

# MODELS AND THEORIES IN SCIENCE

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Forthcoming in Oxford Bibliographies Online

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## Introduction

An important aspect of science is the construction of models and theories. Philosophy of science aims to elucidate this practice by asking various questions, such as: “What is a theory?” “What is a model?” “How do models and theories relate to one another?” “How do models and theories

relate to the world?” The so-called syntactic view of theories, which originated in the tradition of logical empiricism and logical positivism in the 1920s, construes scientific theories as axiomatized logical calculi whose nonlogical terms are interpreted in terms of observables. This view came under criticism after World War II and was eventually supplanted with the so-called semantic view of theories. According to that view, theories are sets of models, where models are construed as nonlinguistic entities that relate to reality via either a set-theoretical mapping (such as isomorphism) or similarity. A common denominator of both views is that they see models as subordinate to theories. The syntactic view sees models as alternative interpretations of a calculus, which is primarily of pedagogical interest. The semantic view sees them as being the building blocks of theories. In parallel to these schools of thought, there was always a strand of research focusing on the practice of science, on case studies and the methods in specific scientific disciplines, rather than on overarching philosophical concerns. Heterogeneous in character and orientation, what binds projects in this tradition together is the belief that large parts of science are not in the business of devising exact and all-encompassing theories but rather use a variety of different techniques and ingredients to construct models that are locally adequate. Models are now seen as the center of scientific attention and theories are relegated to the status of a tool (among others) for model construction. The beginnings of this tradition can be traced back to the 1920s; it gained prominence for the first time in the 1960s and blossomed in the last two decades of the 20th century. In more recent years, new questions have come into focus, in particular the issues of scientific representation, the use of data, and the role of computer simulation in both modeling and theorizing. This entry provides a guide to these intellectual traditions. In doing so, it sets aside a number of related issues, in particular scientific realism, explanation, confirmation, and the application of mathematics.

### **General Overviews**

Novices to the subject can gain an overview of the different positions and problems in Frigg and Hartmann 2012.

Frigg, Roman, and Stephan Hartmann. “\*Models in Science[<http://Plato.Stanford.Edu/Archives/Fall2012/Entries/Models-Science/>]\*.” In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University Press, 2012. [class:dataSetItem-database]

This article-length encyclopedia entry is the most extensive overview currently available of the most important positions and problems concerning models and theories.

## **Bibliographies**

Bailer-Jones 2009 contains a helpful bibliography about models.

Bailer-Jones, Daniela. *Scientific Models in Philosophy of Science*. Pittsburgh, PA: Pittsburgh University Press, 2009. [ISBN: 9780822943761]

At the end of the book there is a chronological bibliography listing publications about models from 1902 to 2009. The bibliography is not complete, but it provides ample reading for someone wishing to gain an overview.

## **The Syntactic View of Theories**

The so-called syntactic view of theories was the dominant analysis of scientific theories between approximately 1920 and 1960. The view emerged within the movements of logical empiricism and logical positivism, and many (but not all) elements of the view are attempts to embed core ideas of logical empiricism/positivism in clear analysis of scientific theories.

## **Core Texts**

Duhem 1906 puts forward the view that theories are abstract structures at the heart of which lie general principles. Carnap 1923 gives this idea an empiricist formulation. Carnap 1936 grapples with the definition of theoretical terms. Nagel 1961 provides the most detailed statement of the empiricist approach to theories. Carnap 1956 provides a critical discussion of the achievements and failures of that approach to theoretical discourse, and Hempel 1969 sums up the main ideas as well as their problems.

Carnap, Rudolf. “Über die Aufgabe der Physik und die Anwendung des Grundsatzes der Einfachstheit.” *Kant Studien* 28 (1923): 90–107.

This early publication of Carnap’s was the first paper to give a clear statement of what was to become the core idea of the syntactic view of theories: the core of the theory is an axiomatic calculus whose terms are interpreted empirically.

Carnap, Rudolf. “Testability and Meaning.” *Philosophy of Science* 3 (1936): 419–471.

This landmark paper makes contains the admission that theoretical terms cannot be given explicit definition in an observational language, and proposes so-called reduction sentences as a

solution to this problem. These sentence provide theoretical terms with a partial interpretation. Continued in *Philosophy of Science* 4 (1937): 1–40.

Carnap, Rudolf. “The Methodological Character of Theoretical Concepts.” In *The Foundations of Science and the Concepts of Psychology and Psychoanalysis*. Edited by Herbert Feigl and Michael Scriven, 38–76. Minneapolis: University of Minnesota Press, 1956.

This paper provides a succinct summary and critical discussion of the logical empiricist approach to theoretical language.

Duhem, Pierre. *La théorie physique, Son objet et sa structure*. Paris: Chevalier & Rivière, 1906.

Duhem sees the aim of science as the formulation of abstract theories at the core of which lie general principles. Theories have wide scope and present their subject matter in a systematic and logically structured way. He regards a model-based approach to science as inferior.

English translation by Philip P. Wiener published as *The Aim and Structure of Physical Theory* (Princeton, NJ: Princeton University Press, 1954).

Hempel, Carl G. “On the Structure of Scientific Theories.” In *The Isenberg Memorial Lecture Series, 1965–66*. Edited by Carl G. Hempel, 11–38. East Lansing: Michigan State University Press, 1969.

Written by one of its proponents after the downfall of the syntactic view, this paper provides a clear and upfront yet sympathetic discussion of the syntactic view and its problems.

Nagel, Ernest. *The Structure of Science*. London: Routledge and Kegan Paul, 1961.

Nagel’s book is the most advanced, detailed, and complete statement of the logical empiricist approach to theories; it contains an in-depth discussion of the nature of scientific theories in that tradition.

### **Ramsey Sentence and Epsilon Operator**

Understanding the nature of theoretical terms is one of the core problems of the syntactic view of theories: How can they be introduced into a theory, and what is their meaning? An influential response to this conundrum uses a logical technique now known as the *Ramsey sentence*. This technique was introduced in Ramsey 1931. Braithwaite 1953 uses the Ramsey sentence to analyze theoretical terms. Carnap 1995 extends the approach and introduces what is now known as the *Carnap sentence*. Hempel 1965 critically assesses its success, and Ketland 2004 provides a discussion of the Ramsey sentence with a focus on structural realism. Psillos 2000 contains

Carnap's paper applying Hilbert's epsilon operator to theoretical terms. Lewis 1970 offers an analysis along the same lines, but Lewis's approach differs from Carnap's in some essential respects.

Braithwaite, Richard. *Scientific Explanation*. Cambridge, UK: Cambridge University Press, 1953.

Chapter 3 of Braithwaite's book is one of the first extended discussions of the application the Ramsey sentence to the issue of the meaning of theoretical terms.

Carnap, Rudolf. *An Introduction to the Philosophy of Science*. New York: Dover, 1995. [ISBN: 9780486283180]

Provides an in-depth analysis of the meaning of theoretical terms using Ramsey sentences and introduces what is now known as the *Carnap sentence*. Reprint of *Philosophical Foundations of Physics: An Introduction to the Philosophy of Science* (New York: Basic Books, 1966).

Hempel, Carl G. "The Theoretician's Dilemma." In *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science*. By Carl G. Hempel, 173–226. New York: Free Press, 1965.

Provides a detailed discussion of the pros and cons of a number of attempts to reduce theoretical observable terms, among them the Ramsey sentence approach.

Ketland, Jeffrey. "Empirical Adequacy and Ramsification." *British Journal for the Philosophy of Science* 55 (2004): 287–300.

Discusses the Ramsey sentence from the point of view of modern logic and with a focus on structural realism and Newman's problem.

Lewis, David. "How to Define Theoretical Terms." *Journal of Philosophy* 67 (1970): 427–446.

Offers an analysis of theoretical terms that is similar in spirit to Carnap's, but which adds the requirement of unique instantiation.

Psillos, Stathis. "Rudolf Carnap's 'Theoretical Concepts in Science.'" *Studies in History and Philosophy of Science* 31 (2000): 151–172.

This paper publishes for the first time Carnap's "Theoretical Concepts in Science," which he wrote in 1959 but did not publish at the time. Psillos adds a helpful introduction locating Carnap's text in a historical and intellectual context.

Ramsey, Frank P. "Theories." In *The Foundations of Mathematics and Other Logical Essays*. Edited by Richard Braithwaite, 212–236. London: Routledge and Kegan Paul, 1931.

In this paper, Ramsey introduces what has become known as the *Ramsey sentence* (or the technique of *Ramsification*).

### **Criticisms**

Suppe 1977 is a collection of essays engaging critically with the syntactic view of theories.

Maxwell 1962 argues that there is no nonarbitrary distinction between observable and unobservable entities, and Putnam 1962 and Achinstein 1968 subject the bifurcation of a theory's vocabulary into theoretical and observational terms to severe criticism. Hanson 1958 submits that all observation is theory laden, and Feyerabend 1965 argues that the meaning of observational statements depends on the theoretical context in which they are embedded.

Achinstein, Peter. *Concepts of Science: A Philosophical Analysis*. Baltimore: Johns Hopkins Press, 1968.

In the eight chapters of this book, Achinstein attacks the core views of logical empiricism, in particular the linguistic analysis of theories and the bifurcation of the vocabulary into observable and unobservable terms.

Feyerabend, Paul K. "Problems of Empiricism." In *Beyond the Edge of Certainty*. Edited by Robert G. Colodny, 145–260. Englewood Cliffs, NJ: Prentice Hall, 1965.

This paper provides an in-depth discussion of the various problems that empiricism faces and formulates the thesis of meaning holism, the view that the meaning of observation sentences is determined by the theories with which they are connected.

Hanson, Norwood R. *Patterns of Discovery*. Cambridge, UK: Cambridge University Press, 1958.

Hanson gives a forceful statement of the claim that all observation is theory laden: there is no such thing as the "immaculate perception," and a certain theoretical framework is presupposed in every observation, no matter how elementary.

Maxwell, Grover. "The Ontological Status of Theoretical Entities." In *Scientific Explanation, Space, and Time*. Minnesota Studies in the Philosophy of Science 3. Edited by Herbert Feigl and Grover Maxwell, 3–15. Minneapolis: University of Minnesota Press, 1962.

Using the example of a microscope, Maxwell argues that there is no nonarbitrary way to draw a distinction between observable and unobservable entities, and that the distinction is irrelevant to understanding science.

Putnam, Hilary. "What Theories Are Not." In *Logic, Methodology, and the Philosophy of Science*. Edited by Ernest Nagel, Patrick Suppes, and Alfred Tarski, 240–252. Stanford, CA: Stanford University Press, 1962.

Putnam attacks the bifurcation of a theory's vocabulary into theoretical and observational terms and points out that theoretical terms are ones that come from a scientific *theory*, which, however, does not imply that their referents are unobservable.

Suppe, Frederick, ed. *The Structure of Scientific Theories*. Urbana: University of Illinois Press, 1977. [ISBN: 9780252006555]

This massive book is a collection of contributions by a number of important authors. The essays aim to put the problems of the syntactic view on the table and assess their severity. Suppe's 200plus-page introduction provides a helpful survey of the state of the debate in the late 1970s.

### **The Semantic View of Theories**

The syntactic view of theories was superseded by the so-called semantic view of theories. The view crystallized in the early 1960s in Stanford in the work of Suppes (conveniently collected in Suppes 2002, cited under \*Mainstream Core Texts\*). In the 1970s the movement effectively split into two factions. On the one hand, there is what one could call the mainstream, the versions of the semantic view that developed as a part of a majority Anglo-American philosophy of science (although it should be emphasized that Brazilian philosophers made a notable contribution to this tradition). On the other hand, there is what has become known as "Munich structuralism" (often referred to simply as "structuralism" by its proponents; the qualification "Munich" is owed to the fact that Munich has been the epicenter of the movement for a long time). This version of the semantic view has been developed predominantly by philosophers working in German- and Spanish-speaking countries. The reasons for this schism are hard to trace and, with hindsight, difficult to rationalize. There are no clearly identifiable points of fundamental philosophical disagreement between the two camps, and the diversity within the mainstream is so considerable that some mainstream positions are closer to structuralist views than to other mainstream positions.

## Mainstream Core Texts

Suppes 2002 incorporates the author's work from the late 1950s and the early 1960s, which was the foundation stone of the semantic view. A strictly empiricist version of the view is developed in van Fraassen 1980. Da Costa and French 2003 presents a partial structure version of the view. Giere 1988 and Suppe 1989 develop views based on an informal notion of models, and Lloyd 1994 applies the semantic approach to biological theories.

da Costa, Newton C. A., and Steven French. *Science and Partial Truth: A Unitary Approach to Models and Scientific Reasoning*. Oxford: Oxford University Press, 2003. [ISBN: 9780195156515]

This book offers a systematic presentation of the partial structures version of the semantic view that da Costa and French have been developing since the 1980s: a theory is a family of partial structures standing in the relation of partial isomorphism to a target system, of which it provides a representation that can be partially true.

Giere, Ronald. *Explaining Science: A Cognitive Approach*. Chicago: University of Chicago Press, 1988. [ISBN: 9780226292052]

Giere develops a nonstructural version of the semantic view of theories, which regards models as abstract systems that represent their target systems by being similar to them in certain respects and to certain degrees.

Lloyd, Elisabeth. *The Structure and Confirmation of Evolutionary Theory*. Princeton, NJ: Princeton University Press, 1994. [ISBN: 9780691000466]

Most versions of the semantic view of theories focus on physics. Lloyd, by contrast, uses the semantic view to analyze the structure of evolutionary theory, which she applies to a number of problems in evolutionary biology.

Suppe, Frederick. *The Semantic Conception of Theories and Scientific Realism*. Urbana: University of Illinois Press, 1989. [ISBN: 9780252016059]

Suppe offers a version of the semantic view that regards models as highly abstract and idealized replicas of phenomena, which stand in relation of counterfactual truth to the target: they are characterizations of how the phenomena would have behaved had the idealized conditions been met.

Suppes, Patrick. *Representation and Invariance of Scientific Structures*. Stanford: CSLI Publications, 2002. [ISBN: 9781575863337]

This book is something like a “summa” of Suppes’ work and it incorporates Suppes’ pathbreaking work on the semantic view, data models, and the axiomatization of classical mechanics from the early sixties.

van Fraassen, Bas C. *The Scientific Image*. Oxford: Oxford University Press, 1980. [ISBN: 9780198244240]

Van Fraassen develops his constructive empiricism and introduces a structuralist version of the semantic view of theories based on the notion that target systems are isomorphic to an empirical substructure of a model of a theory.

### **Mainstream Criticisms**

The semantic approach has been criticized for a number of reasons. Cartwright 1999 argues that the semantic view works with a notion of model that is at odds with scientific practice, which is what French and Ladyman 1999 denies. Suárez 2003 and Frigg 2006 take issue with the theory of representation that is embodied in the semantic view. Muller 2011 and Thomson-Jones 2006 criticize the view’s analysis of theories and propose alternatives. Many of the contributions listed in the section \*Models in Scientific Practice\* are in one way or other written in opposition to the semantic view, and the reader interested in a critical discussion of the semantic view should also consult the entries in that section.

Cartwright, Nancy. *The Dappled World: A Study of the Boundaries of Science*. Cambridge, UK: Cambridge University Press, 1999. [ISBN: 9780521643368]

Cartwright criticizes the semantic view for embodying what she calls the “vending machine view” (p. 181) of theories—the view that a theory already contains all the resources necessary for the representation of what happens in a certain domain, and hence cannot account for the complex process of the construction of models.

French, Steven, and James Ladyman. “Reinflating the Semantic Approach.” *International Studies in the Philosophy of Science* 13 (1999): 103–121.

This paper defends the semantic approach against Cartwright’s criticisms. French and Ladyman argue that the approach can account for the variety of models employed in scientific practice, and that the sense of “model” used in scientific practice is in fact in line with the one used in the semantic view.

Frigg, Roman. “Scientific Representation and the Semantic View of Theories.” *Theoria* 55 (2006): 49–65.

In this paper Frigg reflects on the basic questions a theory of representation has to answer and introduces what he calls the three conundrums of representation. He then argues that the semantic view of theories does not offer a satisfactory response to the conundrums.

Muller, Frederik A. “Reflections on the Revolution at Stanford.” *Synthese* 183 (2011): 87–114.

Muller offers a critical reflection on Suppes’ version of the semantic view and reaches the conclusion that the philosophical problem of what a scientific theory is has not been solved yet. He proposes a way to fix the problems he identifies and explores the implications for scientific representation.

Suárez, Mauricio. “Scientific Representation: Against Similarity and Isomorphism.”

*International Studies in the Philosophy of Science* 17 (2003): 225–244.

Suárez argues against the reduction of representation to either isomorphism or similarity. He goes on to distinguish between what he calls the means and the constituents of representation, and submits that similarity and isomorphism are common but not universal means of representation.

Thomson-Jones, Martin. “Models and the Semantic View.” *Philosophy of Science* 73 (2006): 524–535.

Thomson-Jones distinguishing two notions of model, the notion of a truth-making structure and the notion of a mathematical model. He argues that excising truth-making from the semantic view leads to a better version of the view.

### **Munich Structuralism**

Sneed 1971 marks the beginning of the movement that was later to be called Munich Structuralism. Sneed’s ideas were developed and transformed in Stegmüller 1979, and they found their canonical expression in Balzer, et al. 1987. Balzer, et al. 2000 is a collection with essays applying the apparatus of the approach to case studies beyond physics. Lorenzano 2013 provides a summery and rebuttal of a number of objections against the program.

Balzer, Wolfgang, C. Ulises Moulines, and Joseph D. Sneed. *An Architectonic for Science: The Structuralist Program*. Dordrecht, The Netherlands: Reidel, 1987. [ISBN: 9789027724038]

This book is the *summa* of the Munich structuralist account of theories; it presents the canonical analysis of the synchronic structure of theories, their diachronic evolution, and their intertheoretical relations, with applications to several case studies.

Balzer, Wolfgang, C. Ulises Moulines, and Joseph Sneed, eds. *Structuralist Knowledge Representation: Paradigmatic Examples*. Amsterdam: Rodopi, 2000. [ISBN: 9789042006805]

This collection brings together a number of essays providing a Munich structuralist analysis of a number of scientific theories outside physics (which had been the focus of earlier studies), among them chemistry, economics, psychology, fundamental measurement, and game theory.

Lorenzano, Pablo. “The Semantic Conception and the Structuralist View of Theories: A Critique of Suppe’s Criticisms.” *Studies in History and Philosophy of Science* 44 (2013): 600–607.

Lorenzano reviews a number of criticisms that have been put forward against the Munich structuralist program, and argues that they are either mistaken or based on a misunderstanding of the program.

Sneed, Joseph D. *The Logical Structure of Mathematical Physics*. Dordrecht, The Netherlands: Reidel, 1971. [ISBN: 9789027701664]

Sneed’s monumental tome marks the beginning of what has become known as Munich Structuralism. Intended as a response to Kuhn, Sneed presents model-theoretical analysis of the structure of theories, with the aim of giving a formal reconstruction of theory change.

Stegmüller, Wolfgang. *The Structuralist View of Theories*. Berlin: Springer 1979. [ISBN: 9780387094601]

Intended as a response to Feyerabend, this book takes as its starting point Sneed’s ideas about theory structure and theory change, reformulating some of them and further developing some others. Kuhn refers to this book when he remarks that the Sneed-Stegmüller formalism is the account of theories that best captures his own ideas.

## **Scientific Models**

Models in science have attracted philosophical attention for a long time. Initially, this interest was driven by philosopher’s interest in what was going on in the sciences. In many cases, scientists do not seem to aim to construct exact theories with a wide scope, but instead try to build models that represent the target systems in a simplified and idealized way. From the 1980s

onwards, this literature also started engaging with the semantic view of theories, which many writers on models regard as something between unhelpful and misguided.

### **Early Work**

Campbell 1920 emphasizes the importance of models in physics. Black 1962 and Achinstein 1968 discuss different kind of models that appear in scientific practice, and Hesse 1963 offers an in-depth analysis of analogical models.

Achinstein, Peter. *Concepts of Science: A Philosophical Analysis*. Baltimore: Johns Hopkins Press, 1968.

Contains a discussion of models in scientific practice and offers one of the first taxonomies of models, which is based on the distinction between analogical, representational, theoretical, and imaginary models.

Black, Max. *Models and Metaphors: Studies in Language and Philosophy*. Ithaca, NY: Cornell University Press, 1962.

This book brings together a number of essays discussing the different kinds of models and their relation to metaphors. Black provides an analysis of scale models and icons, and warns about pitfalls in their applications.

Campbell, Norman. *Physics: The Elements*. Cambridge, UK: Cambridge University Press, 1920.

Discusses the structure of physics and emphasizes the importance of models to physical theorizing as well as the application of physical theory to specific problems. Reprinted as *Foundations of Science* (New York: Dover, 1957).

Hesse, Mary. *Models and Analogies in Science*. London: Sheed and Ward, 1963.

Hesse offers an in-depth discussion of the use of analogical models, in the course of which she introduces the concepts of positive, negative, and neutral analogy, as well as the notion of formal analogy.

### **Models in Scientific Practice**

The 1980s saw an explosion of work on modeling, much of which emphasized the independence of models from theory. Cartwright 1983 and Morrison 1998 argue for this independence. Morgan and Morrison 1999 brings together essays on models in scientific practice based on the premise that models mediate between theory and the world. Harré 2004 collects the author's work on models, edited by Daniel Rothbart, paying particular attention to iconic models. Teller 2001

emphasizes the idealizing and simplifying nature of models, and Bailer-Jones 2009 stresses the importance of analogies. Herfel, et al. 1995 and Jones and Cartwright 2005 are important collections of papers on models.

Bailer-Jones, Daniela. *Scientific Models in Philosophy of Science*. Pittsburgh, PA: Pittsburgh University Press, 2009. [ISBN: 9780822943761]

Bailer-Jones provides an analysis of how models have been used both in historical and contemporary science. She distinguishes different kinds of models and pays special attention to analogies, which she sees as key in understanding both the representational content of many models as well as the relations between different branches of science.

Cartwright, Nancy. *How the Laws of Physics Lie*. Oxford: Oxford University Press, 1983. [ISBN: 9780198247005]

Using a number of detailed case studies, Cartwright argues that models rather than theories are the units of science, which provide a representation of a target system. Theories are tools to construct models, but they do not perform a representational function.

Harré, Rom. *Modeling: Gateway to the Unknown*. Edited by Daniel Rothbart. Amsterdam: Elsevier, 2004. [ISBN: 9780444514646]

A collection of Rom Harré's work on modeling in science, with a special focus on physics and psychology. Harré pays special attention to iconic models, which he sees as pivotal for representing real-world structures, explaining phenomena, manipulating instruments, constructing theories, and acquiring data.

Herfel, William E., Wladyslaw Krajewski, Ilkka Niiniluoto, and Ryszard Wojcicki, eds. *Theories and Models in Scientific Processes*. Poznan Studies in the Philosophy of Science and the Humanities 44. Amsterdam: Rodopi, 1995. [ISBN: 9789051838343]

A collection of papers presented at two conferences in 1994, discussing a number of different aspects of scientific modeling.

Jones, Martin R., and Nancy Cartwright, eds. *Idealization XII: Correcting the Models; Idealization and Abstraction in the Sciences*. Poznan Studies in the Philosophy of the Sciences and the Humanities 86. Amsterdam: Rodopi, 2005. [ISBN: 9789042019553]

This is the (so far) penultimate volume in a long series of books dedicated to the issue of idealization. It brings together papers offering philosophical reflections on idealization and

realism as well as ones analyzing modeling and idealization in physics, economics, and biology.

Morgan, Mary, and Margaret Morrison, eds. *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge, UK: Cambridge University Press, 1999. [ISBN: 9780521650977]

An influential collection of essays whose unifying theme is that models mediate between theory and the world. To do so, models have to be given the status of independent entities— independent of both theory and their target systems.

Morrison, Margaret. “Modelling Nature: Between Physics and the Physical World.” *Philosophia Naturalis* 35 (1998): 65–85.

In this paper, Morrison drives a wedge between models and theories and establishes models as autonomous entities. In doing so, she discusses phenomenal and theoretical models and examines their function in the production of scientific knowledge.

Teller, Paul. “Twilight of the Perfect Model.” *Erkenntnis* 55 (2001): 393–415.

Teller discusses what he calls the “Perfect Model Model,” the view that the aim of science is to produce a perfect simile of nature, a perfect model. He criticizes this view as untenable and suggests an alternative that sees science as producing approximate and idealized models.

### **Models in the Special Sciences**

An important aspect of the literature on models in this tradition is the focus on scientific practice. Since practice is often discipline specific, a significant body of literature is dedicated to issues in a particular field. Redhead 1980 and Hartmann 1998 examine the use of models in quantum field theory; Morgan 2012 and Reiss 2012 discuss the use of models in economics; and Lewins 1984 and Wimsatt 2007 study models in biology.

Hartmann, Stephan. “Idealization in Quantum Field Theory.” In *Idealization in Contemporary Physics*. Edited by Niall Shanks, 99–122. Amsterdam: Rodopi, 1998. [ISBN: 9789042006423]

In this paper, Hartmann first distinguishes different kinds theoretical approaches in quantum field theory, and then discusses the cognitive and pragmatic roles idealizations play in quantum field theory. He illustrates his points with a case study from hadron physics.

Lewins, Richard. “The Strategy of Model Building in Population Biology.” In *Conceptual Issues in Evolutionary Biology*. Edited by E. Sober, 18–27. Cambridge, MA: MIT Press, 1984. [ISBN: 9780262192200]

In his discussion about models in biology, Lewins observes that there are three different goals in modeling: realism, precision, and generality. This forces modelers to make trade-offs, which both constrain and guide the work of scientists.

Mäki, Uskali. "Isolation, Idealization and Truth in Economics." In *Idealization VI: Idealization in Economics*. Poznan Studies in the Philosophy of the Sciences and the Humanities 38. Edited by Bert Hamminga and Neil B. De Marchi, 147–168. Amsterdam: Rodopi, 1994. [ISBN: 9789051835519]

Mäki challenges the view that good models necessarily involve simplifications and therefore cannot be true. He does so by distinguishing between the "whole truth" and "truth" (p. 147–148), and he submits that a model can be true even if it is partial and idealized.

Morgan, Mary. *The World in the Model: How Economists Work and Think*. Cambridge, UK: Cambridge University Press, 2012. [ISBN: 9781107002975]

Morgan provides a detailed account of models in economics and describes how economics has become social science based on mathematical models. A series of case studies illustrate the analysis and introduce the reader to the way economists think.

Redhead, Michael. "Models in Physics." *British Journal for the Philosophy of Science* 31 (1980): 145–163.

This paper considers the role of models in modern theoretical physics, discussing the circumstances in which models arise and the uses to which they are put: probing of theories, the discovery of new theories, and the empirical testing of theories.

Reiss, Julian. "The Explanation Paradox." *Journal of Economic Methodology* 19 (2012): 43–62.

This article argues that modeling in economics is characterized by an "explanation paradox": (1) all models are false; (2) some economic models explain; (3) only true accounts explain.

Existing views of what economic models do are examined and rejected as inadequate responses to the paradox.

Wimsatt, William. *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality*. Cambridge, MA: Harvard University Press, 2007. [ISBN: 9780674015456]

In this book Wimsatt discusses a number of issues in the philosophy of biology, among them model building. He sees modeling as a self-correcting process in which false models serve as a means for the construction of correct theories.

## **Models and Fiction**

Many models are not material objects. But what are they then? Recently, a number of authors have put forward the view that such models are best understood as being akin to literary fiction. This position is clearly articulated in Godfrey-Smith 2006. Frigg 2010 and Toon 2012 give different rationalizations of this idea. Suárez 2009 and Frigg and Hunter 2010 bring together essays exploring the idea further.

Frigg, Roman. “Models and Fiction.” *Synthese* 172 (2010): 251–268.

This paper offers an account of the fictional character of models using Walton’s pretense theory. It outlines the theory, shows how it can be applied to models, and then develops a general picture of scientific modeling based on it.

Frigg, Roman, and Matthew Hunter. *Beyond Mimesis and Nominalism: Representation in Art and Science*. Berlin and New York: Springer, 2010. [ISBN: 9789048138500]

This is a collection of essays exploring the relation between representation in art and science; a number of them are concerned with the relation between fiction and modeling.

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

Godfrey-Smith provides a clear statement of what has become known as the “fiction view of models,” the position that we ought to take at face value the fact that modelers often take themselves to be describing imaginary systems, and that these are best treated as similar to the imagined objects of literary fiction such as Tolkein’s Middle-earth.

Suárez, Mauricio, ed. *Fictions in Science: Philosophical Essays on Modelling and Idealization*. London and New York: Routledge, 2009. [ISBN: 9780415990356]

This collection brings together a number of essays that center around the idea the fictions are crucial to the practice of science. They explore the issue using both theoretical analysis and case studies, which are drawn from the empirical and mathematical sciences, including engineering.

Toon, Adam. *Models as Make-Believe: Imagination, Fiction and Scientific Representation*. Basingstoke, UK: Palgrave Macmillan, 2012. [ISBN: 9780230301214]

This book develops an approach to modeling by likening models to children’s games of make-believe. Drawing on philosophical discussions of art and fiction, Toon offers a unified

framework to discuss the problems posed by modeling and at the same time help to make sense of scientific practice.

### **Material Models**

Some models are material objects. Griesemer 1990 points out that material models are crucial in biology, and Ankeny 2000 and Leonelli and Ankeny 2012 focus on the use of model organisms. Sterrett 2002 and Weisberg 2013 direct attention to material models in physics, and Toon 2011 discusses their role in chemistry. Morgan and Boumans 2004 discusses the so-called Phillips machine, a material model in economics.

Ankeny, Rachel A. “Fashioning Descriptive Models in Biology: Of Worms and Wiring Diagrams.” *Philosophy of Science* 67, Suppl., (2000): 260–272.

Ankeny observes that so-called model organisms have become increasingly important in biology. Using the case study of the nematode worm *Caenorhabditis elegans*, she argues that in order to understand scientific practice, such models need to be complemented with a descriptive model.

Griesemer, James R. “Material Models in Biology.” In *PSA 1990: Proceedings of the Biennial Meeting of the Philosophy of Science Association*. Vol. 2. Edited by Arthur Fine, Micky Forbes, and Linda Wessels, 79–93. East Lansing, MI: Philosophy of Science Association. [ISBN: 9780917586309] [class:conference-paper]

This is one of the first extensive discussions of material models in biology. Griesemer points out that, in biology, manipulated systems of material objects often function as theoretical models.

Leonelli, Sabina, and Rachel A. Ankeny. “Re-Thinking Organisms: The Epistemic Impact of Databases on Model Organism Biology.” *Studies in the History and Philosophy of the Biological and Biomedical Sciences* 43 (2012): 29–36.

The possibility of processing large amounts of data had a profound impact on biology. This paper studies how community databases have changed research practices in model organism biology by focusing on the history and current use of such databases.

Morgan, Mary, and Marcel Boumans. “The Secrets Hidden by Two-Dimensionality: The Economy as a Hydraulic Machine.” In *Model: The Third Dimension of Science*. Edited by

Soraya de Chadarevian and Nick Hopwood, 369–401. Stanford, CA: Stanford University Press, 2004. [ISBN: 9780804739719]

In the late 1940s, Phillips and Newlyn constructed a large hydraulic machine to represent an economy (commonly referred to as the “Phillips Machine”). Morgan and Boumans trace the history of this machine and explain how a material system of pipes and reservoirs is used to represent the functioning of an economy.

Sterrett, Susan. “Physical Models and Fundamental Laws: Using One Piece of the World to Tell about Another.” *Mind and Society* 3 (2002): 51–66.

Sterrett analyzes the methodology of experimental scale modeling (also known as “physical similarity”). She studies the role of fundamental laws in the construction of experimental scale models. She points out that these models offer the opportunity to use observations on one piece of the world to make inferences about another piece of the world.

Toon, Adam. “Playing with Molecules.” *Studies in History and Philosophy of Science* 42 (2011): 580–589.

In this paper, Toon applies his “make-believe” theory of modeling to an empirical study of molecular models. He analyzes users’ interaction with molecular models as an imaginary activity, from which he derives a new account of how models are used to learn about the world.

Weisberg, Michael. *Simulation and Similarity*. New York: Oxford University Press, 2013. [ISBN: 9780199933662]

Weisberg’s book contains a discussion of a scale model of the San Francisco Bay: a large tank with the topography of the bay occupying an area of about 6,000 m<sup>2</sup> and a variety of hydraulic pumps allow engineers to simulate currents, tidal streams, and river flows in the bay. Weisberg analyzes this model using a similarity-based account of the model-world relationship.

### **Further Topics**

Once models are recognized as independent entities, one can start asking a number of philosophical questions about them and direct one’s attention to traditional philosophical issues from the perspective of a model-based approach. Four of these are singled out here as particularly interesting: representation, data, computer simulation, and idealization.

## **Models and Representation**

How do models represent their target systems? The discussion can be divided into two strands: models that address the issue of representation within the framework of the semantic view of theories, and models that stand outside the semantic view. Díez and Frigg 2006 and Contessa 2010 are collections of essays containing contributions from both sides.

Contessa, Gabriele, ed. *Special Issue: The Ontology of Scientific Models. Synthese* 172.2 (2010).

This special issue brings together papers addressing the ontological question of what scientific models are, striking a good balance between different views.

Díez, José, and Roman Frigg, eds. *Special Issue: Scientific Representation. Theoria* 21.1 (2006).

The contributions to this special issue focus on the question, “What does it mean to scientifically represent something?” The issue covers the spectrum of positions. Available

\*online[<http://www.ehu.es/ojs/index.php/THEORIA/issue/view/57>]\*.

### Approaches outside the Semantic View of Theories

Approaches outside the semantic view are either independent of the semantic view or they stand in declared opposition to it. Hughes 1997 presents the so-called DDI account of representation. Suárez 2004 introduces an inferentialist conception. Contessa 2007 presents an interpretationalist theory. Frigg 2010 develops an account of representation in analogy with maps. Elgin 2010 presents a theory of how models represent based on the notion of exemplification.

Contessa, Gabriele. “Scientific Representation, Interpretation, and Surrogative Reasoning.”

*Philosophy of Science* 74 (2007): 48–68.

Contessa develops an interpretational account of epistemic representation, according to which a vehicle represents a target for a certain user if and only if the user adopts an interpretation of the vehicle in terms of the target, which would allow the user to perform valid (but not necessarily sound) surrogative inferences from the model to the system.

Elgin, Catherine Z. “Telling Instances.” In *Beyond Mimesis and Convention: Representation in Art and Science*. Edited by Roman Frigg and Matthew C. Hunter, 1–17. Berlin and New York: Springer, 2010. [ISBN: 9789048138500]

Offers an account of how models represent based on the notion of exemplification: a model exemplifies a number of properties, refers to its target, and imputes the properties it exemplifies to the target.

Frigg, Roman. "Fiction and Scientific Representation." In *Beyond Mimesis and Convention: Representation in Art and Science*. Edited by Roman Frigg and Matthew Hunter, 97–138. Berlin and New York: Springer, 2010. [ISBN: 9789048138500]

Departing from an analogy between maps and scientific models, Frigg develops an account that analyzes representation in terms of two conditions: a model represents a target if the model denotes the target and if there is a translation key that converts facts about the model into claims about the target.

Hughes, R. I. G. "Models and Representation." *Philosophy of Science* 64, Suppl., (1997): 325–336.

This paper introduces Hughes' so-called DDI account of scientific representation. The account analyzes representation in terms of three concepts: denotation, demonstration, and interpretation. Hughes applies the account to a number of examples from scientific practice.

Suárez, Mauricio. "An Inferential Conception of Scientific Representation." *Philosophy of Science* 71, Suppl., (2004): 767–779.

In this paper, Suárez introduces and defends what he calls an "inferential conception of scientific representation" (p. 767). This conception characterizes representation by two necessary conditions: its essential intentionality and its capacity to allow surrogate reasoning and inference.

#### Approaches Based on the Semantic View of Theories

The semantic view of theories incorporates a view of representation (see entries under \*The Semantic View of Theories: Mainstream Core Texts\*). In part driven by questions internal to the semantic view and in part in response to criticisms, a number of authors have recently reconsidered representation from the perspective of the semantic view. Van Fraassen 2008 offers an empiricist structuralist view of representation. Giere 2004 emphasizes the importance of users. Bueno and French 2011 responds to criticisms that have been leveled against a structuralist view of representation, and French 2014 offers a structuralist analysis of representation as part of a broader structural realist metaphysics. Pincock 2012 discusses the role of mathematics in scientific representation, with a special angle on structures.

Bueno, Otávio, and Steven French. "How Theories Represent." *British Journal for the Philosophy of Science* 62 (2011): 857–894.

The account of representation in terms of partial structures and partial morphisms is further developed, and the authors argue that the account successfully addresses a variety of criticisms that have been leveled against it.

French, Steven. *The Structure of the World: Metaphysics and Representation*. Oxford: Oxford University Press, 2014. [ISBN: 9780199684847]

This book articulates a structural realism at the heart of which lies the view that there are no objects in the world. Part of this package is a structuralist theory of representation in the tradition of the semantic view.

Giere, Ronald N. "How Models Are Used to Represent Reality." *Philosophy of Science* 71 (2004): 742–752.

Giere argues that rather than focusing on the dyadic relationship between models and the world, we should focus on the pragmatic activity of representing, so that the basic representational relationship has the following form: scientists use models to represent aspects of the world for specific purposes.

Pincock, Christopher. *Mathematics and Scientific Representation*. Oxford: Oxford University Press, 2012. [ISBN: 9780199757107]

Pincock tackles the perennial issue of the roles of mathematics in science and of how mathematics is used in scientific representation. He then discusses alternative approaches focusing on the potential benefits for scientific discovery and scientific explanation. Although not *expressis verbis* in the tradition of the semantic view, his emphasis on structures sits well with it.

van Fraassen, Bas C. *Scientific Representation: Paradoxes of Perspective*. Oxford: Oxford University Press, 2008. [ISBN: 9780199278220]

Van Fraassen begins with an inquiry into the nature of representation in general, drawing on such diverse sources as Plato's dialogues and the development of perspectival drawing in the Renaissance. He offers a detailed discussion of measurement and then defends an empiricist structuralist version of the "picture theory" of science.

### **Idealization**

Models typically involve idealizations. McMullin 1985 discusses the tradition of idealization that originates in Galileo and became prevalent in many modern sciences. Weisberg 2007

distinguishes three different kinds of idealizations. Cartwright 1989 contrasts idealization and abstraction, and Norton 2012 disentangles idealization and approximation. Laymon 1991 explores the connection between idealization and limiting behavior, and Batterman 2002 provides a detailed study of limits in physics. Woody 2000 emphasizes the importance of approximations in the derivation of chemical regularities from quantum mechanics. Shanks 1998 is a collection of essays on idealization in physics.

Batterman, Robert W. *The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction, and Emergence*. Oxford: Oxford University Press, 2002. [ISBN: 9780195146479]  
The book offers a detailed study of what happens when a certain parameter (e.g., Planck's constant) in a theory tends towards a certain limit (e.g., zero). In this asymptotic regime, new phenomena can appear and the behavior in the limit at zero is suddenly different. Batterman offers philosophical lessons concerning explanation, reduction and emergence, and idealization.

Cartwright, Nancy. *Nature's Capacities and Their Measurement*. Oxford: Oxford University Press, 1989. [ISBN: 9780198244776]

Chapter 5 introduces what Cartwright calls the “problem of material abstraction” (p. 185)—that much of modern science works by abstraction—and laments that there is no good philosophical account of it. Abstraction is contrasted with idealization, and first steps towards a remedy of the problem are made.

Laymon, Ronald. “Thought Experiments by Stevin, Mach and Gouy: Thought Experiments as Ideal Limits and as Semantic Domains.” In *Thought Experiments in Science and Philosophy*. Edited by Tamara Horowitz and Gerald J. Massey, 167–191. Savage, MD: Rowman and Littlefield, 1991. [ISBN: 9780847677061]

Proposes an analysis of idealizations as ideal limits: idealizations are benign if it can be shown that the real situation they aim to capture can be, at least in principle, refined, and thereby made to approach the situation postulated in the model.

McMullin, Ernan. “Galilean Idealization.” *Studies in the History and Philosophy of Science* 16 (1985): 247–273.

Reviews techniques of idealization that can be described as broadly “Galilean,” namely those that involve deliberate simplifications—either by distortion or omission—of something

complicated, with a view to achieve at least a partial understanding of it, and critically examines their epistemic implications in the natural sciences.

Norton, John. “Approximation and Idealization: Why the Difference Matters.” *Philosophy of Science* 79 (2012): 207–232.

Norton observes that even though approximation and idealization are often mentioned in one breath, the two ought to be distinguished carefully: approximations are inexact descriptions of a target system, while idealizations are surrogate systems whose properties are closely related to the ones of the target system. Drawing this difference helps one understand how idealizations and approximations are used.

Shanks, Niall, ed. *Idealization in Contemporary Physics*. Amsterdam: Rodopi, 1998. [ISBN: 9789042006423]

This edited collection contains a number of excellent essays on idealization in various branches of modern physics, ranging from quantum theory, relativity theory, and cosmology to chaos theory.

Weisberg, Michael. “Three Kinds of Idealization.” *Journal of Philosophy* 104 (2007): 639–659.

Distinguishes three different kinds of idealization—Galilean idealization, minimalist idealization, and multiple-models idealization—and argues that these are tied to three different strands in scientific practice.

Woody, Andrea. “Putting Quantum Mechanics to Work in Chemistry: The Power of Diagrammatic Representation.” *Philosophy of Science* 67 (2000): 612–627.

Discusses approximations involved in retrieving molecular orbital theory as used in chemistry from fundamental quantum mechanics. Woody observes that approximations are crucial and that full chemical theory cannot be retrieved by non-approximative *ab initio* calculations.

### **Models and Data**

Data play an important role in modeling. Suppes points out that in processing raw data we construct a data model, and a number of authors see data models as the target system that theoretical models represent (see entries under \*The Semantic View of Theories: Mainstream Core Texts\*. But what role do they play exactly? Harris 2003 emphasizes the importance of data models. Bogen and Woodward 1988 draws an influential distinction between data and

phenomena, which is crucially discussed in McAllister 1997 and Glymour 2000. Machamer 2011 and Richardson 2010 are collections of papers on data and phenomena.

Bogen, James, and James Woodward. "Saving the Phenomena." *Philosophical Review* 97 (1988): 303–352.

Bogen and Woodward distinguish between phenomena and data. The former are stable features of the world, which are described and explained by theories, whereas the latter are gathered in experiments and have no direct connection to theories. The two should not be conflated: data have an important evidential function, but phenomena are not reducible to data.

Glymour, Bruce. "Data and Phenomena: A Distinction Reconsidered." *Erkenntnis* 52 (2000): 29–37.

Glymour argues that both McAllister and Bogen and Woodward are mistaken in thinking that the distinction between data and phenomena is essential, and he submits that the empirical support for theories is not necessarily theory laden in the way McAllister says they are.

Harris, Todd. "Data Models and the Acquisition and Manipulation of Data." *Philosophy of Science* 70 (2003): 1508–1517.

Harris offers an analysis of data manipulation in scientific experiments. He emphasizes that science does not produce raw and unprocessed data, but rather a form of processed data that will be referred to as a "data model." This helps us understand cases in which data acquisition and data manipulation cannot be separated into two independent activities.

Machamer, Peter, ed. *Special Issue: Phenomena, Data and Theories. Synthese* 182.1 (2011).

This special issue brings together a number of papers engaging with the distinction between phenomena and data, and its implications for our understanding of the relation between theories and experiments.

McAllister, James W. "Phenomena and Patterns in Data Sets." *Erkenntnis* 47 (1997): 217–228.

McAllister questions the distinction between phenomena and data by pointing out that if one sees, as Bogen and Woodward do, phenomena as corresponding to patterns in data sets, then it is inadmissible to regard them as investigator-independent entities. Phenomena are theory-laden, and Bogen and Woodward's account of phenomena is therefore incoherent.

Richardson, Alan, ed. *PSA 2008: Proceedings of the 2008 Biennial Meeting of the Philosophy of Science Association, Part II—Symposia Papers*. Chicago: University of Chicago Press, 2010.

[class:conference-proceeding]

This volume of the proceedings of the 2008 biennial meeting of the PSA contains the papers of a symposium on phenomena and data.

### **Models and Computer Simulation**

Sismondo and Gissis 1999 offers a collection of essays on conceptual issues that arise in connection with computer simulations. Humphreys 2004 and Winsberg 2010 assess the use of computer simulations in science from a philosophical point of view. Frigg, et al. 2009 and Frigg, et al. 2011 are collections of essays on the topic of simulation.

Frigg, Roman, Cyrille Imbert, and Stephan Hartmann, eds. *Special Issue: Models and Simulations. Synthese* 169.3 (2009).

This special issue contains selected papers of the conference “Models and Simulations,” held in Paris. The papers engage with the methodology and philosophy of computer simulations.

Frigg, Roman, Cyrille Imbert, and Stephan Hartmann, eds. *Special Issue: Models and Simulations 2. Synthese* 180.1 (2011).

This special issue is the sequel of Frigg, et al. 2009. It contains selected papers from the conference “Models and Simulations 2” that took place in Tilburg. As with the papers in the first volume, the contributions engage with the methodology and philosophy of computer simulations.

Humphreys, Paul. *Extending Ourselves: Computational Science, Empiricism, and Scientific Method*. Oxford: Oxford University Press, 2004. [ISBN: 9780195158700]

*Extending Ourselves* offers a systematic philosophical account of computer simulation and argues that it requires a different approach to scientific method. Simulation technology gives rise to a new form of empiricism, where human abilities are no longer the ultimate standard of epistemological correctness.

Sismondo, Sergio, and Snait Gissis, eds. *Special Issue: Modeling and Simulation. Science in Context* 12.2 (1999).

The contributions to this special issue were among the first to offer systematic reflection on the use of computer simulations in science from a philosophical and science studies perspective.

Winsberg, Eric. *Science in the Age of Computer Simulation*. Chicago: University of Chicago Press, 2010. [ISBN: 9780226902029]

Winsberg explores the impact of computer simulation on philosophical issues such as nature of scientific evidence, the role of values in science, the relationship between simulation and experiment, and the role of data. The gist of the discussion is that simulations have a profound impact on core issues in philosophy of science.