University of Oslo : Department of Informatics

INF4820: Algorithms for Artificial Intelligence and Natural Language Processing

Generalized Chart Parsing

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Overview

Last Time

- Context-Free Grammar
- Treebanks
- Probabilistic CFGs
- Syntactic Parsing
  - Naïve: Recursive-Descent
  - Dynamic Programming: CKY

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- Syntactic Parsing
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Today

- Generalized Chart Parsing
- Inside the Parse Forest
- Viterbi Tree Decoding
- Parser Evaluation

CFGs (Formally, this Time)

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- P is a set of category rewrite rules (aka *productions*)

$$\text{S} \rightarrow \text{NP VP} \qquad \text{NP} \rightarrow \text{Kim}$$
$$\text{VP} \rightarrow \text{V NP} \qquad \text{NP} \rightarrow \text{snow}$$
$$\text{V} \rightarrow \text{adores}$$

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S → NP VP	NP → Kim
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	V → adores

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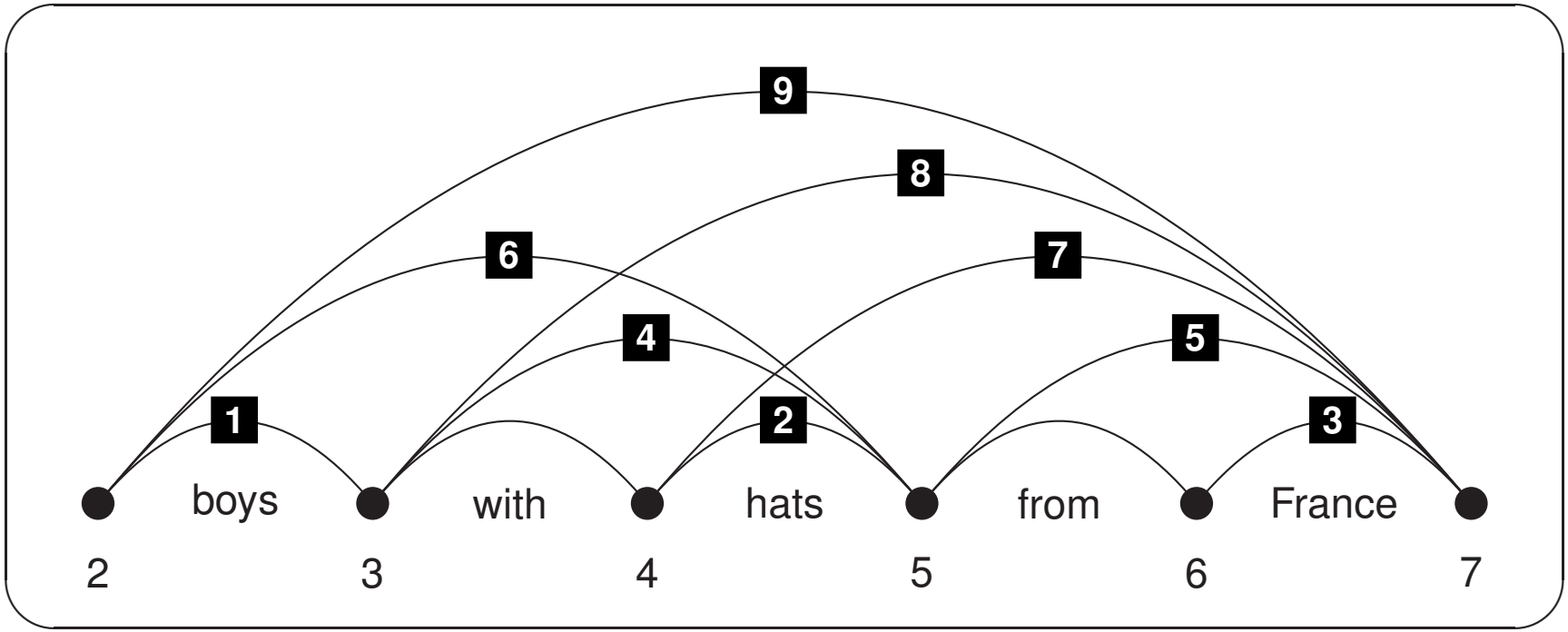
$$\begin{array}{ll} \text{S} \rightarrow \text{NP VP} & \text{NP} \rightarrow \text{Kim} \\ \text{VP} \rightarrow \text{V NP} & \text{NP} \rightarrow \text{snow} \\ & \text{V} \rightarrow \text{adores} \end{array}$$

- $S \in C$ is the *start symbol*, a filter on complete results;
- for each rule $\alpha \rightarrow \beta_1, \beta_2, ..., \beta_n \in P$: $\alpha \in C$ and $\beta_i \in C \cup \Sigma$

A Key Insight: Local Ambiguity

- For many substrings, more than one way 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].



The CKY (Cocke, Kasami, & Younger) Algorithm

for ($0 \leq i < |\mathit{input}|$) do
  $\mathit{chart}_{[i,i+1]} \leftarrow \{\alpha \,|\, \alpha \rightarrow \mathit{input}_i \in P\}$;
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
        $\mathit{chart}_{[i,i+l+1]} \leftarrow \mathit{chart}_{[i,i+l+1]} \cup \{\alpha\}$;

Kim adored snow in Oslo

	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).

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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.

Chart Parsing — Specialized Dynamic Programming

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.

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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.

Chart Parsing: Key Ideas

- The parse *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: $\alpha \rightarrow \beta_1 \ldots \beta_{i-1} \bullet \beta_i \ldots \beta_n$;
- *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

$$[i,\ j,\ \alpha \rightarrow \beta_1 \ldots \beta_{i-1} \bullet \beta_i \ldots \beta_n] + [j,\ k,\ \beta_i \rightarrow \gamma^+ \bullet]$$
$$\mapsto [i,\ k,\ \alpha \rightarrow \beta_1 \ldots \beta_i \bullet \beta_{i+1} \ldots \beta_n]$$

An Example of a (Near- and Over-)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 NP •
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 (and Passive) Edges

	0	1	2	3
0	$S \rightarrow \bullet\ NP\ VP$ $NP \rightarrow \bullet\ NP\ PP$ $NP \rightarrow \bullet$ kim	$S \rightarrow NP \bullet VP$ $NP \rightarrow NP \bullet PP$ $NP \rightarrow$ kim $\bullet$ kim		$S \rightarrow NP\ VP \bullet$
1		$VP \rightarrow \bullet\ VP\ PP$ $VP \rightarrow \bullet\ V\ NP$ $V \rightarrow \bullet$ adores	$VP \rightarrow V \bullet NP$ $V \rightarrow$ adores $\bullet$ adores	$VP \rightarrow VP \bullet PP$ $VP \rightarrow V\ NP \bullet$
2			$NP \rightarrow \bullet\ NP\ PP$ $NP \rightarrow \bullet$ snow	$NP \rightarrow NP \bullet PP$ $NP \rightarrow$ snow $\bullet$ snow
3				

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

Combinatorics: 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'.

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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: Recording the Derivation History

	0	1	2	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.

Ambiguity Packing in the Chart

General Idea

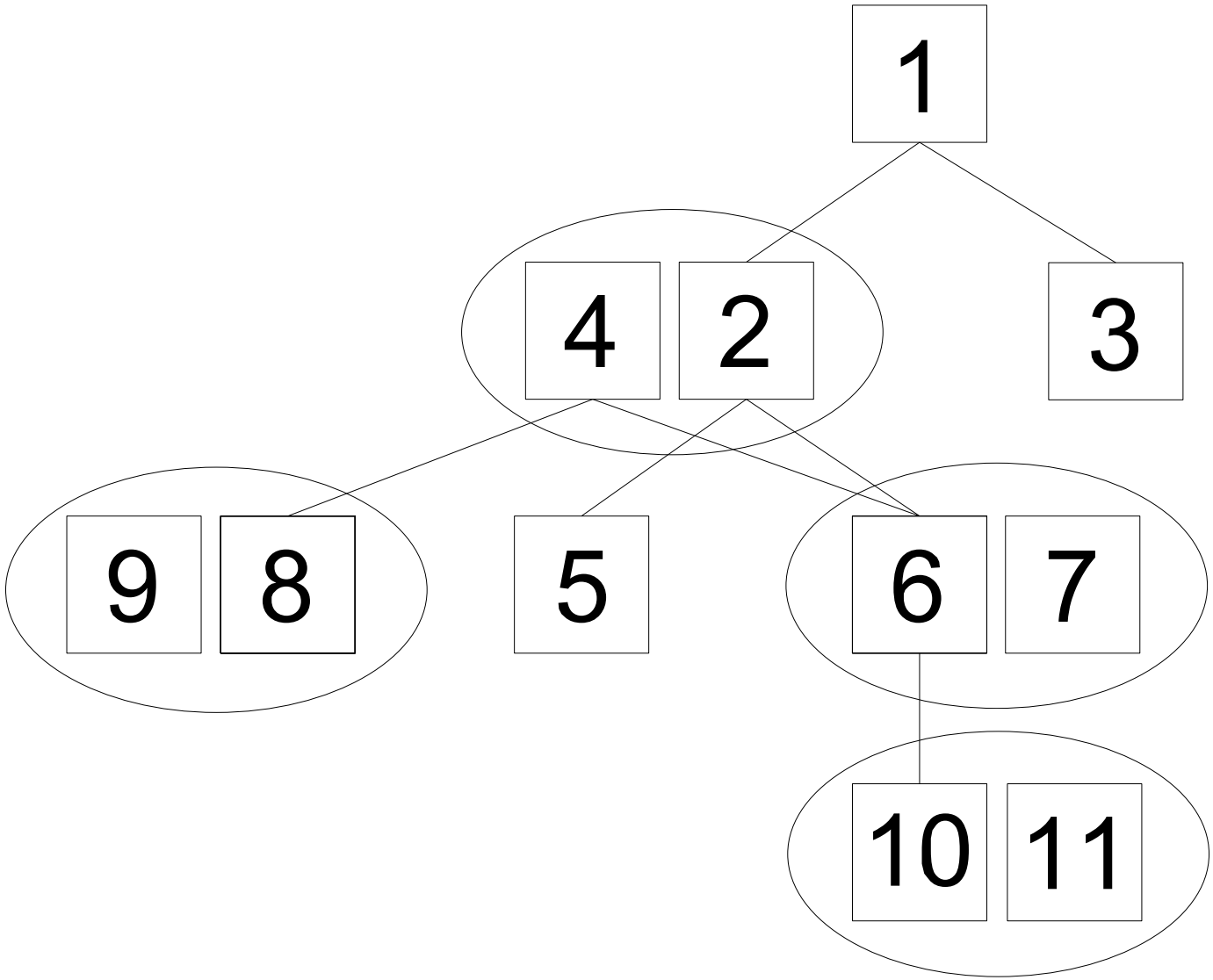
- Maintain only one edge for each α from i to j (the 'representative');
- record alternate sequences of daughters for α in the representative.

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.

An Example (Hypothetical) Parse Forest



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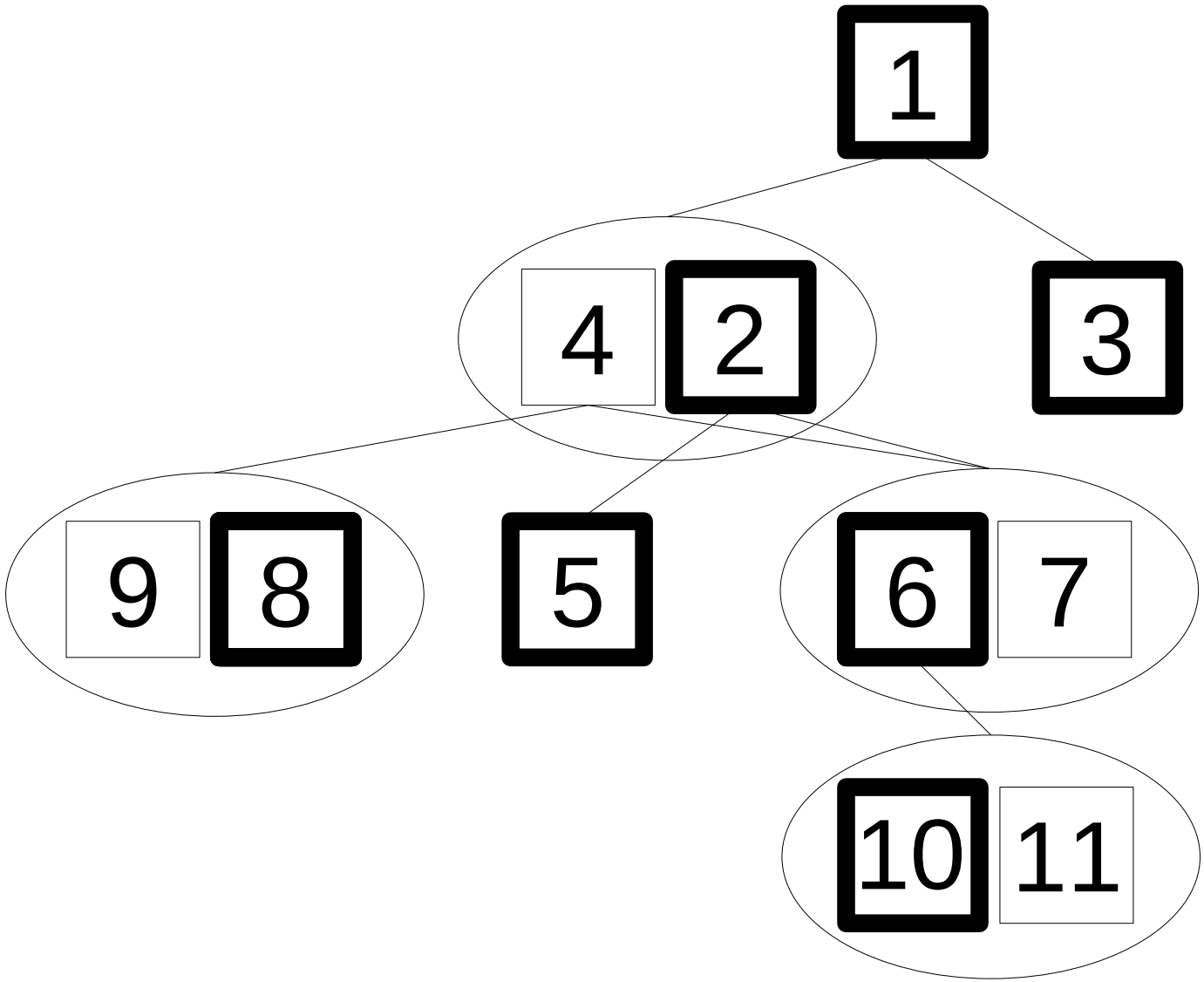
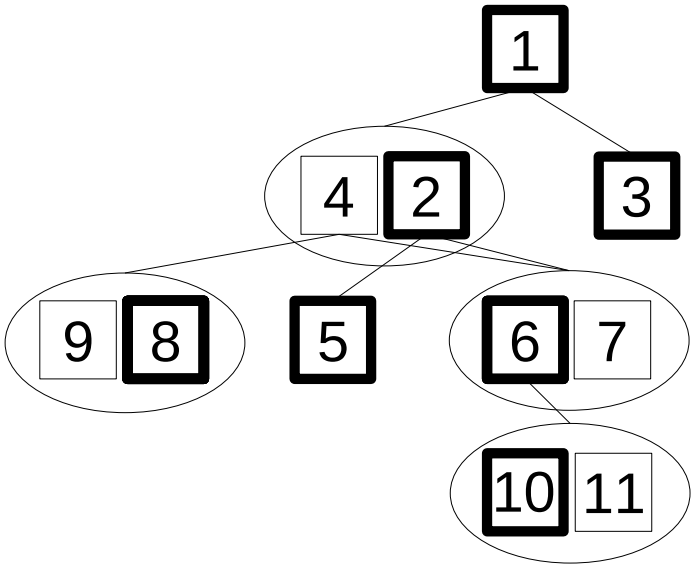


Unpacking: Cross-Multiplying Local Ambiguity



$$
\begin{aligned}
1 &\rightarrow \langle 2\ 3 \rangle \mid \langle 4\ 3 \rangle \\
2 &\rightarrow \langle 5\ 6 \rangle \mid \langle 5\ 7 \rangle \\
4 &\rightarrow \langle 8\ 6 \rangle \mid \langle 8\ 7 \rangle \mid \langle 9\ 6 \rangle \mid \langle 9\ 7 \rangle \\
6 &\rightarrow \langle 10 \rangle \mid \langle 11 \rangle
\end{aligned}
$$

How many complete trees in total?

In Conclusion—What Happened this Far

Syntactic Structure

- Languages (formal or natural) exhibit complex, hierarchical structures;
- grammars encode rules of the language: dominance and sequencing;
- context-free grammar ‘generates’ a language: strings and derivations;
- ambiguity in natural language grows exponentially: a search problem;
- bounding (or ‘packing’) of local ambiguity madantory for tractability;
- chart parsing uses dynamic programming: free order of computation.

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Coming up Next

- Viterbi adaptation over parse forest; PTB parsing; parser evaluation.

Ambiguity Resolution Remains a (Major) Challenge

The Problem

- With broad-coverage grammars, even moderately complex sentences typically have multiple analyses (tens or hundreds, rarely thousands);
- unlike in grammar writing, exhaustive parsing is useless for applications;
- identifying the 'right' (intended) analysis is an 'AI-complete' problem;
- inclusion of (non-grammatical) sortal constraints nowadays undesirable.

Once Again: Probabilities to the Rescue

- Design and use statistical models to select among competing analyses;
- for string S, some analyses T_i are more or less likely: maximize $P(T_i|S)$;

$\rightarrow$ Probabilistic Context Free Grammar (PCFG) is a CFG plus probabilities.

Probability Theory and Natural Language?

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Every time I fire a linguist, system performance improves. (Fredrick Jelinek, 1980s)

Generalized Chart Parsing

Initialization

- for each *word* in input string
  - add passive lexical edge $\langle word \bullet \rangle$ to chart
  - for each $\alpha \rightarrow word \in P$
    - add passive $\langle \alpha \rightarrow word \bullet \rangle$ edge to agenda

Main Loop

- while *edge* $\leftarrow$ pop-agenda()
  - if equivalent edge in chart, pack; otherwise insert *edge*
  - if *edge* is passive
    - for each active edge *a* to the left, fundamental-rule(*a*, *edge*)
    - predict new edges from P, and add to the agenda
  - else
    - for each passive edge *p* to the right, fundamental-rule(*edge*, *p*)

Termination

- return all edges with category S that span the full input

Viterbi Decoding over the Parse Forest

- Recall the Viterbi algorithm for HMMs

$$v_i(x) = \max_{k=1}^{L} [v_{i-1}(k) \cdot P(x|k) \cdot P(o_i|x)]$$

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- In our parse forest, we no longer have a linear order, but we can still build up cached Viterbi values successively:

$$v(e) = \max \left[P(\beta_1, \ldots \beta_n|\alpha) \times \prod_i v(\beta_i) \right]$$

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- Implementation: Cache the highest-scoring edge within e, recording the maximum probability of its sub-tree and the daughter sequence that led to it.