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Basic Notions of Dependency Grammar and Dependency Parsing

Joakim Nivre

Uppsala University
Linguistics and Philology

Based on previous tutorials with Ryan McDonald

Overall Plan

1. Basic notions of dependency grammar and dependency parsing
2. Graph-based and transition-based dependency parsing
3. Advanced graph-based parsing techniques
4. Advanced transition-based parsing techniques
5. Neural network techniques in dependency parsing
6. Multilingual parsing from raw text to universal dependencies

Plan for this Lecture

- Dependency grammar:
  - Basic concepts
  - Terminology and notation
  - Dependency graphs
- Dependency parsing
  - Grammar-driven methods
  - Data-driven methods
- Pros and cons of dependency parsing

Dependency Grammar

- The basic idea:
  - Syntactic structure consists of lexical items, linked by binary asymmetric relations called dependencies.
- In the words of Lucien Tesnière [Tesnière 1959]:
  - La phrase est un *ensemble organisé* dont les éléments constituants sont les *mots*. [1.2] Tout mot qui fait partie d'une phrase cesse par lui-même d'être isolé comme dans le dictionnaire. Entre lui et ses voisins, l'esprit aperçoit des *connexions*, dont l'ensemble forme la charpente de la phrase. [1.3] Les connexions structurales établissent entre les mots des rapports de *dépendance*. Chaque connexion unit en principe un terme *supérieur* à un terme *inférieur*. [2.1] Le terme supérieur reçoit le nom de *régissant*. Le terme inférieur reçoit le nom de *subordonné*. Ainsi dans la phrase *Alfred parle* [. . .], *parle* est le régissant et *Alfred* le subordonné. [2.2]

Dependency Grammar

- The basic idea:
  - Syntactic structure consists of lexical items, linked by binary asymmetric relations called dependencies.
- In the 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]

Dependency Structure

Economic	news	had	little	effect	on	financial	markets	.
adj	noun	verb	adj	noun	prep	adj	noun	.

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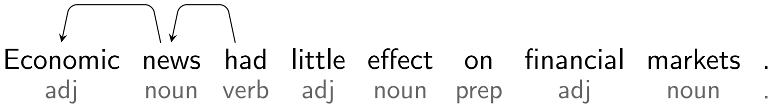

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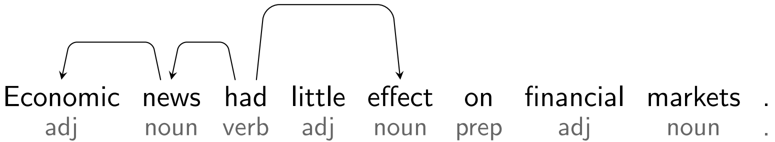

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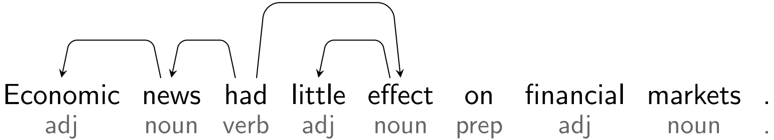

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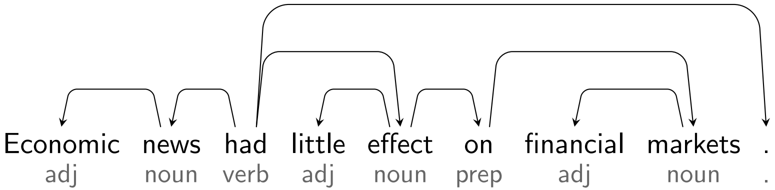

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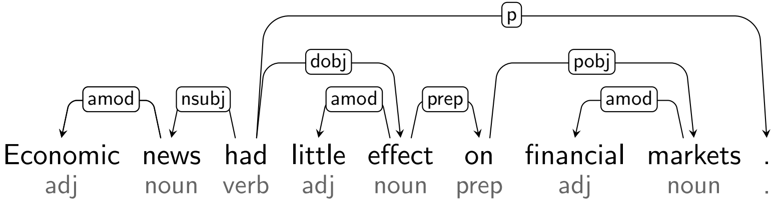

Terminology

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

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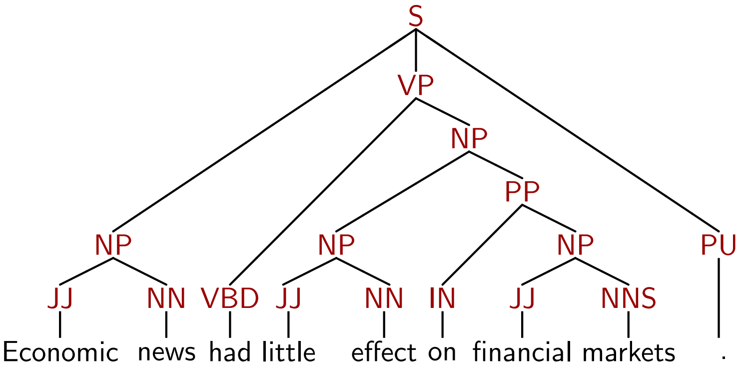
Phrase Structure



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, Hudson 2007]
- Functional Generative Description (FGD) [Sgall et al. 1986]
- Dependency Unification Grammar (DUG) [Hellwig 1986, Hellwig 2003]
- Meaning-Text Theory (MTT) [Mel'čuk 1988, Milićević 2006]
- (Weighted) Constraint Dependency Grammar ([W]CDG) [Maruyama 1990, 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]

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?
  - Multiword expressions?
- 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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Criteria for Heads and Dependents

- Criteria for a syntactic relation between a head H and a dependent D in a construction C [Zwicky 1985, Hudson 1990]:
  1. H determines the syntactic category of C; H can replace C.
  2. H determines the semantic category of C; D specifies H.
  3. H is obligatory; D may be optional.
  4. H selects D and determines whether D is obligatory.
  5. The form of D depends on H (agreement or government).
  6. The linear position of D is specified with reference to H.
- Issues:
  - Syntactic (and morphological) versus semantic criteria
  - Exocentric versus endocentric constructions

Some Clear Cases

Construction	**Head**	**Dependent**
Exocentric	Verb	Subject (nsubj)
	Verb	Object (dobj)
Endocentric	Verb	Adverbial (advmod)
	Noun	Attribute (amod)

Economic	news	suddenly	affected	financial	markets	.
adj	noun	adv	verb	adj	noun	.

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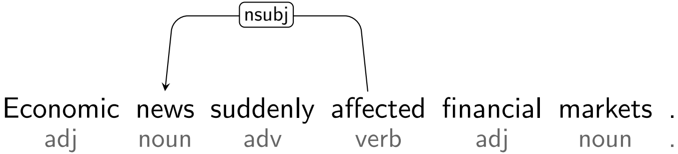

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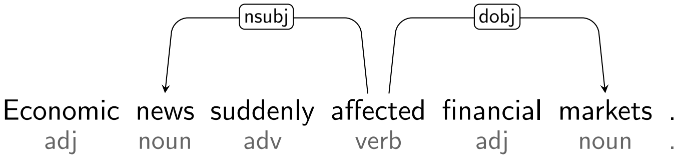

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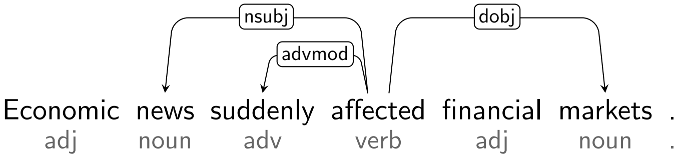

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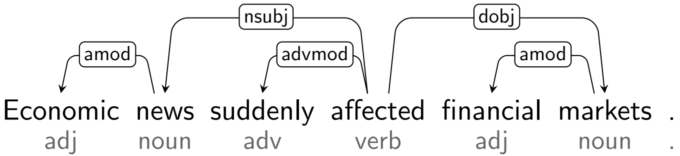

Some Tricky Cases

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

I	can	see	that	they	rely	on	this	and	that	.
pron	aux	verb	sconj	pron	verb	adp	pron	conj	pron	p

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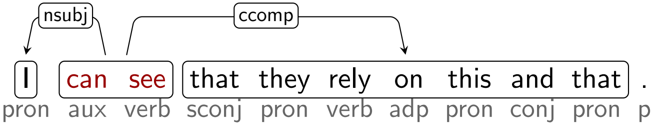

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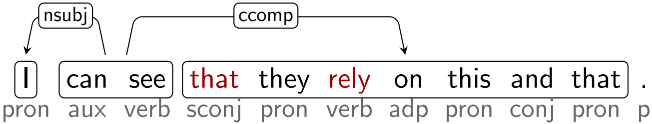

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Dependency Graphs

- A dependency structure can be defined as a directed graph G, consisting of
  - a set V of nodes (vertices),
  - a set A of arcs (directed edges),
  - a linear precedence order $<$ on V (word order).
- Labeled graphs:
  - Nodes in V are labeled with word forms (and annotation).
  - Arcs in A are labeled with dependency types:
    - $L = \{l_1, \ldots, l_{|L|}\}$ 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 Graph Notation

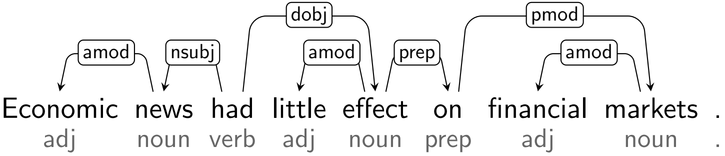
- For a dependency graph $G = (V, A)$
- With label set $L = \{l_1, \ldots, l_{|L|}\}$
  - $i \rightarrow j \;\; \equiv \;\; \exists k : (i, j, k) \in A$
  - $i \leftrightarrow j \;\; \equiv \;\; i \rightarrow j \vee j \rightarrow i$
  - $i \rightarrow^* j \;\; \equiv \;\; i = j \vee \exists i' : i \rightarrow i', \, i' \rightarrow^* j$
  - $i \leftrightarrow^* j \;\; \equiv \;\; i = j \vee \exists i' : i \leftrightarrow i', \, i' \leftrightarrow^* j$

Formal Conditions on Dependency Graphs

- G is (weakly) connected:
  - If $i, j \in V$, $i \leftrightarrow^* j$.
- G is acyclic:
  - If $i \rightarrow j$, then not $j \rightarrow^* i$.
- G obeys the single-head constraint:
  - If $i \rightarrow j$, then not $i' \rightarrow j$, for any $i' \neq i$.
- G is projective:
  - If $i \rightarrow j$, then $i \rightarrow^* i'$, for any i' such that $i < i' < j$ or $j < i' < i$.

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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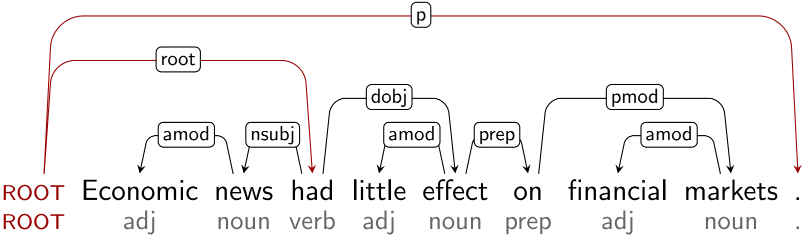
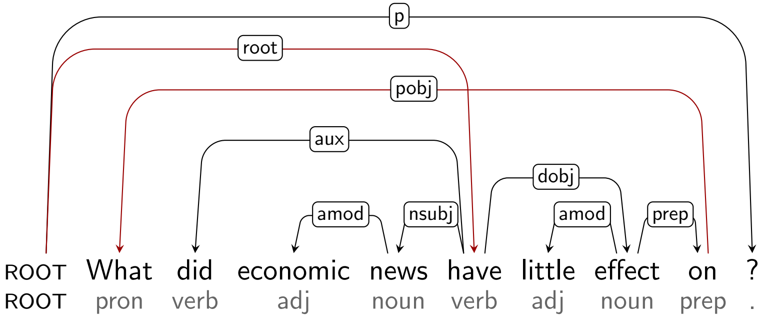


Projectivity

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



Dependency Parsing

- Input: Sentence $x = w_0, w_1, \ldots, w_n$ with $w_0 = \text{ROOT}$
- Output: Dependency graph $G = (V, A)$ for x
  - $V = \{0, 1, \ldots, n\}$ is the node set,
  - A is the arc set, i.e., $(i, j, k) \in A$ iff $w_i \xrightarrow{l_k} w_j$

- Grammar-based parsing
  - Context-free dependency grammar
  - Constraint dependency grammar
- Data-driven parsing
  - Graph-based models
  - Transition-based models

Evaluation Metrics

- Standard setup:
  - Test set $\mathcal{E} = \{(x_1, G_1), (x_2, G_2), \ldots, (x_n, G_n)\}$
  - Parser predictions $\mathcal{P} = \{(x_1, G'_1), (x_2, G'_2), \ldots, (x_n, G'_n)\}$
- Evaluation on the word (arc) level:
  - Labeled attachment score (LAS) = head and label
  - Unlabeled attachment score (UAS) = head
  - Label accuracy (LA) = label
- Evaluation on the sentence (graph) level:
  - Exact match (labeled or unlabeled) = complete graph
- NB: Evaluation metrics may or may not include punctuation

Context-Free Dependency Grammar

- Dependency grammar as lexicalized context-free grammar:

$$H \longrightarrow L_1 \cdots L_m \, h \, R_1 \cdots R_n$$

  - Standard context-free parsing algorithms (CKY, Earley, etc.)
  - Projective, unlabeled dependency trees only
  - Weakly equivalent to arbitrary CFGs [Hays 1964, Gaifman 1965]
- Related approaches:
  - Link Grammar [Sleator and Temperley 1991]
  - Bilexical grammars [Eisner 1996, Eisner 2000]

Constraint Dependency Grammar

- Parsing as constraint satisfaction [Maruyama 1990]:
  - Variables $h_1, \ldots, h_n$ with domain $\{0, 1, \ldots, n\}$
  - Grammar G = set of boolean constraints
  - Parsing = search for dependency graph satisfying G
  - Handles non-projective labeled dependency graphs
  - Parsing intractable in the general case
- Recent developments:
  - Weighted Constraint Dependency Grammar [Menzel and Schröder 1998, Foth et al. 2004]
  - Probabilistic Constraint Dependency Grammar [Harper and Helzerman 1995, Wang and Harper 2004]
  - Topological/Extensible Dependency Grammar [Duchier and Debusmann 2001, Debusmann et al. 2004]

Graph-Based Models

- Basic idea:
  - Define a space of candidate dependency graphs for a sentence.
  - Learning: Induce a model for scoring an entire dependency graph for a sentence.
  - Parsing: Find the highest-scoring dependency graph, given the induced model.
- Characteristics:
  - Global training of a model for optimal dependency graphs
  - Exhaustive search/inference

Transition-Based Models

- Basic idea:
  - Define a transition system (state machine) for mapping a sentence to its dependency graph.
  - Learning: Induce a model for predicting the next state transition, given the transition history.
  - Parsing: Construct the optimal transition sequence, given the induced model.
- Characteristics:
  - Local training of a model for optimal transitions
  - Greedy search/inference

Pros and Cons of Dependency Parsing

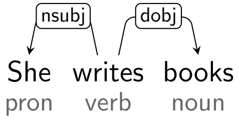
- What are the advantages of dependency-based methods?
- What are the disadvantages?
- Four types of considerations:
  - Complexity
  - Transparency
  - Word order
  - Expressivity

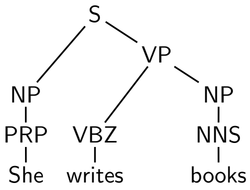
Complexity

- Practical complexity:
  - Given the Single-Head constraint, parsing a sentence $x = w_1, \ldots, w_n$ can be reduced to labeling each token w_i with:
    - a head word h_i,
    - a dependency type d_i.
- Theoretical complexity:
  - By exploiting the special properties of dependency graphs, it is sometimes possible to improve worst-case complexity compared to constituency-based parsing:
    - Lexicalized projective parsing in $O(n^3)$ time [Eisner 1996]
    - Arc-factored non-projective parsing in $O(n^2)$ time [McDonald et al. 2005]

Transparency

- Direct encoding of predicate-argument structure



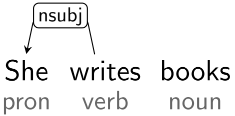


Transparency

- Direct encoding of predicate-argument structure
- Fragments directly interpretable

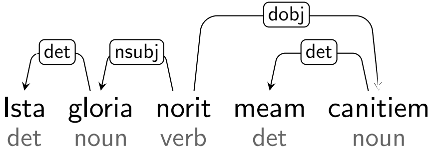
Transparency

- Direct encoding of predicate-argument structure
- Fragments directly interpretable
- But only with labeled dependency graphs



Word Order

- Dependency structure independent of word order
- Suitable for free word order languages



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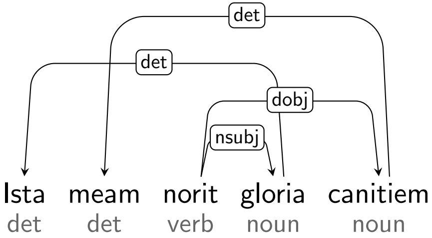

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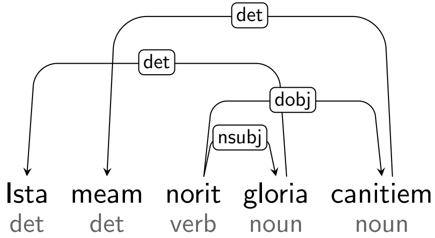
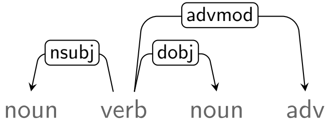
- But only with non-projective dependency graphs



Expressivity

- Limited expressivity:
  - Every projective dependency grammar has a strongly equivalent context-free grammar, but not vice versa [Gaifman 1965].
  - Impossible to distinguish between phrase modification and head modification in unlabeled dependency structure [Mel'čuk 1988].



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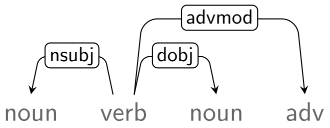

- What about labeled non-projective dependency structures?

Coming Up Next

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References and Further Reading

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