PROBABILISTIC REASONING IN MULTIAGENT SYSTEMS

This book investigates the opportunities in building intelligent decision support systems offered by multiagent distributed probabilistic reasoning.

Probabilistic reasoning with graphical models, also known as Bayesian networks or belief networks, has become an active field of research and practice in artificial intelligence, operations research, and statistics in the past two decades. The success of this technique in modeling intelligent decision support systems under the centralized and single-agent paradigm has been striking. In this book, the author extends graphical dependence models to the distributed and multiagent paradigm. He identifies the major technical challenges involved in such an endeavor and presents the results from a decade's research.

The framework developed in the book allows distributed representation of uncertain knowledge on a large and complex environment embedded in multiple cooperative agents and effective, exact, and distributed probabilistic inference.

Yang Xiang is Associate Professor of Computing and Information Science at the University of Guelph, Canada, where he directs the Intelligent Decision Support System Laboratory. He received his Ph.D. from the University of British Columbia and developed the Java-based toolkit WebWeavr, which has been distributed to registered users in more than 20 countries. He also serves as Principal Investigator in the Institute of Robotics and Intelligent Systems (IRIS), Canada.

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A Graphical Models Approach

YANG XIANG
University of Guelph

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Preface

This book investigates opportunities for building intelligent decision support systems offered by multiagent, distributed probabilistic reasoning. Probabilistic reasoning with graphical models, known as Bayesian networks or belief networks, has become an active field of research and practice in artificial intelligence, operations research, and statistics in the last two decades. Inspired by the success of Bayesian networks and other graphical dependence models under the centralized and single-agent paradigm, this book extends them to representation formalisms under the distributed and multiagent paradigm. The major technical challenges to such an endeavor are identified and the results from a decade's research are presented. The framework developed allows distributed representation of uncertain knowledge on a large and complex environment embedded in multiple cooperative agents and effective, exact, and distributed probabilistic inference.

Under the single-agent paradigm, many exact or approximate methods have been proposed for probabilistic reasoning using graphical models. Not all of them admit effective extension into the multiagent paradigm. Concise message passing in a compiled, treelike graphical structure has emerged from a decade's research as one class of methods that extends well into the multiagent paradigm. How to structure multiple agents' diverse knowledge on a complex environment as a set of coherent probabilistic graphical models, how to compile these models into graphical structures that support concise message passing, and how to perform concise message passing to accomplish tasks in model verification, model compilation, and distributed inference are the foci of the book. The advantages of concise message passing over alternative methods are also analyzed.

It would be impossible to present multiagent probabilistic reasoning without an exposition of its single-agent counterpart. The results from single-agent inference have been the subject of several books (Pearl [52]; Neapolitan [43]; Lauritzen [36]; Jensen [29]; Shafer [62]; Castillo, Gutierrez, and Hadi [6]; and Cowell et al. [9]). Only a small subset of these results, which were most influential

to the work presented on multiagent probabilistic reasoning, is included in this book. In particular, only the theory and algorithms central to concise message-passing methods are covered in detail. These results are attributed mainly to the work of J. Pearl and his disciples as well as the Hugin researchers in Denmark. In presenting these results, instead of describing them as given solutions, the book is structured to emphasize why essential aspects of these solutions are necessary. Results from the author's own research in this regard are presented.

The book is organized into two parts. The first part includes Chapters 1 through 5 and covers probabilistic inference by concise message passing under the single-agent paradigm. Readers are prepared for comprehension of the second half of the book on multiagent probabilistic inference. The second part comprises Chapters 6 through 10 in which a formal framework is elaborated for distributed representation of probabilistic knowledge in a cooperative multiagent system and for effective, exact, and distributed inference by the agents.

Chapter 1 outlines the roles of intelligent agents and multiagent systems in decision support systems and substantiates the need for uncertain reasoning. Chapter 2 introduces Bayesian networks as a concise representation of probabilistic knowledge and demonstrates the idea of belief updating by concise message passing. Chapter 3 introduces cluster graphs as alternative models for effective belief updating by concise message passing. Through analyses of possible types of cycles in cluster graphs, this chapter formally establishes that belief updating by concise message passing requires cluster trees and, in particular, junction tree models. Chapter 4 defines graphical separation criteria in three types of graphical models and the concept of I-maps. The chapter describes stepwise how to compile a Bayesian network into a junction tree model while preserving the I-mapness as much as possible. Chapter 5 defines common operations on potentials and presents laws governing mixed operations. Algorithms for belief updating by passing potentials as messages in a junction tree are presented. Chapter 6 sets forth five basic assumptions on uncertain reasoning in a cooperative multiagent system. The logic consequences of these assumptions, which imply a particular knowledge representation formalism termed a multiply sectioned Bayesian network (MSBN), are derived. Chapter 7 presents a set of distributed algorithms used to compile an MSBN into a collection of related junction tree models, termed a linked junction forest, for effective multiagent belief updating. Chapter 8 describes a set of algorithms for performing multiagent communication and belief updating by concise message passing. The material presented in this chapter establishes that multiagent probabilistic reasoning using an MSBN is exact, distributed, and efficient (when the MSBN is sparse). Chapter 9 addresses the issues of model construction and verification and presents distributed algorithms for ensuring the integration of independently developed agents into a syntactically and semantically correct MSBN.

Chapter 10 puts the state of affairs in cooperative multiagent probabilistic reasoning in perspective and outlines several research issues in extending MSBNs into more powerful frameworks for future intelligent decision support systems.

The book is intended for researchers, educators, practitioners, and graduate students in artificial intelligence, multiagent systems, uncertain reasoning, operations research, and statistics. It can be used for self-study, as a handbook for practitioners, or as a supplemental text for graduate-level courses on multiagent systems or uncertain reasoning with graphical models. A set of exercises is included at the end of most chapters for teaching and learning. Familiarity with algorithms and mathematical exposure from a typical computer science undergraduate curriculum (discrete structure and probability) are sufficient background. Previous exposure to artificial intelligence and distributed systems is beneficial but not required.

The book treats major results formally with the underlying ideas motivated and explained intuitively, and the algorithms as well as other results are demonstrated through many examples. All algorithms are presented at sufficient levels of detail for implementation. They are written in pseudocode and can be implemented with languages of the reader's choice. The executable code of a Java-based toolkit *WebWeavr*, which implements most of the algorithms in the book, can be downloaded from

http://snowhite.cis.uoguelph.ca/faculty_info/yxiang/

Most of the chapters (Chapters 2 through 9) contain a Guide to Chapter section as a short roadmap to the chapter. Styled differently from the rest of the chapter, this section presents no formal materials. Instead, the main issues, ideas, and results are intuitively described and often illustrated with simple examples. These sections can be used collectively as a quick tour of the more formal content of the book. They can also be used by practitioners to determine the right focus of materials for their needs.

The following convention is followed in numbering theorem-like structures: Within each chapter, all algorithms are numbered with a single sequence, and all other formal structures are numbered with another sequence, including definitions, lemmas, propositions, theorems, and corollaries.

The input, inspiration, and support of many people were critical in making this book a reality, and I am especially grateful to them: David Poole introduced me to the literature on uncertain reasoning with graphical models. Michael Beddoes made the PainULim project, during which the framework of single-agent oriented MSBNs was born, possible. Andrew Eisen and Bhanu Pant provided domain expertise in the PainULim project, and their intuition inspired the ideas behind the formal MSBN framework. Judea Pearl acted as the external examiner for my Ph.D. dissertation in which the theory of MSBNs was first documented. I owe a great deal to Bill

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