Automata and Formal Languages (3)

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Regular Expressions

In programming languages they are often used to recognise:

- symbols, digits
- identifiers
- numbers (non-leading zeros)
- keywords
- comments

http://www.regexper.com

Last Week

Last week I showed you a regular expression matcher which works provably correctly in all cases.

$$matcher\ r\ s \quad \text{if and only if} \quad s \in L(r)$$

by Janusz Brzozowski (1964)

The Derivative of a Rexp

$$
\begin{array}{lcl}
der\, c\, (\varnothing) & \stackrel{\text{def}}{=} & \varnothing \\
der\, c\, (\epsilon) & \stackrel{\text{def}}{=} & \varnothing \\
der\, c\, (d) & \stackrel{\text{def}}{=} & \text{if } c = d \text{ then } \epsilon \text{ else } \varnothing \\
der\, c\, (r_1 + r_2) & \stackrel{\text{def}}{=} & der\, c\, r_1 + der\, c\, r_2 \\
der\, c\, (r_1 \cdot r_2) & \stackrel{\text{def}}{=} & \text{if } nullable(r_1) \\
 & & \text{then } (der\, c\, r_1) \cdot r_2 + der\, c\, r_2 \\
 & & \text{else } (der\, c\, r_1) \cdot r_2 \\
der\, c\, (r^*) & \stackrel{\text{def}}{=} & (der\, c\, r) \cdot (r^*) \\
ders\, []\, r & \stackrel{\text{def}}{=} & r \\
ders\, (c :: s)\, r & \stackrel{\text{def}}{=} & ders\, s\, (der\, c\, r)
\end{array}
$$

To see what is going on, define

$$Der\,c\,A \stackrel{\text{def}}{=} \{s \mid c :: s \in A\}$$

For $A = \{"foo", "bar", "frak"\}$ then

$$\begin{array}{lcl}
Der\,f\,A & = & \{"oo", "rak"\} \\
Der\,b\,A & = & \{"ar"\} \\
Der\,a\,A & = & \varnothing
\end{array}$$

The Idea of the Algorithm

If we want to recognise the string $"abc"$ with regular expression r then

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The matching algorithm works similarly, just over regular expression instead of sets.

Input: string "abc" and regular expression r

1. $der\, a\, r$
2. $der\, b\, (der\, a\, r)$
3. $der\, c\, (der\, b\, (der\, a\, r))$

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1. $der\, a\, r$
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4. finally check whether the last regular expression can match the empty string

We proved already

$$nullable(r) \;\text{ if and only if }\; \texttt{""} \in L(r)$$

by induction on the regular expression.

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by induction on the regular expression.

Any Questions?

We need to prove

$$L(der\, c\, r) = Der\, c\, (L(r))$$

by induction on the regular expression.

Proofs about Rexps

- P holds for $\varnothing$, ϵ and $\mathtt{c}$
- P holds for $r_1 + r_2$ under the assumption that P already holds for r_1 and r_2.
- P holds for $r_1 \cdot r_2$ under the assumption that P already holds for r_1 and r_2.
- P holds for r^* under the assumption that P already holds for r.

Proofs about Natural Numbers and Strings

- P holds for 0 and
- P holds for $n + 1$ under the assumption that P already holds for n

- P holds for "" and
- P holds for $c :: s$ under the assumption that P already holds for s

Languages

A language is a set of strings.

A regular expression specifies a language.

A language is regular iff there exists a regular expression that recognises all its strings.

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not all languages are regular, e.g. $a^n b^n$.

Regular Expressions

r	$::=$	$\varnothing$	null
	$\mid$	ϵ	empty string / "" / []
	$\mid$	c	character
	$\mid$	$r_1 \cdot r_2$	sequence
	$\mid$	$r_1 + r_2$	alternative / choice
	$\mid$	r^*	star (zero or more)

How about ranges $[a\text{-}z]$, r^+ and $\sim r$? Do they increase the set of languages we can recognise?

Negation of Regular Expr's

- $\sim r$ (everything that r cannot recognise)
- $L(\sim r) \stackrel{\text{def}}{=} UNIV - L(r)$
- $nullable(\sim r) \stackrel{\text{def}}{=} not\,(nullable(r))$
- $der\,c\,(\sim r) \stackrel{\text{def}}{=} \sim (der\,c\,r)$

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Used often for recognising comments:

$$/ \cdot * \cdot (\sim ([a\text{-}z]^* \cdot * \cdot / \cdot [a\text{-}z]^*)) \cdot * \cdot /$$

Negation

Assume you have an alphabet consisting of the letters a, b and c only. Find a regular expression that matches all strings except ab and ac.

Regular Exp's for Lexing

Lexing separates strings into "words" / components.

- Identifiers (non-empty strings of letters or digits, starting with a letter)
- Numbers (non-empty sequences of digits omitting leading zeros)
- Keywords (else, if, while, ...)
- White space (a non-empty sequence of blanks, newlines and tabs)
- Comments

Automata

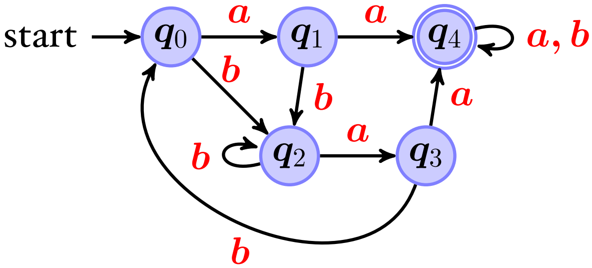
A deterministic finite automaton consists of:

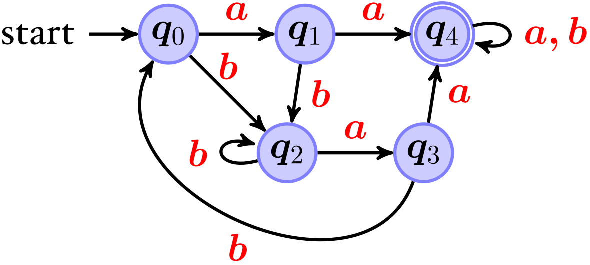
- a set of states
- one of these states is the start state
- some states are accepting states, and
- there is transition function

  which takes a state as argument and a character and produces a new state

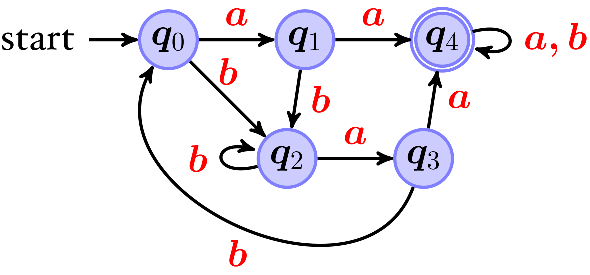
  this function might not be everywhere defined

$$A(Q, q_0, F, \delta)$$


start
q_0
q_1
q_2
q_3
q_4
a
b
a, b



- start can be an accepting state
- it is possible that there is no accepting state
- all states might be accepting (but does not necessarily mean all strings are accepted)



for this automaton δ is the function

$$\begin{array}{lll} (q_0, a) \rightarrow q_1 & (q_1, a) \rightarrow q_4 & (q_4, a) \rightarrow q_4 \\ (q_0, b) \rightarrow q_2 & (q_1, b) \rightarrow q_2 & (q_4, b) \rightarrow q_4 \end{array} \quad \ldots$$

Accepting a String

Given

$$A(Q, q_0, F, \delta)$$

you can define

$$\begin{aligned}\hat{\delta}(q, \text{""}) &= q\\ \hat{\delta}(q, c :: s) &= \hat{\delta}(\delta(q, c), s)\end{aligned}$$

Accepting a String

Given

$$A(Q, q_0, F, \delta)$$

you can define

$$\begin{aligned} \hat{\delta}(q, "") &= q \\ \hat{\delta}(q, c :: s) &= \hat{\delta}(\delta(q, c), s) \end{aligned}$$

Whether a string s is accepted by A?

$$\hat{\delta}(q_0, s) \in F$$

Non-Deterministic Finite Automata

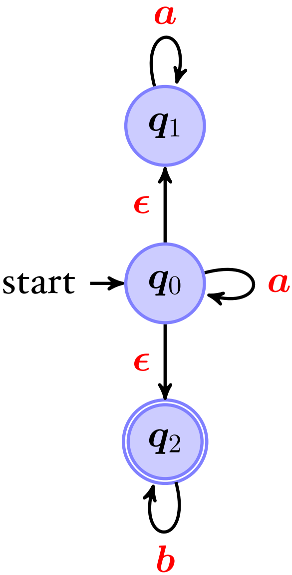
A non-deterministic finite automaton consists again of:

- a finite set of states
- one of these states is the start state
- some states are accepting states, and
- there is transition relation

$$(q_1, a) \rightarrow q_2$$
$$(q_1, a) \rightarrow q_3$$

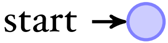
$$(q_1, \epsilon) \rightarrow q_2$$

An NFA Example

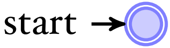


Rexp to NFA

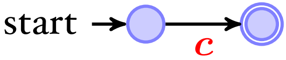
$\varnothing$



ϵ

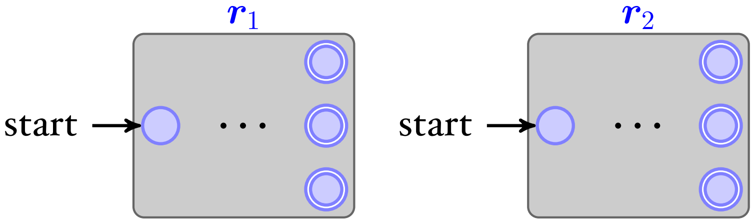


c



Case $r_1 \cdot r_2$

By recursion we are given two automata:



We need to (1) change the accepting nodes of the first automaton into non-accepting nodes, and (2) connect them via ϵ-transitions to the starting state of the second automaton.

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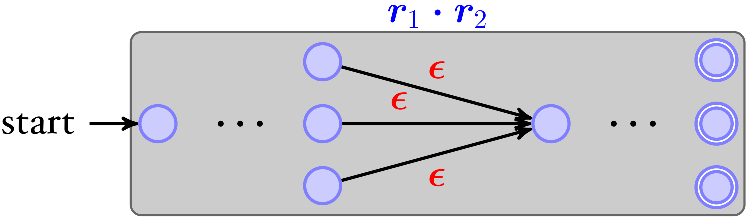

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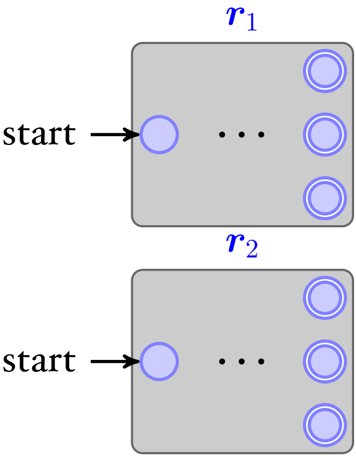

We (1) need to introduce a new starting state and (2) connect it to the original two starting states.

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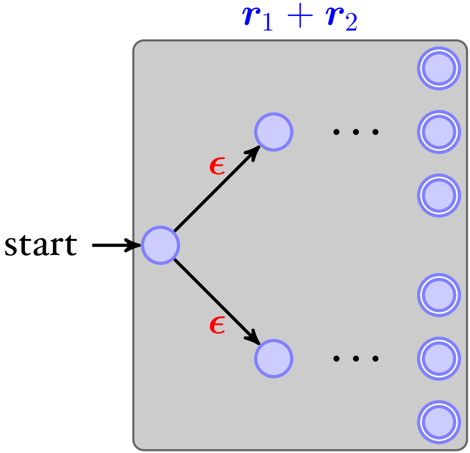

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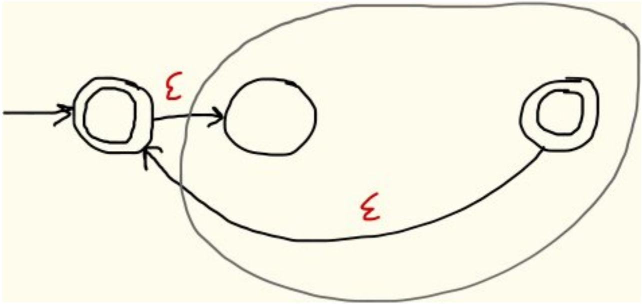
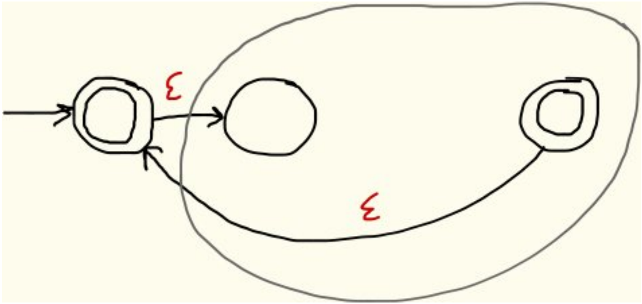
Rexp to NFA



r^*

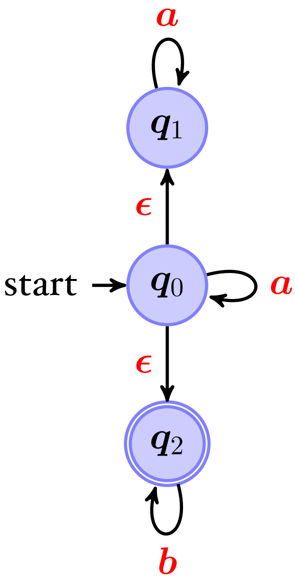
Rexp to NFA

r*



Why can't we just have an epsilon transition from the accepting states to the starting state?

Subset Construction



	a	b
$\varnothing$	$\varnothing$	$\varnothing$
$\{0\}$	$\{0, 1, 2\}$	$\{2\}$
$\{1\}$	$\{1\}$	$\varnothing$
$\{2\}$	$\varnothing$	$\{2\}$
$\{0, 1\}$	$\{0, 1, 2\}$	$\{2\}$
$\{0, 2\}$	$\{0, 1, 2\}$	$\{2\}$
$\{1, 2\}$	$\{1\}$	$\{2\}$
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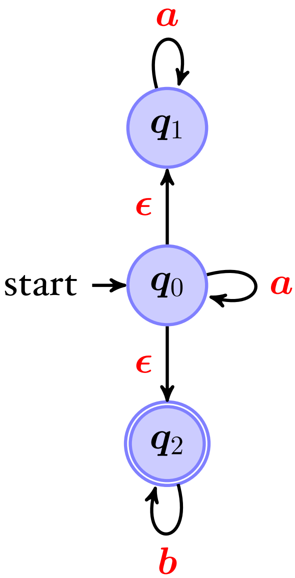

	a	b
$\varnothing$	$\varnothing$	$\varnothing$
$\{0\}$	$\{0, 1, 2\}$	$\{2\}$
$\{1\}$	$\{1\}$	$\varnothing$
$\{2\}$ *	$\varnothing$	$\{2\}$
$\{0, 1\}$	$\{0, 1, 2\}$	$\{2\}$
$\{0, 2\}$ *	$\{0, 1, 2\}$	$\{2\}$
$\{1, 2\}$ *	$\{1\}$	$\{2\}$
s: $\{0, 1, 2\}$ *	$\{0, 1, 2\}$	$\{2\}$

Regular Languages

A language is regular iff there exists a regular expression that recognises all its strings.

or equivalently

A language is regular iff there exists a deterministic finite automaton that recognises all its strings.

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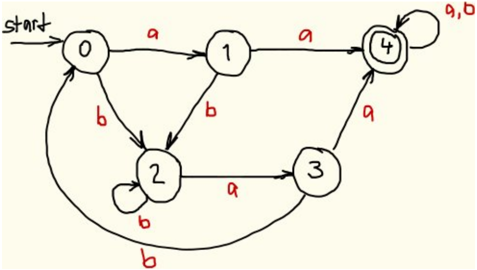
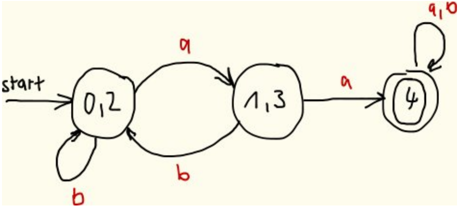
Why is every finite set of strings a regular language?





minimal automaton

1. Take all pairs (q, p) with $q \neq p$
2. Mark all pairs that are accepting and non-accepting states
3. For all unmarked pairs (q, p) and all characters c tests wether

$$(\delta(q,c), \delta(p,c))$$

   are marked. If yes, then also mark (q, p)
4. Repeat last step until no chance.
5. All unmarked pairs can be merged.

Given the function

$$\begin{aligned}
rev(\varnothing) &\stackrel{\text{def}}{=} \varnothing\\
rev(\epsilon) &\stackrel{\text{def}}{=} \epsilon\\
rev(c) &\stackrel{\text{def}}{=} c\\
rev(r_1 + r_2) &\stackrel{\text{def}}{=} rev(r_1) + rev(r_2)\\
rev(r_1 \cdot r_2) &\stackrel{\text{def}}{=} rev(r_2) \cdot rev(r_1)\\
rev(r^*) &\stackrel{\text{def}}{=} rev(r)^*
\end{aligned}$$

and the set

$$Rev\, A \stackrel{\text{def}}{=} \{s^{-1} \mid s \in A\}$$

prove whether

$$L(rev(r)) = Rev(L(r))$$