Part I Introduction

Chapter 1

What Is the Cognitive Science of Science?

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Explaining Science

Science is one of the greatest achievements of human civilization, contributing both to the acquisition of knowledge and to people's wellbeing through technological advances in areas from medicine to electronics. Without science, we would lack understanding of planetary motion, chemical reactions, animal evolution, infectious disease, mental illness, social change, and countless other phenomena of great theoretical and practical importance. We would also lack many valuable applications of scientific knowledge, including antibiotics, airplanes, and computers. Hence it is appropriate that many disciplines such as philosophy, history, and sociology have attempted to make sense of how science works.

This book endeavors to understand scientific development from the perspective of cognitive science, the interdisciplinary investigation of mind and intelligence. Cognitive science encompasses at least six fields: psychology, neuroscience, linguistics, anthropology, philosophy, and artificial intelligence (for overviews, see Bermudez 2010, Gardner 2005, Thagard 2005). The main intellectual origins of cognitive science are in the 1950s when thinkers such as Noam Chomsky, George Miller, Marvin Minsky, Allan Newell, and Herbert Simon began to develop new ideas about how human minds and computer programs might be capable of intelligent functions such as problem solving, language, and learning. The organizational origins of cognitive science are in the 1970s with the establishment of the journal *Cognitive Science* and the Cognitive Science Society, and the first published uses of the term "cognitive science" (e. g. Bobrow and Collins 1975).

Cognitive science has thrived because the problem of understanding how the mind works is far too complex to be approached using ideas and methods from only one discipline. Many researchers whose primary backgrounds are in psychology, philosophy, neuroscience, linguistics, anthropology, and computer science have realized the advantages of tracking work in some of the other fields of cognitive science. Many successful projects have fruitfully combined methodologies from multiple fields, for example research on inference that is both philosophical and computational, research on language that is both linguistic and neuroscientific, and research on culture that is both anthropological and psychological.

Naturally, cognitive science has also been used to investigate the mental processes required for the practice of science. The prehistory of the cognitive science of science goes back to philosophical investigation of scientific inference by Francis Bacon, David Hume, William Whewell, John Stuart Mill, and Charles Peirce. Modern cognitive science of science began only in the 1980s when various psychologists, philosophers, and computer scientists realized the advantages of taking a multidisciplinary approach to understanding scientific thinking. Pioneers include: Lindley Darden, Ronald Giere, and Nancy Nersessian in philosophy; Bruce Buchanan, Pat Langley, and Herbert Simon in computer modeling; and William Brewer, Susan Carey, Kevin Dunbar, David Klahr, and Ryan Tweney in experimental psychology. Extensive references are given in the next section. The earliest occurrence of the phrase "cognitive science of science" that I have been able to find is in Giere (1987), although the idea of applying cognitive psychology and computer modeling to scientific thinking goes back at least to Simon (1966).

This chapter provides a brief overview of what the component fields of cognitive science bring to the study of science, along with a sketch of the merits of combining methods. It also considers alternative approaches to science studies that are often antagonistic to the cognitive science of science, including formal philosophy of science and postmodernist history and sociology of science. I will argue that philosophy, history, and sociology of science can all benefit from ideas drawn from the cognitive sciences. Finally, I give an overview of the rest of the book by sketching how the cognitive science of science can investigate some of the most important aspects of the development of science, especially explanation, discovery, and conceptual change.

Approaches to the Cognitive Science of Science

It would take an encyclopedia to review all the different approaches to science studies that have been pursued. Much more narrowly and concisely, this section reviews what researchers from various fields have sought to contribute to the cognitive science of science.

My own original field is the philosophy of science, and I described in the preface how concern with the structure and growth of scientific knowledge led me to adopt ideas and methods from psychology and artificial intelligence, generating books and articles that looked at different aspects of scientific thinking (e,g. Thagard 1988, 1992, 1999, 2000). Independently, other philosophers have looked to cognition to enhance understanding of science, including Lindley Darden (1991, 2006), David Gooding (1990), Ronald Giere (1988, 1999, 2010), and Nancy Nersessian (1984, 2009).

Andersen, Barker, and Cheng (2006), Magnani (2001, 2009), and Shelley (2003) also combine philosophy of science, history of science, and cognitive psychology. Collections of work on philosophical approaches to the cognitive science of science include Giere (1992) and Carruthers, Stich, and Siegal (2002).

Philosophy of science is not just a beneficiary of cognitive science but also a major contributor to it. Since the 1600s work of Francis Bacon (1960), philosophers have investigated the nature of scientific reasoning and contributed valuable insights on such topics as explanation (Whewell 1967), causal reasoning (Mill 1970), and analogy (Hesse 1966). Philosophy of science was sidetracked during the logical positivist era by (1) a focus on formal logic as the canonical way of representing scientific information and (2) a narrow empiricism incapable of comprehending the theoretical successes of science. Logical positivism was as inimical to understanding scientific knowledge as behaviorism was to understanding thinking in general.

In response to logical positivism, Russell Hanson (1958), Thomas Kuhn (1962) and others spurred interest among philosophers in the history of science, but there was a dearth of tools richer than formal logic for examining science, although Hanson and Kuhn occasionally drew on insights from Gestalt psychology. In the 1980s, when philosophers looked to cognitive science for help in understanding historical developments, we brought to the cognitive science of science familiarity with many aspects of high-level scientific thinking. The method that philosophy of science can most valuably contribute to the cognitive science of science consists of careful analysis of historical case studies.

Most psychologists concerned with scientific thinking adopt a very different method - behavioral experiments. Such experimentation is a crucial part of cognitive science, providing data about many different kinds of thinking that theories aim to explain. Actual scientists are rarely available for psychological experiments, but participants can be recruited from among the modern-day lab rats of cognitive psychologists - university undergraduates. Much of the valuable work on scientific thinking has been motivated by an attempt to understand how children can develop an understanding of science, a worthy enterprise that is part of both developmental and educational psychology.

Experimental and theoretical work on the development of scientific knowledge has been conducted by many psychologists (e.g. Carey 1985, 2009; Dunbar 1997, 2001; Dunbar and Fugelsang 2005; Gentner et al. 1997; Klahr 2000; Schunn and Anderson 1999; Tweney, Doherty, and Mynatt 1981; Vosniadiou and Brewer 1992). Like all cognitive scientists, psychologists can contribute to the development of theories about scientific thinking, but their main methodological contribution consists in behavioral experiments, although some psychologists such as Dedre Gentner and Ryan Tweney also undertake historical studies. Useful collections of work on the psychology of science include Crowley, Schunn and Okada (2001), Gholson et al. (1989), Gorman et al. (2005), and Proctor and Capaldi (forthcoming). Other works in the psychology of science tied less closely to experimental cognitive psychology include Feist (2006), Simonton (1988), and Sulloway (1996). The introductory chapters below for parts II, III, and IV provide further references to work in the psychology of science on the more specific topics of explanation, discovery, and conceptual change.

In addition to philosophical/historical studies and behavioral experiments, the cognitive science of science has made extensive use of computational models, which have been theoretically and methodologically important since the 1950s. The theoretical usefulness comes from the fruitfulness of the hypothesis that thought is a kind of computation: thinking consists of applying processes to representations, just as computing consists of applying algorithms to data structures (see Thagard 2005 for a review). This hypothesis was far more powerful than previous attempts to understand the mind in terms of familiar mechanisms such as clockwork, vibrating strings, hydraulic systems, or telephone switchboards.

Moreover, computer modeling provides theorizing about the mind with a novel methodology – writing and running computer programs. Beginning with the seminal work on problem solving by Newell, Shaw, and Simon (1958), computer modeling has provided an invaluable tool for developing and testing ideas about mental processes (Sun, 2008b). Computational models of scientific thinking have been developed both by researchers in the branch of computer science called artificial intelligence, and by philosophers and psychologists who have adopted computer modeling as part of their methodological toolkit. There are many notable examples of computer simulations of different aspects of scientific thinking (e.g. Bridewell et al. 2008; Bridewell and Langley 2010; Kulkarni 1990; Langley et al. 1987; Lindsay, Buchanan, Feigenbaum, and Lederberg, 1980; Schrager and Langley 1990, Thagard 1992, Valdes-Perez 1995). The next section gives a more detailed discussion of how computational modeling contributes to the cognitive science of science.

Experimental neuroscience has so far made little contribution to understanding scientific thinking, even thought it is becoming increasingly important to cognitive psychology and other areas such as social, developmental, and clinical psychology. The role of neuroscience in cognitive science has increased dramatically in the past two decades because of new technologies for observing neural activity using brain scanning tools such as functional magnetic resonance imaging (fMRI). The complementary theoretical side of neuroscience is the development of computational models that take seriously aspects of neural processing such as spiking neurons and interconnected brain areas that were neglected in the connectionist models of the 1980s, (see e.g. Dayan and Abbott 2001; Eliasmith and Anderson 2003). There has not yet emerged a distinct enterprise one would call the "neuroscience of science", although some of the kinds of thinking most relevant to scientific thought such as analogy, causal reasoning, and insight are beginning to get experimental and theoretical investigation. What neuroscience can contribute to the understanding of science is knowledge about the neural processes that enable scientists to generate and evaluate ideas. Some of my own most recent work in chapters 3, 4, 8, and 19 employs ideas from theoretical neuroscience.

To complete this review of how the different fields of cognitive science contribute to the understanding of science, I need to include linguistics and anthropology. Unfortunately, I am not aware of much relevant research, although I can at least point to the work of Kertesz (2004) on the cognitive semantics of science, and to the work of Atran and Medin (2008) on folk concepts in biology across various cultures. Let me now return to why computer modeling is important for the cognitive science of science.

Methodology of Computational Modeling

What is the point of building computational models? One answer might come from the hypothetico-deductive view of scientific method, according to which science proceeds by generating hypotheses, deducing experimental predictions from them, and then performing experiments to see if the predicted observations occur. On this view, the main role of computational models is to facilitate deductions. There are undoubtedly fields such as mathematical physics and possibly economics where computer models play something like this hypothetico-deductive role, but their role in the cognitive sciences is much larger.

The hypothetico-deductive method is rarely applicable in biology, medicine, psychology, neuroscience, and the social sciences, where mathematically exact theories and precise predictions are rare. These sciences are better described by what I shall whimsically call the *mechanista* view of scientific method. Philosophers of science have described how many sciences aim for the discovery of mechanisms rather than laws, where a mechanism is a system of interacting parts that produce regular changes (e.g. Bechtel 2008; Bechtel and Richardson, 1993; Bunge 2003; Craver, 2007; Darden, 2006; Machamer, Darden, and Craver 2000; Thagard 2006; Wimsatt 2007). Biologists, for example, can rarely derive predictions from mathematically-expressed theories, but they have been highly successful in describing mechanisms such as genetic variation and evolution by natural selection that have very broad explanatory scope. Similarly, I see cognitive science as primarily the search for mechanisms that can explain many kinds of mental phenomena such as perception, learning, problem solving, emotion, and language.

Computer modeling can be valuable for expressing, developing, and testing descriptions of mechanisms, at both psychological and neural levels of explanation. In contemporary cognitive science, theories at the psychological level postulate various kinds of mental representations and processes that operate on them to generate thinking. For example, rule-based theories of problem solving from Newell and Simon (1972) to Anderson (2007) postulate (1) representations of goals and if-then rules and (2) search processes involving selection and firing of rules. The representations are the parts and the processes are the interactions that together provide a mechanism that explains mental changes that accomplish tasks. Other cognitive science theories can also be understood as descriptions of mechanisms, for example connectionist models that postulate simple neuron-like parts and processes of spreading activation that produce mental changes (Rumelhart and McClelland 1986). Computational neuroscience now deals with much more biologically realistic neural entities and processes than connectionism, but the aim is the same: to describe the mechanisms that explain neuropsychological phenomena.

Expressing and developing such theoretical mechanisms benefits enormously from computational models. It is crucial to distinguish between theories, models, and programs. On the mechanista view, a theory is a description of mechanisms, and a model is a simplified description of the mechanisms postulated to be responsible for some phenomena. In computational models, the simplifications consist of proposing general kinds of data structures and algorithms that correspond to the parts and interactions that the theory postulates. A computer program produces a still more specific and idealized account of the postulated parts and interactions using data structures and algorithms in a particular programming language. For example, the theory of problem solving as rule application using means-ends reasoning gets a simplified description in a computational model with rules and goals as data structures and means-ends search as interactions. A computer program implements the model and theory in a particular programming language such as LISP or JAVA that makes it possible to run simulations. Theoretical neuroscience uses mathematically sophisticated programming tools such as MATLAB to implement computational models of neural structures and processes that approximate to mechanisms that are hypothesized to operate in brains.

Rarely, however, do computer modelers proceed simply from theory to model to program in the way just suggested. Rather, thinking about how to write a computer program in a familiar programming language enables a cognitive scientist to express and develop ideas about what parts and interactions might be responsible for some psychological phenomena. Hence development of cognitive theories, models, and programs is a highly interactive process in which theories stimulate the production of programs and vice versa. It is a mistake, however, to identify theories with programs, because any specific program will have many details arising from the peculiarities of the programming language used. Nevertheless, writing computer programs helps enormously to develop theoretical ideas expressed as computer models. The computer model provides a general analog of the mechanisms postulated by the theory, and the program provides a specific, concrete, analogical instantiation of those mechanisms.

In the biological, social, and cognitive sciences, descriptions of mechanism are rarely so mathematical that predictions can be deduced, but running computer programs provides a looser way of evaluating theories and models. A computer program that instantiates a model that simplifies a theory can be run to produce simulations whose performance can be compared to actual behaviors, as shown in systematic observations, controlled behavioral experiments, or neurological experiments.

There are three degrees of evaluation that can be applied, answering the following questions about the phenomena to be explained:

1. Is the program capable of performing tasks like those that people have been observed doing?
2. Does the behavior of the program qualitatively fit with how people behave in experiments?
3. Does the behavior of the program quantitatively fit numerical data acquired in experiments?

Ideally, a computer program will satisfy all three of these tests, but often computer modeling is part of a theoretical enterprise that is well out in front of experimentation. In such cases, the program (and the model and theory it instantiates) can be used to suggest new experiments whose resulting data can be compared against the computer simulations. In turn, data that are hard to explain given currently available mechanisms may suggest new mechanisms that can be simulated by computer programs whose behaviors can once again be compared to those of natural systems. The three questions listed in this paragraph apply to models of psychological behavior, but analogous questions can be asked about computational simulations of neural data.

The general interactive process of mechanism-based theory development using computational models is shown in figure 1.1, which portrays an interactive process with no particular starting point. Note that the arrows between mechanisms and models, and between models and simulations, are symmetrical, indicating that models can suggest mechanisms and programs can suggest models, as well as vice versa. In one typical pattern, experimental results prompt the search for explanatory mechanisms that can be specified using mathematical/computational models that are then implemented in computer programs. Simulations using these programs generate results that can be compared with experimental results. This comparison, along with insights gained during the whole process of generating mechanisms, models, and simulations, can in turn lead to ideas for new experiments that produce new experimental results.

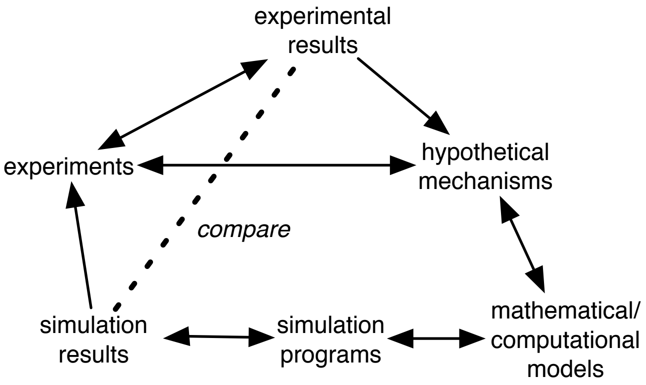

Figure 1.1 The role of computer models in developing and testing theories about mechanisms. Lines with arrows indicate causal influences in scientific thinking. The dashed line indicates the comparison between the results of experiments and the results of simulations.

Unified Cognitive Science Research

I have described philosophical, psychological, computational, and neuroscientific contributions to the understanding of science, but cognitive science at its best combines insights from all of its fields. We can imagine what an ideal research project in the cognitive science of science would like, one beyond the scope of any single researcher except perhaps Herbert Simon. Consider a team of researchers operating with a core set of theoretical ideas and multiple methodologies. Let "ASPECT" stand for some aspect of scientific thinking that has been little investigated. We can imagine a joint enterprise in which philosophers analyze historical cases of ASPECT, psychologists perform behavioral experiments on how adults and children do ASPECT, neuroscientists perform brain scans of people doing ASPECT, and computational modelers write programs that can simulate ASPECT. Linguists and anthropologists might also get involved by studying whether ASPECT varies across cultures. Representatives of all six fields could work together to generate and test theories about the mental structures and processes that enable people to accomplish ASPECT. My own investigations into the cognitive science of science do not have anything like the scope of this imaginary investigation of ASPECT, but they variously combine different parts of the philosophical, historical, psychological, computational, and neuroscientific investigation of scientific thinking.

Unified investigations in the cognitive science of science can be normative as well as descriptive. It is sometimes said that philosophy is normative, concerned with how things ought to be, in contrast to the sciences which are descriptive, concerned with how things are. This division is far too simple, because there are many applied sciences, from engineering to medicine to clinical and educational psychology, that aim to improve the world, not just to describe it (Hardy-Vallée and Thagard 2008). Conversely, if the norms that philosophy seeks to develop are to be all relevant to actual human practices, they need to be tied to descriptions of how the world, including the mind, generally works. I have elsewhere defended the naturalistic view that philosophy is continuous with science, differing in having a greater degree of generality and normativity (Thagard 2009, 2010a). This book assumes the priority of scientific evidence and reasoning over alternative ways of fixing belief such as religious faith and philosophical thought experiments, but the assumption is argued for in Thagard (2010a, ch. 2).

The cognitive science of science can take from its philosophical component and also from its applied components a concern to be normative as well descriptive. An interdisciplinary approach to science can aim not only to describe how science works, but also to develop norms for how it might work better. The methodology is captured by the following normative procedure (adapted from Thagard 2010a, p. 211):

1. Identify a domain of practices, in this case ways of doing scientific research.
2. Identify candidate norms for these practices, such as searching for mechanisms.
3. Identify the appropriate goals of the practices in the given domain, such as truth, explanation, and technological applications.
4. Evaluate the extent to which different practices accomplish the relevant goals.
5. Adopt as domain norms those practices that best accomplish the relevant goals.

The descriptive side of cognitive science is essential for all of steps 1-4, but description can quickly lead to normative conclusions via the assessment shown in steps 4-5. My concern in the cognitive science of science is primarily descriptive, but normative issues will arise in chapters on climate change (ch. 5), truth (ch. 6) and values (ch. 17).

Other Approaches to Studying Science

Cognitive science is not the only way to study the practices and results of science, and there are alternative approaches that are antagonistic to it. Cognitive science is scorned by some philosophers, historians, and sociologists who view it as fundamentally inadequate to understand the process of science and other important aspects of human life. I will now concisely review some of these alternatives, and describe why I think their opposition misses the mark.

Within philosophy, the cognitive science of science exemplifies naturalism, the view that philosophical deliberations should be tied to scientific evidence. Naturalistic philosophy has a venerable history, with practitioners such as Aristotle, Epicurus, Bacon, Locke, Hume, Mill, Peirce, Dewey, Quine, and many contemporary philosophers of science and mind. But philosophy also has a strong anti-naturalistic strain, which challenges the relevance of science to philosophy from various directions. One prominent challenge seeks philosophical truths from reason alone, independent of scientific evidence; such truths are pursued by Plato, Kant, Frege, Husserl, and contemporary philosophers who try to use thought experiments to arrive at conceptual truths (for critiques of this approach, see Thagard 2009, 2010a). This reason-based approach to philosophy tends to be antagonistic to cognitive science on the grounds that mind, like everything else, can be understood most deeply by methods that are a priori - independent of sense experience.

The anti-psychologistic tendency of philosophy is also evident in contemporary work in the philosophy of science that employs formal methods such as symbolic logic, set theory, and probability theory. All of these tools are potentially relevant to the cognitive science of science, but formal philosophy of science uses them to the exclusion of many other tools (including the varied computational ones mentioned above) that cognitive science can bring to the examination of scientific knowledge. Formal philosophy of science follows in the tradition of the logical positivists in assuming that scientific theories are best viewed as abstract structures rather than as mental representations. Such abstractions are of limited use in understanding the actual practice of science and the details of the growth of scientific knowledge. It is particularly odd that the philosophy of science should ignore branches of science such as psychology that are highly relevant to understanding how science works, but the continuing influence of the Fregean, antipsychologistic strain of analytic philosophy is large.

A very different challenge to naturalistic philosophy comes from a more nihilistic direction that is generally skeptical of scientific and philosophical claims to achieve knowledge. Philosophers such as Nietzsche, Heidegger, Derrida, Foucault, and Lyotard rejected Enlightenment values of evidence, rationality, and objectivity. From a postmodernist perspective, science is just another human enterprise beset by power relations, whose discourse can be investigated by the same hermeneutic means that apply to other institutions. Cognitive science is then merely an attempt by scientists and science-oriented philosophers to exaggerate their own importance by privileging one style of thinking. In contrast, chapter 6 below provides a defense of scientific realism, the view that science aims to achieve truth and sometimes succeeds.

The postmodernist rejection of science as a way of knowing the world has infected much work in the history and philosophy of science. Around the same time that the cognitive science of science was taking off, an alternative movement arose that managed to take over science studies programs at many universities. Sociologists of science produced a research program called the Sociology of Scientific Knowledge that abandoned the normative assessment of science in favor of purely sociological explanations of how science develops (e.g. Barnes, Bloor, and Henry 1998). Latour and

Woolgar (1986) even called for a ten-year moratorium on cognitive explanations of science until sociologists had had a chance to explain all aspects of scientific development. That moratorium has long expired, and sociologists have obviously left lots of science to be explained. Moreover, some prominent proponents of postmodern sociology of science have made the shocking discovery that science and technology might even have something to do with reality (Latour 2004)!

In contrast to the imperialism of sociologists who think they can explain everything about scientific development, the cognitive science of science is friendly to sociological explanations. Power relations are undoubtedly an important part of scientific life, from the local level of laboratory politics to the national level of funding decisions. Like some analytic philosophers, some sociologists suffer from psychophobia, the fear of psychology, but cognitive approaches to science are compatible with recognition of important social dimensions of science. For example, in my study of the development and acceptance of the bacterial theory of ulcers, I took into account social factors such as collaboration and consensus as well as psychological processes of discovery and evaluation (Thagard 1999). Other works in the cognitive science of science have similarly attended to social dimensions (e.g. Dunbar 1997, Giere 1988). The cognitive and the social sciences should be seen as complements, not competitors, in a unified enterprise that might be called *cognitive social science*. Anthropology, sociology, politics, and economics can all be understood as requiring the integration of psychological and social mechanisms, as well as neural and molecular ones (Thagard 2010b, forthcoming-c). Novel kinds of computer models are needed to explore how the behavior of groups can depend recursively on the behavior of individuals who think of themselves as members of groups. Agent-based models of social phenomena are being developed, but are only just beginning to incorporate psychologically realistic agents (Sun 2008a; Thagard 2000, ch. 7, presents a cognitive-social model of scientific consensus). The aim of these models is not to reduce the social to the psychological and neural, but rather to show rich interconnections among multiple levels of explanation. My hope is that future work using on cognitive-social interactions will provide ways of simulating social aspects of science using techniques under development (Thagard forthcoming-c).

Studies in the Cognitive Science of Science

In the rest of this book, however, I largely neglect social factors in science in order to concentrate on philosophical, psychological, computational, and neural aspects. Even within the cognitive realm, the investigations reported here are selective, dealing primarily with explanation, discovery, and conceptual change. I understand science broadly to include medicine and technology, which are discussed in several of the chapters.

Part II considers cognitive aspects of explanation and related scientific practices concerned with the nature of theories and theory choice. After a brief overview that makes connections to related work, four chapters develop cognitive perspectives on the nature of explanation, mental models, theory choice, and resistance to scientific change. Climate change provides a case study where normative models of theory acceptance based on explanatory coherence are ignored because of psychological factors. This part also includes the most philosophical chapter in the book, arguing that coherence in science sometimes leads to truth.

Part III concerns scientific discovery understand as a psychological and neural process. Formal philosophy of science and sociological approaches have had little to say about how discoveries are made. In contrast, this part contains a series of studies about the psychological and neural processes that led to breakthroughs in science, medicine, and technology.

Part IV shows how discoveries of new theories and explanations lead to conceptual change, ranging from the mundane addition of new concepts to the dramatic reorganizations required by scientific revolutions. Four chapters describe conceptual change in the fields of biology, psychology, and medicine.

Finally, Part V presents two new essays concerned with the nature of values and with the neural underpinnings of scientific thinking. The chapter on values shows how the cognitive science of science can integrate descriptive questions about how science works with normative questions about how it ought to work. The final chapter builds on Chris Eliasmith's recent theory of semantic pointers to provide a novel account of the nature of scientific concepts such as *force, water,* and *cell*. Please note that this book uses the following conventions: items in italics stand for concepts and items in quotes stand for words. For example, the concept *car* is expressed in English by the word "car" and applies to many things in the world, including my 2009 Honda Civic.

The cognitive science of science inherits from the philosophy of science the problem of characterizing the structure and growth of scientific knowledge. It greatly expands the philosophical repertoire for describing the structure of knowledge by introducing much richer and empirically supported accounts of the nature of concepts, rules, mental models, and other kinds of representations. Even greater is the expansion of the repertoire of mechanisms for explaining the growth of scientific knowledge, through computationally rich and experimentally testable models of the nature of explanation, coherence, theory acceptance, inferential bias, concept formation, hypothesis discovery, and conceptual change. Adding an understanding of the psychological and neural processes that help to generate and establish scientific knowledge does not undercut philosophical concerns about normativity and truth, nor need it ignore the social processes that are also important for the development of scientific knowledge. Although the cognitive science of science is only a few decades old, I hope that the essays in this book, along with allied work by others, show its potential for explaining science.

REFERENCES

Andersen, H., Barker, P., & Cheng, X. (2006). *The cognitive structure of scientific revolutions*. Cambridge: Cambridge University Press.

Anderson, J. R. (2007). *How can the mind occur in the physical universe?* Oxford: Oxford University Press.

Atran, S., & Medin, D. L. (2008). *The native mind and the cultural construction of nature*. Cambridge, MA: Cambridge University Press.

Bacon, F. (1960). *The New Organon and related writings*. Indianapolis: Bobbs-Merrill.

Barnes, B., Bloor, D., & Henry, J. (1996). *Scientific knowledge: A sociological analysis*. Chicago: University of Chicago Press.

Bechtel, W. (2008). *Mental mechanisms: Philosophical perspectives on cognitive neuroscience*. New York: Routledge.

Bechtel, W., & Richardson, R. C. (1993). *Discovering complexity*. Princeton: Princeton University Press.

Bermudez, J. L. (2010). *Cognitive science: An introduction to the science of the mind*. Cambridge: Cambridge University Press.

Bobrow, D. G., & Collins, A. (Eds.). (1975). *Representation and understanding: Studies in cognitive science*. New York: Academic Press.

Bridewell, W., Langley, P., Todorovski, L., & Dzeroski, S. (2008). Inductive process modeling. *Machine learning, 71*, 1-32.

Bunge, M. (2003). *Emergence and convergence: Qualitative novelty and the unity of knowledge*. Toronto: University of Toronto Press.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press/Bradford Books.

Carruthers, P., Stich, S., & Siegal, M. (Eds.). (2002). *The cognitive basis of science*. Cambridge: Cambridge University Press.

Craver, C. F. (2007). *Explaining the brain*. Oxford: Oxford University Press.

Crowley, K., Schunn, C. D., & Okada, T. (Eds.). (2001). *Designing for science: Implications from everyday, classroom, and professional settings*. Mawah, NJ: Erlbaum.

Darden, L. (1991). *Theory change in science: Strategies from Mendelian genetics*. Oxford: Oxford University Press.

Darden, L. (2006). *Reasoning in biological discoveries*. Cambridge: Cambridge University Press.

Dayan, P., & Abbott, L. F. (2001). *Theoretical neuroscience: Computational and mathematical modeling of neural systems*. Cambridge, MA: MIT Press.

Dunbar, K. (1997). How scientists think: On-line creativity and conceptual change in science. In T. B. Ward, S. M. Smith & J. Vaid (Eds.), *Creative thought: An investigation of conceptual structures and processes* (pp. 461-493). Washington: American Psychological Association.

Dunbar, K. (2001). What scientific thinking reveals about the nature of cognition. In K. Crowley, C. D. Schunn & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings*. (pp. 115-140). Mawah, NJ: Erlbaum.

Dunbar, K., & Fugelsang, J. (2005). Scientific thinking and reasoning. In K. J. Holyoak & R. Morrison (Eds.), *Cambridge handbook of thinking and reasoning* (pp. 705-726). Cambridge: Cambridge University Press.

Eliasmith, C., & Anderson, C. H. (2003). *Neural engineering: Computation, representation and dynamics in neurobiological systems*. Cambridge, MA: MIT Press.

Feist, G. J. (2006). *The psychology of science and the origins of the scientific mind*. New Haven: Yale University Press.

Gardner, H. (1985). *The mind's new science*. New York: Basic Books.

Gentner, D., Brem, S., Ferguson, R., Wolff, P., Markman, A. B., & Forbus, K. (1997). Analogy and creativity in the works of Johannes Kepler. In T. B. Ward, S. M. Smith & J. Vaid (Eds.), *Creative thought: An investigation of conceptual structures and processes* (pp. 403-459). Washington, DC: American Psychological Association.

Gholson, B., Shadish, W., Neimeyer, R., & Houts, A. (Eds.). (1989). *Psychology of science : Contributions to metascience*. Cambridge: Cambridge University Press.

Giere, R. (1987). The cognitive study of science. In N. Nersessian (Ed.), *The process of science* (pp. 139-160). Berlin: Springer.

Giere, R. (1988). *Explaining science: A cognitive approach*. Chicago: University of Chicago Press.

Giere, R. (2010). *Scientific perspectivism*. Chicago: University of Chicago Press.

Giere, R. N. (1999). *Science without laws*. Chicago: University of Chicago Press.

Gooding, D. (1990). *Experiment and the nature of meaning*. Dordrecht: Kluwer.

Gorman, M. E., Tweney, R. D., Gooding, D. C., & Kincannon, A. P. (Eds.). (2005). *Scientific and technological thinking*. Mawah, NJ: Lawrence Erlbaum Associates.

Hanson, N. R. (1958). *Patterns of discovery*. Cambridge: Cambridge University Press.

Hardy-Vallée, B., & Thagard, P. (2008). How to play the ultimatum game: An engineering approach to metanormativity. *Philosophical Psychology, 21*, 173-192.

Hesse, M. (1966). *Models and analogies in science*. Notre Dame, IN: Notre Dame University Press.

Kertesz, A. (2004). *Cognitive semantics and scientific knowledge: Case studies in the cognitive science of science*. Amsterdam: John Benjamins.

King, R. D. e. a. F. (2009). The automation of science. *Science, 324*, 85-89.

Klahr, D. (2000). *Exploring science: The cognition and development of discovery processes*. Cambridge, MA: MIT Press.

Kuhn, T. (1962). *The structure of scientific revolutions (2nd edition, 1970)* (2 ed.). Chicago: University of Chicago Press.

Kulkarni, D., & Simon, H. (1990). Experimentation in scientific discovery. In J. Shrager & P. Langley (Eds.), *Computational models of discovery and theory formation*. (pp. 255-273). San Mateo, CA: Morgan Kaufman.

Langley, P., Simon, H., Bradshaw, G., & Zytkow, J. (1987). *Scientific discovery*. Cambridge, MA: MIT Press/Bradford Books.

Latour, B. (2004). Why has critique run out of steam? From matters of fact to matters of concern. *Critical Inquiry, 30*, 225-247.

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton, N.J.: Princeton University Press.

Lindsay, R., Buchanan, B., Feigenbaum, E., & Lederberg, J. (1980). *Applications of organic chemistry for organic chemistry: The DENDRAL project*. New York: McGraw Hill.

Machamer, P., Darden, L., & Craver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science, 67*, 1-25.

Magnani, L. (2001). *Abduction, reason, and science: Processes of discovery and explanation*. New York: Kluwer/Plenum.

Magnani, L. (2009). *Abductive cognition: The epistemological and eco-cognitive dimensions of hypothetical reasoning*. Berlin: Springer.

Mill, J. S. (1970). *A system of logic* (8 ed.). London: Longman.

Nersessian, N. (1984). *Faraday to Einstein: Constructing meaning in scientific theories*. Dordrecht: Martinus Nijhoff.

Nersessian, N. (2008). *Creating scientific concepts*. Cambridge, MA: MIT Press.

Newell, A., Shaw, J. C., & Simon, H. (1958). Elements of a theory of human problem solving. *Psychological Review, 65*, 151-166.

Proctor, R., & Capaldi, E. J. (Eds.). (forthcoming). *Psychology of science*. Oxford: Oxford University Press.

Rumelhart, D. E., & McClelland, J. L. (Eds.). (1986). *Parallel distributed processing: Explorations in the microstructure of cognition*. Cambridge MA: MIT Press/Bradford Books.

Schunn, C. D., & Anderson, J. R. (1999). The generality/specificity of expertise in scientific reasoning. *Cognitive Science, 23*, 337-370.

Shelley, C. (2003). *Multiple analogies in science and philosophy*. Amsterdam: John Benjamins.

Shrager, J., & Langley, P. (Eds.). (1990). *Computational models of scientific discovery and theory formation*. San Mateo: Morgan Kaufmann.

Simon, H. A. (1966). Scientific discovery and the psychology of problem solving. In R. G. Colodny (Ed.), *Mind and cosmos: Essays in contemporary science and philosophy*. Pittsburgh: University of Pittsburgh Press.

Simonton, D. (1988). *Scientific genius: A psychology of science*. Cambridge: Cambridge University Press.

Sulloway, F. J. (1996). *Born to rebel: Birth order, family dynamics, and creative lives* (1st ed.). New York: Pantheon Books.

Sun, R. (2008a). Cognitive social stimulation. In R. Sun (Ed.), *Cambridge handbook of computational psychology* (pp. 530-548). Cambridge: Cambridge University Press.

Sun, R. (Ed.). (2008b). *The Cambridge handbook of computational psychology*. Cambridge: Cambridge University Press.

Thagard, P. (2000). *Coherence in thought and action*. Cambridge, MA: MIT Press.

Thagard, P. (2005). *Mind: Introduction to cognitive science* (2nd ed.). Cambridge, MA: MIT Press.

Thagard, P. (2006). *Hot thought: Mechanisms and applications of emotional cognition*. Cambridge, MA: MIT Press.

Thagard, P. (2009). Why cognitive science needs philosophy and vice versa. *Topics in Cognitive Science, 1*, 237-254.

Thagard, P. (2010). Explaining economic crises: Are there collective representations? *Episteme, 7*, 266-283.

Thagard, P. (forthcoming). Mapping minds across cultures. In R. Sun (Ed.), *Grounding social sciences in cognitive sciences*. Cambridge, MA: MIT Press.

Tweney, R. D., Doherty, M. E., & Mynatt, C. R. (Eds.). (1981). *On scientific thinking*. New York: Columbia University Press.

Valdés-Pérez, R. E. (1995). Machine discovery in chemistry: New results. *Artificial Intelligence, 74*, 191-201.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535-585.

Whewell, W. (1967). *The philosophy of the inductive sciences*. New York: Johnson Reprint Corp (originally published 1840).

Wimsatt, W. C. (2007). *Re-engineering philosophy for limited beings*. Cambridge, MA: Harvard University Press.