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A SYNTHETIC APPROACH TO TEMPORAL INFORMATION PROCESSING*

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ABSTRACT

A representation and processing scheme for temporal (time-based) information is presented. Previous computer science approaches to temporal information processing are analyzed. Linguistic analysis of tense, aspect and temporal adverbials provide motivation for an automated general temporal understanding system. A synthetic approach is proposed, combining possible-worlds branching time theory with inertia futures, elements of Montague Grammar, a four-valued logic and the interval semantics time model. Key portions of the model are implemented and demonstrated in a PASCAL program.

I INTRODUCTION

The Artificial Intelligence research community approaches the natural language understanding problem from two angles: on the computer's terms and on the human's. The former approach encourages the design of programs which are competent in narrow linguistic domains. The latter approach currently results in the creation of models for processing language on the broader scale on which humans naturally communicate. The first approach is most useful for technological achievement, and the second for scientific advancement. There are benefits to be gained from both pursuits.

This paper describes a fundamental representation and processing scheme for English temporal phenomena based on the second approach cited above. This perspective calls for a synthesis of results of investigations in linguistics, existing epistemological models of time, and previous efforts in the automated understanding of time-based information. The model can later be enhanced and refined as these theories advance. The fundamental scheme can be programmed immediately. Modest success in all of the above tasks is reported here.

II LINGUISTIC MOTIVATION

Many linguists have investigated temporal phenomena of English, such as verb tense, temporal adverbial phrases, and time deictics. Perhaps the most robust and formalized is the work of Dowty [3]. Basing his work on the structures of Montague Grammar [4], Dowty examines English temporal phenomena through the mechanisms of interval semantics and a branching time theory. In his approach, "truth" is relative to a possible world and possible time interval. Dowty analyzes the following temporally complex sentence and in so doing motivates many processing needs.

(1.) *John was leaving on Thursday yesterday.*

Through linguistic argumentation, Dowty shows the following phenomena occur within this single example:

Past/future relations
Adverbial phrase interval bounds
Alternate worlds and times
Vague event durations
Deictics ("now," "Thursday," "yesterday")
Futurate Progressive tense/aspect
(which entails: expectation, uncertainty)

A fully general, automated natural language understanding system which handles temporal information of English must adequately process these phenomena. Limited attempts to capture each of these time-related features have been made but in disparate research fields. A synthesis of useful elements from each of these fields is described below.

III USEFUL AUTOMATION TECHNIQUES

Several programs and models have already been constructed to represent and process time-based information of various sorts. Bruce [2] has defined a number of interval relations and "tenses" which I do not find convincingly supported by currently accepted linguistic evidence and analysis, but also has offered interesting before/after temporal definitions. Findler and Chen [5] have produced a question-answering system for the storage and retrieval of "events" of fixed durations using a restriction/connectivity matrix. This approach may be useful in limited applications, but does not attempt to model natural language expressions.

Finally, Kahn and Gorry [8] have created a so-called "time specialist." This system is noteworthy for its development of appropriate representation schemes for varying temporal event relations. Separate data structures are used for

*An expanded version of this paper appears as [7].

events linked by dates, by undated temporal order and by reference events. For the first time, events with fuzzy bounds are represented. However, it is open to question how to use three separate knowledge representations concurrently. Kahn and Gorry acknowledge that their effort to produce a temporal *idiot savant* ignores syntactic and semantic time-based knowledge.

IV SYNTHESIS AND IMPLEMENTATION

Since the understanding of time is intimately related to our understanding of the nature of the temporal events we experience, a more fruitful (longer-term) approach is one in which the processing scheme is based on the information and operators shown to exist by linguistic analysis. This is the second approach discussed in the Introduction--basing automated capabilities on natural (human) linguistic capabilities.

Using this paradigm, a model of an automated general temporal understander was constructed. The model centers around those processes and information schemes motivated by Dowty's linguistic analysis and by branching time theory. The top-level organization appears as Figure 1.

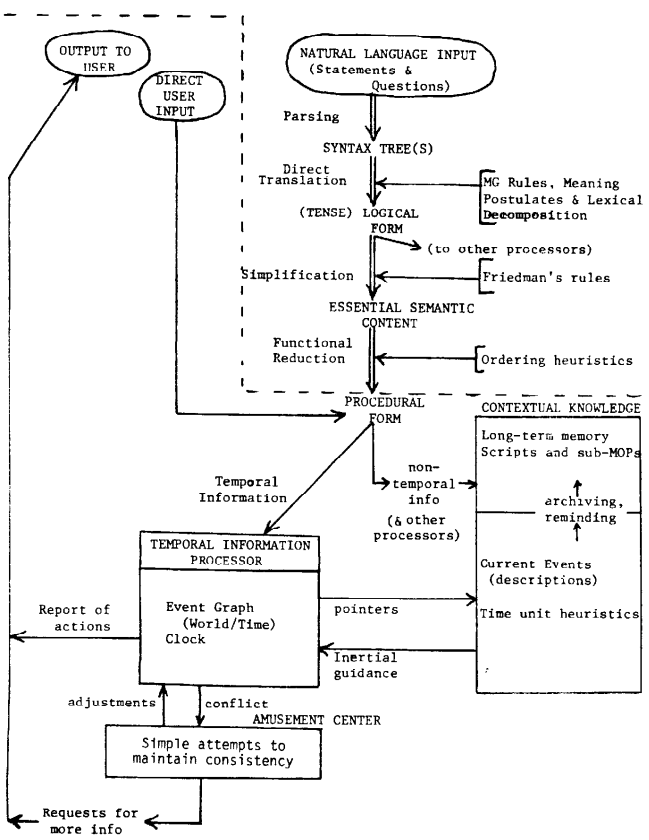

FIGURE 1

A General Temporal Understanding System

The assumed input is a sentence of English which can be parsed by Montague Semantics methods as modified by Dowty's translations rules. Friedman [6] offers such a parsing scheme, although it is presumed that Dowty's tense rules could be added to her work. Friedman also describes several simplification techniques to reduce the result of translation into a more extensional formula. This formula is then reduced further to a procedural form, i.e., LISP-like notation in preorder. For example, Dowty's translation for sentence (1.) is

$$(2.)\ \forall t_1\ [\ PAST(t_1) \wedge t_1 \subseteq \underline{yesterday}' \wedge AT(t_1,\ PROG\ [\ \forall t_2\ [\ PAST(t_2) \wedge AT(t_2,\ \underline{predetermined}'\ (^\wedge \forall t_3\ [\ t_3 \subseteq \underline{Thursday}' \wedge FUT(t_3) \wedge AT(t_3,\ \underline{leave}'(j))\ ]))\ ]\ ])\ ]$$

where $\forall$ means "there exists" or "for some"

$\wedge$ means "and"

$^\wedge$ is the intension operator

PROG is the progressive operator

The procedural form of this statement appears as Figure 2.

```
( POSIT
[ FORSOME TM1 (AND (PAST TM1)
                   (CONTAINED-IN TM1 YESTERDAY)
                   (AT TM1 [ φ1 ] ) )])

where φ1 is [ PROG ( FORSOME TM2 (AND (PAST TM2)
                                      (AT TM2 [ φ2 ] ))) ]

where φ2 is [ PREDETERMINED-INT (FORSOME TM3 [ φ3 ] )]

where φ3 is [ AND (CONTAINED-IN TM3 THURSDAY)
                  (FUTURE TM3)
                  (AT TM3 (LEAVE-JOHN))  ]
```

FIGURE 2

Procedural Form of

John was leaving on Thursday yesterday.

This form is the input to the implemented portion of the model, encompassing those processes below the dashed line of Figure 1.

The input is assumed to be a statement (a belief to be posited, i.e., stored) or a question (a belief to be interrogated, i.e., searched for). Of course, system commands can also appear in the input. Such commands are primarily deictic definitions to be stored in contextual memory, but also are for attention management and I/O control.

Statements are processed by storing or moving instances of generic events (written in "Cambridge Polish") on nodes in a directed world/time graph without cycles. In contrast to an outward-branching tree structure, the network allows the system to combine portions of histories which are

"identical" because no distinguishing occurrences are known. Although extensively defined in [7], some operators and functions are briefly described here:

FORESOME: existential quantification over time. Produces search interval bounds nested to the depth of quantification.

AND: conjoins a heuristically ordered list of temporal interval restrictions including deictics, PAST and FUTURE (single bounds) and specific moments.

PROG: creates alternate futures (uncertainty) where an event does not "happen" in all branches, but does in inertia futures (Dowty's term). Inertia worlds are "expected." Expectation is managed by a scripted event series (*a la* Schank [10]).

PREDETERMINED: establishes initial link in a chain of scripted events.

AT: simple, "primitive" event occurrence in a specific world and time.

Additional information stored in the graph allows further processing shown useful by other investigators. For instance, reference counts for each event are stored. This can be used not only for garbage collection, but for memory decay modelling. That is, if a hypothetical past event is considered once, but never again, one can cause that possible event to fade from memory. (See also Schank [*op.cit.*]). Related to this phenomenon is the allowance of deviant, but expected, events in the script. Further, each node contains an inertia ratio which is used as a rough expectation metric. Thus, a search across worlds at a given moment will be ordered by the amount of scripted information which appears. No attempt was made to consider rapidly changing contexts.

Tables of deictic variables (intervals and moments) are kept in contextual memory. These definitions can be changed as the speaker's time changes. They provide links between the event graph and the speaker's world.

Question-answering is accomplished by a four-valued belief logic [1, 9]. For coherent questions the answers can be:

T The event occurs given the worlds and time intervals considered in the question.

F The system has been told that the event does not occur.

B It has been told both about the occurrence and non-occurrence of the event (in different possible worlds).

Z It has no (zero) information relevant to the question.

Search and storage/retrieval is accomplished by narrowing down temporal intervals by layered and stacked time bounds. These bounds are established by conjoined deictic and moment references, as well as before/after relations inherited from higher quantified (local) time interval variable bounds.

A sample situation in graph form appears in Figure 3.

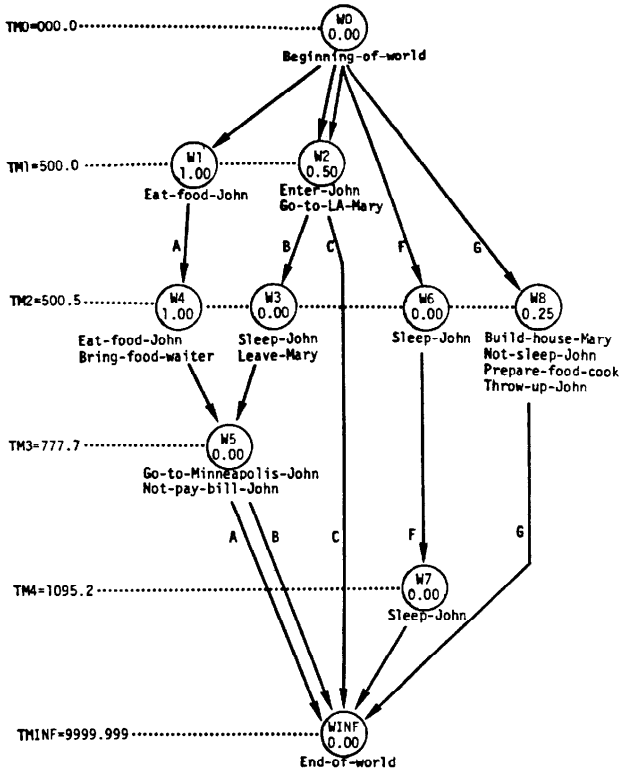

FIGURE 3

Sample Situation

The implemented portion of the model was accomplished in a 3100-line PASCAL program which includes 65 small procedures and seven files. The complete text of the program and a detailed demonstration run appears as appendices to [7]. A brief example of the four resultant belief values for elementary question-answering operations appears in Figure 4.

Input/*Meaning*	Answer
With "now" = TM2:	
(Q (FORSOME T (AT T PAY-BILL-JOHN))) *Does John pay the bill?*	F
(Q (FORSOME T (AT T LEAVE-JOHN))) *Does John leave?*	Z
(Q (FORSOME T (AT T SLEEP-JOHN))) *Does John sleep?*	B
but . . . with "now" = TM4:	T

FIGURE 4

Sample Program Response

Notice that as "now" changes, so does the answer to the last question. Such non-monotonicity is a natural and expected result.

The model, while certainly incomplete, allows further experimentation with such phenomena as possible translations of temporal adverbial phrases (e.g., *since yesterday*). As workers such as Dowty provide similar Montague-based definitions, this model can act as a vehicle for examining computational implications. Many problematical cases remain.

V CONCLUSIONS

Automated understanders of natural language phenomena can be based on processes illuminated by linguists, using organizing schemes of epistemologists, and representation and processing techniques of computer scientists. Such a synthesis allows cautious expansion from a reasonable foundation. Features of the model provide mechanisms to experiment with expectation and script construction, memory management (methods of "forgetting"), deixis, unusual tense and aspect combinations, multiple-valued logic, and various "possible worlds" phenomena (e.g., contrafactives and epistemic modalities).

This methodology should also be reassuring to researchers moving from natural language to programs through general model design rather than by attempting to capture only narrow temporal phenomena or by ignoring useful results in linguistics and epistemology.

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