Grammars and Parsing

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1. **Context Free Grammars (CFGs)**
2. Efficiency and Expressivity
3. Features and Unification
4. Dependency Grammars
5. Resolving Ambiguity
6. Treebanks and Evaluation

1. Context Free Grammars

- Grammars
- Context Free Grammars (CFGs)
- Basic Parsing Strategies for CFGs
  - Top-Down
  - Bottom-Up
- Parsing and Search
- Redundancy in Parsing

Grammars

- A *grammar* is a 4-tuple $G = (N, \Sigma, P, S)$, where
  - N is a finite set of *nonterminal symbols*
  - Σ is a finite set of *terminal symbols*, disjoint from N
  - P is a set of rules, i.e. a finite subset of

    $$(N \cup \Sigma)^* N (N \cup \Sigma)^* \times (N \cup \Sigma)^*$$

    Productions $(\alpha, \beta) \in P$ are usually written $\alpha \rightarrow \beta$
  - S is a distinguished symbol in N called the start symbol

Chomsky hierarchy

Different types of grammars/languages according to the definition of *P*:

- Regular grammars/languages
- Context-Free grammars/languages
- Context-Sensitive grammars/languages
- Unrestricted grammars/languages

Rules

- Regular Grammars:

$$A \rightarrow xB$$

$$A \rightarrow x$$

where A and B are in $\boldsymbol{N}$ and x is in $\boldsymbol{\Sigma}$*

- Context-Free Grammars:

$$A \rightarrow \alpha$$

where A is in $\boldsymbol{N}$ and α is in $(\boldsymbol{N} \cup \boldsymbol{\Sigma})^*$

- Context-Sensitive Grammars:

$$\alpha \rightarrow \beta$$

where $|\alpha| \leq |\beta|$

Phrase Structure

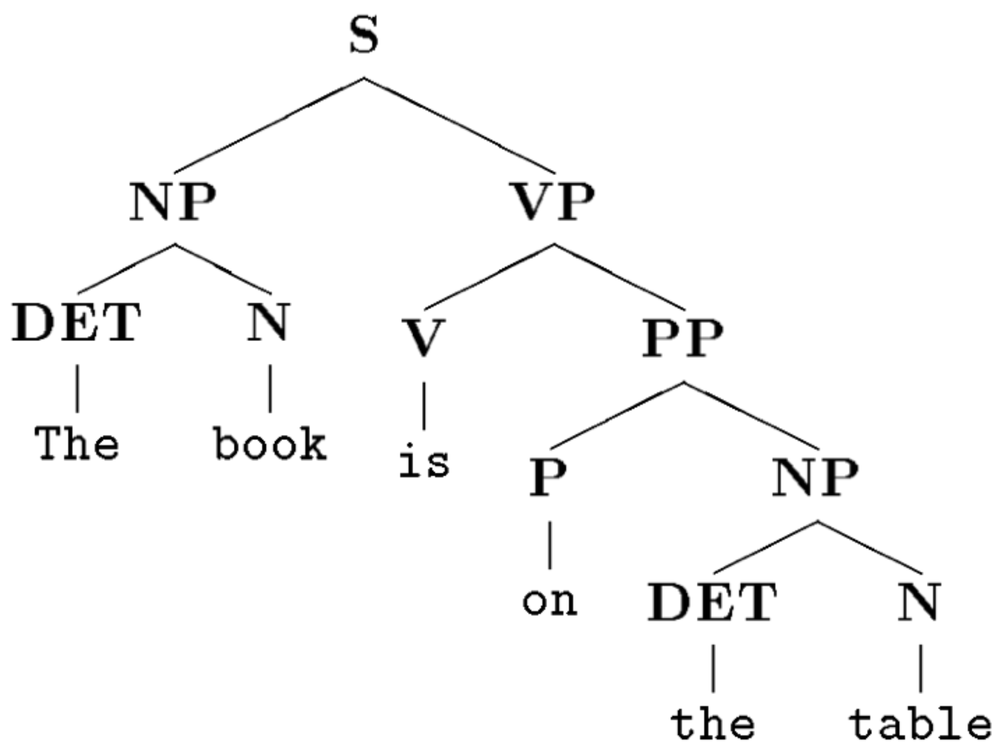
- *Language* = collection of *strings*
  but …
- Importance of hierarchical structure as well as linear structure of a given sentence

  the book is on the table

Sentence:

the book is on the table

Parse tree:



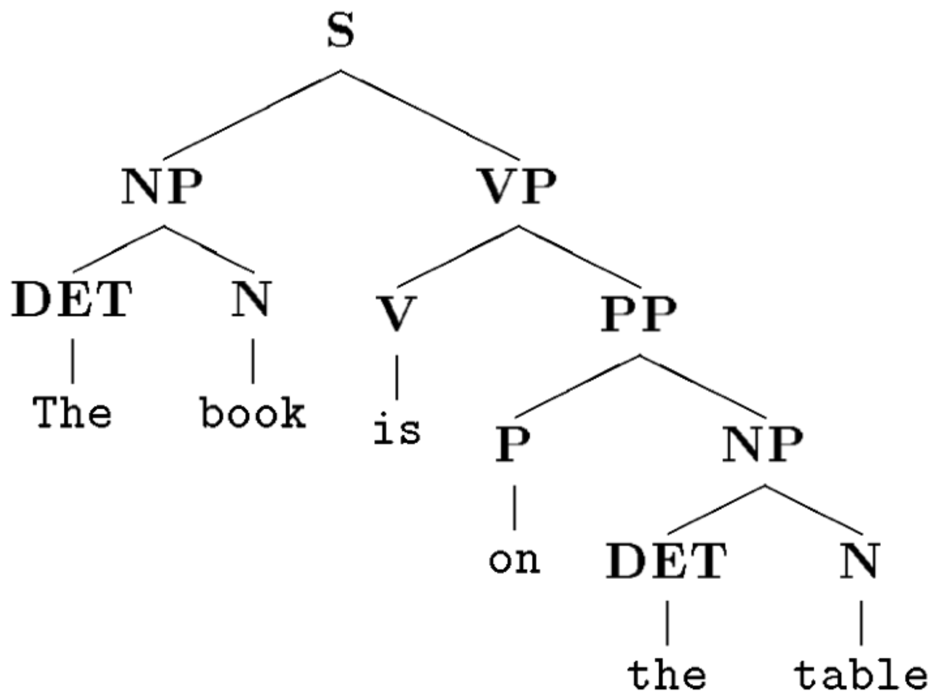
- Lexical elements:
  - *the* (DET)
  - *book, table* (Noun)
  - *is* (Verb)
  - *on* (Preposition)
- Constituent phrases:
  - *the book* (Noun Phrase)
  - *the table* (Noun Phrase)
  - *on the table* (Prepositional Phrase)
  - …

Phrase Structure

Constituents can be indicated either by bracketing

[$_{S}$ [$_{NP}$ [$_{DET}$ *the*] [$_{N}$ *book*]] [$_{VP}$ [$_{V}$ *is*] [$_{PP}$ *on* [$_{NP}$ [$_{DET}$ *the*] [$_{N}$ *table*]]]]]

or by means of parse trees



Phrase Structure

- Hierarchical information about constituents (dominance)
- Linear precedence information
- Labelling information (syntactic categories)

Context-Free Grammars

Phrase structure grammars (PSGs) provide a means of characterizing the structure of sentences

A Context-Free (Phrase Structure) Grammar consists of a set of rules of the following form:

$$A \rightarrow X_1\ X_2\ \ldots\ X_k\ (k \geq 0)$$

- A is a *nonterminal* (a category name; e.g. N, NP, VP, DET, etc.)
- each X_i is either a *nonterminal* or a terminal (i.e. a word)

An example of a simple CFG

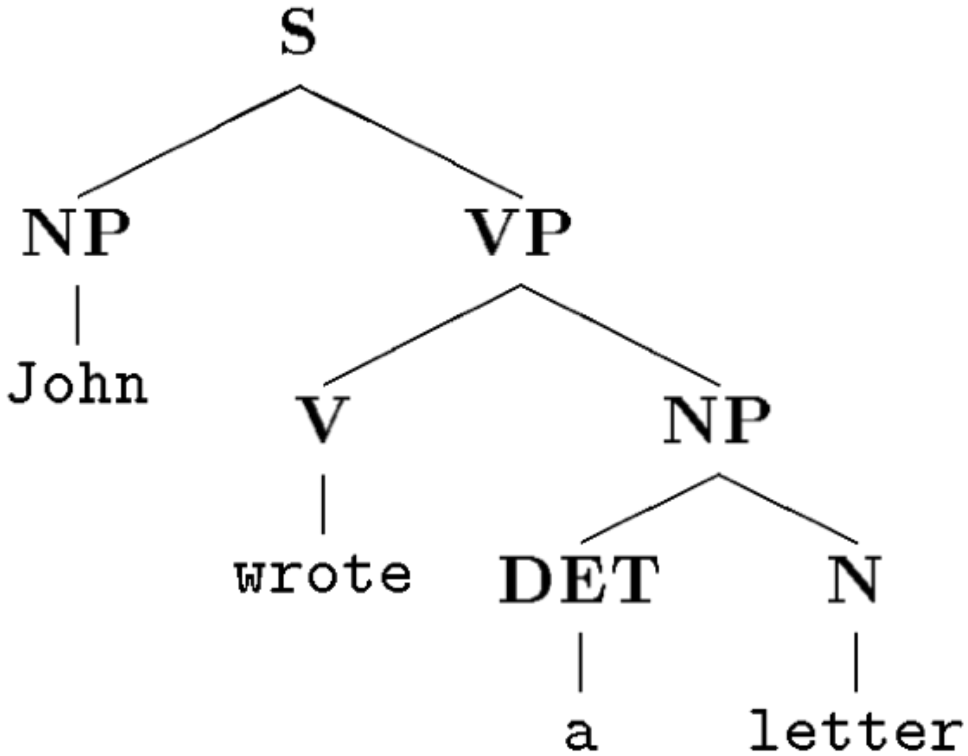
1. S → NP VP
2. NP → *John*
3. NP → *Mary*
4. NP → DET N
5. DET → *a*
6. N → *letter*
7. VP → V NP
8. VP → V NP PP
9. VP → V PP
10. V → *wrote*
11. PP → P NP
12. P → *to*

John wrote a letter

John wrote a letter to Mary

John wrote to Mary

…



Three questions

- Are there effective procedures for recognition/ generation of CFGs?
- How do we use CFGs to *parse* (i.e. assign structure to) strings?
- How do CFGs compare with FSLs computationally/descriptively?

Basic Parsing Strategies

Top-Down: A *goal-driven* strategy:

1. assume you are looking for *S* (i.e. sentence);
2. use rules ‘forward’ to ‘expand’ symbols until input is derived (else **fail**)

Bottom-Up: A *data-driven* strategy:

1. assume you are looking for *S*;
2. use rules ‘backward’ to ‘combine’ symbols until you get *S* (else **fail**)

Basic Parsing Strategies

Other dimensions:

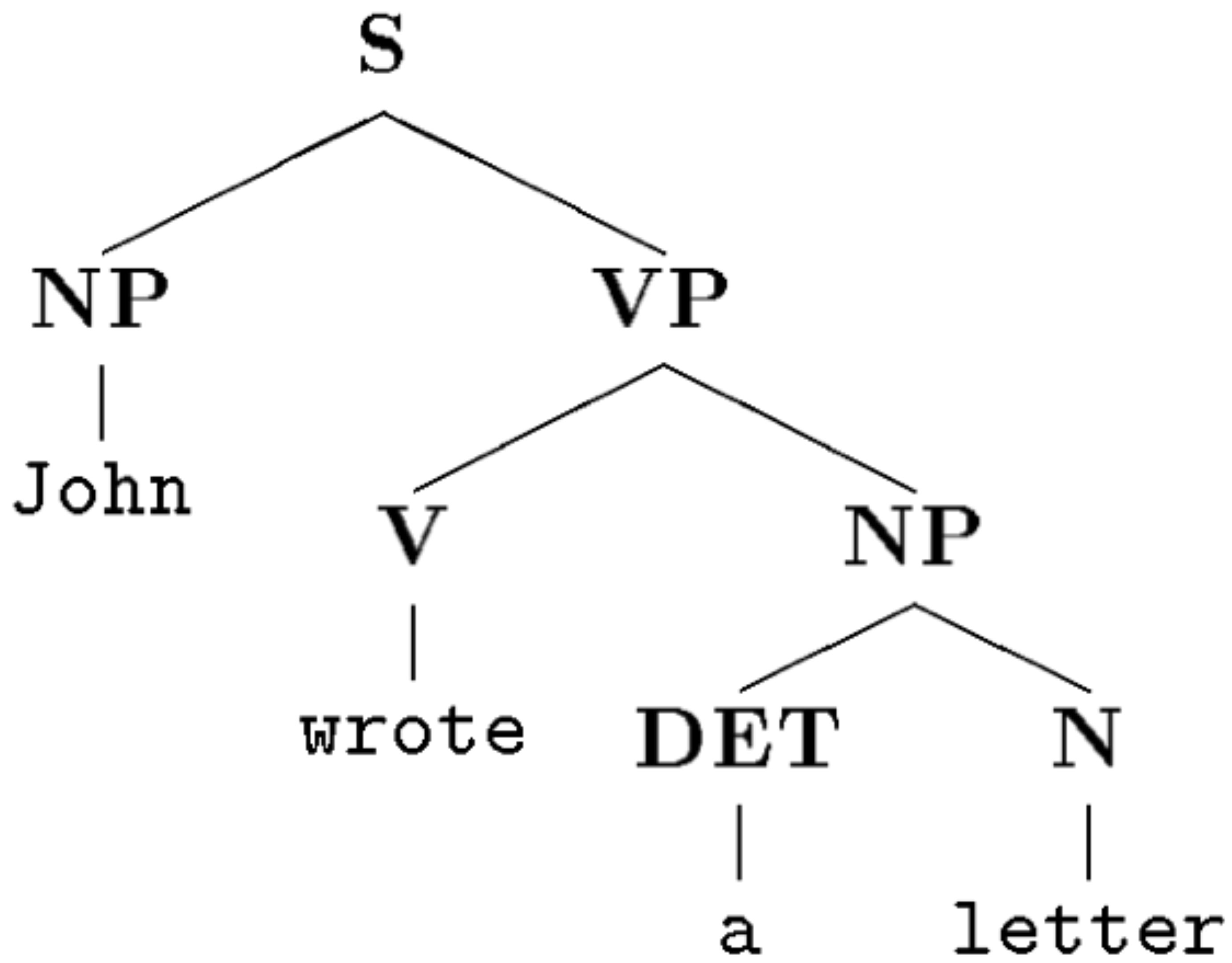
- *left-to-right* vs. *right-to-left* (but also *head-driven* or *island-driven*)
- *depth-first* vs. *breadth-first*

In the following examples, *left-to-right* and *depth-first* are usually adopted

Top-Down Strategy

Input: *John wrote a letter*

1	S	:	*John wrote a letter*	
2	NP VP	:	*John wrote a letter*	S → NP VP
3	VP	:	*wrote a letter*	NP → *John*
4	V NP	:	*wrote a letter*	VP → V NP
5	NP	:	*a letter*	V → *wrote*
6	DET N	:	*a letter*	NP → DET N
7	N	:	*letter*	DET → *a*
8		:		N → *letter*


S
NP
VP
John
V
NP
wrote
DET
N
a
letter

Crucial Points (1)

Non-determinism: at step 4, we could have chosen to 'expand' VP according to rule 8:

3	VP	:	*wrote a letter*	
4	V NP PP	:	*wrote a letter*	VP → V NP PP

Need some way of exploring the possibilities and recovering if necessary (backtracking)

Crucial Points (2)

Left recursion: a problem for top-down strategy.
If we added a new rule:

(13) VP → VP PP

3	VP	:	*wrote a letter*	
4	VP PP	:	*wrote a letter*	VP → VP PP
5	VP PP PP	:	*wrote a letter*	VP → VP PP

and so on…

Bottom-Up Strategy

Input: *John wrote a letter*

1	*John wrote a letter*	
2	NP *wrote a letter*	NP → *John*
3	NP V *a letter*	V → *wrote*
4	NP V DET *letter*	DET → *a*
5	NP V DET N	N → *letter*
6	NP V NP	NP → DET N
7	NP VP	VP → V NP
8	S	S → NP VP

Crucial Points

Empty productions: a problem for bottom-up strategy. Empty productions have the form:

$$A \rightarrow \varepsilon$$

E.g.:

NP → DET AP N
AP → ε
AP → ADJ AP
ADJ → *lengthy*
ADJ → *interesting*

Crucial Points

These new rules allow NPs such as:

a lengthy letter

a lengthy interesting letter

a letter

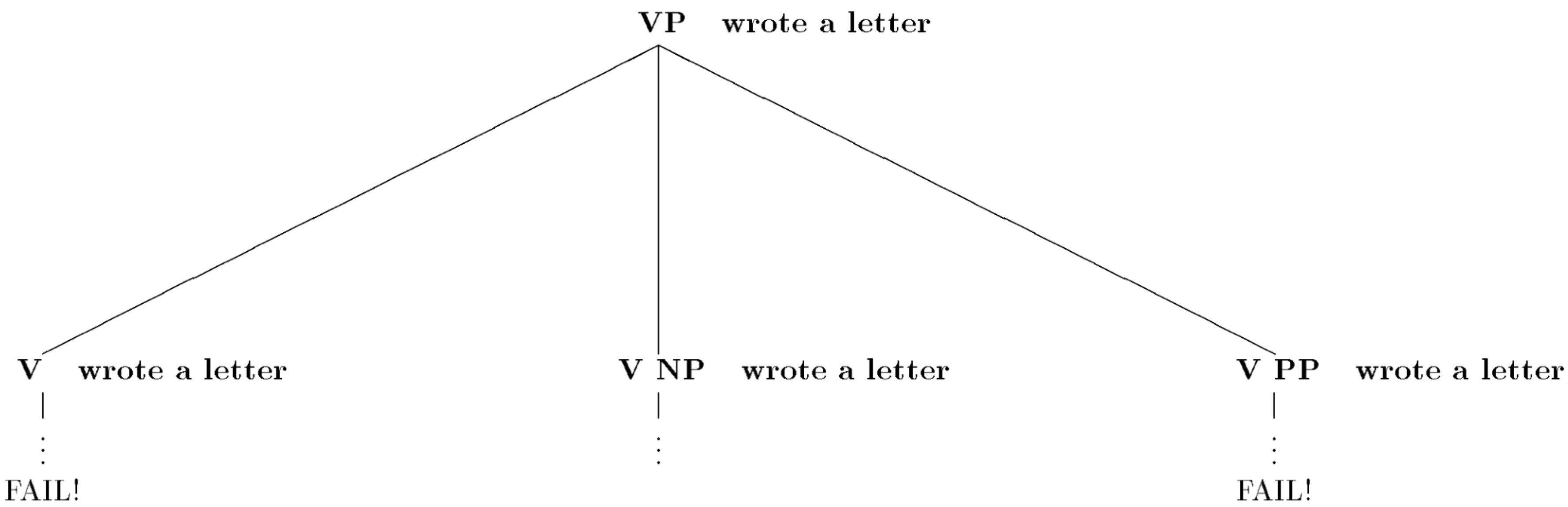
Note, however, that the rule AP $\rightarrow$ ε is always applicable!

Parsing and Search

In general, CFG parsing is *non-deterministic*.

Top-Down Example:

At different stages in the parsing process, more than one rule may be applicable:



Parsing and Search

Parsing algorithms need to explore the search space systematically.

To recover from errors, it is necessary to record the state of a parse each time a choice occurs.

Parsing and Search

E.g., considering the previous example,

The parse state:

VP : *wrote a letter*

has three different successor states:

V : *wrote a letter*

V NP : *wrote a letter*

V NP PP : *wrote a letter*

Parsing and Search

Parse maintains a list of parse states called an *agenda*:

- remove states from agenda;
- generate successor states;
- add successors to agenda;

Parse terminates successfully if the goal state (:) is generated.

Parse terminates unsuccessfully if it runs out of parse states to explore (i.e. the agenda is empty).

Parsing and Search

Search strategy:

this is determined by the order in which agenda items are considered:

Rule $S \rightarrow S_1\ S_2\ \ldots\ S_k$

σ = rest on agenda

Depth-first:

$$S\ \sigma \Rightarrow S_1\ S_2\ \ldots\ S_k\ \sigma$$

Breadth-first:

$$S\ \sigma \Rightarrow \sigma\ S_1\ S_2\ \ldots\ S_k$$

Redundancy in Parsing

Input: *John sang a song*

1	S	:	*John sang a song*	
2	NP VP	:	*John sang a song*	S → NP VP
3	VP	:	*sang a song*	NP → *John*
4	V NP PP	:	*sang a song*	VP → V NP PP
5	NP PP	:	*a song*	V → *sang*
6	DET N PP	:	*a song*	NP → DET N
7	N PP	:	*song*	DET → *a*
8	PP	:		N → *song*
9	P NP	:		PP → P NP

Redundancy in Parsing

4'	V NP	:	*sang a song*	VP → V NP
5'	NP	:	*a song*	V → *sang*
6'	DET N	:	*a song*	NP → DET N
7'	N	:	*song*	DET → *a*
8'		:		N → *song*

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2. Efficiency and Expressivity

- Efficiency
  - Redundancy in Parsing
  - Active Chart Parsing
- Expressivity
  - comparing CFGs and FSAs
  - Pros and Cons of CFGs
    - Agreement, subcategorization, …

Chart Parsing

Dynamic programming technique which keeps track of what has been done and of partial hypotheses. Resulting data structure is called the *active chart*.

The chart contains data structures called *edges*, which represent (partially) recognized constituents.

Dotted Rules

'Dotted Rules': edges have labels of the general form:

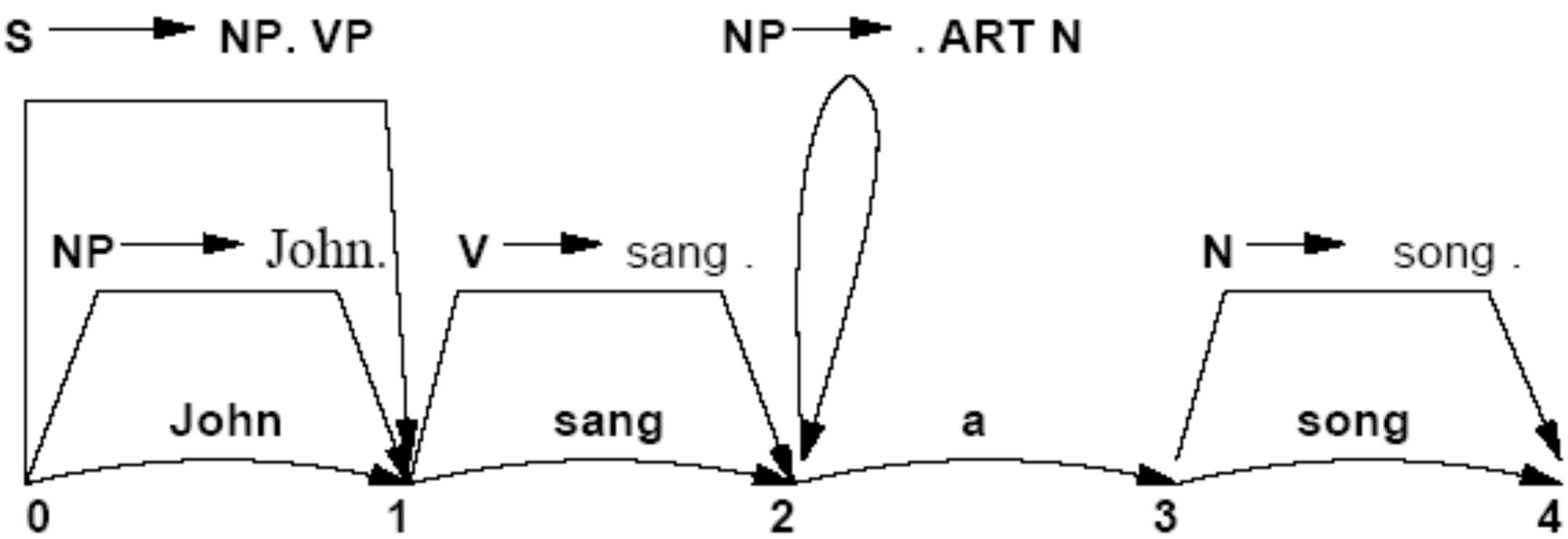
$$C \rightarrow X_1 \ldots X_j \bullet X_{j+1} \ldots X_k$$

Symbols on the left of the dot (•) have been already 'found' (confirmed hypotheses). Symbols on the right are still to be found.

Chart Parsing

$NP \rightarrow DET \bullet N$	**active edge**
$S \rightarrow \bullet\ NP\ VP$	**active and empty edge**
$VP \rightarrow V\ NP \bullet$	**inactive edge**

Chart Parsing



The chart has edges of the form

$$(i, j, A \rightarrow \alpha \bullet \beta)$$

Fundamental Rule of Chart Parsing

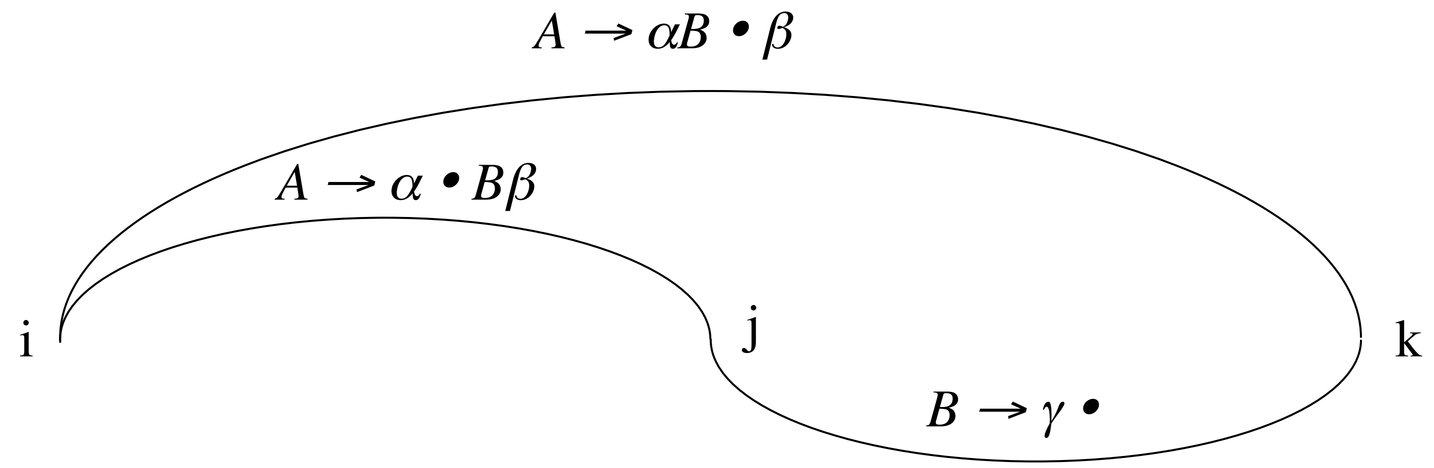
IF the chart contains the edges:

$$(i, j, A \rightarrow \alpha \bullet B\beta) \text{ and } (j, k, B \rightarrow \gamma \bullet)$$

THEN add the new edge:

$$(i, k, A \rightarrow \alpha B \bullet \beta)$$

(α, β, γ possibly empty strings of symbols)



Fundamental Rule of Chart Parsing

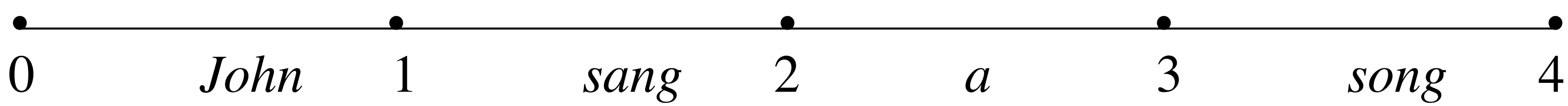
Fundamental rule only applies to chart containing active and inactive edges.

- How do we get started

Initialization:

Initially chart contains inactive edges corresponding to words in the input string:

e.g. for input *John sang a song*



Rule Invocation

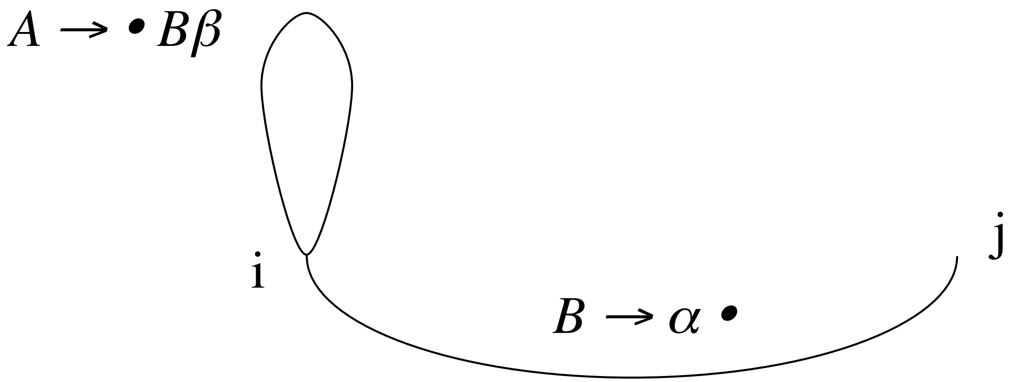
Bottom-Up :

IF you add an edge $(i, j, B \rightarrow \alpha \bullet)$

THEN for every rule of the form

$$A \rightarrow B\beta$$

add an edge $(i, i, A \rightarrow \bullet B\beta)$



Rule Invocation

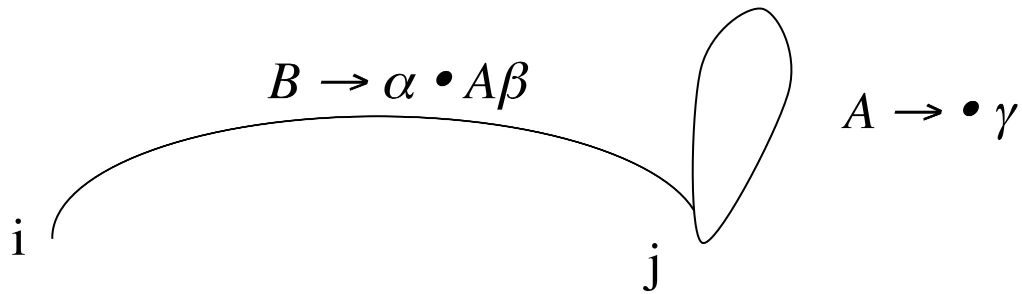
Top-Down:

IF you add an edge $(i, j, B \rightarrow \alpha \bullet A\beta)$

THEN for every rule of the form

$$A \rightarrow \gamma$$

add an edge $(j, j, A \rightarrow \bullet \gamma)$



Comparing CFGs and FSAs

FSAs:

- recognition is efficient – linear time; but
- the formalism is not very expressive.

CFGs:

- the basic parsing (recognition) strategies are not efficient – exponential time; but
- using dynamic programming techniques we can do better than this (Chart parsing; CKY algorithm; Earley algorithm); and
- CFGs are more expressive than FSAs

Comparing CFGs and FSAs

- Any language describable with a FSA is describable with a CFG.
- There are languages that can be described with a CFG that cannot be described with a FSA.

  Regular $\subset$ Context Free
- There is a general agreement that NLs are not Regular languages (i.e. cannot be adequately described with FSAs)
- Much of the syntax of the world's NLs seems to be Context Free (i.e. can be adequately described with CFGs).

Pros and Cons of CFGs

Advantages:

- Can describe infinite languages and assign appropriate syntactic structures
- Recognition (parsing) procedures can be implemented reasonably efficiently – $O(n^3)$:
  - Earley algorithm (Chart Parsing)
  - Cocke-Kasami-Younger (CKY) algorithm
  - Tomita's generalized LR parser

Pros and Cons of CFGs

- NLs ≅ CFGLs?
  - Long-standing argument
  - Arguably some NLs are non-CFLs (e.g. Swiss German – Shieber 1985)

Pros and Cons of CFGs

Disadvantages:

- Difficult to capture certain NL phenomena appropriately/adequately/elegantly:
  - agreement
  - subcategorization
  - generalizations over word/constituent order
  - relationships between different sentence types
- Some NL phenomena appear to require greater mathematical expressivity (i.e. there is evidence that some NLs are not CFLs)

Grammar equivalence

- Two grammars are **weakly equivalent** if they generate the same language (i.e. the same set of strings)
- Two grammars are **strongly equivalent** if they generate the same language *and* they assign the same phrase structure to each sentence

Mildly context-sensitive grammars (e.g. TAGs, Tree Adjoining Grammars)

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3. Features and Unification

- Limitations of CFGs
- Unification-Based Grammars
  - Feature Structures
  - Unification
  - The PATR Formalism
  - Typed Feature Structures

Agreement phenomena

Verbs have to “agree” with subjects

NP	VP	
the boy	*sees the girl(s)*	singular
the boys	*see the girl(s)*	plural

Agreement phenomena

S → NPs VPs	VPs → Vs NPs
S → NPp VPp	VPs → Vs NPp
NPs → DETs Ns	VPp → Vp NPs
NPp → DETp Np	VPp → Vp NPp
DETs → *the*	Vs → *sees*
DETp → *the*	Vp → *see*
Ns → *boy*	Ns → *girl*
Np → *boys*	Np → *girls*

Subcategorization

Different verbs may require different complements

VP $\rightarrow$ V1	(*die*)
VP $\rightarrow$ V2 NP	(*love*)
VP $\rightarrow$ V3 NP NP	(*give*)
VP $\rightarrow$ V4 NP PP	(*put*)
VP $\rightarrow$ V5 NP S	(*tell*)
VP $\rightarrow$ V6 S	(*believe*)
and so on…	

Unbounded Dependency Constructions

E.g. Wh-questions:

Who did Bill see ε?

Who did Tom say that Bill saw ε?

Who did Anna believe Tom said that Bill saw ε?

- Correct interpretation of *who* depends on structure which is arbitrarily distant
- Difficult to capture UDCs with simple CFGs

Criteria for Formalism Design in NLP

Generative Power: can the formalism describe the language at all?

Notational Expressivity: can the formalism capture the appropriate generalizations?

Computational Effectiveness: does the formalism have a sensible, practical computational interpretation?

Note: simple CFGs score quite well on the first and third criteria; less well on the second.

Unification-Based Grammars

A family of related grammar formalisms.

UBGs can be viewed as extensions of CFGs which

- make use of constraints on feature values (to capture agreement, etc.)
- make use of syntactic features and allow underspecification of linguistic objects (categories or other representations)
- employ unification as a consistency checking / information merging operation

Examples of UBGs

- FUG (Kay)
- LFG (Bresnan & Kaplan)
- GPSG (Gazdar, Klein, Pullum & Sag)
- HPSG (Pollard & Sag)
- PATR (Shieber)
- CUG (Uszkoreit)
- UCG (Calder et el.)
- DUG (Hellwig)
- RUG (Carlson)
- TUG (Popovich)

Feature Structures

UBGs employ record-like objects to represent categories.

Third person singular NP:

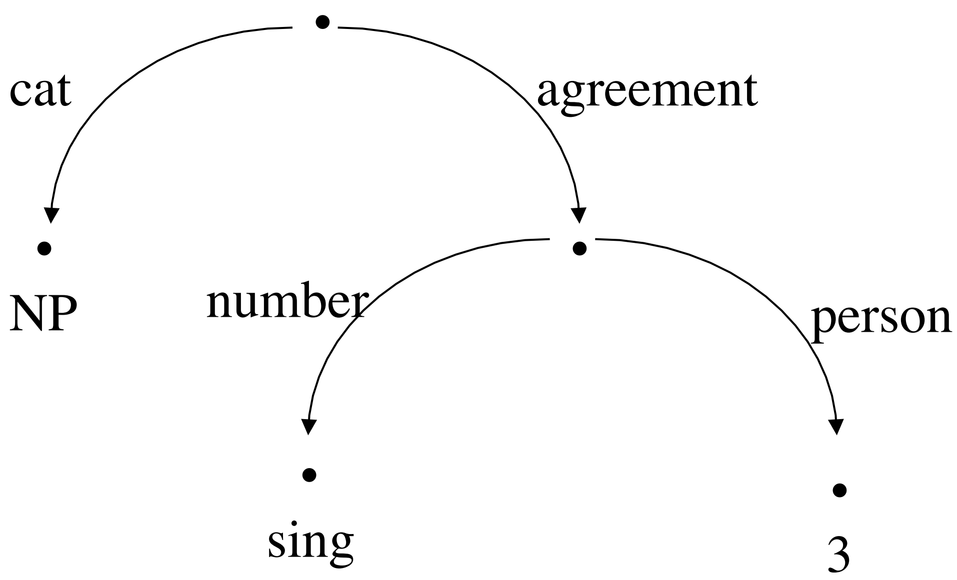
$$\begin{bmatrix} \textsc{cat} & \text{NP} \\ \textsc{agreement} & \begin{bmatrix} \textsc{number} & \text{sing} \\ \textsc{person} & 3 \end{bmatrix} \end{bmatrix}$$

- made up of features (`cat`, `agreement`, `number`, `person`) and values
- values may be *simple* (e.g., `NP`, `sing` and `3`) or *complex*:

$$\begin{bmatrix} \textsc{number} & \text{sing} \\ \textsc{person} & 3 \end{bmatrix}$$

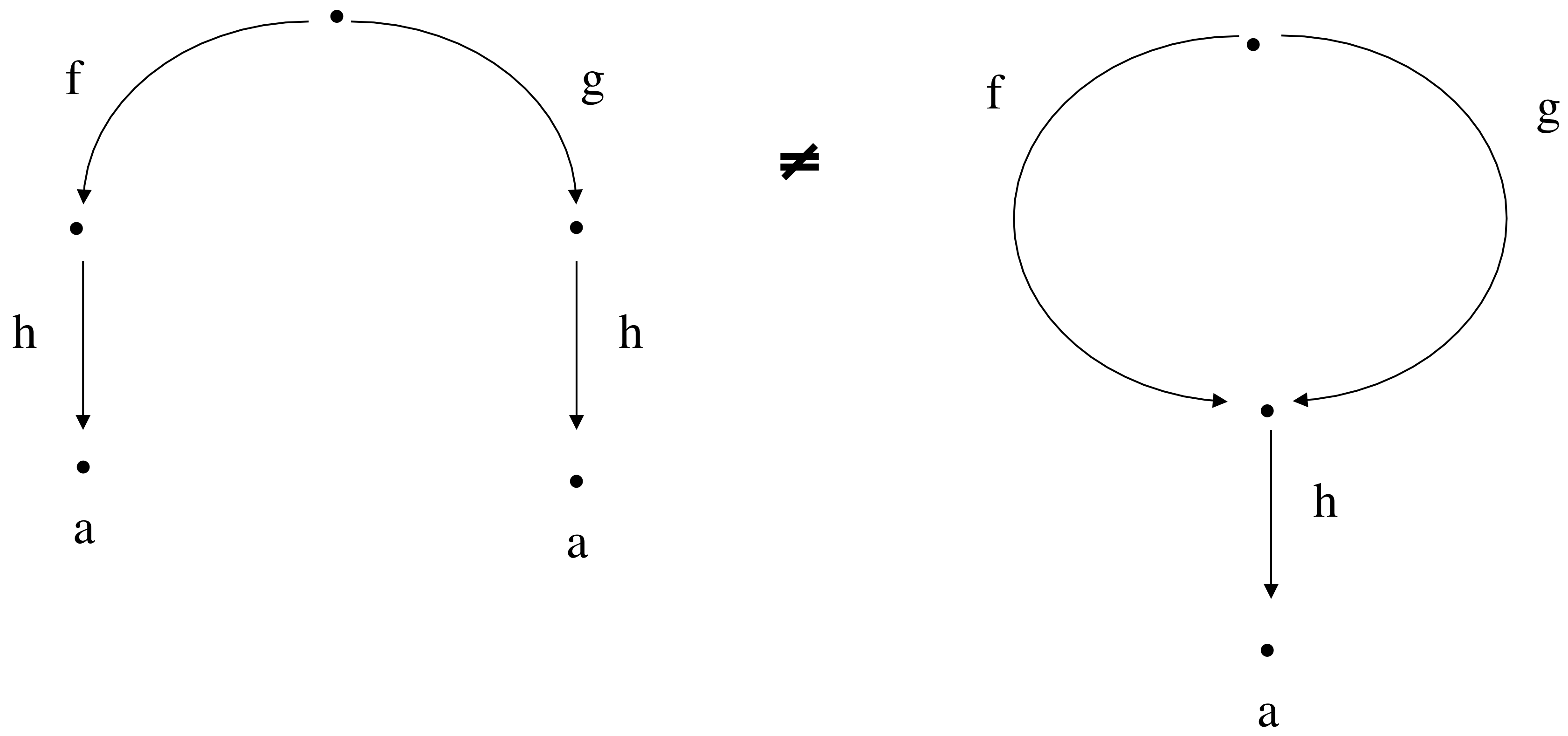
Feature Structures

Feature structures may be drawn as directed graphs:



Feature Structures

Feature structures may be *re-entrant*:



Feature Structures

Feature structures may be *re-entrant*:

$$\begin{bmatrix} \mathrm{F} & \begin{bmatrix} \mathrm{H} & \mathrm{a} \end{bmatrix} \\ \mathrm{G} & \begin{bmatrix} \mathrm{H} & \mathrm{a} \end{bmatrix} \end{bmatrix} \neq \begin{bmatrix} \mathrm{F} & \boxed{1} \begin{bmatrix} \mathrm{H} & \mathrm{a} \end{bmatrix} \\ \mathrm{G} & \boxed{1} \end{bmatrix}$$

Reentrant Feature Structures

A linguistic example:

$$\begin{bmatrix} \text{CAT} & \text{S} \\ \text{HEAD} & \begin{bmatrix} \text{AGREEMENT} & \boxed{1} \begin{bmatrix} \text{NUMBER} & \textsc{sg} \\ \text{PERS} & \textsc{3rd} \end{bmatrix} \\ \text{SUBJECT} & \begin{bmatrix} \text{AGREEMENT} & \boxed{1} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Feature Structures

Feature structures allow for underspecification of categories

Singular NP:

$$\begin{bmatrix} \text{CAT} & \text{NP} \\ \text{AGREEMENT} & \begin{bmatrix} \text{NUMBER} & \text{sing} \end{bmatrix} \end{bmatrix}$$

Nominative NP:

$$\begin{bmatrix} \text{CAT} & \text{NP} \\ \text{CASE} & \text{nom} \end{bmatrix}$$

Unification

F1 =

$$\begin{bmatrix} \text{CAT} & \text{NP} \\ \text{AGREEMENT} & \begin{bmatrix} \text{NUMBER} & \text{sing} \end{bmatrix} \end{bmatrix}$$

F2 =

$$\begin{bmatrix} \text{CAT} & \text{NP} \\ \text{AGREEMENT} & \begin{bmatrix} \text{PERSON} & 3 \end{bmatrix} \\ \text{CASE} & \text{nominative} \end{bmatrix}$$

F1 $\cup$ F2 =

$$\begin{bmatrix} \text{CAT} & \text{NP} \\ \text{AGREEMENT} & \begin{bmatrix} \text{NUMBER} & \text{sing} \\ \text{PERSON} & 3 \end{bmatrix} \\ \text{CASE} & \text{nominative} \end{bmatrix}$$

Unification

Unification fails when feature structures are incompatible

$$\mathbf{F3} = \begin{bmatrix} \text{CAT} & \text{VP} \\ \text{AGREEMENT} & \begin{bmatrix} \text{NUMBER} & \mathbf{sing} \\ \text{PERSON} & 3 \end{bmatrix} \end{bmatrix}$$

$$\mathbf{F4} = \begin{bmatrix} \text{CAT} & \text{VP} \\ \text{AGREEMENT} & \begin{bmatrix} \text{NUMBER} & \mathbf{plu} \end{bmatrix} \\ \text{VFORM} & \text{tensed} \end{bmatrix}$$

$$\mathbf{F3} \cup \mathbf{F4} = \mathbf{FAIL}$$

The PATR Formalism

Originally introduced by Shieber and his colleagues at SRI International

$S \longrightarrow NP\ VP$

$C_0 \longrightarrow C_1\ C_2$

$\langle C_0 \text{ cat}\rangle = \text{S}$

$\langle C_1 \text{ cat}\rangle = \text{NP}$

$\langle C_2 \text{ cat}\rangle = \text{VP}$

$\langle C_1 \text{ case}\rangle = \text{nominative}$

$\langle C_1 \text{ agreement}\rangle = \langle C_2 \text{ agreement}\rangle$

Typed Feature Structures

Limitations of simple feature structure formalisms:

- No way to constrain possible values of a feature (e.g., the feature `NUMBER` can take only `SING` and `PLU` values)
- No way to capture generalization across feature structures (e.g., different types of English verb phrases)

Solution: use of **types**.

Typed Feature Structures

- Each feature structure is labeled by a type
- Each type has **appropriateness conditions** expressing which features are appropriate for it
- Types are organized in a **type hierarchy**
- Unification should take into account the types of feature structures in addition to unifying attributes and values

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4. Dependency Grammars

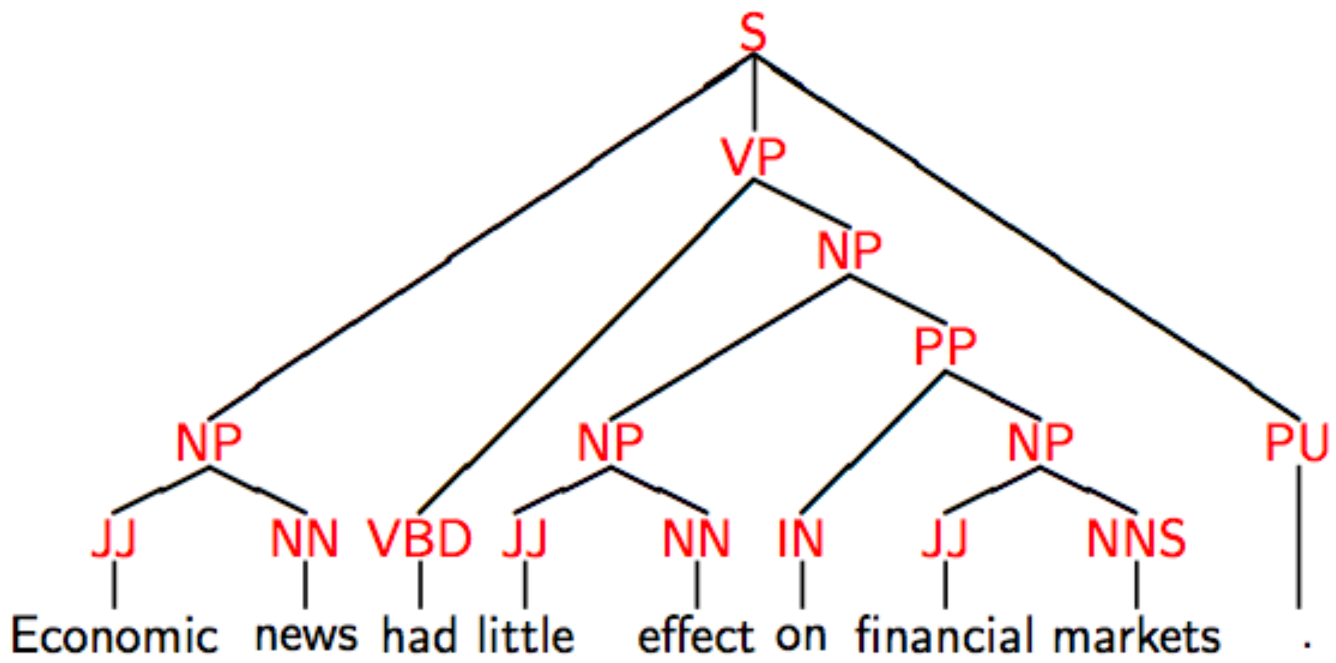
- Constituency vs. Dependency
- Dependency Grammars
- Dependency Parsing

some material taken from McDonald & Nivre ESSLLI 2007 course
“Introduction on Data-Driven Dependency Parsing”

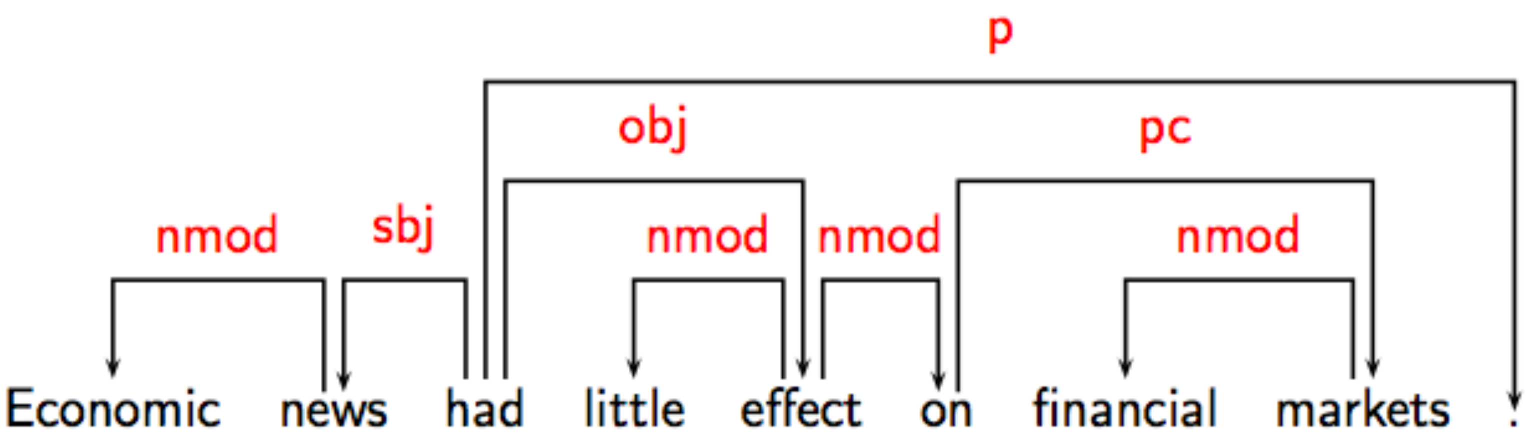
Dependency Grammars

- [Tesnière 1959]
- Syntactic structure of a sentence consists of lexical items, linked by binary asymmetric relations called dependencies.
- Dependency relations hold between a *head* (parent) and a *dependent* (daughter)

Phrase Structure



Dependency Structure



Constituency vs. Dependency

Phrase structure grammars

- Words appear only as leaves
- Internal nodes of trees consist of non-terminals

Dependency grammars

- No non-terminals
- Only words and binary relations between them

Constituency vs. Dependency

- Phrase structures explicitly represent
  - phrases (non-terminal nodes),
  - structural categories (non-terminal labels),
  - possibly some functional categories (grammatical functions).
- Dependency structures explicitly represent
  - head-dependent relations (directed arcs),
  - functional categories (arc labels),
  - possibly some structural categories (PoS).

Dependency Grammars

Family of grammatical formalisms differing in:

- Terminology (head/dependent, governor/ modifier, regent/subordinate, ...)
- Criteria adopted to establish dependency relations
- Criteria to identify heads and dependents

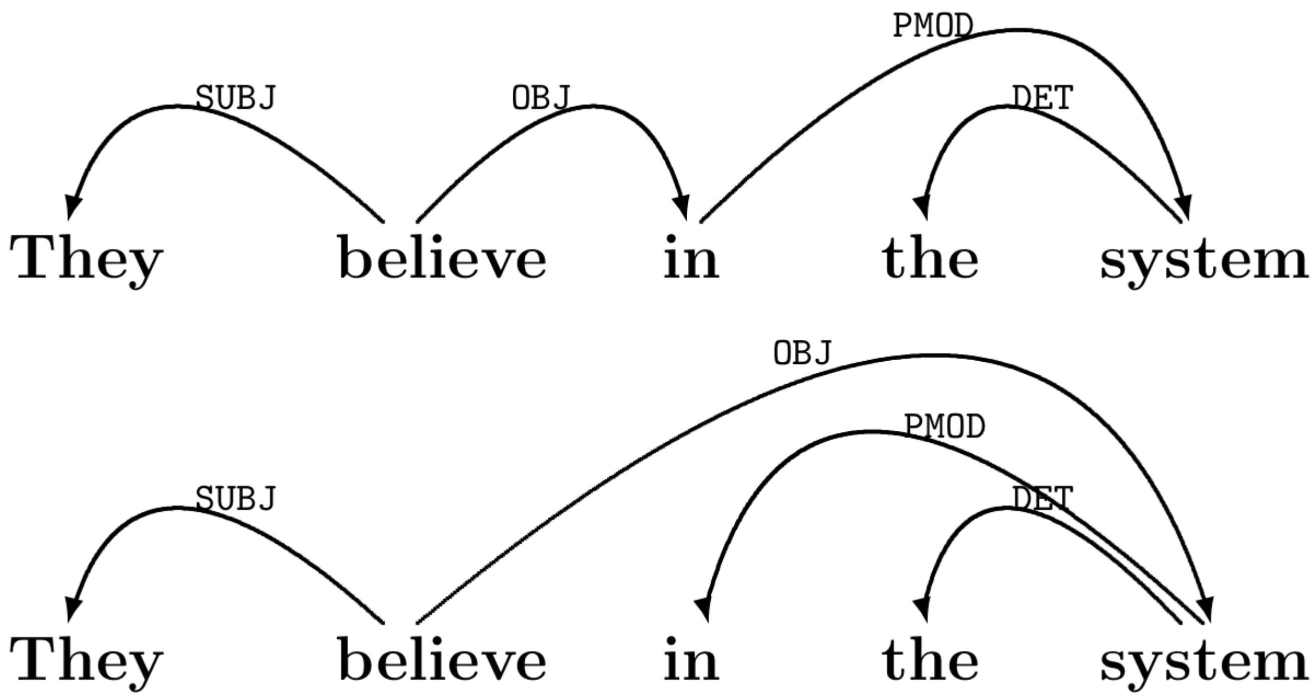
Dependency Relations

- Surface-oriented grammatical functions: *subject*, *object*, *adverbial*, …
- Semantically oriented roles: *agent*, *patient*, *goal*, …

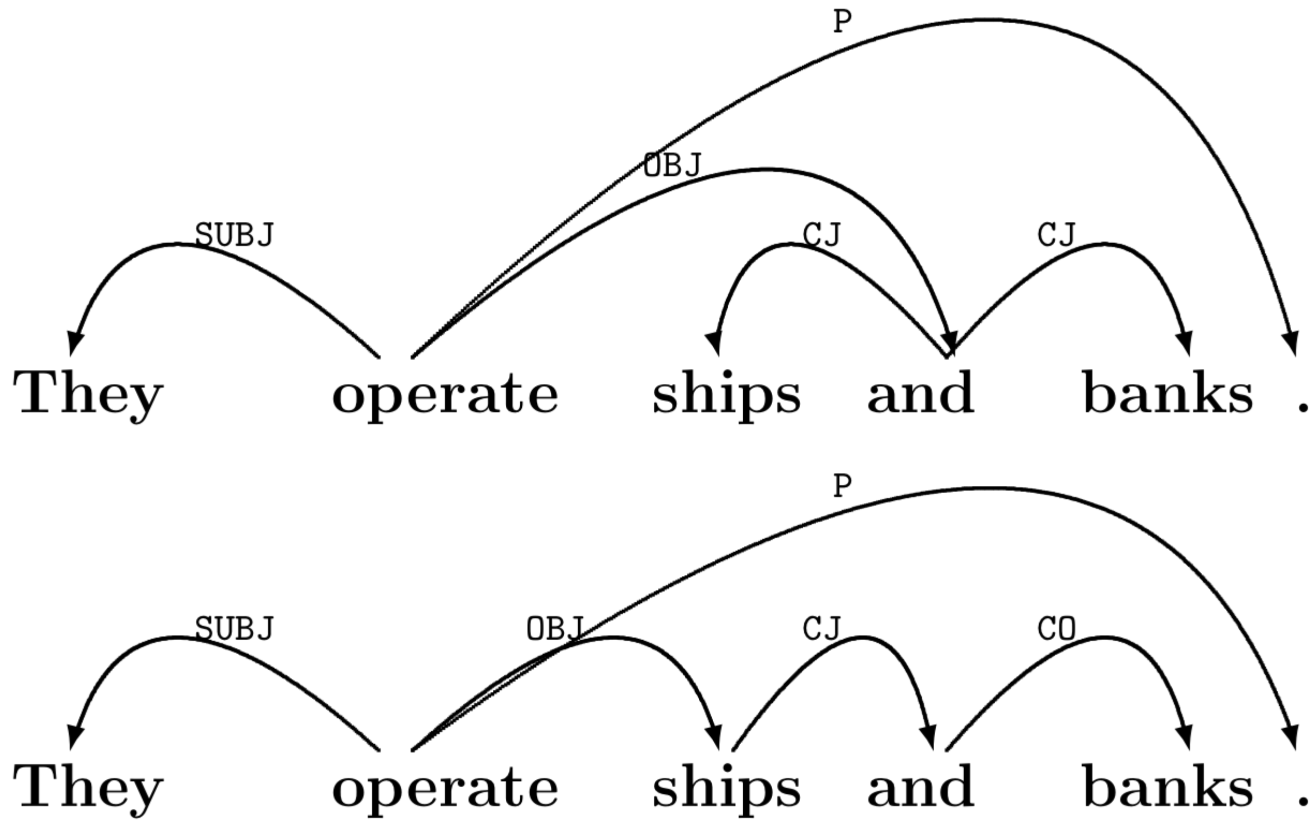
Problematic Constructions

- Grammatical function words: *syntactic* versus *semantic* heads
- Coordination: problematic in general

Function words



Coordination



Dependency Graphs

- A dependency structure can be defined as a directed graph *G*, consisting of
  - a set *V* of nodes (vertices),
  - a set *A* of arcs (directed edges),
  - a linear precedence order < on *V* (word order).

Dependency Graphs

- Labeled graphs:
  - Nodes in *V* are labeled with word forms (and annotation).
  - Arcs in *A* are labeled with dependency types:
    - $L=\{l_1, . . . , l_{|L|}\}$ is the set of permissible arc labels.
    - Every arc in *A* is a triple (i, j, k), representing a dependency from w_i to w_j with label l_k.

Dependency Parsing

- The problem:
  - Input: Sentence x=w_0, w_1, …, w_n with w_0=root
  - Output: Dependency graph $G = (V, A)$ for x where:
    - V={0, 1, . . . , n} is the vertex set,
    - A is the arc set, i.e., $(i, j, k) \in A$ represents a dependency from w_i to w_j with label $l_k \in L$