Scientific Models as Information Carrying Artifacts

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Abstract

We present an information theoretic account of models as scientific representations, where scientific models are understood as information carrying artifacts. We propose that the semantics of models should be based on this information coupling of the model to the world. The information theoretic account presents a way of avoiding the need to refer to agents' intentions as constitutive of the semantics of scientific representations, and it provides a naturalistic account of model semantics, which can deal with the problems of asymmetry, relevance and circularity that afflict other currently popular naturalistic proposals.

1. Introduction

In science, models are important, because they play a significant role in the acquisition of scientific knowledge. For instance, they are used to articulate and to test empirical hypotheses, to help in theory formation, to analyse and visualize data and so on. Scientists construct and study the behaviors of constructed models, and compare their behavior to observed behavior of a target system. The modeler´s goal is to gain an understanding of the complex real world systems via studying simpler, typically abstracted and idealized hypothetical systems that represent the real world in some relevant respects[1].

We propose that for this to be possible models must *carry information* about their targets, and that the *semantics* of models as scientific representations is based on this information-carrying property of models. When models are viewed as information carrying entities, reference to model builders'

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[1] Exactly what kind of things models are has been one of the most debated issues in the literature of models. Following Morgan and Morrison (1999) many divide accounts of (mathematical) models in to two traditions; the abstract and the concrete tradition. The abstract tradition includes, for instance, accounts of models as set theoretical structures (Suppes) or models as trajectories through state space (van Fraassen). The concrete tradition includes the accounts, which take the models to be like imaginary system structures that would be concrete, if they were real. Godfrey-Smith is one recent proponent of this view (Godfrey-Smith, 2006). There is yet another sense of "model", and a different use of models in science: a system that is simple and can be more easily investigated can stand in for a larger class of systems (for example the fruit fly as a model of inheritance and genetic regulation of development, or the mouse as a model of human responses to anti-inflammatory drugs). Our concern in this paper is strictly with models that are scientific representations constructed in order to inform us about some aspects of nature, for instance the causal structure of a real world system.. From that perspective models can be seen as public, man-made artifacts (the term "artefact" is borrowed from Knuuttila, 2005). They are not abstract entities (Giere, 1988), nor thoughts or other mental representations (Mäki, 2009a, 2009b) - unless one considers these to be manmade artifacts, of course. Models can still be abstract – e.g. mathematical or computational models - or concrete, such as Watson & Crick's physical scale model of the DNA molecule. The fully abstract ("metalogical") sense of models as set-theoretic structures satisfying a set of axioms is not included in the target of our analysis. Also, symbolic representation of some purely conceptual (mathematical or computational) structure is not included in our present definition of "model".

intentions and interpretations becomes redundant, as the information coupling of models and the world can be used as a basis for a representational theory, analogous to information-theoretic naturalization of representation in the philosophy of mind (Dretske, 1981; Fodor, 1992; Millikan, 1998; Eliasmith, 2005; Usher 2001). On this view, the semantic relationship between a model and a target system is *mind-independent*, or objective, in the sense that scientific models obtain their fundamental representational properties directly from their (statistical) connections to the world, independently of the intentions of model users or builders. Historically, one of the main motivations for these "objective" views of scientific representations (and for science in general) is that a model can be used for an indirect or direct analysis of the world only if it offers access to properties of the real world. As Anjan Chakravarty has written, "in the absence of substantive relations of "similarity" it would be a mystery how these [models] represent things in scientifically interesting way" (Chakravarty, 2009, p. 7). While Chakravarty suggests that this substantive relation is an instance of some kind similarity, we propose that the information theoretic account may offer a better criterion as to what constitutes a representation, and it may also offer a principled account of what makes a similarity relation into a substantive one. In addition, the information theoretic account provides an account, which can deal the problems of asymmetry, relevance and circularity that afflict other currently popular naturalistic proposals.

2. The problem of representation

While there is a general agreement about the significance of models in science, there remains a disagreement over how, and even whether, models represent their targets. One reason for this is that some philosophers find the whole concept of representation dubious, and attempts to sharpen the definition of representational relationships ambiguous, circular, or unsatisfactory for other reasons. For many, these and other difficulties have been reason enough to suggest giving up the attempts to say anything substantive about scientific models as "representations". For instance, Teller (2001, p.397) writes “I take the stand that, in principle, anything can be a model, and that what makes a thing a model is the fact that it is regarded or used as a representation of something by the model users. Thus in saying what a model is the weight is shifted to the problem of understanding the nature of [mental] representation.” Some philosophers of science, such as Suárez (2004), on the other hand, have argued for a “minimalist account of representation”, according to which we should not try to define scientific representation naturalistically, on the basis of the properties of the models and their relation to the world, but instead on the pragmatics of the ways that competent users use models as representations. The common wisdom of these accounts seems to be that there can be no workable user independent account of the representational character of models (see e.g. Teller, 2001, Suárez, 2004, also Callender and Cohen, 2005 to mention few examples).

However, we think it is premature to give up on the idea of the intrinsic representational character of models or the attempt to naturalize the scientific representations through defining the representational relationship without reference to intentional states of the model interpreters. As a body of literature in the philosophy of mind indicates (Dretske, 1981; Cummins, 1989; Fodor, 1992; Millikan, 1998), it is possible to build an account of representation that naturalizes representation directly based on the informational connection between a representation and its target. In the following chapter we will present our proposal, where we apply that account into the discussion concerning the representational characteristics of scientific models.

3. The Accounts of Representational Relationships

Representations are things that stand in for something. Now, there are two ways to approach the question of the semantics of models and other scientific representations, which can be called the *pragmatist* account and the *naturalist* account. The first of these, the pragmatist account, states that it is inter alia our intentional relations to models that constitutes their semantics. A model A represents a target B because we *use* it to represent B or because we *interpret* A to represent B (where use and interpretation is understood in intentional terms). The second account, naturalism, on the other hand, assumes that there is some (e.g. information theoretic) relation between a model A and a target B, that is constitutive of the model's semantics, and we can *only* use A to represent B (in the ways appropriate for scientific investigation) if A is in fact a representation of B.

The two approaches and their different varieties can be represented as different versions of the following schema:

A represents B if and only if C

While there is a general agreement about the importance representation is science, it is difficult to explicate what it is for one thing to stand in for another thing. Many naturalistically oriented philosophers of science have usually seen representation to be some kind of similarity relation, some degree structural "fit", between the model and some aspect of the world. This conception conceives condition C as follows:

(1a) A *represents if and only if is similar to B.*

This conception problematic is on many grounds. First, if truth as well as reference is defined in terms of similarity the model *cannot* radically misrepresent or be completely false about its target, as the target is, *by definition,* whatever the model is also true of. This problem can be called as the *circularity problem*.

Second, similarity is a vague notion that needs more rigorous characterization. There are many attempts to offer such a characterization. For instance, according to Giere scientific representations are similar to their target systems in certain specified respects to certain degree (Giere, 1988). Other philosophers have appealed various "morphisms" in order to specify the notion of "similarity" (da Costa and French, 2003; French, 2003; van Fraassen, 1980, etc). Now, let´s take a look at (1b), which is a more precise version of (1a):

(1b) A represents B if and only if the structure exemplified by A is isomorphic to the structure exemplified by B.

This conception characterizes the condition C as “isomorphism”, “partial isomorphism” or in some cases also “resemblance[2]” etc. (for instance, Giere, 1988; French, 2002; Mäki, 2009). These conceptions clarify the notion of similarity, but they still leave open some problems. First, these accounts have been disputed also on the logical grounds. Putting it briefly, an isomorphism or similarity relation between any systems – *a fortiori* a model and its target system - must be symmetrical, reflexive and transitive (Cummins, 1989; Fodor, 1990; Suárez, 2003). The representation relation as commonly understood is none of these things. Representation is asymmetric, since representations – and a fortiori scientific models - represent their targets, but targets do not represent the representations or models. Representation is also intransitive, since if the target system B of model A is itself a representation of some S, the model A does not thereby represent S. (If we notice this connection, we may of course choose to use A to represent S, but that is another matter). Finally, representation is not reflexive, as a model rarely if ever represents itself. These problems of *asymmetry*, *transitivity* and *reflexivity* need to be accounted for by all accounts of model semantics, pragmatist and naturalist, and here the similarity based accounts especially have troubles.

A fourth problem is the problem of *relevance*. A model typically cannot be perfectly “similar” with the target system, since almost *any* target system is too complex. It is an inescapable feature of scientific model building that it is not usually (or perhaps ever) possible to construct a full fidelity model of how a target system works in all its detail. Abstraction is used to reduce the degree of complexity, and counterfactual assumptions are put in place in order to create an idealized, but

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[2] There are also interpretations of resemblance which are not based on the idea of isomorphism. But in the present context resemblance- relation is typically considered to be a variant of isomorphism.

workable model[3]. This implies that models should be "sufficiently isomorphic" to the target in the *relevant* respects. Constraints on the arbitrary ways that a model and some system might resemble each other need to be put in place, since what is important for the modelers, and for assessing the semantics and/or truth of the model is that the model and the target should be sufficiently isomorphic in nonarbitary respects.

However, it is quite tricky to characterize "sufficiency" and "relevance" in a precise manner, especially in naturalist terms, which is why many scholars have been tempted by pragmatist semantics. Many have invoked the intentions, or intentional "use" of models in order to solve the problem of relevance: the relevant properties are those that the users of models take to be relevant (for example Giere, 2006; Mäki, 2009a, 2009b). Consider, for example, an attempt to solve this problems by Mäki (2009b): "Agent A uses object M (the model) as a representative of target system R for purpose P; addressing audience E; at least potentially prompting genuine issues of resemblance between M and R to arise; describing M and drawing inferences about M and R in terms of one or more model descriptions D; and applies commentary C to identify the above

[3] As well known, models are typically *abstract* (lacking features *known to be present* in the intended target), *idealized* (incorporating assumptions that are *counterfactual*, i.e. *known to be false* about the intended target), and *simplified* (representing only a few dependencies from among a multitude). This has led some to ask whether the view of models as representational makes any sense, if models are inaccurate or false descriptions of the world. For instance, insofar as idealization is taken to require the assertion of falsehood (e.g. Jones, 2005), idealization makes the models false descriptions. However, it is important to make a distinction between the conditions for A to be a representation of B, and the conditions for A to be an accurate or a *true* representation of B. After all, A can only be false about B if A is *about* B (a similar approach can be found for example in Callender & Cohen, 2005).

elements and to align them with one another… I join those, such as Giere, who have emphasized the importance of purposes and intentionality in the notion of model as representation. The relationship so conceived has the form: A uses M to represent R for purpose P… So for an object to represent at all, an agent's intentionality is required."

This solution refers back to the modelers' intentions to use the model A as a model for B (rather than some X it just happens to resemble). The intentionality (of the mental systems of) the models' users create not only the constraints of relevance, but it forms also the semantic relationships. Indeed, some have even suggested that models represent whatever the scientists themselves postulate or *intend* them to represent (for example, Teller, 2001, also Callender and Cohen, 2005). In philosophy of mind this kind of idea is known as the "derived intentionality" account (Searle, 1992):

(2) *A represents* B, *iff it is so interpreted by intentional agents*.

The derived intentionality account will thus make accounts of scientific representations dependent on prior intentional characterization of the users, and on empirical facts about how scientists interpret their models.

However, there are some good reasons to be dissatisfied with this solution. First, merely postulating (or intending) a representational relation to hold between a model and an intended target does not magically create a proper representational relation between them. Intentionality as such does not create a representational state of affairs between a model and its target. The modeling practices of scientists must involve *more* than good intentions, or merely talk. Second, since empirically the interpretational practices of scientists are complicated and not at all well understood, the issue becomes unnecessarily complicated. Third, it can be argued that as a solution to the problem of representation, pragmatist reference to the representationality of scientists' intentions is question begging. As Roman Frigg writes, "to say S is turned into a representation because a scientists intends S to represent T is a paraphrase of the problem [of giving an account of scientific representation – of explaining why or how S represents T] rather than a solution" (Frigg, 2006, p. 54).

What is more, the problem of relevance arises again, if the "pragmatic constraints" of *all* the modelers' interpretational activities are taken as constitutive of model semantics. We really must ask *which of these* activities are constitutive of the semantics of models? This problem cannot be solved by merely saying that those scientists intentions or interpretations are constitutive, which are relevant for scientists intending to represent B with A. The solution for this problem requires more than just an appeal to intentions, and probably it will involve establishing a some sort of substantive connection between the model and its target[4]. One might ask here: isn´t that precisely what isomorphisms (and other morphisms) are meant to do in those accounts, which are combinations of isomorphism and intentionality based views? In those accounts isomorphism regulates the way in which the (intended) model relates to the target system, and thus it imposes constraints on what kinds of representation are admissible (Frigg, 2006). Without such regulation an account of representation solely based on intentions would allow that everything can represent anything, if someone intends them to do so. So, it seems to us that in this sense isomorphism may solve some aspects of the problem of relevance by imposing some structural constraints for the model-target relationships. However, it does not solve the problem of semantic relevance, since isomorphism alone does not offer a substantive constraint on which aspects of the model are semantically connected to the target, and therefore relevant for the isomorphism. Before one can inquire into the isomorphism of two structures, one must first identify the elements and relations, and here the combined account relies on unrestricted subjective interpretations. Thus it cannot help with the question, which constraint on modelers intentions or interpretations are relevant in the constitution

[4] This interpretation is based on Frigg`s analysis (Frigg, 2006, p.7.).

of semantics. As Frigg has pointed out, isomorphism as such does not contribute to explain where a model´s representational power comes from, since it is the appeal to intentions that do all that kind of explanation (Frigg, 2006).

Many of these problems – the problems of asymmetry, intransitivity and reflexivity, and the problem of relevance, plus also the problems related to the issue of derived intentionality – are strictly analogous to the problems that crop up in information semantics in the computational philosophy of mind, and have been extensively discussed there since the 80's. So, if a naturalist does not want to commit herself to isomorphism/morphism- based or to intentionality based accounts, there are other ways for a naturalist to pursue. In the philosophy of mind there is a group of semantic theories called information semantics, and they largely superseded the isomorphism-view in the naturalistic analysis of representation (see e.g. Cummins, 1989). These accounts naturalize the representation directly without agent based- intentionality (Dretske, 1981; Millikan, 1989; Fodor, 1992). The information semantic accounts can be described as follows:

(3a) *A represents B if and only if A carries information about B.*

The causal-informational theories of semantics[5] hold that the content of a mental representation is grounded in the information it carries about what does or would cause it to occur (Dretske, 1981; Fodor, 1992). This connection is provided by a causal-informational relationship between the representation and the things in the world. This account uses the notion of *statistical information* (Shannon, 1948) to combine the statistic theories of information with the concepts of probability theory[6]. The concepts of probability theory provide exact statistical concepts with which to define

[5] There is a rich variety of information semantics, but in this paper we focus only on causal theories.

[6] This informational relationship is "physical" in the sense that we can think about physical phenomena carrying information about other physical phenomena, but the properties of information

the reference of representations (Usher, 2001).

These causal information theoretic accounts can deal *the problem of asymmetry,* because in the information semantic view the representational relation is defined as a directional relation - the information relationship is estimated by a *causal process*. Since informational connectedness is also *statistical*, the information semantic account should not be equated with a causal theory of reference (e.g. Kripke, 1980). In causal theories of reference a proper name refers to whatever (token) occasioned the original use of the name. Scientific representations are not proper names, but universals describing the type structure of the world. Thus in this account the statistical properties of the information gathering method that fixes the reference of models, *not* just the causal history of model making.

The information theoretic account can also deal *the problem of circularity*. Reference X of model element D is defined information semantically as statistically the type of X for which mutual information between the referent and the model is maximized (Eliasmith, 2005; Usher, 2001). Factors such as observational noise etc. may lead to situations where the actual target (token) from which information is being extracted *does not* correspond to the referent (type), thus making the model *false* about the target [7].

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are not defined in terms of physical causation but statistical dependencies.

[7] In the philosophy of mind, this is known as the problem of misrepresentation. The problem is one of defining the informational causal-information coupling in a non-circular way (so that models do not turn out to represent whatever happens to cause them). Marius Usher´s (2001) statistical reference theory is one very sophisticated example of those theories, where the problem of misrepresentation is taken seriously. The basic idea of it is that when a representation is tokened, the information it carries is about the class of items it carries the most information about, and not

As discussed on the previous section, similarity based views face the problem that a model might resemble many things which, intuitively, we would not consider to be among the model's targets. Constraints on the arbitrary ways that a model and some system might resemble each other need to be put in place, since what is important for the modelers, and for assessing the semantics and/or truth of the model is that the model and the target should be similar in the *relevant* respects. Thus (3) is too weak, since the model A may carry information about a lot of things, not only the "relevant" or "interesting" aspects of B. Let´s consider next,

(3b) *A represents B iff there is an iterative data gathering and hypothesis testing method* M *that supports a reliable statistical connection between some aspects F of A*, *and some aspects* X of B.

The reliable connection is implemented by the model building process[8]. It includes, for example, the experimental and data analysis methods, hypothesis and concept formation. Since the information relation is supported by an iterative, self correcting, process of interaction with the phenomenon (data gathering and model fitting), this process ensures non-accidental convergence between the world and the structure or behavior of (some parts of) the model. The representational character of models is a product of, and defined by, the iterative model building process, in which

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about what caused it in a singular case. Usher actually offers a neat technical definition that uses the notion of mutual information for dealing this problem. According to Usher A represents B if A carries information about B and for any C that A carries information about, this information is lower than for B. (See Usher, 2001 for details).

[8] This solution reminds the goldmanian analysis of reliable method of knowledge gathering (Goldman, 1986). In the philosophy of mind in Fodor's (1992) information semantics and Ryder's (2004) account of mental representation in terms of the mind/brain as a Model Making Mechanisms have similar features.

information about a phenomenon (coming through from the empirical data) is incorporated into the model. Now, since the information semantic account requires that there is a reliable information processing mechanism M, the model building process, that supports the information connection between A and B, it ensures *non-accidental convergence* between parts of the model and parts of the world. That is, for the model to be useful as a stand-in for the world, the "similarity" must be built into the model by adopting appropriate methods of observation and data-analysis. This is an essential part of the model building process and involves more than just talk or establishing arbitrary resemblances. Actually, when scientists build a model of some target system they *work very hard* to try to *ensure* that the model really represents the real world system. They debug their operational criteria and data analysis methods, they do parallel experiments to verify auxiliary assumptions, they relate their model to known background theory on the functioning of their measurement devices etc.. Not only do they manipulate the properties of the target system and try to record the systematic effects of these manipulations, but they also conduct a lot of parallel methodological research on the parts of the model in order to be able to present sufficient evidence that the model is representing the elements of target system.

On our view, the semantically "relevant" aspects of the world X are the parts of the world that this kind of model building process ends up *tracking*, and the relevant parts of the model F are the ones that end up performing this tracking– whether or not these properties are the ones the model builders *intend* or *believe* to be involved. The model building processes may well be *directed* by the intentions and assumptions about mappings made by the modelers. Scientific models are artifacts; they aren´t intrinsically models. Objects become scientific models, because scientists construct and intend them to serve as models. However, these intentions do not enter into the definition of the semantic relation itself. In the context of information semantics the semantic of models is a result of information carrying properties of the models that emerge from the model building *process*, not the modeler´s intentions *per se*.

These two - the question of semantics and the question of pragmatics of models - can be, and perhaps should be, kept distinct in the context of information semantics. One reason for this is that cannot always identify the relevant (and on the present view semantics-constituting) parts of the model *a priori* or simply by probing the scientists intuition, i.e. asking the scientists to identify them (although in practice this might often be the most reliable method). This is because *semantic relevance* is based on a real model-world relation, not only the purposes or intentions of a scientist. An individual scientist might be inclined to consider his or her pet template as “the most relevant” part of the model, or might consider the parts that are required to make the model cohere with his or her preconceived world view or general metaphysics as the parts that it is most important to "get right". Genuine information carrying representations differ from mere stipulations, since they allow us to obtain information about the intrinsic properties of target systems that we would not be able to do on the basis of representations based on arbitrary resemblance. In this sense an information theoretic account is not only a descriptive, but also a normative theory for representations: It gives a criterion for distinguishing a “genuine” representation from arbitrary mappings.

5. Conclusions

Recent discussions of scientific representations offer roughly two broad approaches to the question of specifying the nature of representational relationship between a model and its target system. On the one hand, there are accounts that emphasize that this relationship is some kind of objective, mind-independent relation such as similarity or isomorphism. On the other hand, the other broad approach to scientific representations sees their representational status as products of model users or constructors intentions and interpretations.

In this paper, we have presented briefly an information theoretic view of models as scientific representations, where models are understood as information carrying artifacts. The account we propose is based on the idea that the representational relationship is an objective relationship.

We have suggested that the semantics of models should be traced to the information coupling of the model to the world, rather than the intentions and interpretations of the models' users. We have proposed that the view that the parts of models carry statistical information about parts of the world can be used to counter the antinaturalistic critiques, and develop a detailed account of model building and representation with the added benefit of direct relations to parallel work in the philosophy of mind.

From this perspective, a crucial aspect of models, or at least precisely definable parts of them, is that they *carry information* about the properties of their targets. When models are viewed as information carrying entities, this property of models can be used as a foundation for a representational theory analogous to information-theoretic naturalization of representation in the philosophy of mind. There are many advantages to this approach compared to qualitative discussions of "pragmatics" of modeling, among them increased conceptual precision and the opportunity to define semantics of scientific representations directly, without reference to prior intentionality of the users' intentions. Of course, there are many problems left open by an information theoretic account. It is not trivial to work out the details about which aspects X of B a model making mechanism M makes the product, A, to represent and which not. However, many of these problems are strictly analogous to the problems that crop up in information semantics in the computational philosophy of mind, and have been extensively discussed there since the 80's with significant recent developments.

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