# Parsing

CSCI 3130 Formal Languages and Automata Theory

Siu On CHAN

Fall 2021

Chinese University of Hong Kong

# Context-free versus regular

Write a CFG for the language $(0+1)^*111$

$$S \to U111$$
$$U \to 0U \mid 1U \mid \varepsilon$$

Can you do so for every regular language?

# Context-free versus regular

Write a CFG for the language $(0+1)^*111$

$$S \to U111$$
$$U \to 0U \mid 1U \mid \varepsilon$$

Can you do so for every regular language?

**Every regular language is context-free**

regular expression $\Longleftrightarrow$ NFA $\Longleftrightarrow$ DFA

# From regular to context-free

| regular expression | $\Rightarrow$ CFG |
| --- | --- |
| $\varnothing$ | grammar with no rules |
| $\varepsilon$ | $S \to \varepsilon$ |
| x (alphabet symbol) | $S \to \mathrm{x}$ |
| $E_1 + E_2$ | $S \to S_1 \mid S_2$ |
| $E_1 E_2$ | $S \to S_1 S_2$ |
| $E_1^*$ | $S \to S S_1 \mid \varepsilon$ |

$S$ becomes the new start variable

# Context-free versus regular

Is every context-free language regular?

# Context-free versus regular

Is every context-free language regular?

$S \to 0S1 \mid \varepsilon \qquad L = \{0^n 1^n \mid n \geqslant 0\}$

Is context-free but not regular

# Ambiguity

# Ambiguity

$$E \to E\text{+}E \mid E\text{*}E \mid (E) \mid N$$
$$N \to 1 \mid 2$$

1+2*2


$= 6$ $= 5$

A CFG is ambiguous if some string has more than one parse tree

# Example

Is $S \to SS \mid \mathrm{x}$ ambiguous?

# Example

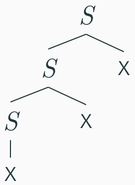
Is $S \to SS \mid \text{x}$ ambiguous?

Yes, because

Two parse trees for xxx

# Disambiguation

$$S \to SS \mid \mathsf{x} \quad \Longrightarrow \quad S \to S\mathsf{x} \mid \mathsf{x}$$

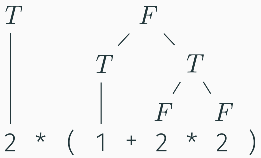



Sometimes we can rewrite the grammar to remove ambiguity

$$E \rightarrow E + E \mid E * E \mid (E) \mid N$$
$$N \rightarrow 1 \mid 2$$

+ and * have the same precedence!

Decompose expression into terms and factors



# Disambiguation

$$E \to E + E \mid E * E \mid (E) \mid N$$
$$N \to 1 \mid 2$$

An expression is a sum of one or more terms

$$E \to T \mid E + T$$

Each term is a product of one or more factors

$$T \to F \mid T * F$$

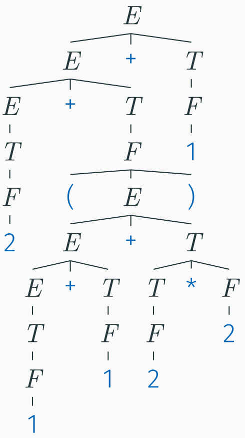
Each factor is a parenthesized expression or a number

$$F \to (E) \mid 1 \mid 2$$

# Parsing example

$$E \rightarrow T \mid E\texttt{+}T$$
$$T \rightarrow F \mid T\texttt{*}F$$
$$F \rightarrow (E) \mid 1 \mid 2$$

Parse tree for
2+(1+1+2*2)+1



# Disambiguation

Disambiguation is not always possible because

1. There exists inherently ambiguous languages
   i.e. ambiguous no matter how you rewrite the grammar
2. There is no general procedure for disambiguation

# Disambiguation

Disambiguation is not always possible because

1. There exists inherently ambiguous languages
   i.e. ambiguous no matter how you rewrite the grammar
2. There is no general procedure for disambiguation

In programming languages, ambiguity comes from the precedence rules, and we can resolve like in the example

In English, ambiguity is sometimes a problem:

I look at the dog with one eye

# Parsing

# Parsing

$S \to 0S1 \mid 1S0S \mid T$

$T \to S \mid \varepsilon$

input: 0011

Is $0011 \in L$?

If so, how to build a parse tree with a program?

# Parsing

$S \to 0S1 \mid 1S0S \mid T$ input: 0011

$T \to S \mid \varepsilon$

Try all derivations?

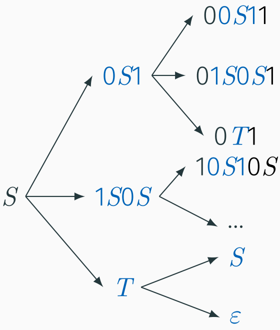
$$\begin{tikzcd}[column sep=small]
 & 0S1 \\
S \arrow[ur] \arrow[r] \arrow[dr] & 1S0S \\
 & T
\end{tikzcd}$$

# Parsing

$S \to 0S1 \mid 1S0S \mid T$ input: 0011

$T \to S \mid \varepsilon$

Try all derivations?

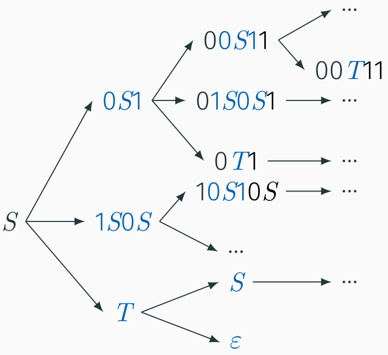


# Parsing

$S \to 0S1 \mid 1S0S \mid T$ input: 0011

$T \to S \mid \varepsilon$

Try all derivations?

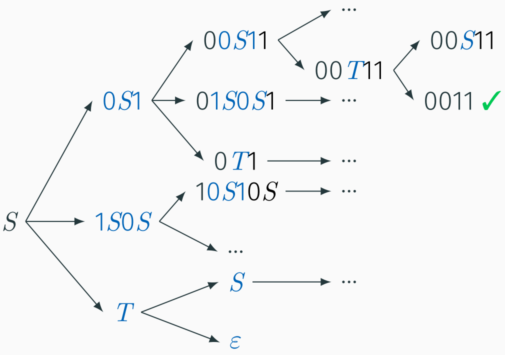


# Parsing

$S \to 0S1 \mid 1S0S \mid T$ input: 0011

$T \to S \mid \varepsilon$

Try all derivations?




This is (part of) the tree of all derivations, not the parse tree

# Problems

1. Trying all derivations may take too long
2. If input is not in the language, parsing will never stop

Let's tackle the 2nd problem

# When to stop

$S \to 0S1 \mid 1S0S \mid T$

$T \to S \mid \varepsilon$

Idea: Stop when
|derived string| > |input|

# When to stop

$$S \to 0S1 \mid 1S0S \mid T$$
$$T \to S \mid \varepsilon$$

Idea: Stop when
|derived string| > |input|

Problems:

$$S \Rightarrow 0S1 \Rightarrow 0T1 \Rightarrow 01$$

Derived string may shrink
because of "$\varepsilon$-productions"

# When to stop

$$S \to 0S1 \mid 1S0S \mid T$$
$$T \to S \mid \varepsilon$$

Idea: Stop when
|derived string| > |input|

Problems:

$$S \Rightarrow 0S1 \Rightarrow 0T1 \Rightarrow 01$$

Derived string may shrink
because of "$\varepsilon$-productions"

$$S \Rightarrow T \Rightarrow S \Rightarrow T \Rightarrow \dots$$

Derviation may loop
because of "unit
productions"

Remove $\varepsilon$ and unit productions

Note: we will remove all $A \to \varepsilon$ rules, except for start variable $A$

# Removing $\varepsilon$-productions

Goal: remove all $A \to \varepsilon$ rules for every non-start variable $A$

① If start variable $S$ appears on RHS of a rule

Add a new start variable $T$
Add the rule $T \to S$

② For every rule $A \to \varepsilon$ where $A$ isn't the (new) start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

$$
\begin{aligned}
S &\to ACD \\
A &\to \mathsf{a} \\
B &\to \varepsilon \\
C &\to ED \mid \varepsilon \\
D &\to BC \mid \mathsf{b} \\
E &\to \mathsf{b}
\end{aligned}
$$

# Removing $\varepsilon$-productions

Goal: remove all $A \to \varepsilon$ rules for every non-start variable $A$

① If start variable $S$ appears on RHS of a rule

Add a new start variable $T$
Add the rule $T \to S$

② For every rule $A \to \varepsilon$ where $A$ isn't the (new) start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

$$
\begin{aligned}
S &\to ACD \\
A &\to \text{a} \\
\cancel{B} &\cancel{\to \varepsilon} \\
C &\to ED \mid \varepsilon \\
D &\to BC \mid \text{b} \\
E &\to \text{b}
\end{aligned}
$$

$D \to C$

Removing $B \to \varepsilon$

# Removing $\varepsilon$-productions

Goal: remove all $A \to \varepsilon$ rules for every non-start variable $A$

① If start variable $S$ appears on RHS of a rule

Add a new start variable $T$
Add the rule $T \to S$

② For every rule $A \to \varepsilon$ where $A$ isn't the (new) start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

$$\begin{aligned} S &\to ACD \\ A &\to \text{a} \\ &\cancel{B \to \varepsilon} \\ C &\to ED \mid \cancel{\varepsilon} \\ D &\to BC \mid \text{b} \\ E &\to \text{b} \end{aligned}$$

$$\begin{aligned} D &\to C \mid B \\ S &\to AD \end{aligned}$$

Removing $C \to \varepsilon$

# Removing $\varepsilon$-productions

Goal: remove all $A \to \varepsilon$ rules for every non-start variable $A$

① If start variable $S$ appears on RHS of a rule

Add a new start variable $T$
Add the rule $T \to S$

② For every rule $A \to \varepsilon$ where $A$ isn't the (new) start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

$$
\begin{aligned}
S &\to ACD \\
A &\to \text{a} \\
&\cancel{B \to \varepsilon} \\
C &\to ED \mid \cancel{\varepsilon} \\
D &\to BC \mid \text{b} \\
E &\to \text{b}
\end{aligned}
$$

$$
\begin{aligned}
D &\to C \mid B \\
S &\to AD \\
D &\to \varepsilon
\end{aligned}
$$

Removing $C \to \varepsilon$

# Removing $\varepsilon$-productions

Goal: remove all $A \to \varepsilon$ rules for every non-start variable $A$

① If start variable $S$ appears on RHS of a rule

Add a new start variable $T$
Add the rule $T \to S$

② For every rule $A \to \varepsilon$ where $A$ isn't the (new) start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

$S \to ACD$
$A \to \text{a}$
$\cancel{B \to \varepsilon}$
$C \to ED \mid \cancel{\varepsilon}$
$D \to BC \mid \text{b}$
$E \to \text{b}$

$D \to C \mid B$
$S \to AD \mid AC$
$\cancel{D \to \varepsilon}$
$C \to E$

Removing $D \to \varepsilon$

# Removing $\varepsilon$-productions

Goal: remove all $A \to \varepsilon$ rules for every non-start variable $A$

① If start variable $S$ appears on RHS of a rule

Add a new start variable $T$
Add the rule $T \to S$

② For every rule $A \to \varepsilon$ where $A$ isn't the (new) start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

$$
\begin{aligned}
S &\to ACD \\
A &\to \text{a} \\
\cancel{B} &\cancel{\to \varepsilon} \\
C &\to ED \mid \cancel{\varepsilon} \\
D &\to BC \mid \text{b} \\
E &\to \text{b}
\end{aligned}
$$

$$
\begin{aligned}
D &\to C \mid B \\
S &\to AD \mid AC \\
\cancel{D} &\cancel{\to \varepsilon} \\
C &\to E \\
S &\to A
\end{aligned}
$$

Removing $D \to \varepsilon$

# Eliminating $\varepsilon$-productions

② For every $A \to \varepsilon$ rule where $A$ is not the start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

Do 2. every time $A$ appears

$B \to \alpha A \beta A \gamma$ yields

$B \to \alpha\beta A\gamma \quad B \to \alpha A \beta\gamma$

$B \to \alpha\beta\gamma$

# Eliminating $\varepsilon$-productions

② For every $A \to \varepsilon$ rule where $A$ is not the start variable

1. Remove the rule $A \to \varepsilon$
2. If you see $B \to \alpha A \beta$
   Add a new rule $B \to \alpha\beta$

Do 2. every time $A$ appears

$B \to \alpha A \beta A \gamma$ yields

$B \to \alpha\beta A\gamma \quad B \to \alpha A \beta\gamma$

$B \to \alpha\beta\gamma$

$B \to A$ becomes $B \to \varepsilon$

If $B \to \varepsilon$ was removed earlier, don't add it back

# Eliminating unit productions

A unit production is a production of the form

$$A \to B$$

Grammar:

$$S \to 0S1 \mid 1S0S \mid T$$
$$T \to S \mid R \mid \varepsilon$$
$$R \to 0SR$$

Unit production graph:

$$\begin{tikzcd} S \arrow[r, bend left] & T \arrow[l, bend left] \arrow[d] \\ & R \end{tikzcd}$$

# Removing unit productions

① If there is a cycle of unit productions

$$A \to B \to \cdots \to C \to A$$

delete it and replace everything with $A$
(any variable in the cycle)

$$S \to 0S1 \mid 1S0S \mid T$$
$$T \to S \mid R \mid \varepsilon$$
$$R \to 0SR$$

$$\begin{tikzcd}
S \arrow[r, bend left] & T \arrow[l, bend left] \arrow[dl] \\
 & R
\end{tikzcd}$$

# Removing unit productions

① If there is a cycle of unit productions

$$A \to B \to \cdots \to C \to A$$

delete it and replace everything with $A$
(any variable in the cycle)

$$S \to 0S1 \mid 1S0S \mid \cancel{T}$$
$$\cancel{T} \to \cancel{S} \mid R \mid \varepsilon$$
$$R \to 0SR$$

$$\begin{tikzcd} S \arrow[r, bend left] & T \arrow[l, bend left] \arrow[d] \\ & R \end{tikzcd}$$

$$S \to 0S1 \mid 1S0S$$
$$S \to R \mid \varepsilon$$
$$R \to 0SR$$

Replace $T$ by $S$

# Removal of unit productions

② replace any chain

$$A \to B \to \cdots \to C \to \alpha$$

by $\quad A \to \alpha, \quad B \to \alpha, \quad \cdots, \quad C \to \alpha$

$$\begin{aligned} S &\to 0S1 \mid 1S0S \\ &\quad \mid R \mid \varepsilon \\ R &\to 0SR \end{aligned}$$

$$\begin{array}{c} S \\ \downarrow \\ R \end{array}$$

# Removal of unit productions

② replace any chain

$$A \to B \to \cdots \to C \to \alpha$$

by $\quad A \to \alpha, \quad B \to \alpha, \quad \cdots, \quad C \to \alpha$

$$\begin{aligned} S &\to 0S1 \mid 1S0S \\ &\mid R \mid \varepsilon \\ R &\to 0SR \end{aligned} \qquad \begin{array}{c} S \\ \downarrow \\ R \end{array} \qquad \begin{aligned} S &\to 0S1 \mid 1S0S \\ &\mid 0SR \mid \varepsilon \\ R &\to 0SR \end{aligned}$$

Replace $\quad S \to R \to 0SR \quad$ by $\quad S \to 0SR, \quad R \to 0SR$

# Recap

Problems:

1. Trying all derivations may take too long
2. If input is not in the language, parsing will never stop ✓

Solution to problem 2:

1. Eliminate $\varepsilon$ productions
2. Eliminate unit productions

Try all possible derivations but stop parsing when

$$|\text{derived string}| > |\text{input}|$$

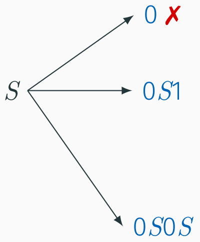
# Example

$$S \to 0S1 \mid 0S0S \mid T$$
$$T \to S \mid 0$$

$$\Longrightarrow$$

$$S \to 0S1 \mid 0S0S \mid 0$$

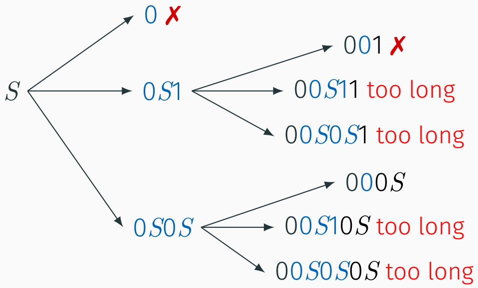
input: 0011



# Example

$$S \to 0S1 \mid 0S0S \mid T \qquad\qquad \Longrightarrow \qquad\qquad S \to 0S1 \mid 0S0S \mid 0$$
$$T \to S \mid 0$$

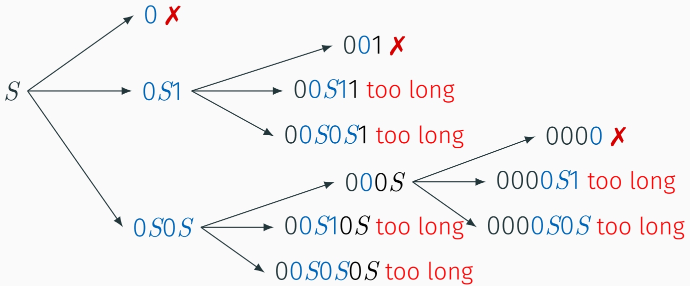
input: 0011



# Example

$$S \to 0S1 \mid 0S0S \mid T \qquad\qquad \Longrightarrow \qquad\qquad S \to 0S1 \mid 0S0S \mid 0$$
$$T \to S \mid 0$$

input: 0011




Conclusion: $0011 \notin L$

# Problems

1. Trying all derivations may take too long
2. If input is not in the language, parsing will never stop

# Preparations

A faster way to parse:

Cocke–Younger–Kasami algorithm

To use it we must perprocess the CFG as follows:

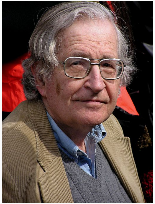
1. Eliminate $\varepsilon$ productions
2. Eliminate unit productions
3. Convert CFG to Chomsky Normal Form

# Chomsky Normal Form

A CFG is in Chomsky Normal Form if
every production is of one of the following

- $A \to BC$
  (exactly two non-start variables on the right)
- $A \to \mathrm{x}$
  (exactly one terminal on the right)
- $S \to \varepsilon$
  ($\varepsilon$-production only allowed for start variable)

where
$A$ : variable
$B$ and $C$ : non-start variables
x : terminal
$S$ : start variable


Noam Chomsky

# Convert to Chomsky Normal Form

$A \to B\mathsf{c}DE$

$\Longrightarrow$ replace terminals with new variables

$A \to BCDE$
$C \to \mathsf{c}$

$\Longrightarrow$ break up sequences with new variables

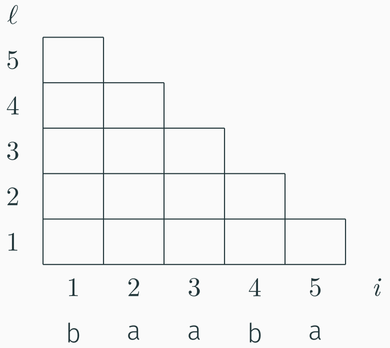
$A \to BX$
$X \to CY$
$Y \to DE$
$C \to \mathsf{c}$

# Cocke–Younger–Kasami algorithm

$$S \to AB \mid BC$$
$$A \to BA \mid \mathsf{a}$$
$$B \to CC \mid \mathsf{b}$$
$$C \to AB \mid \mathsf{a}$$

Input: $x =$ baaba

let $x[i, \ell] = x_i x_{i+1} \dots x_{i+\ell-1}$




For every substring $x[i, \ell]$, remember all variables $R$ that derive $x[i, \ell]$

Store in a table $T[i, \ell]$

# Cocke–Younger–Kasami algorithm

$$S \to AB \mid BC$$
$$A \to BA \mid \mathsf{a}$$
$$B \to CC \mid \mathsf{b}$$
$$C \to AB \mid \mathsf{a}$$

Input: $x =$ baaba

let $x[i, \ell] = x_i x_{i+1} \dots x_{i+\ell-1}$

| $\ell$ | | | | | | |
|---|---|---|---|---|---|---|
| $5$ | | | | | | |
| $4$ | | | | | | |
| $3$ | | | | | | |
| $2$ | | | | | | |
| $1$ | $B$ | | | | | |
| | $1$ | $2$ | $3$ | $4$ | $5$ | $i$ |
| | b | a | a | b | a | |

For every substring $x[i, \ell]$, remember all variables $R$ that derive $x[i, \ell]$

Store in a table $T[i, \ell]$

# Cocke–Younger–Kasami algorithm

$$S \to AB \mid BC$$
$$A \to BA \mid \mathsf{a}$$
$$B \to CC \mid \mathsf{b}$$
$$C \to AB \mid \mathsf{a}$$

Input: $x =$ baaba

let $x[i, \ell] = x_i x_{i+1} \dots x_{i+\ell-1}$

| $\ell$ | | | | | | |
|---|---|---|---|---|---|---|
| 5 | | | | | | |
| 4 | | | | | | |
| 3 | | | | | | |
| 2 | | | | | | |
| 1 | $B$ | $A \vert C$ | $A \vert C$ | $B$ | $A \vert C$ | |
| | 1 | 2 | 3 | 4 | 5 | $i$ |
| | b | a | a | b | a | |

For every substring $x[i, \ell]$, remember all variables $R$ that derive $x[i, \ell]$

Store in a table $T[i, \ell]$

# Cocke–Younger–Kasami algorithm

$$S \to AB \mid BC$$
$$A \to BA \mid \text{a}$$
$$B \to CC \mid \text{b}$$
$$C \to AB \mid \text{a}$$

Input: $x = $ baaba

let $x[i, \ell] = x_i x_{i+1} \ldots x_{i+\ell-1}$

| $\ell$ | | | | | | |
|---|---|---|---|---|---|---|
| 5 | | | | | | |
| 4 | | | | | | |
| 3 | | | | | | |
| 2 | $S \mid A$ | | | | | |
| 1 | $B$ | $A \mid C$ | $A \mid C$ | $B$ | $A \mid C$ | |
| | 1 | 2 | 3 | 4 | 5 | $i$ |
| | b | a | a | b | a | |

For every substring $x[i, \ell]$, remember all variables $R$ that derive $x[i, \ell]$

Store in a table $T[i, \ell]$

# Cocke–Younger–Kasami algorithm

$$
\begin{aligned}
S &\to AB \mid BC \\
A &\to BA \mid \mathsf{a} \\
B &\to CC \mid \mathsf{b} \\
C &\to AB \mid \mathsf{a}
\end{aligned}
$$

Input: $x = $ baaba

let $x[i,\ell] = x_i x_{i+1} \ldots x_{i+\ell-1}$

| $\ell$ | | | | | | |
|---|---|---|---|---|---|---|
| 5 | | | | | | |
| 4 | | | | | | |
| 3 | | | | | | |
| 2 | $S\|A$ | $B$ | $S\|C$ | $S\|A$ | | |
| 1 | $B$ | $A\|C$ | $A\|C$ | $B$ | $A\|C$ | |
| | 1 | 2 | 3 | 4 | 5 | $i$ |
| | b | a | a | b | a | |

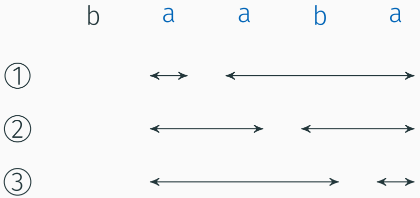
For every substring $x[i,\ell]$, remember all variables $R$ that derive $x[i,\ell]$

Store in a table $T[i,\ell]$

# Computing $T[i, \ell]$ for $\ell \geqslant 2$

Example: to compute $T[2,4]$

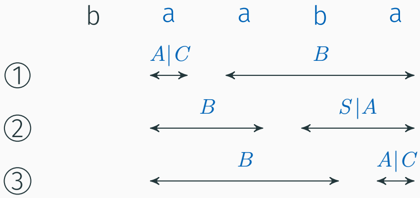
Try all possible ways to split $x[2,4]$ into two substrings



# Computing $T[i, \ell]$ for $\ell \geqslant 2$

Example: to compute $T[2, 4]$

Try all possible ways to split $x[2, 4]$ into two substrings

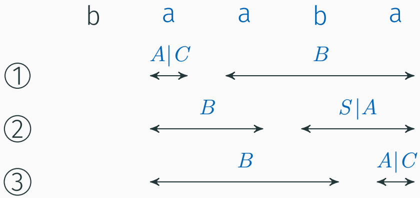



Look up entries regarding shorter substrings previously computed

# Computing $T[i, \ell]$ for $\ell \geqslant 2$

Example: to compute $T[2,4]$

Try all possible ways to split $x[2,4]$ into two substrings




Look up entries regarding shorter substrings previously computed

$$S \to AB \mid BC$$
$$A \to BA \mid \text{a}$$
$$B \to CC \mid \text{b}$$
$$C \to AB \mid \text{a}$$

$$T[2,4] = S|A|C$$

# Cocke–Younger–Kasami algorithm

$$S \to AB \mid BC$$
$$A \to BA \mid \text{a}$$
$$B \to CC \mid \text{b}$$
$$C \to AB \mid \text{a}$$

Input: $x =$ baaba

| $\ell$ | | | | | | |
|---|---|---|---|---|---|---|
| 5 | $S\|A\|C$ | | | | | |
| 4 | - | $S\|A\|C$ | | | | |
| 3 | - | $B$ | $B$ | | | |
| 2 | $S\|A$ | $B$ | $S\|C$ | $S\|A$ | | |
| 1 | $B$ | $A\|C$ | $A\|C$ | $B$ | $A\|C$ | |
| | 1 | 2 | 3 | 4 | 5 | $i$ |
| | b | a | a | b | a | |

# Cocke–Younger–Kasami algorithm

$$S \to AB \mid BC$$
$$A \to BA \mid \text{a}$$
$$B \to CC \mid \text{b}$$
$$C \to AB \mid \text{a}$$

Input: $x =$ baaba

| $\ell$ | | | | | | |
|---|---|---|---|---|---|---|
| 5 | $S\|A\|C$ | | | | | |
| 4 | - | $S\|A\|C$ | | | | |
| 3 | - | $B$ | $B$ | | | |
| 2 | $S\|A$ | $B$ | $S\|C$ | $S\|A$ | | |
| 1 | $B$ | $A\|C$ | $A\|C$ | $B$ | $A\|C$ | |
| | 1 | 2 | 3 | 4 | 5 | $i$ |
| | b | a | a | b | a | |

Get parse tree by tracing back derivations