ON THF, PROBLEMS OF TIME, RETREVAL OF TEMPORAL., RELATIONS, CAUSALITY, AND CO-EXISTENCE*

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ABSTRACT

Intelliqent question-answering proqrams do more than retrieve "ra^w" data? they make deductive inferences in order to return all valid resnonses. They renort loaical inconsistencies, nossiblv at the data innut nhase. similarly, more information is requested from the user if a question asked nroves to be ambiguous.

A question-answerinn svstem of the above tyne has been desirmed and imnlemented. Resides retrieving eynlicit and Imnlicit temporal relations, the system discovers potentially caudal relationshins which also satisfy different time restrictions. Questions concerning a generalized concent of co-existence can also be answered. It is honed that nroarams of a similar nature will become of much nracrmatic use to researchers in physics, chemistry, biologv, and so on,in evaluating comnlex, interrelated exnerimental data. Several additional annlications for this tvne of nroqrams are mentioned, ranaina from nrohlems in criminolorrv to air traffic control. The Associative Memorv, Parallel Processinn Lanquaqe, AM^L-TT , was found rather satisfactory for the project.

It is finally suaqested that the svstem beinrr described could serve as a comnonent to a comnlex coanitive mechanism.

INTRODUCTION

There is an overwhelmina abundance of comnlex events in "real" life. One minht look unon science as a mechanism to heln escane from the unexplained chaos. The basic assumntion of the reductivist is inherent in all scientific investiaations — the existence of (simnle) laws that qovern natural nhenomena.

In the internretation of scientific data, workinn hypotheses are formed that are based on nrima facie relations between patterns of events. The discovery of causality calls for the testina of these workinq hypotheses under a wide variety of conditions. The logic of the concent 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 analvzed, the comnuter should come to the scientist's aid in this non-trivial task. Yet, the nassage of time, one of the most salient of human exneriences, has received relatively little study in question-answerinn nroarams. The time variable is at the heart of nracticallv all physical, biolonical, and osvcholoqical events. Tt is, therefore, the fundamental variable in every "nrocess-descrintive" model.*♦**

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**Both authors worked on the desian of the system. The first author (N.V.F.) suqqested and elaborated the subject matter and was resnonsible for the writing of this paper. Many refinements and improvements are due to the second author (D.c.), who has also done all the proqrammina. An enlaraed version of this work, in the form of a Master's Project, will be submitted to the State University of New york at Puffalo in partial fulfilment of the requirements of David Chen's M.S. dearee.

***Certain paradoxical results of the theory of relativity, that would be of no concern to us here, render it possible to send sinnals into the nast. See, for examnle, Y. P. Terletskiy: Paradoxes in the Theory of Pelativity (Trans 1. P. Hoffmann; Plenum Publ. Corp.: New York, 1968).

♦♦♦♦According to the usual distinction made by Systems Theory (see, for examnle, Simon [4]), systems can often be described by two tvnes of models. The state-descriptive model tells how a system behaves now, whereas the nrocess-descrintive model provides information as to how and throuqh what stanes it has develoned from an initial confiquration 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 qives insiqht 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 qiven and inferred data, and relations between them. This fact and many other aspects of the project are in analocgy with human cognition althouqh no attempt was made to simulate the latter. Inconsistencies and missina information are discovered and reported back to the user. (Missinn information is manifested, in an indirect manner, bv returning a laraer 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 meanina and the role of time, in the abstract sense, are beyond the scope of these investigations.

ON TTME-DFPFNDKNT EVENTS AMD 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 oaradiam:

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

where members of the second bracket may assume either attribute of the first bracket. Meaninoful examples can be found for each of the eiaht ($=2^3$) Possible cases. The distinction betwoon 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 saving

$$\text{Event } \underline{E}_i \text{ occurred} \begin{bmatrix} \text{fully} \\ \text{partially} \end{bmatrix} \begin{bmatrix} \text{before} \\ \text{during} \\ \text{after} \end{bmatrix} \text{event } \underline{E}_j$$

Let us now define two types of events:

(1) A <u>point event</u> 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 disaaree with this...) and its effect 'to be awake' is lasting. Or, 'John starts readina' is, again, a point event which is followed bv a lastinq 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 anythi ng'.

(2) A <u>duration event</u> has distinct startinn an?! f inishing times, and a duration between the two. There are a few exceptions. Explicit or implicit truth statements often do not have startinn and finishinrr times. Unless one accepts reliainus teachings or the Rig Rang theorv of cosmologv, the "world" has no startinn time.

Tn order to be realistic about simultanitv, we have assumed a quantised time scale. In the computer nrogrram described later, one minute is the shortest measurable time interval. (This represents no restriction because a definable, arbitrarv 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 adont in this section the convention that lower case letters refer to time points and upner case letters to time intervals. The letter 'e' will have a special significance, $\underline{e}$ will denote a point event and $\underline{E}$ a duration event.

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

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

Suppose both $\underline{e}_1$ and $\underline{e}_2$ occurred during $\underline{T}$, that is $\underline{t}_1, \underline{t}_2 \in \underline{T}$. Then e_3, related to $\underline{t}_3$, must have occurred during $\underline{T}$, 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, $\underline{T}_1$ precedes $\underline{T}_2$ iff

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

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

$$s_i + D_i = f_i$$

for $i = 1$ and 2

<u>Partial overlap</u> is found between $\underline{E}_1$ and $\underline{E}_2$ iff

$$s_i < s_j < f_i \quad \text{and} \quad f_i < f_j,$$

for $(i,j) = (1,2)$ or $(2,1)$

(Some of the $<$ signs could be replaced selectively by $\leq$ or $\cong$ 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. Tn the case of approximate time specifications, whether absolute or relative to other events, the system must make proper allowances for the changres in the retrieval loqic.

One can establish a simple lonical svstem, on the basis of the previous definitions, usina standard first-order predicate calculus plus axioms with regard to transitivity, irref lexivity, and existence of predecessors and successors. This enables the system to make simnlifications 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 consistencv at a staae as early as possible. At the beainnina of the oroaram, the skeleton of a complex, hierarchical and relational data structure is established. This would then be filled in as need arises throuah the auestions asked. We have not frowned upon redundancv in stored information whenever it shortened or simplified orocessina.

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

The nrorram is divided into three. maior comnone-nts, the innut nhase, the data structuring nhase, and the question answerinn nhase. These will now be discussed briefly.

(1) The inout nhase is concerned with three tvnes of information:

(a) The user defines the symbolic comnonents of an e^ent in the form

(EVENT,EVTNAM,STRTIM,FINTIM,LENGTH)

where EVENT is a reserved word to denote symbolic specification; EVTNAM, STRTIM, FINTIM, 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)

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

Here, the first statement means that T1 is the antecedent of T2, which is the antecedent of T3, etc.; the second one means that T1, T2, T3, ... are equitemporal; and the third one that T1, T2, T3, ... 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 T8', 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 eiaht nodes of indirect snecification, as indicated by an innut parameter. The relative time length that has to be added to or subtracted from another time quantity can be given in

minutes,
hours,
davs,
months,
vears
packed year-month-day-hour-minute mode,
packed month-day mode, and
packed dav-minute mode.

In the last three cases, the addition or subtraction starts at the rightmost unit and nroceeds to the left, for the sake of unambiauity. Proner care has been taken *of* the transition between the Iuliian and Grenorian calendars, the "nissino" year between 1 B.C. and 1 A.D, and similar idiosyncrasies.

There is an important, multinnnose, reserved word, <u>nrLTA</u>. Tn the innnt nhase, it denotes an irrelevant time quantity for which no numerical snecification is to be exnected. We. would nut, for examnle, for time noints TA and TR,

savins that they both are irrelevant (but <u>not</u> equitennoral !) DPLTA can also be nut directly, in lieu of any symbolic name of an event being asked about. Examoles to follow will make this noint clear.

Nested snecifications are also possible. *A* verbalized examnle of this is: 'Event *A* started 20 minutes before the event ended that started at a.m.,

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

Finallv, if one of the three tine quantities, characterizing a duration event, startinrg time, finishing time and length, is missinn, it is comnuted and recorded at this stage. Tn the cases in which nartial chronological information is given in terms of restrictions, longest or shortest nossible time lengths are comnuted and annronriately marked whenever nossible.

(2) The <u>data structuring nhase</u> transforms the innut information into an expandable format, which is narticularlv 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 narallel-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 <u>question-answering phase</u> 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 <u>retrieve the symbolic names</u> of the starting time, finishing time and length of a given event.

(b) To establish whether a particular <u>relation</u> between two time quantities (points or duration) or two events <u>is true</u>. 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 <u>DELTA</u>, 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 <u>DELTA</u> then all valid relations between the given entities are retrieved.

(c) To find the <u>extremum</u> (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 ambiauity. However, the user may also look for an event (or events) whose length is the closest to a qiven duration. Or else, he may soecifv 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 notentiallv 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 continuous, i.e. the finishincr time of the antecedent is the starting time of the successor;

the successive events must nartially or completely overlap each other;

either the starting or the finishincr times, Specifiable by narameters, must be consecutiye with successive events;

the same as above but certain time durations at least must elanse between consecutive startina or finishincr times (cf. problems of causality);

(e) To answer questions concerning a generalized concept of co-existence. There are, say, three sets of events qiven. The proqram 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 (dis-joint events) with any member of the third set. Or, more qenerally, 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 sinqle 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

Programminn was done on a CDC 6H00, with which SLIP and AMPPT,-IT have been resident on the system disk. Only those subnroarams are called into the core that are needed in the nrogram. The total code occupies less than 15k core memorv. The running time, of course, depends on the size of the data base and on the comnlexity (levels of nesting) of the questions asked.

with a moderately sized data base and questions of the tvne below, an answer was obtained on the average in less than half a second if the information was directlv available. However, *if* logical inferences concerning nested questions had to be made, and the data structure had to be undated, 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 dive a list of simple questions and a few nested ones. We note that the same question can often be formulated in several diffrerent wavs.

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

(RFLTRUF , BFFØRE (PTAPTTM E1) ,F,F2) .

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

(2) Does event E_1 co-exist (partial or comnlete overlan) vritu event $E_?$?

(PELTPHFjCpEXTSm^EI^E?) .

'3) Could the completion of event E« immediatelv cause event E_9 ?

(RELT^UE, C^NTTCTJF , E , E 1 , E , F2).

(4) Is event E_1 lonqer than event F ">

(RELTPnF,L0NGFP,E,E1,E,E2).

(5) Which events are such that

(a) their start could cause event E^?

(RELTPTJF,REF<?IPF,!>, (STAPTTM, DFT.TA) ,E,E1) ;

(b) they co-exist with event E^?

(P.FLTWTTF,C^EXTPT,E,nPL^A,E,E1) ;

(c) their completion could cause event E*?

(RELTPUE,REF0RF,P,(FTNTTM,DELTA),E,E1);

(d) their duration is lonoer than that o* event E^?

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

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

(a) (CHAIN,C0NSECUTIVE,FINTIM,STARTIM,E1);

(b) (CHAIN,CØNTIGUE,E1) ;

(c) (CHAIN,ØVERLAP,E1).

(7) Given three sets of events,

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

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,

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

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

(BUTNØT,E31,E32,...)

or

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

E32,...),(CØEXISTENC,E1,E2,(BUTNØT,E3)))

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

(EXTREMUM,E,LØNGEST,(E11,E12,...));

and

(EXTREMUM,E,SHØRTEST,(E11,E12,...)).

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

(EXTREMUM,E,CLØSEST,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?

((INTSECTIØN(RELTRUE,ANTE,P,(FINTIM,E1),P,

(STARTIM,DELTA)),(RELTRUE,AFTER,P,

(STARTIM,E2),E,DELTA)))

or

((RELTRUE,BEFØRE,P,(FINTIM,E1),E,DELTA,

(RELTRUE,ANTE,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,LØNGEST,(RELTRUE,BEFØRE,P,

(FINTIM,E1),E,DELTA,(RELTRUE,BEFØRE,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.

(RELTRUE,DFLTA,P, (FTNTM, (EXTEMUM,E,

LATFPT, (RELTRUE, CØEXTST,E, HELTA, E,E1))) ,

P, (STAPTIM, (EYTPEMTTM^EA^LTES^, (^ELTPUE,

C0EYTPT,E,HELTA,E,E2)))) .

A few more noints are to be noted here. The sot-theoretic functions

INTSEPTT0N and TTMT0^

can be nested in any of the question forms.

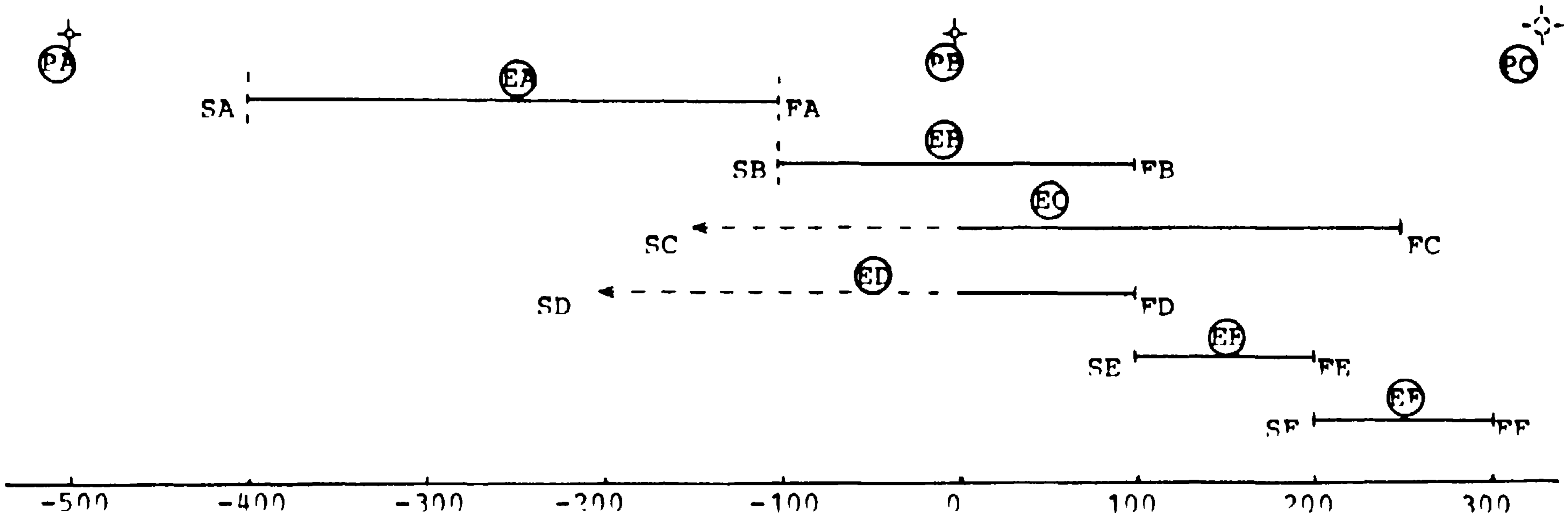
The function

retrieves numerical values of an indefinite number of time points and/or durations. The svmbolic names of these may e refrenced indirectly in a nested form. For examnle, is w/e wish to find the durations of events T1 and T2, and the times of occurrence of those noint ewnts that hannened before noint event P_1 , we nut

(VALUR,TI ,T2, (RELTRUE,A>'r,T>,nrT/^ ,^^1))

T,Then^^<=»r eyact values are not available, a set of routines is called upon to compute the nossibTo ti^e rancre of th« tome noints or duratipns involved.

The folloving a^ram an^ eynornts fron a cn^nnfor outnnf ronr^sent a run with a ST-all data bas^:



Event names are encirled. 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); (SH,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 svstero.)

THE FOLLOWING FACTS ARE GIVEN TC THE SYSTEM :

SIX EVENTS ANO THREE TIME POINTS ARE INVOLVED IN THE FOLLOWING EXAMPLE. THE QUESTIONS ARE NOT NECESSARILY MEANINGFULt THEY ARE USED TO CEMONSTRATE HHAT THE SYSTEM CAN DO.

(WHICH, IN THE LIST FORM, IS :)

(() (FVENT,EA,SA,FA,LA) (EVENT ,EB,S8,FB,L B) (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 everv list structure to be inputted)

HE WANT TO INPUT THE LEAST AMOUNT OF INFORMATION OALY. IN ORCER TO SEE HON THE SYSTEM COMBINES ABSTRACT (SYMBOLIC) AND NUMERICAL INFORMATION, SOME OF THE ENTITIES MILL BE GIVEN NUMERICAL VALUES.

ME OEFINE 3 TIME POINTS PA, P8, AND PC FOR REFERENCE. PA ANTECCDES THE STARTING TIME OF EVENT EA. TINE POINT SO ANTECEOES FA THAT ANTECEOES SB THAT ANTECEOES PB, THE FINISHING TIME OF EVENT EF OCCURS BEFORE PC. FB, F0, ANO SE ARE EOJI-TEHPCRAL TIME POINTS. FA ANO SB ARE CIRCA-EQUI-TEMPORAL. FE IS EQUI-TEMPORAL TO SF. TIME POINTS SO, SC, AND FA ARE IN THIS CHRONOLOGICAL ORDER. SE, FE, FC, LF, PA, ANO PB MILL BE GIVEN NUMERICAL VALUES.

(WHICH, IN THE LIST FORM, IS :)

```
<(PA,PB,PCHANTE,PA(STARTIM,EA>) (ANTE,SO,FA, SB, PB ) (ANTE, (FINTIM,EF} PC)
  (EQUI,FB,FO,SE)  (CEOUI,FA,SB)  (ECUI,FE,SF)  (ANTE,SO,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 ANC LENGTH LF.
```

Following this, the system prints out five list structures: A1 ordering), LSTEQ (equitemporal), LSTCEO (circa-equitemooral), TPL 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 FCUND 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 I

          FINO POSSIBLE CHAINS OF NON-OVERLAPPING AND CONSECUTIVE EVENTS THAT LEAO TO
        EVENT EF.

(WHICH, IN THE LIST FCRM, IS t)

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

ONE OF THE POSSIBLE CHAINS IS t
EA, EF,

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

ONE OF THE POSSIBLE CHAINS IS :
ED, EF.

NC MORE CHAIN.

HE HAVE SPENT  27.79<*0 SECONDS ON THIS QUESTION.

THE NEXT OUESTION 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 t
E0, EC, EF.

NC PORE CHAIN.

HE 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 FCRM, IS :)

        (   (CHAIN, CONTIGUE,EF)   )*

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

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

NC MORE CHAIN.

WE HAVE SPENT  42.7980 SECONDS ON THIS QUESTION.

THE NEXT QUFSITION IS :

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

(WHICH, IN THE LIST FORM, IS :)

          (   <PFLTKUE,ANTE,PtDELTAtP,pCt<RELTQUE,ANTE,P,PA,D,DEI TA)   )   )*

THE FOLLOWING Is THE ANSWER !

PB, FFt SFt FE, SE, FU, FC, F8 58, FA, SA.

WE HAVE SPENT 21.5220 SECONDS ON THIS QUEsTIOw.
```

THE NEXT QUESTION IS 1

FROM AMONG EVENTS EC ,EB,EE,E0,EA, AND EF, SELECT THOSE THAT CO-EXIST WITH EB OR EC. FROM THIS GROUP, DELETE THE EARLIEST ONE OF THOSE THAT ARE COMPLETELY ANTECEOEU BY EVENT EA.

(WHICH, IN THE LIST FORM, IS :)

((NOT (COEXISTENC (EC ,EB,EE,ED ,EA,EF) (EB,EC)) CE XT RE MUH,E ARLIEST, E, < RELTRUE, COMPANTE,E,EA,Et DELTA))))*

THE FOLLOWING IS T HE ANSWER :

EF, EAf EO, EE, EC,

HE HAVE SPENT 37.8020 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS I

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

(WHICH, IN THE LIST FCRM, IS t)

((INTSECTION (RELIRUE,BEFORE,P(STARTIM,EA)E,DELTA)(RELTRUEfBETWEEN, P(FINTIH, DELTA),E,EC)))*

THE FOLLOWING IS THE ANSWER :

EE, EB.

WE HAVE SPENT 16.8860 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS I

FIND THE LONGEST AND THE SHORTEST EVENTS OF EBfEC,EE,EF, ANO EO.

(WHICH, IN THE LIST FORM, IS I)

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

THE FOLLOWING IS THE ANSWER I

EF, EE, ED, EC.

WE HAVE SPENT £.5760 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS I

FINO VALUES OF TIME POINT FA, OF THOSE TIME POINTS THAT OCCUR AFTER PA, ANO OF THOSE TIME DURATIONS THAT ARE EQUAL TO OR LONGER THAh LE ITHE LENGTH OF EVENT EE).

(WHICH, IN THE LIST FORM, IS t)

((VALLE,PA, (REL TRUE, ANTE, P,P A, P, DELTA) (KELT RUE fEQU AL,D ,LE , 0 , OELTA) (RELTRUE,LONGERtD,DELTA,C,(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 CN THIS QUESTION.
```

THE NEXT QUESTION IS :

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

(WHICH, IN THE LIST FORM, IS :)

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

THE FOLLOWING IS THE ANSWER t

EF, EE, EC, EA.

WE HAVE SPENT 43.6560 SECONDS ON THIS QUESTION.

THE NEXT QUESTION IS :

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

(WHICH, IN THE LIST FORM, IS :)

((UNION (EXTREMUM,LONGEST,D,(KELTRUE,LONGER,D,DELTA,E,EF)) ,
(EXTREMUM,EARLIEST,P, (SA,(STARTIM,EC) (FINTIM,EF) ,SD,SB)) CEA,EF,£B)))*

THE FOLLOWING IS THE ANSWER :

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

WE HAVE SPENT 2.4400 SECONDS CN THIS QUESTION.

NO MORE QUESTION, PROCESS TFRMINATES.

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 (comoufced; 1960 leap year)

SF = 1960 12 31, FF = 1971 5 1. LF = 3772 davs (eight reaular and two lean years, the five first months in 1971)

```
   THE FOLLOWING ASSIGNMENT OF NUMERICAL VALLES IS RECOGMZEC
FA                                              19401010000  8
          PA HAS VALUE     194001010000 .
P8                                              195001010000  8
          P8 HAS  VALLE    19540101000C .
FC                1970          01010000                      8
          FC HAS VALUE     19700 10 100100.
SE                                              196001010000  8
          SE HAS VALUE     1960010    10000.
FE                                              196312310000  8
          FE HAS VALUE     19601231000C.
FF                                              197105010000  8
          FF HAS VALUE     197105010 000.
NO-MORE                                                    -0  *
  IT IS FOUND THAT FB HAS VALUE     19600101000 0.
  IT IS FCUNC THAT FU HAS VALUE     19600101C000•
  IT IS FOUND THAT SB HAS VALUE     1960123100 00.
  IT IS FCUND THAT LE   FAS   VALUE     365000.
  IT IS FOUND THAT LF HAS VALUE        37720000.
```

```
THE NEXT QUESTION IS I

          FIND VALUES CF TIME FCINT P A , CF THCSE TIME POINTS THAT CCCUR AFTER FA, ANC OF
        THOSE TIME CURATIONS THAT ARE ECUAL TC OR LCNGER THAN LE (THE LENGTH OF EVENT
        EE).

(WHICH, IN THE LIST FCRM, IS I)

          ((VALUE,PA,(RELTkUE,ANTE,P,PA,P,CELTA) ( REL T RU E ,EQU AL ,D , LE , D, CE LT A)
            (RELTRUE,LONGER,D,DELTA,C, (LENTH,EE>    )    ) *

THE FCLLOWINGS ARE THE ANSWERS :
THE VALUE CF FA IS     194001010000.
THE RANGE OF VALUE CF SA IS   FRCP   I9401010000    TC    195 0010100 0 0.
THE RANGE OF VALUE OF FA IS FROM    1940010 1 00 00 TO    1950010 100 00.
THE RANGE OF VALUE CF SB IS FRCM 1940010100   00 TO    195001010000.
THE VALUE OF FB IS     196001010000.
THE VALUE CF FC IS    1970010100 CO .
THE VALUE OF FD IS     196 0 010100 00.
THE VALUE OF SE IS     1960010100C0.
THE VALUE OF FE IS     196012510000.
THE VALUE OF SF IS     196012310000.
THE VALUE OF FF  IS    197105010000.
THE VALUE OF PB IS     195001010000.
THE RANGE CF VALUE CF FC IS FRCM    197105010000 TC INFINITY.
THE VALUE OF LE IS           3650000.
TFE RANGE OF VALUE CF LB IS FRCM       3652CCG0 TO       73050000.
THE RANGE OF VALUE OF LC IS FFCM       73050000 TC INFINITY.
THE RANGE OF VALUE OF LD IS FROM       36530000 TO INFINITY.
THE VALUE OF LF IS        37^20000.

WE HAVE SPENT  16.15*0 SECONDS CN THIS QUESTION.


NO MORE QUESTION, PROCESS TERMINATES.
```

FURTHER RESEARCH PLANNED

Besides tidying up some parts of the code, other things can vet 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. Pome 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 tvpe of program to prove whether a particular crime could have been committed by a certain individual or several crimes bv the same person, etc.

Turninq to more mundane ideas, air traffic control must be exercised under dynamically chanqing 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 PERT. (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 loaic 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 Programme*—Analyst, Miss Eleanore Lanalev. He could hardly confound his frustration:

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

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

- The Bank of England was to transfer some gold bullions, worth the sum of 640,000,000, to its secret Manchester vaults. The armoured lorries, under the expert leadership of the newly hired security chief, Mr, H. McNauqhton, picked up the shipment at 4:25 p.m. Some of the lorries, carryinq a fake load of liaht 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. McNauqhton tells us, the second qroup qot into a bit of a traffic 1am 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 safelv sittinq in the armoured carriage under the close watch of McNauqhton's ten touqhest quards.

The express train left riant 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 enqineer at qun point. At the same time, one of them poured tear qas into the airconditioninn duct of the armoured carriane. As a response to the threat of exploding the whole train with its passengers, the auards released the snecial doors that could be opened only from inside. Two other qanasters transferred apparently onlv 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 enqineer of the train memorised the license plate number of the holdup lorry. It was found abandoned some 150 miles awav in a little forest. The condition of the roads leadinq to this soot is such that the lorry could not have reached the place in less than 3 hours and 17 minutes. Thev should have transferred the loot here into a bigner bus, ludqinq bv the tyre prints. Rut, 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 lorrv to another while the lighter, fake load can be shifted in about 5 minutes.

That is all T know and T doubt vou can aet more qense out of this with vour blooming grev boxes.

Miss Lanqlev 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 vard's friendly computer. Out came the answers:

```
THE FOLLCWING 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-LORYREAL,F-LORYREAL,L-LORYREAL)
              (EVENT,LORY-FAKE,S-LORYFAKE,F-LORYFAKE,L-LCRYFAKE)
                                        (EVENT,DELAY-LORY,DELTA,DELTA,L-DELALORY)
        (EVENT,HCLD-UP,S-HCLDUP,F-HCLCUP,L-HOLDUP) (EVENT,WAIT-VICT,S-WAIT,F-WAIT,L-WAIT
        )  (EVENT,SFT-ON-TR,S-SFT-CN,F-SFT-ON,L-SFT-ON)  )*

E FOLLCWING IS THE TABLE OF RECOGNIZED EVENTS.

ENT SHIFT-REAL HAS BEEN DEFINED WITH STARTIM DELTA     , FINTIM DELTA      AND LENGTH L-SFT-RE
ENT SHIFT-FAKE HAS BEEN DEFINED WITH STARTIM DELTA     , FINTIM DELTA      AND LENGTH L-SFT-FA
ENT LORY-REAL  HAS BEEN DEFINED WITH STARTIM S-LORYREAL, FINTIM F-LORYREAL AND LENGTH L-LORYRE
ENT LCRY-FAKE  HAS BEEN DEFINED WITH STARTIM S-LORYFAKE, FINTIM F-LORYFAKE AND LENGTH L-LORYFA
ENT DELAY-LCRY HAS BEEN DEFINED WITH STARTIM DELTA     , FINTIM DELTA      AND LENGTH L-DELALO
ENT HOLD-UP    HAS BEEN DEFINED WITH STARTIM S-HOLDUP  , FINTIM F-HOLDUP   AND LENGTH L-HOLDUP
ENT WAIT-VICT  HAS BEEN DEFINED WITH STARTIM S-WAIT    , FINTIM F-WAIT     AND LENGTH L-WAIT
ENT SFT-ON-TR  HAS BEEN DEFINEC 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-RCB  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   19790101042  5.
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     OAY-OF-ROB                         619  9
          F-LORYFAKE  HAS  VALUE    197901010619.
L-DELALORY                                                 9  1
          L-OELALCRY  HAS  VALUE              9.
S-HOLOUP    R         DAY-OF-ROB                         823  9
          S-HOLOUP    HAS  VALUE    197901010823.
F-HOLDUP    R         DAY-OF-ROB                        8 28  9
          F-HOLDUP    HAS  VALUE    197901010 82 8.
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         UAY-OF-KOB                        6228  9
          S-SFT-ON    HAS  VALUE    197901010628.
F-SFT-ON    R         DAY-OF-ROB                        63 7  9
          F-SFT-ON    HAS  VALUE    1979 0101062 7.
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  FOUMD  THAT  L-SFT-ON    HAS  VALUE             9.

THE NEXT CUESTICN IS :

          WHEN COLLD TRANSFER OF REAL BULLIONS TAKE PLACE J

(WHICH, IN THE LIST FORM, IS :)

          ( CR EL TRUE, SHORTEN, D, (L ENTH ,SHIFT-RE AD , E , DELTA) )

 THE FOLLOWING IS THE ANSWER t

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

WE HAVE SPENT     .0880 SECONDS ON THIS QUE^TION.

NO MORE QUESTION PROCESS TERMINATES.
```

Miss Lanqley went back to the Chief and casually remarked:

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