Alternative Grammatical Formalisms

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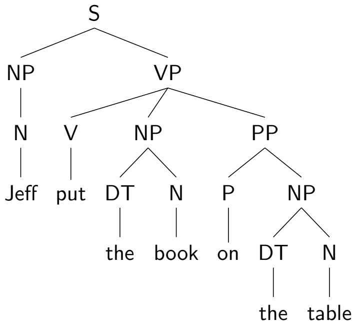
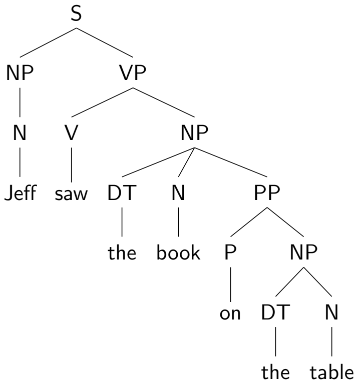
Why use other grammatical formalisms?

- CFGs are useful for describing natural language.
- Unlike regular expressions, they are expressive enough to capture many dependencies in natural language.
- Unlike more expressive formalisms, they can be parsed efficiently in $O(n^3)$ time.
  - For instance, TAG takes $O(n^6)$ time to parse.
  - There is probably no polynomial time algorithm to parse context sensitive grammars.

Limitations of CFGs

- CFGs have trouble capturing non-local dependencies, such as verb subcategorization frames.





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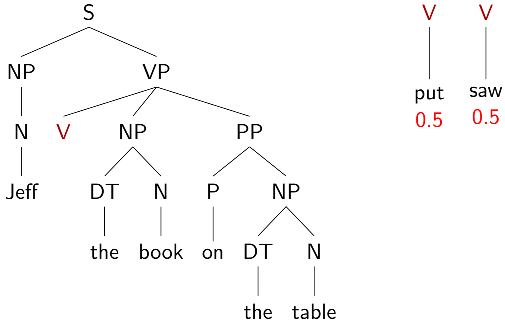
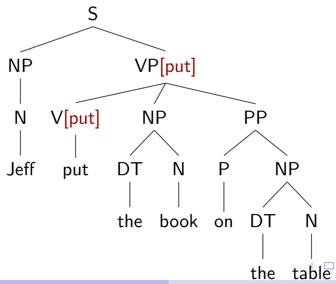


What to do about the limitations of CFGs?

- This is why a CFG read directly off the Penn Treebank has poor parsing performance.
- One solution: create a different CFG which captures this dependency by annotating the nonterminals with additional information capturing these dependencies.
  - Could annotate with specific features, like the head word.
  - Could automatically learn to cluster each symbol into subsymbols.

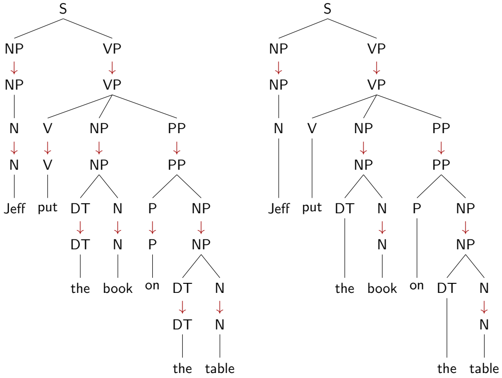


What to do about the limitations of CFGs?

- Another solution: use alternative grammatical formalisms.
- This lecture will present two such formalisms:
  - Tree Substitution Grammar (TSG)
  - Tree Adjoining Grammar (TAG)
- There are many other such formalisms, notably Combinatory Categorial Grammar (CCG).

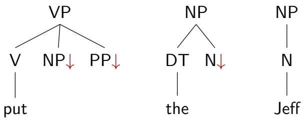
What is a Tree Substitution Grammar?

- A TSG is like a CFG, but instead of rewriting as a string of nonterminals and terminals, each nonterminal rewrites as a whole tree fragment.



Formal Definition

- Formally, a TSG is a 4-tuple $G = (T, N, S, R)$
  - T: terminals
  - N: nonterminals
  - S: distinguished start symbol
  - R: productions
- Each production is a *tree fragment*, also called an *elementary tree*.
  - Internal nodes are nonterminals.
  - Leaf nodes can be terminals or nonterminals.
  - Nonterminals at leaves are called *frontier nodes* or *substitution sites*, marked with $\downarrow$.
  - These are the nonterminals which rewrite as elementary trees.

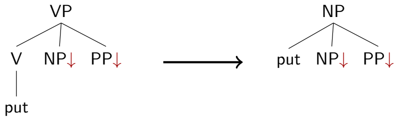


Formal Definition

- The process of rewriting is called *derivation*.
  - It continues until there are no frontier nodes left to replace.
  - The result is called the *derived tree*.
- As usual, once the derivation process is finished, we can read the sentence off the leaves of the tree.

Equivalence of CFGs and TSGs

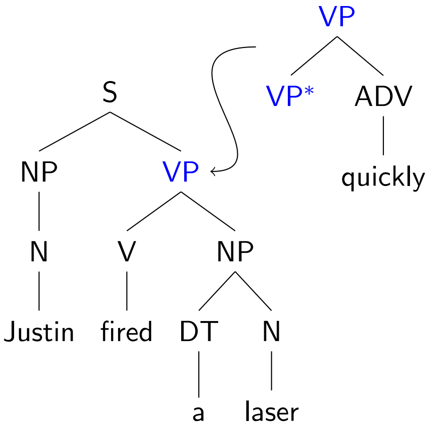
- TSGs and CFGs are formally equivalent.
- Every CFG is just a TSG whose rules all have height 2.
- Every TSG can be converted to a CFG by flattening the rules.
- So TSG is no more expressive than CFG.
- But in practice it's usefulf or learning from the Penn Treebank.
- Lets us capture long-distance dependencies, such as verb subcategorization frames.
- And because it's formally equivalent to CFG, we can still parse in O(n^3) time.



What is a Tree Adjoining Grammar?

- TAG is like TSG, except that in addition to substitution, we also have an operation called adjunction.
- Substitution occurs at frontier nodes and adds things to the bottom of the tree.
- On the other hand, adjunction occurs at internal nodes, and involves a different kind of tree fragment, called *auxiliary trees*.
- An auxiliary tree has a special *foot node*, marked with a $*$, that is the same nonterminal as its root node.

Adjunction in Action



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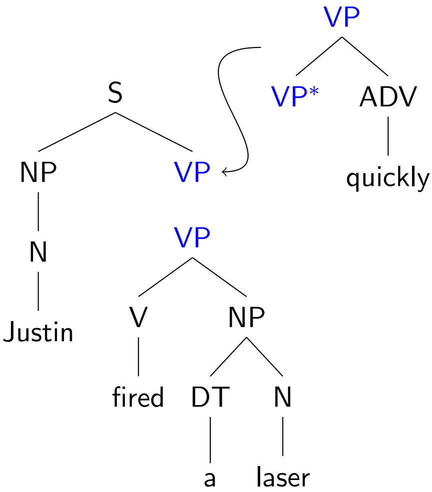

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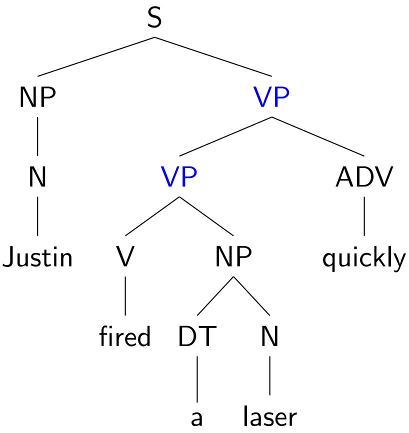

Formal Definition

- Formally, a TAG is a 5-tuple $G = (T, N, S, E, A)$
  - T: terminals
  - N: nonterminals
  - S: distinguished start symbol
  - E: elementary trees
  - A: auxiliary trees
- Some formulations of TAG allow substitution as an operation.
  - Others only allow adjunction.
  - These turn out to be equivalent.
  - If there is no substitution, the elementary trees E will only have terminals on their frontiers.

Formal Properties

- Not formally equivalent to CFG!
- TAG can generate languages like $a^n b^n c^n$, $a, b, c \in T$ and ww, $w \in T^*$, which are not context free.
    - *ww* corresponds to *cross-serial dependencies*, as in the sentence "Jason gave a cookie and some chocolate to Sonja and Jonas, respectively."
- It turns out that TAG is also strictly less powerful than context sensitive languages.
- TAG generates what are called *mildly context sensitive languages*.

Parsing with TAGs

- TAGs can be parsed in $O(n^6)$ time, using a dynamic programming algorithm similar to CKY.
- As with CKY, we restrict the grammar to be binary branching.
- No nonterminal in any tree can have more than two children.
- We also assume (for the sake of simplicity) that the only operation is adjunction.
- Lastly, we follow the restriction that adjunction can only happen once at each node.

Some TAG-Parsing Intuitions (Part 1)

- We will have a CKY-like chart where we keep track of what constituents we've built so far.
- What should these constituents be?
- They can't be entire tree fragments: we can't just parse a whole tree fragment at once, because what if something got adjoined inside it?
- This leads us to the first intuition: *we should split up the tree fragments into their component CFG rules*.
- Using these component rules, we can then parse in a bottom-up fashion.

Some TAG-Parsing Intuitions (Part 2)

- Now that we've decomposed our rules in manner, what's to stop us from applying the CKY algorithm in the usual fashion?
- Let's see what happens if we try it.
- We parse for a bit, start building the bottom of one of our elementary trees α, and then we get to a nonterminal where there could be adjunction of the elementary tree β_1.
- So we start building the auxiliary tree there. But we need to keep track of what elementary tree we were building, so we can finish it later.
- No problem, we say. We'll just pass that information up the tree.

Some TAG-Parsing Intuitions (Part 3)

- But what happens when we're in the middle of parsing auxiliary tree β_1, and we get to a nonterminal that could be the foot of auxiliary tree β_2?
- Well, then we start parsing β_2, but again we need to keep track of the fact that we were in the middle of parsing β_1, while in the middle of parsing α.
- In order to keep track of all this, we'd need a stack.
- Intuitively, this is why we can't just use CKY to parse a TAG.

Parsing Auxiliary Trees First

- How do we get around the problems described above?
- By parsing the auxiliary trees first!
- We start by parsing the auxiliary trees that were adjoined most recently.
- Once these are complete, we can adjoin them in directly while chart parsing, without having to maintain a stack.

Chart Cells

- We will parse auxiliary trees in isolation, before they are adjoined to anything.
- In our chart cells, we need to keep track of the "hole" in the middle where the foot node is.
- Chart cells take the following form: $[N^\gamma, i, j|p, q|adj]$
  - N is the nonterminal.
  - γ records which tree fragment we are parsing.
  - i and j are the start and end positions of the chart cell.
  - p and q are the start and end positions of the hole, $0 \leq i \leq p \leq q \leq j$. (If we are parsing something without a hole, we leave p, q blank.)
  - adj is a boolean to enforce the restriction that we can only adjoin once per node.
- $[N^\gamma, i, j|p, q|adj]$ is true if:
  - $N^\gamma \Rightarrow^* a_{i+1} \dots a_p \, F^\gamma \, a_{q+1} \dots a_j$ (γ must be an auxiliary tree)
  - $N^\gamma \Rightarrow^* a_{i+1} \dots a_j$ (γ could be either kind of tree)

Initializing the Chart

- Terminal rule: $[N^\gamma, i-1, i|-,-|\mathit{false}]$ if $N^\gamma \to a$
- Epsilon rule: $[N^\gamma, i, i|-,-|\mathit{false}]$ if $N^\gamma \to \epsilon$
- Foot rule: $[F^\gamma, i, j|i, j|\mathit{false}]$ if F is the foot node of γ

Rules for Building the Insides of Tree Fragments

- In an auxiliary tree, the path from the root node to the foot node is called the "spine" of the tree fragment.
- Parsing a rule $N^\gamma \to X^\gamma Y^\gamma$ that appears inside a tree fragment.
- Three possibilities: X dominates the foot node (and thus contains a hole), Y dominates the foot node (and thus contains a hole), or neither contains a hole.
- $[N^\gamma, i, j|p, q|false]$ if $N^\gamma \to X^\gamma Y^\gamma$ and one of the following holds:
  - X **has the hole**: $[X^\gamma, i, k|p, q|adj]$ is true, $[Y^\gamma, k, j|-, -|adj]$ is true, and X is on the spine of γ
  - Y **has the hole**: $[X^\gamma, i, k|-, -|adj]$ is true, $[Y^\gamma, k, j|p, q|adj]$ is true, and Y is on the spine of γ
  - **neither has the hole**: $[X^\gamma, i, k|-, -|adj]$ is true, $[Y^\gamma, k, j|-, -|adj]$ is true, and neither is on the spine of γ

Unary Rules and Adjunction

- Unary rule: $[N^\gamma, i, j|p, q|\mathit{false}]$ if $[X^\gamma, i, j|p, q|\mathit{false}]$ and $N^\gamma \to X^\gamma$.
- Adjunction rule: $[N^\gamma, i, j|p, q|\mathit{true}]$ if $[R^\beta, i, j|i', j'|\mathit{adj}]$ and $[N^\gamma, i', j'|p, q|\mathit{false}]$ and $R^\beta = N$
- Chart is four-dimensional, and to parse with the adjunction rule, must examine all i', j' in range.
- Computational complexity is $O(n^6)$