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Models and exploratory models

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1. Introduction

Scientific models have become essential and ubiquitous in contemporary science. Scientists dedicate much of their time to the construction, development, and testing of models. And scientific journals provide forums for their presentation and discussion. Paradigmatic examples include the Lotka-Volterra model of predator-prey population, the Bohr model of hydrogen atoms, Watson and Crick's double helix model of DNA, Kendrew's plasticine model of myoglobin molecules, and Newton's model of the solar system. In recent years there has been an increasing number of philosophical, historical and sociological works on models. Historians and sociologists of science have analysed a vast number of case studies. At the same time, philosophers of science have enquired into fundamental questions concerning their nature and functions.

Axel Gelfert's book, *How to Do Science with Models. A Philosophical Primer,* offers a clear and accessible introduction to the contemporary philosophical debate on models that combines the descriptive aims of historical and sociological studies with the normative-theoretical ambition of philosophy of science. The reader finds interesting philosophical insights, a wide range of case studies from the natural sciences, and some historical context. The first two chapters provide a systematic survey of the contemporary philosophical debate on the nature of models and on how they represent real world phenomena. The third chapter identifies recurring strategies of model building by analysing a wide range of case studies from condensed matter physics to population biology. The last two chapters advance the philosophical debate by identifying exploration as one of the core functions of models together with explanation and prediction, and by developing the idea that models enable and constrain the activities of their users.

Gelfert submits that the main assumption of his book 'is that the key to answering any of the more fundamental questions about scientific models lies in the diversity of their varied uses and functions' (2016, 4). He starts with a survey of the existent explanations of what models are, including the syntactic view of theories[1] (according to which scientific theories are axiomatized collections of sentences in a given logical domain), the semantic view[2] (according to which theories are collections of mathematical models), and the more recent

[1] Carnap (1937, 1966), Hempel (1966).
[2] Giere (1988), Suppes (1960), Suppe (1989), Van Fraassen (1980), French and Ladyman (1999).

fiction view of models[3] (according to which models are ontologically on par with the fictions of literature and the arts). But none of these emerges as his favourite, and he does not offer an alternative explanation.

In the absence of a generally accepted unified account of what models are, some have abandoned the quest altogether in favour of a characterisation of models as functional entities. Among them, Stephen French (2010) argues for a so-called quietist approach to models, according to which we do not need to answer the ontological question in order to explain the scientific practice of modelling. And Gelfert himself endorses a functional characterisation of models and argues that 'the various functions of models in scientific enquiry are our best—and perhaps only—guide when it comes to finding answers to any of the more fundamental questions about scientific models, including those about their ontology, epistemic status, confirmation, and so forth' (ibid., 25). Following Giere (1999), Gelfert distinguishes between two main functional characterisations of models, the *instantial* view and the *representational* view. According to the former, a model of a theory is anything of which the theory is a true description (e.g. Suppes 1960). According to the latter, models are representations of real systems (e.g., Giere 2010, Chakravartty 2010). But models have a number of other functions as well. For example, they are mediators between theories and the world (Morrison and Morgan 1999), they are epistemic artefacts furthering scientific knowledge (Knuuttila 2005), they provide model explanations (Bokulich 2009), and they are tools for theory construction (Hartmann 1995). In fact, I believe that Gelfert's most significant contribution to the contemporary debate on models consists in his identification of *exploration* as a special function of what he calls *exploratory models*.

In what follows I will present the way in which Gelfert develops the notion of exploration in Section 2, and I will critically assess it in Section 3. The upshot will be that while this is a genuinely new notion that deserves to be further developed, Gelfert's characterization is largely incomplete and the use he makes of the term 'exploratory model' needs to be amended to match the current use modellers make in different scientific areas.

2. Gelfert on exploratory models

Philosophers of science have already recognized a general notion of exploration as one of the main functions of models as special tools of scientific enquiry. Some have claimed that models involve a special cognitive function called 'surrogative reasoning' (Swoyer 1991) or 'model-based reasoning' (Magnani and Nersessian 2002, Magnani, Nersessian and Thagard 1999), which consists in the development and manipulation of a model system – a surrogate or analogue of a real system – that licenses certain inferences about reality. Gelfert points out that model-based understanding has been interpreted as involving simulations of model behaviour (Stöckler 1997) and manipulation of model systems (Morgan 2012), and he connects these features to a special 'exploratory mode of interacting with them' (Gelfert 2016, 74).

Gelfert starts by sketching an alternative notion of exploration in terms of Daniel Berlyne's (1960) psychological distinction between *diversive exploration* and *specific exploration*. Diversive exploration is response-oriented in that an agent 'seeks novelty or surprise for its own sake' (Gelfert 2016, 75), while specific exploration is stimulus-oriented in that it 'is a set of behaviours in response to a novel or unexpected stimulus' (ibid*.,* 74). Gelfert suggests that

[3] Frigg (2010), Godfrey-Smith (2006, 2009), Levy (2015), Toon (2012), Salis (2016).

diversive exploration may be a way to generate hypotheses, while specific exploration may be a way to investigate specific hypotheses and their consequences either theoretically or by conducting an experiment. In particular, specific exploration may consist in a set of behaviours such as 'focus our attention on a salient theoretical question, explore ways of completing a mathematical proof, or attempt to resolve an ambiguity in meaning by trying different interpretations' (ibid., 74-5).

Starting from this notion of specific exploration, Gelfert submits that the analogy that is really crucial to the identification of a special exploratory function of models derives from the philosophical literature on so-called *exploratory experiments*. As Burian (1997, 2007) and Steinle (1997, 2002) characterise them, these are experiments that are performed in the absence of a (mature) theory of the phenomena under investigation. Exploratory experiments play a key role in the process of conceptual change and innovation that leads to the formation and stabilization of new conceptual frameworks. Gelfert builds on this analogy to identify a special class of exploratory models that, just like exploratory experiments, play a key role in the formation and stabilization of new conceptual frameworks. In his own words:

> Just as an experiment does not always serve the function of testing a theory, neither does a model always have to render an empirical phenomenon amenable to subsumption under a pre-existing theory. While traditional analyses of modelling may give us a good enough grasp of the various functions of models in situations where the underlying theory cannot be applied directly, an analysis of its exploratory uses is needed to account for situations where an underlying theory is *unavailable*, or where—as James Clerk Maxwell put it—it is essential 'to avoid the dangers arising from a premature theory' (2016, 75).[4]

Gelfert further emphasises that just as exploratory experiments do not limit their possible outcome on the basis of an extant theory, so exploratory models investigate the consequences of specific hypotheses in the absence of an extant theory of the phenomena under investigation. However, he also hurries to add that 'it would be misleading to think of exploration as entirely *theory-free*' (ibid., 78). When devising and interpreting exploratory experiments scientists usually rely on 'significant background knowledge, including background theories' (ibid.).

Gelfert identifies four different kinds of exploratory models in terms of four more specific exploratory functions that he sees as complementary rather than mutually exclusive. First, in the absence of a well-formed theory, exploratory models can function as a *starting point* in a series of models that are more and more realistic. For example, he notices that in the absence of a theory of how humans behave when driving their vehicles in the traffic, early models of traffic flows were sometimes inspired by the physical theory of fluid dynamics. However, a variety of further factors had to be included to produce increasingly realistic models (e.g., roadway conditions, drivers' preferred maximum speed, drivers' reaction time, etc.).

Second, exploratory models may feature in *proofs-of-principle demonstrations* where they may establish that a certain approach can generate representations of a target or that specific mechanisms or processes can exhibit the sort of behaviour that is associated with the target. For example, the significance of the Lotka-Volterra model of dynamical interaction between predator and prey populations does not rely on making empirically adequate predictions about the dynamic interaction of any real populations. Instead, the model opens up a new way of mathematically modelling the dynamic interaction of populations.

[4] Gelfert is here quoting Maxwell (1890, 159).

Third, exploratory models may help us *devise potential explanations* by 'envisaging scenarios that, if true, would give rise to the kinds of phenomena that constitute the explanandum' (Gelfert 2016, 87). For example, Maxwell's mechanical model of the aether helped him to explore the physical geometry of magnetic lines of force by imagining a sea of molecular vortices of aether and ordinary matter.

Fourth, some models may lead to *assessing the suitability of a target*. That is, sometimes models can be explored to identify a target. This happens when knowledge of the target is still largely incomplete and the model itself serves to explore and identify a particular target.

3. Three main concerns with Gelfert's notion of exploratory models

I have three main concerns with Gelfert's notion of exploratory model. First, the analogy between exploratory experiments and exploratory models is only a starting point and more work is needed to understand how important it really is to carve out a notion of specific exploration as a function of exploratory models. The key to the analogy is the idea that exploratory experiments are performed and exploratory models are developed in the absence of a mature theory of the phenomena under investigation. This, however, is quite vague. To what extent can the analogy be further developed? Are there any more similarities between exploratory experiments and exploratory models?

Gelfert remarks that extending the sort of considerations made about exploratory experiments to exploratory models is not straightforward. For example, he submits that the sort of exploratory strategies involved in exploratory experimenting may not be equally interesting and informative in the case of modelling. He reports that Steinle (1997) includes 'varying a large number of different experimental parameters' as one of the main exploratory strategies involved in exploratory experiments. But he claims that 'variation of experimental parameters requires skills and, when successful, constitutes a great achievement' (ibid., 79), while variation of parameters in the case of mathematical models involving polynomial equations 'may come too cheaply' and would be '*exploratory* at best in a generic sense' (ibid., 79, author's original emphasis). But why is it important how difficult any particular strategy is in order to characterize it as exploratory? Gelfert does not offer any principled reason to attribute the label 'exploratory' only to activities that purportedly require more skills than others.

This brings me to my second concern. Gelfert's use of the term 'exploratory model' seems to be at odds with the way in which the term is used within the practice of modelling. Some modellers use it to characterise highly complex mathematical models involving exactly the sort of variation of parameters that Gelfert dismisses as too cheap to count as genuinely exploratory. For example, in a paper called 'From lamprey to salamander: an exploratory modeling study on the architecture of the spinal locomotor networks in the salamander', Bicanski et al. (2013) present a computational model based on the high-level similarity between the salamander and lamprey mode of swimming (anguilliform swinging). The model involves taking an established empirically grounded model of the lamprey locomotor network and exploring which neuronal parameters (such as strength of ionic currency and calcium inflow and decay rates) need to be changed or added to account for salamander's specific biological data. The use of the term 'exploratory' in this context does not seem to be generic but rather specific to the particular computational modelling strategy involved in this area of investigation.

What other strategies used in the oractice of modelling are specifically exploratory? I do not have an answer to this question. But, presumably, a preliminary taxonomy should emerge from careful consideration of the strategies involved in what scientists themselves call exploratory models. Their uses of the term 'exploratory model' may be in need of regimentation. Perhaps some use the term in one way while others use it in another. The work of the philosopher would then be that of observing how scientists think and talk about exploratory models with the aim of discerning certain underlying features, including background epistemic conditions such as lack of a mature theory of the phenomena under investigation, exploratory strategies such as the variation of parameters in a mathematical model, specific purpose of enquiry such as investigating the possible consequences of certain phenomena (I'll come to this below), and possibly more.

Third, Gelfert's characterisation of exploratory models is too narrow. Others have already used the expression 'exploratory model' when reflecting on certain uses of models in areas such as engineering, management and policy analysis. For example, Bankes (1993) distinguishes between two different uses of computer modelling for policy analysis in complex systems such as economic forecasting, global climate change, and military procurement, which he calls *consolidative modelling* and *exploratory modelling*. Consolidative modelling consists in 'building a model by consolidating known facts into a single package and then using it as a surrogate for the actual system' (ibid., 435). The consolidative approach serves the aim of integrating and improving our understanding of the behaviour of complex systems when sufficient information is available. Exploratory modelling, on the contrary, is performed when 'insufficient knowledge or unresolvable uncertainties preclude building a surrogate for the target system' (ibid.). On this interpretation, exploratory models are developed when there isn't enough critical information and data about the phenomena under investigation. In this case, the modeller 'must make guesses at details and mechanisms' and thereby build a model which 'does provide a computational experiment that reveals how the world would behave if the various guesses were correct' (ibid.).

Bankes' characterisation of exploratory models can include Gelfert's characterisation. Exploratory models, on Bankes' account, are characterised in terms of different sorts of missing knowledge of the phenomena under investigation. More specifically, exploratory models are models that cannot be validated experimentally because, for example, experiments cannot be carried out, historical data are incomplete, and inherent uncertainty or the absence of a mature theory do not allow making predictions. Therefore Bankes' notion is broader than Gelfert's notion, but presumably the latter characterizes one species of exploratory models among others. In other owords, the analogy with exploratory experiments may carve out a notion that is too narrow to capture the wider range of types of exploratory models that is captured by Bankes' notion.

The upshot of this discussion is that the analogy between exploratory experiments and exploratory models constitutes an original contribution to the contemporary debate on scientific models. Yet, far more work is needed to understand what the analogy really amounts to. Gelfert does not look at the ways in which scientists use the expression 'exploratory model' and dismisses certain examples of exploratory strategies without providing any good reason. And his original notion seems to be too restrictive in that it excludes several examples of exploratory models that are not characterised in terms of the analogy with exploratory experiments. This calls for a development of the notion of exploratory models that pays attention to scientific practice and identifies certain relevant features of what scientists themselves call 'exploratory models', if and when they do so.

5. Conclusions

Overall Gelfert's book presents an informative introduction to the main issues discussed in the contemporary debate on models that both experts and novices may find useful. Furthermore, Gelfert advances a genuinely new notion of exploratory models that deserves to be further studied.

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