Compilers and Formal Languages

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2 Regular Expressions, Derivatives	7 Compilation, JVM
3 Automata, Regular Languages	8 Compiling Functional Languages
4 Lexing, Tokenising	9 Optimisations
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(Basic) Regular Expressions

$$
\begin{array}{rcll}
r & ::= & \mathbf{0} & \text{nothing} \\
 & | & \mathbf{1} & \text{empty string / "" / []} \\
 & | & c & \text{character} \\
 & | & r_1 \cdot r_2 & \text{sequence} \\
 & | & r_1 + r_2 & \text{alternative / choice} \\
 & | & r^* & \text{star (zero or more)}
\end{array}
$$

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

Negation

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

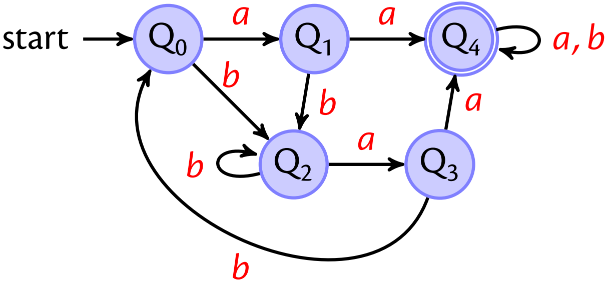
Automata

A **deterministic finite automaton**, DFA, consists of:

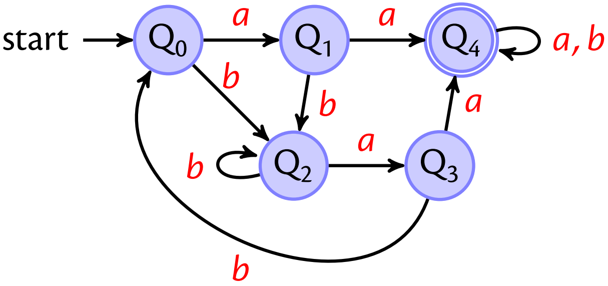
- an alphabet Σ
- a set of states Qs
- one of these states is the start state Q_0
- some states are accepting states F, and
- there is transition function δ

  which takes a state as argument and a character and produces a new state; this function might not be everywhere defined $\Rightarrow$ partial function

$$A(\Sigma, Qs, Q_0, F, \delta)$$



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



for this automaton δ is the function

$$\begin{array}{llll} (Q_0, a) \rightarrow Q_1 & (Q_1, a) \rightarrow Q_4 & (Q_4, a) \rightarrow Q_4 & \\ (Q_0, b) \rightarrow Q_2 & (Q_1, b) \rightarrow Q_2 & (Q_4, b) \rightarrow Q_4 & \ldots \end{array}$$

Accepting a String

Given

$$A(\Sigma, \mathrm{Qs}, \mathrm{Q}_0, F, \delta)$$

you can define

$$\widehat{\delta}(Q, []) \stackrel{\text{def}}{=} Q$$
$$\widehat{\delta}(Q, c :: s) \stackrel{\text{def}}{=} \widehat{\delta}(\delta(Q, c), s)$$

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Whether a string s is accepted by A?

$$\widehat{\delta}(Q_0, s) \in F$$

Regular 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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A **regular expression** specifies a language.

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

Regular Languages (2)

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.

Non-Deterministic Finite Automata

$N(\Sigma, Qs, Qs_0, F, \rho)$

A non-deterministic finite automaton (NFA) consists of:

- a finite set of states, Qs
- some these states are the start states, Qs_0
- some states are accepting states, and
- there is transition relation, ρ

$$
\begin{array}{l}
(Q_1, a) \rightarrow Q_2 \\
(Q_1, a) \rightarrow Q_3
\end{array}
\quad \ldots
$$

Non-Deterministic Finite Automata

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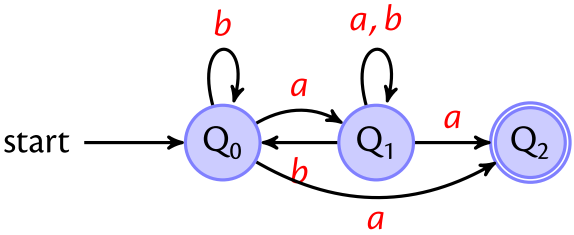
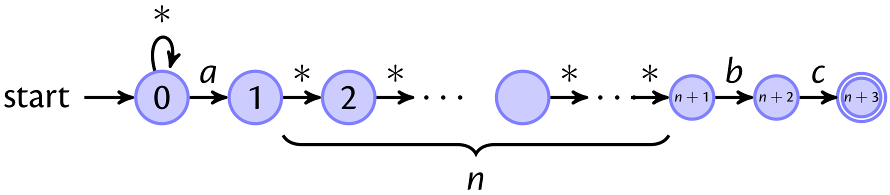
$$\begin{array}{l}(Q_1, a) \rightarrow Q_2\\(Q_1, a) \rightarrow Q_3\end{array} \quad \ldots \qquad\qquad (Q_1, a) \rightarrow \{Q_2, Q_3\}$$

An NFA Example



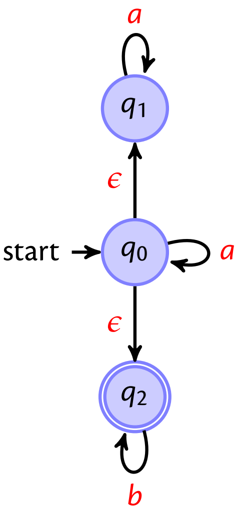
Another Example

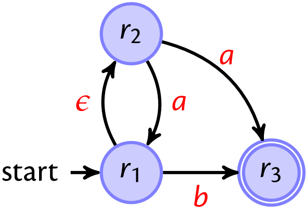
For the regular expression $(.^*)a\,(.^{\{n\}})bc$



Note the star-transitions: accept any character.

Two Epsilon NFA Examples



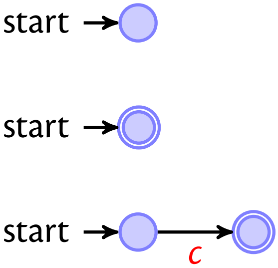


Thompson: Rexp to ϵNFA

$\mathbf{0}$

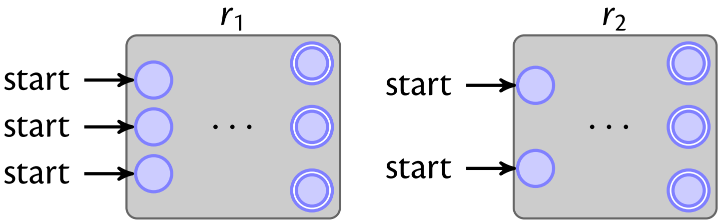
$\mathbf{1}$

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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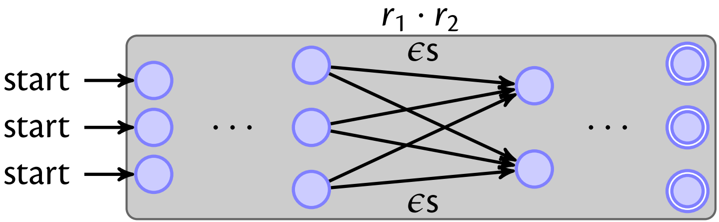

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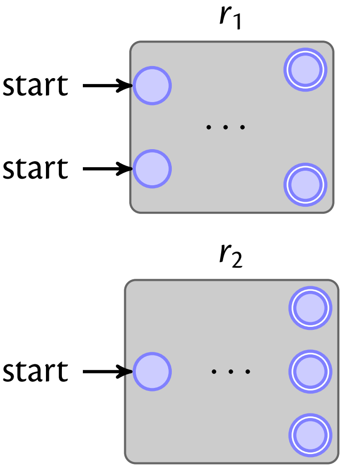

We can just put both automata together.

Case $r_1 + r_2$

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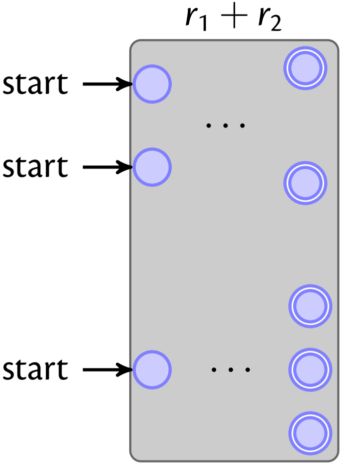
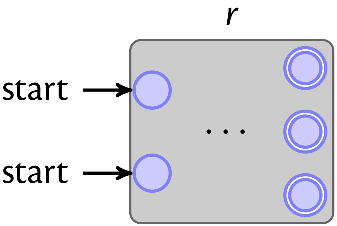


We can just put both automata together.

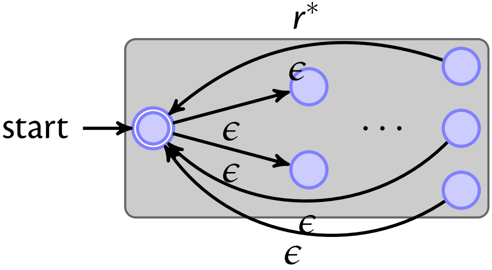
Case r^*

By recursion we are given an automaton for r:



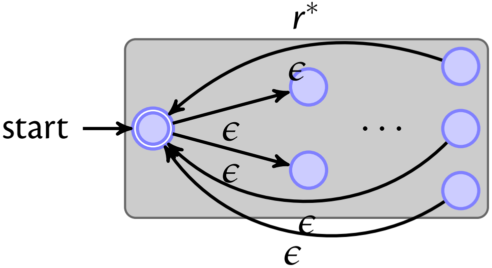
Case r^*

By recursion we are given an automaton for r:



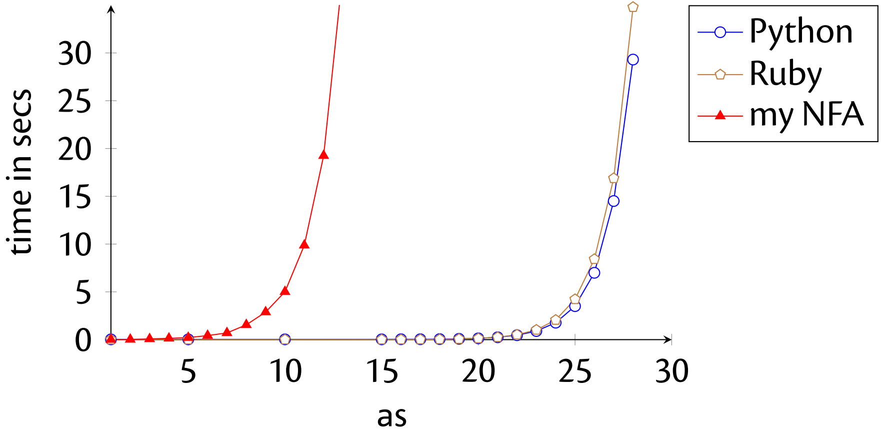
Case r^*

By recursion we are given an automaton for r:

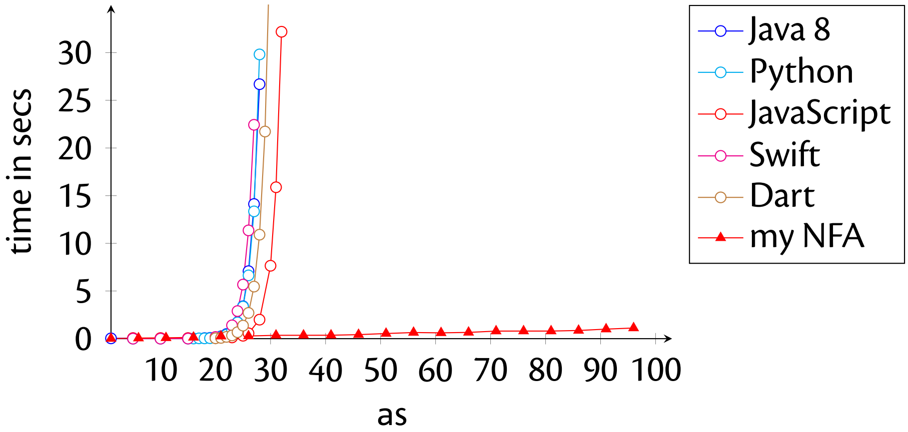


Why can't we just have an epsilon transition from the accepting states to the starting state?

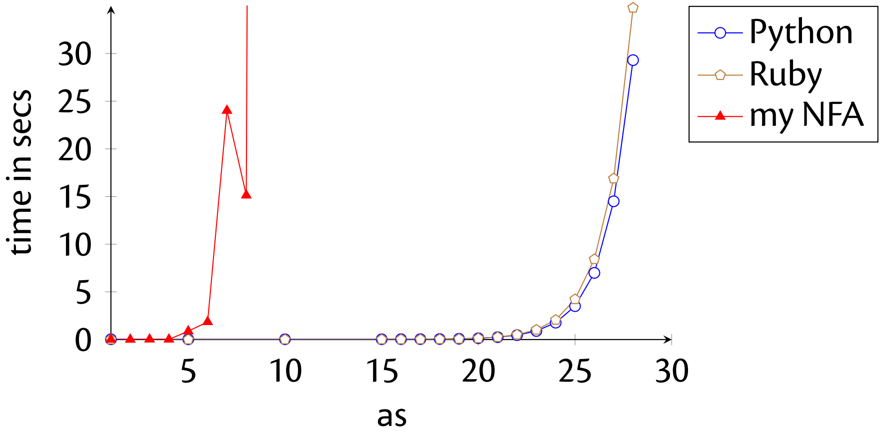
NFA Breadth-First: $a^{?\{n\}} \cdot a^{\{n\}}$



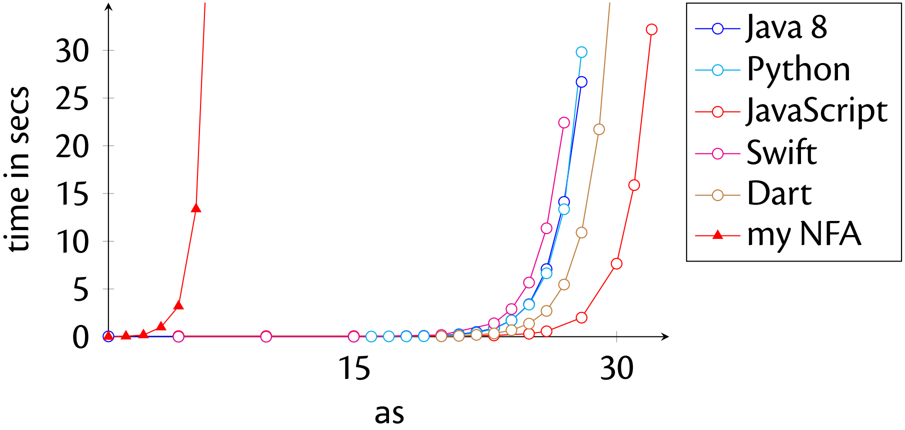
NFA Breadth-First: $(a^*)^* \cdot b$



NFA Depth-First: $a^{?\{n\}} \cdot a^{\{n\}}$

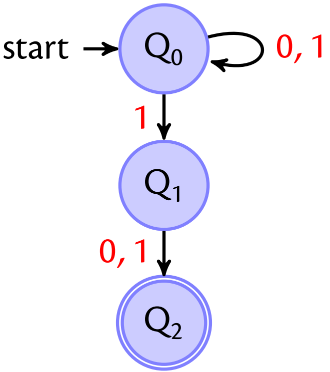


NFA Depth-First: $(a^*)^* \cdot b$



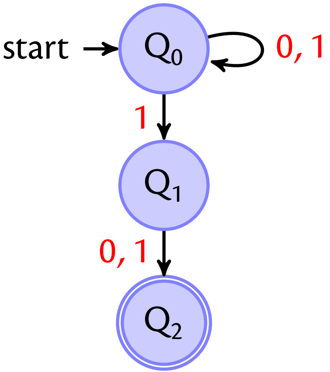
The punchline is that many existing libraries do depth-first search in NFAs (with backtracking).

Subset Construction



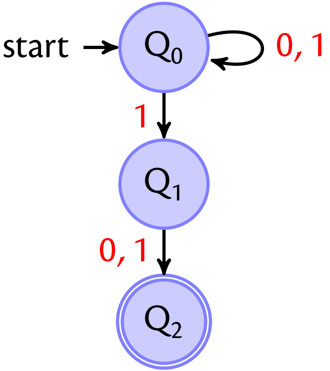
nodes	0	1
$\{\}$		
$\{0\}$		
$\{1\}$		
$\{2\}$		
$\{0,1\}$		
$\{0,2\}$		
$\{1,2\}$		
$\{0,1,2\}$		

Subset Construction



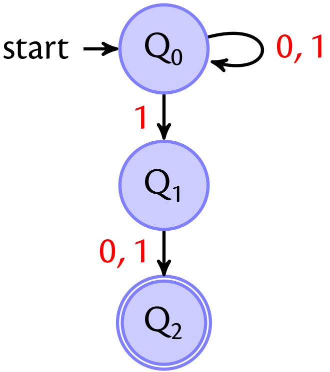
nodes	0	1
$\{\}$	$\{\}$	$\{\}$
$\{0\}$		
$\{1\}$		
$\{2\}$		
$\{0, 1\}$		
$\{0, 2\}$		
$\{1, 2\}$		
$\{0, 1, 2\}$		

Subset Construction



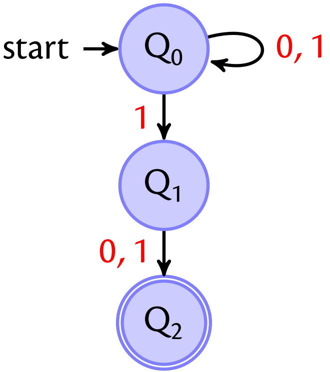
nodes	0	1
$\{\}$	$\{\}$	$\{\}$
$\{0\}$	$\{0\}$	$\{0,1\}$
$\{1\}$	$\{2\}$	$\{2\}$
$\{2\}$	$\{\}$	$\{\}$
$\{0,1\}$		
$\{0,2\}$		
$\{1,2\}$		
$\{0,1,2\}$		

Subset Construction



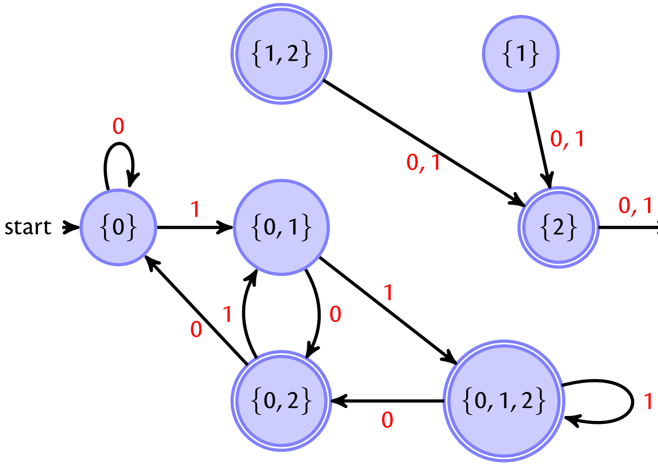
nodes	0	1
$\{\}$	$\{\}$	$\{\}$
$\{0\}$	$\{0\}$	$\{0, 1\}$
$\{1\}$	$\{2\}$	$\{2\}$
$\{2\}$	$\{\}$	$\{\}$
$\{0, 1\}$	$\{0, 2\}$	$\{0, 1, 2\}$
$\{0, 2\}$	$\{0\}$	$\{0, 1\}$
$\{1, 2\}$	$\{2\}$	$\{2\}$
$\{0, 1, 2\}$	$\{0, 2\}$	$\{0, 1, 2\}$

Subset Construction



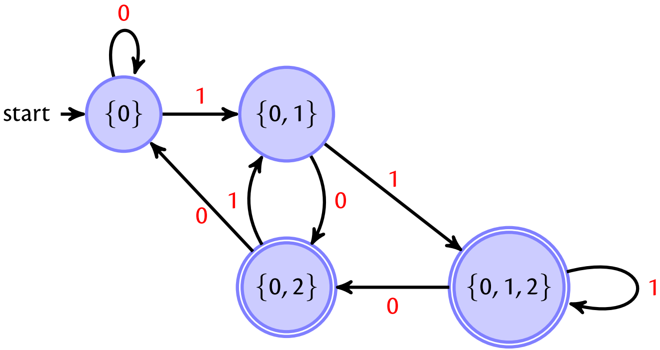
nodes	0	1
$\{\}$	$\{\}$	$\{\}$
s: $\{0\}$	$\{0\}$	$\{0,1\}$
$\{1\}$	$\{2\}$	$\{2\}$
$\{2\}$ *	$\{\}$	$\{\}$
$\{0,1\}$	$\{0,2\}$	$\{0,1,2\}$
$\{0,2\}$ *	$\{0\}$	$\{0,1\}$
$\{1,2\}$ *	$\{2\}$	$\{2\}$
$\{0,1,2\}$ *	$\{0,2\}$	$\{0,1,2\}$

The Result

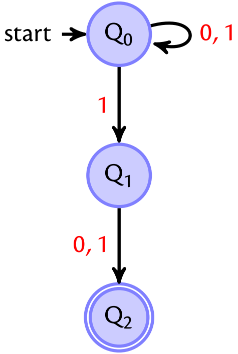


Removing Dead States

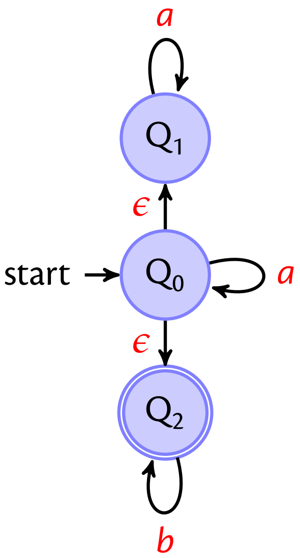
DFA:



(original) NFA:

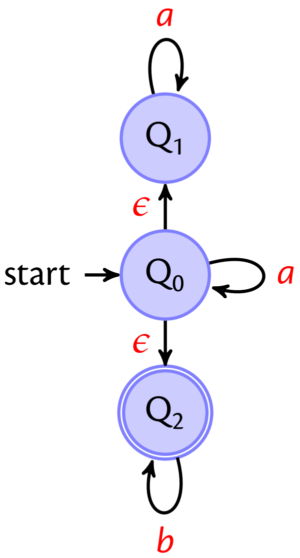


Subset Construction (ϵNFA)



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

Subset Construction (ϵNFA)



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

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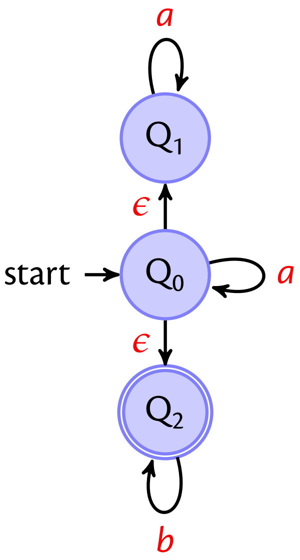

nodes	a	b
$\{\}$	$\{\}$	$\{\}$
$\{0\}$	$\{0,1,2\}$	$\{2\}$
$\{1\}$	$\{1\}$	$\{\}$
$\{2\}$	$\{\}$	$\{2\}$
$\{0,1\}$		
$\{0,2\}$		
$\{1,2\}$		
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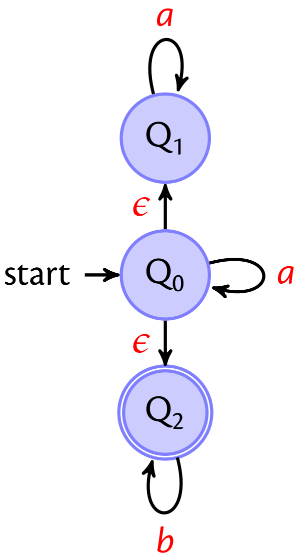
Subset Construction (ϵNFA)



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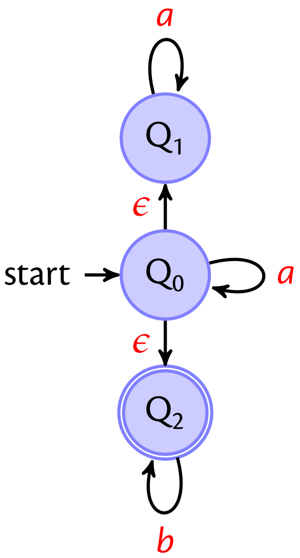
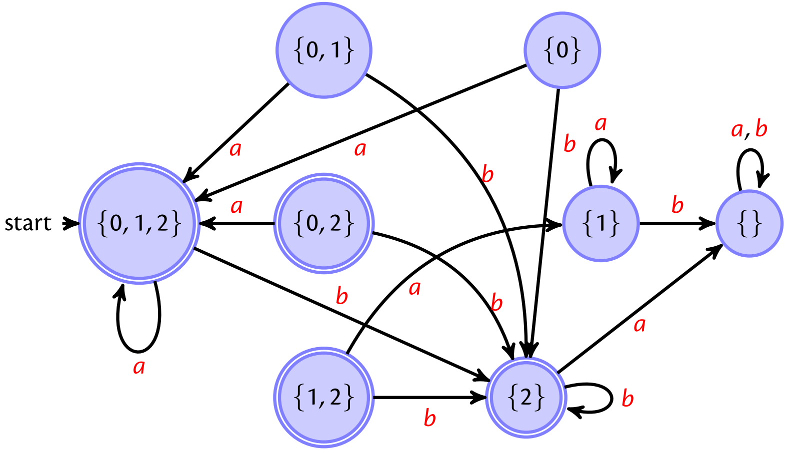
$\{1\}$	$\{1\}$	$\{\}$
$\{2\}$	$\{\}$	$\{2\}$
$\{0,1\}$	$\{0,1,2\}$	$\{2\}$
$\{0,2\}$	$\{0,1,2\}$	$\{2\}$
$\{1,2\}$	$\{1\}$	$\{2\}$
$\{0,1,2\}$	$\{0,1,2\}$	$\{2\}$

Subset Construction (ϵNFA)



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

The Result



Removing Dead States

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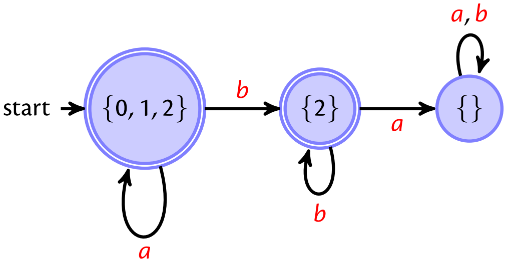
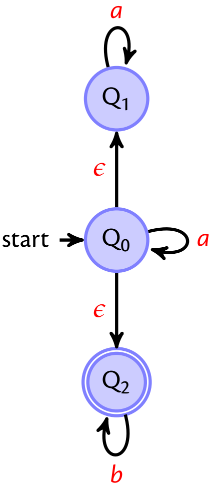


(original) NFA:



Regexps and Automata

Thompson's construction   subset construction

Regexps → **NFAs** → **DFAs**

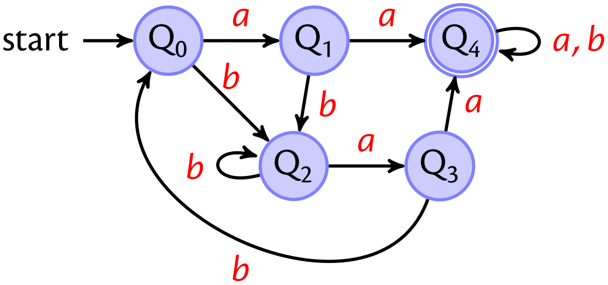
Regexps and Automata

Thompson's construction | subset construction | minimisation

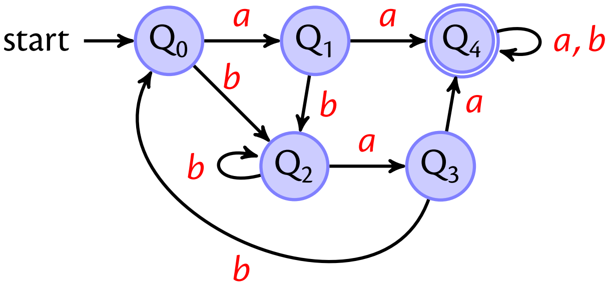
Regexps $\rightarrow$ NFAs $\rightarrow$ DFAs $\rightarrow$ minimal DFAs

DFA Minimisation

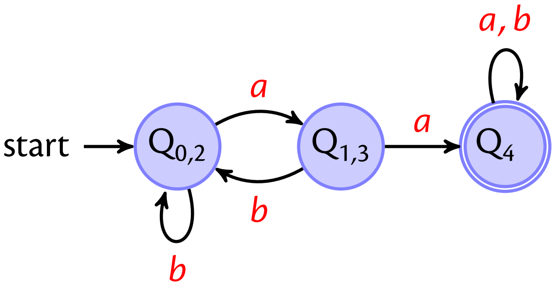
1. Take all pairs (q, p) with $q \neq p$
2. Mark all pairs that accepting and non-accepting states
3. For all unmarked pairs (q, p) and all characters c test whether
$$(\delta(q, c), \delta(p, c))$$
are marked. If yes in at least one case, then also mark (q, p).
4. Repeat last step until no change.
5. All unmarked pairs can be merged.



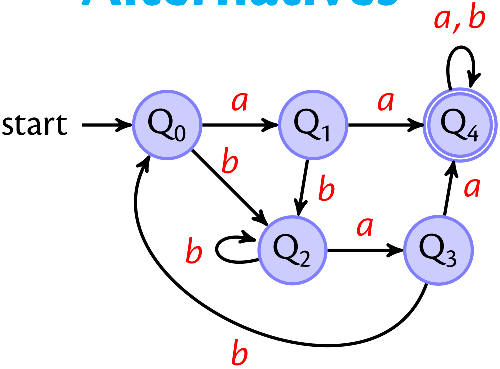
	Q_0	Q_1	Q_2	Q_3
Q_1				
Q_2				
Q_3				
Q_4	$\star$	$\star$	$\star$	$\star$



Q_1	★			
Q_2		★		
Q_3	★		★	
Q_4	★	★	★	★
	Q_0	Q_1	Q_2	Q_3

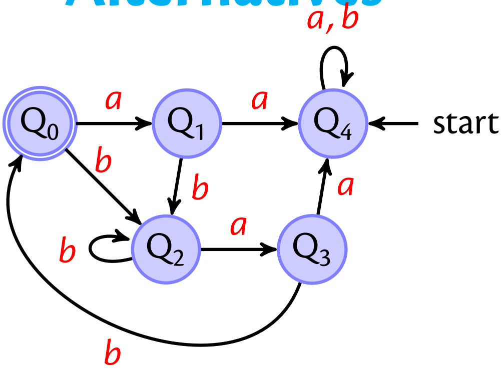


Alternatives



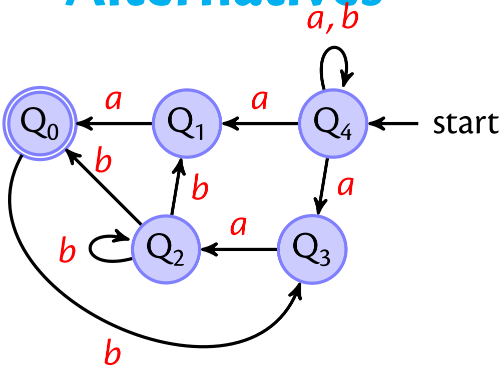
- exchange initial / accepting states

Alternatives



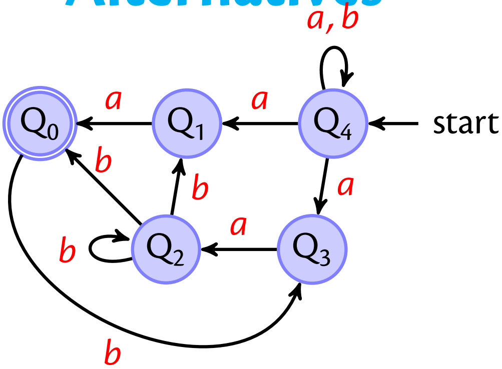
- exchange initial / accepting states
- reverse all edges

Alternatives



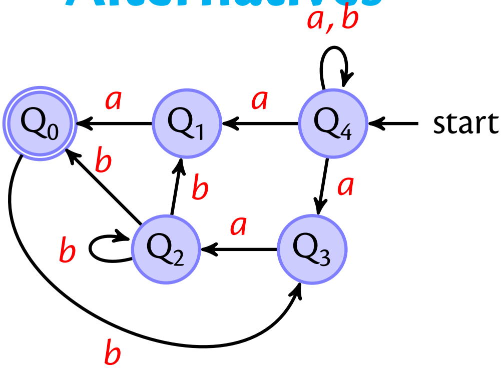
- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA

Alternatives



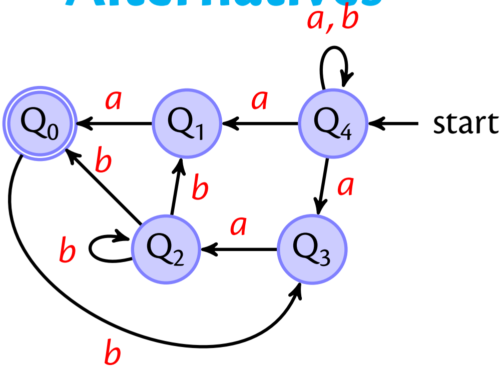
- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA
- remove dead states

Alternatives



- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA
- remove dead states
- repeat once more

Alternatives



- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA
- remove dead states
- repeat once more $\Rightarrow$ minimal DFA

Regexps and Automata

Thompson's construction　　subset construction

Regexps → **NFAs** → **DFAs** → **minimal DFAs**

minimisation

Regexps and Automata

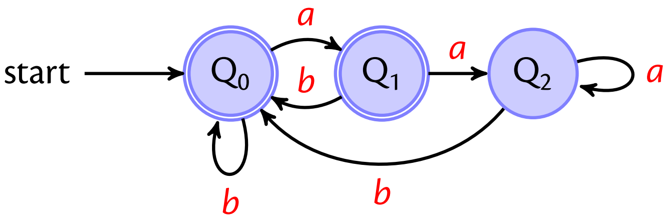
Thompson's construction

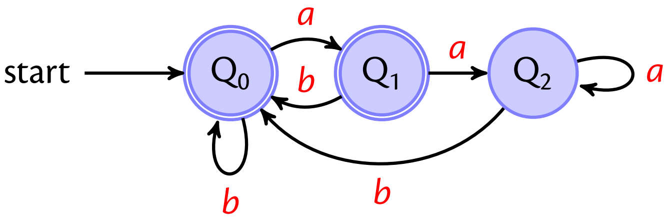
subset construction

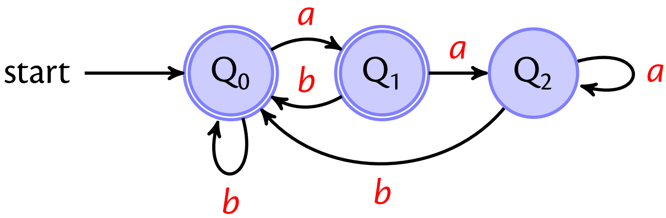
Regexps → **NFAs** → **DFAs** → **minimal DFAs**

minimisation

DFA to Rexp

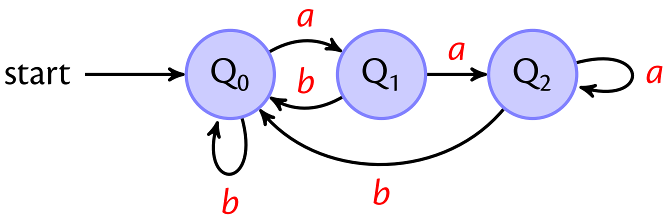


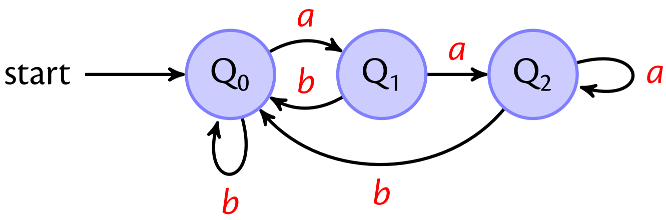

start
Q_0
Q_1
Q_2
a
a
a
b
b
b



You know how to solve since school days, no?

$$
\begin{aligned}
Q_0 &= 2\,Q_0 + 3\,Q_1 + 4\,Q_2 \\
Q_1 &= 2\,Q_0 + 3\,Q_1 + 1\,Q_2 \\
Q_2 &= 1\,Q_0 + 5\,Q_1 + 2\,Q_2
\end{aligned}
$$

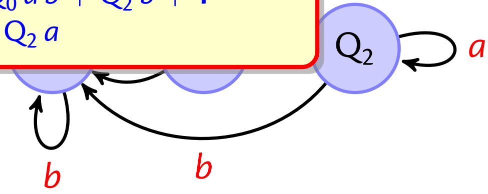

start
Q_0
Q_1
Q_2
a
b
a
a
b
b



$$
\begin{aligned}
Q_0 &= Q_0\, b + Q_1\, b + Q_2\, b + \mathbf{1}\\
Q_1 &= Q_0\, a\\
Q_2 &= Q_1\, a + Q_2\, a
\end{aligned}
$$

substitute Q_1 into Q_0 & Q_2:

$$Q_0 = Q_0\,b + Q_0\,a\,b + Q_2\,b + \mathbf{1}$$
$$Q_2 = Q_0\,a\,a + Q_2\,a$$



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Q_0 &= Q_0\,b + Q_1\,b + Q_2\,b + \mathbf{1}\\
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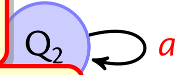

simplifying Q_0:

$$Q_0 = Q_0\, (b + a\, b) + Q_2\, b + \mathbf{1}$$
$$Q_2 = Q_0\, a\, a + Q_2\, a$$

$$\begin{aligned} Q_0 &= Q_0\, b + Q_1\, b + Q_2\, b + \mathbf{1} \\ Q_1 &= Q_0\, a \\ Q_2 &= Q_1\, a + Q_2\, a \end{aligned}$$

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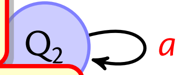

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Arden's Lemma:

If $q = q\, r + s$ then $q = s\, r^*$

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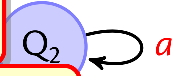

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Arden for Q_2:

$$Q_0 = Q_0\,(b + a\, b) + Q_2\, b + \mathbf{1}$$
$$Q_2 = Q_0\, a\, a\,(a^*)$$

$$Q_1 = Q_0\, a$$

Arden's Lemma:

If $q = q\, r + s$ then $q = s\, r^*$

substitute Q_1 into Q_0 & Q_2:

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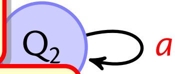

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Arden for Q_2:

$$Q_0 = Q_0\, (b + a\, b) + Q_2\, b + \mathbf{1}$$
$$Q_2 = Q_0\, a\, a\, (a^*)$$

$Q_1 =$

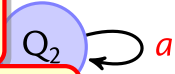
$Q_2 =$

Substitute Q_2 and simplify:

$$Q_0 = Q_0\, (b + a\, b + a\, a\, (a^*)\, b) + \mathbf{1}$$

substitute Q_1 into Q_0 & Q_2:

$$Q_0 = Q_0\, b + Q_0\, a\, b + Q_2\, b + \mathbf{1}$$
$$Q_2 = Q_0\, a\, a + Q_2\, a$$



simplifying Q_0:

$$Q_0 = Q_0\,(b + a\, b) + Q_2\, b + \mathbf{1}$$
$$Q_2 = Q_0\, a\, a + Q_2\, a$$

$\mathbf{1}$

Arden's Lemma:

If $q = q\, r + s$ then $q = s\, r^*$

$Q_1 =$

$Q_2 =$

Substitute Q_2 and simplify:

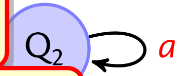
$$Q_0 = Q_0\,(b + a\, b + a\, a\,(a^*)\, b) + \mathbf{1}$$

Arden again for Q_0:

$$Q_0 = (b + a\, b + a\, a\,(a^*)\, b)^*$$

substitute Q_1 into Q_0 & Q_2:

$$Q_0 = Q_0\, b + Q_0\, a\, b + Q_2\, b + \mathbf{1}$$
$$Q_2 = Q_0\, a\, a + Q_2\, a$$



simplifying Q_0:

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Arden for Q_2:

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$$Q_2 = Q_0\, a\, a\, (a^*)$$

$Q_1 =$

$Q_2 =$

Substitute

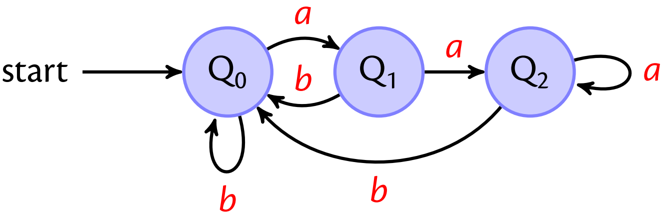
$Q_0 = Q_0$

Arde

Q_0

Finally:

$$Q_0 = (b + a\, b + a\, a\, (a^*)\, b)^*$$
$$Q_1 = (b + a\, b + a\, a\, (a^*)\, b)^*\, a$$
$$Q_2 = (b + a\, b + a\, a\, (a^*)\, b)^*\, a\, a\, (a^*)$$



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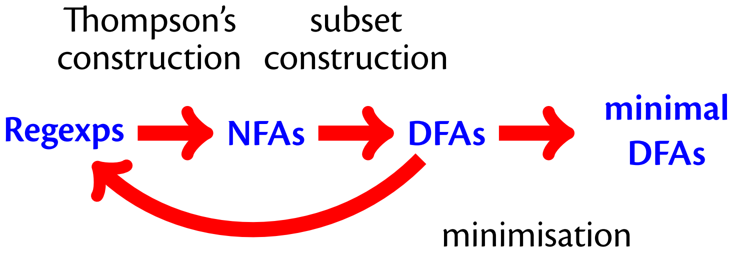
Q_1 &= Q_0\,a\\
Q_2 &= Q_1\,a +
\end{aligned}
$$

Finally:

$$
\begin{aligned}
Q_0 &= (b + a\,b + a\,a\,(a^*)\,b)^*\\
Q_1 &= (b + a\,b + a\,a\,(a^*)\,b)^*\,a\\
Q_2 &= (b + a\,b + a\,a\,(a^*)\,b)^*\,a\,a\,(a^*)
\end{aligned}
$$

Regexps and Automata



Regular Languages (3)

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?

Regexps and Automata

Thompson's construction

subset construction

Regexps → **NFAs** → **DFAs** → **minimal DFAs**

minimisation

Brzozowski's method

Regular Languages

Two equivalent definitions:

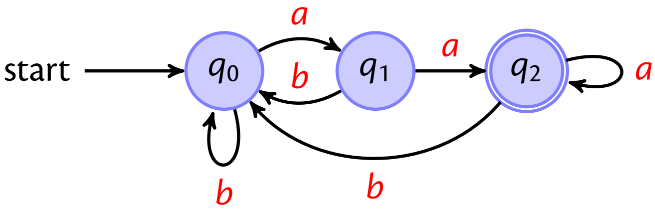
A language is regular iff there exists a regular expression that recognises all its strings.

A language is regular iff there exists an automaton that recognises all its strings.

for example $a^n b^n$ is not regular

Negation

Regular languages are closed under negation:



But requires that the automaton is completed!

Negation

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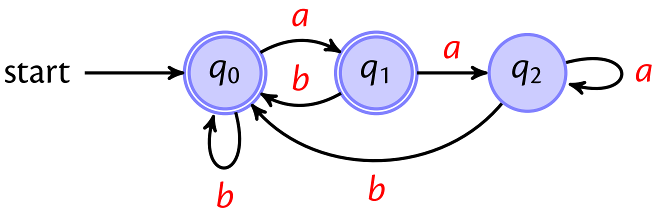
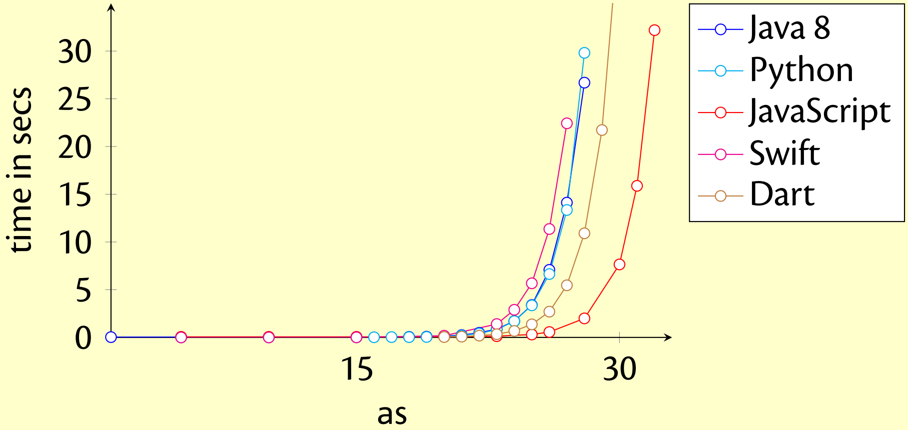
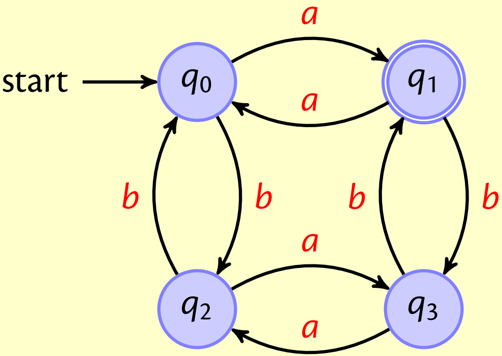


But requires that the automaton is completed!

$(a^*)^* \cdot b$


time in secs
0
5
10
15
20
25
30
15
30
as
Java 8
Python
JavaScript
Swift
Dart



Which language?

I always thought dfa's needed a transition for each state for each character, and if not it would be an nfa not a dfa. Is there an example that disproves this?

Do the regular expression matchers in Python and Java 8 have more features than the one implemented in this module? Or is there another reason for their inefficiency?

- CW / censored some msgs
- power law / proof
- CW feedback
- too polished CW submissions
- no open book