

# Theory of Computer Science

## C1. Formal Languages and Grammars

Gabriele Röger

University of Basel

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# C1.1 Introduction

# Course Contents

Parts of the course:

A. background ✓

▷ mathematical foundations and proof techniques

B. logic (Logik) ✓

▷ How can knowledge be represented?  
How can reasoning be automated?

C. automata theory and formal languages  
(Automatentheorie und formale Sprachen)

▷ What is a computation?

D. Turing computability (Turing-Berechenbarkeit)

▷ What can be computed at all?

E. complexity theory (Komplexitätstheorie)

▷ What can be computed efficiently?

F. more computability theory (mehr Berechenbarkeitstheorie)

▷ Other models of computability

# Example: Propositional Formulas

from the logic part:

## Definition (Syntax of Propositional Logic)

Let  $A$  be a set of **atomic propositions**. The set of **propositional formulas** (over  $A$ ) is inductively defined as follows:

- ▶ Every **atom**  $a \in A$  is a propositional formula over  $A$ .
- ▶ If  $\varphi$  is a propositional formula over  $A$ , then so is its **negation**  $\neg\varphi$ .
- ▶ If  $\varphi$  and  $\psi$  are propositional formulas over  $A$ , then so is the **conjunction**  $(\varphi \wedge \psi)$ .
- ▶ If  $\varphi$  and  $\psi$  are propositional formulas over  $A$ , then so is the **disjunction**  $(\varphi \vee \psi)$ .

## Example: Propositional Formulas

Let  $S_A$  be the set of all propositional formulas over  $A$ .

Such sets of symbol sequences (or **words**) are called **languages**.

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

- ▶ **today:** **grammars**
- ▶ **later:** automata

## Example: Propositional Formulas

### Example (Grammar for $S_{\{a,b,c\}}$ )

Grammar variables  $\{F, A, N, C, D\}$  with start variable  $F$ ,  
terminal symbols  $\{a, b, c, \neg, \wedge, \vee, (, )\}$  and rules

$$\begin{array}{lll}
 F \rightarrow A & A \rightarrow a & N \rightarrow \neg F \\
 F \rightarrow N & A \rightarrow b & C \rightarrow (F \wedge F) \\
 F \rightarrow C & A \rightarrow c & D \rightarrow (F \vee F) \\
 F \rightarrow D & & 
 \end{array}$$

Start with  $F$ . In each step, replace a left-hand side of a rule with its right-hand side until no more variables are left:

$$\begin{aligned}
 F &\Rightarrow N \Rightarrow \neg F \Rightarrow \neg D \Rightarrow \neg(F \vee F) \Rightarrow \neg(A \vee F) \Rightarrow \neg(b \vee F) \\
 &\Rightarrow \neg(b \vee A) \Rightarrow \neg(b \vee c)
 \end{aligned}$$

# C1.2 Alphabets and Formal Languages



# Alphabets and Formal Languages

## Definition (Alphabets, Words 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** (the empty sequence of elements) is denoted by  $\varepsilon$ .

$\Sigma^*$  denotes the set of all words over  $\Sigma$ .

$\Sigma^+$  ( $= \Sigma^* \setminus \{\varepsilon\}$ ) denotes the set of all non-empty words over  $\Sigma$ .

We write  $|w|$  for the **length** of a word  $w$ .

A **formal language** (over alphabet  $\Sigma$ ) is a subset of  $\Sigma^*$ .

**German:** Alphabet, Zeichen/Symbole, leeres Wort, formale Sprache

## Example

$$\Sigma = \{a, b\}$$

$$\Sigma^* = \{\varepsilon, a, b, aa, ab, ba, bb, \dots\}$$

$$|aba| = 3, |b| = 1, |\varepsilon| = 0$$

# Languages: Examples

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

- ▶  $S_1 = \{a, aa, aaa, aaaa, \dots\} = \{a\}^+$
- ▶  $S_2 = \Sigma^*$
- ▶  $S_3 = \{a^n b^n \mid n \geq 0\} = \{\varepsilon, ab, aabb, aaabbb, \dots\}$
- ▶  $S_4 = \{\varepsilon\}$
- ▶  $S_5 = \emptyset$
- ▶  $S_6 = \{w \in \Sigma^* \mid w \text{ contains twice as many } a\text{'s as } b\text{'s}\}$   
 $= \{\varepsilon, aab, aba, baa, \dots\}$
- ▶  $S_7 = \{w \in \Sigma^* \mid |w| = 3\}$   
 $= \{aaa, aab, aba, baa, bba, bab, abb, bbb\}$

## C1.3 Grammars

# Grammars

## Definition (Grammars)

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

- 1  $\Sigma$  finite alphabet of **terminal symbols**
- 2  $V$  finite set of **variables (nonterminal symbols)**  
with  $V \cap \Sigma = \emptyset$
- 3  $P \subseteq (V \cup \Sigma)^+ \times (V \cup \Sigma)^*$  finite set of **rules** (or productions)
- 4  $S \in V$  **start variable**

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

# Rule Sets

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

- ▶  $(V \cup \Sigma)^*$ : all words over  $(V \cup \Sigma)$
- ▶  $(V \cup \Sigma)^+$ : all non-empty words over  $(V \cup \Sigma)$   
in general, for set  $X$ :  $X^+ = X^* \setminus \{\varepsilon\}$
- ▶  $\times$ : Cartesian product
- ▶  $(V \cup \Sigma)^+ \times (V \cup \Sigma)^*$ : set of all pairs  $\langle x, y \rangle$ , where  $x$  non-empty word over  $(V \cup \Sigma)$  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  $(V \cup \Sigma)^+ \times (V \cup \Sigma)^*$ :

$$X \rightarrow XaY$$

$$Yb \rightarrow a$$

$$XY \rightarrow \varepsilon$$

$$XYZ \rightarrow abc$$

$$abc \rightarrow XYZ$$

# Derivations

## Definition (Derivations)

Let  $\langle \Sigma, V, P, S \rangle$  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  $y \rightarrow y' \in P$ .

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  $G = \langle \Sigma, V, P, S \rangle$

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

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

**German:** erzeugte Sprache



# Grammars

Examples: blackboard

# C1.4 Chomsky Hierarchy

# Chomsky Hierarchy

Grammars are organized into the **Chomsky hierarchy**.

## Definition (Chomsky Hierarchy)

- ▶ Every grammar is of **type 0** (all rules allowed).
- ▶ Grammar is of **type 1** (**context-sensitive**) if all rules  $w_1 \rightarrow w_2$  satisfy  $|w_1| \leq |w_2|$ .
- ▶ Grammar is of **type 2** (**context-free**) if additionally  $w_1 \in V$  (single variable) in all rules  $w_1 \rightarrow w_2$ .
- ▶ Grammar is of **type 3** (**regular**) if additionally  $w_2 \in \Sigma \cup \Sigma V$  in all rules  $w_1 \rightarrow w_2$ .

**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

## Example

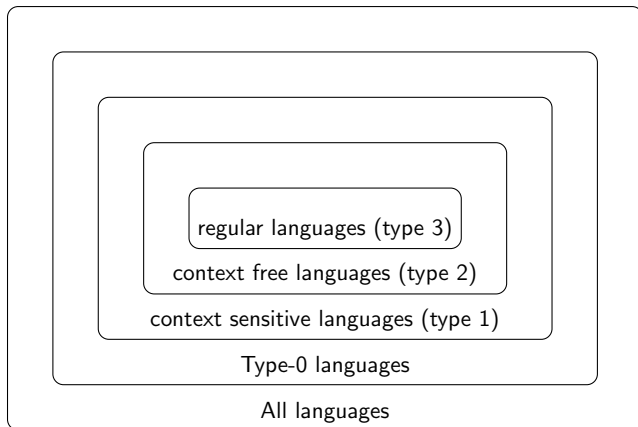
Consider the language  $L$  generated by the grammar  $\langle \{a, b, c, \neg, \wedge, \vee, (, )\}, \{F, A, N, C, D\}, P, F \rangle$  with the following rules  $P$ :

$$\begin{array}{lll} F \rightarrow A & A \rightarrow a & N \rightarrow \neg F \\ F \rightarrow N & A \rightarrow b & C \rightarrow (F \wedge F) \\ F \rightarrow C & A \rightarrow c & D \rightarrow (F \vee F) \\ F \rightarrow D & & \end{array}$$

## 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?](#))

# C1.5 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.

following chapters:

- ▶ more about regular languages
- ▶ automata as alternative representation of languages