

Introduction to Symbolic Plan and Goal Recognition

Synthesis Lectures on Artificial Intelligence and Machine Learning

Editors

Ronald Brachman, *Jacobs Technion-Cornell Institute at Cornell Tech*

Francesca Rossi, *IBM Research AI*

Peter Stone, *University of Texas at Austin*

Introduction to Symbolic Plan and Goal Recognition

Reuth Mirsky, Sarah Keren, and Christopher Geib

2021

Graph Representation Learning

William L. Hamilton

2020

Introduction to Graph Neural Networks

Zhiyuan Liu and Jie Zhou

2020

Introduction to Logic Programming

Michael Genesereth and Vinay Chaudhri

2020

Federated Learning

Qiang Yang, Yang Liu, Yong Cheng, Yan Kang, and Tianjian Chen

2019

An Introduction to the Planning Domain Definition Language

Patrik Haslum, Nir Lipovetzky, Daniele Magazzeni, and Christina Muişe

2019

Reasoning with Probabilistic and Deterministic Graphical Models: Exact Algorithms, Second Edition

Rina Dechter

2019



Series Page

Learning and Decision-Making from Rank Data

Liron Xia

2019

Lifelong Machine Learning, Second Edition

Zhiyuan Chen and Bing Liu

2018

Adversarial Machine Learning

Yevgeniy Vorobeychik and Murat Kantarcioglu

2018

Strategic Voting

Reshef Meir

2018

Predicting Human Decision-Making: From Prediction to Action

Ariel Rosenfeld and Sarit Kraus

2018

Game Theory for Data Science: Eliciting Truthful Information

Boi Faltings and Goran Radanovic

2017

Multi-Objective Decision Making

Diederik M. Roijers and Shimon Whiteson

2017

Lifelong Machine Learning

Zhiyuan Chen and Bing Liu

2016

Statistical Relational Artificial Intelligence: Logic, Probability, and Computation

Luc De Raedt, Kristian Kersting, Sriraam Natarajan, and David Poole

2016

Representing and Reasoning with Qualitative Preferences: Tools and Applications

Ganesh Ram Santhanam, Samik Basu, and Vasant Honavar

2016

Metric Learning

Aurélien Bellet, Amaury Habrard, and Marc Sebban

2015

Graph-Based Semi-Supervised Learning

Amarnag Subramanya and Partha Pratim Talukdar

2014

Robot Learning from Human Teachers

Sonia Chernova and Andrea L. Thomaz

2014

General Game Playing

Michael Genesereth and Michael Thielscher

2014

Judgment Aggregation: A Primer

Davide Grossi and Gabriella Pigozzi

2014

An Introduction to Constraint-Based Temporal Reasoning

Roman Barták, Robert A. Morris, and K. Brent Venable

2014

Reasoning with Probabilistic and Deterministic Graphical Models: Exact Algorithms

Rina Dechter

2013

Introduction to Intelligent Systems in Traffic and Transportation

Ana L.C. Bazzan and Franziska Klügl

2013

A Concise Introduction to Models and Methods for Automated Planning

Hector Geffner and Blai Bonet

2013

Essential Principles for Autonomous Robotics

Henry Hexmoor

2013

Case-Based Reasoning: A Concise Introduction

Beatriz López

2013

Answer Set Solving in Practice

Martin Gebser, Roland Kaminski, Benjamin Kaufmann, and Torsten Schaub

2012

Planning with Markov Decision Processes: An AI Perspective

Mausam and Andrey Kolobov

2012

Active Learning

Burr Settles

2012

Computational Aspects of Cooperative Game Theory

Georgios Chalkiadakis, Edith Elkind, and Michael Wooldridge
2011

Representations and Techniques for 3D Object Recognition and Scene Interpretation

Derek Hoiem and Silvio Savarese
2011

A Short Introduction to Preferences: Between Artificial Intelligence and Social Choice

Francesca Rossi, Kristen Brent Venable, and Toby Walsh
2011

Human Computation

Edith Law and Luis von Ahn
2011

Trading Agents

Michael P. Wellman
2011

Visual Object Recognition

Kristen Grauman and Bastian Leibe
2011

Learning with Support Vector Machines

Colin Campbell and Yiming Ying
2011

Algorithms for Reinforcement Learning

Csaba Szepesvári
2010

Data Integration: The Relational Logic Approach

Michael Genesereth
2010

Markov Logic: An Interface Layer for Artificial Intelligence

Pedro Domingos and Daniel Lowd
2009

Introduction to Semi-Supervised Learning

Xiaojin Zhu and Andrew B. Goldberg
2009

Action Programming Languages

Michael Thielscher
2008

Representation Discovery using Harmonic Analysis

Sridhar Mahadevan

2008

Essentials of Game Theory: A Concise Multidisciplinary Introduction

Kevin Leyton-Brown and Yoav Shoham

2008

A Concise Introduction to Multiagent Systems and Distributed Artificial Intelligence

Nikos Vlassis

2007

Intelligent Autonomous Robotics: A Robot Soccer Case Study

Peter Stone

2007

© Springer Nature Switzerland AG 2022

Reprint of original edition © Morgan & Claypool 2021

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopy, recording, or any other except for brief quotations in printed reviews, without the prior permission of the publisher.

Introduction to Symbolic Plan and Goal Recognition

Reuth Mirsky, Sarah Keren, and Christopher Geib

ISBN: 978-3-031-00461-2 paperback

ISBN: 978-3-031-01589-2 ebook

ISBN: 978-3-031-00034-8 hardcover

DOI 10.1007/978-3-031-01589-2

A Publication in the Springer series

SYNTHESIS LECTURES ON ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Lecture #47

Series Editors: Ronald Brachman, *Jacobs Technion-Cornell Institute at Cornell Tech*

Francesca Rossi, *IBM Research AI*

Peter Stone, *University of Texas at Austin*

Series ISSN

Synthesis Lectures on Artificial Intelligence and Machine Learning

Print 1939-4608 Electronic 1939-4616

Introduction to Symbolic Plan and Goal Recognition

Reuth Mirsky

University of Texas at Austin

Sarah Keren

Harvard University

Christopher Geib

SIFT

*SYNTHESIS LECTURES ON ARTIFICIAL INTELLIGENCE AND
MACHINE LEARNING #47*

ABSTRACT

Plan recognition, activity recognition, and goal recognition all involve making inferences about other actors based on observations of their interactions with the environment and other agents. This synergistic area of research combines, unites, and makes use of techniques and research from a wide range of areas including user modeling, machine vision, automated planning, intelligent user interfaces, human-computer interaction, autonomous and multi-agent systems, natural language understanding, and machine learning. It plays a crucial role in a wide variety of applications including assistive technology, software assistants, computer and network security, human-robot collaboration, natural language processing, video games, and many more.

This wide range of applications and disciplines has produced a wealth of ideas, models, tools, and results in the recognition literature. However, it has also contributed to fragmentation in the field, with researchers publishing relevant results in a wide spectrum of journals and conferences.

This book seeks to address this fragmentation by providing a high-level introduction and historical overview of the plan and goal recognition literature. It provides a description of the core elements that comprise these recognition problems and practical advice for modeling them. In particular, we define and distinguish the different recognition tasks. We formalize the major approaches to modeling these problems using a single motivating example. Finally, we describe a number of state-of-the-art systems and their extensions, future challenges, and some potential applications.

KEYWORDS

plan recognition, goal recognition, activity recognition, behavior recognition, intent recognition, temporal pattern recognition, reasoning under uncertainty, human-AI collaboration, multi-agent systems, symbolic reasoning

To Ilya, for giving me something greater than research, and then letting me have both.

- Reuth Mirsky

To my husband Uri and to my Ph.D. advisors, Avigdor Gal and Erez Karpas. I couldn't have done this without your support.

- Sarah Keren

To Sabra. Shockingly, sometimes words actually do fail me.... R&C.

- Christopher Geib

Contents

Preface	xvii
Acknowledgments	xix
1 Introduction	1
1.1 Some Necessary Remarks on Scope, Pre-History, and Taxonomy	3
1.1.1 Activity Recognition	5
1.1.2 Goal Recognition	6
1.1.3 Plan Recognition	6
1.1.4 Then What is “Intent Recognition”?	7
1.2 The Scope of This Book	7
1.3 Selected Historical Plan Recognition Systems	8
1.3.1 Kautz and Allen: Generalized Plan Recognition	9
1.3.2 Carberry: Plan Recognition in Natural Language Dialogue	11
1.3.3 Vilain: Getting Serious about Parsing Plans: A Grammatical Analysis of Plan Recognition	13
1.3.4 Goldman and Charniak: Probabilistic Text Understanding	13
1.3.5 Pynadath and Wellman: Accounting for Context in Plan Recognition with Application to Traffic Monitoring	14
1.3.6 Avrahami-Zilberbrand and Kaminka: Fast and Complete Symbolic Plan Recognition	15
1.3.7 Geib and Goldman: A Probabilistic Plan Recognition Algorithm Based on Plan Tree Grammars	17
1.4 Selected Historical Goal Recognition Systems	18
1.4.1 The Lumiere Project: Bayesian User Modeling for Inferring the Goals and Needs of Software Users	18
1.4.2 On-Line Student Modeling for Coached Problem Solving Using Bayesian Networks	19
1.4.3 Ramírez and Geffner: Plan Recognition as Planning	20
1.5 Selected Historical Activity Recognition Systems	21
1.5.1 Improving Offensive Performance Through Opponent Modeling ...	21
1.5.2 Hierarchical Conditional Random Fields for GPS-Based Activity Recognition	22

1.5.3	Notes on Prior Work in Markov Processes, Hidden Markov Models, and Related Work	23
1.5.4	Final Thoughts	24
2	Defining a Recognition Problem	25
2.1	Environment	26
2.2	Actor	26
2.3	Observer (Recognition System)	27
2.3.1	Recognition Objective	27
2.3.2	Observability	28
2.3.3	Possible Interventions	28
2.4	Design Considerations	29
3	Implicit vs. Explicit Representation of Knowledge	31
3.1	Shared Assumptions	31
3.2	Explicit Representations	33
3.2.1	Formulating the Problem	35
3.2.2	Running Example	37
3.2.3	Plan Recognition as Parsing	40
3.3	Implicit Representations	42
3.3.1	Formulating the Problem	44
3.3.2	Running Example	46
3.3.3	Plan Recognition as Planning	47
3.4	Final Thoughts on Implicit vs. Explicit Representation	49
4	Improving a Recognizer	53
4.1	Main Improvement Categories	53
4.2	Speed	55
4.2.1	Optimizing Parts of the Recognition Process	55
4.2.2	Delaying Commitment	61
4.2.3	Heuristics	66
4.2.4	Domain Optimization	70
4.3	Representational Richness	72
4.3.1	From Goals to Plans	72
4.3.2	Continuous Domains	73
4.3.3	Multimodal Inputs	74
4.3.4	Belief Modeling	75

4.3.5	First-Order Models	76
4.4	Other Approaches	78
4.5	Summarizing Tables	82
5	Future Directions	85
5.1	Integrating Data-Driven Techniques	85
5.2	Integrating Recognition and Execution	85
5.3	Plan Recognition in the Wild	86
5.4	Final Remarks	87
	Bibliography	89
	Authors' Biographies	99

Preface

This book is based on a tutorial presented by the authors at the 2019 AAAI conference in Hawaii. The wish to create the tutorial came up after the authors had been co-chairing the Plan Activity and Intent (PAIR) workshop at AAAI since 2017. The PAIR workshop, initially named Modeling Others from Observations (MOO), has been taking place at different venues since 2004. Every year, it attracts and brings together researchers from diverse backgrounds and disciplines.

Our experience as co-chairs helped us appreciate the increasing interest in plan and goal recognition. However, it also highlighted the lack of a shared vocabulary and terminology to connect the different lines of work. Our intention for the tutorial and this book is to bridge the gap that exists between different threads of research in the field. We do this by providing an overview of past and state-of-the-art model-based plan and goal recognition literature, by specifying a formalization of the elements of the problem, and by describing a set of practical tools for evaluating and investigating a new recognition problem.

The book is organized into five chapters. Chapter 1 is an introduction to plan and goal recognition and an overview of key past works in the area. Chapter 2 provides a unified recipe for defining a recognition problem, and provides guidelines for choosing an approach for a given recognition task. In Chapter 3, we formalize goal and plan recognition. Chapter 4 describes a variety of state-of-the-art approaches to recognition and suggests ways to extend existing symbolic plan and goal recognition tools. Finally, Chapter 5 highlights possible directions for future work. In all of these chapters we provide references an interested reader can use to continue the exploration of this research space.

We hope this book will enable and encourage researchers to read more widely past work and to build on its lessons to advance plan and goal recognition research. To paraphrase Sir Isaac Newton, our research field truly has been built on the shoulders of giants.

Reuth Mirsky, Sarah Keren, and Christopher Geib
January 2021

Acknowledgments

While the cover of this book lists three authors, no such work is ever completed without the assistance, encouragement, and support of a strictly non-enumerable number of supporters, colleagues, editors, mentors, friends, and family (genetic and chosen). We thank you all. Further, we would like to acknowledge all of the exceptional researchers whose work we reference here. We have worked to the best of our ability at synthesizing a diverse field of research, and if in that effort our characterization of your work has been imperfect, we apologize. We would also like to acknowledge all of the authors of papers at the PAIR and MOO series of workshops that has been such a rich and supportive research community over the years and contributed to and shaped so much of our thinking about these problems. Gal Kaminka the “founding father” of the first MOO workshop deserves special acknowledgment in this regard. We would also like to thank all of the people that encouraged us (before and after) to run the Plan Activity and Intent Recognition Tutorial at AAAI-19 that was the impetus behind this volume.

We would all like to thank Michael Morgan and the whole team at Morgan & Claypool for their patience and support, Peter Stone for suggesting we turn our tutorial into a book, and our reviewers Gita Sukthankar, Shlomo Zilberstein, and David Pynadath for their comments on an earlier draft of this book. It has benefited immeasurably from their efforts and any errors in it were definitely inserted after their commentary. We would like to acknowledge and thank our partners and families for their patience and support during this process. Writing a book is never an easy or fast process and it is not only the authors that pay the costs. Thank you.

More specifically, Reuth would like to thank Kobi Gal for introducing her to the world of PAIR; Chris Geib and Gal Kaminka for being the Gandalf and the Elrond of her first PAIR adventures; Sarah Keren, Mor Vered, and Maayan Shvo for exciting discussions about PAIR and beyond; and Peter Stone for his inspiring mentorship and support.

Sarah would like to thank Avigdor Gal and Erez Karpas, her Ph.D. advisors who helped formulate Goal Recognition Design and introduce it to the world. She also thanks Barbara J. Grosz, David C. Parkes, and Jeffrey S. Rosenschein for supporting her in the process of writing this book and for helping her find new and better ways to make her messages clear.

Finally, Chris would like to thank his co-authors Reuth and Sarah. It is in our discussions, conversations, arguments, and efforts to write down what we know that we clarify our own

xx ACKNOWLEDGMENTS

knowledge. The benefits of having you as such insightful, challenging, and thought-provoking, colleagues has been immeasurable. Thank you.

Reuth Mirsky, Sarah Keren, and Christopher Geib
January 2021