Lecture Notes in Artificial Intelligence 1047

Subseries of Lecture Notes in Computer Science

Edited by J.G. Carbonell and J. Siekmann

Lecture Notes in Computer Science

Edited by G. Goos, J. Hartmanis and J. van Leeuwen

Elżbieta Hajnicz

Time Structures

Formal Description and Algorithmic Representation

Springer

Series Editors

Jaime G. Carbonell
School of Computer Science
Carnegie Mellon Universtiy
Pittsburgh, PA 15213-3891, USA

Jörg Siekmann
University of Saarland
German Research Center for Artificial Intelligence (DFKI)
Stuhlsatzenhausweg 3, D-66123 Germany

Author

Elżbieta Hajnicz
Polish Academy of Sciences, Institute of Computer Science
ul. Ordona 21, PL-01-237 Warszawa, Poland

Cataloging-in-Publication data applied for

Die Deutsche Bibliothek - CIP-Einheitsaufnahme

Hajnicz, Elżbieta:
Time structures : formal description and algorithmic representation / Elżbieta Hajnicz. - Berlin ; Heidelberg ; New York ; Barcelona ; Budapest ; Hong Kong ; London ; Milan ; Paris ; Santa Clara ; Singapore ; Tokyo : Springer, 1996
(Lecture notes in computer science ; 1047 : Lecture notes in artificial intelligence)
ISBN 3-540-60941-5
NE: GT

CR Subject Classification (1991): I.2, F.4.1

ISBN 3-540-60941-5 Springer-Verlag Berlin Heidelberg New York

Typesetting: Camera-ready by author
SPIN 10512635 06/3142 – 5 4 3 2 1 0 Printed on acid-free paper

Preface

The notion of time: the mystery of time passing, the eternal circle of the seasons, of birth, life, and death, the evanescence of what we experience, remembering past things and future misgivings and prospects—all that has fascinated people for ages. The nature of time has been contemplated by philosophers. The reason is that its role is fundamental both in science and in everyday life. We do not all even realize when and how frequently we use this notion. The modern sciences, particularly physics and astronomy, are based on the parameter of time.

Given all this, it is evident that the notion of time plays an important role in artificial intelligence, especially in planning robot activity, natural language processing, and time-varying scenes analysis. In all these disciplines, many experimental and practical algorithmic solutions, as well as formal, logical descriptions and analyses, have been presented. These two approaches are not separate, since many representations and reasoning algorithms are logic-based.

The important characteristic of the notion of time with regard to its applications is that its treatment does not depend on a particular use, and is very specific and different from the treatment of other parameters. On the contrary, description and representation of time strictly depend on the assumptions concerning its structure: whether it is composed of points or of intervals and how these individuals are organized in a particular order.

Thus it seems justified to consider the notion of time separately from its applications and from other parameters utilized in them.

This book is intended to discuss different time structures and their properties from various perspectives. The logical description of time (both by means of classic and modal logics) is a broad discipline itself. The book contains a comprehensive presentation of logical theories of various time structures (point- and interval-based). These theories may be used as a basis for logic-based representations.

On the other hand, there are many representation and reasoning algorithms concerning time. They differ in their expressive power and their algorithmic characteristics (e.g. time and space complexity). Several of them are presented in this book. They are often used in concrete applications from various disciplines.

All these logical theories and algorithmic representations concern specified time structures. Thus these approaches are not independent: they are connected by corresponding time structures. This work aims to show these connections between classic (first order) theories of time structures, modal logic of corresponding structures, and their algorithmic representations. To make this relationship

complete, a formalisation of Allen's famous algorithm is presented (which can be applied for various structures of time), as well as its translation to modal logics. Note that a logical characterization of algorithmic solutions, which are not logic-based, is really helpful.

Thus this book contains a comprehensive analysis of logical description and algorithmic representation of time structures, and will be interesting for many people working on or studying computer science and artificial intelligence.

I am very grateful to Prof. Leonard Bolc, Prof. Andrzej Szałas, Dr Witold Bartol and all my colleagues from the Man-Machine Communication Group at the Institute of Computer Science, Polish Academy of Sciences for their helpful comments and discussions. Without their help and support I would probably not have managed to write this book.

This research was supported in part by the Polish Committee for Scientific Research KBN under grant 3 0700691 01.

November 1995 E. Hajnicz

Contents

1 Introduction 1
1.1 Basic time notions 3
1.1.1 Facts 3
1.1.2 Events 4
1.1.3 Actions 5
1.1.4 Processes 6
1.2 Time notions in artificial intelligence 8
1.2.1 Planning 8
1.2.2 Natural language processing 11
1.2.3 Time-varying scene analysis 15
1.2.4 Temporal databases 17
1.2.5 Program specification and verification 19

2 Description of time structures in the first order predicate calculus 21
2.1 Point structures 22
2.1.1 Non-linear point time structures 23
2.1.2 Metric point time structures 26
2.1.3 Cyclic time structures 29
2.1.4 Defining intervals in point structures 30
2.2 Interval structures 32
2.2.1 The classic axiomatization 32
2.2.2 Allen & Hayes's axiomatization 34
2.2.3 Tsang's axiomatization 38
2.2.4 Comparison of axiomatizations of interval structures . . . 40
2.2.5 Non-linear interval time structures 45
2.2.6 Defining points in interval structures 59

3 Modal temporal logics and description of time structures . . 61
3.1 Point time 62
3.1.1 Classical priorean instant tense logic 62
3.1.2 Additional operators for structure specification 65
3.1.3 Operators "Since" and "Until" 68
3.1.4 Metric tense logic 71

3.2 Interval time 75
3.2.1 Extended tense logic 75
3.2.2 Halpern & Shoham's modal logic of time intervals 79
3.2.3 Comparison of extended tense logic and Halpern & Shoham's logic 89
3.2.4 Non-linear time in extended tense logic 101

4 Temporal reasoning algorithms 107
4.1 Kahn & Gorry's time specialist 107
4.2 Allen's constraint propagation algorithm for relations between intervals 109
4.3 Application of the constraint propagation algorithm to different sets of relations 113
4.3.1 Linear point time 113
4.3.2 Non-linear point time 114
4.3.3 Relativistic point time 118
4.3.4 Metric point time 119
4.3.5 Linear interval time 127
4.3.6 Non-linear interval time 129
4.3.7 Linear interval/point time 136
4.4 Extentions and modifications of Allen's constraint propagation algorithm 139
4.4.1 Direct extensions of the algorithm 139
4.4.2 Metric information for interval/point time 141
4.4.3 Representing the present in the constraint propagation algorithm 142
4.4.4 Absolute duration of events 144
4.4.5 Relative duration of events 145
4.4.6 Interval relation network with distinguished transition chains 148
4.4.7 A more precise constraint propagation algorithm 151
4.5 Constraint propagation for a distinguished interval 155
4.6 Consistent Labeling Problem for interval relations 156
4.7 Efficient algorithms for representation of relations between points 158
4.8 Representation of collections of intervals 163

5 Formalization of the constraint propagation algorithm 167
5.1 Allen & Hayes's formalization 167
5.2 The basis of direct formalization of constraint propagation algorithm 168
5.3 Point calculus for linear time 173

5.4 Dates in the point calculus 179
5.5 Point calculus for non-linear time 180
5.6 Calculus of distances between points 182
5.7 Interval calculus for linear time 187
5.8 Interval calculus for non-linear time 190
5.9 Calculus of points and intervals 193
5.10 A sketch of formalization of a more precise constraint propagation algorithm 195

6 Translations of Allen's calculi into modal temporal logic . . 199
6.1 Translation of the point calculus for linear time into instant tense logic 200
6.2 Translation of the point calculus for non-linear time into instant tense logic 208
6.3 Translation of the calculus of distances between points into metric tense logic 210
6.4 Translation of the interval calculus for linear time into extended tense logic 217
6.5 Translation of the interval calculus for linear time into Halpern & Shoham's logic 225

Bibliography 233