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6. AUTHOR(S)

V. Naidu Gudivada
R. Logananharaj

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Jackson State University
Jackson, MS 39217

8. PERFORMING ORGANIZATION REPORT NUMBER

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13. ABSTRACT *(Maximum 200 words)*

Temporal Reasoning involves the study of a general theory of time and an associated reasoning. Representation of time plays an important role in acquiring and manipulating temporal knowledge. Within the artificial intelligence community, there are two popular approaches to representing time: intervals and points. However, very little work has been done to combine the best aspects of these systems under a single framework.

The main accomplishments of this project are: (a) developed a temporal framework that combines the advantages of both the point-based and the interval-based systems which allow metric bounds on an event's duration, (b) designed algorithms for satisfying temporal constraints, (c) developed an efficient algorithm for propagating temporal constraints, and explored the feasibility of applying parallelism, and (d) designed and implemented a primitive point-based temporal reasoning system.

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TEMPORAL REASONING AND PROBLEM SOLVING

FINAL REPORT

V. NAIDU GUDIVADA
R. LOGANANTHARAJ

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Abstract

Temporal Reasoning involves the study of a general theory of time and an associated reasoning. Representation of time plays an important role in acquiring and manipulating temporal knowledge. Within the artificial intelligence community, there are two popular approaches to representing time: intervals and points. Allen's interval logic defines thirteen relations between intervals and thus offers rich expressive power. Interval logic, however, suffers from inefficient temporal propagation algorithms. On the other hand, point-based systems precisely represent nondisjunctive temporal knowledge and has efficient algorithms for temporal constraint propagation. Unfortunately, very little work has been done to combine the best aspects of these systems under a single framework.

The main accomplishments of this project are:

- developed a temporal framework that combines the advantages of both the point-based and the interval-based systems which allow metric bounds on an event's duration,
- designed algorithms for satisfying temporal constraints,
- developed an efficient algorithm for propagating temporal constraints, and explored the feasibility of applying parallelism, and
- designed and implemented a prototypical point-based temporal reasoning system.

Discussion of the Proposed Problem

Introduction and Background

Temporal reasoning involves the study of general theory of time and an associated reasoning [1]. Extensive work to formalize the notion of time has been done [2,3] by researchers in diverse disciplines such as philosophy, theoretical computer science, databases, and artificial intelligence (AI). The researchers of philosophy have studied the tense logic extensively while the theoretical computer scientists have used model logic for applications such as synthesis of concurrent programs, properties of parallel programming, etc. A temporal database [4] has the capability to retrieve information over different transactions and valid time. It, however, lacks deductive capabilities. For a recent review on temporal databases, refer to [5]. The research within the AI community can be categorized [6] into: **change based** and **time based**. As the name implies, the change based approach is based on actions, events, or entities that change the status of the world or the domain of interest. Situation calculus in AI and dynamic logic in theoretical computer science are examples of this approach. Time based approach, on the other hand, uses explicit representation of time. Under this category, there are two different ways of representing temporal knowledge: using classical first order logic, or using reified sentences. We will emphasize our interest in temporal reasoning within the framework of artificial intelligence.

In the first order logic approach, time can be represented as a pair of terms of a literal. This predicate is true during the time period indicated by the terms corresponding to the time points. For example, the literal *Color(House, Blue,* t_1, t_2*)* may be interpreted as stating the *Color* of the *House* is *Blue* over the time period t_1 to t_2 which is denoted by $<t_1, t_2>$. Using this framework, Bacchus et al. [7] proposed a two--sorted logic for representing temporal knowledge. They mapped the two--sorted logic onto one--sorted, classical first order logic, for the convenience of using existing theorem provers. When the temporal knowledge represents a static world and the inferencing is no more than some monotonic deduction, their system will work. Unfortunately, when the temporal knowledge represents a dynamic world, or when the temporal knowledge is incomplete initially and temporal propagation is required as new temporal knowledge is included, the underlying monotonic reasoning system may fail unless some mechanism is incorporated to handle nonmonotonicity. Time based temporal logic can be categorized as **interval-based** or **point-based** logic depending on the primitives being used. We will clarify these two aspects of representing temporal information in the following section.

Interval Based System

Allen [8] has proposed an interval logic that uses time intervals as primitives. In this logic, the following seven relations and their inverses are defined to express the temporal relations between two intervals: before (after), meets (met-by), overlaps (overlapped-by), starts (started-by), during (contains), ends (ended-by), and equals. Here, the inverse relations are indicated within parentheses. Since the inverse of *equal* is same as itself, there are, in fact, only thirteen relations.

A property, say *p*, of an object over an interval, say I_1, is represented as *HOLD*(p, I_1). A property is true for an interval if and only if (iff) it holds for every subinterval, this is the equality of *homogeneity*. Note here that the negation of *HOLD* on a property is not the same as *HOLD* on the negation of the same property.

An event which changes the world status is defined as *OCCUR*(e, I_1) where *e* is an event type and I_1 is the interval over which it is taking place. There is no subinterval of I_1 in which the event *e* happened. Allen extends his ontology to a *process* which has a similar syntactic structure of an event, but has different semantics. He informally defined a *process* as some activity which does not involve a culmination of an anticipated result as expressed by the statement, "I am working." Using the same syntactic form for both the event and the process is very confusing and it is not clear to state that something is not changing after a process has taken place.

Temporal inferencing is performed by manipulating the network corresponding to the intervals. Each interval maps onto a node in the network and a temporal relation, say *R*, between a pair of intervals, say I_1 and I_2, is indicated by the label *R* on the directed arc from I_1 to I_2. Allen et al. [9] proposed an axiomatization of interval logic using the single primitive ``MEET." In terms of computational efficiency, the formalism is not very useful since it involves several existentially quantified intervals.

Recently, there have been some successful attempts to reduce the size of Allen's transitivity table for intervals which has 144 entries. Loh et al. [10] proposed a method using vertical symmetry to reduce the entries to seventy-four. Ligozat et al. [11] further reduced the entries to forty- three by mapping the interval structure onto two dimensional polygons. However, reduction of the table size may not help to improve the temporal propagation efficiency since each table look up takes constant time regardless of the table size, as long as the table has a reasonable size.

Vilain et al. [12] have shown that the temporal constraint satisfaction problem is NP-complete. Approximation algorithms, however, are available for temporal constraint propagation. Allen proposed an approximation algorithm that has an asymptotic time complexity of $O(N^3)$ where N is the number of intervals. His algorithm is an approximate one in the sense that it does not guarantee obtaining the minimum relations, but it is sound. Malik and Binford [13] proposed a method based on linear programming to determine closure for a subset of interval logic. Intervals are mapped onto points relations and simplex method is used to answer queries which are formulated as maximizing or minimizing functions. The complexity of the simplex method is exponential in the worst case. Valdes-Parez [14] proposed a heuristically pruning algorithm for temporal propagation in interval logic.

Point Based System

McDermott [15] proposed a point-based temporal logic which provides a precedence temporal operator on time points. The time used in this logic is infinite in both directions, dense and continuous. The time is linear in the past. He allows branching only in the future for representing different world situations and hence, these branches cannot meet. Perhaps, this capability is useful to solve certain kinds of problems such as planning. Axioms or facts are interpreted over time points while events are interpreted over intervals Here, interval is represented as a pair of time points corresponding to the beginning and the ending of the interval.

Shoham [6, 16] proposed an elegant formalism for point-based logic which extends and generalizes McDermott's point logic. In his logic, reified sentences are used to represent facts. Even though Shoham's logic uses time points as primitives, each reified sentence accepts a pair of time points corresponding to end points of an interval. That is, assertions are interpreted over intervals, not over time points. He, however, allows intervals of zero duration to simulate statements over time points. He has not discussed any inferencing mechanism or any system that could use the temporal knowledge in an intelligent way.

Kowalski et al. [17] proposed calculus of events for updating databases and narrative understanding. Their work could be viewed as an extension of situation calculus to avoid the frame problem. The choice of the word ``event'' is rather confusing. In their system an event refers to either starting or ending point of a change or an activity to which others refer to as an event. To avoid the frame problem, it is interpreted as, if an event happens its consequences are true at all subsequent time until other events cause them to be no longer true. The event in their system is very close to the way Khemka and Loganantharaj [18, 19] have defined transition.

Vilain and Kautz [12] proposed a temporal propagation algorithm for temporal point algebra. The algorithm is similar to Allen's algorithm and runs in $O(N^3)$ where N is the number of nodes in the temporal network. They claim that the algorithm will always find the minimal relations, but in fact it is also an approximate algorithm. van Beek [20] proposed a better approximation algorithm for point algebra that runs in $O(N^4)$.

Ghallab et al. [21] proposed an approximate algorithm for point-based temporal reasoning. It may be suitable for systems that involve frequent updates. The duration of an event in both the McDermott's and Shoham's logic is assumed to be known or fixed. Sometimes it is desirable to have metric bounds for the duration of events. Dean et al.[22, 23] allowed metric bounds for the duration of events. Events are represented by their end points and are mapped onto a graph called a time map. A label of an arc represents both the lower and the upper bound of the duration of the corresponding event. Their system cannot be applied to continuously changing quantities or even discretely changing quantities. Further qualitative relations between intervals cannot be naturally represented in a time map.

Dechter et al. [24] proposed algorithms based on relaxation methods for propagating temporal constraints in a temporal network similar to the time map. In temporal networks nodes represent end points of events, and each arc has at least one label indicating the maximum and minimum duration of the corresponding event. This is an approximate algorithm and runs in $O(N^3)$ time where N is the number of nodes in the temporal network.

In this study, we focused our investigations on the following:

1. Developing efficient algorithms for temporal propagation,

2. Developing parallel algorithms for path consistency checking,

3. Algorithms to obtain consistent models incrementally by pruning the search space, and

4. Developing a prototypical point-based temporal reasoning system

Summary of the Most Important Results

An efficient temporal propagation algorithm plays an important role in propositional temporal reasoning. Allen's path consistency algorithm has been very well referenced and used in propagating interval constraints. We have studied his algorithm and improved its computational efficiency by removing duplicate propagations and employing heuristic strategies to reduce the search space considerably without sacrificing the results. When we applied our algorithm to the interval constraints generated randomly with one to thirteen relations, our algorithm improved the computation over Allen's algorithm by a factor of 46%. The details of the algorithm and the results are presented in [29].

Many algorithms proposed for propagating temporal constraints are special cases of path consistency algorithm of general constraint satisfaction problem (CSP). We have studied time and space complexity of several path consistency algorithms for boolean constraint satisfaction problems. We proposed a new path consistency algorithm [26] with the best trade off between time and space complexity.

The propagation of the constraints can be further improved by clustering the temporal constraints. An optimal clustering can reduce the propagation time to $O(N^{1.8})$ from the normal propagation time $O(N^3)$. The investigation on clustering the intervals is the focus of our future research.

We have proposed [28] an efficient temporal propagation algorithm for a point based system that runs in $O(kN^2)$ time, where N is the number of temporal points and k is the average branching factor of a node. Since $1 \leq k < N$, the algorithm runs better than any other algorithm proposed for point based systems. This algorithm computes minimal labels for a continuous point based system, but in the presence of discontinuous disjunction, $\neq$, the algorithm computes only the approximate labels, similar to any other three consistency algorithm.

We have proposed a framework [30] for combining qualitative and quantitative temporal constraints for point based system. When the quantitative constraints form convex intervals, the algorithm converges. Investigation is underway to specify metric bounds between a pair of intervals and to propagate the constraints with qualitative constraints.

We have proposed [27] a parallel path consistency algorithm that requires only n processors and runs in $O(n^2)$ time on a CRCW PRAM model or $O(n^2 \log n)$ time on EREW PRAM model. Our algorithm uses only n processors compared to $O(n^3)$ processors required by Ladkin and Maddux recent algorithm to obtain the same time complexity with the similar parallel architectures.

Allen's interval propagation algorithm, like any other three consistency algorithm, detects only the local inconsistency that cannot participate in the global situation. The propagation algorithm, on the other hand, does not guarantee global consistency. Therefore, critical applications in areas such as medical, space, and military cannot rely only on path consistency. Besides, determining consistency by itself does not solve many problems that are mapped as a propositional constraint network. Obtaining a satisfying model, on the other hand, provides a meaningful solution for planning and other problems. As suspected, generating all the models will take exponential time and therefore any algorithm developed must prune the search space and use heuristic techniques to generate the models efficiently. Recently, we have proposed [25] an algorithm to obtain consistent models incrementally by reducing the search space by applying forward pruning technique. Investigation is underway to develop heuristic strategies to prune the search space.

We have implemented a point-based propositional reasoning system to run under Microsoft Windows Graphical User Interface. It supports dynamic addition and deletion of temporal constraints. The query language currently supported is limited to a restricted form of English. We intend to improve the query language. The future plans in this direction also include incorporating interval-based reasoning and thus making the system a hybrid one supporting both points and intervals.

We are pleased to report that we were able to accomplish more than what we originally planed for 1990 - 1991 academic year. The initial success has opened up new issues to be investigated for the proposed research period. Further, we intend to solve a subset of planning problem, known as verification of partial plans, by mapping the partial plans into a propositional temporal constraint network. Satisfiability can be answered in polynomial time if the interval constraints are limited to either points or pointisible subset of intervals. Hence limiting expressive power to achieve tractability is desirable. Research will continue in the direction of developing a language to capture partial plans, and methods to check its satisfiability and to generate a satisfying plan if one exists.

List of All Publications and Technical Reports

1. R. Loganantharaj, D. Mitra, and V.N. Gudivada. "**Consistent Sigleton Models of a Temporal Constraint Network,**" *IEEE Conference on Robotics* (accepted).

2. S. Keretho, R. Loganantharaj, and V.N. Gudivada. "**On the Complexity of Path Consistency Algorithms for Constraint Satisfaction Problems,**" *Tools for Artificial Intelligence*, November 1991.

3. S. Keretho, R. Loganantharaj, and V.N. Gudivada. "**Parallel Path Consistency Algorithms for Constraint Satisfaction Problems,**" *IJCAI Workshop on Parallel Processing in Artificial Intelligence*, August 1991.

4. R. Loganantharaj. "**An Efficient Temporal Propagation Algorithm for Point based Systems,**" *BISFAI Conference on the Foundations of Artificial Intelligence*, June 1991.

5. R. Loganantharaj and S. Keretho. "**Efficient Propagation Algorithms for Temporal Interval Algebra,**" International *Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems*, June 1991.

6. S. Keretho, R. Loganantharaj. "**An Extended Time Point Algebra,**" *International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems*, June 1991.

List of All Participating Scientific Personnel

- V. Griddalur
- A. Gudivada (Degree Awarded: M.S.)
- S. Gummadi (Degree Awarded: M.S.)
- S. Keretho
- D. Mitra
- V. Gudivada
- R. Loganatharaj

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