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Authors
Mahesh, Kavi
Eiselt, Kurt P.

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Uniform Representations for Syntax-Semantics Arbitration

Kavi Mahesh and **Kurt P. Eiselt**
College of Computing
Georgia Institute of Technology
Atlanta, GA 30332-0280
{mahesh, eiselt}@cc.gatech.edu

Abstract

Psychological investigations have led to considerable insight into the working of the human language comprehension system. In this article, we look at a set of principles derived from psychological findings to argue for a particular organization of linguistic knowledge along with a particular processing strategy and present a computational model of sentence processing based on those principles. Many studies have shown that human sentence comprehension is an incremental and interactive process in which semantic and other higher-level information interacts with syntactic information to make informed commitments as **early** as possible at a local ambiguity. Early commitments may be made by using top-down guidance from knowledge of different types, each of which must be applicable independently of others. Further evidence from studies of error recovery and delayed decisions points toward an arbitration mechanism for combining syntactic and semantic information in resolving ambiguities. In order to account for all of the above, we propose that all types of linguistic knowledge must be represented in a common form but must be separable so that they can be applied independently of each other and integrated at processing time by the arbitrator. We present such a uniform representation and a computational model called COMPERE based on the representation and the processing strategy.

Introduction

Psychological investigations of human language processing have led to considerable insight into the working of the language processor. Yet, attempts to build psychologically real computational models of language processing face considerable problems in translating the constraints put forth by psycholinguistic theories into the representations and processes that constitute the computational model. In this article, we summarize a large body of evidence from psycholinguistic literature into a set of principles and use them to derive a computational model of human sentence processing that employs a particular control of processing and a uniform representation of all linguistic knowledge.

We argue that, in order to explain a large variety of findings in human sentence comprehension, the computational model must employ a single arbitration process that can integrate independently proposed syntactic and semantic information to resolve ambiguities. We present a uniform representation for syntactic and semantic knowledge that enables syntactic and semantic interpretations to be integrated through intermediate representations. The representational primitive is a node that specifies part-of and has-part relations to other nodes, preconditions on these relations, and expectations that could be generated from such relations. We show how such representations could be employed by a parser that makes the right commitments at the appropriate times in order to explain a variety of human sentence processing behaviors such as incremental interpretation, immediacy of semantic and conceptual interaction, modular behaviors such as purely structural preferences, early commitment and error recovery, garden paths, and resource-limited delayed decisions. We have developed a model called COMPERE (Cognitive Model of Parsing and Error Recovery) based on such an architecture and tested it in a computer implementation.

Psychological Constraints on Language Comprehension Models

Experimental observations of human sentence processing behavior can be summarized in terms of a set of principles including the following:

1. Incremental Comprehension:

Psychological experiments have confirmed the general intuition that human language comprehension is an incremental process of progressively building a syntactic, semantic, and referential interpretation of a sentence. (e.g., Crain and Steedman, 1985; Marslen-Wilson and Tyler, 1987; Steedman, 1989; Taraban and McClelland, 1988).

2. Early Commitment:

The sentence processor must make early commitments as soon as it has the information necessary to do so (e.g., Crain and Steedman, 1985; Frazier, 1987). Resource limitations such as working memory capacity and the real-time nature of the comprehension task forbid the processor from pursuing all possible paths in parallel until they are ruled out (MacDonald, Just, and Carpenter, 1992). It must use information available from every knowledge source to make a choice as early as possible.

3. Delayed Decisions:

However, the processor must pursue parallel interpretations sometimes to account for delayed decisions. When syntactic and semantic preferences are in conflict, the processor must postpone the decision until further information becomes available (Holmes et al., 1989) or until a decision is forced by limits of memory resources. Moreover, at the resource limit, it appears that syntactic preferences override any semantic preferences (Stowe, 1991). Delayed decisions have also been observed in the presence of lexical ambiguities.

4. Error Recovery:

Early commitment inevitably leads to erroneous decisions at times when later information proves an earlier choice incorrect. The processor must also be able to recover from such errors by switching to an alternative interpretation (e.g., Eiselt, 1989; Stowe, 1991). This error recovery whether in structural or lexical ambiguity resolution, should be possible through a repair process that is incremental. Some parts of the erroneous structures should be reused and others repaired to result in correct structures. Mere reprocessing from scratch does not explain the grades of difficulty exhibited by weak and strong garden-path sentences (Abney, 1989).

5. Interaction:

Apart from incremental processing, the processor supports interaction between different faculties such as syntax, semantics, and reference (e.g., Crain and Steedman, 1985; Marslen-Wilson and Tyler, 1987; Taraban and McClelland, 1988). Natural languages are replete with ambiguities which cannot all be resolved by the use of any one kind of knowledge. An incremental processor builds interpretations of an incomplete sentence at all the different levels that interact with each other and chooses an interpretation that is best with respect to all the knowledge available to the processor at that point. Incrementality, interaction, early commitment, and error recovery can together explain the ability of the human language processor to deal with the proliferation of local ambiguities in natural languages (e.g., Crain and Steedman, 1985).

6. Functional Independence:

A final constraint derivable from a vast body of psycholinguistic studies can be summarized by stating that each kind of knowledge must be capable of being applied independently of other kinds. For instance, it must be possible to apply purely structural principles to resolve an attachment ambiguity for an adjunct. This syntactic knowledge must be represented so that it can be applied no matter what lexical items are involved in the adjunct (Frazier, 1987; Frazier, 1989). Independence is also necessary to explain the behavior seen when delays in commitment are terminated by resource limits (Stowe, 1991). Another important source of evidence for functional independence between levels of language processing lies in behavioral studies with aphasic subjects (e.g., Caramazza and Berndt, 1978). Though the neurological independence between syntactic and semantic knowledge has been questioned by recent studies of cross-linguistic aphasia (Bates, Wulfeck, and MacWhinney, 1991), functional independence would still be necessary to explain the differential impairment of syntactic and semantic abilities in aphasia (Mahesh, 1993).

Moreover, in order to make sure that the actual course of steps in the model agrees with human behavior, not just the end results of processing, the representations, processes, and resources used by the model must all be truthful to psychological data.

The need to combine bottom-up and top-down processes

Data-driven models of language comprehension with bottom-up strategies are compatible with incremental semantic interpretation. Incremental comprehension is best described by a bottom-up strategy that interprets each successively larger constituent as it is built from the next word in the sentence. A top-down strategy would force the processor to commit to a whole constituent before analyzing the parts of the whole. Making such commitments when the processor does not have necessary information results in unwarranted backtracking.

Standard theories of syntax using phrase-structure rules are incompatible with incremental processing given that the steps taken by the parser be psychologically real (Steedman, 1989). Though it is possible to apply a bottom-up strategy to phrase-structure rules, the resulting process will not be incremental since the bottom-up parser waits until it has seen every daughter of a constituent before interpreting it. Phrase-structure rules can be applied to carry out an incremental interpretation only if sentences have a left-branching structure which is not true with a majority of natural languages (Steedman, 1989). What we need is a bottom-up parser with top-down guidance that can make early commitments before actually seeing every part of a constituent so that semantic interpretation can be incremental. Such early commitments may be made by employing top-down influence from a variety of types of knowledge.

Types of Top-Down Guidance to Bottom-Up Parsing

Information providing top-down guidance to the processor can be of three types: grammatical information about the categories involved (Steedman, 1989), general structural principles (Frazier, 1989), and feedback from semantics, reference and discourse interpretation (e.g., Crain and Steedman, 1985; Taraban and McClelland, 1988).

1. Syntactic Expectation:

Grammatical information tells the processor about the arguments that must follow before the current constituent can be complete (and hence grammatical). For instance, after seeing a noun phrase, a verb must follow for the sentence to be complete. We can say that the processor can *expect* to see a verb phrase at this point. The bottom-up parser can use such syntactic expectations to make early commitments at syntactic ambiguities. This grammatical preference for expected structures results in the same behavior as expected by the minimal attachment principle and explains garden-path behavior in reduced relative clause sentences such as (1).

(1) The officers taught at the academy were very demanding.

2. Semantic and Pragmatic Preference:

One way to introduce extra-grammatical top-down influence on attachment ambiguities is through interaction. Semantic and discourse processes feedback to syntactic processing and exert preferences for some attachments over others (e.g., Crain and Steedman, 1985; Stowe, 1991). For instance, semantic feedback can tell the processor that the prepositional phrase (PP) in sentence (2) must be attached to the noun phrase (NP) since a horse cannot be used as an instrument for seeing.

(2) The officer saw the soldier with the horse.

3. Structural Preference:

The processor must also be able to exert purely structural preferences that are independent of the categories and lexical items involved in the ambiguous parts of the sentence. Examples of such a preference are right association and minimal attachment (Frazier, 1987). Such syntactic generalizations allow the syntactic processor to make early commitments for adjuncts as well, thereby explaining several syntactic phenomena (Frazier, 1989). There is psychological evidence in structural ambiguity resolution which demonstrates the need for this kind of top-down influence. For instance, Stowe (1991) has shown that the human sentence processor delays a decision (i.e., does not do an early commitment) when there is a conflict between syntactic and semantic preferences at a structural ambiguity (i.e., when top-down influence from grammar or structural principles and those from semantic feedback contradict each other). Experiments showed that people continue to delay the decision and pursue multiple interpretations until they reach resource limits. At the limit, they make a choice based only on syntactic preferences. This result would be left unexplained but for the presence of a top-down influence of the structural kind.

The Control of Parsing

Top-down guidance from syntactic expectations and structural preferences can be integrated with a bottom-up control of parsing by employing a form of left-corner parsing (Abney and Johnson, 1991). We have developed a variant of left-corner parsing by adding to it the virtues of head-driven parsing. The resulting mechanism that we call *Head-Signaled Left Corner Parsing* produces the right sequence of syntactic commitments to account for a variety of data. The parser has been implemented in the COMPERE model. Lack of space prevents us from further describing the parsing mechanism here, but it is described elsewhere (Mahesh, 1994).

The Need for an Arbitration Mechanism

While top-down and bottom-up influences on sentence comprehension arising from syntactic sources of knowledge can be combined in the parsing algorithm mentioned above, the sentence processor must also combine information coming from semantic and conceptual analyses with the syntactic preferences. This communication between syntax and semantics is necessary to account for evidence from interaction, delayed decisions, early commitment, and error recovery. The left-corner parsing algorithm merely identifies the points when the communication ought to occur but doesn't tell us how the communication is handled or how conflicts are resolved in the best interests of the constraints on behavior. One way to do this is to integrate the representations of the two types of knowledge a priori as in semantic grammars and what are called grammatical constructions in certain other models (e.g., Jurafsky, 1991). Such an approach suffers from reduced generativity and other disadvantages (see the Related Work section below). In order to avoid losing generativity, the sentence processor must keep the knowledge sources separate and introduce an arbitration mechanism that dynamically combines information arising from independent syntactic and semantic sources, resolving any conflicts that might arise in the process.

The arbitrator needs to combine information coming from independent syntactic and semantic sources which talk in different terms. Syntax describes its interpretations in terms of grammatical relations such as subject and object relations while semantics talks in terms of thematic roles.[1] The arbitrator must establish correspondences between these two representations (and between the decisions made by the two). One way to bridge this communication gap between the languages of syntax and semantics is to add a translation procedure in the arbitrator. This procedure would translate grammatical relations to thematic relations and vice versa using other kinds of linguistic information such as active/passive voice, what roles go with a particular event, and so on.

There are two problems with this approach. First, it is a procedural solution with well-known disadvantages over a comparable declarative solution. Second, during error recovery in incremental sentence comprehension, corresponding things will have to be undone in syntax and semantics. This is problematic if the only representation of the correspondence is in the arbitration procedures, since correspondence knowledge is not present in the representations that need to be manipulated by error recovery mechanisms. Also, the only kind of recovery possible is through reprocessing because there are no representations of intermediate decisions to repair or backtrack to.

We propose an alternative to this in which the gap is bridged via intermediate representations. These intermediate roles connect grammatical relations to thematic roles, resulting in a declarative representation of the correspondence knowledge in the form of role hierarchies. Now, with this mechanism, during error recovery, the processor can backtrack just the right amount and recover from the error by repairing the erroneous structure rather than reprocessing from scratch.

Role hierarchies that bridge the gap between syntactic phrases and thematic roles for example sentences are shown in Figure 1.[2] As the sentence progresses from that in (a) to the one in (b) or the one in (c), we can see the role structures being repaired to recover from local errors. It can also be seen that while both (b) and (c) involve repairs to role hierarchies, (c) also involves a reorganization of its syntactic structure to accommodate its reduced relative structure. Thus (c) is more of a garden-path sentence than (b).

The Uniform Representation

In order for the single arbitration process to manipulate both syntactic and semantic types of knowledge both during early commitments and error recovery, we propose a uniform representation of all types of knowledge. The elements of the uniform representation are units called *nodes* comprised of (a) part-whole links, (b) preconditions, (c) expectations, and (d) preference levels. The representations are to be read as (Fig. 2a) "the parts can be linked to the wholes when the preconditions are met and if so, the corresponding expecta-

[1]For purposes of illustration and simplicity, we are employing thematic-role assignment using selectional preferences from the lexicon as our theory of semantics. Our approach however is not limited to thematic roles. For an example of a more structured theory of semantics, see (Peterson and Billman, 1994).

[2]For simplicity, syntactic structures that are linked to the role hierarchies are not shown.

tions can be generated at that point." A node represents all the knowledge about a syntactic or semantic category. Sample representations of syntactic and semantic knowledge in this general form are shown in parts (b) and (c) of Figure 2. The NP node specifies the wholes S, VP, and PP of which it can be a part along with the preconditions and expectations therein. Similarly, the semantic node specifies knowledge of the thematic roles that go with a *Teach* event and the preconditions on the role fillers. The examples shown in Figure 2 are, however, simplified and incomplete.

Intermediate roles such as Active-Subject, Non-Agent-Active-Subject, and Passive-By-NP are used to bridge the grammatical and thematic relations between the parts of a sentence. Their use in backtracking during error recovery can be seen by examining the transition from (a) to (b) and (a) to (c) in the examples in Figure 1.

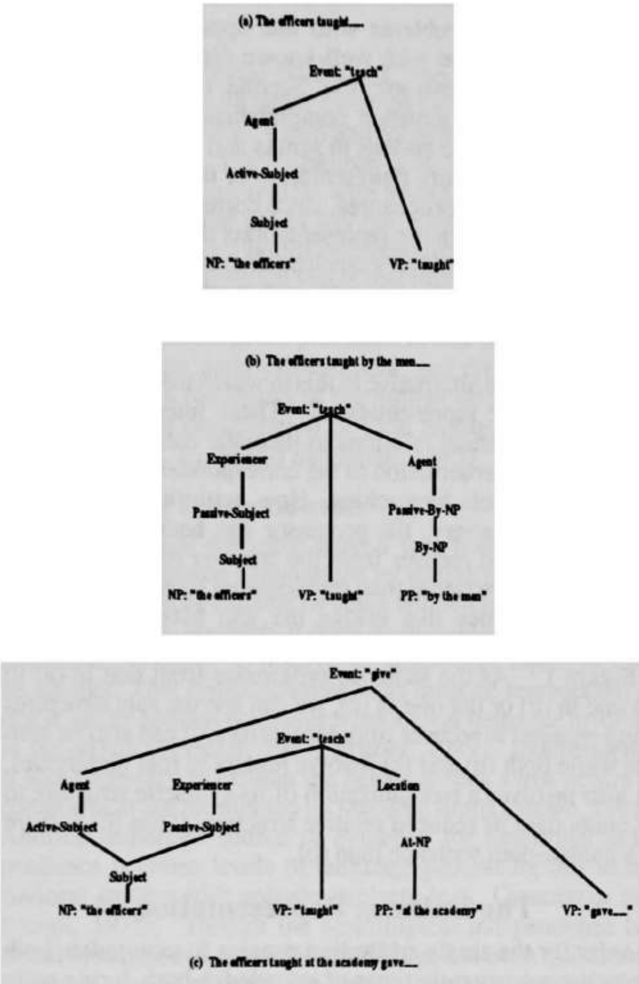

Figure 1: Role Hierarchies: From Phrases to Thematic Roles.

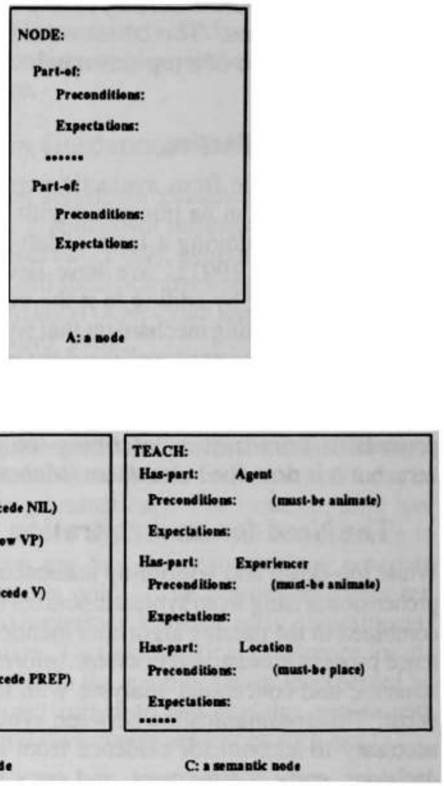

Figure 2: Uniform Representation of Linguistic Knowledge.

As an alternative to uniform representations, if there are separate representations of different types of knowledge in different forms, it becomes hard to support incremental interaction in view of the constraint that the time course of actions taken by the processor must be psychologically real. Especially in the case of error recovery phenomena, it is elegant to have an arbitration process which processes all the kinds of knowledge (i.e., applies common operations on different kinds of knowledge) so that it can make corresponding changes to syntactic and semantic interpretations while recovering from an error.

Processing with Uniform Representations

The arbitration process has been implemented in a sentence understanding program called COMPERE. Its single arbitration process reads words in a left-to-right order, proposes ways of attaching them syntactically and semantically to previously built structures, follows the left-corner parsing algorithm mentioned above in producing the right sequence of decisions, and selects the most preferred attachments at each point by combining the preferences assigned to the alternative attachments proposed bottom-up with the grammatical, semantic, and structural types of top-down influence. COMPERE produces tree structures representing the syntactic structure and thematic role assignment for a sentence. It is capable of representing and pursuing multiple interpretations in parallel when a conflict between syntactic and semantic preferences forces a delay in resolving an ambiguity. Further details of COMPERE's processing mechanisms can be found in (Mahesh, 1993; Eiselt et al, 1993).

COMPERE's arbitration process retains alternative interpretations that it did not select in the first place.[3] If an error is detected at a later point (when there is no way to attach a new constituent, for instance), it recovers from the error by switching over to one of the retained alternatives, performing any repairs to the syntactic and role structures (as shown in Fig. 1 for example) (Eiselt et al., 1993; Holbrook et al., 1992). The intermediate roles in the role hierarchies help maintain the correspondence between the changes made to the syntactic and semantic structures. COMPERE maintains the correspondence information by uniformly connecting every syntactic node to its corresponding semantic node(s) (including the intermediate roles) and vice versa.

In order to model the variety of behaviors, including the findings of Stowe (1991) on limited delayed decisions, the arbitration process must be enhanced by imposing architectural constraints, such as resource limits. The control structure of the process can then order the preferences based on their cost in terms of resources such as working memory. For instance, limited delayed decisions can be modeled by ordering semantic influence on par with syntactic preferences to begin with and by ignoring the semantic preferences when the processor has run out of resources. COMPERE's separation of knowledge sources retains the functional independence between them which is necessary for the above enhancements.

COMPERE can deal with a variety of (psycho)linguistically interesting constructs such as relative clause sentences, complements, and prepositional adjuncts with both lexical and structural ambiguities (including the ones used in the examples above). It can analyze their syntax and assign thematic roles. For example, it can show why sentence (1) is a garden-path sentence using grammatical expectations and early commitment; it can recover from the garden path to reinterpret the sentence; and it can use immediate semantic interaction to show why sentence (3) is not a garden path. The program has demonstrated the computational feasibility of the uniform representation and the arbitration process. However, its semantic competence is limited to thematic role assignment and at this time it does not have the knowledge to carry out discourse and reference processing.

[3]For an account of the Conditional Retention theory of error recovery, see (Eiselt 1989).

(3) The courses taught at the academy were very demanding.

Related Work

Though incremental interaction between syntax and semantics is not a new idea in computational modeling of human sentence comprehension, previous models that subscribed to such an interactive view have sacrificed the ability to apply syntactic and semantic knowledge independently of each other. While syntax-semantics interaction helps us explain a variety of psychological data, it is certainly not sufficient to account for the data on purely structural preferences, on deferred decisions with limited delays, and on error recovery phenomena (Eiselt et al., 1993). Below we briefly describe why some of the other models cannot explain the apparently incompatible data on modular effects (which functional independence can explain) as well as interactive effects (which incremental interaction can explain).

Models with Integrated Representations: These models resort to an *a priori* integration of knowledge sources with a consequent loss of functional independence (e.g., Jurafsky, 1991).

Categorial Grammars: Categorial grammars which establish a strong correspondence between syntactic and semantic categories (Steedman, 1989) also lack functional independence between syntax and semantics.

NL-SOAR: Though this model, a contemporary of COMPERE, has a uniform representation and integrates multiple knowledge sources to resolve ambiguities, it cannot account for delayed decisions since it can only maintain one interpretation at a time. In addition, its chunking operations result in the integration of different types of knowledge with a consequent loss in functional independence (e.g., Lehman et al., 1991; Lewis, 1993).

Connectionist Models: Connectionist models of sentence processing (e.g., Waltz and Pollack, 1985), including the Competition Model of MacWhinney and Bates (Bates et al., 1991), also have uniform representations. However, they do not deal very well with the full syntactic complexity of natural language. It is yet to be seen if the simple computational mechanisms of activation and inhibition in a network can exercise enough control of processing to model the precise mechanisms of arbitration, error recovery, and delayed decisions.

Conclusion

Table 1 summarizes the features of COMPERE that help us satisfy the psychological constraints we started with.

We have shown that in order to explain a variety of human sentence processing behaviors, the sentence processor must use a bottom-up strategy and yet accommodate top-down influence from grammatical, semantic, discourse, and structural preferences. We presented a uniform representation of different kinds of knowledge in a common format but in separate units. Using this representation, we showed how we can arbitrate syntactic and semantic processes and account for a range of behaviors. We have demonstrated the computational feasibility of the model in the COMPERE program. We believe that the combination of an arbitration mechanism and a uniform

Table 1: How COMPERE meets psychological constraints.

Constraint	Features of COMPERE
1. Incrementality	Head-Signaled Left-Corner parsing algorithm.
2. Early Commitment	Grammatical, structural, and semantic top-down guidance to the parser.
3. Delayed Decisions	Arbitration mechanism and retention of alternatives.
4. Error Recovery	Arbitration mechanism, retention, uniform representation, declarative representation of syntax-semantics correspondence through intermediate roles.
5. Semantic Interaction	Arbitration of independently proposed syntactic and semantic preferences.
6. Functional Independence	Separate representation of syntactic and semantic knowledge.

representation will take us a long way in modeling human sentence processing behavior.

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