Abstract Machine for Typed Feature Structures

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Abstract

This paper describes an abstract machine for linguistic formalisms that are based on typed feature structures, such as HPSG. The core design of the abstract machine is given in detail, including the compilation process from a high-level language to the abstract machine language and the implementation of the abstract instructions. The machine’s engine supports the unification of typed, possibly cyclic, feature structures. A separate module deals with control structures and instructions to accommodate parsing for phrase structure grammars. We treat the linguistic formalism as a high-level declarative programming language, applying methods that were proved useful in computer science to the study of natural languages: a grammar specified using the formalism is endowed with an operational semantics.

Topics: Grammar formalisms, feature structures, Parsing, Compilation, WAM.

1 Introduction

Typed feature structures (TFSs) serve as a means for the specification of linguistic information in current linguistic formalisms such as HPSG ([14, 15]) or Categorial Grammar ([12]). Generalizing first-order terms (FOTs), TFSs are also used to specify logic programs and constraint systems in LOGIN ([3]), LIFE ([4]), ALE ([8, 9]), TFS ([18]) and others. General frameworks that are completely independent of any linguistic theory can be used to specify grammars for natural languages. Indeed, most of the above mentioned languages were used for specifying HPSG grammars.

Linguistic formalisms (in particular, HPSG) use TFSs as the basic blocks for representing linguistic data: lexical items, phrases and rules. Usually, no mechanism for manipulating TFSs (e.g., parsing algorithm) is specified. Current approaches for processing HPSG grammars either translate the grammar to Prolog (e.g., [8, 10]) or specify it as a general constraint system. Using general solvers for a specific application, namely parsing, results in disappointing performance. Clearly, efficient processing calls for a different method.

Research in the semantics of programming language has undergone much progress in recent years. At the same time, linguistic theories have become more formal and
grammars for natural languages are nowadays specified with rigor, resembling computer programs. The interaction of computer science and linguistics enables the use of techniques and results of the former to be applied to the latter.

We present an approach for processing TFSs that guarantees both an explicit definition and high efficiency. Our main aim is to provide an operational semantics for TFS-based linguistic formalisms, especially HPSG. We adopt an abstract machine approach for the compilation of grammars, in a formalism that is a subset of ALE. Such approaches were used for processing procedural and functional languages, but they gained much popularity for logic programming languages since the introduction of the Warren Abstract Machine (WAM – see [1]). Most current implementations of Prolog, as well as of other logic languages, are based on abstract machines. The incorporation of such techniques usually leads to very efficient compilers in terms of both space and time requirements. The abstract machine is composed of data structures and a set of instructions, augmented by a compiler from the TFS formalism to the abstract instructions. The effect of each instruction is defined using a low-level language that can be executed on ordinary hardware. Recently, a similar approach was applied to LIFE ([4]), which is a general purpose logic programming language; however, due to differences in the motivation and in the formalisms, our machine is much different. Moreover, the LIFE machine is limited to term unification, whereas our machine includes a control module that enables manipulation of whole grammars.

The abstract machine ensures that a grammars specified using our system are endowed with well defined meaning. It enables, for example, to formally verify the correctness of a compiler for HPSG, given an independent definition. The design of such an abstract architecture must be careful enough to compromise two, usually conflicting, requirements: the closer the machine is to common architectures, the harder it is to develop compilers for it; on the other hand, if such a machine is too complex, then while a compiler for it is easier to produce, it becomes more complicated to execute its language on normal architectures.

The next section sketches the framework for which our machine is designed and defines some basic notions. Section 3 describes the abstract machine core design along with the compilation scheme. In section 4 control structures are added to enable parsing. A conclusion and plans for further research are given in section 5. Due to lack of space, the description is rather general. Refer to [17] for more details.

2 The Framework

2.1 Fundamental Notions

We briefly review the basic notions we use (thoroughly described in [8, 17]). An HPSG grammar consists of a type specification and grammar rules (including principles and lexical rules). The basic entity of HPSG is the (typed) feature structure (TFS), which is a connected, directed, labeled, possibly cyclic, finite graph, whose nodes are decorated with types and whose edges are labeled by features. A TFS is reentrant if it contains two different paths that lead to the same node. The types are ordered according to an inheritance hierarchy where higher types inherit features from their super-types.
Many different formalizations of TFS systems exist; we basically follow the definitions of ([7, 8]). The set of types includes both \( \bot \), the least type, and \( \top \), the greatest one. Types are ordered by subsumption \( \sqsubseteq \) according to their information content, not set inclusion of their denotation. Hence, \( \bot \) is the most general type, subsuming every other, and \( \top \) is the contradictory type, subsumed by every other.

The inheritance hierarchy is required to be bounded complete: every set of consistent types \( t_1, \ldots, t_n \) must have a unique least upper bound \( t_1 \sqcup \cdots \sqcup t_n \neq \top \). Every partial order can be naturally extended to a bounded complete one. The appropriateness function \( \text{Approp}(t, f) \) is required to be monotone and to comply with the feature introduction condition\(^1\). However, we allow appropriateness specifications to contain loops.

The basic operation performed on TFSs is unification \( (\sqcup) \). There are various definitions for TFS unification, and we base our unification algorithm on the definition given in [8]. Two TFSs \( A \) and \( B \) are inconsistent if their unification results in failure, denoted by \( A \sqcup B = \top \).

The TFSs with which we deal are required to be totally well-typed\(^2\) for more efficient processing. This might be problematic for the users who may prefer to specify only partial information about linguistic entities. Therefore, some description language must be provided, allowing partial descriptions from which totally well-typed feature structures can be automatically deduced. As there are efficient algorithms to deduce structures from their descriptions, we prefer not to commit ourselves to one description language. We define our system over explicit representations of TFS, as will be clear from section 2.3.

### 2.2 Type Specification

A program (or a grammar) contains a type specification, consisting of a type hierarchy and an appropriateness specification. We adopt ALE’s format ([7]) for this specification: it is a sequence of statements of the form:

\[
t \; \text{sub} \; [t_1, t_2, \ldots, t_n] \; \text{intro} \; [f_1 : r_1, \ldots, f_m : r_m].
\]

where \( t, t_1, \ldots, t_n, r_1, \ldots, r_m \) are types, \( f_1, \ldots, f_m \) are features and \( n, m \geq 0 \). This statement, which is said to characterize \( t \), means that \( t_1, \ldots, t_n \) are (immediate) subtypes of \( t \) (i.e., for every \( i, 1 \leq i \leq n, t \sqsubseteq t_i \)), and that \( t \) has the features \( f_1, \ldots, f_m \) appropriate for it. Moreover, these features are introduced by \( t \), i.e., they are not appropriate for any type \( t' \) such that \( t' \sqsubset t \). Finally, the statement specifies that \( \text{Approp}(t, f_i) = r_i \) for every \( i \). Each type (except \( \top \) and \( \bot \)) must be characterized by exactly one statement. The arity of a type \( t \), \( \text{Ar}(t) \), is the number of features appropriate for it.

The full subsumption relation is the reflexive transitive closure of the immediate relation determined by the characterization statements. If this relation is not a bounded complete partial order, the specification is rendered invalid. The same is true in case it is not an appropriateness specification.

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\(^1\)This condition states that every feature is introduced by some least type and is appropriate for all the types it subsumes.

\(^2\)A TFS is totally well-typed if it contains all and only the features that are appropriate for its type, and each feature bears an appropriate value. This requirement will be slightly relaxed; see section 3.3.
We use the type hierarchy in figure 1 as a running example, where \texttt{bot} stands for \( \bot \). The type \( \top \) is systematically omitted from type specifications.

\[
\begin{align*}
\text{bot} & \text{ sub } [g,d]. \\
g & \text{ sub } [a,b] \text{ intro } [f3:d]. \\
a & \text{ sub } [c] \text{ intro } [f1:\text{bot}]. \\
c & \text{ sub } [] \text{ intro } [f4:\text{bot}]. \\
b & \text{ sub } [c,e] \text{ intro } [f2:\text{bot}]. \\
d & \text{ sub } [d1,d2]. \\
d1 & \text{ sub } []. \\
d2 & \text{ sub } [].
\end{align*}
\]

Figure 1: An example type hierarchy

### 2.3 Representation of Feature Structures

The most convenient graphical representation of TFSs is attribute-value matrices (AVMs). However, to represent a (totally well-typed) feature structure linearly we use an FOT-like notation, based upon Aït-Kaci’s \( \psi \)-terms ([5, 6]), where the type plays a similar role to that of a function symbol and the features are listed in a fixed order. Reentrancy is implied by attaching identical tags to reentrant TFSs. A term is normal if all its types are tagged, and if the same tag appears more than once, then only its first occurrence carries information. See [17] for the details.

Total well-typedness implies that the names of the features in a TFS can be coded by their position in the argument list of a type, and thus feature-names are omitted from the linear representation. Assuming that the feature names are ordered alphabetically, the linear representation of an example TFS is given in figure 2.

\[
\begin{bmatrix}
b \\
f2: & b \\
f1: & f2: d \\
f3: & d \\
\end{bmatrix}
\]

Figure 2: An example feature structure

### 3 A TFS Unification Engine

#### 3.1 First-Order Terms vs. Feature Structures

While TFSs resemble FOTs in many aspects, it is important to note the differences between them. First, TFSs are typed, as opposed to (ordinary) FOTs. TFSs are
interpreted over more specific domains than FOTs. In addition, TFSs label the arcs by feature names, whereas FOTs use a positional encoding for argument structure. More importantly, while FOTs are essentially trees, with possibly shared leaves, TFSs are directed graphs, within which variables can occur anywhere. Moreover, our system doesn’t rule out cyclic structures, so that infinite terms can be represented, too. FOTs are consistent only if they have the same functor and the same arity. TFSs, on the contrary, can be unified even if their types differ (as long as they have a non-degenerate least upper bound). Moreover, their arity can differ, and the arity of the unification result can be greater than that of any of the unificands. Consequently, many diversions from the original WAM were necessary in our design. In the following sections we try to emphasize the points where such diversions were made.

3.2 Processing Scheme

The machine’s engine is designed for unifying two TFSs: a program and a query. The program is compiled once to produce machine instructions. Each query is compiled before its execution; the resulting code is executed prior to the execution of the compiled program. Processing a query builds a graph representation of the query in the machine’s memory. The processing of a program produces code that, during run-time, unifies the program with a query already resident in memory. The result of the unification is a new TFS, represented as a graph in the machine’s memory. In what follows we interleave the description of the machine, the TFS language it is designed for and the compilation of programs in this language.

3.3 Memory Representation of Feature Structures

Following the WAM, we use a global, one-dimensional array called HEAP of data cells. A global register H points to the (current) top element of HEAP. Data cells are tagged: STR cells correspond to nodes, and store their types, while REF cells represent arcs, and contain the address of their targets. The number of arcs leaving a node of type $t$ is $Ar(t)$, fixed due to total well-typedness. Hence, we can keep the WAM’s convention of storing all the outgoing arcs from a node consecutively following the node. Given a type $t$ and a feature $f$, the position of the arc corresponding to $f$ ($f$-arc) in any TFS of type $t$ can be statically determined; the subgraph that is the value of $f$ can be accessed in one step. This is a major difference from the approach presented in [4], which leads to a more time-efficient system without harming the elegance of the machine design.

It is important to note that STR cells differ from their WAM analogs in that they can be dereferenced when a type is becoming more specific. In such cases, a chain of REF cells leads to the dereferenced STR cell. Thus, if a TFS is modified, only its STR cell has to be changed in order for all pointers to it to ‘feel’ the modification automatically. The use of self-referential REF cells is different, too: there are no real (Prolog-like) variables in our system, and such cells stand for features whose values are temporarily unknown.

One cell is required for every node and arc, so for representing a graph of $n$ nodes and $m$ arcs, $n + m$ cells are needed. Of course, during unification nodes can become more specific and a chain of REF cells is added to the count, but the length of such a chain is bounded by the depth of the type hierarchy and path compression during
dereferencing cuts it occasionally. As an example, figure 3 depicts a possible heap representation of the TFS $b(b(1,d,1),d)$.

| address: | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|---|---|---|---|---|---|---|---|
| tag:     | STR | REF | REF | STR | REF | REF | STR | STR |
| contents:| b  | 4  | 8  | b  | 7  | 7  | d  | d  |

Figure 3: Heap representation of the feature structure $b(b(1,d,1),d)$

### 3.4 Flattening Feature Structures

Before processing a TFS, its linear representation is transformed to a set of “equations”, each having a flat (nesting free) format. To facilitate this a set of registers $\{X_i\}$ that store addresses of TFSs in memory is used. A register Reg[$j$] is associated with each tag $j$ of a normal term. The flattening algorithm is straight-forward and similar to the WAM’s. Figure 4 depicts examples of the equations corresponding to two TFSs.

| Linear representation: | Set of equations |
|------------------------|------------------|
| $a(3,d,1,3)$           | $X1 = a(X2,X2)$  |
|                        | $X2 = d1$        |
| $b(b(1,d,1),d)$        | $X1 = b(X2,X3)$  |
|                        | $X2 = b(X4,X4)$  |
|                        | $X4 = d$         |
|                        | $X3 = d$         |

Figure 4: Feature structures as sets of equations

### 3.5 Processing of a Query

When processing an equation of the form $X_{i_0} = t(X_{i_1}, X_{i_2}, \ldots)$, representing part of a query, two different instructions are generated. The first is put_node $t/n$, $X_{i_0}$, where $n = Ar(t)$. Then, for every argument $X_{i_j}$, an instruction of the form put_arc $X_{i_0}$, $j$, $X_{i_j}$ is generated. put_node creates a representation of a node of type $t$ on top of the heap and stores its address in $X_{i_0}$; it also increments $H$ to leave space for the arcs. put_arc fills this space with REF cells.

In order for put_arc to operate correctly, the registers it uses must be initialized. Since only put_node sets the registers, all put_node instructions must be executed before any put_arc instruction is. Hence, the machine maintains two separate streams of instructions, one for put_node and one for put_arc, and executes the first completely before moving to the other. This compilation scheme is called for by the cyclic character of TFSs: as explained in [4], the original single-streamed WAM scheme would fail on cyclic terms. Consequently, the order of the equations becomes irrelevant, and in the actual implementation they might be processed in any order.

The effect of the two instructions is given in figure 5. Figure 6 lists the result of compiling the term $b(b(1,d,1),d)$. When this code is executed (first the put_node instructions, then the put_arc ones), the resulting representation of the TFS in memory is the one shown above in figure 3.
\begin{verbatim}
put_node t/n, X_i ≡
    HEAP[H] ← <STR, t>;
    X_i ← H;
    H ← H + n + 1;

put_arc X_i, offset, X_j ≡
    HEAP[X_i+offset] ← <REF, X_j>;
\end{verbatim}

Figure 5: The implementation of the put instructions

\begin{verbatim}
put_node b/2, X1 % X1 = b(
    put_arc X1,1, X2 % X2,
    put_arc X1,2, X3 % X3)

put_node b/2, X2 % X2 = b(
    put_arc X2,1, X4 % X4,
    put_arc X2,2, X4 % X4)

put_node d/0, X4 % X4 = d
put_node d/0, X3 % X3 = d
\end{verbatim}

Figure 6: Compiled code for the query \( b(b(1d, 1), d) \)

\subsection{Compilation of the Type Hierarchy}

One of the reasons for the efficiency of our compiler is that it performs an important part of the unification during compile-time: the type unification. The WAM’s equivalent of this operation is a simple functor and arity comparison. It is due to the nature of a typed system that this check has to be replaced by a more complex computation. Efficient methods were suggested for performing least-upper-bound computation during run time (see [3]), but clearly computing during compilation time is preferable. Since type unification adds information by returning the features of the unified type, this operation builds new structures, in our design, that reflect the added knowledge. Moreover, the WAM’s special register \( S \) is here replaced by a stack. \( S \) is used by the WAM to point to the next sub-term to be matched against, but in our design, as the arity of the two terms can differ, there might be a need to hold the addresses of more than one such sub-term. These addresses are stored in the stack. When the type hierarchy is processed, the (full) subsumption relation is computed. Then, a table is generated which stores, for every two types \( t_1, t_2 \), the least upper bound \( t = t_1 \sqcup t_2 \). Moreover, this table lists also the arity of \( t \), its features and their ‘origin’: whether they are appropriate for \( t_1, t_2 \), both or none of them. Out of this table a series of abstract machine language functions are generated. The functions are arranged as a two-dimensional array called `unify_type`, indexed by two types \( t_1, t_2 \). Each such function receives one parameter, the address of a TFS on the heap. When executed, it builds on the heap a skeleton for the unification result: an STR cell of the type \( t_1 \sqcup t_2 \), and a REF cell for each appropriate feature of it.
Consider `unify_type[t1,t2] (addr)` where `addr` is the address of a TFS `A` (of type `t2`) in memory. Let `t = t1 ⊔ t2`, and let `f` be some feature appropriate for `t`. If `f` is inherited from `t2` only, the value of the REF cell is simply set to point to the `f`-arc in `A`. If `f` is inherited from `t1` only, a self-referential REF cell is created. But the information that the actual value for this cell is yet to be seen must be recorded. This is done by means of the global stack `S`, every element of which is a pair `<action, addr>`, where `action` is either ‘copy’ or ‘unify’. In the case we describe, the action is ‘copy’ and the address is that of the REF cell. If `f` is appropriate for both `t1` and `t2`, a REF cell with the address of the `f`-arc in `A` is created, and a ‘unify’ cell is pushed onto the stack. Finally, if `f` is introduced by `t`, a VAR cell is created, with `Approp(t,f)` as its value. VAR cells are explained in section 3.8. As an example, we list below (figure 7) the resulting code for the unification the two types `a` and `b`.

```
unify_type[a,b] (b_addr)
    build_str(c); % since a⊔b = c
    build_self_ref_and_copy;
    build_ref(1);
    build_ref_and_unify(2);
    build_var(bot);
    bind(b_addr,H); % f4 is a new structure.
    H ← H + 5;
    return true;
```

Figure 7: `unify_type[a,b]`

This example code is rather complex; often the code is much simpler: for example, when `t2` is subsumed by `t1`, nothing has to be done. As another example, if `t1` is subsumed by `t2`, then additional features of the program term have to be added to `A`. But if no such features exist, the only required effect is a change of the type of `A`. Another case is when `t1` and `t2` are not compatible: `unify_type[t1,t2]` returns ‘fail’. This leads to a call to the function `fail`, which aborts the unification.

### 3.7 Processing of a Program

The program is stored in a special memory area, the CODE area. Unlike the WAM, in our framework registers that are set by the execution of a query are not helpful when processing a program. The reason is that there is no one-to-one correspondence between the sub-terms of the query and the program, as the arities of the TFSs can differ. The registers are used, but (with the exception of `X1`) their old values are not retained during execution of the program.

Three kinds of machine instructions are generated when processing a program equation of the form `X_{i0} = t(X_{i1},...,X_{in})`. The first instruction is `get_structure t/n,X_{i0}`, where `n = Ar(t)`. For each argument `X_{ij}` of `t` an instruction of the form `unify_variable X_{ij}` is generated if `X_{ij}` is first seen; if it was already seen, `unify_value`
$X_{ij}$ is generated. For example, the machine code that results from compiling the program $a(3,d1,3)$ is depicted in figure 8. The implementation of these three instructions is given in figure 9.

```
get_structure a/2,X1  % X1 = a(
unify_variable X2  %   X2,
unify_value X2     %   X2)
get_structure d1/0,X2  % X2 = d1
```

Figure 8: Compiled code for the program $a(3,d1,3)$.

```
get_structure t/n,Xi ≡
   addr ← deref(Xi); Xi ← addr;
   case HEAP[addr] of
      <REF,addr>: % uninstantiated cell
         HEAP[H] ← <STR,t>;
         bind(addr,H);    % HEAP[addr] ← <REF,H>
      for j ← 1 to n do HEAP[H+j] ← <REF,H+j>
      for j ← n downto 1 do push(copy,H+j);
      H ← H + n + 1;
      <STR,t'>: % a node
         if (unify(type[t,t'](addr) = fail) then fail;

unify_variable Xi ≡
   <action,addr> ← pop();
   Xi ← addr;

unify_value Xi ≡
   <action,addr> ← pop();
   case action of
      copy: HEAP[addr] ← *(Xi);
      unify: if (unify(addr,Xi) = fail) then fail;
```

Figure 9: Implementation of the get/unify instructions

The **get_structure** instruction is generated for a TFS $A_p$ (of type $t$) which is associated with a register $X_i$. It matches $A_p$ against a TFS $A_q$ that resides in memory using $X_i$ as a pointer to $A_q$. Since $A_q$ might have undergone some type inference or previous binding (for example, due to previous unifications caused by other instructions), the value of $X_i$ must first be dereferenced. This is done by the function **deref** which follows a chain of REF cells until it gets to one that does not point to another, different REF-cell. The address of this cell is the value it returns.

The dereferenced value of $X_i$, **addr**, can either be a self-referential REF cell or an STR cell. In the first case, the TFS has to be built by the program. A new TFS is

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3 We use the operator ‘*’ to refer to the contents of an address or a register.
being built on top of the heap (using code similar to that of `put_structure`) with `addr` set to point to it. For every feature of this structure, a ‘copy’ item is pushed onto the stack. The second case, in which \( X_i \) points to an existing TFS of type \( t' \), is the more interesting one. An existing TFS has to be unified with a new one whose type is \( t \). Here the pre-compiled `unify_type[t,t']` is invoked.

The `unify_variable` instruction resembles very much its WAM analog, in the case of `read mode`. There is no equivalent of the WAM’s `write mode` as there are no real variables in our system. However, in `unify_value` there is some similarity to the WAM’s modes, where the ‘copy’ action corresponds to write mode and the ‘unify’ action to read mode. In this latter case the function `unify` is called, just like in the WAM. This function (figure [10]) is based upon `unify_type`. In contrast to the latter, the two TFS arguments of `unify` are in memory, and full unification is performed. The first difference is the reason for removing an item from the stack \( S \) and using it as a part of the unification process; the second is realized by recursive calls to `unify` for subgraphs of the unified graphs.

```plaintext
function unify(addr1, addr2: address): boolean;
begin
    addr1 ← deref(addr1); addr2 ← deref(addr2);
    if (addr1 = addr2) then return(true);
    if (HEAP[addr1] = <REF, addr1>) then
        bind(addr1, addr2); return(true);
    if (HEAP[addr2] = <REF, addr2>) then
        bind(addr2, addr1); return(true);
    H_orig ← H; t1 ← *(addr1); t2 ← *(addr2);
    if (unify_type[t1, t2](addr2) = fail) then return(fail);
    for i ← 1 to Ar(t1) do
        <action, addr> ← pop();
        case action of
            copy: HEAP[addr] ← <REF, addr1+i>;
            unify: if (not (unify (addr, addr1+i))) then return(fail);
        end;
    bind(addr1, H_orig);
    return(true);
end;
```

Figure 10: The code of the `unify` function

When a sequence of instructions that were generated for some TFS is successfully executed on some query, the result of the unification of both structures is built on the heap and every register \( X_i \) stores the value of its corresponding node in this graph. The stack \( S \) is empty.

### 3.8 Lazy Evaluation of Feature Structures

One of the drawbacks of maintaining total structures is that when two TFSs are unified, the values of features that are introduced by the unified type have to be built. For example, `unify_type[a,b]` (figure [7]) has to build a TFS of type `bot`, which is the value
of the \( f4 \) feature of type \( c \). This is expensive in terms of both space and time; the newly built structure might not be used at all. Therefore, it makes sense to defer it.

To optimize the design in this aspect, a new kind of heap cells, VAR-cells, is introduced. A VAR cell whose contents is a type \( t \) stands for the most general TFS of type \( t \). VAR cells are generated by the various \texttt{unify_type} functions for introduced features; they are expanded only when the explicit values of such features are needed: either during the execution of \texttt{get_structure}, where the dereferenced value is a VAR cell, or during \texttt{unify}. In both cases the TFS has to be built, by means of executing the pre-compiled function \texttt{build_most_general_fs} with the contents of the VAR cell as an argument. This function (which is automatically generated by the type hierarchy compiler) builds a TFS of the designated type on the heap, with VAR cells instead of REF cells for the features. These cells will, again, only be expanded when needed. We thus obtain a lazy evaluation of TFSs that weakly resembles Götz's notion of \textit{unfilled feature structures} ([11]). Moreover, we gain another important property, namely that our type hierarchies can now contain loops, since appropriateness loops can only cause non termination when introduced features are fully constructed.

4 Parsing

The previous section delineated a very simple abstract machine, capable of unifying two simple TFSs. We now add to this machine control structures that will enable parsing. We define rules, grammars and parsing, and then describe how the basic machine is extended to accommodate the application of a single rule. We sketch the extensions necessary for manipulating a whole grammar (program). These extensions were not tested yet.

4.1 Grammars

A multi-rooted structure (MRS) is a directed, labeled, finite graph with an ordered non-empty set of distinguished nodes, roots, from which all the nodes are reachable. A rule is a MRS, where the graph that is reachable from the last root is the rule’s head\(^4\) and the ones that are reachable from the rest of the roots form its body\(^5\). A MRS is linearly represented as a sequence of terms, separated by commas, where two occurrences of the same tag, even within two different terms, denotes reentrancy (that is, the scope of the tags is the entire sequence of terms). The head is preceded by ‘\(⇒\)’ rather than by a comma. See [17] for the formal details.

Application of a rule amounts to unifying its body with a MRS resident in memory and producing its head as a result. When two TFSs \( A_1 \) and \( A_2 \) are parts of MRSs \( σ_1 \) and \( σ_2 \), respectively, the unification of \( A_1 \) and \( A_2 \) in the context of \( σ_1 \) and \( σ_2 \) is defined just like ordinary unification, but \( σ_1 \) and \( σ_2 \) might be affected by the process. As an example, the rule \( ρ : a(\text{bot}, \text{d}, \text{d}) \Rightarrow a(\text{d}, \text{d}) \) consists of a MRS of length three. When it is applied to the MRS \( σ : a(\text{d}, \text{d}) \), \( \text{d} \), the result is a new MRS whose head

\(^4\)This use of head must not be confused with the linguistic one, the core features of a phrase.
\(^5\)Notice that the traditional direction is reversed. Note also that the head and the body need not be disjoint.
is $a(d2,d1)$. ρ’s head is modified even though it does not participate directly in the
unification, as it is part of the context.

A grammar is a finite set $R$ of rules together with a start feature structure $A_s$.
The lexicon associates with every word $w$ a TFS $A_w$, its category by means of special
rules of the form $\langle w \Rightarrow A_w \rangle$. The input for the parser, therefore, is a MRS rather than
a string of words. A MRS $σ$ is derived by some TFS $A$ if there exists a rule $ρ \in R$
such that $A$ is obtained by unifying $σ$ with $ρ$’s body in the context of $ρ$’s head. We
abuse the term ‘derive’ to denote also the reflexive transitive closure of this relation.
$A$ is a category if it derives a substring of some input. The language generated by
the grammar is the set of strings of words $\{w_1 \cdots w_n\}$ such that the category of $w_i$ is
$A_i$ for $1 \leq i \leq n$ and $A_s$ derives $A_1, \ldots, A_n$.

A dotted rule (or edge) is a MRS that is more specific than some rule in the
grammar, with an additional dot, indicating a location preceding some element in the
MRS. An edge is complete if its dot precedes the head and is active otherwise. We
denote dotted rules by $\langle A_1, \ldots, A_i \cdot A_{i+1}, \ldots, A_n \Rightarrow A_0 \rangle$. Informally, such a dotted
rule asserts that each of $A_1, \ldots, A_i$ derives a string $σ_1, \ldots, σ_i$ such that $σ_1 \cdots σ_i$ is a
substring of the input. $A_{i+1}, \ldots, A_n$ still have to derive $σ_{i+1}, \ldots, σ_n$ in order for $A_0$ to
be a category deriving $σ_1 \cdots σ_n$.

4.2 Parsing as Operational Semantics

We view parsing as a computational process along the lines of [10]. Given a grammar
$(R, A_s)$, an item is a triple $[i, ρ, j]$ where $i, j$ are natural numbers and $ρ$ is a dotted
rule. A state is a finite set of items. A computation is triggered by some input string
of words $w_1, \ldots, w_n$ of length $n > 0$. The initial state, $\hat{S}$, is $\{[i, \langle w_i \Rightarrow A_i \rangle, i + 1] | 0 \leq
i < n\} \cup \{[i, \langle α \Rightarrow B \rangle, i] | 0 \leq i < n\}$ where $A_i$ is the category of $w_i$ and $\langle α \Rightarrow B \rangle \in R$.
For any state $S$, the next state $S'$ is constructed by the following transition relation
‘$\vdash$’ (the fundamental rule):

For every $[i, \langle α \cdot Bβ \Rightarrow A \rangle, k] \in S$ and $[k, \langle γ \Rightarrow B'' \rangle, j] \in S$ such that
$B \sqcup B'' \neq \top$, add $[i, \langle α'B'β' \Rightarrow A' \rangle, j]$ to $S'$, where $\langle α'B'β' \Rightarrow A' \rangle$
is obtained by unifying $B$ and $B''$ in the contexts of $\langle αBβA \rangle$ and $\langle γB'' \rangle$,
respectively.

A computation is an infinite sequence of states $S_i, i \geq 0$, such that $\hat{S} = S_0$ and
for every $i \geq 0$, $S_i \vdash S_{i+1}$. A computation is terminating if there exists some $m \geq 0$
for which $S_m = S_{m+1}$ (i.e., a fixed-point is reached). A successful computation is a
terminating one, the final state of which contains an item of the form $[0, \langle α \Rightarrow A \rangle, n]$,\nwhere $A_s \subseteq A$; otherwise, the computation fails. The presence of more than one such
item in the final state indicates that the input can be analyzed in more than one way.

To represent a state of the computation the machine uses a chart, structured as a
two-dimensional array storing, in the $(i, j)$ entry, all the dotted rules $ρ$ such that $[i, ρ, j]$ is
a member of the state. Items are added to the chart by means of an agenda that
controls the order of addition.

\footnote{Words can have more than one category, but we ignore ambiguity for the sake of simplicity.}

\footnote{Categories are TFSs rather than the atomic symbols of Context Free Grammars.}

\footnote{If $S \vdash S'$ then $S \subseteq S'$.}
4.3 Application of a Single Rule

To allow the application of a single rule, the syntax of queries is extended from simple TFSs to MRSs. The same code is generated for the queries, with additional **advance** instructions preceding each TFS of the query. The **advance** instruction simply increments the indices of the chart item being manipulated. As a result of executing the query, the \((i, i+1)\) diagonal of the chart is initialized with singleton sets of edges.

The syntax of programs is extended, too, from a TFS to a single MRS. Again, the same code is generated for the TFSs of a program: program-code for each element of the rule’s body and query-code for the head. Before the first TFS, a **start_rule** instruction is generated. A **move_dot** and **next_item** instructions are generated between two consecutive structures, and after the last one, the head, an **end_rule** instruction concludes the generated code.

To understand the effect of these instructions, one must understand the non-uniform internal representation of dotted rules. Each such rule is represented by a record, **edge**, containing three fields. The **seen** field is a list of pointers to the roots of an MRS, for the part of the dotted rule preceding the dot. The **to see** field is a pointer to the code area, for the rest of the rule. A complete edge is represented as a single TFS, its head, since the rest of the structures (that are unaccessible from the head) are irrelevant. An edge with an initial dot is simply a pointer to code.

Since the rules are applied incrementally, a TFS at a time, care must be taken of reentrancies. The rules manipulate registers which must contain the right values when used. To that end the values of the registers are stored after execution of a part of a rule (that is, before moving the dot), and the right values are loaded prior to each such execution (after moving the dot). The field **regs** of an **edge** stores the saved registers.

**start_rule** sets the stage for the application of the rule: it stores the address of the beginning of the query in \(X_1\), where **get_structure** expects to find it. It also records the values of \(i, j\) and \(k\) of the current edges. **move_dot** is executed after the successful unification of one TFS; it copies the newly created edge, including the values of the registers, to the chart (and interacts with the agenda). **next_item** just restores the registers’ values and resumes execution. **end_rule** is executed once a complete edge is constructed; it adds the edge to the chart and selects the next edge to work on.

4.4 Control Structures

When designing the control module, three parameters have to be set: the order of searching chart entries that can combine with a complete edge \(e\); the order of searching active edges within this chart entry; and the search strategy: are all the edges that can combine with \(e\) computed first, and then their consequences (BFS), or rather all the consequences of the first such edge, then the next etc. (DFS). The order the chart is searched for active edges is right to left: from \((i, i)\) to \((0, i)\). There is no way to decide that a certain edge in the chosen chart entry is appropriate save by trying to unify it with the complete edge that was just entered. Hence all edges in a chart entry are considered a disjunctive value, and each of them is tried in turn. Furthermore, upon initialization each entry on the diagonal \((i, i)\) of the chart is set to be a disjunction of all the rules in the grammar. As for the search strategy, we chose to employ BFS; some way to record all the edges that were added as consequences of \(e\) is needed, in order to
compute their consequences next.

Determining the values of these parameters is program-independent: the main-tenance of the chart is fixed. This fact results from the nature of the process the machine implements, namely parsing, and has a desirable consequence: one might change some of these parameters easily without having to modify the compiler or even the set of machine instructions. What has to be changed is the data structures that support the control mechanism. For lack of space we don't detail the control module. Essentially, it employs a list of edges, agenda, and interacts with the machine instructions described above through designated functions.

5 Conclusion

As linguistic formalisms become more rigorous, the necessity of well defined semantics for grammar specifications increases. We presented an operational semantics for TFS-based formalisms, making use of an abstract machine specifically tailored for this kind of applications. In addition, we described a compiler for a general TFS-based language. The compiled code, in terms of abstract machine instructions, can be interpreted and executed on ordinary hardware. The use of abstract machine techniques is expected to result in highly efficient processing.

The TFS unification engine and the type hierarchy compiler were already implemented; the control module will be implemented shortly. We then plan to enhance the machine by adding specific values for lists (and perhaps sets). The implementation will serve as a platform for developing an HPSG grammar for the Hebrew language.

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