Parsing with unification

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Introduction to Computational Linguistics

Outline

1. Motivation
2. Unification
3. Other issues
4. References

Insufficiency of CFGs

- Atomic categories:
  No relation between the categories in a CFG:
  e.g. NP, N, N′, VP, VP_3sg, Nsg
- Hard to express generalisations in the grammar:
  for every rule that operates on a number of different categories, the rule specification has to be repeated

An example

- NP $\rightarrow$ Det N
- NPsg $\rightarrow$ Detsg Nsg
  NPpl $\rightarrow$ Detpl Npl

  Can we throw away the first instance of the rule?
  No: *sheep* is underspecified, just like *the*, ...

  We need to add the cross-product:
- NPsg $\rightarrow$ Detsg N
  NPpl $\rightarrow$ Detpl N
  NPsg $\rightarrow$ Det Nsg
  NPpl $\rightarrow$ Det Npl

An example

- Alternatively, words like *sheep* and *the* could be associated with several lexical entries.
  $\longrightarrow$ only reduces the number of rules somewhat
  $\longrightarrow$ increases the lexical ambiguity considerably

More problems

- The grammar cannot rule out yet: *Those sheep runs*
  $\rightarrow$ subject-verb agreement is not encoded yet
- Subcategorisation frames in their different stages of saturation are to be done as well.
- However: the expansion could be done automatically from feature structure descriptions: e.g.

$$\begin{bmatrix} \text{CATEGORY} & \textit{noun} \\ \text{SUBCAT} & \langle\rangle \\ \text{NUMBER} & \textit{sing} \\ \text{PERSON} & \textit{3} \end{bmatrix} \rightarrow \text{NP\_3sg}$$

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More problems

- The formalism does not leave any room for generalisations like the following:
  - “All verbs have to agree in number and person with their subject.”
    S $\rightarrow$ NP_(*) VP_(*) $\backslash 1 = \backslash 2$
  - “In a headed phrase, the head daughter has the same category as the mother.”
    XP $\rightarrow$ Y X
- Feature structures can do that.
- When a feature structure stands for an infinite set of categories, the grammar cannot be compiled out into a CFG.

Part II

Definitions

Outline

2. Definitions
   - What is a feature structure?
   - What is unification?
3. Parsing
4. Efficiency techniques

Outline

Definition

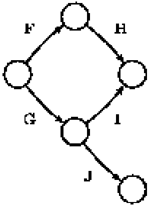
A feature structure is a directed graph, consisting of nodes and labelled edges. One node is special: the *root node*, from which every node can be reached by following edges.

A feature structure is a tuple $\langle Q, \overline{q}, \delta \rangle$:

- Q is a finite set of nodes, rooted at $\overline{q}$
- $\overline{q} \in Q$ is the root node
- δ : Feat $\times$ $Q \rightarrow Q$: a partial feature value function

Notation

- As a graph



- As an AVM $\begin{bmatrix} \mathrm{F} \mid \mathrm{H} & \boxed{1} \\ \mathrm{G} & \begin{bmatrix} \mathrm{I} & \boxed{1} \\ \mathrm{J} & 3 \end{bmatrix} \end{bmatrix}$

Outline

2 Definitions
- What is a feature structure?
- What is unification?

3 Parsing

4 Efficiency techniques

Subsumption

- An order relation between elements of a set:
  $\sqsubseteq : P \times P$ $\qquad \langle P, \sqsubseteq \rangle$
- It is an information ordering:
  a subsumes b iff a contains less information than b,
  alternatively iff a is more general than b.
- Special cases
  - There may be elements a, b such that $a \not\sqsubseteq b$ and $b \not\sqsubseteq a$ (*incomparable*)
  - Each element subsumes itself
    $a \sqsubseteq b \wedge b \sqsubseteq a \Leftrightarrow a = b$
  - In an anti-chain, no two elements are comparable

- Unification is the operation of merging information-bearing structures, without loss of information *if* the unificands are consistent (monotonicity).

Feature structure unification

- Here, $\sqsubseteq$ is a relation in the set of feature structures
- Feature structure unification ($\sqcup$) is the operation of combining two feature structures so that the result is the most general feature structure that is subsumed by the two unificands (*the least upper bound*). If there is no such structure, then the unification *fails*.
- Two feature structures that can be unified are compatible (or consistent). Comparability entails compatibility, but not the other way round.
- There is untyped feature structure unification and typed feature structure unification.

Untyped feature structure unification

- Token-identity: two feature structures are token-identical iff they *are* the same object.
- Consistent/compatible: two feature structures are consistent if they
  - have the same value,
  - the values of their common features are consistent.

Untyped unification: examples

See also Shieber (1986)

- $\begin{bmatrix}\text{CATEGORY} & \textit{noun}\end{bmatrix} \sqcup \begin{bmatrix}\text{NUMBER} & \textit{singular}\end{bmatrix} = \begin{bmatrix}\text{CATEGORY} & \textit{noun} \\ \text{NUMBER} & \textit{singular}\end{bmatrix}$
- $\begin{bmatrix}\text{CAT} & []\end{bmatrix} \sqcup \begin{bmatrix}\text{CAT}\,|\,\text{CASE} & \textit{accusative}\end{bmatrix} = \begin{bmatrix}\text{CAT}\,|\,\text{CASE} & \textit{accusative}\end{bmatrix}$
- $\begin{bmatrix}\text{F} & \boxed{1} \\ \text{H} & \boxed{1}\end{bmatrix} \sqcup \begin{bmatrix}\text{F} & [] \\ \text{H}\,|\,\text{G} & []\end{bmatrix} = \begin{bmatrix}\text{F} & \boxed{1}\begin{bmatrix}\text{G} & []\end{bmatrix} \\ \text{H} & \boxed{1}\end{bmatrix}$
- $\begin{bmatrix}\text{CATEGORY} & \textit{noun}\end{bmatrix} \sqcup \begin{bmatrix}\text{CATEGORY} & \textit{verb}\end{bmatrix} = \text{fail}$

Untyped unification: examples

- $$\begin{bmatrix} \text{AGR} & \boxed{1}\begin{bmatrix}\text{NUM} & \textit{sg}\end{bmatrix} \\ \text{SUBJ} & \begin{bmatrix}\text{AGR:} \ \boxed{1}\end{bmatrix} \end{bmatrix} \sqcup \begin{bmatrix} \text{SUBJ} & \begin{bmatrix}\text{AGR} & \begin{bmatrix}\text{PERS} & \textit{third}\end{bmatrix}\end{bmatrix}\end{bmatrix} =$$
$$\begin{bmatrix} \text{AGR} & \boxed{1}\begin{bmatrix}\text{NUM} & \textit{sg} \\ \text{PERS} & \textit{third}\end{bmatrix} \\ \text{SUBJ} & \begin{bmatrix}\text{AGR} & \boxed{1}\end{bmatrix} \end{bmatrix}$$

Destructive and non-destructive unification

In implementations, there are two ways to perform unification:

- Destructive unification: in the process of unifying two structures, one is modified and will contain the result
- Non-destructive unification: the unificands are not changed, and the result is a totally new structure.

The former is faster, but gives undesirable effects in some cases. For instance, when you apply a grammar rule, you do not want the rule to be different after the application. Non-destructive unification is easier to keep track of, but requires copying. Because it does not change the feature structures, the latter is used in implementations.

Typed unification

- Type-identity: two object are type-identical iff they are of the same type.
- Consistent: two feature structures are consistent if
  - their type values are consistent
  - their features have consistent values.

Type hierarchies

- A type hierarchy is a partially ordered set $\langle \text{Type}, \sqsubseteq \rangle$
- Often type hierarchies have to obey the *bounded complete partial order* requirement:
  "For every set of elements with an upper bound, there is a least upper bound."
  It ensures that every unification is unique
- Every feature structure node q has a typed value: $\theta(q)$
- In a type hierarchy, the more specific types inherit all properties from their supertypes. It is not possible to remove a property.

Typed feature structures

- A typed feature structure is a tuple $\langle Q, \overline{q}, \delta, \theta \rangle$:
  - Q is a finite set of nodes, rooted at $\overline{q}$
  - $\overline{q} \in Q$ is the root node
  - δ : Feat $\times$ $Q \rightarrow Q$: a partial feature value function
  - θ : $Q \rightarrow$ Type: a total type assignment function
- Typed feature structures stand in a subsumption hierarchy, the shape of which is determined by the type hierarchy and feature reentrancies. Even though the type hierarchy is finite, the feature structure hierarchy is not necessarily finite.
- It may not be immediately clear a reentrancy contains more information than a structure without. After all: the latter structure has more nodes. A reentrancy adds the knowledge that two things do not only look the same, they *are* the same.

Typed feature structure unification

Let $F, F' \in \mathcal{F}$ and $F = \langle Q, \overline{q}, \theta, \delta \rangle$, $F' = \langle Q', \overline{q}', \theta', \delta' \rangle$. It is required that $Q \cap Q' = \emptyset$. A least equivalence relation $\bowtie$ is defined on $Q \cup Q'$ such that

- $\overline{q} \bowtie \overline{q}'$
- $\delta(f, q) \bowtie \delta(f, q')$ if both are defined and $q \bowtie q'$

Then $F \sqcup F' = \langle (Q \cup Q')/_{\bowtie}, [\overline{q}]_{\bowtie}, \theta^{\bowtie}, \delta^{\bowtie} \rangle$
with

$$\theta^{\bowtie}([q]_{\bowtie}) = \bigsqcup \{(\theta \cup \theta')(q') | q \bowtie q'\}$$
$$\delta^{\bowtie}(f, [q]_{\bowtie}) =$$
$$\begin{cases} [(\delta \cup \delta')(f, q)]_{\bowtie} & \text{if } (\delta \cup \delta')(f, q) \text{ is defined} \\ \text{undefined} & \text{otherwise} \end{cases}$$

if all joins in $\theta^{\bowtie}$ exist. It is undefined otherwise. (Carpenter, 1992)

$$\begin{bmatrix} \text{F} & \boxed{1} \\ \text{G} & \boxed{1} \end{bmatrix} \sqcup \begin{bmatrix} \text{F} & a \\ \text{G} & b \end{bmatrix} = \begin{bmatrix} \text{F} & \boxed{1}\ a/b \\ \text{G} & \boxed{1} \end{bmatrix}$$

Features

- In an untyped framework, feature may be added anytime anywhere: there are no restrictions.
- In typed feature structures, the occurrence of features is limited by the type hierarchy:
  - Each feature is *introduced* on a unique, most general type
  - Only that type and its subtypes can carry that feature
  - Each feature is introduced with a value, and all valid values have to be subsumed by this value.
- These requirements ensure monotonicity in feature structure unification

Parsing with unification-based grammars

- In most implementations, the rules have a context-free backbone, but feature structures in the categories. Information can be shared between the categories in the rule.
- $\begin{bmatrix} \text{CATEGORY} & \textit{noun} \\ \text{SUBCAT} & \langle\rangle \end{bmatrix} \longrightarrow \boxed{1}\begin{bmatrix} \text{CATEGORY} & \textit{det} \end{bmatrix} \begin{bmatrix} \text{CATEGORY} & \textit{noun} \\ \text{SUBCAT} & \langle \boxed{1} \rangle \end{bmatrix}$
- Sometimes the rules are written in a CFG-like format, sometimes feature structures whereby a feature identifies the daughters.

Parsing

- Is there any difference in parsing?
- No. All known techniques can be used, and you will obtain a working parser, provided that you use non-destructive unification.
- *But* it will be (much) slower: the categories are much bigger, and the unification is non-destructive. A lot of copying is done.

Techniques to improve efficiency

- Packing (subsumption packing)
- Rule filter: not all rules can feed into all other rules
- Quick check: some paths are more likely to fail than others
- Sharing and deleting of daughters: do not keep information that can easily be (re)computed or retrieved
- Delayed copying (Tomabechi): only copy when you are sure that it will be used

Subsumption packing

- With CFGs and chart parsing, every category is only stored once for a given pair of indices to avoid recomputation. The criterion is a simple identity/equality check.
- Suppose we have (among others) the following feature structure in the chart:

$$\begin{bmatrix} \text{CAT} & \textit{noun} \\ \text{AGR} & \begin{bmatrix} \text{PER} & \textit{3} \end{bmatrix} \end{bmatrix}$$

Subsumption packing

- After a rule application, we want to add one of the following feature structures:

1. $\begin{bmatrix} \text{CAT} & \textit{noun} \\ \text{AGR} & \begin{bmatrix} \text{PER} & \textit{1} \end{bmatrix} \end{bmatrix}$

2. $\begin{bmatrix} \text{CAT} & \textit{noun} \\ \text{AGR} & \begin{bmatrix} \text{PER} & \textit{3} \\ \text{NUM} & \textit{sg} \end{bmatrix} \end{bmatrix}$

3. $\begin{bmatrix} \text{CAT} & \textit{noun} \\ \text{AGR} & \begin{bmatrix} \text{NUM} & \textit{sg} \end{bmatrix} \end{bmatrix}$

4. $\begin{bmatrix} \text{CAT} & \textit{noun} \\ \text{AGR} & [\,] \end{bmatrix}$

Subsumption packing

- Which one the two should we take?
  - all: too many solutions (spurious ambiguity)
  - the first, most recent, . . . : may give over/undergeneration

    e.g. with (4) a solution with $\begin{bmatrix} \text{CAT} & \textit{noun} \\ \text{AGR} & \begin{bmatrix} \text{PER} & \textit{1} \end{bmatrix} \end{bmatrix}$ is also possible, although that does not correspond with the original situation
  - in general: when the newer category is more specific, using it may invalidate older analyses (which were based on a more general feature structure; see (2)), and vice versa

Subsumption packing

- In CFGs with atomic catgories, we use an equality check
- With feature structures, we want to *be able* to use unification (it is the operation we use in rule applications), but unification should not be used to perform the check.
- A subsumption check will tell us what is the most general feature structure, and that one should be stored in the chart:
  - if new $\sqsubseteq$ old, then the set of solutions from new will be a superset of the set of solutions from old, so replace old by new.
  - if old $\sqsubseteq$ new, then new should be discarded (it is already implied by old)
  - otherwise, add new.

In this way, no solutions are invalidated.

Part III

Other issues

Statistical processing with feature structures

- Applying statistical techniques to feature structures is very hard, mainly because of the presence of reentrancies (Abney, 1997, See e.g.).
- Very often the following technique is applied: simplify the feature structure, even to the type of the root node only. That way, the categories can be made sufficiently simple. Examples: Bouma et al. (2001); Toutanova et al. (2002)

Default unification

- Credulous default unification: the default FS adds as much information as possible that is not conflicting with the strict FS. It is non-deterministic.
- Sceptical default unification: the default FS adds the information that is common between each variant of credulous default unification.
  (Carpenter, 1993)
- Sensitive to order of processing
- Persistent associative default unification (Lascarides et al., 1996)
- Mainly used for lexical specification

Credulous default unification

- $F \overset{<}{\sqcup}_c G = \{F \sqcup G' | G' \sqsubseteq$
  G is maximal such that $F \sqcup G'$ is defined$\}$
- $\begin{bmatrix} \mathrm{F} & a \end{bmatrix} \overset{<}{\sqcup}_c \begin{bmatrix} \mathrm{F} & \boxed{1}\, b \\ \mathrm{G} & \boxed{1} \\ \mathrm{H} & c \end{bmatrix} = \left\{ \begin{bmatrix} \mathrm{F} & a \\ \mathrm{G} & b \\ \mathrm{H} & c \end{bmatrix}, \begin{bmatrix} \mathrm{F} & \boxed{1} a \\ \mathrm{G} & \boxed{1} \\ \mathrm{H} & c \end{bmatrix} \right\}$

Sceptical default unification

- $F \overset{<}{\sqcup}_s G = \sqcap(F \overset{<}{\sqcup}_c G)$
- $\begin{bmatrix} \text{F} & a \end{bmatrix} \overset{<}{\sqcup}_s \begin{bmatrix} \text{F} & \boxed{1}\, b \\ \text{G} & \boxed{1} \\ \text{H} & c \end{bmatrix} = \sqcap\left\{ \begin{bmatrix} \text{F} & a \\ \text{G} & b \\ \text{H} & c \end{bmatrix}, \begin{bmatrix} \text{F} & \boxed{1}\, a \\ \text{G} & \boxed{1} \\ \text{H} & c \end{bmatrix} \right\} = \begin{bmatrix} \text{F} & a \\ \text{G} & \bot \\ \text{H} & c \end{bmatrix}$

Desirable properties of default unification

- Always well-defined
- All strict information is preserved
- If F and G are consistent, it should give the same result as strict unification
- It is finite

Part IV

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