


01204211 Discrete Mathematics

Lecture 11a: Context-free languages and grammars (1)¹

Jittat Fakcharoenphol

September 12, 2023

¹Based on lecture notes of *Models of Computation* course by Jeff Erickson. 

Building up languages

Regular languages:

- ▶ Contenation
- ▶ Union
- ▶ Kleene star

Building up languages

Regular languages:

- ▶ Contenation
- ▶ Union
- ▶ Kleene star

Context-free grammar:

- ▶ Contenation
- ▶ Union
- ▶ Recursion

Example

$$S \rightarrow 0S1$$

$$S \rightarrow \varepsilon$$

Example

$$S \rightarrow 0S1$$

$$S \rightarrow \varepsilon$$

You can use “|” to write production rules more succinctly.

$$S \rightarrow 0S1 \mid \varepsilon$$

Definition

A **context-free grammar** consists of the following components:

- ▶ a finite set Σ , a set of *symbols* (or *terminals*),
- ▶ a finite set Γ disjoint from Σ , a set of *non-terminals* (you can think of them as variables),
- ▶ a finite set R of *production rules* of the form $A \rightarrow w$ where $A \in \Gamma$ and $w \in (\Sigma \cup \Gamma)^*$ is a string of symbols and variable, and
- ▶ a *starting* non-terminal (usually the non-terminal of the first production rule).

Another example

$$S \rightarrow A \mid B$$

$$A \rightarrow 0A \mid 0C$$

$$B \rightarrow B1 \mid C1$$

$$C \rightarrow \varepsilon \mid 0C1$$

Here $\Sigma = \{0, 1\}$ and $\Gamma = \{S, A, B, C\}$.

Applying the rules

If you have strings $x, y, z \in (\Sigma \cup \Gamma)^*$ and the production rule

$$A \rightarrow y,$$

You can apply the rule to the string xAz . This yields the string

$$xyz.$$

We use the notation

$$xAz \rightsquigarrow xyz$$

to describe this application.

Derivation

We say that z derives from x if we can obtain z from x by production rule applications, denoted by $x \rightsquigarrow^* z$.

Formally, for any string $x, z \in (\Sigma \cup \Gamma)^*$, we say that $x \rightsquigarrow^* z$ if either

- ▶ $x = z$, or
- ▶ $x \rightsquigarrow y$ and $y \rightsquigarrow^* z$ for some string $y \in (\Sigma \cup \Gamma)^*$.

$L(w)$

The *language* $L(w)$ of string $w \in (\Sigma \cup \Gamma)^*$ is the set of all strings in Σ^* that derive from w , i.e.,

$$L(w) = \{x \in \Sigma^* \mid w \rightsquigarrow *x\}.$$

$L(w)$

The *language* $L(w)$ of string $w \in (\Sigma \cup \Gamma)^*$ is the set of all strings in Σ^* that derive from w , i.e.,

$$L(w) = \{x \in \Sigma^* \mid w \rightsquigarrow *x\}.$$

The language **generated by** a context-free grammar G , denoted by $L(G)$ is the language of its starting non-terminal.

$L(w)$

The *language* $L(w)$ of string $w \in (\Sigma \cup \Gamma)^*$ is the set of all strings in Σ^* that derive from w , i.e.,

$$L(w) = \{x \in \Sigma^* \mid w \rightsquigarrow *x\}.$$

The language **generated by** a context-free grammar G , denoted by $L(G)$ is the language of its starting non-terminal.

A language L is **context-free** if there exists some context-free grammar G such that $L(G) = L$.

$S \rightarrow NP VP$
 $NP \rightarrow CN | CN PP$
 $VP \rightarrow CV | CV PP$
 $PP \rightarrow PREP CN$
 $CN \rightarrow ART N$
 $CV \rightarrow V | V NP$
 $ART \rightarrow a | the$
 $N \rightarrow boy | girl | flower$
 $V \rightarrow touches | likes | sees$
 $PREP \rightarrow with$

Small English grammar

$S \rightarrow NP VP$
 $NP \rightarrow CN | CN PP$
 $VP \rightarrow CV | CV PP$
 $PP \rightarrow PREP CN$
 $CN \rightarrow ART N$
 $CV \rightarrow V | V NP$
 $ART \rightarrow a | the$
 $N \rightarrow boy | girl | flower$
 $V \rightarrow touches | likes | sees$
 $PREP \rightarrow with$

► Examples of strings in $L(G_2)$ are:

► a boy sees

Small English grammar

$S \rightarrow NP VP$
 $NP \rightarrow CN | CN PP$
 $VP \rightarrow CV | CV PP$
 $PP \rightarrow PREP CN$
 $CN \rightarrow ART N$
 $CV \rightarrow V | V NP$
 $ART \rightarrow a | the$
 $N \rightarrow boy | girl | flower$
 $V \rightarrow touches | likes | sees$
 $PREP \rightarrow with$

► Examples of strings in $L(G_2)$ are:

- a boy sees
- the boy sees a flower

Small English grammar

$S \rightarrow NP VP$
 $NP \rightarrow CN | CN PP$
 $VP \rightarrow CV | CV PP$
 $PP \rightarrow PREP CN$
 $CN \rightarrow ART N$
 $CV \rightarrow V | V NP$
 $ART \rightarrow a | the$
 $N \rightarrow boy | girl | flower$
 $V \rightarrow touches | likes | sees$
 $PREP \rightarrow with$

► Examples of strings in $L(G_2)$ are:

- a boy sees
- the boy sees a flower
- a girl with a flower likes the boy

Parse tree

$$S \rightarrow A \mid B$$

$$A \rightarrow 0A \mid 0C$$

$$B \rightarrow B1 \mid C1$$

$$C \rightarrow \varepsilon \mid 0C1$$

Parse tree

► 00011

$$S \rightarrow A \mid B$$

$$A \rightarrow 0A \mid 0C$$

$$B \rightarrow B1 \mid C1$$

$$C \rightarrow \varepsilon \mid 0C1$$

Parse tree

► 00011

► 01111

$$S \rightarrow A \mid B$$

$$A \rightarrow 0A \mid 0C$$

$$B \rightarrow B1 \mid C1$$

$$C \rightarrow \varepsilon \mid 0C1$$

Parse tree

$$S \rightarrow A \mid B$$

$$A \rightarrow 0A \mid 0C$$

$$B \rightarrow B1 \mid C1$$

$$C \rightarrow \varepsilon \mid 0C1$$

► 00011

► 01111

► 111110

Parse tree

$$S \rightarrow A \mid B$$

$$A \rightarrow 0A \mid 0C$$

$$B \rightarrow B1 \mid C1$$

$$C \rightarrow \varepsilon \mid 0C1$$

► 00011

► 01111

► 111110

Parse tree

a girl with a flower likes the boy

$S \rightarrow NP VP$

$NP \rightarrow CN|CN PP$

$VP \rightarrow CV|CV PP$

$PP \rightarrow PREP CN$

$CN \rightarrow ART N$

$CV \rightarrow V|V NP$

$ART \rightarrow a|the$

$N \rightarrow boy|girl|flower$

$V \rightarrow touches|likes|sees$

$PREP \rightarrow with$

Ambiguity

► $1 + 1 * 1$

$$S \rightarrow 1 \mid S + S \mid S * S$$

Ambiguity

► $1 + 1 * 1$

► $1 + 1 + 1 + 1 + 1$

$$S \rightarrow 1 \mid S + S \mid S * S$$

Ambiguity

▶ $1 + 1 * 1$

▶ $1 + 1 + 1 + 1 + 1$

$$S \rightarrow 1 \mid S + S \mid S * S$$

- ▶ A string w is **ambiguous** with respect to a grammar G if more than one parse tree for w exists.
- ▶ A grammar G is **ambiguous** if some string is ambiguous with respect to G .