

ON THE PROBLEMS OF TIME, RETRIEVAL OF TEMPORAL
RELATIONS, CAUSALITY, AND CO-EXISTENCE*

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ABSTRACT

Intelligent question-answering programs do more than retrieve "raw" data; they make deductive inferences in order to return all valid responses. They report logical inconsistencies, possibly at the data input phase. Similarly, more information is requested from the user if a question asked proves to be ambiguous.

A question-answering system of the above type has been designed and implemented. Besides retrieving explicit and implicit temporal relations, the system discovers potentially causal relationships which also satisfy different time restrictions. Questions concerning a generalized concept of co-existence can also be answered. It is hoped that programs of a similar nature will become of much pragmatic use to researchers in physics, chemistry, biology, and so on, in evaluating complex, interrelated experimental data. Several additional applications for this type of programs are mentioned, ranging from problems in criminology to air traffic control. The Associative Memory, Parallel Processing Language, AMPPL-II, was found rather satisfactory for the project.

It is finally suggested that the system being described could serve as a component to a complex cognitive mechanism.

INTRODUCTION

There is an overwhelming abundance of complex events in "real" life. One might look upon science as a mechanism to help escape from the unexplained chaos. The basic assumption of the reductionist is inherent in all scientific investigations -- the existence of (simple) laws that govern natural phenomena.

In the interpretation of scientific data, working hypotheses are formed that are based on prima facie relations between patterns of events. The discovery of causality calls for the testing of these working hypotheses under a wide variety of

conditions. The logic of the concept of causality requires that the scientist should, first of all, sort out predecessor-successor relations.*** It seems obvious when huge masses of time-relevant data are to be analyzed, the computer should come to the scientist's aid in this non-trivial task. Yet, the passage of time, one of the most salient of human experiences, has received relatively little study in question-answering programs. The time variable is at the heart of practically all physical, biological, and psychological events. It is, therefore, the fundamental variable in every "process-descriptive" model.****

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**Both authors worked on the design of the system. The first author (N.W.F.) suggested and elaborated the subject matter and was responsible for the writing of this paper. Many refinements and improvements are due to the second author (D.C.), who has also done all the programming. An enlarged version of this work, in the form of a Master's Project, will be submitted to the State University of New York at Buffalo in partial fulfillment of the requirements of David Chen's M.S. degree.

***Certain paradoxical results of the theory of relativity, that would be of no concern to us here, render it possible to send signals into the past. See, for example, Y. P. Terletskiy: Paradoxes in the Theory of Relativity (Transl. B. Hoffmann; Plenum Publ. Corp.: New York, 1968).

****According to the usual distinction made by Systems Theory (see, for example, Simon [4]), systems can often be described by two types of models. The state-descriptive model tells how a system behaves now, whereas the process-descriptive model provides information as to how and through what stages it has developed from an initial configuration to the current one. The latter is usually more valuable, not only because it enables the researcher to extrapolate to the future but, also, because it gives insight into the mechanisms operating within the system.

The present work is aimed at all possible temporal relations between time-dependent events -- an expandable but well-defined universe. The framework of a categorical structure is built during the input phase. As more and more questions are asked, this framework is filled up with directly given and inferred data, and relations between them. This fact and many other aspects of the project are in analogy with human cognition although no attempt was made to simulate the latter. Inconsistencies and missing information are discovered and reported back to the user. (Missing information is manifested, in an indirect manner, by returning a larger set of answers.) The objectives of this work were briefly described in [1].

Finally, we note that we do not wish to enter the realm of philosophy in this work. The meaning and the role of time, in the abstract sense, are beyond the scope of these investigations.

ON TIME-DEPENDENT EVENTS AND TEMPORAL RELATIONS

We shall not be concerned here with stochastic phenomena. (As Einstein said: "The dear God does not play with dice".) The blurring effect of probability distributions is replaced by the following paradigm:

Event E_i has $\begin{bmatrix} \text{relevant} \\ \text{irrelevant} \end{bmatrix} \begin{bmatrix} \text{starting time} \\ \text{duration} \\ \text{finishing time} \end{bmatrix}$

where members of the second bracket may assume either attribute of the first bracket. Meaningful examples can be found for each of the eight ($=2^3$) possible cases. The distinction between relevancy and irrelevancy is indeed useful since chronological data in real life are often incompletely defined because of a lack of information, measurement errors, conflicting data sources, etc.

Further, partial specification of chronological data can be given in the 'irrelevant' case by saying

Event E_i occurred $\begin{bmatrix} \text{fully} \\ \text{partially} \end{bmatrix} \begin{bmatrix} \text{before} \\ \text{during} \\ \text{after} \end{bmatrix}$ event E_j

Let us now define two types of events:

(1) A point event takes place momentarily. However, its effect, which is not necessarily contiguous to the event, may be lasting. For example, 'to wake up' is a point event (although some

people may disagree with this...) and its effect 'to be awake' is lasting. Or, 'John starts reading' is, again, a point event which is followed by a lasting action. It is more difficult to find a point event with no subsequent effect. A moot one is, for example: 'He decided not to do anything'.

(2) A duration event has distinct starting and finishing times, and a duration between the two. There are a few exceptions. Explicit or implicit truth statements often do not have starting and finishing times. Unless one accepts religious teachings or the Big Bang theory of cosmology, the "world" has no starting time.

In order to be realistic about simultaneity, we have assumed a quantized time scale. In the computer program described later, one minute is the shortest measurable time interval. (This represents no restriction because a definable, arbitrary time unit is also available; see later.) Further, we have considered the time co-ordinate unbounded in both directions.

For the sake of some discussion, let us adopt in this section the convention that lower case letters refer to time points and upper case letters to time intervals. The letter 'e' will have a special significance, e will denote a point event and $\bar{E}$ a duration event.

Suppose $\bar{e}_1$ takes place at $\underline{t}_1$ and $\bar{e}_2$ at $\underline{t}_2$. We can then say

$\bar{e}_1$ occurs $\begin{bmatrix} \text{before} \\ \text{simultaneously with} \\ \text{at about the same time as} \\ \text{after} \end{bmatrix} \bar{e}_2$ iff $\begin{bmatrix} \underline{t}_1 < \underline{t}_2 \\ \underline{t}_1 = \underline{t}_2 \\ \underline{t}_1 \approx \underline{t}_2 \\ \underline{t}_1 > \underline{t}_2 \end{bmatrix}$

Suppose both $\bar{e}_1$ and $\bar{e}_2$ occurred during $\bar{T}$, that is $\underline{t}_1, \underline{t}_2 \in \bar{T}$. Then $\bar{e}_3$, related to $\underline{t}_3$, must have occurred during $\bar{T}$, if (weak Condition)

$$\underline{t}_1 \leq \underline{t}_3 \leq \underline{t}_2 \quad \text{or} \quad \underline{t}_1 \geq \underline{t}_3 \geq \underline{t}_2.$$

Also, $\bar{T}_1$ precedes $\bar{T}_2$ iff

$$\underline{t}_1 < \underline{t}_2 \text{ for all } \underline{t}_1 \in \bar{T}_1 \text{ and all } \underline{t}_2 \in \bar{T}_2.$$

When $\bar{T}_1$ is neither before $\bar{T}_2$ nor after $\bar{T}_2$, there is a partial or full overlap between them. Let s denote starting times, f finishing times and D durations. We then have with these events

$$s_i + D_i = f_i$$

for $i = 1$ and 2

Partial overlap is found between $\bar{E}_1$ and $\bar{E}_2$ iff

$s_i < s_j < f_i$ and $f_i < f_j$,
 for $(i,j) = (1,2)$ or $(2,1)$
 (Some of the $<$ signs could be replaced selectively by $<$ or $\leq$ but we shall ignore this now for the sake of notational simplicity.)

Full overlap occurs iff

$s_i < s_j < f_j < f_i$
 for $(i,j) = (1,2)$ or $(2,1)$

The two events are contiguous iff

$s_i < f_i = s_j < f_j$
 for $(i,j) = (1,2)$ or $(2,1)$

Finally, E_1 and E_2 are disjoint iff

$f_i < s_j$
 for $(i,j) = (1,2)$ or $(2,1)$

In the above definitions, all parameters appear to be time-relevant. In the case of approximate time specifications, whether absolute or relative to other events, the system must make proper allowances for the changes in the retrieval logic.

One can establish a simple logical system, on the basis of the previous definitions, using standard first-order predicate calculus plus axioms with regard to transitivity, irreflexivity, and existence of predecessors and successors. This enables the system to make simplifications on and inferences concerning temporal relations between any two of three or more events.

THE PROGRAM

It has been our intention to allow a most general input mode. The data to be used should be checked for consistency at a stage as early as possible. At the beginning of the program, the skeleton of a complex, hierarchical and relational data structure is established. This would then be filled in as need arises through the questions asked. We have not frowned upon redundancy in stored information whenever it shortened or simplified processing.

Many difficult decisions had to be made in regard to input mode, internal representation, data manipulation, search processes, etc. Several times, we had to give up a certain avenue and start on another one. The following represents the current state of affairs, which we may improve and expand yet.

The program is divided into three major components, the input phase, the data structuring phase, and the question answering phase. These will now be discussed briefly.

(1) The input phase is concerned with three types of information:

(a) The user defines the symbolic components of an event in the form

(EVENT, EVENTNAM, STARTIM, FINITIM, LENGTH)

where EVENT is a reserved word to denote symbolic specification; EVENTNAM, STARTIM, FINITIM, LENGTH are symbolic names of the event, its starting and finishing time, and its duration, respectively.

(b) The user also sets up temporal relations between symbolically defined time quantities by the predicates

(ANTE, T1, T2, T3, ... Tn)

(EQUI, T1, T2, T3, ... Tn)

(CFQUI, T1, T2, T3, ... Tn)

Here, the first statement means that T_1 is the antecedent of T_2 , which is the antecedent of T_3 , etc.; the second one means that $T_1, T_2, T_3, \dots$ are equitemporal; and the third one that $T_1, T_2, T_3, \dots$ are circa-equitemporal. (The T 's refer only to time points in case of ANTE.)

(c) Finally, the input phase binds the time parameters of the events, already symbolically specified, to numerical values. Several possibilities exist here. We can either use "natural" units (for a time point, for example, 1970 - DECEMBER - 31 - 11 o'clock - 10 minutes, written in the proper format), or "defined" units the zero point and length of which are arbitrarily set by the user to suit, say, particular experimental conditions (a time period, for example, 870 units long). In one body of information, the two cannot be mixed.

Further, whether natural or defined units are used, a time quantity can be numerically specified either directly, in absolute terms, or indirectly, i.e. relative to another time quantity. Verbalized examples of this are: 'Event A started 15 units before time point T0', or 'Event C is 42 days longer than interval D5'.

Some comments are needed here. Since the number of days in a year (cf. leap years) and the number of days in a month are not constant, whenever a time interval is to be directly specified in combined units (say, years, months, days, hours, minutes), the user must define a dummy event with starting and finishing times so determined that its duration is the right one.

There are eight modes of indirect specification, as indicated by an input parameter. The relative time length that has to be added to or subtracted from another time quantity can be given in

minutes,
hours,
days,
months,
years

packed year-month-day-hour-minute mode,
packed month-day mode, and
packed day-minute mode.

In the last three cases, the addition or subtraction starts at the rightmost unit and proceeds to the left, for the sake of unambiguity. Proper care has been taken of the transition between the Julian and Gregorian calendars, the "missing" year between 1 B.C. and 1 A.D., and similar idiosyncrasies.

There is an important, multipurpose, reserved word, DELTA. In the input phase, it denotes an irrelevant time quantity, for which no numerical specification is to be expected. We would put, for example, for time points TA and TB

(EQUI, DELTA, TA, TB)

saying that they both are irrelevant (but not equitemporal!) DELTA can also be put directly, in lieu of any symbolic name of an event being asked about. Examples to follow will make this point clear.

Nested specifications are also possible. A verbalized example of this is: 'Event A started 20 minutes before the event ended that started at 8 a.m.'

The first stage of checking for inconsistencies is done as soon as possible during the input phase. Contradictions may occur within or between the symbolically and numerically given data. If found, these are reported back to the user and the program aborts.

Finally, if one of the three time quantities, characterizing a duration event, starting time, finishing time and length, is missing, it is computed and recorded at this stage. In the cases in which partial chronological information is given in terms of restrictions, longest or shortest possible time lengths are computed and appropriately marked whenever possible.

(2) The data structuring phase transforms the input information into an expandable format, which is particularly suitable for the last phase, during which questions are asked and answered.

Some of the SLIP list structures established initially are expanded, some others are transcribed into a sequence of content-addressable and parallel-processable AMPPL-II Relations (see [2] or [3]) and then destroyed. Events are

characterized, individually and collectively, in reference to each other. Numerical and symbolic data are used to generate inferences and, again, inconsistencies are discovered and reported back to the user.

(3) The question-answering phase consists of two parts. The first one is the ANALYZER. It dissects each question and expands it into its elementary components. The ANALYZER is essentially a recursive procedure in view of the fact that complex, nested questions can also be asked. The second part is an executive routine that calls in special functions for each question component. These functions can be divided into five groups:

(a) To retrieve the symbolic names of the starting time, finishing time and length of a given event.

(b) To establish whether a particular relation between two time quantities (points or duration) or two events is true. The possible relations are as follows.

(i) between two time points:

one time point is before, at the same time as, or at about the same time as the other one;

(ii) between two time durations:

one time duration is longer than, of equal length as, of about equal length as, or shorter than the other one;

(iii) between a time point and an event: the time point is exactly or about at the same time as the event's starting, finishing point; it occurred before, during or after the event;

(iv) between a duration and an event: the duration is longer than, of equal length as, or of about equal length as, or shorter than the event;

(v) between two events:

one event is partially, completely antecedent of the other; it co-exists with (i.e., partially or completely overlaps), covers the other; it is contiguous to, identical to, about identical to, longer than, of equal length as, of about equal length as, or shorter than the other one.

If one of the time quantities or events is specified as DELTA, then all entities, either on a list specified by the user or in the universe of the system, are searched for those that satisfy the given relation. On the other hand, if a relation is specified as DELTA then all valid relations between the given entities are retrieved.

(c) To find the extremum (extrema) of certain conditions. The latter can be earliest, latest; longest, shortest; closest.

The first two refer to the possible range of (irrelevant) time points. The next two refer to time durations or events with one or two irrelevant limiting end points. The last condition, 'closest', may refer to time points, in which case there is no ambiguity. However, the user may also look for an event (or events) whose length is the closest to a given duration. Or else, he may specify one event and look for another one that has the maximum length of overlap with the given event. If there are several, which for example completely cover the latter, the system can select the shortest event of these.

In general, all potentially acceptable answers are returned when the information available is not sufficient to decide on their acceptability.

(d) To establish chains of events where the mode of chaining must satisfy certain restrictions, such as

the successive events must be contiguous, i.e. the finishing time of the antecedent is the starting time of the successor;

the successive events must partially or completely overlap each other;

either the starting or the finishing times, specifiable by parameters, must be consecutive with successive events;

the same as above but certain time durations at least must elapse between consecutive starting or finishing times (cf. problems of causality);

(e) To answer questions concerning a generalized concept of co-existence. There are, say, three sets of events given. The program will find a subset of the first set, each member of which must co-exist (partial or complete overlap) with at least one member of the second set of events and must not co-exist (disjoint events) with any member of the third set. Or, more generally, we can look for a subset of the first set, each member of which must co-exist with at least one member of an arbitrary number of sets and must not co-exist with any single member of another arbitrary number of other sets of events.

Finally, we note two additional types of side conditions that can be specified for the results. These are

the logical conditions:

for all on a list specified or anywhere in the system (cf. the universal quantifier),

find one (cf. the existential quantifier),

Boolean AND, OR and NOT of sets of events; and

the time conditions:

the resulting time quantity or event must occur before or after a certain time point,

before, during or after an event, within a certain time length.

EXPERIENCE WITH THE PROGRAM

Programming was done on a CDC 6400, with which SLIP and AMPPL-II have been resident on the system disk. Only those subprograms are called into the core that are needed in the program. The total code occupies less than 15% core memory. The running time, of course, depends on the size of the data base and on the complexity (levels of nesting) of the questions asked.

With a moderately sized data base and questions of the type below, an answer was obtained on the average in less than half a second if the information was directly available. However, if logical inferences concerning nested questions had to be made, and the data structure had to be updated, the time required for an answer may take as long as 40 seconds (see later).

To illustrate the notation to be employed by the user, we give a list of simple questions and a few nested ones. We note that the same question can often be formulated in several different ways.

(1) Could the start of event E_1 cause event E_2 ?

(RELTRUE,BEFORE,P,(STARTIM,E1),E,E2).

Here P means that the starting time of event E_1 is a time point and E means that E_2 is an event.

(2) Does event E_1 co-exist (partial or complete overlap) with event E_2 ?

(RELTRUE,CØEXIST,E,E1,E,E2).

(3) Could the completion of event E_1 immediately cause event E_2 ?

(RELTRUE,CØTIGUF,E,E1,E,E2).

(4) Is event E_1 longer than event E_2 ?

(RELTRUE,LØNGER,E,E1,E,E2).

(5) Which events are such that

(a) their start could cause event E_1 ?

(RELTRUE,BEFORE,P,(STARTIM,DELTA),E,E1);

(b) they co-exist with event E_1 ?

(RELTRUE,CØEXIST,E,DELTA,E,E1);

(c) their completion could cause event E_1 ?

(RELTRUE,BEFORE,P,(FINIM,DELTA),E,E1);

(d) their duration is longer than that of event E_1 ?

((RELTRUE, LONGER, E, DELTA, E, E1).

(6) Are there sequences of events [(a) only consecutive, (b) only contiguous, or (c) also overlapping] that lead to event E_1 , and if so, which ones? (N.B. chain of causally connected events.)

(a) (CHAIN, CONSECUTIVE, FINTIM, STARTIM, E1);

(b) (CHAIN, CONTIGUE, E1);

(c) (CHAIN, OVERLAP, E1).

(7) Given three sets of events,

$\{E_1\} : \{E_{11}, E_{12}, \dots, E_{1m}\},$
 $\{E_2\} : \{E_{21}, E_{22}, \dots, E_{2n}\},$
 $\{E_3\} : \{E_{31}, E_{32}, \dots, E_{3p}\},$

find a subset $\{E_4\}$ of $\{E_1\}$, such that each of its members co-exists (partial or complete overlap) with at least one member of $\{E_2\}$ and does not co-exist with any member of $\{E_3\}$. Notationally,

$\{E_4\} := \{E_1\} \otimes \{E_2\} \neg \otimes \{E_3\}.$

(COEXISTENC, (E11, E12, ...), (E21, E22, ...),

(BUTNOT, E31, E32, ...)

or

((E1, E11, E12, ...), (E2, E21, E22, ...), (E3, E31, E32, ...), (COEXISTENC, E1, E2, (BUTNOT, E3)))

(8) From among a set of events $\{E_1\} : \{E_{11}, E_{12}, \dots\}$, which events last shortest and longest?

(EXTREMUM, E, LONGEST, (E11, E12, ...));

and

(EXTREMUM, E, SHORTEST, (E11, E12, ...)).

(9) From among a set of events $\{E_1\} : \{E_{11}, E_{12}, \dots\}$, which event starts or finishes earliest or latest?

(EXTREMUM, P, EARLIEST, ((STARTIM, E11),

(STARTIM, E12), ...));

(EXTREMUM, P, LATEST, ((STARTIM, E11),

(STARTIM, E12), ...));

(EXTREMUM, P, EARLIEST, ((FINTIM, E11),

(FINTIM, E12), ...));

(EXTREMUM, P, LATEST, ((FINTIM, E11),

(FINTIM, E12), ...)).

(10) From among a set of events $\{E_1\} : \{E_{11}, E_{12}, \dots\}$, which event lasts closest to a time interval?

(EXTREMUM, E, CLOSEST, D, R, (E11, E12, ...)),

where R is the name of a certain time duration and D indicates duration.

(11) We can restrict potential causal relationships between two events, E_1 and E_2 , by saying that E_2 must start or finish at least t_{12} time units after E_1 starts or finishes. Suppose there is a matrix of restrictions given, $\|t_{ij}\|$, where the element t_{ij} is the minimum time duration that must elapse between, for example, the finishing time of event E_i and the starting time of E_j for the two events to be causally connected. The following will produce all potentially causal chains of this type leading to event R .

(CHAIN, DEFINED, FINTIM, STARTIM, (E1, E2, E3, ...), (T12, T13, ... T1R, T21, T23, ... T2R, ... T31, T32, ... T3R, ...), R).

(We note that work is not completed on the answer to this type of question.)

(12) Which events take place between the end of event E_1 and the start of event E_2 ?

((INTERSECTION (RELTRUE, ANTF, P, (FINTIM, E1), P, (STARTIM, DELTA)), (RELTRUE, AFTER, P, (STARTIM, E2), E, DELTA)))

or

((RELTRUE, BEFORE, P, (FINTIM, E1), E, DELTA, (RELTRUE, ANTF, P, (FINTIM, DELTA), P, (STARTIM, E2)))).

(13) Which is the longest event that lies between the finishing time of event E_1 and the starting time of event E_2 ?

(EXTREMUM, E, LONGEST, (RELTRUE, BEFORE, P, (FINTIM, E1), E, DELTA, (RELTRUE, BEFORE, P, (FINTIM, DELTA), P, (STARTIM, E2)))).

(14) Suppose there are two sets of events, members of which co-exist with events E_1 and E_2 , respectively. Find the temporal relation between the finishing time of the latest event (i.e. the one that ends the latest) in the first set and the starting time of the earliest event (i.e. the one that starts the earliest) in the second set.

```
(PELTRUE,DELTA,P,(PINTIM,(EXTREMUM,E,
LATEST,(PELTRUE,CØEXIST,E,DELTA,E,E1))),
P,(STARTIM,(EXTREMUM,E,EALIEST,(PELTRUE,
CØEXIST,E,DELTA,E,E2)))).
```

A few more points are to be noted here. The set-theoretic functions

INTERSECTION and UNION

can be nested in any of the question forms.

The function

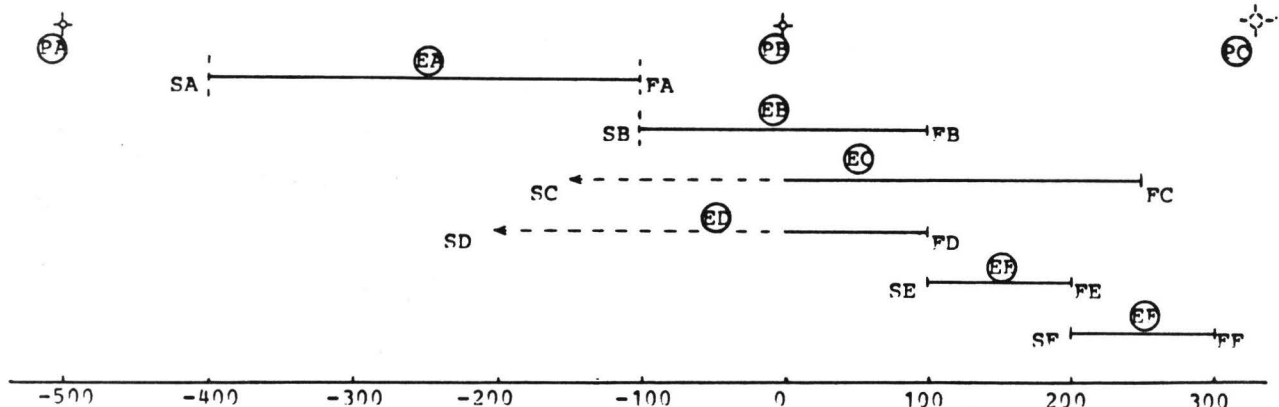
```
(VALUE,TA,TB,...)
```

retrieves numerical values of an indefinite number of time points and/or durations. The symbolic names of these may be referenced indirectly in a nested form. For example, if we wish to find the durations of events T1 and T2, and the times of occurrence of those point events that happened before point event P1, we out

```
(VALUE,T1,T2,(PELTRUE,ANTE,P,DELTA,P,P1))
```

Whenever exact values are not available, a set of routines is called upon to compute the possible time range of the time points or durations involved.

The following diagram and excerpts from a computer output represent a run with a small data base:



Event names are encircled. There are three point events, PA, PB, and PC, and six duration events, EA, EB, EC, ED, EE, and EF. The following symbolic and numerical specifications are to be given to the system:

ANTE: (PA,SA); (SD,FA,SB,PB); (FF,PC); (SD,SC,FA).

EQUI: (FB,FD,SE); (FE,SF).

CEQUI: (FA,SB).

PA=-500, PB=0, FB=100*, FC=250, FD=100*, SE=100,

FE=200, LE=100*, SF=200*, FF=300*, LF=100.

(Those marked with an asterisk are values computed by the system.)

THE FOLLOWING FACTS ARE GIVEN TO THE SYSTEM :

SIX EVENTS AND THREE TIME POINTS ARE INVOLVED IN THE FOLLOWING EXAMPLE. THE QUESTIONS ARE NOT NECESSARILY MEANINGFUL, THEY ARE USED TO DEMONSTRATE WHAT THE SYSTEM CAN DO.

(WHICH, IN THE LIST FORM, IS :)

```
(( (EVENT,EA,SA,FA,LA) (EVENT,EB,SB,FB,LB) (EVENT,EC,SC,FC,LC)
(EVENT,ED,SD,FD,LD) (EVENT,EE,SE,FE,LE) (EVENT,EF,SF,FF,LF) )*)
```

(The SLIP system requires an asterisk at the end of every list structure to be inputted.)

WE WANT TO INPUT THE LEAST AMOUNT OF INFORMATION ONLY. IN ORDER TO SEE HOW THE SYSTEM COMBINES ABSTRACT (SYMBOLIC) AND NUMERICAL INFORMATION, SOME OF THE ENTITIES WILL BE GIVEN NUMERICAL VALUES.

WE DEFINE 3 TIME POINTS PA, PB, AND PC FOR REFERENCE. PA ANTECEDES THE STARTING TIME OF EVENT EA. TIME POINT SD ANTECEDES FA THAT ANTECEDES SB THAT ANTECEDES PB. THE FINISHING TIME OF EVENT EF OCCURS BEFORE PC. FB, FD, AND SE ARE EQUI-TEMPORAL TIME POINTS. FA AND SB ARE CIRCA-EQUI-TEMPORAL. FE IS EQUI-TEMPORAL TO SF. TIME POINTS SD, SC, AND FA ARE IN THIS CHRONOLOGICAL ORDER. SE, FE, FC, LF, PA, AND PB WILL BE GIVEN NUMERICAL VALUES.

(WHICH, IN THE LIST FORM, IS :)

```
((PA,PB,PC) (ANTE,PA (STARTIM,EA)) (ANTE,SD,FA,SB,PB) (ANTE,(FINTIM,EF) PC)
(EQUI,FB,FD,SE) (CEQUI,FA,SB) (EQUI,FE,SF) (ANTE,SD,SC,FA) )*
```

THE FOLLOWING IS THE TABLE OF RECOGNIZED EVENTS.

```
EVENT EA HAS BEEN DEFINED WITH STARTIM SA, FINTIM FA AND LENGTH LA.
EVENT EB HAS BEEN DEFINED WITH STARTIM SB, FINTIM FB AND LENGTH LB.
EVENT EC HAS BEEN DEFINED WITH STARTIM SC, FINTIM FC AND LENGTH LC.
EVENT ED HAS BEEN DEFINED WITH STARTIM SD, FINTIM FD AND LENGTH LD.
EVENT EE HAS BEEN DEFINED WITH STARTIM SE, FINTIM FE AND LENGTH LE.
EVENT EF HAS BEEN DEFINED WITH STARTIM SF, FINTIM FF AND LENGTH LF.
```

Following this, the system prints out five list structures: ANTE (precedence ordering), LSTEQ (equitemporal), LSTCEQ (circa-equitemporal), TPL (recognized time points), and TDL (recognized time durations). For the sake of brevity, these are omitted here. The relevant temporal relations are then transferred to the Simulated Associative Memory.

THE FOLLOWING ASSIGNMENT OF NUMERICAL VALUES IS RECOGNIZED.

PA	R	PB	-500
SE			100
	SE HAS VALUE	100.	
FE			200
	FE HAS VALUE	200.	
FC	R	PA	750
SF	R	SF	0
LF			100
	LF HAS VALUE	100.	
PB			0
	PB HAS VALUE	0.	
	PA HAS VALUE	-500.	
	FC HAS VALUE	250.	
NO-MORE			-0
	IT IS FOUND THAT FB HAS VALUE	100.	
	IT IS FOUND THAT FD HAS VALUE	100.	
	IT IS FOUND THAT SF HAS VALUE	200.	
	IT IS FOUND THAT LE HAS VALUE	100.	
	IT IS FOUND THAT FF HAS VALUE	300.	

The above is partly the echo of the input, partly values inferred by the system. Next, a chronological ordering of time points (list NAL) is printed but is omitted here.

THE NEXT QUESTION IS :

FIND POSSIBLE CHAINS OF NON-OVERLAPPING AND CONSECUTIVE EVENTS THAT LEAD TO EVENT EF.

(WHICH, IN THE LIST FORM, IS :)

((CHAIN,CONSECUTIV,FINTIM,STARTIM,EF))*

ONE OF THE POSSIBLE CHAINS IS :
EA, EF.

ONE OF THE POSSIBLE CHAINS IS :
EA, EB, EF.

ONE OF THE POSSIBLE CHAINS IS :
ED, EF.

NO MORE CHAIN.

WE HAVE SPENT 27.7940 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FIND POSSIBLE CHAINS OF OVERLAPPING EVENTS THAT LEAD TO EVENT EF.

(WHICH, IN THE LIST FORM, IS :)

((CHAIN,CVERLAP,EF))*

ONE OF THE POSSIBLE CHAINS IS :
ED, EC, EF.

NO MORE CHAIN.

WE HAVE SPENT 18.0680 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FIND POSSIBLE CHAINS OF CONTIGUOUS EVENTS THAT LEAD TO EF.

(WHICH, IN THE LIST FORM, IS :)

((CHAIN,CONTIGUE,EF))*

ONE OF THE POSSIBLE CHAINS IS :
EB, EE, EF.

ONE OF THE POSSIBLE CHAINS IS :
ED, EE, EF.

NO MORE CHAIN.

WE HAVE SPENT 42.7980 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

LIST ALL TIME POINTS THAT ANTECEDE PC AND ARE ANTECEDED BY PA.

(WHICH, IN THE LIST FORM, IS :)

((RELTRUE,ANTE,P,DELTA,P,PC,(RELTRUE,ANTE,P,PA,P,DELTA)))*

THE FOLLOWING IS THE ANSWER :

PB, FF, SF, FE, CE, FD, FC, FB, SB, FA, SA.

WE HAVE SPENT 21.5220 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FROM AMONG EVENTS EC,EB,EE,ED,EA, AND EF, SELECT THOSE THAT CO-EXIST WITH EB OR EC. FROM THIS GROUP, DELETE THE EARLIEST ONE OF THOSE THAT ARE COMPLETELY ANTECEDED BY EVENT EA.

(WHICH, IN THE LIST FORM, IS :)

((NOT (COEXISTENC (EC,EB,EE,ED,EA,EF) (EB,EC)) (EXTREMUM,EARLIEST,E,(RELTRUE,COMPANTE,E,EA,E,DELTA)))) *

THE FOLLOWING IS THE ANSWER :

EF, EA, ED, EE, EC.

WE HAVE SPENT 37.8020 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FIND THOSE EVENTS THAT START AFTER STARTING TIME OF EA AND WHOSE FINISHING TIME IS COVERED BY EVENT EC.

(WHICH, IN THE LIST FORM, IS :)

((INTERSECTION (RELTRUE,BEFORE,P(STARTIM,EA)E,DELTA) (RELTRUE,BETWEEN,P(FINTIM,DELTA),E,EC))) *

THE FOLLOWING IS THE ANSWER :

EE, EB.

WE HAVE SPENT 16.8860 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FIND THE LONGEST AND THE SHORTEST EVENTS OF EB,EC,EE,EF, AND ED.

(WHICH, IN THE LIST FORM, IS :)

((EX,EB,EC,EE,EF,ED) (UNION (EXTREMUM,LCNGEST,E,EX) (EXTREMUM,SHORTEST,E,EX))) *

THE FOLLOWING IS THE ANSWER :

EF, EE, ED, EC.

WE HAVE SPENT 5.5760 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FIND VALUES OF TIME POINT PA, OF THOSE TIME POINTS THAT OCCUR AFTER PA, AND OF THOSE TIME DURATIONS THAT ARE EQUAL TO OR LONGER THAN LE (THE LENGTH OF EVENT EE).

(WHICH, IN THE LIST FORM, IS :)

((VALLE,PA,(RELTRUE,ANTE,P,PA,P,DELTA) (RELTRUE,EQUAL,D,LE,D,DELTA) (RELTRUE,LONGER,D,DELTA,D,(LENTH,EE)))) *

THE FOLLOWINGS ARE THE ANSWERS :

THE VALUE OF PA IS -500.
 THE RANGE OF VALUE OF SA IS FROM -500 TO 0.
 THE RANGE OF VALUE OF FA IS FROM -500 TO 0.
 THE RANGE OF VALUE OF SB IS FROM -500 TO 0.
 THE VALUE OF FB IS 100.
 THE RANGE OF VALUE OF SC IS FROM -INFINITY TO 0.
 THE VALUE OF FC IS 250.
 THE RANGE OF VALUE OF SD IS FROM -INFINITY TO 0.
 THE VALUE OF FD IS 100.
 THE VALUE OF SE IS 100.
 THE VALUE OF FE IS 200.
 THE VALUE OF SF IS 200.
 THE VALUE OF FF IS 300.
 THE VALUE OF PB IS 0.
 THE RANGE OF VALUE OF PC IS FROM 300 TO INFINITY.
 THE VALUE OF LE IS 100.
 THE VALUE OF LF IS 100.
 THE RANGE OF VALUE OF LB IS FROM 100 TO 600.
 THE RANGE OF VALUE OF LC IS FROM 250 TO INFINITY.
 THE RANGE OF VALUE OF LD IS FROM 100 TO INFINITY.

WE HAVE SPENT 11.7780 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

FROM AMONG EVENTS EA, EC, ED, EE, AND EF, SELECT THOSE THAT CO-EXIST WITH
 EVENTS ED OR EC AND DO NOT CO-EXIST WITH EVENT EE.

(WHICH, IN THE LIST FORM, IS :)

((COEXISTENC,(EA,EC,ED,EE,EF) (ED,EC) (BUTNOT,EB)))*

THE FOLLOWING IS THE ANSWER :

EF, EE, EC, EA.

WE HAVE SPENT 43.6560 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

THIS EXAMPLE DEMONSTRATES SOME FURTHER USE OF THE FUNCTIONS EXTREMUM AND
 UNION.

(WHICH, IN THE LIST FORM, IS :)

((UNION (EXTREMUM, LONGEST, D, (RELTRUE, LONGER, D, DELTA, E, EF)) ,
 (EXTREMUM, EARLIEST, P, (SA, (STARTIM, EC) (FINTIM, EF), SD, SB)) (EA, EF, EB)))*

THE FOLLOWING IS THE ANSWER :

EB, EF, EA, SA, LD, LC, LB.

WE HAVE SPENT 2.4400 SECONDS ON THIS QUESTION.

NO MORE QUESTION, PROCESS TERMINATES.

To illustrate date-time specification, a data base similar to the one in the
 first example was used with different values. We have, for instance,

SE = 1960 01 01 (January 1, 1960), FF = 1960 12 31. LE = 365 (computed; 1960 leap year)

SF = 1960 12 31, FF = 1971 5 1. LF = 3772 days (eight regular and two leap years, the

five first months in 1971)

THE FOLLOWING ASSIGNMENT OF NUMERICAL VALUES IS RECOGNIZED.

FA			194001010000 8
	PA HAS VALUE	194001010000.	
PB			195001010000 8
	PB HAS VALUE	195001010000.	
FC			197001010000 8
	FC HAS VALUE	197001010000.	
SE			196001010000 8
	SE HAS VALUE	196001010000.	
FE			196012310000 8
	FE HAS VALUE	196012310000.	
FF			197105010000 8
	FF HAS VALUE	197105010000.	
NO-MORE			-0 *
	IT IS FOUND THAT FB HAS VALUE	196001010000.	
	IT IS FOUND THAT FC HAS VALUE	196001010000.	
	IT IS FOUND THAT SE HAS VALUE	196012310000.	
	IT IS FOUND THAT LE HAS VALUE	3650000.	
	IT IS FOUND THAT LF HAS VALUE	37720000.	

THE NEXT QUESTION IS :

FIND VALUES OF TIME POINT FA, OF THOSE TIME POINTS THAT OCCUR AFTER FA, AND OF THOSE TIME DURATIONS THAT ARE EQUAL TO OR LONGER THAN LE (THE LENGTH OF EVENT EE).

(WHICH, IN THE LIST FORM, IS :)

((VALUE,FA,(RELTRUE,ANTE,P,PA,P,DELTA) (RELTRUE,EQUAL,D,LE,D,DELTA)
(RELTRUE,LONGER,D,DELTA,C,(LENGTH,EE)))) *

THE FOLLOWINGS ARE THE ANSWERS :

THE VALUE OF FA IS	194001010000.	
THE RANGE OF VALUE OF SA IS FROM	194001010000 TO	195001010000.
THE RANGE OF VALUE OF FA IS FROM	194001010000 TO	195001010000.
THE RANGE OF VALUE OF SE IS FROM	194001010000 TO	195001010000.
THE VALUE OF FB IS	196001010000.	
THE VALUE OF FC IS	197001010000.	
THE VALUE OF FD IS	196001010000.	
THE VALUE OF SE IS	196001010000.	
THE VALUE OF FE IS	196012310000.	
THE VALUE OF SF IS	196012310000.	
THE VALUE OF FF IS	197105010000.	
THE VALUE OF PB IS	195001010000.	
THE RANGE OF VALUE OF FC IS FROM	197105010000 TO	INFINITY.
THE VALUE OF LE IS	3650000.	
THE RANGE OF VALUE OF LB IS FROM	3650000 TO	73050000.
THE RANGE OF VALUE OF LC IS FROM	73050000 TO	INFINITY.
THE RANGE OF VALUE OF LD IS FROM	3650000 TO	INFINITY.
THE VALUE OF LF IS	37720000.	

WE HAVE SPENT 16.1520 SECONDS ON THIS QUESTION.

NO MORE QUESTION, PROCESS TERMINATES.

FURTHER RESEARCH PLANNED

Besides tidying up some parts of the code, other things can yet be done. There appears to be two interesting lines of attack within the framework of this project.

First, we could investigate statistically defined associative structures. In other words, the more often a particular pattern of events is followed by another pattern of events, the more likely it is that a causal relationship connects the two. Positive and negative reinforcement processes could lead to hypotheses of different strengths. Cyclic or near-cyclic events should also be at work.

The second area of possible further investigations would be with reference to natural language input/output in a reasonably large subset of English. Some preliminary studies have already been conducted by Adrian Walker and one of the present authors (N.V.F.). It is, however, too early to report on these now.

As possible applications, a number of interesting ideas have come to our mind. Many crimes are committed with, and their temporary success depends on, split second precision (at least according to TV writers). Alibis may also depend on certain critical, highly time-dependent events. One might use this type of program to prove whether a particular crime could have been committed by a certain individual or several crimes by the same person, etc.

Turning to more mundane ideas, air traffic control must be exercised under dynamically changing conditions. The program at hand could serve as a component to a computerized system. The on-line optimization of traffic light timing in a metropolitan environment may also incorporate some of our ideas. The scheduling of reconnaissance missions is another potential area of application.

We also note here that this project is closely related to the problems of Critical Path Methods and PEPT. (See, for example, [5].) We may sometime look into the possibility of establishing a link between the two fields of study.

Finally, it should be pointed out that intelligent machines will necessarily have to evaluate dynamically changing environments. In order to act in an optimum manner, they must make hypotheses on causal relationships. It is suggested that the cognitive structure of such machines would contain processes similar to those described in this paper.

ACKNOWLEDGEMENT

The authors appreciate the referee's comments, and his pointing out the rich and exciting world of the calculus of tenses, and the logic of change, action and norms. (See Refs. [6]-[13].)

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APPENDIX

The Second Great Train Robbery

Chief Inspector Joshua Haqqerty of Scotland Yard looked straight into the face of his Programmer-Analyst, Miss Eleanore Langlev. He could hardly confound his frustration:

- All right, we are stuck. This is the first time my intuition has failed to give any b.... signal at all. If you think it may help to have a run of that Findler-Chen program with our data, I don't care - let's try it.

- Listen carefully. I am giving you all the essential information we are certain about. Well, let me tell it to you from the beginning.

- The Bank of England was to transfer some gold bullions, worth the sum of £40,000,000, to its secret Manchester vaults. The armoured lorries, under the expert leadership of the newly hired security chief, Mr. H. McNaughton, picked up the shipment at 4:25 p.m. Some of the lorries, carrying a fake load of light metal, went direct to Victoria Station. They stopped on the way for exactly 14 minutes in order to synchronize their arrival at the station with the other group of lorries that followed a carefully designed indirect route. However, as Mr. McNaughton tells us, the second group got into a bit of a traffic jam and arrived at Victoria Station only at 6:28 p.m., nine minutes later than scheduled.

- By 6:37 p.m., both the real and the fake loads were safely sitting in the armoured carriage under the close watch of McNaughton's ten toughest guards.

- The express train left right on time, at 6:49 p.m., to reach Manchester at 9:17 p.m. However, exactly six minutes after the train rolled out of Birmingham station, at 8:23 p.m., it screeched to a sudden stop. Two masked gangsters held up the loco engineer at gun point. At the same time, one of them poured tear gas

into the airconditioning duct of the armoured carriage. As a response to the threat of exploding the whole train with its passengers, the guards released the special doors that could be opened only from inside. Two other gangsters transferred apparently only the real bullions to a waiting lorry at a terrific speed so that the train was able to continue its journey at 8:28 p.m.

- Luckily, the engineer of the train memorised the license plate number of the holdup lorry. It was found abandoned some 150 miles away in a little forest. The condition of the roads leading to this spot is such that the lorry could not have reached the place in less than 3 hours and 17 minutes. They should have transferred the loot here into a bigger bus, judging by the tyre prints. But, lo and behold, we found there nothing else than another set of fake bullions!

- Oh, another piece of information - added the Chief Inspector with some apprehension in his voice.

- We have made some time-and-motion studies. It takes at least 8 minutes to transfer the real stuff from one lorry to another while the lighter, fake load can be shifted in about 5 minutes.

- That is all I know and I doubt you can get more sense out of this with your blooming grey boxes.

Miss Langley looked unperturbed and optimistic. She sat down at the keypunch to produce a few cards, which she then attached to the end of a small box of punched cards and submitted the lot to the Scotland Yard's friendly computer. Out came the answers:

THE FOLLOWING FACTS ARE GIVEN TO THE SYSTEM :

(WHICH, IN THE LIST FORM, IS :)

```
( (DAY-OF-ROB) (EVENT,SHIFT-REAL,DELTA,DELTA,L-SFT-REAL)
  (EVENT,SHIFT-FAKE,DELTA,DELTA,L-SFT-FAKE)
  (EVENT,LCRY-REAL,S-LCRYREAL,F-LORYREAL,L-LORYREAL)
  (EVENT,LORY-FAKE,S-LORYFAKE,F-LORYFAKE,L-LCRYFAKE)
    (EVENT,DELAY-LORY,DELTA,DELTA,L-DELALORY)
  (EVENT,HOLD-UP,S-HOLDUP,F-HOLDUP,L-HOLDUP) (EVENT,WAIT-VICT,S-WAIT,F-WAIT,L-WAIT
  ) (EVENT,SFT-ON-TR,S-SFT-CN,F-SFT-ON,L-SFT-ON) )*
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THE FOLLOWING IS THE TABLE OF RECOGNIZED EVENTS.

EVENT SHIFT-REAL	HAS BEEN DEFINED WITH STARTIM DELTA	, FINTIM DELTA	AND LENGTH L-SFT-REAL.
EVENT SHIFT-FAKE	HAS BEEN DEFINED WITH STARTIM DELTA	, FINTIM DELTA	AND LENGTH L-SFT-FAKE.
EVENT LORY-REAL	HAS BEEN DEFINED WITH STARTIM S-LORYREAL,	FINTIM F-LORYREAL	AND LENGTH L-LORYREAL.
EVENT LCRY-FAKE	HAS BEEN DEFINED WITH STARTIM S-LORYFAKE,	FINTIM F-LORYFAKE	AND LENGTH L-LORYFAKE.
EVENT DELAY-LCRY	HAS BEEN DEFINED WITH STARTIM DELTA	, FINTIM DELTA	AND LENGTH L-DELALORY.
EVENT HOLD-UP	HAS BEEN DEFINED WITH STARTIM S-HOLDUP	, FINTIM F-HOLDUP	AND LENGTH L-HOLDUP.
EVENT WAIT-VICT	HAS BEEN DEFINED WITH STARTIM S-WAIT	, FINTIM F-WAIT	AND LENGTH L-WAIT.
EVENT SFT-ON-TR	HAS BEEN DEFINED WITH STARTIM S-SFT-ON	, FINTIM F-SFT-ON	AND LENGTH L-SFT-ON.

THE FOLLOWING ASSIGNMENT OF NUMERICAL VALUES IS RECOGNIZED.

DAY-OF-ROB		197901010000	6
DAY-OF-ROB HAS VALUE	197901010000.		
L-SFT-FAKE		5	1
L-SFT-FAKE HAS VALUE	5.		
L-SFT-REAL		8	1
L-SFT-REAL HAS VALUE	8.		
S-LCRYREAL R	DAY-OF-ROB	425	9
S-LORYREAL HAS VALUE	197901010425.		
F-LORYREAL R	DAY-OF-ROB	628	9
F-LORYREAL HAS VALUE	197901010628.		
S-LORYFAKE R	DAY-OF-ROB	425	9
S-LORYFAKE HAS VALUE	197901010425.		
F-LORYFAKE R	DAY-OF-ROB	619	9
F-LORYFAKE HAS VALUE	197901010619.		
L-DELALORY		9	1
L-DELALORY HAS VALUE	9.		
S-HOLDUP R	DAY-OF-ROB	823	9
S-HOLDUP HAS VALUE	197901010823.		
F-HOLDUP R	DAY-OF-ROB	828	9
F-HOLDUP HAS VALUE	197901010828.		
S-WAIT R	DAY-OF-ROB	637	9
S-WAIT HAS VALUE	197901010637.		
F-WAIT R	DAY-OF-ROB	649	9
F-WAIT HAS VALUE	197901010649.		
S-SFT-ON R	DAY-OF-ROB	628	9
S-SFT-ON HAS VALUE	197901010628.		
F-SFT-ON R	DAY-OF-ROB	637	9
F-SFT-ON HAS VALUE	197901010637.		
NO-MORE		-0	*
IT IS FOUND THAT L-LORYREAL HAS VALUE	123.		
IT IS FOUND THAT L-LORYFAKE HAS VALUE	114.		
IT IS FOUND THAT L-HOLDUP HAS VALUE	5.		
IT IS FOUND THAT L-WAIT HAS VALUE	12.		
IT IS FOUND THAT L-SFT-ON HAS VALUE	9.		

THE NEXT QUESTION IS :

WHEN COULD TRANSFER OF REAL BULLIONS TAKE PLACE)

(WHICH, IN THE LIST FORM, IS :)

((RELTRUE, SHORTER, D, (LENTH, SHIFT-REAL), E, DELTA))*

THE FOLLOWING IS THE ANSWER :

SFT-CN-TR , WAIT-VICT , DELAY-LORY, LORY-FAKE , LCRY-REAL .

WE HAVE SPENT .0880 SECONDS ON THIS QUESTION.

NO MORE QUESTION, PROCESS TERMINATES.

Miss Langley went back to the Chief and casually remarked:

- I am sure you already have a warrant to arrest Mr. McNaughton.