Sorting Out Dependency Parsing

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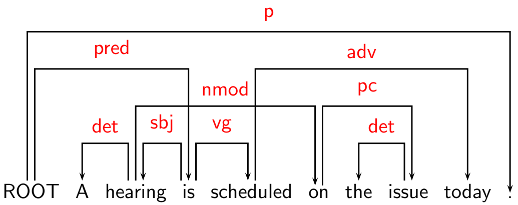
Introduction

- Syntactic parsing of natural language:
  - Who does what to whom?
- Dependency-based syntactic representations
  - have a natural way of representing discontinuous constructions,
  - give a transparent encoding of predicate-argument structure,
  - can be parsed using (simple) data-driven models,
  - can be parsed efficiently.



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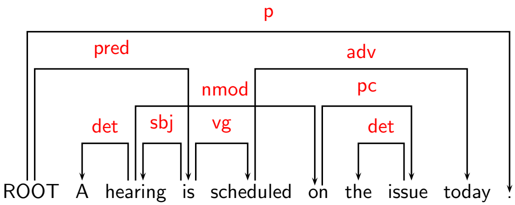

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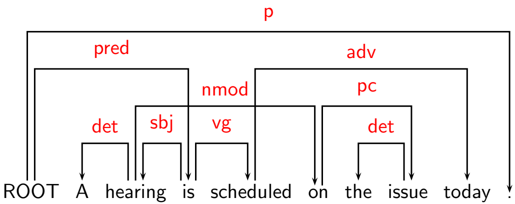


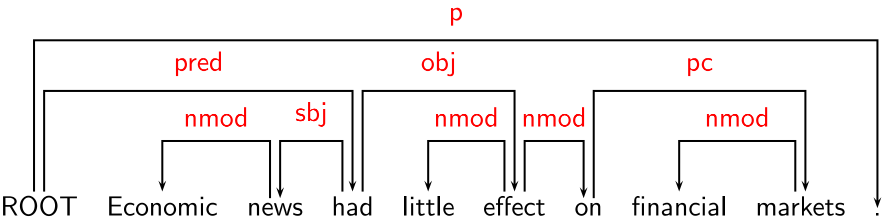
Structure of This Talk

- Part 1:
  - Transition-based dependency parsing
  - Restricted to projective structures
- Part 2:
  - Non-projective dependency parsing
  - Parsing = sorting + projective parsing

Dependency Parsing

Dependency Syntax

- The basic idea:
  - Syntactic structure consists of lexical items, linked by binary asymmetric relations called dependencies.
- Many different theoretical frameworks



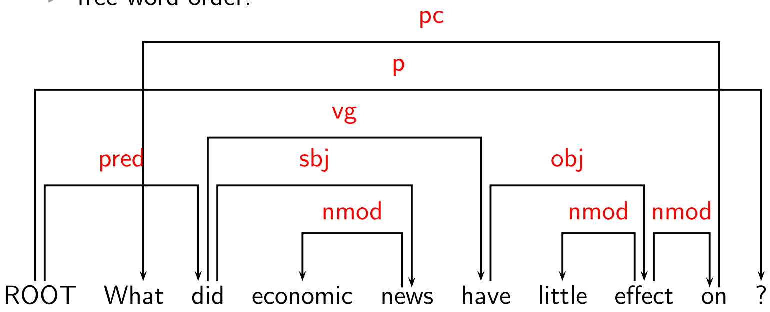
Dependency Trees

- A dependency structure is a labeled directed tree T, consisting of
  - a set V of nodes, labeled with words (including ROOT),
  - a set A of arcs, labeled with dependency types,
  - a linear precedence order $<$ on V,

  with the node labeled ROOT as the unique root.
- **Note:** Some frameworks do not assume that dependency structures are trees but allow general graphs.

Projectivity

- A dependency tree T is projective iff
  - for every arc $w_i \rightarrow w_j$ and every node w_k between w_i and w_j in the linear order, there is a (directed) path from w_i to w_k.
- Most theoretical frameworks do not assume projectivity.
- Non-projective structures are needed to account for
  - long-distance dependencies,
  - free word order.



Non-Projectivity in Natural Language

Language	Sentences	Dependencies
Arabic [Maamouri and Bies 2004]	11.2%	0.4%
Basque [Aduriz et al. 2003]	26.2%	2.9%
Czech [Hajič et al. 2001]	23.2%	1.9%
Danish [Kromann 2003]	15.6%	1.0%
Greek [Prokopidis et al. 2005]	20.3%	1.1%
Russian [Boguslavsky et al. 2000]	10.6%	0.9%
Slovene [Džeroski et al. 2006]	22.2%	1.9%
Turkish [Oflazer et al. 2003]	11.6%	1.5%

Transition-Based Dependency Parsing

Overview of the Approach

- The basic idea:
  - Define a transition system for dependency parsing
  - Train a classifier for predicting the next transition
  - Use the classifier to do parsing as greedy, deterministic search
- Advantages:
  - Efficient parsing (linear time complexity)
  - Robust disambiguation (discriminative classifiers)

Transition System: Configurations

- A parser configuration is a triple $c = (S, Q, A)$, where
  - S = a stack $[\ldots, w_i]_S$ of partially processed nodes,
  - Q = a queue $[w_j, \ldots]_Q$ of remaining input nodes,
  - A = a set of labeled arcs (w_i, w_j, l).
- Initialization:

  $([w_0]_S, [w_1, \ldots, w_n]_Q, \{\,\})$ **NB:** w_0 = ROOT
- Termination:

  $([w_0]_S, []_Q, A)$

Transition System: Transitions

- Left-Arc(l)

$$\frac{([\ldots, w_i, w_j]_S, \quad Q, \quad A)}{([\ldots, w_j]_S, \quad Q, \quad A \cup \{(w_j, w_i, l)\})} \quad [i \neq 0]$$

- Right-Arc(l)

$$\frac{([\ldots, w_i, w_j]_S, \quad Q, \quad A)}{([\ldots, w_i]_S, \quad Q, \quad A \cup \{(w_i, w_j, l)\})}$$

- Shift

$$\frac{([\ldots]_S, \quad [w_i, \ldots]_Q, \quad A)}{([\ldots, w_i]_S, \quad [\ldots]_Q, \quad A)}$$

Deterministic Parsing

- Given an oracle o that correctly predicts the next transition $o(c)$, parsing is deterministic:

$$
\begin{array}{l}
\text{Parse}(w_1, \ldots, w_n) \\
\quad c \leftarrow ([w_0]_S, [w_1, \ldots, w_n]_Q, \{\,\}) \\
\quad \textbf{while } Q_c \neq [\,] \textbf{ or } |S_c| > 1 \\
\quad\quad t \leftarrow o(c) \\
\quad\quad c \leftarrow t(c) \\
\quad \textbf{return } G = (\{w_0, w_1, \ldots, w_n\}, A_c)
\end{array}
$$

Example

$o(c) = \text{Shift}$

$[\![\text{ROOT}]\!]_S \quad [\![\text{Economic news had little effect on financial markets .}]\!]_Q$

ROOT Economic news had little effect on financial markets .

Example

$o(c) = \text{Shift}$

$[\![\text{ROOT Economic}]\!]_S \; [\![\text{news had little effect on financial markets .}]\!]_Q$

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Example

$o(c) = \text{Left-Arc}_{nmod}$

$[\![$ROOT Economic news$]\!]_S$ $[\![$had little effect on financial markets .$]\!]_Q$

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Example

$o(c) = \text{Shift}$

$[\![\text{ROOT} \quad \text{news}]\!]_S \quad [\![\text{had} \quad \text{little} \quad \text{effect} \quad \text{on} \quad \text{financial} \quad \text{markets} \quad .]\!]_Q$

nmod

ROOT Economic news had little effect on financial markets .

Example

$o(c) = \text{Left-Arc}_{sbj}$

$[\![\text{ROOT} \quad \text{news} \quad \text{had}]\!]_S \quad [\![\text{little} \quad \text{effect} \quad \text{on} \quad \text{financial} \quad \text{markets} \quad .]\!]_Q$

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Example

$o(c) = \text{Shift}$

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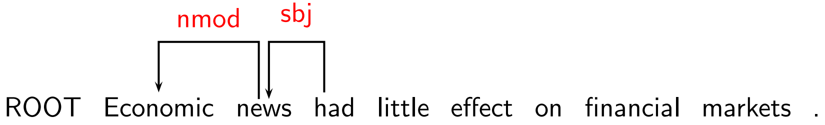

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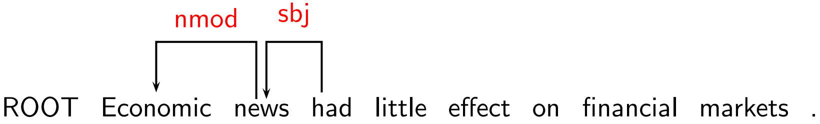

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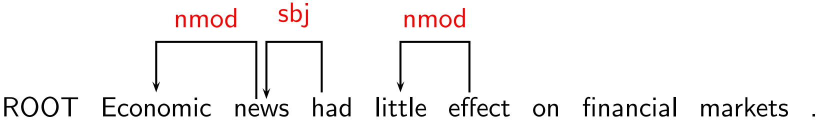

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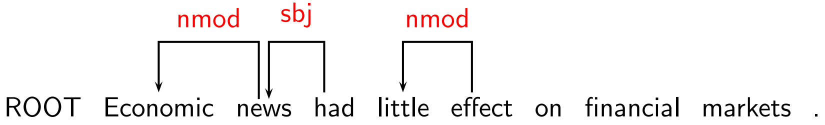

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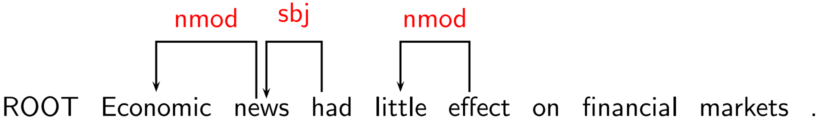

Example

$o(c) = \text{Left-Arc}_{nmod}$

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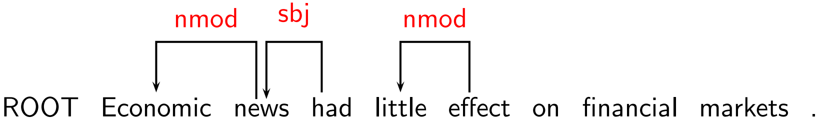
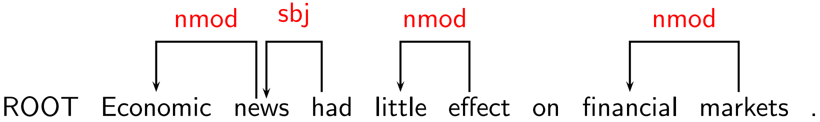


Example

$o(c) = \text{Right-Arc}_{pc}$

$[\![\text{ROOT} \quad \text{had} \quad \text{effect} \quad \text{on} \quad \text{markets}]\!]_S \quad [\![.]\!]_Q$



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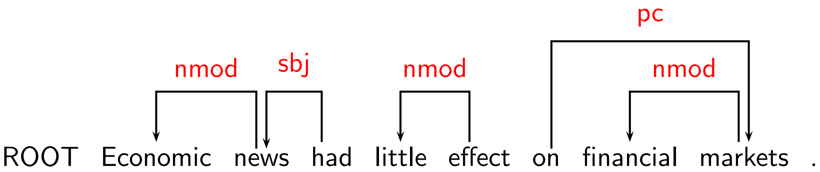
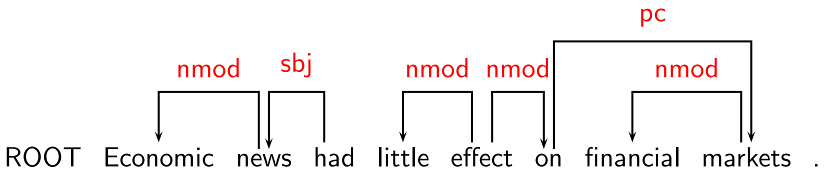


Example

$o(c) = \text{Right-Arc}_{obj}$

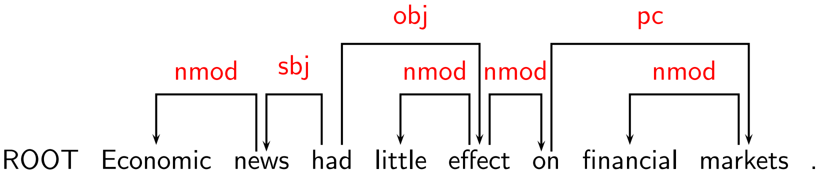
$[\![\text{ROOT} \quad \text{had} \quad \text{effect}]\!]_S \quad [\![.]\!]_Q$



Example

$o(c) = \text{Right-Arc}_{pred}$

$[\![\text{ROOT} \quad \text{had}]\!]_S \quad [\![.]\!]_Q$



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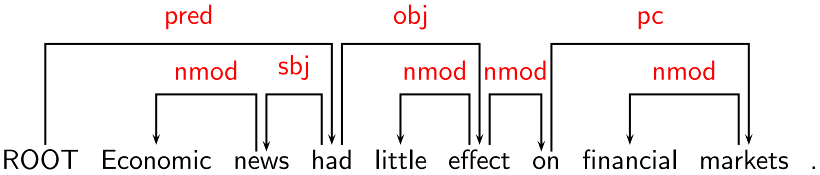
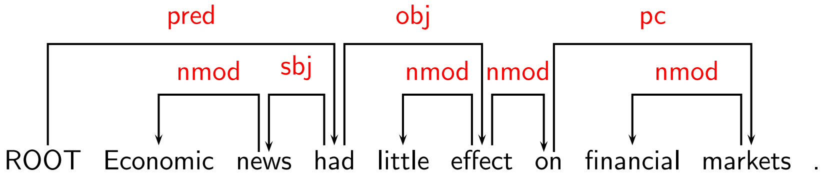


Example

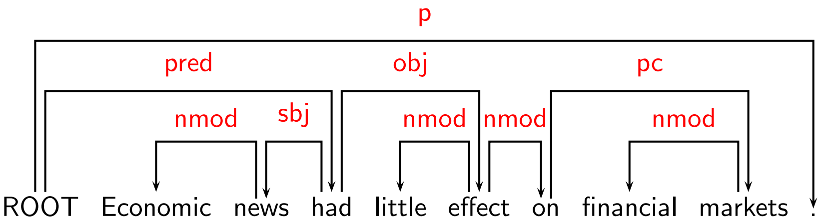
$o(c) = \text{Right-Arc}_p$

$[\![\text{ROOT} \quad .]\!]_S \quad [\![\ ]\!]_Q$



Example

$[\![\mathrm{ROOT}]\!]_S \quad [\![\ ]\!]_Q$



Algorithm Analysis

- Given an input sentence of length n, the parser terminates after exactly $2n$ transitions.
- The algorithm is sound and complete for projective dependency trees.
- The algorithm is arguably optimal with respect to
  - robustness (at least one analysis),
  - disambiguation (at most one analysis),
  - efficiency (linear time).
- Accuracy depends on how well we can approximate oracles using machine learning.

Alternative Parsing Algorithms

- Alternative transition systems:
  - Stack-based:
    - Arc-eager shift-reduce parsing [Nivre 2003]
    - Arc-standard shift-reduce parsing [Yamada and Matsumoto 2003]
    - Restricted non-projective parsing [Attardi 2006]
  - List-based:
    - Unrestricted non-projective parsing [Covington 2001, Nivre 2007]
- Alternative search strategies:
  - Greedy search:
    - Single-pass [Nivre et al. 2004]
    - Iterative [Yamada and Matsumoto 2003]
  - Beam search [Johansson and Nugues 2006, Titov and Henderson 2007]

Oracles as Classifiers

- Learning problem in transition-based dependency parsing:
  - Approximate oracle $o(c)$ by classifier $g(c)$
- History-based feature models:
  - Parse history $c = (S, Q, A)$ represented by feature vector $\mathbf{x}(c)$
  - Individual features $\mathbf{x}_i(c)$ defined by properties of words in c, for example:
    - Lexical properties (FORM or LEMMA)
    - Part-of-speech tags (POSTAG)
    - Morphosyntactic features (FEATS)
    - Labels in the partially built dependency tree (DEPREL)

A Typical Feature Model

$$[\ldots\ w_i\ \ w_j\ \ w_k\ ]_S\ \ [w_m\ \ w_{m+1}\ \ w_{m+2}\ \ldots]_Q$$

	w_i	l_j	w_j	r_j	l_k	w_k	r_k	w_m	w_{m+1}	w_{m+2}
FORM			+			+		+		
LEMMA			+			+				
POSTAG	+		+			+		+	+	+
FEATS			+			+				
DEPREL		+		+	+		+			

Training Data

- Training instances have the form $(\mathbf{x}(c), t)$, where
  1. $\mathbf{x}(c)$ is a feature vector representation of a configuration c,
  2. t is the correct transition out of c (i.e., $o(c) = t$).
- Given a dependency treebank, we can sample the oracle function o as follows:
  - For each sentence we reconstruct the transition sequence $C_{0,m} = (c_0, c_1, \ldots, c_m)$ for the gold standard dependency tree.
  - For each configuration $c_i (i < m)$, we construct a training instance $(\mathbf{x}(c_i), t_i)$, where $t_i(c_i) = c_{i+1}$.

Learning Algorithms

- Discriminative models for classification:
  - Support vector machines (SVM) [Kudo and Matsumoto 2002, Yamada and Matsumoto 2003, Nivre et al. 2006]
  - Memory-based learning [Nivre et al. 2004, Attardi 2006]
  - Maximum entropy [Cheng et al. 2005, Attardi 2006]
  - Perceptron learning [Ciaramita and Attardi 2007]
- State-of-the-art performance:
  - Deterministic transition-based parsing with SVM classifiers
  - CoNLL Shared Task 2006 and 2007 [Buchholz and Marsi 2006, Nivre et al. 2007]

Summing Up

- The approach so far:
  - Transition systems for constructing dependency trees
  - Deterministic linear-time parsing with oracle
  - Oracles approximated by classifiers trained on treebank data
- However:
  - Limited to projective dependency trees
  - What to do with discontinuous constructions?

Non-Projective Dependency Parsing

What's the Problem?

- Non-projective dependency trees are required for representational adequacy (discontinuity, transparency).
- Non-projective dependency parsing is computationally hard:
  - Exact inference is feasible in polynomial time only with drastic independence assumptions (so-called arc-factored models).
  - Greedy deterministic inference is less efficient than in the projective case ($O(n^2)$ vs. $O(n)$).
- Non-projective dependency parsing is empirically hard:
  - Non-projective dependencies often span longer distances and are hard to learn with data-driven models.

Previous Work

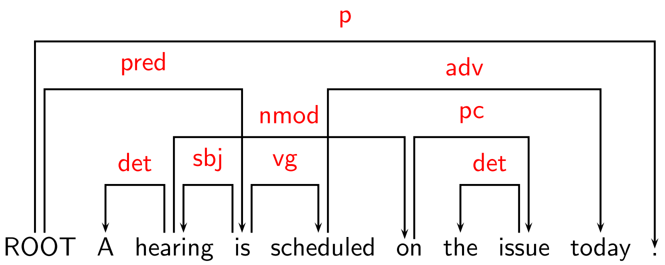
- Algorithms for non-projective dependency parsing:
  - Graph-based parsing using the Chu-Liu-Edmonds algorithm [McDonald et al. 2005]
  - Transition-based parsing for restricted [Attardi 2006] or arbitrary [Nivre 2007] non-projective structures
- Post-processing of projective dependency trees:
  - Pseudo-projective parsing [Nivre and Nilsson 2005]
  - Corrective modeling [Hall and Novák 2005]
  - Approximate spanning tree parsing [McDonald and Pereira 2006]

A New Idea

- Parsing as the result of two interleaved processes:
  - Sorting the words into a projective order
  - Parsing the sorted words into a projective dependency tree
- Potential advantages:
  - Reduces to projective parsing in the best case
  - Brings elements of discontinuous constructions together

Projectivity and Word Order

- Projectivity is a property of a dependency tree only in relation to a particular word order.
- Words can always be reordered to make the tree projective.



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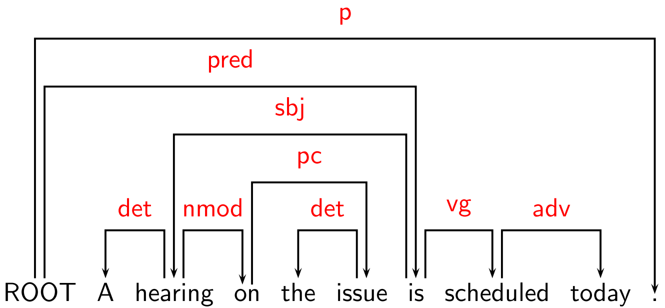
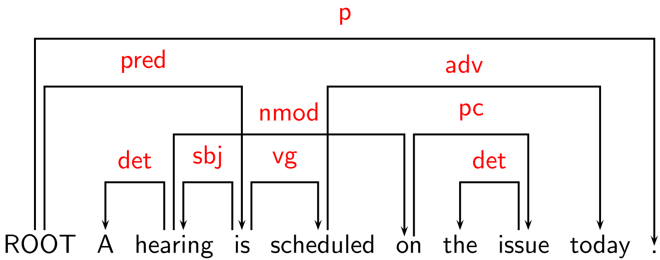


Projective Order

- Given a dependency tree $T = (V, A, <)$, let the projective order $<_p$ be the order defined by an inorder traversal of T with respect to $<$.



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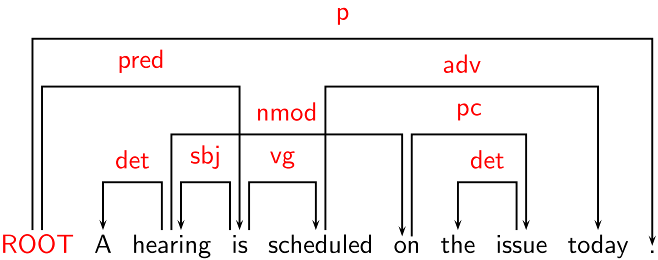

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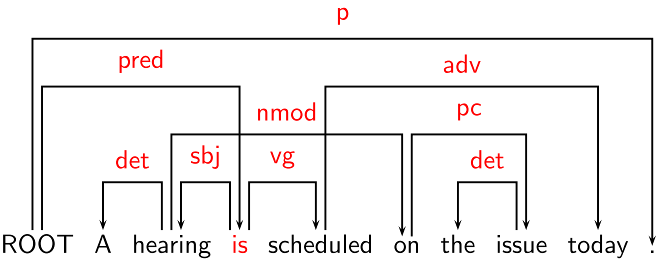

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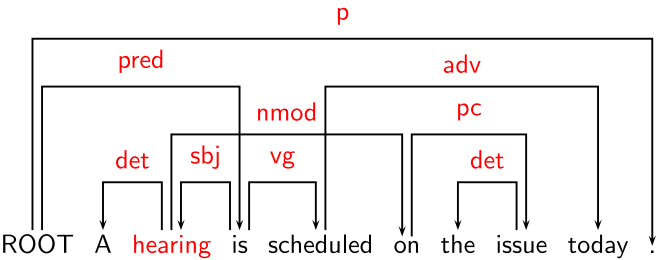

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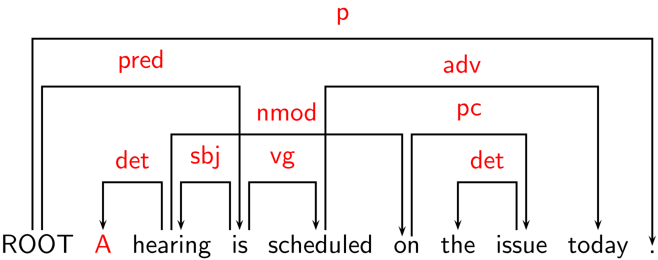

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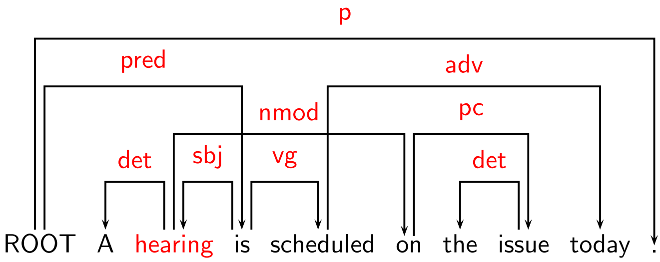

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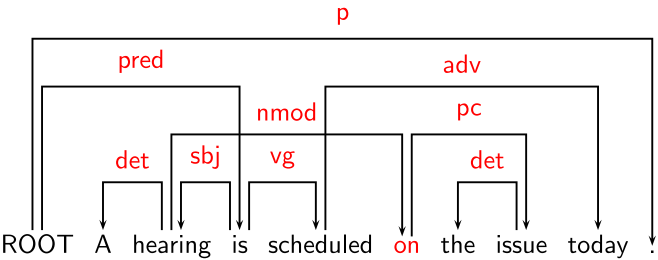

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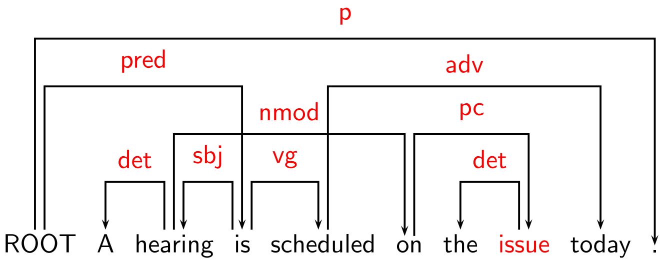

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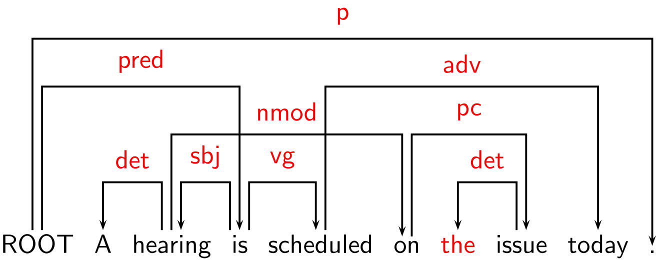

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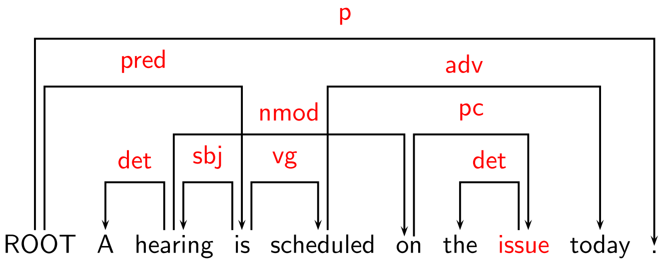

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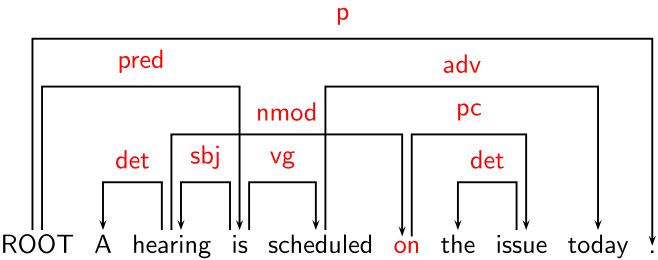

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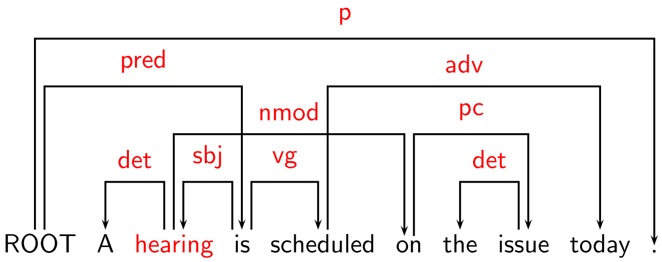

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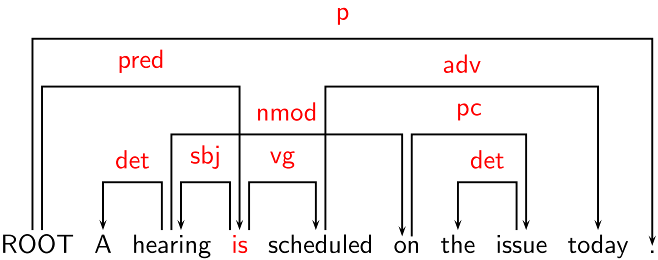

ROOT A hearing on the issue is

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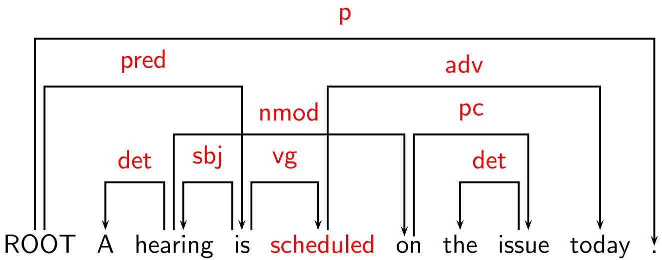

ROOT A hearing on the issue is scheduled

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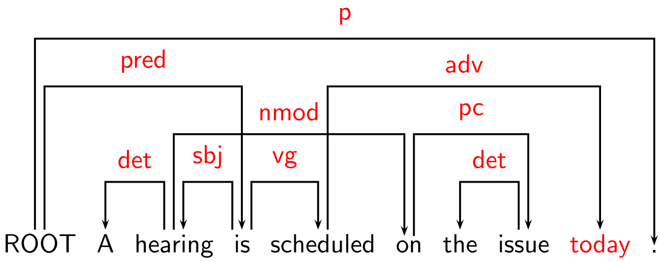

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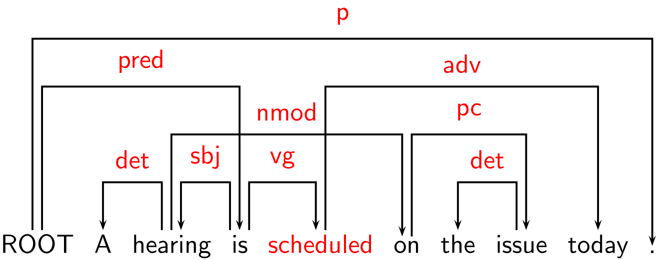

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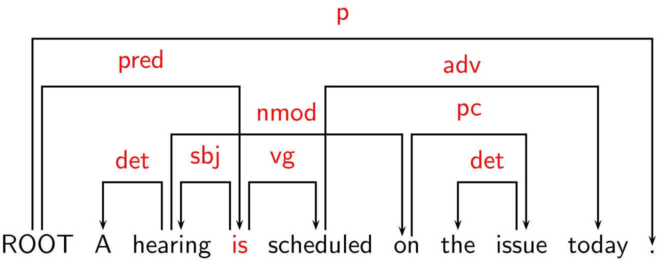

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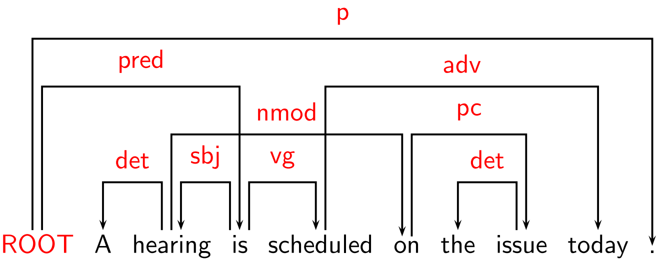

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Projective Order

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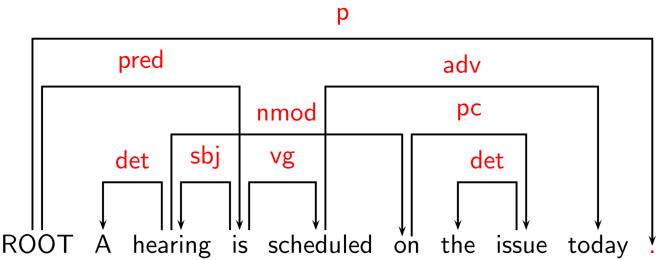

ROOT A hearing on the issue is scheduled today .

Sorting into Projective Order

- Basic idea:
  - Combine an algorithm for sorting words according to the projective order $<_p$ with a transition-based algorithm for constructing a projective dependency tree
- Requirements on sorting algorithm:
  - Online algorithm (sorts in a single left-to-right pass)
  - Exchange sort (sorts by swapping elements)
  - Comparison of adjacent elements (cf. parsing algorithm)
- The simplest sorting algorithm:
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Transition System: Configurations

- A parser configuration is a triple $c = (S, Q, A)$, where
  - $S =$ a stack $[\ldots, w_i]_S$ of partially processed nodes,
  - $Q =$ a stack $[w_j, \ldots]_Q$ of remaining input nodes,
  - $A =$ a set of arcs (w_i, w_j, l).
- Initialization:

  $([w_0]_S, [w_1, \ldots, w_n]_Q, \{\,\})$

  NB: $w_0 =$ ROOT
- Termination:

  $([w_0]_S, [\,]_Q, A)$

Transition System: Transitions

- Swap

$$\frac{([\ldots, w_i, w_j]_S, \quad [\ldots]_Q, \quad A) \quad [i \neq 0, i < j]}{([\ldots, w_j]_S, \quad [w_i, \ldots]_Q, \quad A)}$$

- Left-Arc(l)

$$\frac{([\ldots, w_i, w_j]_S, \quad Q, \quad A) \quad [i \neq 0]}{([\ldots, w_j]_S, \quad Q, \quad A \cup \{(w_j, w_i, l)\})}$$

- Right-Arc(l)

$$\frac{([\ldots, w_i, w_j]_S, \quad Q, \quad A)}{([\ldots, w_i]_S, \quad Q, \quad A \cup \{(w_i, w_j, l)\})}$$

- Shift

$$\frac{([\ldots]_S, \quad [w_i, \ldots]_Q, \quad A)}{([\ldots, w_i]_S, \quad [\ldots]_Q, \quad A)}$$

Deterministic Parsing

- Given an oracle o that correctly predicts the next transition $o(c)$, parsing is deterministic:

Parse$(w_1, \ldots, w_n)$
$c \leftarrow ([w_0]_S, [w_1, \ldots, w_n]_Q, \{\,\})$
while $Q_c \neq [\,]$ **or** $|S_c| > 1$
$\quad t \leftarrow o(c)$
$\quad c \leftarrow t(c)$
return $G = (\{w_0, w_1, \ldots, w_n\}, A_c)$

Example

$o(c) = \text{Shift}$

$[\![\text{ROOT}]\!]_S \quad [\![\text{A hearing is scheduled on the issue today .}]\!]_Q$

ROOT A hearing is scheduled on the issue today .

Example

$o(c) = \text{Shift}$

$[\![\text{ROOT} \;\; \text{A}]\!]_S \;\; [\![\text{hearing} \;\; \text{is} \;\; \text{scheduled} \;\; \text{on} \;\; \text{the} \;\; \text{issue} \;\; \text{today} \;\; .]\!]_Q$

ROOT A hearing is scheduled on the issue today .

Example

$o(c) = \text{Left-Arc}_{det}$

$[\![$ROOT A hearing$]\!]_S$ $[\![$is scheduled on the issue today .$]\!]_Q$

ROOT A hearing is scheduled on the issue today .

Example

$o(c) = \text{Shift}$

$[\![\text{ROOT} \;\; \text{hearing}]\!]_S \;\; [\![\text{is} \;\; \text{scheduled} \;\; \text{on} \;\; \text{the} \;\; \text{issue} \;\; \text{today} \;\; .]\!]_Q$

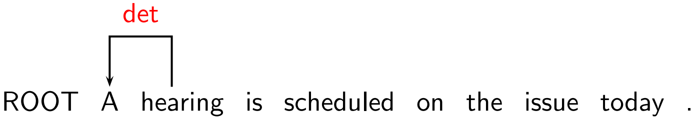
det

ROOT A hearing is scheduled on the issue today .

Example

$o(c) = \text{Shift}$

$[\![\text{ROOT} \quad \text{hearing} \quad \text{is}]\!]_S \quad [\![\text{scheduled} \quad \text{on} \quad \text{the} \quad \text{issue} \quad \text{today} \quad .]\!]_Q$



Example

$o(c) = \text{Shift}$

$[\![\text{ROOT} \quad \text{hearing} \quad \text{is} \quad \text{scheduled}]\!]_S \quad [\![\text{on} \quad \text{the} \quad \text{issue} \quad \text{today} \quad .]\!]_Q$

det

ROOT A hearing is scheduled on the issue today .

Example

$o(c) = \text{Swap}$

$[\![\text{ROOT hearing is scheduled on}]\!]_S \quad [\![\text{the issue today .}]\!]_Q$

det

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Example

$o(c) = \text{Swap}$

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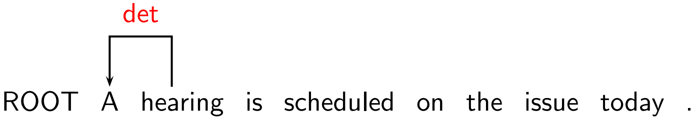

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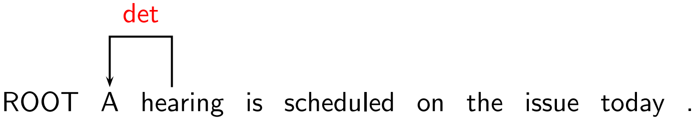


Example

$o(c) = \text{Left-Arc}_{det}$

$[\![$ROOT hearing on the issue$]\!]_S$ $[\![$is scheduled today .$]\!]_Q$

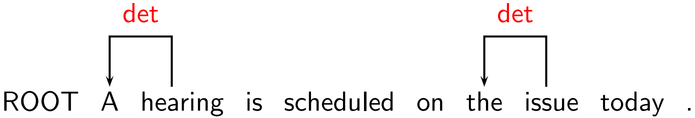
det

ROOT A hearing is scheduled on the issue today .

Example

$o(c) = \text{Right-Arc}_{pc}$

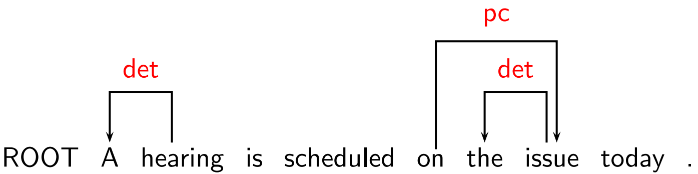
$[\![$ROOT hearing on issue$]\!]_S$ $[\![$is scheduled today .$]\!]_Q$



Example

$o(c) = \text{Right-Arc}_{\color{red}{nmod}}$

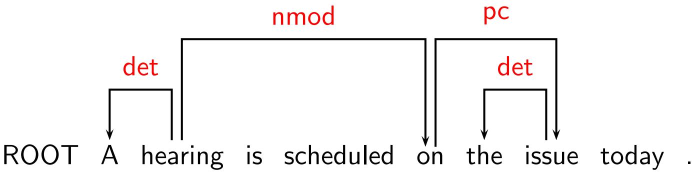
$[\![\text{ROOT} \quad \text{hearing} \quad \text{on}]\!]_S \quad [\![\text{is} \quad \text{scheduled} \quad \text{today} \quad .]\!]_Q$



Example

$o(c) = \text{Shift}$

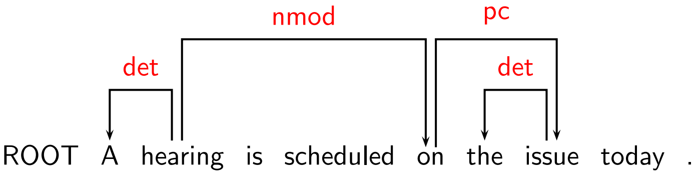
$[\![\text{ROOT} \quad \text{hearing}]\!]_S \quad [\![\text{is} \quad \text{scheduled} \quad \text{today} \quad .]\!]_Q$



Example

$o(c) = \text{Left-Arc}_{sbj}$

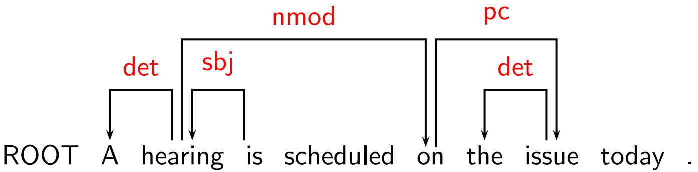
$[\![\text{ROOT} \quad \text{hearing} \quad \text{is}]\!]_S \quad [\![\text{scheduled} \quad \text{today} \quad .]\!]_Q$



Example

$o(c) = \text{Shift}$

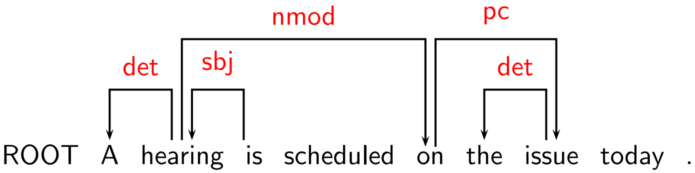
$[\![\text{ROOT} \quad \text{is}]\!]_S \quad [\![\text{scheduled} \quad \text{today} \quad .]\!]_Q$



Example

$o(c) = \text{Shift}$

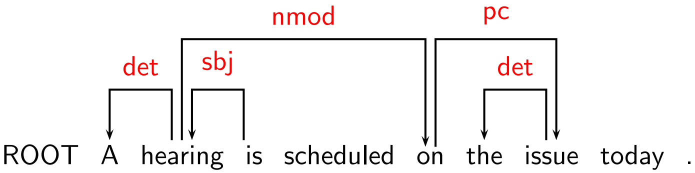
$[\![\text{ROOT} \quad \text{is} \quad \text{scheduled}]\!]_S \quad [\![\text{today} \quad .]\!]_Q$



Example

$o(c) = \text{Right-Arc}_{adv}$

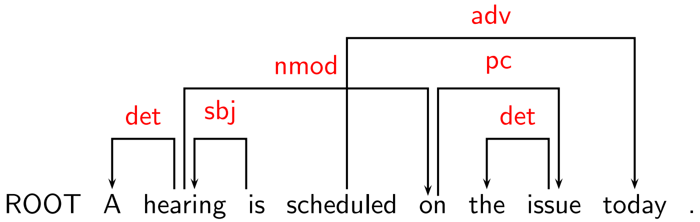
$[\![\text{ROOT} \quad \text{is} \quad \text{scheduled} \quad \text{today}]\!]_S \quad [\![.]\!]_Q$



Example

$o(c) = \text{Right-Arc}_{vg}$

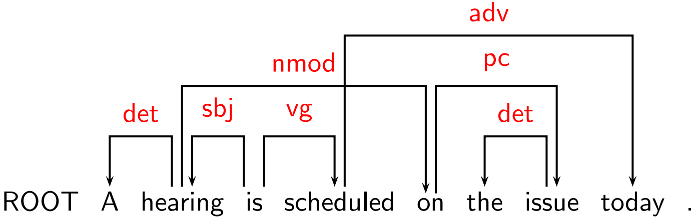
$[\![\text{ROOT is scheduled}]\!]_S \quad [\![.]\!]_Q$



Example

$o(c) = \text{Right-Arc}_{pred}$

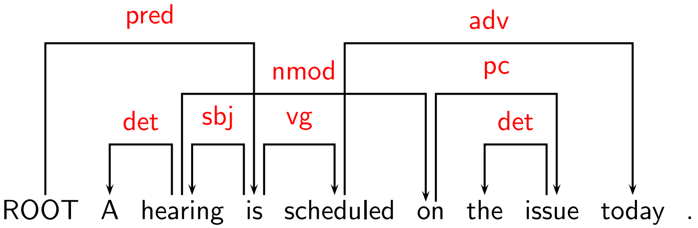
$[\![\text{ROOT} \quad \text{is}]\!]_S \quad [\![.]\!]_Q$



Example

$o(c) =$ Shift

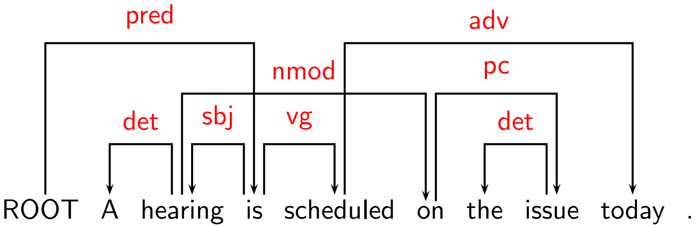
$[\![\text{ROOT}]\!]_S \quad [\![.]\!]_Q$



Example

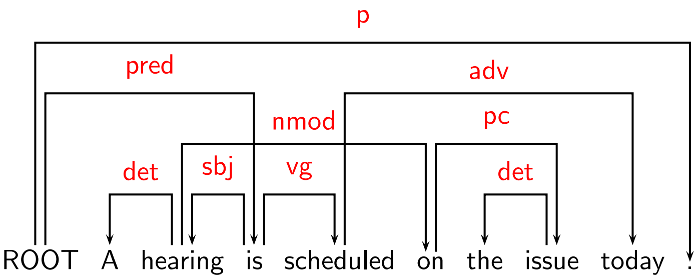
$o(c) = \text{Right-Arc}_p$

$[\![\text{ROOT} \quad .]\!]_S \quad [\![\ ]\!]_Q$



Example

$[\![\mathrm{ROOT}]\!]_S \quad [\![\ ]\!]_Q$



Algorithm Analysis

- Time complexity of parsing:
  - $O(n^2)$ in the worst case ($\frac{n(n-1)}{2}$ swaps)
  - $O(n)$ in the best case (0 swaps)
  - Average case $\approx$ best case?
- Conjecture:
  - Sound and complete for non-projective dependency trees
- Crucial questions:
  - Can we train classifiers to do sorting as well as parsing?
  - Can we maintain linear parsing time on average?

Experimental Evaluation

- Data from the CoNLL-X shared task [Buchholz and Marsi 2006]:
  - Arabic (1.5k, 11.2%)
  - Czech (72.7k, 23.2%)
  - Danish (5.2k, 15.6%)
  - Slovene (1.5k, 22.2%)
  - Turkish (5.0k, 5.4%)
- Classifiers:
  - Support vector machines with polynomial kernel (degree 2)
  - Feature models optimized on development set
- Evaluation metrics:
  - Labeled attachment score (LAS): Percentage of words that are assigned the correct head and dependency label
  - Labeled exact match (LEM): Percentage of sentences that are parsed correctly (including labels)

Labeled Attachment Score

	Ara	**Cze**	**Dan**	**Slo**	**Tur**
NProj	67.1	**82.4**	84.2	75.2	64.9
Proj	67.3	80.9	84.6	74.2	65.3
PProj	67.2	82.1	84.7	74.8	65.5
Malt-06	66.7	78.4	84.8	70.3	65.7
MST-06	66.9	80.2	84.8	73.4	63.2
MST_{Malt}	**68.6**	82.3	**86.7**	**75.9**	**66.3**

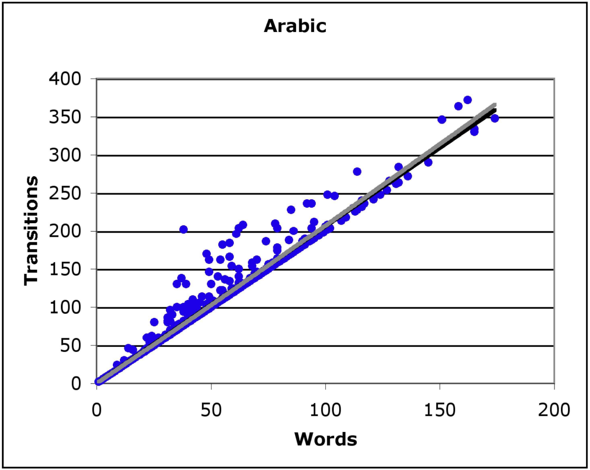
LAS for Non-Projective Arcs

	Ara	**Cze**	**Dan**	**Slo**	**Tur**
NProj	9.1	**73.8**	22.5	23.0	**11.8**
Proj	**18.2**	3.7	0.0	3.4	6.6
PProj	**18.2**	60.7	22.5	20.7	**11.8**
Malt-06	**18.2**	57.9	27.5	20.7	9.2
MST-06	0.0	61.7	**62.5**	26.4	**11.8**
MST_{Malt}	9.4	69.2	60.0	**27.6**	9.2

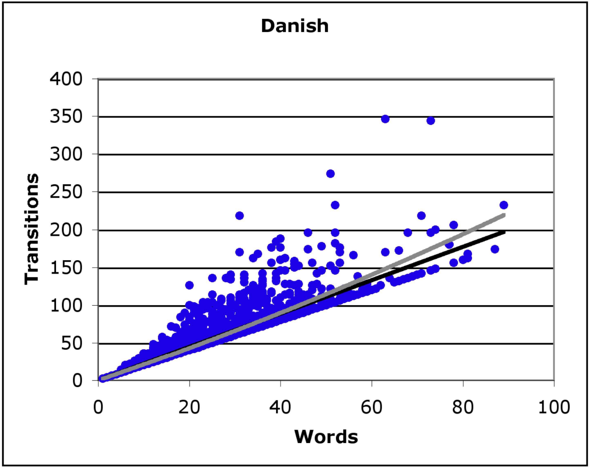
Labeled Exact Match

	Ara	**Cze**	**Dan**	**Slo**	**Tur**
NProj	**11.6**	**35.3**	26.7	**29.9**	**21.5**
Proj	**11.6**	31.2	27.0	**29.9**	21.0
PProj	**11.6**	34.0	28.9	26.9	20.7
Malt-06	11.0	27.4	26.7	19.7	19.3
MST-06	10.3	29.9	25.5	20.9	20.2
$\mathrm{MST}_{\mathrm{Malt}}$	11.0	31.2	**29.8**	26.6	18.6

Abstract Running Time: Arabic



Abstract Running Time: Danish



Conclusion

- Transition-based dependency parsing:
  - Efficient thanks to greedy, deterministic search
  - Accurate thanks to powerful discriminative classification
- Novel approach to non-projective dependency parsing:
  - Interleaved sorting and parsing
  - Efficiency maintained
  - Promising empirical results

Acknowledgments

- My students and co-developers of MaltParser:
  - Johan Hall and Jens Nilsson
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