A. REVISED PROOF PROCEDURE PROGRAM

In Quarterly Progress Report No. 76 (pages 260-270), we described a COMIT program that proves logical arguments expressed in a restricted form of ordinary English. Two examples were given of arguments that the logical evaluation part of the program was unable to prove, even though it was verified by hand computation that the translations into logical symbolism were correct and that the arguments were valid. A more efficient logical proof procedure program has since been devised. It not only proves arguments that the previous program was unable to prove, but it also substantially reduces the computation time (in some cases by a factor of 10) for some arguments and theorems that the previous program was able to prove. While the previous program was based to a large extent on the Davis-Putnam proof procedure algorithm, the new program is an amalgam of the "one-literal clause rule" of Davis-Putnam and the "matching algorithm" of J. R. Guard. Taking its point of departure from the Davis-Putnam algorithm, the program negates an input formula and puts the negated formula into prenex normal form and the matrix into conjunctive normal form. At this point, instead of manufacturing generations of quantifier-free substitution instances (QFSI) and testing for consistency at certain specified points after the manner of Davis-Putnam, the program attempts to produce a proof on the basis of the "one-literal clauses" (i.e., conjuncts containing no disjunction operators) in the matrix. By using Guard's matching algorithm, which enables one to test whether two clauses could generate any common QFSI, the program tests the one-literal clauses in the matrix for consistency. If two such clauses match negatively ("N-match"), i.e., if the two clauses could generate contradictory QFSI, then the matrix is inconsistent and the original formula is valid. If the one-literal clauses are consistent, then the program attempts to generate additional one-literal clauses by N-matching the existing one-literal clauses against the polyliteral clauses. For example, the one-literal clause

\[ F(y, P(x, y)) \]

or FYPXY, in COMIT notation — N-matches the polyliteral clause

\[ \text{not}-F(x, y) \lor G(y, x) \]

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- or NFXY + GYX, in COMIT notation – to produce the one-literal clause

\[ G(P(x, y), y) \]

- or GPXYY, in COMIT notation. Whenever the N-matching procedure produces a new one-literal clause, it is tested for consistency against the existing one-literal clauses. If it is inconsistent with the others, it means that the original formula is valid, and the run is terminated. If one or more polyliteral clauses are produced by this N-matching procedure, they will have one less term than the original clause, and may therefore produce one-literal clauses during a further N-matching. If all possible N-matchings fail to produce a contradictory set of one-literal clauses, or if there were no one-literal clauses to start with, then the program reverts to the older Davis-Putnam method of generating QFSI. The program tests the QFSI for inconsistency after each generation, using an algorithm based on the "one-literal clause rule," which is the most efficient of the three Davis-Putnam rules for propositional logic, and which may be stated as follows: Given a formula C in conjunctive normal form, and a one-literal clause P of C, all conjuncts containing P are deleted from C, and all single occurrences of not-P are deleted from C, thereby producing a reduced formula C' that is consistent if and only if C is consistent.

Since the deletion of single occurrences of not-P may produce new one-literal clauses, the one-literal clauses must be tested for consistency after each application of the rule. The condition of inconsistency is the occurrence of two contradictory one-literal clauses; and the condition of consistency is the deletion of the entire formula C. If the one-literal clause rule fails to prove C either consistent or inconsistent, then C is split into two branches by assuming a term P first true and then false, and making appropriate cancellations according to a method described by Quine. The first branch is formed by deleting all conjuncts containing P and all single occurrences of not-P, and the second branch is formed by deleting all conjuncts containing not-P and all single occurrences of P. The second branch is stored at the front of a shelf, and the first branch remains in the workspace where an attempt is made to apply the one-literal clause rule to it. If this attempt fails, the formula in the workspace is split again in the same way, the first branch remaining in the workspace and the second branch being stored at the front of the shelf. This procedure continues until a branch is obtained to which the one-literal clause rule can be applied. The consistency test terminates when one branch is proved consistent (i.e., is entirely deleted), in which case the entire formula is consistent, or when all branches are proved inconsistent (i.e., contain contradictory one-literal clauses), in which case the entire formula is inconsistent.

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References

1. The revised program is described in greater detail in a memorandum, "A proof procedure program based on the 'one-literal clause rule' and the 'matching algorithm'," Mechanical Translation Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, March 1965.


B. CONSTITUENT STRUCTURE AND WORD-ORDER RULES FOR GERMAN

The following rules represent a segment of the grammar of contemporary standard German. This miniature grammar is directed especially toward the solution of three classical problems in German syntax: (a) the order of nominals (subject and objects) and adverbials with respect to one another and to the finite verb; (b) the way in which independent declarative sentences differ, in particular, from subordinate clauses with respect to this order; and (c) the occurrence of positional es, as in "es kommen viele Leute."

The aspect of the constituent structure which is original is the treatment of the subject nominal (Nom0) as the first among equals in a series of verbal specifiers which includes the object nominals (including the direct object Nom1, and the indirect object Nom2), as well as the adverbial adjuncts (among others, adverbials of location Loc and of manner Mod). All of these specifiers of the verb are immediately dominated by a single common constituent labeled Sp.

The constituent structure presented below differs from those assumed in previous studies in the transformational syntax of German by having an empty constituent (Topic) into which some immediate constituent of Sp may, or under certain conditions must, be incorporated by a transformational rule of Topicalization.

The constituent structure resembles that assumed by Matthews and Rogovin, by Bach, and by Bierwisch, in that the verbal complex originates at the end of the sentence, with finite verb last. A transformational rule of Finite verb placement correctly locates the finite verb in second position (i.e., after the Topic or after the interrogative marker in independent sentences).

The symbols used here have the following interpretations: S sentential clause, W interrogative marker, Kn subordinating conjunction, R relative conjunction, Nom nominal (with subscripts 0,1,2 referring to nominative, accusative, and dative, respectively),
(XVI. MECHANICAL TRANSLATION)

Loc adverbial of location, Mod adverbial of manner, Adj predicate adjective, Sp specifier of the verb, V principal verb, sep separable prefix, Aux verbal auxiliary, M modal verb, T finite tense and person marker, VP verb phrase, # sentence boundary, +pp past participial form, Pro personal pronoun, Reflex reflexive pronoun, inf infinitival form.

Constituent structure:

\[
S \rightarrow \# \text{ Vorfeld} - \text{ VP } \# \\
\text{Vorfeld} \rightarrow \{W(Kn), (R)Kn, \text{ Topic}\} \\
\text{VP} \rightarrow (\text{Sp}) \ V - \text{ Aux} \\
\text{Sp} \rightarrow (\text{Nom}_0)(\text{Nom}_2)(\text{Nom}_1) \left\{\left\{\text{Mod}, \text{ Adj}\right\} \right\} \left(\text{Loc}\right) \\
\text{Aux} \rightarrow (\text{Passive}) \ (\text{M})(\text{M}) \\
\text{Topic} \rightarrow \text{ es}
\]

Transformational structure

I. Topicalization - conditional:

\[
\# \ es[X^1 - \text{ sp} - X^2]_{\text{Sp}} X^3 \\
1 \ 2 \ 3 \ 4 \ \overset{5}{\overbrace{5}} \\
\Rightarrow 1 \ 4 \ 3 \ 0 \ \overset{5}{\overbrace{5}}
\]

where \([... \text{ sp} ...]_{\text{Sp}}\) signifies any constituent immediately dominated by \(\text{Sp}\).

IIa. Intraspecifier word order for personal and reflexive pronouns - conditional:

\[
\# X^1[X^2 - \text{ sp} \left\{\text{Pro}, \text{ Reflex}\right\} X^3]_{\text{Sp}} X^4 \# \\
1 \ 2 \ 3 \ 4 \\
1 \ 3 \ 2 \ 4
\]

Obligatory if:

\[
\# X^1[X^2 \left\{\text{Nom}_1, \text{ Nom}_2\right\} \left\{\text{Pro}, \text{ Reflex}\right\} X^3]_{\text{Sp}} X^4 \# \\
1 \ 2 \ 3 \ 4
\]

Optional if:

\[
\# X^1[X^2 - \text{ Nom}_0 - \text{ Reflex} - X^3]_{\text{Sp}} X^4 \# \\
1 \ 2 \ 3 \ 4
\]

QPR No. 77 318
IIb. Intraspecifier word order for newly introduced versus already mentioned specifiers – conditional:

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
\end{array}
\]

The transformation has least conditions on its applicability when \( sp_1 \) is a non-unique, not previously mentioned specifier (e.g., with indefinite article), and \( sp_2 \) is an already mentioned specifier (e.g., with definite article). The transformation is nonapplicable if \( sp_1 \) is a pronoun and \( sp_2 \) is a noun.

III. Placement of the perfect auxiliary of modal verbs – obligatory (A similar optional rule operates on sehen, hoeren in place of \( M \)):

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
\end{array}
\]

IV. Creation of past participles and finite verb:

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
\end{array}
\]

V. Conversion of uninflected verbs into infinitives – obligatory:

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
\end{array}
\]

where simple concatenation and affixation (indicated by +) are differentiated.
VI. Finite verb placement:

\[
\begin{array}{c}
\begin{array}{c}
\{ \text{W} \} \\
\{ \text{Topic} \}
\end{array}
\end{array}
\begin{array}{c}
\{ \text{V} \} \\
\{ \text{Perfect} \}
\end{array}
\begin{array}{c}
\{ \text{M} \} \\
\{ \text{Passive} \}
\end{array}
\begin{array}{c}
+ \text{T} \\
- \text{X}^2
\end{array}
\]
\]
\]
\]

Comments

Among the conditions on Topicalization are the following: (a) if no other constituent immediately dominated by Sp has been topicalized, then a pronoun subject must be topicalized ("es kommen viele Leute" without topicalization and "viele Leute kommen" with topicalization, but no "es kommt er," only "er kommt"); (b) under certain conditions, a noun already mentioned in a preceding sentence and thus determined by a definite article or its equivalent must be topicalized ("der Mann kam an" versus "es kam der Mann an"); (c) certain pronoun objects may not be topicalized ("sich ereignete ein Unglueck" versus "es ereignete sich ein Unglueck" with positional es and without topicalization, on the one hand, and "ein Unglueck ereignete sich," on the other hand).

The rules for Intraspecifier word order account for the fact that the permissible initial constituents following the interrogative word, if there is one, in questions and following the conjunction in subordinate clauses do not coincide with the constituents that may occur as initial constituent (i.e., as Topic) in independent declarative sentences. Thus, im Zimmer may occur initially as Topic in an independent declarative sentence even if the sentence has a pronoun subject ("im Zimmer spielte er Karten"), but not in a subordinate clause ("weil im Zimmer er Karten spielte,..."), whereas if the subject is a noun (with an indefinite article, particularly), the permutation is possible even in subordinate clauses ("weil im Zimmer ein Gast Karten spielte,..."). Moreover, in a subordinate clause, a reflexive pronoun may occur initially ("weil sich ein Unglueck ereignete,..."). As we have mentioned, topicalization of a reflexive pronoun is not possible ("sich ereignete ein Unglueck").

Transformational rules III, IV, and V account for the following facts: (a) in subordinate clauses the finite perfect auxiliary (habe, hat, etc.) forming the periphrastic perfect of a modal verb occurs at the head, rather than at the end, of the verbal complex, i.e., in front of the principal verb and its separable prefix ("weil er den brief hat schreiben wollen,..." versus "weil er den Brief schreiben wollen wird,..." "weil er den Brief geschrieben hat,..." or "weil der Brief geschrieben worden ist,..."); this order holds only if the modal verb is preceded by an infinitive ("weil er den Brief gewollt hat,..."); (b) the modal verb itself, when immediately preceded by an infinitive, assumes
its infinitival rather than its past participial form in this periphrastic perfect construction; this is the case in independent sentences, as well as in subordinate clauses ("er hat den Brief schreiben wollen" versus "er hat den Brief gewollt"); (c) the ungoverned citation form of verbs, as well as this special perfect, is the infinitive. The grammar accounts for these characteristics by a particular interpretation of German syntax. Rule IV (Creation of past participles and finite verb) interprets verbal government as regressive; i.e., the form of the verb is determined by the constituent to its right. Thus, geben assumes the form gab if one particular form of T is to its right, namely third person singular past; geben assumes the form gegeben if either the Passive (werden) or the Perfect (haben or sein) is to the right. By rule V, any verbal stem that has not undergone some process of suffixation (the incorporation of a marker of tense, a past participial marker, or, though not included in the present miniature grammar, a nominalizing or a present participial marker) automatically assumes its infinitival form. The fact that under certain conditions the modal verbs have infinitival form in the perfect is interpreted as a result of the relative ordering of rules. The rule that places the perfect auxiliary at the head of the verbal complex (rule III) precedes the rules whereby the finite or participial form of a verb, if it is to occur in one of those forms, is determined by the constituent that follows it. The result of this ordering of rules is that the modal verb, since it is no longer followed by the auxiliary of the perfect, is therefore not subject to conversion into its past participial form and thus by rule V becomes an infinitive.

The rule of Finite verb placement in independent sentences (VI) is ordered after the rule for the Placement of the perfect auxiliary of modal verbs and has in its domain not only any finite verb, including the auxiliary of the perfect, which occurs at the end of the verbal complex but also the perfect auxiliary relocated by rules III at the head of the verbal complex. In this way the occurrence of the infinitival perfect form of modal verbs in independent sentences is also accounted for (not only "er hat den Brief gewollt" from an underlying [er] Topic den-Brief-woll-Perfect-T, but also "er hat den Brief schreiben wollen" from an intermediate [er] Topic den-Brief-Perfect-T-schreib-woll).

The following fact about German grammar lends support to the assumption (a) that Finite verb placement in independent sentences (rule VI) occurs after the Placement of the perfect auxiliary of modal verbs (rule III) and after the rule for the Creation of past participles (IV), and (b) that rule VI applies also to the relocated finite perfect auxiliary that heads the verbal complex: namely, for the perfect of certain semimodal verbs like hoeren, the perfect auxiliary is found in subordinate clauses both at the end of the verbal complex, in which case the semimodal must be in its past participial form, gehoert, and at the head of the verbal complex, in which case the semimodal must be in its infinitival form ("weil er ihn abfahren gehoert hat,..." and "weil er ihn hat abfahren hoeren,..."). The double source of the finite perfect auxiliary correctly predicts the occurrence of both infinitival and past participial forms in independent
sentences of otherwise identical form ("er hat ihn abfahren gehoert" from \textit{[er]}\textit{\textsubscript{Topic}} ihm-\textit{ab-fahr-hoer}-Perfect-T and "er hat ihn abfahren hoeren" from an optional intermediate \textit{[er]}\textit{\textsubscript{Topic}} ihm-Perfect-T-\textit{ab-fahr-hoer}).

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1. G. H. Matthews and Syrell Rogovin, German sentence recognition, Mechanical Translation 5, 114-20 (1958); R. B. Lees, Structural grammars, Mechanical Translation 4, 5-10 (1957; E. Bach, The order of elements in a transformational grammar of German, Language 38, 263-9 (1962); M. Bierwisch, Grammatik des deutschen Verbs, Studia Grammatica II (Berlin, 1963).