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Graph-based dependency grammar

Syntactic analysis (5LN455)

2023

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Partially based on slides from Marco Kuhlmann

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Overview

- Dependency grammar and projectivity
- Arc-factored dependency parsing
  - Collins' algorithm
  - Eisner's algorithm
- Evaluation of dependency parsers
- Transition-based dependency parsing
  - The arc-standard algorithm
- Advanced dependency parsing

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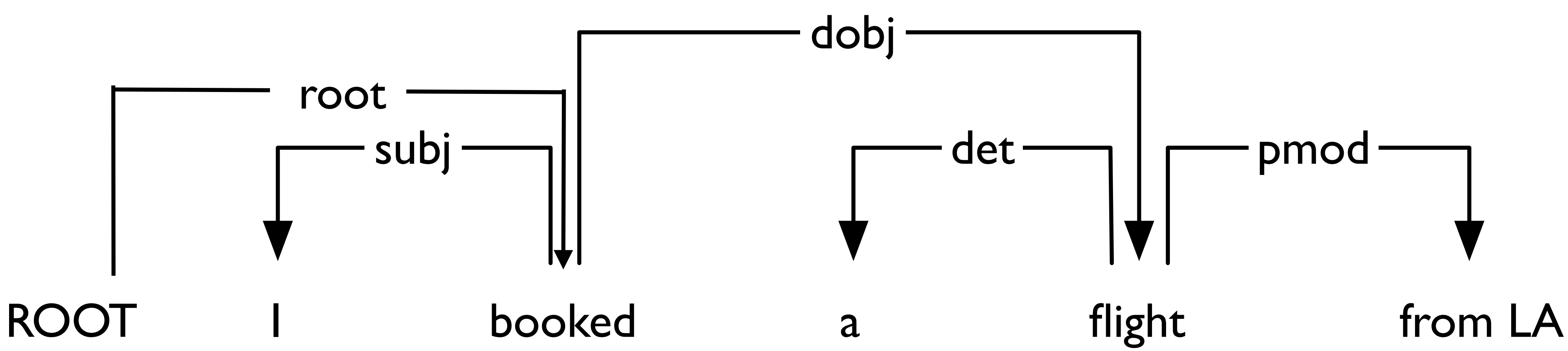
Dependency grammar

Dependency trees



- In an arc $h \rightarrow d$, the word h is called the head, and the word d is called the dependent.
- The arcs form a rooted tree.
- Each arc has a label, l, and an arc can be described as (h, d, l)

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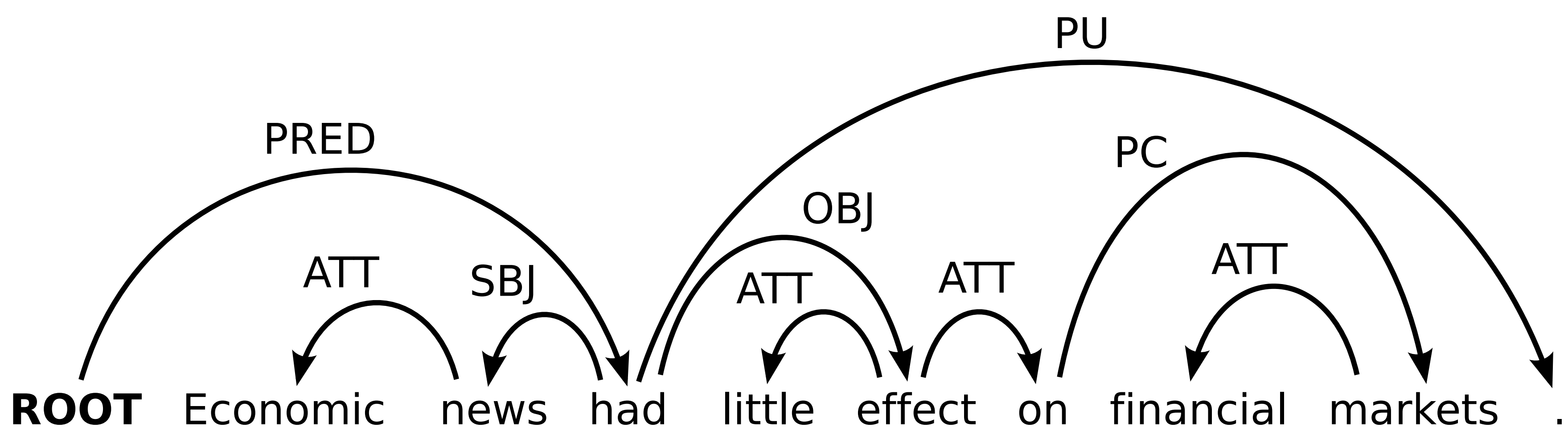
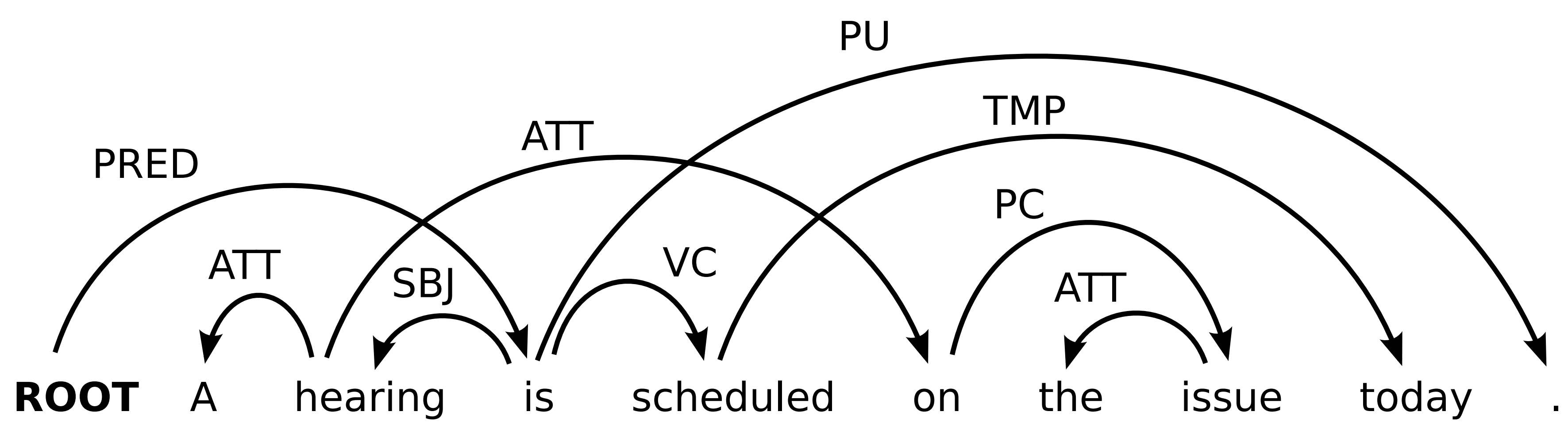
Projectivity

- An important characteristic of dependency trees is projectivity
- A dependency tree is projective if:
  - For every arc in the tree, there is a directed path from the head of the arc to all words occurring between the head and the dependent (that is, the arc (i,l,j) implies that $i \rightarrow^* k$ for every k such that $\min(i, j) < k < \max(i, j)$)

Projective and non-projective trees





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Projectivity and dependency parsing

- Many dependency parsing algorithms can only handle projective trees
- Non-projective trees do occur in natural language
  - How often depends on the language (and treebank)
- In the course: in-depth discussion of projective algorithms, some discussion of non-projective algorithms

Main parsing strategies

- Graph-based dependency parsing:
    - Scores the dependency graph (tree)
- Transition-based dependency parsing:
    - Scores a sequence of transitions
- There are also grammar-based methods, which we will not discuss (not commonly used)

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Arc-factored dependency parsing

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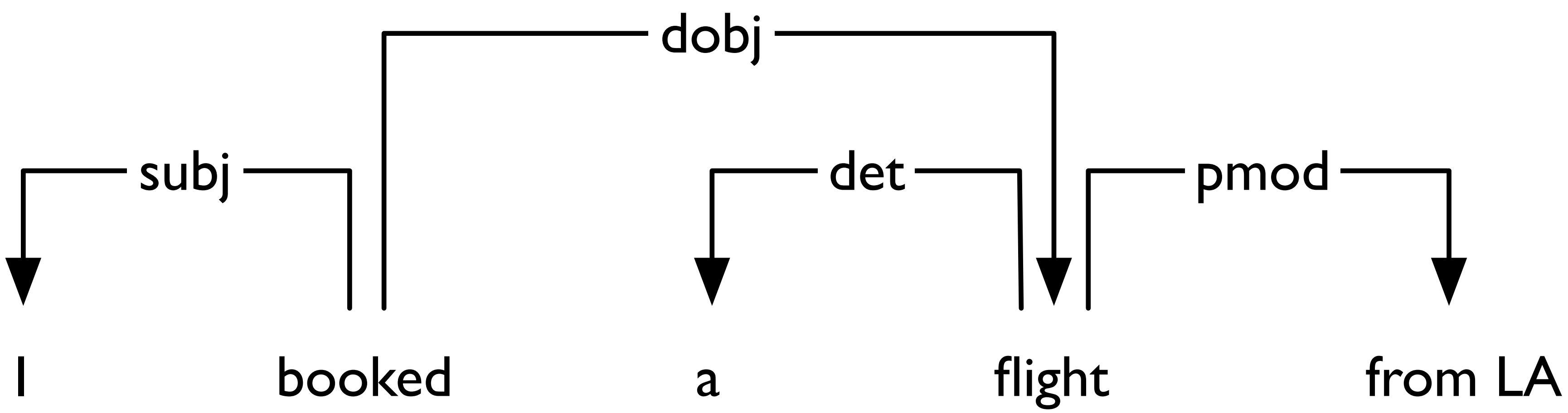
Ambiguity

Just like phrase structure parsing, dependency parsing has to deal with ambiguity.



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Ambiguity

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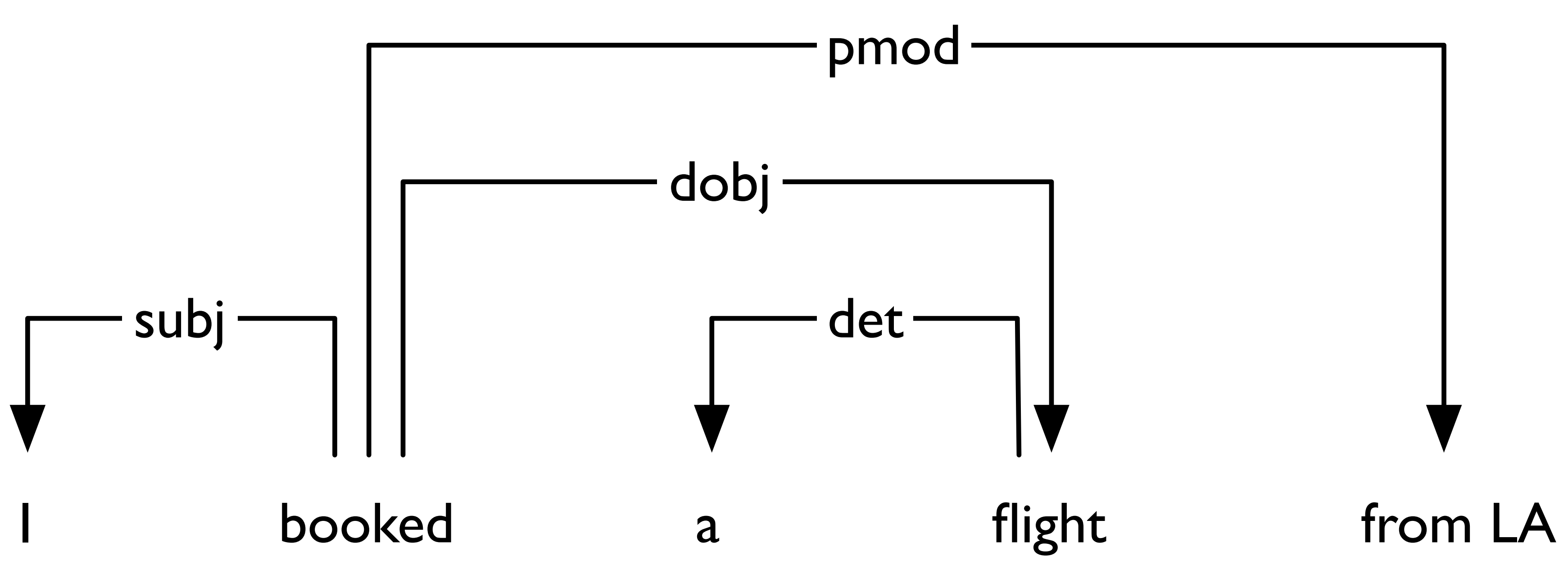

Disambiguation

- We need to disambiguate between alternative analyses.
- We develop mechanisms for scoring dependency trees, and disambiguate by choosing a dependency tree with the highest score.

Scoring models and parsing algorithms

Distinguish two aspects:

- Scoring model:
  How do we want to score dependency trees?
- Parsing algorithm:
  How do we compute a highest-scoring dependency tree under the given scoring model?

The arc-factored model

- Split the dependency tree t into parts $p_1, \ldots, p_n$, score each of the parts individually, and combine the score into a simple sum.

  score(t) = score(p_1) + … + score(p_n)

- The simplest scoring model is the arc-factored model, where the scored parts are the arcs of the tree.

Examples of classic features

- ‘The head is a verb.’
- ‘The dependent is a noun.’
- ‘The head is a verb
and the dependent is a noun.’
- ‘The head is a verb
and the predecessor of the head is a pronoun.’
- ‘The arc goes from left to right.’
- ‘The arc has length 2.’

Training using structured prediction

- Take a sentence *w* and a gold-standard dependency tree *g* for *w*.
- Compute the highest-scoring dependency tree under the current weights; call it *p*.
- Increase the weights of all features that are in *g* but not in *p*.
- Decrease the weights of all features that are in *p* but not in *g*.

Training using structured prediction

- Training involves repeatedly parsing (treebank) sentences and refining the weights.
- Hence, training presupposes an efficient parsing algorithm.

Higher order models

- The arc-factored model is a first-order model, because scored subgraphs consist of a single arc.
- An nth-order model scores subgraphs consisting of (at most) n arcs.
- Second-order: siblings, grand-parents
- Third-order: tri-siblings, grand-siblings
- Higher-order models capture more linguistic structure and give higher parsing accuracy, but are less efficient

Parsing algorithms

- Projective parsing
  - Inspired by the CKY algorithm
    - Collins' algorithm
    - Eisner's algorithm
- Non-projective parsing:
  - Minimum spanning tree (MST) algorithms
    - e.g. Chu-Liu-Edmunds algorithm (CLE)

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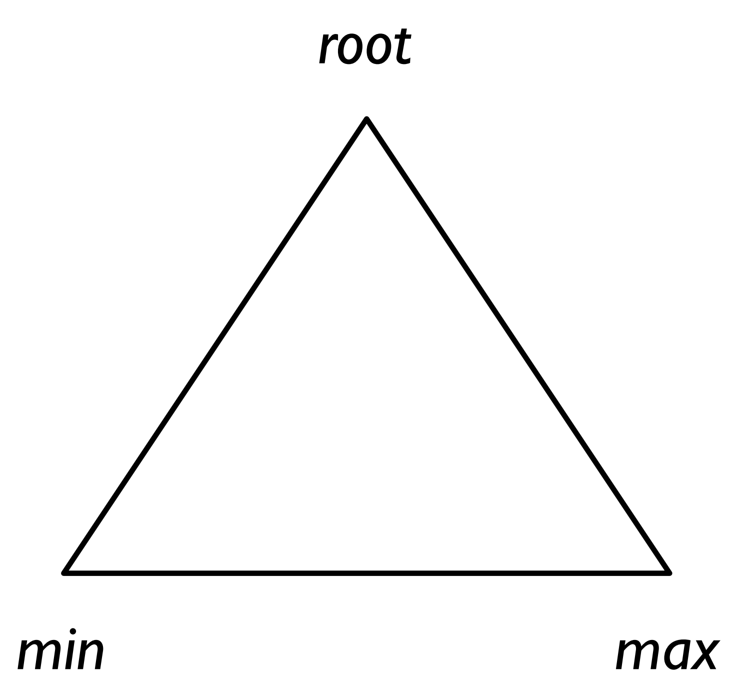
Collins' algorithm

Collins' algorithm

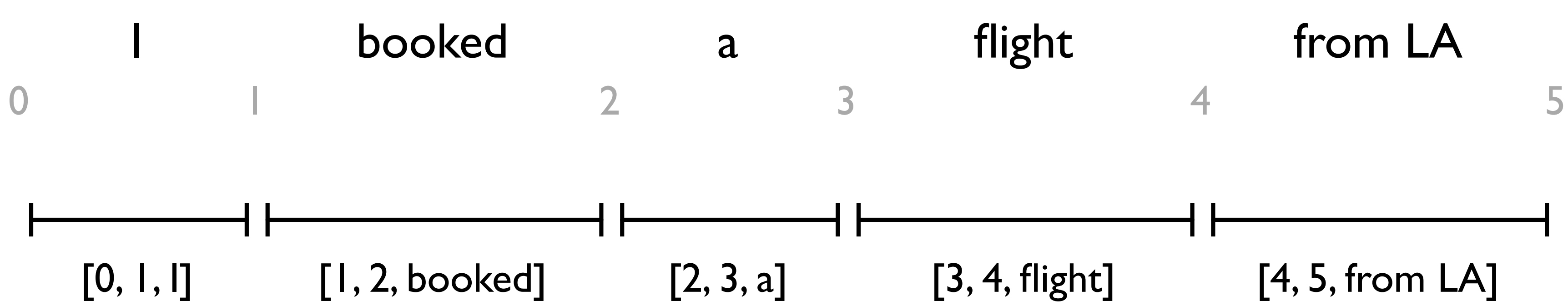
- Collin's algorithm is a simple algorithm for computing the highest-scoring dependency tree under an arc-factored scoring model.
- It can be understood as an extension of the CKY algorithm to dependency parsing.
- Like the CKY algorithm, it can be characterized as a bottom-up algorithm based on dynamic programming.

Signatures, Collins'

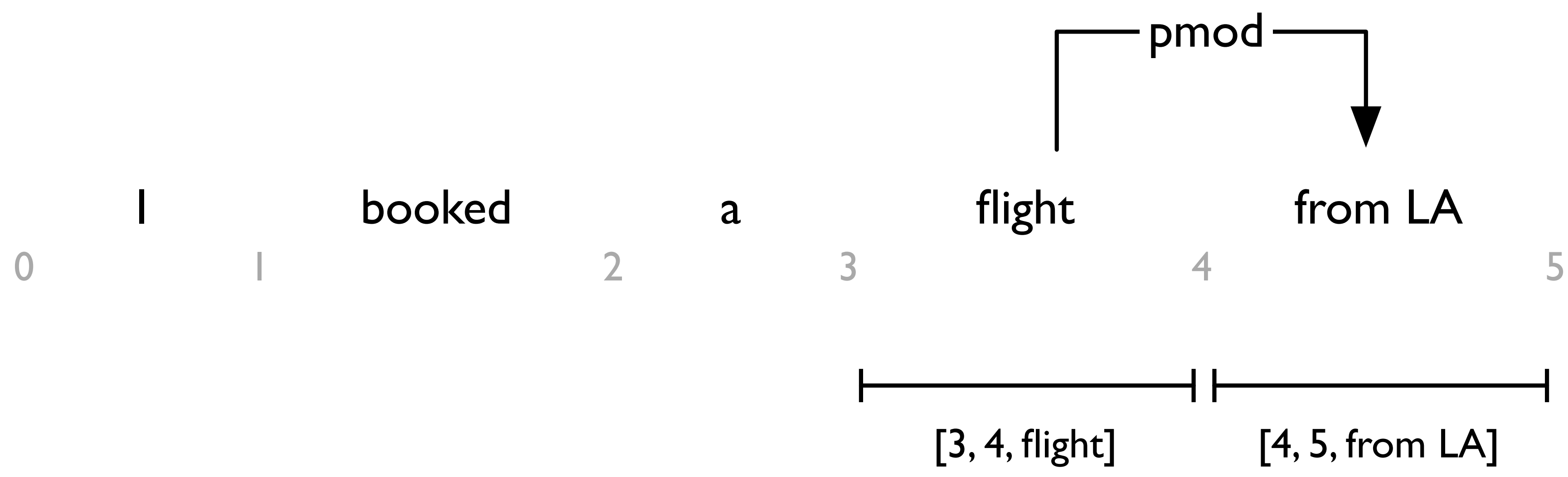


[*min*, *max*, *root*]

Initialization

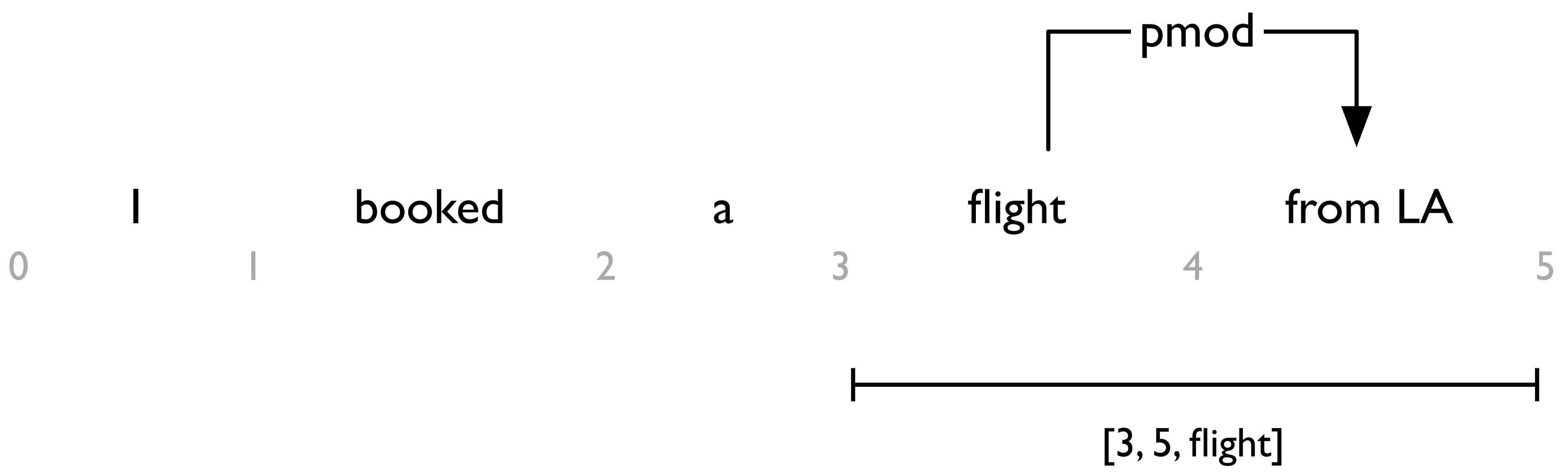


Adding a left-to-right arc



Collins' algorithm

Adding a left-to-right arc



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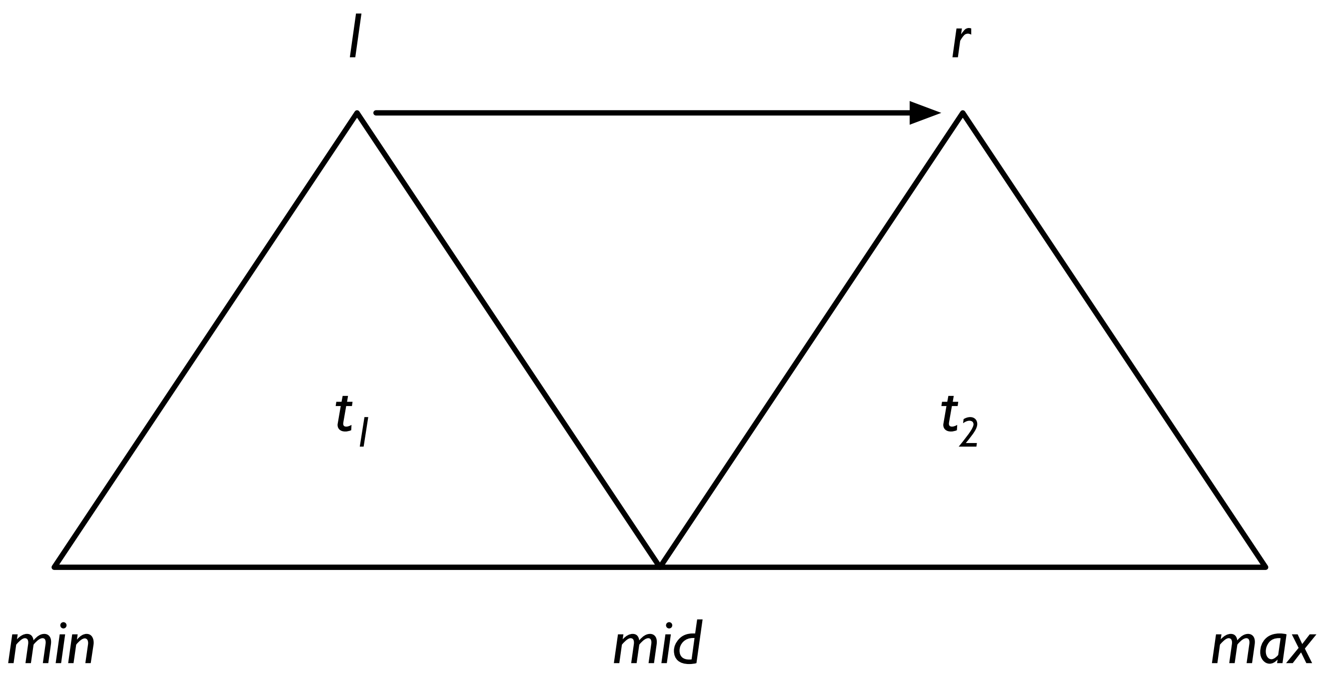
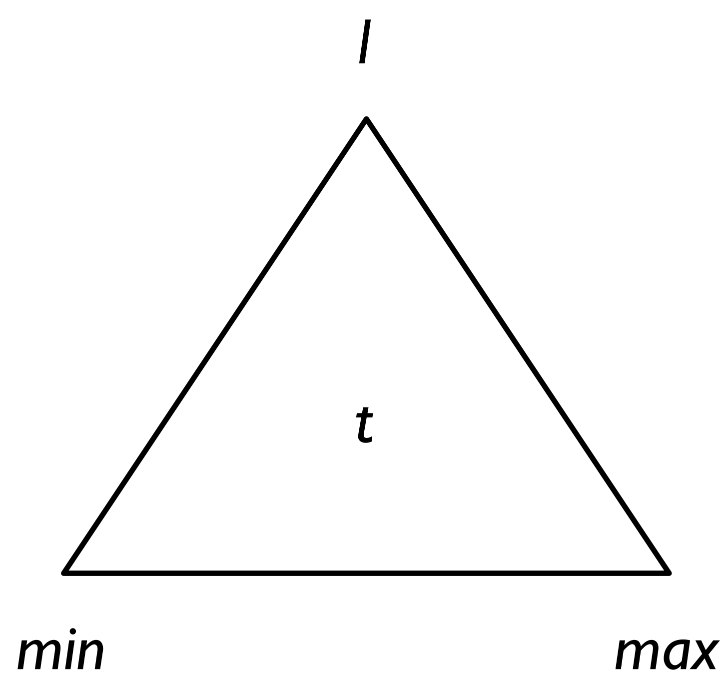


Adding a left-to-right arc



$$\text{score}(t) = \text{score}(t_1) + \text{score}(t_2) + \text{score}(l \rightarrow r)$$

Adding a left-to-right arc

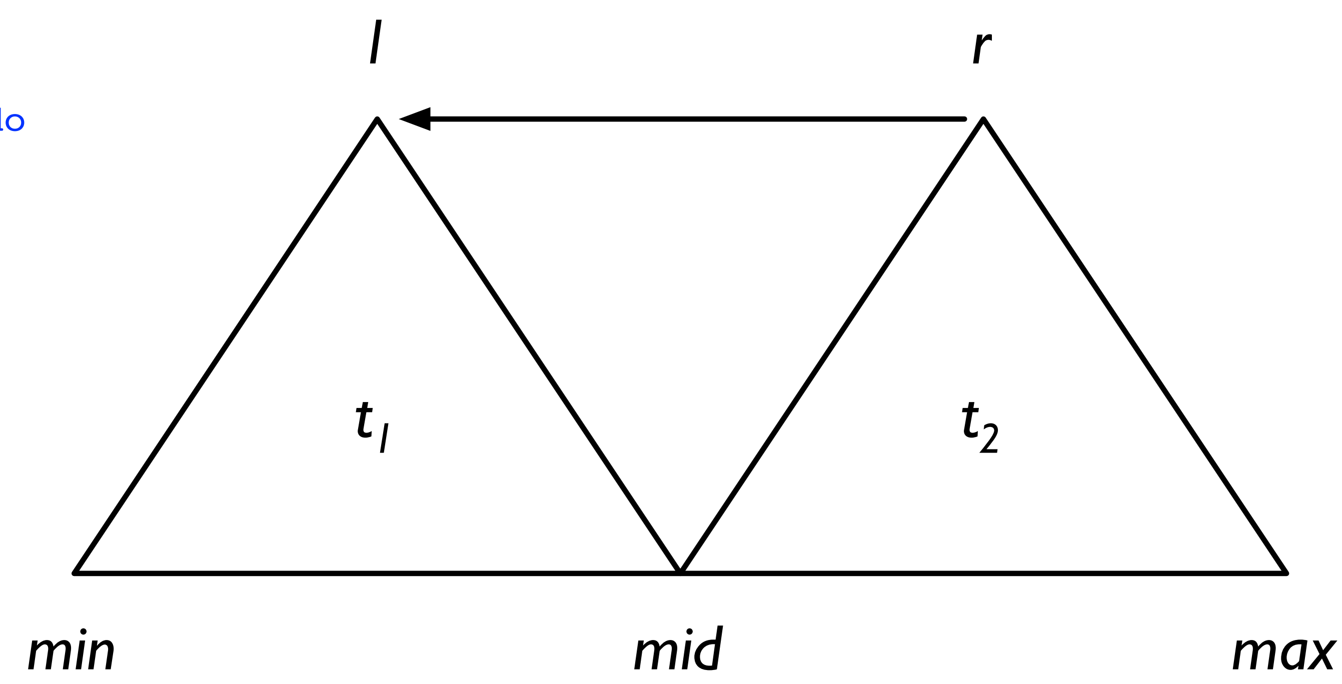
```
for each [min, max] with max - min > 1 do
  for each l from min to max - 2 do
    double best = score[min][max][l]
    for each r from l + 1 to max - 1 do
      for each mid from l + 1 to r do
        t1 = score[min][mid][l]
        t2 = score[mid][max][r]
        double current = t1 + t2 + score(l → r)
        if current > best then
          best = current
    score[min][max][l] = best
```

Collins' algorithm

Complexity analysis

- Runtime?
- Space?

```
for each [min, max] with max - min > 1 do
  for each r from min + 1 to max - 1 do
    double best = score[min][max][r]
    for each l from min to r - 1 do
      for each mid from l + 1 to r do
        t₁ = score[min][mid][l]
        t₂ = score[mid][max][r]
        double current = t₁ + t₂ + score(r → l)
        if current > best then
          best = current
    score[min][max][r] = best
```



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Complexity analysis

- Space requirement:
  $O(|w|^3)$
- Runtime requirement:
  $O(|w|^5)$

Extension to the labeled case

- It is important to distinguish dependencies of different types between the same two words.

  Example: subj, dobj

- For this reason, practical systems typically deal with labeled arcs.
- The question then arises how to extend Collins' algorithm to the labeled case.

Smart approach

- Before parsing, compute a table that lists, for each head-dependent pair (h, d), the label that maximizes the score of arcs $h \rightarrow d$.
  - This is guaranteed to be the arcs that could be used in a highest-scoring tree
- During parsing, simply look up the best label in the pre-computed table.
- This adds (not multiplies!) a factor of $|L||w|^2$ to the overall runtime of the algorithm.

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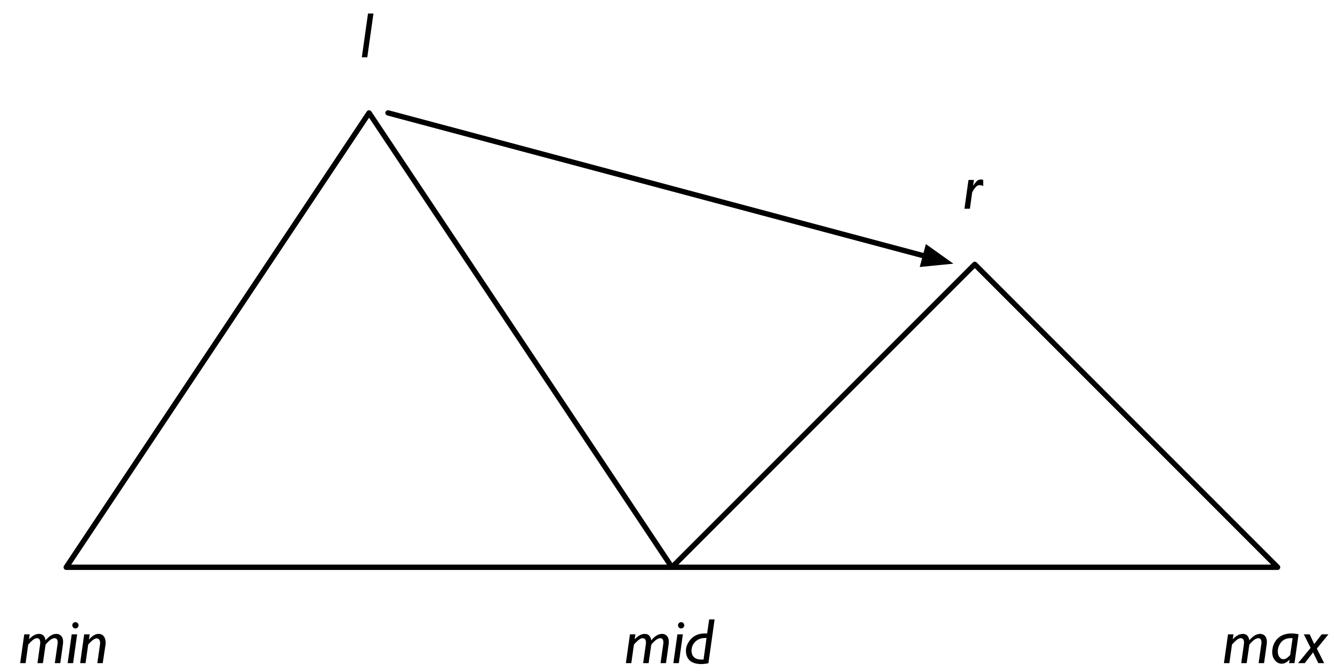
Eisner's algorithm

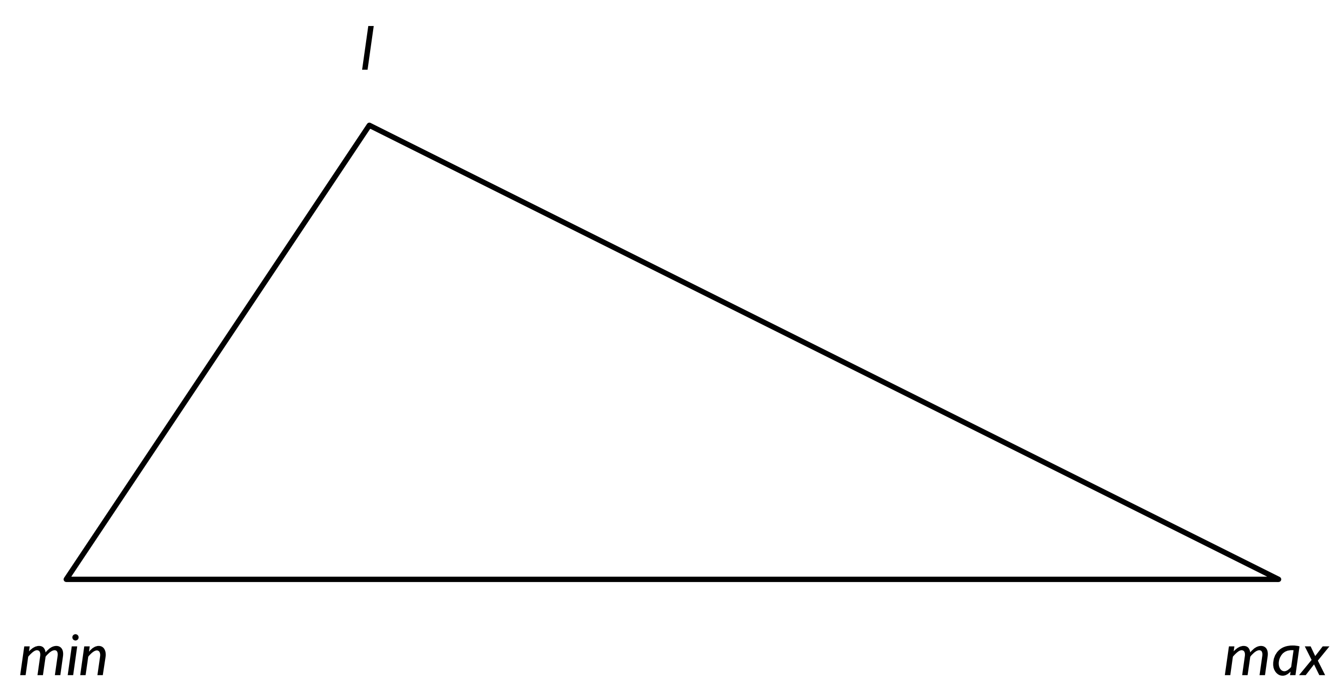
- With its runtime of $O(|w|^5)$, Collins' algorithm may not be of much use in practice.
- With Eisner's algorithm we will be able to solve the same problem in $O(|w|^3)$.
    - Intuition: collect left and right dependents independently

Basic idea



In Collins' algorithm, adding a left-to-right arc is done in one single step, specified by 5 positions.

Basic idea



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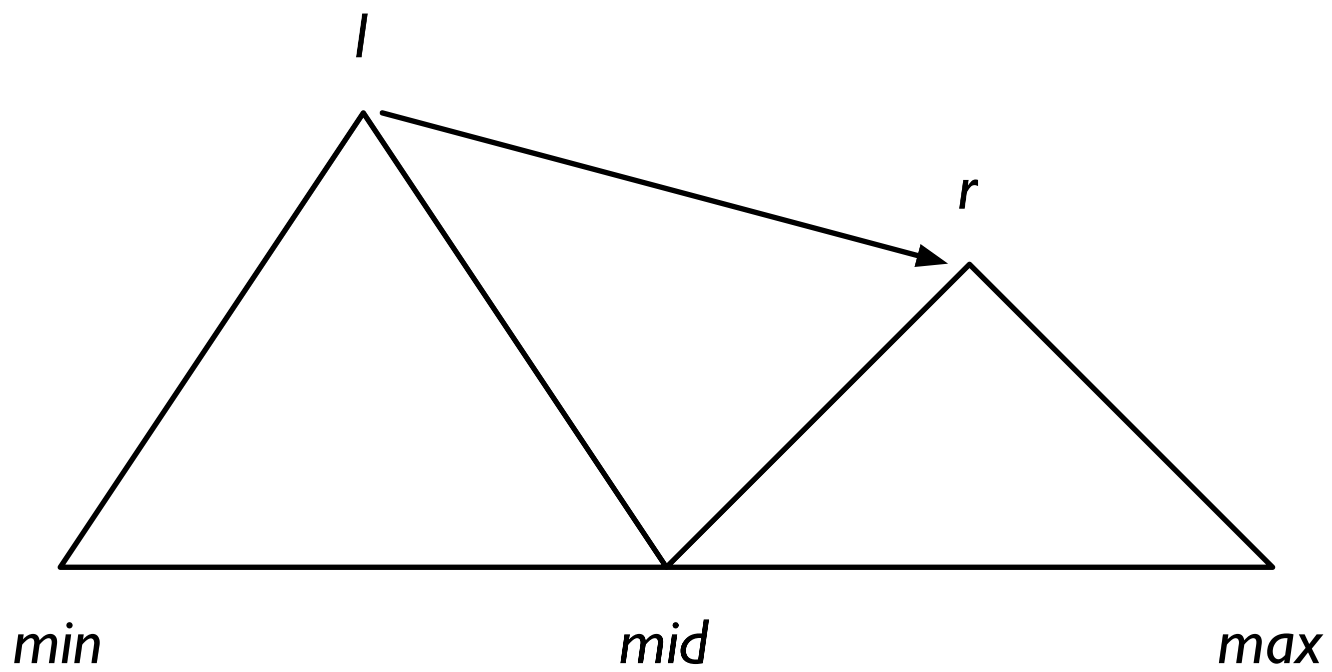
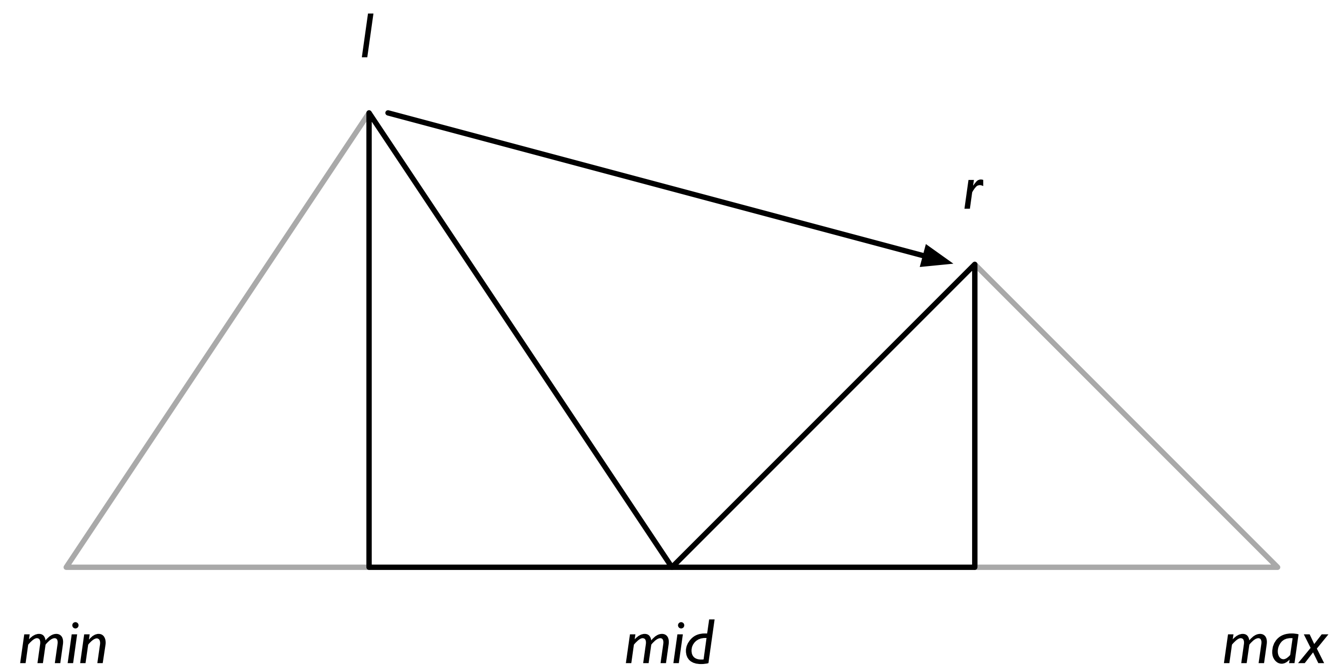


In Eisner's algorithm, the same thing is done in three steps, each one specified by 3 positions.

Basic idea



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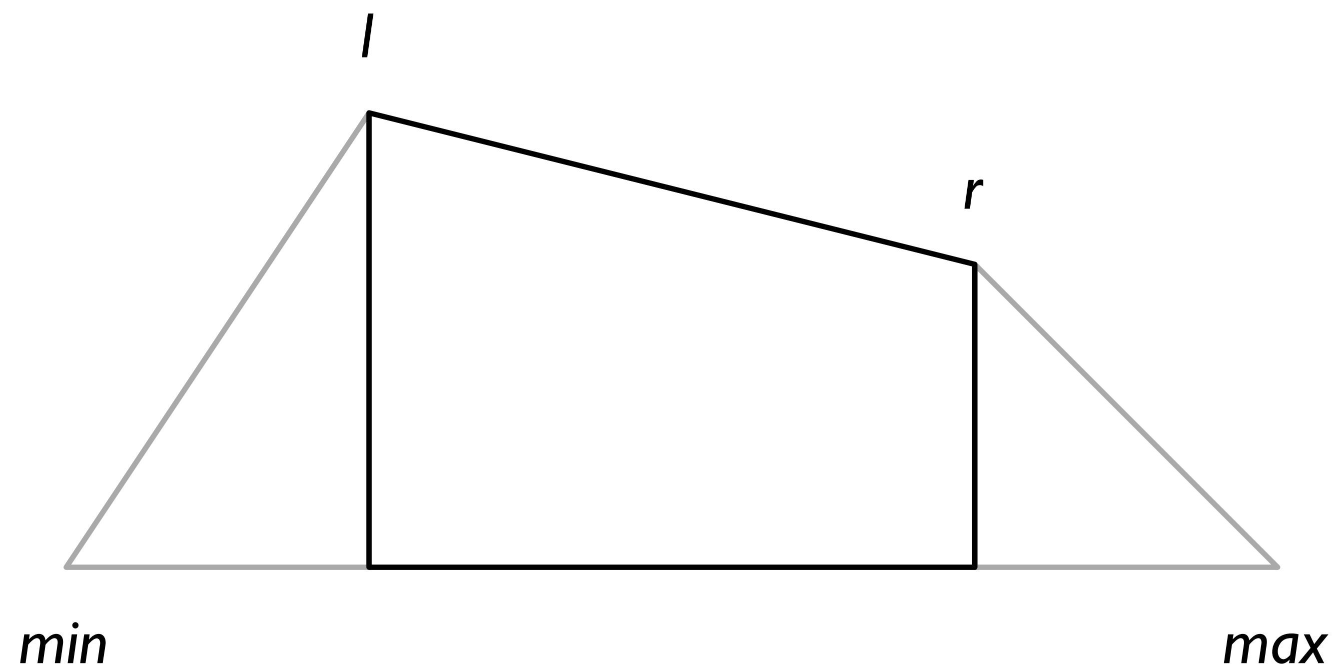

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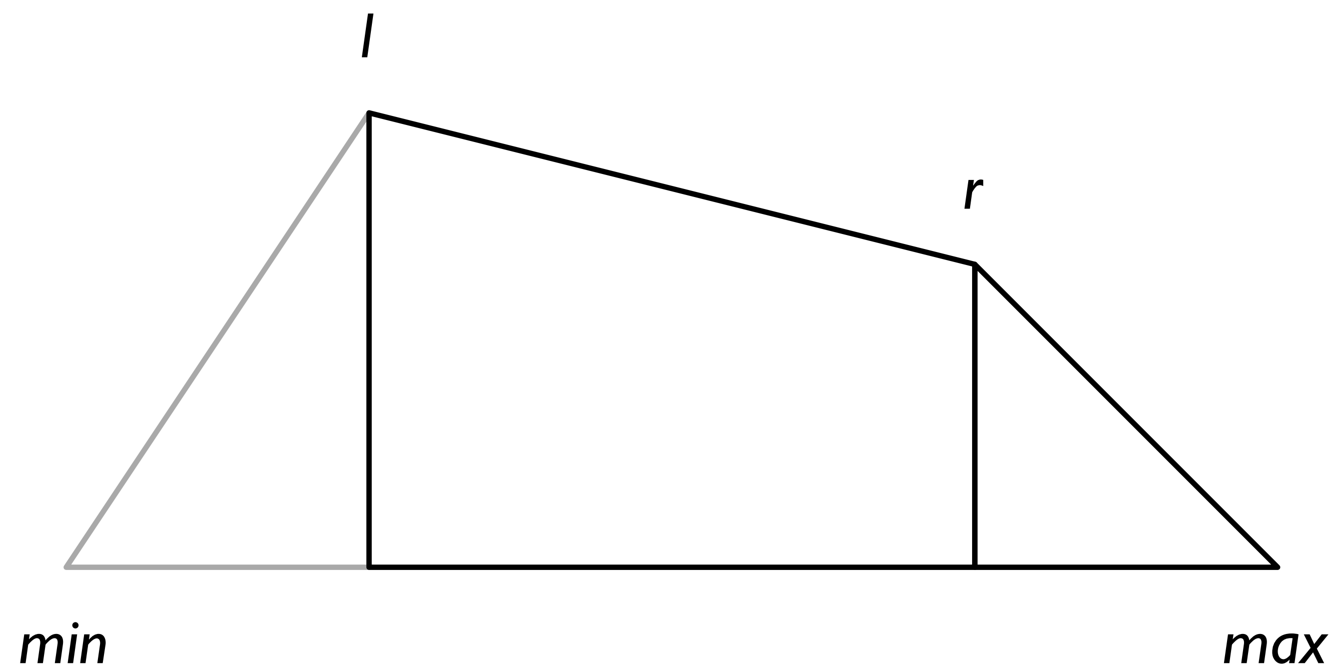

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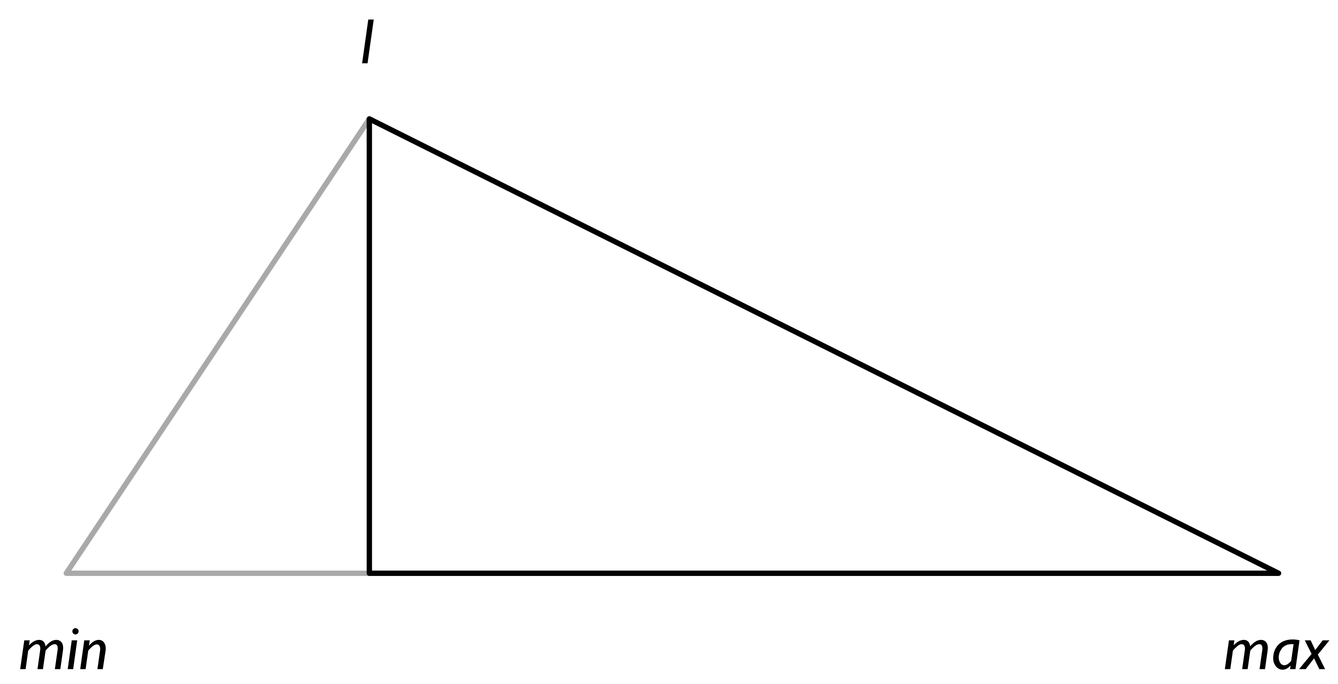

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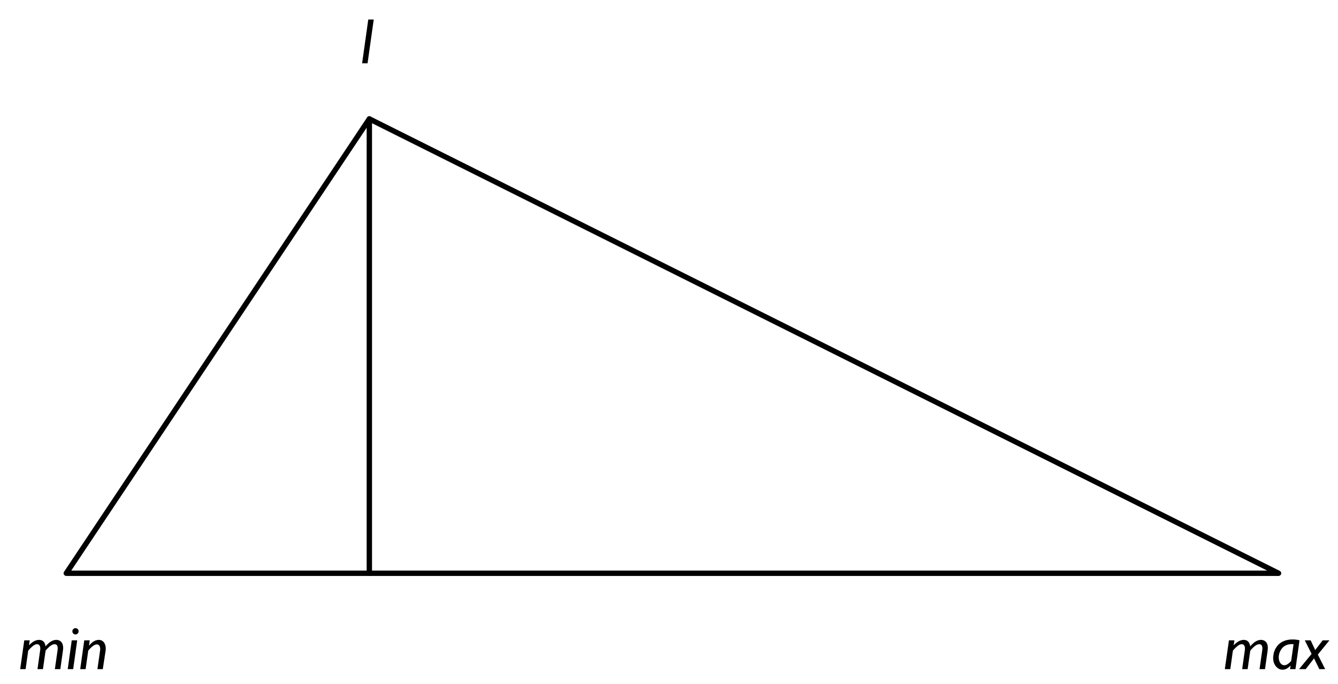

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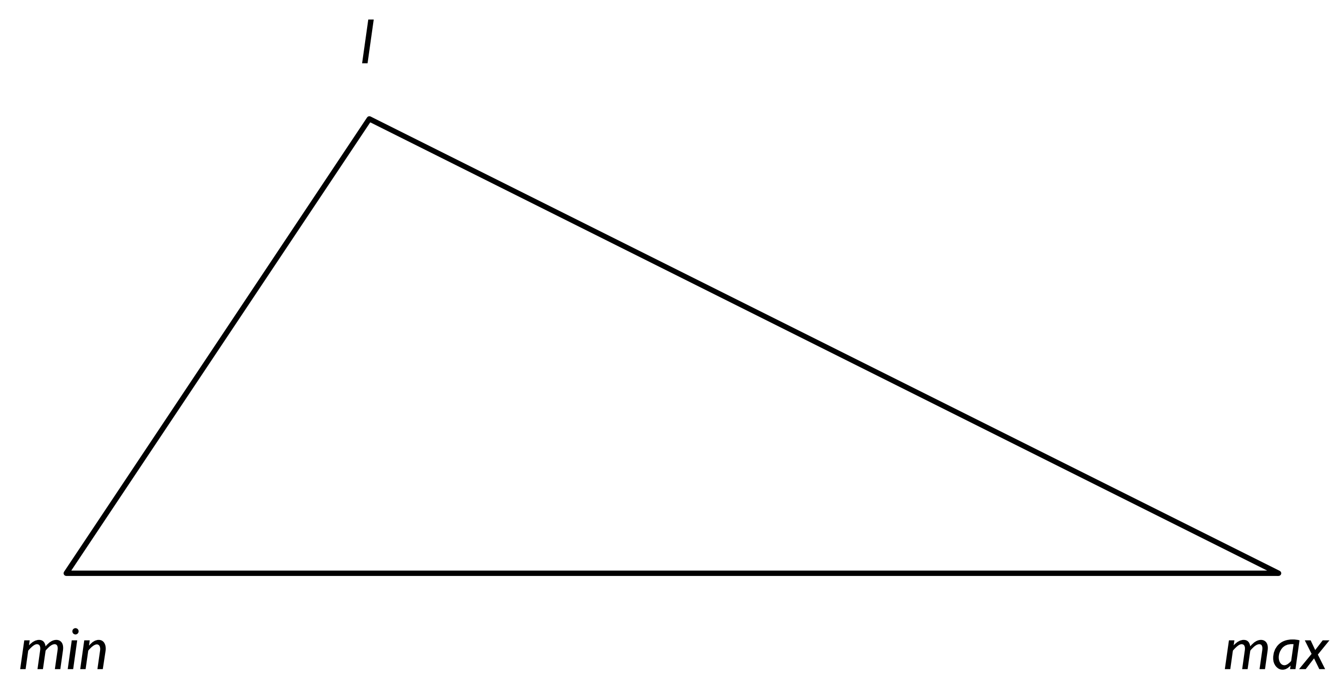

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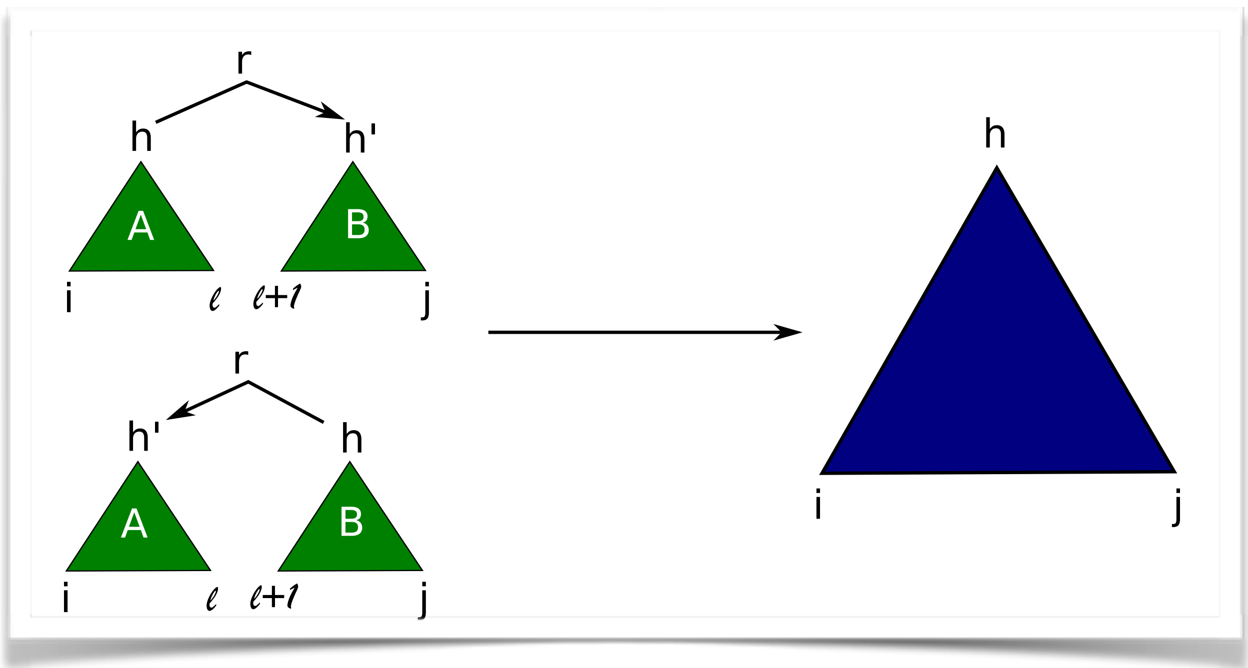
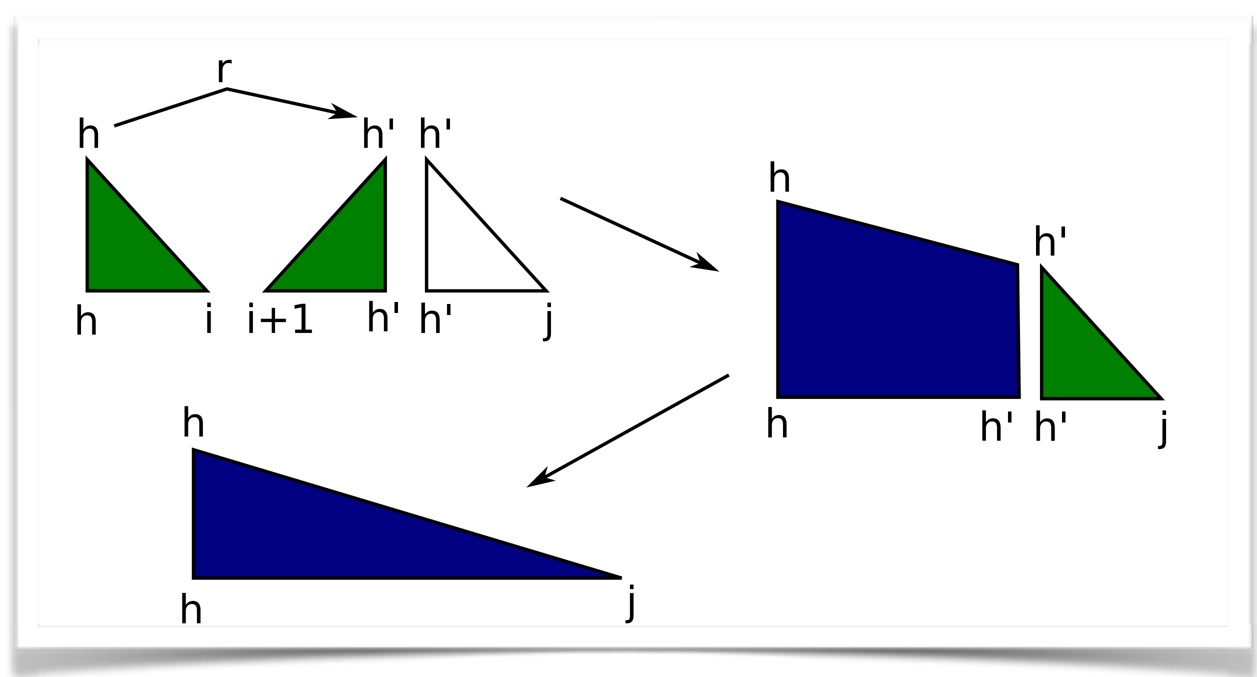
Comparison



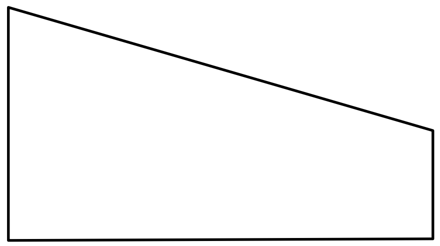


Dynamic programming tables

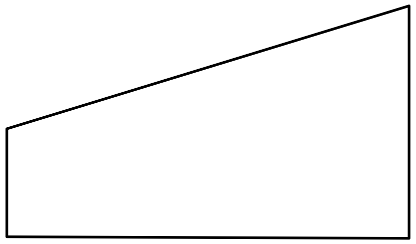
- Collins':
  - [min,max,head]
- Eisner's
  - [min,max,head-side,complete]
    - head-side (binary): is head to the left or right?
    - complete (binary:) is the non-head side still looking for dependents?

Graphic representation

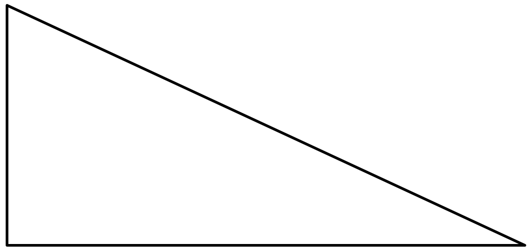
- [min,max,left,yes]



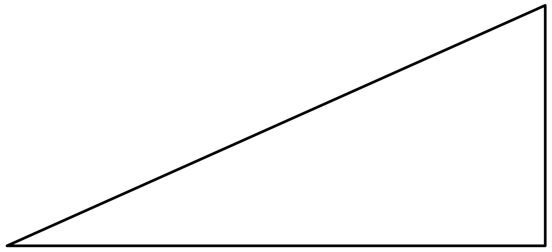
- [min,max,right,yes]



- [min,max,left,no]



- [min,max,right,no]



Graphic representation

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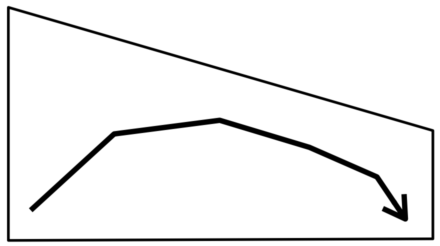

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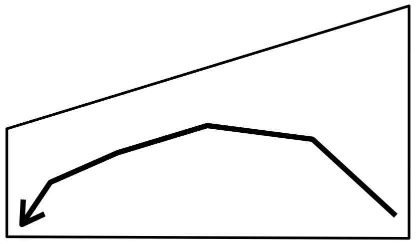

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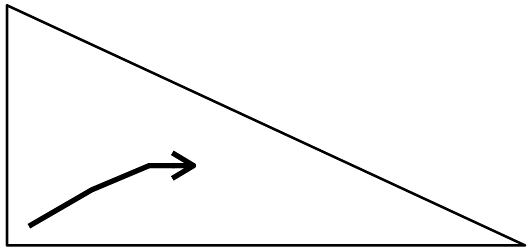

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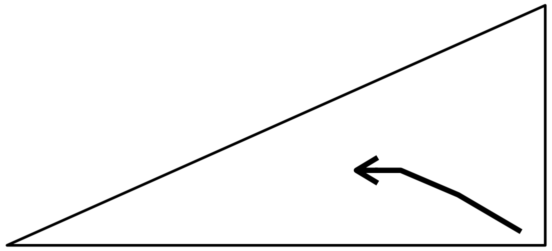
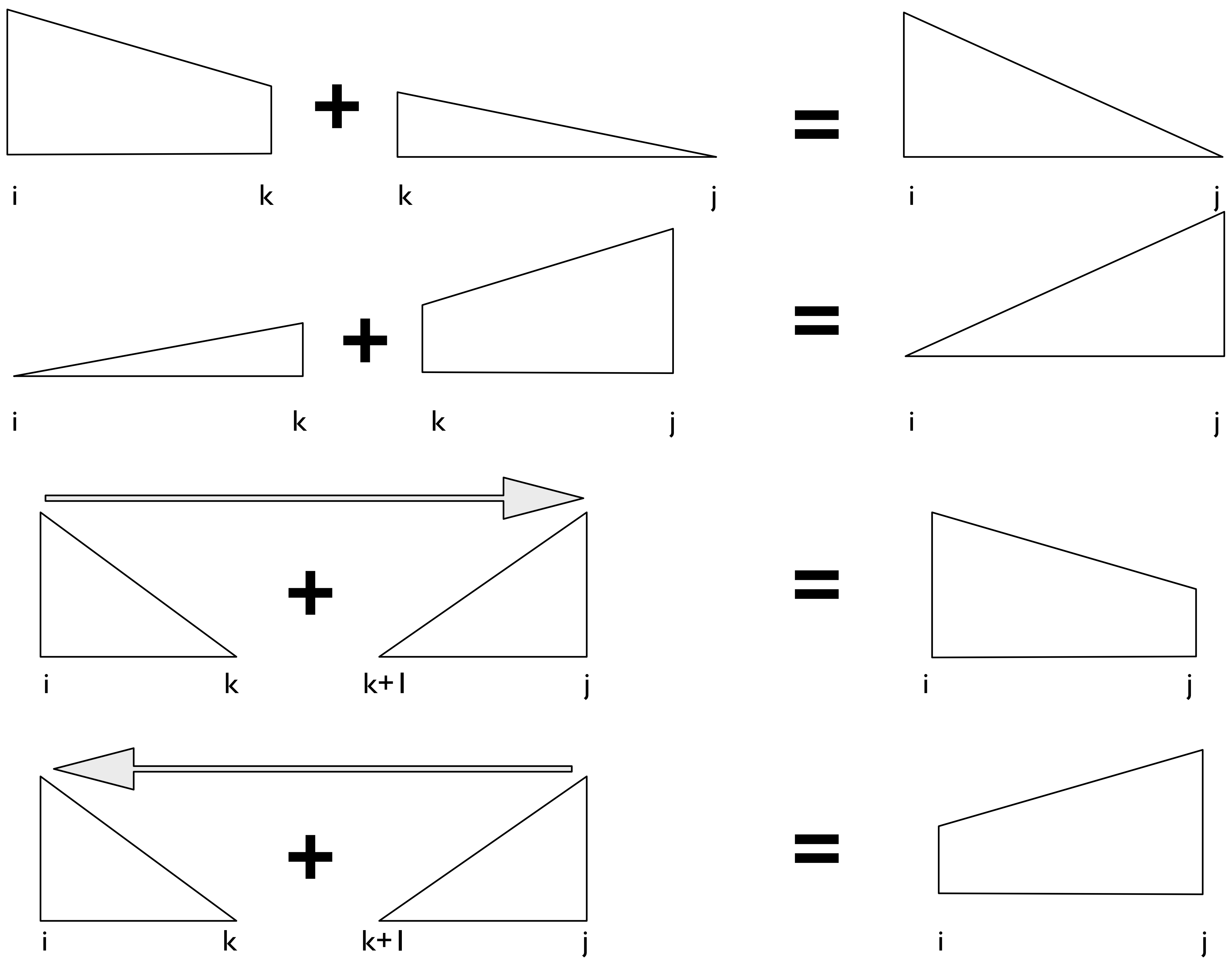


Eisner's algorithm

Possible operations



Pseudo code

```
for each i from 0 to n and all d,c do
  C[i][i][d][c] = 0.0
for each m from 1 to n do
  for each i from 0 to n-m do
     j = i+m
     C[i][j][←][1] = max_{i≤q<j}(C[i][q][→][0] + C[q+1][j][←][0]+score(w_j,w_i)
     C[i][j][→][1] = max_{i≤q<j}(C[i][q][→][0] + C[q+1][j][←][0]+score(w_i,w_j)
     C[i][j][←][0] = max_{i≤q<j}(C[i][q][←][0] + C[q][j][←][1])
     C[i][j][→][0] = max_{i≤q<j}(C[i][q][→][1] + C[q][j][→][0])
return [0][n][→][0]
```

Summary

- Eisner's algorithm is an improvement over Collin's algorithm that runs in time $O(|w|^3)$.
- The same scoring model can be used.
- The same technique for extending the parser to labeled parsing can be used, adding $O(|L||w|^2)$ to the run time.
- Eisner's algorithm is the basis of current arc-factored dependency parsers.

Minimum-spanning tree parsing

- Based on graph algorithms to find the minimum spanning tree
  - Often: Chu-Liu-Edmonds algorithm (CLU)
- Directly produces non-projective trees
- First suggested in the MSTparser
- One of the most popular algorithms today

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Minimum-spanning tree parsing

- **Intuition:**
- Score all word pairs in both directions
- Create a fully connected graph with these scores
- Remove all edges going into ROOT
- For each node, greedily keep only the highest-scoring incoming arc
    - If this produces a tree: done!
    - Otherwise: handle each cycle in the graph

Evaluation of dependency parsers

- labelled attachment score (LAS):
percentage of correct arcs,
relative to the gold standard
- labelled exact match (LEM):
percentage of correct dependency trees,
relative to the gold standard
- unlabelled attachment score/exact match (UAS/UEM):
the same, but ignoring arc labels

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Accuracy vs precision/recall

- Attachment score is an accuracy score
- For phrase-structure parsing we reported precision and recall
- Why is that not done for dependency parsing?

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Coming up

- Monday, Feb 20: guest lecture, Paola Merlo, 2-K1023
- Wednesday, Feb 22, Lecture:
  - Transition-based parsing (watch videos first)
- Sign up for a project and hand in a proposal in Studium (DL: February 27)
- Literature seminar 2, March 2
- Do assignment 2, literature review (DL: March 6)
- Start looking at the dependency assignment (DL: March 13)
  - Supervision: Feb 27 and March 8