The Fiction View of Models Reloaded

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In this paper we explore the constraints that our preferred account of scientific representation places on the ontology of scientific models. Pace the Direct Representation view associated with Arnon Levy and Adam Toon we argue that scientific models should be thought of as imagined systems, and clarify the relationship between imagination and representation.

1. Introduction

The leading idea of what has become known as the 'fiction view of models' is that scientific models are akin to the objects, characters or places of literary fiction. Different versions of the view locate the analogy in different places and diverge on how it ought to be articulated, but they all depart from the ontological problem of what models are. The idea behind this way of proceeding seems to be that we first have to understand what models are before we can explain how they represent. In this paper we reverse this order of proceeding.

We begin by formulating an account of representation, and to remain neutral as regards fiction our discussion focuses on material models. Using Kendrew's plasticine model of myoglobin, we introduce what we call the DEKI account of representation, named after its key elements: denotation, exemplification, keying up, and imputation (Section 2). Then we ask what in the account would have to change to be carried over to non-material models and derive a set of conditions of adequacy that any ontology of models has to satisfy (Section 3). Meeting some of these conditions is

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costly and so we consider whether Direct Representation, a parsimonious alternative to DEKI, would fit the bill. Our verdict is negative and so we need an account of models that meets the conditions of adequacy (Section 4). We develop such an account using Walton's theory of make-believe and articulate the idea that models are in important ways akin to fiction. In doing so we also put material models into the context of make-believe, which offers a solution to a problem that was left open in Section 2. So combining DEKI with make-believe leads to a comprehensive theory of modelling covering both material and non-material models (Section 5).

2. The DEKI Account of Representation

Proteins are chains of amino acids covalently bonded together by peptide bonds. A description of a protein involves three structural components. A protein's primary structure is the sequence of amino acids. The secondary structure is a description of the three-dimensional form of local segments of the chain (a common example is an α-helix: a right handed spiral). The tertiary structure is a description of how the entire chain is arranged in three-dimensional space.[2] The chemical and physical properties of a protein depend on all three structures.

Determining tertiary structure of proteins is a difficult task, and its successful completion in the case of myoglobin, a globular protein smaller than haemoglobin that is found in many animal cells, won John Kendrew (along with Max Perutz) the 1962 Nobel Prize in chemistry. Kendrew's investigation contained two important elements. Firstly, through the process of X-ray diffraction and complex calculations on the results, he and his team in the Cavendish Laboratory at the University of Cambridge were able to determine the electron density throughout the molecule. Second, Kendrew built a physical model of myoglobin. The model consisted of a series of vertical supporting rods (like a bed of nails with very long nails) on which

[2] Molecules made up of multiple polypeptide chains have a quaternary structure as well.

was stuck a rope of plasticine, which twisted, turned, and folded back on itself.[3] The rods held the rope in place and the spatial arrangement of the rope represented the tertiary structure of myoglobin with a resolution of 6Å.[4]

The rope model was constructed on the basis of electron density data. But it wasn't simply a summary of these data, or a tool to communicate effectively the information the data contained. The model provided epistemic access to the tertiary structure of the molecule in a way that the electron density data alone could not (de Chadarevian 2004, 344). On the basis of the model Kendrew was able to ascertain that myoglobin folded to form a flat disk of dimensions about 43Å x 35Å x 23Å, that the chains within the disk turn at large angles, that neighbouring chains lie 8-10 Å apart, that the molecule consists of two layers of chains, and so on (Kendrew et al. 1958, 665).

In virtue of what does the rope model – a system of rods and a folded rope of plasticine – represent myoglobin, a protein molecule found in muscle tissue? And what is it about the model that allows us to learn about myoglobin by investigating the model? The answer to these questions, we submit, lies in the notion of *representation-as*. Representation-as involves a vehicle, *X*, representing a target system, *Y,* as a *Z*. A famous caricature (*X*) represents Churchill (*Y*) as a bulldog (*Z*), and an iconic scene (*X*) of the movie *Pink Floyd - The Wall* represents schools (*Y*) as sausage grinders (*Z*). In our example, the plasticine rope (*X*) represents myoglobin (*Y*) as a folded chain of amino acids (*Z*). The DEKI account explains what these three elements are and how they interact. The account builds on the analysis of pictorial representation-as by Goodman and Elgin, and extends that analysis to scientific models.[5]

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[3] Thinking about the model is greatly aided by looking a picture of it. See de Chadarevian (2004) or image 10321094 in the London Science museum image bank. The model is occasionally referred to as Kendrew's 'sausage' model. We prefer the term 'rope' to 'sausage' since it more accurately describes the model's shape.

[4] Ångström (Å) is unit of length used in chemistry, where 1Å = 10^{-10}m.

[5] Goodman and Elgin's discussions of representation-as can be found in Goodman (1976) and Elgin (1983; 1996; 2004; 2007; 2010). See Frigg and Nguyen (forthcoming; m.s) for our account.

In order to understand representation-as we first have to introduce the concept of *Z*-representation and offer a definition of a model. Goodman and Elgin emphasise the distinction between something being a representation-of a *Z*, and something being a *Z*-representation.[6] A painting of a unicorn is a unicorn-representation because it shows a unicorn, but it is not a representation of a unicorn because there are no unicorns. Being a *Z*-representation is a one-place predicate that categorises representations according to their subject matter, being a representation-of is a binary relation that holds between a symbol and that which it denotes. The two can but need not coincide. Some dog-representations are representations-of a dog. But not every dog-representation is representation-of a dog (like the Churchill caricature) and not every representation-of a dog is a dog-representation (like the lightening bolt that is a representation-of the fastest greyhound at the races).

This raises the question of what turns something into a *Z*-representation. The answer to this question lies in the notion of *interpretation*. The vehicle of a representation is, first and foremost, an object, with an associated set of properties: being such and such a size, being made out of such and such materials, and so on. These vehicles' material constitutions matter and so we introduce a term of art to refer to them; we can call them *O*-objects. As used here, '*O*' is simply a specification of what kind of thing an object is.[7] Derivatively we speak of *O*-properties to designate properties that *X* has qua *O*-object. In our example the *O* is plasticine-around-rods-object with *O*-properties such as not forming knots and bending at certain angles.

An *O*-object becomes a *Z*-representation if the *O*-properties are *interpreted* in terms of *Z*-properties. Let $\mathcal{O} = \{O_1,...,O_n\}$ and $\mathcal{Z} = \{Z_1,...,Z_n\}$ be sets of relevant *O*-

[6] Throughout this paper we sacrifice grammatical precision by using 'representation-of' rather than 'representation of' to clearly distinguish between different uses of the term 'representation'.

[7] *X* does not uniquely determine *O*. Kendrew's rope could also be described as a calcium-salt-and-petroleum-jelly-object, as a post-war-production-object, or as a registered-trademark-product-object. Any property (or set of properties) instantiated by *X* could ground *O*. There is also no expectation that *O* be a natural kind.

properties. An Interpretation *I* is a bijective function $I : \mathcal{O} \rightarrow \mathcal{Z}$.[8] The plasticine rope becomes a protein-representation by mapping plasticine-rope-properties onto protein-properties: we associate the rope with the amino chain, the shape of the rope with the shape of the amino chain, and so on. We therefore say that a *Z-representation* is a pair $\langle X, I \rangle$, where X is an *O*-object, and *I* is an interpretation.

We now identify scientific models with *Z*-representations in the following manner: a *model* is a *Z*-representation where *X* is an *O*-object that is used as the vehicle of the model in a certain context (either due to convention or the stipulation of a scientist, or group thereof) and *I* is an interpretation. We then write $M = \langle X, I \rangle$ and also speak of a *Z*-model. So the plasticine-on-sticks-system becomes a protein-model when endowed with an interpretation.

It is a deliberate choice that this definition of a model contains no reference to a target system. There are models that don't have target systems, and therefore we should distinguish between the notions of being a scientific model and being a scientific representation. Some *Z*-models are also representations of a *Z*, others aren't. Kendrew's protein-model is also representation-of protein. Maxwell's aether-model is not a representation-of aether, but it is an aether-representation nevertheless.

Exemplification is a mode of reference that occurs when an object refers to a property it instantiates. This is established relative to a context. We can define it as follows: *X* exemplifies *P* in a certain context *C* iff *X* instantiates *P* and the context highlights a property, where a property is highlighted if it is identified in the context as relevant and epistemically accessible to users of *X*. An item that exemplifies a property is an *exemplar*. Consider, for example, a sample of granite you see in a kitchen showroom. The sample instantiates the specific colour of the stone, and the context highlights this property. Instantiation is therefore a necessary condition for

[8] If an *O*-property is quantitative (for instance, being *x* m long or being curved by α degrees), the interpretation also contains a function associating the values of the *O*-property with the values of the corresponding *Z*-property. In simple cases these functions are just scale transformations.

exemplification. But the converse does not hold: not every property that is instantiated is also exemplified. Exemplification is selective. The sample block exemplifies being made out of granite, but not rectangularity, being six inches long, and being stored next to the Corian sample, even though it instantiates all these properties. Only selected properties are exemplified, and which properties are selected depends on the context.

Models are *Z*-representations and so we want them to be able to exemplify *Z*-properties. Our model is a myoglobin-representation which we take to exemplify properties like forming a flat disk of dimensions about 43Å×35Å×23Å. But the properties in the codomain of the interpretation aren't instantiated and hence cannot be exemplified whenever $\mathcal{O} \neq \mathcal{Z}$. To fix this problem we introduce the notion of *I*-instantiation: $M = \langle X, I \rangle$ *I*-instantiates a *Z*-property *P* iff *X* instantiates *O*-property *P*' and *P*' is mapped onto *P* under *I*. This allows a model to *I*-instantiate properties that it does not instantiate. As a consequence, when we say that a model has property *P* we say something that is not genuinely true (because *X* does not instantiate *P*). The notion of *I*-instantiation and the associated notion of 'truth under an interpretation' need some unpacking, and we come back to this issue in Section 5 where we offer an account of these notions in terms of make-believe. For now we can think of it in terms of the association of properties with each other without detriment. We can now say that a model *I*-exemplifies properties that it *I*-instantiates and that have been highlighted in the context under consideration.

Equipped with this definition of a model we now analyse the notion of representation-as in a scientific context. For a model to represent a target as *Z* two further conditions have to hold. The first is that the model *denote* its target system. Denotation is the core of representation. It establishes representation-of. Nevertheless it is only necessary and not sufficient for representation-as. Denotation does not explain how *M* can be used to learn about *T*, but it is a hallmark feature of models that if they represent a target, they do so in a way that allows us to perform formulate claims about the target based on the model.

This is where the second condition comes into play. The basic idea is that properties *I*-exemplified by the model are *imputed* onto the target. Imputation can be analysed in terms of stipulation. The model user may simply stipulate that the *I*-exemplified properties hold in the target system, and this is what establishes that the model represents the target as having those properties.

But the properties imputed are rarely *exactly* those *I*-exemplified by the model. The model could, for instance, *I*-exemplify being frictionless, but the property imputed to the target is something like 'having sufficiently low friction to be negligible in the current context'. In some cases the imputed properties could diverge significantly from those *I*-exemplified by the model. It is therefore crucial that the relation between them is articulated with precision. For this reason we build an explicit specification of how the *I*-exemplified properties are related to properties imputed into our account of scientific representation by means of a 'key'. Let $P_1, \ldots, P_n$ be the *Z*-properties *I*-exemplified by the model, and let $Q_1, \ldots, Q_m$ be the properties that the model imputes to *T* (*n* and *m* are positive natural numbers which can but need not be equal). Then the representation must come with a key *K* specifying how exactly $P_1, \ldots, P_n$ are converted into $Q_1, \ldots, Q_m$. Borrowing notation from algebra we can write the key as a function K taking *I*-exemplified properties as arguments and mapping them onto to-be-imputed properties: $K(\{P_1, ..., P_n\}) = \{Q_1, ..., Q_m\}$.

In the case of the plasticine model, the key allows some flexibility between the properties directly *I*-exemplified by the protein model and those that are imputed onto Myoglobin itself. Although the plasticine rope in the model is a rope of uniform width throughout the model, Kendrew explicitly imputed a different property onto the molecule "as it is at corners that the chain must lose the tightly packed configuration that makes it visible at this resolution" and proposed that perhaps 70% of the chain was an α-helix whilst the rest was fully extended (Kendrew et al. 1960, 665). Likewise, it is unlikely that Kendrew was confident that the 43Å×35Å×23Å dimensions *exactly* corresponded to the dimensions of the molecule. There were clear margins for error in the process leading to the construction of the molecule, so it is more likely that something like 'being a flat disk of 43Å±10%×35Å±10%×23Å±10% dimensions' was imputed.

Gathering together the pieces we have discussed yields the DEKI account of representation: Let $M = \langle X, I \rangle$ be a model, where *X* is an *O*-object that serves as the vehicle of the model and I is an interpretation. Let *T* be the target system. *M* represents *T* as *Z* iff all of the following conditions are satisfied:

(i) *M* denotes *T* (and in some cases parts of *M* denote parts of *T*).

(ii) *M I*-exemplifies Z-properties $P_1, ..., P_n$.

(iii) *M* comes with key *K* associating the set $\{P_1, ..., P_n\}$ with a set of properties $\{Q_1, ..., Q_m\}$: $K(\{P_1, ..., P_n\}) = \{Q_1, ..., Q_m\}$

(iv) *M* imputes at least one of the $\{Q_1, ..., Q_m\}$ to *T*.

Figure 1 demonstrates how the various aspects of the account fit together.

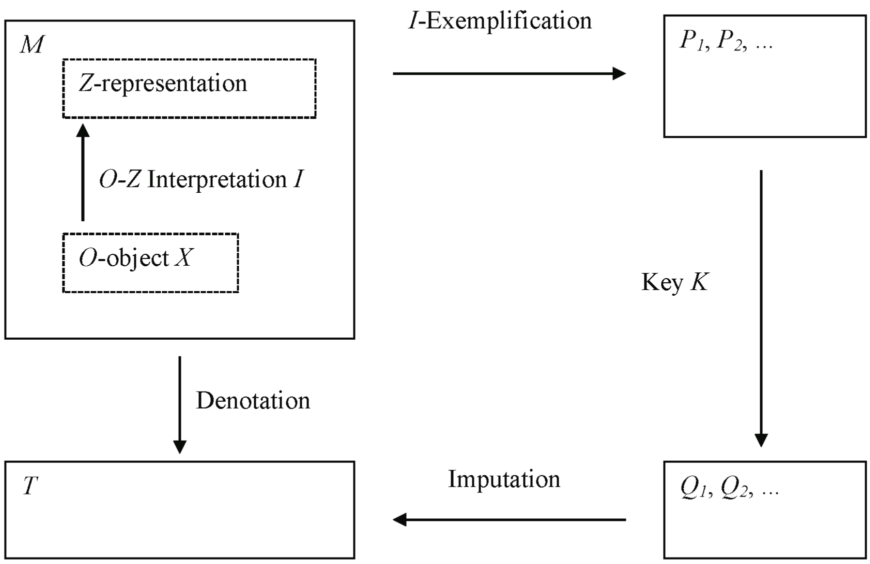

Figure 1 – The DEKI account of representation

The account owes its name to the key ingredients: denotation, exemplification, keying up, imputation. Understanding how these conditions are met in the case of the plasticine model illustrates how our account works. *X* is a plasticine-on-sticks object (*O*), which is endowed with an interpretation *I* associating plasticine-properties with-protein properties. *X* and *I* together form a protein-model. The model denotes myoglobin, which makes it a representation-of myoglobin. The model also *I*-exemplifies protein properties in virtue of the research context highlighting them, for instance consisting of two layers of chains (P_1), forming a flat disk of dimensions about 43Å x 35Å x 23Å (P_2), and having a uniform configuration throughout (P_3). These properties are related to other properties with key *K*: identity in case of P_1, applying with a tolerance threshold of around 10% in the case of P_2 and only applying to straight lengths of the polypeptide chain in the case of P_3. So the model imputes consisting of two layers of chains (Q_1); being a flat disk of dimensions 43Å±10%×35Å±10%×23Å±10% (Q_2); and having a uniform configuration in only 70% of the chain (Q_3) to the target *T*. These conditions establish how the hose model (*M*), represents myoglobin (*T*), as being a protein with such and such a tertiary structure (*Z*).

3. From Plasticine Ropes to Immortal Rabbits

The DEKI account explains how a material object becomes a model and how a model represents a target system. The explanation it offers makes use of the material constitution of the vehicle *X* in that *X* is said to instantiate properties, and these properties are crucial to generate knowledge about the target. But DEKI is not the only account of representation to emphasise the objectual character of models. When introducing the DDI account of representation, Hughes observes that a model is a "secondary object that has, so to speak, a life of its own" and that "the representation has an internal dynamic whose effects we can examine" (1997, 331), and Weisberg (2007) sees the introduction of a model system that is distinct from the target as one of the defining aspects of the practice of modelling.

As long as models are material objects this is unproblematic. But many scientific models are not material objects. Newton's model of the sun-earth system consists of two perfect spheres with a homogeneous mass distribution gravitationally interacting with each other but nothing else; Fibonacci's model of a population consists of immortal rabbits reproducing indefinitely at a constant rate living in an environment that places no restrictions on either food or space; and when studying the exchange of goods, economists consider situations with only two goods, two perfectly rational agents, no restrictions on available information, no transaction costs, no money, and immediate transactions. These are not physical objects. Hacking says that they are things that "one holds in one's head, rather than one's hands" (1983, 216), and Thomson-Jones calls them "missing systems" (2010).

The tension is now apparent: how can a missing system, or something you hold in your head rather than your hands, instantiate properties, and what does it mean to say that it has an internal dynamics that we can study? We follow Thomson-Jones and call vehicles of this kind 'non-concrete' (2012, 762). The negative characterisation is deliberate because at this point we want to remain non-committal and leave it open what kind of things such vehicles are, or, indeed, whether they are things at all.

A discussion about the nature of non-concrete vehicles must begin by getting clear on what exactly is required to get the DEKI account off the ground,[9] and we should avoid hasty ontological over-commitment (indeed, as we shall see below, there are ways of meeting these requirements without committing to the existence of objects). We think there are at least eight constraints that the DEKI account places on vehicles.

Identity conditions. Different authors can present the same vehicle in different ways. This means that we need to know under what conditions they are talking about the same vehicle, and this requires identity conditions.

[9] Similar questions can also be asked about other accounts of representation, in particular about accounts like Giere's (1988; 2004; 2010), Mäki's (2009; 2011), and Weisberg's (2012; 2013), which require models to be the sorts of things that can be similar to their targets.

Property attribution. The above formulation of DEKI rests on the notion that vehicle instantiates properties. This need not be understood literally: it is in fact not necessary that a vehicle *physically* instantiates properties. It is necessary, however, that properties can be attributed to a vehicle. Statements of the form 'the vehicle has property *P*' must be meaningful. The challenge is to give an analysis of such statements that is compatible with one's other commitments.

Truth about vehicles. In the case of concrete models claims about the vehicle are true or false in the same way in which claims about ordinary physical objects are true or false. What plays the role of truth and falsity in the case of non-concrete vehicles? It is crucial to DEKI that there is right and wrong about a vehicle, but on what basis are claims about vehicles classified as right or wrong if the claims concern non-concrete vehicles? What we need is an account of truth about vehicles, which, first, explains what it means for a claim about a vehicle to be true or false and which, second, draws the line between true and false statements at the right place.

Epistemology. The truths about model systems cannot be inaccessible to us. We need an epistemology that explains how do we find out about these truths, and how do we justify our claims about vehicles.

Highlighting. Models must be able to exemplify properties. This does not only require that they instantiate them, it requires that they do so in such a way that they are selected as relevant in the research context, and more importantly, in a way that makes them epistemically accessible. How do models allow us access to their properties in this way?

Denotation. In order for a model to represent a target system, it must denote it. Standardly denotation is understood as the relation between a symbol and an object, where a symbol is a material object (a mark on paper or a painting, for instance). How can non-concrete objects denote concrete target systems?

Comparative statements. Comparing a model system and its target is essential to many aspects of modelling. We customarily say things like 'the surface of the real sun is unlike the surface of the model sun', and a representation's key compares exemplified properties with properties to be imputed onto a real target system. But how can we compare something non-concrete with a concrete target? Likewise, we also compare models with other models, and so we would like an account of comparative statements to covers model comparisons as well.

Applicability of mathematics. Many models are mathematized, and mathematics plays a prominent role in many modelling projects. How are we to make sense of the contribution that mathematics makes to scientific representation?

4. Getting Started on the Wrong Foot?

The list of issues in the last section is no small feat. Addressing these challenges gets us into discussions of abstract objects, fictional characters, the metaphysics of properties, the nature of mathematical entities, and a number of other unfathomable problems. So one might argue that we got started on the wrong foot and should rework the notion of representation in a way that avoids these problems.

This is the project of Toon (2010; 2010; 2012) and Levy (2012; 2015). Toon labels accounts like DEKI, which posit a representational vehicle that is distinct from the target, as *indirect views* of representation (2012, 43) and contrasts them with what he calls the *direct view*. On the direct view there are no vehicles and indeed no models. Instead, modelling consists in providing an "imaginative description of real things" (Levy 2012, 741).

Toon and Levy articulate this basic idea within the framework of Walton's (1990) theory of make-believe (MB). At the heart of this theory is the notion of a game of make-believe. The simplest examples of these games are children's plays (*ibid*., 11). In one such play we imagine that stumps are bears and if we spot a stump we imagine that we spot a bear. In Walton's terminology the stumps are *props*, and the rule that we imagine a bear when we see a stump is a *principle of generation*. Together a prop and principle of generation prescribe what is to be imagined. If a proposition is prescribed to be imagined in a game of make believe, then it is *fictional* in the relevant game. Hence fictionality in this sense is what is often called 'truth in fiction'.

Two kinds of props are important in the current context. The first are artistic objects like statues. A statue showing Napoleon on horseback is a prop that mandates certain imaginings about Napoleon (Toon 2012, 37). The second are texts of literary fiction. When reading *The War of the Worlds* (*ibid*., 39), the text together with certain principles of generation prescribes us to imagine that the dome of St Paul's Cathedral has been attacked by aliens and now has a gaping hole on its western side.

The crucial move now is to say that models are props in games of make believe. Material models are like the statue of Napoleon (*ibid*., 37). Kendrew's plasticine rope is a prop in a game of make-believe prescribing those involved in the game to imagine certain things about myoglobin. Non-concrete models are like the text of *The War of the Worlds*: they are descriptions that mandate the reader to imagine certain things about the target system (*ibid*., 39-40). A model of the ideal pendulum, for instance, is a description that prescribes us to imagine that the target, the real ball and spring system we have in front of us, is exactly as the text presents it: we have to imagine the spring as perfectly elastic and the bob as a point mass. Using Toon's own terminology we call this account *Direct Representation*.

This account is more parsimonious than DEKI. Representation is explained in terms of there being the prescription to imagine certain things about the target, thus getting rid of denotation, exemplification and keys. At the same time vehicles, understood as 'secondary systems', are rendered otiose, which dissolves any metaphysical questions about these systems.

There is no austerity programme without casualties, and Direct Representation is no exception. A defining feature of scientific modelling is that models allow us to perform *surrogative reasoning* (*cf.* Swoyer 1991): we can use a model to (attempt to) learn about its target systems. It is unclear how this this is done in Toon's framework. Imagining that a target has a certain feature tells us nothing about whether or not we should import that feature, or some other, onto the target system itself. Imagining the pendulum bob to be a point mass tells us nothing about which, if any, claims about point masses we should take to be true of the real bob. One can imagine almost anything about almost any object, but unless there is criterion telling us which of these imaginings should be regarded as true of the target, these imaginings don't licence any surrogative reasoning.

At one place Toon suggest that principles of generation fit the bill: "principles of generation often link properties of models to properties of the system they represent in rather direct way. If the model has a certain property then we are to imagine that system does too" (2012, 68-69). At least within Walton's framework that isn't the case: principles of generation generate a set of fictional propositions and leave it unspecified whether or not they should also be taken to be true of the target. One could consider extending the framework by building a fictional-to-truth inference rule into it, but that would be a Pyrrhic victory. What a model (or model-description) prescribes us to imagine rarely, if ever, corresponds exactly to what a competent model user claims about the target itself. Neither did Newton take the real sun to be a perfect sphere; nor did Fibonacci believe for a moment that rabbits were immortal. Many model-properties are imputed to targets only after having undergone transformations, which often involve de-idealisation and approximation. DEKI accounts for these transformations in the key, but Direct Representation leaves the transfer mechanism between model and target unspecified.

Levy (2015) explicitly identifies this as a gap in Toon's account, and sets about to fill it. In his (2012, 744) he proposed that the problem be conceptualised in analogy with metaphors, but immediately added that this was only a beginning which requires substantial elaboration. In his (2015, 792-796) he takes a different route and appeals to Yablo's (2014) theory of partial truth. The core idea of this view is that a statement is partially true "if it is true when evaluated only relative to a subset of the circumstances that make up its subject matter – the subset corresponding to the relevant content-part" (Levy 2015, 792). The ideal gas model, for instance, prescribes us to imagine all kind of things we know full well to be false (for instance that gas molecules don't collide) and yet the model "is partially true and partially untrue: true with respect to the role of energy distribution, but false with respect to the role of collisions" (2015, 793).

This is a step forward, but it does not take us all the way. Levy himself admits that there are other sorts of cases that don't fit the mould (*ibid*., 794). Such cases often are ones in which distortive idealisations are crucial and cannot be set aside. These require a different treatment and it's an open question what this treatment would be. These kinds of idealisations are ubiquitous in physics and play an important role in other sciences too, and hence Direct Representation remains incomplete until it has a means to deal with such cases.

Another supposed advantage of Direct Representation is its ontological parsimony due to its elimination of vehicles (or 'secondary systems') from an account of representation. This proposal runs into difficulties with targetless models. Some of these are models of discredited entities like the aether and phlogiston. But not all models without targets are errors. Architectural models of buildings that have never been erected, and models of theoretical constructs like three-sex populations or Yang-Mills particles that were known all along not to exist are cases in point. Such models are a problem for Direct Representation because if there is no target there is nothing to imagine something about. Toon is aware of this problem and offers a solution, by drawing another analogy with literary fiction. Not all novels are like reading *The War of the Worlds*, which has an object (namely St Paul's Cathedral). Passages from *Dracula*, for instance, "do not represent any actual, concrete object but are instead about fictional characters" (*ibid*., 54). Models without a target are like passages from *Dracula*. If a model has no real-world target, then it is about a fictional character. As Toon admits, this "gives rise to all the usual problems with fictional characters" (*ibid*.). So at least in the case of targetless models Direct Representation is not ontologically parsimonious.

Levy (2015) offers a different and radical solution to the problem of models without targets: there aren't any! He first broadens the notion of a target system, allowing for models that are only loosely connected to targets (*ibid*., 796-797). To this end he appeals to Godfrey-Smith's notion of "hub-and-spoke" cases: families of models where only some have a target (which makes them the hub models) and the others are connected to them via conceptual links (spokes) but don't have specific targets. Levy points out that in such cases models should be understood as having a *generalised target*. If something that looks like a model doesn't meet the requirement of having at least a generalised target, then it's not a model at all. Levy mentions structures like the game of life and observes that they are "bits of mathematics" rather than models (*ibid*., 797). This is supposed to eliminate the need for fictional characters in the case of targetless models.

The core idea of Direct Representation is that a model is nothing but an act of imagining something about a concrete object. However, generalised targets such as population growth are not concrete things, and often not even classes of such things. But one cannot reap the ontological benefits of a view that analyses modelling in terms of imaginings about concrete things and at the same time introduce targets that are no longer concrete. Furthermore, the claim that models without targets are 'just mathematics' does not come out looking very natural when we look back at the above examples. Ontological costs can't be avoided.

Another argument in favour of the direct framework is that imagining something about a concrete object is different from imagining something about a non-concrete object, and that this difference matters to the practice of modelling.[10] To imagine that St Paul's Cathedral in London is attacked by aliens is different from imagining that a cathedral somewhere is attacked. As a real object the Cathedral has myriad of properties, and at least some of them are known to us. By having imaginings about the Cathedral fact about the Cathedral enter the imagination. So the focus on a real object makes a crucial contribution to the content of our imaginings.

This may well be an important aspect of our engagement with certain kinds of literary fiction,[11] but it doesn't lend support to Direct Representation because the imaginative engagement with models is different from the imaginative engagement with stories like *The War of the Worlds*. In fact target systems are inefficacious in the imaginary activity of modelling. Sometimes a model that is thought to have a target turns out not to have one (for instance Maxwell's aether model); sometimes a model

[10] This point has been made to us in personal conversation by Toon and Friend. For a discussion of the claim in the context of literary fiction see Friend (2012).

[11] Notice, however, that by no means all kinds of fiction rely on this mechanism. Toon's own example of *Dracula* is a case in point.

that was thought not to have a target is found to have one after all (for instance Dirac's electron model indicating that there were electrons with a 'wrong' charge, now known as positrons); and sometimes the existence of a target is left open and considered a matter of further study (for instance, models of superstrings). In as far as a model is an act of the imagination, nothing in that act changes when targets come and go. Models cross the border from targetless to targeted (and back) unchanged, or stay happily in the buffer zone between the two. The difference with St Paul's Cathedral is that the 'extra content' is not provided by knowing the object, or even being acquainted with it, but by background theories, and these figure in the principles of generation. So when we learn that there is no aether, the imaginings that constitute the aether model don't change. Of course the presence or absence of a target matters to many other issues, most notably surrogative reasoning (there is nothing to reason about if there is no target!), but it seems to have little, if any, importance for how we imaginatively engage with the scenario presented to us in a model.

We conclude that Direct Representation isn't viable. It has problems explaining how surrogative reasoning with models works; the way that it deals with targetless models jars with its ontological motivations; and targets are imaginatively inefficacious. We submit that DEKI is the more promising option and now turn to the challenges introduced in Section 3. In doing so we will also use the framework of MB, but in a different way and to different ends.

5. Rising to the Challenge

The DEKI account itself places no restriction on the choice of the vehicle *X*. Anything that is an object with properties can, in principle, be used as a vehicle of representation. In particular, there is nothing in DEKI *per se* that would rule out set theoretical structures, and DEKI could in principle be used to articulate a structuralist theory of representation. This, however, is not the route we want to take. Many models have important non-structural aspects, and these are best understood as being fictional in some sense.[12] Our goal in this section is two-fold. First, we aim to articulate in what sense models are fictions and how they can play the role of a vehicle as required in DEKI. Our approach also uses MB, but in a different way than Direct Representation. Second, we aim to show that MB in fact offers a comprehensive framework in which to think about modelling that also covers material models of the kind discussed in Section 2.

Let us begin by having another look at material models. In Section 2 we said that a model is an *O*-object *X* endowed with an interpretation *I* that maps *O*-properties onto *Z*-properties. This fits seamlessly into MB: the model object *X* can be seen as a prop in a game of make-believe and the interpretation *I* provides principles of generation. A model, understood as the pair $M = \langle X, I \rangle$, is then equivalent to prop and set of principles of generation mandating model users to imagine certain things in response to certain features of *X*. On that reading, Kendrew's plasticine rope is a prop in the myoglobin-game-of-make-believe, a game in which we are prescribed to imagine certain myoglobin-properties when confronted with certain plasticine-rope-properties (and which properties are so prescribed to be imagined is specified by *I*).

Putting material models into the context of MB is not merely conceptual retrofitting. This move helps highlighting important aspects of the practice of modelling. Models are not for passive contemplation. Kendrew learned with his model by manipulating it, by experimenting on it, and by intervening into its internal mechanics. At the same time the engagement with the model object is guided by the interpretation. He did not just toy around with plasticine aimlessly; he specifically explored those plasticine properties that were covered by his interpretation. This is exactly what happens in a game of make-believe. We're not just aimlessly walking through the forest; we actively look for stumps and disregard other things because they are not covered by the rule of generation and hence not part of the game.

[12] See Barberousse and Ludwig (2009); Frigg (2006; 2010); Godfrey-Smith (2009); Godfrey-Smith (2006); Levy (2015); and Toon (2012) for arguments to this effect. See Frigg (2010) for a response to criticisms.

MB also offers an analysis of the notion of *I*-instantiation, a problem that was left open in Section 2. *I*-instantiation is in fact pretend instantiation: a model *I*-instantiates a property *P* iff the prop *X* together with the principles of generation given by *I* prescribe *P* to be imagined. The relevant rule may be a straightforward pairing up of properties as suggested in Section 2, prescribing *P* to be imagined in response to being confronted with *P*'. But once *I* is seen as a set of rules of generation in a game of make-believe further possibilities may open up. Truth under an interpretation then is MB's notion of being fictional. *Z*-claims like 'the molecule has the dimensions 43Å×35Å×23Å', which refer to properties that *X* does not instantiate and hence are literally false, are fictional in the game of make-believe defined by the model. Nothing depends on whether *X* literally instantiates *P* – what matter is that it is 'true in the fiction of the model' that the model has *P*, and being fictional in the sense of MB offers the sought-after analysis of that notion.

Understanding *I*-instantiation in this way also helps us understand *I*-exemplification. Whereas exemplification requires that the object literally instantiate the exemplified property, *I*-exemplification in this context requires that we are prescribed to imagine that the object has the property, and as long as this property is also highlighted in the context under consideration, then the object *I*-exemplifies it.

Let us now turn to non-concrete models. As we have seen in the last section, within MB the text of a novel is a prop in a game of make-believe. The text, together with certain principles of generation, mandates the reader to imagine certain things. Non-concrete models are typically presented through descriptions, portraying things like spherical planets and immortal rabbits. We call these descriptions *model descriptions*. This gives us the essential clue: model descriptions are like the text of a novel: they are props in games of make-believe.[13] Fibonacci's description of the

[13] We are not committed to claim the MB offers a successful analysis of *all* literary genres. In fact there is a question whether MB offers a successful account of works in which figures of speech such as irony, sarcasm, cynicism, feature prominently. We submit, however, that MB offers a successful account of straightforward narration of the kind we find in late 19th century novels (by writers such as Zola and Tolstoy). The

population mandates participants in the game of make believe to imagine rabbits with certain specific features, and they then use principles of generation to draw conclusions that have not been written explicitly into the original model description, for instance that the rabbit population grows monotonically and is unbounded.

In contrast with Direct Representation we don't analyse model descriptions as prescribing imaginings *about* a concrete target. A model description prescribes us to imagine certain things, and these are prima facie independent of the presence (or absence) of a target. By mandating those involved in a certain game to imagine certain things, the model description generates the imagined-object that serves as the vehicle X of a representation-as. In our examples, Newton's spherical planets and Fibonacci's immortal rabbits take the place of Kendrew's plasticine rope in the DEKI scheme. So MB's answer to the question at the beginning of Section 3 is that in the case of non-concrete models imagined-objects take the place of X in the DEKI conditions.

The hyphen in 'imagined-object' indicates that we use this locution as a term of art. The reason for this is that we want to remain ontologically non-committal. Game-driven make-believe can be seen as a way to refer to, or even create, a Meinongian fictional entity (Priest 2011), as a method to create an abstract artefact of the kind Thomasson (1999) describes, or simply as inducing mental content in those who play the game. DEKI is compatible with all these options and hence as far as DEKI is concerned there is no need to adjudicate between them.[14]

Imagined-objects are independent of targets. The plasticine rope mandates those playing the game to imagine an alpha helix that is folded up in space in certain

claim is that model descriptions function like texts of that kind and that therefore MB offers a good account of them.

[14] This is not say that different options raise different issues when the details of the account are developed. Our own preference is for an antirealist option where no object is introduced. This option raises questions about the intersubjective identification of characters or things referred to by fictional names. For a discussion of this problem and a solution see Salis (2013).

way. That this is imagined about a real target is not part of the game. Indeed, had it come to light later that myoglobin was to share the fate of phlogiston or the luminiferous aether, the imaginings prescribed by Kendrew's model would remain exactly the same (for the reasons mentioned at the end of Section 4).[15]

MB is attractive for DEKI because it offers a detailed account of constrained imagination that naturally accommodates important aspects of the practice of modelling. Scientists often start with few basic posits, make certain assumptions, rely (often tacitly) on background theories. By actively manipulating these elements under certain constraints, and by seeing what fits together and how, they learn about the posits and about what they imply. This activity is naturally analysed as being involved in a game of make-believe, and in doing so an imagined-object is explored. Due to the use of principles of generation the imagined-object can have properties that have not been written into the original model description, which is why the study of imagined-objects is cognitively relevant. By being involved in such games physicists learn about the geometrical properties of orbits and population biologists about growth of populations, neither of which were explicitly mentioned in the model description.

Games of make believe associated with non-concrete models are more complex than those of material models. The reason is that they do two things at once. In the concrete case *X* is a physical object and claims about *X* are true or false; the imagination only comes into play when explaining how *X* becomes a *Z*-

[15] Imagination need not be pictorial and a view that sees imagination as central to modelling is not committed to the (absurd) claim that all model-based reasoning is pictorial (Salis and Frigg forthcoming). Neither is modelling bound by constraints of possibility. A venerable tradition sees imaginabiliy as a guide to possibility. We do not assume such 'thick' notion of imagination here and there is no presupposition that only possible things, or indeed only consistent things, can be imagined. Models can, at least in principle, contain inconsistencies and the notion of imagination involved in MB should not rule this out. For a discussion of the relation between possibility and imagination see Yablo (1993) and Szabo Gendler and Hawthorne (2002). Finally, we do not have to commit to any particular view of mental content on which, again, nothing hangs as far as DEKI is concerned.

representation. In the non-concrete case *X* itself is a figment of the imagination. So the game of make believe both produces the imagined-object that plays the role of *X* and provides the rules of interpretation turning *X* into a *Z*-representation. A model description *D* therefore has two parts: a part D_X that generates the vehicle *X* and part D_I that provides *I*. Consider again the case of Newton's model of the solar system. D_X generates what is usually called the *two-body system*: a system consisting of two homogeneous perfect spheres, one large and one small, attracted to each other with a $1/r^2$ force. D_I instructs us to imagine the larger sphere as the sun, the smaller sphere as the earth and the force as gravity. History testifies to the distinctiveness of D_X and D_I. The Bohr model of the atom leaves D_X intact but replaces the solar system D_I with a hydrogen atom D_I which instructs us to imagine the large ball as a proton, the small ball as an electron and the force as electrostatic attraction. D_X will operate against the background of principles of generation which allow those involved in the game to reach conclusions that have not been written into the basic specification of the vehicle. For instance that the small sphere moves in an elliptical orbit around the large sphere is a proposition that is fictional in the two-body game of make believe but does not form part of the basic specification of the two-body system. In this way an imagine-object can play the same role in a non-concrete model as a material object in a concrete model.

It is worth noting that D_X and D_I are not always separated as in Newton's model. In fact in many cases the imagined-object of the model is chosen so that it has the properties we are interested in, and the interpretation becomes a simple identity. In Fibonacci's model, for instance, the imagined-object specified by D_X is a rabbit population and the model is a rabbit-population-representation. So the interpretation part is reduced to identity (but not so the key: the properties of Fibonacci's fictional rabbits are not imputed unchanged to real rabbits). This is because the imagination is less constrained than the material world and so it's often easier to find a suitable imagined-object than to come by an appropriate material system. For this reason non-concrete models have identity interpretations more often than material models. But identity interpretations are not a prerogative of non-material models. Scale models are material models with such interpretations, for instance when a small ship is used as a ship-model.

Let us now turn to the challenges from Section 3. As pointed out above, MB offers an analysis of truth in fiction in terms of *being fictional in a story* and an account of models based on MB can inherit this to explain truth in vehicles. It is then true that Fibonacci's rabbit population grows monotonically iff it is fictional in the Fibonacci game of make-believe that the population grows monotonically, i.e., iff the prop of the model together with the principles of generation prescribes us to imagine the population as growing monotonically. Two models are then identical iff the same propositions are fictional in them. Property attribution is then pretend attribution: the imagined-object that plays the role of X has property P iff it is fictional in the model that X has P. Nothing in DEKI depends on there being a real object that literally instantiates a physical property. What matter is that there is right and wrong in property attribution, and MB explains constraints to imagination cogently in terms of facts about the prop and adherence to principles of generation. MB also offers an epistemology for model systems: exploring a model amounts to figuring out what follows from the basic assumptions and the principles of generation. Highlighting is explained in the same way as in the case of concrete models.

Comparing models and targets is common in many contexts, which raises the question of how one can compare an imagined-object and real thing. This question has no straightforward answer and much depends on one's ontological commitments. We refer the reader to Salis (2016) for an in-depth discussion of the problem and a proposed solution. It is worth noting, however, that DEKI itself does not require comparative claims. The fourth condition in DEKI is that properties are imputed to the target. In linguistic terms this means that claims of the form 'target T has property Q' are put forward. These are standard attributive claims rather than comparisons, and as such they raise no problems having to with fiction.

Mathematics can enter models in two places: in the model descriptions and in the rules of generation. Mathematical concepts can be part of descriptions or rules like the topography of a city can be part of a novel. Often the specification of a vehicle already involves mathematical concepts, for instance when we specify that a perfect sphere is part of the vehicle. So the language in which D_X is formulated contains mathematical terms. The principles of generation also contain mathematical rules. In

Fibonacci's case basic arithmetic concepts are used in D_X and the rules of generation applied in the model contain full-fledged arithmetic, which is used to generate the population size numbers at later times (which are not part of the model description). In other cases the principles of generation contain mathematically formulated laws of nature that are assumed to be operable in the model. In Newton's model, for instance, the two bodies are assumed to be governed by Newton's equation of motion, with the mathematical principle being used to find that it is fictional in the model that planets move in elliptical orbits. These rules are independent from D_X and can be changed. This happened, for instance, when, without changing D_X, Newton's equation is replaced by Schrödinger's equation to generate secondary truths about the two-body system.[16]

The last item left from our list is denotation. At this point we can only gesture at the problem and will have to leave a serious discussion for another day. Denotation by itself is formidable problem, and in the current context an additional complication is thrown into the mix. While denotation is standardly construed as relation between a symbol and an object ('Julius Caesar' denotes the historical figure Julius Caesar), it is here construed as relation between a model and target. Those who opt for realism about models will have to say what exactly they are and explain how the denotation of a fictional entity is established. Those who remain antirealists about models will have to offer an account that involves the imagination in various ways and in various places. Both options are possible, but neither is straightforward. A promising antirealist account has been offered by (Salis m.s.), and we are hopeful that an account along those lines will eventually answer the question.

[16] We here explain how mathematics enters modelling understood as analysed in MB. This does not address the fundamental issue of the 'problem of the applicability of mathematics', the question of how it is possible that mathematical properties can be attributed to something non-mathematical. Different solutions have been proposed (see Shapiro (2000) for a survey) and while the issue is important in its own right, DEKI is in principle compatible with any answer and hence there is no need to take a stance here.

The considerations show that MB provides a unified framework for thinking about modelling, both concrete and non-concrete. It offers solutions to a number of problems and casts an interesting light on others, which will, we hope, advance future discussions.

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