THEORY AND ONTOLOGY FOR SHARING TEMPORAL KNOWLEDGE

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ABSTRACT

Using current technology, the sharing or re-using of knowledge-bases is very difficult, if not impossible. ARPA has correctly recognized the problem and funded a knowledge sharing initiative. One of the outcomes of this project is a formal language called Knowledge Interchange Format (KIF) for representing knowledge that could be translated into other languages.

Capturing and representing design knowledge and reasoning with them have become very important for NASA who is a pioneer of innovative design of unique products. For upgrading an existing design for changing technology, needs, or requirements, it is essential to understand the design rationale, design choices, options and other relevant information associated with the design. Capturing such information and presenting them in the appropriate form are part of the ongoing Design Knowledge Capture project of NASA. The behavior of an object and various other aspects related to time are captured by the appropriate temporal knowledge. The captured design knowledge will be represented in such a way that various groups of NASA who are interested in various aspects of the design cycle should be able to access and use the design knowledge effectively. To facilitate knowledge sharing among these groups, one has to develop a very well defined ontology. *Ontology* is a specification of conceptualization. In the literature several specific domains were studied and some well defined ontologies were developed for such domains. However, very little, or no work has been done in the area of representing temporal knowledge to facilitate sharing.

During the ASEE summer program, I have investigated several temporal models and have proposed a theory for time that is flexible to accommodate the time elements, such as, points and intervals, and is capable of handling the qualitative and quantitative temporal constraints. I have also proposed a primitive temporal ontology using which other relevant temporal ontologies can be built. I have investigated various issues of sharing knowledge and have proposed a formal framework for modeling the concept of knowledge sharing. This work may be implemented and tested in the software environment supplied by Knowledge Based System, Inc.

INTRODUCTION

Representation and reasoning with time play an important role in design knowledge capture framework. The temporal knowledge could be as simple as some specific time constraints about the operation of a device, or as complicated as describing a behavior of a device. For example, the proper operating condition of a device, say a relay R_1, may be specified as: the relay must be activated with 5 units of time after the master switch is tuned on. Similarly, a complicated interaction among various devices can be elegantly specified using temporal knowledge representation.

In an established organization, such as NASA, enormous amounts of useful and critical information are accumulated over a period of time and usually are stored in some sort of electronic form in a computer. Sharing, or using such vital and important information is essential for many critical applications, such as, redesigning or maintenance of devices used in NASA space mission. Sharing of information across different platforms and different languages is a challenging problem. ARPA has initiated a project to address exactly the same problem. It is equally challenging to share the information among people of diverse backgrounds and interests. An example will be a typical NASA engineering project that typically employs a variety of different technologies and a distribution of responsibilities among the project members. In this project we study the problem and propose a practical solution.

The objectives of this research project include: (1) Propose a theory of time that is general enough to accommodate the time elements, points and intervals, and flexible enough to support qualitative and quantitative relations among the elements. (2) Develop primitive and minimal temporal ontologies from which one can build complex ontologies that are natural to the problem domain. (3) Study the problem of sharing knowledge and propose initial solutions to solve the problem.

REPRESENTATION OF TIME

Extensive works have been done on representing and reasoning with time by researchers from diverse discipline, such as, philosophy, theoretical computer science, data-base, and artificial intelligence. The approaches taken by the artificial intelligence community in representing time can be categorized broadly into event-based, or time-based. In the event-based approach, time is represented implicitly. Situation calculus is an example of the event-based approach. The order of time is implicitly represented by the corresponding events. Even though, the event-based approach has the mathematical richness of a situation calculus, and is capable of producing partial or the total ordering among the events, it may not be suitable for specifying either the duration, or the exact time of an occurrence of an event. Many of the applications relevant to NASA require that time must be represented explicitly. We, therefore, study time-based approach for representing temporal knowledge.

We will now decide on the time elements for representation. There has been a considerable amount of discussion about whether the points or the intervals should be the basis for representing temporal knowledge. McDermott [McD82] had proposed temporal knowledge representation system with time points. Allen subsequently proposed interval algebra and argued interval must be the elements of time.

In this research project, we take advantage of both the time points and the intervals. For providing equal footing for both points and intervals, we have proposed a new theory for time that integrates both the points and intervals cohesively.

Before we describe our theory of time, let us briefly introduce both the time points and the intervals.

POINTS

McDermott [McD82] introduced point temporal model for branching time. In his model the time is linear in the past while the time is branching in the future. The branching time model will be useful to studying hypothetical reasoning. Vilain et al. [VK86] has proposed point algebra for linear time. They also have proposed consistency algorithm for propagating temporal constraints.

In linear time model, if we consider a pair of time points one is either before, after or coincides with the other point.   We use the notations $<$, $>$, $=$, to denote respectively the relations before, after and coincide. The linearity property for a pair of points t_i and t_j is formally represented as:
$$(t_i < t_j) \vee (t_i > t_j) \vee (t_i = t_j).$$
Note that exactly one relation is true between any two points.

Most of the work done in this area were concerned about propagating temporal constraints and to obtain the minimal labeled temporal constrained network. In a *minimal labeled temporal constraint network* (MLTCN) each label   participates in a consistent solution of the temporal constraints. In other words, showing the availability of a MLTCN is equivalent to showing the satisfiability of the temporal constraints. VanBeek [VanB89] had shown that 4-consistency algorithm is required to obtain minimal labeled temporal constraint network for point-based representation.   4-consistency algorithm takes $O(n^4)$ time for convergence, where n is the number of nodes (time points) in the temporal constraint network.

INTERVALS

Interval is a continuous non-zero span of time.   Allen [All83] has proposed interval algebra for linear time. There are thirteen relations between a pair of intervals. There relationships are, before (B), after (A), meets (M), met by (Mi) , overlaps (O), overlapped by (Oi), starts (S), started by (Si), finishes (F), finished by (Fi), overlaps (O),

overlapped by (Oi), and equal (E). These relations between a pair of intervals, say I_i and I_j, can be neatly presented in a lattice form as shown in Figure 1.
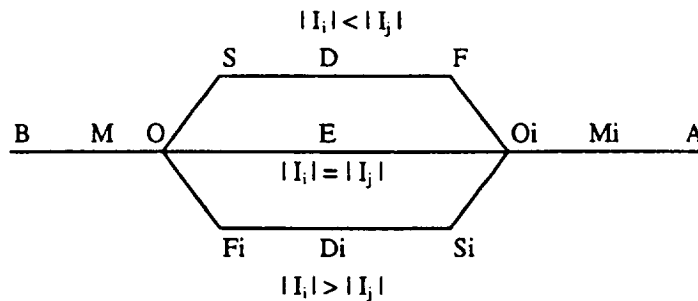
$$|I_i| < |I_j|$$

```
              S       D       F
             /                 \
  B   M   O /        E          \ Oi   Mi   A
            \   |I_i| = |I_j|   /
             \                 /
              Fi      Di      Si
```

$$|I_i| > |I_j|$$

Figure 1

Where, $|I_i| < |I_j|$, $|I_i| > |I_j|$, and $|I_i| = |I_j|$ respectively indicate that the duration of I_i is less than, grater than, or equal to the duration of I_j. Allen has proposed a 3-consistency algorithm to propagate interval temporal constraints. 3-consistency of the interval constraints does not yield minimal labeled temporal constrained network. Note here that obtaining a MLTCN for interval algebra is NP-hard.

ONTOLOGY

Ontology may be thought of as a terminology for representing a conceptualization. A *conceptualization* is an agent's modeling of the objects, or the events and activities occurring in the world. We are interested in capturing events, activities and properties that varies with time. There are two different schools of thought about defining temporal ontologies. One camp believes that one must provide all the necessary ontologies with implicit or explicit semantics, while the other camp believes that one must provide only the primitive ontologies from which other ontologies could be built.

We take the second approach since, we may not know what are the possible ontologies that may be useful for different kinds of problem domains. We have witnessed numerous counter examples that can not be consistently explained by having a pre-defined set of ontologies.

In the early eighties Allen [All84] has proposed a theory for action and time using intervals. He has proposed ontologies for property, event and process. To assert that a property p of an object is holding during an interval I, Allen used an operator HOLDS(p,I). If p holds over an interval I, it must also hold over all the sub intervals of I. Alen has defined a stronger axiom on HOLDS: if p holds over an interval I then for every subinterval of I there must be at least one period within the subinterval in which p must be true. These properties are formally presented as follows:

HOLDS(p,I) $\leftrightarrow$ ($\forall$i IN(i,I) $\rightarrow$ HOLDS(p,i))
HOLDS(p,I) $\leftrightarrow$ ($\forall$i IN(i,I) $\rightarrow$ ($\exists$s IN(s,i) $\land$ HOLDS(p,s)))

An event *e* occurring over an interval *I* is represented by OCCUR(e,I). An event occurs in the entirety of an interval, but can not occur in the subinterval. An event is formally represented as

OCCUR(e,I) → ¬ (∃i IN(i,I) ∧ OCCUR(e,i))

A process *e* occurring in an interval *I* is represented as OCCURRING(e,I). Allen had defined the processes as something that occurs at least once in the given interval and it is formally defined as

OCCURING(e,I) → ∃i IN(i,I) ∧ OCCURING(e,i)

Examples

The status of switch₁ is on over the interval *I* is represented by
        HOLDS(status(switch₁, on), I)
The status of switch₁ is on in all the subintervals of *I*.

The ball changed position from *a* to *b* over   the interval *I*. The ball changing position from *a* to *b* is an event and it is represented by change_pos(ball,a,b).
        OCCUR(change _pos(ball,a,b),I)
Note that the ball can not change position from *a* to *b* in any subintervals of *I*.

John drank water over *I*. The process John drinking water is represented by drink(john,water).
        OCCURRING(drink(john,water),I)
John drinking water is true in at least one subinterval of *I*.

Some weakness of these Ontologies

Allen's ontologies [All84] do not allow one to define precise physical phenomena such as, the status of position or motion of a continuous event at some specific instants [Gal90]. We will illustrate this with couple of examples. Consider a ball that is moving from *a* to *b* on a flat surface over an interval *I*. The ball changing position from *a* to *b* is an   event and   hence   it   is   represented   in   Allen's   ontology   as OCCUR(change_pos(ball, a,b), I). Suppose we are interested in studying the relation between the location of the ball and the time. Say, the ball is at location *c* in the interval, say, *I*. Where *c* is between *a* and *b* and *i* is a subinterval of *I*. The position of the ball at *c* is a property and hence it is represented as HOLDS(position(c),i). The ball being at location *c* over an interval *i* indicates that the ball is stationary that contradicts the fact that the ball is moving.

Consider another example of throwing a ball upwards. The ball looses the velocity under gravitation during the upward movement. It momentarily comes to rest and then

it increases the speed from zero in its downward movements. Let l_1 and l_2 are the intervals during which the ball is moving upward and downward respectively. The status of the ball in the interval l_1 and l_2 are respectively, moving upwards and moving downwards. In Allen's ontology they can be represented as

HOLDS(status(ball, upwards), l_1), and
HOLDS(status(ball, downwards), l_2).

What is the status at the meeting place of l_1 and l_2? Since the status of the ball can not be both upwards and downwards at the meeting point, l_1 cannot meet with l_2. Therefore, l_1 and l_2 must be defined as open at the end, and at the beginning respectively. With this definition of the intervals we can represent the status of the ball, but we still can not represent the status of the ball as stationary at some moment since Allen's ontology does not allow us to define instant.

Theory of time by Allen and Hayes

Allen and Hayes [AH85] axiomatized time using a single relation between intervals called meets. Intervals are used as temporal elements in their theory and points were not considered at all.

The relation meets was introduced informally and it has the common-sense meaning of two objects meeting or touching each other.

The axioms of Allen and Hayes

<M₁> $\forall$ i,j,k,p $\in$ I $\wedge$meets(i,j) $\wedge$ meets(i,k) $\wedge$ meets(p,j) $\rightarrow$ meets(p,k))

<M₂> $\forall$ i,j,k,p $\in$ I $\wedge$ meets(i,j) $\wedge$ meets(k,p) $\rightarrow$ meets(i,p)
            ∇ $\exists$ m $\in$ I $\wedge$ (meets(i,m) $\wedge$ meets(m,p))
            ∇ $\exists$ n $\in$ I $\wedge$ (meets(k, n) $\wedge$ meets(n,j))

∇ denotes exclusive OR here.

<M₃> $\forall$ i $\in$ I $\exists$ j,k $\in$ I (meets(j,i) $\wedge$ meets(i,k))

<M₄> $\forall$ j,k $\in$ I ($\exists$ i, p $\in$I (meets(i,j) $\wedge$ meets(j,p) $\wedge$meets(i,k) $\wedge$ meets(k,p)$\rightarrow$ j=k)

<M₅> $\forall$ i,j $\in$ I (meets(i,j) $\rightarrow$$\exists$ k $\in$ I $\forall$ m,n $\in$I (meets(m,i) $\wedge$meets(j,n))
            $\rightarrow$ meets(m,k) $\wedge$ meets(k,n))

<M₆ > $\forall$ m, n $\in$I (moment(m) $\wedge$moment(n) $\rightarrow$ $\neg$meets(m,n)

where moment is defined by
        $\forall$m $\in$ I (moment(m) $\leftrightarrow$ $\neg$ $\exists$ i, j $\in$ I (m=i+j))

The axiom M_1 states that the meeting place of a pair of intervals is unique. The linearity of the intervals are stated by the axiom M_2

The axiom M_3 states that every interval has at least one interval preceding it and another interval succeeding it. M_4 states that the meeting place uniquely determines the intervals.

The axiom M_5 states that if two intervals, say i and j, meet then there exists another interval that is a concatenation of intervals i and j.

Axiom M_6 states that moments do not meet. Moments are special kinds of intervals that can not be decomposed, but they have other properties of intervals such as having two end points, etc.

Ma et al. [MK94] has extended Allen and Hayes theory of time by allowing time element, *I*, in Allen et al 's theory to be both time points and intervals, and restricting meets relation only to intervals. To improve the flexibility they have removed the linearity property (axiom M2) from Allen and Hayes axioms.

AXIOMS OF OUR APPROACH

We provide a theory of time with time points and intervals.

Notations:

I_s set of intervals
P_s set of points

Linearity property of time points: A pair of points is either coinciding, or one is before or after the other

$$<A_1> \forall \ t_i \ t_j \in P_s \rightarrow t_i < t_j \ \lor \ t_i = t_j \ \lor \ t_i > t_j$$

Time span from minus infinity to plus infinity

$$<A_2> \forall t \ \exists t_i \ \exists t_j \ t, t_i, t_j \in P_s \ \land \ t_i < t \ \land \ t < t_j$$

Pair of intervals meets iff they meet at a point.
$$<A_3> \forall I_i \ I_j \ \in I_s \ I_i \{m\} I_j \leftrightarrow \exists t \in P_s \ I_i \{m\} t \ \land \ t \ \{m\} \ I_j$$

Every interval is non zero duration and has a unique pair of end points
$$<A_4> \forall I_i \in I_s \ \rightarrow \exists t_b, t_e \in P_s \land t_b \{m\} I_i \ \land I_i \{m\} t_e \ \land t_b \ < t_e \ \land \forall t_b' \ t_e' \in P_s$$
$$t_b' \{m\} I_i \land I_i \{m\} t_e' \ \rightarrow t_b = t_b' \land t_e = t_e'$$

For every pair of distinct points there must be a unique interval connecting them
$$<A_5> \forall t_i t_j \in P_s \ t_i \ < t_j \rightarrow \exists I \in I_s \ t_i \{m\} I \land I \{m\} t_j \land \forall I' \in I_s \ t_i \{m\} I' \land$$
$$I' \{m\} t_j \rightarrow I = I'$$

TEMPORAL ONTOLOGY

Temporal ontology should have the capability to describe any conceptualization that associates with time.

Our primitive ontology has the following syntax:

<interval | point >: <proposition | predicate | sentence >

For an interval I and a proposition p, $I:p$ is interpreted as p is true for the interval I. Note that it does not state anything about whether p is true in all the sub interval or not. These properties must be specified by the user or by the ontology that uses this primitive.

Example

A pen is on the table over an interval I. This is a status or the property, therefore, pen on the table must be true throughout the interval, hence it is specified with the primitive as:

$I:pen\_on\_table \leftrightarrow \forall i \in I \rightarrow i:pen\_on\_table$

A ball moves from a to b over an interval I. Since the event, ball moving from a to b, cannot happen in any subinterval of I, it is represented with the primitive as:

$I:change\_pos(ball,a,b) \rightarrow \neg(\exists i \in I \wedge i:change\_pos(ball,a,b))$

The ball is at location a at time t_1. This representation requires that the points and intervals must be represented using end points. If we review A_5 of our theorem it asserts that a pair of end points uniquely identifies an interval, therefore, it is natural to represent an interval with a pair of end points. An interval that is closed at both end points and begins at t_b and ends at t_e is represented by $[t_b\ t_e]$. Similarly an instant t_1 can be represented as $[t_1, t_1]$. Therefore, the ball at location a at time t_1 is represented as

$[t_1, t_1]$: location(ball, a)

The ball is moving in the interval t_1 to t_2. The ball is moving throughout the interval $[t_1, t_2]$, thus it is represented as

$[t_1, t_2]$: status(ball, moving) $\leftrightarrow \forall i \in [t_1, t_2] \rightarrow i$:status(ball, moving)

Consider, for example, throwing a ball up in the air at time t_1. Suppose it reaches its highest point at t_2 and touches the ground at t_3. From the example we can state the

following: the ball is moving upward from t_1 to t_2, The ball is moving downward from t_2 to t_3. The ball is stationary momentarily at t_2. There is a need to support open and closed intervals In our representation we support all variations of intervals: combinations of closed and opened at both end points.

$[t_1\ t_2)$: status(ball,upward)
$(t_2\ t_3]$: status(ball,downward)
$[t_2\ t_2]$: status(ball,stationary)

REDEFINITION OF OTHER ONTOLOGY USING OURS

Allen's ontology

Allen has defined HOLDS to represent a property is holding over a period; occur to define an event occurring over a period.

HOLDS(I,P) : P holds over all the subintervals of I.
HOLDS(I,P) $\leftrightarrow \forall \in$ I i:p

occur(I,e): an event e occur in I; It can not occur in any of the subintervals of I.
occur(I,e) $\leftrightarrow$ I:e $\wedge \neg \exists i \in$ I i:e

occurring(I,e): a process e is occurring in I; It will occur at least one of the
subinterval of I.
occurring(I,e) $\leftrightarrow \exists i \in$ I i:e

Galton's ontology

Galton [Gal90] expanded Allen's ontology by introducing hold_at, hold_on, for specifying something is holding at , and holding within respectively
hold_at(t,P) $\leftrightarrow$ [t,t]:p
hold_on(I,P) $\leftrightarrow$ I:P $\wedge$ ($\forall i \in$ I $\rightarrow$ i:P)

Example: Alert on Instrument Panel

Suppose the following are the instructions for the crew members about a certain alert signal on an instrument panel of a space vehicle. Following the alert, the crew must activate the battery powered backup system and then perform the specific test procedure. The crew usually respond to such alert within 5 minutes. To perform the test procedure it usually takes at least 10 minutes and at most 15 minutes. After the test procedure, the crew must enter the data interactively, and the whole procedure will take about at least 5 minutes and at most 15 minutes. At the end of data entry the computer performs diagnosis which usually takes at least 5 minutes and at most 10 minutes. The diagnosis determines the defective part. It takes at least 20 minutes and at most 30

minutes to replace the defective parts. The instruction further says that the defective part must be replaced before the battery voltage goes below 10% of its set value. The power to the backup system must be reconfigured if the defective part is not replaced when the voltage drops to 10% of its set value. It is estimated that it takes about 45 minutes for the battery to loose its charge to reach 10% drop in its voltage.

Notations

t_0 the alert starts
t_1 crew start the test procedure
t_2 test procedure completes
t_3 start entering the data
t_4 data entry completes
t_5 diagnosis starts
t_6 end of diagnosis
t_7 replacement of defective units begins
t_8 defective unit is replaced

alert starts at t_0
$[t_0, t_0]$: starts(alert)
test procedure starts at t_1
$[t_1, t_1]$: starts(test_procedure)
test procedure ends at t_2
$[t_2, t_2]$: ends(test_procedure)
test procedure is active from t_1 to t_2
$[t_1, t_2]$ status(test_procedure, active) $\rightarrow$ $\forall i \in [t_1, t_2]$ $\rightarrow$i: status(test_procedure, active)
entering data starts at t_3
$[t_3, t_3]$: starts(enter_data)
entering data completes at t_4
$[t_4, t_4]$: ends(enter_data)
data entry is active from t_3 to t_4.
$[t_3, t_4]$:status(data_entry, active) $\rightarrow$ $\forall i \in [t_3, t_4]$ $\rightarrow$i: status(data_entry, active)
diagnosis starts at t_5.
$[t_5, t_5]$: starts(diagnosis)
diagnosis ends at t_6
$[t_6, t_6]$ ends(diagnosis)
diagnosis is active from t_5 to t_6.
$[t_5, t_6]$:   status(diagnosis, active) $\rightarrow$ $\forall i \in [t_5, t_6]$ $\rightarrow$ i: status(diagnosis, active)

$$0 \ <= \ t_1 - t_0 \ <= 5$$
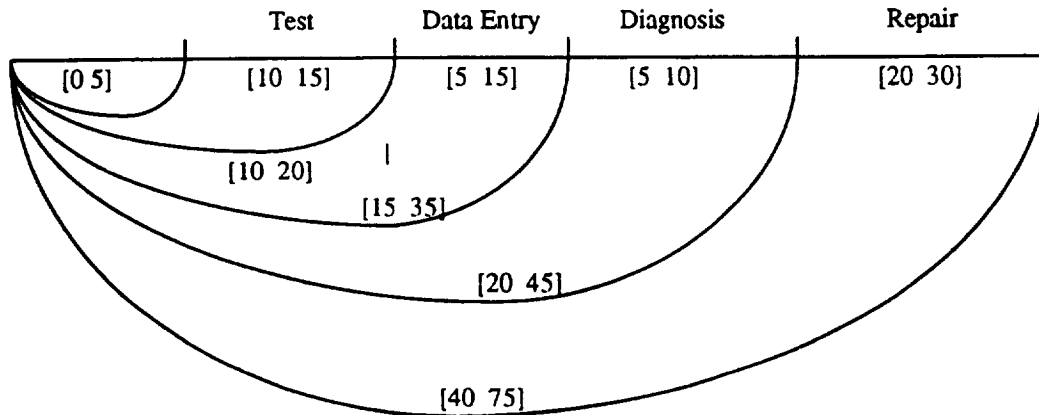$$10 \ <= \ t_2 - t_1 \ <= \ 15$$
$$5 \ <= \ t_4 - t_3 \ <= \ 15$$
$$5 \ <= \ t_6 - t_5 \ <= \ 10$$
$$20 \ <= \ t_8 - t_7 \ <= \ 30$$

Assuming no delays between tasks, we have $t_2 = t_3$; $t_4 = t_5$; $t_6 = t_7$

Constraint Graphs

According to the specifications, the battery will rundown in 45 minutes. The propagation of the constraints indicates that the repair will be completed at least 40 minutes and it will takes at most 75 minutes in the worst case. Therefore, it is desirable to have a backup battery that will last for at least 75 minutes instead of 45 minutes. This information can be captured into the DKC framework as the rationale for having a battery that will last for at least 75 minutes.

KNOWLEDGE SHARING

Knowledge sharing, specially the one that is stored in the electronic form, has tremendous advantages some of which include minimization of effort in recreating the same or the similar information, enable one to build a much larger and comprehensive systems using the existing knowledge and thereby minimizing the overall costs. Sharing the information from one system to another is very challenging because of incompatibility between the systems, representational formats, or languages. Realizing the enormous amount of advantages of sharing the knowledge and the formidable challenges, the ARPA has initiated a knowledge sharing effort at Stanford University and the University of Southern California. The major theme of the ARPA initiative is the research and development of technology for reusing an existing knowledge base or information.

We take a complementary view of sharing knowledge. We focus on the concept of sharing information among the people with different, or diverse backgrounds. An example will be a typical NASA engineering project that typically employs a variety of different technologies and a distribution of responsibilities amongst the project members (software design, mechanical design, financial analysis, etc.). Suppose, two people or agents are communicating together. For them to understand the communication they must use the ontology that is understood by each other precisely,

otherwise they may not understand each other. Similarly, to share the information stored in a computer either the users must understand the ontology of which it is communicating to them, or the computer must understand the ontology of the user.
Pre-defining the commonly used ontology for many domains makes it easier and possible for agents to use or access and share knowledge. While such approaches for knowledge sharing are very useful for common objects, domains, or concepts, they tend to hinder creativity, or to increase the human errors in specialized areas or domains. An alternative approach to knowledge sharing without sacrificing the agent's own ontology is called view-point.

VIEW-POINT

We propose an alternative approach to achieve knowledge sharing without sacrificing the agent's own ontology. View-point is commonly understood as one's perspective or conceptualization. Two view-points of the same object from different agents may not be identical.

Example

Consider a design of a device. Project manager is concerned with the overall cost of the unit while the design engineers are concerned with modeling the expected behavior, realizing it while satisfying most of the important design constraints which include the total weight of the unit. The engineer who is responsible for SMR&QA is concerned about the reliability of the device, backup redundant units, the ease of replacement of the defective units, etc. The production manager is concerned with materials, capacity of the plant, subcontracting or to develop in house, etc..

The differences between views can be attributed to the following factors: Different agents are interested in different aspects or features of the same object; therefore they see or view the object differently. Different agents have different conceptualizations of the same object; worse yet, they may use different ontologies to describe the same feature of an object.

To study and understand the problem, we have formalized the notion of point-of-view. Let O be an object in the world. An object can be concrete, or abstract, primitive, or composite, or it can even be fictional. Suppose there are two agents L and M. Let O_L, and O_M be respectively the L's and M's conceptualization of O. If I_L, and I_M respectively be the interpretation of the agents L and M then we have $I_L(O) = O_L$, and $I_M(O) = O_M$. If the agents, L and M, understand or know each other's interpretation then they can understand each other's conceptualization of the objects. For any meaningful communications we need to add function constants and relation constants. In such expanded environment the agents must understand the semantics of the function and the relation constants. In order to achieve such understanding the agent must know the other agent's believes and knowledge that is not feasible. Therefore, we provide a restricted version of multiple view-points by making the interpretation of all the constant

to be public, and defining all the functional and relational constants in terms of some well known public ontology
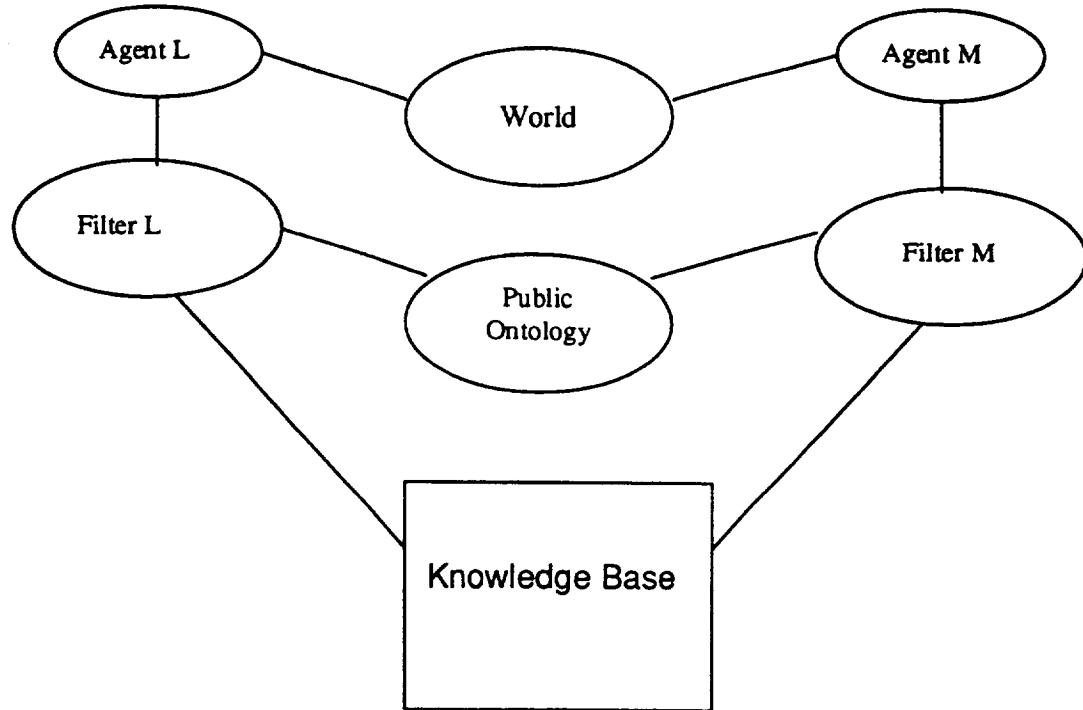
Our solution for sharing knowledge or information is shown in the above diagram.

SUMMARY AND CONCLUSION

We have investigated several temporal models for the purpose of using it to capture the temporal knowledge associated with devices and their behaviors. For an excellent survey on temporal knowledge representation and reasoning, refer to Hayes' [Hay95] recent work. We established the following desirable properties for the temporal representation: representation of explicit time, supporting time points and intervals, representation of qualitative and quantitative constraints. The temporal ontology should be minimal and primitive so as to support any complex ontologies that may be built from the primitive. We were unable to find any previous work that meets our requirements. We, therefore, developed a new theory for time that integrates time points and intervals. We have also proposed a primitive temporal ontology from which any complex ontologies can be built. We have shown that other ontologies can be rewritten using our ontology. Our theory of time subsumes theories of time of Allen and Hayes, and Ma et al's.

In this project we have also investigated the notion of knowledge sharing among various groups of people with diverse backgrounds and needs, and responsibilities. We have proposed a practical framework for sharing knowledge.

For future work we propose the following investigations: (1) temporal constraint propagation and implementation, (2) feasibility study and other issues on knowledge sharing.

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