BOOKS: MATHEMATICS

Representing the World in a Computer

Brian Sleeman

To grasp the essence of mathematical modeling one must begin with a problem or an observation. The problem can be a well-defined physical question requiring a mathematical solution. For example, one might wish to determine the flow of water around a sphere placed in a stream of finite depth. In a sense the modeling aspect of such problems is minimal. Fluid mechanics provides the governing equations. After one specifies the correct flow conditions around the sphere, on the stream bed, and at the free surface, one's mathematical skills are applied to solve the equations and thus determine the flow characteristics of the water. If one is lucky, an analytical solution may be obtained. But this will likely be a formidable task, and even if a solution is found it may not be easily interpreted in physical terms. An alternative approach would be to use a computationally efficient numerical method to obtain a graphical solution. Or one might model the flow with a cellular automata, which simulates the behavior of a set of connected parcels of fluid. These various approaches are among the techniques that Neil Gershenfeld, head of the physics and media group at MIT's Media Lab, describes concisely in *The Nature of Mathematical Modeling*.

The Nature of Mathematical Modeling
by Neil Gershenfeld
Cambridge University Press, Cambridge, 1999. 356 pp. $39.95, £24.95. ISBN 0-521-57095-6.

What Gershenfeld really has in mind are not the formalized problems described above, but more intriguing and open-ended puzzles: "How would you describe the flickering of a flame?... Highway traffic during a rush hour?... The flight of a paper airplane?"

Problems such as these are simultaneously imprecise and challenging, and they can be approached from several directions. To describe the flight of a paper airplane, for example, should one first study the aerodynamics of flight and then apply it to the paper glider? Here there are questions of lift, drag, aspect ratios, wing geometry, and wind conditions. These and other considerations produce a frightening degree of complexity. Another approach would be to try to copy the flight characteristics without recourse to the equations of aerodynamics. In other words, one might develop a sort of mathematical flight simulator. But what mathematics to use? Alternatively, one could attempt to assess the important observable characteristics of paper airplane flight and thus arrive at an "approximate" (reasonably accurate) mathematical description. Again, what mathematics should be used?

In a compact but accessible manner, Gershenfeld offers a wide-ranging overview of mathematical ideas and techniques that provide a number of effective approaches to problem solving. These include traditional concepts such as the analytical use of differential equations and variational principles (which state problems in terms of an unknown function that makes an integral take on an extremum) and classical numerical models including Runge-Kutta approximations and finite element methods. In a more modern vogue, Gershenfeld provides a taste of Fourier transforms, wavelets (families of orthogonal transformations that generalize Fourier transforms), and methods such as simulated annealing and genetic algorithms for parameter optimization.

Although these techniques have traditionally been, and continue to be, of great importance in mathematical modeling, they are not always adequate for coping with problems of current scientific interest. Over the last two decades, we have realized that we do not inhabit a comfortable deterministic world, one in which events and predictions are based on secure initial states and conditions with well-defined outcomes. More commonly, phenomena depend on imprecise "noisy" data and outcomes are far from predictable. This is clearly the case in predicting weather or the behavior of stock markets, but even the bouncing of a tennis ball or the cueing of a billiard ball are not really deterministic: over time, they display chaotic and random outcomes.

Another important aspect that Gershenfeld addresses is the decision between discrete and continuum approaches to modeling events. For example, in a biological model when should one shift the consideration from individual cells to cell densities? His discussions of the purposes and capabilities of techniques such as time series analysis, cellular automata, lattice gases, and state-space reconstructions will help readers model complex realities.

Gershenfeld presents his overview of modeling through a series of problems in which he describes methods and how each should be applied. To keep his text concise, he focuses on the underlying concepts and leaves refinements to a challenging series of problem sets. He hopes that readers will work through these sets because he believes "the study of modeling is inseparable from the practice of modeling." The included solutions focus on developing and extending the various models. Gershenfeld also provides an excellent series of references for readers wishing to develop a deeper understanding of the topics covered.

The Nature of Mathematical Modeling is a great compendium of techniques. It should be kept within easy reach of anyone who wants to build computer models to help understand the world around us.

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BOOKS: NEUROSCIENCE

Themes of Thought and Thinking

C. R. Gallistel

For his compilation, Robert Sternberg persuaded a number of cognitive psychologists to write essays on enduring conceptual themes in the study of cognition. He has organized the contributions into five sections: philosophical and psychological foundations, representation and process, methodology, kinds of cognition, and group and individual differences. The volume is intended for the advanced undergraduate and the graduate student, but many essays in it can be profitably read by the scientifically literate reader. A not always successful attempt is made to give individual chapters and the book as a whole a dialectical structure. The chapters are essays, not reviews. Their coherence and personal flavor make the book much more suitable for students than a collection of reviews of the recent literature on standard topics.

The Nature of Cognition
Robert J. Sternberg, Ed.
MIT Press, Cambridge, MA, 1999. 746 pp. $60. ISBN 0-262-19405-8. Paper, $35. ISBN 0-262-69212-0.

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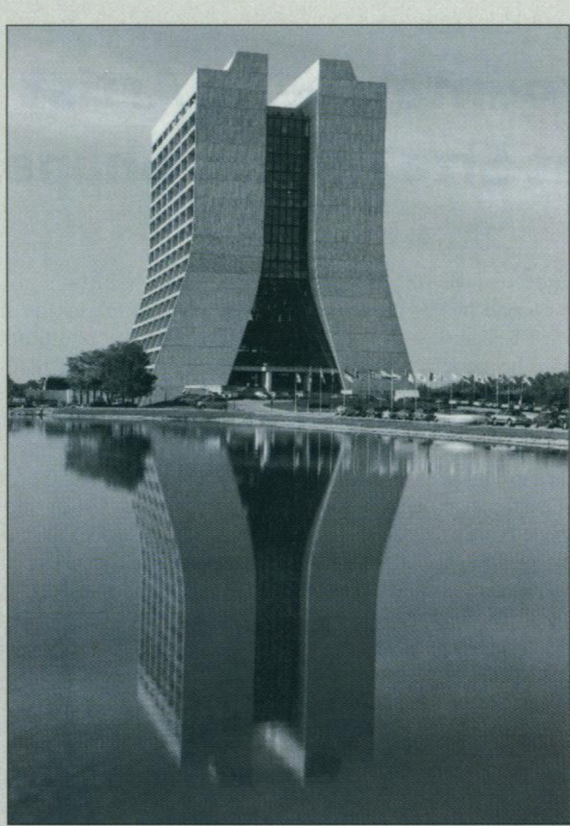
The opening section lays the groundwork for later chapters. Earl Hunt outlines the basics of a computational theory of mind, the mind-body problem, and levels of analysis. Robert Sternberg surveys contrasting views on the nature of mind in Western thought, beginning with the Greeks and finishing with the cognitive revolution. He defines cognitivism as "the belief that much of human behavior can be understood if we understand first how people think." This is an unwarrantedly anthropocentric conception. It misses the essential feature of the cognitive revolution, which was the emergence of computational (information processing) theories of mind and experimental methods for testing them. For example, Saul Sternberg revived the use of differences in reaction time to determine the duration of individual information processing operations, and George Sperling showed how to measure the duration of the information-carrying signals at early stages. Roger Shepard then demonstrated that these techniques could be used to determine properties of such heretofore elusive processes as the rotation of mental images.

Part II begins with Timothy McNamara's even-handed treatment of the debate about propositional versus analogical representations. Proponents of the propositional view argue that the brain represents everything by propositions with a discrete structure, like the structure of a sentence or a line of computer code. Champions of the analogical view argue that some forms of knowledge, such as spatial knowledge, are represented in an analog form, like the form of a conventional map.

The following chapter is, for this reviewer, an unsatisfactory treatment of the problem of domain-general versus domain-specific processes. Its authors, Peter Frensch and Axel Buchner, argue that "central to any [domain-general versus domain-specific] debate is the question of how widely applicable a particular theoretical statement or empirical finding is. Thus, for instance, the empirical phenomenon of negative priming with pictorial material...triggers the question of whether the same results can be obtained with letters." Formulating the dispute this way makes it hard for the student to see that the debate is a continuation of the rationalist-empiricist debate. The central issues are (i) how much problem-specific structure is built into the information processing that the brain brings to experience in a given domain and (ii) what principles about the sources of the data are implicit in that built-in structure.



BROWSINGS

The Architecture of Science. *Peter Galison and Emily Thompson, Eds.* MIT Press, Cambridge, MA. 599 pp. $65, £39.95. ISBN 0-262-07190-8.

How do buildings influence the activities of scientists? How do the sciences impact the practices of architects? The essays in this volume provide a wide range of answers to such questions. In one, the design of the Fermi National Accelerator Laboratory is discussed by its first director, physicist and sculptor Robert Wilson. His aesthetic judgment—and view that "the sky, the sunsets, and the Illinois landscape all looked better" from on high—determined the 16-story height of Fermilab's Central Lab building.

Connectionist modelers (modern-day empiricists) try to minimize the amount of problem-specific structure built into their learning systems, letting the system discover the structure of the problem. In contrast, most researchers in language acquisition agree to varying extents with Noam Chomsky's contention that a device capable of learning a human language must have a universal grammar built into it that specifies the numerous and important characteristics universal in human languages. This problem-specific structure, they argue, is what makes learning possible. Rochel Gelman, Elizabeth Spelke, Susan Carey, and Renee Baillargeon have extended this argument to many aspects of cognitive development.

Patricia Carpenter and Marcel Just open the section on methodologies with a discussion of computational modeling, which they contrast with the hypothesis testing approach. As they seem to recognize, this contrast is something of a stretch; the two approaches hardly constitute a thesis and an antithesis. A later chapter by Elizabeth Phelps considers brain versus behavioral studies of cognition; this seems an even odder contrast. An analysis at the behavioral level lays the foundation for an analysis at the neural level. Without this foundation, there can be no meaningful contribution from the neural level. It is hard to see how these different levels of analysis can be construed as alternate routes to the same goal.

One might expect domain specificity to come to the fore in the section on kinds of cognition—with chapters treating numerical cognition or spatial cognition, for example. But what is in fact discussed in this section are several standard processing dichotomies: implicit versus explicit learning (by Reber *et al.*), short- versus long-term memory (by Engle and Oransky), rational versus arational judgments and decisions (by Sloman), formal rules versus mental models (by Johnson-Laird), and cognition versus metacognition (by Nelson). Dennis Proffitt opens this section with a consideration of inferential versus ecological approaches to perception. Although here there is a true thesis and antithesis, why this chapter belongs in a section devoted to kinds of cognition is unclear.

The Nature of Cognition is not a textbook, but it would make an excellent secondary source of readings in an upper division or graduate level introduction to cognitive psychology. For some instructors, it would probably be satisfactory as the primary textbook. Its value to the field in general is more limited, because few of the essays break new ground. This is not surprising given its didactic purpose.