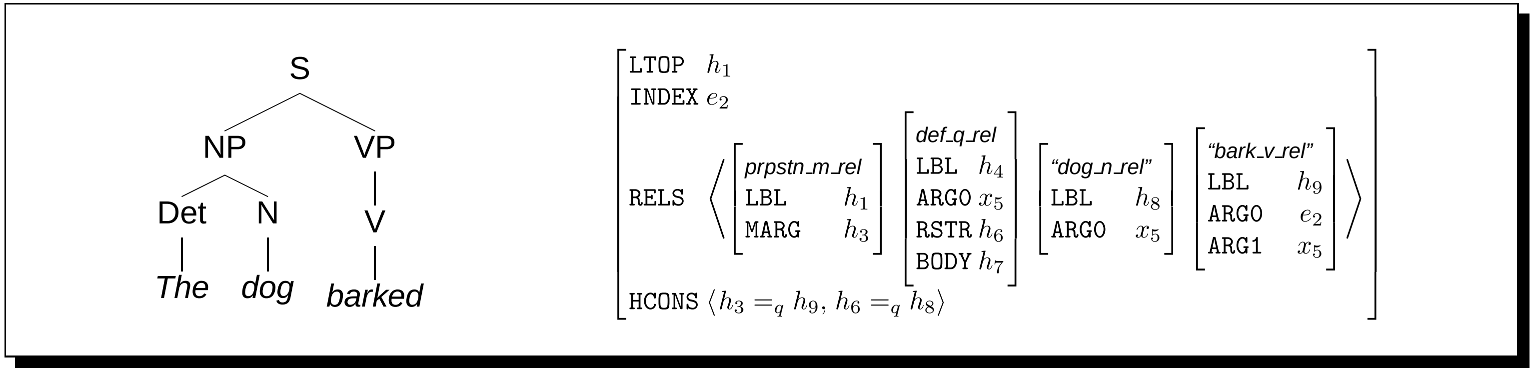
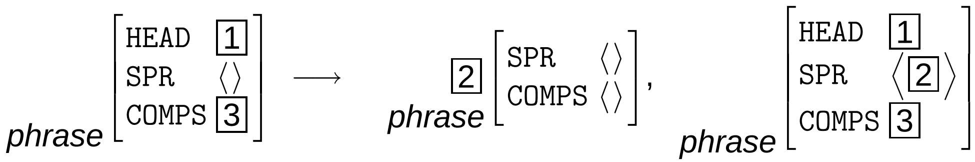



# Computational Linguistics (INF2820 — TFSs)

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# Limitations of (Our) Context-Free Grammars

**Agreement and Valency (For Example)**

*That dog barks.*

**That dogs barks.*

**Those dogs barks.*

*The dog chased a cat.*

**The dog barked a cat.*

**The dog chased.*

**The dog chased a cat my neighbours.*

*The cat was chased by a dog.*

**The cat was chased of a dog.*

...

# A Really Complicated Language

[...] *omdat ik Jan Henk de nijlpaarden zag helpen voeren .*

# More Terminology: Grammatical Functions

**Licensing — Government — Agreement**

*The dog barks.* — **The dog a cat barks* — **The dog barks a cat.*

*Kim depends on Sandy* — **Kim depends in Sandy*

*The class meets on Thursday in 508 at 12:15.*

- **Constituent** node in analysis tree (terminal or instantiation of rule);
- **Head** licenses additional constituents and can govern their form;
- **Specifier** precedes head, singleton, nominative case, agreement;
- **Complement** post-head, licensed and governed, order constraints;
- **Adjunct** 'free' modifier, optional, may iterate, designated position;
- **Government** directed: a property of $c_1$ determines the form of $c_2$;
- **Agreement** bi-directional: co-occurence of properties on $c_1$ and $c_2$.

# An Ambiguous Example

*Kim shoveled snow on lifts.*

# A Highly Ambiguous Example

*The manager placed his bid on my desk.*

# Structured Categories in a Unification Grammar

- All (constituent) categories in the grammar are typed feature structures;
- specific TFS configurations may correspond to ‘traditional’ categories;

→ labels like ‘S’ or ‘NP’ are mere abbreviations, not elements of the theory.

$$\mathit{word}\begin{bmatrix} \texttt{HEAD} & \mathit{noun} \\ \texttt{SPR} & \left\langle \begin{bmatrix} \texttt{HEAD}\ \mathit{det} \end{bmatrix} \right\rangle \\ \texttt{COMPS} & \langle\rangle \end{bmatrix} \qquad \mathit{phrase}\begin{bmatrix} \texttt{HEAD} & \mathit{verb} \\ \texttt{SPR} & \langle\rangle \\ \texttt{COMPS} & \langle\rangle \end{bmatrix} \qquad \mathit{phrase}\begin{bmatrix} \texttt{HEAD} & \mathit{verb} \\ \texttt{SPR} & \left\langle \begin{bmatrix} \texttt{HEAD}\ \mathit{noun} \end{bmatrix} \right\rangle \\ \texttt{COMPS} & \langle\rangle \end{bmatrix}$$

| ‘N’ | ‘S’ | ‘VP’ |
|---|---|---|
| **‘lexical’** | **‘maximal’** | **‘intermediate’** |

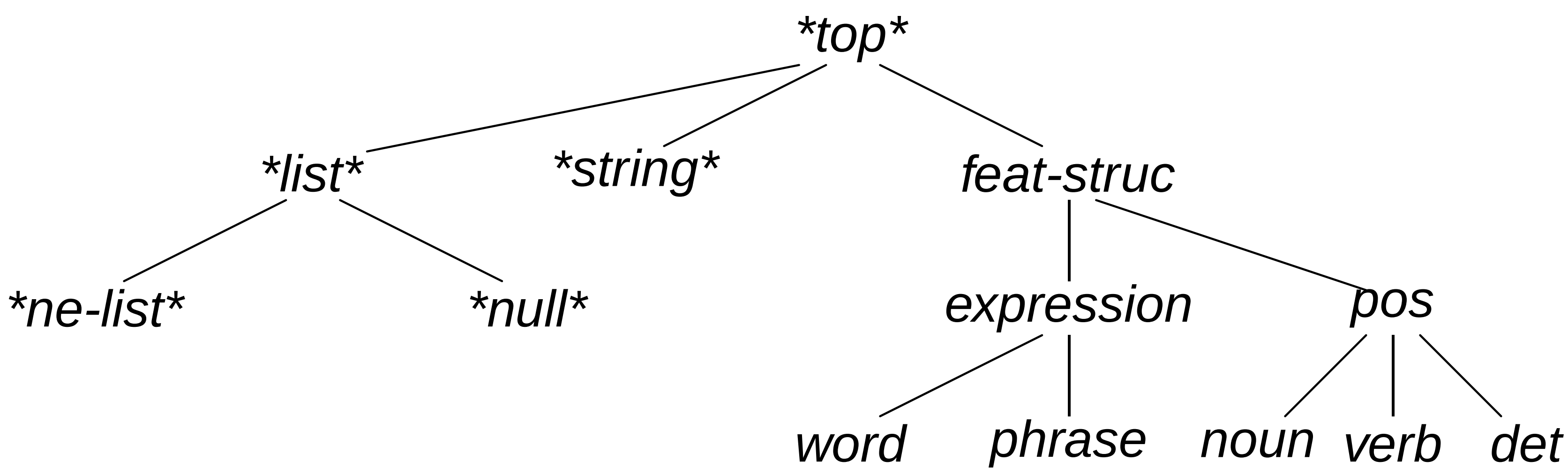
# Interaction of Lexicon and Phrase Structure Schemata

$$\begin{bmatrix} \mathtt{HEAD} & \boxed{1} \\ \mathtt{SPR} & \langle\rangle \\ \mathtt{COMPS} & \boxed{3} \end{bmatrix} \longrightarrow \boxed{2}\begin{bmatrix} \mathtt{SPR} & \langle\rangle \\ \mathtt{COMPS} & \langle\rangle \end{bmatrix}, \begin{bmatrix} \mathtt{HEAD} & \boxed{1} \\ \mathtt{SPR} & \langle\boxed{2}\rangle \\ \mathtt{COMPS} & \boxed{3} \end{bmatrix}$$

$$\begin{bmatrix} \mathtt{ORTH} & \textit{“Kim”} \\ \mathtt{HEAD} & \textit{noun} \\ \mathtt{SPR} & \langle\rangle \\ \mathtt{COMPS} & \langle\rangle \end{bmatrix} \qquad \begin{bmatrix} \mathtt{ORTH} & \textit{“sleeps”} \\ \mathtt{HEAD} & \textit{verb} \\ \mathtt{SPR} & \left\langle \begin{bmatrix} \mathtt{HEAD} & \textit{noun} \\ \mathtt{SPR} & \langle\rangle \\ \mathtt{COMPS} & \langle\rangle \end{bmatrix} \right\rangle \\ \mathtt{COMPS} & \langle\rangle \end{bmatrix}$$

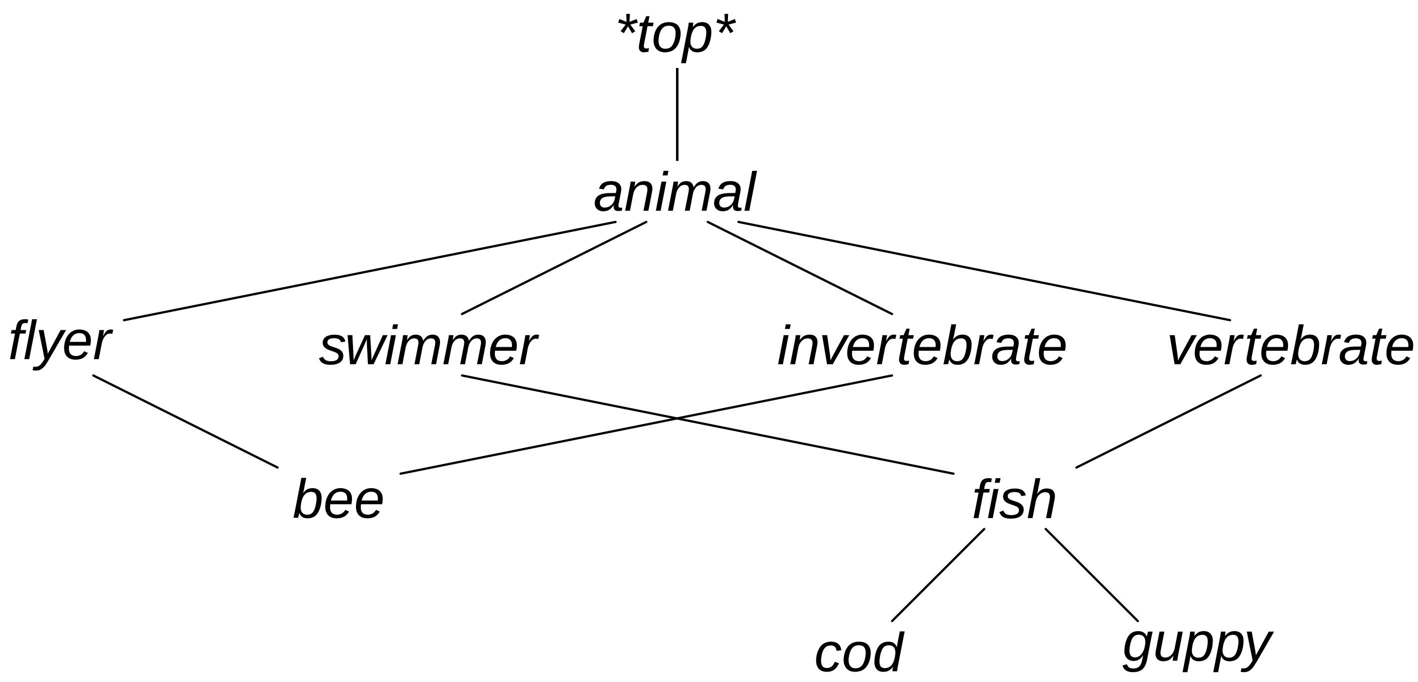
# The Type Hierarchy: Fundamentals

- Types 'represent' groups of entities with similar properties ('classes');
- types ordered by specificity: subtypes inherit properties of (all) parents;
- type hierarchy determines which types are compatible (and which not).



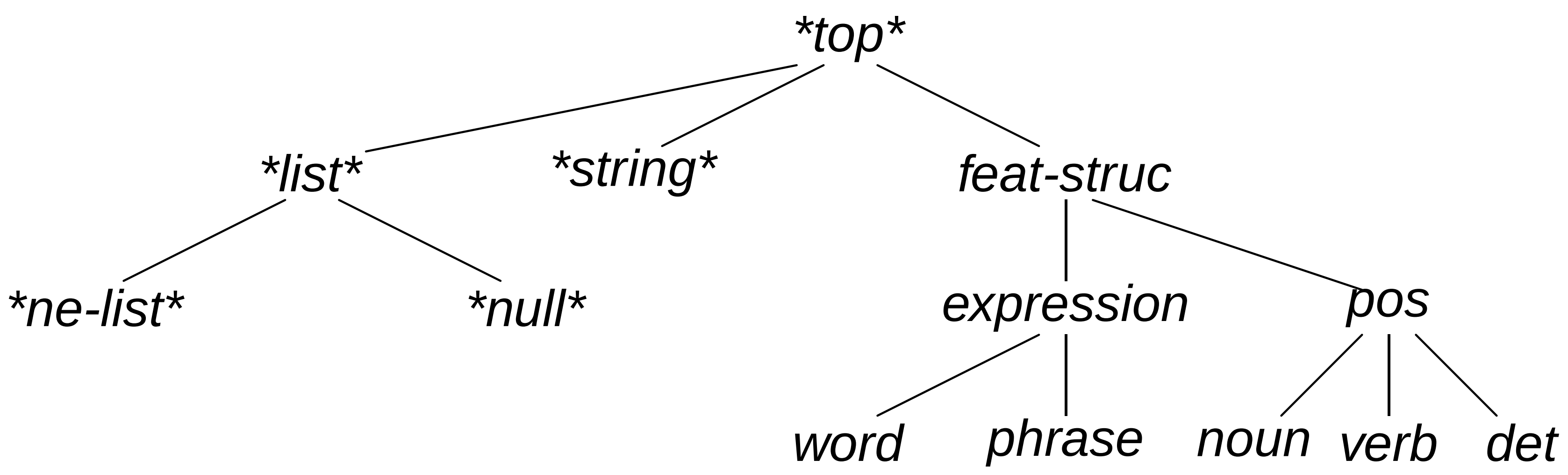
# Multiple Inheritance

- *flyer* and *swimmer* no common descendants: they are incompatible;
- *flyer* and *bee* stand in hierarchical relationship: they unify to subtype;
- *flyer* and *invertebrate* have a unique greatest common descendant.



# The Type Hierarchy — Appropriate Features

- Features record properties of entities; in turn, feature values are TFSs;
- features are defined by a unique most general type: appropriateness;
- feature values constrained to a specific type → monotonic inheritance.



# Typed Feature Structure Subsumption

- Typed feature structures can be partially ordered by information content;
- a more general structure is said to *subsume* a more specific one;
- **top**$\left[\ \right]$ is the most general feature structure (while $\perp$ is inconsistent);
- $\sqsubseteq$ ('square subset or equal') conventionally used to depict subsumption.

Feature structure $F$ subsumes feature structure $G$ ($F \sqsubseteq G$) iff: (1) if path $p$ is defined in $F$ then $p$ is also defined in $G$ and the type of the value of $p$ in $F$ is a supertype or equal to the type of the value of $p$ in $G$, and (2) all paths that are reentrant in $F$ are also reentrant in $G$.

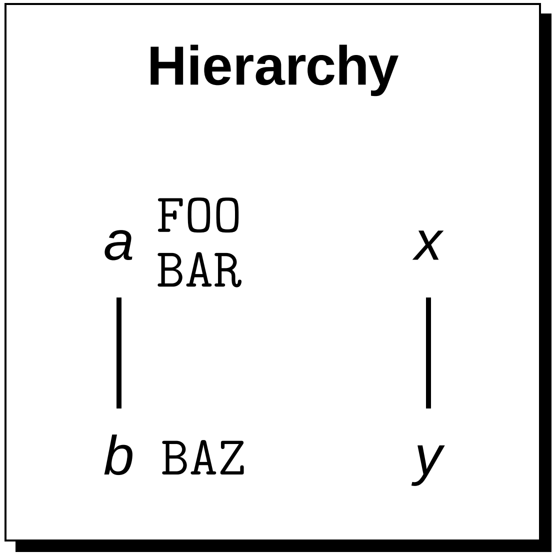
# Feature Structure Subsumption: Examples

TFS$_1$: $a\begin{bmatrix}\text{FOO } x\\ \text{BAR } x\end{bmatrix}$

TFS$_2$: $a\begin{bmatrix}\text{FOO } x\\ \text{BAR } y\end{bmatrix}$

TFS$_3$: $b\begin{bmatrix}\text{FOO } y\\ \text{BAR } x\\ \text{BAZ } x\end{bmatrix}$

TFS$_4$: $a\begin{bmatrix}\text{FOO } \boxed{1}\, x\\ \text{BAR } \boxed{1}\end{bmatrix}$




Feature structure $F$ subsumes feature structure $G$ ($F \sqsubseteq G$) iff: (1) if path $p$ is defined in $F$ then $p$ is also defined in $G$ and the type of the value of $p$ in $F$ is a supertype or equal to the type of the value of $p$ in $G$, and (2) all paths that are reentrant in $F$ are also reentrant in $G$.

# Typed Feature Structure Unification

- Decide whether two typed feature structures are mutually compatible;
- determine combination of two TFSs to give the most general feature structure which retains all information which they individually contain;
- if there is no such feature structure, unification fails (depicted as $\perp$);
- unification *monotonically* combines information from both 'input' TFSs;
- *relation to subsumption* the unification of two structures $F$ and $G$ is the most general TFS which is subsumed by both $F$ and $G$ (if it exists).
- $\sqcap$ ('square set intersection') conventionally used to depict unification.

# Typed Feature Structure Unification: Examples

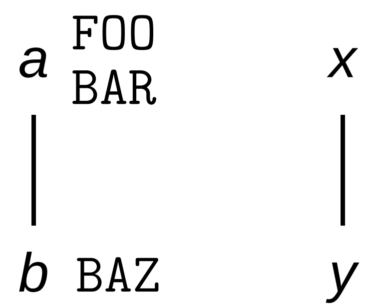
TFS$_1$: $a\begin{bmatrix}\text{FOO } x \\ \text{BAR } x\end{bmatrix}$

TFS$_2$: $a\begin{bmatrix}\text{FOO } x \\ \text{BAR } y\end{bmatrix}$

TFS$_3$: $b\begin{bmatrix}\text{FOO } y \\ \text{BAR } x \\ \text{BAZ } x\end{bmatrix}$

TFS$_4$: $a\begin{bmatrix}\text{FOO } \boxed{1} x \\ \text{BAR } \boxed{1}\end{bmatrix}$

**Hierarchy**




$\text{TFS}_1 \sqcap \text{TFS}_2 \equiv \text{TFS}_2$ $\quad$ $\text{TFS}_1 \sqcap \text{TFS}_3 \equiv \text{TFS}_3$ $\quad$ $\text{TFS}_3 \sqcap \text{TFS}_4 \equiv b\begin{bmatrix}\text{FOO } \boxed{1} y \\ \text{BAR } \boxed{1} \\ \text{BAZ } x\end{bmatrix}$

# Type Constraints and Appropriate Features

- Well-formed TFSs satisfy all *type constraints* from the type hierarchy;
- type constraints are typed feature structures associated with a type;
- the top-level features of a type constraint are *appropriate features*;
- type constraints express generalizations over a ‘class’ (set) of objects.

| **type** | **constraint** | **appropriate features** |
|---|---|---|
| **ne-list** | $\textit{*ne-list*}\begin{bmatrix}\texttt{FIRST} & \textit{*top*} \\ \texttt{REST} & \textit{*list*}\end{bmatrix}$ | FIRST and REST |

# More Interesting Well-Formed Unification

**Type Constraints Associated to *animal* Hierarchy**

$$\textit{swimmer} \rightarrow {}_{\textit{swimmer}}\left[\texttt{FINS}\ \textit{bool}\right] \qquad \textit{mammal} \rightarrow {}_{\textit{mammal}}\left[\texttt{FRIENDLY}\ \textit{bool}\right]$$

$$\textit{whale} \rightarrow {}_{\textit{whale}}\begin{bmatrix}\texttt{BALEEN} & \textit{bool}\\ \texttt{FINS} & \textit{true}\\ \texttt{FRIENDLY} & \textit{bool}\end{bmatrix}$$

$${}_{\textit{mammal}}\left[\texttt{FRIENDLY}\ \textit{true}\right] \sqcap {}_{\textit{swimmer}}\left[\texttt{FINS}\ \textit{bool}\right] \equiv {}_{\textit{whale}}\begin{bmatrix}\texttt{BALEEN} & \textit{bool}\\ \texttt{FINS} & \textit{true}\\ \texttt{FRIENDLY} & \textit{true}\end{bmatrix}$$

$${}_{\textit{mammal}}\left[\texttt{FRIENDLY}\ \textit{true}\right] \sqcap {}_{\textit{swimmer}}\left[\texttt{FINS}\ \textit{false}\right] \equiv \bot$$

# Recursion in the Type Hierarchy

- Type hierarchy must be finite *after* type inference; illegal type constraint:

```
*list* := *top* & [ FIRST *top*, REST *list* ].
```

- needs additional provision for empty lists; indirect recursion:

```
*list* := *top*.
*ne-list* := *list* & [ FIRST *top*, REST *list* ].
*null* := *list*.
```

- recursive types allow for *parameterized list types* ('list of X'):

```
*s-list* := *list*.
*s-ne-list* := *ne-list* & *s-list &
               [ FIRST expression, REST *s-list* ].
*s-null* := *null* & *s-list*.
```

# Notational Conventions

- lists not available as built-in data type; abbreviatory notation in TDL:

```
< a, b > ≡ [ FIRST a, REST [ FIRST b, REST *null* ] ]
```

- underspecified (variable-length) list:

```
< a, ... > ≡ [ FIRST a, REST *list* ]
```

- difference (open-ended) lists; allow concatenation by unification:

```
<! a !> ≡ [ LIST [ FIRST a, REST #tail ], LAST #tail ]
```

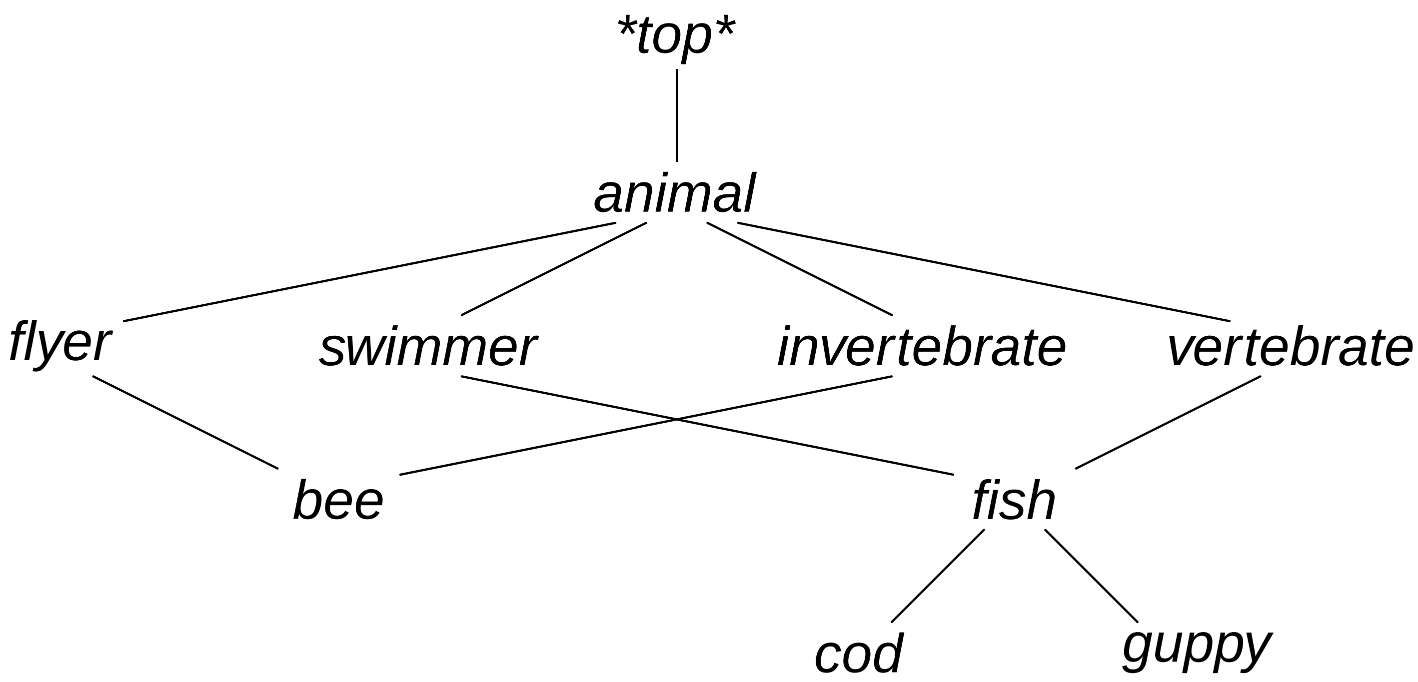
- built-in and ‘non-linguistic’ types pre- and suffixed by asterisk (**top**);
- strings (e.g. *“chased”*) need no declaration; always subtypes of **string**;
- strings cannot have subtypes and are (thus) mutually incompatible.

# Properties of (Our) Type Hierarchies

- **Unique Top** a single hierarchy of all types with a unique top node;
- **No Cycles** no path through the hierarchy from one type to itself;
- **Unique Greatest Lower Bounds** Any two types in the hierarchy are either (a) incompatible (i.e. share no descendants) or (b) have a unique most general ('highest') descendant (called their greatest lower bound);
- **Closed World** all types that exist have a known position in hierarchy;
- **Compatibility** type compatibility in the hierarchy determines feature structure unifiability: two types unify to their greatest lower bound.

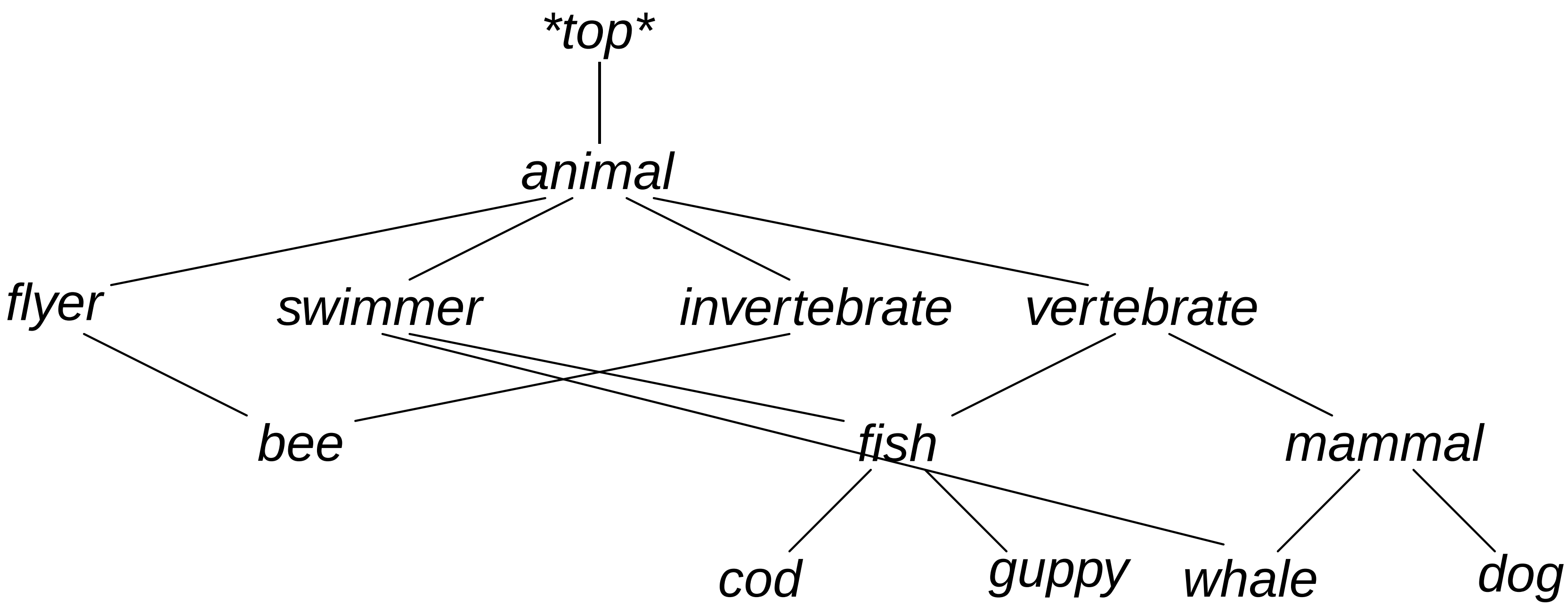
# Multiple Inheritance (Repeated for Convenience)

- *flyer* and *swimmer* no common descendants: they are incompatible;
- *flyer* and *bee* stand in hierarchical relationship: they unify to subtype;
- *flyer* and *invertebrate* have a unique greatest common descendant.



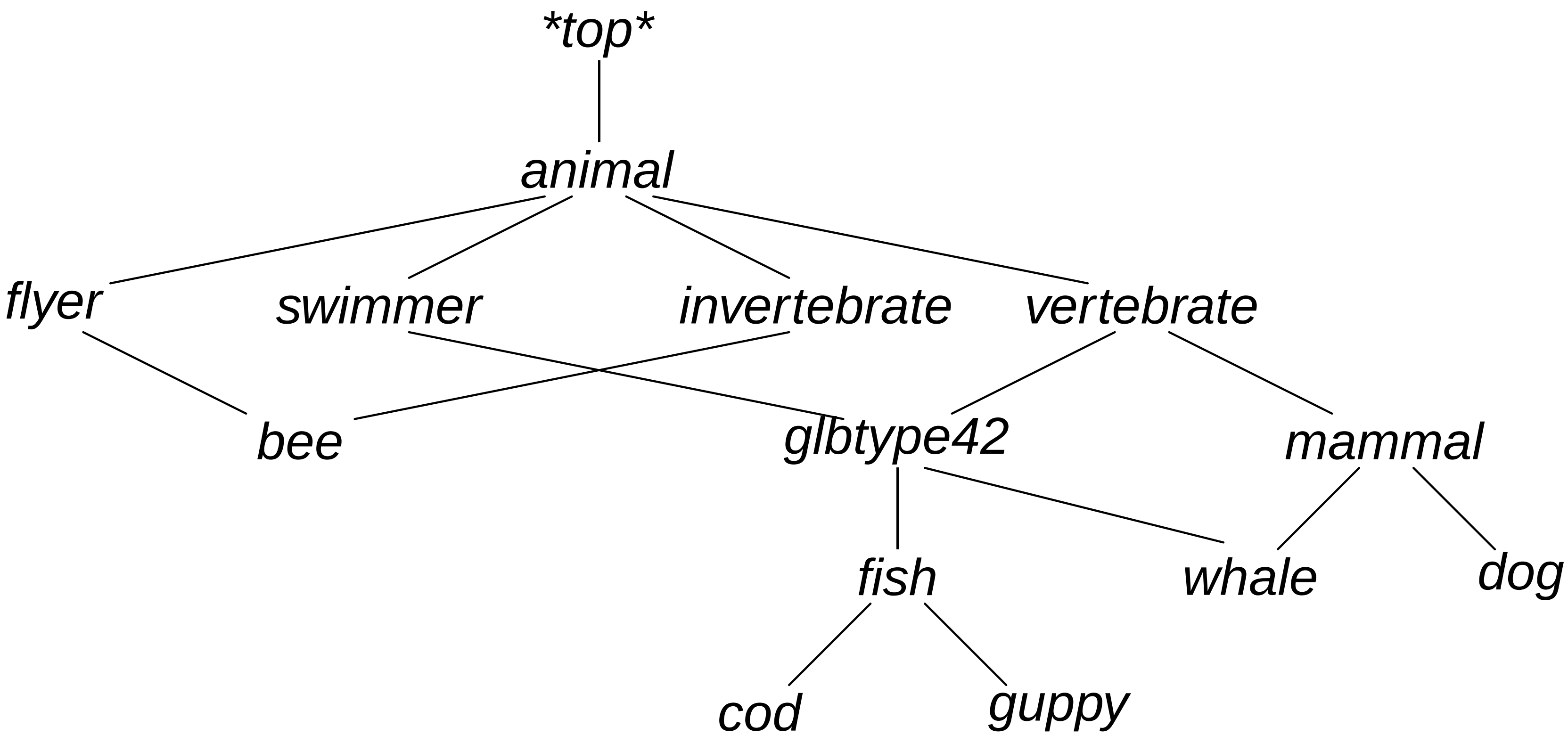
# An Invalid Type Hierarchy

- *swimmer* and *vertebrate* have two joint descendants: *fish* and *whale*;
- *fish* and *whale* are incomparable in the hierarchy: glb condition violated.



# Fixing the Type Hierarchy

- LKB system introduces *glb types* as required: '*swimmer-vertebrate*'.



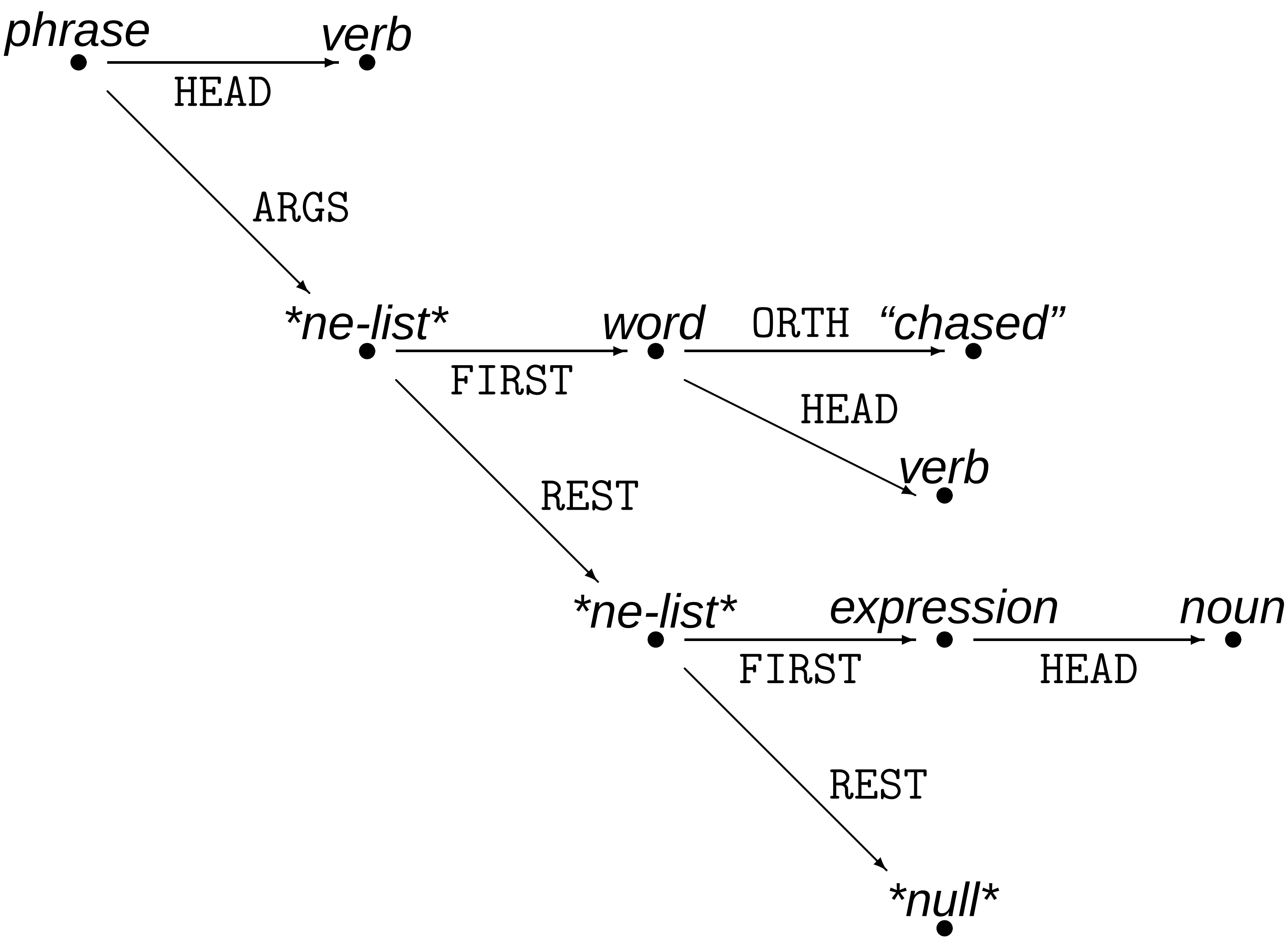
# Properties of (Our) Typed Feature Structures

- **Finiteness** a typed feature structure has a finite number of nodes;
- **Unique Root and Connectedness** a typed feature structure has a unique root node; apart from the root, all nodes have at least one parent;
- **No Cycles** no node has an arc that points back to the root node or to another node that intervenes between the node itself and the root;
- **Unique Features** any node can have any (finite) number of outgoing arcs, but the arc labels (i.e. features) must be unique within each node;
- **Typing** each node has single type which is defined in the hierarchy.

# Typed Feature Structure Example (as AVM)

$$
\textit{phrase}\begin{bmatrix}
\texttt{HEAD}\ \textit{verb} \\
\texttt{ARGS}\ \textit{*ne-list*}\begin{bmatrix}
\texttt{FIRST}\ \textit{word}\begin{bmatrix}\texttt{ORTH}\ \textit{“chased”} \\ \texttt{HEAD}\ \textit{verb}\end{bmatrix} \\
\texttt{REST}\ \textit{*ne-list*}\begin{bmatrix}
\texttt{FIRST}\ \textit{expression}\begin{bmatrix}\texttt{HEAD}\ \textit{noun}\end{bmatrix} \\
\texttt{REST}\ \textit{*null*}
\end{bmatrix}
\end{bmatrix}
\end{bmatrix}
$$

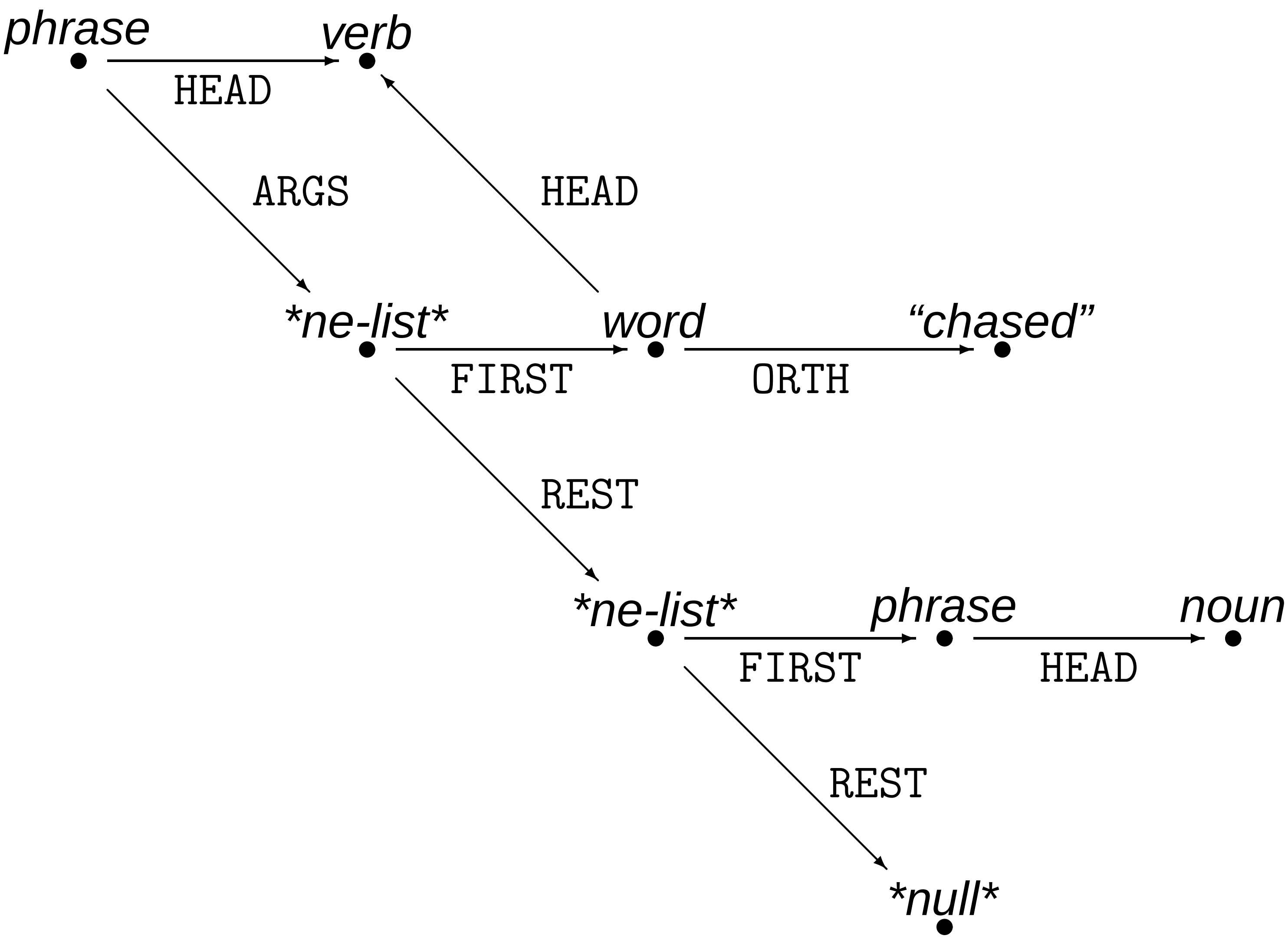
# Typed Feature Structure Example (as Graph)



# Typed Feature Structure Example (in TDL)

```
vp := phrase &
[ HEAD verb,
  ARGS *ne-list* &
       [ FIRST word &
               [ ORTH "chased",
                 HEAD verb ],
         REST *ne-list* &
              [ FIRST expression &
                      [ HEAD noun ],
                REST *null* ]]] .
```

# Reentrancy in a Typed Feature Structure (Graph)



# Reentrancy in a Typed Feature Structure (AVM)

$$
\textit{phrase}\begin{bmatrix} \texttt{HEAD} & \boxed{1}\,\textit{verb} \\ \texttt{ARGS} & \textit{*ne-list*}\begin{bmatrix} \texttt{FIRST} & \textit{word}\begin{bmatrix}\texttt{ORTH} & \textit{“chased”} \\ \texttt{HEAD} & \boxed{1}\end{bmatrix} \\ \texttt{REST} & \textit{*ne-list*}\begin{bmatrix}\texttt{FIRST} & \textit{phrase}\begin{bmatrix}\texttt{HEAD} & \textit{noun}\end{bmatrix} \\ \texttt{REST} & \textit{*null*}\end{bmatrix}\end{bmatrix}\end{bmatrix}
$$

# Reentrancy in a Typed Feature Structure (TDL)

```
vp := phrase &
[ HEAD #head & verb,
  ARGS *ne-list* &
       [ FIRST word &
               [ ORTH "chased",
                 HEAD #head ],
         REST *ne-list* &
              [ FIRST phrase &
                      [ HEAD noun ],
                REST *null* ]]] .
```

# The Linguistic Knowledge Builder (LKB)

**Compiler and Interactive Debugger**

- Grammar definition errors identified at load time by position in file;
- inheritance and appropriateness tracked by type and attributes;
- batch check, expansion, and indexing of full lexicon on demand;
- efficient parser and generator to map between strings and meaning;
- visualization of main data types; interactive stepping and unification.

- Main developers: Copestake (original), Carroll, Malouf, and Oepen;
- implementation: Allegro CL, Macintosh CL, (LispWorks, CMU CL);
- available in open-source and binary form for common platforms.