A GENERAL COMPUTATIONAL METHOD FOR GRAMMAR INVERSION

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ABSTRACT

A reversible grammar is usually understood as a computational or linguistic system that can be used both for analysis and generation of the language it defines. For example, a directive \texttt{pars_gen(Sent,Form)} would assign, depending upon the binding status of its arguments, the representation in \texttt{(Toronto,chased(Fido,John))} to the sentence \texttt{Fido chased John in Toronto}, or it would produce one of the several possible paraphrases of this sentence given its representation. Building such bi-directional systems has long been considered critical for various natural language processing tasks, especially in machine translation. This paper presents a general computational method for automated inversion of a unification-based parser for natural language into an efficient generator. It clarifies and expands the results of earlier work on reversible grammars by this author and the others. A more powerful version of the grammar inversion algorithm is developed with a special emphasis being placed on the proper treatment of recursive rules. The grammar inversion algorithm described here is at the core of the Japanese-English machine translation project currently under development at NYU.

REVERSIBLE GRAMMARS

A reversible grammar is usually understood as a computational or linguistic system that can be used both for analysis and generation of the language it defines. For example, a directive \texttt{pars_gen(Sent,Form)} would assign, depending upon the binding status of its arguments, the representation in \texttt{(Toronto,chased(Fido,John))} to the sentence \texttt{Fido chased John in Toronto}, or it would produce one of the several possible paraphrases of this sentence given its representation. In the last several years, there have been a growing amount of research activity in reversible grammars for natural language, particularly in connection with machine translation work, and in natural language generation. Development of reversible grammar systems is considered desirable for variety of reasons that include their immediate use in both parsing and generation, a reduction in the development and maintenance effort, soundness and completeness of linguistic coverage, as well as the match between their analysis and synthesis capabilities. These properties are important in any linguistic system, especially in machine translation, and in various interactive natural language systems where the direction of communication frequently changes. In this paper we are primarily interested in the computational aspects of reversibility that include bi-directional evaluation and dual compilation of computer grammars, inversion of parsers into efficient generators, and derivation of "generating-versions" of existing parsing algorithms. Some of the recent research in this area is reported in (Calder et al., 1989; Dymetman and Isabelle, 1988; Dymetman et al., 1990; Estival, 1990; Hasida and Isizaki, 1987; Ishizaki, 1990; Shieber, 1988; Shieber et al., 1990; Strzalkowski, 1990a-c; Strzalkowski and Peng, 1990; van Noord, 1990; and Wedekind, 1988). Dymetman and Isabelle (1988) describe a top-down interpreter for definite clause grammars that statically reorders clause literals according to a hand-coded specification, and further allows for dynamic selection of AND goals during execution, using the technique known as the \texttt{goal freezing} (Colmerauer, 1982; Naish, 1986). Shieber et al. (1990) propose a mixed top-down/bottom-up interpretation, in which certain goals, namely those whose expansion is defined by the so-called "chain rules", are not expanded during the top-down phase of the interpreter, but instead they are passed over until a nearest non-chain rule is reached. In the bottom-up phase the missing parts of the goal-expansion tree will be filled in by applying

1 For linguistic aspects of reversible grammars, see (Kay, 1984; Landsbergen, 1987; Neuman, 1990; Steedman, 1987).
2 Literals on the right-hand side of a clause create AND goals; literals with the same predicate names on the left-hand sides of different clauses create OR goals.
3 A chain rule is one where the main binding-carrying argument (the "head") is passed unchanged from the left-hand side to the right. For example, \texttt{assert(P)} \rightarrow \texttt{subj(P1),verb(P2),obj(P1,P2,P)}, is a chain rule with respect to the argument \texttt{P}, assuming that \texttt{P} is the "head" argument.
the chain rules in a backward manner. This technique, known as 'head-driven' evaluation, can be applied quite profitably to various grammar compilation tasks, including the inverse computation, but it requires that the underlying grammar is given in a form where the information about the semantic heads in nonterminals is made explicit. In addition, the procedure, as described in (Shieber et al., 1990), makes no attempt to impose a proper ordering of the "non-chain" goals, which may have an adverse effect on the generator efficiency. ⁴

The grammar inversion method described in this paper transforms one set of PROLOG clauses (representing a parser, e.g.) into another set of clauses (representing a generator) using an off-line compilation process. The generator is thus just another PROLOG program that has the property of being an inverse of the parser program, that is, it performs inverse computation. ⁵ A unification grammar is normally compiled into PROLOG to obtain an executable program (usually a parser). Subsequently, the inversion process takes place at the PROLOG code level, and is therefore independent of any specific grammar formalism used. The obtained inverted program has been demonstrated to be quite efficient, and we noted that the same technique can be applied to parser/generator optimization. Our method is also shown to deal adequately with recursive clauses that created problems in purely top-down compilation. ⁶

The inter-clausal inversion procedure discussed here effects global changes in goal ordering by moving selected goals between clauses and even creating new clauses. The net effect is similar to that achieved in the head-driven evaluation, except that no explicit concept of 'head' or 'chain-rule' is used. The algorithm has been tested on a substantial coverage PROTEUS Parser Grammar (Grishman, 1986), and the Linguistic String Grammar for English (Sager, 1981). ⁷

IN AND OUT ARGUMENTS IN LITERALS

Literals in the grammar clauses can be marked for the "modes" in which they are used. When a literal is submitted to execution then those of its arguments which are bound at that time are called the "in" arguments. After the computation is complete, some of the previously unbound arguments may become bound; these are called the "out" arguments. For example, in concat([a,b],[c,d],Z), which is used for list concatenation, the first two arguments are "in", while the third is "out". The roles are reversed when concat is used for decomposition, as in concat(X,Y,[a,b,c,d]). In the literal subject(A1,A2,NUM,P), taken from an English grammar, A1 and A2 are input and output strings of words, NUM is the number of the subject phrase, and P is the final translation. When the grammar is used for parsing, the "in" argument is A1; the "out" arguments are A2, NUM and P; when it is used for generation, the "in" argument is P; the "out" arguments are A1 and NUM. In generation, A2 is neither "in" nor "out".

"In" and "out" status of arguments in a PROLOG program can be computed statically at compile time. The general algorithm has been described in (Strzalkowski, 1990c; Strzalkowski and Peng, 1990).

ESSENTIAL ARGUMENTS: AN EXTENSION

The notion of an essential argument in a PROLOG literal has been first introduced in (Strzalkowski, 1989), and subsequently extended in (Strzalkowski, 1990bc; Strzalkowski and Peng, 1990). In short, X is an essential argument in a literal p ⋅ ⋅ ⋅ X ⋅ ⋅ ⋅ if X is required to be "in" for a successful evaluation of this literal. By a successful evaluation of a literal we mean here the execution that is guaranteed to stop, and moreover, that will proceed along an optimal path. For instance, an evaluation of the goal mem(a,L), with an intention to find a list L of which a is a member, leads to a non-terminating execution unless L’s value is known. Likewise, a request to generate a main verb in a sentence when the only information we have is its root form (or "logical form") may lead to repeated access to the lexicon until the "correct" surface form is chosen. Therefore, for a lexicon access goal, say acclex(Word,Feats,Root), it is reasonable to require that both Feats and Root are the essential arguments, in other words, that the set {Feat,Root} is a minimal set of essential arguments, or a MSEA, for acclex. The following procedure computes the set of active

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⁴ Some concern has also been voiced (Gardent and Plainfosse, 1990) about the termination conditions of this algorithm.

⁵ Some programs may in fact be multi-directional, and therefore may have several 'inverses' or 'modes'.

⁶ Shieber et al. (1990) have shown that some recursive clauses cannot be executed using top-down evaluation thus motivating the use of a mixed top-down/bottom-up evaluation of their 'head-driven' compilation.

⁷ At present the grammar consists of 400+ productions.
MSEA's in a clause head literal.\footnote{Active MSEA's are those existing with a given definition of a predicate. Other, non-active MSEA's can be activated when the clauses making up this definition are altered in some way. The procedure can be straightforwardly augmented to compute all MSEAs (Strzalkowski, 1990c).}  

\textbf{PROCEDURE MSEAS(MS,MSEA,VP,i,OUT)}  

[computing active MSEAs]  

Given a clause set of active MSEAs in the head predicate \( p \) as follows:  

\[ \text{computing active MSEAs} \]

\[ \text{minimize the number of possible solutions to } 1. \]

(2) For \( i=1, \ldots, s \), let \( M \) be the set of active MSEAs's of \( r_i \), and let \( MR_i = \{ m_{ij} \mid j=1 \cdots r_i \} \) be obtained from \( M \) by replacing all variables by their corresponding actual arguments of \( r_i \).

(3) Compute the set \( MP_i = \{ m_{ij} \mid j=1 \cdots r_i \} \), where \( m_{ij} = \text{VAR}(m_{ij}) \) if \( \text{OUT}_{i-1,k} \) is the set of all "out" arguments in literals \( r_i \) to \( r_i-1 \).

(4) For each \( m_{ij} \) in \( MP_i \), where \( 1 \leq i \leq s \), do the following:

(a) if \( m_{ij} = \emptyset \) then:

(i) compute set \( \text{OUT}_{ij} \) of "out" arguments of \( r_i \);

(ii) compute \( \text{OUT}_{ij} := \text{OUT}_{ij} \cup \text{OUT}_{i-1,k} \);

(iii) call \( \text{MSEAS}(MS_{ij} \cup \{ \text{OUT}_{ij} \}, VP, i+1, \text{OUT}_{ij}) \);

(b) otherwise, if \( m_{ij} \neq \emptyset \) then find all distinct minimal size sets \( v_i \subseteq VP \) such that whenever the arguments in \( v_i \) are "in", then the arguments in \( m_{ij} \) are "out". If such \( v_i \)'s exist, then for every \( v_i \) do:

(i) assume \( v_i \) is "in" in \( p \);

(ii) compute the set \( \text{OUT}_{ij} \) of "out" arguments in all literals from \( r_i \) to \( r_i \);

(iii) call \( \text{MSEAS}(MS_{ij} \cup \{ \text{OUT}_{ij} \}, VP, i+1, \text{OUT}_{ij}) \);

(c) otherwise, if no such \( v_i \) exist, \( MS_{ij} := \emptyset \).

(5) Compute \( MS := \bigcup_{i=1}^{s} MS_{ij} \).

(6) For \( \text{MSEAS}(MS, MSEA, VP, s+1, OUT) \), i.e., for \( i=s+1 \), do \( MS := \{ \text{MSEA} \} \).

As a simple example consider the following clause:

\[ \text{sent}(P) := vp(N,P), np(N). \]

Assuming that MSEA's for \( vp \) and \( np \) are \( \{ P \} \) and \( \{ N \} \), respectively, and that \( N \) is "out" in \( vp \), we can easily compute that \( \{ P \} \) is the MSEA in \( \text{sent} \). To see it, we note that \( MRU_1 \) for \( vp \) is \( \{ \{ P \} \} \) and, therefore, that \( m_{1,1} = \{ P \} \). Next, we note that \( MRU_2 \) for \( np \) is \( \{ \{ N \} \} \), and since \( \text{OUT}_{i-1} \) from \( vp \) is \( \{ N \} \), we obtain that \( m_{2,1} = \emptyset \) and subsequently that \( \{ P \} \) is the only MSEA in \( \text{sent} \).

The procedure presented above is sufficient in many cases, but it cannot properly handle certain types of recursive definitions. Consider, for example, the problem of assigning the set of MSEA's to \( \text{mem}(\text{Elem}, \text{List}) \), where \( \text{mem} \) (list membership) is defined as follows:

\[ \text{mem}(\text{Elem}, \{ \text{First} \mid \text{List} \}) := \text{mem}(\text{Elem}, \text{List}). \]

\[ \text{mem}(\text{Elem}, \{ \text{Elem} \mid \text{List} \}). \]

The \text{MSEAS} procedure assigns \( MS = \{ \{ \text{Elem} \mid \{ \text{List} \} \} \} \), we note however, that the first argument of \( \text{mem} \) cannot alone control the recursion in the first clause since the right-hand side (rhs) literal would repeatedly unify with the clause head, thus causing infinite recursion. This consideration excludes \( \{ \text{Elem} \} \) from the list of possible \text{MSEAs} for mem. In (Strzalkowski, 1989) we introduced the directed relation \text{always unifiable} among terms, which was informally characterized as follows. A term \( X \) is \text{always unifiable} with term \( Y \) if they unify regardless of any bindings that may occur in \( X \), providing that variables in \( X \) and \( Y \) are standardized apart, and that \( Y \) remains unchanged. According to this definition any term is always unifiable with a variable, while the opposite is not necessarily true. For example, the variable \( X \) is not always unifiable with the functional term \( f(Y) \) because binding \( X \) with \( g(Z) \) will make these two terms non-unifiable. This relation can be formally characterized as follows: given two terms \( X \) and \( Y \) we say that \( Y \) is \text{always unifiable} with \( X \) (and write \( X \preceq Y \)) iff the unification of \( X \) and \( Y \) yields \( Y \), where the variables occurring in \( X \) and \( Y \) have been standardized apart.\footnote{So defined, the relation \text{always unifiable} becomes an inverse of another relation: \text{less instantiated}, hence the particular direction of \( \preceq \) sign.} Since \( \preceq \) describes a partial order among terms, we can talk of its transitive closure \( \preceq^* \). Now we can augment the \text{MSEAS} procedure with the following two steps (to be placed between steps (2) and...}
Let \( p(X_0, \ldots, X_k, Y_0, \ldots, Y_k) \) be defined only on certain special sets of terms that the definition of delayed "out" status.

It turns out that this restricted relation is entirely sufficient in the task of grammar inversion, if we assume that the original grammar is itself well-defined.

**DEFINITION 1 (argument series)**

Let \( p(\ldots, Y_0, \ldots) \) be a clause, and let \( r_1, \ldots, r_k \) be an ordered subset of the literals on the right-hand side of this clause. Let \( r_{i+1} \) be either a literal to the right of \( r_i \) or the head literal \( p \). The ordered set of terms \( <Y_0, X_1, Y_1, \ldots, X_k, Y_k, X_{k+1}> \) is an argument series if the following conditions are met:

1. \( X_{k+1} \) is an argument in \( r_{i+1} \).
2. For every \( i=1 \cdots k \), \( X_i \) is different from any \( X_j \) for \( j<i \).
3. For every \( j=1 \cdots k \), \( X_j \) and \( Y_j \) are arguments to \( r_j \) that is, \( r_{i,j}(\ldots, X_j, Y_j, \ldots) \), such that if \( X_j \) is "in" then \( Y_j \) is "out" \(^{12}\), and
4. For every \( j=0 \cdots k \), either \( X_{j+1}=Y_j \) or \( X_{j+1} \neq Y_j \), where \( f(X) \) denotes a term containing a subterm \( X \).

Note that this definition already ensures that the argument series obtained between \( X_0 \) and \( X_{k+1} \) is the shortest one. As an example, consider the following clauses:

\[
vp(X) := np(X, Y), vp(Y).
\]
\[
np(f(X), Y).
\]

Assuming that the argument \( X \) in the literal \( vp(X) \) on the left-hand side (lhs) of the first clause is "in", we can easily check that \( <X, X, Y, Y> \) constitutes an argument series between arguments of \( vp \) in the first clause.

**DEFINITION 2 (weakly ordered series)\(^{13}\)**

An argument series \( <Y_0, X_1, Y_1, \ldots, X_k, Y_k, X_{k+1}> \) in the clause \( p := r_1 \cdots r_k \) is weakly ordered iff \( Y_0 \leq X_{k+1} \) or \( X_{k+1} \leq Y_0 \), where \( \leq \) is a closure of \( \leq \) defined as follows:

1. For every \( i=1 \cdots k \), such that \( r_i(\ldots, X_j, Y_j, \ldots) \) there exists a clause \( r_j(\ldots, X, Y, \ldots) := s_1, \ldots, s_m \), where \( X \) and \( Y \) unify with \( X_j \) and \( Y_j \), respectively, such that \( X \leq Y \) or \( Y \leq X \);
2. For every \( i=0 \cdots k \), \( X_{i+1}=Y_i \) or \( X_{i+1}=f(Y_i) \) or \( Y_i=f(X_{i+1}) \).

Looking back at the definition of \( mem(Elem, List) \) we note that the first (recursive) clause contains two ordered series. The first series, \( <Elem, Elem> \), is not ordered (or we may say it is ordered weakly in both directions), and therefore \( Elem \) on the left-hand side of the clause will always unify with \( Elem \) on the right, thus causing non-terminating recursion. The other series, \( <First\ List, List> \), is ordered in such a way that \( First\ List \) will not be always unifiable with \( List \), and thus the recursion is guaranteed to terminate. This leaves \( [List] \) as the only acceptable MSEA for \( mem \).

Consider now the following new example:

\[
vp(X) := np(X, Y), vp(Y).\]
\[
np(f(X), Y).
\]

Note that the series \( <X, X, Y, Y> \) in the first clause is ordered so that \( X \leq Y \). In other words, \( Y \) in \( vp \) on the rhs is always unifiable with \( X \) on the lhs. This means that a non-terminating recursion will result if we attempt to execute the first clause top-down. On the other hand, it may be noted that since the series is ordered in one direction only, that is, we don't have \( Y \leq X \), we could invert it so as to obtain \( Y \leq X \), but not \( X \leq Y \). To accomplish this, it is enough to swap the arguments in the clause defining \( np \), thus redirecting the recursion. The revised program is guaranteed to

\(^{12}\) A similar concept of guide-structure is introduced in (Dymetman et al., 1990), however the ordered series is less restrictive and covers a larger class of recursive programs.

\(^{13}\) A series can also be strongly ordered in a given direction, if it is weakly ordered in that direction and it is not weakly ordered in the opposite direction.
terminate, providing that vp’s argument is bound, which may be achieved by further reordering of goals.\(^{14}\)

The ordered series relation is crucial in detecting and removing of non-terminating left-recursive rules of the grammar. The first of the following two algorithms finds if an argument series is ordered in a specified direction, without performing a partial evaluation of goals. The second algorithm shows how a directed series can be inverted.

**ALGORITHM 1 (finding if** \(Y_0 \leq X_{k+1}\) **(weakly))**

Given an argument series \(<Y_0, X_1, Y_1, \ldots, X_k, Y_k, X_{k+1}>\) do the following:

1. Find if for every \(i=0 \ldots k\), either \(X_{i+1} = Y_i\) or \(X_{i+1} = f(Y_i)\); if the answer is negative, return NO and quit.

2. For every \(i=1 \ldots k\), find a clause \(r_i(\ldots, X, Y, \ldots) :- s_1, \ldots, s_m\) such that \(X_j\) and \(Y_j\) unify with \(X\) and \(Y\), respectively, and there is a leading series \(<X \ldots Y>\) such that \(X \leq Y\). Return NO if no such clause is found, and quit.

3. In the special case when \(k=0\), i.e., \(p\) has no right-hand side, \(Y_0 \leq X_1\) if either \(Y_0 = X_1\) or \(X_1 = f(Y_0)\). If this is not the case return NO, and quit.

4. Otherwise, return YES.

When **ALGORITHM 1** returns a YES, it has generated an ordered path (i.e., the series with all the necessary subseries) between \(X_0\) and \(X_{k+1}\) to prove it. If this path is ordered in one direction only, that is, there exists at least one pair of adjacent elements \(X_i\) and \(Y_j\) within this path such that either \(X_i = f(Y_j)\) or \(Y_j = f(X_i)\), but not \(X_i = Y_j\), then we say that the path is properly ordered. In addition, if we force **ALGORITHM 1** to generate all the paths for a given series, and they all turn out to be properly ordered, then we will say that the series itself is properly ordered. We can attempt to invert a properly ordered path, but not the one which is only improperly ordered, i.e., in both directions. Therefore, for a series to be invertible all its paths must be properly ordered, though not necessarily in the same direction.\(^{15}\)

**ALGORITHM 2 (inverting properly ordered series)**

Given a clause \(p :- r_1, \ldots, r_n\), and an argument series \(<Y_0, X_1, Y_1, \ldots, X_k, Y_k, X_{k+1}>\) such that it is properly (weakly) ordered as \(X_0 \leq X_{k+1}\) \(\)[or \(X_{k+1} \leq X_0\)], invert it as follows:

1. For each \(r_i(\ldots, X_i, Y_j, \ldots)\) appearing on the rhs of the clause, find all clauses \(r_i(\ldots, X, Y, \ldots) :- s_1, \ldots, s_m\) such that \(X\) and \(Y\) unify with \(X_i\) and \(Y_j\), respectively, and there is a proper ordering \(X \leq Y\) \(\)[or \(Y \leq X\)].

2. Recursively invert the series \(<X \ldots Y>\); for the special case where \(m=0\), that is, \(r_j\) clause has no rhs, exchange places of \(X\) and \(Y\).

3. For every pair of \(Y_i\) and \(X_{i+1}\) \((i=0 \ldots k)\), if either \(Y_i = f(X_{i+1})\) or \(X_{i+1} = f(Y_i)\), where \(f\) is fully instantiated, exchange \(Y_i\) with \(X_{i+1}\), and do nothing otherwise.

We now return to the MSEAS procedure and add a new step (2C), that will follow the two steps (2A) and (2B) discussed earlier. The option in (2C) is used when the expansion of a MSEA rejected in step (2A) has failed in (2B). In an earlier formulation of this procedure an empty MSEA was returned, indicating an non-executable clause. In step (2C) we attempt to rescue those clauses in which the recursion is based on invertible weakly ordered series.

\[2C\]

Find an argument \(Y_i \in m_{i,u}\), a \(t\)-th argument of \(r_i\), such that \(X_i \leq Y_i\), where \(X_i\) is the \(t\)-th argument in the head literal \(p\) and the series \(<X_1 \ldots Y_1>\) is properly ordered. If no such \(Y_i\) is found, augment \(m_{i,u}\) with additional arguments; quit if no further progress is possible.\(^{16}\) Invert the series with **ALGORITHM 2**, obtaining a strongly ordered series \(<X'_1 \ldots Y'_1>\) such that \(Y' \leq X'_1\). Replace \(Y_i\) with \(Y'_i\) in \(m_{i,u}\) and add the resulting set to MRU.\(_i\).

At this point we may consider a specific linguistic example involving a generalized left-recursive production based on a properly ordered series.\(^{17}\)

\[1\] sent(\(V_1, V_3, S_{sem}\)) :-
np(\(V_1, V_2, S_{sem}\)),
vp(\(V_2, V_3, [S_{sem} I, S_{sem}]\)).
\[2\] vp(\(V_1, V_3, [A_{rs}gs, V_{sem}]\)) :-
vp(\(V_1, V_2, [C_{sem} I, A_{rs}gs], V_{sem}\)),
np(\(V_2, V_3, C_{sem}\)).

\(^{14}\) Reordering of goals may be required to make sure that appropriate essential arguments are bound.

\(^{15}\) Recursion defined with respect to improperly ordered series is considered ill-formed.

\(^{16}\) As in step (2B) we have to maintain the minimality of \(m_{i,u}\).

\(^{17}\) This example is loosely based on the grammar described in (Shieber et al., 1990).
INTRA-CLAUSAL INVERSION

The following general rule is adopted for an effective execution of logic programs: never expand a goal before at least one of its active MSEA is "in". This simple principle can be easily violated when a program written to perform in a given direction is used to run "backwards", or for that matter, in any other direction. In particular, a parser frequently cannot be used as a generator without violating the MSEA-binding rule. This problem is particularly acute within a fixed-order evaluation strategy, such as that of PROLOG. The most unpleasant consequence of disregarding the above rule is that the program may go into an infinite loop and have to be aborted, which happens surprisingly often for non-trivial size programs. Even if this does not happen, the program performance can be seriously hampered by excessive guessing and backtracking. Therefore, in order to run a parser in the reverse, we must rearrange the order in which its goals are expanded. This can be achieved in the following three steps:

PROCEDURE INVERSE

(1) Compute "in" and "out" status of arguments for the reversed computation. If the top-level goal parse (String,Sem) is used to invoke a generator, then Sem is initially "in", while String is expected to have "out" status.

(2) Compute sets of all (active and non-active) MSEAs for predicates used in the program.

(3) For each goal, if none of its MSEAs is "in" then move this goal to a new position with respect to other goals in such a way that at least one of its MSEAs is "in". If this "in" MSEA is not an active one, recursively invert clauses defining the goal's predicate so as to make the MSEA become active.

In a basic formulation of the inversion algorithm the movement of goals in step (3) is confined to be within the right-hand sides of program clauses, that is, goals cannot be moved between clauses. The inversion process proceeds top-down, starting with the top-level clause, for example parse (String,Sem) :- sent(String, [], Sere). The restricted movement inversion algorithm INVERSE has been documented in detail in (Strzalkowski, 1990ac). It is demonstrated here on the following clause taken from a parser program, which recognizes yes-no questions:

yesnoq (A1,A4,P) :-
   verb (A1,A2,Num,P2),
   subject (A2,A3,Num,P1),
   object (A3,A4,P1,P2,P).

When rewriting this clause for generation, we would place object first (it has P "in", and A3, P1, P2 "out"), then subject (it has the essential P1 "in", and A2 and Num "out"), and finally verb (its MSEA is either (A1) or (Num, P2), the latter being completely "in" now). The net effect is the following generator clause:

yesnoq (A1,A4,P) :-
   object (A3,A4,P1,P2,P),
   subject (A2,A3,Num,P1),
   verb (A1,A2,Num,P).

INVERSE works satisfactorily for most grammars, but it cannot properly handle certain types of clauses...
where no definite ordering of goals can be achieved even after redefinition of goal predicates. This can happen when two or more literals wait for one another to have bindings delivered to some of their essential arguments. The extended MSEA procedure is used to define a general inversion procedure INTER-CLAUSAL to be discussed next.

INTER-CLAUSAL INVERSION

Consider again the example given at the end of the section on essential arguments. After applying MSEA \([\text{Args}, \text{Vsera}]\) to invert the series \(<\text{Args}, [\text{Csem} \mid \text{Args}]>\) between \(v\) literals. This alters the affected clause \([2]\) as shown below (we show also other clauses that will be affected at a later stage):\(^{21}\)

\[
[1'] \text{sent}(\text{Sem}) := \varepsilon
\]
\[
[2'] \text{vp}'(\{\text{Csem} \mid \text{Args}\}) := \text{vp}'(\text{Args}), \text{np}(\text{Csem}).
\]
\[
[3'] \text{vp}'(\{\text{Vsem}\}) := \text{np}(\text{Vsem}).
\]

This code is executable provided that \(\text{Sem}\) is bound in \(\text{sent}\). Since \(\text{Args}\) is "out" in \(v\), the recursion in \([2']\) is well defined at last. The effect of the interclausal ordering is achieved by adopting the INTER-CLAUSAL procedure described below. The procedure is invoked when a deadlocked clause has been identified by INVERSE, that is, a clause in which the right-hand side literals cannot be completely ordered.

```sql
PROCEDURE INTERCLAUSAL(DLC)

[Inter-clausal inversion]

(1) Convert the deadlocked clause into a special canonical form in which the clause consists exclusively of two types of literals: the unification goals in the form \(X = Y\) where \(X\) is a variable and \(Y\) is a term, and the remaining literals whose arguments are only variables (i.e., no constants or functional terms are allowed). Any unification goals derived from the head literal are placed at the front of the rhs. In addition, if \(p \cdots X \cdots\) is a recursive goal on the rhs of the clause, such that \(X\) is an "in" variable unifiable with the head of an inverted series in the definition of \(p\), then replace \(X\) by a new variable \(X'\) and insert a unification goal \(X' = X\). The clause in \([1]\) above is transformed into the following form:

\[
[1'] \text{sent}(\text{Sem}) :=
\]
\[
\varepsilon(\text{Args}, \text{Sem}), \text{vp}'(\text{Args}).
\]
\[
[2'] \text{vp}'(\{\text{Csem} \mid \text{Args}\}) := \text{vp}'(\text{Args}), \text{np}(\text{Csem}).
\]
\[
[3'] \text{vp}'(\{\text{Vsem}\}) := \text{np}(\text{Vsem}).
\]
```

\(^{21}\) The string variables \(V1, V2, \text{etc.}\) are dropped for clarity.

\(^{22}\) There are situations when a clause would not appear deadlocked but still require expansion, for example if we replace \([1]\) by \(\text{sent}(\text{Sem}, \text{Sem}) : \text{vp}(\text{Sem}, \text{Sem})\) with \(\text{Sem}\) bound in \(\text{sent}\). This clause is equivalent to \(\text{sent}(\text{Sem}, \text{Sem}) : \text{Vsem}(\text{Sem}, \text{vp}(\text{Vsem}, \text{Sem})\), but since the series in \([2]\) has been inverted we can no longer meaningfully evaluate the rhs literals in the given order. In fact we need to evaluate \(\text{vp}\) first which cannot be done until \(\text{Vsem}\) is bound.

\(^{23}\) An alternative is to leave \([1]\) intact (except for goal ordering) and add an "interface" clause that would relate the old \(v\) to the new \(v'\). In such case the procedure would generate an additional argument for \(v'\) in order to return the final value of \(\text{Args}\) which needs to be passed to \(\text{np}\).
Clause:

[1a] \textit{sent}(\textit{Sem}) :-
\begin{align*}
np(\textit{Ssem}), \\
\textit{Args} = [\textit{Ssem}], \\
v(\textit{Args}, \textit{Sem}).
\end{align*}

(5) Find an executable order of the goals in the expanded clause. If not possible, expand more goals by recursively invoking INTERCLAUSAL, until the clause can be ordered or no further expansion is possible. In our example [1a] can be ordered as follows:

[1b] \textit{sent}(\textit{Sem}) :-
\begin{align*}
v(\textit{Args}, \textit{Sem}), \\
\textit{Args} = [\textit{Ssem}], \\
np(\textit{Ssem}).
\end{align*}

(6) Break the expanded clause back into two (or more) "original" clauses in such a way that: (a) the resulting clauses are executable, and (b) the clause which has been expanded is made as general as possible by moving as many unification goals as possible out to the clause(s) used in expansion. In our example \(v(\textit{Args}, \textit{Sem})\) has to remain in [1b], but the remainder of the rhs can be moved to the new \(v'\) clause. We obtain the following clauses (note that clause [2] has thus far remained unchanged throughout this process):

[1b] \textit{sent}(\textit{Sem}) :-
\begin{align*}
v(\textit{Args}, \textit{Sem}), \\
v'(\textit{Args},\_), \\
np(\textit{Csem}).
\end{align*}

[2b] \textit{v'}([\textit{Csem}|\textit{Args}],\textit{Sem}) :-
\begin{align*}
v'(\textit{Args},\textit{Sem}), \\
np(\textit{Csem}).
\end{align*}

[3b] \textit{v'}(\textit{Args},\_):-
\begin{align*}
\textit{Args} = [\textit{Ssem}], \\
np(\textit{Ssem}).
\end{align*}

(7) Finally, simplify the clauses and return to the standard form by removing unification goals. Remove superfluous arguments in literals. The result are the clauses [1'] to [3'] above.

CONCLUSIONS

We described a general method for inversion of logic grammars that transforms a parser into an efficient generator using an off-line compilation process that manipulates parser's clauses. The resulting "inverted-parser" generator behaves as if it was "parsing" a structured representation translating it into a well-formed linguistic string. The augmented grammar compilation procedure presented here is already quite general: it appears to subsume both the static compilation procedure of Strzalkowski (1990c), and the head-driven grammar evaluation technique of Shieber et al. (1990).

The process of grammar inversion is logically divided into two stages: (a) computing the collections of minimal sets of essential arguments (MSEAs) in predicates, and (b) rearranging the order of goals in the grammar so that at least one active MSEA is "in" in every literal when its expansion is attempted. The first stage also includes computing the "in" and "out" arguments. In the second stage, the goal inversion process is initialized by the procedure INVERSE, which recursively reorder's goals on the right-hand sides of clauses to meet the MSEA-binding requirement. Deadlocked clauses which cannot be ordered with INVERSE are passed for the interclausal ordering with the procedure INTERCLAUSAL. Special treatment is provided for recursive goals defined with respect to properly ordered series of arguments. Whenever necessary, the direction of recursion is inverted allowing for "backward" computation of these goals. This provision eliminates an additional step of grammar normalization.

In this paper we described the main principles of grammar inversion and discussed some of the central procedures, but we have mostly abstracted from implementation level considerations. A substantial part of the grammar inversion procedure has been implemented, including the computation of minimal sets of essential arguments, and is used in a Japanese-English machine translation system.24

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24 Further details can be found in (Peng and Strzalkowski, 1990; Strzalkowski and Peng, 1990; and Peng, forthcoming).
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