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Circumstances and Processes

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ABSTRACT

Approaches to pragmatic reasoning in artificial intelligence traditionally have been based upon alternating sequences of instantaneous states and operators. This formulation has encountered difficulty in our attempts to represent activity in real-world task environments. In this paper, we offer an alternative framework based upon notions of circumstance and process, each of which holds or is in progress over an interval of time. Events mark the beginning and ending of each interval; instants represent constraints on event times. We illustrate our approach through definition of a process corresponding to a simple PUSH operator. We briefly discuss aspects of the resultant outlook on planning and pragmatic reasoning.

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Introduction

Reasoning about problems and their associated solution plans has always been a primary focus of artificial intelligence (AI) research. Initially, research on pragmatic reasoning concentrated on issues that arise from problems posed in puzzle-like task domains. Such problems include various water jug and blocks-world problems as well as the classic Tower of Hanoï, monkey and bananas, and missionaries and cannibals problems. Three properties of puzzle-like task domains have proved instrumental in determining the form and content of resultant theories of problem solving and pragmatic reasoning. The first is the single-agent property. By this property, the problem solver is the only active system; if the problem solver does not act, no change occurs in the task environment. The second is the well-modeled property. By this property, relevant aspects of any situation in the task environment can be completely and correctly represented by an agent as a finite set of propositions (or object-attribute-value triples). Furthermore, the effects of any action can be completely and reliably represented as a functional mapping between such sets of propositions. The third property is the time-invariance property. By this property, the length of time that is required to perform an action or that elapses between consecutive actions or the absolute time (i.e., date) at which an action is performed does not affect the outcome of any action or solution plan. This property is largely a consequence of the single-agent property.

These three properties led to theories of problem solving based upon the notion of problem space [8]. A problem space consists of a space of possible states, a set of operators, an initial state, and a goal space. A state is a set of propositions representing a momentary situation in the task environment; an operator is a representation of the preconditions and effects of an action. A solution plan is simply an allowable sequence of operators that transforms the initial state into a state of the goal space. Problem solving can be characterized as search for a sufficient sequence of operators, directed by applicable heuristics such as means-ends analysis.

We have interest not only in representing and solving problems but in reasoning about them and their solution plans as well. The situation calculus [5] was developed as a logical formalism for reasoning about problems and solutions framed within the problem space paradigm. Moore [7] extended the situation calculus to provide a possible-worlds semantics for notions of knowledge and belief as they apply to reasoning about actions and planning. Such approaches to pragmatic reasoning are state-based. They rely fundamentally upon representations of discrete sequences of momentary situations in the task environment. The element states are related not only sequentially but also as preconditions and effects of various operators. Predicates are introduced to describe significant properties of these sequences (or possible trees) of interrelated states. This approach is compatible with traditional definitions of temporal logic [9].

As AI research interest turns from puzzle-like to real-world task domains, the adequacy of state-based approaches to pragmatic reasoning must be questioned. The three properties of puzzle-like domains that justified the state-based outlook no longer apply. Real-world contexts involve multiple agents whose cooperation must be coordinated and competition resolved. One corollary of this change is elimination of the time-invariance property. The same plan executed at different times can have significantly different outcomes in real-world task domains. If one agent arrives too early to meet another, waiting and inefficiency are likely results; too late and apologies must be made. In competitive situations, a plan to deny an opponent satisfaction of a precondition for a necessary action must be completed prior to execution of that action. Time factors, both dates and durations, are major concerns in real-world planning contexts.

The importance of time is further indicated by failure of the well-modeled property in real-world contexts. For various reasons, an agent's representation of a real-world task environment is always inaccurate and incomplete. An agent must rely on information gathering for correction and completion during both planning and plan execution. The import of newly gathered information with respect to current plans depends critically on temporal factors: when did the new information hold, when was it obtained, and when are the actions it may affect planned to occur. For example, consider the impact that news of a winter storm may have upon one's travel plans for next week. If the storm occurred last week at the destination, the impact may be assumed to be minimal. If the storm is predicted to hit there tomorrow, a different assessment is necessary.

For reasons just discussed, recent interest in real-world task domains has produced a flurry of research focused on temporal representation and reasoning [1,12]. First attempts have been made to incorporate time into planning systems. DEVISER [11] represents a marriage of PERT concepts with AI planning technology. Time constraints can be placed on goal states; actions have associated bounds on duration; plans are represented in a standard network form. During planning, a window of allowable starting times is maintained for each action. Carbonell [3] and Wilensky [13] discuss related techniques for introducing temporal factors into competitive and everyday planning situations. McDermott [6] incorporates time into a state-based logic for reasoning about plans; he discusses associated difficulties and presents suggestions for implementation.

These initial attempts all represent state-based approaches to which time factors have been added. Below we outline an alternative formulation of planning and pragmatic reasoning based upon our notions of circumstance and process.

A New Framework

Our formulation reflects the view that activity in a real-world task environment is better represented as an interacting progression of constant and changing circumstances, each holding over an interval of time, than as a discrete sequence of complete, momentary states. A circumstance represents some aspect of the task environment, an object-attribute-value or relation among such entities, that holds (i.e., is true in the environment) over some interval of time. A CONSTANT circumstance represents an aspect that does not change over the associated time interval. A CHANGING circumstance represents that, and possibly how, some aspect varies during the interval over which the circumstance holds. Circumstances are similar to the notion of persistences that others have recently found valuable in formalizing pragmatic reasoning [2,6]. The state of the task environment at any point in time can be inferred from circumstances holding at that time. In our formulation, state is a derived concept and is not the basic representational element upon which pragmatic reasoning is based.

In addition to circumstances, there are processes, each in progress over some interval of time. Thus, at any point in time, there are a set of circumstances that hold and a set of processes in progress sufficient to imply a current state. Processes organize (more strongly, are reasons for or causes of) circumstances. As we shall see below, to describe a process in our framework is to specify a set of associated circumstances and to indicate when those circumstances hold relative to the interval over which the process is in progress.

Each circumstance and process has associated with it two events, a beginning and an ending. An event is an instantaneous occurrence corresponding to the beginning or ending of an interval over which a circumstance holds or a process is in progress. Each event has an associated time of occurrence, represented by an instant. An instant embodies information regarding the time of occurrence of the event with which it is associated. This may include a date (at some level of specificity) in addition to constraints relating it to the times of occurrence of other events. For example, the ending event associated with a given circumstance or process necessarily follows in time the beginning event.

Figure 1 presents the skeleton of a circumstance or process representation. In an initial implementation [10], we have assumed that an instant does not include a specific date. Rather, at any point during planning or execution monitoring, an event only can be constrained to occur between the TA and TB time values of its associated instant. This interval is maintained by the propogation of constraints corresponding to temporal assertions made at the planning level. These assertions interrelate the time intervals associated with processes and circumstances. A set of basic relational assertions that can hold among time intervals has been discussed elsewhere [1,12]. They can be defined in terms of three basic predicates involving events presented in Figure 2. The correspondence with constraints on TA and TB values of associated instants is indicated. Figure 3 defines a set of temporal assertions useful for our example below.

<u>An Example</u>

In this section we present an example process description. The example will serve as basis for contrasting our formulation of planning and pragmatic reasoning with that of state-based approaches.

Figure 4 describes a process corresponding to a typical, state-based PUSH operator. The description is simplified and incomplete, but illustrates important features of our approach. A process description begins with a specification of a set of arguments, being formal variables each of a particular type (implicit in our example), that play important roles with respect to the process described. Then a set of circumstances is specified in the form of propositions involving arguments of the operator. Finally, a set of temporal assertions are indicated that interrelate time intervals of the circumstances with each other and with that of the process. Duration assertions can be included. In the example, one is shown as a function of the length of the path between Loc1 and Loc2 and a constant pushrate.

The bottom of Figure 4 provides a graphic representation of our specification of PUSH. Note that circumstance intervals can extend beyond that over which the process is in progress, as do A1 through A4 in our example. These represent a generalization of the state-based notions of operator preconditions and effects. Though not illustrated by our example, such <u>extended circumstances</u> may end or begin within the interval associated with the process or may even be disjoint from it. Durations can be associated with extended circumstances. We could assert DURATION(A3, [5,MAXDUR]) to require that an object be at a particular location for at least five time units before it can be pushed.

The notion of goal is likewise generalized within our formulation. A goal is a set of temporally interrelated circumstances and processes. Figure 5 presents a description of the goal that I be reading <u>War and Peace</u> in the living room when you arrive home. Occurrences, such as arriving, can be represented as meeting pairs of circumstances that indicate the change associated with the occurrence. We hint at the use of hierarchic reference frames and that a changing value (your location) can be represented as constant from an appropriate perspective. A plan is merely a generalization of our notion of process that allows processes (as subplans) as well as circumstances to be specified. This allows for hierarchic planning in a straightforward manner. A solution plan for a goal is a plan that extends the currently holding set of circumstances and processes into a future containing the temporal pattern of circumstances and processes required by the goal.

Discussion

The representation of CHANGING circumstances is an issue we have not yet fully addressed. It has been a topic of research interest in AI for several years. Forbus presents one approach in his qualitative process theory [4]; McDermott raises the issue, discussing 'fluents' as a representation [6]. To completely describe a changing attribute value, a path between initial and final values must be specified as well as how in time (intermittently, continuously, functionally) the change occurs. The path represents the sequence of values encountered during the transition. Our example from Figure 4 (A5) deserves brief discussion. There we represent that the location of Obj is changing; more specifically, that Obj is moving continuously (in time) along a physical path between Loc1 and Loc2. Our representation would allow us to prove that, for any date within an interval over which a PUSH is in progress, the object's location is on the path and is changing; for any location Loc on the path between Loc1 and Loc2, we are able to prove there exists a (at least one) time within the interval when Obj is at Loc. We are able to represent that an object is instantaneously at some location (that there exists a state containing AT(Obj Loc)) while representing that the object is at the same time moving (through the location).

We are currently investigating planning and pragmatic reasoning methods based upon our formulation. As noted above, operators and plans can be represented as processes. We are developing mechanisms for updating projected circumstances when an operator is added to a plan to be executed over some constrained time interval. We have an initial implementation of constraint propogation over the TA and TB values of instants. We have experimented with this implementation in recognizing whether a set of time-stamped observations is consistent with a known plan.

In closing, we have proposed an alternative ontological basis for pragmatic reasoning about real-world task domains. The traditional state-based approach is not appropriate as those properties which led to its development do not hold in real-world contexts. There is much research yet to be done to determine the eventual usefulness of our notions and of other proposals.

References

[1] Allen, J., Maintaining knowledge about temporal intervals", (TR-86) University of Rochester, Computer Science Department, 1981.

[2] Allen, J., "A general model of action and time", (TR-97) University of Rochester, Computer Science Department, 1981.

[3] Carbonell, J. G., "Counterplanning: A strategy-based model of adversary planning in real-world situations", Artificial Intelligence 16 (3), p 295-330, 1981.

[4] Forbus, K. D., "Qualitative process theory", AI Memo 664, MIT AI Lab., 1982.

[5] McCarthy, J. and Hayes, P.J., "Some philosophical problems from the standpoint of artificial intelligence", in Meltzer and Michie (eds) Machine Intelligence 4, Edinburgh University Press, 1969.

[6] McDermott, D., "A temporal logic for reasoning about processes and plans", Cognitive Science 6, 101-155, (1982).

[7] Moore, R. "Reasoning about knowledge and action", Technical Report 191, AI Center, SRI International, 1980.

[8] Newell, A. and Simon, H.A., Human Problem Solving, Englewood Cliffs, NJ: Prentice-Hall, 1972.

[9] Rescher, N. and Urquhart, A. Temporal Logic, New York: Springer-Verlag, 1971.

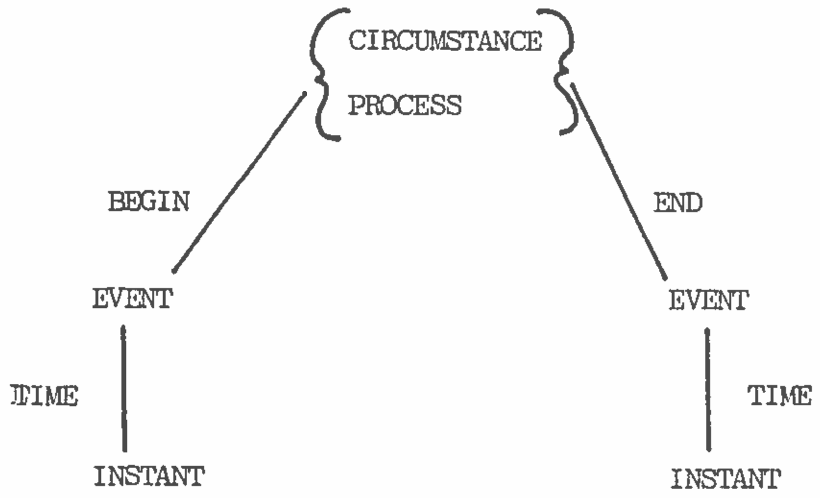
[10] Tyson, M., Garvey, T., and Farley, A., "Adaptive modeling and real-time simulation, Interim Project Report, AI Center, SRI International, Menlo Park, CA, November, 1982.

[11] Vere, S., "Planning in time: windows and durations for activities and goals", Technical Report, Jet Propulsion Lab., Pasadena, CA, 1971.

[12] Vilain, M., "A system for reasoning about time", Proceedings of AAAI-82, Pittsburgh, Pa, p 197-201, 1982.

[13] Wilensky, R. Planning and Understanding: A computational approach to human reasoning, Addison-Wesley: Reading,Massachusetts, 1983.

FIGURE 1 Elements of CIRCUMSTANCE and PROCESS Representation



INSTANT Properties

- TA: Time After which the associated event must occur
- TB: Time Before which the associated event must occur
- TAC: constraints on TA
- TBC: constraints on TB

TA is the earliest date consistent with TAC; TB is latest consistent with TBC. In a satisfiable representation, (*LT* TA(i) TB(i)) holds for every INSTANT i.

FIGURE 2 Basic Relations and Correspondence with INSTANT Constraints

```
AT(e,t):
            (*GE*  TA(TIME(e)) early(t))
            (*LE*  TB(TIME(e)) late(t))

SAMETIME(e1,e2):
            (*EQ*  TA(TIME(e1)) TA(TIME(e2)))
            (*EQ*  TB(TIME(e1)) TB(TIME(e2)))

AFTER(e1,e2,d):
            (*GE*  TA(TIME(e1)) (*PLUS* TA(TIME(e2)) short(d)))
            (*LE*  TA(TIME(e1)) (*PLUS* TA(TIME(e2)) long(d)))
            (*GE*  TB(TIME(e1)) (*PLUS* TB(TIME(e2)) short(d)))
            (*LE*  TB(TIME(e1)) (*PLUS* TB(TIME(e2)) long(d)))
```

where

e, e1, and e2 refer to EVENTS, t to a time interval (early,late), and d to a duration bounds [short,long]. All inverse constraints are implied.

FIGURE 3 A Useful Set of Temporal Assertions

```
THROUGHOUT(cp1,cp2) == AFTER(BEGIN(cp2),BEGIN(cp1),MAXINT) and
                       AFTER(END(cp1),END(cp2),MAXINT)

MEETS(cp1,cp2) == SAMETIME(BEGIN(cp1),END(cp2))

BEGINWITH(cp1,cp2) == SAMETIME(BEGIN(cp1),BEGIN(cp2))

ENDWITH(cp1,cp2) == SAMETIME(END(cp1),END(cp2))

TOGETHER(cp1,cp2) == BEGINWITH(cp1,cp2) and ENDWITH(cp1,cp2)

DURATION(cp1,d) == AFTER(END(cp1),BEGIN(cp1),d)
```

where

cp1 and cp2 refer to CIRCUMSTANCEs or PROCESSes, d to a bounds on duration, and MAXINT to duration bounds 0,MAXDUR .

FIGURE 4 A Description of PROCESS PUSH

Arguments:

Agt
Obj
Loc1
Loc2

CIRCUMSTANCEs:

A1: (CONSTANT PUSHABLE Obj)
A2: (CONSTANT INCONTACT Agt Obj)
A3: (CONSTANT AT Obj Loc1)
A4: (CONSTANT AT Obj Loc2)
A5: (CHANGING AT Obj (PATH(Loc1,Loc2),continuously))

Assertions:

THROUGHOUT(A1,PUSH)
THROUGHOUT(A2,PUSH)
MEETS(PUSH,A3)
MEETS(A4,PUSH)
TOGETHER(A5,PUSH)
DURATION(PUSH,[short(length(PATH(Loc1,Loc2)),pushrate),
long(length(PATH(Loc1,Loc2)),pushrate)])

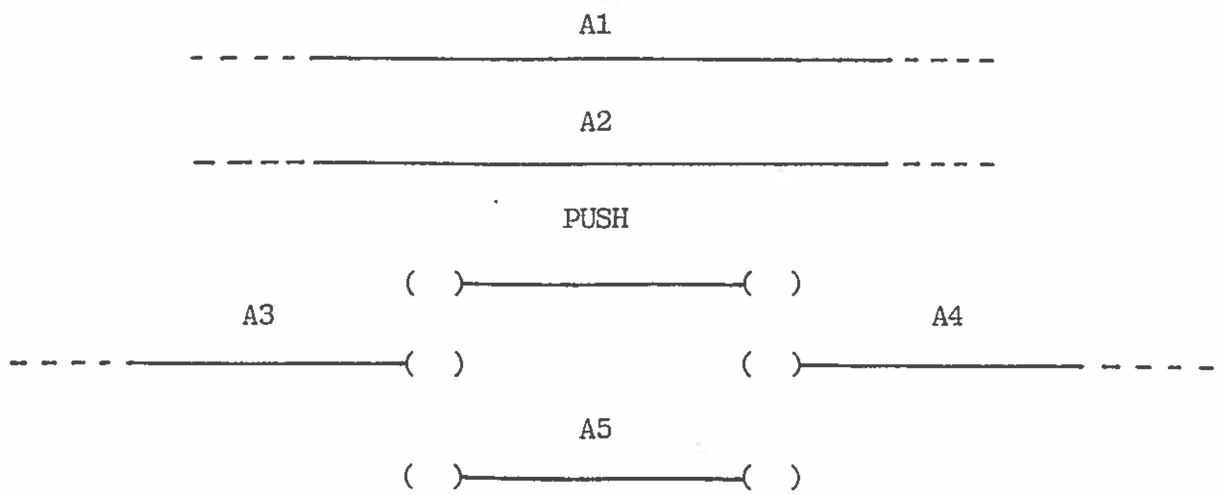


FIGURE 5 An Example Goal Description

Circumstances:

C1: AT(ME, (HOME, LIVINGROOM))
C2: AT(YOU, (WORLD, elsewhere))
C3: AT(YOU, (WORLD, HOME))

Processes:

P1: DO(ME, READ(WAR AND PEACE))

Assertions:

MEETS(C3,C2) "the occurence of arriving"
ENDIN(C2,C1)
ENDIN(C2,P1)

where

elsewhere is any location in the world other than HOME
and ENDIN has the natural interpretation, such that
ENDIN(C2,C1) and MEETS(C3,C2) implies BEGININ(C3,C1).