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Automated Modeling of Physical Systems

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To Mala and my parents

Foreword

It is a privilege for me to write the foreword to this important, powerful, and elegant piece of Artificial Intelligence research. In both substance and method, it is the quintessence of what today's AI research should be like.

The prelude to doing an important work is to seek out an important problem. Nayak's problem area is important for two reasons.

- For most tasks whose solution requires intelligence, the AI will have to be able to reason about the world of physical objects, physical systems, and engineered artifacts. The path from the earliest AI programs (e.g. the Logic Theorist and the Geometry Theorem Proving Program) to the expert systems of the 1980s and 1990s has not included much work on physics and engineering problem solving. The exception of course is the thinly populated field of qualitative physics research, of which Nayak's work is an example.
- In expert systems ("where the rubber meets the road" for most of applied AI), the models of domains are very extensive and detailed. Indeed, it is the hallmark of expert systems that their knowledge bases are relatively large and their reasoning methods simple (usually just Aristotelian and/or Bayesian logic). A narrow pinnacle of knowledge (literally a pinnacle of excellence) allows the expert system to perform at high levels of competence for a narrow class of problems. But from pinnacles it is possible to fall precipitously, for example when the problem presented lies outside of the narrow band of knowledge. What is needed is a soft landing on a much more gentle slope of generalized knowledge. Such knowledge contains the generalized models and equation systems that we learn in courses on physics and engineering. Of course, this "generalized" knowledge is also somewhat domain-specific, but its breadth is much greater than the specialists' knowledge used in expert systems. The increased scope and power of the "broad" knowledge does not come for free. To use it, the reasoning processes can no longer be simple – more powerful methods are needed. To develop the necessary representation and reasoning methods is the goal of qualitative physics research, and the contribution of Nayak's research.

Here are some specific points to keep in mind as you read this monograph.

- Carefully chosen problem representations are crucial to effective problem-solving. Amarel, as early as the 1960s, discussed this issue extensively in his landmark paper "On representations of problems of reasoning about actions" [Amarel, 1968], where he provides various representations for the Missionaries and Cannibals problem. The choice of problem representations is equally crucial in engineering problem-solving, where one has to carefully balance the veracity of a model against its complexity. An overly detailed model can be too complex, while simple models may miss important problem features. Hence, in modeling physical systems, it is important to identify just the relevant physical phenomena, and to identify just the appropriate level of detail to model each phenomenon. Nayak's research elegantly treats and combines both the theoretical and practical sides of this problem.
- On the theoretical side, the research develops a precise formalization of the problem of selecting adequate models of physical systems. It casts the problem as a search problem, and provides clear definitions for the search space and the goal criterion. Such a precise formalization is essential for applying computational tools to the problem. It then uses the formalization to analyze the difficulty of finding adequate models, and for understanding the different reasons for its intractability. Finally, it uses the analysis of the reasons for intractability to identify special cases of the problem that can be solved very efficiently. These special cases stem from the identification and use of a special class of approximations called causal approximations. Importantly, the research shows that causal approximations are very common in modeling the physical world, making the special cases broadly applicable and useful.
- On the practical side, Nayak's work analyzes the representation and reasoning issues that arise in building practical systems for constructing adequate device models. It develops a class-level description for device models that facilitates knowledge base construction and supports focused generation of device models. It develops a novel order of magnitude reasoning algorithm for reasoning about a device's behavior, and incorporates it into the efficient model selection algorithm developed above. The resulting algorithm has been implemented in Common Lisp.
- Nayak tests and validates his methods and algorithms by running his implementation on a large knowledge-base of device models. The range of devices is not only interesting but significant, and the testing is a necessary activity to ground the research in reality and to add credibility to Nayak's approach.

In recommending Nayak's work to the Association for Computing Machinery for its dissertation award, I remember using a word that I rarely use: "brilliant." In reviewing the work again as a prelude to writing this foreword, I am once again excited by the work and am reminded of why I used the strong B word. Proceed with haste to the first page so that you can find out for yourself. You will be richly rewarded.

October 1995

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Preface

Effective reasoning about complex physical systems requires the use of models that are adequate for the task. Constructing such adequate models is often difficult. In this dissertation, we address this difficulty by developing efficient techniques for automatically selecting adequate models of physical systems. We focus on the important task of generating parsimonious causal explanations for phenomena of interest. Formally, we propose answers to the following: (a) what is a model and what is the space of possible models; (b) what is an adequate model; and (c) how do we find adequate models.

We define a model as a set of *model fragments,* where a model fragment is a set of independent equations that partially describes some physical phenomenon. The space of possible models is defined implicitly by the set of applicable model fragments: different subsets of this set correspond to different models. An adequate model is defined as a simplest model that can explain the phenomenon of interest, and that satisfies any domain-independent and domain-dependent constraints on the structure and behavior of the physical system.

We show that, in general, finding an adequate model is intractable (NP-hard). We address this intractability, by introducing a set of restrictions, and use these restrictions to develop an efficient algorithm for finding adequate models. The most important restriction is that all the approximation relations between model fragments are required to be *causal approximations*. In practice this is not a serious restriction because most commonly used approximations are causal approximations.

We also develop a novel *order of magnitude* reasoning technique, which strikes a balance between purely qualitative and purely quantitative methods. The order of magnitude of a parameter is defined on a logarithmic scale, and a set of rules propagate orders of magnitudes through equations. A novel feature of these rules is that they effectively handle non-linear simultaneous equations, using linear programming in conjunction with backtracking.

The techniques described in this dissertation have been implemented and have been tested on a variety of electromechanical devices. These tests provide empirical evidence for the theoretical claims of the dissertation.

Acknowledgements In preparing this dissertation I have been greatly influenced by a number of different people, and have benefited enormously from my discussions with them. I would like to thank my advisor, Ed Feigenbaum, for his guidance, encouragement, and support. He gave me the freedom to pursue my research interests, while always reminding me of the importance of real problems. Leo Joskowicz participated actively in my research and helped me clarify the ideas. Sanjaya Addanki, Richard Fikes, Rich Keller, and Jean-Claude Latombe provided valuable feedback on various aspects of this research. Surajit Chaudhuri and Alon Levy shared the ups and downs of graduate student life with me and helped to make research genuinely fun. Members of the How Things Work project, Bob Englemore, Tom Gruber, Yumi Iwasaki, and Jim Rice, provided a challenging and educational environment for research.

Grace Smith, Michelle Perrie, and Margaret Timothy provided superb administrative support. IBM supported me financially during the course of this research through an IBM Graduate Technical Fellowship. Additional support for this research was provided by the Defense Advanced Research Projects Agency under NASA Grant NAG 2-581 (under ARPA order number 6822), by NASA under NASA Grant NCC 2-537, and by IBM under agreement number 14780042.

On a more personal note, my friends from IIT and Stanford made my years at Stanford enjoyable and memorable. My family in the US helped alleviate any home-sickness I might have felt. My parents and my sister supported me with their love and encouragement throughout my life. My parents taught me that in any endeavor, it is the effort that is important, not the result. It is because of them that I am what I am. And last, but by no means least, Mala's constant friendship, support, and love has made this research possible. This dissertation is as much a result of her efforts, as it is a result of mine.

P. Pandurang Nayak
October 1995

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