ANLP Lecture 12
Parsing Algorithms

Alex Lascarides
(slides from Sharon Goldwater, Henry Thompson, Alex Lascarides, Mark Steedman and Philipp Koehn)

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Recap: Syntax

Two reasons to care about syntactic structure (parse tree):

• As a guide to the semantic interpretation of the sentence

• As a way to prove whether a sentence is grammatical or not

But having a grammar isn’t enough.

We also need a parsing algorithm to compute the parse tree for a given input string and grammar.
Parsing algorithms

Goal: compute the structure(s) for an input string given a grammar.

- As usual, ambiguity is a huge problem.
  - For correctness: need to find the right structure to get the right meaning.
  - For efficiency: searching all possible structures can be very slow; want to use parsing for large-scale language tasks (e.g., used to create Google’s “infoboxes”)

Global and local ambiguity

- We’ve already seen examples of **global ambiguity**: multiple analyses for a full sentence, like *I saw the man with the telescope*.

- But **local ambiguity** is also a big problem: multiple analyses for parts of sentence.
  - *the dog bit the child*: first three words could be NP (but aren’t).
  - Building useless partial structures wastes time.
  - Avoiding useless computation is a major issue in parsing.

- Syntactic ambiguity is rampant; humans usually don’t even notice because we are good at using context/semantics to disambiguate.
Parser properties

All parsers have two fundamental properties:

- **Directionality**: the sequence in which the structures are constructed.
  - **top-down**: start with root category (S), choose expansions, build down to words.
  - **bottom-up**: build subtrees over words, build up to S.
  - **Mixed** strategies also possible (e.g., left corner parsers)

- **Search strategy**: the order in which the search space of possible analyses is explored.
Example: search space for top-down parser

- Start with S node.

- Choose one of many possible expansions.

- Each of which has children with many possible expansions...

- etc
Search strategies

• **depth-first search**: explore one branch of the search space at a time, as far as possible. If this branch is a dead-end, parser needs to **backtrack**.

• **breadth-first search**: expand all possible branches in parallel (or simulated parallel). Requires storing many incomplete parses in memory at once.

• **best-first search**: score each partial parse and pursue the highest-scoring options first. (Will get back to this when discussing statistical parsing.)
Recursive Descent Parsing

• A recursive descent parser treats a grammar as a specification of how to break down a top-level goal (find S) into subgoals (find NP VP).

• It is a top-down, depth-first parser:
  – Blindly expand nonterminals until reaching a terminal (word).
  – If multiple options available, choose one but store current state as a backtrack point (in a stack to ensure depth-first.)
  – If terminal matches next input word, continue; else, backtrack.
RD Parsing algorithm

Start with subgoal = $S$, then repeat until input/subgoals are empty:

- If first subgoal in list is a **non-terminal** $A$, then pick an expansion $A \rightarrow B \ C$ from grammar and replace $A$ in subgoal list with $B \ C$

- If first subgoal in list is a **terminal** $w$:
  - If input is empty, backtrack.
  - If next input word is different from $w$, backtrack.
  - If next input word is $w$, match! i.e., consume input word $w$ and subgoal $w$ and move to next subgoal.

If we run out of backtrack points but not input, no parse is possible.
Recursive descent example

Consider a very simple example:

- Grammar contains only these rules:
  
  \[
  S \rightarrow \text{NP} \ \text{VP} \quad \text{VP} \rightarrow \text{V} \\
  \text{NP} \rightarrow \text{DT} \ \text{NN} \quad \text{DT} \rightarrow \text{the} \\
  \text{NN} \rightarrow \text{bit} \quad \text{V} \rightarrow \text{bit} \\
  \text{NN} \rightarrow \text{dog} \quad \text{V} \rightarrow \text{dog}
  \]

- The input sequence is the dog bit
## Recursive descent example

<table>
<thead>
<tr>
<th>Step</th>
<th>Op.</th>
<th>Subgoals</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td>the dog bit</td>
</tr>
<tr>
<td>1</td>
<td>E</td>
<td>NP VP</td>
<td>the dog bit</td>
</tr>
<tr>
<td>2</td>
<td>E</td>
<td>DT NN VP</td>
<td>the dog bit</td>
</tr>
<tr>
<td>3</td>
<td>E</td>
<td>the NN VP</td>
<td>the dog bit</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>NN VP</td>
<td>dog bit</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>bit VP</td>
<td>dog bit</td>
</tr>
<tr>
<td>6</td>
<td>B4</td>
<td>NN VP</td>
<td>dog bit</td>
</tr>
<tr>
<td>7</td>
<td>E</td>
<td>dog VP</td>
<td>dog bit</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>VP</td>
<td>bit</td>
</tr>
<tr>
<td>9</td>
<td>E</td>
<td>V</td>
<td>bit</td>
</tr>
<tr>
<td>10</td>
<td>E</td>
<td>bit</td>
<td>bit</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Operations:**
  - Expand (E)
  - Match (M)
  - Backtrack to step \( n \) (B\( n \))
Further notes

• The above sketch is actually a recognizer: it tells us whether the sentence has a valid parse, but not what the parse is. For a parser, we’d need more details to store the structure as it is built.

• We only had one backtrack, but in general things can be much worse!
  – See Inf2a Lecture 17 for a much longer example showing inefficiency.
  – If we have left-recursive rules like $\text{NP} \rightarrow \text{NP PP}$, we get an infinite loop!
Shift-Reduce Parsing

- Search strategy and directionality are orthogonal properties.

- **Shift-reduce** parsing is **depth-first** (like RD) but **bottom-up** (unlike RD).

- Basic shift-reduce recognizer repeatedly:
  - Whenever possible, **reduces** one or more items from top of stack that match RHS of rule, replacing with LHS of rule.
  - When that’s not possible, **shifts** an input symbol onto a stack.

- Like RD parser, needs to maintain backtrack points.
Shift-reduce example

- Same example grammar and sentence.
- Operations:
  - Reduce (R)
  - Shift (S)
  - Backtrack to step $n$ (B$n$)
- Note that at 9 and 11 we skipped over backtracking to 7 and 5 respectively as there were actually no choices to be made at those points.
Depth-first parsing in practice

- Depth-first parsers are very efficient for unambiguous structures.
  - Widely used to parse/compile programming languages, which are constructed to be unambiguous.

- But can be massively inefficient (exponential in sentence length) if faced with local ambiguity.
  - Blind backtracking may require re-building the same structure over and over: so, simple depth-first parsers are not used in NLP.
  - But: if we use a probabilistic model to learn which choices to make, we can do very well in practice (coming next week...)
Breadth-first search using dynamic programming

- With a CFG, you should be able to avoid re-analysing any substring because its analysis is **independent** of the rest of the parse.

$[he]_{np}$ $[\text{saw her duck}]_{vp}$

- **chart parsing** algorithms exploit this fact.
  - use dynamic programming to store and reuse sub-parses, composing them into a full solution.
  - So multiple potential parses are explored at once: a breadth-first strategy.
Parsing as dynamic programming

- For parsing, subproblems are analyses of substrings, memoized in chart (aka well-formed substring table, WFST).

- Chart entries are indexed by start and end positions in the sentence, and correspond to:
  - either a complete constituent (sub-tree) spanning those positions (if working bottom-up),
  - or a prediction about what complete constituent might be found (if working top-down).
What’s in the chart?

• We assume *indices* between each word in the sentence:

\[ 0 \text{ he 1 saw 2 her 3 duck 4} \]

• The chart is a matrix where cell \([i, j]\) holds information about the word span from position \(i\) to position \(j\):
  – The root node of any constituent(s) spanning those words
  – Pointers to its sub-constituents
  – (Depending on parsing method,) predictions about what constituents might follow the substring.
Algorithms for Chart Parsing

Many different chart parsing algorithms, including

- the **CKY algorithm**, which memoizes only complete constituents
- various algorithms that also memoize predictions/partial constituents
  - often using mixed bottom-up and top-down approaches, e.g., the Earley algorithm described in J&M, and left-corner parsing.
CKY Algorithm

CKY (Cocke, Kasami, Younger) is a **bottom-up, breadth-first** parsing algorithm.

- Original version assumes grammar in Chomsky Normal Form.

- Add constituent $A$ in cell $(i, j)$ if there is:
  - a rule $A \rightarrow B$, and a $B$ in cell $(i, j)$, **or**
  - a rule $A \rightarrow B \ C$, and a $B$ in cell $(i, k)$ and a $C$ in cell $(k, j)$.
CKY Algorithm

CKY (Cocke, Kasami, Younger) is a bottom-up, breadth-first parsing algorithm.

- Original version assumes grammar in Chomsky Normal Form.
- Add constituent $A$ in cell $(i, j)$ if there is:
  - a rule $A \rightarrow B$, and a $B$ in cell $(i, j)$, or
  - a rule $A \rightarrow B \ C$, and a $B$ in cell $(i, k)$ and a $C$ in cell $(k, j)$.
- Fills chart in order: only looks for rules that use a constituent from $i$ to $j$ after finding all constituents ending at $i$. So, guaranteed to find all possible parses.
CKY Pseudocode

- Assume input sentence with indices 0 to \( n \), and chart \( c \).

for \( len = 1 \) to \( n \):  #number of words in constituent
  for \( i = 0 \) to \( n-len \):  #start position
    \( j = i+len \)  #end position
    #process unary rules
    foreach \( A \rightarrow B \) where \( c[i,j] \) has \( B \)
      add \( A \) to \( c[i,j] \) with a pointer to \( B \)
    for \( k = i+1 \) to \( j-1 \)  #mid position
      #process binary rules
      foreach \( A \rightarrow B \ C \) where \( c[i,k] \) has \( B \) and \( c[k,j] \) has \( C \)
        add \( A \) to \( c[i,j] \) with pointers to \( B \) and \( C \)

- Takes time \( O(Gn^3) \), where \( G \) is the number of grammar rules.
CKY Example

S → NP VP
NP → D N | Pro | PropN
D → PosPro | Art | NP ’s
VP → Vi | Vt NP | Vp NP VP
Pro → i | we | you | he | she | him | her
PosPro → my | our | your | his | her
PropN → Robin | Jo
Art → a | an | the
N → cat | dog | duck | saw | park | telescope | bench
Vi → sleep | run | duck
Vt → eat | break | see | saw
Vp → see | saw | heard
**CKY Example**

**POS ambiguities**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Vt,Vp,N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pro, PosPro</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>N,Vi</td>
<td></td>
</tr>
</tbody>
</table>

- We’ve added all POSs that are allowed for each word.
CKY Example

Larger Constituents: Unary rule \( \text{NP} \rightarrow \text{Pro} \)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Vt,Vp,N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>Pro, PosPro</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>N,Vi</td>
</tr>
</tbody>
</table>

- red shows which children create which parents.
- Normally we'd add pointers from parent to child to store this info permanently, but we'd end up with too many arrows here to see what's going on!
**CKY Example**

Larger Constituents: Unary rule $\text{NP} \rightarrow \text{Pro}$ (again!)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Vt, Vp, N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>Pro, PosPro, NP</td>
<td></td>
</tr>
<tr>
<td>3</td>
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CKY Example

Larger Constituents: Unary rule \( D \rightarrow \text{PosPro} \)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Vt, Vp, N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pro, PosPro, NP, D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>N, Vi</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- red shows which children create which parents.
- Normally we'd add pointers from parent to child to store this info permanently, but we'd end up with too many arrows here to see what's going on!
### CKY Example

#### Larger Constituents: Binary rule $\text{VP} \rightarrow \text{Vt} \ \text{NP}$

<table>
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<th>2</th>
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<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Vt, Vp, N</td>
<td>VP</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Pro, PosPro, NP, D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>N, Vi</td>
</tr>
</tbody>
</table>

- Vt from (1,2) plus NP from (2,3) makes a VP from (1,3).
- For cell (0,2) there was nothing in the possible child cells, $[(0,1), (1,2)]$ that can combine to make a larger phrase.
CKY Example

Larger Constituents: Binary rule $\text{NP} \rightarrow D \text{ N}$

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</tr>
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<td>2</td>
<td></td>
<td>Pro, PosPro, NP, D</td>
<td>NP</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>N,Vi</td>
<td></td>
</tr>
</tbody>
</table>

- D from (2,3) plus N from (3,4) makes a NP from (2,4).
CKY Example

Larger Constituents: Binary rule $S \rightarrow NP \ VP$

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Vt,Vp,N</td>
<td></td>
<td>VP</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pro, PosPro, NP, D</td>
<td>NP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>N, Vi</td>
<td></td>
</tr>
</tbody>
</table>

- NP from (0,1) plus VP from (1,3) makes an S from (0,3).
- So, we found an S, but it doesn’t span the whole sentence.
CKY Example

Larger Constituents: Binary rule $\text{VP} \rightarrow \text{Vt, NP}$

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<td>VP</td>
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<td></td>
<td>Pro, PosPro, NP, D</td>
<td>NP</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>N,Vi</td>
<td></td>
</tr>
</tbody>
</table>

- Vt from (1,2) plus NP from (2,4) makes a VP from (1,4).
- For cell (1,4) we also consider (1,3) plus (3,4) but there’s nothing in those cells that can combine to make a larger phrase.
# CKY Example

## Larger Constituents: alternate parses

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td></td>
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<td></td>
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<tr>
<td>1</td>
<td>Vt, Vp, N</td>
<td>VP</td>
<td>VP</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pro, PosPro, NP, D</td>
<td>NP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>heₙ₁</td>
<td>saw₂</td>
<td>herₙ₃</td>
<td>duckₙ₄</td>
</tr>
</tbody>
</table>

- We also have another way to build the same VP (1,4). Add more pointers to remember this new analysis.
- (Not standard CKY because we used a ternary rule! In reality we would have converted this rule into CNF, but still ended up with two parses for VP.)
CKY Example

Larger Constituents: Binary rule $S \rightarrow NP \ VP$

<table>
<thead>
<tr>
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<th>3</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pro, NP</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Vt,Vp,N</td>
<td>VP</td>
<td>VP</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pro, PosPro, NP, D</td>
<td>NP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>N,Vi</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- When we build the $S$, it doesn’t matter anymore that there are two VP analyses, we just see the $VP$.
- Ambiguity is only clear if we go to reconstruct the parses using our backpointers.
A note about CKY ordering

- Notice that to fill cell \((i, j)\), we use a cell from row \(i\) and a cell from column \(j\).

- So, we must fill in all cells down and left of \((i, j)\) before filling \((i, j)\).

- Here, we filled in all short entries, then longer ones, but other orders can work (e.g., J&M fill in all spans ending at \(j\), then increment \(j\).)
CKY in practice

- Avoids re-computing substructures, so much more efficient than depth-first parsers (in worst case).
- Still may compute a lot of unnecessary partial parses.
- Simple version requires converting the grammar to CNF (may cause blowup: remember time depends on grammar too!).

Various other chart parsing methods avoid these issues by combining top-down and bottom-up approaches (see J&M2).

But rather than going that way, next time we’ll focus on statistical parsing which can help with both ambiguity and efficiency issues.
Questions for review/practice

• What is the difference between global and local ambiguity? Construct example sentences illustrating each type of ambiguity (different from those given in the lecture).

• What are two examples of depth-first parsing algorithms, and what is the difference between them?

• Add a $VP \rightarrow V \ NP$ rule to the grammar on slide 10, and hand-simulate the different parsing strategies on the inputs the dog bit, the dog dog, and the dog bit the dog.

• What is the big disadvantage of (non-probabilistic) depth-first parsers? How does CKY avoid this disadvantage?