

Theory of Computer Science

B3. Finite Automata

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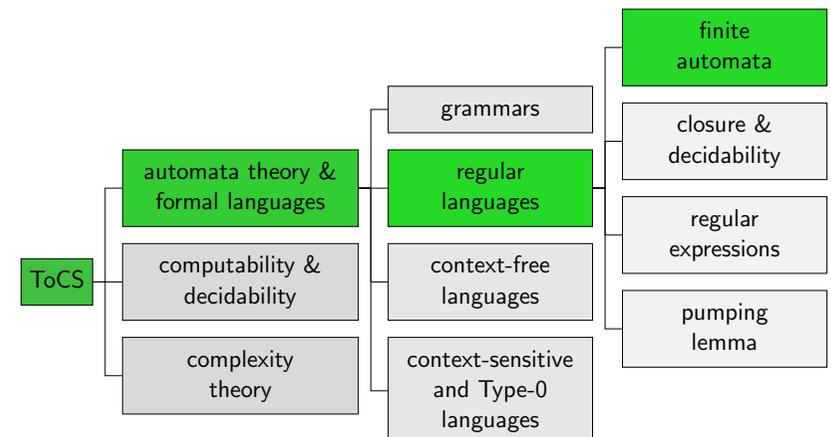
B3.1 Introduction

B3.2 DFAs

B3.3 NFAs

B3.1 Introduction

Content of the Course

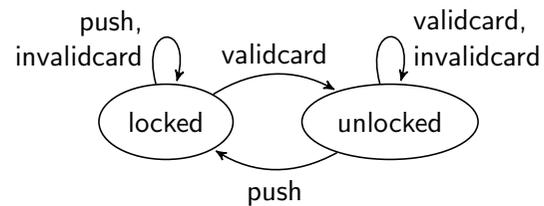


A Controller for a Turnstile



CC BY-SA 3.0, author: Stolbovsky

- ▶ simple access control
- ▶ card reader and push sensor
- ▶ card can either be valid or invalid



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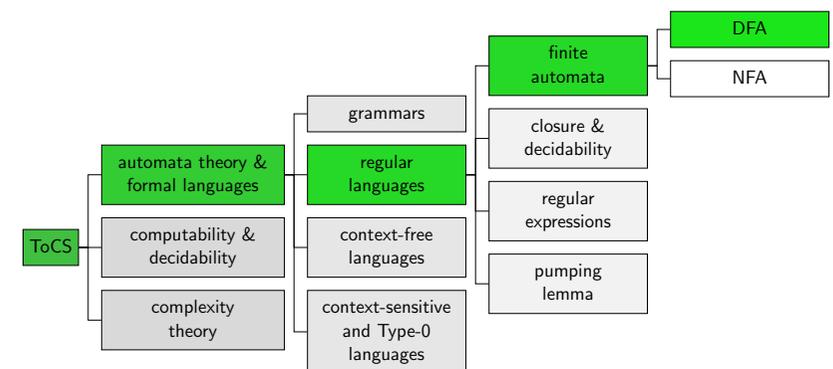
- ▶ Finite automata are a good model for computers with very limited memory.
Where can the turnstile controller store information about what it has seen in the past?
- ▶ We will not consider automata that run forever but that process a **finite input sequence** and then classify it as **accepted** or not.

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B3.2 DFAs

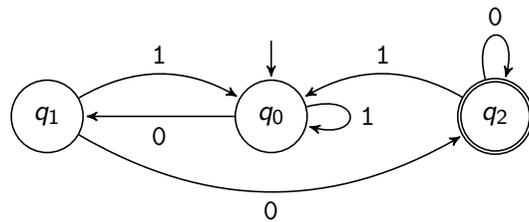
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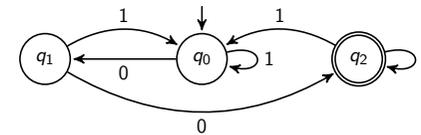
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Finite Automaton: Example



When reading the input 01100 the automaton visits the states $q_0, q_1, q_0, q_0, q_1, q_2$.

Finite Automata: Terminology and Notation



- ▶ states $Q = \{q_0, q_1, q_2\}$
- ▶ input alphabet $\Sigma = \{0, 1\}$
- ▶ transition function δ
- ▶ start state q_0
- ▶ accept states $\{q_2\}$

$$\begin{aligned} \delta(q_0, 0) &= q_1 \\ \delta(q_0, 1) &= q_0 \\ \delta(q_1, 0) &= q_2 \\ \delta(q_1, 1) &= q_0 \\ \delta(q_2, 0) &= q_2 \\ \delta(q_2, 1) &= q_0 \end{aligned}$$

δ	0	1
q_0	q_1	q_0
q_1	q_2	q_0
q_2	q_2	q_0

table form of δ

Deterministic Finite Automaton: Definition

Definition (Deterministic Finite Automata)

A **deterministic finite automaton (DFA)** is a 5-tuple $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ where

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

DFA: Accepted Words

Intuitively, a DFA **accepts a word** if its computation terminates in an **accept state**.

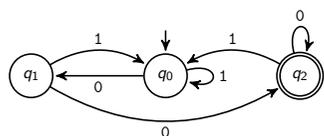
Definition (Words Accepted by a DFA)

DFA $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ **accepts the word** $w = a_1 \dots a_n$ if there is a sequence of states $q'_0, \dots, q'_n \in Q$ with

- 1 $q'_0 = q_0$,
- 2 $\delta(q'_{i-1}, a_i) = q'_i$ for all $i \in \{1, \dots, n\}$ and
- 3 $q'_n \in F$.

Example

Example



accepts:

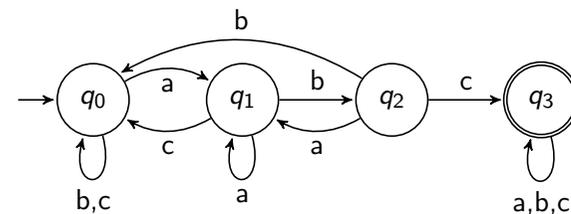
00
10010100
01000

does not accept:

ϵ
1001010
010001

Exercise (slido)

Consider the following DFA:



Which of the following words does it accept?

- ▶ abc
- ▶ ababcb
- ▶ babbc



DFA: Recognized Language

Definition (Language Recognized by a DFA)

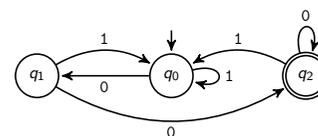
Let M be a deterministic finite automaton.

The **language recognized by M** is defined as

$\mathcal{L}(M) = \{w \in \Sigma^* \mid w \text{ is accepted by } M\}$.

Example

Example



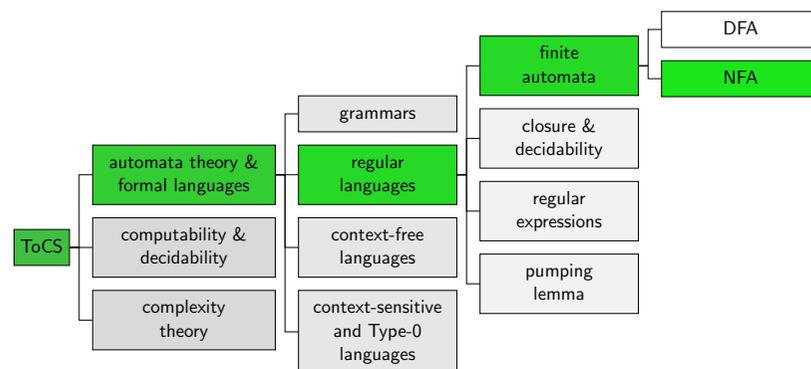
The DFA recognizes the language
 $\{w \in \{0, 1\}^* \mid w \text{ ends with } 00\}$.

A Note on Terminology

- ▶ In the literature, “accept” and “recognize” are sometimes used synonymously or the other way around.
DFA recognizes a word or accepts a language.
- ▶ We try to stay consistent using the previous definitions (following the text book by Sipser).

B3.3 NFAs

Content of the Course



Nondeterministic Finite Automata

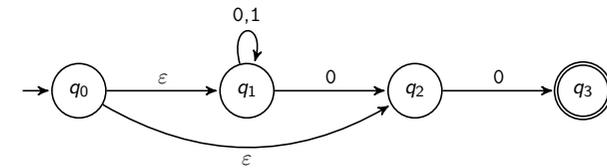
Why are DFAs called **deterministic** automata? What are **nondeterministic** automata, then?



In what Sense is a DFA Deterministic?

- ▶ A DFA has a single fixed state from which the computation starts.
- ▶ When a DFA is in a specific state and reads an input symbol, we know what the next state will be.
- ▶ For a given input, the entire computation is determined.
- ▶ This is a **deterministic** computation.

Nondeterministic Finite Automata: Example



differences to DFAs:

- ▶ transition function δ can lead to **zero** or **more** successor states for the **same** $a \in \Sigma$
- ▶ **ϵ -transitions** can be taken without “consuming” a symbol from the input
- ▶ the automaton accepts a word if there is **at least one** accepting sequence of states

Nondeterministic Finite Automaton: Definition

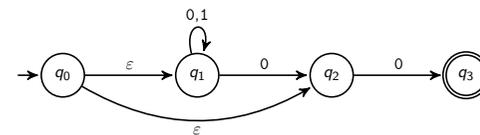
Definition (Nondeterministic Finite Automata)

A **nondeterministic finite automaton (NFA)** is a 5-tuple $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ where

- ▶ Q is the finite set of **states**
- ▶ Σ is the **input alphabet**
- ▶ $\delta : Q \times (\Sigma \cup \{\epsilon\}) \rightarrow \mathcal{P}(Q)$ is the transition function (mapping to the **power set** of Q)
- ▶ $q_0 \in Q$ is the **start state**
- ▶ $F \subseteq Q$ is the set of **accept states**

DFAs are (essentially) a special case of NFAs.

Accepting Computation: Example



$w = 0100$

\rightsquigarrow computation tree on blackboard

ε -closure of a State

For a state $q \in Q$, we write $E(q)$ to denote the set of states that are reachable from q via ε -transitions in δ .

Definition (ε -closure)

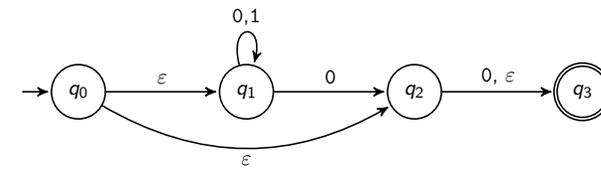
For NFA $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ and state $q \in Q$, state p is in the ε -closure $E(q)$ of q iff there is a sequence of states q'_0, \dots, q'_n with

- 1 $q'_0 = q$,
- 2 $q'_i \in \delta(q'_{i-1}, \varepsilon)$ for all $i \in \{1, \dots, n\}$ and
- 3 $q'_n = p$.

$q \in E(q)$ for every state q

Exercise (slido)

Consider the following NFA:



Which states are in the ε -closure $E(q_0)$?

- ▶ q_0
- ▶ q_1
- ▶ q_2
- ▶ q_3



NFA: Accepted Words

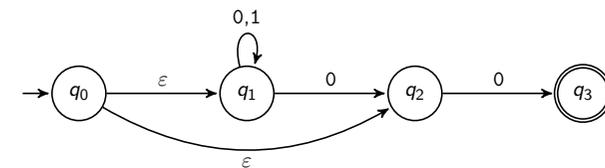
Definition (Words Accepted by an NFA)

NFA $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ **accepts the word** $w = a_1 \dots a_n$ if there is a sequence of states $q'_0, \dots, q'_n \in Q$ with

- 1 $q'_0 \in E(q_0)$,
- 2 $q'_i \in \bigcup_{q \in \delta(q'_{i-1}, a_i)} E(q)$ for all $i \in \{1, \dots, n\}$ and
- 3 $q'_n \in F$.

Example: Accepted Words

Example



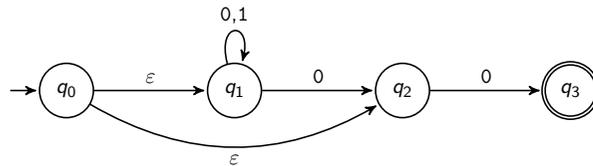
accepts:

0
10010100
01000

does not accept:

ε
1001010
010001

Exercise (slido)



Does this NFA accept input 01010?

NFA: Recognized Language

Definition (Language Recognized by an NFA)

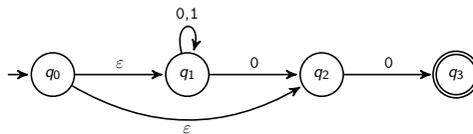
Let M be an NFA with input alphabet Σ .

The **language recognized by M** is defined as

$$\mathcal{L}(M) = \{w \in \Sigma^* \mid w \text{ is accepted by } M\}.$$

Example: Recognized Language

Example



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

Summary

- ▶ **DFAs** are automata where **every state transition is uniquely determined**.
- ▶ **NFAs** can have zero, one or more transitions for a given state and input symbol.
- ▶ **NFAs** can have ϵ -transitions that can be taken without reading a symbol from the input.
- ▶ **NFAs** accept a word if there is **at least one accepting sequence of states**.