Dependency Parsing

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INTRO / CHART PARSING

Adapted from slides by Neelamadhav Gantayat and Ryan MacDonald

Dependency Syntax

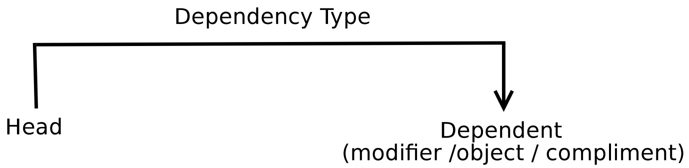
- Turns sentence into syntactic structure
- Essential for information extraction and other NLP tasks

Lucien Tesnière, 1959

The sentence is an organized whole, the constituent elements of which are words. 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 percieves connections, the totality of which forms the structure of the sentence. The structural connections establish dependency relations between the words.

Dependency Grammar

- **Basic Assumption:** Syntactic structure essentially consists of lexical items linked by binary asymmetrical relations called dependencies.



Example of dependency parser output

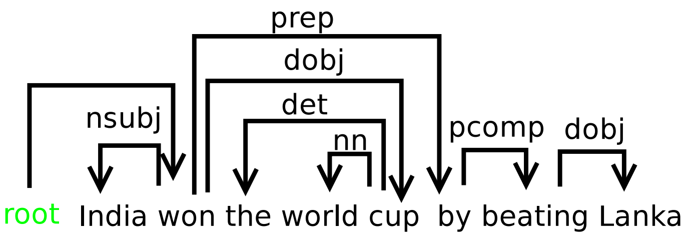


Figure: Output of Stanford dependency parser

Example of dependency parser output

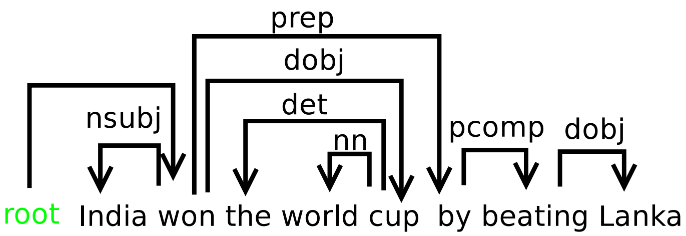


Figure: Output of Stanford dependency parser

- Verb has an artificial root
- Notion of phrases: “by” and its children
- So how do we choose these edges?

Criteria for dependency

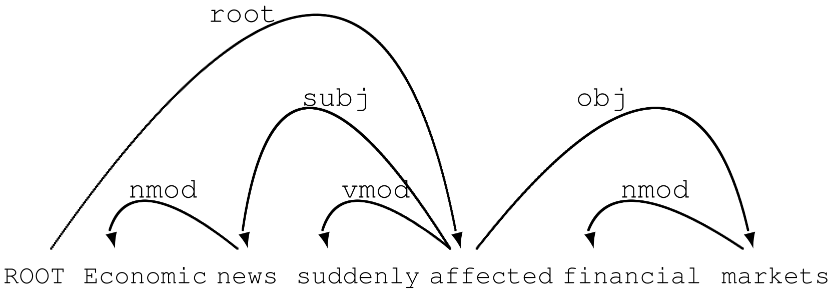
D is likely a dependent of head *H* in construction *C*:

- *H* determines syntactic category of *C* and can often replace *C*
- *H* gives semantic specification of *C*; *D* specifies *H*
- *H* is obligatory; *D* may be optional
- *H* selectes *D* and determines whether *D* is obligatory
- The form of *D* depends on *H* (agreement or government)
- The linear position of *D* is specified with reference to *H*

Which direction?

Some clear cases . . .

- Modifiers: “nmod” and “vmod”
- Verb slots: “subject” and “object”



Which direction?

Some tricky cases . . .

- Complex verb groups
- Subordinate clauses
- Coordination
- Prepositions
- Punctuation

```
I   can see that they rely on this and that.
```

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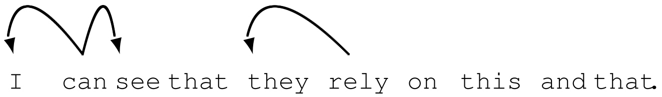

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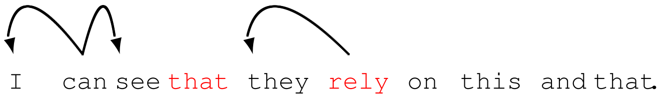

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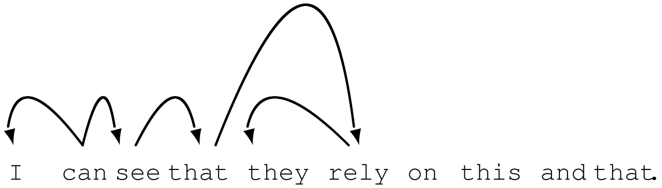

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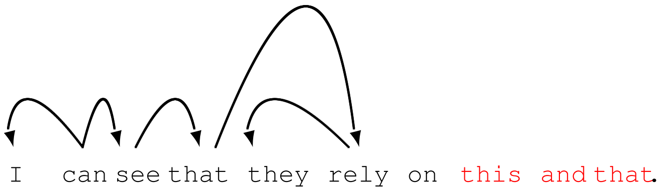

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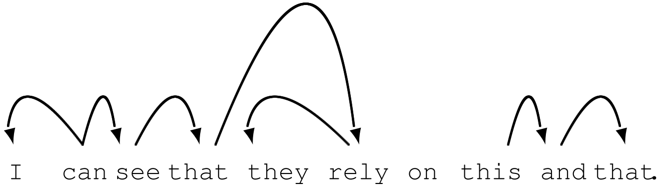

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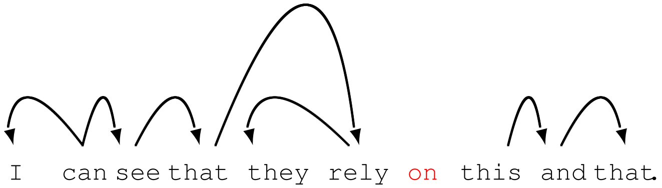

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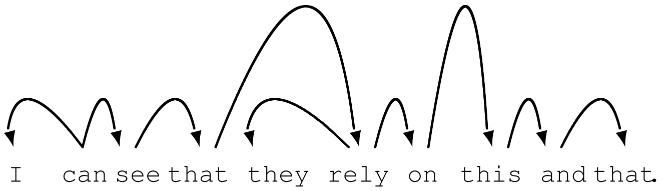

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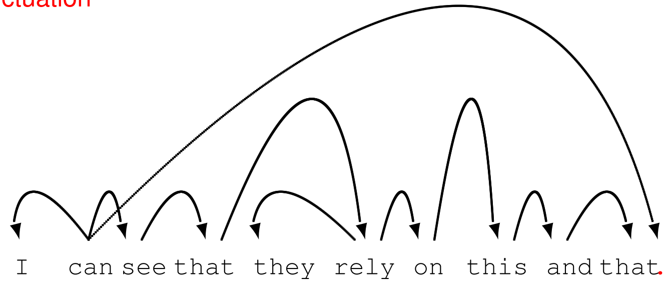

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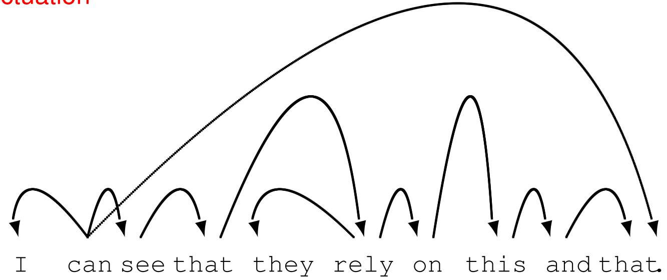


Dependency Parsing

- Input: Sentence $x = w_0, w_1, ..., w_n$
- Output: Dependency graph $G = (V, A)$ for x where:
    - $V = 0, 1, ..., n$ is the vertex set,
    - A is the arc set, i.e., $(i, j, k) \in A$ represents a dependency from w_i to w_j with label $l_k \in L$
- Notational Conventions
    - $i \rightarrow j \equiv \exists k : (i, j, k) \in A$ (unlabeled dependency)
    - $i \longleftrightarrow j \equiv i \rightarrow \vee j \rightarrow i$ (undirected dependency)
    - $i \rightarrow *j \equiv i = j \vee \exists i' : i \rightarrow i', i' \rightarrow *j$ (unlabeled closure)
    - $i \longleftrightarrow *j \equiv i \vee \exists i' : i \longleftrightarrow i',' i \longleftrightarrow *j$ (undirected closure)

Conditions

- Intuitions
  - Syntactic structure is complete (Connectedness)
  - Syntactic structure is hierarchical (Acyclic)
  - Every word has at most one syntactic head (Single-Head)
- Connectedness is enforced by adding special root node

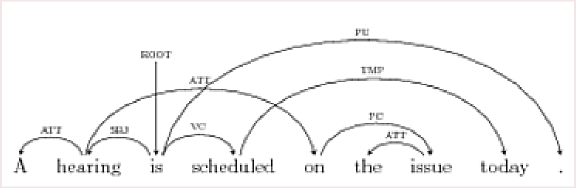
Conditions

- Connected: $\forall i, j \in V, i \longleftrightarrow * j$
- Acyclic: If $i \longrightarrow j$, then not $j \longrightarrow * i$
- Single-head: If $i \longrightarrow j$, then not $i' \longrightarrow j \forall i' \neq i$
- Projective: If $i \longrightarrow j$, then $i \longrightarrow * i'$ for any i' such that $i < i' < j$ or $j < i' < i$.

Projectivity

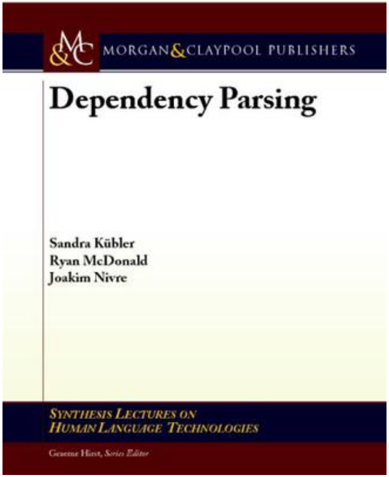
- Equivalent to planar embedding
- Most theoretical frameworks do not assume projectivity
- Non-projective structures needed for free word order and long-distance dependencies

Non-projective example



- The algorithm later we'll discuss is projective

- Many algorithms exist (good overview in Kübler et al)
- We will focus on a arc-factored projective model
  - arc-factored: Score factorizes over edges
  - projective: no crossing lines (planar embedding)
- This is a common, but not universal assumption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Dependency Parsing

Sandra Kübler
Ryan McDonald
Joakim Nivre

SYNTHESIS LECTURES ON HUMAN LANGUAGE TECHNOLOGIES

Graeme Hirst, Series Editor

How good is a given tree?

1. $\text{score}(G) = \text{score}(V, A) \in \mathbb{R}$
2. Arc-factored assumption:

$$\text{score}(G) = \sum_{(w_i, r, w_j) \in A} \psi_{w_i, r, w_j} \tag{1}$$

3. Further simplification for class:

$$\text{score}(G) = \sum_{(w_i, w_j) \in A} \psi_{w_i, w_j} \tag{2}$$

4. You can think about this probabilistically when

$$\psi_{w_i, w_j} \equiv log\left(p((w_i, w_j) \in A)\right) \tag{3}$$

Dynamic Programming

- A parser should avoid re-analyzing sub-strings because the analysis of a substring is independent of the rest of the parse.
- The parsers exploration of its search space can exploit this independence: dynamic programming (CS) / chart parsing (ling)
- Once solutions to sub-problems have been accumulated, solve the overall problem by composing them
- Sub-trees are stored in a chart, which records all substructures:
  - re-parsing: sub-trees are looked up, not reparsed
  - ambiguity: chart implicitly stores all parses

Central Idea: Spans

- Like Viterbi algorithm, we'll solve sub problems to find the overall optimum
- Our overall goal is to find the **best parse** for the **entire sentence**

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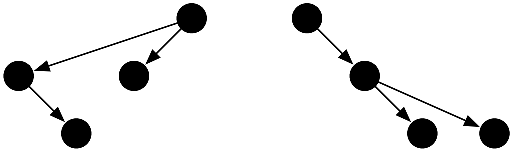

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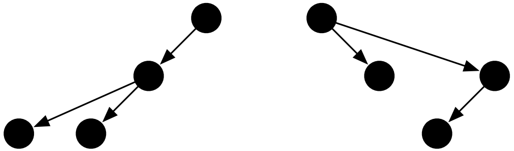

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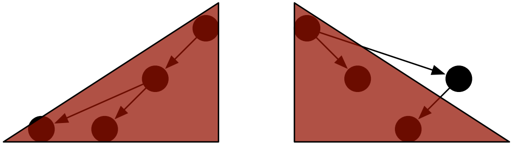

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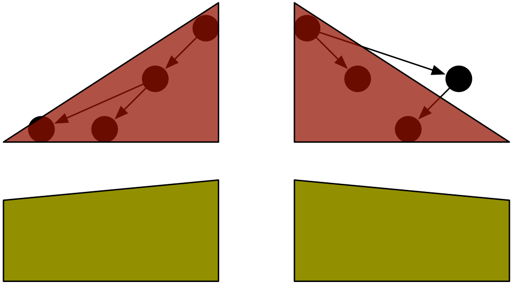

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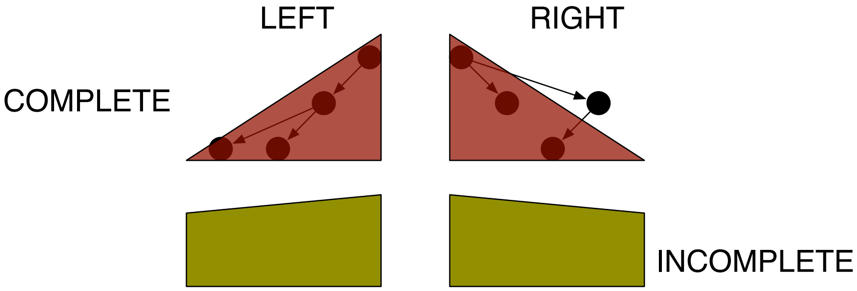
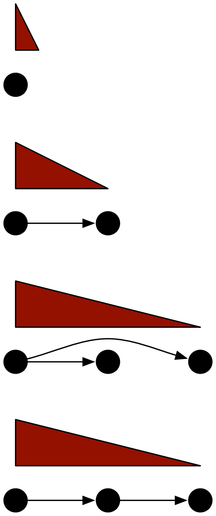


Central Idea: Spans

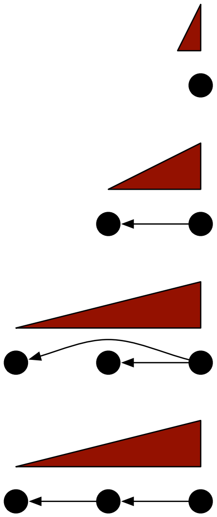
- To do this, we'll find the **best parse** for contiguous **spans** of the sentence, characterized by
    - start $0 \dots n$
    - stop $0 \dots n$
    - direction $\leftarrow, \rightarrow$
    - completeness $\circ, \cdot$
- Each span gets an entry in a 4D chart (same as 2D chart for POS tagging)
- Find the overall tree that gives highest score

Right Complete Spans

- We write the total score of these spans $C[s][t][\rightarrow][\cdot]$
- "Root" of this subtree is at word s
- Can have arbitrary substructure until word t, but cannot take additional right children



Left Complete Spans



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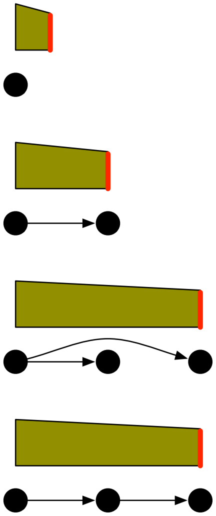

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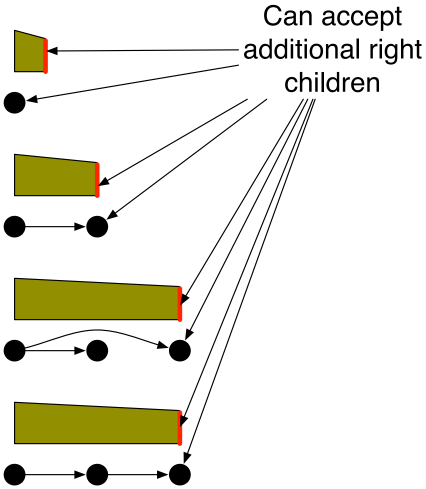

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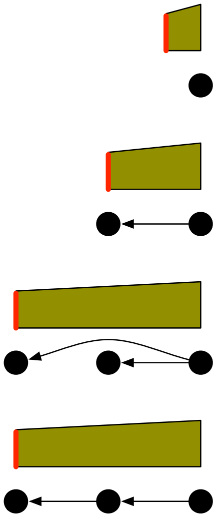

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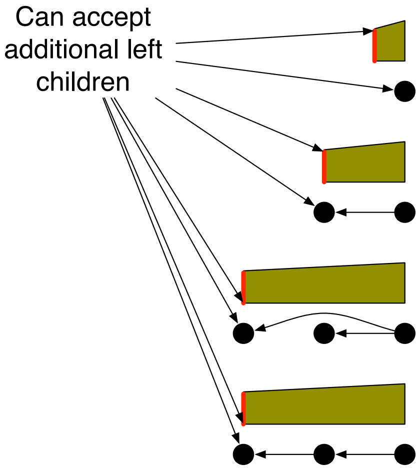

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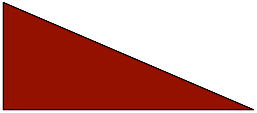
Dynamic Programming Intuition

$C[0][L][\rightarrow][\cdot]$ contains the best score for the overall tree.



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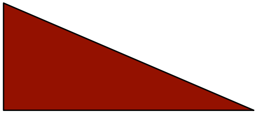

Where's the main verb?

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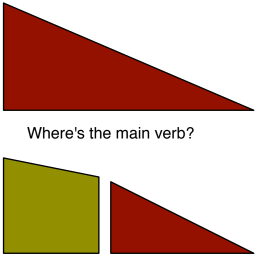

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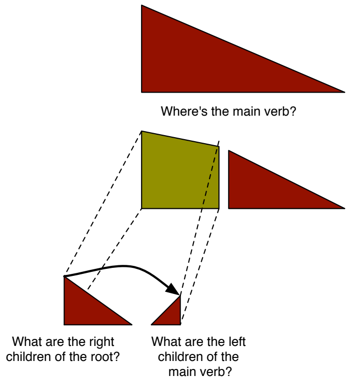
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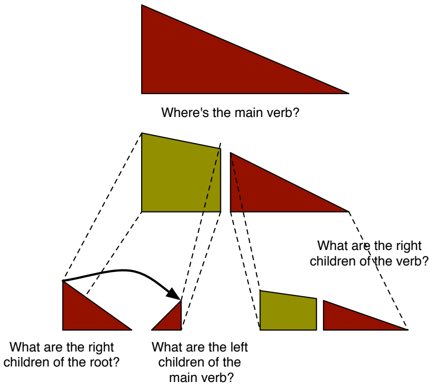
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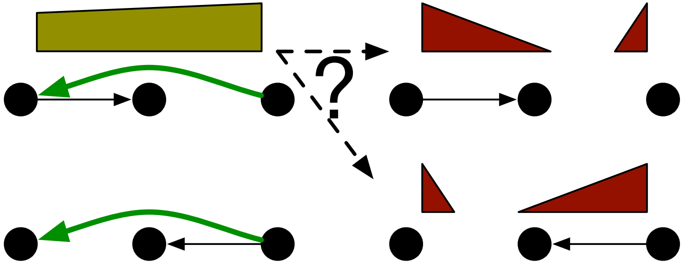
Building Incomplete Spans

Left incomplete spans are built by joining left complete to right complete

$$C[s][t][\leftarrow][\circ] = \max_{s \leq q < t} C[s][q][\rightarrow][\cdot] + C[q+1][t][\leftarrow][\cdot] + \lambda_{(w_t, w_s)} \quad (4)$$



Building Incomplete Spans

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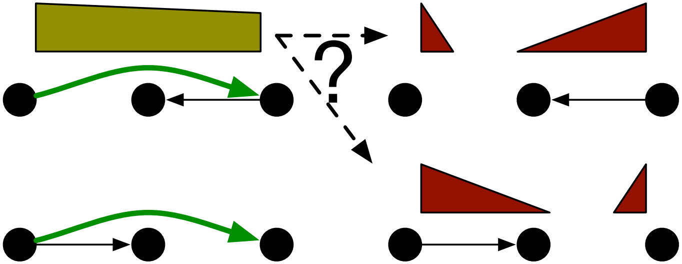

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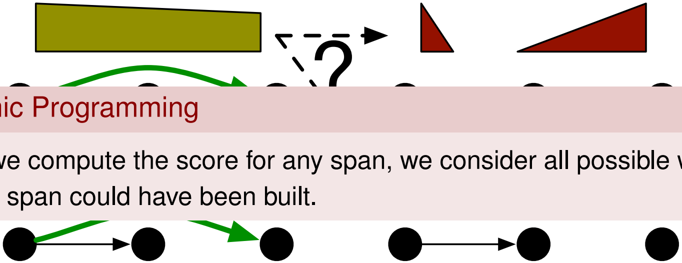

Dynamic Programming

When we compute the score for any span, we consider all possible ways that the span could have been built.

Building Incomplete Spans

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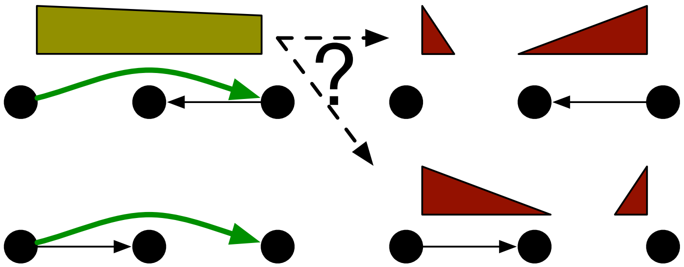
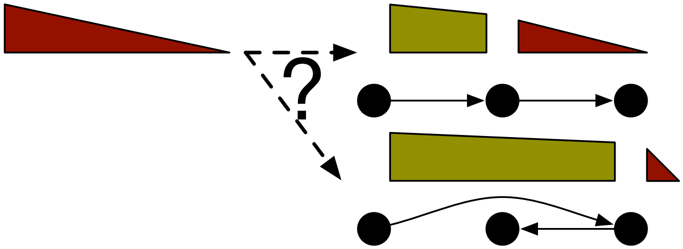


Completing Spans

Right complete spans are built by taking an incomplete right span and then "completing" it with a right complete span

$C[s][t][\rightarrow][\cdot] = \max_{s<q\leq t} C[s][q][\rightarrow][\circ] + C[q][t][\rightarrow][\cdot]$



Completing Spans

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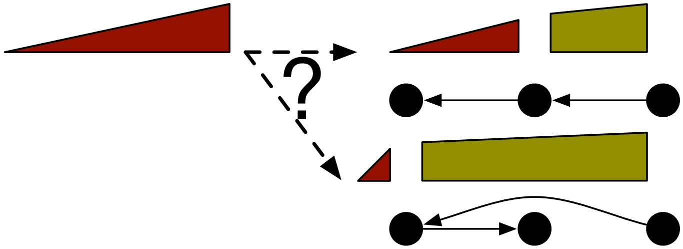

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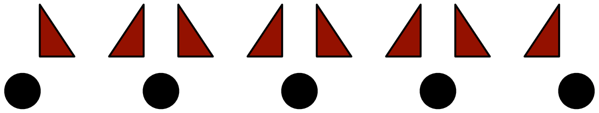

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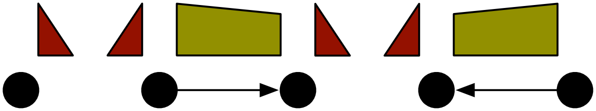

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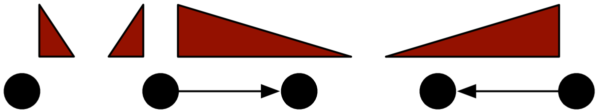

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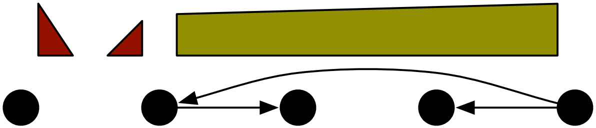

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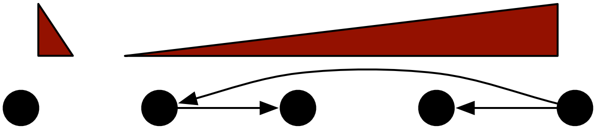

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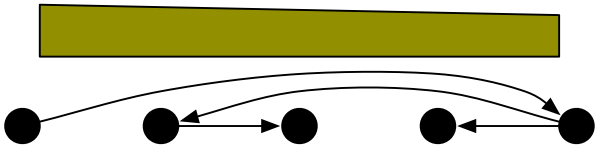

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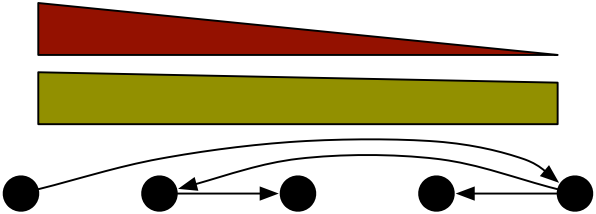

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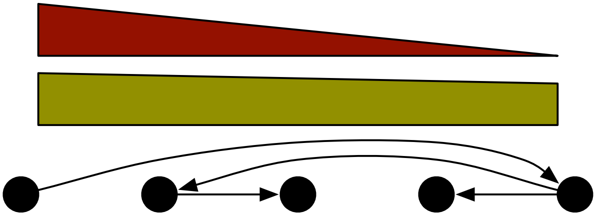

Final step

Look at cell at corresponding to 0 to the length of the sentence, complete, and directed to the right. That is the best parse.

What's left: Breadcrumbs and Complexity

- As you build the chart, you must keep track of what the best subtrees were to construct each cell; call this b
- Then look at $b[0][L][\rightarrow][\cdot]$, and recursively build the tree
- Complexity is $O(n^3)$:
  - Table is size $O(n^2)$
  - Each cell requires at most n possible subtrees

Extensions to Dependency Parsing

- Horizontal and vertical Markovization (node depends on siblings and grandparents in tree—logical!)
  - “saw with telescope” more likely than “bridge with telescope” (grandparent)
  - “fast sports car” more likely than “fast slow car” (sibling)
- Graph algorithms: allow non-projectivity
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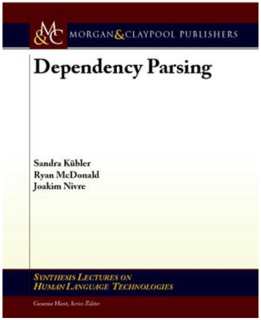
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- Language model: vertical rather than horizontal
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- Discriminative models: minimize errors

Evaluation Methodology

- How many sentences are exactly correct

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- Edge accuracy
  1. Labeled attachment score (LAS):
     i.e. Tokens with correct head and label
  2. Unlabeled attachment score (UAS):
     i.e. Tokens with correct head
  3. Label accuracy (LA):
     i.e. Tokens with correct label
- Performance on downstream task (e.g., information extraction)