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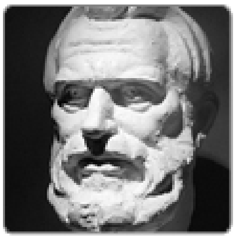

Models and Theories in Science

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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?”, and “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 twentieth century. In more recent years, new questions have come into focus, in particular the issues of scientific representation, model-word relations (including idealization and analogy), the use of data, and the role of computer simulation in both modeling and theorizing, the use of models in scientific explanations and scientific understanding, and the problem of multi-model situations. This article provides a guide to these intellectual traditions. In doing so, it sets aside a number of related issues, in particular scientific realism, 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 2020 and then deepen their understanding with Downes 2021. Frigg 2023 provides an advanced introduction and documents the state of play in various debates.

Downes, Stephen M. *Models and Modeling in the Sciences: A Philosophical Introduction*. New York and London: Routledge, 2021.

Begins by presenting a wide range of models from different scientific disciplines and then discusses how models shed light on some of the core questions in philosophy of science and epistemology. The discussion is accessible throughout, and with just over 100 pages the book has a length that is manageable also for novices.

Frigg, Roman. *Models and Theories: A Philosophical Inquiry*. London: Routledge, 2023.

An advanced-level introduction to the core problems concerning models and theories. Contains sixteen chapters, organized in four parts, which cover different aspects of the syntactic and the semantic view of theories, scientific representation, analogy, idealization, different model-theory relations, the ontology of models, and multi-model approaches. Chapters are self-contained and can also be read in isolation.

Frigg, Roman, and Stephan Hartmann. "Models in Science." In *The Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University Press, 2020.

This article-length encyclopedia entry an extensive yet accessible overview 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.

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* 28.1–2 (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* 3.4 (1936): 419–471.

This landmark paper 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 sentences 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.

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.

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. Duhem 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.

The most advanced, detailed, and complete statement of the logical empiricist approach to theories; 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. The author of 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; Ketland 2004 and Díez 2005 provide a discussion of the Ramsey sentence with a focus on realism and the meaning of theoretical terms. 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 of 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.

Provides an 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).

Díez, José A. "The Ramsey Sentence and Theoretical Content." In *F.P. Ramsey: Critical Reassessments*. Edited by Maria J. Frápolli, 70–103. London: Continuum, 2005.

Provides an in-depth and clear discussion of the logical properties of the Ramsey sentence and its use to elucidate the meaning of theoretical terms.

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* 55.2 (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* 67.13 (1970): 427–446.

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

Psillos, Stathis. "Rudolf Carnap's 'Theoretical Concepts in Science.'" *Studies in History and Philosophy of Science* 31.1 (2000): 151–172.

Publishes for the first time Carnap's "Theoretical Concepts in Science," which he wrote in 1959 but did not publish at the time. 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.

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 University Press, 1968.

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.

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.

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*. Edited by Herbert Feigl and Grover Maxwell, 3–15. Minnesota Studies in the Philosophy of Science 3. 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.

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.

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 200-plus-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 crystalized 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 in 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 owned 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.

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.

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.

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.

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, CA: CSLI Publications, 2002.

Something like a "summa" of Suppes's work. Incorporates Suppes's pathbreaking work on the semantic view, data models, and the axiomatization of classical mechanics from the early 1960s.

van Fraassen, Bas C. *The Scientific Image*. Oxford: Oxford University Press, 1980.

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 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.

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, it 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* 13.2 (1999): 103–121.

Defends the semantic approach against Cartwright's criticisms. Argues 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* 21.1 (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* 183.1 (2011): 87–114.

Offers a critical reflection on Suppes's version of the semantic view and reaches the conclusion that the philosophical problem of what a scientific theory is has not been solved yet. 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* 17.3 (2003): 225–244.

Argues against the reduction of representation to either isomorphism or similarity. 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* 73.5 (2006): 524–535.

Distinguishes two notions of model, the notion of a truth-making structure and the notion of a mathematical model. 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.

The *summa* of the Munich structuralist account of theories. 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 D. Sneed, eds. *Structuralist Knowledge Representation: Paradigmatic Examples*. Amsterdam: Rodopi, 2000.

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* 44.4 (2013): 600–607.

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.

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.

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.

Beyond the Syntactic/Semantic Divide

In the last decade, the discussion about the nature of theories has changed focus in two ways. First, there was growing recognition that the strict dichotomy between syntactic and sematic approaches was untenable and that a realistic construal of theories will have to acknowledge models and languages as being part of theories. Arguments for this conclusion are given in Hudetz 2019 and Lutz 2017. Second, the development away from the strict dichotomy has in a large part been driven by a renewed interest in the question of when two theories are identical. Halvorson 2012 raised the issue and used it for frontal attack on the semantic view. Van Fraassen 2014 replies, and Barrett 2020 elaborates on the arguments. Coffey 2014 and Nguyen 2017 draw attention to the connection between discussions of equivalence and representation. Dewar 2022, Weatherall 2019a, and Weatherall 2019b provide intermediate-level surveys of the debate, and Halvorson 2019 offers an advanced overview.

Barrett, Thomas W. "Structure and Equivalence." *Philosophy of Science* 87.5 (2020): 1184–1196.

Critically discusses and evaluates the claim that two theories are equivalent if they ascribe the same structure to the world, and inequivalent if they posit different structures.

Coffey, Kevin. "Theoretical Equivalence as Interpretative Equivalence." *British Journal for the Philosophy of Science* 65.4 (2014): 821–844.

Argues that standard approaches to the problem of theoretical equivalence, which focus on formal relations between theoretical structures, are ultimately unsuccessful because they fail to consider how theories relate to the world. This problem is addressed by introducing the notion of interpretive equivalence.

Dewar, Neil. *Structure and Equivalence*. Cambridge, UK: Cambridge University Press, 2022.

Short introduction to the problem of what it means for two theories to be equivalent. First provides a synoptic overview of the formal tools that are used in these discussions, and then uses these in a detailed case study of Newtonian mechanics.

Halvorson, Hans. "What Scientific Theories Could Not Be." *Philosophy of Science* 79.2 (2012): 183–206.

Argues that the semantic view, according to which theories are classes of models, delivers the wrong verdicts on questions of theoretical identity: it regards theories as identical that are not and vice versa. One of the first papers to raise this issue and has become the reference point in the discussion of theoretical equivalence.

Halvorson, Hans. *The Logic in Philosophy of Science*. Cambridge, UK: Cambridge University Press, 2019.

Discusses philosophical claims that have been made based on novel logical discoveries (such as Putnam's claim that the Löwenheim–Skølem theorem refutes realism) and then presents a systematic and formally rigorous account of the notions of theory, equivalence, translation, reduction, and model.

Hudetz, Laurenz. "The Semantic View of Theories and Higher-Order Languages." In *Special Issue on Systematicity: The Nature of Science? Synthese* 196.3 (2019): 1131–1149.

Makes two claims. First, there is no reason to restrict models to set-theoretical structures; they can just as well be construed as model-theoretic structures of higher-order logic. Second, every family of set-theoretic structures has an associated language of higher-order logic, which implies that every syntactic criterion of theoretical equivalence can be carried over to the semantic view.

Lutz, Sebastian "What Was the Syntax-Semantics Debate in the Philosophy of Science About?" *Philosophy and Phenomenological Research* 95.2 (2017): 319–352.

Argues that the debate between the syntactic and the semantic view of theories is illusory because neither a purely syntactic nor a purely semantic view is plausible. A tenable account of theories sees them as consisting both of language and of models, and the remaining question is how exactly the two are integrated.

Nguyen, James. “Scientific Representation and Theoretical Equivalence.” *Philosophy of Science* 84.5 (2017): 982–995.

Argues that debates about theoretical equivalence cannot be conducted in isolation and have to be run together with discussions about scientific representation. Proposes a criterion whereby two theories are equivalent if their models license the same claims about the same target systems.

van Fraassen, Bas C. “One or Two Gentle Remarks about Hans Halvorson’s Critique of the Semantic View.” *Philosophy of Science* 81.2 (2014): 276–283.

A response to Halvorson 2012. Argues that Halvorson’s criticism misfires and that the semantic view is able to address the problems Halvorson identifies.

Weatherall, James O. “Part 1: Theoretical Equivalence in Physics” *Philosophy Compass* 14.5 (2019a): e12592.

The first part of a two-part review of the philosophical literature about theoretical equivalence, including the closely related concepts of empirical and definitional equivalence.

Weatherall, James O. “Part 2: Theoretical Equivalence in Physics.” *Philosophy Compass* 14.5 (2019b): e12591.

The second part of a two-part review of the philosophical literature about theoretical equivalence. It discusses interpretational and categorial equivalence, as well as the relation between equivalence and duality.

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, they try to build models that represent the target systems in a simplified and idealized way. From the 1980s onward, 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 University 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 among analogical, representational, theoretical, and imaginary models.

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

Brings together a number of essays discussing the different kinds of models and their relation to metaphors. 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. Gelfert 2016 examines the exploratory function of models. 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.

Provides an analysis of how models have been used both in historical and in contemporary science. 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.

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.

Gelfert, Axel. *How to Do Science with Models: A Philosophical Primer*. Cham, Switzerland: Springer, 2016.

Discusses models as they are used in scientific practice and describes the diversity of models one finds, ranging from toy models and scale models to theoretical and mathematical models, and emphasizes the exploratory function of models.

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

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: Proceedings of AFOS '94 Workshop, August 15–20, Madralin and IUHPS Conference, August 27–29, Warszawa*. Poznan Studies in the Philosophy of Science and the Humanities 44. Amsterdam: Rodopi, 1995.

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.

The (so far) penultimate volume in a long series of books dedicated to the issue of idealization. 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.

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* 35.1 (1998): 65–85.

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* 55.3 (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.

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.

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*. Edited by Bert Hamminga and Neil B. De Marchi, 147–168. Poznan Studies in the Philosophy of the Sciences and the Humanities 38. Amsterdam: Rodopi, 1994.

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.

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* 31.2 (1980): 145–163.

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

Reiss, Julian. "The Explanation Paradox." *Journal of Economic Methodology* 19.1 (2012): 43–62.

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.

Discusses a number of issues in the philosophy of biology, among them model building. 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? A number of works 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, Toon 2012, and Salis 2021 give different rationalizations of this idea. Knuuttila 2017 criticizes the notion and submits that models should be understood as artifacts instead. Frigg and Nguyen 2021 defends the fiction view against a number of criticisms. Suárez 2009, Frigg and Hunter 2010, and Levy and Godfrey-Smith 2020 bring together essays exploring the idea further.

Frigg, Roman. "Models and Fiction." *Synthese* 172.2 (2010): 251–268.

Offers an account of the fictional character of models using Walton's pretense theory. 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.

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.

Frigg, Roman, and James Nguyen. "Seven Myths about the Fiction View of Models." In *Models and Idealizations in Science: Artifactual and Fictional Approaches*. Edited by Alejandro Casini and Juan Redmond, 133–157. Cham, Switzerland: Springer, 2021.

Offers a detailed response to the main strands of criticism that have been put forward against the fiction view of models.

Godfrey-Smith, Peter. "The Strategy of Model-Based Science." *Biology and Philosophy* 21.5 (2006): 725–740.

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 Tolkien's Middle-Earth.

Knuuttila, Tarja. "Imagination Extended and Embedded: Artifactual versus Fictional Accounts of Models." *Synthese* 198, suppl. 21 (2017): 5077–5097.

Offers a critique of the fiction view of models, centering around the issue that the view has problems accommodating surrogative reasoning as an important characteristic of scientific modeling. Proposes an alternative, artifactual, view which focuses on culturally established external representational tools.

Levy, Arnon, and Peter Godfrey-Smith, eds. *The Scientific Imagination*. New York: Oxford University Press, 2020.

Brings together contributions from many of the key contributors to the debate about the nature of models and fiction. As the title indicates, the focus is on the scientific imagination and on how models feature in the imagination.

Salis, Fiora. "The new fiction view of models." *British Journal for the Philosophy of Science* 72.3 (2021): 717–742.

Presents a new version of the fiction view of models that pays particular attention the demands that a theory of scientific representation presents to an account of models. On the new view, models are akin to fictional stories; they represent real-world phenomena if they stand in a denotation relation with reality; and they enable knowledge of reality via the generation of theoretical hypotheses, model–world comparisons, and direct attributions.

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

Brings together a number of essays that center around the idea the fictions are crucial to the practice of science. These essays 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.

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 Ankeny and Leonelli 2020 focus on the use of model organisms in biological research. Levy and Currie 2015 argues that model organisms, their name notwithstanding, have little to do with many other scientific models. Sterrett 2002, Weisberg 2013, and Pincock 2022 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.

Ankeny, Rachel A., and Sabina Leonelli. *Model Organisms*. Cambridge, UK: Cambridge University Press, 2020.

A book-length exploration of the concept of a *model organism* in contemporary biology. Argues that model organisms are a distinctive way of doing research. Analyzes this way and the research practices that attach to them, and offers an analysis of model organisms as scientific representations.

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, 1990.

One of the first extensive discussions of material models in biology. Points out that, in biology, manipulated systems of material objects often function as theoretical models.

Levy, Arnon, and Adrian Currie. “Model Organisms Are Not (Theoretical) Models.” *British Journal for the Philosophy of Science* 66.2 (2015): 327–348.

Argues that model organisms have an epistemic character different from other scientific models such as the Lotka–Volterra model of predator-prey dynamics and submits that they work via empirical extrapolation rather than representation.

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.

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.

Pincock, Christopher. “Concrete Scale Models, Essential Idealization and Causal Explanation.” *British Journal for the Philosophy of Science* 73.2 (2022): 299–323.

This paper argues that concrete or physical models remain important in science and engineering, that they are often essentially idealized, and that, despite these idealizations, some of these models may be reliably used for the purpose of causal explanation.

Sterrett, Susan. “Physical Models and Fundamental Laws: Using One Piece of the World to Tell about Another.” *Mind and Society* 3.1 (2002): 51–66.

Analyzes the methodology of experimental scale modeling (also known as “physical similarity”). Studies the role of fundamental laws in the construction of experimental scale models. 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* 42.4 (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.

Contains a discussion of a scale model of the San Francisco Bay: a large tank with the topography or the bay occupying an area of about 6,000 m^2 and a variety of hydraulic pumps allow engineers to simulate currents, tidal streams, and river flows in the bay. 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; Contessa 2010; and Lawler, et al. 2022 are collections of essays containing contributions from all sides. Frigg and Nguyen 2021 offers an article-length introduction, and Nguyen and Frigg 2022 is a book-length survey with extensive case studies.

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.

Frigg, Roman, and James Nguyen. "Scientific Representation." In *Stanford Encyclopedia of Philosophy*. Edited by Edward N. Zalta. Stanford, CA: Stanford University, 2021.

An article-length encyclopedia entry offers a comprehensive and yet accessible introduction to the problem of scientific representation and the various positions in the debate.

Lawler, Insa, Kareem Khalifa, and Elay Shech, eds. *Scientific Understanding and Representation: Modeling in the Physical Sciences*. London and New York: Routledge, 2022.

This edited collection assembles contributions from leading authors in the debates about models and scientific understanding. It has the format of "critical conversation," integrating many replies to papers and thereby bringing contrary positions in direct contact.

Nguyen, James, and Roman Frigg. *Scientific Representation*. Cambridge, UK: Cambridge University Press, 2022.

Offers a philosophical exploration of the notion of scientific representation by focusing on scientific models. Begins by disentangling different aspects of the problem of representation and then discusses the dominant accounts in the philosophical literature. Provides extensive case studies.

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. Callender and Cohen 2006 presents what the authors call a "Gricean" account of representation according to which the problem of scientific representation reduces to the problem of mental representation. Ruyant 2021 formulates a revised version of the account. 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. This account is further developed in Frigg and Nguyen 2020, resulting in the DEKI account. Levy 2015 and Toon 2012 formulate a "direct" account of representation. Bolinska 2013 argues that a theory of representation should analyze faithful representation before turning to representation *tout court*.

Bolinska, Agnes. "Epistemic Representation, Informativeness and the Aim of Faithful Representation." *Synthese* 190.2 (2013): 219–234.

Takes models to be epistemic representations, meaning that they are tools for gaining information about the target, and argues that a user's aim of faithfully representing the target system is necessary for securing this feature.

Callender, Craig, and Jonathan Cohen. "There Is No Special Problem about Scientific Representation." *Theoria* 55 (2006): 67–85.

Argues that scientific representation is a special case of a more general notion of representation, namely mental representation. Once mental representation is understood, the problem of scientific representation is solved a fortiori. This view anchors the philosophy of H. Paul Grice, which is why the position is known as Griceanism.

Contessa, Gabriele. "Scientific Representation, Interpretation, and Surrogative Reasoning." *Philosophy of Science* 74.1 (2007): 48–68.

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.

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.

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.

Frigg, Roman, and James Nguyen. *Modelling Nature: An Opinionated Introduction to Scientific Representation*. Cham, Switzerland: Springer, 2020.

This book pursues three aims. First, it differs five different problems that are often lumped together under the heading of "the problem of scientific" representation and offers conditions on adequacy for answers. Second, it surveys the literature and discusses how currently available accounts fare with the identified questions and conditions. Third, it develops what the authors call the DEKI account of representation.

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

Introduces Hughes's so-called DDI account of scientific representation. Analyzes representation in terms of three concepts: denotation, demonstration, and interpretation. Applies the account to a number of examples from scientific practice.

Levy, Arnon. "Modeling without Models." *Philosophical Studies* 172.3 (2015): 781–798.

Argues against the view that models are objects, and that the representation is relation between a model and target. Instead, we should take models to be descriptions that directly describe a target in the world, often in simplified and idealized way.

Ruyant, Quentin. "True Griceanism: Filling the Gaps in Callender and Cohen's Account of Scientific Representation." *Philosophy of Science* 88.3 (2021): 533–553.

Further develops the Gricean position in Callender and Cohen 2006 by introducing a distinction between contextual representational use and general representational status, which is then analyzed in terms of the notion of indexicality.

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

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.

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

Distinguishes between direct and indirect accounts of representation, and then argues for a direct account according. This view does not recognize models as objects and instead aims to explain epistemic representation as a form of imaginative description of the target.

Approaches Based on the Semantic View of Theories

The semantic view of theories incorporates a view of representation (see entries under 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 provides a similarity account of representation, emphasizing the importance of users. Khosrowi 2020 presents a different similarity account, based on the notion of shared features in Weisberg 2013 (cited under Material Models). 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* 62.4 (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.

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* 71.5 (2004): 742–752.

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.

Khosrowi, Donal. “Getting Serious About Shared Features.” *British Journal for the Philosophy of Science* 71.2 (2020): 523–546.

Weisberg 2013 (cited under Material Models) formulates similarity-based account of the model–world relation. Khosrowi articulates a number of difficulties for this account and then reformulates the account so that these are avoided.

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

Tackles the perennial issue of the roles of mathematics in science and of how mathematics is used in scientific representation. 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.

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. 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, a classification that is further developed in Elliott-Graves and Weisberg 2014. 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. Nguyen and Frigg 2020 offers an analysis of limit idealizations, and Shech 2018 offers a survey of the discussion about limits. Portides 2007 discusses the relation between idealizations and closely related notion of approximation. 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.

Offers a detailed study of what happens when a certain parameter (e.g., Planck's constant) in a theory tends toward 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.

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 toward a remedy of the problem are made.

Elliott-Graves, Alkistis, and Michael Weisberg. "Idealization." *Philosophy Compass* 9.3 (2014): 176–185.

This survey article reviews the recent literature on idealization with a focus on scientific modeling. The authors argue that idealization is not a unified concept and that there are three different types of idealization: Galilean, minimalist, and multiple models, each with its own justification.

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.

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 History and Philosophy of Science Part A* 16.3 (1985): 247–273.

Reviews techniques of idealization that can be described as broadly "Galilean," namely those that involve deliberate simplifications—either by distortion or by 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.

Nguyen, James, and Roman Frigg. "Unlocking Limits." *Argumenta* 6.1 (2020): 31–45.

Analyzes how limits are used in idealizations and explains how such idealizations give rise to a key in the DEKI account (developed in Frigg and Nguyen 2020, cited under Approaches Outside the Semantic View of Theories).

Norton, John. "Approximation and Idealization: Why the Difference Matters." ***Philosophy of Science*** **79.2 (2012): 207–232.**

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 surrogates 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.

Portides, Demetris "The Relation between Idealisation and Approximation in Scientific Model Construction." ***Science & Education*** **16.7–8 (2007): 699–724.**

Discusses the relation between idealization and approximation and puts forward a view of approximation as mathematical relation.

Shanks, Niall, ed. ***Idealization in Contemporary Physics*****. Amsterdam: Rodopi, 1998.**

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.

Shech, Elay. "Infinite Idealizations in Physics." ***Philosophy Compass*** **13.9 (2018): e12514.**

This survey article reviews the debate about infinite and essential idealizations in physics. Draws a contrast between essentialists and dispensabilists, who disagree on whether idealizations are essential or indispensable for scientific accounts of certain physical phenomena.

Weisberg, Michael. "Three Kinds of Idealization." ***Journal of Philosophy*** **104.12 (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.S3 (2000): 612–627.**

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

Analogy

Some models involve an analogical relation to their target systems. Hesse 1963 and Achinstein 1968 are classical discussions of the use of analogies in science and scientific modeling. Bartha 2010 offers an analysis of analogical reasoning in science. Darden and Rada 1988 examines the heuristic use of analogies, and Kroes 1989 scrutinizes structural analogies between physical systems. Gentner 1982 offers dimensions along which the quality of analogy can be evaluated. Dardashti, et al. 2019 argues that analogical models can provide knew knowledge, a claim that is disputed in Crowther, et al. 2021.

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

Offers a discussion of many aspects of scientific models and analyzes how models can stand in different analogical relations to their targets.

Bartha, Paul F. A. *By Parallel Reasoning: The Construction and Evaluation of Analogical Arguments*. Oxford and New York: Oxford University Press, 2010.

Offers a comprehensive philosophical examination of analogical reasoning and proposes a normative theory with special focus on the use of analogies in mathematics and science.

Crowther, Karen, Niels S. Linnemann, and Christian Wüthrich. "What We Cannot Learn from Analogue Experiments." *Synthese* 198.Suppl. 16 (2021): 3701–3726.

Argues, contra Dardashti, et al. 2019, that analogue experiments are not capable of confirming the existence of particular phenomena in inaccessible target systems: they are doomed to beg the question because they must assume the physical adequacy of the modelling framework used to describe the inaccessible target system.

Dardashti, Radin, Stephan Hartmann, Karim P. Y. Thébault, and Eric Winsberg. "Hawking Radiation and Analogue Experiments: A Bayesian Analysis." *Studies in History and Philosophy of Modern Physics* 67 (2019): 1–11.

Argues that analogue models, and analogue experiments, are able to provide knew knowledge, and supports this with a Bayesian analysis of confirmation. Discusses this position with particular reference to Hawking radiation.

Darden, Lindley, and Roy Rada. "Hypothesis Formation Using Part-Whole Interrelations." In *Analogical Reasoning: Perspectives of Artificial Intelligence, Cognitive Science, and Philosophy*. Edited by David H. Helman, 341–375. Dordrecht, The Netherlands: Kluwer, 1988.

Offers an analysis of the heuristic use of analogies in the formulation of new hypotheses with special focus on the role of "part-whole" relations.

Gentner, Dedre. "Are Scientific Analogies Metaphors?" In *Metaphor: Problems and Perspectives*. Edited by David S. Miall, 106–132. Brighton UK: Harvester, 1982.

Offers four dimensions along which analogies can be evaluated: base specificity, clarity, richness, and systematicity.

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

A classical discussion of models and analogies in science, which also introduces the now-common notions of material analogy and formal analogy.

Kroes, Peter. "Structural Analogies between Physical Systems." *British Journal for the Philosophy of Science* 40.2 (1989): 145–154.

Discusses structural analogies between physical systems and argues that this type of analogy plays an important role in the physical and technological sciences. A formal, set-theoretic description of structural analogies between physical systems is presented.

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 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. Leonelli 2016 and Leonelli 2019 discuss the use of big data in biological and medical research. Lyon 2014 offers a survey of philosophical issues that arise in connection with data.

Bogen, James, and James Woodward. “Saving the Phenomena.” *Philosophical Review* 97.3 (1988): 303–352.

Distinguishes 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* 52.1 (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* 70.5 (2003): 1508–1517.

Offers an analysis of data manipulation in scientific experiments. 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.

Leonelli, Sabina. *Data-Centric Biology: A Philosophical Study*. Chicago: University of Chicago Press, 2016.

Analyzes the way in which researchers process and understand scientific data in contemporary biological and biomedical sciences, which use a data-intensive approach and novel methods to produce, store, distribute, and interpret huge amounts of data.

Leonelli, Sabina. “What Distinguishes Data from Models?” *European Journal for Philosophy of Science* 9 (2019): Article 22.

Proposes a framework that explicates and distinguishes the epistemic roles of data and models within empirical inquiry in terms of their use in scientific practice and illustrates the view with the case of exploratory research in plant phenotyping.

Lyon, Aidan. “Data.” In *The Oxford Handbook of Philosophy of Science*. Edited by Paul Humphreys, 738–758. Oxford: Oxford University Press, 2014.

This survey paper provides an over the philosophical issues that arise in connection with data. In addition to the discussion of classical conceptions, the paper also examines so-called big data and the corresponding concept of big science.

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* 47.2 (1997): 217–228.

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.

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.

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.

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.

Models, Explanation, and Understanding

Models not only represent and produce predictions; they also explain process in the target and provide understanding of the target domain. Batterman and Rice 2014, Bokulich 2011, Graham Kennedy 2012, and Jebeile and Graham Kennedy 2016 formulate different accounts of how models provide explanations. Schindler 2014 offers a critique of Bokulich’s account. Bokulich 2017 provides a review of different accounts of model explanation. De Regt 2017, Elgin 2017, Khalifa 2017, and Potochnik 2017 all focus on scientific understanding rather than explanation and argue, each in their own way, the models, even though they are false when taken literally, can provide understanding.

Batterman, Robert W., and Collin C. Rice. “Minimal Model Explanations.” *Philosophy of Science* 81.3 (2014): 349–376.

Discusses minimal models, which are highly simplified models that disregard much of the details in the target system. Such models can nevertheless explain the behavior of the target if they belong to a universality class of models.

Bokulich, Alisa. “How Scientific Models Can Explain.” *Synthese* 180.1 (2011): 33–45.

Argues that idealized models can explain because the idealizations in a model can help uncover explanatory patterns of counterfactual dependence.

Bokulich, Alisa. “Models and Explanation.” In *Springer Handbook of Model-Based Science*. Edited by Lorenzo Magnani, and Tommaso Bertolotti, 103–118. Dordrecht, The Netherlands: Springer, 2017.

This survey chapter provides a comprehensive review of different accounts of how models explain, focusing on the role of falsehood, the use of mathematics, and tradeoffs.

de Regt, Henk. *Understanding Scientific Understanding*. Oxford: Oxford University Press, 2017.

Locates scientific understanding in intelligible theories that are both empirically adequate and internally consistent. Emphasizes that idealizations contribute to understanding an ineliminable way: removing idealizations would annihilate understanding.

Elgin, Catherine Z. *True Enough*. Cambridge, MA: MIT Press, 2017.

Argues that idealizations, if interpreted literally, are falsehoods, which does not make them dispensable expedients. On the contrary, they are “felicitous falsehoods.” Scientific understanding is nonfactive, which allows false models to contribute to our understanding of a domain.

Graham Kennedy, Ashley. “A Non Representationalist View of Model Explanation.” *Studies in History and Philosophy of Science Part A* 43.2 (2012): 326–332.

Focusing on idealized models in astrophysics, this paper argues that idealizations explain because they generate comparisons which help uncover causal mechanisms.

Jebeile, Julie, and Ashley Graham Kennedy. “Explaining with Models: The Role of Idealizations.” *International Studies in the Philosophy of Science* 29.4 (2016): 383–392.

First outlines, and then criticizes, several representationalist accounts of explanation. Argues that idealizations, even though they are false when taken literally, play an important role in facilitating the identification of the explanatory components within a model.

Khalifa, Kareem. *Understanding, Explanation, and Scientific Knowledge*. Cambridge, UK: Cambridge University Press, 2017.

Argues that the traditional view, which sees understanding as nothing more than knowledge of an explanation, should be revised but not abandoned entirely. On this revised view, idealizations provide understanding, but they should be seen as quasi-factive rather than non-factive, which requires approximate truth.

Potochnik, Angela. *Idealization and the Aims of Science*. Chicago: University of Chicago Press, 2017.

Argues that scientific understanding is often furthered by sacrificing truth and accuracy. Shows that recognizing simple patterns is cognitively valuable and that idealizations aid scientists in the pursuit of simple patterns, which is why idealizations, even though they are falsehoods, promote understanding.

Schindler, Samuel. “Explanatory Fictions—for Real?” *Synthese* 191.8 (2014): 1741–1755.

Criticizes Bokulich’s view that fictional models can be genuinely explanatory by drawing attention to a tension in her account between the claim that model fictions are explanatorily autonomous and the demand that model fictions be justified in order for them to be genuinely explanatory.

Multi-Model Situations

In many contexts, the scientific community produces multiple different, and sometimes conflicting, models of the same target system. Morrison 2011 gives an account of this model diversity. Three different reactions to this situation can be identified if models seem to be in conflict with each other. The first is robustness analysis, which focuses on results that are robust across all models. Although the method has a long history, it has reached prominence in the philosophical discussion with Levins 1966. Orzack and Sober 1993 provides a critical discussion of Levins's approach, and Schupbach 2018 provides a reformulation of the approach in terms of explanation. Grüne-Yanoff and Marchionni 2018 and Kuorikoski, et al. 2010 apply the method in the context of economic modelling, and Harris 2021 provides a critique of the latter's approach. Lloyd 2015 applies the method to climate models; Harris and Frigg 2023a and Harris and Frigg 2023b provide and extensive review of discussion of robustness in the context of climate modelling. The second approach is perspectivalism. Massimi 2022 provides a contemporary statement of perspectival realism; Massimi and McCoy 2020 is a collection of recent essays on the topic. The third approach does not resolve the tension between different models and construes the situation as one where decisions have to be made under uncertainty. Roussos, et al. 2021 provides a decision-theoretic framework to manage severe uncertainty. These three approaches are also discussed in Chapter 15 of Frigg 2023 (referenced in the section General Overviews).

Grüne-Yanoff, Till, and Caterina Marchionni. "Modeling Model Selection in Model Pluralism." *Journal of Economic Methodology* 25.3 (2018): 265–275.

Discusses Rodrik's view that multiple models of the same target are acceptable as long as each model serves a different purpose. Formalizes this procedure and then offers a critical discussion.

Harris, Margherita. "The Epistemic Value of Independent Lies: False Analogies and Equivocations." *Synthese* 199.5–6 (2021):14577–14597.

Offers a critical analysis of the argument of Kuorikoski, et al. 2010 for the epistemic import of model-based robustness analysis. Reasons that the argument is unsound and concludes that the epistemic import of model-based robust analysis cannot be established through probabilistic independence.

Harris, Margherita, and Roman Frigg. "Climate Models and Robustness Analysis – Part I: Core Concepts and Premises." In *Handbook of Philosophy of Climate Change*. Edited by Gianfranco Pellegrino and Marcello Di Paola. Cham, Switzerland: Springer, 2023a.

The first part of a two-part survey paper discusses different approaches to robustness analysis in the context of climate modelling. Begins by providing a detailed statement of the general structure of robustness analysis and then analyzes the premises of the argument, which concern robust properties, common structures, and so-called robust theorems.

Harris, Margherita, and Roman Frigg. "Climate Models and Robustness Analysis – Part II: The Justificatory Challenge." In *Handbook of Philosophy of Climate Change*. Edited by Gianfranco Pellegrino and Marcello Di Paola. Cham, Switzerland: Springer, 2023b.

The second part of a two-part survey paper discusses different approaches to robustness analysis in the context of climate modelling. Addresses the issue of justifying the inferential steps taking us from the premises to the conclusions.

Kuorikoski, Jaakko, Aki Lehtinen, and Caterina Marchionni. "Economic Modelling as Robustness Analysis." *British Journal for the Philosophy of Science* 61.3 (2010): 541–567.

Focusing on models in economics, the authors formulate an account of model-based robustness analysis that centers around the notion of the robustness of modelling results with respect to particular modeling assumptions.

Levins, Richard. "The Strategy of Model Building in Population Biology." *American Scientist* 54.4 (1966): 421–431.

Draws attention to the problem of competing virtues that models can have, and he notes that this can lead to plurality of models of the same system because it is not possible to maximize all desiderata simultaneously. In response, he proposes what is now known as robustness analysis, the idea that “our truth is the intersection of independent lies.”

Lloyd, Elisabeth A. “Model Robustness as a Confirmatory Virtue: The Case of Climate Science.” *Studies in History and Philosophy of Science Part A* 49 (2015): 58–68.

Discusses robustness analysis in the context of climate modelling. Argues that a distinct type of robustness can play a confirmatory role and she discusses climate models of greenhouse gas global warming in the twentieth century as an example.

Massimi, Michela. *Perspectival Realism*. New York: Oxford University Press, 2022.

Develops the position of perspectival realism, a kind of realism that takes seriously the view that scientific knowledge is always perspectival in the sense of being historically and culturally situated. The position is systematically developed and illustrated with case studies from elementary particle physics, climate science, and learning theory.

Massimi, Michela, and Casey D. McCoy, eds. *Understanding Perspectivism*. New York: Routledge, 2020.

An edited collection that brings together contributions on perspectivism and perspectival realism. Contributions reflect on the methodological promises and scientific challenges of perspectivism in fields as diverse as physics, biology, cognitive neuroscience, and cancer research, just as a few examples.

Morrison, Margaret. “One Phenomenon, Many Models: Inconsistency and Complementarity.” *Studies in History and Philosophy of Science Part A* 42.2 (2011): 342–353.

Discusses multi-model situations, contexts in which science produces many different models of the same target. Points out that, in some cases, this is unproblematic, but, in other cases, it represents genuine difficulties when attempting to interpret the information that models provide. Illustrates the cases with the examples of hydrodynamics and nuclear models.

Orzack, Steven H., and Elliott Sober. “A Critical Assessment of Levins’s *The Strategy of Model Building in Population Biology* (1966).” *Quarterly Review of Biology* 68.4 (1993): 533–546.

Critically assesses the argument of Levins 1966 and robustness analysis in general. Argues that the notion of robustness lacks a proper definition and that the idea that “our truth is the intersection of independent lies” lacks justification.

Roussos, Joe, Richard Bradley, and Roman Frigg. “Making Confident Decisions with Model Ensembles.” *Philosophy of Science* 88.3 (2021): 439–460.

Discusses the problem of making decisions under sever uncertainty when the evidence on which the decision is based comes from an ensemble of models. Introduces a version of the so-called confidence approach that is adapted to the multi-model situation and illustrates how the approach works with the problem of insurance pricing using hurricane models.

Schupbach, Jonah N. “Robustness Analysis as Explanatory Reasoning.” *British Journal for the Philosophy of Science* 69.1 (2018): 275–300.

Investigates the logic of such robustness analysis and formulates an account of model-based robustness analysis based on models’ explanatory power.

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