Compilers and Formal Languages

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Slides & Progs: KEATS (also homework is there)

1 Introduction, Languages	6 While-Language
2 Regular Expressions, Derivatives	7 Compilation, JVM
3 Automata, Regular Languages	8 Compiling Functional Languages
4 Lexing, Tokenising	9 Optimisations
5 Grammars, Parsing	10 LLVM

Scala Book, Exams

- https://nms.kcl.ac.uk/christian.urban/ProgInScala2ed.pdf
- homework (written exam 80%)
- coursework (20%)

- short survey at KEATS; to be answered until Sunday

(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!

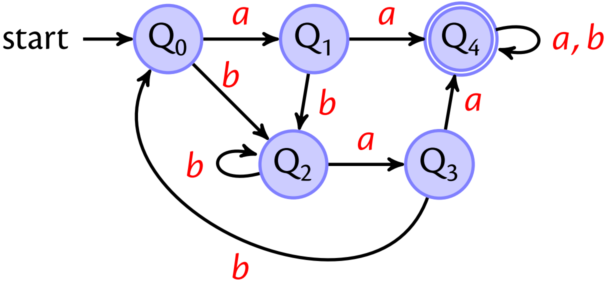
Automata

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

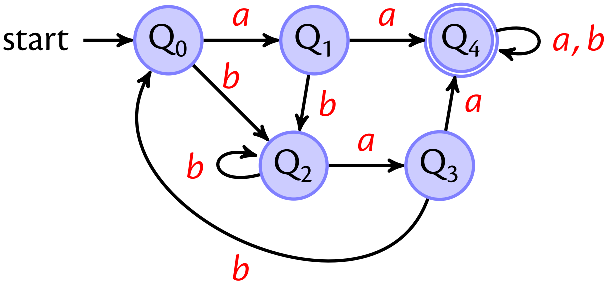
- an alphabet Σ
- a set of states Qs
- one of these states is the start state Q_0
- some states are accepting states F, and
- there is transition function δ

  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

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

Accepting a String

Given

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

you can define

$$\begin{aligned}
\widehat{\delta}(q, []) &\stackrel{\text{def}}{=} q \\
\widehat{\delta}(q, c :: s) &\stackrel{\text{def}}{=} \widehat{\delta}(\delta(q, c), s)
\end{aligned}$$

Accepting a String

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\end{aligned}$$

Whether a string s is accepted by A?

$$\widehat{\delta}(\mathrm{Q}_0, s) \in F$$

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

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

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

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

Non-Deterministic Finite Automata

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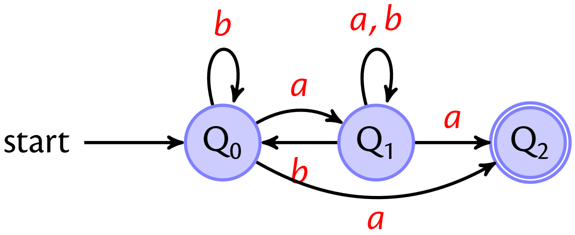
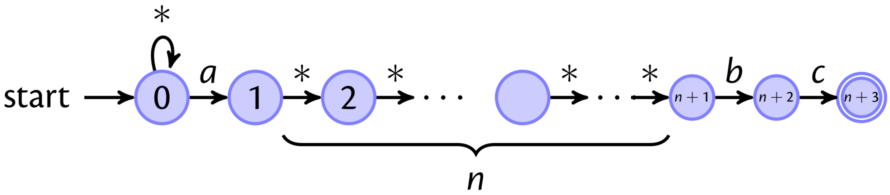
$$\begin{array}{l}(Q_1, a) \rightarrow Q_2 \\ (Q_1, a) \rightarrow Q_3\end{array} \quad \ldots \qquad (Q_1, a) \rightarrow \{Q_2, Q_3\}$$

An NFA Example



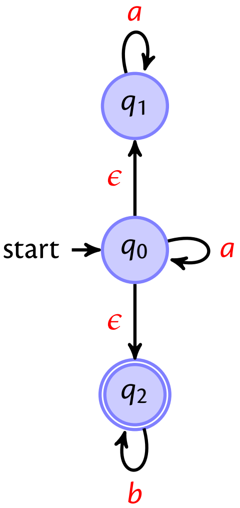
Another Example

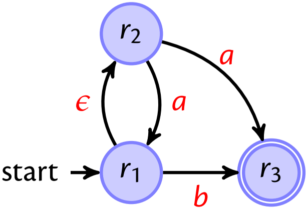
For the regular expression $(.^*)a\,(.^{\{n\}})bc$



Note the star-transitions: accept any character.

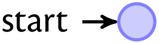
Two Epsilon NFA Examples



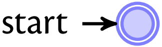


Rexp to NFA

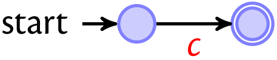
$\mathbf{0}$



$\mathbf{1}$

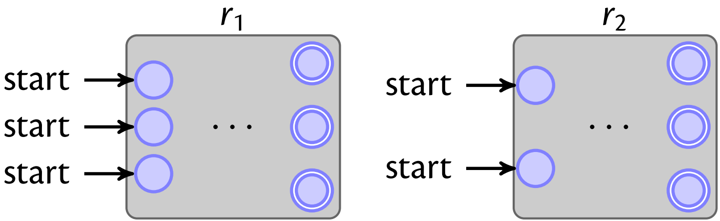


c



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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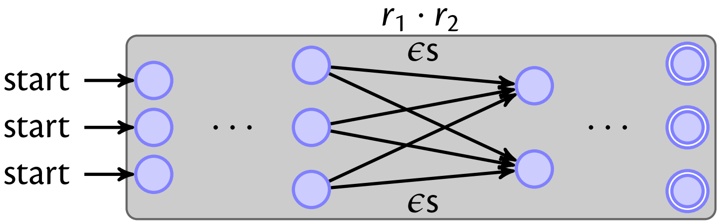

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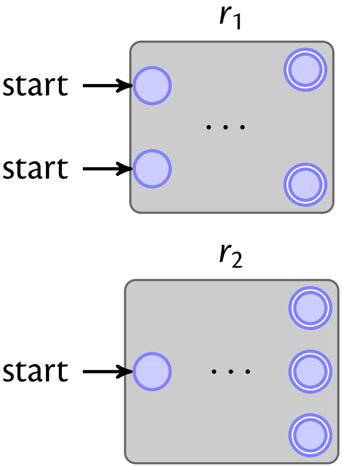

We can just put both automata together.

Case $r_1 + r_2$

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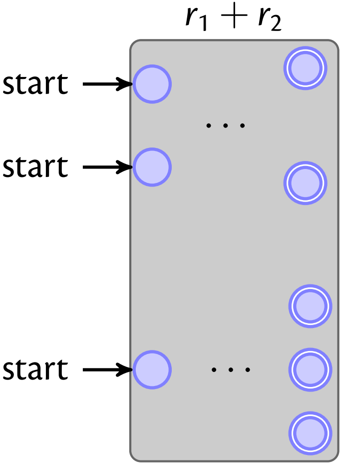
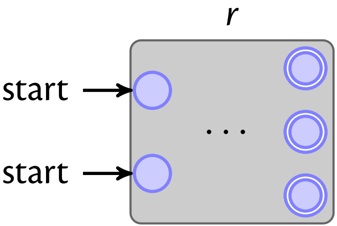


We can just put both automata together.

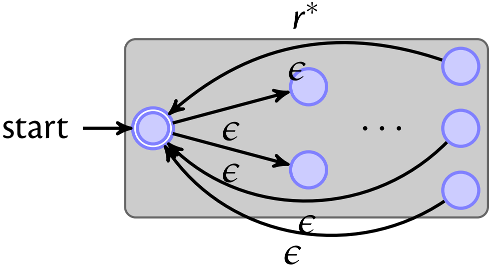
Case r^*

By recursion we are given an automaton for r:



Case r^*

By recursion we are given an automaton for r:



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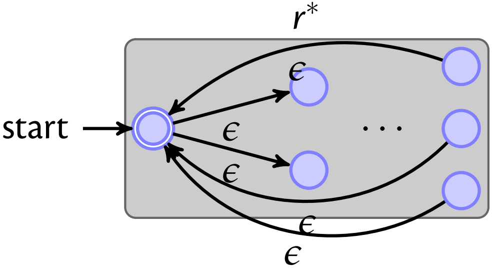
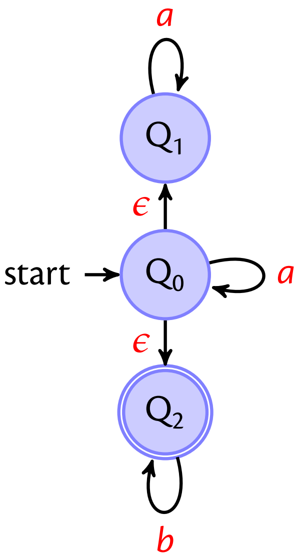


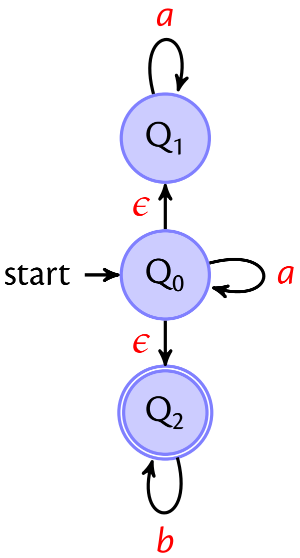
Why can't we just have an epsilon transition from the accepting states to the starting state?

Subset Construction



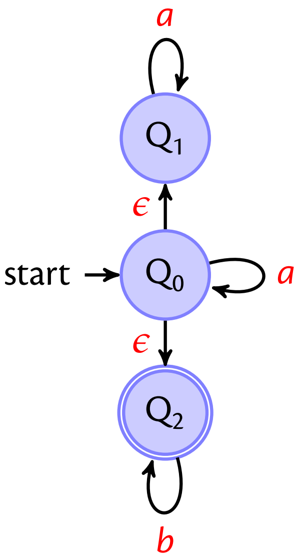
nodes	a	b
$\{\}$		
$\{0\}$		
$\{1\}$		
$\{2\}$		
$\{0,1\}$		
$\{0,2\}$		
$\{1,2\}$		
$\{0,1,2\}$		

Subset Construction



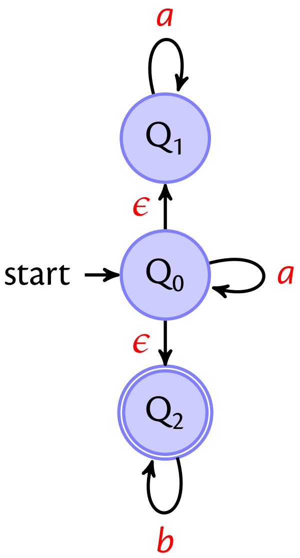
nodes	a	b
$\{\}$	$\{\}$	$\{\}$
$\{0\}$		
$\{1\}$		
$\{2\}$		
$\{0,1\}$		
$\{0,2\}$		
$\{1,2\}$		
$\{0,1,2\}$		

Subset Construction



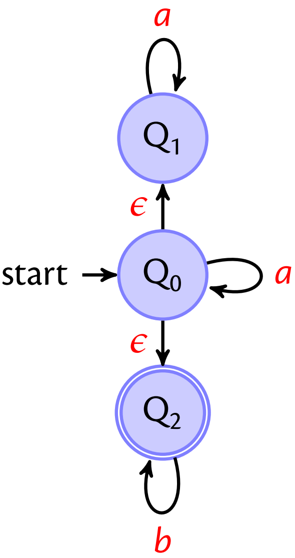
nodes	a	b
$\{\}$	$\{\}$	$\{\}$
$\{0\}$	$\{0,1,2\}$	$\{2\}$
$\{1\}$	$\{1\}$	$\{\}$
$\{2\}$	$\{\}$	$\{2\}$
$\{0,1\}$		
$\{0,2\}$		
$\{1,2\}$		
$\{0,1,2\}$		

Subset Construction



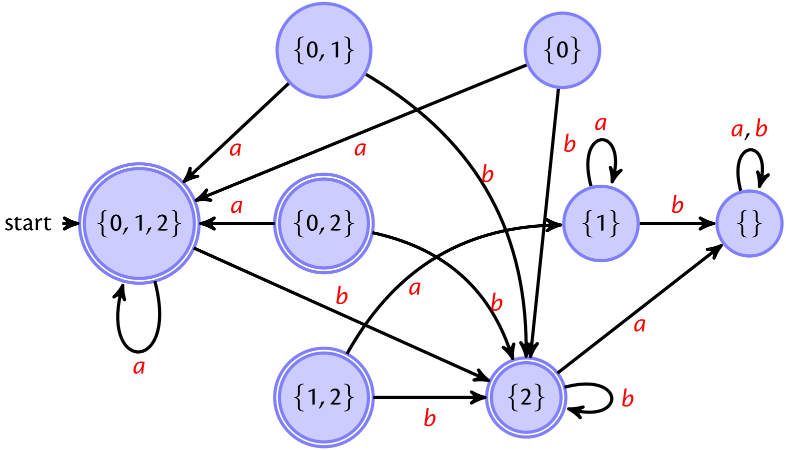
nodes	a	b
$\{\}$	$\{\}$	$\{\}$
$\{0\}$	$\{0,1,2\}$	$\{2\}$
$\{1\}$	$\{1\}$	$\{\}$
$\{2\}$	$\{\}$	$\{2\}$
$\{0,1\}$	$\{0,1,2\}$	$\{2\}$
$\{0,2\}$	$\{0,1,2\}$	$\{2\}$
$\{1,2\}$	$\{1\}$	$\{2\}$
$\{0,1,2\}$	$\{0,1,2\}$	$\{2\}$

Subset Construction



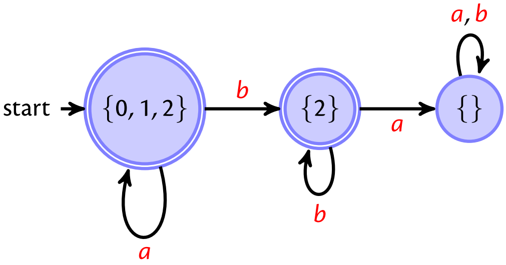
nodes	a	b
$\{\}$	$\{\}$	$\{\}$
$\{0\}$	$\{0,1,2\}$	$\{2\}$
$\{1\}$	$\{1\}$	$\{\}$
$\{2\}$ *	$\{\}$	$\{2\}$
$\{0,1\}$	$\{0,1,2\}$	$\{2\}$
$\{0,2\}$ *	$\{0,1,2\}$	$\{2\}$
$\{1,2\}$ *	$\{1\}$	$\{2\}$
s: $\{0,1,2\}$ *	$\{0,1,2\}$	$\{2\}$

The Result

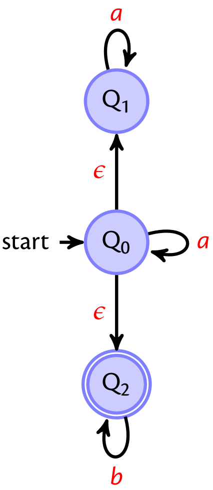


Removing Dead States

DFA:



(original) NFA:



Regexps and Automata

$$\text{Regexps} \xrightarrow{\text{Thompson's construction}} \text{NFAs} \xrightarrow{\text{subset construction}} \text{DFAs}$$

Regexps and Automata

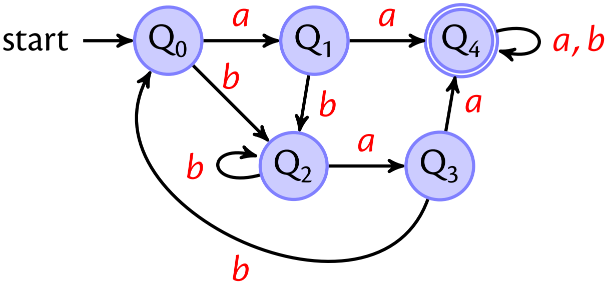
Thompson's construction		subset construction		minimisation	
Regexps	$\rightarrow$	**NFAs**	$\rightarrow$	**DFAs**	$\rightarrow$ **minimal DFAs**

DFA Minimisation

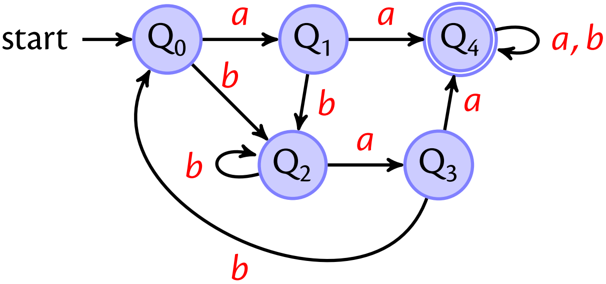
1. Take all pairs (q, p) with $q \neq p$
2. Mark all pairs that accepting and non-accepting states
3. For all unmarked pairs (q, p) and all characters c test whether

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

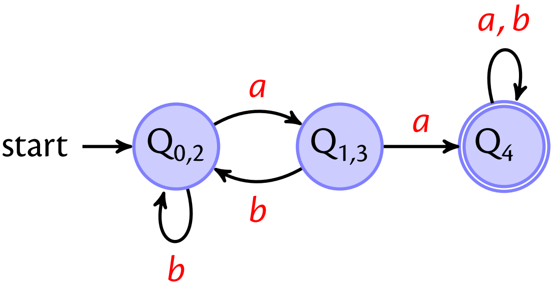
   are marked. If yes in at least one case, then also mark (q, p).
4. Repeat last step until no change.
5. All unmarked pairs can be merged.



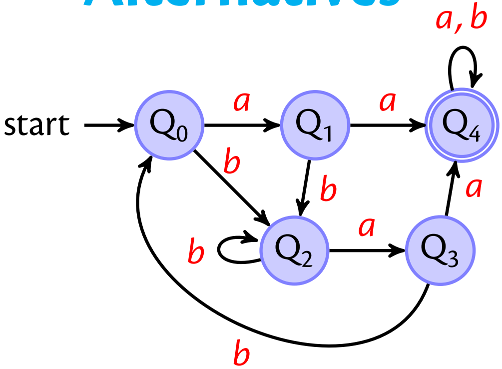
Q_1				
Q_2				
Q_3				
Q_4	$\star$	$\star$	$\star$	$\star$
	Q_0	Q_1	Q_2	Q_3



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

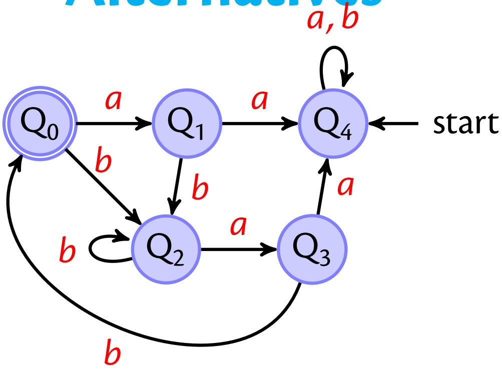


Alternatives



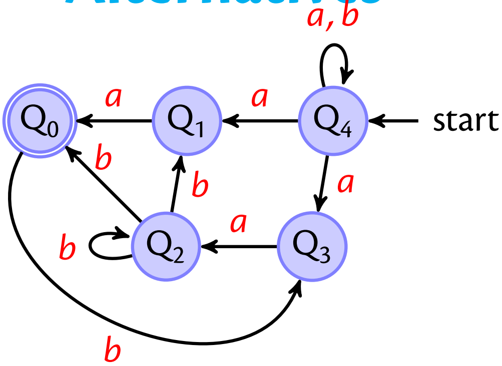
- exchange initial / accepting states

Alternatives



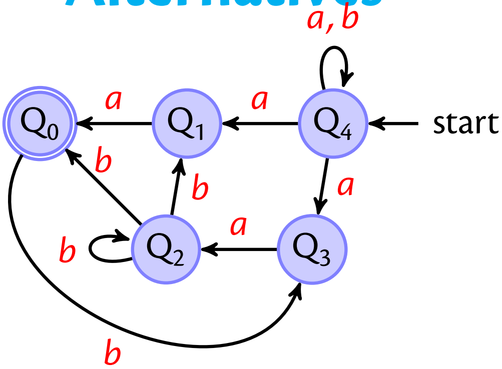
- exchange initial / accepting states
- reverse all edges

Alternatives



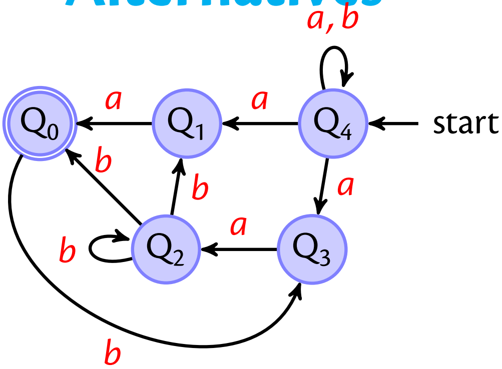
- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA

Alternatives



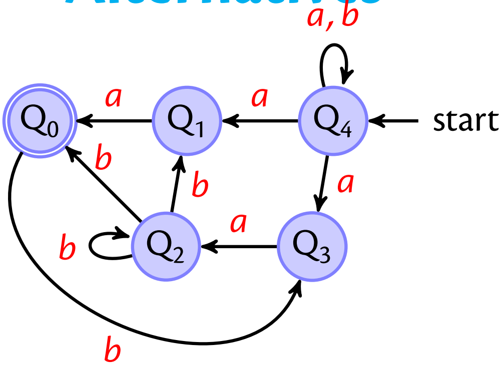
- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA
- remove dead states

Alternatives



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

Alternatives



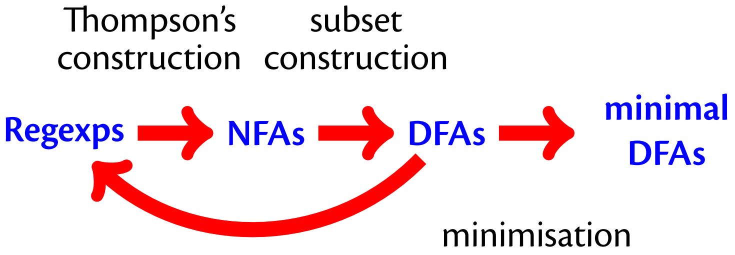
- exchange initial / accepting states
- reverse all edges
- subset construction $\Rightarrow$ DFA
- remove dead states
- repeat once more $\Rightarrow$ minimal DFA

Regexps and Automata

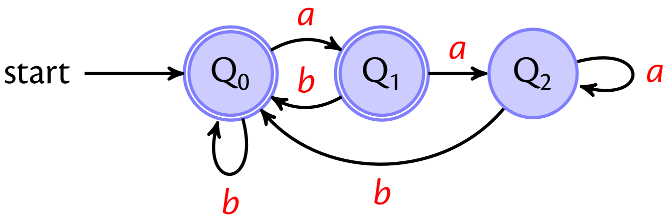
Thompson's construction | subset construction | minimisation

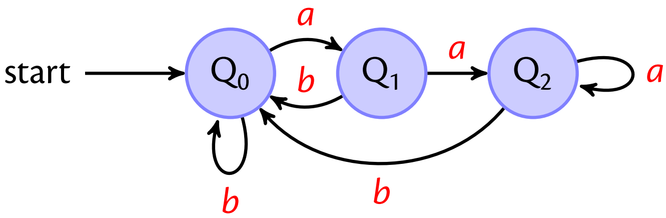
Regexps → **NFAs** → **DFAs** → **minimal DFAs**

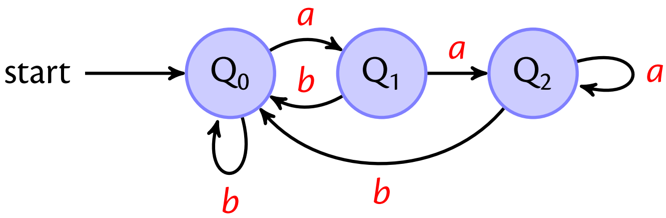
Regexps and Automata



DFA to Rexp

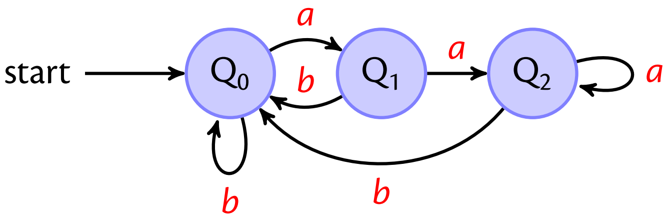


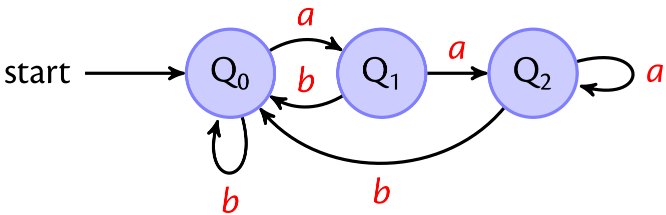

start
Q_0
Q_1
Q_2
a
b
a
a
b
b



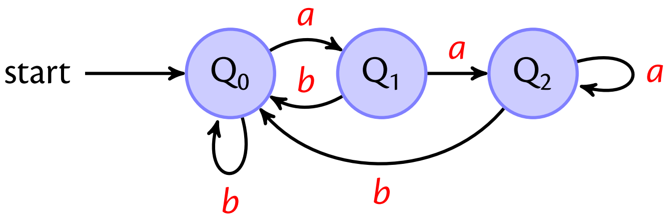
You know how to solve since school days, no?

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


start
Q_0
Q_1
Q_2
a
b
a
a
b
b



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



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\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}
$$

Arden's Lemma:

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

Regexps and Automata

Thompson's construction

subset construction

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

minimisation

Regular Languages (3)

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

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Why is every finite set of strings a regular language?

Given the function

$$\begin{aligned}
rev(\mathbf{0}) &\stackrel{\text{def}}{=} \mathbf{0} \\
rev(\mathbf{1}) &\stackrel{\text{def}}{=} \mathbf{1} \\
rev(c) &\stackrel{\text{def}}{=} c \\
rev(r_1 + r_2) &\stackrel{\text{def}}{=} rev(r_1) + rev(r_2) \\
rev(r_1 \cdot r_2) &\stackrel{\text{def}}{=} rev(r_2) \cdot rev(r_1) \\
rev(r^*) &\stackrel{\text{def}}{=} rev(r)^*
\end{aligned}$$

and the set

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

prove whether

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