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SCIENTIFIC REPRESENTATION

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INTRODUCTION

Scientific representation is a booming field nowadays within the philosophy of science, with many papers published regularly on the topic every year, and several yearly conferences and workshops on related topics. Historically the topic originates in two different strands in 20th century philosophy of science. One strand begins in the 1950s with philosophical interest upon the nature of scientific theories. As the received or 'syntactic' view gave way to a "semantic" or "structural" conception, representation progressively gained the centre stage. Yet, there is another, older, strand that links representation to fin de siècle modelling debates, particularly in the emerging 'bildtheorie' of Boltzmann and Hertz, and to the ensuing discussion amongst philosophers

thereafter. Both strands feed into present day philosophical work on scientific representation. There are a number of different orthogonal questions that philosophers ask regarding representation. One may ask about the nature of the representational relation between theories or models, on the one hand, and the real-world systems they purportedly represent. Such questions lie at the more metaphysical and abstract end of the spectrum – and are often addressed with the abstract tools of the analytical metaphysician. They constitute what we may refer to as the "analytical inquiry" into representation. On the other hand there are questions regarding the use that scientists put some representations to in practice – these are questions that are best addressed by means of some of the philosopher of science's favourite tools – descriptive analysis, illustration by means of case studies, induction, exemplification, inference from practice, etc – and are best referred to as the "practical inquiry" into representation. The notion of representation invoked in such inquiries may be 'deflationary' or 'substantive' – depending on whether it construes representation as a primitive notion, or as susceptible to further reduction or analysis in terms of something else.

GENERAL OVERVIEWS

Discussion of representation amongst scientists – physicists in particular – and philosophers alike goes back to the 19th century. Yet, explicit and articulate reflections upon representation within philosophy of science are much more recent, and arguably only emerge about 15 years ago. Already a historical document, Hughes 1997 started the interest of many of us on the topic. A number of recent book-length treatments such as Pincock 2012 and Winsberg 2011 provide general overviews from different angles and philosophical persuasions – thus bearing witness to the extraordinary fertility of the topic within recent years. There are as of today very few state of the art papers such as Suárez 2010; but fortunately many of the recent book length contributions start off by setting some of the required background – see Boniolo 2007 and Van Fraassen 2008. The selection in this section attends mainly to accessibility as an introduction and / or overview.

Boniolo, Giovanni. On Scientific Representations: From Kant to a New Philosophy of Science. London and New York: Palgrave MacMillan, 2007

> A historical introduction to the topic emphasizing its sources in semantics and epistemology from Kant onwards. It then discusses on the nature of theories and models, thought experiments, and fictions and possible world semantics. The historical ambition is awesome, but the book is rather brief – so, inevitably, much detail is missing. Yet, the tone is light, and the level is appropriate for the uninitiated.

Hughes, RIG. “Models and Representation.” Philosophy of Science, 64 (1997): 325-36.

This paper inspired many subsequent contributions to the topic. A major towering achievement by a contemporary philosopher, it not only put scientific representation on the table, it also managed to provide (within scarcely 10 pages) both the backbones of one of the most fertile deflationary approaches, *and* the outlines of criticisms against substantive notions of representation.

Pincock, Christopher. Mathematics and Scientific Representation, Oxford: Oxford University Press, 2012.

A well argued and thought through and discussion of representation by means of mathematical structures. It discusses some of the major alternatives fairly and concisely, and provides a view of its own, which tries out the unfashionable route to build a substantive theory of representation as structural matching.

Van Fraassen, Bas. Scientific Representation: Paradoxes of Perspective. Oxford: Oxford University Press, 2008.

By now already a classic oeuvre by one of the most accomplished philosophers of science of our generation, and a pioneer on the topic. Van Fraassen’s life work traces a significant route from a concern chiefly with the structure of theories towards more pragmatic issues regarding the use of models in scientific practice, which culminates in this major work.

Suárez, Mauricio. “Scientific Representation.” Philosophy Compass, 5: 1 (2010): 91-101.

One of the few state of the art papers available on the topic. It introduces some of the distinctions employed in this bibliography – such as analytical vs. practical inquiries, and substantive vs. deflationary conceptions –, and can serve as a helpful complement to the present document.

Winsberg, Eric. Science in the Age of Computer Simulation. Chicago: University of Chicago Press, 2011.

This is a concise and readable account of simulation, idealization and fiction in scientific representation. It raises many significant issues in

the area and provides a roughly instrumentalist answer to several key questions concerning the use of idealizations and fictions in representation.

ANTHOLOGIES AND EDITED COLLECTIONS

As mentioned, representation is a growing and expanding field. The six volumes listed here in one way or another resulted from some of the most important events – conferences and workshops – that have taken place in recent years, and display some of the intense levels of activity and excitement that nowadays surrounds this topic. Díez and Frigg 2006 is a pioneering collection edited by a team of two young European philosophers with credentials on structuralism and models. Gelfert 2011 contains essays devoted to a practical inquiry into representation. Humphreys and Imbert 2012, and Vorms and Pincock 2013, arise out of the series of conferences on Models and Simulations that have been taking place annually over the last 6 or so years. Lynch and Woolgar 1990 is a sociological approach to the topic. Morrison and Morgan 1999 is well-known for launching the 'mediating models' movement.

Díez, José, and Roman Frigg, eds. "Scientific Representation." Theoria (special issue), 21: 1 (2006): 5-85.

It includes papers by Andreas Bartels (defending homomorphism as an account of representation); Andoni Ibarra and Thomas Mormann (defending an 'interventionist' approach to representation); Mauricio Suárez and Albert Solé (defending the plurality of deflationary approaches); Roman Frigg (criticizing the semantic conception); and Craig Callender and Jonathan Cohen (defending a Gricean account of representation as stipulation).

Gelfert, Axel, ed. "Model-Based Representation in Scientific Practice." Studies in History and Philosophy of Science (special issue), 42, 2 (2011): 251-398.

It includes essays by Tarja Knuuttila (discussing an artefactual approach to model-based representation); Axel Gelfert (on the inferential uses of mathematical representation), Marion Vorms (on the format of imaginary models in scientific practice), Demetris Portides (on phenomenological model-building) and Margaret Morrison (on the underdetermination of models).

Humphreys, Paul, and Ciryl Imbert. Models, Simulations, and Representations. London: Routledge, 2012.

It contains a range of different essays by senior and younger scholars alike with a focus on the relation between simulation and representation in general, and provides a good entry point into the subject.

Lynch, Michael, and Steven Woolgar, eds. Representation in Scientific Practice. Cambridge, Mass.: MIT Press, 1990.

This is a well-known collection in the sociology of science edited by two prominent scholars on techniques of representation across the sciences. It contains some fine sociological discussions of representational practices in diverse fields such as physics, the life sciences, socio-biology, physiology and cognitive science.

Morrison, Margaret, and Mary Morgan, eds. Models as Mediators: Perspectives on Natural and Social Science. Cambridge: Cambridge University Press, 1999.

This volume collects essays resulting from a pioneering research project at the London School of Economics, Amsterdam's Tinbergen Institute, and Berlin's Wissenschaftkolleg in the mid 1990s. The project, and ensuing volume established the so-called "mediating models" movement, according to which models are autonomous and independent of both theory and data.

Vorms, Marion, and Christopher Pincock, eds. "Models and Simulations 4". Synthese (special issue), 2013.

It contains essays engaged in a practical inquiry into representation and simulation. Three essays in particular explicitly address scientific representation, namely those by: Agnes Bolinska (a critique of the inferential conception), Gordon Purves (a critique of Winsberg's account of fictional representation); and Peter Gildenhuys (on representational practices in classical population genetics).

HISTORICAL BACKGROUND

One of the main strands of philosophical work that feeds into contemporary discussions is the long modelling tradition in science – as well as philosophical commentary and reflection upon this tradition. Three key primary sources are Boltzmann 1902, Maxwell, 1990 (1856), and Hertz 1956 (1894). They are followed by a selection of a few amongst many philosophical discussions and reactions that they have prompted.

Primary Sources

Ludwig Boltzmann, James Clerk Maxwell and Heinrich Hertz stand as some of the towering thinkers that started a tradition of philosophically minded physical science, where modelling and representation play a main role. More specifically Maxwell initiated a novel way to carry out modelling as analogical reasoning, Hertz gave a full development of the theory of representations characteristic of the neo-Kantian German speaking modelling tradition, and Boltzmann attempted an imaginative rebranding of both in the form of a radical Viennese tradition. Together they helped put modelling centre stage.

Boltzmann, Ludwig. "Models". Encyclopedia Britannica 10th Edition (1902): 788 – 791.

> This is a classic text on models as representations by one of the most imaginative and reflective physicists of the late 19th century. It discusses both the nature of models as images of the world, and the role that models play in the development of mathematical physics.

Maxwell, James Clerk. "Analogies in Nature: Essay for the Apostles". Reprinted in Harman, Peter, ed. The Scientific Letters and Papers of James Clerk Maxwell. Cambridge: Cambridge University Press (1990): 376-383.

> Maxwellian electrodynamics is at the heart of the methodological revolution in late 19th century physics that brought about the new modelling tradition. This is Maxwell's most philosophical essay where he discusses some debts and implications of his modelling attitude. Originally published in 1856.

Hertz, Hermann. The Principles of Mechanics Presented in a New Form. New York: Dover Publications, 1956.

> This is the translation into English of what is probably the most important work in the development of the bildtheorie, or theory of representations – the view that came to dominate the philosophical language and landscape amongst German-speaking scholars in the early 20th century. Originally published in 1894, it contains some perspicuous discussions of the role and nature of scientific representation, and remains unsurpassed in its clarity and depth.

Secondary Sources

Bailer-Jones 2009 reviews the history of philosophical reflection upon models; Hunt 1991 recounts the history of modelling in the 19th century; De Regt 2005 links the 19th century Bildtheorie to current concerns regarding explanation; and Nersessian 2008 is a study of the cognitive structures underlying Maxwell's work.

Bailer-Jones, Daniela. Scientific Models in Philosophy of Science. Pittsburgh: University of Pittsburgh Press, 2009.

> This book is a comprehensive historical account of philosophical interest on models and representation, and it will attract anyone with an interest in the history of the philosophy of science. It discusses 19th century science views on analogy, Pierre Duhem's disparaging reaction, the logical empiricist confinement of models to heuristics, and the 1960's British reaction in favour of models, as well as more recent debates.

De Regt, Henk. "Ludwig Boltzmann's 'Bildtheorie' and Scientific Understanding". Synthese, 119 (2005): 113-134.

> This paper brings Boltzmann's version of the bildtheorie to bear on current debates regarding the nature of explanation and, in particular, the explanatory force of representation. Highly recommended for those looking for a historical introduction to the topic – and a good example of contemporary iH&PS (integrated History and Philosophy of Science)—style work at its best.

Hunt, Bruce J. The Maxwellians. Ithaca and London: Cornell University Press, 1991.

> A comprehensive account of the birth of the modelling attitude in Victorian 19th century physics. It discusses the models and modelling techniques of Maxwell, Thomson, Lodge, Heaviside and Fitzgerald in detail, and provides invaluable historical background to the origin of philosophical reflection upon the techniques of representation that developed in the British Isles.

Nersessian, Nancy. Creating Scientific Concepts. Cambridge, Mass.: MIT Press, 2008.

> A study of the cognitive practices underlying James Clerk Maxwell's development of his vortex models of the ether. It interprets Maxwell's modelling methodology in terms of model-based reasoning, and provides an elegant account of how representational practices may serve to generate new concepts.

THE SYNTATIC AND SEMANTIC VIEWS

One of the main strands that feeds into contemporary debates on the nature of representation concerns the nature of scientific theory, and is a direct descendant of attempts – in the logical empiricist tradition of Hempel, Carnap and others –, to develop an account of the confirmation and explanatory power of scientific theories. Representation comes to the fore in the 1980's when a semantic conception of theories comes to replace the language-based, or syntactic, conception of the logical empiricists. Suppe 1977 recounts the history of the received or syntactic view, and the reasons that led many to abandon it; Giere 1988 defends a model-based version of the semantic conception; Suppes 2002 promotes a roughly structural version; and Van Fraasseen 1980 outlines a phase space version.

Giere, Ronald N. Explaining Science. Chicago: University of Chicago Press, 1988.

A classic text introducing a cognitive science-based version of the semantic view. Chapter 3 in particular is the source of a widespread division, within the semantic conception, between a theoretical 'definition' and a theoretical 'hypothesis'. Note that Giere's version of the semantic view does not require a structural or model-theoretic understanding of models.

Suppes, Patrick. Representation and Invariance of Scientific Structures. CSLI Publications. Leland Stanford Junior University, 2002.

A classic and very influential text by one of the major figures in analytical philosophy of science in the second half of the 20th century. The original text goes back to the early 1970's, and is reprinted here virtually unchanged. It provides a thorough defence of the applicability of mathematical methods to data and measurement structures, and advances the structural version of the semantic conception of theories.

Suppe, Frederik. The Structure of Scientific Theories. Illinois and Chicago: University of Illinois Press, 1977.

The is a celebrated collection containing several essays on the nature of theory, at a time when the so-called 'received' or syntactic view was opening the way to the new semantic view. Philosophers who, in the tradition of logical empiricism, pursue questions regarding the nature

of scientific theories are thus enabled to adopt representation as the key notion in the relation of theories to the world.

Van Fraassen, Bas. The Scientific Image. Oxford: Oxford University Press, 1980.

Another classic text in the epistemology of science, defending both a semantic conception of theories – in Van Fraassen's preferred phase space version – and a form of anti-realism regarding the hypothetical unobservable entities postulated in such theories.

MODELLING AND IDEALIZATION

The other strand that feeds into contemporary debates on representation is the large and very intense philosophical literature of the last 20 or so years on modelling and idealization. The texts below constitute just a very small selection within that large body of literature dealing with scientific modelling. Cartwright 1983 and Galison 1997 are some key advanced research references. Hartmann and Frigg 2006 is an accessible introduction. Jones and Cartwright 2005 and Magnani et al. 1999 are collections of papers on idealization and representation with varying degrees of difficulty. Weisberg 2007 is an example of recent ground breaking research in the area. Woods 2010 is unusual in its focus on fiction within science and literature, and may provide a good point of entry for those in aesthetics, literary theory and criticism, and other areas of philosophy outside the philosophy of science.

Cartwright, Nancy. How the Laws of Physics Lie. Oxford: Oxford University Press, 1983.

Cartwright's first book defends realism for phenomenological laws, and antirealism regarding explanatory theory. Its simulacrum account of explanation is particularly well known, as is the view that explanatory or covering law power is often inversely related to descriptive accuracy.

Galison, Peter. Image and Logic. Chicago: Chicago University Press, 1997.

It details the development of theoretical practices as major representational tools in 20th century particle physics. Galison's work was key in setting the view that theory involves its own practice – thus inviting the view that representation in general is also a practice.

Hartmann, Stephan, and Roman Frigg. “Models in Science”. Stanford Encyclopedia of Philosophy, 2006.

A concise and clear introduction to the general topic of models and representation, separating the main issues in 3 distinct areas (semantics, ontology and epistemology), and reviewing some of the most general philosophical implications.

Jones, Martin, and Nancy Cartwright, eds. Correcting the Model: Idealisation and Abstraction in the Sciences. Poznan Studies in the Philosophy of the Sciences and Humanities, 68. New York: Rodopi, 2005.

This collection of essays chiefly deals with the distinction between abstraction and idealization, and other concomitant notions. The distinction is key to the idea that representation in science involves either fiction or misrepresentation of one or another sort.

Magnani, Lorenzo, et al. (eds.), Model-Based Reasoning in Scientific Discovery. Kluwer Academic Publishers, 1999.

This is one of the first volumes to have appeared in the series collecting the proceedings of the conferences that Lorenzo Magnani and collaborators have put together in Pavia, Italy, on topics closely related to scientific representation. The book contains some key papers by Giere, Hartmann, Bailer-Jones, etc., on the ways in which models represent their intended targets.

Weisberg, Michael. “Who is a Modeler?”. British Journal for the Philosophy of Science, 58: 2 (2007): 207-233.

A defence of a model-based strategy in science as a form of indirect representation of systems of interest, suitably emphasising both the provisional and idealized character of models, and their capacity to instruct and inform regarding observed phenomena.

Wood, John, ed. Fictions and Models: New Essays. Munich: Philosophia Verlag, 2010.

A recent collection of essays on the topic of fictional representation in science and elsewhere, which includes interesting analogies between the modes of representation in science and those in mathematics, art and literature. The emphasis is on the fictional character of many scientific representations, and how this may or not be consistent with a realist attitude to representation in general.

ANALYTICAL INQUIRIES INTO SCIENTIFIC REPRESENTATION

Inquiries into the nature of representation are not new, they have a long history that takes them back at least to the 19th century. There is an analytical type of inquiry that asks questions regarding the necessary and sufficient conditions on the concept of representation. In other words it aims to define the concept. Typically representation is here understood to be a relation between what we may call sources and targets – where the sources are the vehicles (i.e. models) and the targets are the intended objects of the representation. More complex analytical inquiries do not suppose the relations are necessarily dyadic, but they do assume representation can be defined analytically. Peirce 1931 contains some pioneering reflections on scientific representation, which opened up the field of semiotics. He founded both the analytical and the practical inquiry into representation. Bolinska 2013 and Rusanen and Lappi 2012 exemplify recent attempts to provide necessary and sufficient conditions on representation as the conveyor of information – they will appeal to anyone with an interest on the role of information. Frigg 2010 and Toon 2012 deal with fictional representation – and will interest those with literary and artistic backgrounds. Swoyer 1991 is a foundational text that should interest everyone, even though it is hardly introductory.

Peirce, Charles Sanders. Collected Papers, Volume 2: Elements of Logic. Edited by Charles Hartshorne and Paul Weiss. Cambridge, Mass: Harvard University Press, 1931.

> Peirce is the originator of the field of semiotics, or the science of signs. He distinguished three kinds of signs and developed a complex and influential view, according to which representation is not dyadic, but triadic; it involves not only a source and a target, but also an interpretation of the source that allows it to stand for the target.

Bolinska, Agnes. “Epistemic Representation, Informativeness and the Aim of Faithful Representatioin”, Synthese 190: 2 (2013): 219-234.

> This paper by a young and promising scholar addresses directly the notion of information that appears as part of the inferential conception of representation (see below: *Deflationary approaches*). It argues for a completion of the inferential conception in terms of necessary and sufficient conditions deriving from information.

Rusanen, Anna-Mari, and Otto Lappi. “An Information Semantic Account of Scientific Models”. In De Regt, Henk, Stephan Hartmann and Samir Okasha,

eds. EPSA Philosophy of Science: Amsterdam 2009. Dordrecht: Springer (2012): 315-327.

> It goes beyond extant accounts in providing a complementary information-based view. Again, very much in the spirit of the analytic inquiry, searching for a complete set of conditions that define the abstract concept of representation, yet sensitive to issues of practical applications too.

Frigg, Roman. "Models and Fiction", Synthese, 172, 2 (2010): 251-268.

> One of the earliest attempts to apply the full machinery of Walton's pretence theory of fictions to scientific modelling. It proposes a two-tiered account of representation by models.

Toon, Adam. Models as Made-Believe: Imagination, Fiction and Scientific Representation. Palgrave Macmillan, 2012.

> Another impressive attempt by a young scholar to apply Walton's theory of fictions to scientific representation, thus providing a set of supposedly necessarily and sufficient conditions on the representation of systems by model sources.

Swoyer, Christopher. "Structural Representation and Surrogative Reasoning". Synthese, 87 (1991): 449 – 508.

> One of the first papers to pay attention to the essential role of representation in reasoning and inference in scientific contexts. The paper attempts to ground such activities upon a roughly structural account, although it presciently announces that no particular type of morphism, or structural mapping, will do for representation.

PRACTICAL INQUIRIES INTO SCIENTIFIC REPRESENTATION

A practical inquiry into representation will raise questions regarding the typical means that representations take in practice, without worrying too much as to whether these typical means may be part of the definition of the concept. Thus philosophers, historians and sociologists of science who are involved in a practical inquiry will describe modelling practice and attempt to understand the types of properties of representations that play an active role in the way that scientists use them. Practical and analytical inquiries are not always exclusive, but can be complimentary, and Peirce's original theory of signs also has an origin in his practical work as a scientist in charge of geodetic surveys in the East coast during the 1870s and 1880s. Hughes 2010 is a book-length treatment of modelling from the perspective of a practical inquiry. Suárez 2009 is a selection of papers on fictional representation – all

oriented towards a practical inquiry. Graham Kennedy 2012, Knuuttila 2009, Perini 2010, and Peschard 2011 are all very good examples of recent practical inquiries – and, incidentally, all written by women.

Graham Kennedy, Ashley. "A Non-Representationalist View of Model Explanation". Studies in History and Philosophy of Science, 43: 2 (2012): 233-240.

> It describes some modelling practices in astrophysics, and aims to establish on this ground that explanation does not require representation. However, it defines representation narrowly in a substantive sense, so a reinterpretation of the work is invited that furnishes a description of some representational means in practice.

Hughes, RIG. The Theoretical Practices of Physics. Cambridge: Cambridge University Press, 2010.

> A very thorough and charismatic treatment of representational practices and means in a variety of historical episodes in theoretical physics, from Galileo to the Ising model. The textual analysis approach lends it a refreshingly novel outlook. Hughes was one of the key original thinkers on this topic, and this book summarizes his work in this area over the years.

Knuuttila, Tarja. "Some Consequences of the Pragmatist Approach to Representation: Decoupling the Model-Target Dyad and Indirect Reasoning." In M. Suárez, M. Dorato and M. Rédei, eds. EPSA Epistemology and Methodology: Launch of the European Philosophy of Science Association. Dordrecht: Springer, 2009: 139-148.

> An analysis of both recent pragmatist approaches to representation and indirect reasoning accounts. It nicely signals a shift from the analytical to the practical inquiry into representation, and argues for it on philosophical as well as practical grounds.

Perini, Laura. "Scientific Representation and the Semiotics of Pictures". In Magnus, P.D. and Jacop Busch, eds. New Waves in Philosophy of Science. London: Palgrave Macmillan (2010): 131-154.

> This paper argues by means of a number of detailed case studies that some commonplace assumptions about visual representation in science are mistaken. In particular it shows that visual representations may convey truths; and that a visual representation need not hold any relevant similarity or resemblance to its target. Perini argues

convincingly for a semiotic understanding of visual representations as complex signs in symbol systems á la Goodman.

Peschard, Isabelle. "Making Sense of Modeling: Beyond Representation". European Journal for Philosophy of Science 1: 3 (2011): 335 -352.

A research paper that, on the basis of some interesting contemporary models in fluid dynamics, urges philosophers to overcome the notion of representation in philosophy of science. It does so by focusing on representation as an activity and not as a relation (or at any rate not a relation between our concepts and the external world).

Suárez, Mauricio, ed. Fictions in Science: Philosophical Essays on Modeling and Idealization. London: Routledge, 2009.

It contains nine papers on the practical ways in which scientists employ fictional and idealizing assumptions as part of their representations. Arthur Fine's seminal article "Fictionalism" (1993) is reprinted, and appears alongside others that were first delivered at a conference in Madrid in February 2006, and are now pioneering contributions to the growing literature on fictional representation in the sciences (see Frigg 2010 and Toon 2012 cited under *Analytical Inquiries into Representation* above).

SUBSTANTIVE APPROACHES

A substantive approach to representation will try to reduce it to some other notion, or to otherwise define it away in terms of necessary and sufficient conditions. Substantive accounts have tended to come in two varieties: structural isomorphism, or similarity.

Isomorphism

Amongst the former: Bueno et al. 2002 and French 2003 defend partial isomorphism; Mundy 1986 and Suppes 2002 (cited under *The Syntatic and Semantic Views*) propose homomorphism; while Van Fraassen 1987 suggests embedding (i.e. isomorphism to a substructure).

Bueno, Otavio, Steven French and James Ladyman. "On Representing the Relationship between the Mathematical and the Empirical". Philosophy of Science, 69: 3 (2002): 452 – 473.

It discusses some of the objections to the partial isomorphism approach to representation, and argues for an extension to what the authors refer to as "partial homomorphism".

French, Steven. "A Model-Theoretic Account of Representation (or, I Don't Know Much About Art … but I Know it Involves Isomorphism)." Philosophy of Science, 70: 5 (2003): 1472-1483.

It argues against Suárez 2003 (cited under *Critiques*) and Hughes 1997 (cited under *Denotation / Stipulation*) that isomorphism may be both necessary and sufficient for representation. It also argues that this may be the case throughout the board – i.e. both in science and in the arts.

Mundy, Brent. "On the General Theory of Meaningful Representation". Synthese, 67 (1986): 391 - 437.

An early attempt to understand representation as isomorphism in the physical sciences, particularly in relation to spacetime theories. The claim is often made in this context that diffeomorphism invariance is akin to theoretical equivalence, which prima facie lends credence to the representation-as-isomorphism view.

Van Fraassen, Bas. "The Semantic Approach to Scientific Theories." In Nancy Nersessian, ed. The Process of Science. Dordrecht: Kluwer (1987): 105-124.

Here Van Fraassen comes tantalizingly close to explicitly endorsing a structural conception of representation, roughly as follows: a theory represents a phenomenon if it contains structures with substructures isomorphic to the phenomena. Van Fraassen has refined his views in later works, explicitly embracing a deflationary notion instead.

Similarity

Amongst defenders of similarity, Aronson et al. 1995, and Giere 2004, are early proponents; Godfrey-Smith 2006, and Weisberg 2012 are more sophisticated developments.

Aronson, Jerry, Eileen Way, and Rom Harré. Realism Rescued. London: Duckworth, 1995.

Rom Harré is one of the pioneers of philosophical interest on modelling, as a member of a prominent group of mainly British philosophers working in the late 1960's and early 1970s on the topic, which included

also Richard Braithwaite, Max Black, and Mary Hesse. The book advances the view that targets and sources of representations are similar, and builds an ontological hierarchy on these grounds.

Giere, Ronald. "How Models are Used to Represent Reality", Philosophy of Science 71: 5 (2004): 742-752.

Ron Giere has long been a champion of similarity, and in this paper he expands on his early views by turning representation into a 4-place relation, with perceived similarity playing a key role. He then explores the ways in which representation is an effective modelling strategy.

Godfrey-Smith, Peter. "The Strategy of Model-Based Science." Biology and Philosophy, 21 (2006): 725-740.

It brings together a number of relevant issues, such as fictions and representation, and shows how they play a role in model-based science. It also offers a brief but clear defence of the role of similarity in scientific representation, which takes from Giere's earlier work and leads to some subsequent work by some of Godfrey-Smith's students.

Weisberg, Michael. Getting Serious about Similarity. Philosophy of Science, 79: 5 (2012): 785-794.

The basic problem with similarity as an account of representation is that it just seems to have the wrong logical properties to analyse representation. Similarity appears prima facie to be a symmetrical and reflexive relation, while representation patently is neither. In this paper Weisberg shows how to apply the insights into similarity judgements developed by empirical psychologists.

Critiques

Defenders of similarity and isomorphism tend to argue for the universality and necessity of either for representation. Critics (Frigg 2006; Suárez, 2003) point out that the putatively reducing notions lack some fundamental logical properties of representation, so they can hardly constitute the reductive basis. Others (Downes 1992; Toon 2012) point to the manifest diversity of representational means. Van Fraassen is a remarkable critique of isomorphism as substantive account of representation on epistemic grounds.

Downes, Steven. "The Importance of Models in Scientific Theorizing: A Deflationary Semantic Approach." In D. Hull, M. Forbes and K. Okruhlik, eds. Proceedings of the Philosophy of Science Association, 1 (1992): 142-153.

This is an early and pioneering defence of deflationism. Although it frames the issue within the semantic conception, it presciently anticipates some of the subsequent moves against substantive accounts of representation.

Frigg, Roman. "Scientific Representation and the Semantic View of Theories." Theoria, 55 (2006): 49-65.

Not all defenders of the semantic conception have considered the issue of application, and not all have, in so doing, defended a structural version of the view. However, this paper argues convincingly that the semantic conception of the application of theories lends itself naturally to a structural conception of representation as isomorphism – and proceeds to criticize it for doing so.

Suárez, Mauricio. "Scientific Representation: Against Similarity and Isomorphism." International Studies in the Philosophy of Science, 17: 3 (2003): 225-244.

It proposes five different arguments against similarity and isomorphism, and concludes that representation cannot be naturalised by reducing it to any relational dyadic version of either. It ends by suggesting non-relational versions of these views, and indeed several philosophers reacted by developing more sophisticated accounts of their views in response.

Toon, Adam. "Similarity and Scientific Representation". International Studies in the Philosophy of Science, 26 (2012): 241-257.

This is an example of a recent paper in the contemporary critical trend against substantive theories. It takes extant criticisms of similarity further, by arguing against some sophisticated developments of the similarity view, such as Giere's (2004).

Van Fraassen, Bas. "Representation: The Problem for Structuralism." Philosophy of Science, 73 (2006): 536 -547.

This is a curious paper in that it raises arguments against what appear to many to be Van Fraassen's earlier views – i.e. against a purely structural conception of representation. The paper culminated with the very explicit endorsement of an intentional and pragmatist conception in Van Fraassen 2008 (*General Overviews*).

DEFLATIONARY APPROACHES

In contrast to substantive approaches, deflationary views typically assume that representation lacks necessary and sufficient conditions. Deflationists typically will defend that representation cannot be reduced to any property, relation, or set of properties or relations, of the objects that play the role of representational source and target. They propose instead to focus philosophical attention upon the features of the use of representations by agents in their particular contexts, attempting to generalize such uses whenever possible. In the recent literature there have been roughly two types of deflationary approaches.

Denotation / Stipulation

One set of views links representation to acts of stipulation by agents that fix the denotation of the signs employed. Callender and Cohen (2006) emphasise the role of the act of stipulation itself; while Goodman 1968, Hughes 1997, and Elgin 2009 chose to emphasise the denotation relation – and the target of the referential relation thus established. On chronological grounds Goodman 1968 is the obvious entry point, but nothing beats Hughes 1997 for clarity and concision.

Callender, Craig, and Jonathan Cohen. "There is no Special Problem About Scientific Representation", Theoria, 21: 55 (2006): 67-85.

> Callender and Cohen argue that scientific representation is merely another instance of (non-natural, i.e. conventional) representation in general, so there is no special problem concerning specifically scientific representation. They show that a Gricean conception sheds light on a number of conundrums raised by scientific representation.

Elgin, Catherine. "Exemplification, Idealization, and Understanding." In M. Suárez, ed. Fictions in Science: Essays on Modelling and Idealization, London: Routledge (2009): 77-90.

> This paper provides an extension of Nelson Goodman's account in terms of denotative function. It confronts the issue of the representation of fictive or non-existent entities, such as unicorns. It argues that denotative function is not a success term so a sign or source with denotative function (a painting of a unicorn) need not denote anything in the actual world.

Goodman, Nelson. Languages of Art: An Approach to a Theory of Symbols. Indianapolis: The Bobbs-Merrill Company, 1968.

> This is the classic statement of the denotation theory. It first raises some criticisms against resemblance or similarity theories, and then goes on to articulate the view that representation is essentially the denotation of an object by a symbol in a complex sign system.

Hughes, RIG. "Models and Representation." Philosophy of Science, 64 (1997): 325-36.

> This paper has already been mentioned as a classic in this area. It merits another mention specifically as a defence of a sophisticated version of Goodman's theory. More particularly, Hughes develops what he calls the Denotation-Demonstration-Interpretation (DDI) account on which representation is typically (although not necessarily) characterised by these three separate components in a model.

Inference

The other set of deflationary views focus on the inferential uses of representations. Suárez 2004 is an early statement of the inferential conception, which led Contessa 2007 to develop his own 'interpretational' variant. Bueno and Colyvan 2011 and Newman 2012 are recent attempts to further apply the inferential conception to specifically mathematical representation and explanation, respectively. Zamora and De Donato 2012 attempt to provide the inferential conception with foundations in Robert Brandom's philosophy of language.

Bueno, Otavio, and Mark Colyvan. "An Inferential Conception of the Application of Mathematics." Nous, 45: 2 (2011): 345-374.

> The authors claim to be developing an inferential account of the sorts of scientific representations afforded by mathematical structures. Although they explicitly oppose a substantive conception of representation – a view they refer to as "the matching account" –, they also attempt to show that the inferential capacities of models ride upon structural relations.

Contessa, Gabriele. "Scientific Representation. Interpretation and Surrogative Reasoning." Philosophy of Science 74 (2007): 48-68.

> The explicit aim of the paper is to further develop extant 'distinctions between denotation, epistemic representation and faithful epistemic representation'. Using the inferential conception as foil, it develops out

of it a substantive account of representation as interpreted surrogative reasoning.

Newman, Mark. “An Inferential Model of Scientific Understanding.” International Studies in the Philosophy of Science, 26: 1 (2012): 1-26.

Another exponent of what we may call the San Diego representation school (together with Callender and Cohen 2006, cited under *Denotation / Stipulation*), this paper further applies insights from an inferential view on representation – and convincingly argues for a distinction between understanding and explanation on these inferential grounds.

Suárez, Mauricio. “An Inferential Conception of Scientific Representation.” Philosophy of Science, 71:5 (2004): 767-779.

It provides a first outline of an inferential conception of representation and it introduces a distinction between the force and the inferential capacity of a representation, which, it argues, drives the dynamics of the model building. Its main virtue, however, may have been to provide critical foil for the development of other inferential views and approaches, including those listed in this section.

Zamora-Bonilla, Jesús, and Xavier De Donato. “Explanation and Modelization in a Comprehensive Inferential Account.” In De Regt, Henk, Stephan Hartmann, and Samir Okasha, eds. EPSA Philosophy of Science: Amsterdam 2009. Dordrecht: Springer (2012): 33-42.

The paper claims that the inferential character of scientific representations (models) may be captured in terms of Robert Brandom’s semantic inferentialism. It then attempts to display the analogues of Brandom’s entitlements and commitments at work in the development of scientific models.

MENTAL REPRESENTATION AND COGNITIVE SCIENCE

There is a large and thriving literature on representation within the philosophy of mind and cognitive science. Philosophers of science often approach these views in order to find inspiration and help, even though the commitment to representation as a mental state that is typical in the philosophy of mind has, on the whole, being eschewed. Yet, some of the debates in the philosophy of science replicate old debates in these areas. For instance, Cummings 1997 develops the analogue for mental representation of

the substantive view of scientific representation as isomorphism. He essentially claims that mental representation is structural. His views have been criticised on grounds similar to those employed by critics of the isomorphism view in the philosophy of science. In particular, Millikan 2000 develops a rather convincing response. A recent account that takes inspiration from the structural isomorphism view, but stops short of attempting a reduction is Shagrir 2012. Within philosophy of science proper, Ronald Giere has long defended the application of cognitive science to scientific representation: Chapter 5 in Giere 2006 is an accessible and up to date introduction.

Cummings, Robert. Representations, Targets, and Attitudes. Cambridge, Mass.: MIT Press, 1997.

The usual reference for structural conceptions of mental representation, this is an advanced book in philosophy of mind by a technically gifted and proficient scholar.

Millikan, Ruth. "Review of Cummings' "Representations, Targets and Attitudes." Philosophy and Phenomenological Research, 60 (2000): 103-113.

This essay review raises a number of objections to the structural conception of mental representation defended by Cummings. Although it provides an elegant summary of the object of its critique, and constitutes a good entry point for the uninitiated, the interested reader is advised to consult some of the larger and more complete works on the topic, including the original source of the critique mentioned above.

Giere, Ronald. Scientific Perspectivism. Chicago: University of Chicago Press, 2006.

This is the last published book by a very prominent philosopher of science, which continues his defence of cognitive science as a tool for understanding scientific modelling in general. Chapter 5, in particular, develops a distributed cognition approach to modelling.

Shagrir, Oron. "Structural Representations and the Brain". British Journal for the Philosophy of Science. 63: 3 (2012): 519-545.

An example of how the cognitive science literature is nowadays leaning towards a consideration of neurobiology and neurology in an attempt to better understand mental representation. It sensibly falls short of reducing mental representation to any structural mappings.

REPRESENTATION IN ART AND SCIENCE

Philosophers of science have been learning a fair amount from their colleagues over in aesthetics and the philosophy of art in recent years. Indeed the analogies between scientific and artistic modes of representation have regularly turned into fertile ground for understanding scientific modelling better.

Representation in Aesthetics

One of the classic texts in the philosophy of art has already been mentioned (Nelson Goodman's 1968, cited under *Denotation / Stipulation*), and it has been made clear that its defence of a theory of representation as denotation has had a considerable impact upon present day discussions on scientific representation. There are other texts in the philosophy of art that have exerted influence, and several have become current objects of discussion amongst philosophers of science concerned with representation. A brief selection is listed in the first section including: Gombrich 1960, which first proposes the substitution account and pretty much sets the field; Kulvicki 2006 which interestingly further develops the Goodman approach; Lopes 1996 which contains all the Goodman-inspired criticisms of resemblance theories; and Wollheim 1987 which is the most ambitious philosophical attempt to date to grapple with the notion of representation in the arts.

Gombrich, Ernst. Art and Illusion. London: Phaidon Press Limited, 1960.

> Enormously influential, it defends a 'substitution' account of representation, best exemplified in the often cited and much discussed example of a hobbyhorse. The substitution view fits in well with current emphasis amongst philosophers of science on the autonomous nature of models.

Kulvicki, John. "Pictorial Representation", Philosophy Compass 1: 6 (2006): 535-546. Blackwell Publishing.

> A state of the art paper that moreover argues originally for a version of Goodman's symbolic system view of representation as denotation by a complex sign. It offers a balanced review, providing an excellent entry point into the field.

Lopes, Dominic. Understanding Pictures. Oxford: Oxford University Press, 1996.

An elegant and comprehensive review of the main positions regarding representation in the philosophy of art. It develops a sustained criticism of resemblance theories of artistic representation, which philosophers of science have gone on to apply to scientific representation. It provides an excellent follow up to Kulvicki 2006 as a thorough and complete introduction.

Wollheim, Richard. Painting as an Art. Princeton: Princeton University Press, 1987.

The book is a classic in the field, by one of its most eminent and distinguished scholars. Wolheim criticises extant views with delicate touch, and goes on to propose a notion of his own, namely "seeing-in", which appeals to some fundamental and primitive psychological dispositions. A challenging but enormously rewarding book.

Scientific and Artistic Representation

The last section lists some key works explicitly dealing with the analogy between scientific and artistic representation: Suárez 1999 puts Wollheim's insights to work in an study of the analogy between artistic and scientific representation; Downes 2009 applies critical lessons from Lopes against isomorphism views; Debs and Redhead 2007 develop a conventionalist account; Frigg and Hunter 2010 is a collection of essays that displays well the considerable recent interest on the art – science analogy.

Debs, Talal A., and Michael Redhead. Objectivity, Invariance and Convention: Symmetry in Physical Science. Chapter 1. Cambridge, Mass.: Harvard University Press, 2007.

Debs and Redhead develop a conventionalist account of representation in science, and distinguish objectivity from structural invariance, or symmetry, to which it often is linked. They instead emphasise the need to select conventional features for any representation, which they very originally illustrate by means of examples from the performance arts.

Downes, Steven. "Models, Pictures, and Unified Accounts of Representation: Lessons from Aesthetics for Philosophy of Science." Perspectives on Science, 17, 4 (2009): 417-428.

Downes applies the lessons from aesthetics to scientific representation in a straightforward and convincing manner. He shows that analogues of Goodman's and Lopes' arguments against resemblance have bite against substantive conceptions of representation too.

Frigg, Roman, and Matthew Hunter, eds. Beyond Mimesis and Convention: Representation in Art and Science. Dordrecht: Springer, 2010.

This book collects some of the papers arising out of a conference on representation in art and science that took place in London in 2006. It contains some papers on fictional representation, models and parables, illocutionary representational speech acts, functional versus informative conceptions of representation, and other relevant topics at the interface of the philosophies of science and art.

Suárez, Mauricio. "Theories, Models, and Representations." In Magnani, Lorenzo, et al., eds. Model-Based Reasoning in Scientific Discovery. Kluwer Academic Publishers (1999): 75-84.

An early attempt to suggest a fruitful analogy between scientific and artistic representation. It introduces a distinction between representational and non-representational uses of theories, and illustrates it by means of three paintings (by Velázquez, Picasso and Mondrian) that have thereafter often been discussed in relation with this analogy.