

The Logical Approach to Temporal Reasoning

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Abstract. Temporal reasoning started to be considered as a subject of study in artificial intelligence in the late '70s. Since that several ways to represent and use temporal knowledge have been suggested. As a result of that there are several formalisms capable of coping with temporal notions in some way or other. They range from isolated proposals to complex systems where the temporal aspect is used together with other important features for the task of modelling an intelligent agent. The purposes of this article are to summarize logic-based temporal reasoning research and give a glance on the different research tracks envisaging future lines of research. It is intended to be useful to those who need to be involved in systems having these characteristics and also an occasion to present newcomers some problems in the area that still wait for a solution.

Keywords: knowledge representation, temporal logic, time, properties, events, actions, processes.

1. Introduction

Change is an ever present and important feature in the world, since humans defined some linguistic conventions in order to give a more precise description of what they needed to say about its different states. During the last half of this century artificial intelligence (AI) has been trying to discover that behaviour that made humans succesful dealing with dynamic environments. As a result of that, several proposals had been made to represent and use time.

There is a natural philosophical interest to elucidate the strategies a human being uses considering time, the kind of temporal concepts we use and the sort of conventions our way of doing temporal reasoning is tied up to. However, although interesting in themselves, the philosophical aspects of the area will not be the main subject of this work. Instead we will explore the field

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looking through the glasses of computing, emphasizing in time representation and its use in solving problems.

The emphasis on the computational side of this area is not a casual one. Computer science has greatly benefited from AI discoveries in that field, often adapting such techniques to a special area where different preferences are forced by the applications in mind. Either with its own tools or with imported strategies, several areas of computer science are increasingly becoming involved with some way of considering time. Some problems whose solutions benefit from the consideration of temporal formalisms are: real time computation, resource allocation in distributed systems, formal program specification and verification, multimedia authoring and temporal databases. The list is by no means exhaustive. This diversity of applications and interests explains the growing attention people are giving to this field and the large amount of material it is possible to find in the literature.

The aim of this work is to bring to the reader a concise account of the logic-based proposals for temporal reasoning in AI. We will try to present different systems keeping the notation and the description of the different approaches simple while describing their main features. The temptation to connect this area with other fields of research like temporal theorem proving, temporal logic programming, planning related works, and other exciting results will be avoided in order to keep this article short. Other sources of information where the interested reader could continue the reading of these notes are the TIME workshop series (Morris and Khatib, 1994; Morris and Khatib, 1995; Chittaro et al., 1996; Morris and Khatib, 1997; Khatib and Morris, 1998; Morris and Khatib, 1999; Goodwin and Trudel, 2000) and the proceedings of the International Conference of Temporal Logic (Gabbay and Ohlbach, 1994; Gabbay and Barringer, 1997; Barringer et al., 2000).

The article comprises a brief comment about the basic temporal concepts given in section 2 that will set a common language. The presentation of the proposals will be organized regarding the goals of the works under consideration. Works addressing time as an isolated issue will be grouped in section 3. Section 4 will be dedicated to modal temporal logics. Finally more complex systems will be considered in section 5 mainly involved with nonmonotonicity but also concerned about temporal representation and reasoning.

Proposals will be presented in chronological order in all these sections. The article ends in section 6 with an analysis of the main approaches, their strengths and weaknesses.

Through this presentation it will be assumed that the reader has some familiarity with basic aspects of first order logic (Mendelson, 1987; Davis, 1988), artificial intelligence in general and nonmonotonicity in particular (Ginsberg, 1994).

2. Some basic notions

The formalization of temporal reasoning proved to be a great task as the literature testifies. Many aspects must be taken into account when defining a proposal with this purpose. There is a necessity to be explicit about what the assumptions on the temporal structure will be because this has a great impact on subsequent aspects of the theory. Also it is important to decide how these characteristics of the class of problems to be considered will be reflected through language in the system. That is to say, what primitives of the language will be used for a description of the dynamic environment. Also there are some choices to make considering some fundamental assumptions about the relation between change and time which leads to quite different languages. In this section a quick account of several of these issues will be provided .

2.1. WHAT DOES TIME LOOK LIKE?

The problem of characterizing the temporal scenario to be assumed strongly influences the theory to be proposed and this, in turn, the tools to be produced. To define a formal system for temporal reasoning some questions should be answered. What kind of substance is time built of?, What properties does time have?, How can we refer to it adequately? Philosophers, since the Greeks, have been exploring these questions. Although there is no consensus about what the answers to these fundamental questions are some alternatives were sketched which could prove to be very useful for people attempting to capture some portion of reality. See (Prior, 1967; Rescher and Urquart, 1971; McArthur, 1976; Davidson, 1980; Newton-Smith, 1980; Galton, 1984; Van Benthem, 1991) for some testimonies of that work. These studies

were further pursued by philosophers and logicians during the last half of this century. They explored these questions mainly from a linguistic perspective. Recently computer science and AI researchers have considered temporal notions as part of the program to characterize the notion of *intelligence* and as a first step to different goals. See for example (Moszkowski, 1986; Galton, 1987; Shoham (b), 1987; Goldblatt, 1987; Allen et al., 1991; Gabbay et al., 1994; Sandewall, 1994; Galton, 1995; Van Benthem, 1996).

In answering how temporal individuals could be arranged several aspects should be considered. What option to adopt in each case is not an easy matter because when a choice is made several aspects of the problem become easier but some others worse. The problem is so rich and complex that researchers in artificial intelligence often end up making a set of choices that seems to promise some computational treatment instead of selecting a set of features that best reflects their conceptions about how the real concepts are. Then, unless stated otherwise it is usually appropriate to consider each set of choices in a proposal as a compromise between conceptions authors have of the issue and an attempt to formalize it in an incremental way of difficulty.

One thing to decide is if time will be considered as linear, branching, circular or with a different structure. Each of these characteristics could be represented axiomatically using a first-order language, see for example (Turner, 1984). Definitely the two first options were the favored ones in the literature, but for some purposes other options are considerable. The most popular way to conceive time is as a line where temporal references could be aligned. This conception of time proved to be popular since the Newtonian physics paradigm was adopted and provides the simplest conception and way to arrange temporal references. Also proved popular in the area a future-branching structure representing past as linear and the present as a distinguished point where the future opens as a bunch of possibilities. The adoption of a future-branching structure could be motivated in several ways. Usually it is the possibility of representing the capability of intelligent agents of choosing between alternatives or a way to provide hypothetical reasoning which is behind its adoption. A past-branching structure could provide a good framework for abductive reasoning, usually needed in medicine and all sorts of

history-based fields like geology, archeology and so on. Circular time could be conceived as *closed-open*, or *static-dynamic*, depending on whether we are interested in the type of facts which recurrently are recreated or in the recreations themselves, which could be seen as non-repeating. The capability to reason over cyclical processes in industrial scenarios could provide reasons to adopt this view of time. See (Newton-Smith, 1980) for philosophical background, (Reynolds, 1994; Cuckierman and Delgrande, 1998) for logical and computational perspectives.

Time may have a beginning moment, a final moment, both or neither. All these choices could also be represented in first order axioms (Turner, 1984). The three first options could be appropriate during the formalization of agents reasoning over problems in which some past or present information relative to a given point in time is not important. The last options do not restrict the temporal references to be taken into account in the system either in the past or the future.

Time could also be considered as organized in other ways, e.g. discrete, dense or continuous. This led to the so called *topological time* because temporal structures could be analyzed under the light of topology. Sometimes it suffices to define the conceptual use of time by an agent as a succession of temporal phenomena organized in a discrete fashion. Simple as this conception could seem at first glance it allows the representation of very interesting concepts and problems. Some problems could be more naturally represented under the hypothesis of a dense or continuous temporal structure like one isomorphic to \mathbb{Q} or \mathbb{R} . However, these steps could not be given without a price to pay. There exists for example the so-called *dividing instant problem* (Van Benthem, 1991) which warns us about some difficulties in continuous change representation. It is important also to remember that the adoption of a particular ontology leads to important differences in the kind of system to be defined. While \mathbb{Q} can be axiomatized in a first-order theory, \mathbb{Z} and \mathbb{R} cannot. Although usually problems of continuous change lead to think that an \mathbb{R} -like structure must be used, some attempts has been made to represent continuous change using discrete structures (Hobbs, 1985; Barber and Moreno, 1997).

It is also useful to know what kind of properties the structure of temporal individuals have as a whole (Van Benthem, 1991). Some of them are *homogeneity* (Are all individuals equal?), *connect-*

edness (Are all individuals comparable by the order relations?), *symmetry* (Is it the same to look to one side or to the other?). If a distinguished entity like *the present* or *the beginning of time* is assumed in the theory and special properties are attached to its interpretation then the temporal structure is not homogeneous. If all temporal references are equally treated, as for instance in the Newtonian time line we have a homogeneous structure. A temporal structure isomorphic to \mathbb{Z} could be considered as symmetric while a forward-branching could not. Usually structures with beginning and ending points are non-homogeneous because these points are treated in a special way relative to the rest of the structure. Connectedness is less easy to associate with some particular topology because it heavily depends on the definition of the order relations. A linear structure with the usual order over numbers could be seen as connected. Some branching structures or some structures admitting gaps could have some problems to fulfill this requirement using standard order relations and to cope with this problem special mechanisms of comparison must be provided.

It remains to consider another fundamental source of choice, the way to reference time. The problem of deciding which kind of reference must be considered more natural has been subject to intense debate. Literature about the philosophy of time provides us with several articles from people sustaining an instant-based view of time (Lin, 1994; McDermott, 1982; Shoham, 1985) while others defend a period-based approach (Russell, 1936; Hamblin, 1972; Allen and Hayes, 1985; Kamp, 1979). Names vary with authors but usually *instants* and *time points* are used to refer to punctual occurrences while *periods*, and *intervals* are used to talk about durative temporal references. Recently some proposals have explored the benefits to allow both kind of references in the same level of importance (Bochman (a), 1990; Bochman (b), 1990; Galton, 1990; Vila, 1994; Augusto, 1998). See (Van Benthem, 1991) for an analysis of the three alternatives, i.e. to consider instants, periods or both. Usually intervals are assumed to be periods with known beginning and end. *convex* periods are usually used in the literature. In van Benthem's terms, if \triangleleft and \sqsubseteq are "precedence" and "part of" relations, such that $p_1 \triangleleft p_2$ if p_1 ends before p_2 starts and $p_1 \sqsubseteq p_2$ if p_1 is fully contained inside p_2 then a period u is

convex when:

$$\forall x \forall y \forall z (x \triangleleft y \triangleleft z \rightarrow ((x \sqsubseteq u \wedge z \sqsubseteq u) \rightarrow y \sqsubseteq u))$$

It is interesting to see that both kinds of references could be defined in terms of each other. For example, periods could be seen as sets of instants or the duration denoted by two instants acting as beginning and ending points. Also instants could be defined as the meeting point between two periods.

It is useful to bear in mind that the above considered set of possibilities for defining different aspects of a temporal structure are independent from each other. For example, the decision if the structure is linear or branching does not rule out considering if it is bounded or not or if it is discrete, dense or continuous.

2.2. WHAT CAN BE SAID IN TIME ?

Another important issue in all temporal theory is to decide what sort of information is subject to change or, in another way, what kind of concepts are involved in the theory beyond time itself. While the information to be associated with temporal concepts can vary from scenario to scenario, some concepts appear repeatedly when we examine temporal reasoning related literature.

Because temporal reasoning involves solving problems in a changing world, there is a need to represent what *properties* the objects of that world can have or do have now. These are supposed to characterize the size, color, shapes, weights and other distinctive features of each object considered in the intended scenarios. The set of objects and their properties define a *state* of the world. A given state of the world is changed by the occurrence of *events*. These are strongly tied to the notion of time because it is natural to think about time as a mechanism to order reasoning about change. *Actions* are identified with the agent's capability of interacting with its world. They are considered event-producers but events could be the effect of just another event. This is the case for example of natural forces changing the shape of earth or collisions and contacts generated by objects in movement.

Some authors (Allen, 1984) find useful to consider the notion of *processes*. Which are intended to describe complex situations, sometimes presented as activities. See (Galton, 1990) to have a glimpse of some of the technical difficulties in defining them.

All the above mentioned notions are quite complex to understand and to give a precise definition of them is far from simple. The above explanation must be considered as a brief sketch of definition in order to give the reader a first approach to them. Further interesting considerations could be found in (Galton, 1995; Galton, 2000).

It is usual to assume that properties are *homogeneous* which means that if a property holds in an interval then it holds in each part of the interval. For example, if we know that “an object had a color c during the whole week” it was the case also in each day of that week and each minute of those days and so on. Instead, events are assumed not to be homogeneous. If an event occurs during an interval it is supposed not to occur as such in any part of that interval. It is possible that another instance of the same type of event occurs but not exactly the previous event instance, which is unique.

A sketch of event classification was brought in (Allen and Ferguson, 1994) where they were grouped depending on how predictable they are. Events are classified into *triggered*, *definite* and *spontaneous*. The first group are events provoked by the system under formalization and its consequences are supposed to be known as in “when the liquid achieved the critical level the valve closed”. Definite events are not provoked by the system but are known by it and could be predicted like in “sun rise here between 6:00 AM and 8:00 AM”. Spontaneous events are unexpected and the system could not predict where and when they could happen, e.g. “an energy cut”.

Actions are a key concept in the formalization of an autonomous system. They provide a way to formalize how a system could interact with its environment. As was said above, actions typically produce events and in that way play a key role in a dynamic environment. They are usually attached to *agents* in a broad sense, e.g. persons, robots, machines and other autonomous or semi-autonomous devices. The reader is invited to see (Goldman, 1970) for further analysis on the many aspects involved in the analysis of actions.

Another word that usually appears in the bibliography is that of *processes* which denotes repetition as “eating an apple”, “travelling from one city to another” and “writing a book”. Some authors describe them as a “state of change” as a way to differentiate

them from events which could be defined as a “change of state” (Galton, 1995). If they can be considered as primitive objects in a theory of change or not is still a matter of debate. Allen (Allen, 1984) assumed they must be considered from the very beginning. He characterized processes as those occurring at least in a part of an interval but not necessarily in all the interval. These assumptions are criticized in (Galton, 1990). In general there is no consensus about what sort of concepts this word really involves and some researchers prefer not to include them at the same level as the aforementioned notions (Van Benthem, 1991).

As a way to sketch a picture of how these concepts interact with each other we could consider the phrase “He erased the whiteboard during the class”. It denotes the repetition of the action “move the arm with the rubber in hand” which causes the event of “the rubber moving from a place A to B” changing the position of the rubber from being in A to being in B and also erases the ink in the whiteboard in between A and B. This causes the world continuously passing through a succession of states where the position of the arm, the rubber and the surface of the whiteboard are changing their properties. Naturally this is an oversimplified description of the usual state of affairs in such scenarios with the only intention of putting together all the aforementioned concepts.

2.3. WHAT IS CHANGE ?

The literature offers two main ways to talk about change and make temporal references. One is by using absolute time references like “He was born on the 28th of september”. Other kind of references often do not make explicit mention of chronological time like in “His birthday is next month”, “I will visit you” and “I have been looking for the bus since I arrived”. In these last examples, time is mentioned as constructions relative to the notion of *present*. This is not to say that each kind of temporal references cannot be recreated in the other approach but instead that they are favoured in each case.

The first case is more akin to what is called the Newtonian paradigm, later also adopted by B. Russell and W. Quine, where time is conceived as an unbounded line of instants. Time is conceived to have existence from the very beginning and the concepts

of states and change are derived from it. First order logic is usually adopted as the tool to handle temporal references of this kind.

The other conception of time relies heavily on the notion of change, which is directly associated to events. They are assumed to exist from the very beginning and temporal concepts are built from this foundation. A new class of temporal logics (Prior, 1967) based on this conception of time where references are relative to the events occurred and their relative order were offered by the middle of this century. Because of its adequacy to represent the kind of temporal notions used in natural language these logics became frequently used by philosophers and linguists.

Historically these conceptions have been considered as competitors originating a debate lasting decades since Quine's and Prior's work. As the reader will see in the following sections it is still unclear if one must be preferred to the other. There is some evidence to think they will continue their coexistence for a long time. The philosophical roots of their divergences on what must be the basis in a theory of change could be further explored in (Haack, 1978). Their consequences for artificial intelligence are better explained in (Galton, 1995). However for the computer science community it is useful to see them as complementary proposals with virtues and drawbacks and the basis for different tools to be applied in usually disjoint sets of problems.

EXAMPLE 1. Having two times i_1 and i_2 and two events associated with each one we could say which occurred before, if not simultaneously (see figure 1).

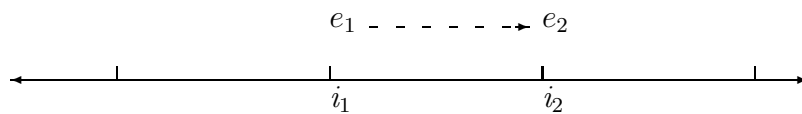


Figure 1. Deriving event order from instants.

△

EXAMPLE 2. Two states of the world associated with two different instants are said to be different if the first has a property which is not present in the second one. Given the situation represented in figure 2 we say there was a change between i_1 and i_2 and

the world evolved from a state S_{i_1} to another S_{i_2} . Because there was a change between i_1 and i_2 we could suppose that an event occurred.



Figure 2. Discovering a change.

△

In this proposal, change is not directly encoded but inferred as a byproduct of time. Temporal references are usually numeric and it is easy to represent quantitative temporal relations but also qualitative relations are possible, e.g. if an instant is before another or if two periods have something in common. A state of the world is conceived as a blackboard with an infinite set of labels to which information is attached. In this sense information could be said to be *referentially neutral*, in the sense it is allowed to be used without care of its relative position with the “present”. Some subtleties about referential neutrality are considered in (Rescher and Urquart, 1971).

In the Leibnizian paradigm, change is considered the fundamental concept and the concept of time must be built from it. In this case from an ordered succession of events the precedence of two moments of time can be inferred (see figure 3).

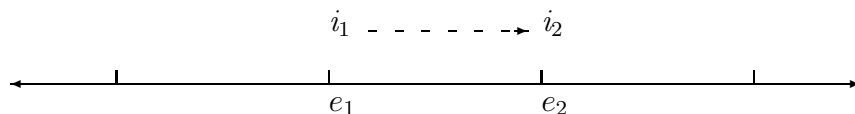


Figure 3. Deriving the order of instants from events.

The usual relations to be used in this framework are *simultaneity* and *precedence* although others can be also useful such as “to be between two given events”. In this case also occurrence is usually considered instantaneous and the structure is assumed to be unbounded and continuous. Durative events could also be considered (Allen, 1984; Galton, 1987; Augusto, 1998). Change is

represented directly in this approach and not as a by-product of comparing the knowledge in two states of the world.

3. Time specialists

This section deals with those proposals offering systems formalizing time specialists in which to represent and use some kind of temporal knowledge. Because the scope of artificial intelligence is still today subject to debate the process of delimiting the material to be included here is not a trivial one. Proposals will be cited as long as they were published in technical sources directly related to AI. It is worth mentioning that the amount of space is not proportional to importance as the relative strengths and weaknesses of most proposals are still a matter of study.

3.1. A LOGIC OF INTERVALS

Some milestone works in temporal reasoning were Bruce's program *chronos* and Kahn's and Gorry's time specialist (Bruce, 1972; Kahn and Gorry, 1977). Both pursued the goal of having programs with some kind of ability to understand and process temporal references. *Chronos* is a question-answering program intended to provide some natural language support to another system while Kahn's work focuses on the problem of organizing and checking consistency of temporal knowledge.

The beginning of the following decade provided a new proposal that proved also to be one of the most influential in the area since then. Allen's work started to provide a more precise framework to solve the same kind of works as his predecessors. A *temporal logic of intervals*, *TLI*, was suggested in (Allen, 1983) that was based on the notion of *interval* and considered thirteen primitive relations in them. These relations are the following seven relations and their inverses which are obtained interchanging arguments:

1. *Before*(i_1, i_2): the end of i_1 is previous to the beginning of i_2
2. *Meets*(i_1, i_2): i_2 begins exactly when i_1 finishes
3. *Overlap*(i_1, i_2): i_1 starts before i_2 and i_1 finishes before i_2

4. *Starts*(i_1, i_2): i_1 starts simultaneously with i_2 but it finishes sooner
5. *During*(i_1, i_2): i_1 starts after and ends before i_2
6. *Finishes*(i_1, i_2): i_1 starts later than i_2 but they finishes at the same time
7. *Equal*(i_1, i_2): both are the same interval

All these relations are axiomatizable in *TLI* (Allen and Ferguson, 1994). There are several ways to do it depending on which relation is assumed as the primitive one (Allen and Hayes, 1989). These primitive relations were proposed previously by Hamblin (Hamblin, 1972) but it was Allen's work that made them one of the most popular ways of representing and using temporal knowledge in AI. This step was continued in (Allen and Koomen, 1983; Allen, 1984) where it is shown how to use these temporal concepts to represent knowledge about natural language processing and other useful issues for the AI community such as modelling beliefs, intentions and plans. Some people reject the hypothesis that time must be viewed as interval-based. Some part of Allen's work was devoted to defending his view on this assumption (Allen and Hayes, 1985; Allen and Hayes, 1989; Allen, 1991; Allen, 1991; Allen and Ferguson, 1994). Recently, this logic was used as a basis for defining a planning system in a cooperative multi-agent framework (Ferguson and Allen, 1994; Ferguson, 1995).

To summarize, Allen implicitly offers a Many-Sorted predicate calculus logic with an interval-based ontology which is used to allow the representation of properties, events and processes. A linear temporal structure is assumed. Other features must be set by the programmer once the application is known. There is neither a commitment to a discrete, dense or continuous, nor to a bounded or unbounded temporal structure.

In (Allen, 1983) a transitivity table was presented showing how to infer temporal relations between intervals i and k from our knowledge about i and j plus our knowledge about j and k . For example from $Starts(i, j) \wedge Overlaps(j, k)$ we could infer it must be the case that $Before(i, k) \vee Overlaps(i, k) \vee Meets(i, k)$. Sometimes we could infer exactly one relation (as with

$During(i, j) \wedge Before(j, k)$) but sometimes nothing could be inferred by this way (as when $Before(i, j) \wedge Before(k, j)$).

In *TLI* knowledge associated with an interval can be a *property*, an *event* or a *process*. Properties are assumed homogeneous, but events are not. Actions are considered a special sort of events, those performed by agents. Processes are defined as an intermediate notion between properties and events. They must not be true over the whole associated interval but they must be true over some part of it.

The first clues regarding the implementation of *TLI* were given in (Allen, 1983) where a graph-based algorithm to reason about intervals is proposed. Intervals are attached to the nodes where an arc denotes the existence of relations between two particular intervals. The relations between them are made explicit by labeling the arcs. Everytime a new relation between intervals is added all the consequences are computed. This means calculating the transitive closure of all the relations. This process is expensive and a substantial part of the literature was devoted to proposing alternative ways of making this process as well as to detecting subclasses of the general problem where better algorithms can be found. In (Allen, 1983) it is suggested to use the *Reference Intervals* technique as suggested in (Kahn and Gorry, 1977) for the task of getting new information. The problem of consistently adding new information is explored in (Davis and Carnes, 1991; Dorn, 1992; Gerevini and Schubert, 1993; Golumbic and Shamir, 1992; Nebel and Bürckert, 1995).

In (Freksa, 1992) the basic relations between intervals used by Allen are extended by allowing some incompleteness in the knowledge about the interval boundaries. This new way to do reference time is called *semi-intervals*. The author also extends the transitivity table to the new set of 29 relations. To consider semi-intervals considerably enlarges the set of problems that can be represented but also the uncertainty of the information stored in the knowledge base.

More works related to the ontology assumed by Allen are (Ladkin, 1986; Ladkin, 1987; Ladkin and Maddux, 1988; Ladkin and Maddux, 1992; Lin, 1994). For details about the underlying algebra for the temporal structure see (Ligozat, 1986; Ligozat and Bestougeff, 1989; Ligozat (a), 1990; Ligozat (b), 1990; Ligozat (c), 1990; Ligozat, 1991). A comparison between the basic assumptions

on Allen's proposal and some others proposals of the literature is done in (Hajnicz, 1987).

3.2. THE EVENT CALCULUS

This is a different approach proposed in the middle of the '80s by Kowalski and Sergot (Kowalski and Sergot, 1986) that lies on an event-based conception of time. As stated previously, this provides an approach directly based on the notion of change while time could be later associated with events.

Events are assumed as primitive objects in the ontology of the Event Calculus, *EC*. Emphasis is put on bringing the possibility of representing the events' effect as well as their properties and relations. There are two binary functions in its language directly related to time intervals: *after* and *before*. Both take an action and a property as arguments to denote the name of a period. For example, $after(E, Possess(Gabriela Book-1))$ represents the period when a person called *Gabriela* starts to possess a book denoted with *Book-1* after event *E*. The predicate $Holds(after(e,r))$ could be used to denote that a relation *r* holds for the period $after(e,r)$. For example, $Holds(after(E3, assigned-to(Gabriela Q)))$ expresses that *Gabriela* is assigned to the job *Q* after the event *E3*. It is assumed in *EC* that whenever $Holds(p)$ is true for a period *p* and *u* is the relation associated with *p*, then *p* is a maximal period of time where *u* holds. Another salient feature is the use of *negation as failure* as a way to express the negation of formulas. This means that a formula $\neg p$ is regarded as true if the system is unable to prove that *p* is true. The theory is also provided with a rule:

$$Holds(after(e,r)) \text{ if } Happens(e) \text{ and } Initiates(e,r)$$

$Initiates(e,r)$ and $Terminates(e,r)$ are useful predicates denoting when a relation *r* starts or finishes as a result of the occurrence of an event *e*. In (Sadri, 1987) the Event Calculus is compared against Allen's *TLI* proposal and the system for temporal deductive databases made in (Lee et al., 1985). Several proposals for temporal information representation are compared in (Kowalski, 1992) from the perspective of database dynamics.

A main characteristic of *EC* is that it was one of the first implemented systems, offering its definition through a Prolog program

(Sadri, 1987). Nowadays, *EC* continues to attract the researchers of the field (Shanahan, 1990; Borillo and Gaume, 1990; Proveti, 1994; Van Belleghem et al., 1995; Chitaro and Montanari, 1996; Cervesato et al. (e), 1998; Cervesato et al. (d), 1998) for some attempts to improve the proposal. A simpler but still useful variant of the Event Calculus is presented in (Sadri and Kowalski, 1995).

3.3. A TIME MAP MANAGER

An alternative system for handling temporal references was offered by Dean as the *Time Map Manager*, *TMM*, (Dean, 1985; Dean and Mc Dermott, 1987; Dean and Boddy, 1988; Dean, 1989). The system was initially developed as a LISP program but later developments define it in a logic program style, making easy the comparison with other proposals on this area to be mentioned later. The main goal motivating the proposal is to provide an efficient way to do temporal reasoning in order to solve planning and scheduling problems.

The main structure in which to represent time is the so-called *Time Map*. A set of programs to handle this temporal information defines the “Map Manager”. The Time Map has a sequence of facts associated to time periods, a set of precedence relations between these facts and the rest of the temporal knowledge base. The time map manager is allowed to do usual inferences on the stored temporal knowledge but it is also possible to do causal reasoning. Basic knowledge is stored through *facts* like `walking(Robot)`. This information is attached to a temporal interval through a predicate `holds(t1,t2,fact)` which situates the truth value of `fact` between two time points, possibly coincident. Two order relations help to define the time map: `precedes(t1,t2)` and `coincident(t1,t2)`, denoting precedence or coincidence between two time points. The predicate `distance(t1,t2,bounds)` denotes that `t1` and `t2` are two real numbers defining the boundaries of the interval. A temporal constant ∞ is used to denote lack of knowledge regarding the beginning or end of an interval. Persistence of the property `P` to the future or the past of the point `t1` is represented through `persistf(t1,P)` and `persistb(t1,P)`. When a conflict arises consistency is maintained through “Persistence Clipping” by giving priority to the incoming information.

TMM also allows one to explore hypothetical situations, some sort of abductive reasoning and a way of monitoring the validity of conditional predictions. In (Dean, 1989) it is explained how to handle big time maps using a hierarchy of events in a similar way as done in (Sacerdoti, 1977; Kahn and Gorry, 1977; Allen, 1983; Song and Cohen, 1991; Davis and Carnes, 1991). An extension to deal with cases where events are ambiguously ordered is proposed in (Schrag et al., 1992). The proposal to deal with persistency of facts is appropriately extended.

TMM provides other ways to represent incomplete knowledge other than using ∞ to say it is not known exactly where an interval starts or ends. There is also the possibility of saying that the beginning and end of an interval are within a specified range. $\text{elt}(Pt_1, [lower, high], Pt_2)$ denotes that between two points Pt_1 and Pt_2 , there exists a distance ranging between $[lower, \dots, high]$. $[0, +\infty]$ indicates that it is just known there is a precedence relation.

3.4. OTHER APPROACHES

The number of proposals for temporal reasoning forced us to consider those that have motivated a deeper research. However, we will dedicate some space to mention alternative proposals.

Bacchus (Bacchus et al., 1991) presented a temporal logic which is aimed to be general enough to subsume many of the known proposals of AI in the '80s. The temporal logic is presented by its authors as a many-sorted first order logic without reification.

Trudel (Trudel, 1990) developed a first order logic for temporal reasoning based on a continuous temporal structure. Its syntax and semantics are formally specified and some applications are suggested. One of the main topics of the proposal is the consideration of what Trudel termed "the interval representation problem" (Trudel (a), 1991). By this phrase he means that usually assertions are associated with intervals in the literature, but in his conviction, what could be an interval is entirely dependent on its constituent points. See also (Trudel (b), 1991; Goodwin and Trudel (a), 1991; Goodwin et al.(a), 1991; Goodwin et al.(c), 1992; Goodwin et al.(b), 1992; Ho and Trudel, 1994) for implementational and persistence-related issues.

One of the most recent proposals for temporal reasoning includes both instants and intervals in its ontology (Vila, 1994; Vila and Reichgelt, 1993). Vila defines a many-sorted temporal logic with an alternative formulation of reification. The temporal structure is assumed to be dense and a solution to the *dividing instant problem* is proposed. He also provides an analysis of expressiveness between his proposal and those related in the literature by using the semantics of his logic as a bridge. He also states (Vila and Reichgelt, 1993) that his token reification proposal improves previous attempts in the literature.

4. Modal based temporal reasoning

4.1. A MODAL LOGIC OF INTERVALS

A logic which combines modalities and time was proposed in (Halpern and Shoham, 1986) and (Halpern and Shoham, 1991). The logic is an extension of a propositional logic by including temporal operators. Then, if φ is a proposition and R^{-1} the inverse relation to R the meaning of the following formulas is related to a *current interval* \mathcal{N} as follows,

$\langle A \rangle \varphi$ is read as *after* (it corresponds to $Meet(\mathcal{N}, \varphi)$ in *TLI*)

$\langle B \rangle \varphi$ is read as *begins* (it corresponds to $Start^{-1}(\mathcal{N}, \varphi)$ in *TLI*)

$\langle E \rangle \varphi$ is read as *ends* (it corresponds to $Finishes^{-1}(\mathcal{N}, \varphi)$ in *TLI*)

$\langle \overline{A} \rangle \varphi$ is *after*⁻¹ (it corresponds to $Meet^{-1}(\mathcal{N}, \varphi)$ in *TLI*)

$\langle \overline{B} \rangle \varphi$ is *begins*⁻¹ (it corresponds to $Starts(\mathcal{N}, \varphi)$ in *TLI*)

$\langle \overline{E} \rangle \varphi$ is *ends*⁻¹ (it corresponds to $Finishes(\mathcal{N}, \varphi)$ in *TLI*)

For example, $\langle A \rangle \varphi$ is interpreted as *possibly φ after the current interval*. Using the above mentioned operators it is possible to define the other possible relations over intervals considered in *TLI*. Also could be defined their duals $[X]\varphi =_{def} \neg \langle X \rangle \neg \varphi$ expressing that the relation holds for every possible current interval \mathcal{N} . Intervals, $\langle s, t \rangle$, are assumed as all points between s and t such that $s \leq t$, begin and end included. Points are denoted as $\langle s, s \rangle$.

Formal syntax and semantics are given but, leave unspecified what the main features of the temporal structure could be. For example, it is left open the possibility to use this framework together with a structure that is discrete or continuous, linear or branching and so on. The authors supply this fact providing clues about how to characterize these possibilities through formulas in the logic. It is shown how to translate the logic to its first-order version. They also investigate how some possible assumptions over the temporal structure can affect validity of formulas in each case.

4.2. EVENT LOGIC

The roots of this proposal has as an important milestone the *Logic of Aspect* (Galton, 1984) which provides the philosophical motivations and foundation of an event-based logic. In (Galton, 1984) a series of aspectual problems are analyzed centering the attention in the perfective and imperfective aspects in narratives. The author's view on the subject is contrasted against other theories like Prior's. More philosophical considerations such as causation, intention, and possibility are considered.

In (Galton, 1987) an *Event Logic* and several variations are formally defined and investigated. Event Logic is an extension of modal temporal logic retaining Prior's operators P, sometimes in the past, and F, sometimes in the future. The extension is made guided by the proposal described in (Galton, 1984). A set of *aspect operators*: *Perf*, *Prog* and *Pros* are considered where

1. *PerfE* is true now if some occurrence of the event denoted by *E* is wholly in the past
2. *ProgE* is true now if some occurrence of the event denoted by *E* is partly in the past, partly present and partly future
3. *ProsE* is true now if some occurrence of the event denoted by *E* is wholly in the future

A set of symbols denoting *event radicals* is also included which are intended to denote event-types. Time is conceived as an irreflexive and transitive line. Some classes of events are distinguished and some theories based on each different class defined both in syntax and semantics. The cases of *punctual*, *durative* and *once-only*

classes of events are considered leading in turn to *Punctual Event Logic*, *Once-only Event Logic* and *Durative Event Logic*. Soundness and completeness results for each class of logic are given. Also an analysis is made on how to represent explicit temporal references and how to decompose some events in their constituent internal states.

4.3. OTHER APPROACHES

Reichgelt (Reichgelt, 1989) has proposed a temporal modal logic, *TM*, that besides the usual modal operators P for “sometimes in the past”, F for “sometimes in the future”, H for “always in the past” and G for “always in the future”, allows references to specific time points. The temporal structure has a special individual n designating the present or *now*. This allows one to refer to time points in addition to intervals in the proposal. A function *ind* is used to specify the individuals assumed to exist in each point of the temporal structure which defines a dynamic ontology. *TM* is compared with regard to other logics of the literature and also with respect to five criteria which are intended to capture some of the essential features of temporal logics. These points are efficiency of implementation, naturalness of expression, the possibility of representing both precise and imprecise knowledge, the possibility of combining it with logics and the capability of representing changing ontologies.

An extension to *EC* was presented (Cervesato et al., 1994; Cervesato et al., 1995; Cervesato et al. (a), 1997) which provides a way to deal with incomplete information about event ordering. One of the problems addressed is that of deriving the *maximal validity intervals* where some properties affected by a given set of events holds. Two solutions to the problem are considered, each one related to an extension of the *EC*. One extension leads to a Skeptical Event Calculus, *SKEC*, and the other to a Credulous Event Calculus, *CREC*. Given some uncertainty regarding several possible orders on the events’ occurrence *SKEC* gives just maximal time intervals true in all possible orders while *CREC* gives all maximal time intervals where a given fact is considered true at least in one possible order. This naturally leads to the consideration of necessity and possibility which is the basic conceptual extension performed over the traditional *EC*.

This proposal is extended in (Cervesato et al. (b), 1997) by considering a wide range of modal event calculi and studying their relative expressiveness and complexity. In (Cervesato et al. (c), 1997) some limitations on the expressiveness of *EC* are removed allowing preconditions to be used to indicate when the occurrence of an event starts or finishes an interval where a property holds. Also preconditions are allowed to be combined with modal operators.

In (Leasure, 1996) a modal approach is offered extending the proposal of (Lifschitz and Rabinov, 1989) to handle the frame problem allowing one also to cope with the ramification problem, the qualification problem and concurrent actions. The proposal is based in the modal logic Z (Brown, 1991) which provides a consistency-based approach to non-monotonic reasoning. It is an extension of first-order logic and S5 modal logic (Chellas, 1980) including the necessity operator, \Box , quantification and equality. It also provides the possibility to quantify over objects or propositions and in that sense it is a restricted form of second order logic.

In Z *defaults* are represented by $(A \wedge \langle k \rangle B) \rightarrow C$ which is interpreted as “if *A* holds and it is possible (or consistent) to assume *B*, then conclude *C*” allowing non-monotonicity in the theory. In (Leasure, 1996) this sort of default is used in combination with axioms considering ramifications and concurrent actions. A strategy of prioritization of defaults is used giving preference to minimization of miracles over occurrences and occurrences over inertia.

L_nint, (Guzmán and Rossi, 1995; Guzmán et al., 1995), is a modal logic unifying different aspects for modeling time. In this proposal discrete as well as continuous representations are allowed, points and intervals and also absolute and relative time references. L_nint’s syntax and semantics have been formally specified which makes attractive this proposal for further studies about its properties and adequacy.

5. Temporal nonmonotonic reasoning

It was not until the late '70s that some AI researchers started to realize that some mental processes seemed to be in disagreement with their representation using classical logic. One of the

problems discovered involved a property of classical logic called *monotonicity*. It states that whenever we add theorems to the logic the set of inferred truths cannot decrease. Logic-based research in AI discovered that human behaviour seems not to behave in that way, looking attractive instead the idea to model it as a system with the non-monotonicity property. That is to say, most of the researchers think that sometimes new information leads to a decrease in the consequences of a theory. The literature abounds in examples where new information arriving to the systems force us to give up one, like in the famous scenario where we do not believe anymore that a given bird flies after being informed it is a penguin. Researchers in non-monotonic systems were mostly not involved with temporal reasoning until the *Yale Shooting Problem* was formulated by Hanks and McDermott (Hanks and McDermott, 1986; Hanks and McDermott, 1987). This problem concerns reasoning about the effects of shooting a loaded weapon to a vital center of a person. Simple as its formulation is, it provoked a huge amount of research. Now the literature has several proposals about how to deal with it and some of its useful variations (Sandewall, 1993; Sandewall, 1994). This section is intended to bring a brief account about this set of proposals providing temporal reasoning capabilities embedded in non-monotonic systems.

5.1. SHOHAM'S NON-MONOTONIC TEMPORAL LOGIC

Shoham defined a non-monotonic logic based on model preference (Shoham, 1985; Shoham (a), 1987; Shoham (b), 1987; Shoham (c), 1987; Shoham (a), 1988; Shoham (b), 1988; Shoham and McDermott, 1988). As a criterion to define a partial order between the models he uses the one called *Chronological Ignorance*. This criterion prefers those models where a fact holds as late as possible. It is assumed that the temporal structure is isomorphic to the set of integers. The *Logic of Chronological Ignorance*, *CI*, extends his previous proposal for a Temporal Logic of Intervals given in (Shoham (b), 1987). It is a modal logic based on the well-known *possible worlds* semantics of Kanger and Kripke where an interpretation is a set of parallel time lines. Each world describes a possible event succession and a possible history of the universe. In different worlds facts can have different values over the same interval. Shoham also offers a theory of causal reasoning (Shoham, 1990) within the

framework of his modal temporal logic. See (Galton, 1991) for comments on Shoham's proposal, specially regarding the use of modal operators and the assumptions underlying the causal theory. (Vila and Reichgelt, 1993) criticize the way Shoham describes his proposal saying he does not define a truly reified logic as claimed. In (Morgenstern and Stein, 1988; Sandewall, 1994; Fusaoka, 1996) some alternative strategies for model preference are offered.

5.2. EXTENDED SITUATION CALCULUS

Since the very beginning of the AI project the *Situational Calculus* (McCarthy and Hayes, 1969) was used as a language to represent knowledge, including some proposals about change. The language of the Situation Calculus was widely used but, having no way to represent time explicitly later studies in temporal reasoning and planning (see (Allen, 1991) for example) were showing some convenience in representing time explicitly to easily tackle some problems as:

1. the possibility of allowing easy reference to dates
2. to reason on a continuous ontology
3. to represent concurrent actions
4. a more efficient treatment of the frame problem
5. the representation of complex, i.e. non primitive, events
6. the representation of multiple agents

Most of these features are considered in (Pinto, 1994) where the Situation Calculus is extended with an explicit time line. Situational calculus is usually presented as a second order, many-sorted language with equality, although it can be reformulated as a first order language (Pinto, 1994). There are four classes of objects distinguished from the beginning in the theory: actions, situations, fluents and other domain objects. The application could lead one to consider more types.

One of the main characteristics of the theory is that it allows us to represent and reason about *situations*. See (Allen, 1991) for an analysis of the difference between the concepts of "situation" and

“state of the world”. It is assumed in the theory that different actions necessarily lead to different situations and this is represented using a branching temporal structure. There exists in the theory a distinguished *initial situation*. Other situations are obtained as the result of an action sequence applied to that initial situation. Each property that is verified in some situation is termed a *fluent* which denotes the possibility of “flow”, or change, of its truth value through the different situations. One distinguished fluent in the logic is $Result(p, a, s)$, which is a function producing the situation resulting from a person p doing an action a in the situation s . Sorts \mathcal{A} , \mathcal{S} and \mathcal{F} are considered to represent the set of actions, situations and fluents respectively. Important functions and relations in the theory are $do : \mathcal{A} \times \mathcal{S} \rightarrow \mathcal{S}$, $<\subseteq \mathcal{S} \times \mathcal{S}$, $Poss \subseteq \mathcal{A} \times \mathcal{S}$ and $holds \subseteq \mathcal{F} \times \mathcal{S}$ denoting respectively actions, temporal order between situations, possible actions and fluents.

Some situations could be distinguished as *actual*, which represent the situations arising in the actual world. An important predicate for representing actions is

$$Poss(A, s) \supset \pi_A^j(s)$$

where A is an action, s a situation and $\pi_A^j(s)$ a state formula termed *simple* because it satisfies some restrictions. These restrictions are: to be a first order formula, not to use more than one state-type variable and not to mention either the predicate $Poss$ or the order relations $<$ and \leq . All necessary conditions for the execution of an action are supposed to be known. There exists an axiom for each action A of type $Poss(A, s) \equiv \pi_A^1(s) \vee \dots \vee \pi_A^n(s)$ where $\pi_A^i(s)$; $i = 1, \dots, n$ is considered if and only if there is a precondition action axiom of the form $Poss(A, s) \supset \pi_A^i(s)$.

The predicate $holds$ is used to indicate a given fluent f is true in a situation s through $holds(f, s)$. In this way fluents are objects which could be referred to in the language, technically they are said to be *reified*. The predicate $occurs(e, s)$ is used to indicate the relationship between types of events and situations. A predicate *actual* defined over situations, is used to indicate when a situation is located on that branch describing the real world evolution.

Each actual situation after S_0 is related to a unique action that occurred and which leads to s . There are more interesting features in the extension of (Pinto, 1994) to the situation Calculus as the consideration of *concurrent* and *complex*, i.e. non-primitive,

actions. Another feature is that an implementation is provided (Pinto and Reiter, 1993) ending some tradition to consider situation calculus only as a theoretical proposal allowing one to talk about change. The implementation is given together with a soundness result for the axiomatization of the theory, relative to Clark's completion (Clark, 1978).

More work has been done in connection with this proposal. For example, in (Miller, 1996) an extension considering the reals as the temporal structure is considered providing a basis to solve problems related to continuous change. In the last few years a lot of work around situational calculus and its capability to represent intelligent behaviour has been made in the Cognitive Robotics Research Group at University of Toronto. One entry point for the reader is (Lespérance et al., 1999).

5.3. FEATURES AND FLUENTS

Sandewall (Sandewall, 1993; Sandewall, 1994) had offered a framework to compare different proposals to represent and reason in dynamic worlds. The notion of an *inhabited dynamical system* is introduced which is defined over the notions of *world* and *ego*. Given an initial world state, a world can evolve through successive *developments* alternating moves with the ego. A taxonomy of ontological characteristics is introduced reflecting different classes of problems that could arise in dynamical problems. Each of the sets of characteristics is represented by one *scenario*. Some of the most simple classes of scenarios are called *chronicles*. Some methods to reason about chronicles and scenarios are delineated and then related to some subset of ontological characteristics.

The *trajectory semantics* is introduced based on the set of features influenced by an action applied to a state of the world. Using this semantics the set of intended models for a chronicle are defined and this in turn allows the comparison between different reasoning methods when applied to a given scenario. A *Discrete Feature Logic* is defined using time points in a discrete and branching time structure. This logic combined with the trajectory semantics is used to describe some chronicles that correspond with well-known problems of the literature or some variations of them. *Chronicle Completion* is the construction of the smallest set of intended models in a chronicle from the set of classical models. It provides

the non-monotonic layer to the theory and because it is based on model preference it is a bridge between this proposal and previous works in the literature. It is also intended to be a generalization of the idea of model selection as usually defined in that literature. These methods are analyzed as particular cases of the general framework proposed and an *assessment* of the various techniques regarding the scenarios previously introduced is presented. The author explores several strategies to cope with the various problems offered by the different scenarios. Sometimes the scenario is reformulated but usually different entailments are analyzed and also the option of changing the base logic is considered. Several interesting classes of actions are considered, outstandingly, actions taking different durations to complete and composite actions in the forms of sequences, loops or conditional expressions.

5.4. DEFEASIBLE TEMPORAL REASONING

Special kinds of “non monotonic reasoning systems” are those called “argumentation systems” (Chesñevar et al., 1999). These systems characterize the skill that allows us to reason about a changing world where available information is incomplete or little reliable. When new information is available, new reasons to obtain further conclusions or better reasons to sustain previous conclusions can be considered. But it could happen that some conclusions lose support. Through this inference dynamic, argumentation systems provides the ability to change conclusions according to the new information that arrives in the system.

The conclusions obtained by the system are “justified” through a set of “arguments” of the form $\langle A, C \rangle$ supporting their consideration. In each argument $\langle A, C \rangle$ the element A denotes a set of *defeasible rules* of the form $\alpha \succ \beta$. These defeasible rules are read as *reasons to accept α are reasons to accept β* . They provide a way to represent weaker knowledge than that usually expressed through material implication. While classical implication could be seen as representing secure knowledge as mathematical theorems and such eternal truths, defeasible rules are meant to represent weaker knowledge. That kind of knowledge abounds in daily reasoning. It is tentative and not always applicable as the non-defeasible one. In addition, an argument could be seen as a “defeasible proof” for a conclusion. The knowledge of new facts can lead one to prefer a

conclusion instead of a previous one, or to consider that a previous inference is no longer correct. In particular an argument could exist for a conclusion C and a “counter-argument”, contradicting in some way the argument for C . If an atemporal language is used this contradiction is direct as when we have $\langle A_1, C \rangle$ and $\langle A_2, \neg C \rangle$. An argument is a justification for a conclusion C if it is better than any other counter-argument for C . To establish the preference of an argument over the others the definition of preference criteria is required. Several preference methods are possible. One that is widely used is “specificity” which means that more specific information, i.e. better informed arguments, are preferred. It is important to highlight that argumentation systems emphasize the role of justification of inferences and the dialectical process related to reasoning activities.

Some systems had been developed to embed temporal reasoning in defeasible reasoning. In (Ferguson and Allen, 1994) an argumentation system was proposed based on the notion of *interval* and in (Augusto and Simari, 1994; Augusto and Simari, 1999) one based on *instants*. The work done in (Augusto, 1998; Augusto and Simari, 2001) is an attempt to subsume and enhance both proposals. A temporal argumentation system is defined allowing both instant and interval-based temporal references. This work includes the proposal of a temporal logic, an extension to the argumentation system using this language and the consideration of problems arising from their interaction. The logic is based on a many-sorted language with types and equality. Because of the specific interest in providing means to solve temporal reasoning problems this language has as pre-established sorts those of properties, events, actions and temporal references. The temporal structure corresponds to an unbounded and discrete time line. Because a temporal language is used, a different way to define the notion of *arguments in conflict* is considered. Two arguments $\langle A_1, C \rangle$ and $\langle A_2, \neg C \rangle$ are in conflict with each other if the temporal reference of C has some intersection with that of $\neg C$ when the respective temporal references are seen as sets.

5.5. OTHER APPROACHES

Nute had offered an answer to the Yale Shooting Problem in (Nute, 1989; Nute, 1990) through his logic called *DL* (Defeasible Logic).

This proposal could be easily implemented as an extension to Prolog. It uses two kind of rules to encode general knowledge. The usual kind of rules based on material implication are called *absolutes* and the new ones are called *defeasibles*. There are special mechanisms associated with this kind of rules allowing their comparison and selection based on syntactical grounds. His work was influential on the previously considered argumentation systems.

Lifschitz (Lifschitz, 1987) proposed a formalization for reasoning with actions in the framework of the situation calculus (McCarthy and Hayes, 1969). He offered some improvements to classical circumscription (McCarthy, 1980; McCarthy, 1986) to solve the frame problem when reasoning in such context (see also the solutions offered in (Schubert, 1990; Schubert, 1994)). He also offered evidence of the inadequacy of Shoham's proposal for handling temporal projection problems. A many-sorted logic is assumed, with a separate sort for actions, under the *unique names assumption*: if ground terms cannot be proved unequal they must be assumed equal. The proposal consists in a series of considerations about the adequacy of applying circumscription to problems involving temporal and change-based reasoning exemplifying it on the Yale Shooting Problem problem.

Morgenstern and Stein (Morgenstern and Stein, 1988) presented a general theory of non-monotonic temporal reasoning. The emphasis is made in problems of temporal projection and how to get explanations associated with an unexpected result. The motivations are the authors' disapproval of previous forward-reasoning based proposals (Shoham (b), 1987; Kautz, 1986). They also reject Lifschitz's proposal as he circumscribes over "types of actions" and hence it is limited to Situational Calculus-like theories where the set of actions is totally known. They propose a first-order non-monotonic temporal logic based on the notions of actions and events that *only happen if motivated*. Time is assumed to be isomorphic to integers and actions take a unit of time. Non-monotonicity is achieved through model preference, in this case models "where the least amount of unexpected actions and events occur". Persistency rules explicitly indicate the non occurrence of some events. The use of the system is exemplified in cases where it is needed to reason both forward and backward. Causality rules are used to obtain *explanations* about why the world did not evolve in the expected way.

A different approach to temporal reasoning is offered in (Goody and Galton, 1997) through a system called *Transition Calculus*. This is intended to be a high-level language to represent and use knowledge about actions and change. Transitions are conceived as state-change producers. For example, $\ll S_1, S_2 \gg$ denotes a *transition type* leading to a change from state S_1 to S_2 . There is also proposed an *action language*. Some examples are offered showing how to use it in solving well-known problems of the literature. Also a transition-based planning system is offered based on the STRIPS assumption (Fikes and Nilson, 1971). A *penalty points* system is introduced as a way to prefer some transition sequences over others. This strategy minimizes unexplained state changes. This criterion leads the system to draw the same conclusions as in (Sandewall, 1994) for the set of benchmark problems there proposed. A very short and efficient implementation has been made in Prolog. Also an explicit-time semantics could be associated with the proposal: $\ll S_1, S_2 \gg$ is assumed to have a transition interval when the event or action takes place between those states associated with S_1 and S_2 .

6. Conclusions

The literature offers us a plethora of proposals to provide temporal reasoning capabilities. We restricted ourselves in this article to consider the main logic-based proposals. Works were grouped depending on the language they use. A first group of proposals emphasizing temporal reasoning using logics more akin to the first-order approach were presented in section 3. Systems using modal logics were grouped in section 4. Non-monotonic hybrid systems were presented in section 5.

Undoubtedly the proposal that has received most attention in the literature is Hamblin's and Allen's interval-based logics. However temporal reasoning has proved to be a quite elusive subject of study as there are many aspects to consider in its formalization. These aspects were described in section 2 where it was also mentioned that different groups of these basic assumptions can define equally valuable dynamic scenarios. Different proposals start from some set of temporal hypotheses defining the logic and its language according with the way time is conceived. An exception to this

being *TLI* where no particular temporal framework is assumed. It acts as a general proposal where some slots must be filled out at implementation time. The logic must be supplemented with axioms specifying the temporal structure to be and a solution to each set of particular problems associated with the task of reasoning in the chosen structure must be provided by the programmer. Other approaches assume a given temporal structure providing these solutions as part of the proposal. Logics described in section 3 emphasise the role of temporal information avoiding the addition of extra features. Most of them could be viewed as temporal specialists to be used in connection with other systems requiring temporal reasoning. Usually these systems provide, or suggest to use Prolog-based implementations because basically the proposals define first-order languages.

Modal based logics combine temporal or non-temporal modal operators with time references through intervals or events, sometimes extending non-modal temporal proposals. One find fewer implemented proposals within this group compared with the previous one. This may also reflect the lack of a Prolog-like standard in modal temporal logic programming. However, this could be improved as there is an increasing interest to fill this gap as can be seen in (Orgun and Ma, 1994).

Several non-monotonic temporal logics have been developed as an attempt to provide a formalization for rationality. This group of proposals provides different departing points regarding ontologies and languages as well as the way to provide non-monotonicity, both by syntactic and semantics means.

There are still several topics asking for further research. Ontology is still a matter of debate. Some proposals have been made for the main options but more discussion will offer more knowledge about the effects of the basic temporal assumptions of each theory. Language is also another aspect offering several options and still facing the half-century old controversy on the utility of either first-order or modal oriented options. Some works offer more integrated views on the subject (Galton, 1987; Bohlen et al., 1996) explaining how to use both kind of languages highlighting the best of each one. As regards implementation there are some offers, mainly based in Prolog or some of its ad hoc extensions. However there are also attempts to provide new programming languages based on temporal concepts through operator-based languages (Orgun and

Ma, 1994) which hopefully will increase the available tools to solve this class of problems effectively.

At the theoretical level there can be observed a lack of deep comparative works showing what is the relation between the various proposals as well as their strengths and weaknesses. The interested reader has just few works on this line. In (Sadri, 1987) the event calculus and Allen's Interval Logic are compared showing that they share several features. Event calculus is also compared with Situational Calculus in (Kowalski and Sadri, 1994; Miller, 1995). A core of both calculi is selected and rewritten through logic programs which allow one to prove their expressive equivalence. More work on several aspects of each proposal still remains to be done to get efficient and trustable tools. A good point to start would be to plan further in deep, systematic and detailed comparison works to make publicly available what we had until now and what is still needed to achieve.

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