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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