The SAGE Encyclopedia of THEORY IN SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS

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THEORY IN SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS

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Edited by

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James Mattingly is Associate Professor of Philosophy at Georgetown University. Originally from the Silicon Valley in California, he studied Great Books at St. John's College in Annapolis, Maryland, and physics at University of California, Santa Cruz. He then returned to a study of the history and philosophy of science at Indiana University, where he received his PhD in 2002. Shortly before that, he was appointed assistant professor in the Georgetown University Department of Philosophy, where he has been ever since. His research is primarily in philosophy of science. He spends his efforts there about equally between general issues involving conceptual change in the sciences, the epistemology of science, the nature of scientific theories, scientific experiments, and scientific explanation on the one hand, and issues more specific to philosophy of physics on the other, including quantum gravity, general relativity, black holes and singularities, gauge theories, thermodynamics, and electrodynamics. He also has research interests in early modern philosophy, the foundations of logic and mathematics, and the history of logical empiricism and other movements that attempted to come to grips with the profound conceptual reorientation made necessary by the revolutionary changes in science at the turn of the 20th century. He has written and lectured extensively on scientific theories, epistemology of science, the nature of scientific experimentation, and the foundations of physics. He is the author of *Information and Experimental Knowledge*, published in 2021 by The University of Chicago Press.

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Introduction

The word "theory" has fascinating origins. In ancient Greek, the primary meaning of the word "θεωρία" (theory) seems to have been "looking at, viewing, beholding".[1] It also referred to ambassadors sent out to observe the oracle, or, on other occasions, the Olympic games. A variation of the word, *theorem,* can refer to the results of some science or technical discipline (what we might think of as engineering), and this is the word that Euclid uses to refer to the things that he proves in the *Elements*, our first systematic geometry book. In those cases, the theorems, or the things observed using the discipline, were tightly linked to the act of showing and seeing, to making plain. Today we might refer to, say, number theory and some of the things that we discover or prove or explain using number theory as its theorems. While "theory" is often associated with abstraction, with complication, with abstruseness it is grounded in the concrete, observable, repeatable results of the crafts, mathematics, and science.

The word "theory" is also, ironically, tightly linked equally to certainty and to pure speculation. On the one hand, in the popular imagination, theory seems sometimes associated to, say, the quantum theory, or the theory of relativity, two disciplines that have achieved unprecedented accuracy and experimental confirmation in the century since they were first formulated. On the other hand, it is common to hear, in response to a claim about the origin of various species on the earth, that natural selection is *only* a theory. Generally, people who study scientific theories insist, and rightly so, that speculation ungrounded in prior disciplinary work and without strong observational support does not merit being called "theory." Theories are generally well-supported explanatory systems that organize the understanding of some discipline or sector of it. While novel theories are propounded in order to try to explain puzzling or novel data and are not accepted until they have themselves been tested, when used to make assertions about the world and what we can expect to see, a theory typically has already been stringently tested and found to be observationally adequate.

Why an Encyclopedia of Theory, and Why STEM?

A collection of articles about scientific theory in its various aspects seems worthwhile for a number of reasons. First and foremost our scientific theories are the vehicles of what we know where the results and understanding of various disciplines are codified so that they can be transmitted, taught to new members of the discipline, and integrated with the results of other disciplines. They are, relatedly, tools for understanding and controlling the phenomena studied in a discipline. This is enough to make the theories themselves of significant and enduring interest. But in addition to the multitude of individual theories in the various STEM disciplines, there is also the matter of theory as itself a topic worthy of study.

My own academic discipline is neither science, nor technology, nor engineering, nor mathematics. Instead, it is philosophy of science. Philosophers of science do make contributions, sometimes, to science (or technology, or engineering, or mathematics) but that is not what their main focus is. Their main focus is to understand science and related disciplines as *themselves* objects of study. They ask: How does physics relate to chemistry? What do biologists mean when they use the expression "species"? Do experiments in social science give secure knowledge? Beyond such discipline specific questions though philosophers of science are

1. H. G. Liddell & R. Scott (Eds.). (1945). *An intermediate Greek-English lexicon.* Oxford University Press.

interested in big questions about the nature of scientific inquiry, and one of the main foci of philosophy of science has long been the theories that are produced and used in the sciences. What kind of thing is a theory? Is it a collection of true remarks about some field? Is it a calculus for predicting things? Is it a vehicle for understanding the subject matter of some discipline? Or is it something else altogether? These are important concerns to philosophers. But philosophers' concerns are not always the concerns of scientists, and are rarely those of students. We are often seen as out of touch with the real, grounded, day to day understanding of things and we are seen as nit-picking to little effect. Happily, however, philosophers are not the only ones who ask and answer such questions. So too do sociologists of science, scientific practitioners themselves, engineers, mathematicians, logicians, and so on. These have joined in with philosophers to contribute to this encyclopedia. What you will find across the many entries in this encyclopedia is a broad diversity of disciplinary background, but it is a diversity that displays unity of purpose if not of method or disciplinary assumptions. These many perspectives highlight just some of the important ways of understanding theory in philosophy and the sciences and make it clear that there are a number of roads into an understanding of theory.

As noted earlier, this encyclopedia is designed to support the study of theory in itself as well as the study of specific theories. The reasons for this are many. First, the scope of the encyclopedia allows for highlighting the vast range of topics that fall under the concept and also highlight key developments of theory along with key uses in various STEM disciplines. Next, putting things together this way can help to normalize the proper sense of "theory" as it is used in the sciences, and allow for nuanced discussion of the limits and scope of the claims made in the sciences without falling into bimodal habits of excessive deference or thoughtless dismissal. The concreteness of the specific disciplines' theories and the variety of tools and techniques that arise in one and find application in another provides an interesting contrast. This contrast can help to illustrate the fruitfulness over time of feedback between study of theory and development of theory as an object of use in STEM disciplines, and transfer of innovations in theory between disciplines. Finally, this encyclopedia, covering as it does such a range of topics displays the importance of interactions and feedback between theory as it used and theory as it is . . . well . . . theorized.

The encyclopedia is an attempt to shed some light on the nature of theories in the STEM disciplines. I have talked about reasons to focus on theory. But why focus on STEM? First, it may not seem to be a good category in some respects, either as an academic umbrella term or as a unified object of study. The classification of STEM fields under an umbrella term that joins the abstract pursuits of modern sciences like quantum theory and mathematics together with the concrete and practical practices of technological production and engineering may seem like a novelty thought up by ambitious administrators trying to figure out where best to direct institutional efforts and funding at fields that are likely to return measurable fruits. While there is some truth to that, it is almost precisely what Robert Boyle and folks like him were trying to do when they instituted the practice of modern science. Out of fractured and individualized practices and closely guarded techniques and knowledge developed in secret, Boyle attempted to produce an open society of inquiry, grounded in observation and reason, dedicated to improving human lives.

In any case, STEM is a term of current use, and moreover can be useful here as a demarcation criterion between a number of ways "theory" can be employed. In some academic disciplines, theory has more to do with providing an interpretation of various kinds of activity or features of the world so that some new phenomena can be revealed. Maybe an analysis of various patterns of speech in a community can be seen to reveal important background assumptions of that community, and sometimes "theorizing" is a way of capturing the activity involved in making it possible to be aware of those assumptions. This use of "theory" has its own life and vast disciplinary context, one that is importantly different from what will be found in these pages. Here the use of "theory," although broad, is constrained in different ways from much of what is found in other disciplines. It would be silly to say that one use is correct and the other not, and it would also be silly to suppose that there is nothing to be learned about one way of deploying the concept theory from studying other ways, for there will be important points of contact. However, STEM is a natural domain of application for one way of thinking about the concept, and there is utility for students in fields broadly under this umbrella, or who are trying to learn about topics related to those fields, to have a ready and broadly unified resource for orienting themselves to the way theory is used and developed in those fields. And as an aside it is the one that hews most closely to my own disciplinary competence.

The Organization and Rationale of the Encyclopedia

My main aims for the encyclopedia are two. On the one hand, I want users to find here examples of the various technical and conceptual components of what it is to be a theory, in general terms and not merely as these theories appear in and are used by various STEM focused disciplines as a way of organizing, grasping, making use of, critiquing, and expanding our knowledge of some subject matter. To reflect that part of the aim included here are a number of entries that are concerned with theory itself, in some way detached from any particular subject matter concerning which one might construct or employ a theory. On the other hand, I want users to see the way that various STEM disciplines theorize about their subject matters, both how they make use of existing understanding of what theories are and how they function and how the individual disciplines, by attempting to make theories adequate to the peculiarities of their subject matter, fruitfully extend the very meaning of what it is to be a theory. While these subject matter entries will contain framing material about the theory of their subject matter, their main task will be to illuminate what role theory plays in the discipline and what insights into the nature of theory follows from that illumination.

The entries for the *Encyclopedia of Theory in STEM* range widely. There are 173 entries comprising nearly 625,000 words of text in entries ranging from 1,500 to 7,000 words. The entries have been grouped into 13 categories: there are four broad categories with several further categories grouped under two of them. The categories and their respective entries form the Reader's Guide, which follows the List of Entries in the front matter of the encyclopedia. The categories are also listed below. I have chosen to group according to discipline, widely understood, as the most perspicuous way of navigating the topics of the encyclopedia. There is inevitable categorical overlap in a number of disciplines, and some inevitable awkward fits given our scope constraints, and the fact that some of the disciplines considered here are generally thought to be situated in non-STEM-covering disciplines, but seemed necessary to include for reasons of coherence.

The first division in the structure of the encyclopedia is between *general* matters having to do with science and theory and *specific* matters having to do with particular disciplines within STEM.

I. General Theory of Science: Here you will find entries having to do with the nature of science, including its authoritativeness, the way its claims are tested, in short the basic conceptual features of the scientific enterprise as a whole.

II. Nature and Structure of Theories: Here the discussion remains general and at a high level of abstraction but the focus is more specifically on the nature of scientific theory. What kind of thing is a theory? How is it connected to other things we do in the sciences? What have theorists about theories learned over the last century from science and from analysis of science, and what has science itself learned from such theorizing.

Turning to the more specific disciplines we see the second division, between disciplines more on the empirical side of things and those on the formal side. Here are found discussions both of matters having to do specifically with the day-to-day features of these disciplines and of general issues that frame and clarify their scope and limits. While these entries give accessible overviews of the subject matter of the disciplines, those overviews are no substitute for extensive study of the disciplines. Instead just enough is presented to make it possible to understand the role of theory in these disciplines.

III. Formal Disciplines: These disciplines are less grounded in empirical data and more focused on concepts. But that is not to say that empirical matters can be entirely neglected. Even in logic and mathematics, but especially in computer science questions of resources and the role of complexity make it impossible to fully detach oneself from facts about the world. Even so entries here are more focused on structural features of theories, in addition to specific disciplinary matters. This topic is further divided into:

1. Computer Science
2. Logic and Mathematics

IV. Empirical Disciplines: The empirical disciplines as well are not monolithically empirical. Constraints from the nature of mathematics and logic have an impact on the kinds of theory that are possible here. But these entries are more directed to specific developments in observationally testable domains as well as to the connection between theoretical and observational features. This topic is further divided into:

1. Biological Science
2. Chemistry
3. Cognitive Sciences
4. Earth and Space Sciences
5. Engineering
6. Physics
7. Technology

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