Theory of Computer Science
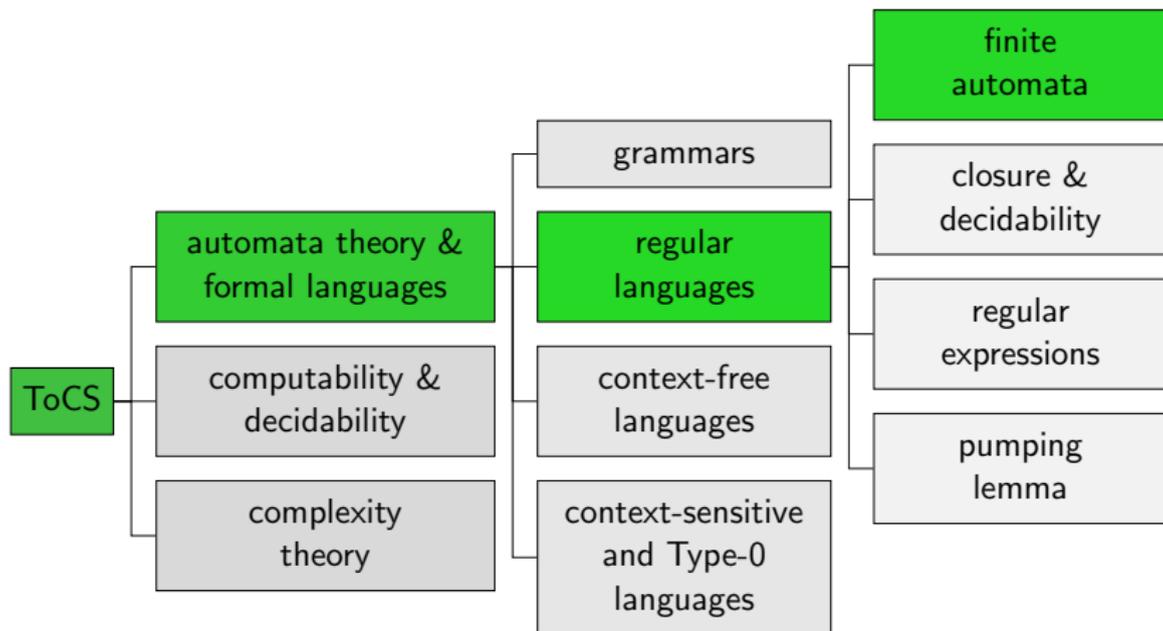## B4. Finite Automata: Characterization

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Introduction
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DFAs vs. NFAs
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Introduction

Finite Automata

Last chapter:

- Two kinds of finite automata: DFAs and NFAs.
- DFAs can be seen as a special case of NFAs.

Finite Automata

Last chapter:

- Two kinds of finite automata: DFAs and NFAs.
- DFAs can be seen as a special case of NFAs.

Questions for today:

- Are there languages that can only be recognized by one kind of finite automaton (but not the other)?
- Can we characterize the languages that DFAs/NFAs can recognize, e.g. within the Chomsky hierarchy?

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DFAs vs. NFAs

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DFAs are No More Powerful than NFAs

Observation

Every language recognized by a DFA is also recognized by an NFA.

We can transform a DFA into an NFA by replacing every transition $\delta(q, a) = q'$ with $\delta(q, a) = \{q'\}$.

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Question

DFAs are
no more powerful than NFAs.
But are there languages
that can be recognized
by an NFA but not by a DFA?

Picture courtesy of imagerymajestic / FreeDigitalPhotos.net

NFAs are No More Powerful than DFAs

Theorem (Rabin, Scott)

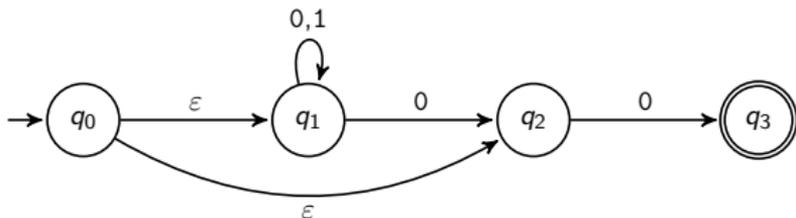*Every language recognized by an NFA is also recognized by a DFA.*

NFAs are No More Powerful than DFAs

Theorem (Rabin, Scott)

Every language recognized by an NFA is also recognized by a DFA.

The proof of the theorem is constructive and shows how we can convert an NFA to an equivalent DFA. Let's first have a look at the idea by means of an example (on the blackboard).

Conversion of an NFA to an Equivalent DFA: Example

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NFAs are No More Powerful than DFAs

Theorem (Rabin, Scott)

Every language recognized by an NFA is also recognized by a DFA.

Proof.

For every NFA $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ we can construct
a DFA $M' = \langle Q', \Sigma, \delta', q_0', F' \rangle$ with $\mathcal{L}(M) = \mathcal{L}(M')$.
Here M' is defined as follows:

- $Q' := \mathcal{P}(Q)$ (the power set of Q)
- $q_0' := E(q_0)$
- $F' := \{ \mathcal{Q} \subseteq Q \mid \mathcal{Q} \cap F \neq \emptyset \}$
- For all $\mathcal{Q} \in Q'$: $\delta'(\mathcal{Q}, a) := \bigcup_{q \in \mathcal{Q}} \bigcup_{q' \in \delta(q,a)} E(q')$

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NFAs are No More Powerful than DFAs

Theorem (Rabin, Scott)

Every language recognized by an NFA is also recognized by a DFA.

Proof (continued).

For every $w = a_1 a_2 \ldots a_n \in \Sigma^*$:

$w \in \mathcal{L}(M)$
iff there is a sequence of states $p_0, p_1, \ldots, p_n$ with
   $p_0 \in E(q_0)$, $p_n \in F$ and
   $p_i \in \bigcup_{q \in \delta(p_{i-1}, a_i)} E(q)$ for all $i \in \{1, \ldots, n\}$
iff there is a sequence of subsets $\mathcal{Q}_0, \mathcal{Q}_1, \ldots, \mathcal{Q}_n$ with
   $\mathcal{Q}_0 = q_0'$, $\mathcal{Q}_n \in F'$ and $\delta'(\mathcal{Q}_{i-1}, a_i) = \mathcal{Q}_i$ for all $i \in \{1, \ldots, n\}$
iff $w \in \mathcal{L}(M')$ $\square$

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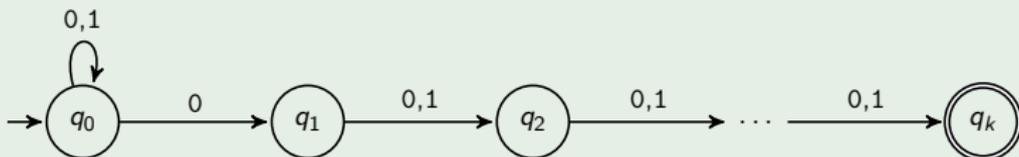
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NFAs are More Compact than DFAs

Example

For $k \geq 1$ consider the language
$L_k = \{w \in \{0, 1\}^* \mid |w| \geq k$ and the k-th last symbol of w is $0\}$.

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NFAs are More Compact than DFAs

Example

For $k \geq 1$ consider the language
$L_k = \{w \in \{0,1\}^* \mid |w| \geq k$ and the k-th last symbol of w is $0\}$.

The language L_k can be recognized by an NFA with $k + 1$ states:

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NFAs are More Compact than DFAs

Example

For $k \geq 1$ consider the language
$L_k = \{w \in \{0,1\}^* \mid |w| \geq k \text{ and the } k\text{-th last symbol of } w \text{ is } 0\}$.

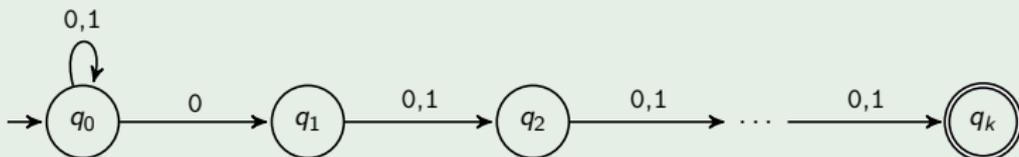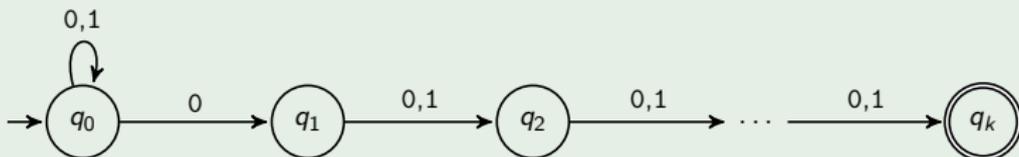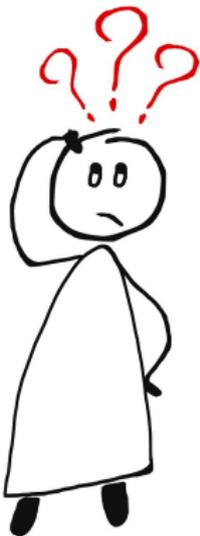The language L_k can be recognized by an NFA with $k+1$ states:

There is no DFA with less than 2^k states that recognizes L_k
(without proof).

NFAs are More Compact than DFAs

Example

For $k \geq 1$ consider the language
$L_k = \{w \in \{0, 1\}^* \mid |w| \geq k$ and the k-th last symbol of w is $0\}$.

The language L_k can be recognized by an NFA with $k + 1$ states:

There is no DFA with less than 2^k states that recognizes L_k
(without proof).

NFAs can often represent languages more compactly than DFAs.

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Finite Automata vs. Regular Languages

Languages Recognized by DFAs are Regular

Theorem

Every language recognized by a DFA is regular (type 3).

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Languages Recognized by DFAs are Regular

Theorem

Every language recognized by a DFA is regular (type 3).

Proof.

Let $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ be a DFA.
We define a regular grammar G with $\mathcal{L}(G) = \mathcal{L}(M)$.

Define $G = \langle Q, \Sigma, R, q_0 \rangle$ where R contains

- a rule $q \to aq'$ for every $\delta(q, a) = q'$, and

- a rule $q \to \varepsilon$ for every $q \in F$.

(We can eliminate forbidden epsilon rules as described in Ch. B2.)

. . .

Languages Recognized by DFAs are Regular

Theorem

Every language recognized by a DFA is regular (type 3).

Proof (continued).

For every $w = a_1 a_2 \ldots a_n \in \Sigma^*$:
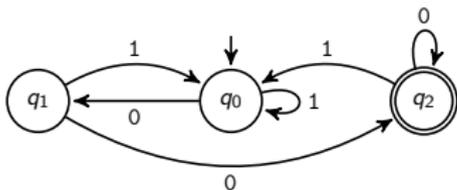
$w \in \mathcal{L}(M)$

iff there is a sequence of states $q_0', q_1', \ldots, q_n'$ with
$q_0' = q_0$, $q_n' \in F$ and $\delta(q_{i-1}', a_i) = q_i'$ for all $i \in \{1, \ldots, n\}$

iff there is a sequence of variables $q_0', q_1', \ldots, q_n'$ with
q_0' is start variable and we have $q_0' \Rightarrow a_1 q_1' \Rightarrow a_1 a_2 q_2' \Rightarrow$
$\cdots \Rightarrow a_1 a_2 \ldots a_n q_n' \Rightarrow a_1 a_2 \ldots a_n$.

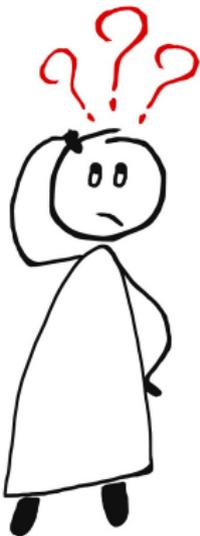iff $w \in \mathcal{L}(G)$ □

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Exercise

Specify a regular grammar that generates the
language recognized by this DFA.

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Question

Is the inverse true as well:
for every regular language, is there a
DFA that recognizes it? That is, are the
languages recognized by DFAs exactly
the regular languages?

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Question

Is the inverse true as well:
for every regular language, is there a
DFA that recognizes it? That is, are the
languages recognized by DFAs exactly
the regular languages?

Yes!
We will prove this via a detour.

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Regular Grammars are No More Powerful than NFAs

Theorem

For every regular grammar G there is an NFA M
with $\mathcal{L}(G) = \mathcal{L}(M)$.

Proof illustration:

Consider $G = \langle \{S, A, B\}, \{a, b\}, R, S \rangle$ with the following rules in R:

$$S \to \varepsilon \qquad S \to aA \qquad A \to aA \qquad A \to aB$$

$$A \to a \qquad B \to bB \qquad B \to b$$

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Regular Grammars are No More Powerful than NFAs

Theorem

For every regular grammar G there is an NFA M
with $\mathcal{L}(G) = \mathcal{L}(M)$.

Proof.

Let $G = \langle V, \Sigma, R, S \rangle$ be a regular grammar.
Define NFA $M = \langle Q, \Sigma, \delta, q_0, F \rangle$ with

$$Q = V \cup \{X\}, \quad X \notin V$$
$$q_0 = S$$
$$F = \begin{cases} \{S, X\} & \text{if } S \to \varepsilon \in R \\ \{X\} & \text{if } S \to \varepsilon \notin R \end{cases}$$
$$B \in \delta(A, a) \text{ if } A \to aB \in R$$
$$X \in \delta(A, a) \text{ if } A \to a \in R$$

Regular Grammars are No More Powerful than NFAs

Theorem

For every regular grammar G there is an NFA M
with $\mathcal{L}(G) = \mathcal{L}(M)$.

Proof (continued).

For every $w = a_1 a_2 \ldots a_n \in \Sigma^*$ with $n \geq 1$:

$w \in \mathcal{L}(G)$

iff there is a sequence on variables $A_1, A_2, \ldots, A_{n-1}$ with
$\quad S \Rightarrow a_1 A_1 \Rightarrow a_1 a_2 A_2 \Rightarrow \cdots \Rightarrow a_1 a_2 \ldots a_{n-1} A_{n-1} \Rightarrow a_1 a_2 \ldots a_n$.
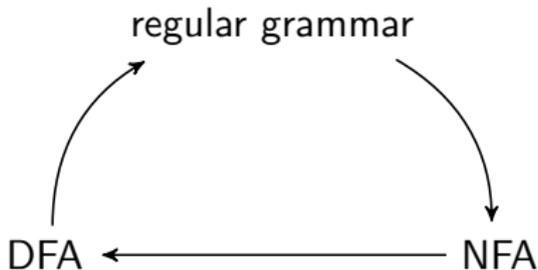
iff there is a sequence of variables $A_1, A_2, \ldots, A_{n-1}$ with
$\quad A_1 \in \delta(S, a_1), A_2 \in \delta(A_1, a_2), \ldots, X \in \delta(A_{n-1}, a_n)$.

iff $w \in \mathcal{L}(M)$.

Case $w = \varepsilon$ is also covered because $S \in F$ iff $S \to \varepsilon \in R$. $\qquad\square$
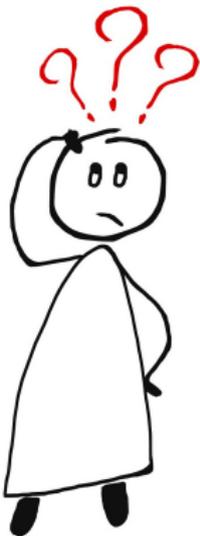
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In particular, this implies:

Corollary

$\mathcal{L}$ regular $\iff$ $\mathcal{L}$ is recognized by a DFA.

$\mathcal{L}$ regular $\iff$ $\mathcal{L}$ is recognized by an NFA.

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Summary

- DFAs and NFAs recognize the same languages.
- These are exactly the regular languages.