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Imagination in scientific modeling

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Abstract

Modeling is central to scientific inquiry. It also depends heavily upon the imagination. In modeling, scientists seem to turn their attention away from the complexity of the real world to imagine a realm of perfect spheres, frictionless planes and perfect rational agents. Modeling poses many questions. What are models? How do they relate to the real world? Recently, a number of philosophers have addressed these questions by focusing on the role of the imagination in modeling. Some have also drawn parallels between models and fiction. This chapter examines these approaches to scientific modeling and considers the challenges they face.

Introduction

Our commonsense view of science invites conflicting reactions to the idea that imagination plays an important role in scientific inquiry. On the one hand, the world of make-believe seems far removed from the slow, painstaking accumulation of facts we commonly take to be characteristic of the scientific method. On the other hand, we celebrate stories of great, creative leaps of the imagination in science, such as the famous story of August Kekulé's discovery of the ring structure of benzene after dreaming of a snake swallowing its own tail. This chapter will focus on the role of the imagination in one important part of scientific inquiry, namely scientific modeling. Modeling plays a crucial role in scientists' attempts to understand the world. And yet it is also puzzling since, in modeling, scientists appear to be able to learn about the world by first learning about things that don't exist, like perfect spheres or frictionless surfaces. As a result, modeling poses a range of questions for philosophers of science: What are models? How do they represent real systems in the world? How can learning about models help us to learn about those systems?

Scientists often talk of modeling in terms of the imagination. When we are presented with the Newtonian model of the solar system, for example, we might be told to "imagine that the sun and earth are perfect spheres, isolated from the other planets…". In a similar manner, a biology textbook might ask us to "imagine a population of predators and prey, which interact in the following way…". When we read such passages, it seems, we are being invited to turn our attention away from the blooming, buzzing confusion we find around us to ponder a simpler, more straightforward world before our mind's eye. Recently, a number of authors have suggested that paying closer attention to the imagination might help us to address the philosophical issues raised by scientific modeling. Some have also developed this idea by drawing on work in philosophy of art and fiction. These approaches fall into two camps: *indirect fiction views* and *direct fiction views*. According to indirect fiction views, when scientists represent the world in modeling they do so indirectly, via a *model system*. Model systems are simplified or idealised versions of the real world that the scientist asks us to imagine. Proponents of this approach often compare model systems to fictional characters, like Sherlock Holmes or Madame Bovary. By contrast, direct fiction views reject this appeal to model systems. According to direct fiction views, scientists represent the world directly, by asking us to imagine things about it. Proponents of this approach sometimes compare models to works of historical fiction, which represent real people, places or events. This chapter will examine both of these approaches to scientific modeling in detail and consider the motivation behind them, as well as some objections that have been raised against them.

Scientific modeling

Scientific models may be divided into two categories: *physical models* and *theoretical models*. As the name suggests, physical models are actual, physical objects. If an engineer wishes to build a bridge, for example, she might first build a scale model to test her plans. Other well-known examples of physical models include wax anatomical models, "ball-and-stick" molecular models or mechanical orreries that show the movements of the planets in the solar system. In contrast, theoretical models are not actual, physical objects. Consider the standard Newtonian model of the orbit of the earth. This model makes many simplifying assumptions. For example, it assumes that the sun and earth are perfect spheres and that they are isolated from the other planets in the solar system. These assumptions are known to be false of the sun and earth. And yet by making them scientists are able to apply Newton's laws to predict the motion of the planets. This is a case of theoretical modeling. To apply Newton's laws we *model* the sun and earth as perfect spheres isolated from the other planets. Another familiar example is the billiard ball model of gases. In this model, we treat the molecules of a gas as if they were a collection of tiny billiard balls. Once again, this description is false in various respects. For example, it assumes that when the gas molecules collide, they ping off each other like billiard balls whereas, in reality, their interactions are more complicated. And yet, as with the Newtonian model of the planets, making these assumptions allows us to make sense of an extremely complicated real world system and make good predictions for its behaviour.

Theoretical modeling is extremely common in science. Indeed, some authors argue that modeling is involved in all attempts to apply scientific theories to the world (Cartwright, 1983; Giere, 1988). For others, modeling is a more specialized activity, which should be distinguished from other forms of theorizing (Godfrey-Smith 2006; Weisberg 2007). On all accounts, however, theoretical modeling is a widespread and important part of scientific practice. And yet it can also seem a rather puzzling activity. One way to see this is to consider the contrast between physical and theoretical modeling. When the engineer models her bridge, she builds an actual, physical object from wood, metal or plastic. In theoretical modeling, as we have seen, scientists don’t construct any physical object that serves as their model. Indeed, there typically are no actual, concrete objects that would satisfy the scientists’ equations and assumptions. There are no perfect spheres that we could take out of the lab store cupboard and use to build a Newtonian model of the solar system, for example. And yet scientists often talk about theoretical and physical modeling in similar sorts of ways. The engineer builds her scale model so that she can investigate the properties of the model and thereby learn about the properties of the finished bridge. Similarly, it is often said that, in theoretical modeling, what scientists do is to construct a simplified or idealised system, called the *model system*. For example, the Newtonian model system consists of two perfect spheres isolated from the other planets and obeying Newton’s law of gravitation. Like the engineer with her scale model, the scientist then investigates the properties of her model system to learn about the properties of the real system that she wishes to understand. For example, the scientist might discover that the orbit of the earth in the Newtonian model is elliptical and thereby conclude that the orbit of the earth itself is also elliptical (or at least almost elliptical).

Theoretical modeling therefore presents us with certain puzzles. How can we make sense of the fact that a large part of scientific practice seems to involve talking and learning about things that do not exist? There are several questions here. First, how should we interpret scientists' *model descriptions* (that is, the equations and assumptions that scientists write down when they formulate a theoretical model)? Model descriptions look like descriptions of actual, concrete objects (model systems). And yet, as we have seen, there typically are no such objects. What, then, is the function of model descriptions? Second, how should we interpret scientists' subsequent talk in theoretical modeling, which seems to assume that there *are* model systems which the scientists are investigating? Martin Thomson-Jones (2007, 2010) refers to this aspect of modeling as the *face value practice*, since it appears to take model descriptions at face value, as descriptions of actual, concrete objects. If these objects don't exist, then what makes some of the statements scientists utter when they engage in the face value practice *correct* (e.g. that the model earth moves on an ellipse) and some *incorrect* (e.g. that the model earth spirals into the sun)? Third, how can we make sense of the idea that scientists are able to *learn* about model systems? It seems that the scientist who uses the Newtonian model can *discover* things about her model system, such as the shape of the earth's orbit or its time period. But how is this possible when there is no actual, concrete object whose behaviour she can investigate? Of course, as well as these questions concerning the nature of theoretical models, we must also ask how it is that these models allow us to learn about the real world. How is it that finding out about the behaviour of tiny billiard balls or perfect spheres allows us to learn about real gases or the planets in the solar system? As we shall see, different accounts of the nature of theoretical models suggest different ways of addressing this question as well.

Abstract object views

The most common way to try to make sense of theoretical modeling is to claim that, although there is no actual, concrete object that satisfies scientists' model descriptions, there is some other object that does satisfy them. To borrow another term from Thomson-Jones (2007, 2010), most accounts of modeling posit *description-fitting objects* to serve as model systems. One popular version of this approach treats model systems as *abstract objects*. According to Ronald Giere (e.g. 1988, 1999a, 1999b, 2004), for example, model systems are abstract objects that are defined by scientists' model descriptions. Giere understands theoretical modeling as a two-stage process. In the first stage, the scientists' model description defines an abstract object, which is the model system. In the second stage, scientists use this model system to represent a real system. They do so by specifying its similarity to the real system in certain respects and to certain degrees. According to this account, then, scientists represent the world *indirectly,* via an (abstract) model system (Figure 1). This approach suggests answers to each of the questions introduced above. First, it appears to offer a way to understand scientists' model descriptions: these are *definitions* of abstract objects. Second, this approach also seems to make sense of scientists' subsequent talk in theoretical modeling. When scientists engage in the face value practice, it might be argued, they are simply making claims about an abstract object (their model system). Third, the abstract object view might allow us to explain how it is that we can learn about a model system. Learning about a theoretical model is a matter of finding out about the properties of an abstract object, in much the same way that learning about a physical model is finding out about the properties of an actual, concrete object.

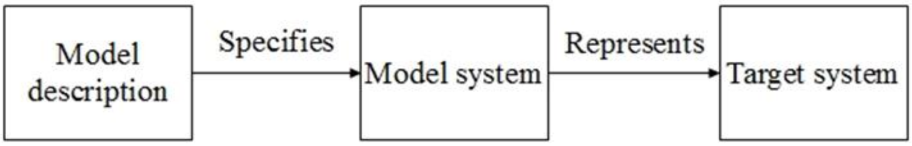

Figure 1: Indirect views of modeling

The abstract object view of models has enjoyed considerable popularity and there are a number of different versions of this approach. Some of these understand models in more formal terms than Giere's account, as set-theoretical structures (Suppes 1960), trajectories through phase-space (van Fraassen 1980), or mathematical structures more broadly construed (Weisberg 2013). Despite its popularity, however, the abstract object view of models also faces some challenges. First, it seems to have difficulty dealing with much of scientists' talk about models (Godfrey-Smith 2006; Thomson-Jones 2010). As we have seen, scientists often talk about model systems as if they were actual, concrete objects with spatiotemporal properties. For example, the model earth might be said to follow an elliptical orbit with a particular time period. And yet abstract objects are typically taken not to have spatiotemporal properties. The abstract object view seems to have trouble making sense of this way of talking about models. Second, critics have questioned whether the abstract object view can account for the relationship between models and the world (Hughes 1997; Thomson-Jones 2010). According to Giere (e.g. 1988, 2004), models are similar to the world in certain respects and to certain degrees. Normally, if we say two objects are similar, we mean that they share certain properties. And yet if models are abstract, it is difficult to see how they could be similar to real systems with respect to properties such as mass or time period. One response to this worry is to try to capture the relevant similarity using more formal notions, such as isomorphism (e.g. French and Ladyman 1999).

Third, some authors have argued that the abstract object view of models faces difficulties in accounting for theoretical models that are not mathematical (Downes 1992; Levy forthcoming). For example, descriptions of biological mechanisms are often given in concrete, non-mathematical terms, specifying the various parts of the mechanism and the way that they interact. Such descriptions are simplified and idealised in various ways, and commonly described as models by scientists themselves. And yet it is difficult to see how they can be incorporated into the abstract object view (for an attempt to do so see Weisberg 2013: 19). Finally, and perhaps most importantly, the abstract object view offers little explanation for the role that the imagination seems to play in scientific modelling. When scientists are engaged in modeling, it seems, they don't simply carry out various mathematical calculations. Instead, they imagine the concrete scenarios that the models invoke, like collections of billiard balls colliding with each other or populations of predators devouring their prey. This imaginative engagement seems to play an important role in the way that scientists develop models and explore their properties. And yet, if models are abstract objects they would seem to lack the concrete, visualisable properties that would allow them to be brought before the mind's eye in this way (Levy forthcoming). In response to this worry, Michael Weisberg (2013) argues that the abstract object view can still find room for the imagination to play an important role in modelling.

Indirect fiction views

Recently, a number of philosophers of science have suggested that paying closer attention to the role of the imagination in modeling provides the key to understanding what models are and how they are used to represent the world. To develop this idea, many of these authors draw parallels between scientific modeling and other practices involving the imagination, especially our interaction with works of fiction. As discussed earlier, fiction-based accounts of modeling fall into two camps: *indirect fiction views* and *direct fiction views*. Proponents of indirect fiction views are struck by parallels between scientists' model systems and fictional characters. Peter Godfrey-Smith (2006: 734-5) introduces the idea in the following way:

> Roughly, we might say that model systems are often treated as "imagined concrete things" - things that are imaginary or hypothetical, but which would be concrete if they were real. […] In making this argument, I take at face value the fact that modelers often *take* themselves to be describing imaginary biological populations, imaginary neural networks, or imaginary economies. An imaginary population is something that, if it was real, would be a flesh-and-blood population, not a mathematical object. Although these imagined entities are puzzling, I suggest that at least much of the time they might be treated as similar to something that we are all familiar with, the imagined objects of literary fiction.

According to the indirect fiction view, then, model systems should be understood in the same way as fictional characters, like Sherlock Holmes. When scientists put forward a theoretical model they ask us to imagine a fictional model system, just as Conan Doyle asks us to imagine the exploits of a fictional detective. This idea suggests a rather different approach to the various puzzles raised by theoretical modeling from that taken by the abstract object view. On the indirect fiction view, scientists' model descriptions are understood in the same manner as works of fiction that portray fictional characters. Consider the following passage from *The Hound of the Baskervilles*:

> Holmes leaned forward in his excitement and his eyes had the hard, dry glitter which shot from them when he was keenly interested. (Conan Doyle 1902/2003: 22)

Like scientists' model descriptions, it seems, there is no actual, concrete object that this passage describes: there is no real, flesh-and-blood detective that satisfies the description Conan Doyle gives of Holmes. And yet, just as scientists talk as if there were objects that satisfied their model descriptions, so we talk as if there were a Sherlock Holmes: we say that Holmes is highly intelligent, that he smokes a pipe and plays the violin. The indirect fiction view thus seems to offer us a way to make sense of scientists' engagement in the face value practice: it is to be understood in the same way as our talk about fictional characters. Finally, this approach suggests that there is nothing too mysterious in the idea that scientists can discover properties of model systems that go beyond those specified in their model description. After all, fictional characters have properties that go beyond those explicitly described in the text. We assume that Sherlock Holmes has a heart, and that he needs oxygen to survive, even if Conan Doyle never bothers to mention this in the story.

The indirect fiction view has a number of advantages over the abstract object view of models. First, recall that the abstract object view had difficulty accounting for the fact that scientists often talk about model systems as if they were concrete objects and ascribe spatiotemporal properties to them. We often attribute spatiotemporal properties to fictional characters, however. We say that Holmes is tall, for example, or that he lived at 221B Baker Street. Second, we saw that, if model systems are abstract, it would be difficult to see how they could be similar to real systems in any straightforward sense. But we seem to have no problem comparing fictional characters to the world. We say that Holmes is more intelligent than any real detective or compare our political situation today to that in Orwell's *1984*. The indirect fiction view also has no difficulty accounting for models that are introduced in non-mathematical terms, or even using pictures or diagrams. Fictional characters may be represented in many different ways. When they were first published in *The Strand Magazine*, the Sherlock Holmes stories featured line drawings illustrating the great detective's exploits.

Finally, unlike the abstract object view, the indirect fiction view puts the imagination centre stage in its account of models.

Despite its attractions, the indirect fiction view faces a number of challenges. First, critics have asked what determines the properties of model systems in this approach (Weisberg 2013: Chapter 4). The indirect fiction view claims that model systems have properties that go beyond those specified in the model description, just as fictional characters have properties that go beyond those mentioned in the text. Spelling out the principles that “fill out” fictional worlds in this way has proved difficult, however. One natural proposal, sometimes called the *reality principle,* suggests that we take fictional worlds to be as much like the real world as possible, unless the text explicitly tells us otherwise (Walton 1990, Chapter 4). So even if the London of *The Hound of the Baskervilles* is unlike the real Victorian London in being home to the world’s greatest detective, we still assume that it is the capital of the United Kingdom, that the people who live there have blood in their veins, and so on. In the case of fiction, the reality principle faces a number of problems. For example, it seems to result in an explosion in the content of fictional world: if we follow the reality principle, it will be part of the content of *The Hound of the Baskervilles* that the Second World War ended in 1945 and the Berlin Wall fell in 1989, since nothing in the story contradicts this. Parallel problems arise in the case of theoretical models. Presumably, we don’t wish to count it as part of the content of the Newtonian model that the earth’s atmosphere contains 78% nitrogen and 21% oxygen, that the sun produces energy through nuclear fusion, and so on. Models also seem to pose their own difficulties. One issue is that some features of the mathematics in model descriptions are not carried over to model systems because they have no physical interpretation. When we read the equations for the predator prey model, for example, we know that we are not supposed to imagine non-integer numbers of foxes or rabbits.

One challenge for proponents of the indirect fiction view, then, is to spell out the principles that determine the properties of model systems. A second objection to the indirect fiction view concerns its starting point, namely the prevalence of the face value practice in modeling. As we saw, a major motivation behind the appeal to fiction was that scientists often talk about model systems as if they were concrete objects. But critics argue that this is not always the case: sometimes models are presented in highly abstract mathematical terms and have no obvious concrete interpretation (Weisberg 2013: Chapter 4). While the indirect fiction view might be able to accommodate such cases, they would seem to undermine at least some of the initial motivation behind the approach. Perhaps more seriously, it might also be argued that such cases are beyond the reach of our imagination. Can we really imagine complex probability distributions, for example, or high dimensional vector spaces?

Finally, the most obvious challenge for the indirect fiction view concerns the ontology of model systems. The indirect fiction view compares model systems to fictional characters. Unfortunately, the nature of fictional characters is notoriously unclear, and is itself the subject of longstanding debate. *Realists* about fictional characters argue that, even if he is not a regular, flesh-and-blood detective, we must grant Holmes *some* form of existence if we want to make sense of fictional characters. Realists therefore posit *fictional entities* and offer different accounts of the nature of these entities. For example, Alexius Meinong (1904/1960) famously draws a distinction between *being* and *existence*. On this view, Holmes possesses all the properties that we normally take him to have, like living at 221B and smoking a pipe. It is simply that, unlike a regular detective, he lacks the property of existence. Other realists argue that fictional entities are abstract entities of some kind (van Inwagen 1977, Thomasson 1999). By contrast, *antirealists* try to make sense of fictional characters and our talk about them without positing fictional entities (e.g. Russell 1905/1956; Walton 1990). The best known antirealist theory follows Bertrand Russell (1905/1956) and analyses a sentence like

‘Holmes smokes a pipe’ as the claim that ‘there exists exactly one x such that x satisfies the Holmes-description and x smokes a pipe’. The statement ‘Holmes smokes a pipe’ is then perfectly meaningful and contains no reference to any fictional entity. The trouble is that ‘Holmes smokes a pipe’ is now judged to be false, along with claims like ‘Holmes is an idiot’. And yet intuitively there seems to be an important difference between these claims. (For an excellent overview of the issues raised by fictional characters, see Friend 2007.) Given the ongoing dispute between realists and antirealists, comparing model systems to fictional characters seems to offer little chance of progress.

Proponents of the indirect fiction view have responded to this challenge concerning the ontology of model systems in two main ways. First, some authors have argued that philosophers of science may simply defer problems concerning the ontology of fictional characters to philosophers of fiction. In this vein, Godfrey-Smith (2006: 735) suggests that we might accept such objects as part of the “folk ontology” of scientific modeling, even if in the end we require an account of these objects “for general philosophical reasons” (for a similar view, see Giere 2009). The difficulty with this approach is that the indirect fiction view threatens to become more of a promissory note than a fully-fledged account of what is going on in scientific modeling. For example, consider the problem of explaining how model systems represent the world. Proponents of the indirect fiction view often describe the relationship between model systems and the world in terms of similarity or resemblance (Giere 2009; Godfrey-Smith 2006). And yet if, in the end, we were to adopt an antirealist account of fictional characters, then we would conclude that, strictly speaking, there are no model systems. As a result, all talk of similarity or resemblance between model systems and the world would have to be radically reinterpreted. (For a discussion of this “deferral strategy”, see Thomson-Jones 2007.)

The second way in which proponents of the indirect fiction view have responded to the ontological challenge is to draw on existing theories of fiction. Thus, Roman Frigg (2010a, 2010b) has proposed a version of the indirect fiction view that draws on an influential theory of fiction due to Kendall Walton (1990). According to Walton, the text of a novel functions as a "prop" in games of make-believe: when we read the text, we are supposed to engage in certain imaginings according to the rules appropriate for works of that kind (1990: Chapter 2). (See "Imagining and Fiction") Frigg offers an application of Walton's theory to scientists' model descriptions. In this account, when we read the model description for the Newtonian model of the solar system, "we imagine an entity which has all the properties that the description specifies. The result of this process is the *model-system*, the fictional scenario which is the vehicle of our reasoning: an imagined entity consisting of two spheres, etc." (2010b: 133; emphasis in original). After imagining her model system, the scientist goes on to connect it to the real system. In this case, for example, she might specify that "the sphere with mass m_e in the model-system corresponds to the earth and the sphere with mass m_s to the sun' (2010b: 134). Once this is done, she can "start translating facts about the model system into claims about the world" (2010b: 135).

Walton's theory is antirealist concerning fictional characters. Frigg's account thus promises to preserve the structure of the indirect view of modeling while avoiding positing fictional entities to serve as model systems. The account has also been subject to criticism, however. Godfrey-Smith (2009) argues that, although it avoids positing fictional entities, Frigg's approach is committed to uninstantiated properties, which are equally mysterious (see also Levy forthcoming). Toon (2012: Chapter 2) argues an antirealist stance on model systems is at odds with Frigg's overall, indirect view of modeling. (For a more realist take on the comparison between model systems and fictional characters, see Contessa 2010.)

Direct fiction views

Both the abstract object and the indirect fiction view claim that modelers represent the world indirectly, via model systems (Figure 1). Direct fiction views reject this claim. According to direct fiction views, there are no model systems. Instead, scientists represent the world directly, by asking us to imagine things about it (Figure 2). Adam Toon (2010, 2012) develops this approach by drawing on Walton's theory of fiction, while Arnon Levy (forthcoming) defends a similar view based on Walton's work on metaphor (Walton 1993). Recall that the indirect fiction view treats model descriptions like passages about fictional characters. By contrast, Toon (2012) introduces the direct fiction view by comparing model descriptions to works of fiction that represent real people, places and events. Consider the following passage, from Robert Graves' novel *I, Claudius*:

> Augustus assumed Antony's Eastern conquests as his own and became, as Livia had intended, the sole ruler of the Roman world. (Graves 1934/2006: 23)

In Walton's analysis, this passage is not about any fictional character, but about the real Emperor Augustus, as well as his wife Livia and Mark Antony. *I, Claudius* represents these people by asking us to imagine propositions about them. Some of these propositions are true, such as that Augustus defeated Mark Antony. Others appear to be entirely fabricated by Graves and so probably false, such as that Augustus was manipulated by the scheming Livia. The direct fiction view understands model descriptions in the same way. When the scientist introduces the Newtonian model of the solar system, she does not conjure up any abstract or fictional model system. Instead, she asks us to imagine things about the solar system itself. Specifically, we are asked to imagine that the sun and earth are perfect spheres with certain masses, that they interact only with each other, and so on. Some of this is true (e.g. that the earth and sun have certain masses) while some is known to be false (e.g. that they interact only with each other).

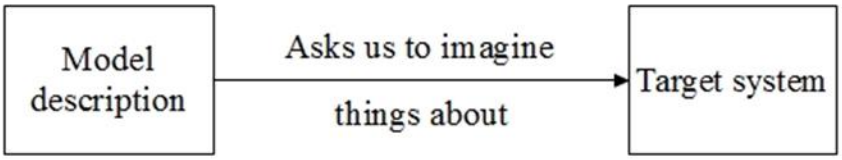

Figure 2: The direct fiction view of modeling

The direct fiction view thus offers a way to interpret scientists' model descriptions: these are prescriptions to imagine the world in a certain way. Put in Walton's terms, model descriptions are "props" in games of make-believe which prescribe imaginings about real systems. Interpreting model descriptions in this way means we need not posit abstract or fictional objects to serve as model systems. This might seem to cause problems when it comes to interpreting the face value practice, however. As we have seen, scientists talk as if there were objects that satisfied their model description. How can a direct view make sense of this? Toon (2012) offers a deflationary analysis of such talk. According to this analysis, when scientists talk about theoretical models as objects, we should not take this talk too seriously. Instead, they are engaging in pretence, "going along with" the model to tell us what it asks us to imagine. For example, if a scientist tells us that "the sun and earth are isolated from the other planets", she is not describing an abstract or fictional object; she is simply telling us that the model asks us to imagine this about the sun and earth.

The direct fiction view also aims to explain how we can learn about models without positing model systems. In this approach, learning about a model is not a matter of discovering facts about an abstract or fictional model system; it is a matter of exploring the web of imaginings prescribed by a scientist's model description. For example, the Newtonian model description asks us to imagine that various assumptions hold of the sun and earth, such as that the force between them obeys Newton's law of gravitation. If we accept these initial assumptions, however, we are also to imagine that the earth moves in an ellipse, since this follows from the equation that we write down. This is simply part of the conventions that govern our interpretation of model descriptions. That the earth moves in an ellipse is therefore part of the content of the model, even though this was not specified in the model description.

The direct fiction view has a number of advantages. Like the indirect fiction view, it acknowledges the importance of the imagination in scientific modeling and explains why modelers think and talk about models as if they were concrete objects. At the same time, it is a deflationary position that avoids the ontological problems posed by fictional characters. Critics have raised a number of objections against this approach, however. First, some have argued that the direct view fails to capture the practice of modeling. Thus, Weisberg (2007, 2013) argues that what distinguishes modeling from other forms of theorising is precisely that it is indirect. Modelers try to understand real systems by first constructing a model system. By eliminating model systems, Weisberg argues, the direct view fails to capture this crucial aspect of modeling. In response, supporters of the direct view might agree that modelers talk as if they were constructing a model system and that this way of talking is distinctive of modeling as a theoretical practice. They simply deny that such talk should be mirrored in our metaphysical picture of what is really going on this practice.

A second objection to the direct fiction view is that some models lack "targets", that is, they do not represent any real system (Contessa 2010; Weisberg 2007). For example, a predator-prey model might invite us to consider a population consisting of two species, predator and prey, whose numbers are governed by certain equations. And yet it might do so without claiming to represent any real population of, say, foxes and rabbits out in the world. In response, Toon (2012: Chapter 3) suggests that such cases may also be understood in terms of make-believe. Taking a different line, Levy (forthcoming) argues that many apparently "targetless" models turn out either to have targets after all, or should be regarded not as models but simply pieces of mathematics.

Finally, critics have questioned whether the direct fiction view can account for the relationship between models and the world. As we have seen, this relationship is often thought of in terms of similarities between model systems and the world. And yet the direct view denies the existence of model systems. As a result, it seems that proponents of the direct view must find a different way of thinking about the relationship between models and the world. Toon (2012: Chapter 3) suggests we think of this relationship in terms of the truth or falsity of the imaginings that a model prescribes, while Levy (forthcoming) suggests we may better understand this relationship by invoking the notion of "partial truth" (Yablo 2014).

Physical models

So far we have focused on theoretical modeling. What about physical modeling? Does imagination play any role here? We might think that the imagination is less important in physical modeling since in these cases we have an actual, concrete object that serves as the model. Why would a scientist need to use her imagination when the model is right there in front of her on the lab bench? In fact, however, there are reasons to think that the imagination might also play an important role in physical modeling. Toon (2011) describes an empirical study examining the use of plastic "ball-and-stick" models of molecules. One finding of this study is that people who build and manipulate molecular models routinely talk as if they were building and manipulating the molecules themselves. Toon argues that we may make sense of this way of talking, as well as other aspects of the practice of molecular modeling, by understanding molecular models in a similar way to children's dolls or toy trucks. In this view, scientists imagine their plastic ball-and-stick models to be molecules, in much the same way that children imagine a doll to be a baby.

On this approach, both theoretical *and* physical models are understood as props in games of make-believe. There remain important differences between the two, however. One key difference between theoretical and physical models concerns the forms of imaginative *participation* that they allow. When we participate in a game of make-believe, we ourselves prescribe imaginings within the game. For example, if a child raises a cup to a doll, the children playing the game are to imagine that she is feeding the baby. Some games allow for more participation than others. According to Walton (1990), in the games we play with paintings, looking at a painting of Napoleon counts as looking at Napoleon. However, picking up the painting doesn't count as picking up Napoleon. On the other hand, picking up a doll *does* count as picking up a baby.

The games we play with dolls thus allow for a greater degree of participation than those we play with paintings. In a similar manner, models also differ in the degree of participation that they allow. As we saw, the direct fiction view understands the face value practice as a form of *verbal* participation in make-believe: when scientists talk about model systems, they are engaging in acts of (verbal) pretence within the game prescribed by the model. Physical models allow for a much greater degree of participation, however. For example, Toon (2011) argues that ball-and-stick molecular models allow for *visual* and *tactile* participation. In this view, scientists learn about the world using molecular models by conducting *imagined experiments*, imagining the various actions that they carry out on the models to be carried out on the molecule instead. In this way, scientists imagine themselves looking at molecules, putting them together and feeling them resist as they try to twist them or pull them apart. Focusing on the role of the imagination might thus help us to understand the way that scientists use physical models to learn about the world. (For more on physical models, see de Chadarevian and Hopwood 2004; Sterrett 2002; Weisberg 2013.)

Conclusion

Modeling is central to scientists' attempts to understand the world. While it seems clear that modeling often involves the imagination, it is only recently that philosophers of science have begun to place the imagination at the centre of their accounts of what models are and how they represent the world. Many of these accounts draw on parallels with fiction. According to indirect fiction views, scientists' model descriptions are like passages about fictional characters. By contrast, direct fiction views compare model descriptions to works of fiction that represent real people, places or events. Deciding between these approaches is likely to involve a trade-off between competing philosophical aims: while indirect views seem to remain closer to scientists' own talk about modeling, direct views appear to involve fewer troublesome metaphysical commitments. Whichever approach we follow, paying closer attention to the role of the imagination promises to provide a richer understanding of the practice of modeling and the crucial role it plays in scientific inquiry.

Further reading

R. Giere, *Explaining Science: A Cognitive Approach* (Chicago: University of Chicago Press, 1988) offers an influential indirect account of modeling. M. Weisberg, *Simulation and Similarity: Using Models to Understand the World*. (Oxford: Oxford University Press, 2013) is a recent defence of the abstract object view. P. Godfrey-Smith, "The strategy of model-based science," *Biology and Philosophy* 21 (2006) and R. Frigg, "Models and fiction", *Synthese* 172 (2010) endorse the indirect fictions view. A. Toon, *Models as Make-Believe: Imagination, Fiction and Scientific Representation* (Basingstoke: Palgrave Macmillan, 2012) and A. Levy "Modeling without Models," *Philosophical Studies* (forthcoming) both develop versions of the direct fiction view. S. de Chadarevian and N. Hopwood (Eds.), *Models: The Third Dimension of Science* (Stanford: Stanford University Press, 2004) is an excellent collection of essays on physical models.

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