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.

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.)

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

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:
  \[
  \begin{align*}
  S &\rightarrow NP \ \ VP \\
  VP &\rightarrow V \ \ NN \\
  V &\rightarrow bit \\
  NN &\rightarrow bit \\
  NP &\rightarrow DT \ \ NN \\
  DT &\rightarrow the \\
  NN &\rightarrow dog \\
  V &\rightarrow dog
  \end{align*}
  \]

- The input sequence is the dog bit

---

**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 \( NP \rightarrow NP \ PP \), 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.

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...)

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.

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

- **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 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

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  - 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 \( c \).

```plaintext
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->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->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 \rightarrow NP VP**

**NP \rightarrow D N | Pro | PropN**

**D \rightarrow PosPro | Art | NP ’s**

**VP \rightarrow Vi | Vt NP | Vp NP VP**

**Pro \rightarrow i | we | you | he | she | him | her**

**PosPro \rightarrow my | our | your | his | her**

**PropN \rightarrow Robin | Jo**

**Art \rightarrow a | an | the**

**N \rightarrow cat | dog | duck | saw | park | telescope | bench**

**Vi \rightarrow sleep | run | duck**

**Vt \rightarrow eat | break | see | saw**

**Vp \rightarrow see | saw | heard**

POS ambiguities

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</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>
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<tr>
<td>3</td>
<td>N, Vi</td>
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<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>
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<tr>
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<tr>
<td>3</td>
<td>N,Vi</td>
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</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!

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CKY Example

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

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>4</th>
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</thead>
<tbody>
<tr>
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<td>Pro, NP</td>
<td></td>
<td></td>
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<td>1</td>
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<tr>
<td>2</td>
<td>Pro, PosPro, NP</td>
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<td></td>
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- 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!

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CKY Example

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

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<tbody>
<tr>
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<tr>
<td>3</td>
<td>N,Vi</td>
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<td></td>
<td></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.

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CKY Example

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

<table>
<thead>
<tr>
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<th>1</th>
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<th>3</th>
<th>4</th>
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- 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.

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CKY Example

Larger Constituents: Binary rule \( NP \rightarrow D \ N \)

<table>
<thead>
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<tr>
<td>2</td>
<td>Pro, PosPro, NP, D, NP</td>
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<tr>
<td>3</td>
<td>( \omega \text{he}_1, \text{saw}_2, \text{her}_3, \text{duck}_4 )</td>
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</tr>
</tbody>
</table>

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

CKY Example

Larger Constituents: Binary rule \( S \rightarrow NP \ VP \)

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<tr>
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</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 \( VP \rightarrow Vt \ NP \)

<table>
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</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>
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<tr>
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</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>
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<tbody>
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<td>Pro, NP</td>
<td>S</td>
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<tr>
<td>1</td>
<td>Vt,Vp,N</td>
<td>VP</td>
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<td>Pro, PosPro, NP, D</td>
<td>NP</td>
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<tr>
<td>3</td>
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</tbody>
</table>

\( \text{he}_1 \) | \( \text{saw}_2 \) | \( \text{her}_3 \) | \( \text{duck}_4 \)

- 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?