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# A Logical Foundation of Preference-based Disambiguation

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# A Logical Foundation of Preference-based Disambiguation

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**Abstract**

In natural language understanding, resolving ambiguity is a very important and difficult problem. A promising method for disambiguation is to use grammatical and semantical preferences and many natural language understanding systems have been built by using this method. In this paper, we give a logical foundation of such systems. We believe that the logical foundation is useful in understanding of mechanism of disambiguation in a more abstract manner and building more well-behaved systems.

The idea of formalizing preference-based disambiguation is as follows. We regard first-order formulas translated from background knowledge and input sentences as axioms. Then, preferences can be regarded as an order over logical interpretations of such axioms since preferences express criteria to select plausible readings of input sentences. To express such an order, we can use model-theoretical meta-language [8] which we have already used in formalizing *soft constraints* in scheduling and design [7]. Since we notice strong concurrence between natural language understanding and scheduling in use of preferences, we would like to show that the technique of formalizing soft constraints in scheduling can be used to give a logical foundation of resolving ambiguity by preferences.

**Topic:** Natural Language

**Subtopic:** Understanding

**Keywords:** disambiguation, preference, soft constraints, interpretation order, circumscription

I declare that this paper is not submitted to any other conferences or any journals.

## 1 Introduction

Disambiguation is an inevitable problem in natural language understanding. A promising way of resolving ambiguity is to use preference heuristics grammatically and semantically. Many researches have been conducted along this line [2, 10, 3]. The aim of this paper is to provide a logical foundation for such systems. We believe that by providing a logical foundation of preference-based disambiguation, we can understand usages of preferences in a more abstract manner and this understanding helps for building more well-behaved systems for natural language understanding.

As far as we know, the previous works of logical foundations for resolving ambiguity are [3, 1, 6, 11]. However, Nagao's work [6] only considers a representation of ambiguity by a multiple-world model and suggests an obscure method for disambiguation. A method of Hobbs et al. [3] resolves ambiguity by using abduction with attached costs to formulas and Charniak's work [1] deals with noun-phrase reference determination by extending unification. Zadrozny [11] gives a correspondence between paragraphs and logical models based on three-level semantics of commonsense reasoning [12]. Among the above researches, Zadrozny's work is the most rigorous and general. However, because of its extra levels of inference, this framework is complex. In this paper, we also will give a general logical framework for disambiguation by adapting a formalization of preferences in scheduling and design [7]. This work is a generalization of circumscription [5] based on ordering over logical interpretation [8] and, therefore, easily understood than Zadrozny's work in a model-theoretical point of view.

The idea of formalizing soft constraints[1] in [7] is as follows. Let hard constraints be represented in the first-order formulas. Then a logical interpretation which satisfies all of these first-order formulas can be regarded as a solution. Then, soft constraints can be regarded as an order over these logical interpretations because soft constraints represent criteria over solutions to choose the most preferable ones. In [7] we use a model-theoretical metalanguage [8] which represents a preference order directly. This meta-language can be translated into the second-order formula to provide a syntactical definition of the most preferred solutions.

[1] In [7], preferences are called *soft constraints* whereas restrictions which every solution must satisfy are called *hard constraints*

This idea can be applied to natural language understanding as well. We assume that we can translate input sentences into logical formulas. If there is an ambiguity, then the logical formula contains disjunctions each of whose disjuncts expresses a possible reading. Then, we regard logical formulas translated from background knowledge and input sentences as axioms. Since preferences in natural language are criteria over possible readings, we can regard these preferences as an order over logical interpretations satisfying the above axioms. Then, disambiguation means selecting the most preferred logical interpretations defined with respect to the axioms and the order. We, therefore, can use our framework to formalize disambiguation.

There are preferences in natural language (same as design and scheduling) which conflict each other as well as preferences with various priorities. Moreover, with input sentences added, preferences may no longer be applicable or new preferences may be usable. Therefore, preference rules should be ready for being retracted at anytime when the stronger preference rules are found. We demonstrate these phenomena by examples.

# 2 Formalization of Preferences

We briefly review our framework [7] to represent a preference by logical interpretation ordering. Before doing that, we introduce notations for brevity. Let $\mathbf{P}$ be a tuple of predicate constants or a tuple of predicate variables, and $x_1, ..., x_n$ be individual variables. $E(\mathbf{P}, x_1, ..., x_n)$ denotes a formula which includes some of these predicate constants or variables and these individual variables as free variables.

$M' \leq_{\phi}^{E(\mathbf{P}, x_1, ..., x_n)} M$ is an abbreviation of the following model-theoretical meta-statement:

$$\forall \phi_{x_1} \in \Phi_D ... \forall \phi_{x_1 x_2 ... x_n} \in \Phi_D ( \\ (M \models_{\phi_{x_1 ... x_n}} E(\mathbf{P}, x_1, ..., x_n)) \supset (M' \models_{\phi_{x_1 ... x_n}} E(\mathbf{P}, x_1, ..., x_n))).$$

Here, $E(\mathbf{P}, x_1, ...., x_n)$ is a logical expression of a preference and the above model-theoretical formula intuitively means that for all $x_1, ..., x_n$, if $M$ satisfies $E(\mathbf{P}, x_1, ...., x_n)$ then $M'$ satisfies it as well.

And $M' =_{\phi}^{E(\mathbf{P}, x_1, ..., x_n)} M$ is an abbreviation of the following model-theoretical meta-statement:

$$(M' \leq_{\phi}^{E(\mathbf{P},x_1,...,x_n)} M) \wedge (M \leq_{\phi}^{E(\mathbf{P},x_1,...,x_n)} M').$$

$E(\mathbf{P}, x_1, ..., x_n) \leq E(\mathbf{Q}, x_1, ..., x_n)$ is an abbreviation of the following formula:

$$\forall x_1 \forall x_2 ... \forall x_n (E(\mathbf{Q}, x_1, ..., x_n) \supset E(\mathbf{P}, x_1, ..., x_n)).$$

And $E(\mathbf{P}, x_1, ..., x_n) = E(\mathbf{Q}, x_1, ..., x_n)$ is an abbreviation of the following formula:

$$\forall x_1 \forall x_2 ... \forall x_n (E(\mathbf{Q}, x_1, ..., x_n) \equiv E(\mathbf{P}, x_1, ..., x_n)).$$

In this paper, we only consider preferences with priorities which are needed for natural language understanding. More general cases are found in [7]. Let formulas which should be satisfied in the first place be

$$E_1^1(\mathbf{P}, x_1, ..., x_{n_1^1}), ..., E_{m_1}^1(\mathbf{P}, x_1, ..., x_{n_{m_1}^1}),$$

and formulas which should be satisfied in the second place be

$$E_1^2(\mathbf{P}, x_1, ..., x_{n_1^2}), ..., E_{m_2}^2(\mathbf{P}, x_1, ..., x_{n_{m_2}^2}), ...$$

and formulas which should be satisfied in the $k$-th place be

$$E_1^k(\mathbf{P}, x_1, ..., x_{n_1^k}), ..., E_{m_k}^k(\mathbf{P}, x_1, ..., x_{n_{m_k}^k}).$$

Then, an order that $M'$ is more preferable than $M$ is defined as follows:

$$M' <_{\phi} M \stackrel{\text{def}}{\equiv} (M' \leq_{\phi} M) \wedge \neg(M \leq_{\phi} M').$$

where $M' \leq_{\phi} M$ is an abbreviation of $(M' \leq_{\phi}^1 M) \wedge ... \wedge (M' \leq_{\phi}^k M)$ and $M' \leq_{\phi}^i M$ is an abbreviation of the following model-theoretical statement:

$$(\wedge_{j=1}^{i-1} \wedge_{l=1}^{m_j} (M' =_{\phi}^{E_l^j(\mathbf{P},x_1,...,x_{n_l^j})} M)) \supset (\wedge_{l=1}^{m_i} (M' \leq_{\phi}^{E_l^i(\mathbf{P},x_1,...,x_{n_l^i})} M)),$$

where $M' \leq_{\phi}^1 M$ is a meta-statement without conditional part.

This relation means that interpretations which satisfy $E_1^1, ..., E_{m_1}^1$ as much as possible are preferable and if there are interpretations which satisfy the same formulas in the first place, then interpretations which satisfy $E_1^2, ..., E_{m_2}^2$ as much as possible are preferable and, ... if there are interpretations which satisfy the same formulas in the $(k-1)$-th place, then interpretations which satisfy $E_1^k, ..., E_{m_k}^k$ as much as possible are preferable.

Then, we can show a syntactic definition of the most preferable interpretations in the above order which satisfy hard constraints denoted as $A(\mathbf{P})$:

$$A(\mathbf{P}) \wedge \neg \exists \mathrm{p}(A(\mathrm{p}) \wedge (\mathrm{p} \leq \mathbf{P}) \wedge \neg(\mathbf{P} \leq \mathrm{p})),$$

where $\mathrm{p} \leq \mathbf{P}$ is an abbreviation of $(\mathrm{p} \leq^1 \mathbf{P}) \wedge ... \wedge (\mathrm{p} \leq^k \mathbf{P})$ and $\mathrm{p} \leq^i \mathbf{P}$ is an abbreviation of the following formula:

$$(\bigwedge_{j=1}^{i-1} \bigwedge_{l=1}^{m_j} (E_l^j(\mathbf{p}, x_1, ..., x_{n_l^j}) = E_l^j(\mathbf{P}, x_1, ..., x_{n_l^j}))) \supset$$
$$(\bigwedge_{l=1}^{m_i} (E_l^i(\mathbf{p}, x_1, ..., x_{n_l^i}) \leq E_l^i(\mathbf{P}, x_1, ..., x_{n_l^i})))$$

If we regard axiom $A(\mathbf{P})$ as a logical representation of background knowledge and input sentences and we regard the order $M' <_\phi M$ as preferences in natural language, then the above syntactic definition expresses the most preferable readings. And this syntactic definition actually coincides with a definition of prioritized formula circumscription [5] if we minimize the negation of each of the above preferences with the same priority.

# 3 Representation Issues

## 3.1 Logical Representation of Sentences and Background Knowledge

A semantic representation used in this paper is an adaptation of Kowalski's event calculus [4]. However, the idea of formalizing disambiguation does not depend on a particular representation. We assume that each sentence expresses an event. For example, a sentence "John gave the telescope to the man" is represented as the following formula.

$$act(E, Give) \land actor(E, John) \land object(E, Telescope) \land recipient(E, Man)$$

A complex sentence is supposed to be decomposed into a set of simple sentences which is translated into the above representation. Ambiguities are expressed by disjunctions. For example, a sentence "John saw a man with a telescope" has the following ambiguity in meaning of "with a telescope".

1. John used the telescope as an instrument.

2. The man had the telescope.

This sentence is expressed as follows. The last conjunct expresses the above ambiguity.

$$time(E, T) \land act(E, See) \land actor(E, John) \land object(E, Man) \land$$
$$(instrument(E, Telescope) \lor$$
$$(time(E', T) \land act(E', Have) \land actor(E', Man) \land object(E', telescope)))$$

In addition to the semantic representation, we also use syntactical information from a parser so that grammatical preference rules can be used. For example, we show some of the grammatical information of the sentence "John gave the telescope to the man" as follows. (We assume that sentence number is 1).

$$subj(1, John) \wedge verb(1, Give) \wedge direct\_obj(1, Telescope) \wedge$$
$$indirect\_obj(1, Man) \wedge in\_the\_sentence(1, John)$$

By using these basic predicates, we can represent background knowledge which are always valid. For example, background knowledge "If $a$ use $o$ as an instrument at time $i$ then $a$ has $o$ at time $i$" can be expressed in the following formula.

$$\forall e \forall i \forall a \forall o((time(e, i) \wedge actor(e, a) \wedge instrument(e, o)) \supset$$
$$\exists e_1(time(e_1, i) \wedge act(e_1, have) \wedge actor(e_1, a) \wedge object(e_1, o)))$$

## 3.2 Logical Representation of Preferences

We can represent preferences as a formula which should be satisfied as much as possible. A priority among preferences can be handled by putting stronger preferences into a stronger hierarchy of preferences and a context can be represented by including them conditional parts of preference rules.

For example, consider the following two grammatical preferences.

1. If "$He$" appears in a sentence as the subject and the subject in the previous sentence is male, then it is preferable that "$He$" refers to the previous subject.

2. If "$He$" appears in a sentence as the subject and someone in the previous sentence is male, then it is preferable that "$He$" refers to that one in the previous sentence.

Suppose that the former is stronger than the latter. This priority of the preferences means that the formula:

$$(is(a, Male) \wedge subj(i, a) \wedge in\_the\_sentence(i + 1, He)) \supset eq(a, He)$$

should be satisfied as much as possible for every $a$ and $i$, and if it is maximally satisfied then the following formula:

$$(is(a, Male) \wedge in\_the\_sentence(i, a) \wedge in\_the\_sentence(i + 1, He)) \supset$$

$eq(a, He)$

should be satisfied as much as possible for every $a$ and $i$.

Note that preferences are conditional sentences. If a conditional part of a preference is not true, then the preference is not applicable. This expresses contextual dependency of preference because if the context entails the conditional part of a preference, then the preference is applicable.

We can represent semantic preferences as well. For example, a preference "If $a_1$ sees $a_2$, then $a_2$ and $a_1$ are not equal" means that the following expression should be satisfied as much as possible for every $e, a_1$ and $a_2$:

$$(act(e, See) \wedge actor(e, a_1) \wedge object(e, a_2)) \supset \neg eq(a_2, a_1)$$

# 4 Examples

We use the following sets of sentences. This example is adapted from [6].

1. John just saw a man with a telescope.
2. He bought the telescope yesterday.
3. But, he gave the telescope to the man this morning.

In the following analysis, there are some points which should be mentioned.

1. We assume that we can translate a sentence into a logical formula discussed in the previous section. We think that this kind of translation is easy by using a parsing tree of the sentence.
2. We assume that we can attach time stamp (expressed as integer) for events if it is possible. For example, in the above set of sentences, we assume that "yesterday" means time 0 and "this morning" means time 1 and "just" means time 2. This attachment of time stamp should be flexible if more input sentences are added.
3. We do not consider multiple-reference of pronoun "$He$", so "$He$" has only one denotation. Moreover, we assume that "$He$" is used only as the subjective case. However, these restrictions are imposed because of space limitation of this paper and can be removed.

4. In the following logical representation, we omit irrelevant information in the above sentences. For example, we show only logical formulas for grammatical information needed for analysis.

We consider the following background knowledge which are always true. We denote the conjunctions of the following axioms as $A_0(\mathbf{P})$ where $\mathbf{P} \stackrel{def}{=} (eq, is, time, act, actor, object, recipient, instrument, subj, in\_the\_sentence)$.

1. If $a_1$ is equal to $a_2$ then $a_2$ is equal to $a_1$.

   $\forall a_1 \forall a_2 (eq(a_1, a_2) \supset eq(a_2, a_1))$

2. If $a_1$ and $a_2$ are equal and $a_2$ and $a_3$ are equal, then $a_1$ and $a_3$ are equal.

   $\forall a_1 \forall a_2 \forall a_3 ((eq(a_1, a_2) \wedge eq(a_2, a_3)) \supset eq(a_1, a_3))$

3. If $a_1$ is equal to $a_2$, then $a_2$ is an actor of $a_1$'s action, too.

   $\forall e \forall a_1 \forall a_2 ((eq(a_1, a_2) \wedge actor(e, a_1)) \supset actor(e, a_2))$

4. If $a$ use $o$ as an instrument at time $i$ then $a$ has $o$ at time $i$.

   $\forall e \forall i \forall a \forall o ((time(e, i) \wedge actor(e, a) \wedge instrument(e, o)) \supset$
   $\exists e_1 (time(e_1, i) \wedge act(e_1, have) \wedge actor(e_1, a) \wedge object(e_1, o)))$

5. If $a_1$ has $o$ at time $i$ and $a_1$ and $a_2$ are not equal then $a_2$ does not have $o$ at time $i$.

   $\forall e \forall i \forall a_1 \forall a_2 \forall o \forall e_1 ($
   $(time(e, i) \wedge act(e, Have) \wedge actor(e, a_1) \wedge object(e, o) \wedge \neg eq(a_1, a_2)) \supset$
   $((time(e_1, i) \wedge act(e_1, Have) \wedge actor(e_1, a_2)) \supset \neg object(e_1, o)))$

We consider the following preferences.

1. If $a_1$ sees $a_2$, then $a_1$ and $a_2$ are not equal.

   $E_1^1(\mathbf{P}, e, a_1, a_2) =$
   $(act(e, See) \wedge actor(e, a_1) \wedge object(e, a_2)) \supset \neg eq(a_1, a_2)$

2. If $a_1$ gives something to $a_2$, then $a_1$ and $a_2$ are not equal.

   $E_2^1(\mathbf{P}, e, a_1, a_2) =$
   $(act(e, Give) \wedge actor(e, a_1) \wedge recipient(e, a_2)) \supset \neg eq(a_1, a_2)$

3. If $a$ is male and $a$ is the subject of $i$-th sentence and "$He$" is in the next sentence, then $a$ is equal to "$He$".

   $E_1^2(\mathbf{P}, e, a, i) =$

   $(is(a, Male) \wedge subj(i, a) \wedge in\_the\_sentence(i+1, He)) \supset$

   $eq(a, He)$

4. If $a$ is male and $a$ is in $i$-th sentence and "$He$" is in the next sentence, then $a$ is equal to "$He$".

   $E_1^3(\mathbf{P}, a, i) =$

   $(is(a, Male) \wedge in\_the\_sentence(i, a) \wedge in\_the\_sentence(i+1, He)) \supset$

   $eq(a, He)$

5. If someone gives $o$ to $a$ at time $i$, then $a$ has $o$ at time $i+1$. This expresses inertia of ownership.

   $E_1^4(\mathbf{P}, e, a, o, i) =$

   $(act(e, Give) \wedge object(e, o) \wedge recipient(e, a) \wedge time(e, i)) \supset$

   $\exists e_1(act(e_1, Have) \wedge actor(e_1, a) \wedge object(e_1, o) \wedge time(e_1, i+1))$

6. If $a$ buys $o$ at time $i$, then $a$ has $o$ at time $i+2$. This preference is weaker than the former preference because time interval is longer than the former preference.

   $E_1^5(\mathbf{P}, e, a, o, i) =$

   $(act(e, Buy) \wedge actor(e, a) \wedge object(e, o) \wedge time(e, i)) \supset$

   $\exists e_1(act(e_1, Have) \wedge actor(e_1, a) \wedge object(e_1, o) \wedge time(e_1, i+2))$

We assume that $E_1^1$ and $E_2^1$ are formulas which should be satisfied in the first place, $E_1^2$ in the second place, $E_1^3$ in the third place, $E_1^4$ in the fourth place and $E_1^5$ in the fifth place.

We first show a logical representation of the following sentence and denote it as $A_1(\mathbf{P})$.

**John just saw a man with a telescope.**

$time(E_1, 2) \wedge act(E_1, See) \wedge actor(E_1, John) \wedge object(E_1, Man) \wedge$
$is(John, Male) \wedge is(Man, Male) \wedge subj(1, John) \wedge$

$in\_the\_sentence(1, John) \wedge in\_the\_sentence(1, Man) \wedge$
$(instrument(E_1, Telescope) \vee$
$(actor(E_1', Man) \wedge time(E_1', 2) \wedge act(E_1', Have) \wedge object(E_1', telescope)))$

We can not solve ambiguity of this sentence even if we use the above preferences. So, this sentence is essentially ambiguous.

However, suppose we add the following sentence.

**He bought the telescope yesterday.**

We show a logical representation related to this sentence and denote it as $A_2(\mathbf{P})$.

$time(E_2, 0) \wedge act(E_2, Buy) \wedge actor(E_2, He) \wedge object(E_2, Telescope) \wedge$
$in\_the\_sentence(2, He)$

The syntactic definition of the most preferable readings is as follows.

$$A(\mathbf{P}) \wedge \neg\exists \mathbf{p}(A(\mathbf{p}) \wedge (\mathbf{p} \leq \mathbf{P}) \wedge \neg(\mathbf{P} \leq \mathbf{p})),$$

where $A(\mathbf{P})$ is equivalent to $A_0(\mathbf{P}) \wedge A_1(\mathbf{P}) \wedge A_2(\mathbf{P})$,
and $\mathbf{p} \leq \mathbf{P}$ is an abbreviation of $(\mathbf{p} \leq^1 \mathbf{P}) \wedge ... \wedge (\mathbf{p} \leq^5 \mathbf{P})$ and each $\mathbf{p} \leq^i \mathbf{P}$ is defined in the same way as in Section 2.

We show an intuitive explanation of inference as follows. From the preference 3, "$He$" preferably refers to John and from the preference 6, we infer that John had the telescope at time 2 and therefore the man cannot have the telescope at time 2 from the background knowledge 5 and therefore the telescope was used as an instrument from the last disjunction in $A_1(\mathbf{P})$. This inference can be done because the used preferences do not conflict each other. We can actually infer $instrument(E_1, telescope)$ from the above syntactic definition of the most preferable readings.

Suppose we add the following sentence to the previous sentences.

**But, he gave the telescope to the man this morning.**

A logical representation related to this sentence is as follows. We denote the formula as $A_3(\mathbf{P})$.

$time(E_3, 1) \wedge act(E_3, Give) \wedge actor(E_3, He) \wedge object(E_3, Telescope) \wedge$
$recipient(E_3, Man)$

If we replace $A(\mathbf{P})$ by $A(\mathbf{P}) \wedge A_3(\mathbf{P})$ and $A(\mathbf{p})$ by $A(\mathbf{p}) \wedge A_3(\mathbf{p})$ in the syntactic definition, the meaning of "with" is changed. From preference 5, the man should have had the telescope at time 2. This preference overrides preference rule 6 because the priority of the former is higher than the latter.

It is interesting to see if we replace the third sentence by the following sentence.

**But, he gave the telescope to John this morning.**

A logical representation related to this sentence is as follows. This formula is added to $A(\mathbf{P})$.

$time(E_3, 1) \wedge act(E_3, Give) \wedge actor(E_3, He) \wedge object(E_3, Telescope) \wedge$
$recipient(E_3, John)$

In this case, the preference 2 is used and "$He$" is assumed not to be John. Then, the preference 4 instead of the preference 3 is used because the preference 2 overrides the preference 3. Then, we can infer that "$He$" should be the man and from the preference 5, we can conclude that John used the telescope as an instrument.

We can calculate the above results semi-automatically by using the hierarchical logic programming language called **CHAL**(Contrainte Hierarchiques avec Logique) [9] which can be used as a propositional circumscription prover. In this computation, we manually introduce Skolem functions for existential-quantified variables and instantiate universal-quantified variables in background knowledge and preferences with relevant constants in the input sentences. Then, we can use CHAL to calculate a propositional circumscription because background knowledge and preferences are ground, that is, propositional.

# 5 Discussion

(1) **Computability:**

Since a syntactic definition of the most preferable readings is represented in a second-order formula, it is not computable in general. However, in natural language understanding, we believe that we can delete existential-quantified variable by introducing Skolem functions and restrict range of universal-quantified variables to constants in input sentences. If it is true, all preferences and background knowledge become propositional and calculating the most preferable readings becomes computable. We have to check if this method is always applicable by examining many examples.

(2) **Avoiding Combinatorial Explosion:**

Although a disjunctive representation of ambiguity reduces combinatorial explosion, we think that the best way is to introduce parsing rules as first-order axioms so that parsing results need not be represented explicitly. This means an integration of grammatical process and semantic process into unified representation of first-order logic so that various proof strategy can be used to avoid combinatorial explosion.

(3) **Representation of Contexts and Preferences:**

One might think that a representation of contexts and preferences will be difficult. However, we believe that the following methods help to find a suitable representation of contexts and preferences.

1. **Categorization:**
   We categorize contexts and preferences so that hierarchical description can be used. However, this method needs a careful analysis of contexts and preferences.

2. **Debugging:**
   If we do not get the intended meaning by the current preferences, then we debug inference process to find unintended preferences and introduce a new context to avoid using unintended preferences. We believe that this process is relatively easy because of a logical representation of preferences.

3. **Learning:**
   The best is to learn contexts automatically from reading a lot of texts. This method must involve statistical analysis of texts to produce preferences among possible readings.

Although these three methods have not been proved to be successful yet, we believe that this paper gives a theoretical springboard for these further studies.

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