CMPT-413
Computational Linguistics

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Writing a grammar for natural language: Grammar Development

- **Grammar development** is the process of writing a grammar for a particular language
- This can be either for a particular application or concentrating on a particular phenomena in the language under consideration
- Check against text corpora to check the **coverage** of your grammar – to do this you need a parser
- Also consider generalizations provided by a linguistic analysis

Real Grammars get Messy

- Consider the grammar development using CFGs for the ATIS Corpus
- To capture all the morphological details which affect the syntax, the CFG ends up with rules like:

$$
\begin{aligned}
S &\rightarrow \textit{3sgAux 3sgNP VP} \\
S &\rightarrow \textit{Non3sgAux Non3sgNP VP} \\
\textit{3sgAux} &\rightarrow \textit{does} \mid \textit{has} \mid \textit{can} \mid \ldots \\
\textit{Non3sgAux} &\rightarrow \textit{do} \mid \textit{have} \mid \textit{can} \mid \ldots
\end{aligned}
$$

Real Grammars get Messy

- This is to deal with sentences like:
  1. Do I get dinner on this flight ? (1sg = 1st person singular)
  2. Do you have a flight from Boston to Fort Worth ? (2sg = 2nd person singular)
  3. Does he visit Toronto ? (3sg = 3rd person singular)
  4. Does Delta fly from Atlanta to San Diego ? (3sg = 3rd person singular)
  5. Do they visit Toronto ? (3pl = 3rd person plural)

Real Grammars get Messy

- Not just grammatical features but also subcategorization (what kind of arguments does a verb expect?):

VP	→	*Verb-with-NP-complement NP*	"prefer a morning flight"
VP	→	*Verb-with-S-complement S*	"said there were two flights"
VP	→	*Verb-with-Inf-VP-complement VPinf*	"try to book a flight"
VP	→	*Verb-with-no-complement*	"disappear"

Solution to non-terminal and rule blowup: Feature Structures

- **Feature structures** provide a natural way to provide complex information with each non-terminal. In some formalisms, the non-terminal is replaced with feature structures, resulting in a potentially infinite set of non-terminals.
- Feature structures are also known as f-structures, feature bundles, feature matrices, functional structures, terms (as in Prolog), or dags (directed acyclic graphs)

Feature Structures

- A *feature structure* is defined as a partial function from features to their values.
- For instance, we can define a function mapping the feature *number* onto the value *singular* and mapping *person* to *third*. The common notation for this function is:

$$\begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix}$$

Feature Structures

- Feature values can themselves be feature structures:

$$\begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \end{bmatrix}$$

Feature Structures

- Consider features *f* and *g* with two distinct feature structure values of the same type:

$$\begin{bmatrix} \text{f}: \begin{bmatrix} \text{h}: \text{a} \end{bmatrix} \\ \text{g}: \begin{bmatrix} \text{h}: \text{a} \end{bmatrix} \end{bmatrix}$$

Feature Structures

- Feature structures can also share values. For instance, *g* shares the same value as *f* in:

$$\begin{bmatrix} \text{f: } \boxed{1}\begin{bmatrix}\text{h: a}\end{bmatrix} \\ \text{g: } \boxed{1} \end{bmatrix}$$

- The shared value is written using a co-indexation – indicating that the value is stored only once, with the index acting as a pointer.

Feature Path Notation

- The feature structure:

$$\begin{bmatrix} \text{agreement:} & \boxed{1}\begin{bmatrix} \text{number: sg} \\ \text{person: 3} \end{bmatrix} \\ \text{subject:} & \begin{bmatrix} \text{agreement: } \boxed{1} \end{bmatrix} \end{bmatrix}$$

is represented as:

```
<agreement number>=sg
<agreement person>=3
<subject agreement>=<agreement>
```

or:

```
[ agreement = (1) [ number = 'sg', person = 3 ],
subject = [ agreement->(1) ] ]
```

or:

```
[ agreement = ?n [ number = 'sg', person = 3 ],
subject = [ agreement = ?n ] ]
```

Subsumption

- Feature structures have different amounts of information. Can we find an ordering on feature structures that corresponds to the compatibility and relative specificity of the information contained in them.
- **Subsumption** is a precise method of defining such an ordering over feature structures.

Subsumption

- Consider the feature structure:

$$D_{np} = \begin{bmatrix} \text{cat: NP} \end{bmatrix}$$

- Compare with the feature structure:

$$D_{np3sg} = \begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \end{bmatrix}$$

Subsumption

- D_{np} makes the claim that a phrase is a noun phrase, but leaves open the question of what the agreement properties of this noun phrase are.
- D_{np3sg} also contains information about a noun phrase, but makes the agreement properties specific.
- The feature structure D_{np} is said to carry *less information* than, or to be *more general* than, or to *subsume* the feature structure D_{np3sg}

Subsumption

- $D_{var} = []$
- $D_{np} = \begin{bmatrix} \text{cat: NP} \end{bmatrix}$
- $D_{npsg} = \begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \begin{bmatrix} \text{number: singular} \end{bmatrix} \end{bmatrix}$
- $D_{np3sg} = \begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \end{bmatrix}$
- $D_{np3sgSbj} = \begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \\ \text{subject: } \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \end{bmatrix}$
- $D'_{np3sgSbj} = \begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \boxed{1} \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \\ \text{subject: } \boxed{1} \end{bmatrix}$
- The following subsumption relations hold:
  $D_{var} \sqsubseteq D_{np} \sqsubseteq D_{npsg} \sqsubseteq D_{np3sg} \sqsubseteq D_{np3sgSbj} \sqsubseteq D'_{np3sgSbj}$

Unification

- Two feature structures might have different and incompatible information:

$$\begin{bmatrix} \text{cat: NP} \\ \text{agreement:} \begin{bmatrix} \text{number: singular} \end{bmatrix} \end{bmatrix}$$

$$\begin{bmatrix} \text{cat: NP} \\ \text{agreement:} \begin{bmatrix} \text{number: plural} \end{bmatrix} \end{bmatrix}$$

- In this case, there is no feature structure that is subsumed by both feature structures

Unification

- Subsumption is only a partial order – that is, not every two feature structures are in a subsumption relation with each other.
- Two feature structures might have different but compatible information:

$$\begin{bmatrix} \text{cat: NP} \\ \text{agreement:} \begin{bmatrix} \text{number: singular} \end{bmatrix} \end{bmatrix}$$

$$\begin{bmatrix} \text{cat: NP} \\ \text{agreement:} \begin{bmatrix} \text{person: 3} \end{bmatrix} \end{bmatrix}$$

Unification

- If two feature structures have different but compatible information then there always exists a more specific feature structure that is subsumed by both feature structures:

$$\begin{bmatrix} \text{cat: NP} \\ \text{agreement: } \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \end{bmatrix} \end{bmatrix}$$

Unification

- But there are many feature structures subsumed by both of the original feature structures:

$$\begin{bmatrix} \text{cat: NP} & \\ \text{agreement:} & \begin{bmatrix} \text{number: singular} \\ \text{person: 3} \\ \text{gender: masculine} \end{bmatrix} \end{bmatrix}$$

- So instead of considering all such feature structures we only consider the most general FS that is subsumed by the two original FSs
- This definition provides a feature structure that contains information from both input FSs but no additional information.

Unification

- Now we can define **unification**
- The *unification* of two feature structures D' and D" is defined as the most general feature structure D such that D' $\sqsubseteq$ D and D" $\sqsubseteq$ D.
- This operation of unification is denoted as D = D' $\sqcup$ D"

Unification

$$[] \sqcup \begin{bmatrix} \text{cat: NP} \end{bmatrix} = \begin{bmatrix} \text{cat: NP} \end{bmatrix}$$

Unification

$$\begin{bmatrix}\text{person: sg}\end{bmatrix} \sqcup \begin{bmatrix}\text{number: 3}\end{bmatrix} = \begin{bmatrix}\text{person: sg} \\ \text{number: 3}\end{bmatrix}$$

Unification

$$\begin{bmatrix} \text{agreement}: \begin{bmatrix} \text{number}: \text{sg} \end{bmatrix} \\ \text{subject}: \begin{bmatrix} \text{agreement}: \begin{bmatrix} \text{number}: \text{sg} \end{bmatrix} \end{bmatrix} \end{bmatrix} \sqcup$$

$$\begin{bmatrix} \text{subject}: \begin{bmatrix} \text{agreement}: \begin{bmatrix} \text{person}: 3 \end{bmatrix} \end{bmatrix} \end{bmatrix} =$$

$$\begin{bmatrix} \text{agreement}: \begin{bmatrix} \text{number}: \text{sg} \end{bmatrix} \\ \text{subject}: \begin{bmatrix} \text{agreement}: \begin{bmatrix} \text{number}: \text{sg} \\ \text{person}: 3 \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Unification

$$\begin{bmatrix} \text{agreement: } \boxed{1}\begin{bmatrix}\text{number: sg}\end{bmatrix} \\ \text{subject: } \begin{bmatrix}\text{agreement: } \boxed{1}\end{bmatrix} \end{bmatrix} \sqcup \begin{bmatrix}\text{subject: } \begin{bmatrix}\text{agreement: } \begin{bmatrix}\text{person: 3}\end{bmatrix}\end{bmatrix}\end{bmatrix} =$$

$$\begin{bmatrix} \text{agreement: } \boxed{1}\begin{bmatrix}\text{number: sg} \\ \text{person: 3}\end{bmatrix} \\ \text{subject: } \begin{bmatrix}\text{agreement: } \boxed{1}\end{bmatrix} \end{bmatrix}$$

Algorithms for Unification

- Represent input feature structure as a directed acyclic graph (dag). Unification is equivalent to the **union-find** algorithm.
- Unification is more efficient if it can be destructive: it destroys the input feature structures to create the result of unification.
- The (destructive) unification algorithm in J&M (page 423) does it in two steps: represent feature structures as dags, and then perform graph matching (and merging)
- Note that this algorithm can produce as output a dag (i.e. a feature structure) containing cycles.
  A feature structure can have part of itself as a subpart:
  $$\left[\text{f: } \boxed{1}\left[\text{g: }\left[\text{h: } \boxed{1}\right]\right]\right]$$
- This can be avoided with an explicit check for each call to the `unify` algorithm called the **occur check**.
- Computationally expensive since we have to traverse the whole dag at each step

Feature Structures in CFGs

- Feature Structures impose constraints on CFG derivations:

$$
\begin{array}{lcl}
S & \rightarrow & NP\left[\text{case: nominative}\right]\ VP \\
VP & \rightarrow & V\ NP\left[\text{case: accusative}\right] \\
V & \rightarrow & saw \\
NP\left[\text{case: } \boxed{1}\right] & \rightarrow & he\left[\text{case: } \boxed{1} \text{ nominative}\right] \\
NP\left[\text{case: } \boxed{1}\right] & \rightarrow & him\left[\text{case: } \boxed{1} \text{ accusative}\right] \\
NP\left[\text{case: } \boxed{1}\right] & \rightarrow & John\left[\text{case: } \boxed{1} \text{ nominative} \mid \text{accusative}\right]
\end{array}
$$

- This CFG derives: *he saw him* but not: $*$*him saw he*
- Also derives: *John saw him*, *he saw John*.
- Co-indexing in each FS is local to each CFG rule.

Feature Structures in CFGs

- A more complex example for encoding subcategorization as feature structures:

$$S \rightarrow NP\ VP \begin{bmatrix} \text{subcat: } \boxed{1} \begin{bmatrix} \text{first: } [] \\ \text{rest: end} \end{bmatrix} \end{bmatrix}$$

$$VP \begin{bmatrix} \text{subcat: } \boxed{1} \end{bmatrix} \rightarrow Verb \begin{bmatrix} \text{subcat: } \boxed{1} \end{bmatrix}$$

$$VP \begin{bmatrix} \text{subcat: } \boxed{1} \end{bmatrix} \rightarrow VP \begin{bmatrix} \text{subcat: } \begin{bmatrix} \text{first: } \boxed{2} \\ \text{rest: } \boxed{1} \end{bmatrix} \end{bmatrix} X \begin{bmatrix} \text{cat: } \boxed{2}\ \text{NP} \end{bmatrix}$$

Feature Structures in CFGs

- In the above example, the CFG can generate an arbitrary number of NPs in the subcat feature structure for the verb.
- In effect, the above steps of unification in a CFG derivation creates a list containing the subcat elements. The subcat feature structure uses **first** and **rest** to construct the list in the recursive rule $VP \rightarrow VP\ X$.
- The lexical terminal *Verb* can impose a constraint on which subcat frame is required.
- Other categories can be added simply by adding a new *cat* attribute for X: e.g. $\begin{bmatrix}\text{cat: S}\end{bmatrix}$ for verbs that can have a subcat of $NP\ S$.

Unification Algorithm

```
function unify(f1, f2):
  returns f-structure or failure

  if f1.content == null: f1.pointer = f2
  if f2.content == null: f2.pointer = f1
  if f1.content == f2.content: f1.pointer = f2
  if f1.content and f2.content are complex f-structures:
      f2.pointer = f1
      for each f in f2.content:
          other-feature = find or create feature
              corresponding to f in f1.content
          if unify(f, other-feature) == failure:
              return failure
   return f1
```

Unification in Earley Parsing

- predictor: if $(A \rightarrow \alpha \bullet B\ \beta, [i,j], \mathrm{dag}_{A_1})$ then $\forall (B \rightarrow \gamma, \mathrm{dag}_{B_1})$ enqueue$((B \rightarrow \bullet\gamma, [j,j], \mathrm{dag}_{B_1})$, chart[$j$])
- scanner: if $(A \rightarrow \alpha \bullet a\ \beta, [i,j], \mathrm{dag}_{A_1})$ and $a = \mathrm{tokens}[j]$ then enqueue$((A \rightarrow \alpha a \bullet\ \beta, [i,j+1], \mathrm{dag}_{A_1})$, chart[$j+1$])
- completer: if $(B \rightarrow \gamma\bullet, [j,k], \mathrm{dag}_{B_1})$, for each $(A \rightarrow \alpha \bullet B\ \beta, [i,j], \mathrm{dag}_{A_1})$ enqueue$((A \rightarrow \alpha\ B\ \bullet \gamma, [i,k],$ copy-and-unify$(\mathrm{dag}_{A_1}, \mathrm{dag}_{B_1}))$, chart[$k$]) unless copy-and-unify$(\mathrm{dag}_{A_1}, \mathrm{dag}_{B_1})$ fails
- copy-and-unify means that we make copies of the dags before unification because we are using a destructive unification algorithm
- copy-and-unify ensures that dag A_1 in state $(A \rightarrow \alpha \bullet B\ \beta, [i,j], \mathrm{dag}_{A_1})$ is not destroyed since it can be used in the completer with other states and unify with them.

Unification in Earley Parsing

- Consider two different enqueue requests:
  enqueue($(A \rightarrow \alpha\ B\ \bullet\ \gamma, [i,k], \mathrm{dag}_{A_1})$, chart[$k$])
  enqueue($(A \rightarrow \alpha\ B\ \bullet\ \gamma, [i,k], \mathrm{dag}_{A_2})$, chart[$k$])
- Consider the case where:
  $\mathrm{dag}_{A_1} = \left[\text{tense: past} \mid \text{plural}\right]$ and
  $\mathrm{dag}_{A_2} = \left[\text{tense: past}\right]$
  Clearly, $\mathrm{dag}_{A_1} \sqsubseteq \mathrm{dag}_{A_2}$

Unification in Earley Parsing

- Which feature structure should be selected after the two enqueue commands above?
  Three options: $\mathrm{dag}_{A_1}, \mathrm{dag}_{A_2}, \mathrm{dag}_{A_1} \sqcup \mathrm{dag}_{A_2}$
- In general, the feature inserted should subsume both dag_{A_1} and dag_{A_2}
- In practice exactly one of the following conditions is always true:
  - If $\mathrm{dag}_{A_1} \sqsubseteq \mathrm{dag}_{A_2}$ then enqueue picks dag_{A_1},
  - If $\mathrm{dag}_{A_2} \sqsubseteq \mathrm{dag}_{A_1}$ then enqueue picks dag_{A_2}.
  - If $\mathrm{dag}_{A_1} \not\sqsubseteq \mathrm{dag}_{A_2}$ and $\mathrm{dag}_{A_2} \not\sqsubseteq \mathrm{dag}_{A_1}$ then enqueue picks $\mathrm{dag}_{A_1} \sqcup \mathrm{dag}_{A_2}$

Unification in Earley Parsing

- During the enqueue of a state, we always pick the most general feature structure possible.
- To see why consider an example:
  - Consider a chart which contains the state:
    $S_1 = (NP \rightarrow \bullet\ DT\ NP, [i, i], dag_{S_1} = [])$
  - The parser then tries to enqueue a new state:
    $S_2 = (NP \rightarrow \bullet\ DT\ NP, [i, i], dag_{S_2} = \left[\text{DT.num} = \text{sing}\right])$
  - Consider two possible situations:
    1. a singular DT is scanned, then either dag_{S_1} or dag_{S_2} would unify and parsing would continue.
    2. a plural DT is scanned, then if we picked dag_{S_2} we have a unification failure; on the other hand picking the more general feature structure dag_{S_1} allows parsing to continue.
- So, if there are two possible ways to derive a span, then the most general feature structure is the one we must choose.

Summary

- Feature structures generalize the notion of non-terminals in a grammar.
- Complex morphological details can be encoded into a feature structure.
- Feature structures can have shared or co-referential parts.
- Feature structures can implement arbitrary lists (the notation is very computationally powerful).
- Unification provides a means to combine the information in two feature structures.
- Feature structures can be used in a context-free grammar, and
- Unification is done while parsing to ensure that the constraints specified in the features are not violated.