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by

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# A DATA STRUCTURE FOR COGNITIVE INFORMATION RETRIEVAL

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A new data structure developed in connection with a natural language question-answering system is described. The data structure is based upon a new high-order calculus. It allows a great degree of expressiveness and is suitable for extensive logical deduction.

The inadequacies of low-order schemes for the representation of natural language information are given. A formal description of the new high-order structure which overcomes these inadequacies is then presented along with the properties that make it more suitable and attractive for machine processing of natural language information.

# A DATA STRUCTURE FOR COGNITIVE INFORMATION RETRIEVAL

## I. Introduction

The storage and subsequent retrieval of large amounts of information has posed some very interesting problems about data structures and their utilization for efficient retrieval purposes. These problems become more acute when the system must deal with the answering of questions posed in natural language. This is due to the fact that a natural language question-answering system must be able to synthesize retrieved information in order to construct the answer to any given question. The internal structure of such systems, therefore, must reflect subtle semantic differences.

The purpose of this paper is to report a new data structure developed in connection with a natural language question-answering system. This data structure is based upon a new high-order calculus. It allows a great degree of expressiveness and is suitable for extensive logical deduction.

Early attempts to perform natural language question-answering were based in part upon the logical properties of the propositional calculus such as Darlington.[2] The DEACON [12] and PROSYNTHEX [11] systems relied more heavily upon the syntactic properties of natural language. There are two very well written surveys of natural language question-answering systems, both by Simmons.[8,9]

Due to the inadequacy of the propositional calculus as a data structure model for question-answering, a variety of other approaches using a limited number of predicates were reported.[1,4] Robinson [5] developed a semi-decision algorithm for the first-order predicate calculus and Green and Raphael [3] showed this to be a much more reasonable structure for representing and manipulating natural language information.

It became evident that even the first-order predicate calculus could not represent much of the information that is encountered in natural language. Robinson then developed a semi-decision procedure for a high-order representation.[6] The use of a high-order structure as the basic scheme for the representation of natural language information has far more potential than any of the lower-order schemes. One basic advantage in using the high-order representation lies in the fact that anything that can be represented or manipulated within a lower-order representation can be accomplished more efficiently in a high-order representation. In addition, the embedding properties of the high-order structure allow many things that were heretofore impossible to represent.

It is important to note that the concept of using a data structure that permits the embedding of information is not unique to the structure developed in this paper. Simmons, Burger, and Schwarcz [7,10] used a similar type representation scheme which was the best structure available for natural language question-answering until recently. However, the structure did not have the flexibility to allow powerful deduction.

The embedding properties of both of these approaches makes the use of lower-order structures less attractive for natural language question-answering systems. Motivation for the use of the new high-order structure based upon a logical calculus is given in Section II. Section III gives a formal definition of this high-order structure along with a number of annotated examples demonstrating its application.

## II. Structural Representation for Natural Language Information

Suppose that it is necessary to represent the sentence "John is in the crosswalk" in some formal structure. One such formal structure is the propositional calculus. We can represent this sentence in the propositional calculus by calling it the proposition

$$p \equiv \text{John is in the crosswalk}$$

The language of the propositional calculus consists of the propositional variables, p,q,r,... and the logical connectives $\sim$, $\wedge$, $\vee$, $\Rightarrow$. The sentences of this language are made up in the following way: the propositions and negations of propositions are sentences, and if P and Q are propositions then $P\wedge Q$, $P\vee Q$, $P\Rightarrow Q$ are sentences.

We can consider the propositions of this calculus in terms of a relational structure. Thus "John is in the crosswalk" can be written as the relation

$$p \equiv \text{in(John,crosswalk)}.$$

If we treat this sentence strictly as a proposition, then there is no way of comparing it to related sentences such as:

$$q \equiv \text{in(John,intersection)}$$

$$r \equiv \text{in(John,street)}$$

However, if these sentences are treated as true relations they can be compared so that the relationships that do exist can be recognized. These relationships may be used advantageously in data organization. For example, the data might be organized into property lists. For the example given above the property list of John might be:

John
in-crosswalk
⋮

The above structures are well defined and do allow a certain amount of deductive capability. Thus, if we are given the above property list, the rule

$$in(a,b) \wedge in(b,c) \Rightarrow in(a,c),$$

and the additional relation

$$in(crosswalk,intersection),$$

then it may be deduced that

$$in(John,intersection).$$

This structure is insufficient for natural language systems. This can be demonstrated with the following propositions

p = "Every boy is a person"

and

q = "John is a boy"

Within the propositional calculus it is impossible to deduce that John is a person from p and q. In order to be able to handle this type of deduction we must expand this structure to allow variables to appear in place of objects and allow quantification of these variables. In such a structure p might be represented by

$$\forall x(is(x,boy) \Rightarrow is(x,person)).$$

Then, knowing that

$$is(John,boy)$$

we can deduce

$$is(John,person).$$

A formal structure which does allow the use of variables ranging over objects and quantification over those variables is the first-order predicate calculus.

The language of the first-order predicate calculus is made up of predicate symbols P, Q, R,..., variables $x_1,x_2,\ldots$ which range over individuals, constant symbols, function symbols, the quantifiers $\forall$(for all) and $\exists$(there exists), and the logical operations $\sim$, $\wedge$, $\vee$, $\Rightarrow$. Terms are defined to be:

1. Constants and variables,
2. If $c_1\ldots c_n$ are terms and f is an n-ary function symbol then $fc_1\ldots c_n$ is a term.

The formulas of this language are made up in the following way:

1. If P is an n-ary predicate and $c_1,\ldots,c_n$ are terms then $Pc_1,\ldots,c_n$ is an atomic formula.
2. If A and B are formulas then $\sim A$, $A \wedge B$, $A \vee B$, and $A \Rightarrow B$ are formulas.
3. If A is a formula and x is a variable then $\forall xA$ and $\exists xA$ are formulas.
4. Nothing is a formula unless forced to be one by 1, 2, and 3.

Internal to a computer the sentences of the first-order predicate calculus, are represented as LISP expressions in Skolem prenex conjunctive normal form. Thus,

Every boy is a person

would be represented as

$$\forall x(\text{is}(x,\text{boy}) \Rightarrow \text{is}(x,\text{person}))$$

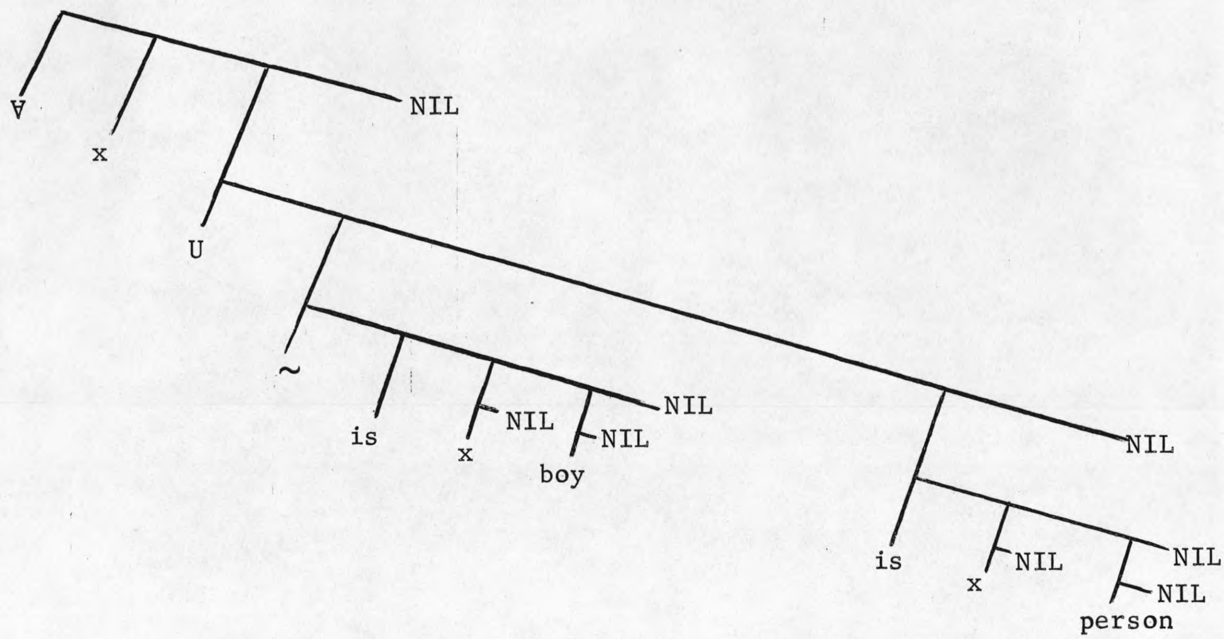
which in Skolem prenex conjunctive normal form would be

$$\forall x(\sim \text{is}(x,\text{boy}) \vee \text{is}(x,\text{person})).$$

The corresponding LISP expression is

```
(FA X (LOR (NEG IS (X) (BOY)) (IS (X) (PERSON))))
```

or equivalently




Even though the first-order predicate calculus is an improvement over the propositional and relational structures, it is still not powerful enough to be really useful in a natural language system. The main reasons for this are the inability to express relationships between relations, and to allow variables to range over relations as well as objects.

For example, suppose it is necessary to put into the first-order structure the sentences

John crossed the street after the light changed

or

A car must always yield to a pedestrian.

In the first case we are unable to put the sentence into the first-order structure because we have a relation, namely <u>after</u>, whose arguments are forced to be relations, namely crossed and changed, rather than some individuals. In the second case we cannot put the sentence into the first-order structure because we are faced with the quantification of a variable which ranges over situations not individuals. That is, the sentence states that for all possible situations a certain condition holds (i.e., that a car must yield to a pedestrian).

With the development given in this section one can see that the propositional, relational, and first-order structures have certain inadequacies in representing and manipulating natural language information. In the following section a high-order structure that overcomes these inadequacies is presented.

## III. A Data Structure Based on a High-Order Representation

For the reasons given in Section II we have gone to a higher-order structure for the representation of natural language information. In some ways the higher-order structure is similar to the first-order structure we defined previously. However, it is an extension of that structure in that we now allow relations to be embedded in other relations and we allow variables to range over these more complex structures. As a consequence, it is possible to represent situations as variables, the relationship between relations, and the modifications of terms. These features permit the representation of a wide range of natural language information. In addition, because of the generality of the structure chosen, the manipulation of information represented is greatly simplified.

A formal definition of this high-order structure will now be given: The following are defined within some natural language discourse $\mathcal{D}$.

1. $a_1$ is a <u>constant</u> iff $a_1$ is an object within $\mathcal{D}$.
2. $m_1$ is a <u>basic modifier</u> iff $m_1$ is a simple modifier within $\mathcal{D}$.
3. $c_1$ is a <u>modifying marker</u> iff $c_1$ indicates the occurrance of a modifier that is not simple in $\mathcal{D}$.

The high-order structure is made up of constant symbols $a_1, a_2, \ldots$, modifier symbols $m_1, m_2, \ldots$, modifying marker symbols $c_1, c_2, \ldots$, function symbols $f_1, f_2, \ldots$, variables that range over constants $x_1, x_2, \ldots$, n-ary relation symbols $P_1, P_2, \ldots$, variables that range over complex structures $y_1, y_2, \ldots$, and the logical symbols $\sim, \wedge, \vee, \Rightarrow$.

Terms are defined to be either:

1. constant symbols
2. all variables

3. complex structures, which are defined as either

   a. modified objects written $\bar{m}(\bar{a})$ where $\bar{m}$ is either a modifier, or a variable; and $\bar{a}$ is either a constant, a variable, or a complex structure (the interpretation of $\bar{m}(\bar{a})$ in $\mathfrak{D}$ is that $\bar{m}$ modifies $\bar{a}$). A modifier is either a basic modifier or, is of the form $c_1(\bar{b})$ where $c_1$ is a modifying marker and $\bar{b}$ is a constant or a modified object.

   b. n-ary relations over the terms $q_1,\ldots,q_n$ written $P(q_1,\ldots,q_n)$ where P is either an n-ary relation symbol or a variable which ranges over complex structures (this is interpreted to mean that $q,\ldots q_{n-1}$ and $q_n$ are in the relation P with each other).

4. if $t_1\ldots t_n$ are terms and f is an n-ary function symbol then $f(t_1\ldots t_n)$ is a term.

Formulas are defined in the following way:

1. n-ary relations and variables that range over n-ary relations are atomic formulas.
2. if A is an atomic formula and $\bar{m}$ is a modifier, then $\bar{m}(\bar{a})$ is a formula.
3. if A and B are formulas then $A \vee B$, $A \wedge B$, $\sim A$, $A \Rightarrow B$ are formulas.
4. if A is a formula and x is any variable then $\forall x(A)$ and $\exists x(A)$ are formulas.

For example, if the domain $\mathfrak{D}$ consists of English discourse relating to the operation of motor vehicles, then objects like car, driveway, and pedestrian are constants, and green, fast, and heavy are modifiers. Suppose

green car

appears in $\mathfrak{D}$. This would be represented as the modified object green(car)

because green is a modifier, car is a constant and green modifies car in 𝔇.

In order to appreciate this formalism think of green as a function whose value is equal to its argument with the additional property of being green. Thus, anything that applies to the object car, without qualification, also applies to the modified object green(car).

Similarly, if

the green car in the driveway

appears in 𝔇, then it would be represented by the modified object

(in(driveway))(green(car)).

This can be seen by first noting that in(driveway) is a modifier because in is a modifying marker and driveway is a constant. From the example above we know that green(car) is a modified object and a modifier followed by a modified object is itself a modified object. It also follows from the definition that

The green car in the driveway must yield to the pedestrian.

would be represented by the complex structure

must(yield((in(driveway))(green(car)),pedestrian)).

Notice, here, that yield is a binary relation between the objects

(in(driveway))(green(car))

and

pedestrian.

The binary relation yield is in turn modified by must.

Note that one might want to represent

(in(driveway))(car)

as the binary relation

in(car,driveway).

Using the new structure developed we can now represent the sentences which we could not handle previously. Thus, the sentence

A car must always yield to a pedestrian

would become

$$\forall_y (y \Rightarrow must(yield(car,pedestrian)))$$

where y is a variable that ranges over complex structures such as

(in(driveway))(car)

or

(in(crosswalk))(drunk(pedestrian)).

In the same manner, the sentence

John crossed the street after the light changed

would become

after(cross(John,street),change(light))

where _after_ is, in this example, an n-ary relation relating _cross_ and _change_. An algorithm for transforming natural language into this high-order structure is under development and will be discussed in a forthcoming paper.

The high-order structure described above permits the representation of all sentences which are representable in the lower-order structures (that is, the propositional, relational, and first-order structures). In addition to subsuming all lower-order structures, the high-order structure enables the representation of much information that could not be represented before. This increased generality makes it easier to represent natural language information. Furthermore, a deduction algorithm for the high-order structure has been developed. The algorithm is based upon Robinson's resolution principle. The details of this algorithm will be discussed in a forthcoming paper.

As an example of deductive capability within this high-order structure consider the sentence

A car must always yield to a pedestrian

and the question

Must a car in a driveway yield to a pedestrian in a crosswalk?

In the high-order representation scheme these would be

$$\forall y(y \Rightarrow must(yield(car,pedestrian))) \quad (1)$$

and

$$must(yield((in(driveway))(car),(in(crosswalk))(pedestrian))) \quad (2)$$

respectively. The answer to this question will be yes if it can be demonstrated that (2) is true. That is, by showing that it can be deduced from the information available in the system (namely (1) in this case). From (1) we can imply that

$$\forall y_1 \forall y_2(must(yield(y_1(car),y_2(pedestrian))) \quad (3)$$

must hold.

To see this, note that $y_1$ and $y_2$ are modifiers of car and pedestrian, respectively. That means that a car in all situations $y_1$ must yield to a pedestrian in all situations $y_2$, but that's just what (1) says when restricted to situations dealing with cars and pedestrians.

Now, consider the following assignment for variables $y_1$ and $y_2$ in (3):

$y_1 \equiv$ (in(driveway)), and
$y_2 \equiv$ (in(crosswalk))

Then (3) would appear as:

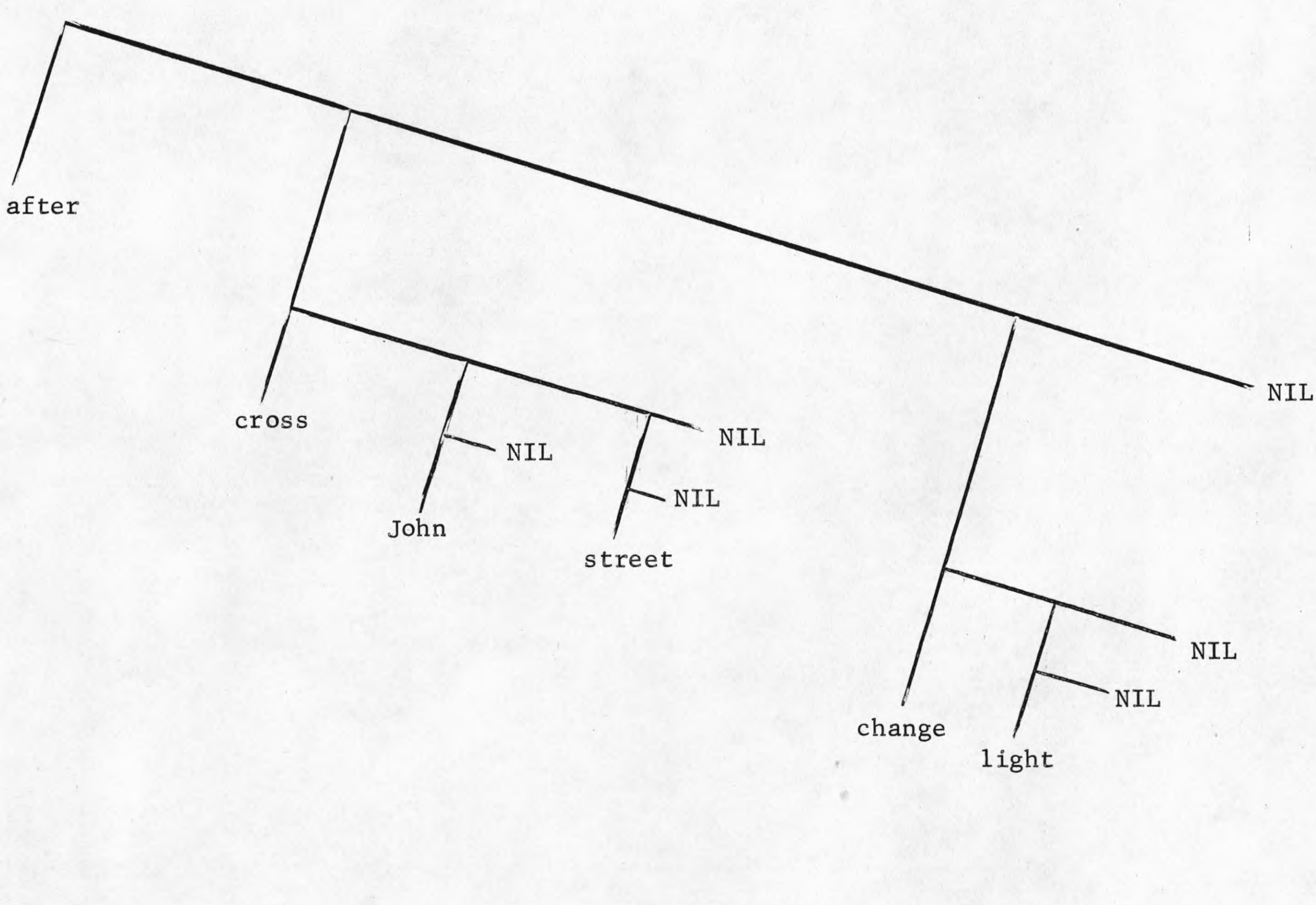
$$must(yield((in(driveway))(car),(in(crosswalk))(pedestrian))) \quad (4)$$

But (4) is exactly what we set out to deduce, so the answer would be yes.

Internally the new structure can be considered in certain respects as an extension of the first-order structure. Thus, where only objects appeared in the LISP expressions in the first-order structure, complex structures may now appear. The sentence "John crossed the street after the light changed" would appear as the LISP expression:

(AFTER (CROSS (JOHN) (STREET)) (CHANGE (LIGHT)))

or equivalently



## IV. Conclusion

In any high quality natural language question-answering system one must have:

1. an internal data structure sufficiently rich to represent natural language information.
2. a method of transforming natural language into that structure.
3. a strong deduction algorithm for manipulating the information in that structure.

It should be pointed out that these are not separate problems. In fact, the data structure plays the central role in such a system for the two following reasons. First, the realization of a transformational algorithm is completely dependent upon the characteristics of the internal structure. Secondly, the deduction algorithm can only be as powerful as the expressiveness of the internal data structure.

In this paper we have discussed the inadequacies of low-order schemes for the representation of information in natural language systems. A new high-order structure for the representation of natural language information was then presented. It has been shown that within this new structure a much wider range of natural language information can be represented. The powerfulness of representation of the high-order structure is due to its embedding property and its ability to allow quantification over complex structures.

Extensive investigation indicates that this high-order structure is extremely well suited for both the transformation of natural language information and powerful deduction, thus making it desirable for high quality natural language question-answering systems.

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13. ABSTRACT

A new data structure developed in connection with a natural language question-answering system is described. The data structure is based upon a new high-order calculus. It allows a great degree of expressiveness and is suitable for extensive logical deduction.

The inadequacies of low-order schemes for the representation of natural language information are given. A formal description of the new high-order structure which overcomes these inadequacies is then presented along with the properties that make it more suitable and attractive for machine processing of natural language information.

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