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Causal temporal constraint networks for representing temporal knowledge

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Abstract

In this work we describe causal temporal constraint networks (CTCN) as a new computable model for representing temporal information and efficiently handling causality. The proposed model enables qualitative and quantitative temporal constraints to be established, introduces the representation of causal constraints, and suggests mechanisms for representing inexact temporal knowledge. The temporal handling of information is achieved by structuring the information in different interpretation contexts, linked to each other through an inference mechanism which obtains interpretations that are consistent with the original temporal information. In carrying out inferences, we take into account the temporal relationships between events, the possible inexactitude associated with the events, and the atemporal or static information which affects the interpretation pattern being considered. The proposed schema is illustrated with an application developed using the CommonKADS methodology.
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1. Introduction

The computational treatment of temporal information commenced at the end of the 1960s and was consolidated throughout the 1970s. The software crisis focused searches on more formal specification techniques for concurrent programs, based on modal temporal logics (Gotzhein, 1992), in which time is implicit in the modal operators (Marín & Taboada, 1996). In a recent study, Kautz (1999) indicated that the temporal information handling approaches can be classified in three different categories: algebraic systems, temporal logics and action logics.

Algebraic systems focus on the relationships between temporal points or intervals, which are represented by named variables. A set of quantitative or qualitative equations restricts the values that can be assigned to temporal variables. These equations can take the form of a constraint satisfaction problem (CSP), a set of linear equations, or even a set of assertions in a subset of first-order logic. The aim of the reasoning problem may be to determine consistency, find the minimum CSP labelling, or find consistent links for all the variables in a set of mathematical objects. In these models, time itself is typically modelled as a continuous linear structure—although there has been some research into discrete linear time models (Dechter, Meiri, & Pearl, 1991) and branched time models.

Temporal algebra does not reveal anything on how temporal intervals or points associate with events or propositions. In practice, an external mechanism (such as a planning system) generates samples of intervals or points which are used to temporally mark or order states in a knowledge base. This external mechanism processes some of the constraints between the temporal samples, which should agree with the semantics of the knowledge base. Thus, the algebraic reasoning motor must be consulted in order to process the consequences of these assertions.

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By contrast, *temporal logics* directly represent temporal relationships between propositions, and do not explicitly consider temporal representations based on points or on intervals (Van Benthem, 1983; Thayse, 1989). There are modal logics which extend first-order logic to temporal operators. Although temporal logics are frequently used for verification and in data base communities, their use is not yet widespread in artificial intelligence. Their applications include specification and verification of real time, reactive planners (Rosenschein & Kaelbling, 1995; Williams & Nayak, 1997), and specification of extended temporal goals and search control rules (Bacchus & Kabanza, 1996).

Lastly, in *action logics,*temporal reasoning is implicitly achieved by all systems used to represent and reason on action and change, such as situational calculus (McCarthy & Hayes, 1969) and dynamic logic (Harel, 1979). A general approximation may also be used for modelling continuous branched time. Using this approach successful planning systems have constructed which use a discrete linear time model, in which states are simply natural numbers used to order temporal variation predicates (Blum & Furst, 1995; Kautz & Selman, 1996).

In this work, we describe a new computable model for representing temporal information and efficiently handling causality. Our approach goes deeper into the doctrine of algebraic systems and addresses the temporal question as a temporal constraints satisfaction problem (Marín & Navarrete, 2003). The proposed model allows qualitative and quantitative temporal constraints to be established, introduces the representation of causal constraints, and suggests mechanisms for representing inexact temporal knowledge.

The validity of the proposed model has been tested using an actual application: the design and development of a framework for implementing symbolic information temporal correlation tasks using the CTCN model for representing knowledge. This framework is described at a conceptual level, independently of any specific domain. The CommonKADS methodology was used to develop this framework (Alonso Betanzos, Guijarro Berdiñas, Lozano Tello, Palma Méndez, & Taboada Iglesias, 2004; Schreiber et al., 2000).

2. Temporal constraint satisfaction

Formally, a constraint satisfaction problem (CSP) is a triad (X, D, C) where X is a set of n variables $\{X_1, \ldots, X_n\}$. Each variable X_i has a non-empty domain D_i of possible values, and each constraint C_i implies some subset of variables and specifies the acceptable value combinations for this subset.

A state of the problem is defined by the assignation of values to one or all the variables, or instantiation, $\{X_i = v_i, X_j = v_j \ldots\}$. An assignation that does not violate any constraint is called a consistent or legal assignation. A complete assignation is an assignation in which each variable is mentioned, and a CSP solution is a complete assignation that satisfies all the constraints. Some CSPs also require a solution that maximises an objective function (Russell & Norvig, 2003).

Basically the solutions aspired to through a CSP are as follows: (a) any solution, with no preferences, (b) all the solutions, or (c) an optimum or at least a satisfactory solution.

Although the temporal constraint satisfaction problem (TCSP) derives from the CSP, there are a number of fundamental differences between them (Schwalb, 1998).

A temporal constraint C_{ij} takes the form $(X_i r_1 X_j) \vee \cdots \vee (X_i r_k X_j)$, where X_i, X_j are temporal variables and $r_1, \ldots, r_k$ is a set of basic temporal relations. This can be expressed briefly as $X_i\ \{r_1, \ldots, r_k\}\ X_j$ or $C_{ij} = \{r_1, \ldots, r_k\}$. This constraint is satisfied if, as a minimum, one of the relations $r_1, \ldots, r_k$ is maintained between X_i and X_j.

For example, let X_i and X_j be two intervals, and let $r_1 = \text{before}$ and $r_2 = \text{after}$. The corresponding temporal constraint is $(X_i \text{ before } X_j) \vee (X_i \text{ after } X_j)$, which can be written briefly as X_i {before, after} X_j or, alternatively, as $C_{ij} = \{\text{before, after}\}$ (Schwalb, 1998).

Temporal constraint models tackle the problem of temporal reasoning by representing the temporal labels associated with facts as algebraic relations between pairs of temporal entities. These relations contain the original temporal information supplied, and are combined with a view to obtaining new information on the occurrence times (Marín & Taboada, 1996).

The CSP paradigm is a simple and intuitive way to formalise models on which a temporal reasoner is based. In fact, a temporal reasoning problem can be considered as a particular case of the CSP, in which the variables represent temporal entities – such as instants or intervals – and the constraints represent the temporal relationships permitted between the temporal entities (Schwalb & Vila, 1998).

An advantage of modelling temporal problems as CSPs is that they can be resolved using the wide range of algorithms available for general CSPs. A TCSP contains the original temporal information supplied for the problem. Algorithms based on constraint propagation, which exhaustively combine the known temporal information, are used to infer new temporal information on the occurrence time of events (Marín & Navarrete, 2003).

From the practical applications perspective, an important issue that may arise with these models is the computational complexity associated with different temporal reasoning problems. There are important differences in the efficiency of the algorithms used for different models. Obviously, the greater the expressive capacity of a model, the greater the associated computational complexity (Marín & Navarrete, 2003).

3. The temporal model

Below, we describe a new computable model for representing temporal information, efficiently handling causality and representing the imprecision associated with the occurrence of events. The approach explores the doctrine of alge-

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