Computational Linguistics

Lecture 4 – Parsing

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EXAM DATE

- Thursday, 2016-07-28, 8:00 - 10:00

Grammars

- Grammars generate sentences (“words”)

S → NP VP	DET → *the*
NP → DET N	DET → *a*
NP → NP PP	N → *student*
PP → P NP	N → *book*
VP → V	N → *library*
VP → V NP	V → *works*
VP → VP PP	V → *reads*
	P → *in*

The student works

The student works in the library

The student reads a book

The student reads a book in the library

[...]

Context-free Grammars

- Context-free grammar $G = \langle N, T, R, S \rangle$
  - Nonterminal symbols N
  - Terminal symbols T
  - Start symbol $S \in N$
  - Finite set of production rules: $R \subseteq N \times (N \cup T)^*$

Derivations

- Let $x, y, u, v, w, z \in (N \cup T)^*$
- We write $x \Rightarrow_G y$ iff
  - $x = uvw$
  - $y = uzw$
  - $v \rightarrow z \in R$
- **Derivation of w_n from w_0:**
  - $w_0 \Rightarrow_G w_1 \Rightarrow_G \cdots \Rightarrow_G w_n$
- **Language generated by $G = \langle N, T, R, S \rangle$**
  - $L(G) = \{ w \mid S \Rightarrow_G^* w \}$
  - $\Rightarrow_G^*$ is the reflexive, transitive closure of $\Rightarrow_G$

An Example

$$
\begin{aligned}
S &\Rightarrow_G \text{NP VP} \\
&\Rightarrow_G \text{DET N VP} \\
&\Rightarrow_G \text{the N VP} \\
&\Rightarrow_G \text{the student VP} \\
&\Rightarrow_G \text{the student V} \\
&\Rightarrow_G \text{the student works}
\end{aligned}
$$

S → NP VP	DET → *the*
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“the student works” $\in$ L(G)

Another Example

$$
\begin{aligned}
S &\Rightarrow_G \text{NP VP} \\
&\Rightarrow_G \text{NP V} \\
&\Rightarrow_G \text{NP works} \\
&\Rightarrow_G \text{DET N works} \\
&\Rightarrow_G \text{the N works} \\
&\Rightarrow_G \text{the student works}
\end{aligned}
$$

S → NP VP	DET → *the*
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“the student works” ∈ L(G)

Parse trees

- Context-free grammar $G = \langle N, T, R, S \rangle$
- **Parse trees** are trees where
  - inner nodes are labeled with symbols $\in N$
  - leaf nodes are labeled with symbols $\in T \cup \{\varepsilon\}$
  - if v is a node with label A and its child nodes $v_1, \ldots, v_n$ are labeled with $A_1, \ldots, A_n$, then $A \rightarrow A_1 \ldots A_1$ is a rule of G
  - if v is a leaf node with label ε, then v is the only child of its parent node

Leftmost derivation

- **Leftmost derivation:** replace the leftmost nonterminal symbol in each step of the derivation
- $x \Rightarrow_L y$ iff there are $A \in N$, $a, b \in (N \cup T)^*$, $w \in T^*$ such that
  - $x = wAb$
  - $y = wab$
  - $A \rightarrow a \in R$
- **Rightmost derivation:** analogously

Theorem (Lewis & Papadimitriou)

- Let $G = \langle N, T, R, S \rangle$ be a context-free grammar
- The following statements are equivalent
  - $A \Rightarrow^*_G w = w_1 \ldots w_n$
  - There is a parse tree with root A and yield w
  - There is a leftmost derivation $A \Rightarrow_L^* w$
  - There is a rightmost derivation $A \Rightarrow_R^* w$

Ambiguity

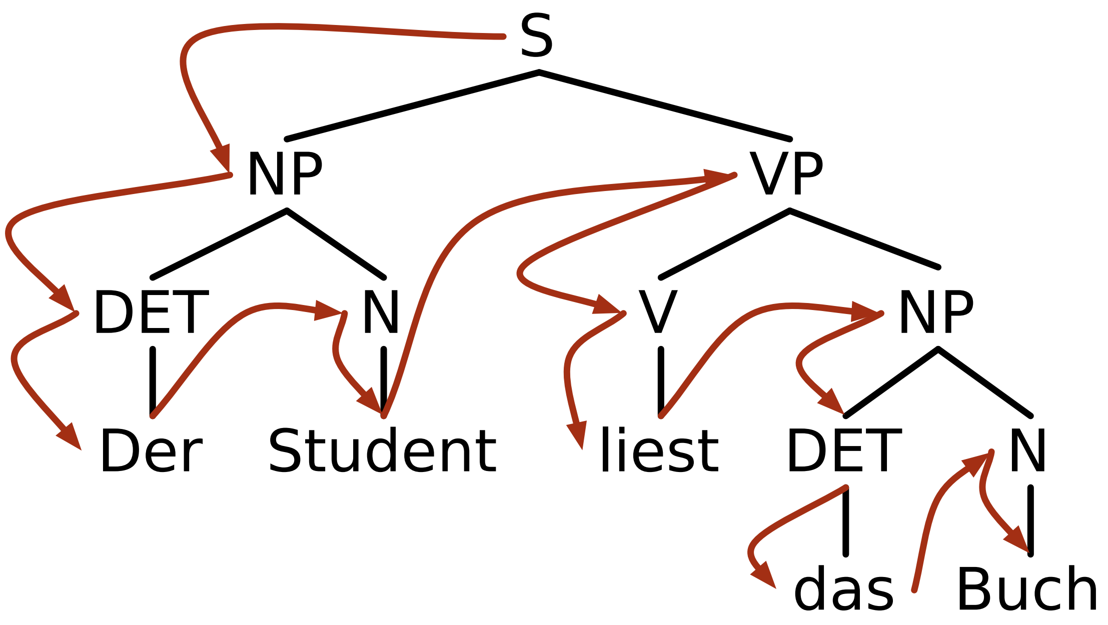
- $w = w_1 \ldots w_n$ may have two or more parse trees.
- The grammar is said to be ambiguous in this case.
- Otherwise, we say that the grammar is unambiguous.

Recognizer & Parser

- **Recognizer**
  - Is $w = w_1 \dots w_n \in L(G)$?
- **Parser**
  - What are the parse trees of $w = w_1 \dots w_n$?

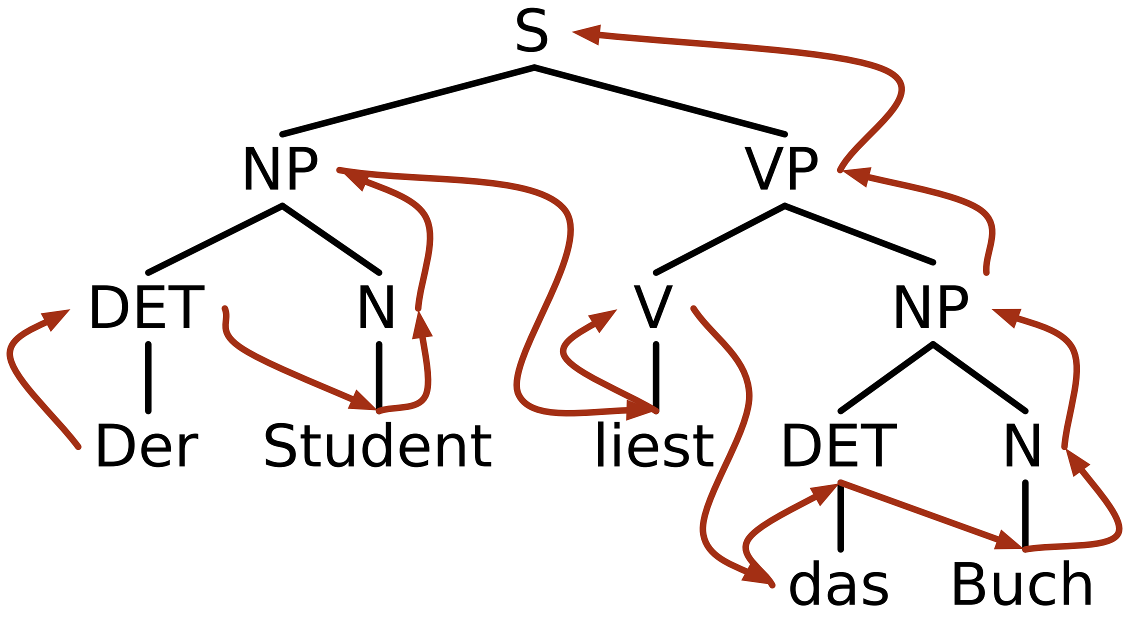
Basic Parsing Strategies

- **A top-down parser / recognizer …**
  - starts with the start symbol (= root node)
  - applies production rules "from left to right"
  - and tries to match the input sequence



Basic Parsing Strategies

- **A bottom-up parser / recognizer …**
  - starts with the input sequence (= leaf nodes)
  - scans the input for subsequences that match the right-hand side of some rule and applies it “from right to left”



Shift-Reduce Parsing (Bottom-up)

- **Initial configuration** for input sequence $w_1 \dots w_n$:
  - $\langle [], [w_1, \dots, w_n] \rangle$

stack

the input that still needs to be processed

- **Accepting configuration**
  - $\langle [S], [] \rangle$
- In each step we can perform …
  - shift – move a symbol to the stack
  - reduce – apply a matching rule to the topmost elements on the stack

Shift

- The shift operation moves one symbol to the stack
- **Configuration:**
  - $\langle [A_1, \ldots, A_k], [w_i, w_{i+1}, \ldots, w_n] \rangle$
- **New configuration:**
  - $\langle [A_1, \ldots, A_k, w_i], [w_{i+1}, \ldots, w_n] \rangle$

Reduce

- Reduce replaces the topmost symbols on the stack by the lefthand side of a matching rule
- **Configuration:**
  - $\langle [A_1, \ldots, A_{j-1}, A_j, \ldots, A_k], [w_i, \ldots, w_n] \rangle$
- **Rule:**
  - $B \rightarrow A_j, \ldots, A_k$
- **New Configuration:**
  - $\langle [A_1, \ldots, A_{j-1}, B], [w_i, \ldots, w_n] \rangle$

An Example

S → NP VP	DET → *the*
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NP → NP PP	N → *student*
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VP → V NP	V → *works*
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⟨[], [*the student works*]⟩

$\Rightarrow_{\text{shift}}$ ⟨[*the*], [*student works*]⟩

$\Rightarrow_{\text{red}}$ ⟨[DET], [*student works*]⟩

$\Rightarrow_{\text{shift}}$ ⟨[DET *student*], [*works*]⟩

$\Rightarrow_{\text{red}}$ ⟨[DET N], [*works*]⟩

$\Rightarrow_{\text{red}}$ ⟨[NP], [*works*]⟩

$\Rightarrow_{\text{shift}}$ ⟨[NP *works*], []⟩

$\Rightarrow_{\text{red}}$ ⟨[NP V], []⟩

$\Rightarrow_{\text{red}}$ ⟨[NP VP], []⟩

$\Rightarrow_{\text{red}}$ ⟨[S], []⟩

Shift or Reduce?

- How can we decide whether we should perform a shift or a reduce operation?
  - For certain (unamabiguous) grammars, it is possible to decide this automatically
  - In general $\Rightarrow$ Search

Python

```
def recognize(sent):
    agenda = [([], sent)]
    while agenda:
        (stack, sent) = agenda.pop()
        if sent == [] and stack == ['S']:
            return True
        if sntnc != []:
            agenda.append(shift(stack, sent))
        for (lhs, rhs) in rules:
            if len(stack) >= len(rhs):
                if matches(stack, rhs):
                    agenda.append(reduce(stack, sent, lhs, rhs))
    return False
```

Python

```
rules = [( 'S', ['NP', 'VP']), ('NP', ['DET', 'N']), ...]

def shift(stack, sent):
    return (stack + [sent[0]], sent[1:])

def reduce(stack, sent, lhs, rhs):
    return (stack[:-len(rhs)] + [lhs], sent)

def matches(stack, rhs):
    for (s, r) in zip(stack[-len(rhs):], rhs):
        if s != r:
            return False
    return True
```

Example – *The student works*

	⟨stack, sent⟩	agenda
1	–	⟨[] [the student works]⟩
2	⟨[] [the student works]⟩	⟨[the] [student works]⟩
3	⟨[the] [student works]⟩	⟨[DET] [student works]⟩ ⟨[the student] [works]⟩
4	⟨[DET] [student works]⟩	⟨[DET student] [works]⟩ ⟨[the student] [works]⟩
5	⟨[DET student] [works]⟩	⟨[DET N] [works]⟩ ⟨[DET student works] []⟩ ⟨[the student] [works]⟩
6	⟨[DET N] [works]⟩	⟨[NP] [works]⟩ ⟨[DET N works] []⟩ ⟨[DET student works] []⟩ …
7	⟨[NP] [works]⟩	⟨[NP works] []⟩ ⟨[DET N works] []⟩ ⟨[DET student works] []⟩ …
8	⟨[NP works] []⟩	⟨[NP V] []⟩ ⟨[DET N works] []⟩ ⟨[DET student works] []⟩ …
9	⟨[NP V] []⟩	⟨[NP VP] []⟩ ⟨[DET N works] []⟩ ⟨[DET student works] []⟩ …
10	⟨[NP VP] []⟩	⟨[S] []⟩ ⟨[DET N works] []⟩ ⟨[DET student works] []⟩ …
11	⟨[S] []⟩	⟨[DET N works] []⟩ ⟨[DET student works] []⟩ …

Example – *The student reads …*

- [⇒ Handout]

Problematic Rules

- Bottom-up parsers cannot deal with certain types of grammars (the parser may not terminate)
- Rules of the form $A \rightarrow \varepsilon$
  - $\langle [A_1, \ldots, A_k], [w_i, \ldots, w_n] \rangle$
  - $\langle [A_1, \ldots, A_k, A], [w_i, \ldots, w_n] \rangle$ (reduce)
  - $\langle [A_1, \ldots, A_k, A, A], [w_i, \ldots, w_n] \rangle$ (reduce)
  - $\langle [A_1, \ldots, A_k, A, A, A], [w_i, \ldots, w_n] \rangle$ (reduce)
  - [...]

Problematic Rules

- Bottom-up parsers cannot deal with certain types of grammars (the parser may not terminate)
- Cyclic rules: $A \rightarrow B$, $B \rightarrow A$
  - $\langle [A_1, \ldots, A_k, A], [w_i, \ldots, w_n] \rangle$
  - $\langle [A_1, \ldots, A_k, B], [w_i, \ldots, w_n] \rangle$ (reduce)
  - $\langle [A_1, \ldots, A_k, A], [w_i, \ldots, w_n] \rangle$ (reduce)
  - $\langle [A_1, \ldots, A_k, B], [w_i, \ldots, w_n] \rangle$ (reduce)
  - [...]

Another Problem …

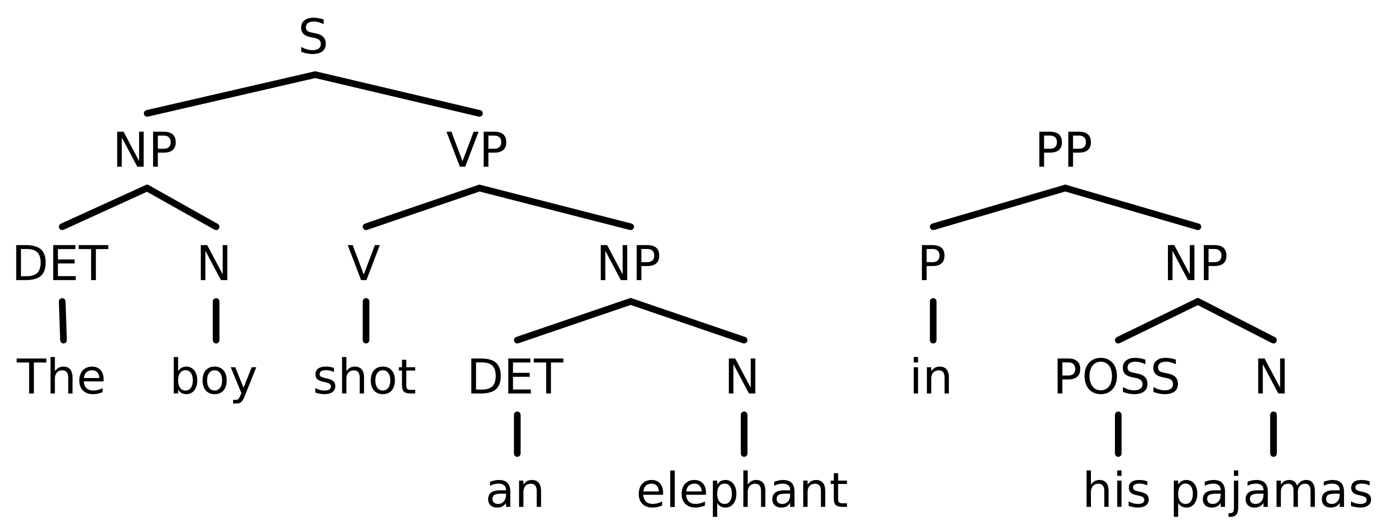
The boy shot an elephant in ...

$\langle$[], [*the boy shot an elephant in his pajamas*]$\rangle$

$\Rightarrow^*$ $\langle$[NP VP], [*in his pajamas*]$\rangle$

$\Rightarrow$ $\langle$[S], [*in his pajamas*]$\rangle$

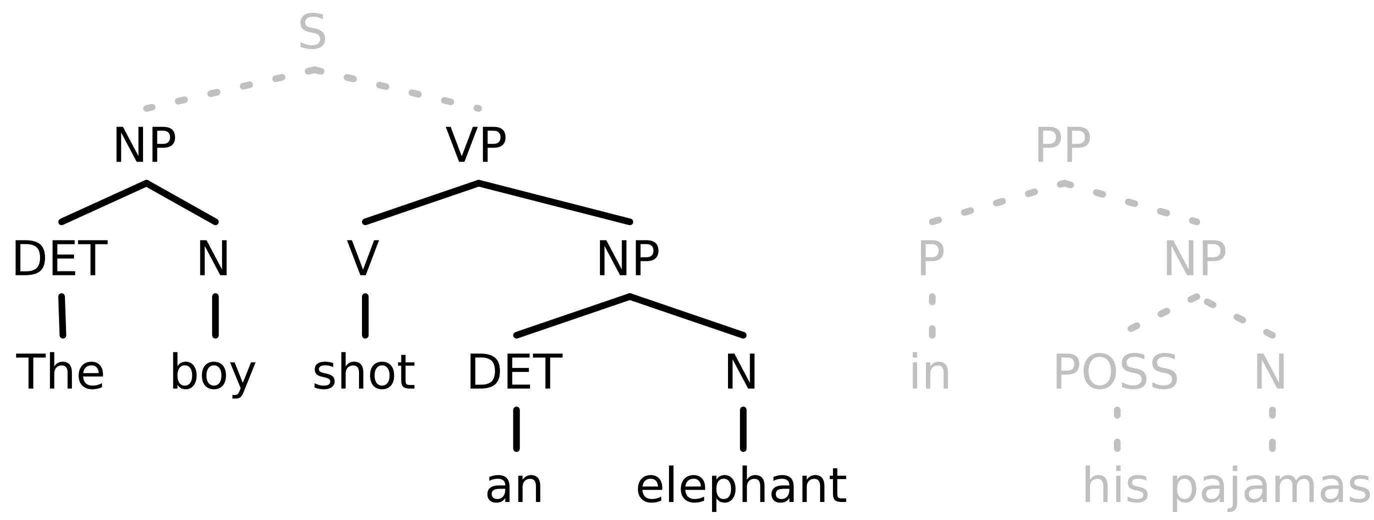
$\Rightarrow^*$ $\langle$[S PP], []$\rangle$ $\Rightarrow$ Failure, Backtracking



The boy shot an elephant in ...

$\langle [\,], [\textit{the boy shot an elephant in his pajamas}] \rangle$

$\Rightarrow^* \langle [\text{NP VP}], [\textit{in his pajamas}] \rangle$

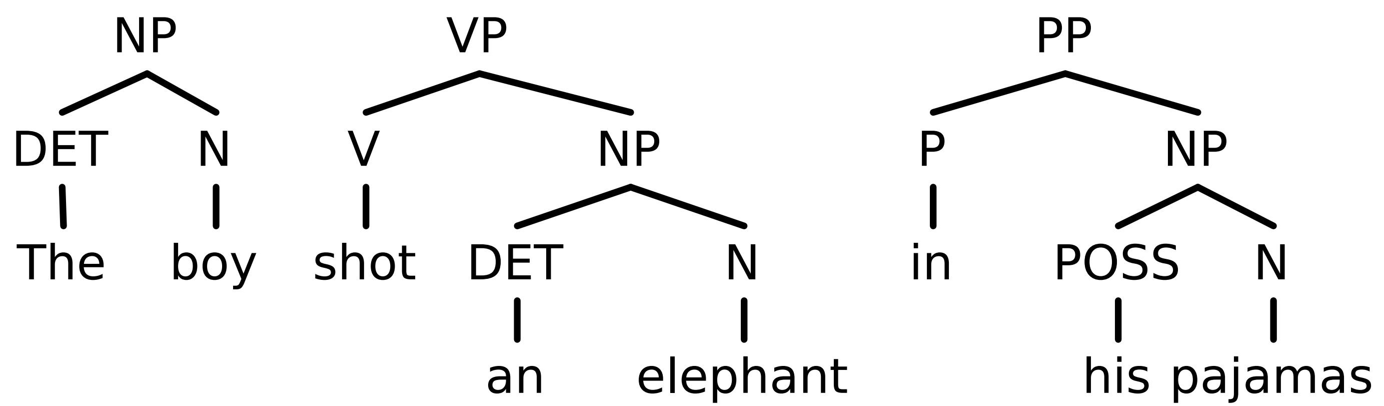


The boy shot an elephant in ...

$\langle[], [\textit{the boy shot an elephant in his pajamas}]\rangle$

$\Rightarrow^* \langle[\text{NP VP}], [\textit{in his pajamas}]\rangle$

$\Rightarrow^* \langle[\text{NP VP PP}], []\rangle$



The boy shot an elephant in ...

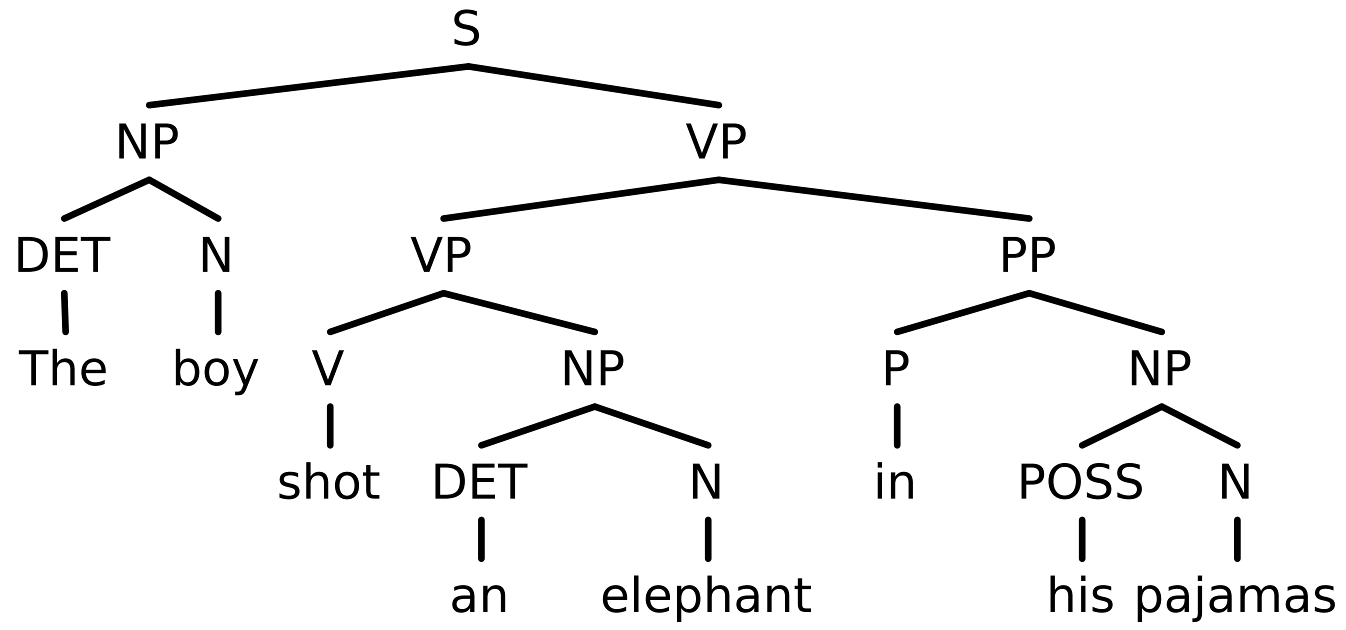
$\langle[\,], [\textit{the boy shot an elephant in his pajamas}]\rangle$

$\Rightarrow^* \langle[\text{NP VP}], [\textit{in his pajamas}]\rangle$

$\Rightarrow^* \langle[\text{NP VP PP}], [\,]\rangle$

$\Rightarrow^* \langle[\text{NP VP}], [\,]\rangle$

$\Rightarrow^* \langle[\text{S}], [\,]\rangle$



Dynamic Programming

- **Context-free grammar:** whether or not a rule can be applied does not depend on the context.

NP NP NP

The boy shot an elephant in his pajamas

NP

- **Chart-Parsing:** store intermediate results for already analysed constituents in a “chart”
- **Charts** are compact representations of all possible analyses (“parse forest”)

Chart-Parsing

- **Chart-Parsing:** store intermediate results for already analysed constituents in a “chart”
- **Charts** are compact representations of all possible analyses (“parse forest”)
- Charts can contain
  - complete constituents
  - hypotheses for possible constituents
- Many different chart-parsers:
  - Cocke-Younger-Kasami, Earley, …

Charts as Matrices

S → NP VP	DET → *the*
NP → DET N	DET → *an*
NP → POSS N	N → *boy*
NP → NP PP	N → *elephant*
PP → P NP	N → *pajamas*
VP → V NP	V → *shot*
VP → VP PP	P → *in*
	POSS → *his*

- **A ∈ T[i, j]** iff $A \Rightarrow^* w_{i+1} \ldots w_j$

1	DET							
2	NP	N						
3	∅	∅	V					
4	∅	∅	∅	DET				
5	S	∅	VP	NP	N			
6	∅	∅	∅	∅	∅	P		
7	∅	∅	∅	∅	∅	∅	POSS	
8	S	∅	VP	NP	∅	PP	NP	N
	0	1	2	3	4	5	6	7
	The	boy	*shot*	*an*	*elephant*	*in*	*his*	*pajamas*

0 1 2 3 4 5 6 7 8

Cocke-Younger-Kasami

- The algorithm by Cocke, Younger, Kasami (CYK) is a simple chart-based bottom-up parser
- **Restriction:** the algorithm can be applied to grammars in Chomsky normal form only:
  - $A \rightarrow w$ (w terminal symbol)
  - $A \rightarrow B\ C$ (B and C nonterminal symbols)
  - $S \rightarrow \varepsilon$ (S start symbol, only if $\varepsilon \in L$)
- **Note:** we will assume here that $\varepsilon \notin L$, thus the grammar will not contain rules $S \rightarrow \varepsilon$

CYK (Recognizer, Pseudo-code)

```
function CYK(G, w1 ... wn):
    for i in 1 ... n do
        T[i-1, i] = { A | A → wi ∈ R }
        for j in i - 2 ... 0 do
            T[j, i] = ∅
            for k in j + 1 ... i - 1 do
                T[j, i] = T[j, i] ∪
                    { A | A → B C, B ∈ T[j,k], C ∈ T[k, i] }
            done
        done
    done
    if S ∈ T[0, n] then return True else return False
```

An Example

- [⇒ blackboard]

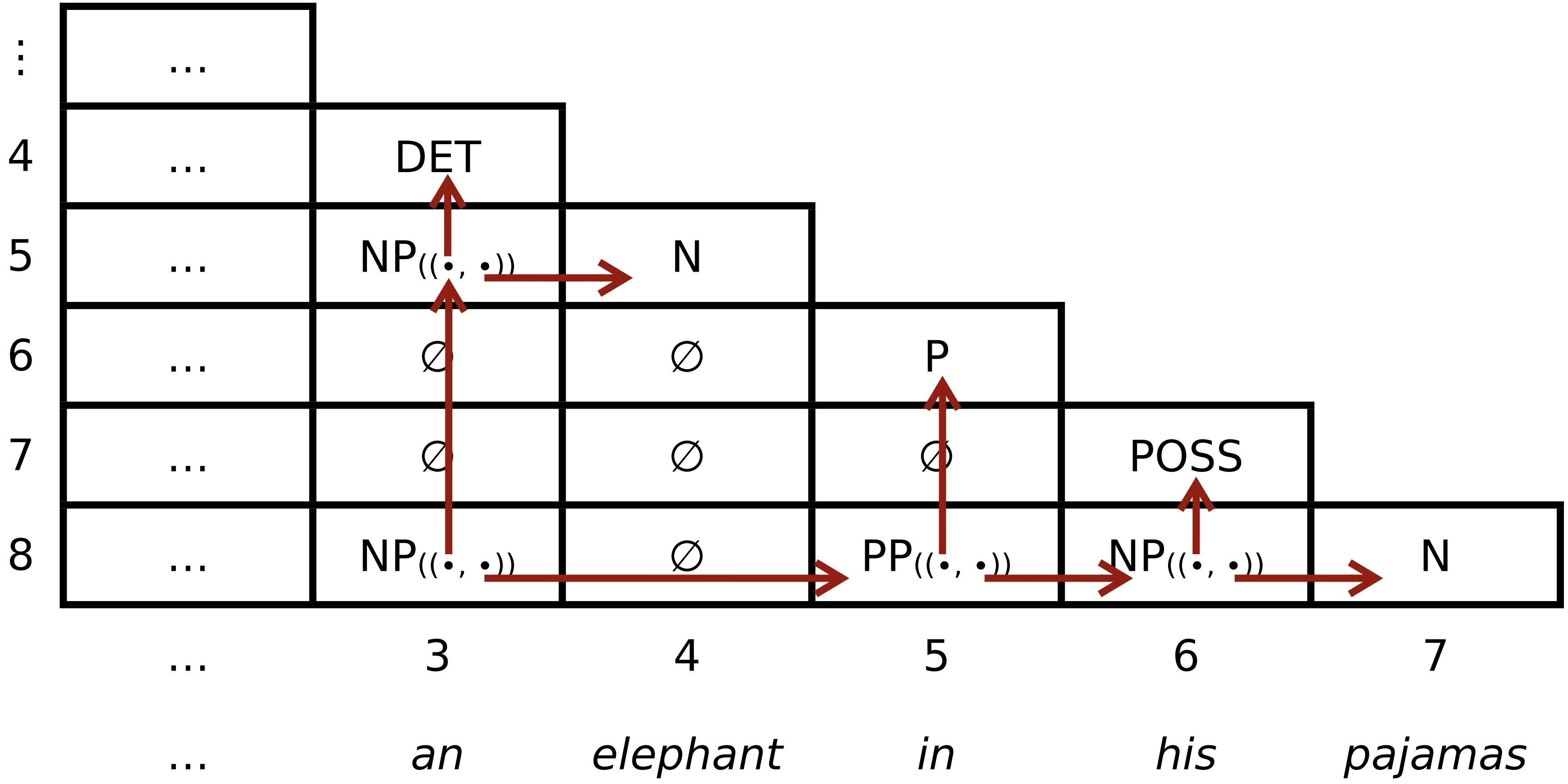
Properties

- **Correct:**
  If $S \in T[0, n]$, then $S \Rightarrow^* w_1 \ldots w_n$
- **Complete:**
  If $S \Rightarrow^* w_1 \ldots w_n$, then $S \in T[0, n]$
- **Runtime:**
  Polynomial in the input length: $O(n^3)$

Recognizer → Parser

- The recognizer can be extended to a parser if we store, for each category A, a list of pointers to other entries in the chart that have been used to derive A

CYK (Parser)



Binarization

left binarization(G):

while G contains rules $A \to A_1\ A_2\ A_3\ \ldots\ A_k$, $k \geq 3$

delete the rule from G

add rule $\langle A_1, \ldots, A_{k-1} \rangle \to A_1\ \ldots\ A_{k-1}$

add rule $A \to \langle A_1, \ldots, A_{k-1} \rangle\ A_k$

right binarization(G):

while G contains rules $A \to A_1\ A_2\ A_3\ \ldots\ A_k$, $k \geq 3$

delete the rule from G

add rule $\langle A_2, \ldots, A_k \rangle \to A_2\ \ldots\ A_k$

add rule $A \to A_1\ \langle A_2, \ldots, A_k \rangle$

Implementation variants

- $T[i,j] = T[i,j] \cup \{ A \mid A \rightarrow B\ C, B \in T[i,k], C \in T[k,j] \}$
  - $\Rightarrow$ can be implemented in different ways
- **Method 1**
  - Iterate over all rules $A \rightarrow B\ C$
  - Check if $B \in T[i,k]$ and $C \in T[k,j]$
- **Method 2**
  - Iterate over all $B \in T[i,k]$
  - Iterate over all rules $A \rightarrow B\ C$
  - Check if $C \in T[k, j]$

Implementierungsvarianten

- $T[i,j] = T[i,j] \cup \{ A \mid A \rightarrow B\ C, B \in T[i,k], C \in T[k,j] \}$
  - $\Rightarrow$ can be implemented in different ways
- **Method 3**
  - Iterate over all $C \in T[k,j]$
  - Iterate over all rules $A \rightarrow B\ C$
  - Check if $A \in T[i,k]$
- **Method 4**
  - Iterate over all $B \in T[i,k]$ and $C \in T[k,j]$
  - Check if a rule $A \rightarrow B\ C$ exists

Song &al. (EMNLP 2008)

- Experiments mit CYK & Wall Street Journal
- Runtime depends on …
  - right binarization ⇒ method 3 is most efficient
  - left binarization ⇒ method 2 is most efficient