Efficient Parameterizable Type Expansion for Typed Feature Formalisms

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Abstract
Over the last few years, constraint-based grammar formalisms have
become the predominant paradigm in natural language processing and com-
putational linguistics. From the viewpoint of computer science, typed
feature structures can be seen as a record-like data structure that allow
the representation of linguistic knowledge in a uniform fashion.
Type expansion is an operation that makes the idiosyncratic and inher-
ited constraints defined on a typed feature structure explicit and thus
determines its satisfiability. We describe an efficient expansion algorithm
that takes care of recursive type definitions and permits the exploration of
different expansion strategies through the use of control knowledge. This
knowledge is specified on a separate layer, independent of grammatical
information. The algorithm, as presented in the paper, has been fully im-
plemented in COMMON LISP and is an integrated part of the typed feature
formalism TDL that is employed in several large NL projects.

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1 Introduction

Over the last few years, constraint-based grammar formalisms [Shieber 1986] have become the predominant paradigm in natural language processing and computational linguistics. While the first approaches relied on annotated phrase structure rules (e.g., PATR-II [Shieber et al. 1983]), modern formalisms try to specify grammatical knowledge as well as lexicon entries entirely through feature structures. In order to achieve this goal, one must enrich the expressive power of the first unification-based formalisms with different forms of disjunctive descriptions. Later, other operations came into play, e.g., (classical) negation.

However the most important extension to formalisms consists of the incorporation of types, for instance in modern systems like TFS [Zajac 1992], CUF [Döre and Dorna 1993], or TDC [Krieger and Schäfer 1994]. Types are ordered hierarchically as is known from object-oriented programming languages, a feature heavily employed in lexicalized grammar theories like Head-Driven Phrase Structure Grammar (HPSG) [Pollard and Sag 1987]. This leads to multiple inheritance in the description of linguistic entities. In general, not only is a type related to other types through the inheritance hierarchy, but is also provided with feature constraints that are idiosyncratic to this type. Hence, a type symbol can serve as an abbreviation for a complex expression and an untyped feature structure becomes a typed one. If a formalism is intended to be used as a stand-alone system, it must also implement recursive types if it does not provide phrase-structure recursion directly (within the formalism) or indirectly (via a parser/generator). In addition, certain forms of relations (like append) or additional extensions of the formalism (like functional uncertainty) can be nicely modelled through recursive types.

Now, because types allow us to refer to complex constraints through the use of symbol names, we need an operation that is responsible for deducing the constraints that are inherent to a type. This means, reconstructing the idiosyncratic constraints of a type, plus those that are inherited from the supertypes. We will call such a mechanism type expansion (TE) or type unfolding. Thus TE is faced with two main tasks:

1. making some or all feature constraints explicit (TE is a structure-building operation)
2. determining the global consistency of a type or more generally, of a typed feature structure (if this is possible)

1For instance, ALE employs a bottom-up chart parser, whereas TFS relies entirely on type deduction. Note that recursive types can be substituted by definite clauses (equivalences), as is the case for CUF, such that parsing/generation roughly corresponds to Prolog’s SLD resolution.

2It is worth noting that our notion of TE shares similarities with Aï-Kaci’s sort unfolding [Aï-Kaci et al. 1993] and Carpenter’s total well-typedness [Carpenter 1992, Ch. 6]. However, the latter notion is not well-defined for true recursive typed feature structures in that such structures cannot be totally well-typed within finite time and space.
Types not only serve as a shorthand, like templates, but also provide other advantages which can only be accomplished if a mechanism for TE is available:

- **Structuring Knowledge**
  Hierarchically-ordered types allow for a modular way of representing linguistic knowledge. Generalizations can be put at the appropriate levels of representation. *Type expansion*, then, is responsible for gathering the distributed information that is attached to the type symbols.

- **Saving Memory**
  In practice, it is not possible to hold huge lexica in full detail in memory. However, only the idiosyncratic information of a lexicon entry needs to be represented. *Type expansion* is employed in making the constraints imposed by lexical types explicit.

- **Efficient Processing**
  Working with type symbols only or with partially expanded typed feature structures minimizes the costs of copying during processing and speeds up unification. This can only be accomplished if the system makes a mechanism for *type expansion* available.

- **Type Discipline**
  Type definitions allow a grammarian to declare which attributes are appropriate for a given type and which types are appropriate for a given attribute, therefore disallowing one from writing inconsistent feature structures. Again, *type expansion* is necessary to determine the global consistency of a given description.

- **Recursive Types**
  Recursive types give a grammar writer the opportunity to formulate certain functions or relations as recursive type specifications. Working in the type deduction paradigm forces a grammar writer to replace the context-free backbone through recursive types. Here, parameterized delayed *type expansion* is the key to controlled linguistic deduction [Uszkoreit 1991].

- **Anytime Behaviour**
  Complex architectures for NL processing require modules that can be interrupted at any time, returning an incomplete, nevertheless useful result [Wahlster 1993]. Such modules are able to continue processing with only a negligible overhead, instead of having been restarted from scratch. *Type expansion* can serve as an anytime module for linguistic processing.

In the next section, we introduce the basic inventory to describe our own novel approach to TE. We then describe the basic structure of the algorithm, present several improvements, and show how it can be parameterized w.r.t. different dimension. Finally, we have a few words on theoretical results and
compare our treatment with others. Further detailed material on this theme can be found in the PhD thesis of the first author [Krieger 1995a] and the master’s thesis of the second [Schäfer 1995].

2 Preliminaries

In order to describe our algorithm, we need only a small inventory to abstract from the concrete implementation in TDC [Krieger and Schäfer 1994] and to make the approach comparable to others. First of all, we assume pairwise disjoint sets of features (attributes) \( F \), atoms (constants) \( A \), logical variables \( V \), and types \( T \). In the following, we refer to a type hierarchy \( I \) by a pair \( \langle T, \preceq \rangle \), such that \( \preceq \subseteq T \times T \) is a decidable partial order, i.e., \( \preceq \) is reflexive, antisymmetric, and transitive. A typed feature structure (TFS) \( \theta \) is essentially either a \( \psi \)-term or an \( \epsilon \)-term [Alf-Kaci 1986], i.e.,

\[
\theta ::= \langle x, \tau, \Phi \rangle \mid \langle x, \tau, \Theta \rangle
\]

such that \( x \in V, \tau \in T, \Phi = \{ f_1 = \theta_1, \ldots, f_n = \theta_n \} \), and \( \Theta = \{ \theta_1, \ldots, \theta_n \} \), where each \( f_i \in F \) and \( \theta_i \) is again a TFS. We will call the equation \( f = \theta \) a feature constraint (or an attribute-value pair).\(^3\) \( \Phi \) is interpreted conjunctively, whereas \( \Theta \) represents a disjunction. Variables are used to indicate structure sharing.

Let us give a small example to see the correspondences. The typed feature structure

\[
\langle x, \text{cyc-list}, \{ \text{FIRST }= 1, \text{REST }= x \} \rangle
\]

should denote the same set of objects as the following two-dimensional attribute-value matrix (AVM) notation:

\[
\begin{bmatrix}
\text{cyc-list} \\
\text{FIRST } 1 \\
\text{REST } x
\end{bmatrix}
\]

It is worth noting that for the purpose of simplicity and clarity, we restrict TFS to the above two cases. Actually, our algorithm is more powerful in that it handles other cases, for instance conjunction, disjunction, and negation of types and feature constraints.

A type system \( \Omega \) is a pair \( \langle \Theta, I \rangle \), where \( \Theta \) is a finite set of typed feature structures and \( I \) an inheritance hierarchy. Given \( \Omega \), we call \( \theta \in \Theta \) a type definition.

\(^3\)It should be noted that we define TFS to have a nested structure and not to be flat (in contrast to feature clauses in a more logic-oriented approach, e.g., [Alf-Kaci et al. 1993]) in order to make the connection to the implementation clear and to come close to the structured attribute-value matrix notation.
Our algorithm is independent of the underlying deduction system—we are not interested in the normalization of feature constraints (i.e., how unification of feature structures is actually done) nor are we interested in the logic of types, e.g., whether the existence of a greatest lower bound is obligatory (TFS [Zajac 1992]; ALE [Carpenter and Penn 1994]) or optional as in TDL [Krieger and Schäfer 1994]. We assume here that typed unification is simply a black box and can be accessed through an interface function (say unify-tfs). From this perspective, our expansion mechanism can be either used as a stand-alone system or as an integrated part of the typed unification machinery.

We only have to say a few words on the semantic foundations of our approach at the end of this paper. This is because we could either choose extensions of feature logic [Smolka 1989] or directly interpret our structures within the paradigm of (constraint) logic programming [Lloyd 1987; Jaffar and Lassez 1987].

3 Algorithm

The overall design of our TE algorithm was inspired by the following requirements:

- support a complete expansion strategy
- allow lazy expansion of recursive types
- minimize the number of unifications
- make expansion parameterizable for delay and preference information
- make expansion incremental to serve as an anytime module

Before we describe the algorithm, we modify the syntax of TFS to get rid of unimportant details. First, we simplify TFS in that we omit variables. This can be done without loss of generality if variables are directly implemented through structure-sharing (which is the case for our system). Hence conjunctive TFS have the form \( \langle \tau, \{ f_1 = \theta_1, \ldots, f_n = \theta_n \} \rangle \), whereas disjunctive are of the form \( \langle \tau, \{ \theta_1, \ldots, \theta_n \} \rangle \).

Given a TFS \( \theta \), type-of(\( \theta \)) returns the type of \( \theta \), whereas typedef(\( \tau \)) then obtains the type definition without inherited constraints as given by the type system \( \Omega = \langle \Theta, I \rangle \). We call this TFS a skeleton. It is either \( \langle \sigma, \{ \theta_1, \ldots, \theta_n \} \rangle \) or \( \langle \sigma, \{ f_1 = \theta_1, \ldots, f_n = \theta_n \} \rangle \), where \( \sigma \) are the direct supertypes of \( \tau \).

Because the algorithm should support partially expanded (delayed) types, we enrich each TFS \( \theta \) by two flags:

1. \( \Delta\text{-expanded}(\theta) = \text{true} \) iff typedef(type-of(\( \theta \))) and the definitions of all its supertypes have been unified with \( \theta \); false otherwise.
2. \( \text{expanded}(\theta) = \text{true} \), iff \( \Delta\text{-expanded}(\theta) = \text{true} \) and \( \text{expanded}(\theta_i) = \text{true} \) for all elements \( \theta_i \) of TFS \( \theta \); false otherwise.

Hence \( \Delta\text{-expanded} \) is a local property of a TFS that tells whether the definition of its type is already present, while \( \text{expanded} \) is a global property which indicates that all substructures of a TFS are \( \Delta\text{-expanded} \). Clearly, atoms and types that possess no features are always expanded. The exploitation of these flags leads to a drastic reduction of the search space in the expansion algorithm.

### 3.1 Basic Structure

The following functions briefly sketch the basic algorithm. It is a destructive depth-first algorithm with a special treatment of recursive types that will be explained in Section 3.3.

\( \text{expand-tfs} \) is the main function that initializes TE. The while loop is executed until the TFS \( \theta \) is expanded or so-called “resolved” (see keyword :resolved-predicate in Section 3.5). Several passes may be necessary for recursive TFS.

\[
\text{expand-tfs}(\theta) :=
\]

\[
\text{while not (expanded-p(}\theta\text{) or resolved-p(}\theta\text{) or no unification occurred in last pass)}
\]

\[
\text{depth-first-expand(}\theta\text{).}
\]

\[
/* \text{or types-first-expand(}\theta\text{), resp.} */
\]

\( \text{depth-first-expand} \) and \( \text{types-first-expand} \) recursively traverse a TFS. Which of both functions is employed, can be specified by the user. The visited check is done by comparing variables (actually, structure-sharing in the implementation makes variables obsolete). \( \text{types-first-expand} \) is defined analogously by first expanding the root type of a TFS, and then processing the feature constraints.

\[
\text{depth-first-expand}(\theta) :=
\]

\[
\text{if } \theta \text{ has been already visited in this pass}
\]

\[
\text{then return}
\]

\[
\text{else}
\]

\[
\text{if } \theta = \langle \tau, \{\theta_1, \ldots, \theta_n\} \rangle
\]

\[
\text{then}
\]

\[
\text{for every } \theta \in \{\theta_1, \ldots, \theta_n\} : 
\]

\[
\text{depth-first-expand(}\theta\text{)}
\]

\[
\text{else do } /* \theta = \langle \tau, \{f_1 = \theta_1, \ldots, f_n = \theta_n\} \rangle */
\]

\[
\text{for every } \theta \in \{\theta_1, \ldots, \theta_n\} : 
\]

\[
\text{depth-first-expand(}\theta\text{)};
\]
if not $\Delta$-expanded($\theta$)
     then unify-type-and-node($\tau, \theta$)
od.

unify-type-and-node destructively unifies $\theta$ with the expanded TFS of $\tau$. The index $i$ specifies which “prototype” of $\tau$ is chosen (see Section 3.2).

unify-type-and-node($\tau, \theta$) :=
if $\tau = \lnot \sigma$
     then unify-tfs (negate-tfs (expand-type($\sigma, i$)), $\theta$)
else unify-tfs (expand-type($\tau, i$), $\theta$);
$\Delta$-expanded($\theta$) $\leftarrow$ true.

We adapt Smolla’s treatment of negation for our TFS [Smolla 1989]. Note that we only depict the conjunctive case here.

negate-tfs($\theta = \langle \tau, \{ f_1 = \theta_1, \ldots, f_n = \theta_n \} \rangle$) :=
return
$\langle \top, \{} \rangle,$
$\langle \top, \{ f_1 \uparrow \} \rangle,$
$\langle \top, \{ f_1 = \text{negate-tfs}(\theta_1) \} \rangle,$
$\ldots,$
$\langle \top, \{ f_n \uparrow \} \rangle,$
$\langle \top, \{ f_n = \text{negate-tfs}(\theta_n) \} \rangle.$

3.2 Indexed Prototype Memoization

The basic idea of memoization [Michie 1968] is to tabulate results of function applications in order to prevent wasted calculations. We adapt this technique to the type expansion function. The argument of our memoized expansion function is a pair consisting of a type name (or a name of a lexicon entry or a rule) and an arbitrary index that allows access to different TFS of the same type which may be expanded in different ways (fully expanded or partially w.r.t. to a certain specification). Such feature structures are called prototypes.

Once a prototype has been expanded according to the attached control information, its expanded version is recorded and all future calls return a copy of it, instead of repeating the same unifications once again:

expand-type($\tau, index$) :=
if protomemo($\tau, index$) undefined
     then $\theta \leftarrow$ expand-tfs(typedef($\tau$));
     protomemo($\tau, index$) $\leftarrow$ $\theta$;
Most of these computations can be done at compile time (*partial evaluation*), and hence speed up unification at run time. The prototypes can serve as “basic blocks” for building a partially expanded grammar.

Some empirical results indicate the usefulness of indexed prototype memoization. Figure 1 contains statistical information about the expansion of a mid-size HPSG grammar with approx. 900 type definitions. About 250 additional lexicon entries and rules have been expanded from scratch, i.e., all types are unexpanded (are skeletons) at the beginning. The type and instance skeletons together consist of about 9000 nodes, whereas the resulting structures have a total size of approx. 50000 nodes (nodes undergoing garbage collections are not counted).

The measurements show that memoization speeds up expansion by a factor of 5 here (or 10 if all types except the lexicon entries are pre-expanded which seems to be the optimal setting at run time). These factors are directly proportional to the number of unifications. The time difference between the memoized and non-memoized algorithm may be even bigger if disjunctions are involved (in the ideal case exponential). The sample grammar contains only a few disjunctions.

```
return copy-tfs(θ)
else return copy-tfs(proto memo(τ, index)).
```

![Table](https://example.com/table.png)

**Figure 1:** Efficiency of depth-first vs. types-first expansion with/without indexed prototype memoization.

### 3.3 Detecting Recursion

The memoization technique is also employed in detecting recursive types. This is important in order to prevent infinite computations. We use the so-called “expand stack” of `expand-type` to check whether a type is recursive or not (see
Section 3.4). Each call of expand-type(τ, index) will push τ onto the expand stack. This stack then is passed to expand-tfs.

If a type τ on top of the expand stack also occurs below in the stack (τ, σ₁, . . . , σₙ, τ, ρₙ, . . . , ρ₁), we immediately know that the types τ, σₙ, . . . , σ₁ are recursive. Furthermore, these types form a strongly connected component (SCC) of the type dependency (or occurrence) graph, i.e., each type in the SCC is reachable from every other type in the SCC. Examples for such SCCs are (cons list) and (state 1) in the example below (Section 3.4).

Testing whether a type is recursive or not thus reduces to a simple find operation in a global list that contains all SCCs. The expansion algorithm uses this information in expand-tfs to delay recursive types if the expand stack contains more than one element. Otherwise, prototype memoization would loop.

If a recursive type occurs in a TFS and this type has already been expanded under a subpath, and furthermore no features or other types are specified at this node, then this type will be delayed, since it would expand forever (we call this lazy expansion). An instance of such a recursive type for which type expansion stops is the recursive version of list, as defined below.

### 3.4 Example

In the following, we define a finite automaton A as a family of recursive type definitions. A consists of two states and accepts the language \( L(A) = a^* (a+b) \).\(^4\)

The input is specified through a list under path INPUT; cf. the definition of type ab below. The distributed (or named) disjunction [Eisele and Dörre 1990] headed by \( \& \) in type state 1 is used to map input symbols to state types (and vice versa). Defining FA this way provides a solid basis for the integration of automata-based allomorphy (e.g., 2-level morphology) and morphotactics within the same constraint-based formalism (cf. [Krieger et al. 1993]).

\[
\begin{align*}
\text{list} & \Rightarrow \{\text{cons}, ()\} \\
\text{cons} & \Rightarrow \begin{bmatrix} \text{FIRST} & \text{T} \\
\text{REST} & \text{list} \end{bmatrix} \text{ we abbreviate cons via \{\ldots\}} \\
\text{non-final} & \Rightarrow \begin{bmatrix} \text{INPUT} & \langle \text{con} \text{e} \rangle \\
\text{EDGE} & \text{\text{\textit{input}}} \end{bmatrix}
\end{align*}
\]

\(^4\)In [Krieger 1995b], it is shown that this special kind of encoding allows us to reconstruct all the nice properties of finite automata/regular expressions (viz., closedness under intersection, union, complement, concatenation, and Kleene closure) in terms of operations of the underlying feature calculus.
Fig. 2 shows a trace of the expansion of type $ab$. The algorithm is depth-first-expand without any delay or preference information. In this trace, we assume that it was not known before that the types $\text{cons}$, $\text{list}$, and $\text{state1}$ are recursive, hence the SCCs will be computed on the fly.

<table>
<thead>
<tr>
<th>step</th>
<th>expand-type</th>
<th>in type</th>
<th>under path</th>
<th>expand stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{cons}$</td>
<td>$ab$</td>
<td>input, rest</td>
<td>$\text{ab}$</td>
</tr>
<tr>
<td>2</td>
<td>$\text{list}$</td>
<td>$\text{cons}$</td>
<td>rest, $\text{cons ab}$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$\text{cons}$</td>
<td>$\text{list}$</td>
<td>$\epsilon$, $(\text{list cons ab})$ → $(\text{cons list})$ new SCC, delay $\text{cons}$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$\text{cons}$</td>
<td>$ab$</td>
<td>input, $\text{ab}$</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$\text{state1}$</td>
<td>$ab$</td>
<td>$\epsilon$, $\text{ab}$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$\text{state1}$</td>
<td>$\text{state1}$</td>
<td>next, $(\text{state1 ab})$ → $(\text{state1})$ new SCC, delay $\text{state1}$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>final</td>
<td>$\text{state1}$</td>
<td>next, $(\text{state1 ab})$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>non-final</td>
<td>$\text{state1}$</td>
<td>$\epsilon$, $(\text{state1 ab})$</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$\text{cons}$</td>
<td>non-final</td>
<td>input, $(\text{non-final state1 ab})$</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$\text{state1}$</td>
<td>$ab$</td>
<td>next, $(\text{ab})$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Tracing the expansion of type $ab$. $ab$ is consistent, hence the finite automata accepts input $\langle a, b \rangle$.

The result of $\text{expand-type}(ab)$ is the following feature structure:

$$
\text{expand-type}(ab) \Rightarrow \\
\begin{cases}
\text{INPUT} \langle \text{a, b, (\text{b, (a, b)})} \rangle \\
\text{EDGE} \\
\text{NEXT} \\
\end{cases}
$$

If we ran our automaton on the input $\text{abb}$,
\[ \text{it would be rejected: } \text{expand-type}(\text{abb}) \Rightarrow \text{fail.} \]

### 3.5 Declarative Specification of Control Information

Control information for the expansion algorithm can be specified globally, locally for each \textit{prototype}, as well as for a specific \textit{expand-tfs} call. The following control keywords have been implemented so far.

- \textit{:expand-function} \{\textit{depth}\mid\textit{types}\}\text{-first-expand} specifies the basic expansion algorithm.
- \textit{:delay} \{ \{ \textit{type} \mid \{ \textit{type} \mid \textit{pred}[]\}\}\{\textit{path}\}^+ \}\}^* \text{ specifies types at } \textit{path} \text{ to be delayed. } \textit{path} \text{ may be a feature path or a complex path pattern with wildcard symbols } *,+,?, \text{ feature and segment variables. } \textit{pred} \text{ is a test predicate to compare types, } \text{e.g., } = \text{ or } \leq \text{ (checked in unify-type-and-node).}
- \textit{:expand}\{\textit{expand-only}\}\{ \{ \textit{type} \mid \{ \textit{type} \mid \textit{index}\mid \textit{pred}[]\}\}\{\textit{path}\}^+ \}\}^* \text{ There are two mutually exclusive modes, concerning the expansion of types. If the expand-only list is specified, only types in this list will be expanded with the specified prototype index. All others will be delayed. If the expand list is specified, all types will be expanded (checked in unify-type-and-node).}
- \textit{:maxdepth} \text{ integer} \text{ specifies that all types at paths longer than } \text{integer} \text{ will be delayed anyway (checked in unify-type-and-node).}
- \textit{:attribute-preference} \{\textit{attribute}\}^* \text{ defines a partial order on attributes that will be considered in the functions depth-first-expand and types-first-expand. The substructures at the attributes leftmost in the list will be expanded first. This non-numerical preference may speed up expansion if no numerical heuristics are known.}
- \textit{:use}\{\textit{conj}\}\{\textit{disj}\}\text{-heuristics} \{\textit{nil}\} \text{ [Uszkoreit 1991] suggested exploiting numerical preferences to speed up unification. Both keywords control the use of this information in functions depth-first-expand and types-first-expand.}
- \textit{:resolved-predicate} \{\textit{resolved-p}\mid\textit{always-true}\mid\ldots\} \text{ This slot specifies a user definable predicate that may be used to stop recursion (see function expand-tfs). Such a predicate might suffice in practice to guarantee a terminating expansion without violating correctness. The default predicate is always-true which leads to a complete expansion algorithm (if no other delay information is specified).}
• :ask-disj-preference {t|nil} If this flag is set to t, the expansion algorithm interactively asks for the order in which disjunction alternatives should be expanded (checked in depth-first-expand and types-first-expand). This option is useful during the debug phase of a grammar.

• :ignore-global-control {t|nil} Specifies whether globally specified :expand-only, :expand, and :delay information should be ignored or not.

Let us give an example to show how control information can be employed. Note that we formulate this example in the concrete syntax of TDL.

```
defcontrol verb
  ;; delay all subtypes of sign under spec. path pattern
  ;; ? matches INHERITED and TO-BIND
  (:delay ((sign Subsumes) SYNSEM.NONLOCAL.?SLASH))
  ;; attribute preference during expansion by this order
  (:attribute-preference SYNSEM DTRS SUBCAT HEAD)
  (:use-disj-heuristics T)
  (:ignore-global-control T)
  ;; expand type local with index initial
  ;; * matches type local
  (:expand ((local initial) *))
  ;; these control specs are used for type verb with index 1
  :index 1.
```

### 3.6 How to Stop Recursion

Type expansion with recursive type definitions is undecidable in general, i.e., there is no complete algorithm that halts on arbitrary TFS and decides whether a description is satisfiable or not (see also Section 5). However, there are several ways to prevent infinite expansion in our framework:

• The first method is part of the expansion algorithm (lazy expansion) as described before.

• The second way is brute force: use the :maxdepth slot to cut expansion at a suitable path depth.

• The third method is to define :delay patterns or to select the :expand-only mode with appropriate type and path patterns.

• The fourth method is to use the :attribute-preference list to define the “right” order for expansion.

• Finally, one can define an appropriate :resolved-predicate that is suitable for a class of recursive types.
4 Applications

In Section 3.4, we have already mentioned an NL application in which type expansion was employed, viz., in the formulation of the interface between allomorphy and morphotactics [Krieger et al. 1993]. Let us quickly present two other areas that profit from type expansion: parsing/generation as type expansion and distributed parsing with partially expanded information.

Parsing and generation can be seen in the light of type expansion as a uniform process, where ideally only the phonology (for parsing) or the semantics (for generation) must be given, for instance:

\[
\text{Parsing: } \left[ \begin{array}{c}
\text{phrase} \\
\text{PHON} \langle \text{“John” “likes” “bagels”} \rangle
\end{array} \right]
\]

Type expansion together with a sufficiently specified grammar then is responsible in both cases for constructing a fully specified feature structure which is maximal informative and compatible with the input structure.

Distributed parsing is a strategy which reduces the representational overhead: given one grammar which cospecifies syntax and semantics, proper constraints (i.e., filters) are separated from purely representational constraints. The resulting subgrammars are then processed by two parsers in parallel [Diagne et al. 1995]. This presupposes that we can properly handle partially expanded typed feature structures.

5 Theoretical Results

It is worth noting that testing for the satisfiability of feature descriptions admitting recursive type equations/definitions is in general undecidable. [Rounds and Manaster-Ramer 1987] were the first to have shown that a Kasper-Rounds logic enriched with recursive types allows one to encode a Turing machine. Later, [Smolka 1989] argued that the undecidability result is due to the use of coreference constraints. He demonstrated his claim by encoding the word problem of Thue systems. Hence, our expansion mechanism is faced with the same result in that expansion might not terminate.

However, we conjecture that non-satisfiability and thus failure of type expansion is semi-decidable. The intuitive argument is as follows: given an arbitrary recursive TFS and assuming a fair type unfolding strategy, the only event under which TE terminates in finite time follows from a local unification failure which then leads to a global one. In every other case, the unfolding process goes on by substituting types through their definitions. Recently, [Aft-Kaci et al. 1993] have formally shown a similar result by using the compactness theorem of first-order logic. However, their proof assumes the existence of an infinite OSF clause (generated by unfolding a \(\psi\)-term). Furthermore, they have not addressed disjunction.
Thus, our algorithm might not terminate if we choose the complete expansion strategy. However, we noted above that we can even parameterize the complete version of our algorithm to ensure termination, for instance to restrict the depth of expansion (analogous to the off-line parsability constraint). The non-complete version always guarantees termination and might suffice in practice.

Semantically, we can formally account for such recursive feature descriptions (with respect to a type system) in different ways: either directly on the descriptions, or indirectly through a transformational approach into first-order logic (see [Krieger 1995c] for a transformational approach of typed feature structures into definite equivalences). Both approaches rely on the construction of a fixpoint over a certain (downward) continuous function. The first approach is in general closer to an implementation (and thus to our algorithm) in that the function which is involved in the fixpoint construction corresponds more or less to the unification/substitution of TFS (see for instance [Aït-Kaci 1986] or [Pollard and Mosher 1990]). The latter approach is based on the assumption that TFS are only syntactic sugar for first-order formulae. If we transform these descriptions into an equivalent set of definite clauses, we can employ techniques that are fairly common in logic programming, viz., characterizing models of a definite program through fixpoints. Take, for instance, our cyc-list example from the beginning to see the outcome of such a transformation (assume that cyc-list is a subtype of list):

\[
\forall x. \text{cyc-list}(x) \leftrightarrow \exists y, z. \text{list}(x) \land \\
\text{FIRST}(x, y) \land \text{REST}(x, z) \land \\
y = 1 \land z = x
\]

Under the least fixpoint interpretation, cyc-list will be assigned an empty denotation (assuming a rational tree domain), whereas the greatest fixpoint interpretation leads to a non-empty denotation, containing even infinite feature trees ([Krieger 1995c] is a detailed investigation of this and other related areas).

6 Comparison to other Approaches

To our knowledge, the problem of type expansion within a typed feature-based environment was first addressed by Hassan Aït-Kaci [Aït-Kaci 1986]. The language, he described, was called KBL and shared great similarities with LOGIN; see [Aït-Kaci and Nasr 1986]. However, his expansion mechanism was order dependent in that it substituted types by their definition instead of unifying the information. Moreover, it was non-lazy, thus it will fail to terminate for recursive types and performs TE only at definition time as is the case for ALE.

\footnote{In both cases, there is, in general, more than one fixpoint, but it seems desirable to choose the greatest one, as it would not rule out, for instance, cyclic structures or types which are not “grounded” on atoms.}
However, ALE provides recursion through a built-in bottom-up chart parser and through definite clauses. Allowing TE only at definition time is in general space consuming, thus unification and copying is expensive at run time.

Another possibility one might follow is to integrate TE into the typed unification process so that TE can take place at run time. Systems that explore this strategy are TFS [Zajac 1992] and LIFE [Aït-Kaci 1993]. However, both implementations are not lazy, thus hard to control and moreover, might not terminate. In addition, if prototype memoization is not available, TE at run time is inefficient; cf. Fig. 1). A system that employs a lazy strategy on demand at run time is CUF [Dörre and Dorna 1993]. Laziness can be achieved here by specifying delay patterns as is familiar from Prolog. This means delaying the evaluation of a relation until the specified parameters are instantiated.

7 Summary

Type expansion is an operation that makes constraints of a typed feature structure explicit and determines its satisfiability. We have described an expansion algorithm that takes care of recursive types and allows us to explore different expansion strategies through the use of control knowledge. Efficiency is addressed through specialized techniques: (i) prototype memoization reduces the number of unifications, and (ii) preference information directs the search space. Because our notion of type expansion is conceived as a stand-alone module, one can freely choose the time of its invocation, e.g., during typed unification, parsing, etc.

The algorithm, as presented in the paper, has been fully implemented within the TDL/UDINE system [Krieger and Schäfer 1994; Backofen and Weyers 1994] and is an integrated part of Disco [Uszkoreit et al. 1994].

We are convinced that our approach is also of interest to those who are working with (possibly recursive and hierarchically-ordered) record-like data structures in other areas of computer science.

References


