HEURISTICS:
Intelligent Search Strategies for Computer Problem Solving

To fully appreciate Professor Pearl's book, begin with a careful reading of the title. It is a book about "..Intelligent-..Strategies.." for the discovery and use of "Heuristics.." to allow computers to solve "..Search.." problems. Search is a critical component in AI programs (Nilsson 1980, Barr and Feigenbaum 1982), and in this sense Pearl's book is a strong contribution to the field of AI. It serves as an excellent reference for the researcher/practitioner and is useful as a textbook as well. As a book about search, it is thorough, at the state of the art, and contains expositions that will delight the expert with their clarity and depth. However, it is not, per se, a book about AI (nor was it intended to be [1]) or about the history, philosophy or cognitive aspects of heuristic knowledge. These are not intended as criticisms, but rather to define the scope of the work.

The book is divided into three parts: (1) problem-solving (search) strategies and the nature of heuristic information (as evaluation functions), (2) performance analysis of the heuristics presented in the first part, and (3) applications of these concepts and results to game playing programs, with a tidbit on circuit design. The approach taken is computation-oriented and aimed at developing computer programs that can search for problem solutions and also discover heuristics to improve search strategies. Algorithms are presented in an informal and easy to follow style that avoids excessive notation, yet maintains clarity and rigor.

The analysis of heuristic search procedures presented in Chapter 2 includes a classification of graph search strategies that puts into perspective the approaches found in typical presentations of search procedures such as in Nilsson 1980, Horowitz and Sahni 1978. The analysis of formal properties of these strategies in Chapter 3 is largely restricted to an analysis of A^*. However, given the complexity of the mathematical analysis, this is a choice in favor of clarity in the presentation of the underlying concepts. Chapter 3 also exhibits a characteristic common throughout the book; namely, that some of the best motivation and interesting reading is contained in the "Bibliographical and Historical Remarks" at the end of each chapter.

In Chapter 4, probability-based heuristics for search are introduced. Chapter 4 also uses a Stripslike representation as a framework in which to develop techniques for the discovery of search heuristics. Probability theory and the Strips formalism are the main tools Professor Pearl exploits to develop and analyze heuristic search strategies. The AI community would have benefited more from Professor Pearl's approach if he had taken time to better motivate his choice of tools and to expound upon the relationships between these and the numerous techniques for representing knowledge and uncertainty in common use in mainstream AI.

Chapter 5 begins a quantitative performance analysis of heuristic search strategies. This includes a nice exposition on branching processes, although the mathematically unsophisticated reader may find it difficult. Here Pearl introduces probabilistic models to complement probabilistic heuristics. He continues, in Chapter 6, to a probabilistic complexity analysis of search heuristics, and to a probabilistic analysis of nonadmissible heuristics in Chapter 7. Although many readers may find the text mathematically challenging, the blend of work from AI, computer science, operations research, and statistics and probability is smoothly executed. The reviewers feel that the infusion of coherent and theoretically sound techniques from other disciplines as tools for AI research is highly desirable, and in this regard alone, *Heuristics* is a significant work.

Implementing and verifying the results of part 3 (chapters 8-10) on applications of the theory to games might be some of the most fun for students using this book as a text. In general, the book is oriented more for the teacher than for the student. Students using the book have tended to find the presentation terse, lacking in motivation, often requiring greater mathematical sophistication than the typical computer science graduate student possesses.[2] In particular, the material in chapters 5-7, while deep and elegantly presented, is probably impenetrable to most students without lengthy and careful lectures about the material. Future editions would benefit from having a solution key included or made available as a separate volume. A strong reason for using *Heuristics* as a textbook is that it includes most of the known results in the field of heuristic search. However, we believe it is too specialized to serve as a primary text in a general AI course. For this reason, we suggest that it be used as a collateral, rather than primary, textbook for AI courses, or at least supplemented with readings in knowledge representation, inference, etc.

On the other hand, as a volume on heuristic strategies for search, it is insightful and sometimes brilliant. Section 4.2, for example, on the "Mechanical Generation of Admissible Heuristics" presents a paradigm for machine discovery of search heuristics that is succinct, clearly stated and powerful. The approach requires that the world and problem to be solved be represented as a set of predicates and actions in the tradition of Strips (Fikes and Nilsson 1971). That is, the current world state is defined as the conjunction of the current truth values of the set of all possible logical expressions over a set of primitive predicates. Each action has associated pre-

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condition (i.e., set of applicable world states), add (i.e., set truth value true), and delete (i.e., set truth value false) lists of predicates that define the effect of the action on a world state. This is isomorphic to a graph representation where nodes are possible world states and arcs correspond to actions that transform one state to another. Heuristics are discovered by "relaxing" this problem model by incrementally deleting preconditions of actions.

Experts will recognize the generality of this representation and will be capable of translating the essential techniques to domains beyond games and optimization (Pearl's main examples), and to knowledge representations besides state spaces, logic and graphs. Nonetheless, the chief criticism of this book, from a mainstream AI perspective, must be its lack of attention to the issue of problem representation, and the effect that altering problem representations can have on the problem solving process.

Pearl devotes only four pages (pp.26-29) to heuristics for selecting problem representations (although he does not call them heuristics), pointing out the link between interacting problem sub-goals and problem representation. He hints at deeper issues when he discusses analogical and metaphorical models (p.117) and also when he points out that decomposing predicates into expressions involving a finer set of primitive predicates, and relaxing a model by deleting a new, finer primitive predicate " . . . results in a new model, closer to the original than that created by deleting the entire original primitive> predicate" (p.121). However, he does not follow up with discussions of heuristics for (meta-) search at the level of representation, claiming, that " . . . the use of analogical models by computers would . . . be beneficial only when we learn to build efficient data-driven expert systems for at least one problem domain of sufficient richness . . . " (p. 118).

This is the point at which those who revere heuristics as a key technique in nonformalist approaches may feel the greatest heartburn. The paucity of analytic work on a broad variety of problem formulation and problem-solving heuristics has tended to promote the special position of heuristics in our discipline. It is arguable, for instance, that the technique of knowledge-based programming allows us to "heuristically" use a computer to assist in tackling a problem before we make a crisp statement of what the problem is. Some have considered work on the precise characterization of heuristics with the tools of formal analysis inappropriate in many areas of research on intelligence. For example, a previous review of Pearl's book in this magazine (Rankin 1986) suggested that such formal analysis is limited in that it is epistemologically constrained to a classical framework and method.

We believe that this perspective on *Heuristics* is, for the most part, unwarranted. The extraordinary usefulness of the crisp characterization of the properties of a strategy outweighs the possible tendency to dwell within a narrow paradigm. Furthermore, having solved a problem, perhaps using nonformal or ad-hoc methods, it seems highly desirable to attempt to characterize and generalize the nature of the solution using formal concepts like those Professor Pearl has so cleanly presented. Even, or perhaps especially, in the event that a solution evades characterization, we would expect that an understanding of why this is so would be of great interest.

As in any science, a chief goal of our discipline should be one of seeking understanding. We believe that the continued shedding of light on the "hallowed halls" of the heuristic is beneficial to AI research. Although the thrust of Pearl's book is focused on a particular category of heuristic strategies, we heartily recommend it both as reference and textbook, and as a significant milestone in the pursuit of the comprehension of heuristic behavior.

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[1]Personal communication from J Pearl, August, 1986

[2]Personal communications from professors on the use of HEURISTICS as a textbook.

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Judea Pearl (Reading, Massachusetts: Addison-Wesley 1984 382 pages $17 95)

Tod S. Levitt,
Advanced Decision Systems, Mountain View, California
Eric J Horvitz,
Stanford University, Stanford, California