Logic-based Temporal Inferences in Natural Language

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This paper concerns temporal inferences in natural language. The concept of time is crucially important because of its highly frequent use in utterances. However, time can appear in numerous forms, for example, tense or time adverbials. It also may be implicitly specified by other events associating with some temporal conjunctions, such as *when*, *before*, *after*, etc. A logic-based approach is adopted to represent temporal information. Situations and time adverbials can be formally represented. Lexical knowledge about time and implications of situations also expressed in terms of logical clauses. Then we propose a temporal reasoning model. Various basic types of questions such as "When did event X happen?", "How long did event X last for?", "Did event X happen at time expression T ?", etc. can be interpreted into temporal queries. Finally, we also use the same framework of logic to evaluate temporal queries, carry out computation and do the further deduction.

1. Introduction

This paper concerns temporal inferences in natural language. The concept of time has become crucially important because of its highly frequent use in utterances. However, time can appear in numerous forms, for example, tense or time adverbials. Time adverbials may refer to some date in the calendar such as *Nov. 18, 1989*, or some deictic adverbials such as *yesterday*. Temporal reference can be an exact point of time such as *2 o'clock*, or vague period of time such as *last year*. The above information may refer to the beginning point, the end point, or the duration of event. The event time also may be implicitly specified by other events with associated some temporal conjunctions, such as *when, before, after*, etc. Much of temporal knowledge is distributed within and across distinct constituents and may be implicit and imprecise.

One of the most important applications of natural language processing is the development of a natural language query system. However, currently available natural language systems have not attempted to support temporal queries, except in a trivial sense. Kahn's time specialist (Kahn & Gorry (1977)) only accepts LISP-like input and handles only explicit temporal information; Kowalski and Sergot's calculus of event (Kowalski & Sergot (1986)), and Lee *et al,'s* logic of time and events (Lee et al. (1985)) concern only the explicit date associated with the event and have concentrated on the representation of temporal information in data bases. Those are not general enough in natural language and can not do make deductions among time adverbials either. The systems of Hirschman (1981) and Obermeier (1985) both deal with implicit and explicit temporal information, but they are restricted to domain-specific medical texts.

The aim of this study is to adopt a logic-based approach to make some deductions about temporal information. Natural language sentences that we considered are very general not just for domain-specific texts and not for the explicit date. We can represent them in a formal way, make temporal deductions among time adverbials, and propose a temporal reasoning model to answer several types of questions about time. Here, we assume a syntactic component could be developed to translate relevant information into logical representation. This logical representation can accurately capture the time, duration, or the precedence relation about the event. It has been discussed in detail in (Lee et al. (1990)). In this paper, we can restrict our attention to the conceptual framework underlying such representation for further temporal reasoning.

This paper is organized as follows. Section 2 briefly describes the logical representation of natural language sentences. Sections 3 translates the basic types of questions into queries about time written in PROLOG. Next, our temporal reasoning system is described in Section 4, and how to reason temporal informaion is also discussed. Section 5 has an example for illustration and Section 6 is the concluding remarks.

2. Temporal Representation

In a natural language sentence, its temporal meaning is composed by the situation and the time adverbial. An analysis of situations is as indispensable as that of time adverbials for natural language understanding and machine translation. How to represent them in a formal way will be discussed in the subsequent sections.

2.1. Situations

Traditionally, **situations** have been classified into four categories, i. e., **accomplishments, achievements, activities,** and **states** (Vendler (1967)). However, this classification is not appropriate for us. By considering the following two sentences,

John built this house last year. (1)

John was building this house last year. (2)

the same time adverbial *last year* appears and plays different roles. In the former *last year* is the whole time of house-building, while in the latter *last year* was just a part of time of house-building. This is because the above two sentences have the different **aspect** notions. Aspect serves to distinguish such things as whether the beginning, middle, or end of an event is being referred, and whether the event is completed or possibly left incomplete (Comrie (1976)). Therefore, it seems to reasonable for us to expand the traditional classification by considering aspect together. Situations are further classified into subcategories and shown in Table 1.

Table 1. The Classification of Situations and Their Corresponding Representation

Situation Types	Examples	Corresponding Representation
simp_ahvt (simple achievement)	John died.	situ(simp_ahvt, "John die")
prog_ahvt (progressive achievement)	John was dying.	situ(prog_ahvt, "John die")
simp_acty (simple activity)	John read books.	situ(simp_acty, "John read books")
prog_acty (progressive activity)	John was reading books.	situ(prog_acty, "John read books")
inch_acty (inchoative activity)	John began to read books.	situ(inch_acty, John read books)

term_acty (terminative activity)	John finished reading books.	situ(term_acty, "John read books")
simp_apsh (simple accomplishment)	John built this house.	situ(simp_apsh, "John build this house")
prog_apsh (progressive accomplishment)	John was building this house.	situ(prog_actu, "John build this house")
inch_apsh (inchoative accomplishment)	John began to build this house.	situ(inch_apsh, "John build this house")
term_apsh (terminative accomplishment)	John finished building this house.	situ(term_apsh, "John build this house")
simp_state (simple state)	John liked Mary.	situ(simp_state, "John like Mary")
inch_state (inchoative state)	John began to like Mary.	situ(inch_state, "John like Mary")

In our model, each subcategory of situation is represented by a unique predicate

situ(Stype, Prop)

with two arguments: one for situation type *Stype* and the other is for the tense-less proposition *Prop*. The possible values of *Stype* are *simp_ahvt*, *prog_ahvt*, *simp_apsh*, etc. The tense—less proposition can be interpreted as some kind of logical formulae. Since many formalisms (Colmerauer (1982), Dahl (1981), McCord (1986)) have been proposed to represent the logical formula succcessfully, we do not consider this problem here and just represent propositions as strings for simplicity. Thus the situations in sentences (1) and (2) are represented as

situ(simp_apsh, "John build this house"),

and

situ(prog_apsh, "John build this house")

respectively.

2.2. Time Adverbials

It is common for sentences with time adverbials. The functions of time adverbials are to specify temporal relations between events, to place events in calendrical intervals, and to give the duration of events. In our system, the classification of time adverbials is shown in Fig. 1.

Time adverbials are divided into two categories: one for **when-adverbials**, and the other for **aspectual adverbials.** When-adverbials that are used as answers to "when" questions are subclassified into **deictic adverbials** and **locational adverbials.** Deictic adverbials are adverbials

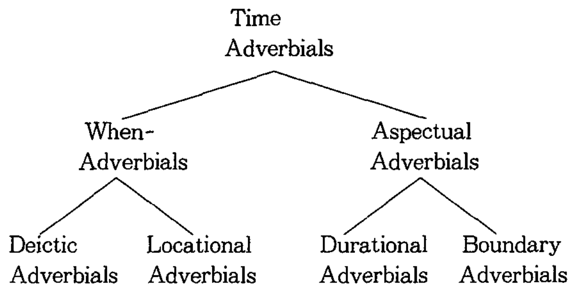

Fig. 1. The Classification of Time Adverbials

that have explicit relations with the moment of speech, for example, *yesterday, three days ago, last year, next week, this month,* etc. Locational adverbials are adverbials that identify the location of time without any reference to the speech time, such as dates (e. g. *Nov. 18, 1989),* days (e. g. *Wednesday*) and times (e. g. *2 o'clock*). On the other hand, aspectual adverbials are used as answers to "how long" questions. They are subclassified into **durational adverbials** and **boundary adverbials.** Durational adverbials specify the periods of time (e. g. *two months, three days*), and boundary adverbials (e.g. *since*···, *from*···*to*···) give the beginning points and/or the end points of the intervals. The representation of time adverbials are shown in Table 2.

Table 2. The Representation of Time Adverbials

Time Adverbials	Examples	Corresponding Representation
Deictic Adverbial	yesterday	yesterday
Locational Adverbial	Nov. 18, 1989	calendar(1989, 11, 18)
Durational Adverbial	for three days	have_duration(3, day)
Boundary Adverbial	from ten years ago to last year	have_period(n_cal_age(10, year), last_year)

2.3. Natural Language Sentences

In preceding sections, we have a logic-based temporal representation of situations and time adverbials. Now, we can get the representation of natural language sentence by clause

sentence(S, T)

where S denotes the situation in the simple sentence or the situation in the main clause of the complex sentence, and T is the temporal information about S. The temporal information may be the duration time of the situation specified by duration adverbials or boundary adverbials. For example,

John lived in Taipei for 10 years. (3)

John lived in Taipei from 1970 to 1980. (4)

are represented as

```
sentence(situ (simp_state,
  "John live in Taipei"),
  have_duration(10, year)).
```

and

```
sentence(situ(simp_state,
  "John live in Taipei"),
  have_period(calendar(1970),
  calendar(1980))).
```

respectively.

On the other hand, there are at least two ways to specify the occurrence time of situation. That is, we can use when-adverbials in simple sentences, and make use of temporal conjunction in complex sentences. For example, the simple sentence

John began to build this house seven years ago. (5)

is represented as

```
sentence(situ(inch_apsh,
    "John build this house"),
    n_cal_ago(7, year)).
```

and the following two compound sentences:

John began to build this house before
Mary began to go to college. (6)

Mary graduated when John finished
building this house. (7)

are represented as

```
sentence(situ(inch_apsh,
    "John build this house"),
    before: situ(inch_apsh,
    "Mary go to college")).
```

and

sentence(situ (simp_ahvt,
"Mary graduate")),
eq : situ(term_apsh,
"John build this house")).

respectively. It is noted that the situation in the subordinate clause and its associated temporal conjunction both contribute the occurrence time of situation in the main clause. Our system is based on the work of Allen (1984). There are thirteen kinds of primitive relations among intervals of time, i. e. *before*, *after*, *eq*, *meet*, *meet_inv*, *overlap*, *overlap_inv*, *during*, *during_inv*, *start*, *start_inv*, *finish*, and *finish_inv*. They are mutually exclusive. Temporal conjunctions *when*, *before*, and *after* correspond to the Allen's relation *eq*, *before*, and *after* respectively.

3. Questions about Time

The basic types of questions about time include "when" questions, "how long" questions and "yes/no" questions.

3.1. "When" Questions

"When" questions are those questions that interrogate the occurrence time of the event. In our system, we represent this type of questions by

when (S, Tlist)

where *S* denotes the situation and *Tlist* is the answer that tells the event time. For example, the question

When did John began to build this house? (8)

is translated into the goal

?-when(situ(inch_apsh,
"John build this house"), Tlist).

3.2. "How long" Questions

"How long" questions are those questions interrogating a span of time that may be the duration time of the event lasting for or may be the temporal distance between the situation and the moment of now. We represent such questions as

how_long(S, N, Cal)

where *S* denotes the situation, *N* is the length of time, and *Cal* is the time unit (such as *day*). A span of time is specified by *N* and *Cal.* Those situation types such as *simp_apsh, simp_acty* or *simp_state* asked by "how long" questions must be the period of time that they last for. For example, the question

How long did John read books? (9)

is translated into the goal

?-how_long(situ(simp_acty,
"John read books"), N, Cal).

The other situation types (excluding the above situation types) asked by the "how long" questions must be the distance between the situation and the moment of now. For example, the question

How long is it since Mary graduated? (10)

is translated into the goal

?-how long(situ(simp_ahvt,
"Mary graduate"), N, Cal).

And the goal of the question

How long is it since John began to build this house? (11)

is

?-how_long(situ (inch_apsh
"John build this house"),
N, Cal).

3.3. "Yes/No" Questions

The questions of "Did event X happen at time expression T?" and "Is it a period of time since the event X happen?" are "yes/no" questions to verify the truth about the event in temporal data base. They can be represented as the structure

yn_when(S, T)

or

yn_how_long(S, N, Cal)

with all the arguments instantiated. For example, the question

Did Mary graduate two years ago? (12)

is represented as

?_yn_when(situ(simp_abvt,
"Mary graduate"), n_cal_ago(2, year)).

And the goal of the question

Is it two years since Mary graduated? (13)

is

?_yn_how_long(situ(simp_ahvt,
"Mary graduate"), 2, year).

There are some other "yes/no" questions interrogating the temporal relation holding between two events. For example,

Did Mary graduate before John finished building this house? (14)

is represented as

?_event_before(situ(simp_ahvt, "Mary graduate"),
situ(term_apsh, "John build this house")).

The answer is "yes" if the statement in the question is compatible with the facts in temporal data base, otherwise "no" is generated as its response.

4. A Temporal Reasoning System

Our temporal reasoning system consists of the following main components: a time module, an event module, and an inference module. They are discussed in subsequent sections.

4.1. Time Module

This time module contains knowledge about time. It is expressed as a collection of terms such as *calendar(1990)*, *yesterday*, *n_cal_ago(3, day)*, *have_duration(10, year)*, etc. that represent calendar structures, lengths of time and a variety of time descriptions.

4.2. Event Module

This module contains a collection of *sentence* and *transition* clauses written in PROLOG. They are the knowledge about event. *Sentence* clauses, which represent kinds of situation and their temporal relations, are generated by parsing process of natural language sentences. *Transition* clauses, which denote some possible transitions among situations are obtained by sitwhich denote some possible transition among situations are obtained by situation implications and lexical knowledge.

4.2.1. Situation Implications

Recall that situations discussed Section 2.1 are represented by

```
situ(Stype, Prop).
```

It is obvious that there exists some relationship between situations of same proposition. We call these relationships as situation implications and represent them by clause

```
transition(
    situ(Stype 1, Prop),
    situ(Stype 2, Prop),
    Rel).
```

Rel is the temporal relation between two situations. By adopting Allen's notation, it can be *after*, *before*, *during*, etc. For example, if *P* stands for proposition "John build this house", then *situ(simp_apsh, P)* denotes the simple accomplishment situation in sentence *John built this house*, and *situ(prog_apsh, P)* denotes the progressive accomplishment situation in sentence *John was building this house*. It can be observed that the time of the former contains the time of the latter. This is represented as

```
transition(
    situ(simp_apsh, P),
    situ(prog_apsh, P),
    during_inv).
```

The other situation implications about accomplishment are

```
transition(
    situ(simp_apsh, P),
    situ(inch_apsh, P),
    start_inv).
transition(
    situ(simp_apsh, P),
    situ(term_apsh, P),
    finish_inv).
```

4.2.2. Lexical Knowledge

In this paper, though we do not attempt to discuss the identification process of situation type in natural language sentences, it can be observed that many constituents (such as verbal aspect, locative prepositional phrase, objects, etc.) have something to do with it. Thus, the same verb with or without a location of destination may denote different situation types.

John was walking. (15)

John was walking to the store. (16)

Sentence (15) denotes a progressive activity situation, and sentence (16) denotes a progressive accomplishment situation. There exists certain relationship between these two situations, for example,

if *John was walking to the store at T*

then at the same time *John was walking.*

In our system, such kind of knowledge(we call it **lexical knowledge**) is expressed by the clause

```
transition(
    situ(Stype 1, Prop 1),
    situ(Stype 2, Prop 2),
    Rel).
```

Rel is the temporal relation between the two situations, that can be one of Allen's primitive relations (i.e. *after*, *before*, *during*, etc.) or *have_distance (N, Cal)*. Note that *N* can be positive or negative. The relation *have_distance (N, Cal)* specifies that there exists a gap of time between two situations, and the gap in terms of unit *Cal* is *N*. For instance,

```
transition(S1, S2, have_distance(3, day)).
```

means the time of situation S1 is earlier than the time of situation S2, and its distance is three days long; and

```
transition(S1, S2, have_distance(-3, day)).
```

in turn means S1 is later than S2. For the two situations in sentences (15) and (16), therefore, we have clause

```
transition(
    situ(prog_apsh,
    "John walk to the store"),
    situ(prog_acty, "John walk"), eq).
```

Let's take another example. It is known that the time of "going to college" has something to do with the time of "graduation". We represent it by the following clauses:

```
transition(
    situ(term_apsh, "Mary go to college"),
    situ(simp_ahvt, "Mary graduate"),
    eq).
transition(
    situ(simp_ahvt, "Mary graduate"),
    situ(term_apsh, "Mary go to college"),
    eq).
transition(
    situ(inch_apsh, "Mary go to colldege"),
    situ(simp_ahvt, "Mary graduate"),
    have_distance(4, year)).
transition(
    situ(simp_ahvt, "Mary graduate"),
    situ(inch_apsh, "Mary go to college"),
    have_distance(-4, year)).
```

That means the end time of "going to college" is equal to the time of "graduation"; the beginning time of "going to college" is earlier than the time of "graduation" and their distance is four years long.

4.3. Inference Module

The inference module knows how to actively use the knowledge in modules of time and event. Thus temporal inferencing in this study contains two parts. One part concerns inferences about time and the other part concerns inferences about event.

4.3.1. Inferences about Time

When-adverbials have their own separate interpretation. In our system, clause get_date is used to interpret the meanings of when-adverbials and to get their corresponding calendar date. For example, the interpretation of *yesterday* is "one day ago" and we can use the following clause to get its corresponding date.

```
get_date(yesterday, X) :-
    today(D),
    distance_day(X, D, 1), !.
```

Clause *distance_day(X, D, N)* is used to get the date of *X* that is *N* days precedes *D*. In order to do this computation, a calendar should be included in the system.

In addition, we also have several rules to check temporal relation between time words. For example,

time_during(last_month, last_year)

is used to check whether the time of last month is during the time of last year. These inferences about time are also useful later.

4.3.2. Inferences about Event

For each *sentence* clause, there is a situation (composed by the situation type and the proposition), and its associated temporal information. In addition, a lot of situation implications and lexical knowledge are represented by *transition* clauses. By means of *sentence* and *transition* clauses, a temporal network can be established. The elliptical nodes represent situations, the rectangular nodes denote time adverbials that are associated with adjacent situations, and arcs between situations are labeled to indicate their inter relationship. Then, the temporal reasoning system can evaluate the query by tracing this temporal network to find its answer.

4.3.3. Question Answering

The temporal reasoning system searches the whole temporal network to find any temporal information about the situation. The queries that we can deal with will include

--when something happened;

--how long it lasted; and

--how events are related to one another in time.

The problem of finding the occurrence time of situation is equivalent to find a path from the given situation (the start node) to some final situation. Certainly, it is trivial in the case that the system has the direct temporal information about the given situation (i.e. with time adverbials specified). Otherwise, it should trace along the path that is formed by those situations related to each other. We adopt a depth_first strategy to search the solution path. The search will be terminated in the case of finding a situation with a time adverbial specified or no situations can be found any more. To prevent infinite loop, a cyclic check mechanism is added in the implementation of depth_first search.

"How long" questions are those questions interrogating a span of time. For *simp_apsh*, *simp_acty*, and *simple_state* situations, the answer is the duration time of the event lasting for. Thus, out system will trace the network to find the durational information about the event by directly searching the situation node itself or searching its corresponding inchoative and terminative situation node to get their distance between their occurrence time. As for other situations, the answer of a "how long" question is the temporal distance between the situation and the moment of now. It also can be solved in a similar way.

To answer "yes/no" questions about time such as *yn_when(S, T)*, the system will first find the answers of corresponding *when(S, Tlist)* questions, and then check the compatibleness between *T* and *Tlist*. Other kinds of "yes/no" questions are handled similarly.

5. An Example

Now, we illustrate the inference mechanism by the following example. Assume that we have sentences (5), (6), and (7), i.e.

John began to build this house
seven years ago. (5)

John began to build this house
before Mary began to go to college. (6)

Mary graduated when John finished
building this house. (7)

These sentences are represented as Fig. 2 to Fig. 4, respectively. After adding lexical knowledge and situation implications, Fig. 5 shows the temporal network of this example. We thus ask the question

When did John finish building this house?

that is expressed as

when(situ(term_apsh,
"John build this house"), Tlist).

Our system will trace the network and get a path from the elliptical node *situ(term_apsh, P)*, along *situ(simp_ahvt, R)*, and *situ(inch_apsh, Q)*, and finally to *situ(inch_apsh, P)*. All the temporal relations and the time adverbials along this path are recorded as

[eq, have_distance(-4, year), after,
n cal_ago(7, year)]

It is the answer of this query. From the answer produced by the system, we know that the time of "John finished building this house" is equal to the time T1, T1 is four years later than T2, T2 is later than T3, and T3 is seven years ago.

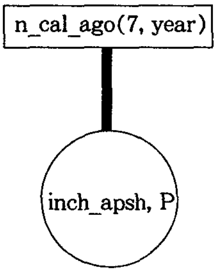

Fig. 2. Representation of Sentence "John began to build this house(P) seven years ago."

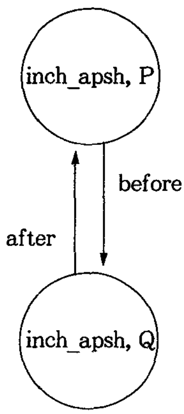

Fig. 3. Representation of Sentence "John began to build this house(P) before Mary began to go to college(Q)."

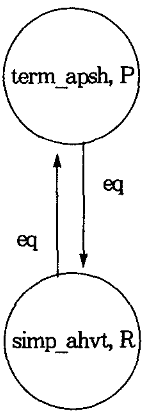

Fig. 4. Representation of Sentence "Mary graduated(R) when John finished building this house(P)."

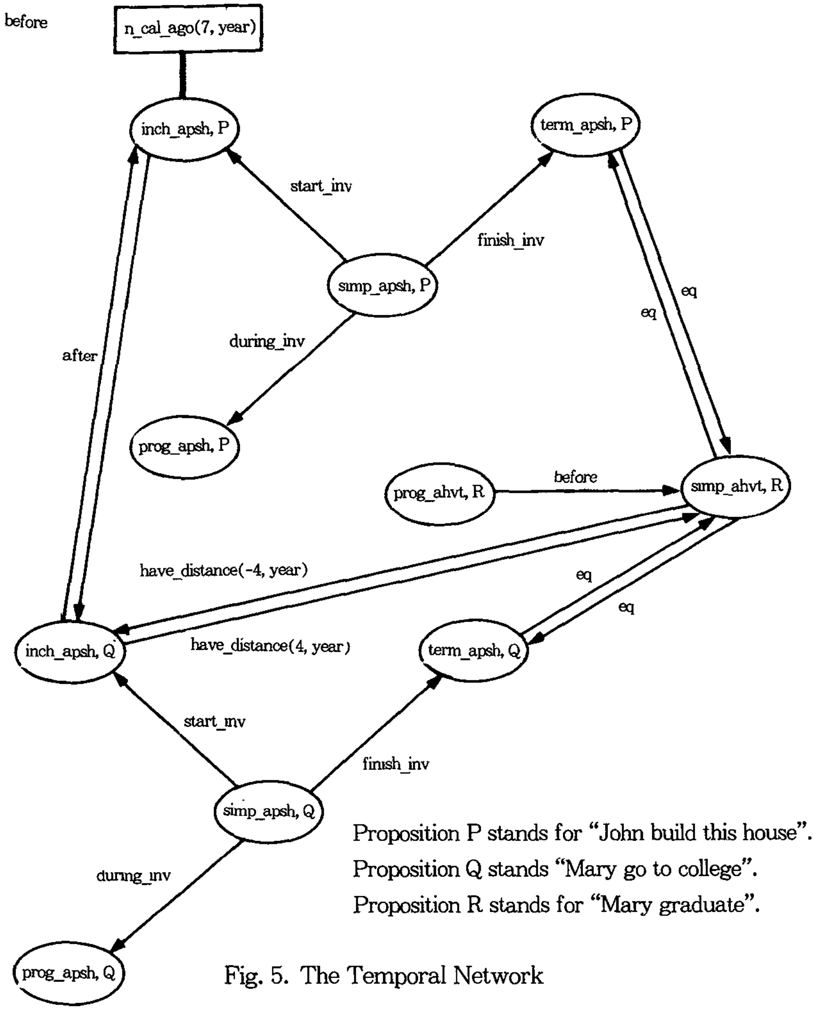

Fig. 5. The Temporal Network

6. Conclusion

Within AI and computational linguistics, only a few theories have been proposed for the processing of temporal information. In our research, an approach is adopted for representing and reasoning time and events within a logic programming framework. We also incorporate aspect notions into situations. Therefore, we can comprehend temporal relations in a written text that are more complex than data base updates and temporal information that we handle can be implicit, not just for dates.

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