

Foundations of Informatics: a Bridging Course

Week 3: Formal Languages and Semantics

Part A: Regular Languages

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<http://cosec.bit.uni-bonn.de/students/teaching/10us/10us-bridgingcourse/>
<http://www-i2.informatik.rwth-aachen.de/i2/b-it10/>

b-it, Bonn, Winter semester 2010/11

- Schedule:
 - lecture 9:00-10:30, 11:00-12:30 (Mon-Fri)
 - 9:30-11:00, 11:15-12:45?
 - exercises 14:00-14:45, 15:15-16:00 (Mon-Thu)
 - 14:00-15:30?
- Examination at end of week 4 (April 1st)
- Please ask questions!

- ① Regular Languages
- ② Context-Free Languages
- ③ Processes and Concurrency

- J.E. Hopcroft, R. Motwani, J.D. Ullmann: *Introduction to Automata Theory, Languages, and Computation*, 2nd ed., Addison-Wesley, 2001
- A. Asteroth, C. Baier: *Theoretische Informatik*, Pearson Studium, 2002 [in German]
- <http://www.jflap.org/>
(software for experimenting with automata formal languages and automata)

1 Formal Languages

2 Finite Automata

- Deterministic Finite Automata
- Operations on Languages and Automata
- Nondeterministic Finite Automata
- More Decidability Results

3 Regular Expressions

4 The Pumping Lemma

5 Outlook

- Computer systems transform data
- Data encoded as (binary) **words**

⇒ Data sets = sets of words = **formal languages**,
data transformations = **functions on words**

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⇒ Data sets = sets of words = **formal languages**,
data transformations = **functions on words**

Example A.1

Java = {all valid Java programs},

Compiler : $\text{Java} \rightarrow \text{Bytecode}$

The atomic elements of words are called symbols (or letters).

Definition A.2

An **alphabet** is a finite, non-empty set of symbols (“letters”).

Σ, Γ, \dots denote alphabets

a, b, \dots denote letters

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- ➋ Latin alphabet $\Sigma_{\text{latin}} := \{a, b, c, \dots, z\}$

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- ❹ Morse alphabet $\Sigma_{\text{morse}} := \{\cdot, -, \sqcup\}$

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- The **concatenation** of two words $v = a_1 \dots a_m$ ($m \in \mathbb{N}$) and $w = b_1 \dots b_n$ ($n \in \mathbb{N}$) is the word

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- If $w = a_1 \dots a_n$, then $w^R := a_n \dots a_1$.

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- ① over $\mathbb{B} = \{0, 1\}$: set of all bit strings containing 1101
- ② over $\Sigma = \{I, V, X, L, C, D, M\}$: set of all valid roman numbers
- ③ over Σ_{key} : set of all valid Java programs

Seen:

- Basic notions: alphabets, words
- Formal languages as sets of words

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- Formal languages as sets of words

Open:

- Description of computations on words?

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Example: Pattern Matching

Example A.7 (Pattern 1101)

- ① Read Boolean string bit by bit
- ② Test whether it contains 1101
- ③ Idea: remember which (initial) part of 1101 has been recognized
- ④ Five prefixes: ε , 1, 11, 110, 1101
- ⑤ Diagram: on the board

Example: Pattern Matching

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- ⑤ Diagram: on the board

What we used:

- finitely many (storage) states
- an initial state
- for every current state and every input symbol: a new state
- a successful state

Definition A.8

A deterministic finite automaton (DFA) is of the form

$$\mathfrak{A} = \langle Q, \Sigma, \delta, q_0, F \rangle$$

where

- Q is a finite set of **states**
- Σ denotes the **input alphabet**
- $\delta : Q \times \Sigma \rightarrow Q$ is the **transition function**
- $q_0 \in Q$ is the **initial state**
- $F \subseteq Q$ is the set of **final** (or: **accepting**) **states**

Example A.9

Pattern matching (Example A.7):

- $Q = \{q_0, \dots, q_4\}$
- $\Sigma = \mathbb{B} = \{0, 1\}$
- $\delta : Q \times \Sigma \rightarrow Q$ on the board
- $F = \{q_4\}$

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- $\Sigma = \mathbb{B} = \{0, 1\}$
- $\delta : Q \times \Sigma \rightarrow Q$ on the board
- $F = \{q_4\}$

Graphical Representation of DFA:

- states \Rightarrow nodes
- $\delta(q, a) = q' \Rightarrow q \xrightarrow{a} q'$
- initial state: incoming edge without source state
- final state(s): double circle

Definition A.10

Let $\langle Q, \Sigma, \delta, q_0, F \rangle$ be a DFA. The **extension** of $\delta : Q \times \Sigma \rightarrow Q$,

$$\delta^* : Q \times \Sigma^* \rightarrow Q,$$

is defined by

$$\delta^*(q, w) := \text{state after reading } w \text{ in } q.$$

Formally:

$$\delta^*(q, w) := \begin{cases} q & \text{if } w = \varepsilon \\ \delta^*(\delta(q, a), v) & \text{if } w = av \end{cases}$$

Thus: if $w = a_1 \dots a_n$ and $q \xrightarrow{a_1} q_1 \xrightarrow{a_2} \dots \xrightarrow{a_n} q_n$, then $\delta^*(q, w) = q_n$

Acceptance by DFA I

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Example A.11

Pattern matching (Example A.9): on the board

Definition A.12

- \mathfrak{A} **accepts** $w \in \Sigma^*$ if $\delta^*(q_0, w) \in F$.
- The **language recognized** (or: accepted) by \mathfrak{A} is

$$L(\mathfrak{A}) := \{w \in \Sigma^* \mid \delta^*(q_0, w) \in F\}.$$

- A language $L \subseteq \Sigma^*$ is called **DFA-recognizable** if there exists some DFA \mathfrak{A} such that $L(\mathfrak{A}) = L$.
- Two DFA $\mathfrak{A}_1, \mathfrak{A}_2$ are called **equivalent** if

$$L(\mathfrak{A}_1) = L(\mathfrak{A}_2).$$

Example A.13

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on the board

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- ② Two (equivalent) automata recognizing the language

$$\{w \in \mathbb{B}^* \mid w \text{ contains } 1\} :$$

on the board

- ③ An automaton which recognizes

$$\{w \in \{0, \dots, 9\}^* \mid \text{value of } w \text{ divisible by } 3\}$$

Idea: test whether sum of digits is divisible by 3 – one state for each residue class (on the board)

Seen:

- Deterministic finite automata as a model of simple sequential computations
- Recognizability of formal languages by automata

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- Deterministic finite automata as a model of simple sequential computations
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Open:

- Composition and transformation of automata?
- Which languages are recognizable, which are not (alternative characterization)?
- Language definition \mapsto automaton and vice versa?

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Simplest case: Boolean operations (complement, intersection, union)

Question

Let $\mathfrak{A}_1, \mathfrak{A}_2$ be two DFA with $L(\mathfrak{A}_1) = L_1$ and $L(\mathfrak{A}_2) = L_2$.

Can we construct automata which recognize

- $\overline{L_1}$ ($:= \Sigma^* \setminus L_1$),
- $L_1 \cap L_2$, and
- $L_1 \cup L_2$?

Theorem A.14

If $L \subseteq \Sigma^$ is DFA-recognizable, then so is \overline{L} .*

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Proof.

Let $\mathfrak{A} = \langle Q, \Sigma, \delta, q_0, F \rangle$ be a DFA such that $L(\mathfrak{A}) = L$. Then:

$$w \in \overline{L} \iff w \notin L \iff \delta^*(q_0, w) \notin F \iff \delta^*(q_0, w) \in Q \setminus F.$$

Thus, \overline{L} is recognized by the DFA $\langle Q, \Sigma, \delta, q_0, Q \setminus F \rangle$. □

Language Complement

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$$w \in \overline{L} \iff w \notin L \iff \delta^*(q_0, w) \notin F \iff \delta^*(q_0, w) \in Q \setminus F.$$

Thus, \overline{L} is recognized by the DFA $\langle Q, \Sigma, \delta, q_0, Q \setminus F \rangle$. □

Example A.15

on the board

Theorem A.16

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Theorem A.16

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Proof.

Let $\mathfrak{A}_i = \langle Q_i, \Sigma, \delta_i, q_0^i, F_i \rangle$ be DFA such that $L(\mathfrak{A}_i) = L_i$ ($i = 1, 2$). The new automaton \mathfrak{A} has to accept w iff *both* \mathfrak{A}_1 and \mathfrak{A}_2 accept w

Idea: let \mathfrak{A}_1 and \mathfrak{A}_2 run in parallel

- use pairs of states $(q_1, q_2) \in Q_1 \times Q_2$
- start with both components in initial state
- a transition updates both components independently
- for acceptance both components need to be in a final state



Proof (continued).

Formally: let the **product automaton**

$$\mathfrak{A} := \langle Q_1 \times Q_2, \Sigma, \delta, (q_0^1, q_0^2), F_1 \times F_2 \rangle$$

be defined by

$$\delta((q_1, q_2), a) := (\delta_1(q_1, a), \delta_2(q_2, a)) \text{ for every } a \in \Sigma.$$

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This definition yields

$$\delta^*((q_1, q_2), w) = (\delta_1^*(q_1, w), \delta_2^*(q_2, w)) \quad (*)$$

for every $w \in \Sigma^*$.

Proof (continued).

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for every $w \in \Sigma^*$.

Thus we have:

$$\begin{aligned} & \mathfrak{A} \text{ accepts } w \\ \iff & \delta^*((q_0^1, q_0^2), w) \in F_1 \times F_2 \\ \stackrel{(*)}{\iff} & (\delta_1^*(q_0^1, w), \delta_2^*(q_0^2, w)) \in F_1 \times F_2 \\ \iff & \delta_1^*(q_0^1, w) \in F_1 \text{ and } \delta_2^*(q_0^2, w) \in F_2 \\ \iff & \mathfrak{A}_1 \text{ accepts } w \text{ and } \mathfrak{A}_2 \text{ accepts } w \end{aligned}$$



Example A.17

on the board

Theorem A.18

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Idea: reuse product construction

Construct \mathfrak{A} as before but choose as final states those pairs $(q_1, q_2) \in Q_1 \times Q_2$ with $q_1 \in F_1$ or $q_2 \in F_2$. Thus the set of final states is given by

$$F := (F_1 \times Q_2) \cup (Q_1 \times F_2).$$



Definition A.19

The **concatenation** of two languages $L_1, L_2 \subseteq \Sigma^*$ is given by

$$L_1 \cdot L_2 := \{v \cdot w \in \Sigma^* \mid v \in L_1, w \in L_2\}.$$

Abbreviations: $w \cdot L := \{w\} \cdot L$, $L \cdot w := L \cdot \{w\}$

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Example A.20

- ① If $L_1 = \{101, 1\}$ and $L_2 = \{011, 1\}$, then

$$L_1 \cdot L_2 = \{101011, 1011, 11\}.$$

Language Concatenation

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- ① If $L_1 = \{101, 1\}$ and $L_2 = \{011, 1\}$, then

$$L_1 \cdot L_2 = \{101011, 1011, 11\}.$$

- ② If $L_1 = 00 \cdot \mathbb{B}^*$ and $L_2 = 11 \cdot \mathbb{B}^*$, then

$$L_1 \cdot L_2 = \{w \in \mathbb{B}^* \mid w \text{ has prefix 00 and contains 11}\}.$$

Conjecture

If $L_1, L_2 \subseteq \Sigma^*$ are DFA-recognizable, then so is $L_1 \cdot L_2$.

DFA-Recognizability of Concatenation

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Proof (attempt).

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Idea: choose $Q := Q_1 \cup Q_2$ where each $q \in F_1$ is identified with q_0^2

But: on the board



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But: on the board



Conclusion

Required: automata model where the successor state (for a given state and input symbol) is not unique

Definition A.21

- The ***nth power*** of a language $L \subseteq \Sigma^*$ is the n -fold composition of L with itself ($n \in \mathbb{N}$):

$$L^n := \underbrace{L \cdot \dots \cdot L}_{n \text{ times}} = \{w_1 \dots w_n \mid \forall i \in \{1, \dots, n\} : w_i \in L\}.$$

Inductively: $L^0 := \{\varepsilon\}$, $L^{n+1} := L^n \cdot L$

- The ***iteration*** (or: ***Kleene star***) of L is

$$L^* := \bigcup_{n \in \mathbb{N}} L^n = \{w_1 \dots w_n \mid n \in \mathbb{N}, \forall i \in \{1, \dots, n\} : w_i \in L\}.$$

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Remarks:

- we always have $\varepsilon \in L^*$ (since $L^0 \subseteq L^*$ and $L^0 = \{\varepsilon\}$)
- $w \in L^*$ iff $w = \varepsilon$ or if w can be decomposed into $n \geq 1$ subwords v_1, \dots, v_n (i.e., $w = v_1 \cdot \dots \cdot v_n$) such that $v_i \in L$ for every $1 \leq i \leq n$
- again we would suspect that the iteration of a DFA-recognizable language is DFA-recognizable, but there is no simple (deterministic) construction

Seen:

- Operations on languages:
 - complement
 - intersection
 - union
 - concatenation
 - iteration
- DFA constructions for:
 - complement
 - intersection
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Open:

- Automata model for (direct implementation of) concatenation and iteration?

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Idea:

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- an input word generally induces several state sequences (“runs”)
- the word is accepted if at least one accepting run exists

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- the word is accepted if at least one accepting run exists

Advantages:

- simplifies representation of languages
(example: $\mathbb{B}^* \cdot 1101 \cdot \mathbb{B}^*$; on the board)
- yields direct constructions for concatenation and iteration of languages
- more adequate modeling of systems with nondeterministic behaviour (communication protocols, multi-agent systems, ...)

Definition A.22

A **nondeterministic finite automaton (NFA)** is of the form

$$\mathfrak{A} = \langle Q, \Sigma, \Delta, q_0, F \rangle$$

where

- Q is a finite set of **states**
- Σ denotes the **input alphabet**
- $\Delta \subseteq Q \times \Sigma \times Q$ is the **transition relation**
- $q_0 \in Q$ is the **initial state**
- $F \subseteq Q$ is the set of **final states**

Definition A.22

A **nondeterministic finite automaton (NFA)** is of the form

$$\mathfrak{A} = \langle Q, \Sigma, \Delta, q_0, F \rangle$$

where

- Q is a finite set of **states**
- Σ denotes the **input alphabet**
- $\Delta \subseteq Q \times \Sigma \times Q$ is the **transition relation**
- $q_0 \in Q$ is the **initial state**
- $F \subseteq Q$ is the set of **final states**

Remarks:

- $(q, a, q') \in \Delta$ usually written as $q \xrightarrow{a} q'$
- every DFA can be considered as an NFA
 $((q, a, q') \in \Delta \iff \delta(q, a) = q')$

Definition A.23

- Let $w = a_1 \dots a_n \in \Sigma^*$.
- A w -labeled **\mathfrak{A} -run** from q_1 to q_2 is a sequence

$$p_0 \xrightarrow{a_1} p_1 \xrightarrow{a_2} \dots p_{n-1} \xrightarrow{a_n} p_n$$

such that $p_0 = q_1$, $p_n = q_2$, and $(p_{i-1}, a_i, p_i) \in \Delta$ for every $1 \leq i \leq n$ (we also write: $q_1 \xrightarrow{w} q_2$).

- \mathfrak{A} **accepts** w if there is a w -labeled \mathfrak{A} -run from q_0 to some $q \in F$
- The **language recognized** by \mathfrak{A} is

$$L(\mathfrak{A}) := \{w \in \Sigma^* \mid \mathfrak{A} \text{ accepts } w\}.$$

- A language $L \subseteq \Sigma^*$ is called **NFA-recognizable** if there exists a NFA \mathfrak{A} such that $L(\mathfrak{A}) = L$.
- Two NFA $\mathfrak{A}_1, \mathfrak{A}_2$ are called **equivalent** if $L(\mathfrak{A}_1) = L(\mathfrak{A}_2)$.

Acceptance Test for NFA

Algorithm A.24 (Acceptance Test for NFA)

Input: NFA $\mathfrak{A} = \langle Q, \Sigma, \Delta, q_0, F \rangle$, $w \in \Sigma^*$

Question: $w \in L(\mathfrak{A})$?

Procedure: Computation of the *reachability set*

$$R_{\mathfrak{A}}(w) := \{q \in Q \mid q_0 \xrightarrow{w} q\}$$

Iterative procedure for $w = a_1 \dots a_n$:

① let $R_{\mathfrak{A}}(\varepsilon) := \{q_0\}$

② for $i := 1, \dots, n$: let

$$R_{\mathfrak{A}}(a_1 \dots a_i) := \{q \in Q \mid \exists p \in R_{\mathfrak{A}}(a_1 \dots a_{i-1}) : p \xrightarrow{a_i} q\}$$

Output: “yes” if $R_{\mathfrak{A}}(w) \cap F \neq \emptyset$, otherwise “no”

Remark: this algorithm solves the *word problem* for NFA

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Output: “yes” if $R_{\mathfrak{A}}(w) \cap F \neq \emptyset$, otherwise “no”

Remark: this algorithm solves the *word problem* for NFA

Example A.25

on the board

Definition of NFA looks promising, but... (on the board)

Definition of NFA looks promising, but... (on the board)

Solution: admit empty word ε as transition label

Definition A.26

A nondeterministic finite automaton with ε -transitions (ε -NFA) is of the form $\mathfrak{A} = \langle Q, \Sigma, \Delta, q_0, F \rangle$ where

- Q is a finite set of **states**
- Σ denotes the **input alphabet**
- $\Delta \subseteq Q \times \Sigma_\varepsilon \times Q$ is the **transition relation** where $\Sigma_\varepsilon := \Sigma \cup \{\varepsilon\}$
- $q_0 \in Q$ is the **initial state**
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Remarks:

- every NFA is an ε -NFA
- definitions of runs and acceptance: in analogy to NFA

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Remarks:

- every NFA is an ε -NFA
- definitions of runs and acceptance: in analogy to NFA

Example A.27

on the board

Theorem A.28

If $L_1, L_2 \subseteq \Sigma^$ are ε -NFA-recognizable, then so is $L_1 \cdot L_2$.*

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Proof (idea).

on the board



Theorem A.29

If $L \subseteq \Sigma^$ is ε -NFA-recognizable, then so is L^* .*

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Proof (idea).

on the board



Syntax diagrams (without recursive calls) can be interpreted as ε -NFA

Example A.30

decimal numbers (on the board)

Types of Finite Automata

- ① DFA
- ② NFA
- ③ ε -NFA

- ① DFA
- ② NFA
- ③ ε -NFA

Corollary A.31

- ① *Every DFA-recognizable language is NFA-recognizable.*
- ② *Every NFA-recognizable language is ε -NFA-recognizable.*

- ① DFA
- ② NFA
- ③ ε -NFA

Corollary A.31

- ① *Every DFA-recognizable language is NFA-recognizable.*
- ② *Every NFA-recognizable language is ε -NFA-recognizable.*

Goal: establish reverse inclusions

Theorem A.32

Every NFA can be transformed into an equivalent DFA.

Theorem A.32

Every NFA can be transformed into an equivalent DFA.

Proof.

Idea: let the DFA operate on **sets of states** (“powerset construction”)

- Initial state of DFA := {initial state of NFA}
- $P \xrightarrow{a} P'$ in DFA iff there exist $q \in P, q' \in P'$ such that $q \xrightarrow{a} q'$ in NFA
- P final state in DFA iff it contains some final state of NFA



Proof (continued).

Let $\mathfrak{A} = \langle Q, \Sigma, \Delta, q_0, F \rangle$ be a NFA.

Powerset construction of $\mathfrak{A}' = \langle Q', \Sigma, \delta', q'_0, F' \rangle$:

- $Q' := 2^Q := \{P \mid P \subseteq Q\}$
- $\delta' : Q' \times \Sigma \rightarrow Q'$ with
$$q \in \delta'(P, a) \iff \text{there exists } p \in P \text{ such that } (p, a, q) \in \Delta$$
- $q'_0 := \{q_0\}$
- $F' := \{P \subseteq Q \mid P \cap F \neq \emptyset\}$

This yields

$$q_0 \xrightarrow{w} q \text{ in } \mathfrak{A} \iff q \in \delta'^*(\{q_0\}, w) \text{ in } \mathfrak{A}'$$

and thus

$$\mathfrak{A} \text{ accepts } w \iff \mathfrak{A}' \text{ accepts } w$$



Proof (continued).

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Example A.33

on the board

Theorem A.34

Every ε -NFA can be transformed into an equivalent NFA.

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Proof (idea).

Let \mathfrak{A} be a ε -NFA. We construct the NFA \mathfrak{A}' by eliminating all ε -transitions, adding appropriate direct transitions: if $p \xrightarrow{\varepsilon}^* q$, $q \xrightarrow{a} q'$, and $q' \xrightarrow{\varepsilon}^* r$ in \mathfrak{A} , then $p \xrightarrow{a} r$ in \mathfrak{A}' .

□

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Example A.35

on the board

From ε -NFA to NFA

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Proof (idea).

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Example A.35

on the board

Corollary A.36

All types of finite automata recognize the same class of languages.

Seen:

- Definition of ε -NFA
- Determinization of (ε -)NFA

Seen:

- Definition of ε -NFA
- Determinization of (ε -)NFA

Open:

- More decidability results

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Definition A.37

The **word problem for DFA** is specified as follows:

Given a DFA \mathfrak{A} and a word $w \in \Sigma^*$, decide whether

$$w \in L(\mathfrak{A}).$$

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As we have seen (Def. A.10, Alg. A.24, Thm. A.34):

Theorem A.38

*The word problem for DFA (NFA, ε -NFA) is **decidable**.*

Definition A.39

The **emptiness problem for DFA** is specified as follows:

Given a DFA \mathfrak{A} , decide whether

$$L(\mathfrak{A}) = \emptyset.$$

The Emptiness Problem

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Theorem A.40

*The emptiness problem for DFA (NFA, ε -NFA) is **decidable**.*

Proof.

It holds that $L(\mathfrak{A}) \neq \emptyset$ iff in \mathfrak{A} some final state is reachable from the initial state (simple graph-theoretic problem). □

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It holds that $L(\mathfrak{A}) \neq \emptyset$ iff in \mathfrak{A} some final state is reachable from the initial state (simple graph-theoretic problem). □

Remark: important result for formal verification (unreachability of bad (= final) states)

Definition A.41

The **equivalence problem for DFA** is specified as follows:

Given two DFA $\mathfrak{A}_1, \mathfrak{A}_2$, decide whether

$$L(\mathfrak{A}_1) = L(\mathfrak{A}_2).$$

The Equivalence Problem

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Theorem A.42

*The equivalence problem for DFA (NFA, ϵ -NFA) is **decidable**.*

Proof.

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*The equivalence problem for DFA (NFA, ε -NFA) is **decidable**.*

Proof.

$$\begin{aligned} & L(\mathfrak{A}_1) = L(\mathfrak{A}_2) \\ \iff & L(\mathfrak{A}_1) \subseteq L(\mathfrak{A}_2) \text{ and } L(\mathfrak{A}_2) \subseteq L(\mathfrak{A}_1) \end{aligned}$$

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Seen:

- Decidability of word problem
- Decidability of emptiness problem
- Decidability of equivalence problem

Seen:

- Decidability of word problem
- Decidability of emptiness problem
- Decidability of equivalence problem

Open:

- Non-algorithmic description of languages

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Example A.43

Consider the set of all words over $\Sigma := \{a, b\}$ which

- ① start with one or three a symbols
- ② continue with a (potentially empty) sequence of blocks, each containing at least one b and exactly two a 's
- ③ conclude with a (potentially empty) sequence of b 's

Corresponding **regular expression**:

$$(a + aaa)(\underbrace{bb^*ab^*ab^*}_{b \text{ before } a's} + \underbrace{b^*abb^*ab^*}_{b \text{ between } a's} + \underbrace{b^*ab^*abb^*}_{b \text{ after } a's})^*b^*$$

Definition A.44

The set of **regular expressions** over Σ is inductively defined by:

- \emptyset and ε are regular expressions
- every $a \in \Sigma$ is a regular expression
- if α and β are regular expressions, then so are
 - $\alpha + \beta$
 - $\alpha \cdot \beta$
 - α^*

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 - $\alpha + \beta$
 - $\alpha \cdot \beta$
 - α^*

Notation:

- \cdot can be omitted
- $*$ binds stronger than \cdot , \cdot binds stronger than $+$
- α^+ abbreviates $\alpha \cdot \alpha^*$

Definition A.45

Every regular expression α defines a language $L(\alpha)$:

$$L(\emptyset) := \emptyset$$

$$L(\varepsilon) := \{\varepsilon\}$$

$$L(a) := \{a\}$$

$$L(\alpha + \beta) := L(\alpha) \cup L(\beta)$$

$$L(\alpha \cdot \beta) := L(\alpha) \cdot L(\beta)$$

$$L(\alpha^*) := (L(\alpha))^*$$

Definition A.45

Every regular expression α defines a language $L(\alpha)$:

$$\begin{aligned}L(\emptyset) &:= \emptyset \\L(\varepsilon) &:= \{\varepsilon\} \\L(a) &:= \{a\} \\L(\alpha + \beta) &:= L(\alpha) \cup L(\beta) \\L(\alpha \cdot \beta) &:= L(\alpha) \cdot L(\beta) \\L(\alpha^*) &:= (L(\alpha))^*\end{aligned}$$

A language L is called **regular** if it is definable by a regular expression, i.e., if $L = L(\alpha)$ for some regular expression α .

Example A.46

- ① $\{aa\}$ is regular since

$$L(a \cdot a) = L(a) \cdot L(a) = \{a\} \cdot \{a\} = \{aa\}$$

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- ② $\{a, b\}^*$ is regular since

$$L((a + b)^*) = (L(a + b))^* = (L(a) \cup L(b))^* = (\{a\} \cup \{b\})^* = \{a, b\}^*$$

Example A.46

- ① $\{aa\}$ is regular since

$$L(a \cdot a) = L(a) \cdot L(a) = \{a\} \cdot \{a\} = \{aa\}$$

- ② $\{a, b\}^*$ is regular since

$$L((a + b)^*) = (L(a + b))^* = (L(a) \cup L(b))^* = (\{a\} \cup \{b\})^* = \{a, b\}^*$$

- ③ The set of all words over $\{a, b\}$ containing abb is regular since

$$L((a + b)^* \cdot a \cdot b \cdot b \cdot (a + b)^*) = \{a, b\}^* \cdot \{abb\} \cdot \{a, b\}^*$$

Theorem A.47 (Kleene's Theorem)

To each regular expression there corresponds an ε -NFA, and vice versa.

Theorem A.47 (Kleene's Theorem)

To each regular expression there corresponds an ε -NFA, and vice versa.

Proof.

- ⇒ using induction over the given regular expression α , we construct an ε -NFA \mathfrak{A}_α
 - with exactly one final state q_f
 - without transitions into the initial state
 - without transitions leaving the final state
(on the board)
- ⇐ by solving a regular equation system (details omitted)



Corollary A.48

The following properties are equivalent:

- L is regular
- L is DFA-recognizable
- L is NFA-recognizable
- L is ε -NFA-recognizable

Implementation of Pattern Matching

Algorithm A.49 (Pattern Matching)

Input: regular expression α and $w \in \Sigma^*$

Question: does w contain some $v \in L(\alpha)$?

Procedure: ① let $\beta := (a_1 + \dots + a_n)^* \cdot \alpha$ (for $\Sigma = \{a_1, \dots, a_n\}$)

② determine ε -NFA \mathfrak{A}_β for β

③ eliminate ε -transitions

④ apply powerset construction to obtain DFA \mathfrak{A}

⑤ let \mathfrak{A} run on w

Output: “yes” if \mathfrak{A} passes through some final state, otherwise “no”

Remark: in UNIX/LINUX implemented by `grep` and `lex`

Regular Expressions in UNIX (grep, flex, ...)

Syntax	Meaning
printable character	this character
\n, \t, \123, etc.	newline, tab, octal representation, etc.
.	any character except \n
[<i>Chars</i>]	one of <i>Chars</i> ; ranges possible ("0-9")
[^ <i>Chars</i>]	none of <i>Chars</i>
\\", \., \[, etc.	\, ., [, etc.
" <i>Text</i> "	<i>Text</i> without interpretation of ., [, \, etc.
^ α	α at beginning of line
α \$	α at end of line
α ?	zero or one α
α *	zero or more α
α +	one or more α
$\alpha\{n,m\}$	between n and m times α (" m " optional)
(α)	α
$\alpha_1\alpha_2$	concatenation
$\alpha_1 \alpha_2$	alternative
α_1/α_2	α_1 but only if followed by α_2 (lookahead)

Seen:

- Definition of regular expressions
- Equivalence of regular and DFA-recognizable languages

Seen:

- Definition of regular expressions
- Equivalence of regular and DFA-recognizable languages

Open:

- Limitations of regular languages?

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Observation: a language L is DFA-recognizable (and thus regular) if the membership of a word w can be tested by **symbol-wise reading** of w , using a **bounded memory**

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Conjecture: languages of the form $\{a^n b^n \mid n \in \mathbb{N}\}$ are not regular since the test for membership requires the capability of comparing the number of a symbols to the number of b symbols (which can grow arbitrarily large)

Theorem A.50 (Pumping Lemma for Regular Languages)

*If L is regular, then there exists $n \geq 1$ (called **pumping index**) such that any $w \in L$ with $|w| \geq n$ can be decomposed as $w = xyz$ where*

- $y \neq \varepsilon$ and
- for every $i \geq 0$, $xy^i z \in L$

The Pumping Lemma II

Proof (idea).

Let $\mathfrak{A} = \langle Q, \Sigma, \delta, q_0, F \rangle$ be a DFA such that $L(\mathfrak{A}) = L$. Choose $n := |Q|$, and let $w \in L$.

Then: $w = a_1 \dots a_k$ with $k \geq n$

\implies the accepting run visits $k + 1 \geq n + 1$ states:

$$q_0 \xrightarrow{a_1} q_1 \xrightarrow{a_2} \dots \xrightarrow{a_k} q_k$$

\implies some state in Q occurs (at least) twice:

there exist $1 \leq i < j \leq k$ such that $q_i = q_j$

Choose $y := a_{i+1} \dots a_j$ to be the substring which is read between the two visits of q . Clearly, $y \neq \varepsilon$. Moreover the cycle can be omitted or repeated such that $xz \in L$, $xyz \in L$, $xy^2z \in L$, ...

□

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Proof (idea).

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□

Remark: Pumping Lemma states a **necessary condition** for regularity

\implies can only be used to show the **non-regularity** of a language

Example A.51

① $L := \{a^k b^k \mid k \in \mathbb{N}\}$ is not regular. Proof by contradiction:
Assume that L is regular, and let n be a pumping index. Consider $w := a^n b^n$. Since $|w| \geq n$, it can be decomposed as $w = xyz$ with $y \neq \varepsilon$. The following cases are possible:

- $y \in L(a^+)$: then $xy^2z \notin L$ (more as than bs)
- $y \in L(b^+)$: then $xy^2z \notin L$ (less as than bs)
- $y \in L(a^+b^+)$: then $xy^2z \notin L$ (a follows b)

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- ➋ Similarly: the set of all arithmetic expressions is not regular

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 - $y \in L(a^+)$: then $xy^2z \notin L$ (more as than bs)
 - $y \in L(b^+)$: then $xy^2z \notin L$ (less as than bs)
 - $y \in L(a^+b^+)$: then $xy^2z \notin L$ (a follows b)
- ➋ Similarly: the set of all arithmetic expressions is not regular

Conclusion

Finite automata are **too weak** for defining the syntax of programming languages ($a = "(", b = ")"$)!

Seen:

- Necessary condition for regularity of languages
- Counterexamples

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Open:

- More expressive formalisms for describing languages?

1 Formal Languages

2 Finite Automata

- Deterministic Finite Automata
- Operations on Languages and Automata
- Nondeterministic Finite Automata
- More Decidability Results

3 Regular Expressions

4 The Pumping Lemma

5 Outlook

- **Minimization** of DFA
- More **language operations** (reversion, homomorphisms, ...)
- Construction of **scanners** for compilers