Lecture 12 – Examples of Context-Free Grammars

COSE215: Theory of Computation

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PLRG

2024 Spring

Recall

- A **context-free grammar (CFG)**:

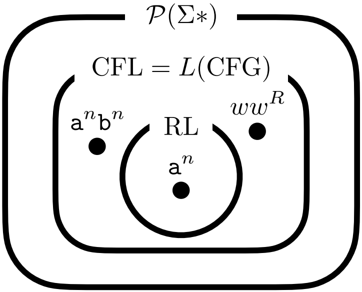
$$G = (V, \Sigma, S, R)$$

- The **language** of a CFG G:

$$L(G) = \{w \in \Sigma^* \mid S \Rightarrow^* w\}$$

- A language L is a **context-free language (CFL)**:

$$\exists \text{ CFG } G.\ L(G) = L$$



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Regular Languages are Context-Free

Theorem (RLs are CFLs)

All regular languages are context-free.

Proof) There are two ways to prove this theorem:

1. Converting regular expressions to equivalent CFGs
2. Converting ϵ-NFAs to equivalent CFGs

Regular Expressions to CFGs

For a given regular language L, let's construct an equivalent CFG G using the equivalent regular expression R. $L(G) = L(R)$.

RE R	CFG G
$\varnothing$	$S \to S$
ϵ	$S \to \epsilon$
$a \in \Sigma$	$S \to a$
$R_1 \mid R_2$	$S \to S_1 \mid S_2$
$R_1 \cdot R_2$	$S \to S_1 S_2$
R_1^*	$S \to \epsilon \mid S_1 S$
(R_1)	$S \to S_1$

where S_1 and S_2 are start variables of CFGs G_1 and G_2 such that $L(G_1) = L(R_1)$ and $L(G_2) = L(R_2)$, respectively.

Regular Expressions to CFGs – Examples

For a given RE R, construct a CFG G such that $L(G) = L(R)$.

- $R = \epsilon|\texttt{ab}|\texttt{ba}$

$$S \rightarrow F \mid D \qquad A \rightarrow \texttt{a} \qquad C \rightarrow AB \qquad E \rightarrow \epsilon$$
$$B \rightarrow \texttt{b} \qquad D \rightarrow BA \qquad F \rightarrow E \mid C$$

  Its simplified version:

$$S \rightarrow \epsilon \mid \texttt{ab} \mid \texttt{ba}$$

- $R = (\epsilon|\texttt{a})^*$

$$S \rightarrow \epsilon \mid AS \qquad A \rightarrow \epsilon \mid \texttt{a}$$

- $R = (\texttt{0}|\texttt{1}(\texttt{0}\texttt{1}^*\texttt{0})^*\texttt{1})^*$

$$S \rightarrow \epsilon \mid AS \qquad A \rightarrow \texttt{0} \mid \texttt{1}B\texttt{1} \qquad C \rightarrow \texttt{0}D\texttt{0}$$
$$B \rightarrow \epsilon \mid CB \qquad D \rightarrow \epsilon \mid \texttt{1}D$$

ϵ-NFAs to CFGs

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For a given ϵ-NFA $N^\epsilon = (Q, \Sigma, \delta, q_0, F)$, let's construct a CFG G as:

- For each state $q \in Q$ of N^ϵ, introduce a non-terminal A_q.
- For each transition $q \xrightarrow{a} q'$ of N^ϵ, introduce a production rule:

$$A_q \rightarrow aA_{q'}$$

- For each ϵ-transition $q \xrightarrow{\epsilon} q'$ of N^ϵ, introduce a production rule:

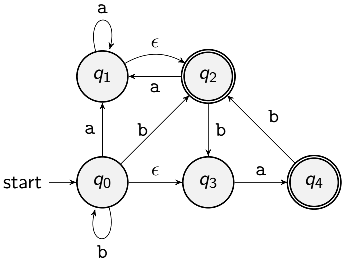
$$A_q \rightarrow A_{q'}$$

- For each final state $q \in F$ of N^ϵ, introduce a production rule:

$$A_q \rightarrow \epsilon$$

- The start variable of G is A_{q_0}.

ϵ-NFAs to CFGs – Examples

$N^\epsilon =$ 

We can construct a CFG G (A_0 is the start variable) for N^ϵ:

$$
\begin{aligned}
A_0 &\to \mathtt{b}A_0 \mid \mathtt{a}A_1 \mid \mathtt{b}A_2 \mid A_3 \\
A_1 &\to \mathtt{a}A_1 \mid A_2 \\
A_2 &\to \mathtt{a}A_1 \mid \mathtt{b}A_3 \mid \epsilon \\
A_3 &\to \mathtt{a}A_4 \\
A_4 &\to \mathtt{b}A_2 \mid \epsilon
\end{aligned}
$$

For example, we can derive $\mathtt{ba} \in L(N^\epsilon)$ using G:

$$A_0 \Rightarrow \mathtt{b}A_0 \Rightarrow \mathtt{b}A_3 \Rightarrow \mathtt{ba}A_4 \Rightarrow \mathtt{ba}$$

Contents

Example 1: $\mathtt{b}^n\mathtt{a}^m\mathtt{b}^{2n}$

Construct a CFG for the language:

$$L = \{\mathtt{b}^n\mathtt{a}^m\mathtt{b}^{2n} \mid n, m \geq 0\}$$

Let's split a word $w \in L$ using shorter words in L.

$$\forall w \in L.\ w = \begin{cases} (1)\ \mathtt{a}^m & \text{for some } m \geq 0 \\ (2)\ \mathtt{b}w'\mathtt{bb} & \text{for some } w' \in L \end{cases} \implies S \to A \mid \mathtt{b}S\mathtt{bb}$$

$$\forall m \geq 0.\ \mathtt{a}^m = \begin{cases} (1)\ \epsilon \\ (2)\ \mathtt{a}\mathtt{a}^{m-1} \end{cases} \implies A \to \epsilon \mid \mathtt{a}A$$

Therefore, the following is a CFG for L:

$$\begin{aligned} S &\to A \mid \mathtt{b}S\mathtt{bb} \\ A &\to \epsilon \mid \mathtt{a}A \end{aligned}$$

Example 2: Well-Formed Brackets

Construct a CFG for the language:

$$L = \{w \in \{(,),\{,\},[,]\}^* \mid w \text{ is well-formed}\}$$

Let's split a word $w \in L$ using shorter words in L.

$$\forall w \in L.\ w = \begin{cases} ① \ \epsilon & \\ ② \ (w') & \text{for some } w' \in L \\ ③ \ \{w'\} & \text{for some } w' \in L \\ ④ \ [w'] & \text{for some } w' \in L \\ ⑤ \ w_1 w_2 & \text{for some } w_1, w_2 \in L \end{cases}$$

Therefore, the following is a CFG for L:

$$S \to \epsilon \mid (S) \mid \{S\} \mid [S] \mid SS$$

Example 3: Equal Number of a's and b's

Construct a CFG for the language:

$$L = \{w \in \{\mathtt{a}, \mathtt{b}\}^* \mid N_{\mathtt{a}}(w) = N_{\mathtt{b}}(w)\}$$

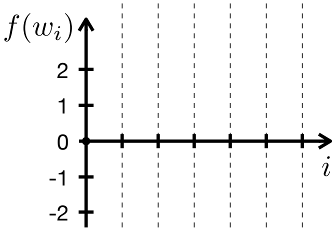
where $N_{\mathtt{a}}(w)$ and $N_{\mathtt{b}}(w)$ are the number of a's and b's in w, respectively.

Consider a function $f(w) = N_{\mathtt{a}}(w) - N_{\mathtt{b}}(w)$.

For example, if $w = \mathtt{abbaaa}$, then $f(w) = N_{\mathtt{a}}(w) - N_{\mathtt{b}}(w) = 4 - 2 = 2$.

If a word $w = a_1 a_2 \cdots a_n \in \{\mathtt{a}, \mathtt{b}\}^*$, let $w_i = a_1 a_2 \cdots a_i$ for $0 \leq i \leq n$.

Let's draw a graph for $f(w_i)$ for $0 \leq i \leq n$:



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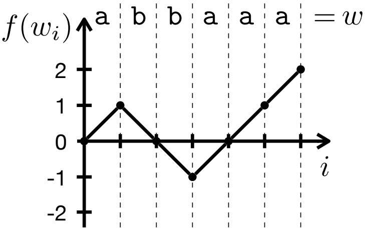
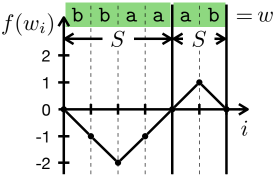


Example 3: Equal Number of a's and b's

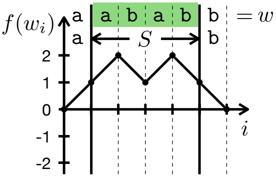
Let's split a word $w \in L$ using shorter words in L.

For a given $w \in L$, there are four cases:

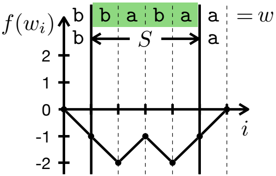
① $w = \epsilon$



② $w = w_1 w_2$



③ $w = \mathtt{a}w'\mathtt{b}$



④ $w = \mathtt{b}w'\mathtt{a}$

Therefore, the following is a CFG for L:

$$S \to \epsilon \mid SS \mid \mathtt{a}S\mathtt{b} \mid \mathtt{b}S\mathtt{a}$$

Example 4: Unequal Number of a's and b's

Construct a CFG for the **complement** of the language in Example 3:

$$L = \{w \in \{\mathtt{a}, \mathtt{b}\}^* \mid N_{\mathtt{a}}(w) \neq N_{\mathtt{b}}(w)\}$$

where $N_{\mathtt{a}}(w)$ and $N_{\mathtt{b}}(w)$ are the number of a's and b's in w, respectively.

We can categorize $w \in \{\mathtt{a}, \mathtt{b}\}^*$ into three cases using the function f:

- $L_Z = \{w \in \{\mathtt{a}, \mathtt{b}\}^* \mid f(w) = 0\}$ – equal number of a's and b's
- $L_P = \{w \in \{\mathtt{a}, \mathtt{b}\}^* \mid f(w) > 0\}$ – more a's than b's
- $L_N = \{w \in \{\mathtt{a}, \mathtt{b}\}^* \mid f(w) < 0\}$ – more b's than a's

The language L is the disjoint union of L_P and L_N:

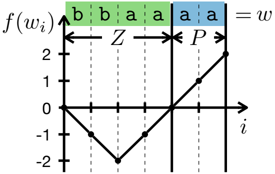
$$L = L_P \uplus L_N$$

Let's define production rules for L_P and L_N using graphs for $f(w_i)$.

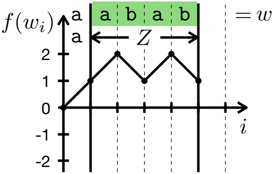
Example 4: Unequal Number of a's and b's

Let's split a word $w \in L_P$ using shorter words in L_Z, L_P, and L_N.

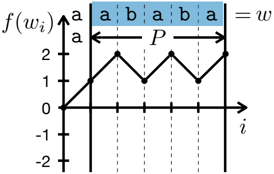
For a given $w \in L_P$, there are three cases:



① $w = w_1 w_2$
$(w_1 \in L_Z, w_2 \in L_P)$



② $w = \mathtt{a}w'$
$(w' \in L_Z)$

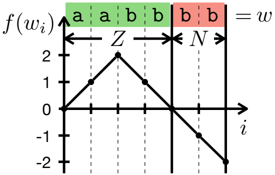


③ $w = \mathtt{a}w'$
$(w' \in L_P)$

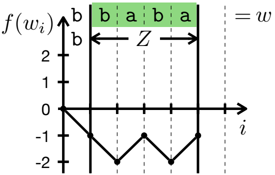
Therefore, the following is production rules for L_P:

$$P \to ZP \mid \mathtt{a}P \mid \mathtt{a}Z$$

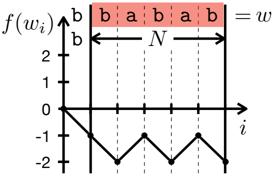
Example 4: Unequal Number of a's and b's



① $w = w_1 w_2$
$(w_1 \in L_Z, w_2 \in L_N)$



② $w = \mathtt{b}w'$
$(w' \in L_Z)$



③ $w = \mathtt{b}w'$
$(w' \in L_N)$

Similarly, the following is production rules for L_N:

$$N \rightarrow ZN \mid \mathtt{b}N \mid \mathtt{b}Z$$

Therefore, the CFG for L is:

$$\begin{aligned} S &\rightarrow P \mid N \\ P &\rightarrow ZP \mid \mathtt{a}P \mid \mathtt{a}Z \\ N &\rightarrow ZN \mid \mathtt{b}N \mid \mathtt{b}Z \\ Z &\rightarrow \epsilon \mid ZZ \mid \mathtt{a}Z\mathtt{b} \mid \mathtt{b}Z\mathtt{a} \end{aligned}$$

Example 5: Arithmetic Expressions

An **arithmetic expression** is defined with the following CFG:

$$\begin{array}{lcl} S & \rightarrow & N \mid X \mid S\texttt{+}S \mid S\texttt{*}S \mid \texttt{(}S\texttt{)} \\ N & \rightarrow & \texttt{0} \mid \cdots \mid \texttt{9} \mid \texttt{0}N \mid \cdots \mid \texttt{9}N \\ X & \rightarrow & \texttt{a} \mid \cdots \mid \texttt{z} \end{array}$$

We can **derive** an arithmetic expression `13*(2+x)` as follows:

$$\begin{array}{lllllll} S & \Rightarrow & S\texttt{*}S & \Rightarrow & N\texttt{*}S & \Rightarrow & \texttt{1}N\texttt{*}S \\ & \Rightarrow & \texttt{13*}S & \Rightarrow & \texttt{13*(}S\texttt{)} & \Rightarrow & \texttt{13*(}S\texttt{+}S\texttt{)} \\ & \Rightarrow & \texttt{13*(}N\texttt{+}S\texttt{)} & \Rightarrow & \texttt{13*(2+}S\texttt{)} & \Rightarrow & \texttt{13*(2+}X\texttt{)} \\ & \Rightarrow & \texttt{13*(2+x)} & & & & \end{array}$$

Example 6: Regular Expressions

Consider a language representing the **syntax of regular expressions**:

$$L = \{w \in \{\varnothing, \varepsilon, \mathtt{a}, \mathtt{b}, \mathtt{|}, \mathtt{*}, \mathtt{(}, \mathtt{)}\}^* \mid w \text{ is a regular expression over } \{\mathtt{a}, \mathtt{b}\}\ \}$$

Is this language L **regular**? or **context-free**?

We can prove that L is **not regular** using the pumping lemma.
(Hint: consider a word $\mathtt{(}^n\varepsilon\mathtt{)}^n$ for a given $n > 0$)

However, the language L is **context-free**:

$$S \rightarrow \varnothing \mid \varepsilon \mid \mathtt{a} \mid \mathtt{b} \mid S\mathtt{|}S \mid SS \mid S\mathtt{*} \mid \mathtt{(}S\mathtt{)}$$

We can **derive** a regular expression `(b|ab)*` as follows:

$$\begin{array}{llllll} S & \Rightarrow & S\mathtt{*} & \Rightarrow & \mathtt{(}S\mathtt{)*} & \Rightarrow & \mathtt{(}S\mathtt{|}S\mathtt{)*} \\ & \Rightarrow & \mathtt{(}S\mathtt{|}SS\mathtt{)*} & \Rightarrow & \mathtt{(}S\mathtt{|}S\mathtt{b)*} & \Rightarrow & \mathtt{(}S\mathtt{|ab)*} \\ & \Rightarrow & \mathtt{(b|ab)*} \end{array}$$

Example 7: Simplified Scala Syntax

We can define a CFG for a simplified version of Scala syntax[1]:

$$
\begin{array}{lrcl}
\text{(Scala Program)} & S & \rightarrow & E \mid S \; \texttt{;} \; E \\
\text{(Expressions)} & E & \rightarrow & N \mid X \mid E \; \texttt{+} \; E \mid E \; \texttt{-} \; E \mid E \; \texttt{*} \; E \mid E \; \texttt{/} \; E \\
 & & \mid & \texttt{val} \; X \texttt{:} \; T \; \texttt{=} \; E \\
 & & \mid & \texttt{def} \; X \texttt{(} \; P \; \texttt{):} \; T \; \texttt{=} \; E \\
 & & \mid & E \; \texttt{(} \; A \; \texttt{)} \\
 & & \mid & \texttt{if} \; \texttt{(} \; E \; \texttt{)} \; E \; \texttt{else} \; E \\
 & & \mid & \texttt{enum} \; T \; \texttt{\{} \; D \; \texttt{\}} \\
 & & \mid & E \; \texttt{match} \; \texttt{\{} \; C \; \texttt{\}} \\
\text{(Numbers)} & N & \rightarrow & \texttt{0} \mid \cdots \mid \texttt{9} \mid \texttt{0}N \mid \cdots \mid \texttt{9}N \\
\text{(Variables)} & X & \rightarrow & Y \mid YX \\
 & Y & \rightarrow & \varnothing \mid \texttt{a} \mid \cdots \mid \texttt{z} \mid \texttt{A} \mid \cdots \mid \texttt{Z} \\
\text{(Types)} & T & \rightarrow & X \mid T \; \texttt{[} \; T \; \texttt{]} \mid T \; \texttt{=>} \; T \\
\text{(Parameters)} & P & \rightarrow & \epsilon \mid X \; \texttt{:} \; T \mid P \; \texttt{,} \; X \; \texttt{:} \; T \\
\text{(Arguments)} & A & \rightarrow & \epsilon \mid E \mid A \; \texttt{,} \; E \\
\text{(Cases)} & C & \rightarrow & \texttt{case} \; E \; \texttt{=>} \; E \mid C \; \texttt{;} \; \texttt{case} \; E \; \texttt{=>} \; E \\
\text{(Enum Cases)} & D & \rightarrow & \texttt{case} \; T \; \texttt{(} \; P \; \texttt{)} \mid D \; \texttt{;} \; \texttt{case} \; T \; \texttt{(} \; P \; \texttt{)}
\end{array}
$$

[1] https://docs.scala-lang.org/scala3/reference/syntax.html

Example 7: Simplified Scala Syntax

```scala
def sum(n: Int): Int = n match { case 0 => 0; case n => n + sum(n - 1) }
```

A derivation for this program:

$S \Rightarrow$ $\texttt{def}\ X\texttt{(}\ P\ \texttt{):}\ T\ \texttt{=}\ E$ $\Rightarrow^* \texttt{def sum(}\ P\ \texttt{):}\ T\ \texttt{=}\ E$

$\Rightarrow^* \texttt{def sum(}\ X\texttt{:}\ T\ \texttt{):}\ T\ \texttt{=}\ E$ $\Rightarrow^* \texttt{def sum(n: Int): Int =}\ E$

$\Rightarrow^* \texttt{def sum(n: Int): Int =}\ E\ \texttt{match \{}\ C\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{}\ C\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case}\ E\ \texttt{=>}\ E\ \texttt{;}\ C\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case 0 => 0;}\ C\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case 0 => 0; case}\ E\ \texttt{=>}\ E\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case 0 => 0; case n =>}\ E\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case 0 => 0; case n =>}\ E\ \texttt{+}\ E\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case 0 => 0; case n => n +}\ E\ \texttt{\}}$

$\Rightarrow^* \texttt{def sum(n: Int): Int = n match \{ case 0 => 0; case n => n + sum(n - 1) \}}$

Summary

1. Regular Languages are Context-Free
    - Regular Expressions to CFGs
    - ϵ-NFA to CFG

2. Examples of Context-Free Grammars
    - Example 1: $\mathtt{b}^n\mathtt{a}^m\mathtt{b}^{2n}$
    - Example 2: Well-Formed Brackets
    - Example 3: Equal Number of a's and b's
    - Example 4: Unequal Number of a's and b's
    - Example 5: Arithmetic Expressions
    - Example 6: Regular Expressions
    - Example 7: Simplified Scala Syntax

Midterm Exam

- The midterm exam will be given in class.
- **Date:** 13:30-14:45 (1 hour 15 minutes), April 24 (Wed.).
- **Location:** 604, Woojung Hall of Informatics (우정정보관 604호)
- **Coverage:** Lectures 1 – 13
- **Format:** 7–9 questions with closed book and closed notes
  - Filling blanks in some tables, sentences, or expressions.
  - Construction of automata or grammars for given languages.
  - Proofs of given statements related to automata or grammars.
  - Yes/No questions about concepts in the theory of computation.
  - etc.
- Note that there is **no class** on **April 22 (Mon.)**.
- Please refer to the **previous exams** in the course website:

https://plrg.korea.ac.kr/courses/cose215/

Next Lecture

- Parse Trees and Ambiguity

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