Dependency Parsing

L545

With thanks to Joakim Nivre and Sandra Kübler

Dependency Grammar

- Not a coherent grammatical framework: wide range of different kinds of dependency grammar
  - just as there are wide ranges of "generative syntax"
- Different core ideas than phrase structure grammar
- We will base a lot of our discussion on [Mel'čuk(1988)]

Dependency grammar is important for those interested in CL:

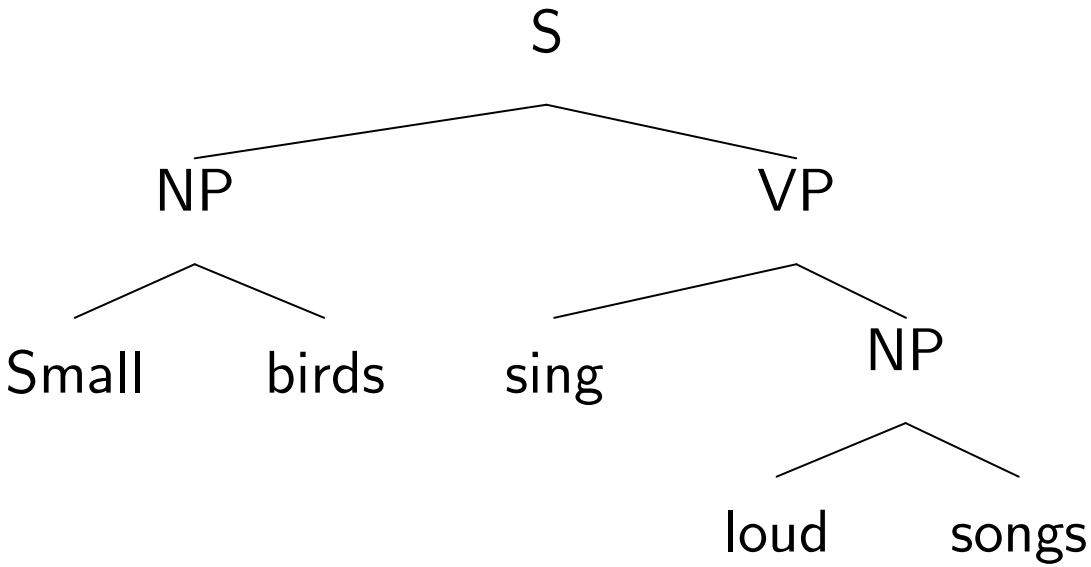
- Increasing interest in dependency-based approaches to syntactic parsing in recent years (e.g., CoNLL-X shared task, 2006)

Dependency Syntax

- The basic idea:
  - Syntactic structure consists of lexical items, linked by binary asymmetric relations called dependencies.
- In the (translated) words of Lucien Tesnière [Tesnière(1959)]:
  - The sentence is an *organized whole*, the constituent elements of which are *words*. [1.2] Every word that belongs to a sentence ceases by itself to be isolated as in the dictionary. Between the word and its neighbors, the mind perceives *connections*, the totality of which forms the structure of the sentence. [1.3] The structural connections establish *dependency* relations between the words. Each connection in principle unites a *superior* term and an *inferior* term. [2.1] The superior term receives the name *governor*. The inferior term receives the name *subordinate*. Thus, in the sentence *Alfred parle* [. . .], *parle* is the governor and *Alfred* the subordinate. [2.2]

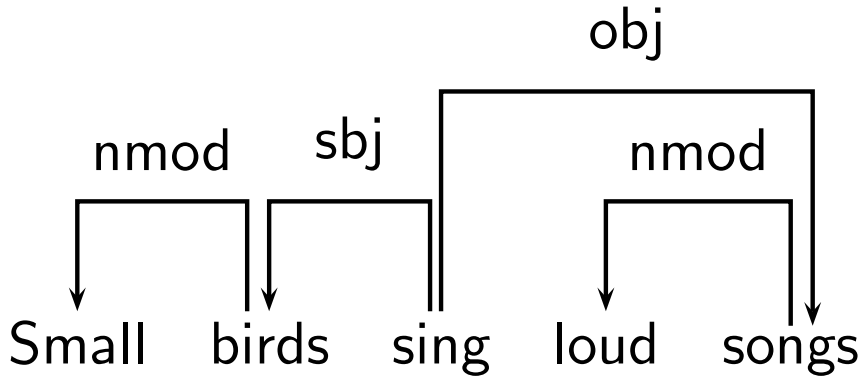
Overview: constituency

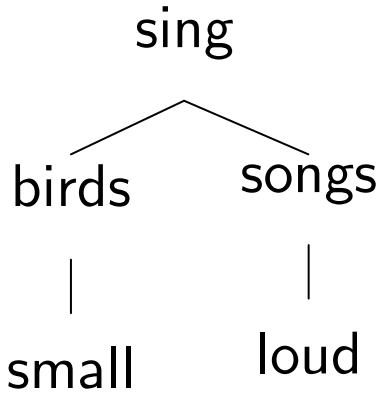
(1) Small birds sing loud songs



Overview: dependency

The corresponding dependency tree representations [Hudson(2000)]:





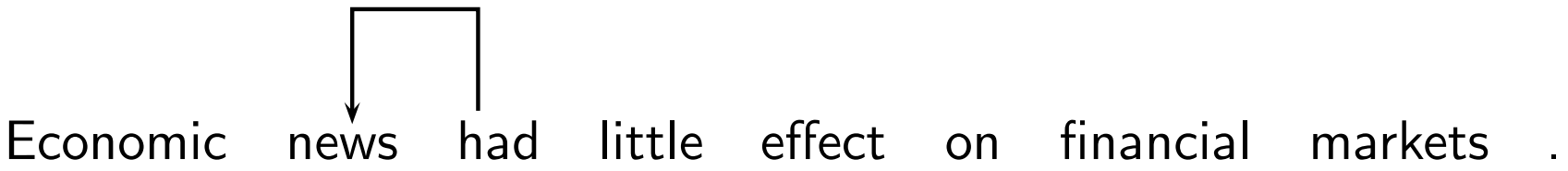
Constituency vs. Relations

- Dependency grammar is based on relationships between words, i.e., **dependency relations**
  - A $\rightarrow$ B means *A governs B* or *B depends on A* ...
  - Dependency relations can refer to syntactic properties, semantic properties, or a combination of the two
  - Relation examples: subject, object, complement, (pre-/post-)adjunct, etc.
    - Subject/Agent: *John* fished.
    - Object/Patient: Mary hit *John*.
- Phrase structure grammar is based on constituents
  - Grammatical relations are not usually seen as primitives, but as being derived from structure

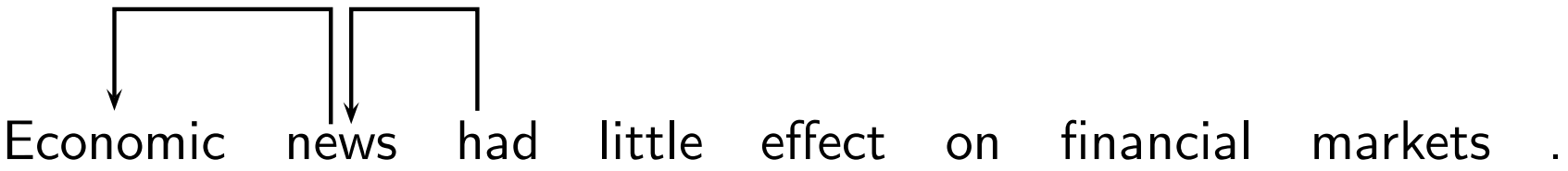
Dependency Structure

Economic news had little effect on financial markets .

Dependency Structure



Dependency Structure



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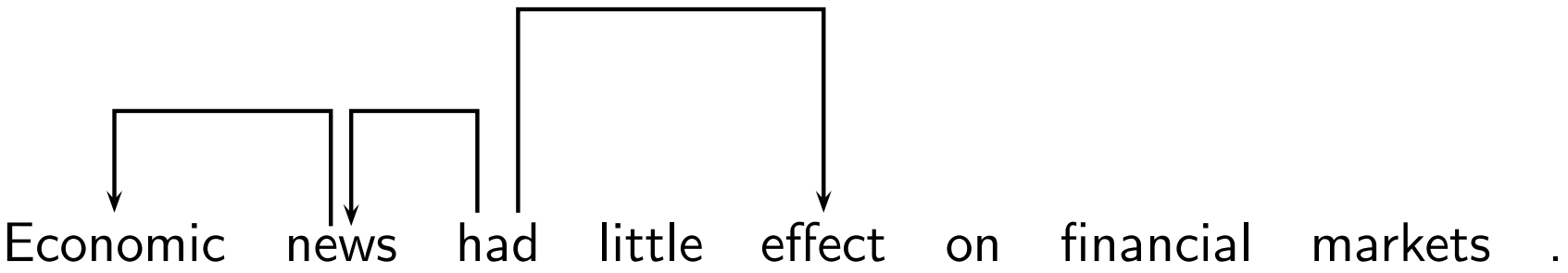

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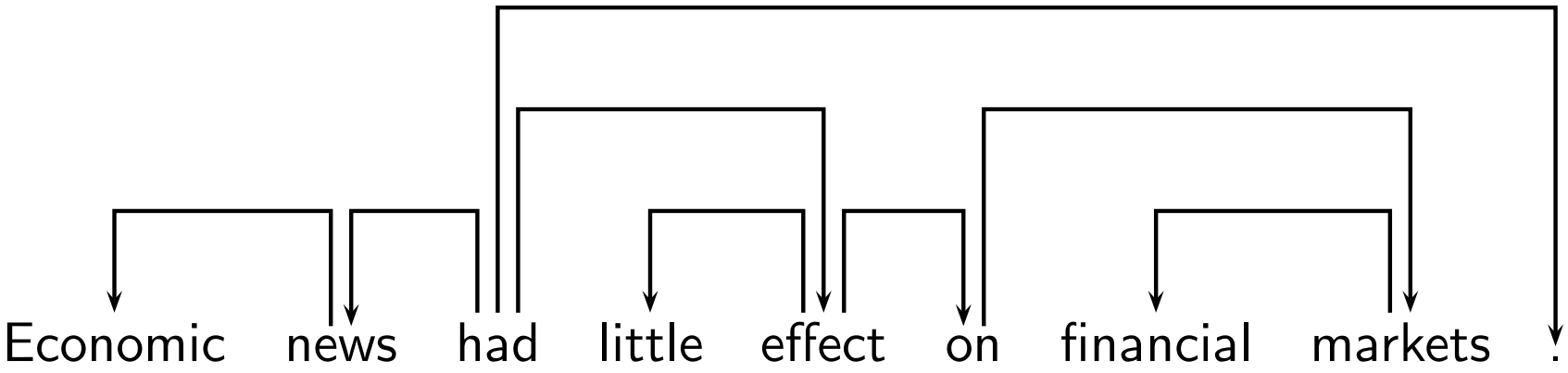

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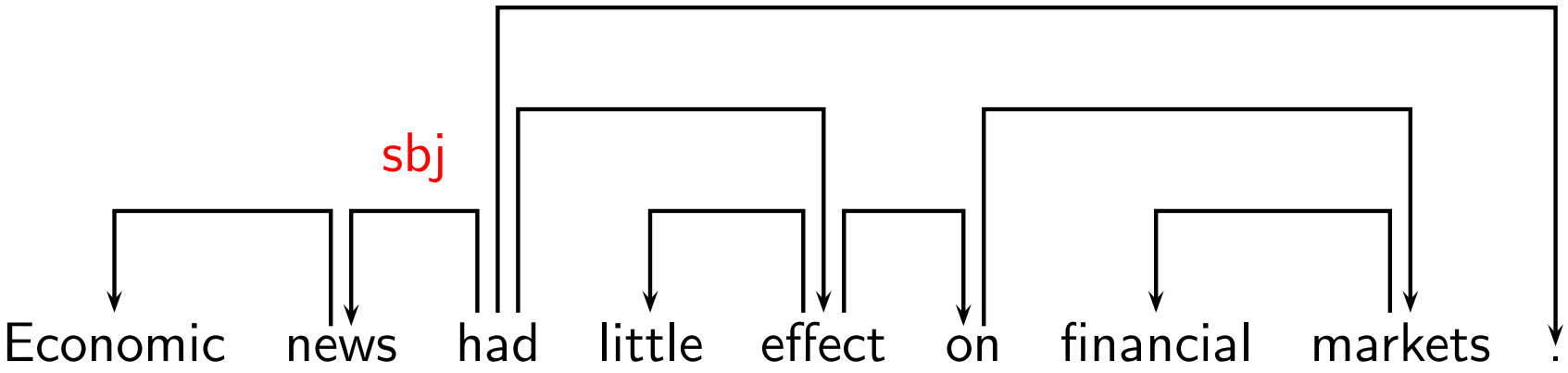

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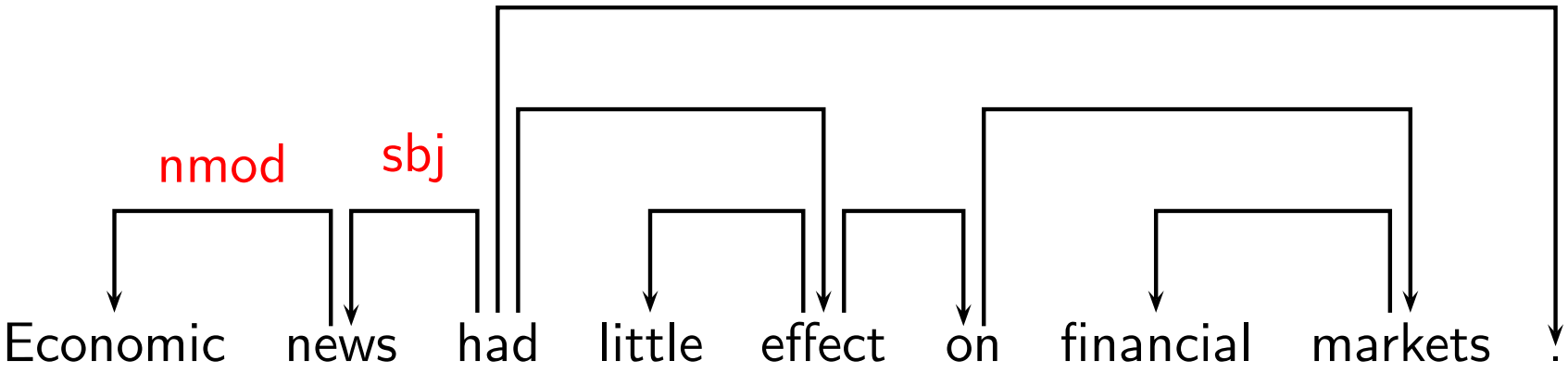

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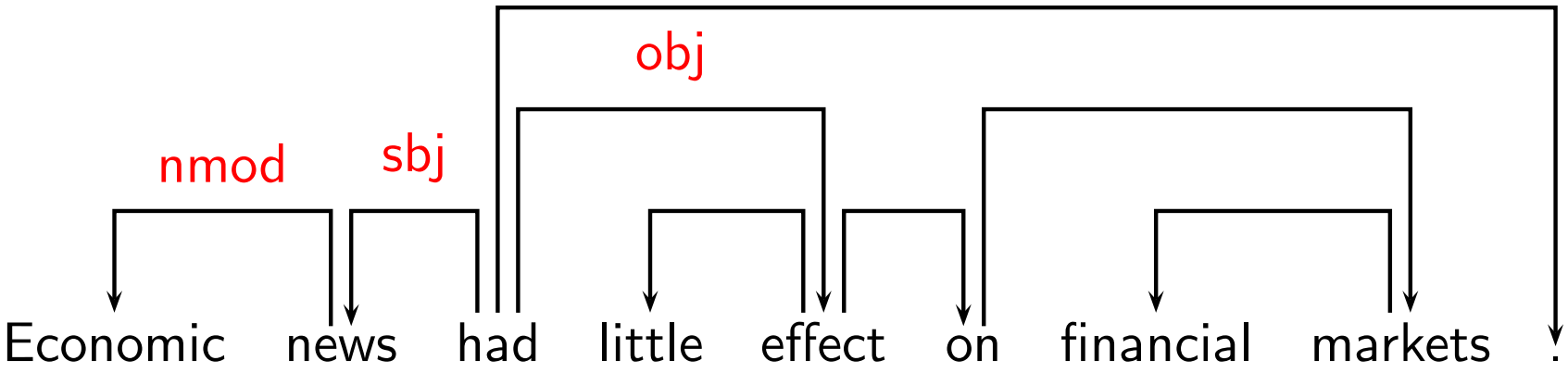

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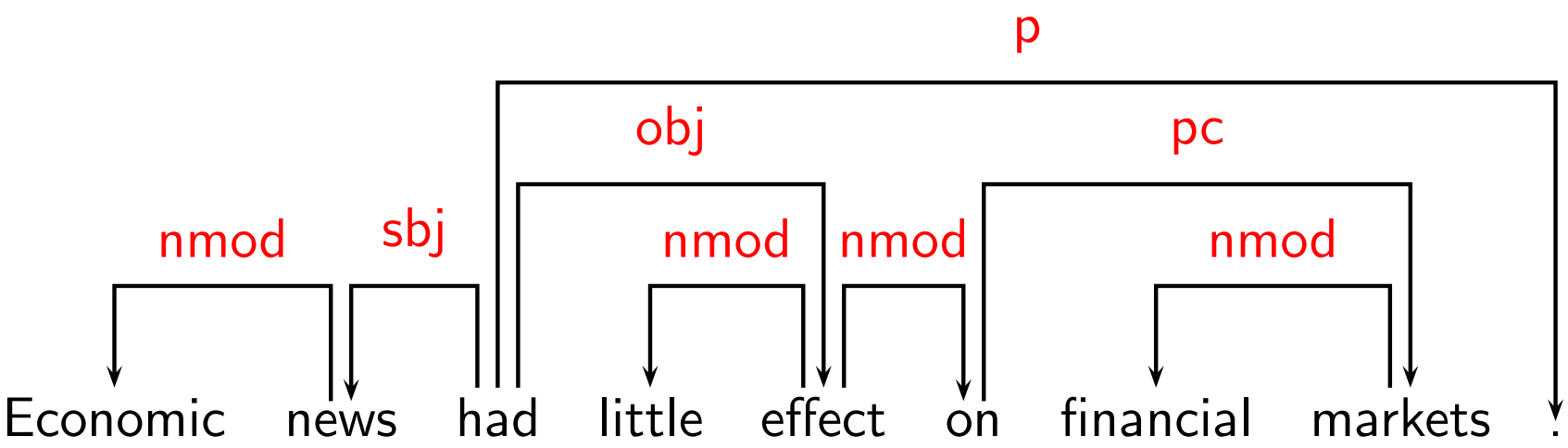
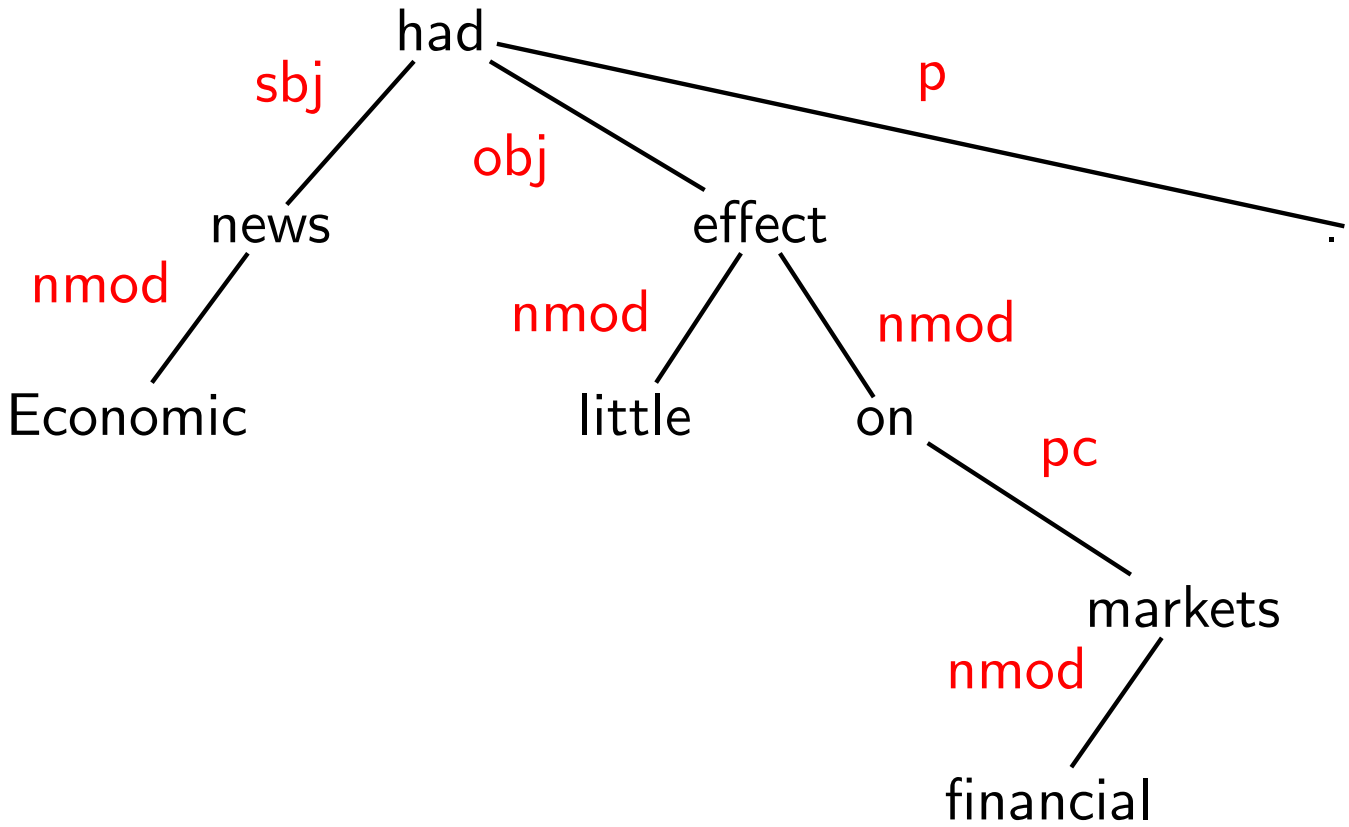


Terminology

Superior	**Inferior**
Head	Dependent
Governor	Modifier
Regent	Subordinate
⋮	⋮

Notational Variants



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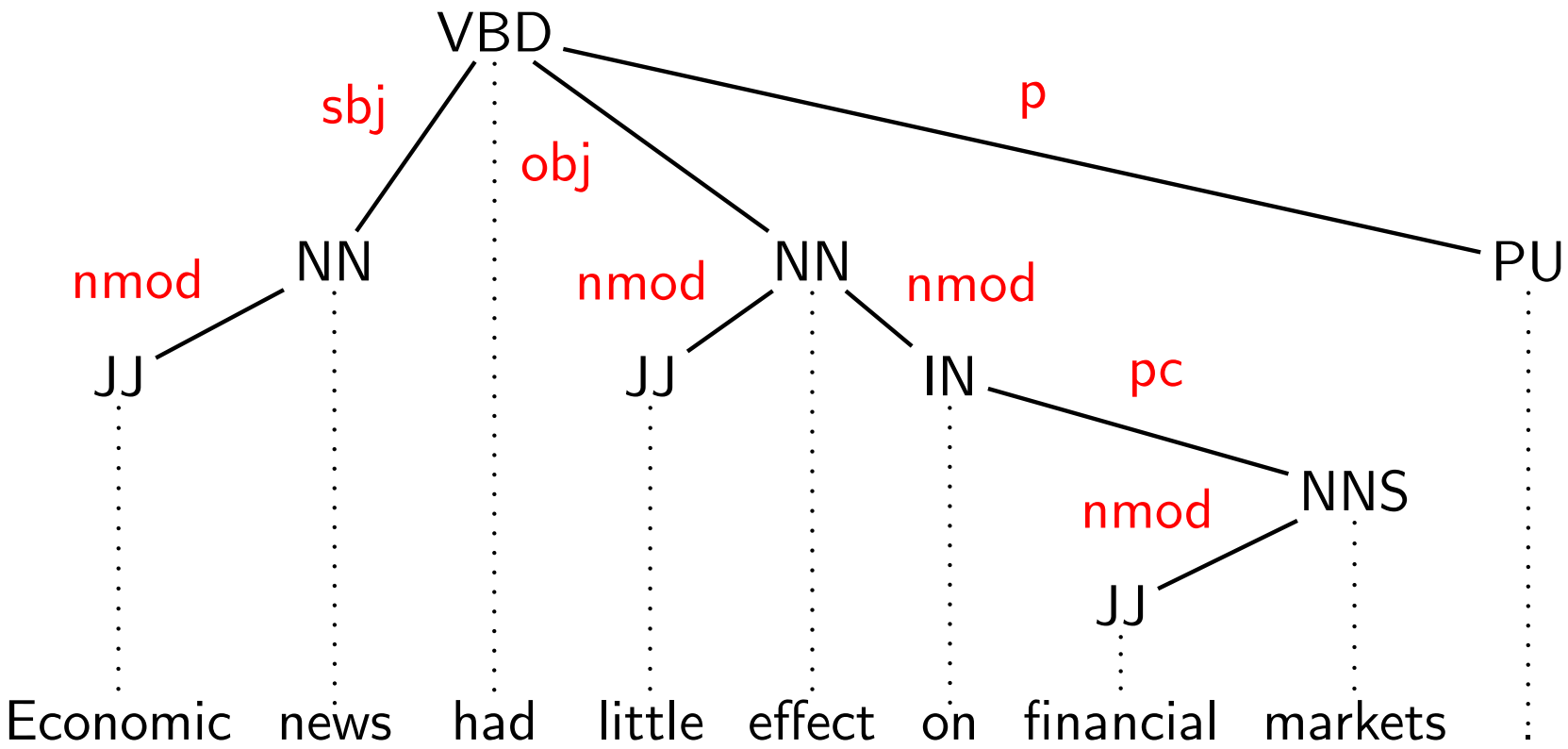

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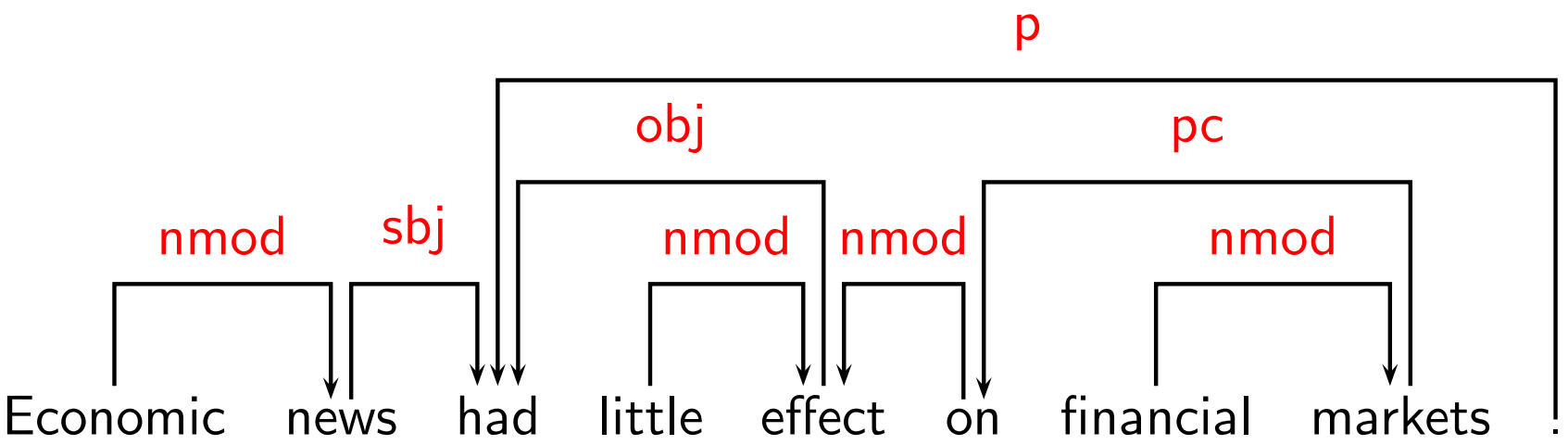

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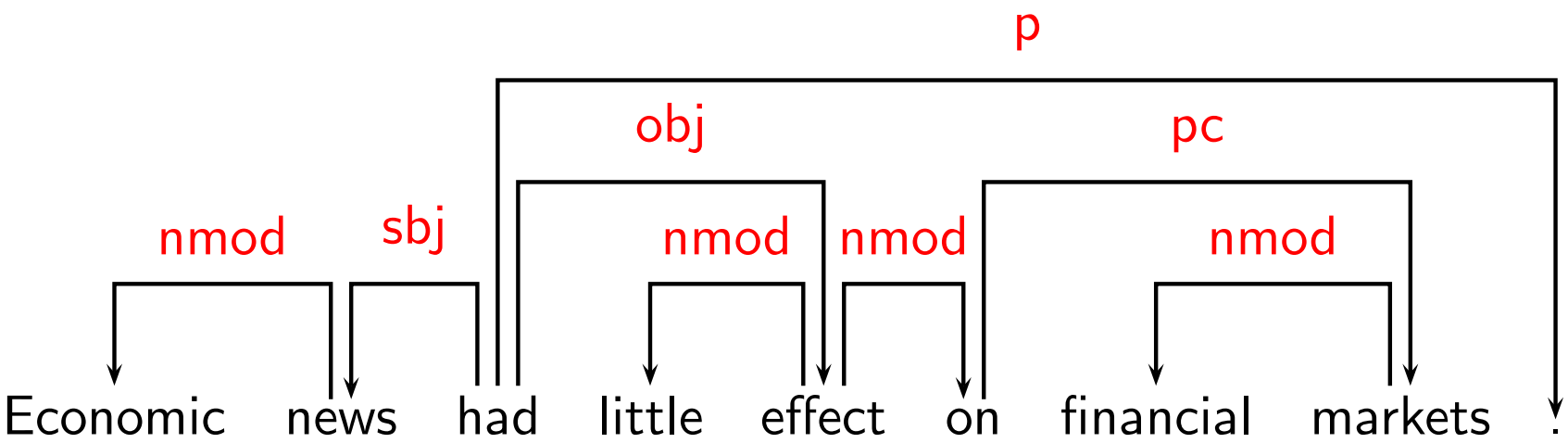
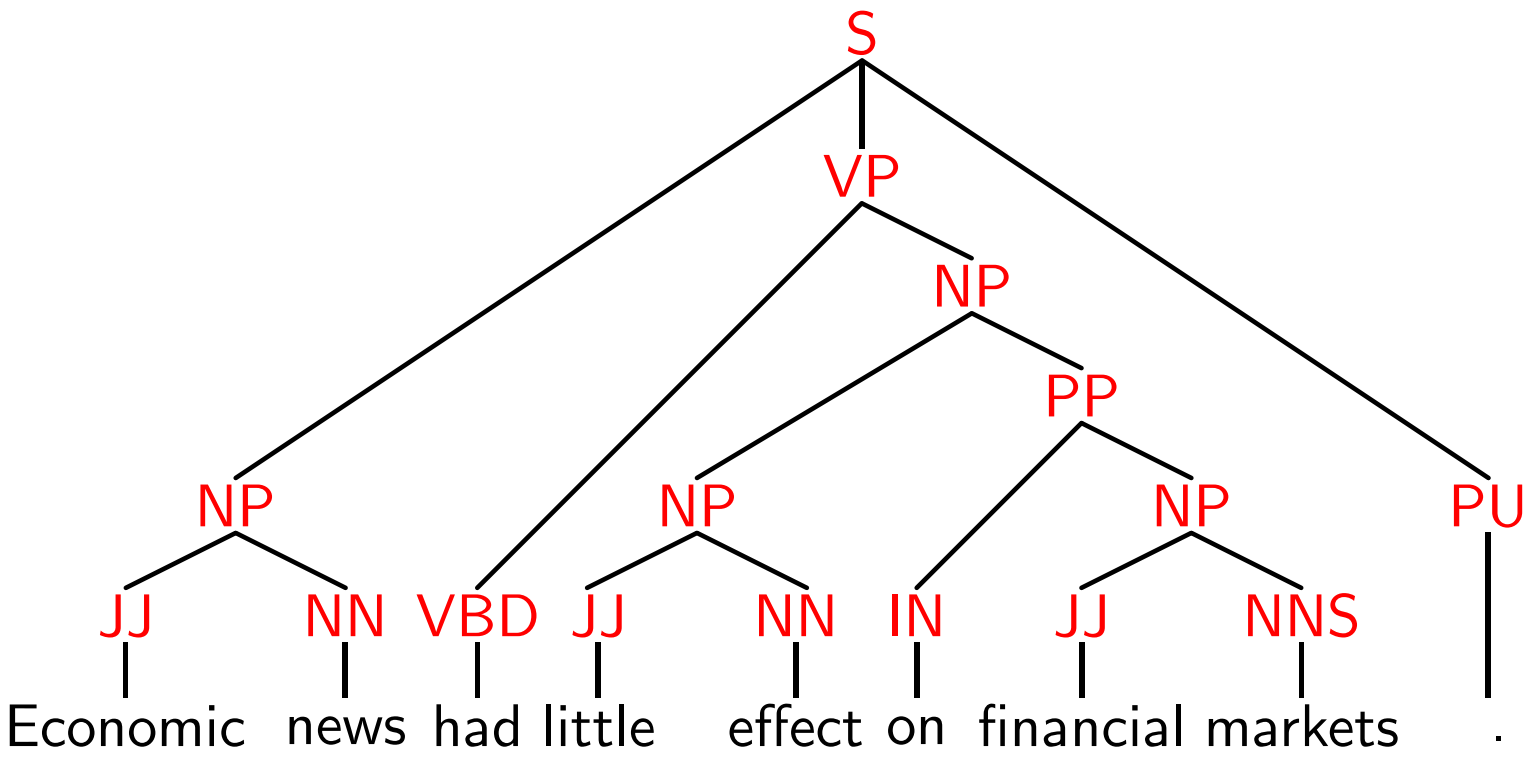


Phrase Structure



Comparison

- Dependency structures explicitly represent
  - head-dependent relations (directed arcs),
  - functional categories (arc labels),
  - possibly some structural categories (parts-of-speech).
- Phrase structures explicitly represent
  - phrases (nonterminal nodes),
  - structural categories (nonterminal labels),
  - possibly some functional categories (grammatical functions).
- Hybrid representations may combine all elements.

Some Theoretical Frameworks

- Word Grammar (WG) [Hudson(1984), Hudson(1990)]
- Functional Generative Description (FGD)
  [Sgall et al.(1986)Sgall, Hajičová and Panevová]
- Dependency Unification Grammar (DUG)
  [Hellwig(1986), Hellwig(2003)]
- Meaning-Text Theory (MTT) [Mel'čuk(1988)]
- (Weighted) Constraint Dependency Grammar ([W]CDG)
  [Maruyama(1990), Harper and Helzerman(1995),
  Menzel and Schröder(1998), Schröder(2002)]
- Functional Dependency Grammar (FDG)
  [Tapanainen and Järvinen(1997), Järvinen and Tapanainen(1998)]
- Topological/Extensible Dependency Grammar ([T/X]DG)
  [Duchier and Debusmann(2001),
  Debusmann et al.(2004)Debusmann, Duchier and Kruijff]

Some Theoretical Issues

- Dependency structure sufficient as well as necessary?
- Mono-stratal or multi-stratal syntactic representations?
- What is the nature of lexical elements (nodes)?
  - Morphemes?
  - Word forms?
  - Multi-word units?
- What is the nature of dependency types (arc labels)?
  - Grammatical functions?
  - Semantic roles?
- What are the criteria for identifying heads and dependents?
- What are the formal properties of dependency structures?

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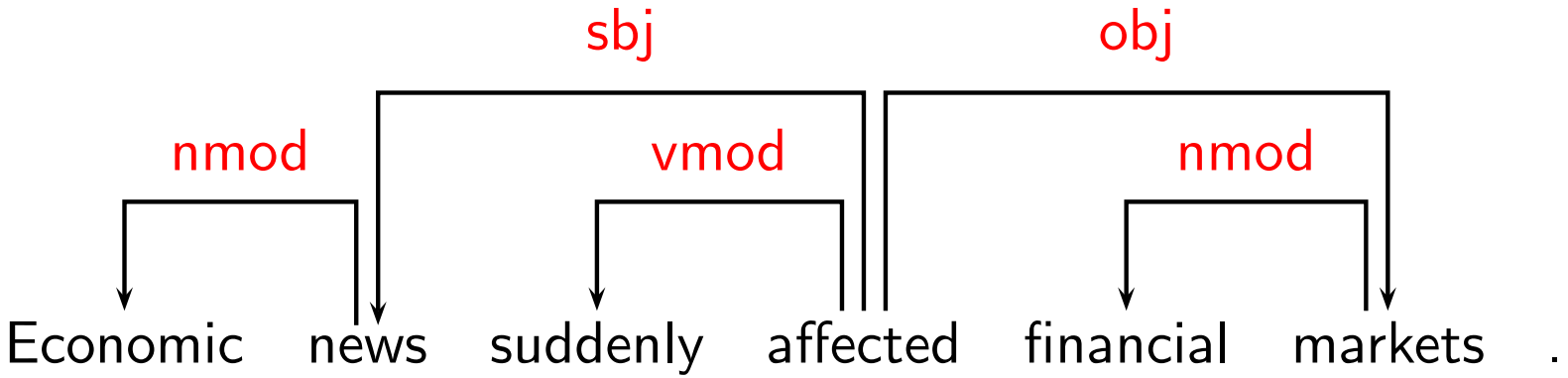
Some Clear Cases

Construction	Head	Dependent
Exocentric	Verb	Subject (sbj)
	Verb	Object (obj)
Endocentric	Verb	Adverbial (vmod)
	Noun	Attribute (nmod)



Some Tricky Cases

- Complex verb groups (auxiliary $\leftrightarrow$ main verb)
- Subordinate clauses (complementizer $\leftrightarrow$ verb)
- Coordination (coordinator $\leftrightarrow$ conjuncts)
- Prepositional phrases (preposition $\leftrightarrow$ nominal)
- Punctuation

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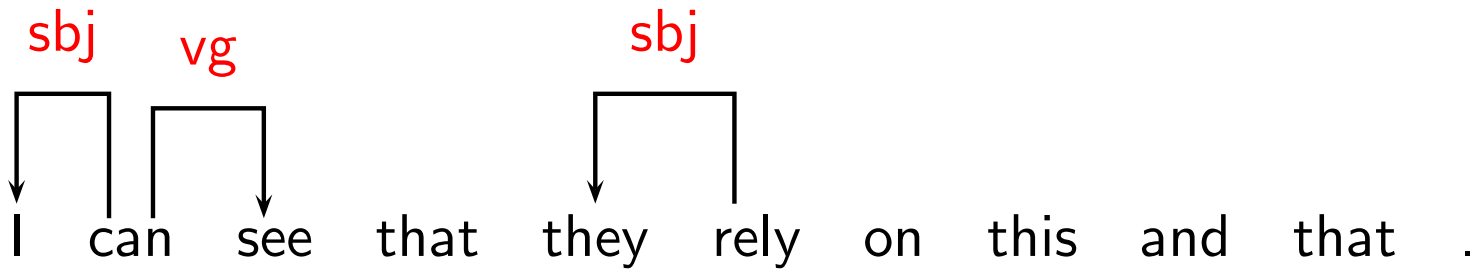

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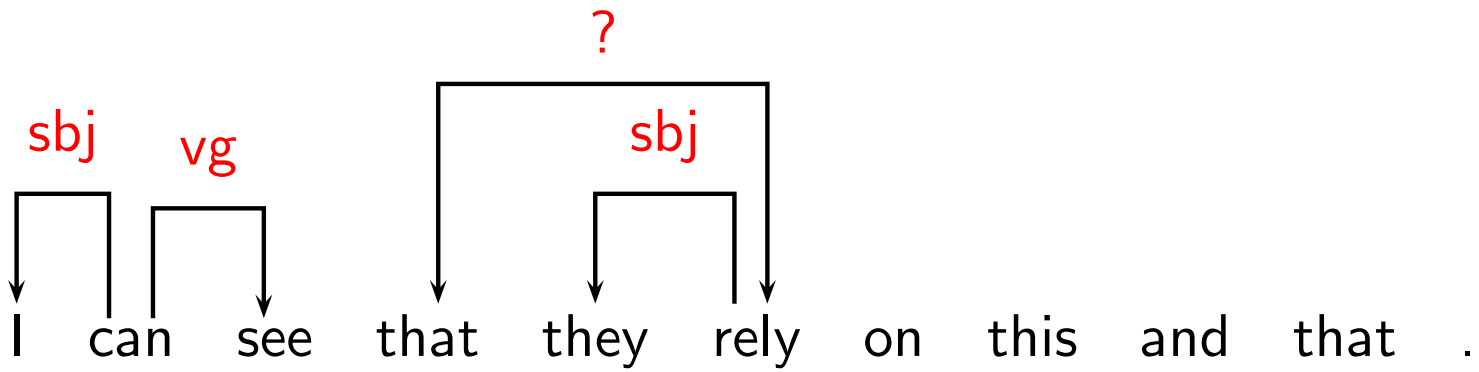

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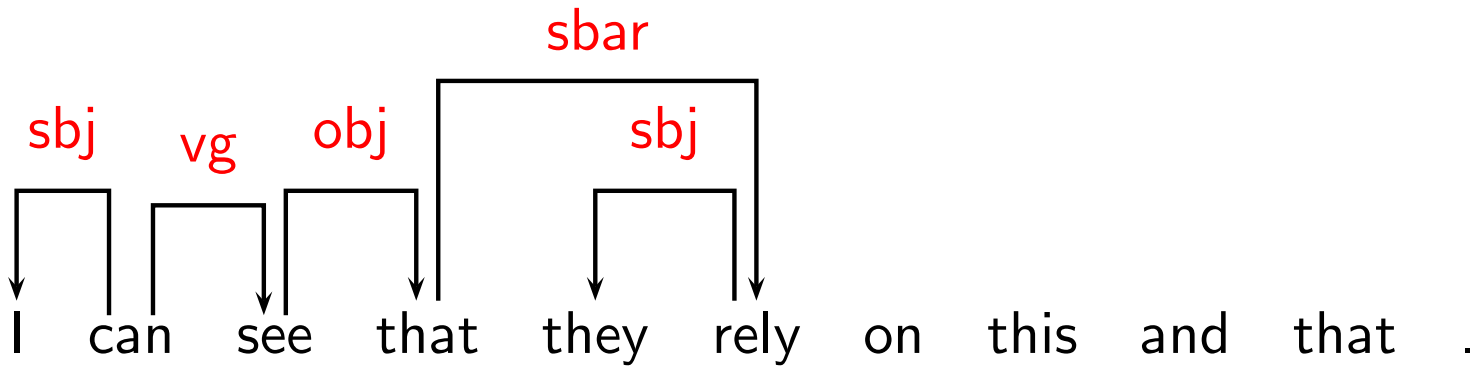

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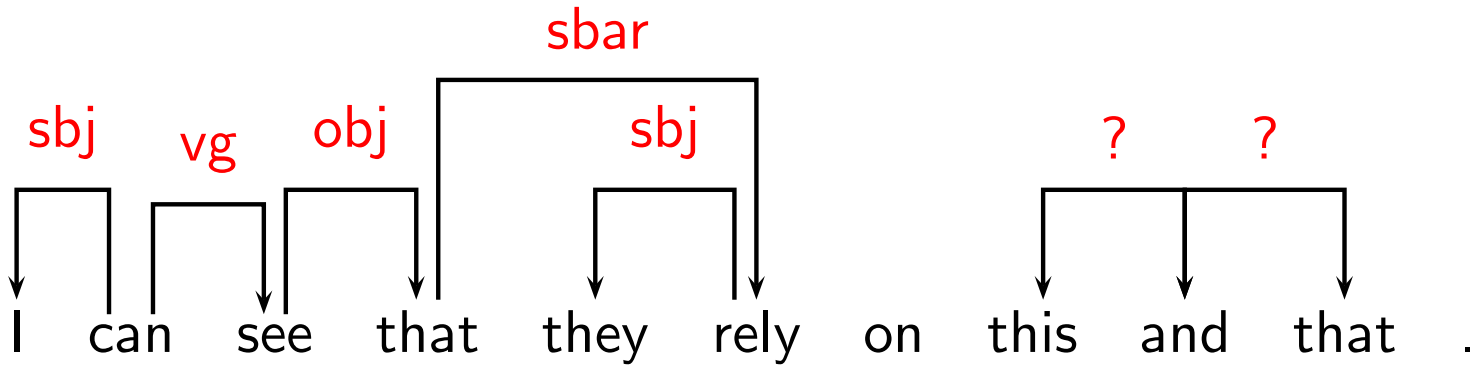

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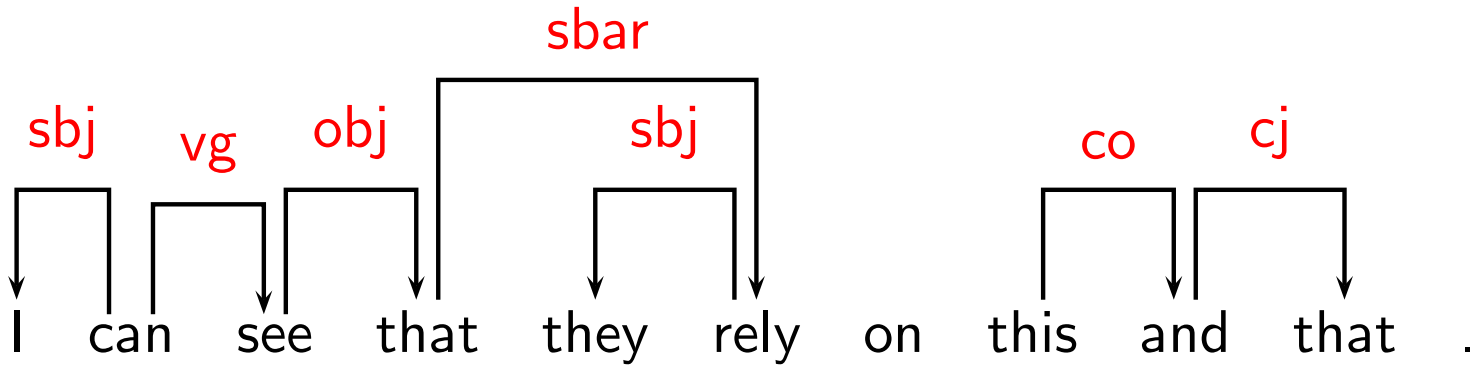

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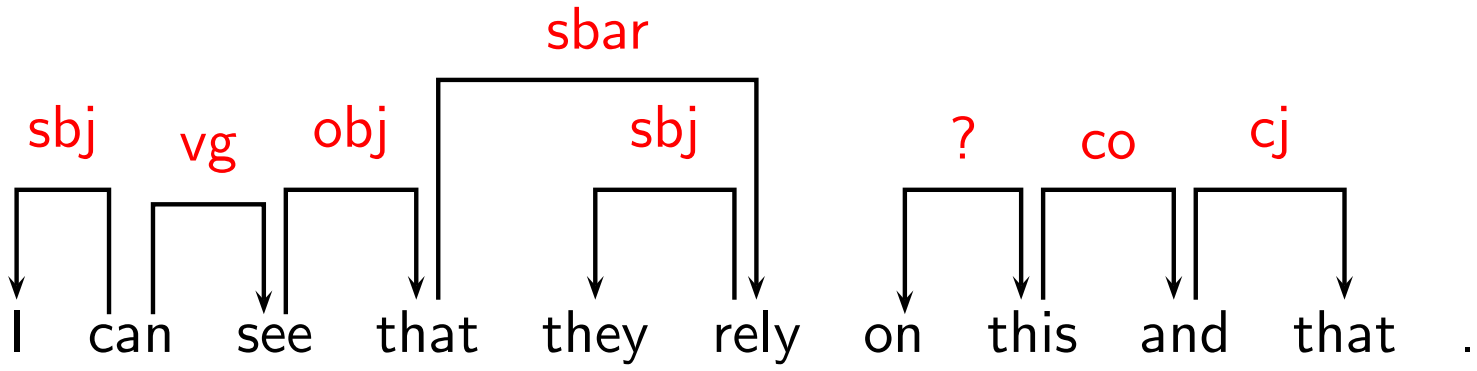

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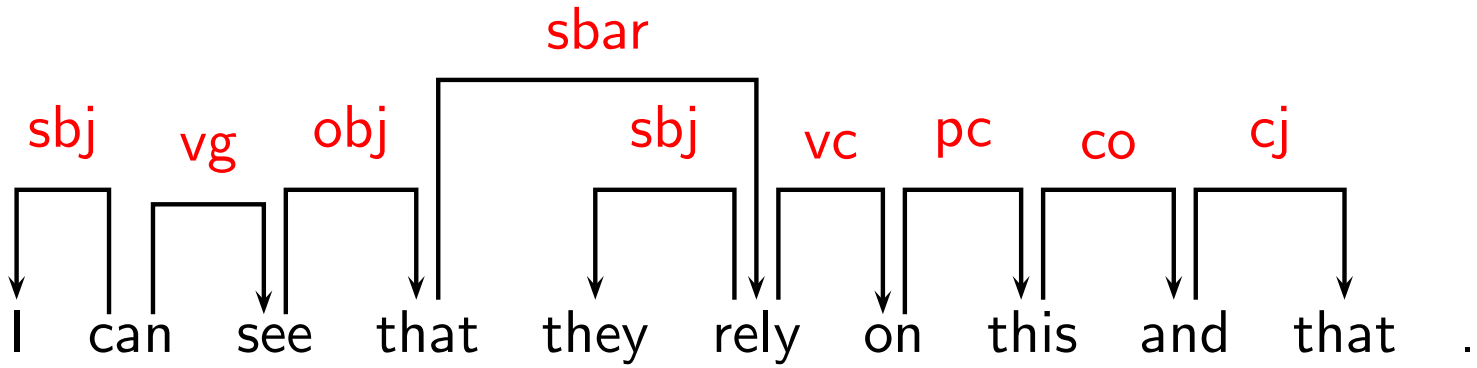

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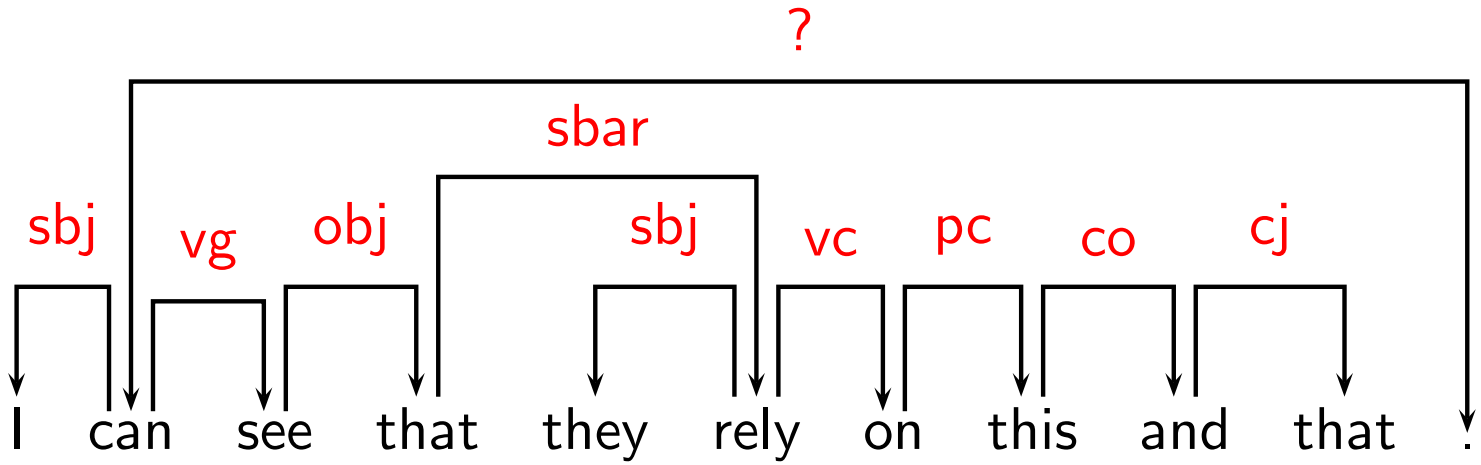

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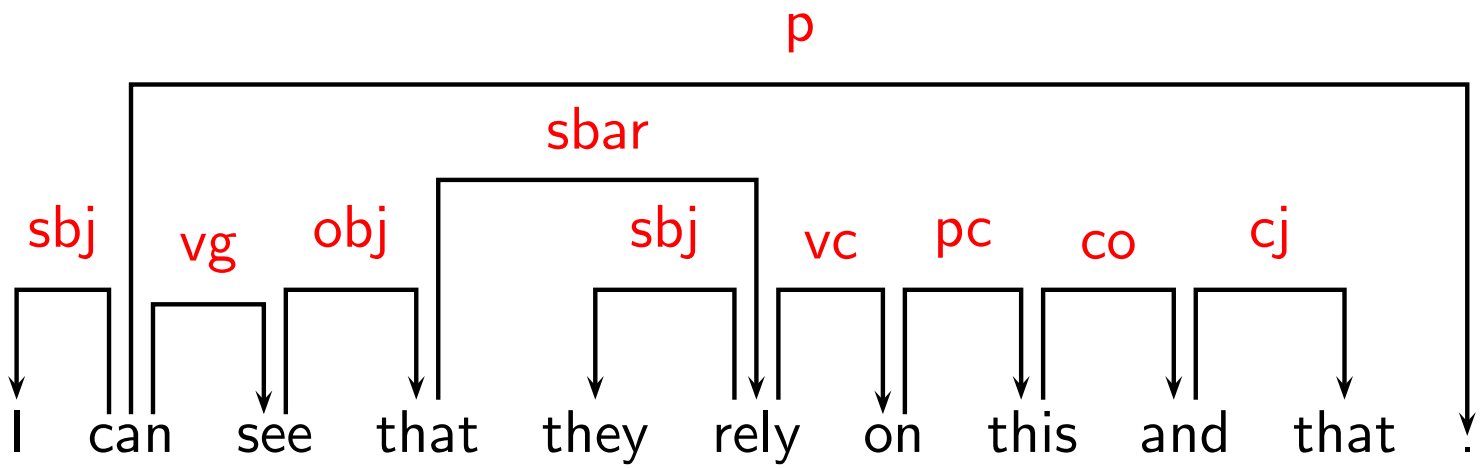


Dependency Graphs

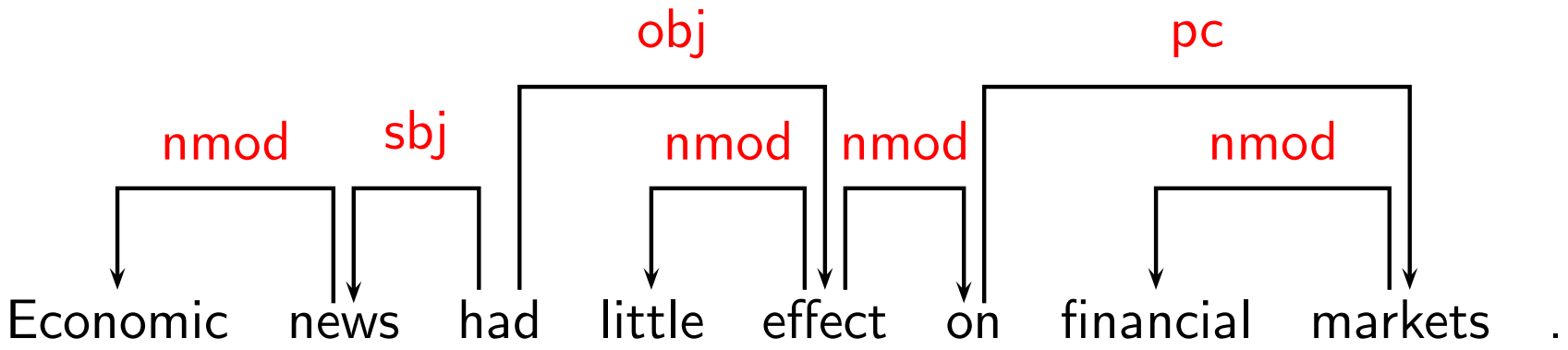
- A dependency structure can be defined as a directed graph G, consisting of
  - a set V of nodes,
  - a set E of arcs (edges),
  - a linear precedence order $<$ on V.
- Labeled graphs:
  - Nodes in V are labeled with word forms (and annotation).
  - Arcs in E are labeled with dependency types.
- Notational conventions ($i, j \in V$):
  - $i \rightarrow j \;\equiv\; (i,j) \in E$
  - $i \rightarrow^* j \;\equiv\; i = j \vee \exists k : i \rightarrow k,\ k \rightarrow^* j$

Formal Conditions on Dependency Graphs

- G is (weakly) connected:
  - For every node i there is a node j such that $i \rightarrow j$ or $j \rightarrow i$.
- G is acyclic:
  - If $i \rightarrow j$ then not $j \rightarrow^* i$.
- G obeys the single-head constraint:
  - If $i \rightarrow j$, then not $k \rightarrow j$, for any $k \neq i$.
- G is projective:
  - If $i \rightarrow j$ then $i \rightarrow^* k$, for any k such that $i < k < j$ or $j < k < i$.

Connectedness, Acyclicity and Single-Head

- Intuitions:
  - Syntactic structure is complete (Connectedness).
  - Syntactic structure is hierarchical (Acyclicity).
  - Every word has at most one syntactic head (Single-Head).
- Connectedness can be enforced by adding a special root node.



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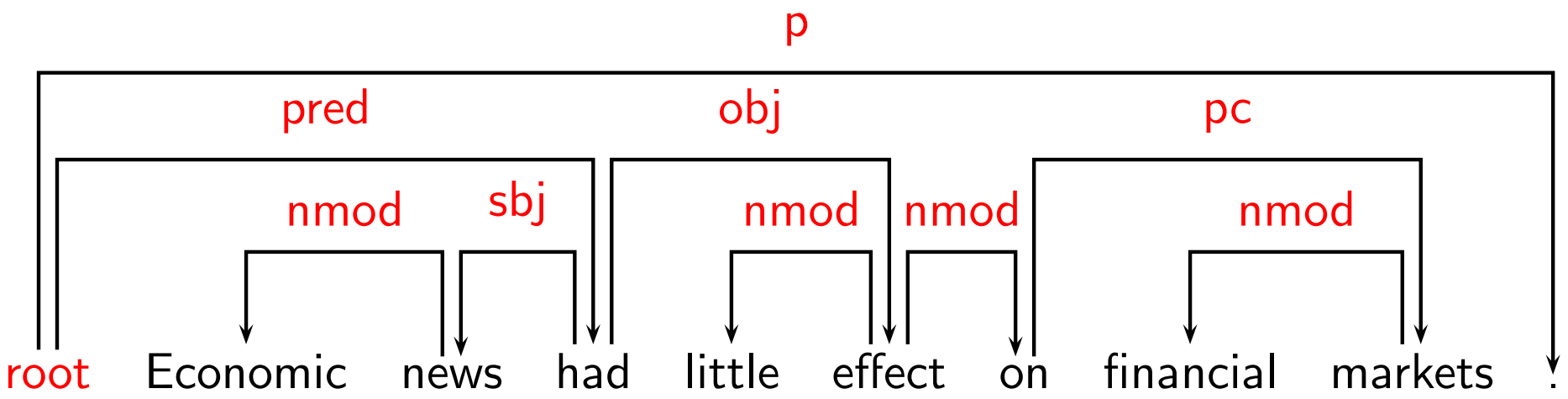
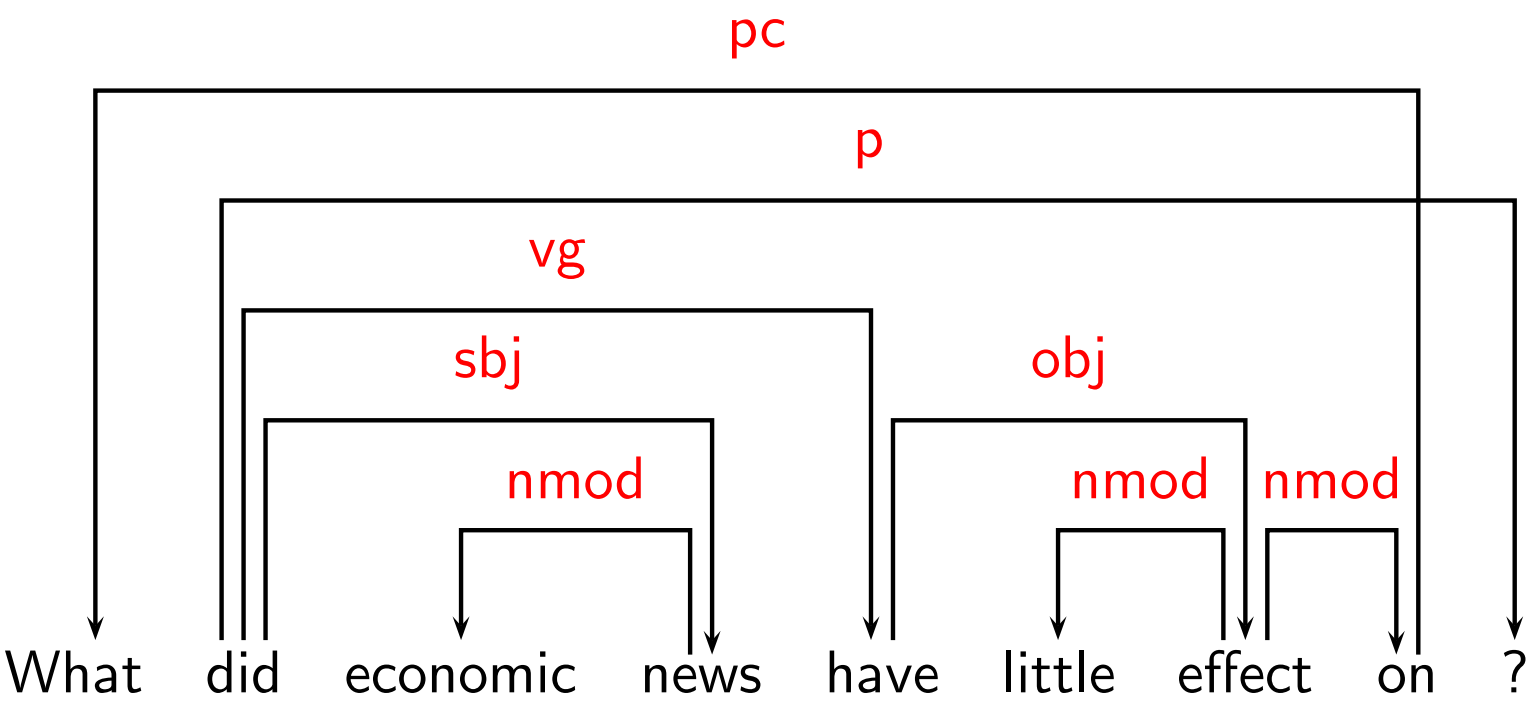


Projectivity

- Most theoretical frameworks do not assume projectivity.
- Non-projective structures are needed to account for
  - long-distance dependencies,
  - free word order.



Where we're going

- Dependency parsing:
  - Input: Sentence $x = w_1, \ldots w_n$
  - Output: Dependency graph G
- Focus today:
  - Computational methods for dependency parsing
  - Resources for dependency parsing (parsers, treebanks)

Parsing Methods

- Three main traditions:
  - Deterministic parsing (specifically: **Transition-based parsing**)
  - Dynamic programming (specifically: **Graph-based parsing**)
  - Constraint satisfaction (not covered today)
- Special issue:
  - Non-projective dependency parsing

Deterministic Parsing

- Basic idea:
  - Derive a single syntactic representation (dependency graph) through a deterministic sequence of elementary parsing actions
  - Sometimes combined with backtracking or repair
- Motivation:
  - Psycholinguistic modeling
  - Efficiency
  - Simplicity

Covington's Incremental Algorithm

- Deterministic incremental parsing in $O(n^2)$ time by trying to link each new word to each preceding one [Covington(2001)]:

$\textsc{Parse}(x = (w_1, \ldots, w_n))$
1 **for** $i = 1$ **up to** n
2 **for** $j = i - 1$ **down to** 1
3 $\textsc{Link}(w_i, w_j)$

$$\textsc{Link}(w_i, w_j) = \begin{cases} E \leftarrow E \cup (i, j) & \text{if } w_j \text{ is a dependent of } w_i \\ E \leftarrow E \cup (j, i) & \text{if } w_i \text{ is a dependent of } w_j \\ E \leftarrow E & \text{otherwise} \end{cases}$$

- Different conditions, such as Single-Head and Projectivity, can be incorporated into the Link operation.

Shift-Reduce Type Algorithms

Transition-based parsing

- Data structures:
  - Stack $[\ldots, w_i]_S$ of partially processed tokens
  - Queue $[w_j, \ldots]_Q$ of remaining input tokens
- Parsing actions built from atomic actions:
  - Adding arcs ($w_i \rightarrow w_j$, $w_i \leftarrow w_j$)
  - Stack and queue operations
- Left-to-right parsing in $O(n)$ time
- Restricted to projective dependency graphs

Yamada's Algorithm

- Three parsing actions:

$$\text{Shift} \quad \frac{[\ldots]_S \quad [w_i, \ldots]_Q}{[\ldots, w_i]_S \quad [\ldots]_Q}$$

$$\text{Left} \quad \frac{[\ldots, w_i, w_j]_S \quad [\ldots]_Q}{[\ldots, w_i]_S \quad [\ldots]_Q \quad w_i \rightarrow w_j}$$

$$\text{Right} \quad \frac{[\ldots, w_i, w_j]_S \quad [\ldots]_Q}{[\ldots, w_j]_S \quad [\ldots]_Q \quad w_i \leftarrow w_j}$$

- Algorithm variants:
  - Originally developed for Japanese (strictly head-final) with only the Shift and Right actions [Kudo and Matsumoto(2002)]
  - Adapted for English (with mixed headedness) by adding the Left action [Yamada and Matsumoto(2003)]
  - Multiple passes over the input give time complexity $O(n^2)$

Nivre's Algorithm

- Four parsing actions:

$$\text{Shift} \quad \frac{[\ldots]_S \quad [w_i, \ldots]_Q}{[\ldots, w_i]_S \quad [\ldots]_Q}$$

$$\text{Reduce} \quad \frac{[\ldots, w_i]_S \quad [\ldots]_Q \quad \exists w_k : w_k \rightarrow w_i}{[\ldots]_S \quad [\ldots]_Q}$$

$$\text{Left-Arc}_r \quad \frac{[\ldots, w_i]_S \quad [w_j, \ldots]_Q \quad \neg\exists w_k : w_k \rightarrow w_i}{[\ldots]_S \quad [w_j, \ldots]_Q \quad w_i \overset{r}{\leftarrow} w_j}$$

$$\text{Right-Arc}_r \quad \frac{[\ldots, w_i]_S \quad [w_j, \ldots]_Q \quad \neg\exists w_k : w_k \rightarrow w_j}{[\ldots, w_i, w_j]_S \quad [\ldots]_Q \quad w_i \overset{r}{\rightarrow} w_j}$$

- Characteristics:
  - Integrated labeled dependency parsing
  - Arc-eager processing of right-dependents
  - Single pass over the input gives time complexity $O(n)$

Example

[root]$_S$ [Economic news had little effect on financial markets .]$_Q$

Example

[root Economic]$_S$ [news had little effect on financial markets .]$_Q$

Shift

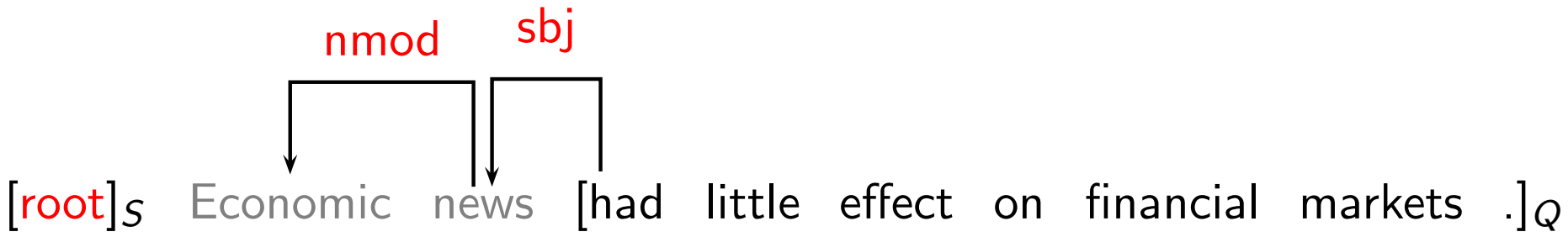
Example

Left-Arc$_{nmod}$

Example

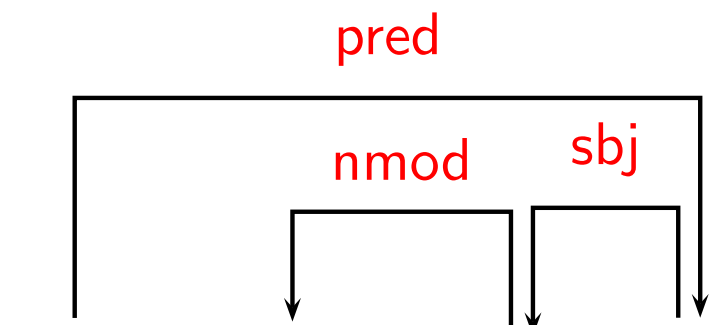
Shift

Example



Left-Arc$_{sbj}$

Example



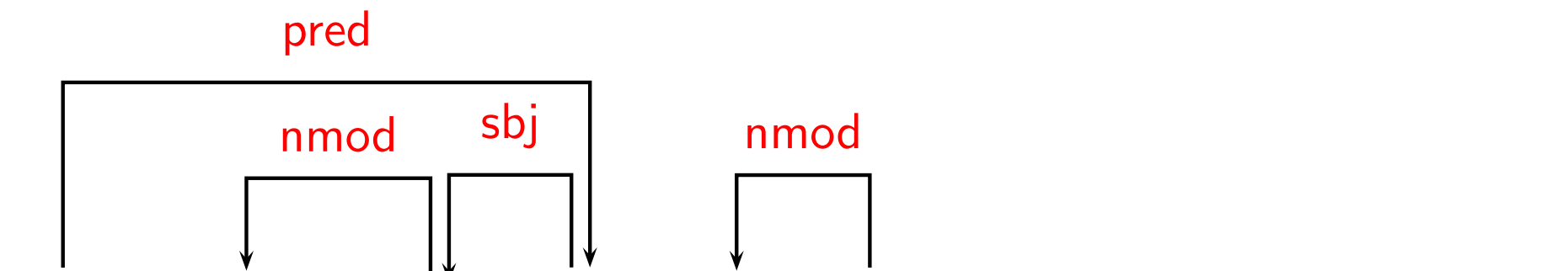
[root Economic news had]$_S$ [little effect on financial markets .]$_Q$

Right-Arc$_{pred}$

Example

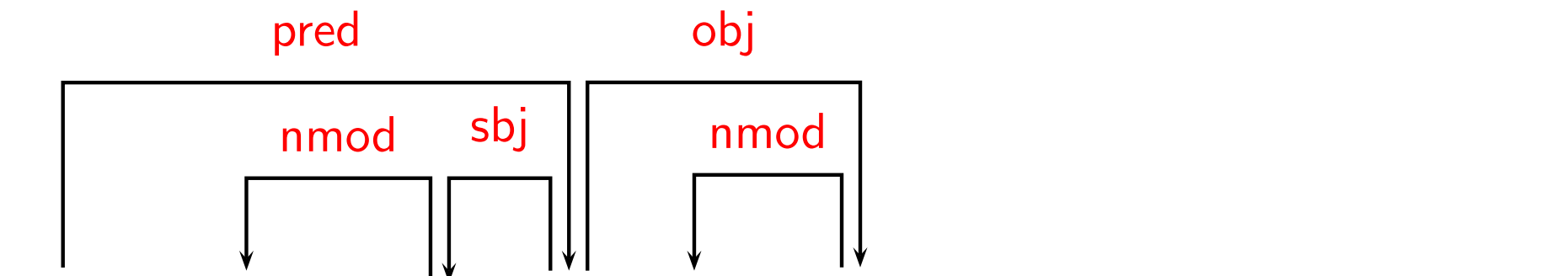
Shift

Example



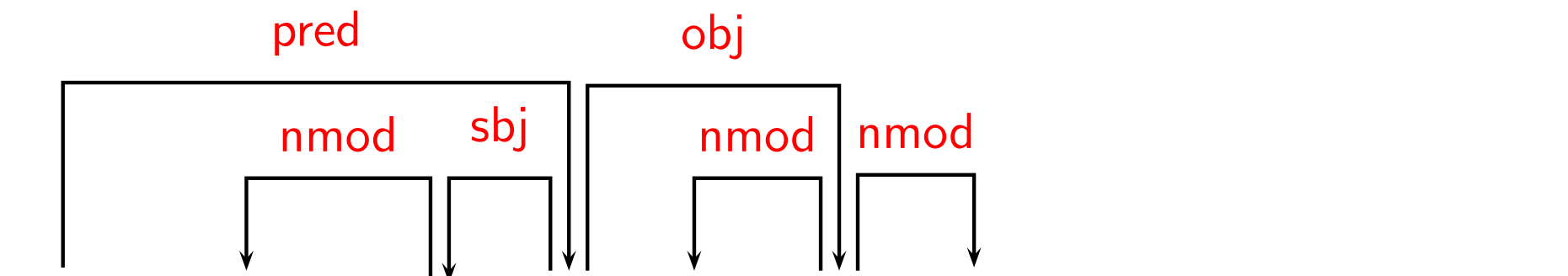
Left-Arc$_{nmod}$

Example



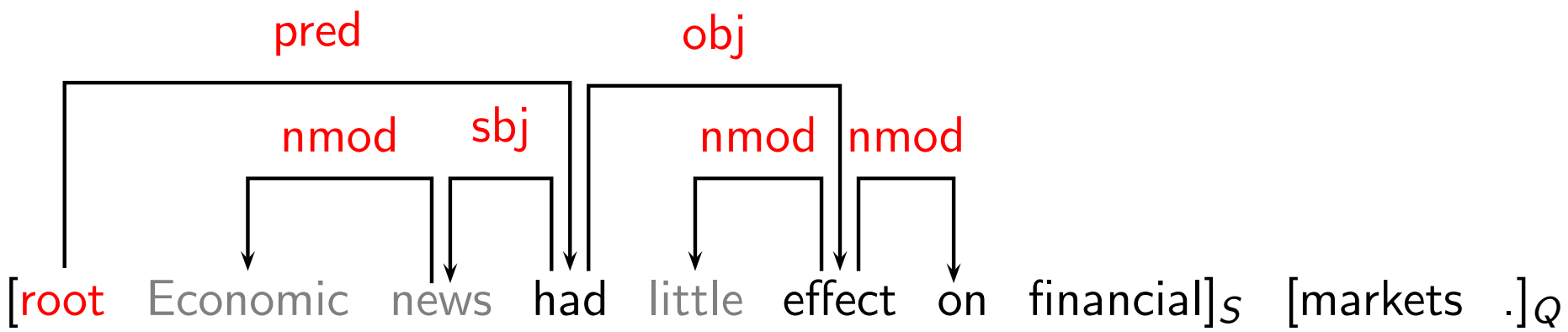
Right-Arc$_{obj}$

Example



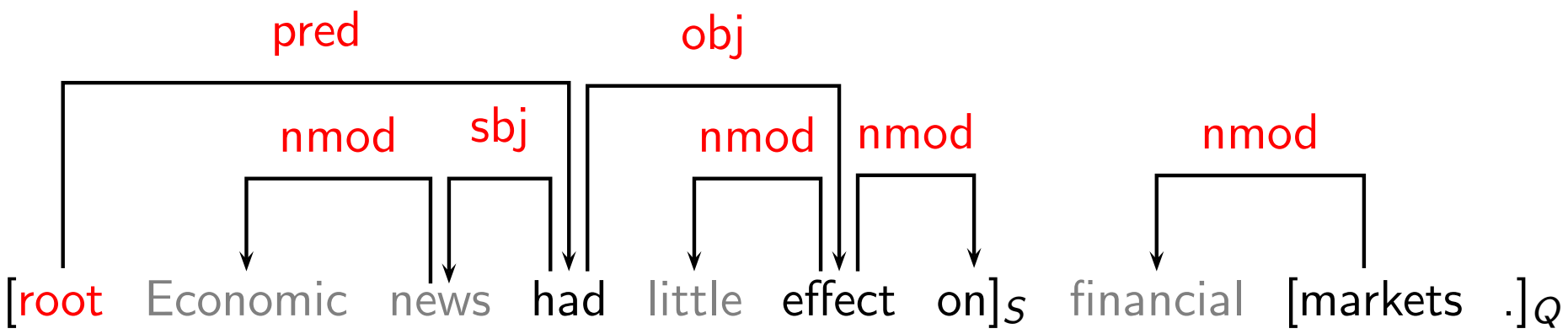
Right-Arc$_{nmod}$

Example



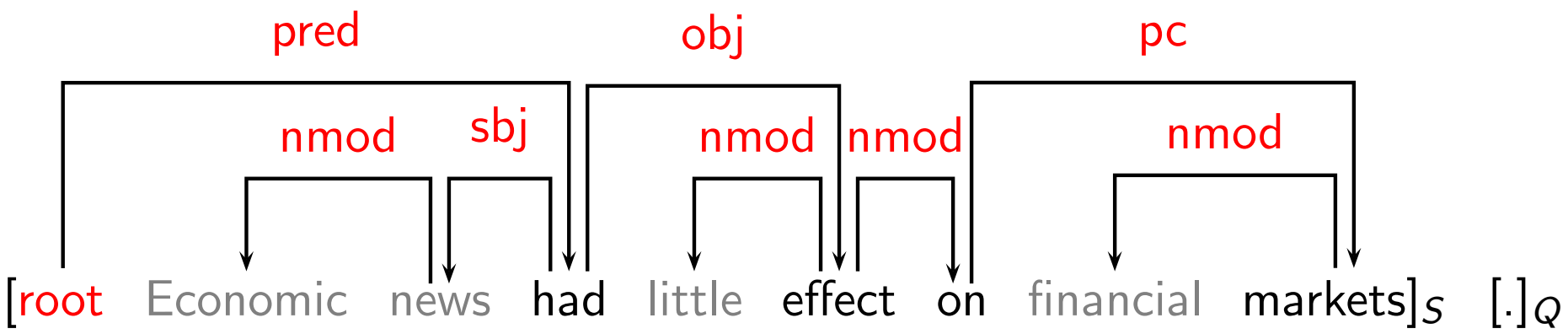
Shift

Example



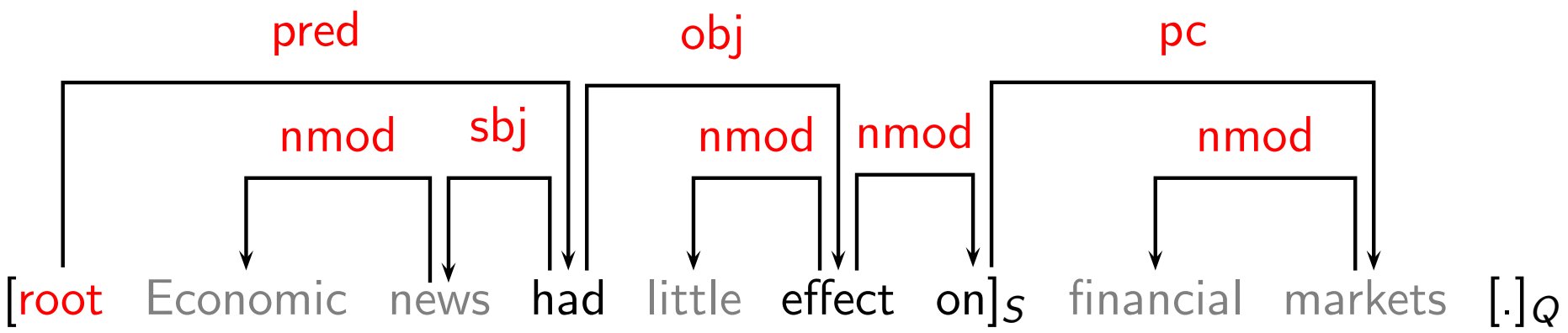
Left-Arc$_{nmod}$

Example



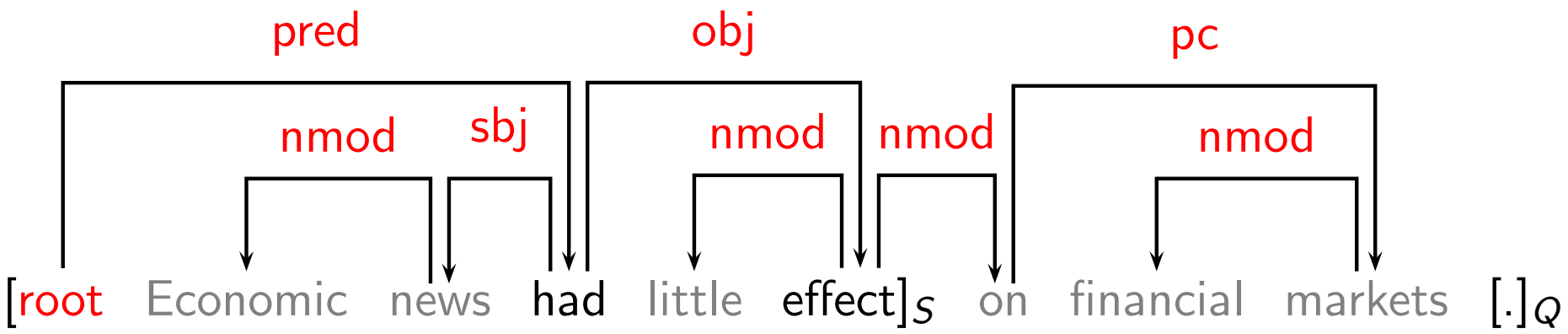
Right-Arc$_{pc}$

Example



Reduce

Example



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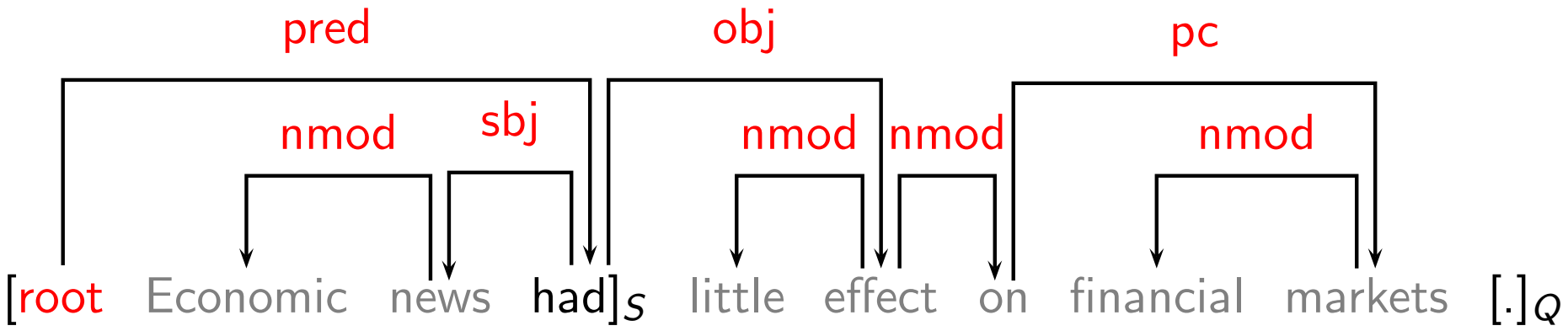

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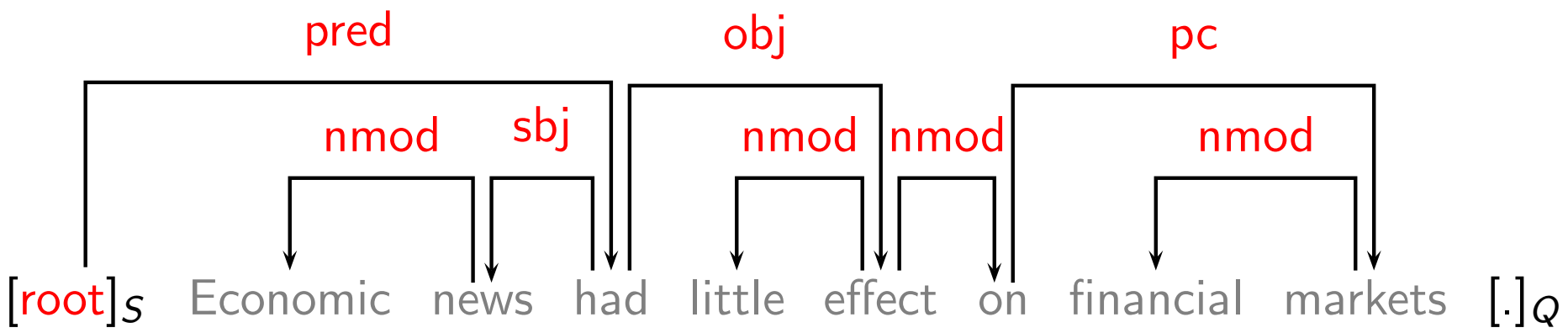

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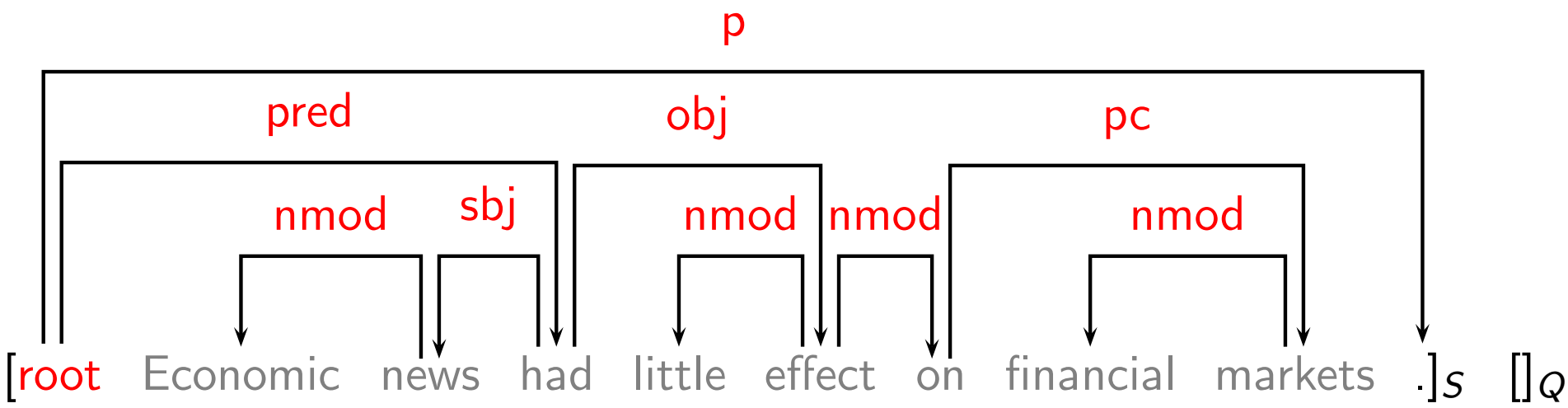

Right-Arc$_p$

Classifier-Based Parsing

- Data-driven deterministic parsing:
  - Deterministic parsing requires an oracle.
  - An oracle can be approximated by a classifier.
  - A classifier can be trained using treebank data.
- Learning methods:
  - Support vector machines (SVM)
    [Kudo and Matsumoto(2002), Yamada and Matsumoto(2003), Isozaki et al.(2004)Isozaki, Kazawa and Hirao, Cheng et al.(2004)Cheng, Asahara and Matsumoto, Nivre et al.(2006)Nivre, Hall, Nilsson, Eryiğit and Marinov]
  - Memory-based learning (MBL)
    [Nivre et al.(2004)Nivre, Hall and Nilsson, Nivre and Scholz(2004)]
  - Maximum entropy modeling (MaxEnt)
    [Cheng et al.(2005)Cheng, Asahara and Matsumoto]

Feature Models

- Learning problem:
  - Approximate a function from parser states, represented by feature vectors to parser actions, given a training set of gold standard derivations.
- Typical features:
  - Tokens:
    - Target tokens
    - Linear context (neighbors in S and Q)
    - Structural context (parents, children, siblings in G)
  - Attributes:
    - Word form (and lemma)
    - Part-of-speech (and morpho-syntactic features)
    - Dependency type (if labeled)
    - Distance (between target tokens)

Comparing Algorithms

- Parsing algorithm:
  - Nivre's algorithm gives higher accuracy than Yamada's algorithm for parsing the Chinese CKIP treebank [Cheng et al.(2004)Cheng, Asahara and Matsumoto].
- Learning algorithm:
  - SVM gives higher accuracy than MaxEnt for parsing the Chinese CKIP treebank [Cheng et al.(2004)Cheng, Asahara and Matsumoto].
  - SVM gives higher accuracy than MBL with lexicalized feature models for three languages [Hall et al.(2006)Hall, Nivre and Nilsson]:
    - Chinese (Penn)
    - English (Penn)
    - Swedish (Talbanken)

Dynamic Programming

- Basic idea: Treat dependencies as constituents.
- Use, e.g., CYK parser (with minor modifications).
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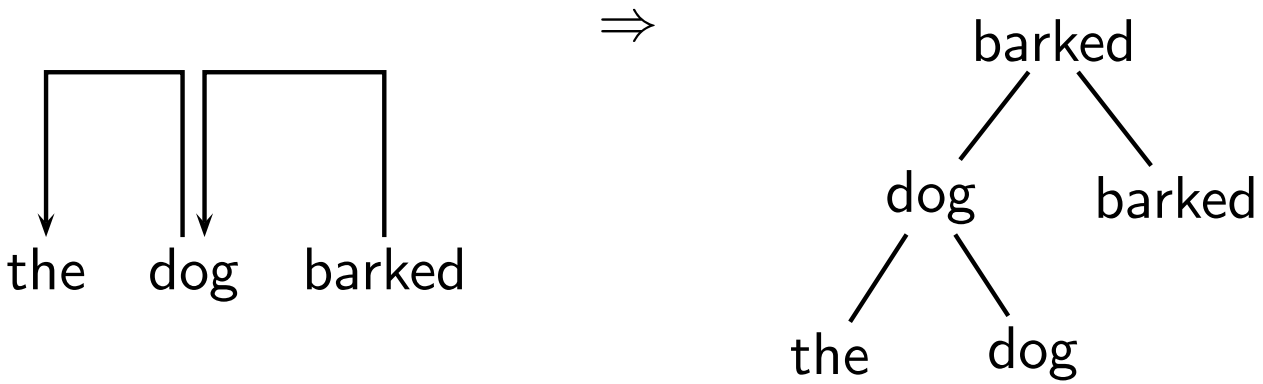

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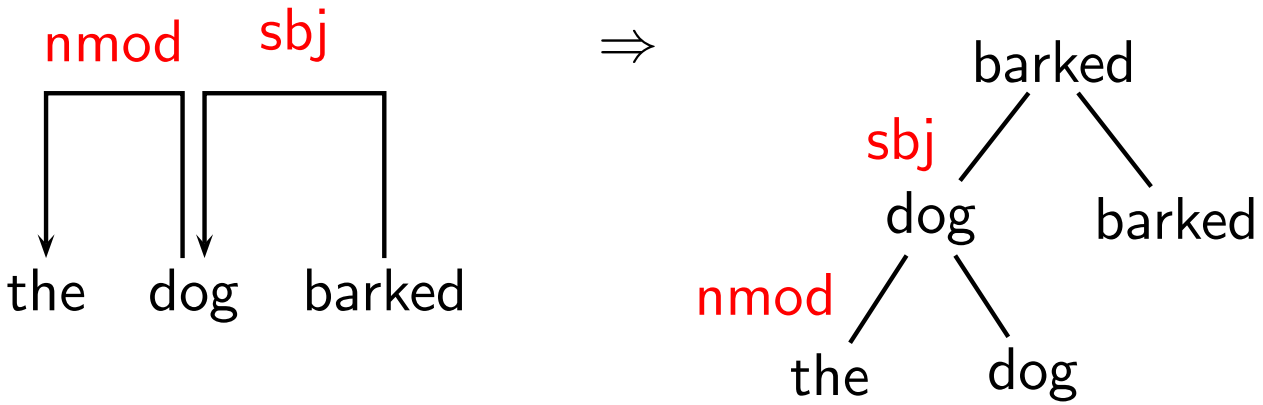


Dependency Chart Parsing

- Grammar is regarded as context-free, in which each node is lexicalized.
- Chart entries are subtrees, i.e., words with all their left and right dependents.
- Problem: Different entries for different subtrees spanning a sequence of words with different heads.
- Time requirement: $O(n^5)$.

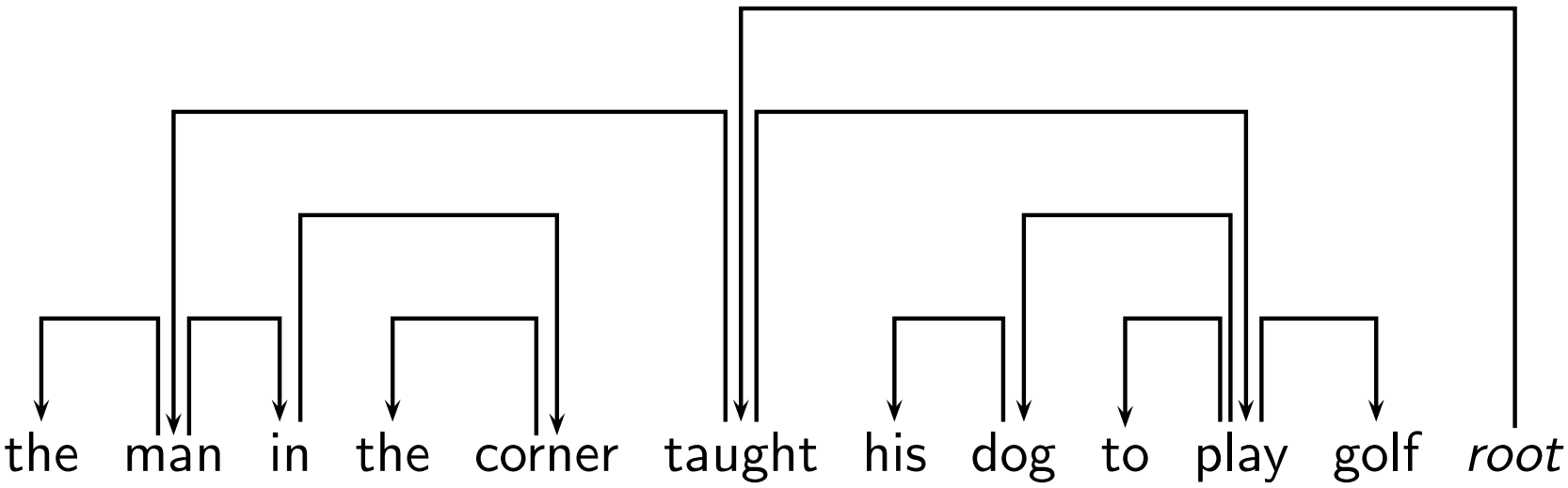
Dynamic Programming Approaches

- Original version: [Hays(1964)]
- Link Grammar: [Sleator and Temperley(1991)]
- Earley-style parser with left-corner filtering: [Lombardo and Lesmo(1996)]
- Bilexical grammar: [Eisner(1996a), Eisner(1996b), Eisner(2000)]
- Bilexical grammar with discriminative estimation methods: [McDonald et al.(2005a)McDonald, Crammer and Pereira, McDonald et al.(2005b)McDonald, Pereira, Ribarov and Hajič]

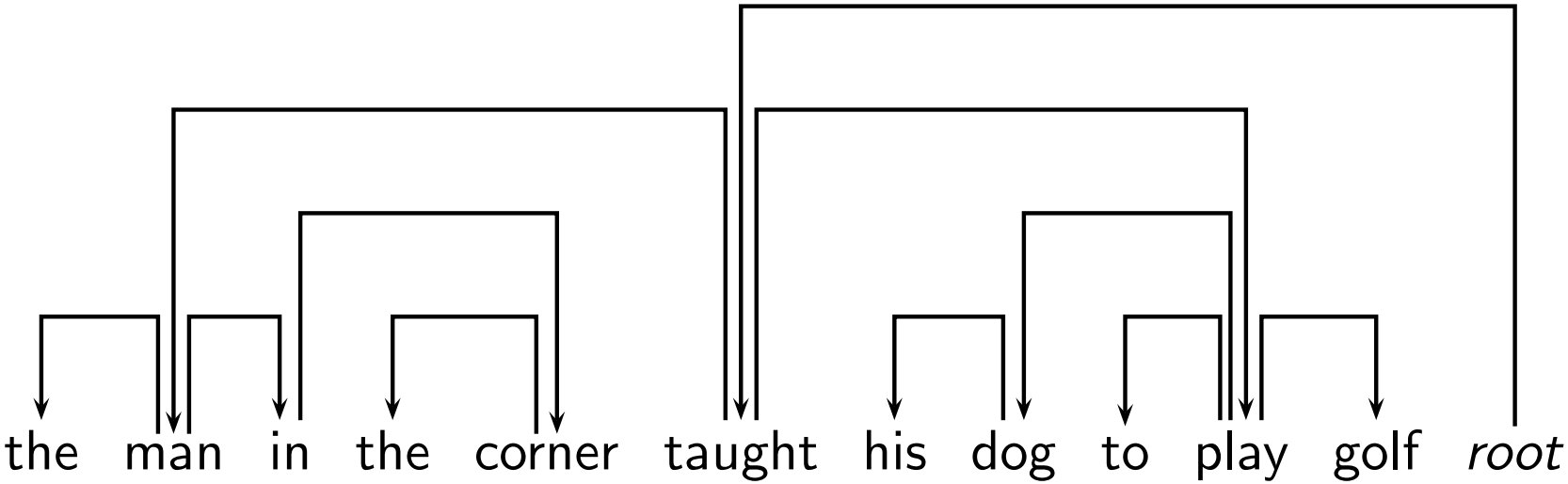
Eisner's Bilexical Algorithm

- Two novel aspects:
  - Modified parsing algorithm
  - Probabilistic dependency parsing
- Time requirement: $O(n^3)$.
- Modification: Instead of storing subtrees, store spans.
- Def. span: Substring such that no interior word links to any word outside the span.
- Underlying idea: In a span, only the endwords are active, i.e. still need a head.
- One or both of the endwords can be active.

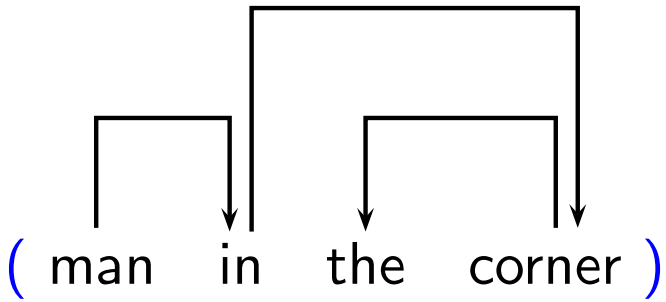
Example

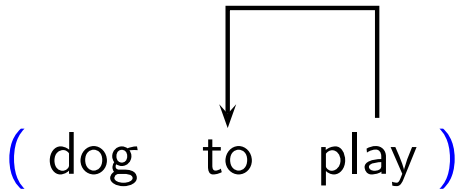


Example



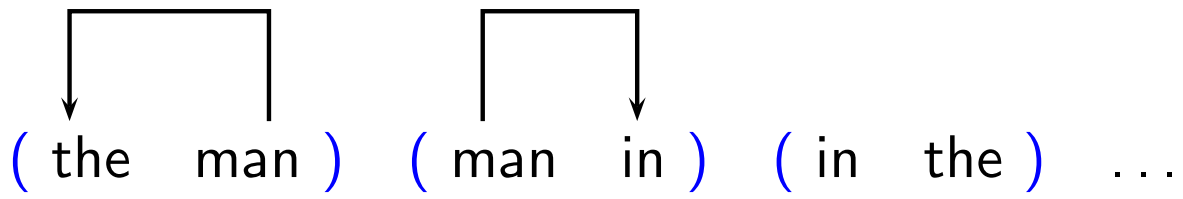
Spans:





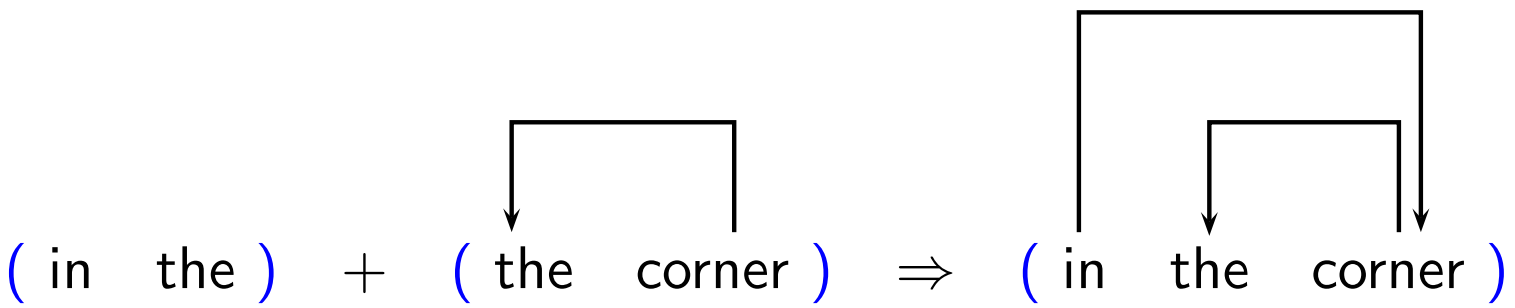
Assembly of Correct Parse

Start by combining adjacent words to minimal spans:



Assembly of Correct Parse

Combine spans which overlap in one word; this word must be governed by a word in the left or right span.



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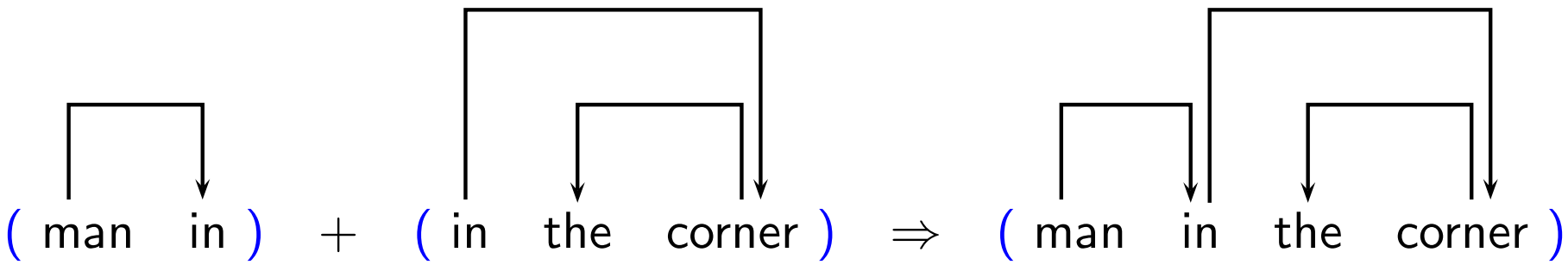

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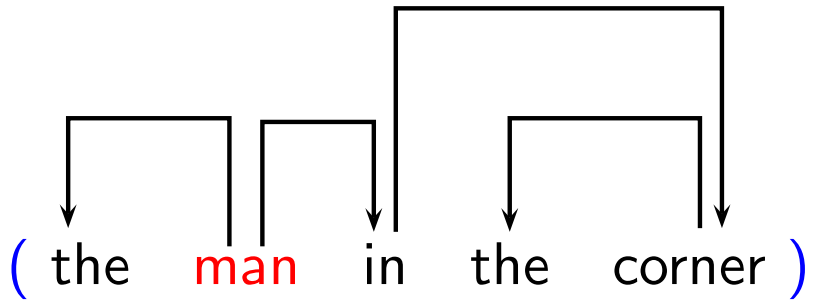
Invalid span:



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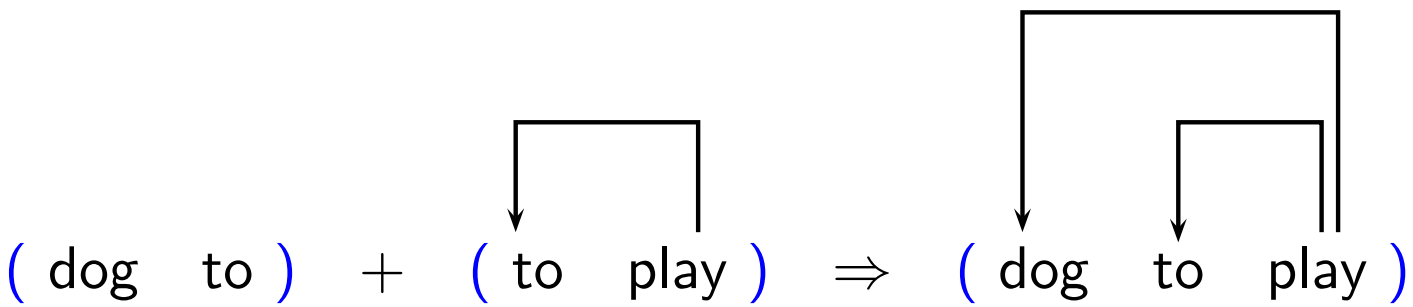

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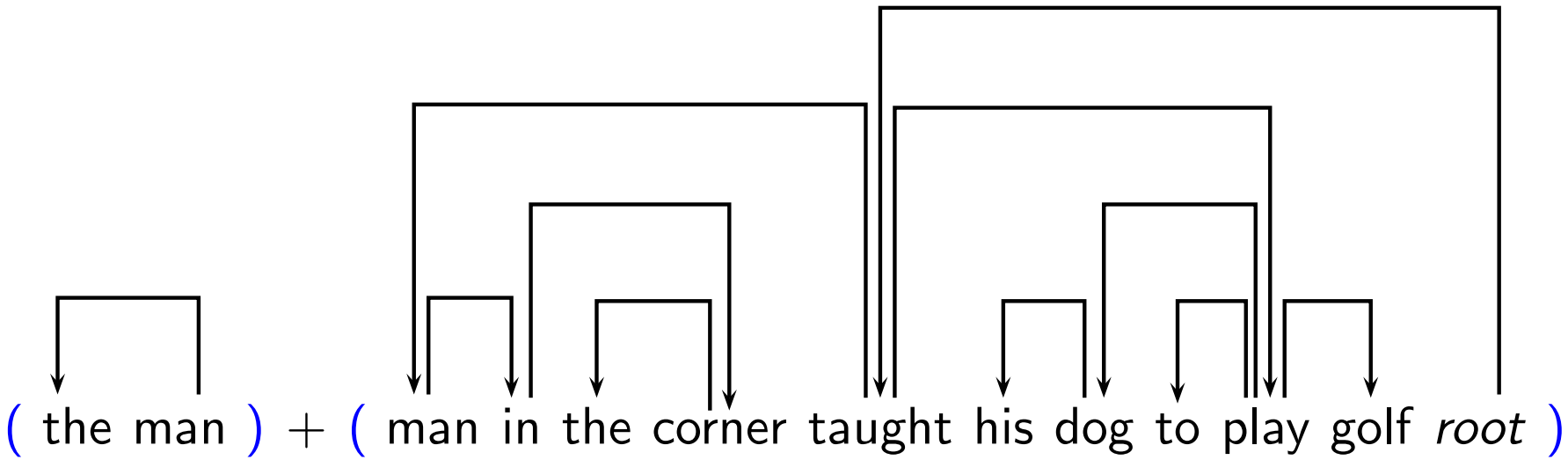

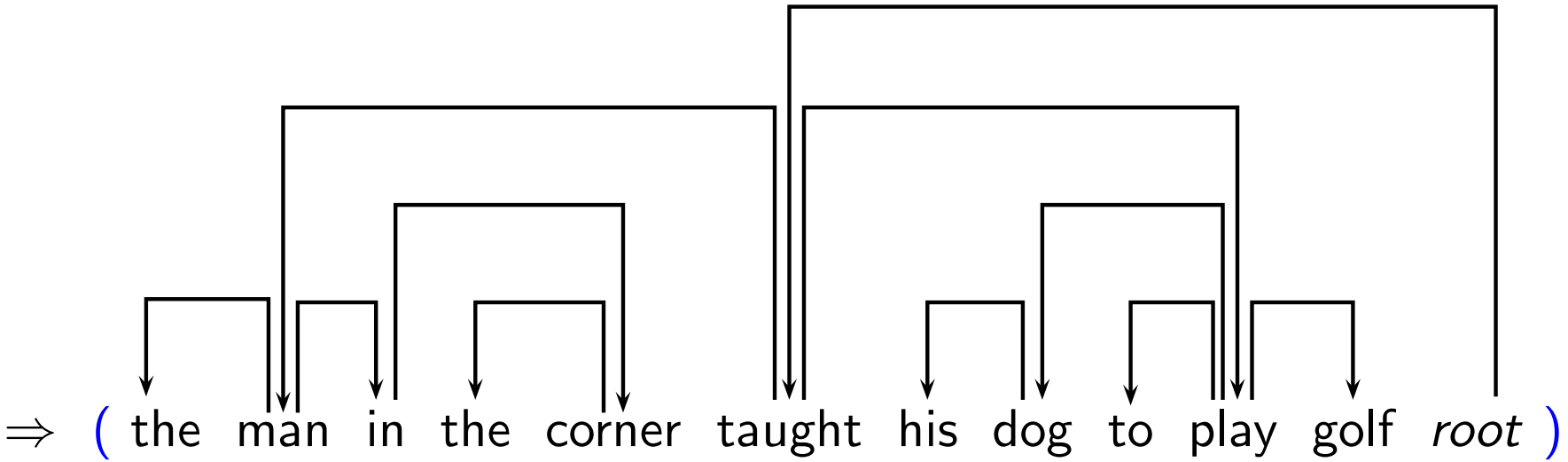

Eisner's Probability Models

- Model A: Bigram lexical affinities
  - First generates a trigram Markov model for POS tagging.
  - Decides for each word pair whether they have a dependency.
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- Model C: Recursive Generation
  - Each word generates its actual dependents.
  - Two Markov chains:
    - Left dependents
    - Right dependents
  - Model is not leaky.

Eisner's Model C

$$Pr(words, tags, links) = \prod_{1 \le i \le n} \left(\prod_{c} Pr(tword(dep_c(i)) \mid tag(dep_{c-1}(i)), tword(i)) \right)$$

c $= -(1 + \#left - deps(i)) \ldots 1 + \#right - deps(i),\ c \neq 0$

or: $dep_{c+i}(i)$ if $c < 0$

Eisner's Results

- 25 000 Wall Street Journal sentences
- Baseline: most frequent tag chosen for a word, each word chooses a head with most common distance
- Model X: trigram tagging, no dependencies
- For comparison: state-of-the-art constituent parsing, Charniak: 92.2 F-measure

Model	**Non-punct**	**Tagging**
Baseline	41.9	76.1
Model X	–	93.1
Model A	too slow	
Model B	83.8	92.8
Model C	86.9	92.0

Maximum Spanning Trees

[McDonald et al.(2005a)McDonald, Crammer and Pereira,

McDonald et al.(2005b)McDonald, Pereira, Ribarov and Hajič]

Graph-based parsing

- Score of a dependency tree = sum of scores of dependencies
- Scores are independent of other dependencies.
- If scores are available, parsing can be formulated as maximum spanning tree problem.
- Two cases:
  - Projective: Use Eisner's parsing algorithm.
  - Non-projective: Use Chu-Liu-Edmonds algorithm for finding the maximum spanning tree in a directed graph [Chu and Liu(1965), Edmonds(1967)].
- Use online learning for determining weight vector **w**: large-margin multi-class classification (MIRA)

Maximum Spanning Trees (2)

- Complexity:
  - Projective (Eisner): $O(n^3)$
  - Non-projective (CLE): $O(n^2)$

$$score(sent, deps) = \sum_{(i,j) \in deps} score(i,j) = \sum_{(i,j) \in deps} \mathbf{w} \cdot f(i,j)$$

Online Learning

Training data: $\mathcal{T} = (sent_t, deps_t)_{t=1}^{\mathcal{T}}$

1. $\mathbf{w} = 0$; $\mathbf{v} = 0$; $i = 0$;
2. for $n : 1..\mathcal{N}$
3. for $t : 1..\mathcal{T}$
4. $\mathbf{w}^{(i+1)} =$ update $\mathbf{w}^{(i)}$ according to $(sent_t, deps_t)$
5. $\mathbf{v} = \mathbf{v} + \mathbf{w}^{(i+1)}$
6. $i = i + 1$
7. $\mathbf{w} = \mathbf{v}/(\mathcal{N} \cdot \mathcal{T})$

MIRA

MIRA weight update:

min $||\mathbf{w}^{(i+1)} - \mathbf{w}^{(i)}||$ so that

$$score(sent_t, deps_t) - score(sent_t, deps') \geq L(deps_t, deps')$$

$$\forall deps' \in dt(sent_t)$$

- $L(deps, deps')$: loss function
- $dt(sent)$: possible dependency parses for sentence

Results by McDonald et al. (2005a, 2005b)

- Unlabeled accuracy per word (W) and per sentence (S)

	English		Czech	
Parser	**W**	**S**	**W**	**S**
k-best MIRA Eisner	90.9	37.5	83.3	31.3
best MIRA CLE	90.2	33.2	84.1	32.2
factored MIRA CLE	90.2	32.2	84.4	32.3

- New development (EACL 2006):
  - Scores of dependencies are not independent any more
  - Better results

Evaluation on English

- Evaluation:
  - Penn Treebank (WSJ) converted to dependency graphs
  - Unlabeled accuracy per word (W) and per sentence (S)
    - Deterministic classifier-based parsers
      [Yamada and Matsumoto(2003),
      Isozaki et al.(2004)Isozaki, Kazawa and Hirao]
    - Spanning tree parsers with online training
      [McDonald et al.(2005a)McDonald, Crammer and Pereira,
      McDonald and Pereira(2006)]
    - Collins and Charniak parsers with same conversion

Parser	**W**	**S**
Charniak	92.2	45.2
Collins	91.7	43.3
McDonald and Pereira	91.5	42.1
Isozaki et al.	91.4	40.7
McDonald et al.	91.0	37.5
Yamada and Matsumoto	90.4	38.4

Parsing Methods

- Three main traditions:
  - Deterministic parsing (specifically: **Transition-based parsing**)
  - Dynamic programming (specifically: **Graph-based parsing**)
  - Deterministic parsing
- Special issue:
  - Non-projective dependency parsing

Non-Projective Dependency Parsing

- Many parsing algorithms are restricted to projective dependency graphs.
- Is this a problem?
- Statistics from CoNLL-X Shared Task [Buchholz and Marsi(2006)]
  - NPD = Non-projective dependencies
  - NPS = Non-projective sentences

Language	%NPD	%NPS
Dutch	5.4	36.4
German	2.3	27.8
Czech	1.9	23.2
Slovene	1.9	22.2
Portuguese	1.3	18.9
Danish	1.0	15.6

Two Main Approaches

- Algorithms for non-projective dependency parsing:
  - Constraint satisfaction methods
    [Tapanainen and Järvinen(1997), Duchier and Debusmann(2001), Foth et al.(2004)Foth, Daum and Menzel]
  - McDonald's spanning tree algorithm
    [McDonald et al.(2005b)McDonald, Pereira, Ribarov and Hajič]
  - Covington's algorithm [Nivre(2006)]
- Post-processing of projective dependency graphs:
  - Pseudo-projective parsing [Nivre and Nilsson(2005)]
  - Corrective modeling [Hall and Novák(2005)]
  - Approximate non-projective parsing
    [McDonald and Pereira(2006)]

Non-Projective Parsing Algorithms

- Complexity considerations:
  - Projective (Proj)
  - Non-projective (NonP)

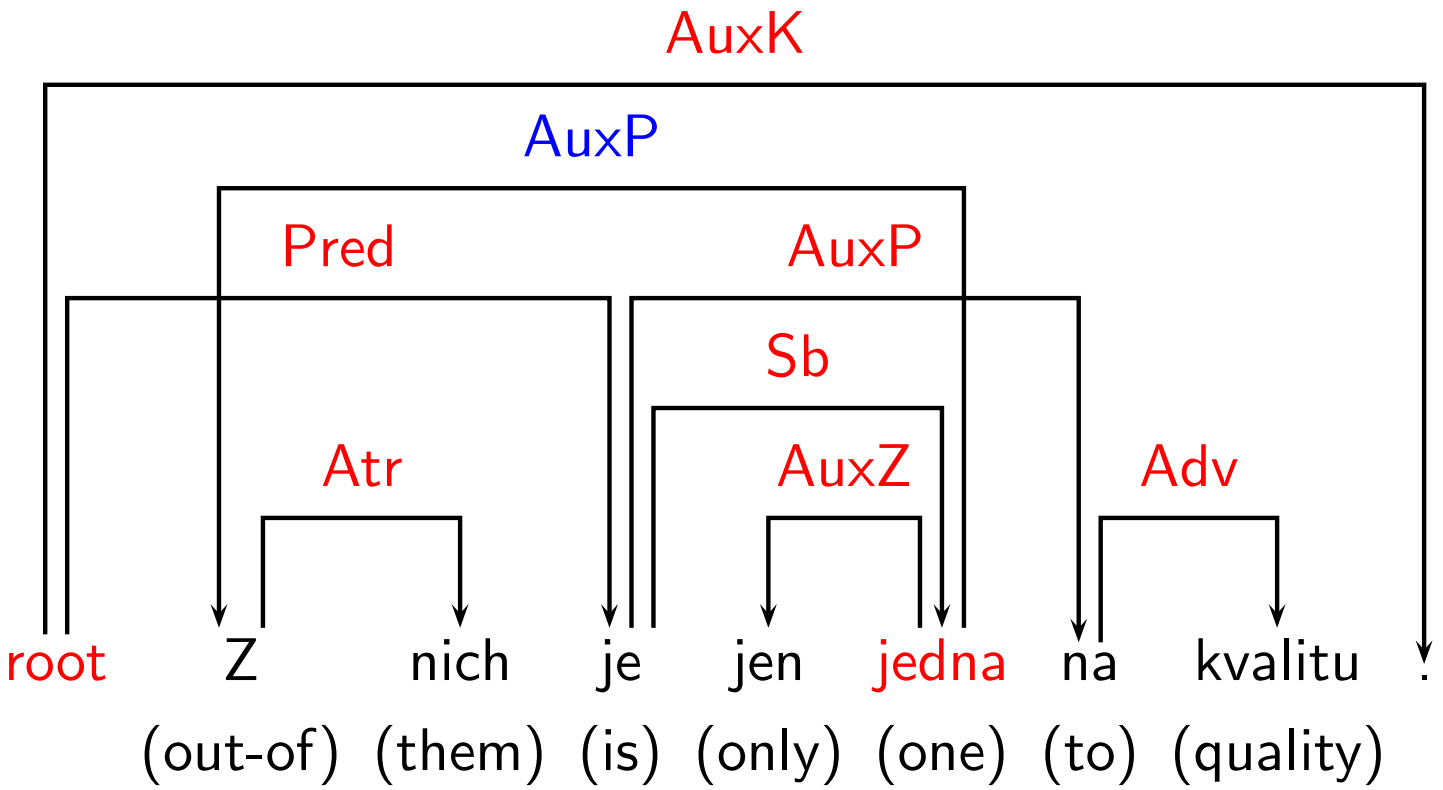
Problem/Algorithm	Proj	NonP
Complete grammar parsing [Gaifman(1965), Neuhaus and Bröker(1997)]	P	NP hard
Deterministic parsing [Nivre(2003), Covington(2001)]	$O(n)$	$O(n^2)$
First order spanning tree [McDonald et al.(2005b)McDonald, Pereira, Ribarov and Hajič]	$O(n^3)$	$O(n^2)$
Nth order spanning tree ($N > 1$) [McDonald and Pereira(2006)]	P	NP hard

Post-Processing

- Two-step approach:
  1. Derive the best projective approximation of the correct (possibly) non-projective dependency graph.
  2. Improve the approximation by replacing projective arcs by (possibly) non-projective arcs.
- Rationale:
  - Most "naturally occurring" dependency graphs are primarily projective, with only a few non-projective arcs.
- Approaches:
  - Pseudo-projective parsing [Nivre and Nilsson(2005)]
  - Corrective modeling [Hall and Novák(2005)]
  - Approximate non-projective parsing [McDonald and Pereira(2006)]

Pseudo-Projective Parsing

- Projectivize training data:
  - Projective head nearest permissible ancestor of real head
  - Arc label extended with dependency type of real head



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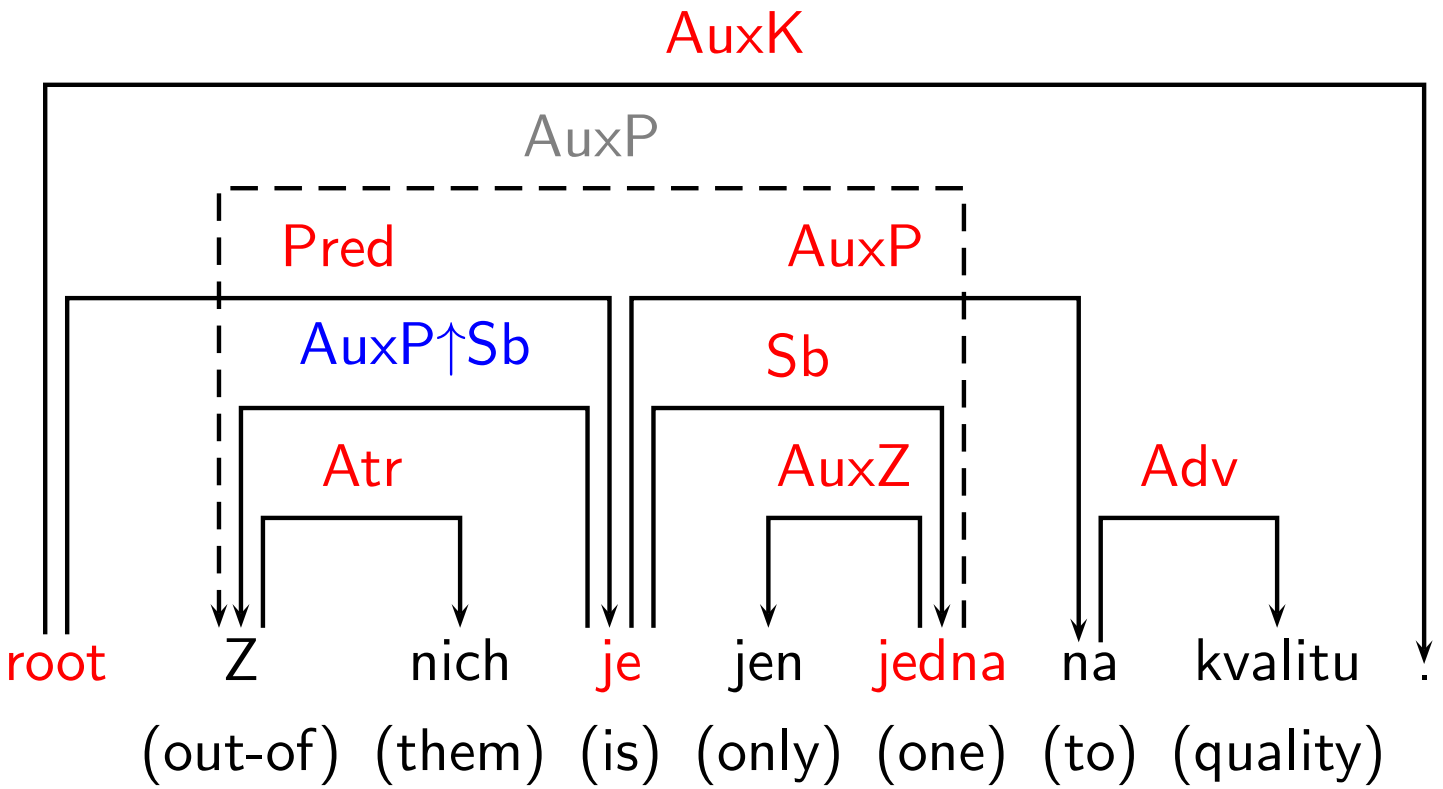

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- Deprojectivize parser output:
  - Top-down, breadth-first search for real head
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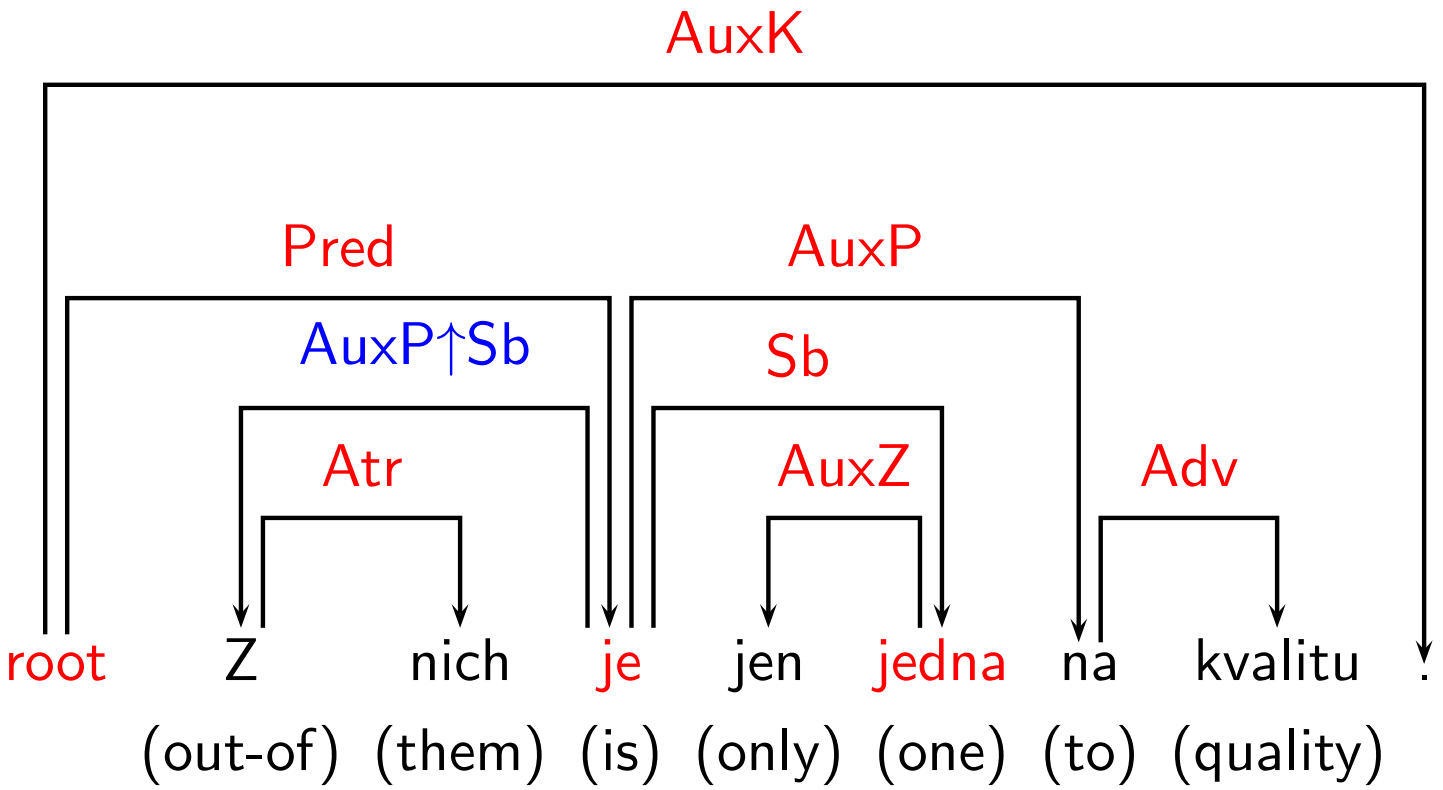

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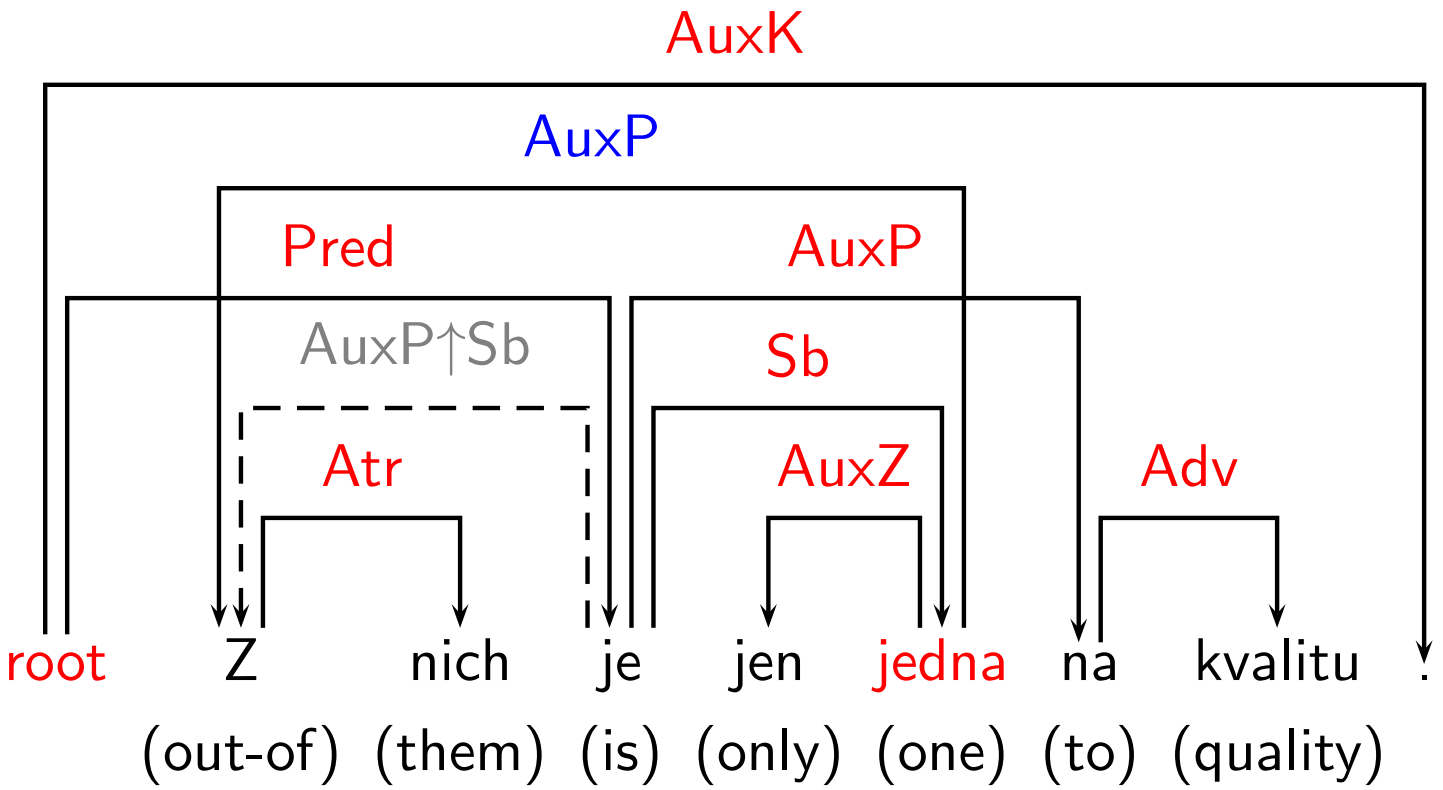

Evaluation on Czech

- Evaluation:
  - Prague Dependency Treebank (PDT)
  - Unlabeled accuracy per word (W) and per sentence (S)
    - Non-projective spanning tree parsing
      [McDonald et al.(2005b)McDonald, Pereira, Ribarov and Hajič]
    - Corrective modeling on top of the Charniak parser
      [Hall and Novák(2005)]
    - Approximate non-projective parsing on top of a second-order projective spanning tree parser [McDonald and Pereira(2006)]
    - Pseudo-projective parsing on top of a deterministic classifier-based parser
      [Nilsson et al.(2006)Nilsson, Nivre and Hall]

Parser	W	S
McDonald and Pereira	85.2	35.9
Hall and Novák	85.1	—
Nilsson et al.	84.6	37.7
McDonald et al.	84.4	32.3
Charniak	84.4	–

Multilingual Parsing

- CoNLL-X Shared Task: 12 (13) languages
- Organizers: Sabine Buchholz, Erwin Marsi, Yuval Krymolowski, Amit Dubey
- Main evaluation metric: Labeled accuracy per word
- Top scores ranging from 91.65 (Japanese) to 65.68 (Turkish)
- Top systems (over all languages):
  - Approximate second-order non-projective spanning tree parsing with online learning (MIRA)
    [McDonald et al.(2006)McDonald, Lerman and Pereira]
  - Labeled deterministic pseudo-projective parsing with support vector machines
    [Nivre et al.(2006)Nivre, Hall, Nilsson, Eryiğit and Marinov]

Practical Issues

- Where to get the software?
  - Dependency parsers
  - Conversion programs for constituent-based treebanks
- Where to get the data?
  - Dependency treebanks
  - Treebanks that can be converted into dependency representation

Parsers

- Trainable parsers
- Parsers with manually written grammars

Parsers

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- Parsers with manually written grammars

- Concentrate on freely available parsers

Trainable Parsers

- Jason Eisner's **probabilistic dependency parser**
  - Based on bilexical grammar
  - Contact Jason Eisner: jason@cs.jhu.edu
  - Written in LISP
- Ryan McDonald's **MSTParser**
  - Based on the algorithms of
    [McDonald et al.(2005a)McDonald, Crammer and Pereira, McDonald et al.(2005b)McDonald, Pereira, Ribarov and Hajič]
  - URL:
    `http://www.seas.upenn.edu/~ryantm/software/MSTParser/`
  - Written in JAVA

Trainable Parsers (2)

- Joakim Nivre's **MaltParser**
  - Inductive dependency parser with memory-based learning and SVMs
  - URL:

    `http://w3.msi.vxu.se/~nivre/research/MaltParser.html`
  - Executable versions are available for Solaris, Linux, Windows, and MacOS (open source version planned for fall 2006)

Parsers for Specific Languages

- Dekang Lin's **Minipar**
  - Principle-based parser
  - Grammar for English
  - URL: `http://www.cs.ualberta.ca/~lindek/minipar.htm`
  - Executable versions for Linux, Solaris, and Windows
- Wolfgang Menzel's **CDG Parser**:
  - Weighted constraint dependency parser
  - Grammar for German, (English under construction)
  - Online demo:
    `http://nats-www.informatik.uni-hamburg.de/Papa/ParserDemo`
  - Download:
    `http://nats-www.informatik.uni-hamburg.de/download`

Parsers for Specific Languages (2)

- Taku Kudo's **CaboCha**
  - Based on algorithms of [Kudo and Matsumoto(2002)], uses SVMs
  - URL: `http://www.chasen.org/~taku/software/cabocha/`
  - Web page in Japanese
- Gerold Schneider's **Pro3Gres**
  - Probability-based dependency parser
  - Grammar for English
  - URL: `http://www.ifi.unizh.ch/CL/gschneid/parser/`
  - Written in PROLOG
- Daniel Sleator's & Davy Temperley's **Link Grammar Parser**
  - Undirected links between words
  - Grammar for English
  - URL: `http://www.link.cs.cmu.edu/link/`

Treebanks

- Genuine dependency treebanks
- Treebanks for which conversions to dependencies exist

- See also CoNLL-X Shared Task
  URL: `http://nextens.uvt.nl/~conll/`

- Conversion strategy from constituents to dependencies

Dependency Treebanks

- Arabic: Prague Arabic Dependency Treebank
- Czech: Prague Dependency Treebank
- Danish: Danish Dependency Treebank
- Portuguese: Bosque: Floresta sintá(c)tica
- Slovene: Slovene Dependency Treebank
- Turkish: METU-Sabanci Turkish Treebank

Dependency Treebanks (2)

- Prague Arabic Dependency Treebank
  - ca. 100 000 words
  - Available from LDC, license fee
    (CoNLL-X shared task data, catalogue number LDC2006E01)
  - URL: `http://ufal.mff.cuni.cz/padt/`
- Prague Dependency Treebank
  - 1.5 million words
  - 3 layers of annotation: morphological, syntactical, tectogrammatical
  - Available from LDC, license fee
    (CoNLL-X shared task data, catalogue number LDC2006E02)
  - URL: `http://ufal.mff.cuni.cz/pdt2.0/`

Dependency Treebanks (3)

- Danish Dependency Treebank
  - ca. 5 500 trees
  - Annotation based on Discontinuous Grammar [Kromann(2005)]
  - Freely downloadable
  - URL: `http://www.id.cbs.dk/~mtk/treebank/`
- Bosque, Floresta sintá(c)tica
  - ca. 10 000 trees
  - Freely downloadable
  - URL:
    `http://acdc.linguateca.pt/treebank/info_floresta_English.html`

Dependency Treebanks (4)

- Slovene Dependency Treebank
  - ca. 30 000 words
  - Freely downloadable
  - URL: `http://nl.ijs.si/sdt/`
- METU-Sabanci Turkish Treebank
  - ca. 7 000 trees
  - Freely available, license agreement
  - URL: `http://www.ii.metu.edu.tr/~corpus/treebank.html`

Constituent Treebanks

- English: Penn Treebank
- Bulgarian: BulTreebank
- Chinese: Penn Chinese Treebank, Sinica Treebank
- Dutch: Alpino Treebank for Dutch
- German: TIGER/NEGRA, TüBa-D/Z
- Japanese: TüBa-J/S
- Spanish: Cast3LB
- Swedish: Talbanken05

Constituent Treebanks (2)

- Penn Treebank
  - ca. 1 million words
  - Available from LDC, license fee
  - URL: `http://www.cis.upenn.edu/~treebank/home.html`
  - Dependency conversion rules, available from e.g. [Collins(1999)]
  - For conversion with arc labels: Penn2Malt: `http://w3.msi.vxu.se/~nivre/research/Penn2Malt.html`
- BulTreebank
  - ca. 14 000 sentences
  - URL: `http://www.bultreebank.org/`
  - Dependency version available from Kiril Simov (`kivs@bultreebank.org`)

Constituent Treebanks (3)

- Penn Chinese Treebank
  - ca. 4 000 sentences
  - Available from LDC, license fee
  - URL: `http://www.cis.upenn.edu/~chinese/ctb.html`
  - For conversion with arc labels: Penn2Malt:
    `http://w3.msi.vxu.se/~nivre/research/Penn2Malt.html`
- Sinica Treebank
  - ca. 61 000 sentences
  - Available Academia Sinica, license fee
  - URL:
    `http://godel.iis.sinica.edu.tw/CKIP/engversion/treebank.htm`
  - Dependency version available from Academia Sinica

Constituent Treebanks (4)

- Alpino Treebank for Dutch
  - ca. 150 000 words
  - Freely downloadable
  - URL: `http://www.let.rug.nl/vannoord/trees/`
  - Dependency version downloadable at
    `http://nextens.uvt.nl/~conll/free_data.html`
- TIGER/NEGRA
  - ca. 50 000/20 000 sentences
  - Freely available, license agreement
  - TIGER URL:
    `http://www.ims.uni-stuttgart.de/projekte/TIGER/TIGERCorpus/`
    NEGRA URL:
    `http://www.coli.uni-saarland.de/projects/sfb378/negra-corpus/`
  - Dependency version of TIGER is included in release

Constituent Treebanks (5)

- TüBa-D/Z
  - ca. 22 000 sentences
  - Freely available, license agreement
  - URL: `http://www.sfs.uni-tuebingen.de/en_tuebadz.shtml`
  - Dependency version available from SfS Tübingen
- TüBa-J/S
  - Dialog data
  - ca. 18 000 sentences
  - Freely available, license agreement
  - Dependency version available from SfS Tübingen
  - URL: `http://www.sfs.uni-tuebingen.de/en_tuebajs.shtml` (under construction)

Constituent Treebanks (6)

- Cast3LB
  - ca. 18 000 sentences
  - URL: `http://www.dlsi.ua.es/projectes/3lb/index_en.html`
  - Dependency version available from Toni Martí (amarti@ub.edu)
- Talbanken05
  - ca. 300 000 words
  - Freely downloadable
  - URL:
    `http://w3.msi.vxu.se/~nivre/research/Talbanken05.html`
  - Dependency version also available

- Buchholz, Sabine and Erwin Marsi (2006). CoNLL-X Shared Task on Multilingual Dependency Parsing.
  In *Proceedings of the Tenth Conference on Computational Natural Language Learning*.
- Cheng, Yuchang, Masayuki Asahara and Yuji Matsumoto (2004). Determinstic Dependency Structure Analyzer for Chinese.
  In *Proceedings of the First International Joint Conference on Natural Language Processing (IJCNLP)*. pp. 500–508.
- Cheng, Yuchang, Masayuki Asahara and Yuji Matsumoto (2005). Machine Learning-Based Dependency Analyzer for Chinese.
  In *Proceedings of International Conference on Chinese Computing (ICCC)*. pp. ?–?
- Chu, Y. J. and T. J. Liu (1965). On the Shortest Arborescence of a Directed Graph.
  Science Sinica 14, 1396–1400.
- Collins, Michael (1999). Head-Driven Statistical Models for Natural Language Parsing.
  Ph.D. thesis, University of Pennsylvania.
- Covington, Michael A. (2001). A Fundamental Algorithm for Dependency Parsing.
  In *Proceedings of the 39th Annual ACM Southeast Conference*. pp. 95–102.

- Debusmann, Ralph, Denys Duchier and Geert-Jan M. Kruijff (2004). Extensible Dependency Grammar: A New Methodology.
  In *Proceedings of the Workshop on Recent Advances in Dependency Grammar*. pp. 78–85.
- Dubey, Amit (2005). What to Do when Lexicalization Fails: Parsing German with Suffix Analysis and Smoothing.
  In *Proceedings of the 43rd Annual Meeting of the Association for Computational Linguistics*. Ann Arbor, MI.
- Duchier, Denys (1999). Axiomatizing Dependency Parsing Using Set Constraints.
  In *Proceedings of the Sixth Meeting on Mathematics of Language*. pp. 115–126.
- Duchier, Denys (2003). Configuration of Labeled Trees under Lexicalized Constraints and Principles.
  Research on Language and Computation 1, 307–336.
- Duchier, Denys and Ralph Debusmann (2001). Topological Dependency Trees: A Constraint-based Account of Linear Precedence.
  In *Proceedings of the 39th Annual Meeting of the Association for Computational Linguistics (ACL)*. pp. 180–187.
- Edmonds, J. (1967). Optimum Branchings.
  Journal of Research of the National Bureau of Standards 71B, 233–240.

- Eisner, Jason M. (1996a). *An empirical comparison of probability models for dependency grammar*.
  Tech. Rep. IRCS-96-11, Institute for Research in Cognitive Science, University of Pennsylvania.
- Eisner, Jason M. (1996b). Three new probabilistic models for dependency parsing: An exploration.
  In *Proceedings of the 16th International Conference on Computational Linguistics (COLING)*. pp. 340–345.
- Eisner, Jason M. (2000). Bilexical grammars and their cubic-time parsing algorithms.
  In Harry Bunt and Anton Nijholt (eds.), *Advances in Probabilistic and Other Parsing Technologies*, Kluwer, pp. 29–62.
- Foth, Kilian, Michael Daum and Wolfgang Menzel (2004). A Broad-Coverage Parser for German Based on Defeasible Constraints.
  In *Proceedings of KONVENS 2004*. pp. 45–52.
- Foth, Kilian, Ingo Schröder and Wolfgang Menzel (2000). A Transformation-based parsing technique with anytime properties.
  In *Proceedings of the Sixth International Workshop on Parsing Technologies (IWPT)*. pp. 89–100.
- Gaifman, Haim (1965). Dependency systems and phrase-structure systems.

Information and Control 8, 304–337.

- Hall, Johan, Joakim Nivre and Jens Nilsson (2006). Discriminative Classifiers for Deterministic Dependency Parsing.
  In *Proceedings of COLING-ACL*.
- Hall, Keith and Vaclav Novák (2005). Corrective modeling for non-projective dependency parsing.
  In *Proceedings of the 9th International Workshop on Parsing Technologies (IWPT)*. pp. 42–52.
- Harper, Mary P. and R. A. Helzerman (1995). Extensions to constraint dependency parsing for spoken language processing.
  Computer Speech and Language 9, 187–234.
- Hays, David G. (1964). Dependency Theory: A Formalism and Some Observations.
  Language 40, 511–525.
- Hellwig, Peter (1986). Dependency Unification Grammar.
  In *Proceedings of the 11th International Conference on Computational Linguistics (COLING)*. pp. 195–198.
- Hellwig, Peter (2003). Dependency Unification Grammar.
  In Vilmos Agel, Ludwig M. Eichinger, Hans-Werner Eroms, Peter Hellwig, Hans Jürgen Heringer and Hening Lobin (eds.), *Dependency and Valency*, Walter de Gruyter, pp. 593–635.

- Hudson, Richard A. (1984). *Word Grammar*. Blackwell.
- Hudson, Richard A. (1990). *English Word Grammar*. Blackwell.
- Hudson, Richard A. (2000). Dependency Grammar Course Notes. `http://www.cs.bham.ac.uk/research/conferences/esslli/notes/hudson.\html`.
- Isozaki, Hideki, Hideto Kazawa and Tsutomu Hirao (2004). A Deterministic Word Dependency Analyzer Enhanced with Preference Learning. In *Proceedings of the 20th International Conference on Computational Linguistics (COLING)*. pp. 275–281.
- Järvinen, Timo and Pasi Tapanainen (1998). Towards an Implementable Dependency Grammar. In Sylvain Kahane and Alain Polguère (eds.), *Proceedings of the Workshop on Processing of Dependency-Based Grammars*. pp. 1–10.
- Karlsson, Fred (1990). Constraint grammar as a framework for parsing running text. In Hans Karlgren (ed.), *Papers presented to the 13th International Conference on Computational Linguistics (COLING)*. pp. 168–173.
- Karlsson, Fred, Atro Voutilainen, Juha Heikkilä and Arto Anttila (eds.) (1995). *Constraint Grammar: A language-independent system for parsing unrestricted text*.

Mouton de Gruyter.

- Kromann, Matthias Trautner (2005). *Discontinuous Grammar: A Dependency-Based Model of Human Parsing and Language Learning*. Doctoral Dissertation, Copenhagen Business School.
- Kübler, Sandra, Erhard W. Hinrichs and Wolfgang Maier (2006). Is it Really that Difficult to Parse German? In *Proceedings of the 2006 Conference on Empirical Methods in Natural Language Processing, EMNLP 2006*. Sydney, Australia.
- Kudo, Taku and Yuji Matsumoto (2002). Japanese Dependency Analysis Using Cascaded Chunking. In *Proceedings of the Sixth Workshop on Computational Language Learning (CoNLL)*. pp. 63–69.
- Lin, Dekang (1995). A Dependency-Based Method for Evaluating Broad-Coverage Parsers. In *Proceedings of IJCAI-95*. pp. 1420–1425.
- Lin, Dekang (1998). A Dependency-Based Method for Evaluating Broad-Coverage Parsers. *Natural Language Engineering* 4, 97–114.
- Lombardo, Vincenzio and Leonardo Lesmo (1996). An Earley-type Recognizer for Dependency Grammar.

In *Proceedings of the 16th International Conference on Computational Linguistics (COLING)*. pp. 723–728.

- Maruyama, Hiroshi (1990). Structural Disambiguation with Constraint Propagation.
  In *Proceedings of the 28th Meeting of the Association for Computational Linguistics (ACL)*. pp. 31–38.
- McDonald, Ryan, Koby Crammer and Fernando Pereira (2005a). Online Large-Margin Training of Dependency Parsers.
  In *Proceedings of the 43rd Annual Meeting of the Association for Computational Linguistics (ACL)*. pp. 91–98.
- McDonald, Ryan, Kevin Lerman and Fernando Pereira (2006). Multilingual Dependency Analysis with a Two-Stage Discriminative Parser.
  In *Proceedings of the Tenth Conference on Computational Natural Language Learning (CoNLL)*.
- McDonald, Ryan and Fernando Pereira (2006). Online Learning of Approximate Dependency Parsing Algorithms.
  In *Proceedings of the 11th Conference of the European Chapter of the Association for Computational Linguistics (EACL)*. pp. 81–88.
- McDonald, Ryan, Fernando Pereira, Kiril Ribarov and Jan Hajič (2005b). Non-Projective Dependency Parsing using Spanning Tree Algorithms.

In *Proceedings of the Human Language Technology Conference and the Conference on Empirical Methods in Natural Language Processing (HLT/EMNLP)*. pp. 523–530.

- Mel'čuk, Igor (1988). *Dependency Syntax: Theory and Practice*. State University of New York Press.
- Menzel, Wolfgang and Ingo Schröder (1998). Decision Procedures for Dependency Parsing Using Graded Constraints. In Sylvain Kahane and Alain Polguère (eds.), *Proceedings of the Workshop on Processing of Dependency-Based Grammars*. pp. 78–87.
- Neuhaus, Peter and Norbert Bröker (1997). The Complexity of Recognition of Linguistically Adequate Dependency Grammars. In *Proceedings of the 35th Annual Meeting of the Association for Computational Linguistics (ACL) and the 8th Conference of the European Chapter of the Association for Computational Linguistics (EACL)*. pp. 337–343.
- Nilsson, Jens, Joakim Nivre and Johan Hall (2006). Graph Transformations in Data-Driven Dependency Parsing. In *Proceedings of COLING-ACL*.
- Nivre, Joakim (2003). An Efficient Algorithm for Projective Dependency Parsing. In Gertjan Van Noord (ed.), *Proceedings of the 8th International Workshop on Parsing Technologies (IWPT)*. pp. 149–160.

- Nivre, Joakim (2006). Constraints on Non-Projective Dependency Graphs.
  In *Proceedings of the 11th Conference of the European Chapter of the Association for Computational Linguistics (EACL)*. pp. 73–80.
- Nivre, Joakim, Johan Hall and Jens Nilsson (2004). Memory-Based Dependency Parsing.
  In Hwee Tou Ng and Ellen Riloff (eds.), *Proceedings of the 8th Conference on Computational Natural Language Learning (CoNLL)*. pp. 49–56.
- Nivre, Joakim, Johan Hall, Jens Nilsson, Gülsen Eryiğit and Svetoslav Marinov (2006). Labeled Pseudo-Projective Dependency Parsing with Support Vector Machines.
  In *Proceedings of the Tenth Conference on Computational Natural Language Learning (CoNLL)*.
- Nivre, Joakim and Jens Nilsson (2005). Pseudo-Projective Dependency Parsing.
  In *Proceedings of the 43rd Annual Meeting of the Association for Computational Linguistics (ACL)*. pp. 99–106.
- Nivre, Joakim and Mario Scholz (2004). Deterministic Dependency Parsing of English Text.
  In *Proceedings of the 20th International Conference on Computational Linguistics (COLING)*. pp. 64–70.
- Schröder, Ingo (2002). Natural Language Parsing with Graded Constraints.

Ph.D. thesis, Hamburg University.

- Sgall, Petr, Eva Hajičová and Jarmila Panevová (1986). *The Meaning of the Sentence in Its Pragmatic Aspects*.
  Reidel.
- Sleator, Daniel and Davy Temperley (1991). *Parsing English with a Link Grammar*.
  Tech. Rep. CMU-CS-91-196, Carnegie Mellon University, Computer Science.
- Tapanainen, Pasi and Timo Järvinen (1997). A non-projective dependency parser.
  In *Proceedings of the 5th Conference on Applied Natural Language Processing*. pp. 64–71.
- Tesnière, Lucien (1959). *Éléments de syntaxe structurale*.
  Editions Klincksieck.
- Yamada, Hiroyasu and Yuji Matsumoto (2003). Statistical Dependency Analysis with Support Vector Machines.
  In Gertjan Van Noord (ed.), *Proceedings of the 8th International Workshop on Parsing Technologies (IWPT)*. pp. 195–206.
- Zwicky, A. M. (1985). Heads.
  Journal of Linguistics 21, 1–29.