Features & Unification

Ling 571
Deep Processing Techniques for NLP
January 31, 2011

Roadmap

- Features: Motivation
  - Constraint & compactness
- Features
  - Definitions & representations
- Unification
- Application of features in the grammar
  - Agreement, subcategorization
- Parsing with features & unification
  - Augmenting the Earley parser, unification parsing
- Extensions: Types, inheritance, etc
- Conclusion

Constraints & Compactness

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  - Violate agreement (number), subcategorization

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  - Explosive!, loses key generalizations

Features

- person: 1^{st}, 2^{nd}, 3^{rd}
  - I, we; you; he, she, they
  - am, are, is

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- animacy: +/-
- etc

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    - Number, person, gender, etc
- Augment CF rules with feature constraints
  - Develop mechanism to enforce consistency
  - Elegant, compact, rich representation

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  - Features: atomic symbols from a finite set

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$$\begin{bmatrix} \text{NUMBER} & \text{PL} \\ \text{PERSON} & 3 \end{bmatrix}$$

$$\begin{bmatrix} \text{CAT} & \text{NP} \\ \text{NUMBER} & \text{PL} \\ \text{PERSON} & 3 \end{bmatrix}$$

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    - Atomic symbols from a finite set
  - Values may also be feature structures themselves

Attribute-value matrix (AVM)

$$\begin{pmatrix} \text{CAT} & \text{NP} \\ \text{AGREEMENT} & \begin{pmatrix} \text{NUMBER} & \text{PL} \\ \text{PERSON} & 3 \end{pmatrix} \end{pmatrix}$$

Feature Representations

- Feature path:
  - Sequence of features through a feature structure leading to a particular value

$$\left[\begin{array}{ll} \text{CAT} & \text{NP} \\ \text{AGREEMENT} & \left[\begin{array}{ll} \text{NUMBER} & \text{PL} \\ \text{PERSON} & 3 \end{array}\right] \end{array}\right]$$

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$$
\begin{pmatrix}
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\end{pmatrix}
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<AGREEMENT NUMBER> -> PL

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\end{bmatrix}
$$

<AGREEMENT NUMBER> -> PL
<AGREEMENT PERSON> -> 3

Feature Representations

- Reentrant feature structures
  - Features share some feature structure as value
    - Not merely equal values
    - Shared substructure
    - Feature paths lead to same node

$$
\begin{bmatrix}
\text{CAT} & \text{S} \\
\text{HEAD} & \begin{bmatrix}
\text{AGREEM'T} & \boxed{1} \begin{bmatrix} \text{NUMBER} & \text{PL} \\ \text{PERSON} & 3 \end{bmatrix} \\
\text{SUBJECT} & \begin{bmatrix} \text{AGREEMENT} & \boxed{1} \end{bmatrix}
\end{bmatrix}
\end{bmatrix}
$$

Head-Subject Agreement

$$
\begin{bmatrix}
\text{CAT} & \text{S} \\
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\text{AGREEM'T} & \boxed{1}\begin{bmatrix} \text{NUMBER} & \text{PL} \\ \text{PERSON} & 3 \end{bmatrix} \\
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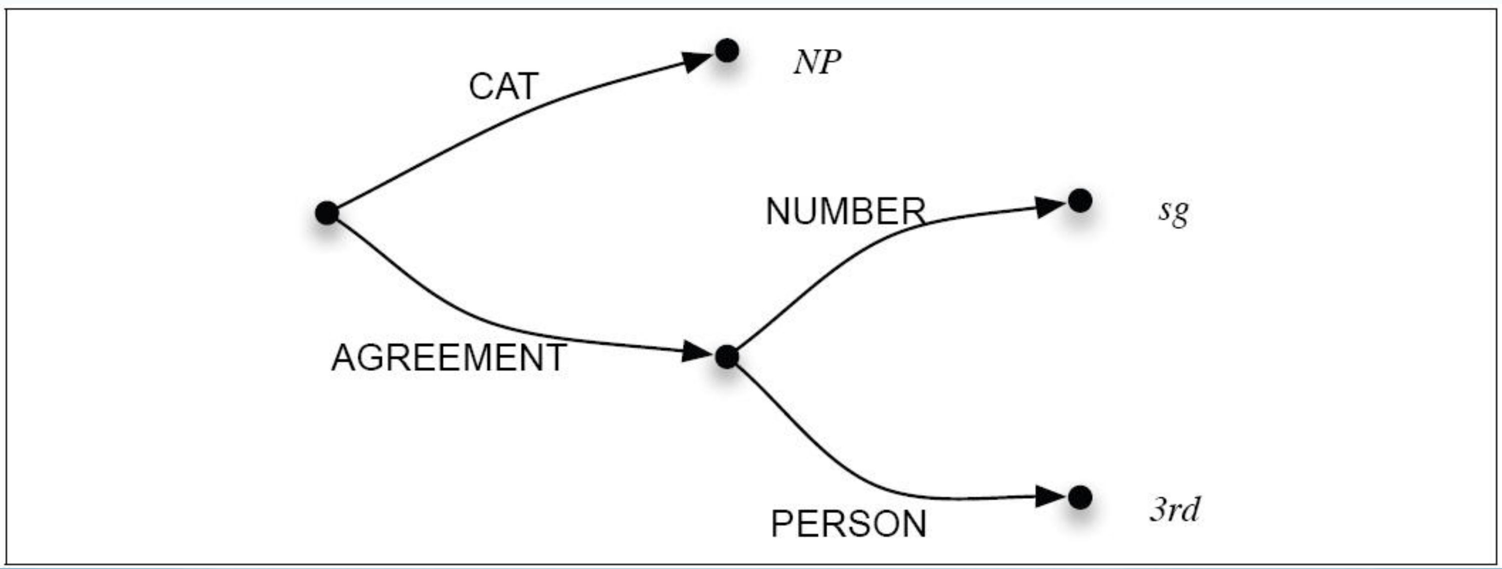
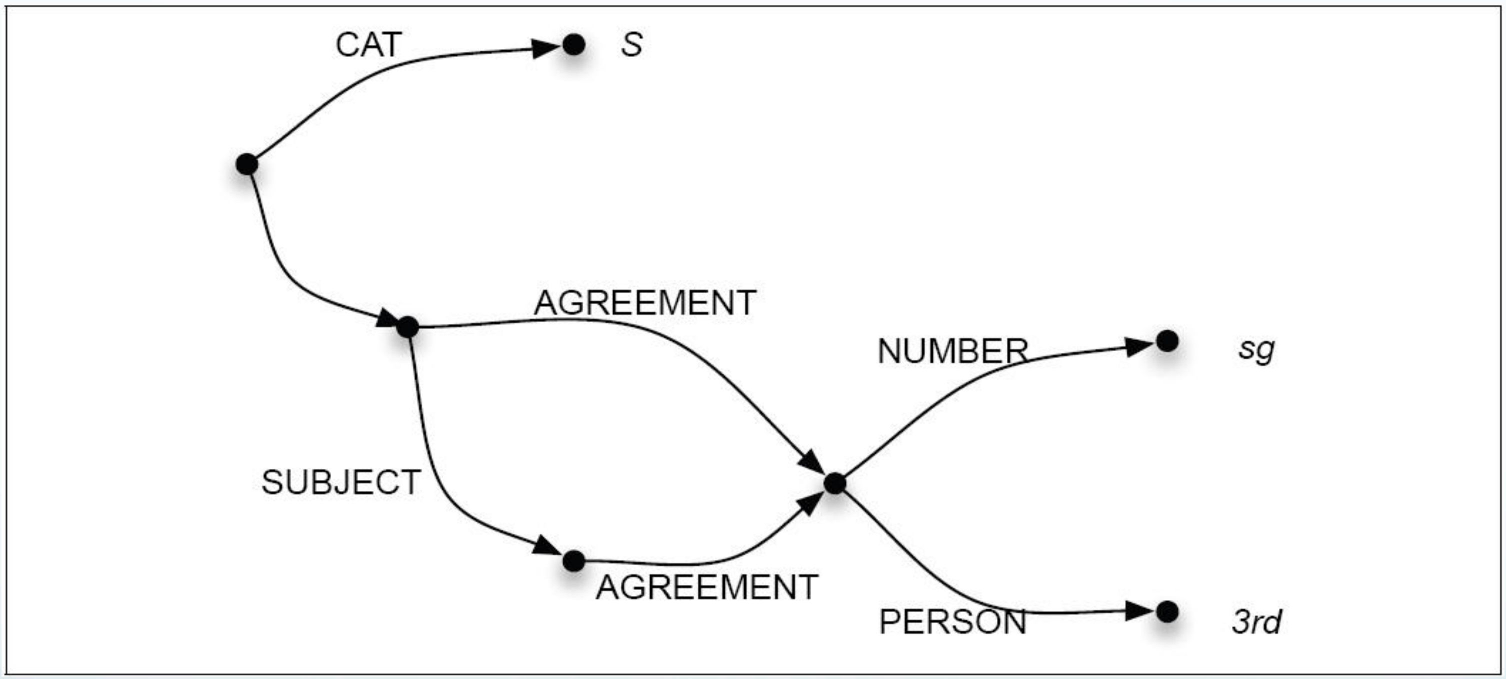
\end{bmatrix}
\end{bmatrix}
$$

Feature representations

- Feature structures can also be represented as DAGs
  - Directed, acyclic graphs
    - Edges are features
    - Nodes values



Reentrant DAG



Unification

- Two key roles:

Unification

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  - Feature structures match where both have values, differ in missing or underspecified
    - Resulting structure incorporates constraints of both

Subsumption

- Relation between feature structures
  - Less specific f.s. subsumes more specific f.s.
  - F.s. F subsumes f.s. G iff
    - For every feature x in F, F(x) subsumes G(x)
    - For all paths p and q in F s.t. F(p)=F(q), G(p)=G(q)

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    - Partial order on f.s.

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  - [Person 3]
- Mismatched
  - [Number SG] U [Number PL] -> Fails!

More Unification Examples

$$
\begin{bmatrix}
\text{AGREEMENT} & [1] \\
\text{SUBJECT} & \begin{bmatrix} \text{AGREEMENT } [1] \end{bmatrix}
\end{bmatrix}
\cup
$$

$$
\begin{bmatrix}
\text{SUBJECT} & \begin{bmatrix} \text{AGREEMENT} & \begin{bmatrix} \text{PERSON} & 3 \\ \text{NUMBER} & \text{SG} \end{bmatrix} \end{bmatrix}
\end{bmatrix}
=
$$

$$
\begin{bmatrix}
\text{AGREEMENT} & [1] \\
\text{SUBJECT} & \begin{bmatrix} \text{AGREEMENT } [1] & \begin{bmatrix} \text{PERSON} & 3 \\ \text{NUMBER} & \text{SG} \end{bmatrix} \end{bmatrix}
\end{bmatrix}
$$

Features in CFGs: Agreement

- Goal:
  - Support agreement of NP/VP, Det Nominal
- Approach:
  - Augment CFG rules with features
  - Employ head features
    - Each phrase: VP, NP has head
      - Head: child that provides features to phrase
        - Associates grammatical role with word
        - VP – V; NP – Nom, etc

Agreement with Heads and Features

VP -> Verb NP
<VP HEAD> = <Verb HEAD>

NP -> Det Nominal
<NP HEAD> = <Nominal HEAD>
<Det HEAD AGREEMENT> = <Nominal HEAD AGREEMENT>

Nominal -> Noun
<Nominal HEAD> = <Noun HEAD>

Noun -> flights
<Noun HEAD AGREEMENT NUMBER> = PL

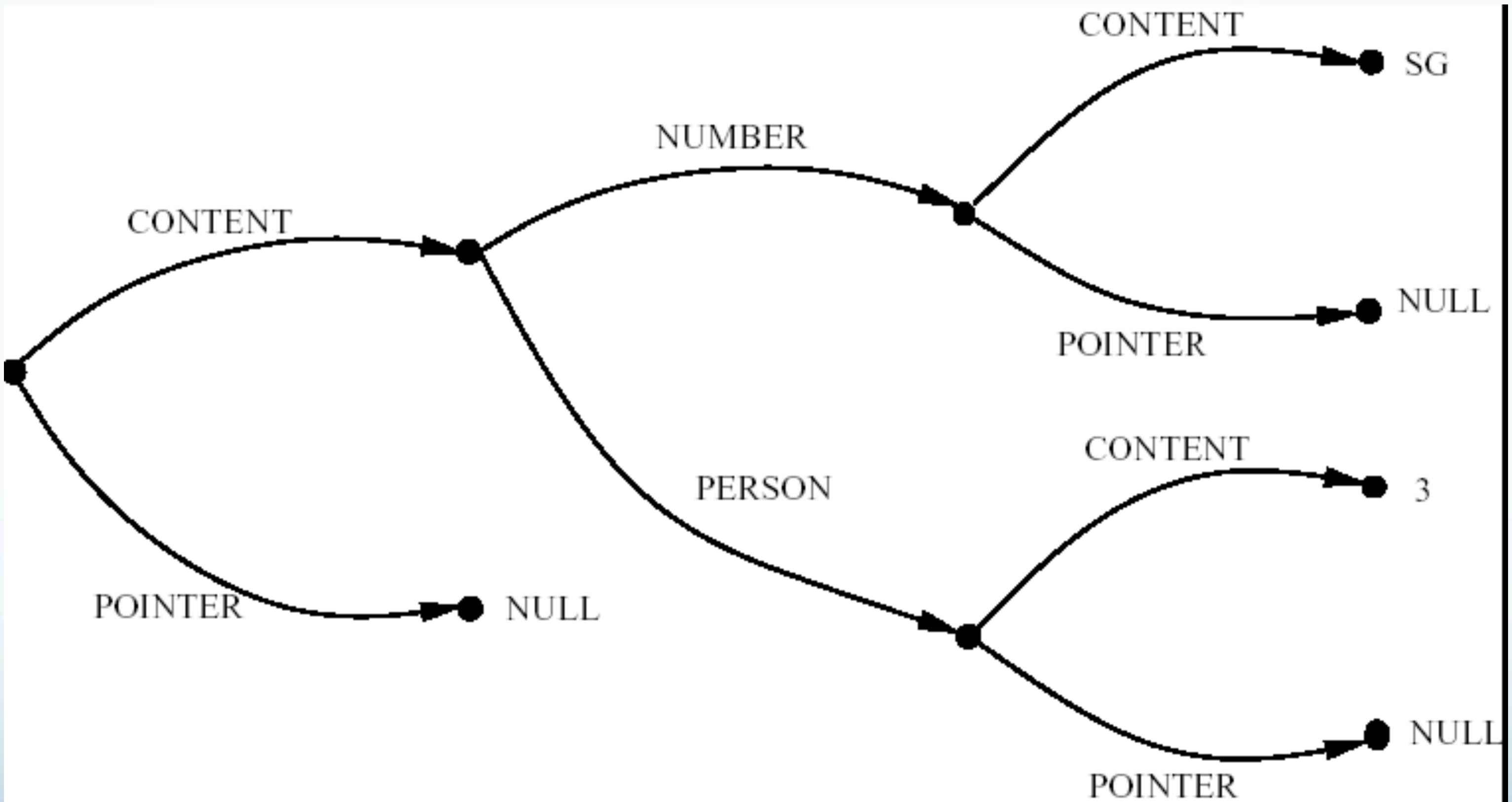
Verb -> serves
<Verb HEAD AGREEMENT NUMBER> = SG
<Verb HEAD AGREEMENT PERSON> = 3

Feature Applications

- Subcategorization:
  - Verb-Argument constraints
    - Number, type, characteristics of args (e.g. animate)
    - Also adjectives, nouns
- Long distance dependencies
  - E.g. filler-gap relations in wh-questions, rel

Implementing Unification

- Data Structure:
  - Extension of the DAG representation
  - Each f.s. has a content field and a pointer field
    - If pointer field is null, content field has the f.s.
    - If pointer field is non-null, it points to actual f.s.


CONTENT
SG
NUMBER
CONTENT
NULL
POINTER
CONTENT
PERSON
3
POINTER
NULL
NULL
POINTER

Implementing Unification: II

- Algorithm:
  - Operates on pairs of feature structures
    - Order independent, destructive
  - If fs1 is null, point to fs2
  - If fs2 is null, point to fs1
  - If both are identical, point fs1 to fs2, return fs2
    - Subsequent updates will update both
  - If non-identical atomic values, fail!

Implementing Unification: III

- If non-identical, complex structures
  - Recursively traverse all features of fs2
  - If feature in fs2 is missing in fs1
    - Add to fs1 with value null
  - If all unify, point fs2 to fs1 and return fs1

Unification

```
function UNIFY(f1-orig, f2-orig) returns f-structure or failure

 f1 ← Dereferenced contents of f1-orig
 f2 ← Dereferenced contents of f2-orig

 if f1 and f2 are identical then
    f1.pointer ← f2
    return f2
 else if f1 is null then
    f1.pointer ← f2
    return f2
 else if f2 is null then
    f2.pointer ← f1
    return f1
 else if both f1 and f2 are complex feature structures then
    f2.pointer ← f1
    for each f2-feature in f2 do
       f1-feature ← Find or create a corresponding feature in f1
       if UNIFY(f1-feature.value, f2-feature.value) returns failure then
          return failure
    return f1
 else return failure
```

Example

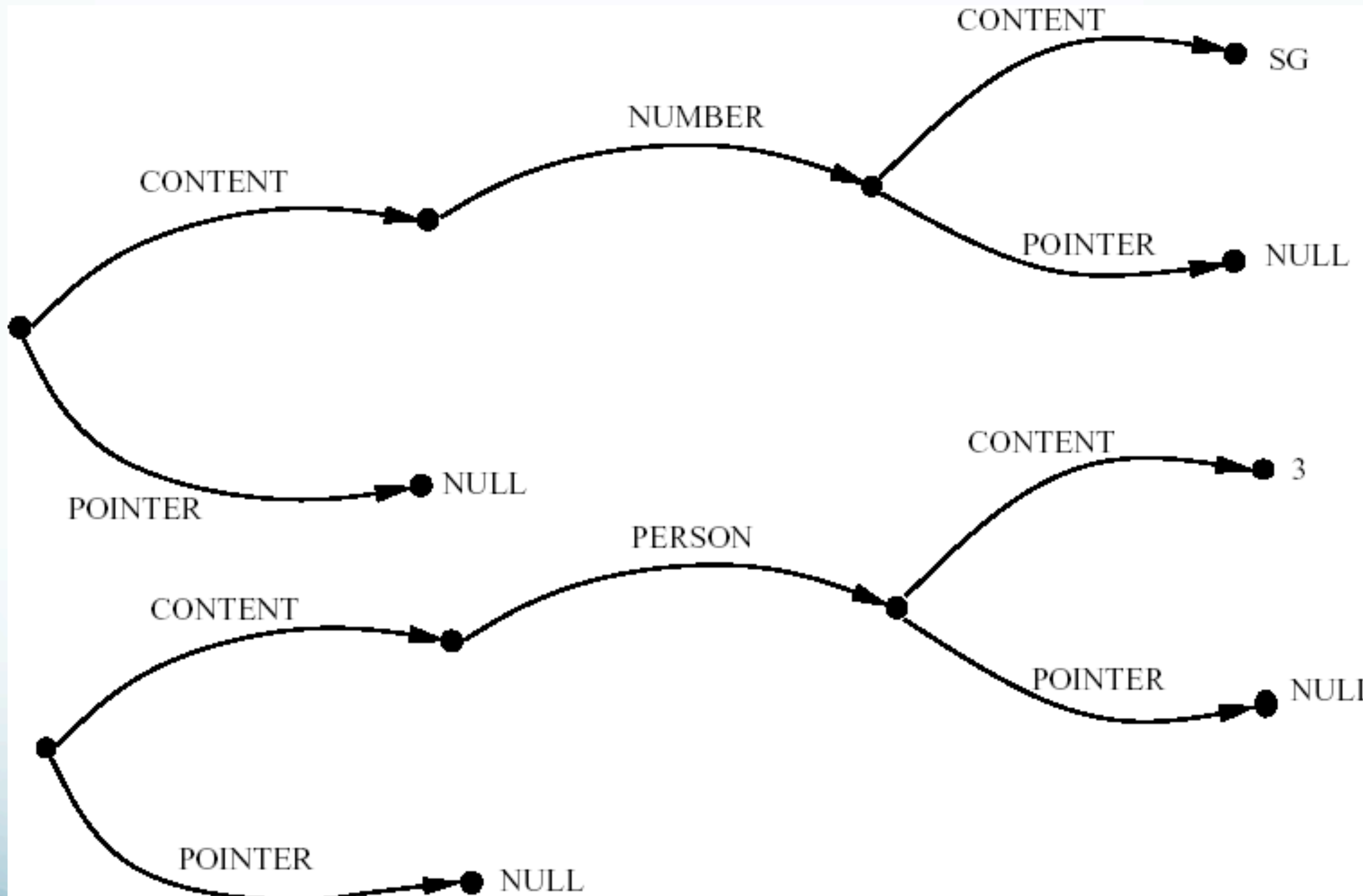
$$\begin{bmatrix} \text{AGREEMENT [1]} & \\ \text{SUBJECT} & \begin{bmatrix} \text{NUMBER} & \text{SG} \\ \text{AGREEMENT [1]} & \end{bmatrix} \end{bmatrix} \text{ U}$$

$$\begin{bmatrix} \text{SUBJECT} & \begin{bmatrix} \text{AGREEMENT} & \begin{bmatrix} \text{PERSON} & 3 \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

[AGREEMENT [1]] U [AGREEMENT [PERSON 3]]

[NUMBER SG] U [PERSON 3]

[NUMBER SG] U [PERSON 3]
[PERSON NULL]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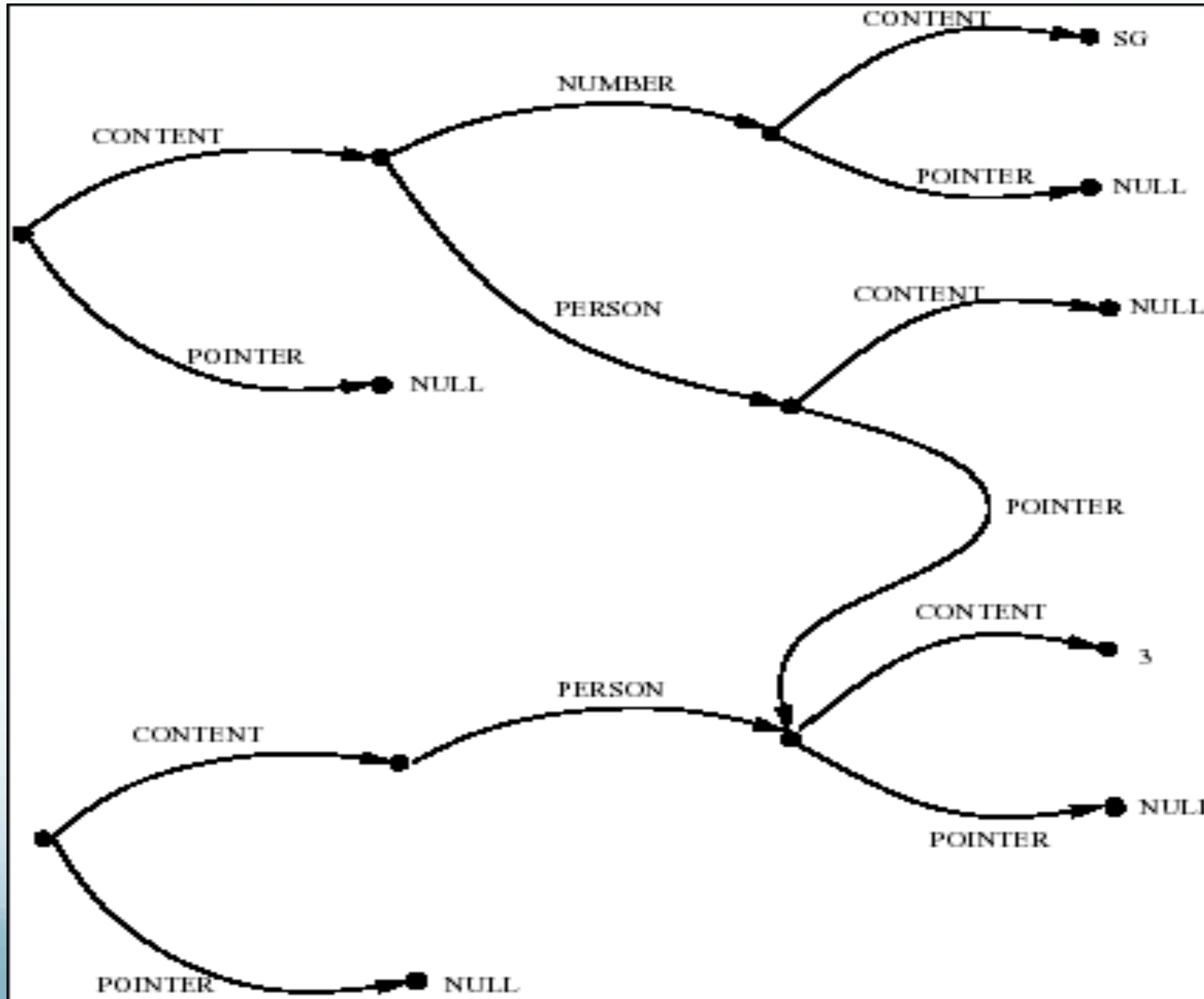
POINTER
NULL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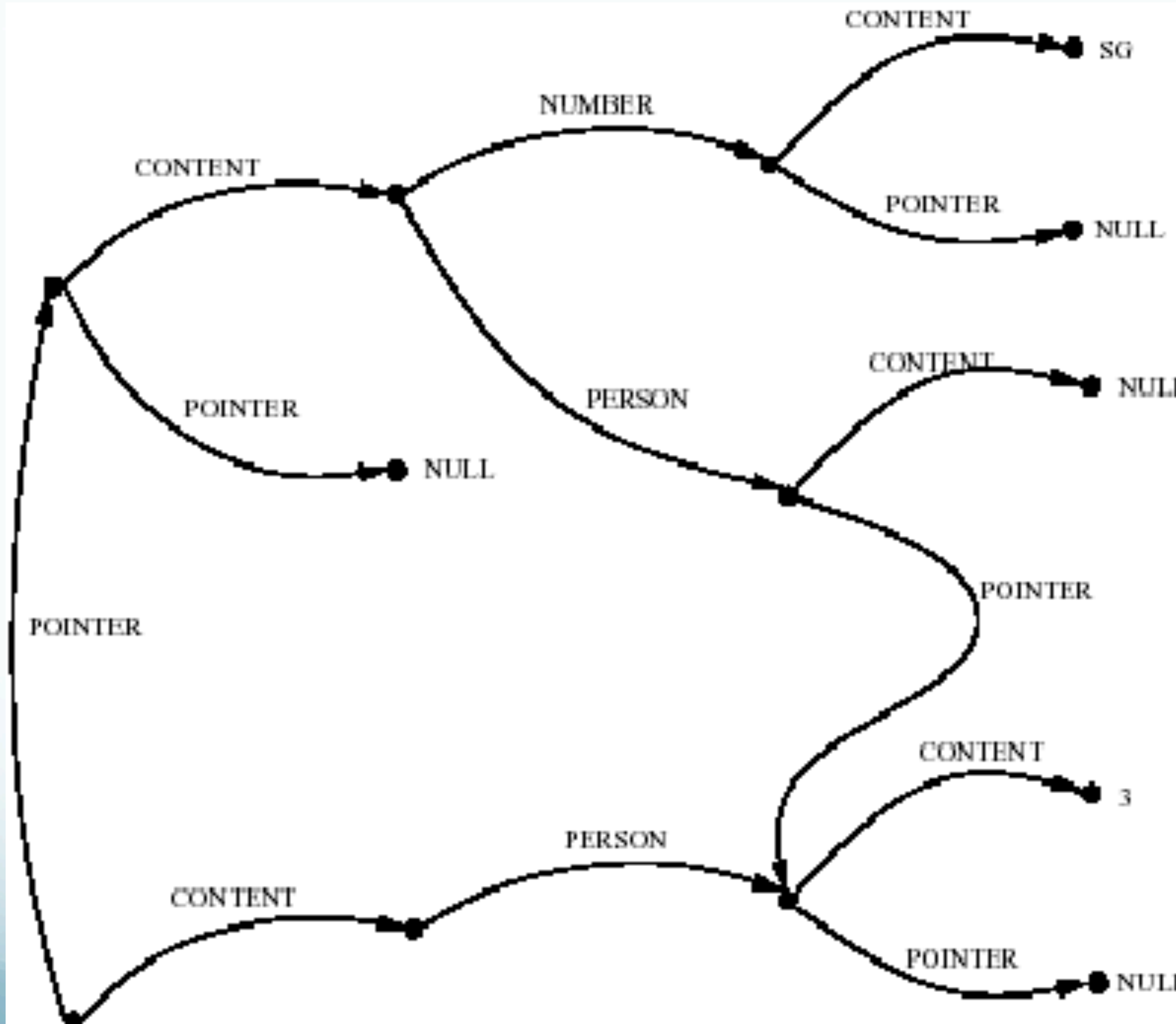
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Unification Example

$$\begin{bmatrix} \text{cat} & \text{S} \\ \text{voice} & \text{active} \\ \text{agent} & \boxed{1}\begin{bmatrix} \text{cat} & \text{NP} \\ \text{number} & \boxed{4} \end{bmatrix} \\ \text{process} & \boxed{2}\begin{bmatrix} \text{cat} & \text{VB} \\ \text{number} & \boxed{4} \end{bmatrix} \\ \text{patient} & \boxed{3}\begin{bmatrix} \text{cat} & \text{NP} \end{bmatrix} \\ \text{pattern} & \begin{bmatrix} \text{subject} & \boxed{1} \\ \text{verb} & \boxed{2} \\ \text{object} & \boxed{3} \end{bmatrix} \end{bmatrix}$$

Grammar entry for sentence

(From S.F., 2010)

Unification Example

$$
\begin{bmatrix}
\text{cat} & \text{NP} \\
\text{spec} & \boxed{1}\begin{bmatrix} \text{cat} & \text{DT} \\ \text{number} & \boxed{3} \\ \text{definite} & \boxed{4} \end{bmatrix} \\
\text{head} & \boxed{2}\begin{bmatrix} \text{cat} & \text{NN} \\ \text{number} & \boxed{3} \end{bmatrix} \\
\text{number} & \boxed{3} \\
\text{definite} & \boxed{4} \\
\text{pattern} & \begin{bmatrix} \text{first} & \boxed{1} \\ \text{second} & \boxed{2} \end{bmatrix}
\end{bmatrix}
$$

Grammar entry for NP

(From S.F., 2010)

Unification Example

$$\begin{bmatrix} \text{cat} & \text{DT} \\ \text{definite} & \text{yes} \\ \text{number} & \text{SG} \\ \text{form} & \text{"the"} \end{bmatrix}$$

$$\begin{bmatrix} \text{cat} & \text{DT} \\ \text{definite} & \text{yes} \\ \text{number} & \text{PL} \\ \text{form} & \text{"these"} \end{bmatrix}$$

Lexical entries

(From S.F., 2010)

Unification Example

Unifying a noun phrase with a determiner

$$\begin{bmatrix} \text{cat} & \text{NP} \\ \text{spec} & \boxed{1}\begin{bmatrix}\text{cat} & \text{DT}\\ \text{number} & \boxed{3} \\ \text{definite} & \boxed{4}\end{bmatrix} \\ \text{head} & \boxed{2}\begin{bmatrix}\text{cat} & \text{NN}\\ \text{number} & \boxed{3}\end{bmatrix} \\ \text{number} & \boxed{3} \\ \text{definite} & \boxed{4} \\ \text{pattern} & \begin{bmatrix}\text{first} & \boxed{1}\\ \text{second} & \boxed{2}\end{bmatrix} \end{bmatrix} \sqcup \begin{bmatrix} \text{cat} & \text{DT} \\ \text{definite} & \text{yes} \\ \text{number} & \text{PL} \\ \text{form} & \text{“these”} \end{bmatrix}$$

(From S.F., 2010)

Unification Example

$$\begin{bmatrix} \text{cat} & \text{DT} \\ \text{number} & \boxed{3} \\ \text{definite} & \boxed{4} \end{bmatrix} \sqcup \begin{bmatrix} \text{cat} & \text{DT} \\ \text{definite} & \text{yes} \\ \text{number} & \text{PL} \\ \text{form} & \text{``these''} \end{bmatrix} = \begin{bmatrix} \text{cat} & \text{DT} \\ \text{definite} & \text{yes} \\ \text{number} & \text{PL} \\ \text{form} & \text{``these''} \end{bmatrix}$$

Unifying NP with Determiner

(From S.F., 2010)

Unification Example

Result of unification

$$\begin{bmatrix} \text{cat} & \text{NP} \\ \text{spec} & \boxed{1}\begin{bmatrix} \text{cat} & \text{DT} \\ \text{number} & \text{PL} \\ \text{definite} & \text{yes} \\ \text{form} & \text{``these''} \end{bmatrix} \\ \text{head} & \boxed{2}\begin{bmatrix} \text{cat} & \text{NN} \\ \text{number} & \text{PL} \end{bmatrix} \\ \text{number} & \text{PL} \\ \text{definite} & \text{yes} \\ \text{pattern} & \begin{bmatrix} \text{first} & \boxed{1} \\ \text{second} & \boxed{2} \end{bmatrix} \end{bmatrix}$$

(From S.F., 2010)

Unification and the Earley Parser

- Employ constraints to restrict addition to chart
- Actually pretty straightforward
  - Augment rules with feature structure
  - Augment state (chart entries) with DAG
    - Prediction adds DAG from rule
    - Completion applies unification (on copies)
      - Adds entry only if current DAG is NOT subsumed

Parsing with Features

- One strategy:
  - Parse as usual
  - Test completed parses for unification constraints

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  - Parse as usual
  - Test completed parses for unification constraints
- Pros:
  - Simple, requires little modification
- Cons:
  - Wasted effort
  - Builds many partial parses that can't unify

Parsing with Features

- One strategy:
  - Parse as usual
  - Test completed parses for unification constraints
- Pros:
  - Simple, requires little modification
- Cons:
  - Wasted effort
  - Builds many partial parses that can't unify
- Integrate unification in parse construction

Parsing, Unification, & Earley

- Augment existing Earley parser for unification
  - Fairly straightforward
- Modify representations:
  - Augment CFG rules with constraints
    - Use constraints to create feature structure as DAG
  - Add DAG to state representation
    - E.g., S -> • NP VP, [0,0],[],Dag

Integrating Unification

- Main change: Completer
  - Advances • in rules where next constituent matches a just-completed constituent
  - Now, unifies Dag from completed constituent with the part of the feature structure in rules advanced
    - If fails, no new entry in chart
- Second change:
  - Only add state if NOT subsumed by states in chart

function EARLEY-PARSE(*words, grammar*) **returns** *chart*

ADDTOCHART($(\gamma \rightarrow \bullet S,\ [0,0],\ dag_\gamma), chart[0]$)
for $i \leftarrow$ **from** 0 **to** LENGTH(*words*) **do**
  for each *state* **in** *chart*[*i*] **do**
    if INCOMPLETE?(*state*) **and**
        NEXT-CAT(*state*) is not a part of speech **then**
      PREDICTOR(*state*)
    elseif INCOMPLETE?(*state*) **and**
        NEXT-CAT(*state*) is a part of speech **then**
      SCANNER(*state*)
    else
      COMPLETER(*state*)
  end
end
return(*chart*)

```
procedure PREDICTOR((A → α • B β, [i, j], dag_A))
   for each (B → γ) in GRAMMAR-RULES-FOR(B, grammar) do
      ADDTOCHART((B → • γ, [j, j], dag_B), chart[j])
   end

procedure SCANNER((A → α • B β, [i, j], dag_A))
   if B ∈ PARTS-OF-SPEECH(word[j]) then
      ADDTOCHART((B → word[j]•, [j, j+1], dag_B), chart[j+1])

procedure COMPLETER((B → γ •, [j,k], dag_B))
   for each (A → α • B β, [i, j], dag_A) in chart[j] do
      if new-dag ← UNIFY-STATES(dag_B, dag_A, B) ≠ Fails!
         ADDTOCHART((A → α B • β, [i,k],new-dag), chart[k])
   end

procedure UNIFY-STATES(dag1, dag2, cat)
  dag1-cp ← COPYDAG(dag1)
  dag2-cp ← COPYDAG(dag2)
  UNIFY(FOLLOW-PATH(cat, dag1-cp), FOLLOW-PATH(cat, dag2-cp))

procedure ADDTOCHART(state, chart-entry)
   if state is not subsumed by a state in chart-entry then
      PUSH-ON-END(state, chart-entry)
   end
```

Unification Parsing

- Abstracts over categories
  - S-> NP VP =>
    - X0 -> X1 X2; <X0 cat> = S; <X1 cat>=NP;
    - <X2 cat>=VP
  - Conjunction:
    - X0->X1 and X2; <X1 cat> =<X2 cat>;
    - <X0 cat>=<X1 cat>
- Issue: Completer depends on categories
- Solution: Completer looks for DAGs which unify with the just-completed state’s DAG

Extensions

- Types and inheritance
  - Issue: generalization across feature structures
    - E.g. many variants of agreement
      - More or less specific: 3^{rd} vs sg vs 3rdsg
  - Approach: Type hierarchy
    - Simple atomic types match literally
    - Multiple inheritance hierarchy
      - Unification of subtypes is most general type that is more specific than two input types
    - Complex types encode legal features, etc

Conclusion

- Features allow encoding of constraints
  - Enables compact representation of rules
  - Supports natural generalizations
- Unification ensures compatibility of features
  - Integrates easily with existing parsing mech.
- Many unification-based grammatical theories