PREFACE

This special issue of the journal *Foundations of Science* "Model-based reasoning in science: learning and discovery" is based on a selection of the papers that were presented at the International Conference *Model-Based Reasoning in Scientific Discovery* (MBR '98), held at the Collegio Ghislieri, University of Pavia, Pavia, Italy, in December 1998. Over fifty papers exploring how scientific thinking uses models in exploratory reasoning to produce creative changes in theories and concepts were presented at the conference.

The study of diagnostic, visual, spatial, analogical, and temporal reasoning has demonstrated that there are many ways of performing intelligent and creative reasoning that cannot be described with the help only of traditional notions of reasoning such as provided by classical logic. Traditional accounts of scientific reasoning have restricted the notion of reasoning primarily to deductive and inductive arguments. Understanding the contribution of modeling practices to discovery and conceptual change in science requires expanding scientific reasoning to include complex forms of creative reasoning that are not always successful and can lead to incorrect solutions. The study of these heuristic ways of reasoning is situated at the crossroads of philosophy, artificial intelligence, cognitive psychology, and logic; that is, at the heart of cognitive science.

Several key ingredients common to the various forms of model-based reasoning have been considered. The models are intended as interpretations of target physical systems, processes, phenomena, or situations. The models are retrieved or constructed on the basis of potentially satisfying salient constraints of the target domain. In the modeling process, various forms of abstraction are utilized. Evaluation and adaptation take place in light of structural, causal, and/or

Foundation of Science **5:** 121–127, 2000.

functional constraints. Simulation can be used to produce new states and enable evaluation of behaviors and other factors.

In traditional philosophical accounts what we call model-based reasoning practices are considered ancillary, inessential aids to thinking. At most they have constituted – and continue to constitute – fringe topics in the literature in philosophy of science. Embracing these modeling practices as the reasoning through which problem solutions are generated requires expanding philosophical notions of scientific reasoning to encompass forms of creative reasoning, most of which cannot be reduced to an algorithm in application, are not always productive of solutions, and can lead to incorrect solutions. To do this requires challenging one of the most sacrosanct notions in philosophy: "reasoning". In the traditional view, the identification of reasoning with argument, and thus with logic, is deeply ingrained. So, before we can develop a notion of "model-based reasoning" in science, we need first to address the question "What is reasoning?" and, specifically, "What is scientific reasoning?"

In standard philosophical accounts reasoning is applying deductive or inductive algorithms to sets of propositions. The understanding of deductive reasoning provided by classical logic stands as the model. Here the essential notion is soundness: true premises plus good reasoning yields true conclusions. A major objective of logical positivism in this century was to develop a notion of soundness for induction similar to that for deduction, to be applied in inductive justification of rationally reconstructed scientific reasoning. Loosely construed, starting from maximally probable premises and using correct inductive logic one should arrive at maximally probable conclusions.

Note that we have switched to talking about "justification" and "rationally reconstructed scientific reasoning" in discussing induction. On extending the traditional notion of reasoning to what goes on in the domain of scientific "discovery" a problem arises immediately. Good reasoning, with *T* premises can lead to incorrect solutions or to no solution at all. For example, Newton's path to the concept of universal gravitational force was largely through *analogy*. Analogical argument is a notoriously weak form of argument and one could hold that concerns about it have been borne out in this case. According to the general theory of relativity, that conclusion is wrong. There is no gravitational force, falling bodies are just following their natural trajectory in a curved space-time. But, of course, we know this could prove to be wrong as well. The problem of unsoundness has been a factor in the contention of philosophers of various persuasions that there is no “logic of discovery”. Some nontraditional philosophical accounts have allowed for the possibility of *abductive* inference, but these accounts leave mysterious the nature of the reasoning *processes* underlying abductive inference and hypothesis generation. Analyzing modeling practices provides a way of specifying the nature of some abductive reasoning processes.

Following Magnani (1988, 1992, 1999a) we have to distinguish between *sentential* and *model-based* abduction. Many attempts have been made to model abduction by developing some formal tools in order to illustrate its computational properties and the relationships with the different forms of deductive reasoning (see, for example, Bylander et al., 1991). Some of the more recent formal models of abductive reasoning are based on the theory of the *epistemic state* of an agent (Boutilier and Becher, 1995), where the epistemic state of an individual is modeled as a consistent set of beliefs that can change by expansion and contraction (*belief revision framework*). These formal tools are all devoted to illustrate sentential abduction and present some limitations (Magnani, 1999b). It may be said that logical accounts of abduction certainly illustrate much of what is important in abductive reasoning, especially the objective of selecting a set of hypotheses (diagnoses, causes) that are able to dispense good (preferred) explanations of data (observations), but fail in accounting for many cases of explanations occurring in science or in everyday reasoning. If we want to provide a suitable framework for analyzing the most interesting cases of conceptual changes in science we do not have to limit ourselves to the *sentential* view of abduction but we have to consider a broader *inferential* one which encompasses both sentential and *model-based* sides of creative abduction.

Many kinds of abductions involving analogies, diagrams, thought experimenting, visual imagery, etc. in scientific discovery processes, can be called *model-based*. We believe that research in the cognitive sciences, especially cognitive psychology, artificial intelligence, and computational philosophy, have established that heuristic procedures are reasoned. Among the various kinds of model-based reasoning, analogy has received a particular attention from the point of view of computational models designed to simulate aspects of human analogical thinking: for example, Thagard et al., have developed ARCS (Analog Retrieval by Constraint Satisfaction, 1990) and ACME (Analogical Mapping by Constraint Satisfaction, Holyoak and Thagard, 1989), computational programs that are built on the basis of a multiconstraint theory. Thagard and Croft have also shown that analogical reasoning is present in some kinds of model-based questioning relevant to technological innovation (1999). Nersessian (1984, 1992) has demonstrated how the practices of analogical modeling, visual modeling, and thought experimenting have played generative roles in concept formation in science and she has developed a "cognitive-historical" account of how these model-based reasoning function in conceptual innovation and change (1999).

The various contributions to this special issue are written by interdisciplinary researchers in philosophy, artificial intelligence, and cognitive science who are active in the area of creative reasoning in science. They illustrate some of the most recent results and achievements about the role of model-based reasoning in human and machine learning and discovery. The papers focus on such issues as the characterization of discovery as a high-level kind of learning: the so-called "tunnel effect" as a kind of productive model-based reasoning contrasted with analogical reasoning (A. Cournejols, A. Tiberghien and G. Collet), the role of the multilevel creative dynamic agencies, as a new proposal for an epistemology of scientific discovery (F. Amigoni, V. Schiaffonati and M. Somalvico), the inconveniences and paradoxes of the recent formalization of Occam's razor in terms of the so-called "minimun description length" (J. Hernandez-Horallo and T. Garcia-Varea), the various kinds of modeling heuristics operating in the formation of Einstein's theory of relativity (A. Cerroni), the role of learning from Darwinian mechanisms employed in evolving neural networks (R.T. Pennock), and the similarity between cognitive processes that underlie science with the ones that underlie much of cognitive development ("little scientist" thesis) (R. Viale and D. Osherson).

The conference, and thus indirectly this volume, was made possible through the generous financial support of the University of Pavia and of CARIPLO (Cassa di Risparmio delle Provincie Lombarde). Their support is gratefully acknowledged.

The editors, and co-chairs of the conference, would like to express their appreciation to the other members of the Scientific Committee for their assistance: R. Giere, Department of Philosophy, University of Minnesota, Minneapolis, USA; David Gooding, Department of Psychology, University of Bath, Bath, United Kingdom; Joke Meheus, University of Ghent, Ghent, Belgium; Claudio Pizzi, Department of Philosophy and Social Sciences, University of Siena, Siena, Italy; Mario Stefanelli, Department of Computer Science, University of Pavia, Pavia, Italy; Raul Valdés-Pérez, Department of Computer Science, Carnegie Mellon University, Pittsburgh, USA.

Special thanks to the members of the Local Organizing Committee Maria Teresa Oldani, Stefania Pernice, Giulio Poletti, and Stefano Rini, for their contribution in organizing the conference, and to the copy-editor Linda d'Arrigo. The preparation of the volume would not have been possible without the contribution of resources and facilities of the Computational Philosophy Laboratory and of the Department of Philosophy, University of Pavia.

Several papers deriving from the presentations given at the Conference have already been published in the book L. Magnani, N.J. Nersessian and P. Thagard eds., *Model-Based Reasoning in Scientific Discovery*, Kluwer Academic/Plenum Publishers, New York, 1999. The book is divided in three parts. The first part, *Models, mental models, and representations*, that contains the contributions of N.J. Nersessian; D. Bailer-Jones; R. Giere; K. Knoespel; M. Suarez and K. Dunbar. The second part *Discovery processes and mechanisms* is composed of the papers of D. Gooding and T.R. Addis; P. Thagard and D. Croft; T. Harris; V. Raisis; S.

Krauss, L. Martignon and U. Hoffrage; and F.T. Arecchi. Finally, the last part, *Creative inferences and abduction*, include the contributions of J. Meheus; L. Magnani; I. Niiniluoto; E. Winsberg; F. Hendricks and J. Faye; C. Pizzi; J. Zytkow.

Other selected papers will appear in two Special Issues of the Journal *Philosophica*, “Abduction and scientific discovery,” and “Analogy and mental modeling in scientific discovery.”

REFERENCES

Boutilier, C. and V. Becher: 1995, Abduction as belief revision. *Artificial intelligence* 77: 43–94.

Bylander, T., D. Allemang, M.C. Tanner and J.R. Josephson: 1991, The computational complexity of abduction. *Artificial Intelligence* 49: 25–60.

Holyoak, K.J. and P. Thagard: 1989, Analogical mapping by constraint satisfaction. *Cognitive Science* 13: 295–355.

Magnani, L.: 1988, Epistémologie de l’invention scientifique. *Communication & Cognition* 21: 273–291.

Magnani, L.: 1992, Abductive Reasoning: Philosophical and Educational Perspectives in Medicine. In D.A. Evans and V.L. Patel (eds.), *Advanced Models of Cognition for Medical Training and Practice*. Berlin: Springer, 21–41.

Magnani, L.: 1999a, Model-Based Creative Abduction. In L. Magnani, N.J. Nersessian and P. Thagard (eds.), *Model-Based Reasoning in Scientific Discovery*. New York: Kluwer Academic/Plenum Publishers, 219–239.

Magnani, L.: 1999b, Inconsistencies and Creative Abduction in Science. In: *AI and Scientific Creativity. Proceedings of the AISB99 Symposium on Scientific Creativity*. Edinburgh: Edinburgh College of Art and Division of Informatics University of Edinburgh, 1–8.

Nersessian, N.J.: 1984, *Faraday to Einstein: Constructing Meaning in Scientific Theories*. Dordrecht: Martinus Nijhoff.

Nersessian, N.J.: 1992, How Do Scientists Think? Capturing the Dynamics of Conceptual Change in Science. In R. Giere (ed.), *Cognitive Models of Science, Minnesota Studies in the Philosophy of Science 15*, Minneapolis: University of Minnesota Press, 3–44.

Nersessian, N.J.: 1999, Model-Based Reasoning in Conceptual Change. In L. Magnani, N.J. Nersessian and P. Thagard (eds.), *Model-Based Reasoning in Scientific Discovery*. New York: Kluwer Academic/Plenum Publishers, 5–22.

Thagard, P., K.J. Holyoak, G. Nelson and D. Gochfeld: 1990, Analog retrieval by constraint satisfaction. *Artificial Intelligence* 46: 259–310.

Thagard, P. and D. Croft: 1999, Scientific Discovery and Technological Innovation: Ulcers, Dinosaur Extinction, and the Programming Language Java. In L. Magnani, N.J. Nersessian and P. Thagard (eds.), *Model-Based Reasoning in Scientific Discovery*. New York: Kluwer Academic/Plenum Publishers, 125–137.

Lorenzo Magnani
Department of Philosophy
University of Pavia, Pavia, Italy; also
Georgia Institute of Technology
Atlanta, GA, USA
E-mail: lmagnani@cc.gatech.edu

Nancy J. Nersessian
School of Public Policy and College of Computing
Georgia Institute of Technology
Atlanta, GA, USA
E-mail: nancyn@cc.gatech.edu

Paul Thagard
Philosophy Department, University of Waterloo
Waterloo, Ontario, Canada
E-mail: pthagard@watarts.uwaterloo.ca