

COSE215: Theory of Computation

Lecture 9 — Context-Free Grammars

Hakjoo Oh
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Context-Free Languages

An extension of the regular languages. Many applications in CS:

- Most programming languages (e.g., C, Java, ML, etc).
- Markup languages (e.g., HTML, XML, etc).
- Essential to design of programming languages and construction of compilers.

Example: Palindromes

- A string is a palindrome if it reads the same forward and backward.
- $L = \{w \in \{0, 1\}^* \mid w = w^R\}$
- L is not regular, but context-free.
- Every context-free language is defined by a recursive definition.
 - ▶ Basis: ϵ , 0 , and 1 are palindromes.
 - ▶ Induction: If w is a palindrome, so are $0w0$ and $1w1$.
- The recursive definition is expressed by a context-free grammar.

$$P \rightarrow \epsilon$$

$$P \rightarrow 0$$

$$P \rightarrow 1$$

$$P \rightarrow 0P0$$

$$P \rightarrow 1P1$$

Context-Free Grammars

Definition (Context-Free Grammars)

A context-free grammar G is defined as a quadruple:

$$G = (V, T, S, P)$$

- V : a finite set of *variables* (*nonterminals*)
- T : a finite set of symbols (*terminals* or *terminal symbols*)
- $S \in V$: the start variable
- P : a finite set of *productions*. A production has the form

$$x \rightarrow y$$

where $x \in V$ and $y \in (V \cup T)^*$.

Example: Palindromes

$$G = (\{P\}, \{0, 1\}, P, A)$$

where A is the set of five productions:

$$P \rightarrow \epsilon$$

$$P \rightarrow 0$$

$$P \rightarrow 1$$

$$P \rightarrow 0P0$$

$$P \rightarrow 1P1$$

Example: Simple Arithmetic Expressions

$$G = (\{E, I\}, \{+, *, (,), a, b, 0, 1\}, E, P)$$

where P is a set of productions:

$$E \rightarrow I$$

$$E \rightarrow E + E$$

$$E \rightarrow E * E$$

$$E \rightarrow (E)$$

$$I \rightarrow a$$

$$I \rightarrow b$$

$$I \rightarrow Ia$$

$$I \rightarrow Ib$$

$$I \rightarrow I0$$

$$I \rightarrow I1$$

Derivation

Definition (Derivation Relation, \Rightarrow)

Let $G = (V, T, S, P)$ be a context-free grammar. Let $\alpha A \beta$ be a string of terminals and variables, where $A \in V$ and $\alpha, \beta \in (V \cup T)^*$. Let $A \rightarrow \gamma$ is a production in G . Then, we say $\alpha A \beta$ derives $\alpha \gamma \beta$, and write

$$\alpha A \beta \Rightarrow \alpha \gamma \beta.$$

Definition (\Rightarrow^* , Closure of \Rightarrow)

\Rightarrow^* is a relation that represents zero, or more steps of derivations:

- Basis: For any string α of terminals and variables, $\alpha \Rightarrow^* \alpha$.
- Induction: If $\alpha \Rightarrow^* \beta$ and $\beta \Rightarrow \gamma$, then $\alpha \Rightarrow^* \gamma$.

Example

A derivation for $a * (a + b00)$:

$$\begin{aligned} E &\Rightarrow E * E \Rightarrow I * E \Rightarrow a * E \Rightarrow a * (E) \Rightarrow \\ a * (E + E) &\Rightarrow a * (I + E) \Rightarrow a * (a + E) \Rightarrow a * (a + I) \Rightarrow \\ a * (a + I0) &\Rightarrow a * (a + I00) \Rightarrow a * (a + b00) \end{aligned}$$

Thus, $E \Rightarrow^* a * (a + b00)$.

Leftmost and Rightmost Derivations

- Leftmost derivation: replace the leftmost variable at each derivation step
- Rightmost derivation: replace the rightmost variable at each derivation step

The right most derivation for $a * (a + b00)$:

$$\begin{aligned} E &\Rightarrow E * E \Rightarrow E * (E) \Rightarrow E * (E + E) \Rightarrow E * (E + I) \Rightarrow \\ E * (E + I0) &\Rightarrow E * (E + I00) \Rightarrow E * (E + b00) \Rightarrow E * (I + b00) \Rightarrow \\ E * (a + b00) &\Rightarrow I * (a + b00) \Rightarrow a * (a + b00) \end{aligned}$$

Language of a Grammar

Definition

Let $G = (V, T, S, P)$ be a context-free grammar. The language of G , denoted $L(G)$, is the set of terminal strings that have derivations from the start symbol. That is,

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

Definition (Context-free Language)

If a language L is the language of some context-free grammar G , i.e., $L = L(G)$, then we say L is a context-free language, shortly CFL.

Sentential Forms

Definition (Sentential Forms)

If $G = (V, T, S, P)$ is a context-free grammar, then any string $\alpha \in (V \cup T)^*$ such that $S \Rightarrow^* \alpha$ is a *sentential form*.

- If $S \Rightarrow^* \alpha$ is a leftmost derivation, α is a *left-sentential form*.
- If $S \Rightarrow^* \alpha$ is a rightmost derivation, α is a *right-sentential form*.

Example

- Leftmost:

$$E \Rightarrow E * E \Rightarrow I * E \Rightarrow a * E \Rightarrow a * (E)$$

$$a * (E + E) \Rightarrow a * (I + E) \Rightarrow a * (a + E) \Rightarrow a * (a + I) \Rightarrow$$

$$a * (a + I0) \Rightarrow a * (a + I00) \Rightarrow a * (a + b00)$$

- Neither leftmost nor rightmost:

$$E \Rightarrow E * E \Rightarrow E * (E) \Rightarrow E * (E + E) \Rightarrow E * (I + E)$$

Exercises

- $L = \{ww^R \mid w \in \{a, b\}^*\}$
- $L = \{a^n b^n \mid n \geq 0\}$
- $L = \{a^n b^m \mid n \neq m\}$
- The language of balanced parentheses.
 - ▶ E.g., ϵ , $()$, $()()$, $(())$, $(())()$

Mid-term Exam

- April 24 (Wed), in class
- Coverage: Lectures 1 – 9