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Paralleling recent shifts within Grammatical Theory away from rule-based and toward principle-based systems, there has arisen widespread interest in the possibility of similar refocusing with respect to natural language processing (cf. Abney (1988), Berwick & Weinberg (1984), Clark (1987), Fong (1990), Gibson (1987), Johnson (1988), Kashket (1988), Pritchett (1987, 1988, 1990, in press, forthcoming), Stabler (1989), among others). Fundamental to principle-based as opposed to rule-based models of parsing is the hypothesis that the Parser itself adheres to a version of the **Projection Principle** which maintains that each level of syntactic representation is a projection of the lexical properties of heads. With respect to parsing, the PP implies that a node cannot be projected before the occurrence of its head since the relevant features which determine its categorical identity and license its own and its arguments' attachment are theretofore undetermined. This paper describes an ongoing project in the implementation of an object-oriented (Smalltalk-80™) Government and Binding parser which adheres to the *strong competence* hypothesis that principles of Universal Grammar are employed directly in parsing. Specifically, the parse operates by projecting phrasal structure as determined by the lexical properties of heads and licensing local attachments which maximally satisfy on-line principles of Universal Grammar at every point during a parse. Though this model was originally motivated with regard to its psychological plausibility, in this paper we focus primarily on issues of implementation (see Pritchett: *op. cit.* for a more detailed discussion of the psycholinguistic issues).

In the implemented parser, the following new Object subclasses are defined:

```
Object
  PrincipleBasedParser
  Lexicon
  LexicalItem
  Node
    EmptyNode
    FullNode
      DoubleBarNode
      SingleBarNode
      ZeroBarNode
  Chain
  LicensingRelation
    ThetaRoleAssignment
    CaseAssignment
    SpecHeadAgreement
    XPSelection
```

An instance of PrincipleBasedParser (henceforth simply the parser) itself acts as the

buffer for tree structures. The parse of a string succeeds if at the end of input, there is exactly one tree in the parser and all grammatical principles are satisfied for every Node in that tree.

The syntactic structures actually created and manipulated by the parser are subinstances of the class Node. Nodes accord with a binary-branching version of X' Theory and each Node exists as an element of a maximal projection: [XP [YP] [X' [X] [ZP]]]. Phrase Structure constraints on the linear order of Nodes is specified in the pool variable, HeadParameter; in this note we assume the English configuration. The specifier and complement positions themselves are either fully specified maximal projections or instances of the special class EmptyNode. Nodes respond in the expected fashion to a range of messages concerning configurational structure, such as c-commands:, m-commands:, governs:, mother, sister, etc.

Each Node may be associated (coindexed) with other Nodes via an instance of the class Chain, a subclass of SortedCollection, where Node α precedes Node β in an instance of Chain iff α c-commands β . Given this definition, two Nodes may cooccur within the same Chain only if they are contained in the same tree structure. Every Node has an associated Chain, though in the default case a Node is the Chain's singleton member. For a Node to be globally licit, all relevant grammatical principles must be satisfied with respect to a its Chain.

Subinstances of the abstract class LicensingRelation represent the actual principles of Grammar which license Nodes, such as the θ -criterion and Case Theory. Each Node keeps track of all licensing relations in which it participates via the instance variables licenserRelations and licenseeRelations.

As an illustration of the model as discussed so far, consider how a simple sentence, *Vampires were seen*, is processed.

This sentence is fed to the processor one PF-word at a time by the procedure:

```
| parser |
parser ← PrincipleBasedParser
      newEnglishParser.
parser newWord: 'vampires'.
parser newWord: 'were'.
parser newWord: 'seen'.
↑parser output
```

First a parser with an English lexicon and English parameter settings (e.g. the

HeadParameter) is created by sending PrincipleBasedParser the message newEnglishParser. Next, the string 'vampires' is sent to the parser with the message newWord:, which operates as follows:

```
newWord: aWord
| lexicalItem maximalProjection|
maximalProjection←lexicon
project: aWord.
self addLast: maximalProjection.
self changed
```

The lexicon is queried and returns a maximal projection in response to the message project: 'vampires'. This maximal Projection: [NP [e] [N' [N vampires] [e]]] is added to the parser, where the *e* indicates instances of the class EmptyNode, which may ultimately be filled by or coindexed with other Nodes. Next, and crucial to the on-line application of grammatical principles, the changed message is sent, indicating that the parser's contents have altered and signaling that the reapplication of grammatical principles is relevant. Whenever the parser receives the message changed, it is automatically sent the message update: by the Smalltalk-80™ system, which is defined as follows:

```
update: dummy
self attachLastTwoTrees.
self expandLastTree.
self buildChainsInLastTree
```

The most important message in this method is attachLastTwoTrees wherein the θ -criterion and Case Theory (among others) actively determine attachments. Furthermore, if any of the three messages sent by update: itself makes changes to the parser's contents, it too will in turn send changed messages to the parser, again triggering the sending of update:. In this way, the parser manipulates its contents continually until a local steady state is reached with all grammatical principles maximally satisfied. Hence, this changed/update: message sequence is fundamental to the parser's operation as it is in this fashion that grammatical principles are represented as *on-line* in the system.

Returning to the example, none of the messages within update has any effect when the parser contains only the NP *vampires*, and the parser reaches a steady state with no licenser available and the NP unavoidably left locally roleless. No higher structure, including IP, is projected as relevant heads have not been encountered.

Next, the word 'were' is sent to the parser, and its maximal projection, an IP, added: [NP [e] [N' [N vampires] [e]]], [IP [e] [I' [I were] [e]]]. As a result, a changed message is sent, and the update: message's method is executed. This time, the message attachLastTwoTrees will have an effect. This method examines the last two trees in the parser and attempts all possible attachments of one into positions in the

other. The method then chooses the attachment which is licensed to the highest degree. An attachment is defined as licensed to degree *n* if by making the attachment, *n* different licensing relations will be newly discharged. (See Pritchett cited above for psycholinguistic justification of this selection procedure as well as some alternative approaches to the notion 'maximally licensed'.) Given adjacency requirements, two attachments are considered. In this example: the attachment of the IP into the complement of NP and the attachment of the NP into the specifier of IP. Only the second results in the discharge of a licensing relation, namely the case assigned by *I* under government. Hence, this attachment is chosen, so that the parser now contains only one element: [IP [vampires] [I' [I were] [e]]]. The requirements of Case Theory are satisfied to the maximum degree possible in the local string—both with respect to the target NP which requires these features and the head which must discharge them.

Next the method expandLastTree is sent. In this case, the method causes the IP to expand into a CP. As a result, the contents of the parser becomes: [CP [e] [C' [C] [IP [vampires] [I' [I were] [e]]]]]. The last message in the method for update:, buildChainsInLastTree is sent but has no effect. Since the first two messages sent in update: caused changes to the contents of the parser, they both send changed messages, with the result that update: is executed again. However, none of the three messages in update: has any effect this time around as there is a single tree in the parser, and a local steady state has been reached, with all structure licensed to the maximum degree possible with respect to UG principles.

Finally, the word *seen* is sent to the parser. *Seen* is identified as a passive participle which, as a lexical property, assigns an internal θ -role but no Case. In the VP which is projected, the *V* acts as the licenser in a licensing relation, namely an instance of ThetaRoleAssignment under government. Again, since the parser's contents have changed, update: is sent, invoking attachLastTwoTrees forcing the VP attachment as a complement of INFL: [CP [e] [C' [C] [IP [vampires] [I' [I were] [[VP [e] [V' [v seen] [e]]]]]]]. (This is carried out by means of an instance of XPSelection— a subclass of LicensingRelation relevant to functional heads.) The message expandLastTree is sent but has no effect. Next, the message buildChainsInLastTree is sent. The method associated with this message attempts to associate Nodes and EmptyNodes (through Chain building) in order to more fully satisfy Case Theory and the θ -criterion. In this example the empty complement of VP is added to the Chain associated with the NP *vampires* and the *V*'s θ -role assigned to this empty position. As a

result, the Chain possesses both a θ -role and Case since its head (the NP) is in a Case position and its tail (the empty node) in θ -position. The contents of the parser are now: [CP [e] [C' [C] [IP [NP vampires]₁ [I' [I were] [[VP [e] [v' [v seen] [e]₁]]]]]]. Input terminates and the message output is sent to the parser, which checks that all mandatory licensing relations have been fulfilled and returns the final structure.

At this point, we will briefly discuss how the head-driven principle-based model here predicts certain psycholinguistic facts. This discussion will be schematic and the reader is referred to Pritchett (*op. cit.*). Consider for example, well-known garden-path effects of the sort found in an example like, *After John drank the water evaporated*. Informally, the problem for the human parser in such examples is that the post verbal NP is prematurely construed as the complement of the verb, which causes difficulty when it must be reinterpreted as a subject. In terms of our implementation, once the parser has been sent the words up through *water*, it contains the following tree: [CP [e] [C' [C after] [IP [NP John] [I' [I e₁] [[VP [e] [v' [v drank]₁] [NP the water]]]]]]. Subsequently, the word *evaporated* is sent, and the projected VP added to the parser, however there is no licensing position into which it can attach. This remains true when the VP subsequently expands to IP and CP: [CP [e] [C' [C] [IP [e] [I' [I e] [[VP [e]₁] [v' [v evaporated]₁] [e]]]]]]. The initial misanalysis of the NP *the water* results from the parser's premature construal of a global subject as a local object in order to satisfy Case and θ -theory, which results in global failure. The reason that reanalysis is not possible in instances of this sort is due to the hypothesis licensed positions are indelible and is discussed in detail in Pritchett (*op. cit.*). What is crucial is that a principle-based parser of this sort makes the initial parsing error as a result of its fundamental strategy to maximally satisfy grammatical principles locally at every point during the parse.

The architecture of the parser also arguably provides a processing, as opposed to a grammatical, account of effects deriving from Huang's (1982) Constraint on Extraction Domains which prohibits movement from within positions which are not properly governed. For example, it proscribes examples such as, **Who_i do pictures of e_i bother John*. To give just one example, according to our parsing-theoretic account, extraction from within subjects is impossible since there is simply no local option of forming the requisite Chain at the time the subject constituent is being parsed, given the fact that the parser is strictly head driven. Recall that a sentence (IP) is not projected until either an inflectional element or a verb possessing inflectional features is

processed. Before a category is projected, it is impossible to license its specifier, the subject. Consequently, in the previous example, after the word *of* is processed, the parser contains the following two unintegrated Nodes: [CP [NP who] [C' [C do] [e]]], and [NP [e] [N' [N pictures] [PP [P of] [e]]]]. These two Nodes cannot be locally integrated before the projection of IP and hence the requisite Chain cannot be formed between the *wh*-word in SPEC-CP into the NP *pictures of* as the two phrases are not locally constituents of the same parse tree. In other words, the NP is not locally a subject at that point during the parse but is rather unattached. See Pritchett (to appear) for details. Thus our implementation begins to provide an existence proof that a parser driven by the Projection Principle and the on-line application of global grammatical principles is both psychologically and implementationally realistic.

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