergo propter hoc? *The Quarterly Journal of Economics*, 84(2), 301-317.
- Toon, A. (2011). Playing with molecules. *Studies in History and Philosophy of Science Part A*, 42(4), 580-589.
- Toon, A. (2012). *Models as make-believe: Imagination, fiction and scientific representation*. Chippenham and Eastbourne: Palgrave Macmillan.
- Voltolini, A. (2003). How fictional works are related to fictional entities. *Dialectica*, , 225-238.
- Vorms, M. (2011). Representing with imaginary models: Formats matter. *Studies in History and Philosophy of Science Part A*, 42(2), 287-295.
- Walton, K. L. (1990). *Mimesis as make-believe: On the foundations of the representational arts*. Cambridge, MA: Harvard University Press.
- Weisberg, M. (2007). Who is a modeler? *The British Journal for the Philosophy of Science*, 58(2), 207-233.
- Weisberg, M. (2013). *Simulation and similarity: Using models to understand the world*. New York, NY: Oxford University Press.
- Weisberg, M., & Reisman, K. (2008). The robust Volterra principle. *Philosophy of Science*, 75(1), 106-131.

Zhang, Jiajie (1997). The Nature of External Representations in Problem Solving. *Cognitive Science* 21, 179-217.