24
SCIENTIFIC MODELS AND THOUGHT EXPERIMENTS

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1. Introduction

Thought experiments (TEs) and models are devices at the heart of modern science with a history of usage long predating their modern names. They are created, interpreted, reinterpreted, published in research, and used in pedagogy. It is possible to tell the whole story of science via either of them.

Recently, philosophers have been drawing attention to their similarities. El Skaf and Imbert (2013) argue that in some cases TEs and (computational) models could be treated as functionally, but not epistemically, substitutable. Arcangeli (2018) distinguishes between the different processes of mental simulation that play a role in TEs and computer simulations, which she understands as implemented models. Salis and Frigg (2020) argue that the same fictionalist epistemological framework can be applied to TEs and models insofar as they employ the same kind of imagination. Stuart (2022) also categorizes TEs and models together by putting them under the same consequentialist epistemological framework.

The above contributions highlight similarities and differences between TEs and models, but there is still much more to be said about this connection. Following Frigg and Hartmann (2020), the discussion in this entry is divided into three categories: ontology, semantics, and epistemology. In each category, the relevant work on TEs and models is summarized, pointing out cases where insights about one kind of device can be extended to the other. It will also turn out that a sharp separation between ontology, semantics, and epistemology can only be achieved with lots of gymnastics, seeing that each is informed by and builds on the others.

2. Ontology

2.1 Scientific models

What, exactly, are models? A popular option for discussing them is pluralism: i.e., models are not one single kind of thing (Callender and Cohen 2006; Suárez 2004; Swoyer 1991). So, what are the different kinds of models?

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Some models are material; they can be found in the world, not (just) in the mind. Some material models are scale models, e.g., a model of a ship in water. Some material models are used expressly because of the material similarities between model and target. However, others share almost no relevant material properties with their targets, like Watson and Crick's model of DNA, which was made of metal sheets, rods, and clamps, not nucleotides. In some cases, destroying some particular material construction would also destroy the model. For example, destroying a scale model of an airplane destroys that model. In other cases, destroying a specific material token would not destroy the model because the model is a *type*: destroying a particular fruit fly would not destroy drosophila as a model organism, though destroying *all* drosophila might.

Models can also be non-material. One important starting point when analyzing non-material models is to differentiate between model descriptions and model systems. It is the *model description* that we find in textbooks and papers, typically in the form of equations, text, or code. These descriptions define, specify, or constrain the *model system*. For example, there are simple population growth models in ecology that are given by the logistic equation. In such cases, the model system is the population whose growth is described by that equation. But what is such a population? More generally, what are model systems?

There are many possibilities. They might be Meinongian (or neo-Meinongian) objects, possible objects, abstract entities (Giere 1988), Platonic forms, set-theoretic structures (da Costa and French 2003), abstract cultural artifacts (Thomasson 2020), imagined concrete objects (Godfrey-Smith 2006), or entities that only exist inside a fiction. This last option, fictionalism, is now quite popular. It is really a family of different views, many of which are based on Walton's (1990) pretense theory of fiction. Briefly stated, the idea is that models involve model descriptions, which prescribe that certain model systems are to be imagined as described. This has typically been an anti-realist position, in that model systems only live in scientists' imaginations (Fine 1998; Frigg 2010). In any case, there are two variants of fictionalism that are importantly different with respect to ontology. The first commits itself only to model descriptions and denies the existence of model systems (Levy 2012; Toon 2012). The second commits itself ontologically to both model descriptions and model systems. Salis' "new fiction view" draws on both by reconceptualizing models as "complex objects constituted by model-descriptions and model-contents" (Salis 2021).

Finally, there is an "artifactualist" approach, according to which models are human-made tools that fulfill certain purposes (Knuuttila 2011; 2017; 2021; Sanches de Oliveira 2021; 2022; Parker 2020). On this kind of view, a model could be either abstract or concrete. What makes it the thing it is, is its purpose or function. The most radical version of this approach (Sanches de Oliveira 2022) denies that non-material models exist. This kind of artifactualist provides a unified deflationist answer to the ontology of models: all models are (just) material tools. Less radical artifactualists are open to non-material "representational modes," but remain committed to the materiality of "representational media" (Knuuttila 2011). This kind of artifactualism continues to portray models primarily as epistemic tools, but allows that those tools can be partially non-material. In either case, identifying models with tools only pushes back the ontological question, until we know what tools are.

2.2 Scientific thought experiments

One interesting difference between TEs and models is that ontological issues have not historically played much of a role in discussions of TEs. Given this, metaphysical views about

TEs tend to remain implicit. Another difference is that ontological views about TEs tend to be less pluralistic than views about models.

What are TEs? According to the argument view, pioneered by John D. Norton, TEs are just picturesque arguments (Norton 1991). While equating TEs with arguments is clearly an ontological claim, this move is not typically characterized ontologically. But it could be. We tend to think of arguments as being "made of" inferences and propositions. What are propositions? There is a long history of debate about this, with positions ranging from Fregean thoughts, senses of (declarative) sentences, predicated subjects, "pictures" of the world, sets of possible worlds, properties, and abstract mind-independent entities (King 2017). What are inferences? Norton does not want to say that these are mental actions (Norton 2021, 20). Instead, inferences seem to be something like a *rule* (when the argument is deductive) that describes a logical connection, or a transformation of propositions, or a *fact* (when the argument is inductive) that licenses an expansion of the domain of reference. Thus, for Norton, deductive TEs appear to be hylomorphic duos of form and content (Stuart 2020, El Skaf 2021), while inductive TEs can perhaps be reduced entirely to facts (Stuart 2020).

Another monolithic ontology is extractable from the "mental models account" of TEs (Miščević 1992; Nersessian 1992, 2007). The main thing to note here is that TEs are portrayed not as facts, rules, or propositions, but rather as a combination of mental states and processes, including mental actions. "Mental model" is a term of art taken from psychology and cognitive science, and it refers to a structure in the mind. Different accounts adopt different definitions of what mental models are, but they all share several common ideas: TEs have a narrative form that enables us to construct, and reason upon, mental models. Instead of focusing on the TE itself, the focus shifts to *reasoning through a TE*, which is a non-propositional *activity* aimed at building and manipulating mental models and "seeing" what happens in those models. The ontology of this account is the ontology of (mental) action, beliefs, knowledge, memory, imagination, and imagery.

A third option is to portray TEs as actual experiments (Sorensen 1992; Buzzoni 2008; Stuart 2016b). But what is an experiment? It seems there are at least two options: an experiment is a set of actions that people perform, or it is a set of instructions for actions that people *could* perform. TEs can be interpreted as experiments in either way. On these views, then, the ontology of TEs plausibly reduces to the ontology of actions, or of instructions. Focusing on actions, many thorny problems arise, concerning, e.g., how to differentiate between actions and events, how actions relate to intentions, whether an action is the same under different descriptions (e.g., the moving of a trigger finger vs. the firing of a gun vs. the killing of a person), and whether actions exist in space-time and if so how to say where and when an action begins/ends. Focusing on instructions, different options exist, e.g., depending on how we characterize the "could" in "instructions for actions that people *could* perform." Specifically, should we require (or expect) that the scenario of a good scientific TE will *not* include instructions for actions that are theoretically/nomologically impossible or indeterminate? If that is a necessary criterion for TEs to be portrayed as (a limiting case of) actual experiments, then it seems that some interesting case studies can not be counted as "successful" TEs (El Skaf 2017).

A fourth option is akin to the artifactualist and deflationist approaches to models, in which we define TEs by their function or purpose. For more details on these functions, see Section 4.2.

A fifth option is to adopt a fictionalist view of TEs (Meynell 2014; Salis and Frigg 2020; Sartori 2023). As with fictionalism about models, these accounts adopt Kendall Walton's pretense view such that TEs are real-world props (e.g., some text on a page), which, in combination with implicit and explicit rules, prescribe imaginings in a game of make believe.

2.3 Similarities, differences, and new possibilities

Accounts of the ontology of models and TEs overlap considerably. For example, Norton's argument view of TEs mirrors views about models that portray them as sets of inferences (Beisbart 2018; Suárez 2004). There are also fictionalist views of both models and TEs, and while there are no explicitly artifactualist accounts of TEs, many authors do treat TEs as epistemic tools in a way that accords with artifactualism about models.

However, there are also some important differences. In the literature on models, ontological pluralism was accepted relatively quickly: there are different kinds of models, which are "made of" different kinds of stuff. The literature on TEs seems to be more essentialist: whatever TEs are, they are all "made of" the same kind of thing (e.g., arguments, mental actions, fictions) or they are a single thing with a blurry definition (McComb 2013). Perhaps this is because there is more inherent variety among models or less among TEs. But arguments would have to be given to substantiate such a claim.

We also note that while there are material models, there are no material TEs. TEs can become "real" experiments when actualized, but models remain models whether they are material or non-material. Also, models can be quite general (e.g., a mere analogy or calculation device), while TEs seem always to focus on specific particular situations.

Comparing the views on models and TEs can be helpful for inspiring a number of potentially interesting new positions. One is applying the (admittedly no-longer very popular) view of models as abstract entities to TEs. Another would be to apply the mental models view of TEs (i.e., that TEs are mental actions on mental structures) to models. On such a view, we downplay the thing-like nature of models in favor of an emphasis on the kinds of mental actions they afford (for a start, see Boesch 2019; Brewer 2001; Nersessian 1999; 2008; 2022). Finally, we could apply the experimentalist view of TEs to models. There are views that are similar to this already, e.g., Morrison (2009) has argued that models can function as measuring instruments and simulating a model in a computer can count as an experimental measurement. However, this only portrays models as important parts of experiments, without yet claiming that models *are* experiments (see Knuuttila and Loettgers 2021 for a discussion of models as experiments).

3. Semantics

There are several ways to think about the semantics of things like models and TEs. We begin by separating two questions: what kinds of things are proper objects of semantic analysis, and what are semantic properties themselves? With respect to the first, we want to keep our options open in order to maximize potentially interesting applications of insights from the philosophy of language. Thus, we will consider words, concepts, sentences, propositions, texts, and actions, as well as models and TEs themselves, as potential carriers of semantic content.

The second issue is about what makes the above entities "semantic," or, in other words, what it means to say that something has meaning or makes reference. This is highly contested, to say the least. We might think of an entity's "meaning" as merely the experiences that gave rise to it (as the early British empiricists allegedly did). One wrinkle here is that many words refer to things that are not experienced, and others to things that could not be experienced. Following Frege, philosophers have tackled this issue by separating an entity's intention/sense/connotation from its extension/reference/denotation. This distinguishes between the more subjective, cognitive significance of an entity, and what it "points to" in the real world, which allows for meaning even in the absence of reference to real-world entities.

What is important for present purposes is that there are many semantic questions we can ask about models and TEs other than how they refer. The reference question is of special interest in light of the epistemic question of how we learn from models. But asking about the semantic content of (parts of) models and TEs can be a fruitful way of analyzing these two scientific tools, beyond the question of how they represent, which is the question we will mainly tackle in the following subsections.

3.1 Scientific models

Different kinds of models and targets exist, be they actual or merely possible, general or particular. So, how do models represent their targets? This has become the main semantic concern in the literature on models, especially since it is taken to solve, among other things, a central (epistemic) problem; that of surrogative reasoning. Surrogative reasoning enables one to draw inferences about the target system based on investigating the model (Swoyer, 1991; El Skaf et al., 2022). Models are thus tools that generate (explanatory, explorative) hypotheses, as well as predictions about target systems, to name a few functions of models. But what surrogate inferences are licensed is an epistemological issue. The semantics underlying epistemic uses of models is usually understood as follows: we (arguably, according to representationalists see Section 4.1) are justified in our surrogative inferences as long as the model represents its target. In addition, models being representational devices could also be understood as an ontological claim (Sanches de Oliveira 2022). In this section, the focus will be only on semantics.

There are different ways to cash out how a model represents its target (for an extensive discussion, see Frigg and Nguyen 2020). One account claims that models represent by stipulative fiat (Callender and Cohen 2006). That is, a model represents whatever a scientist says it does. Another possibility is that a model represents its target in virtue of being relevantly similar, and similar enough, to it (e.g., Giere 1988). There are also structuralist accounts of representation (e.g., da Costa and French 2003; Bueno, French, and Ladyman 2002). On these accounts, models are set-theoretic structures that represent their targets by having (some of) their elements mapped onto elements of the target. These mappings might be monomorphic, isomorphic, homomorphic, or partially isomorphic. There is also an "inferential" view, according to which a model represents its target if its users can draw inferences about that target from the model (see, e.g., Suárez 2004), and an "interpretational" view, according to which a model represents its target if the model is interpreted in terms of that target (Contessa 2007; 2011).

Proponents of the fictionalist accounts of models have also developed theories of scientific representation. Roughly, the postulation of the usefulness of fictional model systems has divided the fictional view into direct representationalism (Toon 2012; Levy 2012; 2015) and indirect representationalism (Frigg and Nguyen, 2016; 2020). The former denies the existence and even the utility of postulating a fictional model system that lives in scientists' imaginations, and argues that the model description prescribes imaginings that are directly about some real-world target, while the latter calls upon a fictional model system to stand between the model description and the target.

The best-developed indirect view is the DEKI account (Frigg and Nguyen 2016; 2020). On this view, what a model is "about" is determined by an act of denotation. This is the

"D" in DEKI (the rest: Exemplification, Keying-up, and Imputation). For material models, the model system is a material entity, but for non-material models, the model system is a fiction. In both cases, the model system represents its target if: it denotes the target, exemplifies certain features, there is a key that associates those features to a new set of features, and at least one of those features in the new set is imputed to the target.

3.2 Scientific thought experiments

It is rare to find an analysis of TEs in terms of representation between a source and a target. There are, however, some exceptions. In the mental models literature, Nersessian (1992) argues that it is the representation relation (usually a structural similarity) between the mental model and the real-world phenomena that does the justificatory work in TEs. And Sartori (2023) applies both Frigg's fictionalist approach to the ontology of models and Frigg and Nguyen's DEKI model of scientific representation to epistemically analyze TEs.

Despite there not being a lot of direct discussion about the semantic properties of TEs, we can extrapolate somewhat. If TEs are arguments, we should equate the semantic content of TEs with the semantic content of their underlying arguments. Norton defines TEs in a way that makes it necessary that they contain imaginative "particulars" which are not relevant to the generality of the conclusion and are thus eliminable from the reconstructed argument (see Norton's elimination thesis in Norton 1991). It is hard to say what "particulars" are in Norton's analysis, but think about experimental details that appear in TEs, such as the material make-up of Galileo's falling bodies, or the details of the weighing procedure in Einstein's photon box. Indeed, in Norton's reconstructions of TEs into arguments, many of these particulars do not appear, and when they do, they are absent from the (more general) conclusion. This makes sense: Norton's claim is an epistemological one, according to which TEs can be reconstructed into arguments without epistemic loss. It is not a semantic claim about what the content of a TE is. Adherents of the argument view can perhaps allow for extra semantic content in the TE that is not in the argument.

If TEs are a kind of real experiment, then their semantic content consists either of actions that could be performed, or they are actions. This makes it hard to say what their semantic content might be. Of course, actions can be interpreted as having semantic content. For example, while driving on a country road at night, someone might flash their car headlights to communicate police presence up ahead. For experiments to have semantic content, they must likewise be performed with a communicative or representational intention. This is possible in some pedagogical contexts, for example, where an experiment demonstrates something to a classroom of students. We think that in the majority of cases, TEs are not performed (merely or mainly) to communicate some definite semantic content, but rather to aid in exploring something from a first-person perspective.

However, Buzzoni adapts the Kantian dictum about concepts and experience to thought and real experiments, such that "TEs without real experiments are empty, and real experiments without TEs are blind" (Buzzoni 2018, 327). TEs are required to give meaning to experience, but they also get their content from previous experience. This point has been extended in an explicitly semantic direction, such that many famous TEs have been reinterpreted as something like Kantian schemata that help scientists and students of science to "fill in" the semantic content of new theoretical structures when they are first introduced (Stuart 2016a; 2017; 2018).

Finally, for a Platonist, we might expect platonic TEs not to have semantic content, given that they are *routes* to knowledge, and routes do not, on their own, have semantic content.

However, for Brown (the main defender of Platonism about TEs), TEs are not *merely* routes. Brown provides two different interpretations of TEs, one wide and one narrow (2007, 158). On the narrow interpretation, the TE is the mental experience we undergo. Here, the TE has the semantic content of the relevant mental states. On the wide interpretation, the TE encompasses the theory and background assumptions, plus the mental experience, and then also the theoretical interpretation of the experience. In this case, the TE has the semantic content of the mental experience but also whatever content the theory, background, and interpretation have.

3.3 Similarities, differences, and new possibilities

It should be possible to extend the work done on the semantic content of TEs to models. For example, if TEs sometimes have semantic aims, perhaps models do as well. In other words, if at least some models are created and used to increase our understanding of the "meaning" of some bit of theory or reality, then we can perhaps explain successful models in the same way that we explain successful TEs that have the same aim—in terms of imaginatively supplying and exploring possible experiences that we would have in a given scenario, drawing on tacit knowledge, background knowledge, and previous experience. Then, rather than judging a model on how well it increases knowledge about a target system, it could be judged in terms of how much useful semantic content it tends to make accessible.

What about going in the other direction? One frequently gets the impression from the literature on models that if we only knew the nature of scientific representation, we would be able to answer all the other questions about models, including about their ontology and epistemology. One does *not* get this impression from the literature on TEs. Why is this? Perhaps one reason is that models were commonly framed as relations between symbols/structures and the world, whereas TEs were seen from the start as arguments or mental activities. Indeed, insofar as the literature on TEs has touched on representation, it is mostly about *mental* representation, instead of scientific representation. Perhaps TEs involve first-personal, subjective mental representations, while models involve or require some kind of intersubjective representation. But whatever the differences, representation *is* part of thought experimentation, and so, perhaps the literature on TEs could benefit from the well-developed discussion on representation in models. For example, the literature on models shows that similarity is not necessarily the best way to understand representation. A mapping account might be preferred, or something like the DEKI account, which was designed to solve issues about representation. For example, Elgin argues that TEs teach us about the world by instantiating features of interest. But a TE cannot really instantiate features like mass or movement, so the instantiation must be "metaphorical." One motivation for the DEKI account was to avoid postulating metaphorical instantiation, and so those working on TEs who are attracted to Elgin's account but want to avoid metaphorical instantiation can perhaps do so by adopting the view of representation we find attached to the DEKI account.

One obstacle to directly applying insights from the representational literature on models to TEs is that representation might not have the same function in TEs and models: that of extrapolating from the model system to some target system. Let us suppose, following El Skaf and Imbert (2013), that both TEs and models are functionally similar, i.e., they both unfold scenarios and arrive at an output. Now, the outputs of TEs seem different from the outputs of models. The former are often propositions like the following: two objects fall both faster and slower (Galileo's falling bodies TE), Maxwell's demon separates fast from slow molecules without expenditure of work, Schrödinger's cat is dead and alive at the same time, Langvin's twin is both younger and older than his brother, the heat of matter lowered from a lab near a black hole could be converted to work with 100% efficiency (Geroch's engine TE), and the total entropy of the universe may have decreased when we throw two cups of tea into a black hole (Wheeler's demon TE). These outputs present apparent inconsistencies (El Skaf 2021; El Skaf and Palacios 2022). Certainly, TEs' narratives represent this and that, but the output does not seem to represent anything real about the world, since the world is (arguably) not inconsistent. This is not what we find with models. In modeling, the output often tends to be a specific claim about the model system, which is then extrapolated – via some theory of scientific representation – as a claim about actual or possible real-world target systems. To see things more clearly, consider Galileo's TE about falling bodies (El Skaf 2018), and "Malileo's" model of the same scenario using classical or relativistic mechanics (Salis and Frigg 2020). Despite unfolding the same sort of scenario, one difference between them is that Malileo's seems designed to produce predictions with precise values of the rate of fall of these and other falling bodies, while Galileo's is not. Another is that Galileo uses the TE to criticize the dominant framework by revealing an inconsistency, while Malileo *applies* the dominant framework.

4. Epistemology

There are three main epistemic issues about models and TEs: (1) Do they produce epistemic good(s)? (2) If so, which? And (3), if so, how? There are interesting similarities and differences between the answers given to these questions in the literatures on models and TEs.

4.1 Scientific models

It is generally agreed that models do provide some epistemic good(s). Even a cursory glance at the history and practice of science shows that models are important, if not central, to scientific progress, and respect for this fact motivates philosophers to accept that models provide some epistemic good(s).

But which epistemic good(s) do they provide? There are a number of ways to answer. For example, Alexandrova (2008) argues that idealized deductive models are best understood as contributing causal hypotheses. Others claim that models produce knowledge about their target systems, but only if the model accurately represents the target and there are no "defeaters" present that would invalidate inferences from the model to the target. For example, a model in economics might cause us to infer that if the price of a commodity increases, demand will decrease. That might be correct, *as long as* the price of competing commodities does not also increase.

Still others focus on the less-obviously epistemic properties of models, for example, their status as a means by which theory can be applied to particular cases (Morgan and Morrison 1999), as a means of theory-building (Hartmann 1995), or as a vehicle of explanations (De Regt 2017). Given the important role of models in explanations, there is also a case to be made that (good) models increase scientific understanding, whether this is in addition to, as part of, or as opposed to, increasing scientific knowledge (Elgin 2017; Dellsén 2020; Potochnik 2017; Sullivan 2022; Stuart and Nersessian 2019). Echoing Section 2, pluralism is generally a popular option, such that some models produce one kind of epistemic good, and others produce others.

In answer to the third question, the philosophical literature on models seems to be roughly divided into two camps: one representational and the other non-representational, with subdivisions in each. In the representational camp, an epistemological account can sometimes be drawn from the details of a given account of representation, and sometimes this is made explicit. For example, proponents of a similarity account can claim that things learned about the model will also hold in the target if the model and target are relevantly similar. Structuralists can claim that things learned about the structure of a model can be extrapolated to the target by means of an appropriate mapping relation. Inferentialists define models as things that license inferences about targets, and the question then becomes one about defining "correct" inferences. Fictionalists have different ways of answering the question, but those who follow Walton's pretense view of fiction will claim that the model is a prop in a game of make believe that we explore while constrained by implicit and explicit rules, to see what is true in the fiction. On the direct view, what is true in the fiction can be true about the target because the fiction was always "about" the target. On the indirect view, what is true in the fiction requires keying up and imputation to the target and can be true about the target depending on how the fiction's features are chosen, interpreted, and keyed up.

The non-representational camp, as we understand it, combines different approaches under the umbrella of artifactualism. They share the idea that an analysis of "scientific models in general will, at best, be limited" (Sanches de Oliveira 2022, 6). The epistemic contribution of models should be assessed on a case-by-case basis. In a series of papers, Knuuttila (2011; 2017; 2021) argues that what and how we can learn from models depends on the way the model is constructed to explore a particular scientific question. This question can be general in nature or address only what is possible or impossible. In line with fictionalist and other indirect representation accounts, Knuuttila distinguishes between internal representation and external representation: what is represented within a model does not yet make the model a representation of some determinable social or natural target system. However, the artifactual account also pays attention to the epistemic affordances of the specific representational modes and media used in model construction.

Parker (2020) also emphasizes the importance of problem-solving. She develops a view of models that evaluates them for their adequacy for a purpose, not in terms of representational accuracy. While this is usually assessed on a case-by-case basis, Parker claims in general "what is required is that the model stands in a suitable relationship with a target, (type of) user, (type of) methodology, (type of) circumstances, and purpose jointly. Put differently, the model must constitute a 'solution' in a kind of problem space" (Parker 2020, 475).

In addition to epistemic concerns about targets, philosophers also raise epistemic questions about how we learn about models themselves. Learning about material models raises questions akin to those of laboratory experiments: we manipulate models, subject them to tests, interpret the results, and so on. Learning about non-material model systems is a different story. It has been suggested (by Frigg and Hartmann 2020) that we learn about some abstract models by doing TEs. On this view, abstract models and TEs are complementary tools: scientists write down the description of a model and use a TE to mentally manipulate the fictional system described. However, other models are more easily unfolded by implementation in a computer simulation. In the case where a model is unfolded by a TE, the epistemology of TEs is part of the epistemology of models. Where a model is unfolded by a computer simulation, the epistemology of simulations is part of the epistemology of models. There are still further ways of thinking about the epistemology of models, e.g., as (or as including) metaphors (Camp 2020; Levy 2020; Stuart and Wilkenfeld 2022), analogies

(Hesse 1966; Nersessian 2015), diagrams (Sheredos and Bechtel 2020), and idealizations (Cassini and Redmond 2021).

4.2 Scientific thought experiments

Like models, TEs are mostly accepted as being epistemically profitable. What sorts of epistemic good(s) do TEs provide? Here, there is just as much pluralism as with models. TEs might generate new knowledge (Brown 2011; Norton 2004; Nersessian 2018; Miščević 2022) or understanding (Brown 2014; Lipton 2009; Murphy 2020a; Stuart 2016a; 2018), new theoretical possibilities (Stuart 2021, El Skaf 2021), reveal and resolve inconsistencies (El Skaf 2021; El Skaf and Palacios 2022; Sorensen 1992; Häggqvist 2009; 2019), give examples, illustrate a claim (Brown 1991; Schabas 2018; Peacock 2018), demonstrate pursuitworthiness (Miller 2002; Šešelja and Straßer 2014; El Skaf 2021), control variables (Sorensen 1992), exemplify features (Elgin 2014), give "hypothetical explanations" (Schlaepfer and Weber 2018), and test a theory's non-empirical virtues (Bokulich 2001).

How do TEs produce the epistemic goods they do? Norton (e.g., 1991; 1996; 2004) argues that TEs can always be reconstructed as deductive or inductive arguments. This means that the new insight that TEs provide depends on the type of argument that underlies the TE. If the argument constructed from a TE is deductive, the TE would just serve to rearrange our existing knowledge without adding any new knowledge. If the argument is inductive, the TE could extend our knowledge to new cases, in the same way as inductive arguments do.

Brown (1991) has defended a different approach. In contrast to Norton, he does not identify TEs with arguments, and provides a detailed taxonomy of the different types of TEs, which are associated with different epistemic functions of TEs, such as constructive, conjectural and "platonic." The most controversial are the platonic TEs, which, according to Brown, can provide us with a priori access to the laws of nature, without the need for any new empirical data. They do this by producing mental phenomena which serve as evidence for claims about connections between universals. If the Dretske-Tooley-Armstrong account of laws of nature is correct that laws of nature are relations between universals, and Brown is correct that TEs give us insights about universals, then platonic TEs are capable of providing us with knowledge of laws of nature.

Defenders of the mental model account of TEs (e.g., Miščević 2022; Nersessian 2018) have rejected the view that the justificatory power of TEs can be reduced to the logical structure of their propositional content and that the experimental details are irrelevant and eliminable. Nersessian, for instance, argues that we acquire new knowledge about the real-world target system by mentally modeling a structural analog of that system and not (only) by mentally reasoning through a set of logically related propositions.

Those who portray TEs as genuine members of the experiment family understand the epistemology of TEs in the same way as the epistemology of experiments. Thus, a TE will be epistemologically good insofar as it meets the conditions of a good experiment, such as Franklin's five criteria (1986): the experimental system must be well-isolated, experimental bias must be eliminated, sources of error must be identified and accounted for, instruments must be calibrated as well as possible, and there should be a theory of our instruments (see Stuart 2016b).

El Skaf (2021) and El Skaf and Palacios (2022) argue that many TEs, both from the history of physics and from ongoing physics such as black hole thermodynamics, aim at revealing and resolving inconsistencies. These two functions have different epistemic forces and are justified differently: while the revelation of the inconsistency could be analyzed as conclusive knowledge, its resolution is only conjectural.

The above epistemological accounts of TEs mostly deal with the question of how TEs produce new knowledge. Different accounts might be necessary to explain how TEs can produce other epistemic goods. For example, Stuart (2018) has argued that TEs are capable of producing all three of the major types of understanding: explanatory, objectual, and practical, and the way they do this might be different in each case.

4.3 Similarities, differences, and new possibilities

One interesting thing to note in comparing the epistemologies of models and TEs is that in both cases, most of the work is offloaded onto accounts of more traditional "ways of knowing," including logical inference, pure reason, metaphor, analogy, representation, experiment, and storytelling. Another point of consilience is that in both literatures, the epistemological issue is usually phrased as concerning how models and TEs produce new knowledge, even though in practice what philosophers discuss is much more varied, and perhaps not all the epistemic goods produced can or should be reduced to knowledge. A third point of agreement is that constraints play a major role in explaining how epistemic goods are generated. These might be reduced to two kinds of constraints: logical constraints on valid reasoning, and representational constraints on accurate reasoning.

Another similarity concerns the use of imagination, which appears to be at the root of both models and TEs (Salis and Frigg 2020; Stuart 2022). This explains the fact that there are fictionalist views about both models and TEs. But it raises the following question: Can imagination produce new knowledge or understanding, or does it only mediate that production? This has been called the question of the "epistemic generativity of imagination" (Miyazono and Tooming 2022), and it will be crucial moving forward to see whether a positive answer can address skepticism about the epistemic power of imagination (for discussion, see, e.g., Kinberg and Levy 2022; Myers 2021; Stuart 2019; 2022).

Nevertheless, there are also interesting differences. Unlike with models, the question of how we can learn *about* TEs is not asked. Perhaps it should be. Also, as we noted in Section 3.3, the literature on TEs has not focused as much on representation as the literature on models. Perhaps some of the insights about representation in models could be used in the case of the epistemology of TEs. Although, if non-representationalists about the epistemology of models are correct, perhaps not.

Interestingly, and contrary to TEs, the epistemological question of how we learn from models was only a derivative concern in the philosophical literature on models, given the large consensus (before artifactualism) that an account of representation is all we need. Put differently, semantics took center stage in the epistemological literature on models, unlike in TEs.

Additionally, scientists often learn about and from models by intervening on them numerically. That is not exactly the case with how scientists engage with TEs: thought experimental scenarios are manipulated by playing around with the theoretical statements or with some qualitative and technical experimental detail, not with numerical values of parameters and variables. Probably this difference explains some of the differences in their respective epistemologies.

Finally, there are tantalizing opportunities for epistemic "cross-pollination" between the literatures. The artifactualist view about models could surely be applied to TEs in more detail. The Kantian, phenomenological (Hopp 2014; Wiltsche 2018), unfolding-based, understanding-based, and experimentalist perspectives on TEs could also be applied to models.

5. Conclusion

This entry has summarized work done on the ontology, semantics, and epistemology of both models and TEs, pointing out similarities and differences, and hinting at new philosophical possibilities. Other comparative lenses could have been taken up as well, such as the aesthetics of models and TEs. Do scientists employ different standards of aesthetic value for these? Are there different ways that aesthetic features relate to non-aesthetic (e.g., semantic or epistemic) features? Another potentially interesting lens is social epistemology: usually, models are team-built, and TEs can also be understood as social uses of imagination (Molinari 2022), even though they are usually conceived by a single scientist. A third lens is ethics. Models play a key role in justifying scientific claims, which then go on to justify ethically relevant actions, e.g., concerning climate change and pandemic lockdowns. The ethical features of models are gaining attention (Winsberg and Harvard 2022), however, the ethics of TEs is not yet a topic of much discussion (except in jest, see Lerner 2010, Norton 2010). A fourth lens is functional. What functions are common to both, and which are not? Can we find a more general function that both TEs and models all perform? One has been suggested by El Skaf and Imbert, who argue that all tools that unfold scenarios are "composed of functionally similar parts" (2013, 3455). They call the set of these parts a "CUI pattern of inquiry" where this stands for the Construction of a scenario in the context of an inquiry, Unfolding of the scenario, and Interpretation of the result. Thus, instead of focusing on ontological, semantic, or epistemological differences, TEs and models could be pragmatically analyzed as functionally similar in that they share the CUI pattern, and they are both tools that unfold scenarios, though also different in the sense that they often have different kinds of outputs.

Another way to take the discussion further would be to expand what the lenses focus on. We talked about models and TEs, but many scholars have drawn connections between both of these and simulations, and laboratory experiments, analogy, metaphor, and much else. Many who discuss different tools of scientific reasoning discuss two or three of these, but there have been few attempts to bring all their literatures together to find points of resonance and dissonance.

Finally, it could be worthwhile to analyze the underlying cognitive nature of models and TEs to see how they compare. One question concerns what kind of imagination fuels both. Salis and Frigg (2020) argue that we need only talk about *propositional* imagination. This cannot be reconciled with the work of philosophers of mind, who argue that imagination is fundamentally sensory, or imagistic (Kind 2001; Nanay forthcoming). For this and other reasons, Murphy (2020b) argues we should be pluralists about what kind of imagination is relevant for TEs. If correct, this will affect discussions of the epistemology of imagination in both models and TEs.

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