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Temporal Representation and Reasoning in Artificial Intelligence: A Review

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Abstract—The explicit representation and reasoning about time is an important problem in many areas of artificial intelligence Over the last 10–15 years, it has been attracting the attention of many researchers Several temporal reasoning systems, differing in design issues related to ontology of time, underlying temporal logic, temporal constraints used and algorithms employed, have been developed In this survey, important representational issues which determine a temporal reasoning system are introduced In particular, several important notions like change, causality, actions are described in terms of time For each issue different choices available in the literature are discussed The most influential approaches to temporal reasoning in artificial intelligence are analyzed in terms of these major representational issues © 2001 Elsevier Science Ltd All rights reserved

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1. INTRODUCTION

Philosophy has always drawn inspiration from close association with other intellectual disciplines Computer science is no exception in this regard In recent years, it has increasingly been argued that philosophers can no longer afford to ignore the fundamental innovations in concepts and methods introduced by practitioners of various disciplines, in computer science notably in the study of artificial intelligence (AI) Work in many of the traditional problems of philosophy, particularly those associated with language and mind, has to receive fresh impetus from the insight of those who have sought to tackle related problems from a practical or computational viewpoint Conversely, computer science has a good deal to learn from philosophy and indeed computer scientists are showing greater awareness and interest in those aspects of philosophy, which have relevance to their own discipline

The concept of time is quite profound and long has been regarded as the domain of philosophy It started, in the form of tense logic and was pursued for many years by philosophers and logicians without any regard to its possible applications outside their subject Their main motivation was

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natural language understanding In addition, they also had objectives of understanding the nature of time and seeking answers to some fundamental questions Is time discrete or continuous? Is it bounded or unbounded? Is it linear, parallel, branching, or circular? Many of these questions still remain unresolved, nevertheless endeavours of philosophers have provided useful insight into understanding the nature of time

The notion of time is ubiquitous in any activity that requires intelligence The human perception and understanding of the real world deeply incorporate the concept of time Everything appears related by its temporal reference Events occur temporally related between them Objects remain in a certain state for a while until a certain event happens Time seems to be a fundamental entity to which the rest of objects in the world are related with, so it appears to play the role of a common universal reference

The literature on the nature and representation of time is full of disputes and contradictory theories This is surprising since the nature of time does not cause any worry to the people in their day to day affairs This suggests that there is some form of commonsense knowledge about time that is rich enough to enable people to deal with the world and which is universal enough to allow communication and cooperation between people

A useful distinction is often made in psychological and philosophical literature among three categories of time, namely *natural*, *conventional*, and *logical* Cognition of the natural time is based on the natural phenomena of occurrence of day and night, the (lunar) month, and the occurrence of seasons Conventional time refers to the temporal structure based on the social conventions Some of these are derived from natural time and include seconds, minutes, hours, days, months, and years Logical time refers to the logico-mathematical structure of time and operations thereon such as ordering and transitivity [1]

From our earliest days we learn to perceive time as a result of important cognitive abilities The awareness of change around us and the ability to detect regularities in that change Time is fundamental to reason about *change* and *action* When we say that something changes, we are talking about different *states* or conditions of the same thing and we are forced to define how they are related This relation is temporal, either implicit or explicit Conversely, the passage of time is important only because changes are possible [2] In a static world where nothing changes, it would not make sense to talk about time

The problem of representing temporal knowledge and temporal reasoning arises in wide range of disciplines, including computer science, philosophy, psychology, and linguistics In computer science, it is a core problem in information systems design, program verification, AI, and other areas involving process modelling

While considering different applications of AI, it becomes necessary to make the concept of time explicit An example is cited from *planning* Given a description of a state of the world over some period of time and the physics of actions (law governing changes) in the world, a planner is required to produce a sequence of actions over time that would result in the desired world starting from the current world In order to plan, the planner needs a representation, which allows him/her to address about how the effects of an action change the world over time and how long they remain true and also what remains unchanged over time There are several effects that just cannot be captured by a change-based approach For example consider, "he ran around the track three times", there is no net change in the position of the runner but still nobody will deny that an action has indeed taken place Clearly, a different kind of reasoning system is needed to deal with time naturally

This difficulty can be tackled by explicitly mentioning the time during which the action occurred irrespective of the change in state So there is a need to introduce the additional time dimension instead of shying away from it

TEMPORAL REASONING (TR) Consists of formalizing the notion of time and providing means to represent and reason about the temporal aspect of knowledge [3] Hence, a TR framework

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