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Scientific Models and Representation

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0. Introduction

My two daughters would love to go tobogganing down the hill by themselves, but they are just toddlers and I am an apprehensive parent, so, before letting them do so, I want to ensure that the toboggan won't go too fast. But how fast will it go? One way to try to answer this question would be to tackle the problem head on. Since my daughters and their toboggan are initially at rest, according to classical mechanics, their final velocity will be determined by the forces they will be subjected to between the moment the toboggan will be released at the top of the hill and the moment it will reach its highest speed. The problem is that, throughout their downhill journey, my daughters and the toboggan will be subjected to an extraordinarily large number of forces—from the gravitational pull of any massive object in the universe to the weight of the snowflake that is sitting on the tip of one of my youngest daughter's hairs—so that any attempt to apply the theory directly to the real-world system in all its complexity seems to be doomed to failure.

A more sensible way to try to tackle the problem would be to use a simplified model of the situation. In this case, I may even be able to use a simple off-the-shelf model from classical mechanics such as the inclined plane model. In the inclined plane model, a box sits still at top of an inclined, frictionless plane, where its potential energy, U_i, is equal to mgh (where m is the mass of the box, g is its gravitational acceleration, and h is the height of the plane) and its kinetic energy, KE_i, is zero. If the box is let go of, it will slide down the plane and, at the bottom of the slope, all of its initial potential energy will have turned into kinetic energy ($E_f = KE_f + U_f = ½mv_f^2 + 0 = mgh + 0$) and so its final velocity, v_f, will be $(2gh)^{½}$. The final velocity of the box, therefore, depends only on its initial height and on the strength of the gravitational field it is in. But what does this tell me about how fast my daughters would go on their toboggan? And why should I believe what the model tells me about the real situation in the first place?

The practice of using scientific models to represent real-world systems for the purpose of predicting, explaining or understanding their behaviour is ubiquitous among natural and social scientists, engineers, and policy-makers, but until a few decades ago philosophers of science did not take scientific models very seriously. The received view (often also misleadingly labelled as the "syntactic view") was that scientific theories were sets of sentences or propositions, which related to the world by being true or false of it or at least by having true or false empirical consequences. In this picture, scientific models were taken to play at most an ancillary, heuristic role (see, e.g., Duhem 1914: 117, Carnap 1939: 68, Hesse 1963).

As my initial example suggests, however, most real-world systems are way too messy and complicated for us to be able to apply our theories to them directly and it is only by using models that we can apply the abstract concepts of our theories and the mathematical machinery that often comes with them to real-world systems.[1] In light of these and other considerations, today, most philosophers of science have abandoned the received picture based on propositions and truth in favour of one of two views in which models play a much more central role. Those who adopt what we could call the *model view* (or, as it is often misleadingly called, the "semantic view") deny that scientific theories are collections of propositions and prefer to think of them as collections of models.[2] Those who opt for what we could call the *hybrid view*, on the other hand, think that models are to a large extent autonomous from theories but play crucial mediating role between our theories and the world.[3]

Despite their differences, there are two crucial points on which the supporters of both views seem to agree. The first point is that scientific models play a central role in science. The second is that scientific models, unlike sentences or propositions and like tables, apples and chairs, are not truth-apt—i.e. they are not capable of being true or false. So, whereas according to the received view, scientific theories related to the world by being true or false of it (or at least by having true or false consequences), they cannot do so on either the model view or the hybrid view, because, on either views, it is models (and not sentences or propositions) that relate (more or less directly) to the world.

But how do models relate to the world if not by being true or false of it? The most promising and popular answer to this question is that they do so like maps and pictures do—by representing aspects or portions of it. As models gained centre stage in the philosophy of science, a new picture of science emerged (or, perhaps, an old one re-emerged)[4], one according to which, science provides us with (more or less faithful) representations of the world as

[1] This point has been made most forcefully by Nancy Cartwright (see, in particular, (Cartwright 1983) and (Cartwright 1999)).

[2] The so-called semantic view originated with the work of Patrick Suppes in the 1960s (see, e.g., (Suppes 1960) but also (Suppes 2002)) and can be safely considered the new received view of theories counting some of the most prominent philosophers of science among its supporters (see, e.g., (van Fraassen 1980), (Giere 1988), (Suppe 1989), (da Costa and French 1990)). How exactly the so-called semantic view of theories relates to the view that theories are collections of models is an exegetical question that is beyond the scope of this paper to pursue.

[3] This view, sometimes referred to as the models-as-mediators view, is developed and defended, for example, by many of the contributors to (Morgan and Morrison 1999). The most developed defense of this view is perhaps to be found in (Cartwright 1999).

[4] See, e.g., (van Fraassen 2008, Ch. 8).

opposed to (true or false) descriptions of it.[5] In this essay, I will discuss some of the philosophical questions raised by this representational picture of science and in particular by taking scientific models to be representations of their target system. I will first briefly consider some of the questions related to the nature and function of scientific models and then focus on the issues surrounding the use of the notion of representation in this context.

1. Models

There are at least two distinct senses in which scientists and philosophers of science talk of models. In a first sense, 'model' can be used to refer to what, more precisely, we could call a *model of a theory* or a *theoretical model*—i.e. a system of which a certain theory is true. So, for example, the inclined plane model, which I used to represent my daughters on the toboggan, is a model of classical mechanics, in the sense that classical mechanics is true of the model.

In a second sense, 'model' can be used to refer to what we could call a *model of a system* or a *representational model*—i.e. an object used to represent some system for the purpose of, for example, predicting or explaining certain aspects of the system's behaviour. In my initial example, for instance, I used the inclined plane model as a model of my daughters tobogganing down the hill because I used it to represent the system formed by my daughters tobogganing down the hill.

These two notions of scientific model are easily conflated because, as the example illustrates, we often use theoretical models as representational models. However, whereas it would seem that any theoretical model can be used as a representational model, not all representational models need to be theoretical models. To represent my daughters tobogganing down the hill, for example, instead of the inclined plane model, I could have used an ordinary hockey puck sliding down an icy ramp. Alternatively, I could have gathered data about the final velocities of other toboggans going down the hill as well as other variables (such as the mass and cross-sectional areas of their passengers) and found an equation to fit the data and used that equation to predict the final velocity of the toboggan with my daughters.

As R.I.G. Hughes puts it, '[…] perhaps the only characteristic that all [representational] models have in common is that they provide representations of parts of the world' (Hughes 1997, S325). From an ontological point of view for example, my three examples are a mixed bag. The puck is what we could call a *material model* (because unlike the inclined plane, it is an actual concrete physical system made up of actual concrete physical objects just like the system it is meant to represent); the mathematical equation is what we could call a *mathematical model* (an abstract mathematical object that is used to represent (directly) a concrete system); finally, the inclined plane model is what we could call a *fictional model* (because the

[5] How robust the distinction between representing and describing is obviously depends partly on one's views on language and truth.

objects in it, like fictional characters such as Sherlock Holmes, are not actual concrete objects but are said to have qualitative properties (like having a mass or smoking a pipe)).[6]

If there is a variety of devices that can be used as representational models, however, theoretical models still constitute the main stock from which representational models of real-world systems (or at least the building blocks for such models) are drawn. The following is a simple variation on a popular theme.[7] Theoretical principles (the "laws" of our theories) do not describe the world. They merely define certain classes of models—the theoretical models. Theoretical models can be combined, specified, or modified to be used as models of some real-world system. Such representational models can be used either directly to represent some specific real-world system (e.g. my daughters tobogganing down the hill) or some type of real-world system (e.g. *the* hydrogen atom as opposed to some specific hydrogen atom) or some "data model" (i.e. a "smoothed out" representation of data gathered from a certain (type of) system).

No matter how many layers one adds to this picture, the models at the bottom of this layer-cake (be they the data models or, as I will mostly assume here, the representational models) would seem to have to represent directly some aspect or portion of the world if the gap between the theory and the world is to be bridged. It is to the question of how these "bottom" models do so that I will now turn.

2. Representation

2.1. Disentangling 'Representation'

You are visiting London for the first time and you need to reach Liverpool Street station. You enter the nearest tube station, pick up a map of the London Underground and after looking at it you quickly figure out that you have to take an eastbound Central Line train and get off after three stops. What you have just performed seemingly so effortlessly is what, following Chris Swoyer (1991), I shall call a piece of *surrogative reasoning*. The London Underground map and the London Underground network are clearly two distinct objects. One is a piece of glossy paper on which coloured lines, small black circles and names are printed; the other is an intricate system of, among other things, trains, tunnels, rails and platforms. Yet, you have just used one of them (the map) to infer something about the other (the network). More precisely, from 'The circles labelled 'Liverpool Street' and 'Holborn' are connected by a red line' (which expresses a proposition about the map) users infer 'Central Line trains operate between Holborn and Liverpool Street stations' (which expresses a proposition about the network).

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[6] Nancy Cartwright (1983) was one of the first to suggest the analogy between models and fictions. See (Godfrey-Smith 2009), (Contessa 2010), (Frigg 2010), as well as (Suárez 2009) for different takes on this analogy.

[7] For a much more refined and detailed variation on the same theme, see (Giere 1988: Ch 4) and (Giere 200).

The fact that a user performs a piece of surrogative inferences from something (a vehicle) to something else (a target) is the main "symptom" of the fact that the vehicle is being used as an *epistemic representation* of the target by that user.[8][9] So, if you use the map you are holding in your hand to perform a piece of surrogative reasoning about the London Underground network, it is because, for you (as well as for the vast majority of users of the London Underground network), that map is an epistemic representation of the network. Analogously, if, in my initial example, I used the inclined plane model to infer how fast the toboggan would go, it was because I was using it as an epistemic representation of my daughters tobogganing down the hill.

In order for a vehicle to be an epistemic representation of a target, the conclusions of the surrogative inferences one draws from one to the other do not need to be true. For example, if you were to use an old 1930s map of the London Underground today, you would infer that Liverpool Street is the last stop on the Central Line, which is no longer the case. The difference between the old and the new map is not that one is an epistemic representation of today's network while the other is not, but that one is a *completely faithful* epistemic representation of it (or at least so we can assume here) while the other is only a *partially faithful* one—some but not all surrogative inferences from the old map to the network are sound.[10]

Two things are worth noting. First, a vehicle can at the same time represent its target and misrepresent (some aspects of) it, for representation does not require faithfulness. This is particularly important for scientific models, which are rarely if ever completely faithful representations of their targets. Overall, the inclined plane model, for example, is not a very faithful representation of my daughters tobogganing down the hill. Nevertheless, it may be sufficiently faithful for my purposes. Second, unlike representation, faithfulness comes in degrees. A vehicle can be a more or less faithful representation of a certain target but it is either a representation of a certain target (for its users) or it is not.

Once we distinguish between epistemic representation and faithful epistemic representation, it becomes clear that there are two questions a philosophical account of epistemic representation should answer. The first is 'What makes a vehicle an epistemic representation of a certain target?', the second is 'What makes a vehicle a more or less faithful epistemic representation of a certain target?'. Here I will call any attempt to answer the first of these questions an account of *epistemic representation* and any attempt to answer the second an account of *faithful epistemic representation*.

[8] Note that to say that a representation is an epistemic representation is just to say that is a representation that is used for epistemic purposes (i.e. a representation that is used to learn something about its target). So, for example, Pablo Picasso's *Portrait of Daniel-Henry Kahnweiler* represents the art dealer Daniel-Henry Kahnweiler. However, the main purpose of that portrait, presumably, was not that of being an epistemic representation of Kahnweiler (but rather what we could call an aesthetic representation of him).

[9] Here I take surrogative reasoning to be "a symptom" of epistemic representation. However, there may be well "asymptomatic" cases of epistemic representation—cases in which users perform no actual surrogative inference from the vehicle of the target although they would be able to do so if they wanted.

[10] The crucial distinction between what I call 'epistemic representation' and 'faithful epistemic representation' was first emphasized in this context by Mauricio Suárez (2004).

In the literature, these two questions have been often conflated under the heading "the problem of scientific representation". This label, however, may be, in many ways, misleading. One way in which it can be misleading is that it suggests that there is a single problem all contributors to the literature are trying to solve, while there are (at least) two.[11] A better way to describe the situation is that some of the supposedly rival solutions to "the problem of scientific representation" are in fact attempts to answer different questions. On this interpretation, one can find at least three rival accounts of epistemic representation (i.e. three different answers to the question 'What makes a vehicle an epistemic representation of a certain target?')—the *denotational account*, the *inferential account*, and the *interpretational account*—and two (somewhat related) accounts of faithful epistemic representation—the *similarity account* and the *structural account*. I will now sketch these accounts in turn, starting with accounts of epistemic representation.

2.2. Epistemic Representation

The *denotational account* suggests that all there is to epistemic representation is denotation.[12] More precisely, according to the denotational account, a vehicle is an epistemic representation of a certain target for a certain user if and only if the user stipulates that the vehicle denotes the target. The prototype of denotation is the relation that holds between a name and its bearer. So, for example, 'Plato' denotes Plato, but, had different stipulations been in place, 'Plato' could have denoted Socrates and Plato could have been denoted by 'Aristotle'. So, according to this view, if the London Underground map is an epistemic representation of the London Underground network for you or the inclined plane model is an epistemic representation of my daughters tobogganing down the hill for me it is because, respectively, you and I have stipulated that they are. You could equally well have chosen to use an elephant and I a ripe tomato.

Whereas denotation seems to be a necessary condition for epistemic representation, it does not, however, seem to be a sufficient condition. Nobody doubts that you could have used an elephant to denote the London Underground network, but it is not clear how you could have used an elephant to perform surrogative inferences about the network and the user's ability to perform surrogative inferences from the vehicle to the target seems to be the main symptom that she is using the vehicle as an epistemic representation of the target. So, it would seem other conditions need to be in place for a mere case of denotation to turn into one of epistemic representation. But what are these further conditions?

According to the *inferential account* of epistemic representation (see mainly (Suaréz 2004)), the solution to the problem is simply to explicitly add that the user be able to perform surrogative inferences from the vehicle to the target as a further necessary condition for

[11] Another way in which the label 'scientific representation' could be misleading is that it seems to imply that something sets aside scientific representations from non-scientific epistemic representations that are not scientific. See §2.5 below.

[12] If I understand them correctly, Craig Callender and Jonathan Cohen (2006) defend a version of what I call the denotational account.

epistemic representation. So, according to the inferential account, a vehicle is an epistemic representation of a certain target for a certain user (if and)[13] only if (a) the user takes the vehicle to denote the target and (b) the user is able to perform surrogative inferences from the vehicle to the target.

The inferential account thus avoids the problem that faced the denotational account but it does so in a somewhat *ad hoc* and ultimately unsatisfactory manner. In particular, the inferential account seems to turn the relation between epistemic representation and surrogative reasoning upside down. The inferential account seems to suggest that the London Underground map represents the network (for you) *in virtue of* the fact you can perform surrogative inferences from it to the network. However, the reverse would seem to be the case—you can perform surrogative inferences from the map to the network *in virtue of* the fact that the map is an epistemic representation of the network (for you). If you did not take this piece of glossy paper to be an epistemic representation of the London Underground network in the first place, you would never try to use it to perform surrogative inferences about the network.

More seriously, the inferential account seems to suggest that the users' ability to perform surrogative inferences from a vehicle to a target is somehow basic and cannot be further explained in terms of the obtaining deeper conditions, thus making surrogative reasoning and its relation to epistemic representation unnecessarily mysterious. Ideally, an account of epistemic representation should explain what makes a certain vehicle into an epistemic representation of a certain target for a certain user and how in doing so it enables the user to use the vehicle to perform surrogative inferences about the target. This is what the last account of epistemic representation I will consider here attempts to do.[14]

According to the *interpretational account* of epistemic representation, a vehicle is an epistemic representation of a certain target for a certain user if and only if (a) the user takes the vehicle to represent the target and (b*) the user adopts an interpretation of the vehicle in terms of the target (see (Contessa 2007), (Contessa forthcoming), and, possibly, (Hughes 1997)). So, the interpretational conception agrees with both the denotational and the inferential conception in taking denotation to be a necessary condition for epistemic representation but takes the adoption of an interpretation of the vehicle in terms of the target to be what turns a case of mere denotation into one of epistemic representation.

So, for example, a ripe tomato could be used as easily as the inclined plane model to denote the system formed by my daughters tobogganing down the hill if one were to decide to do so, but it is not clear how I could use the ripe tomato to infer how fast the toboggan would go. In the case of the inclined plane model, on the other hand, there is a clear and standard way to interpret the model in terms of the system. In fact, such an interpretation is so obvious that it would seem to be almost superfluous to spell it out if it was not to illustrate

[13] Suaréz seems to think that (a) and (b) are necessary but not sufficient conditions for what I call epistemic representation (see (Suaréz 2004)). However, more recently, (Suaréz and Solé 2006) seems to suggest that (a) and (b) may be jointly sufficent.

[14] Admittedly, the inferential account is meant to provide us with a deflationary or minimalist account of (epistemic) representation. However, it is not clear why one would opt for such a deflationary or minimalist account unless no more substantial account were available.

what an interpretation of a vehicle in terms of a target is: the box in the model denotes the toboggan with my daughters in the system, the mass, the velocity, and the acceleration of the box denote the mass, the velocity, and the acceleration of the toboggan, the inclined plane denotes the slope of the hill, and so on).

The main advantage of the interpretational conception is that it offers a clear account of the relation between epistemic representation and surrogative reasoning. A vehicle is an interpretation of a target for a certain user in virtue of the fact that the user adopts an interpretation of the vehicle in terms of the target (and takes the vehicle to denote the target)[15] and this interpretation provides the user with a set of systematic rules to "translate" facts about the vehicle into (putative) facts about the target. If the final velocity of the box is v_f and, if according to the interpretation of the model I adopt, the box denotes my daughters on the toboggan and the velocity of the box denotes the velocity of the toboggan, then, on the basis of that interpretation of the model in terms of the system, I can infer that the final velocity of the toboggan is v_f. (Note, however, that this does not mean that I need to believe that the final velocity of the toboggan is going to be v_f.)

It is tempting to think that, on the interpretational account, epistemic representation comes too cheaply. After all, nothing seems to prevent me from adopting an interpretation of a ripe tomato in terms of the system formed by my daughters tobogganing down the hill, one according to which, say, the deeper the red of the tomato is, the faster the toboggan will go. This may well be true, but what exactly would be wrong with that? The objection might be that from the tomato I would likely infer only false conclusions about the system. This may well be the case, but the interpretational account is meant to be an account of what makes a vehicle an epistemic representation of a certain target not for what makes it a faithful epistemic representation of the target. Further conditions would need to be in place for the tomato to be a faithful epistemic representation of the system, conditions, which, it is plausible to assume, the tomato (at least under this interpretation) would not meet.

Maybe the objection is that, if all there is to epistemic representation is denotation and interpretation, then using models for prediction is not all that different from using tarots. Of course, there is an enormous difference between using models and using tarots to find out whether my daughters will be safe on the toboggan but the difference may not be necessarily that one but not the other is an epistemic representation of the situation (after all tarots are used to perform surrogative inferences about other things); the difference could rather be that one provides me with what is (hopefully) a much more faithful representation of the situation than the other and that (again, hopefully) I have good reasons to think so.

If epistemic representation appears to come cheaply, on the interpretational account, it may be because epistemic representation *is* cheap. It doesn't take much for someone to be

[15] It might be worth here to explain why, according to the interpretational account, (a) is still needed even if (b*) obtains. Suppose that you find a map of a subway system that does not tell you which subway system (if any) it represents. Since most subway maps are designed on the basis of the same general interpretation, you would still be able to make a number of inferences about the subway network the map represents even if you do not know what system it represents. According to the interpretational account, this is because, in this case, condition (b*) seems to hold but condition (a) does not.

able to perform surrogative inferences from something to something else (but at the same time it does not seem to take as little as the denotational and inferential conceptions suggest.). What does *not* come cheaply are *faithful* epistemic representations and even more lees cheaply epistemic representations that we have good reasons to believe are sufficiently faithful for our purposes. So it is to accounts of faithful epistemic representation that I turn in the next section.

2.3. Faithfulness

Assume that the conditions for a certain vehicle to be an epistemic representation of a certain target for a certain user obtain. What further conditions need to be in place in order for the epistemic representation to be a *faithful* one? According to the *similarity account* of faithful epistemic representation, the further condition is that the vehicle is similar to the target in certain respects and to a certain degree (where what counts as the relevant respects and degrees of similarity largely depends on the specific purposes of the user) (see (Giere 1985), (Giere 1988), (Teller 2001), (Giere 2004)). For example, in the case of the toboggan going down the hill, what I am interested in is that the toboggan will not go too fast. So, in order for the inclined plane model to be a (sufficiently) faithful representation of the system for my purposes, it must at least be the case that the final velocity of the box in the model is sufficiently similar to the highest speed the toboggan will reach. But how similar is sufficiently similar? In this case, it would seem that the most important aspect of similarity is the one between the highest speeds of the box and the toboggan. The speed the toboggan will actually reach should not be (much) higher than the one reached by the box in the model, for, if the velocity of the toboggan were to be much higher than the one of the box, I might inadvertently expose my daughters to an unnecessary risk.[16]

This, however, still seems to be excessively permissive. After all, I might happen to employ a model that, on this particular occasion, happens to predict the highest speed of the toboggan accurately but does so in an entirely fortuitous manner (say, a model based on some wacky theory according to which the speed of the toboggan depends on its colour). Would such an accidental similarity be sufficient to make the model into a faithful epistemic representation of the system for my purposes? This question, it would seem, should be answered negatively (for reasons analogous to the ones that make us deny that cases of epistemic luck constitute cases of knowledge). If accidental similarity was sufficient for faithfulness, then even tarots would sometimes be faithful epistemic representations of their targets. If faithfulness is a matter of similarity, then, to avoid accidental similarities, it would seem that the similarity between the vehicle and the target would need to be somewhat more systematic than the one between the model that predicts the velocity of the toboggan in an accurate but ultimately fortuitous manner. This would seem to guarantee that the model does not only give us the right answer but that it does so reliably and under a range of counterfac-

[16] Maybe, it is also important that the velocity of the toboggan is not going to be much lower than the highest one reached by the box (if the maximum speed of the toboggan were to be much lower than the one of the box, I might prevent my daughters to enjoy a fun and safe ride).

tual circumstances. However, it is not clear whether the similarity account has the resources to explain precisely what these more systematic similarities might be, for the notion of similarity seems to be already sufficiently vague when it comes to more concrete similarities.

The *structural account* of faithful epistemic representation, however, can be seen as trying to capture this more abstract and systematic sense in which a vehicle needs to be similar to a target in order for the former to be a somewhat faithful epistemic representation of the target. The structural account of faithful epistemic representation tries to avoid the problems that beset the similarity account while retaining the basic insight that underlies it—that faithfulness is a matter of similarity. In fact, the structural conception could be considered a version of the similarity conception (for what would a structural relation be if not an abstract similarity (viz. a similarity of structure)?).

According to the *structural account* of faithful epistemic representation, if a certain vehicle is an epistemic representation of a certain target for a certain user, then, if some specific morphism holds between the structure of the vehicle and the structure of the target, it is a faithful epistemic representation of that target (where a morphism is a function from the domain of one structure to the domain of the other that preserves some of the properties, relations, and functions over the domain).[17]

The first problem a structural account of faithful epistemic representation encounters is that morphisms are relations between set-theoretic structures and most vehicles and targets are not set-theoretic structures (see, e.g., Frigg 2006). For example, neither my daughters tobogganing down the hill nor the London Underground network would seem to be a set-theoretic structure. The most promising solution to this problem would seem to claim that whereas most vehicles and targets are not structures, nevertheless they can instantiate structures.[18]

Assuming a viable account of structure instantiation is available, the structural account roughly maintains that a vehicle is a faithful epistemic representation of the target only if some specific morphism holds between the structure instantiated by the vehicle and the one instantiated by the target. But which morphism? In the case of what I have called completely faithful representations, the morphism is arguably an isomorphism (or, more precisely, an "intended" isomorphism). So, for example, the structure instantiated by the new London Underground map is isomorphic to the one instantiated by the London Underground network (This among other things means that for example, every circle on the map can be put into one-to-one correspondence with a station on the network in such a way that circles that are connected by a line of the same colour correspond to stations that are connected by the same a subway line).

The problem, however, is that most epistemic representations and especially most scientific models are not completely faithful representations of their targets. Supporters of the

[17] What I call the structural conception is more or less explicitly embraced by, among others, (da Costa and French 1990, 2000, 2003), (French 2003), (French and Ladyman 1999), (French and Saatsi 2006), (Suppes 2002), and (van Fraassen 1980, 1989, 2008).

[18] For an account of structure instantiation, see (Contessa forthcoming, Ch 4), which draws on (Frigg 2006) and (Cartwright 1999).

structural account generally agree that the solution to this problem is to opt for a morphism that is weaker than isomorphism (such as homomorphism (see, e.g., (Bartels 2006)) or partial isomorphism (see, e.g. (Ladyman and French 1997)). However, it is no easy feat to identify a type of morphism that is weak enough to capture all epistemic representation that are at least partially faithful (no matter how unfaithful) while leaving out all the ones that completely unfaithful.

A more serious problem is that the notion of faithful epistemic representation is a gradable notion, but that of morphism is not. So, whatever type of morphism one opts (no matter how weak), whether or not that morphism holds between the structure instantiated by the vehicle and that instantiated by the target is an yes-or-no question. How faithfully the vehicle represents the target on the other hand, is a matter of degree.

These two problems may be solved in one fell swoop by denying that a structural account of faithful epistemic representation needs to identify a single morphism, one that is weak enough to allow for epistemic representations that are not completely faithful while leaving out the ones that are completely unfaithful. One could instead maintain that faithful epistemic representation is a matter of structural similarity and that the more structurally similar the vehicle and the target are (i.e. the stronger the morphism between the structures instantiated by the vehicle and the target is), the more faithful an epistemic representation of the target the vehicle is (Contessa forthcoming, Ch. 4).

If, as I suggested, the structural account is nothing but a version of the similarity account, at present the similarity account of faithful epistemic representation would not seem to have any genuine rivals. At present, some version of the structural account of representation seems to be the most promising way for the advocates of the similarity account to avoid the charge of vacuity. More work, however, is needed to show that the structural account can be developed into a full-fledged account of faithful epistemic representation and meet all of the challenges it faces.

2.4. Models and Idealization

So far, I have been mostly concerned with the *semantics* of epistemic representation—what makes a vehicle an epistemic representation of a certain target? And what makes an epistemic representation of a certain target a more or less faithful one? In this section, I will focus on the *pragmatics* of epistemic representation and in particular on what philosophers call 'idealization'.

A recurring theme in the literature on scientific models is that successful representation often involves a great deal of *mis*representation. In the terminology used here, scientific models are rarely (if ever) completely faithful epistemic representations of their target systems. Idealization (which consists in the deliberate misrepresentation of certain aspects of a system) is often the key to successful application of the conceptual and mathematical resources of our theories to that system.

The inclined plane model, for example, constitutes a highly idealized epistemic representation of my daughters going down the hill on their toboggan. Just consider one aspect in which the model is idealized. On their way down the hill, my daughters and their toboggan would be subject to an extraordinarily large number of forces (from air friction to the gravitational pull of the Sun). However, in the model, only two forces are acting on the box—a gravitational force (presumably exerted by a uniform gravitational field) and a normal force (exerted by the plane).

One may think that such a crude representation of a system is unsuitable for the purpose of predicting (or explaining) the behaviour of that system. According to what, following Ernan McMullin (1985), we could call '*the Galilean account of idealization*', however, faithfulness and successfulness do not need to go hand in hand in a model, for a less faithful model of a certain system can be as predictively or explanatorily successful as (if not more predictively or explanatorily successful than) a more faithful one.[19] But how is this possible?

First of all, it is important to note that the fact that *overall* the inclined plane is not a very faithful epistemic representation of my daughters on the toboggan does not mean that it is not sufficiently faithful *for my purposes*. After all, all I am interested in is that the toboggan would not reach an unsafe speed and the model is doing its job insofar as it gives me good reasons to think that the toboggan won't go too fast.

Once we draw this distinction, it becomes apparent that a model that is overall a more faithful representation of a system than another is not necessarily a more faithful representation for one's purposes. A model that would take into account, say, the gravitational pull of the Sun on my daughters and their toboggan may well be a more faithful representation of the situation *overall* but would not seem to be any better at predicting whether the toboggan will exceed a safe speed, as the contribution that that force makes to the speed of the toboggan is *negligible* compared to that of other forces.

Some of the forces that have no counterpart in the model however have a non-negligible effect on the final velocity of the toboggan. Frictional forces, for example, would seem to affect dramatically the speed the toboggan will reach. However, since these forces would only contribute to slowing down the toboggan and since including them would result in a more complicated model, if all I am interested is that the my daughters have a safe ride, I might as well use the simpler model.

If I don't want to deprive my daughters of a potentially fun and safe ride, however, the inclined plane model may no longer be sufficiently faithful for my purposes and I might have to abandon it in favour of one of the more complicated models that take into account frictional forces. If the slope is sufficiently smooth and icy, surface friction may be negligible compared to air friction. However, air friction on an object consists in the collision of millions of air particles with the object and is therefore a bewilderingly complicated phenomenon to model. The standard solution is to introduce in the model a force that approximates the net effect of these collisions. For example, air friction on our box can be represented as a force of magnitude $-1/2\ C\rho Av^2$ (where C is a drag coefficient, ρ is the air density and A is the

[19] See, e.g., (Cartwright 1983) and (Mc Mullin 1985). For a slightly different take on idealization, see (Strevens 2004 Ch. 8) and (Weisberg 2007b).

cross-sectional area of the box). In the new model the box would reach a terminal velocity $((2mg\,sin\theta)/C\rho A)^{1/2}$.

As even this simple example illustrates, successful modelling depends on the subtle interplay among different factors, including (i) the aspect of the behaviour of the system the modeller is interested in predicting or explaining, (ii) the features of the system that most significantly contribute to the production of that behaviour, and (iii) practical and principled limits to the representation of those factors. According to the Galilean account of idealization, the reason why a model need not be faithful in order to be (predictively or explanatorily) successful is that usually not all aspects of a system are equally relevant to the production of the specific behaviour we are interested in explaining or predicting. Those aspects that do not significantly contribute to the behaviour we are interested in can thus be safely distorted or ignored by our models (at least insofar as introducing them in the model would not significantly alter that behaviour).

In a few lucky cases, only a handful of easily modellable factors make a significant contribution to the behaviour we happen to be interested in. In most cases, however, Nature is less cooperative and a certain amount of ingenuity and ad hockery is needed to get our models to work. In some cases, it may even seem that the idealizations are essential to the success of models (in the sense that a de-idealized model would not be able to explain or predict the relevant behaviour).[20] In all of these cases, however, the question is not *whether or not* the model is idealized but *to what extent* it is idealized, so, even if it is still unclear if the Galilean account can deal with all of them equally well, what is clear is that we cannot understand the pragmatics of modelling without understanding idealization.

2.5. Models and Realism

While the representational picture of the relation between theories and the world has widely supplanted the descriptive one, it is still not completely clear what consequences, if any, this "representational turn" has on some of the classic debates in philosophy of science. One of the most interesting examples is perhaps the scientific realism debate, which has been traditionally framed in terms of theories and truth. There seem to be at least three views on how the representational turn has affected the scientific realism debate. The first is that the representational turn favours scientific realists, by helping them to side-step some of the notorious difficulties related to semantic notions such as reference and approximate truth (see, e.g., (Giere 1985)) and (Suppe 1989)). The second view is that the representational turn leaves the terms of the scientific realism debate by and large unchanged (see in particular (Chakravartty 2001) and (Chakravartty 2007, Ch. 7). The third is that the representational turn favours scientific antirealism.

In the literature one can find a host of arguments that taken together suggest that, on a representational picture, the notion of empirical success of our theories is either too strong or too weak to sustain the scientific realist's traditional arguments from success to truth. If one

[20] For a few examples of "essential" idealization see (Batterman 2001 and 2010).

adopts a weak notion of empirical success, then, since models from incompatible theories are often successful at representing different aspects or parts of the same real-world system, it would seem that the inference from success to truth would leave us with many true but mutually incompatible theories (see, e.g., (Morrison 2000, Ch. 2) and (Rueger 2005)). If one adopts a strong notion of empirical success, on the other hand, since even the models of our best theories are successful only within relatively small pockets of the world, it would seem that we are only justified in believing that theories are true of those aspects or portions of the world they are successfully at modelling (see (Cartwright 1999, especially Ch 2)). These and similar considerations seem to have caused a shift towards the anti-realist end of the spectrum.[21] It is still a matter of debate whether the representational turn warrants such as shift.

Whatever the case may be, the consequences of the representational turn on the scientific realism debate as well as other traditional debates in philosophy of science are still mostly uncharted territory and the exploration and mapping of such territory seems to be one of the most interesting and potentially fruitful projects for the near future. For the first time since the decline and fall of logical empiricism and the so-called "syntactic" view of theories and the post-Kuhnian "Balkanization" of philosophy of science, the representational turn may provide philosophers of science with a unified framework within which to work. While many important details still need to fall into place, the rough outline of the picture is already clear and seems to be far richer and more realistic than the one that preceded it. Much work still needs to be done to turn this rough outline into a detailed picture, but once most of the details will have been worked out, this new framework will hopefully shed new light on old issues and reveal overlooked connections among them.

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[21] See, for example, Cartwright's "patchwork" realism (Cartwright 1999), Giere's scientific perspectivism (Giere 2006), and van Fraassen's empiricist structuralism (van Fraassen 2008) all of which are partly motivated by the representational turn.

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