

# Theory of Computer Science

## B2. Grammars

Gabriele Röger

University of Basel

March 10, 2021

# Theory of Computer Science

March 10, 2021 — B2. Grammars

## B2.1 Introduction

## B2.2 Grammars

## B2.3 Chomsky Hierarchy

## B2.4 Summary

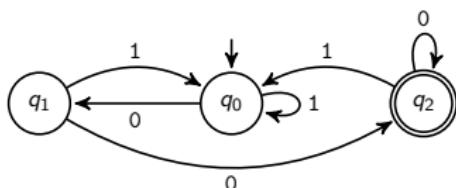
## B2.1 Introduction

# Reminder: Alphabets and Formal Languages

- ▶ An **alphabet**  $\Sigma$  is a finite non-empty set of **symbols**.
- ▶ A **word over  $\Sigma$**  is a finite sequence of elements from  $\Sigma$ .
- ▶ The **empty word** is denoted by  $\varepsilon$ .
- ▶  $\Sigma^*$  denotes the set of **all words** over  $\Sigma$ .
- ▶  $\Sigma^+$  denotes the set of **all non-empty words** over  $\Sigma$ .
- ▶ A **formal language** (over alphabet  $\Sigma$ ) is a subset of  $\Sigma^*$ .

# Reminder: Finite Automata and Formal Languages

## Example



The DFA recognizes the language  $\{w \in \{0, 1\}^* \mid w \text{ ends with } 00\}$ .

- ▶ A finite automaton defines a language, the language it **recognizes**.
- ▶ The specification of the automaton is always finite.
- ▶ The recognized language can be infinite.

# Other Ways to Specify Formal Languages?

**Sought:** General concepts to define  
(often infinite) formal languages  
with finite descriptions.

- ▶ today: **grammars**
- ▶ later: more automata, regular expressions, ...

## Grammar: Example

Variables  $V = \{S, X, Y\}$

Alphabet  $\Sigma = \{a, b, c\}$ .

Production rules:

$$S \rightarrow \varepsilon$$

$$X \rightarrow aXYc$$

$$cY \rightarrow Yc$$

$$S \rightarrow abc$$

$$X \rightarrow abc$$

$$bY \rightarrow bb$$

$$S \rightarrow X$$

You start from  $S$  and may in each step replace the left-hand side of a rule with the right-hand side of the same rule. This way, derive a word over  $\Sigma^*$ .

## Exercise

Variables  $V = \{S, X, Y\}$

Alphabet  $\Sigma = \{a, b, c\}$ .

Production rules:

$$S \rightarrow \varepsilon$$

$$X \rightarrow aXYc$$

$$cY \rightarrow Yc$$

$$S \rightarrow abc$$

$$X \rightarrow abc$$

$$bY \rightarrow bb$$

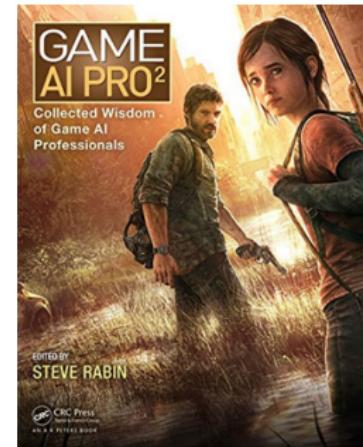
$$S \rightarrow X$$



Derive word aabbcc starting from S.

# Application: Content Generation in Games

- ▶ <http://www.gameaipro.com/>
- ▶ GameAIPro 2, chapter 40  
**Procedural Content Generation: An Overview** by Gillian Smith



## B2.2 Grammars

# Grammars

## Definition (Grammars)

A **grammar** is a 4-tuple  $\langle V, \Sigma, R, S \rangle$  with:

- ▶  $V$  finite set of **variables** (**nonterminal symbols**)
- ▶  $\Sigma$  finite alphabet of **terminal symbols** with  $V \cap \Sigma = \emptyset$
- ▶  $R \subseteq (V \cup \Sigma)^* V (V \cup \Sigma)^* \times (V \cup \Sigma)^*$  finite set of **rules**
- ▶  $S \in V$  **start variable**

A rule is sometimes also called a **production** or a **production rule**.

**German:** Grammatik, Variablen, Terminalalphabet, Regeln/Produktionen, Startvariable

## Rule Sets

What exactly does  $R \subseteq (V \cup \Sigma)^* V (V \cup \Sigma)^* \times (V \cup \Sigma)^* \times (V \cup \Sigma)^*$  mean?

- ▶  $(V \cup \Sigma)^*$ : all words over  $(V \cup \Sigma)$
- ▶ for languages  $L$  and  $L'$ , their **concatenation** is the language  $LL' = \{xy \mid x \in L \text{ and } y \in L'\}$ .
- ▶  $(V \cup \Sigma)^* V (V \cup \Sigma)^*$ : words composed from
  - ▶ a word over  $(V \cup \Sigma)$ ,
  - ▶ followed by a single variable symbol,
  - ▶ followed by a word over  $(V \cup \Sigma)$

→ word over  $(V \cup \Sigma)$  containing at least one variable symbol
- ▶  $\times$ : Cartesian product
- ▶  $(V \cup \Sigma)^* V (V \cup \Sigma)^* \times (V \cup \Sigma)^*$ : set of all pairs  $\langle x, y \rangle$ , where
  - $x$  word over  $(V \cup \Sigma)$  with at least one variable and
  - $y$  word over  $(V \cup \Sigma)$
- ▶ Instead of  $\langle x, y \rangle$  we usually write rules in the form  $x \rightarrow y$ .

# Rules: Examples

## Example

Let  $\Sigma = \{a, b, c\}$  and  $V = \{X, Y, Z\}$ .

Some examples of rules in  $(V \cup \Sigma)^* V (V \cup \Sigma)^* \times (V \cup \Sigma)^*$ :

$$X \rightarrow XaY$$

$$Yb \rightarrow a$$

$$XY \rightarrow \varepsilon$$

$$XYZ \rightarrow abc$$

$$abXc \rightarrow XYZ$$

# Derivations

## Definition (Derivations)

Let  $\langle V, \Sigma, R, S \rangle$  be a grammar. A word  $v \in (V \cup \Sigma)^*$  can be **derived** from word  $u \in (V \cup \Sigma)^+$  (written as  $u \Rightarrow v$ ) if

- ①  $u = xyz$ ,  $v = xy'z$  with  $x, z \in (V \cup \Sigma)^*$  and
- ② there is a rule  $y \rightarrow y' \in R$ .

We write:  $u \Rightarrow^* v$  if  $v$  can be derived from  $u$  in finitely many steps (i. e., by using  $n$  derivations for  $n \in \mathbb{N}_0$ ).

**German:** Ableitung

# Language Generated by a Grammar

## Definition (Languages)

The **language generated** by a grammar  $G = \langle V, \Sigma, P, S \rangle$

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

is the set of all words from  $\Sigma^*$  that can be derived from  $S$  with finitely many rule applications.

German: erzeugte Sprache

# Grammars

## Example (Languages over $\Sigma = \{a, b\}$ )

- ▶  $L_1 = \{a, aa, aaa, aaaa, \dots\} = \{a\}^+$
- ▶  $L_2 = \Sigma^*$
- ▶  $L_3 = \{a^n b^n \mid n \geq 0\} = \{\varepsilon, ab, aabb, aaabbb, \dots\}$
- ▶  $L_4 = \{\varepsilon\}$
- ▶  $L_5 = \emptyset$
- ▶  $L_6 = \{w \in \Sigma^* \mid w \text{ contains twice as many as as bs}\}$   
 $= \{\varepsilon, aab, aba, baa, \dots\}$

## Example grammars: blackboard

# Exercise

Specify a grammar that generates language

$$L = \{w \in \{a, b\}^* \mid |w| = 3\}.$$



## B2.3 Chomsky Hierarchy

# Noam Chomsky

- ▶ Avram Noam Chomsky (\*1928)
- ▶ "the father of modern linguistics"
- ▶ American linguist, philosopher, cognitive scientist, social critic, and political activist
- ▶ combined linguistics, cognitive science and computer science
- ▶ opponent of U.S. involvement in the Vietnam war
- ▶ there is a wikipedia page solemnly on his political positions

→ Organized grammars into the Chomsky hierarchy.



CC BY 2.0 / Andrew Rusk

# Chomsky Hierarchy

## Definition (Chomsky Hierarchy)

- ▶ Every grammar is of **type 0** (all rules allowed).
- ▶ Grammar is of **type 1 (context-sensitive)**  
if all rules are of the form  $\alpha B \gamma \rightarrow \alpha \beta \gamma$   
with  $B \in V$  and  $\alpha, \gamma \in (V \cup \Sigma)^*$  and  $\beta \in (V \cup \Sigma)^+$
- ▶ Grammar is of **type 2 (context-free)**  
if all rules are of the form  $A \rightarrow w$ ,  
where  $A \in V$  and  $w \in (V \cup \Sigma)^*$ .
- ▶ Grammar is of **type 3 (regular)**  
if all rules are of the form  $A \rightarrow w$ ,  
where  $A \in V$  and  $w \in \Sigma \cup \Sigma V$ .

**special case:** rule  $S \rightarrow \varepsilon$  is always allowed if  $S$  is the start variable  
and never occurs on the right-hand side of any rule.

**German:** Chomsky-Hierarchie, Typ 0, Typ 1 (kontextsensitiv),  
Typ 2 (kontextfrei), Typ 3 (regulär)

# Chomsky Hierarchy

## Definition (Type 0–3 Languages)

A language  $L \subseteq \Sigma^*$  is of type 0 (type 1, type 2, type 3) if there exists a type-0 (type-1, type-2, type-3) grammar  $G$  with  $\mathcal{L}(G) = L$ .

# Type $k$ Language: Example (slido)

## Example

Consider the language  $L$  generated by the grammar

$\langle \{F, A, N, C, D\}, \{a, b, c, \neg, \wedge, \vee, (, )\}, R, F \rangle$   
with the following rules  $R$ :

$$F \rightarrow A$$

$$A \rightarrow a$$

$$N \rightarrow \neg F$$

$$F \rightarrow N$$

$$A \rightarrow b$$

$$C \rightarrow (F \wedge F)$$

$$F \rightarrow C$$

$$A \rightarrow c$$

$$D \rightarrow (F \vee F)$$

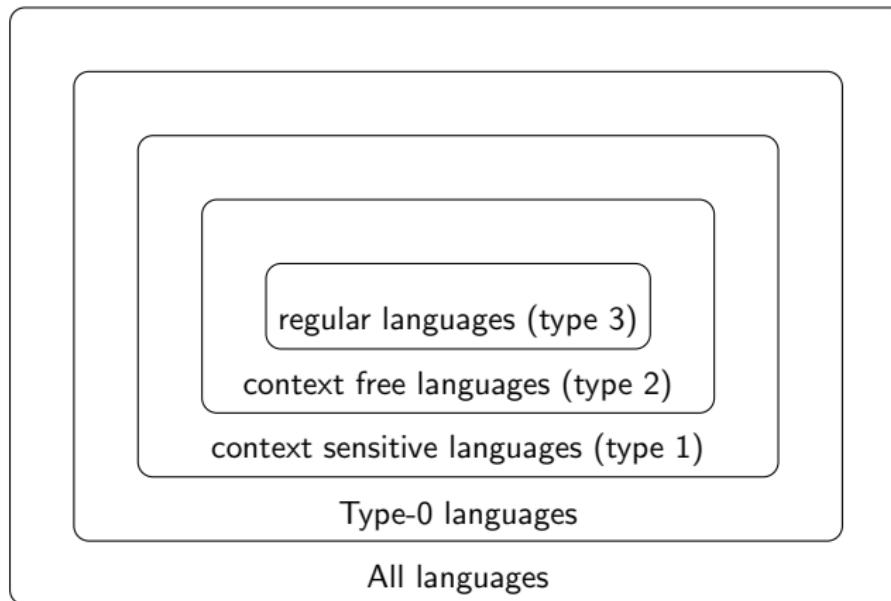
$$F \rightarrow D$$

## Questions:

- ▶ Is  $L$  a type-0 language?
- ▶ Is  $L$  a type-1 language?
- ▶ Is  $L$  a type-2 language?
- ▶ Is  $L$  a type-3 language?



# Chomsky Hierarchy



Note: Not all languages can be described by grammars. (Proof?)

## B2.4 Summary

# Summary

- ▶ **Languages** are sets of symbol sequences.
- ▶ **Grammars** are one possible way to specify languages.
- ▶ Language **generated** by a grammar is the set of all words (of terminal symbols) **derivable** from the start symbol.
- ▶ **Chomsky hierarchy** distinguishes between languages at different levels of expressiveness.