Partial Evaluation for Efficient Access to Inheritance Lexicons

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Abstract

Multiple default inheritance formalisms for lexicons have attracted much interest in recent years. I propose a new efficient method to access such lexicons. After showing two basic strategies for lookup in inheritance lexicons, a compromise is developed which combines to a large degree (from a practical point of view) the advantages of both strategies and avoids their disadvantages. The method is a kind of (off-line) partial evaluation that makes a subset of inherited information explicit before using the lexicon. I identify the parts of a lexicon which should be evaluated, and show how partial evaluation works for inheritance lexicons. Finally, the theoretical results are confirmed by a complete implementation. Speedups by a factor of 10–100 are reached.

1 Introduction

1.1 Motivation

In recent years, lexicons based on inheritance formalisms have attracted much interest in computational linguistics. These formalisms allow to develop highly structured lexicons with only small redundancy. The property of small redundancy leads to positive consequences, e.g., easy construction, modification, and extension of lexicons and support for maintaining consistency and conciseness. Besides the advantages following from nonredundant lexicons, inheritance lexicons are theoretically attractive as they identify linguistically significant classes of lexemes from the vast set of all possible classes (cf. (Flickinger & Nerbonne 92, p. 283)). Finally, descriptive parsimony, which can be achieved by inheritance lexicons, is always an advantage.

Despite the increasing popularity of inheritance lexicons, lookup for these lexicons is often inefficient, or at least not as efficient as possible. There are two basic strategies for access to inheritance lexicons:

1. Calculate the extension of a lexicon before access, i.e., the extension of each class describing a single lexeme (a lexical class) is completely calculated, yielding all word forms of this lexeme each with complete lexical information from the class itself and its direct and indirect superclasses. This information, standardly represented by some kind of feature structure, is stored in a new expanded lexicon. The size of the resulting full-form lexicon is maximal; lookup time is minimal, however, because lookup amounts to index search.

Even if a full-form lexicon can be realized for some applications, it is—from a scientific point of view—still desirable to achieve significant efficiency improvements if they are possible through a reasonable amount of additional work and resources.

2. Calculate an index (or several indices) before access and look up words by using this index (cf. (Russell et al. 92)). For language analysis, an index from word forms to corresponding lexical classes is needed. Lookup of a word in such an indexed inheritance lexicon comprises one index search plus extending (normally) one class.

A lookup in an indexed inheritance lexicon is slower than a lookup in a full-form lexicon, because the latter kind of lookup consists only of an

*Partial evaluation as described in this paper has been successfully applied to the lexicon in the Virtuelle Wissensfabrik (Virtual Knowledge Factory), a project of the German state Nordrhein-Westfalen, which supported this research in part.

1It is assumed that the lexicon contains morphological information to account for inflection. If the lexicon describes only base forms and morphology is treated by a separate component, a lexeme is linked to only one feature structure, which is defined by multiple inheritance. Besides this difference, all arguments about the approach presented in this paper remain valid.

2An extreme access strategy is to calculate the extension of the lexicon for each lookup. An anonymous reviewer pointed out to me (among other improvements) that this strategy is for most applications inadequate.
index search. In this paper, partial evaluation of inheritance lexicons is explained which speeds up lookup significantly (compared to indexed inheritance lexicons).

1.2 Inheritance-based lexicon formalism

In this paper, the lexicon formalism IBL (inheritance-based lexicon formalism), which (Hartrumpf 96) has developed and implemented, is used to illustrate the approach presented in this paper. This formalism is general and powerful and has been successfully applied to partially evaluate several lexicons. The results of this paper can be transferred to other lexicon formalisms with similar inheritance concepts (e.g., ELU’s formalism, (Russell et al. 91; Russell et al. 92)) quite easily. IBL’s basic concepts are summarized in the following as far as it is needed to understand partial evaluation for inheritance lexicons.

IBL is heavily inspired by the lexicon formalism of the Environnement Linguistique d’Unification (ELU), which uses multiple default inheritance as described by (Russell et al. 91; Russell et al. 92). IBL differs from ELU’s formalism in four main ways: feature structures may contain complex disjunctions and complex negations (not just atomic ones); predicative constraints can use coroutining to wait for arguments to become sufficiently instantiated (for coroutining in logic programming cf. (Clark & McCabe 79; SICStus 95)); a class can decide where in the feature structure to inherit information from a superclass (one may call this locating inheritance); IBL is strongly typed, i.e., all feature structures must have a type, while types are optional in ELU.

An IBL lexicon consists of type, generator and class definitions. Types are defined to type feature structures.

IBL’s most important concept are classes. A class is defined by its name, a list of direct superclasses (superclass list), a (possibly empty) main feature structure containing definite information, a (possibly empty) default feature structure containing default information, and a set of variant feature structures defining a set of variants. Variants are mutually exclusive alternatives, which can be used to describe different inflectional forms, for instance. The following class a, which describes basic properties of German adjectives, exemplifies the use of main, default, and variant feature structures.

```
class a
  main
    syn°cat = a,
    concat(mor°a_stem, mor°suffix, form)
  default
    lemma = mor°stem
  variant
    syn°cdegree = pos,
    mor°a_stem = mor°pos_stem
  variant
    syn°cdegree = comp,
    mor°a_stem = mor°comp_stem
  variant
    syn°cdegree = sup,
    mor°a_stem = mor°sup_stem.
```

This class states in its main feature structure that all adjectives belong to category a and word forms (feature form) of adjectives are always the concatenation (predicate concat) of a specific stem mor°a_stem and the suffix mor°suffix. In the next feature structure, it is expressed that the lemma is normally equal to the morphological stem. Finally, three variants prepare the generation of positive, comparative, and superlative adjective forms, all of which are realized within word boundaries. The given class is a nonlexical class as it is not a class that provides word forms for a specific lexeme (lexical class). This distinction is made by (Russell et al. 91).

The default information coming from a superclass can be overwritten in subclasses. Inheritance conflicts are solved by prioritized inheritance which uses the concept of class precedence lists (CPL) as described for the Common Lisp Object System (CLOS) by (Keene 89). The information of a superclass can be inherited by a subclass at a certain position (locating inheritance). The information inherited can not be restricted or selected ((Hartrumpf 96) calls this selective inheritance, which is allowed in DATR (Evans & Gazdar 96),) because this contradicts the principle of data encapsulation and may lead to unwieldy and poorly structured lexicons. To calculate the extension of a lexical class, one adds to it the information from main/variant feature structures of its superclasses by unification and

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3The CPL of a class can be derived by topologically sorting its direct and indirect superclasses, so that classes that appear together in a superclass list of these superclasses keep their order in the CPL and subclasses always precede their superclasses.
the information from default feature structures of its superclasses by default unification.

IBL’s third kind of lexical definitions are generators. A generator is a rule that can be used to generate a new lexical class from another lexical class. Such a rule is applied to an element of the extension if a special feature generator is set to the generator’s name.

In the next section, it is explained how a multiple inheritance hierarchy of classes can be partially evaluated.

2 Partial evaluation of inheritance lexicons

2.1 Background

Lexicon lookup in indexed inheritance lexicons (as described in section 1) consists of two operations: first, searching for the relevant class in the index; second, calculating the extension of this class. As the latter step consumes much more time than the first, it is the main target for improvements.

The idea is to precompute the extension of lexical classes to reduce lookup time. This precomputation represents a kind of (off-line) partial evaluation for inheritance lexicons (with respect to lexicon lookup). In general, there is a trade-off between the size of the partially evaluated lexicon (pe-lexicon) and the work that remains to be done at lookup time. This trade-off can be characterized by the gap between completely extended inheritance lexicons and indexed inheritance lexicons.

In this paper, a compromise for this trade-off is proposed that yields both: speedup of lexicon access by a factor of 10–100 (compared to indexed inheritance lexicons) and moderate lexicon size.

2.2 Partial evaluation without defaults

For our partial evaluation method, indexed inheritance lexicons were the starting point. For indexed inheritance lexicons, the extension of a lexical class c is calculated at lookup time according to algorithm 1 in Figure 1.

Step 2 will be discussed in section 2.3. The idea of our approach is to precompute some of the unification operations in algorithm 1. Two constraints have to be obeyed: first, the number and size of pe-results (results of partial evaluation, which (together with the lexical classes) form the pe-lexicon) must be tolerable; second, there should remain only little to do during lookup.

If one optimizes in favor of the second constraint by doing all unification operations for all lexical classes (This is the complete precomputation strategy.), the number and size of pe-results is unacceptable. But if one excludes the lexical class itself from partial evaluation (i.e., only the unification operations printed in boldface in algorithm 1 are performed during partial evaluation), the number of pe-results shrinks to a tolerable magnitude, especially as in a well structured inheritance lexicon the following holds (C1 is the set of all lexical classes in the lexicon):

\[ n_{cpl} := |\{cpl(c) - c \in C_1\}| \ll |\{cpl(c)\}c \in C_1\} = |C_1| =: n_l \]

For the lexicon further discussed in section 4, \(n_l\) is 1510, while \(n_{cpl}\) is 225.

Empirical results (see Table 1 below) confirm that the number \(n_{cpl}\) doesn’t increase much when the number \(n_l\) of lexical classes in the lexicon exceeds a certain number, or to be more specific, \(n_{cpl}/n_l\) approaches zero for growing \(n_l\). Therefore, the number of parts to be evaluated will be tolerable, if one precomputes only the unification operations that are in boldface in algorithm 1.

The extension \(ext(c)\) of a lexical class c with CPL \(cpl(c) = \langle c_1c_2...c_n\rangle\) is calculated in two steps:

Let \(M_i, D_i, V_i\) \((1 \leq i \leq n)\) be the main feature structure, the default feature structure, and the set of variant feature structures, respectively, of class \(c_i\). (The big unification operator \(\sqcap\) is a unification over two sets of feature structures, i.e., for two sets \(A\) and \(B\) of feature structures, \(A \sqcap B\) is defined as follows:

\[ A \sqcap B := \{F_A \cap F_B | F_A \in A, F_B \in B\} \setminus \{\bot\} \]

\(\sqcap\) is a default unification operator.)

1. \( ext_s(c) := \{M_1\} \sqcap V_1 \sqcap \{M_2\} \sqcap V_2 \sqcap \ldots \{M_n\} \sqcap V_n \)

2. \( ext(c) := (\ldots ((ext_s(c) \sqcap D_1) \sqcap D_2) \ldots \sqcap D_n) \)

Figure 1: Algorithm 1
At lookup time, only the information contained in the feature structures of the current lexical class in the pe-lexicon has to be added by unification to the result of partial evaluation (which can be considered to be the only superclass of that lexical class in the pe-lexicon), i.e., only the unification operations that are not in boldface in algorithm 1 have to be calculated. The number of unifications which are precomputed for the extension of a lexical class is often high (see Table 2 below) as variants may lead to exponential growth of this number.

2.3 Partial evaluation with defaults

The approach presented so far is only correct if the operations used in calculating extensions are associative and commutative because the normal order of operations (bottom-up) is changed by partial evaluation. These conditions are met by the (nondefault) unifications used in step 1 of algorithm 1. However, to add defaults (cf. step 2 of algorithm 1), normally a default unification operation is used which is neither associative nor commutative. This is also true of the prioritized default unification which is used in IBL and which assigns a priority to all atomic feature structures of a default feature structure as defined by (Hartrumpf 96).

To solve the correctness problem for defaults, I use a simple strategy. They are not treated during partial evaluation. Instead, one stores the atomic feature structures of default feature structures in the pe-lexicon and combines them with the pe-result (by prioritized default unification) at lookup time.

To sum up partial evaluation for inheritance lexicons, algorithm 1 in Figure 1 for calculating the extension of a lexical class is separated in a partial evaluation part (the algorithm in Figure 2 for calculating a pe-lexicon) and a lookup part (see next section).

Partial evaluation of inheritance lexicons is exemplified by its effects on the morphosyntactic description of German adjectives like klein (small) in Figure 3. Classes appear below their direct superclasses and are connected by directed edges. Class a is a graphical representation of the class definition in section 1.2. Its direct subclass

for all \( c \in \mathbf{C}_1 \) do:
1. Let \( \text{cpl}(c) = \langle c_1 c_2 \ldots c_n \rangle \). Let \( M_i, D_i, V_i \) \( (1 \leq i \leq n) \) be the main feature structure, the default feature structure, and the set of variant feature structures, respectively, of class \( c_i \).
   Calculate and store as a pe-result (if not already done for another class whose CPL differs only in \( c_1 \)):
   \[
   \{M_2 \} \cap V_2 \cap \ldots \{M_n \} \cap V_n , \text{ and} \\
   \langle D_2 \ldots D_n \rangle
   \]
2. Store for class \( c \) a reference to this pe-result, and \( M_1, V_1, D_1 \) (the feature structures of class \( c \)).

Figure 2: Algorithm for partial evaluation

2.4 Partial evaluation and lexical rules

Lexical rules are considered important in many lexicon formalisms. Although some lexical rules can be replaced by using the variant concept (cf. section 1.2), there remain cases where lexical rules are useful, e.g., for derivational morphology. The role of lexical rules is played in IBL by generators (cf. section 1.2). A generator consists of two parts: a superclass list and a mapping from the current feature structure (the input feature structure) to a new feature structure (the output feature structure). A straightforward treatment of generators by partial evaluation is to store all these output feature structures as new lexical classes (containing only a main feature structure) in the pe-lexicon and to treat the CPL corresponding to the superclass list of a generator like a CPL of a lexical class.

5There are associative and commutative default unification operations (cf. Lascarides & Copestake 93; Lascarides et al. 93); however, they might be too inefficient for applications that heavily use default unification.

6In some systems, it can be useful to delay the application of certain lexical rules.
Figure 3: Effects of partial evaluation for the German adjective *klein* (left side: original lexicon; right side: pe-lexicon)
3 Access to partially evaluated lexicons

A pe-lexicon consists of lexical classes and pe-results. Each lexical class refers to one pe-result that corresponds to its CPL (without the lexical class itself). A pe-result \( p \) comprises a list \( p_f \) of feature structures and a list \( p_d \) of default atomic feature structures (cf. upper right part of Figure 3).

To access a pe-lexicon, an index is used which is identical to the one used for the original indexed inheritance lexicon, i.e., a mapping from a set of key features to the classes whose extensions contain relevant information. For language analysis, this set of key features usually consists only of the (orthographical or phonological) form feature; such an index is assumed in the following. After searching for the relevant lexical class \( c \) in the index, the extension of class \( c \) has to be determined. First, the pe-result \( p_f \) for class \( c \) is retrieved from the pe-lexicon. Second, the main and variant feature structures of class \( c \) are added by unification. Third, the default atomic feature structures of class \( c \) and the default atomic feature structures in \( p_d \) are concatenated and added by default unification. These steps lead to the (complete) extension of class \( c \).

The approach described is slower than necessary when \( p_f \) contains many feature structures (as it is often the case for highly inflected languages) because the second and third step must be done for every member of \( p_f \). This situation is substantially improved by considering only those elements of \( p_f \) that are relevant for the word form \( w \) of a given query. In order to follow this strategy, the index is extended. A word form index has the signature \( W \rightarrow C_1 \times 2^N \) (instead of just \( W \rightarrow C_1 \); \( W \) is the set of all word forms, \( C_1 \) is the set of all lexical classes in the lexicon). The additional set \( S \) of natural numbers in an index entry \( w \rightarrow (c, S) \) identifies those elements of \( p_f \) (of the pe-result for \( \text{cpl}(c) - c \) ) that are relevant for the given word form \( w \). Figure 3 shows a part of an index for an indexed inheritance lexicon and the corresponding part of an index for a pe-lexicon, and Figure 4 contains the complete algorithm for lookup in pe-lexicons.

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7 Again, I simplify by describing only cases with one relevant class.

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1. \( w \rightarrow (c, S) = \text{index entry for word form } w \)
   (Let the lexical class \( c \) refer to a pe-result \( p \) consisting of feature structures \( p_f \) and atomic default feature structures \( p_d = (D_1, D_2, \ldots, D_n) \)).

2. Calculate for the feature structures \( PE \) corresponding to feature structures \( S \) in \( p_f \) the following \( (M_c, D_c, V_c) \) are the main feature structure, the default feature structure, and the variant feature structures for the lexical class \( c \), respectively):

   1. \( \text{ext}'_s(c) := \{ M_c \} \cap V_c \cap PE \)
   2. \( \text{ext}'(c) := (\ldots ((\text{ext}'_{s}(c) \cap D_c) \cap D_1) \cap \ldots \cap D_n) \)

Figure 4: Algorithm for lookup in pe-lexicons

4 Performance of partially evaluated lexicons

4.1 Performance of partial evaluation

As partial evaluation is done in a separate compilation step, the size of the resulting pe-lexicon is much more important than the runtime (which is linear in the number \( n_l \) of lexical classes). A pe-lexicon \( \text{cpl} \) contains in addition to the lexical classes of the original lexicon (with superclass lists replaced by references to pe-results, cf. section 2.2) a set of pe-results. If one follows the strategy described in section 2.2, the size of the pe-lexicon grows only linearly to \( n_{\text{cpl}} \).

The number \( n_{\text{cpl}} \) is bounded by the number \( n_l \) of lexical classes; in realistic lexicons, \( n_{\text{cpl}} \) is much smaller than \( n_l \) as explained in section 2.2. Therefore, the size increase for pe-lexicons is tolerable as reflected in Table 6. The lexicons of this table were created by adding lexemes in the order of a frequency list (see (Rosengren 77, pp. 165–219)), which is based on a German newspaper corpus.

4.2 Performance of lexicon lookup

A lookup in a pe-lexicon comprises two steps: an index entry is searched and a stored partial extension is completed. The first step can be done by standard methods from computer science, e.g.,
### Lexicon | pe-Lexicon | Size Increase
| n_t | n_n | n_cpl | n_lfs | t_e (s) | t_e/n_t (s) | n_lfs | n_lfs(pe-lexicon) / n_lfs(lexicon) |
|-----|-----|-------|-------|--------|-------------|-------|----------------------------------|
| 336 | 96  | 107   | 724   | 24.8   | 0.074       | 1753  | 2.42                             |
| 755 | 118 | 158   | 1196  | 48.2   | 0.064       | 3005  | 2.51                             |
| 1510| 145 | 225   | 2003  | 94.3   | 0.062       | 5193  | 2.59                             |

**Legend**

- $n_t$: number of lexical classes
- $n_n$: number of nonlexical classes
- $n_cpl$: number of different CPLs of lexical classes (excluding the lexical class itself)
- $n_lfs$: number of feature structures in the lexicon
- $t_e$: evaluation time for producing the pe-lexicon (SICStus Prolog 3 on a SUN Ultra 1)

Table 1: Experimental results for partial evaluation

by using hash tables which allow constant time search.

During the second step, one main feature structure and several variant feature structures have to be added by unification and the defaults of the pe-result and of the lexical class have to be added by default unification (as specified in Figure 4). In addition, there might be predicative constraints that had to be delayed during partial evaluation. The coroutining mechanism will initiate their evaluation during this step. This is the worst case; a typical lexical class comprises only a small main feature structure, if the lexicon is well structured.[9]

The results in Table 2 show that partial evaluation achieves significant speedups, especially for complex lexical classes. On the average, lookup in a pe-lexicon is 60 times faster than in the original indexed inheritance lexicon.

### 5 Related work

Partial evaluation is a technique that has been applied—in different ways—in several areas: in logical, functional, and imperative programming (see for instance (Jones et al. 93) for a thorough introduction and (Danvy et al. 96) for current research); for efficient access to methods in programming languages with single inheritance ([Khoo & Sundaresh 91]); etc. The problem of partial evaluation for inheritance lexicons differs in two ways: while behavior is limited to lookup functions, the data is complex due to its large size and high expressivity (multiple inheritance, defaults, disjunctions, negations).

In the context of inheritance lexicons, (Copesstake 93b, p. 240) mentions for the LKB (lexical knowledge base, (Copestake 93a)) that expanded classes (expanded psorts in LKB) can be cached, but does not provide any details. If inheritance proceeds top-down, as in the LKB, partial evaluation will be somewhat easier because the information that is added from the lexical class has always lower priority than the information of its superclasses and thus defaults don’t have to be treated specially by partial evaluation. However, this practice is for most applications counter-intuitive (although it is justified for the original domain of LKB, semiautomatic extraction of lexical information from machine-readable dictionaries, as (Copestake 93a, p. 239) shows) because normally a class should have precedence over its superclasses.

### 6 Perspectives

The results for partial evaluation of inheritance lexicons presented in this paper improve the practical use of such lexicons significantly. Interesting questions for further research remain, however.

The number of pe-results might be too high for some combinations of lexicons and applications. To reduce this number, the set of classes
can be partitioned. According to these partitions, the CPL of a class is split up in parts and only those partial CPLs are evaluated. During lexicon lookup, it will be necessary to combine results from different partial CPLs. This combination will be easier if the class partitions are orthogonal. For example, if, in the lexicon at hand, morphosyntactic and semantic information don’t interact much, one may use a class partition \( \text{mor}_\text{syn} \) and a class partition \( \text{sem} \).

Two more questions arise from the first: How can useful partitions of classes be linguistically defined or automatically determined? And: How do these partitions influence lookup time and size of pe-lexicons?

Another perspective is the use of results from partial evaluation to infer new linguistically relevant classes in inheritance lexicons semi-automatically.

**Table 2: Experimental results for lexicon lookup**

| Word Form | Lexicon | pe-Lexicon | Speedup |
|-----------|---------|------------|---------|
|           | \( n_s \) | \( n_{fs} \) | \( n_{afs} \) | \( t_l \) (ms) | \( n_{fs} \) | \( n_{afs} \) | \( n_{dp} \) | \( t_l \) (ms) | \( t_l^{(\text{lexicon})} \) / \( t_l^{(\text{pe-lexicon})} \) |
| \( \text{wegen} \) (preposition) | 1 | 4 | 7 | 8.0 | 2 | 3 | 0 | 0.7 | 11.4 |
| \( \text{Kreises} \) (noun) | 2 | 18 | 52 | 31.6 | 2 | 8 | 0 | 1.2 | 26.3 |
| \( \text{schönste} \) (adjective) | 4 | 72 | 332 | 168.8 | 2 | 9 | 1 | 4.9 | 34.4 |
| \( \text{laufe} \) (verb) | 7 | 538 | 2204 | 385.1 | 2 | 24 | 2 | 5.3 | 72.7 |
| average (1510) | 3.63 | 153 | 631 | 133.2 | 2.79 | 10.06 | 0.44 | 2.2 | 60.5 |

Legend

\( n_s \) number of superclasses

\( n_{fs} \) number of feature structures in superclasses (added during extending)

\( n_{afs} \) number of atomic feature structures in superclasses (added during extending)

\( t_l \) lookup time (SICStus Prolog 3 on a SUN Ultra 1)

\( n_{dp} \) number of delayed predicates

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