Computational Linguistics II
— Grammars, Algorithms, Statistics —

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(At Least) Three Dimensions to the Parsing Problem

Vertical

- *top-down* successively rewrite S until input is matched (goal-oriented);
- *bottom-up* combine constituents until S is derived (data-oriented).

Depth

- *exhaustive* find all derivations (for each parsing goal) in ‘parallel’;
- *best-first* find one (or set of n-best) derivations as soon as possible.

Horizontal

- *uni-directional* instantiate rule RHSs left-to-right (or right-to-left);
- *bi-directional* instantiate rule RHSs in variable order, e.g. head-driven.

Review: Top-Down vs. Bottom-Up Parsing

Top-Down (Goal-Oriented)

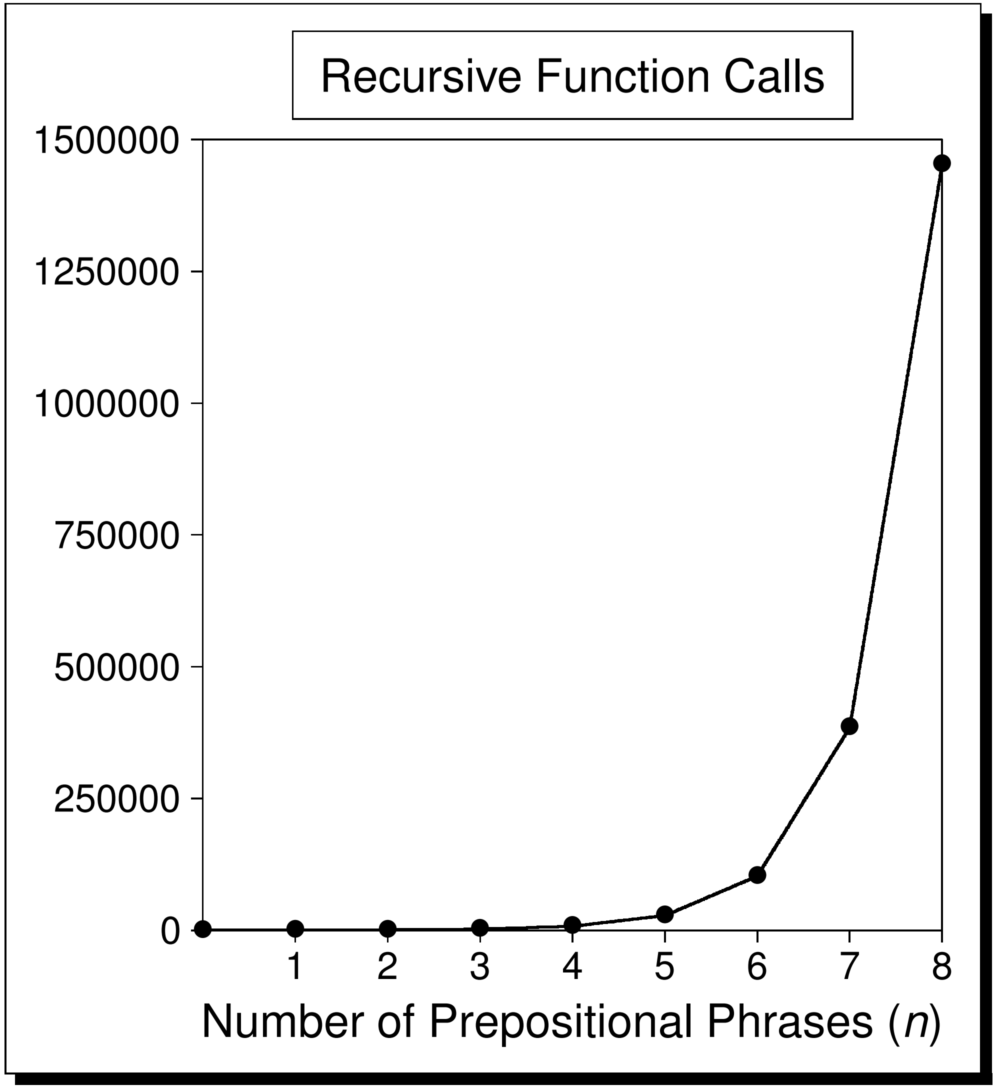
- Left recursion (e.g. the 'VP $\rightarrow$ VP PP' rule) causes infinite recursion;
- grammar conversion techniques (eliminating left recursion) exist, but will often be undesirable for natural language processing applications;

$\rightarrow$ assume bottom-up as basic search strategy for remainder of the quarter.

Bottom-Up (Data-Oriented)

- unary (left-recursive) rules (e.g. 'NP $\rightarrow$ NP') would still be problematic;
- lack of parsing goal: compute all possible derivations for, say, the input *adores snow*; however, it is ultimately rejected since it is not sentential;
- availability of partial analyses desirable for, at least, some applications.

Quantifying the Complexity of the Parsing Task

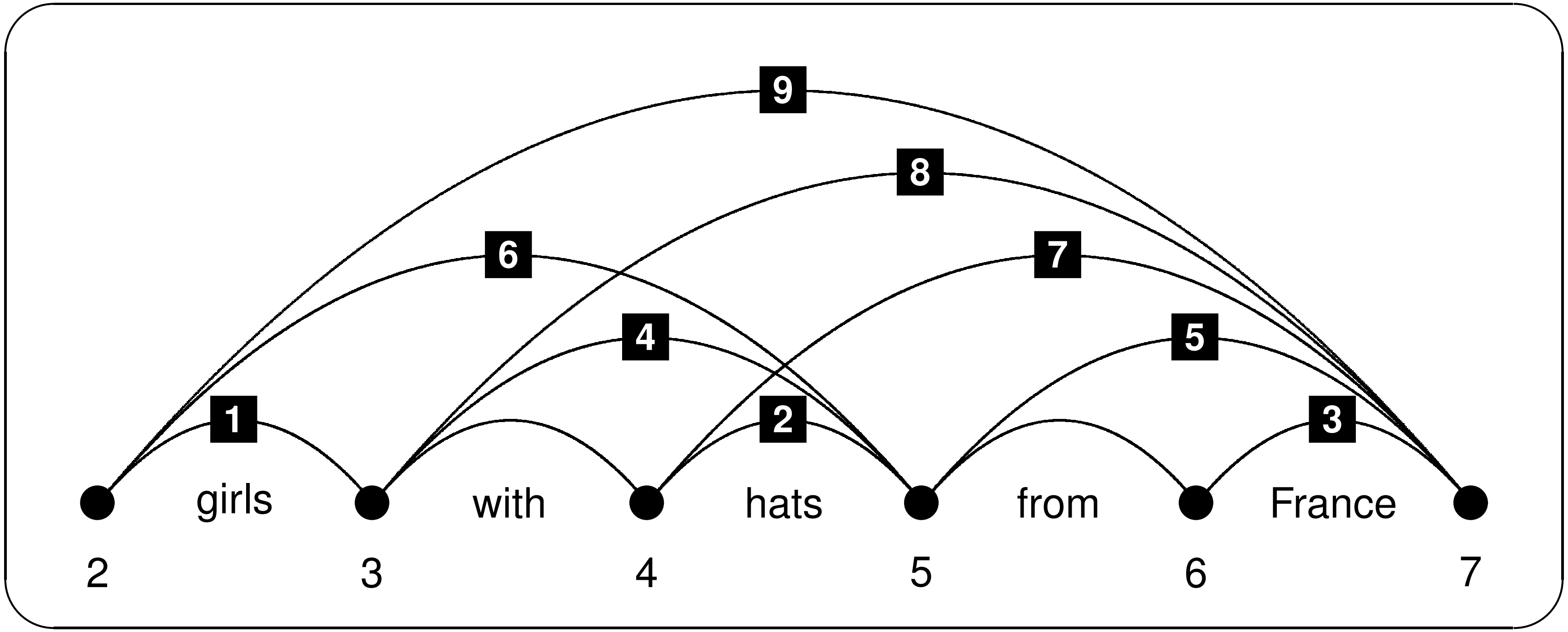


Kim adores snow (in Oslo)^n

n	**trees**	**calls**
0	1	46
1	2	170
2	5	593
3	14	2,093
4	42	7,539
5	132	27,627
6	429	102,570
7	1430	384,566
8	4862	1,452,776
⋮	⋮	⋮

Using the Chart to Bound Ambiguity

- For many substrings, multiple ways of deriving the same category;
- NPs: 1 | 2 | 3 | 6 | 7 | 9; PPs: 4 | 5 | 8; 9 ≡ 1 + 8 | 6 + 5;
- *parse forest* — a single item represents multiple trees [Billot & Lang, 89].



Review: Chart Parsing

Basic Notions

- Use *chart* to record partial analyses, indexing them by string positions;
- count inter-word vertices; CKY: chart row is *start*, column *end* vertex;
- treat multiple ways of deriving the same category for some substring as *equivalent*; pursue only once when combining with other constituents.

Key Benefits

- Dynamic programming (memoization): avoid recomputation of results;
- efficient indexing of constituents: no search by start or end positions;
- compute *parse forest* with exponential 'extension' in *polynomial* time.

The CKY (Cocke, Kasami, & Younger) Algorithm

for ($0 \leq i < |\mathit{input}|$) do
  $\mathit{chart}_{[i,i+1]} \leftarrow \{\alpha \mid \alpha \rightarrow \mathit{input}_i \in P\}$;
for ($1 \leq l < |\mathit{input}|$) do
  for ($0 \leq i < |\mathit{input}| - l$) do
    for ($1 \leq j \leq l$) do
      if ($\alpha \rightarrow \beta_1\,\beta_2 \in P \wedge \beta_1 \in \mathit{chart}_{[i,i+j]} \wedge \beta_2 \in \mathit{chart}_{[i+j,i+l+1]}$) then
        $\mathit{chart}_{[i,i+l+1]} \leftarrow \mathit{chart}_{[i,i+l+1]} \cup \{\alpha\}$;

$[0,2] \leftarrow [0,1] + [1,2]$
$\ldots$
$[0,5] \leftarrow [0,1] + [1,5]$
$[0,5] \leftarrow [0,2] + [2,5]$
$[0,5] \leftarrow [0,3] + [3,5]$
$[0,5] \leftarrow [0,4] + [4,5]$

	1	2	3	4	5
0	NP		S		S
1		V	VP		VP
2			NP		NP
3				P	PP
4					NP

Limitations of the CKY Algorithm

Built-In Assumptions

- *Chomsky Normal Form* grammars: $\alpha \rightarrow \beta_1\beta_2$ or $\alpha \rightarrow \gamma$ ($\beta_i \in C$, $\gamma \in \Sigma$);
- breadth-first (aka exhaustive): always compute all values for each cell;
- rigid control structure: bottom-up, left-to-right (one diagonal at a time).

Generalized Chart Parsing

- Liberate order of computation: no assumptions about earlier results;
- *active edges* encode partial rule instantiations, 'waiting' for additional (adjacent and passive) constituents to complete: $[1, 2, \text{VP} \rightarrow \text{V} \bullet \text{NP}]$;
- parser can fill in chart cells in *any* order and guarantee completeness.

Generalized Chart Parsing

- The *chart* is a two-dimensional matrix of *edges* (aka chart items);
- an edge is a (possibly partial) rule instantiation over a substring of input;
- the chart indexes edges by start and end string position (aka vertices);
- dot in rule RHS indicates degree of completion: $\alpha \rightarrow \beta_1 ... \beta_{i-1} \bullet \beta_i ... \beta_n$
- *active* edges (aka *incomplete* items) — partial RHS: $[1, 2, \text{VP} \rightarrow \text{V} \bullet \text{NP}]$;
- *passive* edges (aka *complete* items) — full RHS: $[1, 3, \text{VP} \rightarrow \text{V NP}\bullet]$;

The Fundamental Rule

$$[x,\ y,\ \alpha \rightarrow \beta_1 ... \beta_{i-1} \bullet \beta_i ... \beta_n] + [y,\ z,\ \beta_i \rightarrow \gamma^{+} \bullet]$$
$$\mapsto [x,\ z,\ \alpha \rightarrow \beta_1 ... \beta_i \bullet \beta_{i+1} ... \beta_n]$$

An Example of a (Near-)Complete Chart

	1	2	3	4	5
0	NP → NP • PP S → NP • VP NP → kim •				S → NP VP •
1		VP → V • NP V → adores •	VP → VP • PP VP → V NP •		VP → VP • PP VP → VP PP • VP → V PP •
2			NP → NP • PP NP → snow •		NP → NP • PP NP → NP PP •
3				PP → P • NP P → in •	PP → P NP •
4					NP → NP • PP NP → oslo •

$_0$ *Kim* $_1$ *adores* $_2$ *snow* $_3$ *in* $_4$ *Oslo* $_5$

(Even) More Active Edges

	0	1	2	3
0	S → • NP VP NP → • NP PP NP → • kim	S → NP • VP NP → NP • PP NP → kim •		S → NP VP •
1		VP → • VP PP VP → • V NP V → • adores	VP → V • NP V → adores •	VP → VP • PP VP → V NP •
2			NP → • NP PP NP → • snow	NP → NP • PP NP → snow •
3				

- Include all grammar rules as *epsilon* edges in each $\textit{chart}_{[i,i]}$ cell.
- after initialization, apply *fundamental rule* until fixpoint is reached.

Our ToDo List: Keeping Track of Remaining Work

The Abstract Goal

- Any chart parsing algorithm needs to check all pairs of adjacent edges.

A Naïve Strategy

- Keep iterating through the complete chart, combining all possible pairs, until no additional edges can be derived (i.e. the fixpoint is reached);
- frequent attempts to combine pairs multiple times: deriving ‘duplicates’.

An Agenda-Driven Strategy

- Combine each pair exactly once, viz. when both elements are available;
- maintain *agenda* of new edges, yet to be checked against chart edges;
- new edges go into agenda first, add to chart upon retrieval from agenda.

Backpointers: Keeping Track of the Derivation History

	0	1	1	3
0	2: S → • NP VP 1: NP → • NP PP 0: NP → • kim	10: S → 8 • VP 9: NP → 8 • PP 8: NP → kim •		17: S → 8 15 •
1		5: VP → • VP PP 4: VP → • V NP 3: V → • adores	12: VP → 11 • NP 11: V → adores •	16: VP → 15 • PP 15: VP → 11 13 •
2			7: NP → • NP PP 6: NP → • snow	14: NP → 13 • PP 13: NP → snow •
3				

- Use edges to record derivation trees: backpointers to daughters;
- a single edge can represent multiple derivations: backpointer sets.

Chart Elements: The Edge Structure

`#[` *id*`:` `(`*i*–*j*`)` α `-->` *edge*$_1$ ... *edge*$_i$ `.` β_{i+1} ... β_n $\{$ *alternate*$_1$ ... *alternate*$_n$ $\}^*$ `]`

Components of the *edge* Structure

- *id* unique edge identifier (automatically assigned my `make-edge()`);
- *i* and *j* starting and ending string index (chart vertices) for this edge;
- α category of this edge (from the set C of non-terminal symbols);
- *edge*$_1$ ... *edge*$_i$ (list of) daughter edges (for β_1 ... β_i) instantiated so far;
- β_{i+1} ... β_n (list of) remaining categories in rule RHS to be instantiated;
- *alternate*$_1$ ... *alternate*$_n$ alternative derivation(s) for α from i to j.

$\rightarrow$ implemented using `defstruct()` plus suitable pretty printing routine.

Ambiguity Packing in the Chart

General Idea

- Maintain only one edge for each α from i to j (the 'representative');
- record alternate sequences of daughters for α in the representative.

Implementation

- Group passive edges into *equivalence classes* by identity of α, i, and j;
- search chart for existing equivalent edge (h, say) for each new edge e;
- when h (the 'host' edge) exists, *pack* e into h to record equivalence;
- e *not* added to the chart, no derivations with or further processing of e;

$\rightarrow$ *unpacking* multiply out all alternative daughters for all result edges.