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Scientific Representation

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Abstract:

Scientific representation is currently a booming topic, both in analytical philosophy and in history and philosophy of science. The analytical inquiry attempts to come to terms with the relation between theory and world; while historians and philosophers of science aim to develop an account of the practice of model building in the sciences. This article provides a review of recent work within both traditions, and ultimately argues for a practice-based account of the means employed by scientists to effectively achieve representations in the modelling sciences.

1. The analytical and the practical inquiries

Representation has become a booming topic in philosophy of science – if judged by the number of conferences, workshops, books and articles produced in the last few years. The

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topic is at the crossroads of attempts in analytical philosophy to come to terms with the relation between theory and the world, and in the philosophy and history of science to develop a proper understanding of the practice of modelling in the sciences. Scientific representation also has overlap with, and has been claimed to have implications for, metaphysics, the philosophies of mind and language, and aesthetics.

The interest from analytical philosophy is related to the notion of reference, and the metaphysics of relations; the interest from philosophy of science is related to an attempt to understand modelling practices. These two distinct forms of inquiry into the nature of representation may be distinguished as the "analytical inquiry" and the "practical inquiry". Although they are not exclusive, they impose different demands and point in different directions. The analytical inquiry seems to have historically preceded the practical one, but the relative importance of the latter has grown to the extent that in recent years it has become dominant. This mainly reflects the intense attention that philosophers have paid to scientific models and modelling practice in the last decades.

The analytical inquiry tends to presuppose that representation is a relation, and focuses on providing an analysis of this relation. It is useful to begin by fixing some terminology as follows. Let us refer to the vehicle of the representation as the 'source'; and the object as its 'target'. (Thus in a portrait the canvas is the source and the person portrayed is the target). Anything can in principle play the role of sources or targets, so these terms are mere place-holders. I shall assume that X is the source and Y is the target if and only if 'X represents Y' is true. The analytical inquiry then, in its most basic form, takes it that representation is a relation R such that the assertion that ‘X represents Y’ is equivalent to the assertion that ‘R holds between X and Y’. (The most basic form assumes a uniquely specified dyadic relation that holds between all sources and targets. But the analytical inquiry can take more complex forms, and there are different ways in which this assumption may be relaxed).

The contemporary literature on the analytical inquiry into representation goes at least as far back as Charles Peirce, who provided one of the earliest and most influential theories of signs – a term he used ambiguously to refer to different sorts of representations and representational sources alike. In more contemporary terms, Peirce’s theory lays down a triadic relation between the *source*, a sign in some symbol system (or, according to Peirce, the *representamen*); its *target* (or *object* in Peirce’s terminology) and an interpretation or understanding of this sign (the *interpretans* for Peirce). Moreover, in Peirce’s terms, a representation is a non-degenerate, e.g. essentially triadic, relation: it can not be further decomposed or analysed into a complex function of more basic dyadic relations between *representamen*, *object* and *interpretans*. [2]

Peirce famously went on to divide all representations into three types: iconic, symbolic, and indexical. Roughly, the sources of iconic representations bear similarities to their targets, those of indexes bear causal relations, while symbols denote their targets conventionally. Thus a portrait is typically an icon of the person portrayed, smoke is often an index of fire, and the word “cat” is a symbol of the feline animal. In all cases the

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[2] See esp. Peirce (1931, ch. 3).

triadic relation is distinct and can not be reduced to a function of the dyadic relations ("similarity", "causation", "denotation") that hold between source and target. [3]

By contrast, the practical inquiry has avoided questions regarding the nature of the representational relation, focusing instead upon the very diverse range of models and modelling techniques employed in the sciences. The presupposition behind this type of inquiry is that these modelling techniques must be properly understood in their context of application. The literature on modelling in science is by now immense. Some of the historical key texts include Norman Campbell's (1920) and Mary Hesse's (1966). In the last two decades the turn towards what I have referred to as the practical inquiry has intensified. This movement takes model building to be the primary form of representational activity, so a very large amount of work has been devoted to studying particular cases of models and modelling in painstaking detail in order to figure out in what specific ways models are helpful to the modellers in their diverse pursuits. [4]

One theme shared by all these attempts to understand modeling is the emphasis on *use*. The assumption runs through that without an appreciation of the particular use of a model in its context of application it is impossible to fully appreciate its role. We need to pull our gaze away from the relation between the entities (equations and so on) that carry out the representational work and their targets, in order to consider also the

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[3] Peirce is not always explicit. For exegesis along these lines, see Hookway (1985, ch. 4).

[4] The following is just a sample. Mary Morgan and Margaret Morrison's edited collection (1999) brought to the fore the autonomy of model-building from both theorising and data-collection. The series of books edited by Lorenzo Magnani and his co-editors arising out of the Pavia conferences, such as (1999), focused on how model-based reasoning differs from typical theorising. De Chadarevian and Hopwood's edited volume (2004) emphasised how important the historical context is for determining the purpose of models.

purposes of those who use and develop the representations. Many different issues become visible when this wider vision is adopted including the phenomenon known as transference – of both knowledge and representational techniques – from one field to another. The same representational source may be used to represent several targets in different fields. [5]

Given these two forms of inquiry into scientific representation, it is not surprising that the questions typically also come in two varieties. First, when we say of a model X (a graph, an equation, a diagram, etc) that it represents a system Y (a physical object, a phenomenon, a population, etc.) we may ask, in an analytical spirit, what exactly is the relation R presupposed between X and Y. In other words, what is the relation R that *constitutes* representation? Let us refer to this as the constitutional question. Second, we may ask about any specific use of a model what kind of features and properties obtain in the wider context of application that allow models to perform their job. In other words, what are the effective *means* that scientists employ to get representations to deliver the required 'goods'? We may refer to this as the pragmatic question.

Section 2 develops some key distinctions to address these questions. Sections 3 and 4 outline some of the main accounts of representation available, and defend a deflationary and non-reductive option, the inferential conception. Section 5 takes stock and draws some conclusions.

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[5] A celebrated, albeit controversial, example is Mirowski (1991), a study of transference between field theories in physics and value theory in econometrics at the turn of the century.

2. **Constituents versus means: Representation and accuracy**

The analytical inquiry pursues definition and conceptual analysis, and it emphasizes what I called the constitutional question. It is interested in the relation R that must conceptually hold between source and target for the source to represent the target. Thus theories of the constituents will typically implicitly answer the question: what is scientific representation? The practical inquiry by contrast focuses on what I call means. It studies those context dependent properties and features of a particular representing situation that make the source useful for scientists as a representation of the target. It is interested in pragmatic questions regarding the actual workings of models, including (but not limited to) judgements of accuracy or faithfulness. Accounts of the means of representation will typically provide case by case analyses of the types of properties, relational or not, of sources, targets, users, purposes, and context – both the context of inquiry and the wider social context – for any given particular representation. [6]

We may attempt some tentative definitions as follows:

Constituents: R is the constituents of representation if and only if for any source-target pair (S,T): S represents T if and only if R (S, T, x), where x sums up whatever additional elements come into the relation of representation. [7]

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[6] Contessa (2007) exemplifies the analytical inquiry into the constitutional question. Knuuttila (2009) is an example of practical inquiry into pragmatic questions regarding means.

[7] In the most basic form of analytical inquiry, R is a binary relation and x is the empty set.

Means: For any source-target pair (S, T) at a given time and in a given context: R' is the means of the representation of T by S if some user of the model employs R' (at that time and in that context) in order to draw inferences about T from S.

Concerning these definitions, the following remarks are in order. First, the constituents are implicitly defined by a necessary and sufficient condition; but the means are simply characterized via a sufficient condition. Second, note the inverted order of quantifiers: R is a unique and universal relation for any source-target pair, while R' is a context-dependent, time-indexed relation, which is not unique even for a particular source-target pair, never mind universally. Finally note that the means are pragmatic and context-dependent, while the constituents are analytical and do not depend on anything that does not come under the definition of the representational relation itself.

The distinction leads naturally to a further and important distinction. Philosophical discussions concerning scientific representation have in the past often focused upon the *accuracy* of scientific models. Fortunately this is no longer the case, and nowadays representation is carefully distinguished from truth, accuracy or faithfulness. [8] The distinction is essential to make sense of the phenomenon of scientific misrepresentation. Models often are inaccurate and misrepresent in some definite ways. This does not however take away any of their representational power: An imperfect and inaccurate model M of some target system T is still a model of T. (Just as an inaccurate portrait, such as a caricature, is still a representation of the person portrayed). The puzzles regarding the notion of representation are prior to and independent of issues of accuracy.

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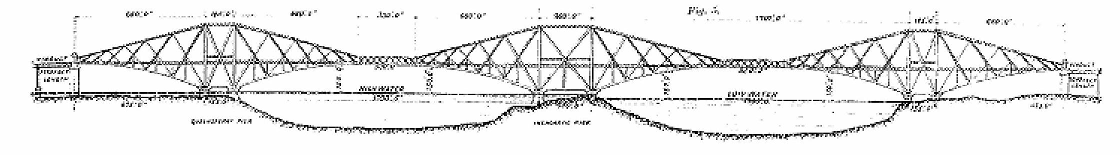
[8] Suárez (2003, p. 226), Frigg (2006), Contessa (2007), Van Fraassen (2008, pp. 13-15).

It may help to focus on a simple and graphical example from the engineering sciences: the Forth Rail Bridge in Edinburgh, one of the first steel-built cantilever bridges in Europe.[9] The following is a graphical representation:



The point is that there are two questions one may ask about this graph. First, what object or system in the world does this graph represent? In our terminology the graph is the source of the representation and the actual bridge is its target. Only once this is established can a further question be meaningfully posed: how accurate, or faithful, is this graph as a representation of the bridge? If the graph represented something else – e.g. the complicated pattern of tensile forces acting on a telegraph line – the assessment of its accuracy might turn out to be very different. So questions of representation must be settled before judgements of accuracy or faithfulness are formulated; otherwise there is no standard against which to draw such judgements. And this shows that the two questions are distinct.

The distinction may be accommodated in terms of the definitions of constituents and means as follows. There are many properties of the graph that a user may take interest in when applying it in order to find out useful information about the bridge. Even among the

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[9] An example studied in depth by the eminent British historian Michael Baxandall in his classic (1985).

geometric properties, we might be interested in the geometric relation between the lines, and use them as a guide regarding the relation between the steel cantilevers – for which the graph above is quite accurate. Or we might look into average distance from the railway to water surface – for which it is less accurate for any particular time and day of the year. Finally we could gain an interest in the shape of the Forth's basin – for which the graph is even more grossly inaccurate. Then there are non-geometrical properties of course. The colour of the lines in the graph is by and large an inaccurate indicator of the colour of the different parts of the bridge. And the texture of the paper the graph is printed on is a very unreliable indicator of the strength of the bridge. Etc. All these are means, each in its context of inquiry. Some are clearly more effective than others in generating accurate representations, but they all provide some benchmark for accuracy judgements. Moreover they are all in principle consistent with the claim that the graph printed on the paper represents the bridge. Whatever constituent *R* is the truth maker of this claim at best one of the means *R'* can be identical to it. Hence means and constituents differ from each other, and the means suffice for accuracy judgements in general.

3. Reductive accounts: Similarity and isomorphism

Let us now first focus on some accounts of the constituents of representation. It is useful to begin by dividing such accounts into different kinds. Two dichotomies will be particularly useful. First, an account of representation in science is reductive if it analytically defines the representational relation R in terms of something else. By contrast the account is primitivist if it claims that the representational relation, if there is any, may not be further analyzed – it is rather a primitive that may be invoked elsewhere, e.g. for explanatory purposes. [10]

Another dichotomy divides substantive from deflationary accounts. A substantive account takes it that representation is a robust property or relation of sources and targets. A deflationary view will take it instead that representation is not a robust property or relation of sources and targets; the term "representation" on this view just picks out some functional dependencies within a particular context of inquiry.

These distinctions are in principle orthogonal to each other. That is, primitivism is compatible with a substantive or a deflationary view; and similarly for reductionism. It stands to reason, however, that substantive theories will be more naturally reductive, while deflationary views will tend towards primitivism. The reduction of one notion to another is typically motivated by an attempt to figure out the real robust properties underlying that notion. [11] A deflationary approach by contrast will normally eschew reduction: although a reduction of some notion X to a further non-substantive notion Y is in principle a possibility, the cognitive gain seems small.

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[10] Compare primitivism vs. reductionism in the analysis of laws, causation and time. A primitivist thinks these notions are not further analyzable. A reductionist will want to analyze them in terms of other properties or relations. For instance a Humean may want to reduce laws to regularities; causation to probability, typically understood as frequency; and time to open conjunctive forks or 'oriented' correlations.

[11] And indeed the Humean offers substantive accounts of regularity, frequency and correlation.

And indeed the two main reductionist accounts available are also substantive. One claims to reduce representation to isomorphism, the other to similarity as follows.[12]

The similarity conception of representation [sim]: A represents B if and only if A and B are similar.[13]

The isomorphism conception of representation [iso]: A represents B if and only if A and B instantiate isomorphic structures.[14]

Both accounts are backed up by some strong intuitions. For instance, the graph of the Forth rail bridge is similar in some relevant respects to the bridge itself: the relative distances and ratios between the cantilevers and girders are preserved, as is the average distance between the bridge's three land stands relative to the distances between the beams in each stand. There are of course other ways in which the piece of paper that the graph is printed on does not seem to be relevantly similar to the bridge, such as its colour or texture. So this already gives us a sense of how "similarity" as a means may be used to ground judgements of representation. The source only represents in those respects that are relevantly similar to the target.

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[12] The terms [iso] and [sim] were first introduced in (Suárez, 2003), and the definitions above are slightly revised versions. Bas Van Fraassen (1980) has been thought to defend something close to [iso], and Ronald Giere (1988) something close to [sim]. However, these are not their considered views, as made clear in Van Fraassen (2008), and Giere (2004). French (2003) provides arguments in favour of isomorphism as a necessary and sufficient condition on representation and thus may be taken to defend [iso], while Aronson, Harré and Way (1995) came close to defending [sim], albeit under a more sophisticated account of similarity.

[13] The *identity theory of similarity* is typically invoked: A is similar to B if and only if A and B share some properties. The disadvantage of this theory is that on a purely formal definition of similarity, any object is similar to any other. So it is important to supplement the theory with some criterion of relevance.

[14] Two structures $S = <D, R_i>$ and $S' = < D', R'_i>$ are isomorphic if there is a one-to-one mapping from the domain of S into the domain of S' which preserves all the relations defined on either.

There are however several powerful arguments against [sim], which make the position untenable. I will only mention one here, the so called ‘logical argument’, which derives from Nelson Goodman’s critique of resemblance in the arts. [15] Goodman pointed out that while representation is non-reflexive, non-symmetric and non-transitive, resemblance is an equivalence relation. Similarity need not be transitive (certainly ‘relevant similarity’ is not) but it is reflexive and symmetrical. So it can not provide a reduction basis for representation in general, since it does not possess the right properties to carry out the job. (To state the obvious counterexample: while the graph represents the Forth rail bridge, the bridge does not represent the graph).

But also note that the similarity discussed is relational, in the sense that what gets preserved in our example are the properties of the structure of beams and cantilevers. Mathematically this may be expressed as an isomorphism between two structures. Suppose that the structure of beams and cantilevers in the rail bridge may be written down as $S_b = <D_b, R^i{}_b>$, where D_b is the set of elements in the structure, and $\{R^i{}_b\}$ are the predicates defined over the elements of D_b. [16] For instance, we may assume that every beam is an element in the structure, and the number of intersections of each beam with other beams are the relations. Hence there will be beams that intersect only once, beams that intersect twice, and so on. And these form a structure. We can similarly write down a

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[15] Goodman (1968, pp. 3-10).

[16] The full definition of structure will typically include a specification of distinct n-place relations R_i^n holding between the elements in the domain, and functions, or operations O_i acting on those elements. Functions are ignored here since irrelevant to our purposes.

structure S_g = $<D_g, R^i_g>$ for the lines and vertices in the graph. And then we can just check for isomorphism between S_b and S_g.

Hence structural similarity is a special case of similarity. And indeed in the mathematical sciences structural similarity is often the only relevant kind. A problem remains however for the view that takes representation in science in general to be reducible to isomorphism. For the sources and targets of a representation are not generally mathematical entities. The graph of the Forth rail bridge is a good example of a representation of a concrete physical object by another concrete physical object. To apply isomorphism to such objects we need to appeal to the *instantiation* of structure.[17] We may say that an object instantiates some structure if there is some division in parts and relations of the object that agrees with the structure. The procedure above then shows that the bridge instantiates S_b, and the graph instantiates S_g.

The definition of [iso] makes all this explicit. But it does not make explicit that instantiation is multiple: every object or system instantiates more than one structure. Suppose for example that instead of considering the beams and cantilevers of the bridge, we take its vertices (the points where at least two beams cross) to constitute the elements of the domain. We can then say that the structure is made up of a number of elements, namely all the vertices, endowed with certain properties such as the number of beams that join together at any given vertex. Hence some vertices join two beams, some join three, and so on. This structure S'_b = $<D'_b, R'^i_b>$ is also instantiated by the bridge. Since the

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[17] In earlier work I used the term 'exemplification' rather than instantiation (Suarez, 2003, pp. 227-8), and others have followed suit – e.g. Frigg (2006, p. 58). But this now strikes me as unfortunate, since there is an entrenched use of 'exemplification' in Goodman's work that differs in crucial respects (see next section).

number of vertices is larger than the number of beams the two structures are not isomorphic and we conclude that the bridge instantiates distinct and non-isomorphic structures. A similar reasoning would seem to go through for any physical object whatsoever. Since there are always different ways of *cutting out* its domain of elements and relations, every physical object instantiates simultaneously several structures. The physical world underdetermines its mathematical structure – which may only be ascribed under a particular description.

Thus the most sophisticated account [iso], while being universally applicable, has a problem with under-determination. Since the structure that sources and targets instantiate is underdetermined, it is also underdetermined whether they stand in the representational relation dictated by [iso]. (Additionally [iso] is prey to the same objection raised against [sim]: unlike representation, isomorphism is an equivalence relation).

So both attempts at reducing representation fail. Some alternative, weaker notions of similarity may be employed in the definition of [sim]; and weaker morphisms have been invoked in the definition of [iso]. But even with such modifications they continue to be subject to a variety of objections. [18] A more promising approach is to give up on the aim to reduce representation to such notions, and either show them to be the by-product of representation in particular domains, or else relax the need for necessary and sufficient conditions. This leads us to consider non-reductive or primitivist accounts.

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[18] For notions of similarity that depart from the identity theory see (Aronson, Harré and Way, 1995). For weakenings of [iso] and their continuing problems see (Suárez, 2003).

4. Non-reductive accounts: “DDI” and the inferential conception

Non-reductive accounts may be deflationary or substantive. Roughly a substantive non-reductive account takes it that representation is a genuine property or relation but it is not further analysable or reducible to other properties. At best we can establish some necessary conditions or point out some of its most general features. So on this view the analytical inquiry is worth applying, although it is limited by the very nature of its subject – which does not allow a proper definition. A deflationary account, by contrast, takes it that the concept of representation is essentially linked to its use, and is thus best characterised by its function or role in the practice of model-building. On this view the analytical inquiry is inappropriate for scientific representation, which is best approached in the first instance via the practical inquiry. Non-reductive accounts will typically line up on a spectrum from strongly substantive to radically deflationary.

An example of non-reductive account is the DDI (Denotation-Demonstration-Interpretation) model developed by RIG Hughes in (Hughes, 1997). On this account representation can not be further reduced. In particular it can not be reduced to the combination of the three typical elements of denotation, demonstration and interpretation; with denotation the most substantive. [19]

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[19] Hughes writes: “I am not arguing that denotation, demonstration and interpretation constitute a set of speech acts individually necessary and jointly sufficient for an act of theoretical representation to take place” (Hughes, 1997, p. 329). And yet, denotation is treated, following Goodman as “the core of representation” (p. 330); so apparently, at least, as a necessary condition.

On this account a representation is a heterogeneous mixture of a relation and activity involving typically three phases. First, the model *denotes* the system modelled. This denotation is essentially conventional, and is the core relation between representational source and target. For example, in the case of the graph of the Forth rail bridge, the graph is supposedly stipulated as a representation of the bridge and is henceforth taken to denote it. Second, a *demonstration* takes place, broadly understood as the proof or derivation of a new result from some general features of the model. For instance, if we measure the relative lengths of vertical and horizontal cantilevers on the graph we can calculate a ratio between the length and the height of the bridge in the graph. The third step involves *interpretation*: bringing these results to bear on the original target of the representation. In the case of our graph calculation, for example, we can apply the ratio directly to the length of the horizontal cantilevers in the actual rail bridge in order to find out its height.

The advantages of the DDI account over the reductive accounts are many and varied. It skilfully avoids many of the objections, including the logical argument, since denotation is essentially involved and is clearly a directional notion: it is non-reflexive, non-symmetric and non-transitive. It also nicely connects the analytical and the practical inquiry, since on the one hand denotation calls for analysis, while on the other hand demonstration and interpretation are activities governed by their corresponding operating norms, and therefore require a practical inquiry.

However, the DDI account also suffers from some difficulties. First, although Hughes does not require demonstration essentially he does take it to be typical of scientific representation. This seems to entail that those models that have not yet been employed in demonstrating new results about their targets do not typically qualify as representations. For instance, suppose that I just come across the graph of the rail bridge, with a label attached to it that clearly stipulates the actual bridge as its proper target. The DDI account seems to entail that I am not entitled to take the graph to be a representation unless I carry out some demonstration on it – such as the ratio calculation mentioned above – which seems counterintuitive. Second, the requirement that the source denotes the target implies that the target must be a real entity. Thus the representation of fictional entities is ruled out, which seems to compromise many scientific models throughout history. (For instance, models of the ether would be turn on this view to be non-representational).

The DDI account may in principle be amended to overcome these difficulties. First, the requirement that sources denote their targets could be replaced by the weaker requirement that they have "denotative function", which allows representation of fictional entities. [20] Second, demonstration could be replaced by the weaker "potential for demonstration" which does not require the actual carrying out of any reasoning on the part of any agent. The resulting account (let us call it the Denotative Function – Potential for Demonstration – Interpretation, or 'DFPDI' account) is certainly not simple, but that may just reflect the fact that representation itself is not simple. (A simpler account that stays within Goodman's tradition would employ the notion of exemplification. On this account a

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[20] Denotation is a success term (nothing denotes unless it successfully refers) but denotative function is not (a symbol may have denotative function while failing to successfully refer to anything). For an elaboration of this point see Elgin (2009, pp. 77-78).

model represents by exemplifying certain features of the target, which does not require reference to the target itself.[21])

A more deflationary account, the inferential conception, has also been argued to overcome these difficulties.[22] On the inferential conception representation is a 'two vector' notion, requiring on the one hand *representational force* and on the other hand *inferential capacities*. The conditions are weak enough (they are in particular weaker than either denotation or demonstration) that we may stipulate them to be necessary on scientific representation without any loss of generality. Representational force is a feature of the practice of using a particular source as a representation, which determines its intended target. On this view the representational target is not determined merely as a result of a convention or stipulation, but must be established by the norms that govern the practice (of this particular representation). Consider the Forth rail bridge graph again. The graph is not a representation of the actual bridge merely by an act of stipulation. On the contrary the graph was constructed already within a practice that took it that its representational target would be the bridge. The relevant practice can of course change over time but representational force is always the feature of that evolving practice that selects the target that corresponds to a particular source at any given time.[23]

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[21] Exemplification requires both instantiation and reference, but only regarding the particular properties exemplified. See Goodman (1968, pp.52-68) for the original insight, and Elgin (1996, chapter VI) for a development of the idea.

[22] See Suárez (2004). Van Fraassen (2008) defends a similarly deflationary approach.

[23] Suppose that the graph was constructed in a completely independent manner (say, randomly and without any purpose in mind) and only by means of some act of stipulation came to be a representational source for the bridge. It is still the case that thereafter any representational use of the graph is embedded in a particular practice of representation – with norms that establish its proper representational force.

The inferential conception adds a second condition, which is specifically required for *scientific* representation. The source must have the capacity to be employed by an informed and competent user in order to draw valid inferences regarding the target – what is known as 'surrogative' reasoning or inference. [24] This requirement certainly requires unravelling, since it brings together several features of the practice of scientific representation. First of all, for the source to have this capacity it needs to be endowed with some internal structure: it must be the case that the source can be divided into parts and the relations between the different parts can be outlined. Secondly, the source's parts and relations are in some way interpreted in terms of the target's own parts and relations. This is an implicit condition without which surrogative inference would be impossible. [25] Finally, there must be some set of norms of inference in place to distinguish clearly those inferences that are correctly drawn from those that are not. Supposedly, in the case of deductive inference, they must include at least those norms that establish logical consequence. But exactly how those are applied in detail, and whether or not additional norms are applicable in surrogative inference, will also depend on the features of the model and the context in which it is employed. [26]

5. Intended use versus intentional conceptions

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[24] The original insight that surrogative reasoning is essential to scientific representation is due to Chris Swoyer (Swoyer, 1991).

[25] Contessa (2007) makes this condition explicit.

[26] Note that the inferential conception does not stipulate the inferences must be to true conclusions. All theories of logical consequence distinguish between correctly drawing inferences, and drawing inferences to true conclusions. And any inaccurate representation will include at least some false premises. Since most authors nowadays accept that all representation is inaccurate to some degree, it follows that the analogous of validity, not soundness, for surrogative inference is the appropriate requirement on representation.

Both denotation and representational force have built in what we may call the 'outwards directionality of representation'. They direct from source to target in the appropriate way, thus allowing the DDI account and the inferential conception to avoid the logical argument against the reductive accounts. Representational sources typically do not represent themselves: the same object is not both source and target of the very same representation. Similarly, the fact that the source represents the target does not imply that the target also represents the source. And certainly neither denotation nor representational force are transitive relations. The word "dove" means and denotes a type of bird that can in turn be used to denote peace, but it does not follow that "dove" means peace. [27]

The directionality of representation has sometimes been conflated or assimilated to its supposed 'intentionality'. [28] Intentionality is a well known hallmark of mental representation – often taken to be the defining feature of mental or cognitive states. The insight of course goes all the way back to Brentano within the phenomenological tradition – which takes intentionality to be a non-natural and non-reducible property. By contrast, the analytical tradition tends to understand intentionality as a natural property, possibly reducible to further physical properties. But in either case the claim that scientific representation is intentional entails that it shares the intrinsic 'aboutness' of mental phenomena. This suggests that a scientific model represents via someone's mental state, i.e. that two objects stand in a representational relation if and only if they are so

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[27] There may be exceptions. One must be careful in stating the logical properties of representation, which is merely non-reflexive, non-symmetric and non-transitive.

[28] Among defenders of an intentional conception of representation in general Van Fraassen (1995), Frigg (2006), Callender and Cohen (2006), and Giere (forthcoming) all favour an 'intentionality' version. Van Fraassen (2008, esp. chapter 2) by contrast endorses an intended use conception akin to those of Hughes (1997) and Suárez (1999).

‘connected’ in the mental or cognitive state of a particular agent. We may even sum up the intentionality conception in the slogan that ‘representation is a property of the mind’.

To return to our example, the graph would be a representation of the bridge because it is so connected in the *mind* of some agent. (The details are somewhat mysterious however: How exactly does the directionality of the graph towards the bridge follow from the aboutness of mental states towards their objects – which after all include both graph and bridge, i.e. both sources and targets?) Note also that an intentionality conception is in principle amenable to an analytical inquiry, albeit not in its most basic form, since representation would not be a simple dyadic relation. But a more sophisticated analysis, such as Peirce’s, whereby representation is essentially triadic, seems viable. [29]

In other words, an intentionality conception seems perfectly apt as a substantive and reductive theory of representation. Consequently a non-reductive or deflationary account is unlikely to trade in intentionality. And indeed neither the DFPDI account nor the inferential conception appeal to mental or cognitive states in any essential way. These accounts instead appeal to the intended *uses* of a representation. The DFPDI account has representation by models equated with a relation (denotation) plus some activities (demonstration and interpretation); and both relation and activities are the product of some act or acts performed by the users of the models. The inferential conception does away even with the relation, and takes representation to be the conjunction of two

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[29] There are some caveats. For example Peirce takes his *interpretans* to always be also a *representamen* in a new representation of the *object*, and so on ad infinitum. (See e.g. Stanford Encyclopedia entry on Charles Sanders Peirce, section 10). This is clearly not required for an intentional conception of representation, since the mental state that provides the ground level connection between the source and the target is not required to be further represented by any other mental state.

activities that are carried out in the context of some established collective practice. It follows that on these accounts representation is not at all ‘in the mind’ of any particular agent. It is rather ‘in the world’, and more particularly in the social world – as a prominent activity or set of activities carried out by those communities of inquirers involved in the practice of scientific modelling.

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Mauricio Suárez is a philosopher of science specialising in philosophy of physics. He has published widely on the philosophy of quantum mechanics, modelling and representation, and scientific epistemology, in journals such as *Erkenntnis*, *Studies in History and Philosophy of Modern Physics*, *Foundations of Physics*, *Philosophy of Science*, *British Journal for the Philosophy of Science*, *History of the Human Sciences*. He is the Editor of *Fictions in Science* (Routledge, 2009) and *Probabilities, Causes and Propensities in Physics* (Springer, forthcoming), as well as co-editor of the Proceedings of the founding conference of the European Philosophy of Science Association (EPSA), which he organised in Madrid in 2007.

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