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Introduction

One of the main things that scientists do is to represent the world. They do so in many different ways, through theories, equations, formulas, diagrams, graphs, photographs, videos, traces, sketches, watercolours, maps, X-rays and more else besides. And they offer us representations of a vast array of different things: subatomic particles, atoms, molecules, electromagnetic fields, microbes, beetles, the migration patterns of birds, dinosaurs, weather systems, world economic markets, the rise in global temperatures, tectonic plates, the movement of planets in the solar system, distant galaxies, black holes and the big bang.

This book is about how scientific representation works. Although scientists use many different representational devices, this book focuses in particular on scientific *models*. Scientists often try to understand a complex, real world phenomenon by first constructing a simplified or idealised model of it. Sometimes they might construct a *physical model*, such as the scale models that engineers build to test new structures. Often, however, scientists simply write down a set of assumptions or equations, and so come up with a *theoretical model*. A scientist might try to understand the solar system by assuming that the planets are perfect spheres subject only to the gravitational field of the sun, for example, or treat the molecules of a gas as if they were a collection of tiny billiard balls. Modelling is extremely important in the sciences. Indeed, some even argue that models are involved whenever complex, mathematical theories are applied to the world (e.g., Cartwright, 1983).

Models raise a number of important questions. Some of these questions concern scientific realism. Realists claim that successful scientific theories are true, or at least approximately true. And yet models typically make many assumptions that are false of the systems they model. The planets are not perfect spheres and molecules are not billiard balls. Even worse, scientists sometimes offer a number of different, incompatible models for the same phenomena, each of which is successful for different purposes. Models also raise questions for our understanding of laws of nature. We normally take these laws to be true in all places and at all times. And yet many of the fundamental laws we find in science are true only in the limited, highly simplified domains described by scientists' models. This also presents problems for our accounts of scientific explanation. According to one common view, we explain a phenomenon by showing how it may be deduced from the laws of nature. But if laws are true only of models, how do we explain the behaviour of the complex, messy systems we find in the real world?

This book will not attempt to address all of the problems posed by scientific models. Instead, it will focus on two key questions: what are models, and how do they represent the world?

The first question asks what models are. It is not difficult to say what physical models are: they are bits of wood or metal or plastic. Theoretical modelling is more problematic, however. In theoretical modelling, scientists often make assumptions that are true of no actual, physical object: there are no perfect spheres, and even real billiard balls do not satisfy the assumptions made in the billiard ball model of gases. And yet scientists commonly talk as if there were such objects and as if they can find out about their properties. They talk as if they were investigating a 'model-system' which satisfies the assumptions they make. Theoretical modelling therefore gives rise to a number of ontological worries: how are we to make sense of the fact that a large part of scientific practice seems to involve talking and learning about things that do not exist?

The second main question addressed in this book asks how models represent the world. Many scientific models represent objects or events in the world: the Bohr model represents the atom, Crick and Watson's famous double-helical model represents DNA, and the billiard ball model of gases could be used to represent helium, or hydrogen or oxygen. The problem of scientific representation asks how these models do this. One way to understand this problem is to compare models to pictures. In itself, it seems, a painting like

Constable's *Salisbury Cathedral from the Meadows* is merely a set of brushstrokes on a piece of canvas. And yet it represents horses pulling a cart through a stream, and Salisbury Cathedral itself beneath a rainbow. The problem of depiction asks how paintings can do this. Similarly, Crick and Watson's original DNA model was simply a collection of metal rods and plates held in place by clamps. And yet it represented the complex helical structure of the DNA molecule. How did the model do this?

This book will offer answers to these questions about scientific modelling by looking to what, at first sight, might seem an unlikely source of inspiration: children's games of make-believe. I shall argue that scientific models function like the dolls and toy trucks of children's imaginative games. In order to develop this idea, I will draw extensively on the work of the philosopher of art Kendall Walton (1990). Walton offers a sophisticated framework for understanding games of make-believe, and uses this framework to provide a general theory of art and fiction. I will draw on Walton's framework throughout this book, although my treatment of models will not rely upon some of the more controversial aspects of Walton's theory of art and fiction. By using this framework, I hope to show that understanding models in terms of make-believe allows us to develop a coherent, general account of scientific modelling, one that explains what models are and how they represent the world.

The discussion will proceed as follows:

Chapter 1 will introduce the two main problems to be addressed. First, we will consider the ontological problems posed by theoretical modelling. As we shall see, some have tried to solve these problems by taking model-systems to be abstract entities. More recently, others have suggested that they are fictional entities, like unicorns or Count Dracula. I shall call these *indirect views* of modelling, since, on these accounts, scientists represent the world indirectly, via abstract or fictional entities. Although recent philosophy of science has seen a great deal of interest in the problem of scientific representation, there is also disagreement over precisely what the problem is. In fact, according to one influential view, 'there is no special problem of scientific representation' (Callender and Cohen, 2006, p. 67). In Chapter 1 I will argue that this view is mistaken, and show why the problem of scientific representation must still be faced.

In Chapter 2, I will introduce Walton's framework for understanding games of make-believe and show how it may be applied to scientific models. I will then go on to show how this *make-believe view* of modelling allows us to solve the ontological problems posed by theoretical models. As we will see, the make-believe view allows us to make sense of what scientists are doing when they model the world without positing any object that satisfies their modelling assumptions. On the make-believe view, there are no model-systems: scientists represent the world directly, not via abstract or fictional entities. We will also look more closely at how this *direct view* differs from those which compare model-systems to fictional entities.

Chapter 3 will focus on the problem of scientific representation. I will show that the make-believe view allows us to offer an account of representation which meets the requirements I introduce in Chapter 1. The account I suggest will point to a parallel between scientific models and works of fiction. There is now a growing body of work in philosophy of science that, in one way or another, seeks to compare models and fiction. Unsurprisingly, there are also those who have objected to this comparison. In Chapter 3, we will pause to consider these objections and see whether they present a problem for the make-believe view. We will then focus on a type of model that often causes difficulties for theories of scientific representation. These are models which are representational, but which represent no actual, concrete object. Unlike existing accounts, the make-believe view is able to make sense of these models, since it does not take scientific representation to be a relation.

As well as helping us to solve philosophical problems, any account of scientific models should also be able to provide a convincing account of the practice of modelling. Historians of science have offered us detailed studies of representation in scientific practice (e.g., Lynch and Woolgar, 1990), and of three-dimensional, physical models in particular (de Chadarevian and Hopwood, 2004). Physical models are often neglected by philosophers of science, however (exceptions include Sterrett, 2002 and Weisberg, forthcoming). Chapters 4 and 5 will focus on an important group of physical models in science, namely molecular models.

Chapter 4 examines the role of models in the work of the Dutch chemist J. H. van't Hoff (1852–1911). Winner of the first Nobel Prize in chemistry, van't Hoff was one of the founders of stereochemistry, the part of chemistry that concerns the spatial arrangement of atoms within molecules. The implications of van't Hoff's work were radical: at a time when even the existence of atoms remained controversial, van't Hoff's 'chemistry in space' claimed to show the way that atoms are arranged within molecules. And yet van't Hoff's work met with surprisingly little opposition. As we shall see, we may better understand the reception of van't Hoff's ideas by focusing on the cardboard models that he used to promote his work. I will argue that the make-believe view offers a framework with which to make sense of these early chemical models and the important role they played in the development of stereochemistry.

While historical studies are important, it is also helpful to be able to observe the way that models are used first-hand. Chapter 5 will assess the make-believe view through an empirical study of some molecular models in use today. I will suggest that the make-believe view gains support when we look at the way that these models are used and the attitude that users take towards them. Users' interaction with molecular models suggests that they imagine the models to be molecules, in much the same way that children imagine a doll to be a baby. Furthermore, I argue, users of molecular models imagine themselves viewing and manipulating molecules, just as children playing with a doll might imagine themselves looking at a baby or feeding it. Recognising this 'participation' in modelling, I suggest, helps us to understand the value of physical models and the bodily manipulation that they allow. It also points towards a new account of how models are used to learn about the world, through what I call *imagined experiments*.

By the end of the book, I hope that the comparison between models and children's dolls and toy trucks will not seem so strange after all. In fact, I believe that it will offer us a rather natural account of what scientific models are and how they are used. We sometimes describe modelling as a process of treating the world 'as if' it were a certain way, or say that it involves 'pretending' that a system obeys certain laws or assumptions. I hope to show how far this way of understanding modelling can get us.

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