Non-deterministic Finite Automata (NFAs)

Lecture 4

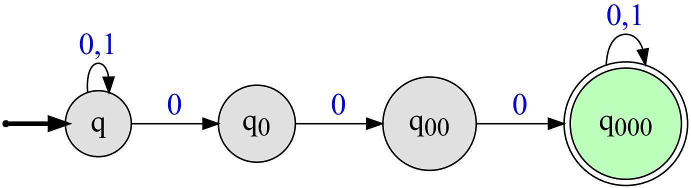
Thursday, September 5, 2024

LaTeXed: September 10, 2024 10:15

4.1
NFA Introduction

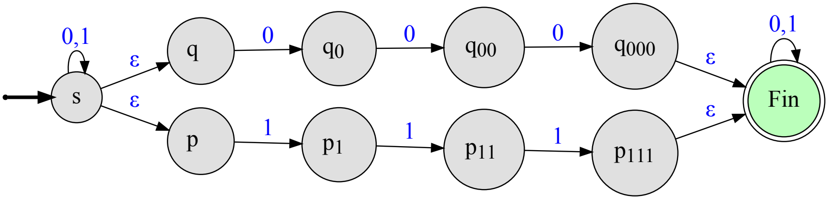
Non-deterministic Finite State Automata by example

When you come to a fork in the road, take it.



Non-deterministic Finite State Automata by example II

..but only if it is made out of silver.



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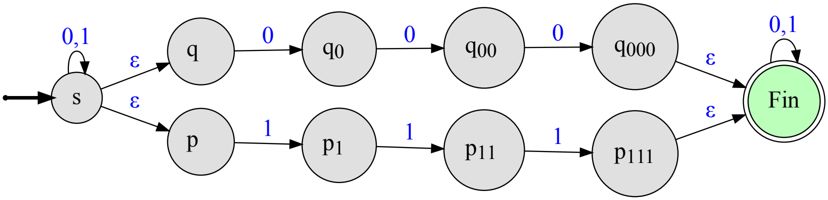

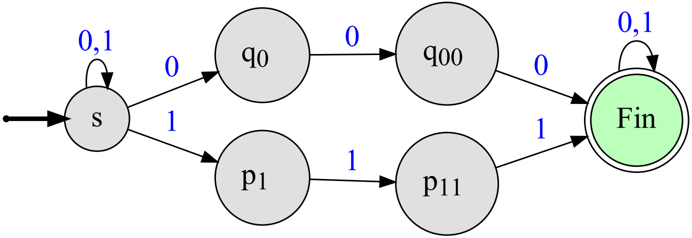

More efficient NFA:

Non-deterministic Finite State Automata by example II

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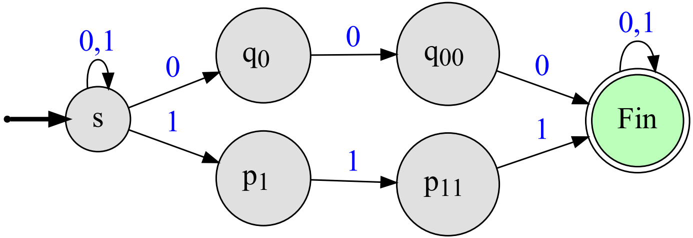
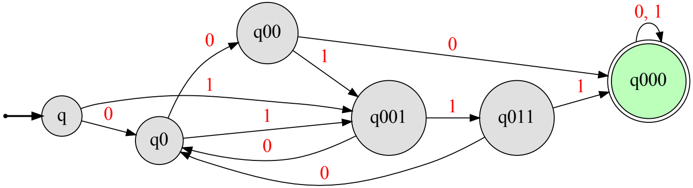
More efficient NFA:



Not the point...
...because DFA can still do it efficiently.



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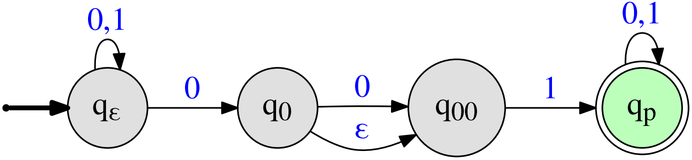

Differences from DFA

- From state q on same letter $a \in \Sigma$ multiple possible states
- No transitions from q on some letters
- ε-transitions!

Questions:

- Is this a "real" machine?
- What does it do?

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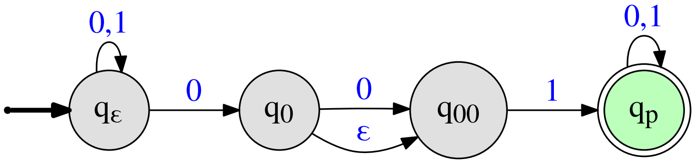

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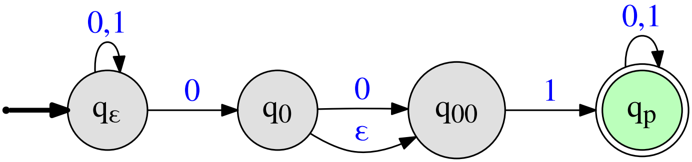

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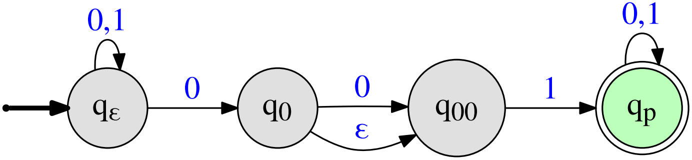
NFA behavior



Machine on input string $\boldsymbol{w}$ from state $\boldsymbol{q}$ can lead to set of states (could be empty)

- From q_ε on $\mathbf{1}$
- From q_ε on $\mathbf{0}$
- From q_0 on ε
- From q_ε on $\mathbf{01}$
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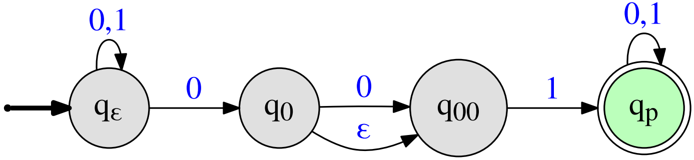
NFA behavior



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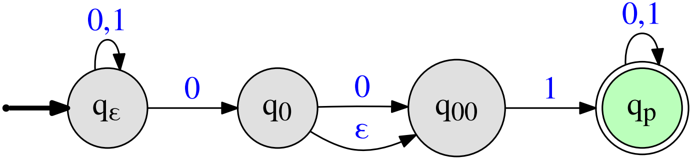

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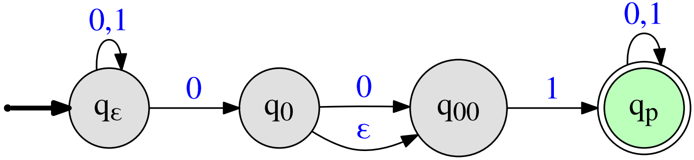

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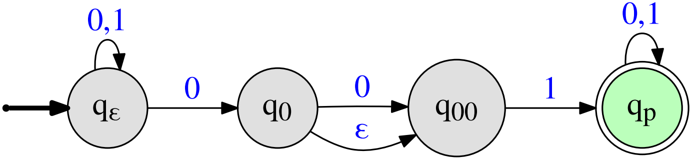

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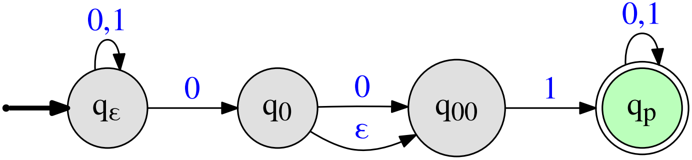

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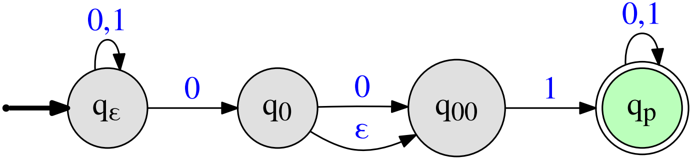
NFA acceptance: informal



Informal definition: An NFA N accepts a string w iff some accepting state is reached by N from the start state on input w.

The language accepted (or recognized) by a NFA N is denote by $L(N)$ and defined as: $L(N) = \{w \mid N \text{ accepts } w\}$.

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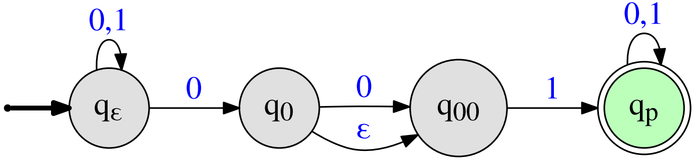

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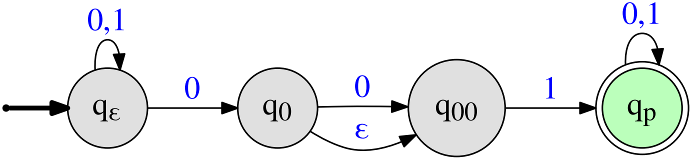

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- Are all strings in **1*01** accepted?
- What is the language accepted by N?

Comment: Unlike DFAs, it is easier in NFAs to show that a string is accepted than to show that a string is **not** accepted.

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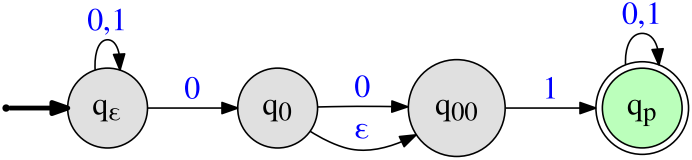

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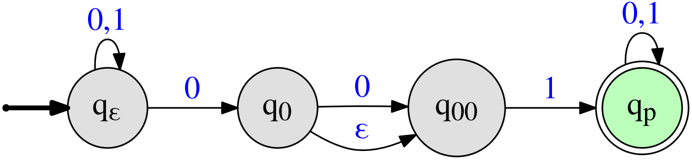

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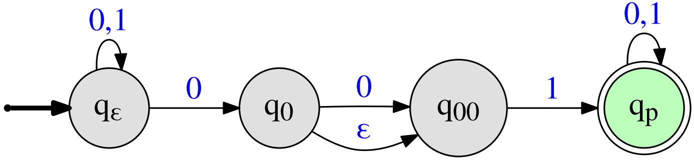

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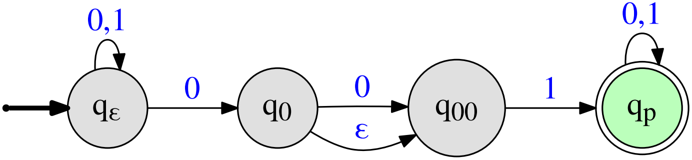

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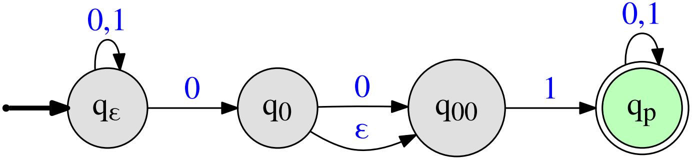

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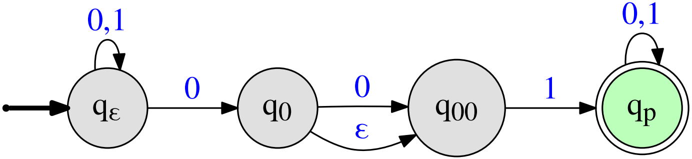

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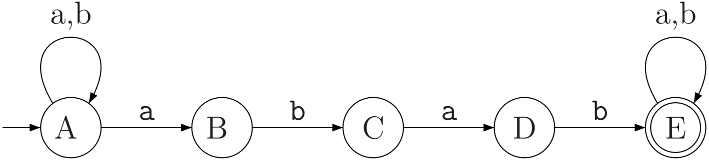
Simulating NFA

Example the first

(N1) 

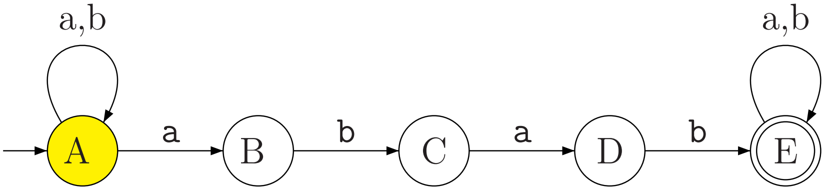
Run it on input ***ababa***.

Idea: Keep track of the states where the NFA might be at any given time.

Simulating NFA

Example the first

$t = 0$:



Remaining input: ***ababa***.

Simulating NFA

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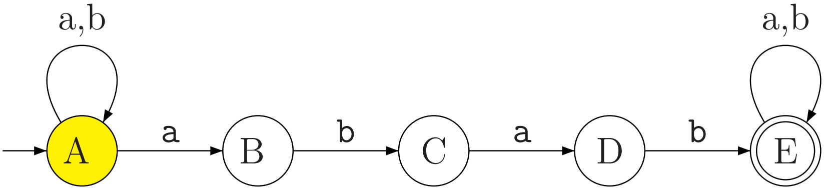
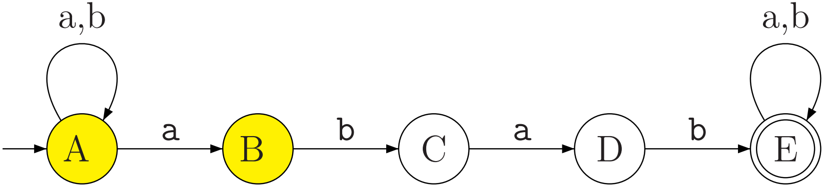


Remaining input: ***ababa***.

$t = 1$:



Remaining input: ***baba***.

Simulating NFA

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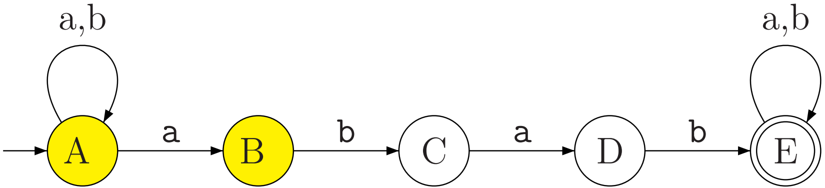

Remaining input: ***baba***.

Simulating NFA

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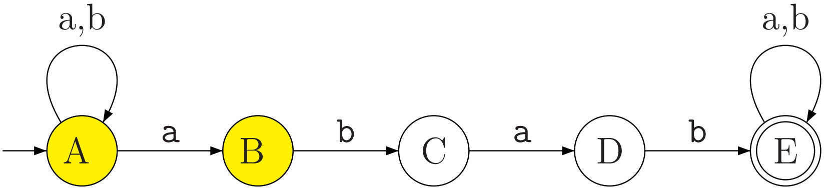
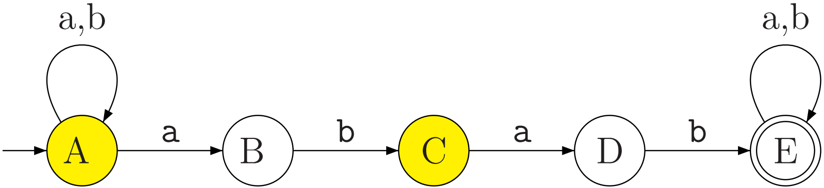


Remaining input: ***baba***.

$t = 2$:



Remaining input: ***aba***.

Simulating NFA

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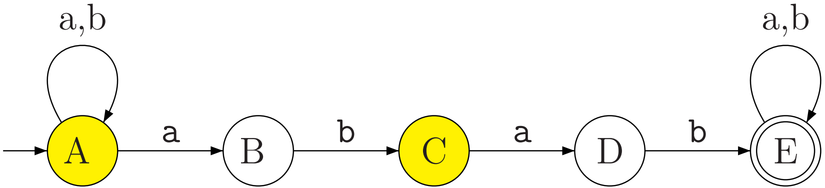

Remaining input: ***aba***.

Simulating NFA

Example the first

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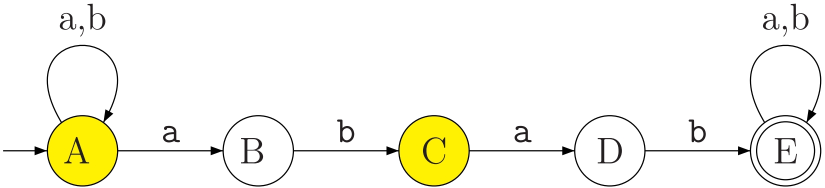
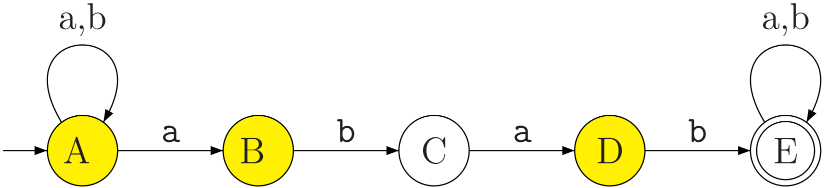


Remaining input: ***aba***.

$t = 3$:



Remaining input: ***ba***.

Simulating NFA

Example the first

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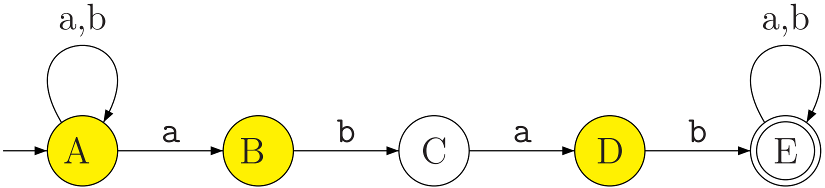

Remaining input: ***ba***.

Simulating NFA

Example the first

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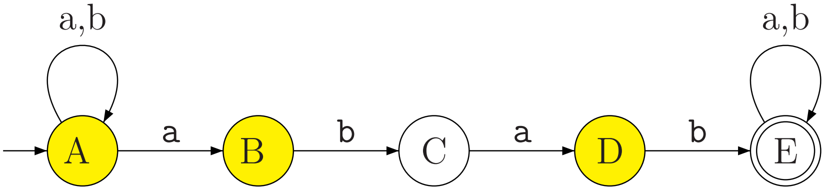
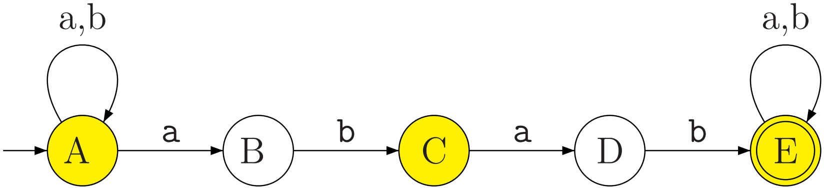


Remaining input: ***ba***.

$t = 4$:



Remaining input: ***a***.

Simulating NFA

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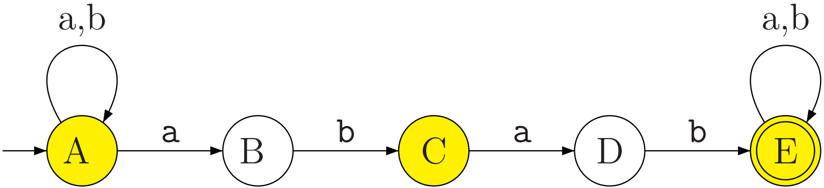

Remaining input: ***a***.

Simulating NFA

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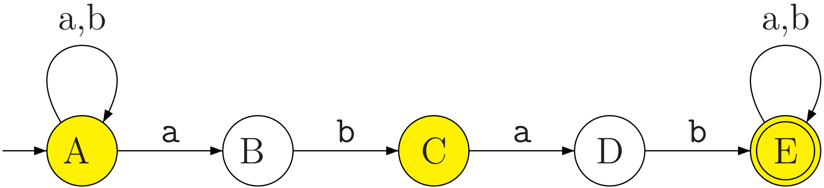
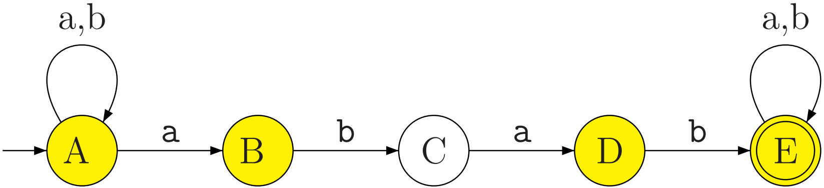


Remaining input: a.

$t = 5$:



Remaining input: ε.

Simulating NFA

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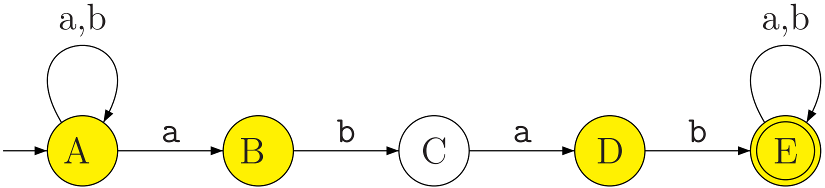


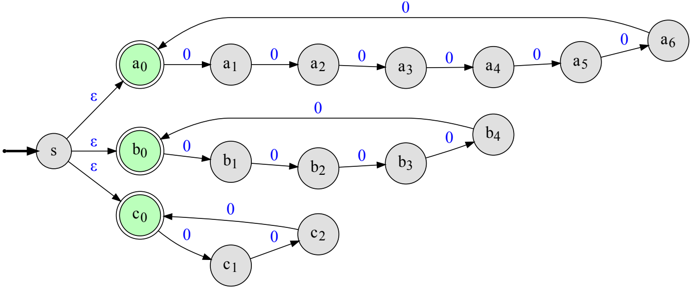
Remaining input: ε.

Accepts: ***ababa***.

An exercise

For you to think about...

A. What is the language that the following NFA accepts?



B. What is the minimal number of states in a DFA that recognizes the same language?

4.1.1
Formal definition of NFA

Reminder: Power set

Q: a set. Power set of Q is: $\mathcal{P}(Q) = 2^Q = \{X \mid X \subseteq Q\}$ is set of all subsets of Q.

Example 4.1.

$Q = \{1, 2, 3, 4\}$

$$\mathcal{P}(Q) = \left\{ \begin{array}{c} \{1,2,3,4\}\,, \\ \{2,3,4\}\,, \{1,3,4\}\,, \{1,2,4\}\,, \{1,2,3\}\,, \\ \{1,2\}\,, \{1,3\}\,, \{1,4\}\,, \{2,3\}\,, \{2,4\}\,, \{3,4\}\,, \\ \{1\}\,, \{2\}\,, \{3\}\,, \{4\}\,, \\ \{\} \end{array} \right\}$$

Formal Tuple Notation

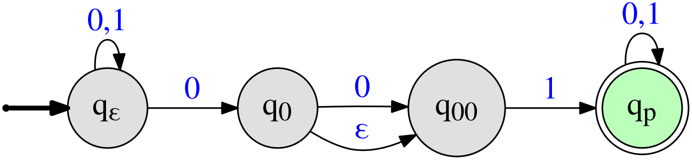
Definition 4.2.

A non-deterministic finite automata (NFA) $N = (Q, \Sigma, \delta, s, A)$ is a five tuple where

- Q is a finite set whose elements are called states,
- Σ is a finite set called the input alphabet,
- $\delta : Q \times \Sigma \cup \{\varepsilon\} \rightarrow \mathcal{P}(Q)$ is the transition function (here $\mathcal{P}(Q)$ is the power set of Q),
- $s \in Q$ is the start state,
- $A \subseteq Q$ is the set of accepting/final states.

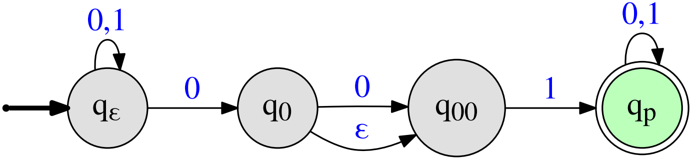
$\delta(q, a)$ for $a \in \Sigma \cup \{\varepsilon\}$ is a subset of Q — a set of states.

Example



- $Q = \{q_\varepsilon, q_0, q_{00}, q_p\}$
- $\Sigma = \{0, 1\}$
- δ
- $s = q_\varepsilon$
- $A = \{q_p\}$

Example



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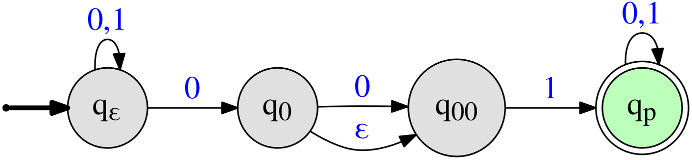

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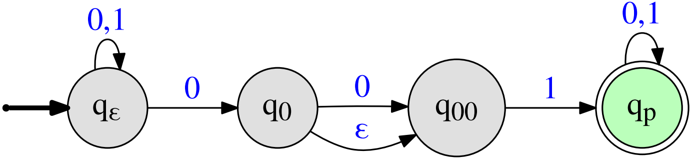

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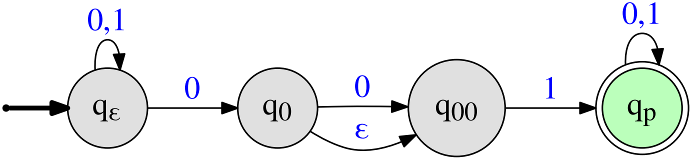

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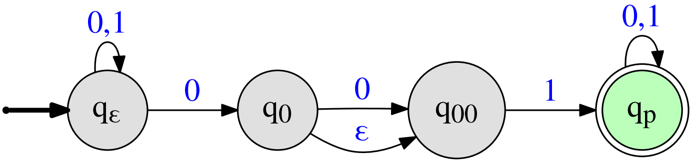

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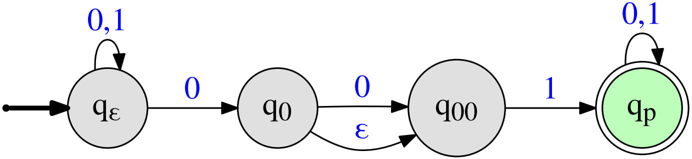

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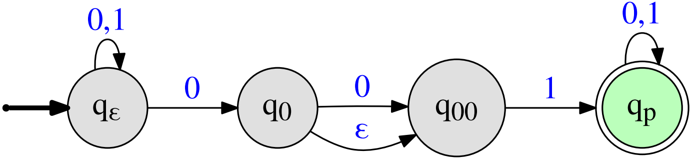
- δ
- $s = q_\varepsilon$
- $A = \{q_p\}$

Example



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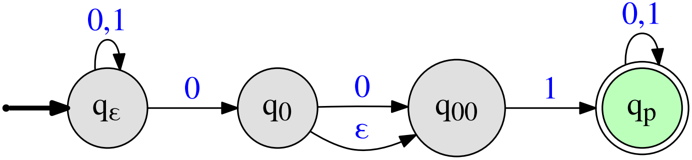

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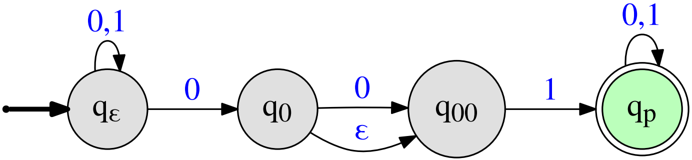
Example

Transition function in detail...



$$\delta(q_\varepsilon, \varepsilon) = \{q_\varepsilon\}$$
$$\delta(q_\varepsilon, 0) = \{q_\varepsilon, q_0\}$$
$$\delta(q_\varepsilon, 1) = \{q_\varepsilon\}$$

$$\delta(q_0, \varepsilon) = \{q_0, q_{00}\}$$
$$\delta(q_0, 0) = \{q_{00}\}$$
$$\delta(q_0, 1) = \{\}$$

$$\delta(q_{00}, \varepsilon) = \{q_{00}\}$$
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$$\delta(q_p, \varepsilon) = \{q_p\}$$
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4.1.2
Extending the transition function to strings

Extending the transition function to strings

1. NFA $N = (Q, \Sigma, \delta, s, A)$
2. $\delta(q, a)$: set of states that N can go to from q on reading $a \in \Sigma \cup \{\varepsilon\}$.
3. Want transition function $\delta^* : Q \times \Sigma^* \to \mathcal{P}(Q)$
4. $\delta^*(q, w)$: set of states reachable on input w starting in state q.

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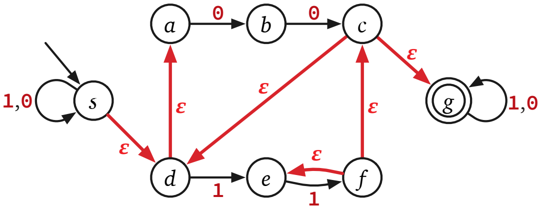
Extending the transition function to strings

Definition 4.3.

For NFA $N = (Q, \Sigma, \delta, s, A)$ and $q \in Q$ the $\epsilon\text{reach}(q)$ is the set of all states that q can reach using only ε-transitions.



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For $X \subseteq Q$: $\epsilon\text{reach}(X) = \bigcup_{x \in X} \epsilon\text{reach}(x)$.

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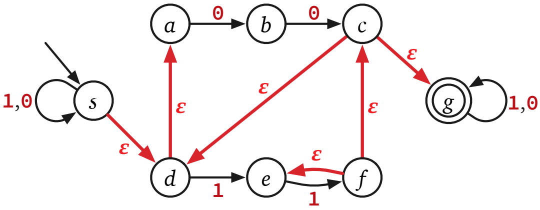

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Extending the transition function to strings

$\epsilon\text{reach}(q)$: set of all states that q can reach using only ε-transitions.

Definition 4.5.

Inductive definition of $\delta^* : Q \times \Sigma^* \to \mathcal{P}(Q)$:

- if $w = \varepsilon$, $\delta^*(q, w) = \epsilon\text{reach}(q)$
- if $w = a$ where $a \in \Sigma$: $\quad \delta^*(q, a) = \epsilon\text{reach}\left(\bigcup_{p \in \epsilon\text{reach}(q)} \delta(p, a) \right)$
- if $w = ax$: $\quad \delta^*(q, w) = \epsilon\text{reach}\left(\bigcup_{p \in \epsilon\text{reach}(q)} \left(\bigcup_{r \in \delta^*(p,a)} \delta^*(r, x) \right) \right)$

Extending the transition function to strings

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Transition for strings: $\mathbf{w = ax}$

Translation...

$$\delta^*(q, w) = \epsilon\text{reach}\left(\bigcup_{p \in \epsilon\text{reach}(q)} \left(\bigcup_{r \in \delta^*(p,a)} \delta^*(r, x)\right)\right)$$

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2. $N = \bigcup_{p \in R} \delta^*(p, a)$: All the states reachable from q with the letter a.
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Formal definition of language accepted by $\mathbf{N}$

Definition 4.6.

A string w is accepted by NFA N if $\delta^*_N(s, w) \cap A \neq \emptyset$.

Definition 4.7.

The language $L(N)$ accepted by a NFA $N = (Q, \Sigma, \delta, s, A)$ is

$$\{w \in \Sigma^* \mid \delta^*(s, w) \cap A \neq \emptyset\}.$$

Important: Formal definition of the language of NFA above uses δ^* and not δ. As such, one does not need to include ε-transitions closure when specifying δ, since δ^* takes care of that.

Formal definition of language accepted by **N**

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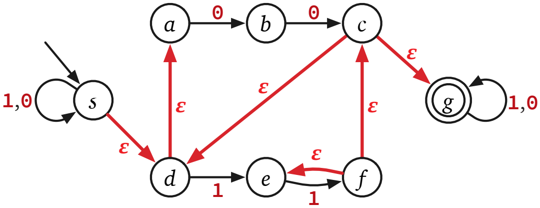
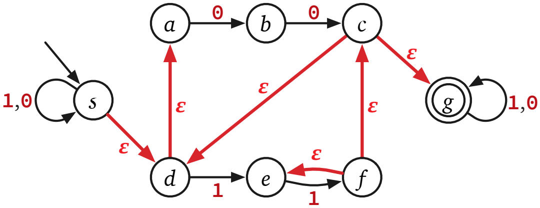
Example



What is:

- $\delta^*(s,\epsilon)$
- $\delta^*(s,0)$
- $\delta^*(c,0)$
- $\delta^*(b,00)$

Example



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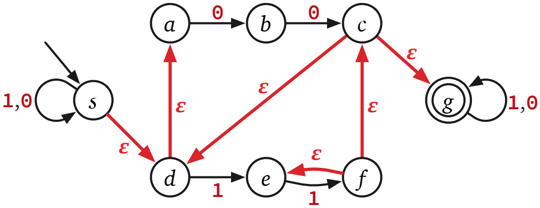

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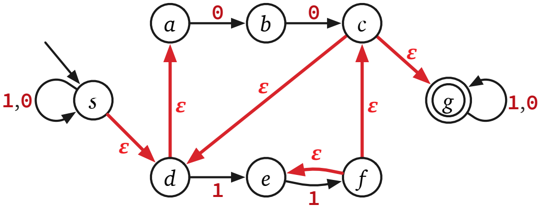

What is:

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Another definition of computation

Definition 4.8.

$q \xrightarrow{w}_N p$: State p of NFA N is **reachable** from q on w $\iff$ there exists a sequence of states $r_0, r_1, \ldots, r_k$ and a sequence $x_1, x_2, \ldots, x_k$ where $x_i \in \Sigma \cup \{\varepsilon\}$, for each i, such that:

- $r_0 = q$,
- for each i, $r_{i+1} \in \delta^*(r_i, x_{i+1})$,
- $r_k = p$, and
- $w = x_1 x_2 x_3 \cdots x_k$.

The sequence $r_0 \xrightarrow{x_1} r_1 \xrightarrow{x_2} \cdots \xrightarrow{x_k} r_k$ is a **trace** of N on w.

Definition 4.9.

$$\delta^*_N(q, w) = \left\{ p \in Q \;\middle|\; q \xrightarrow{w}_N p \right\}.$$

Why non-determinism?

- Non-determinism adds power to the model; richer programming language and hence (much) easier to “design” programs
- Fundamental in **theory** to prove many theorems
- Very important in **practice** directly and indirectly
- Many deep connections to various fields in Computer Science and Mathematics

Many interpretations of non-determinism. Hard to understand at the outset. Get used to it and then you will appreciate it slowly.

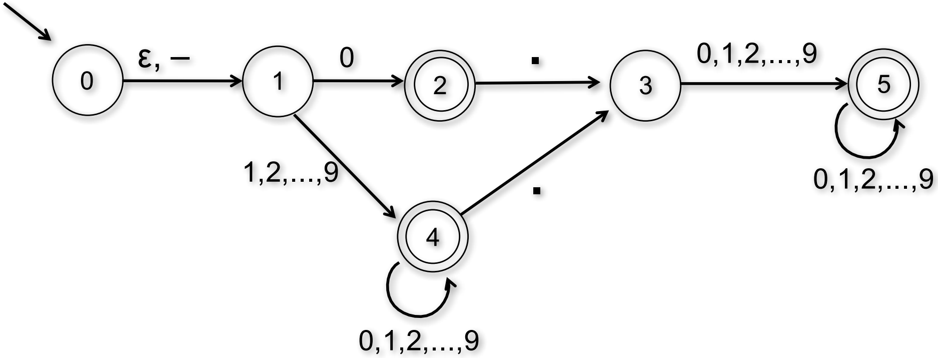
4.2
Constructing NFAs

DFAs and NFAs

- Every DFA is a NFA so NFAs are at least as powerful as DFAs.
- NFAs prove ability to "guess and verify" which simplifies design and reduces number of states
- Easy proofs of some closure properties

Example

Strings that represent decimal numbers.



Example

- {strings that contain CS374 as a substring}
- {strings that contain CS374 or CS473 as a substring}
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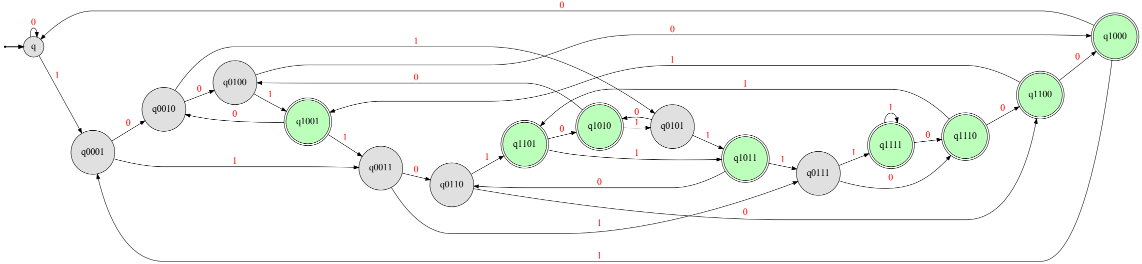
Example

$L_k = \{$bitstrings that have a 1 k positions from the end$\}$

DFA for same task is much bigger...

$L_4 = \{$bitstrings that have a **1** in fourth position from the end$\}$



A simple transformation

Theorem 4.1.

For every NFA N *there is another* NFA N' *such that* $L(N) = L(N')$ *and such that* N' *has the following two properties:*

- N' *has single final state* f *that has no outgoing transitions*
- *The start state* s *of* N *is different from* f

4.3

Closure Properties of NFAs

Closure properties of NFAs

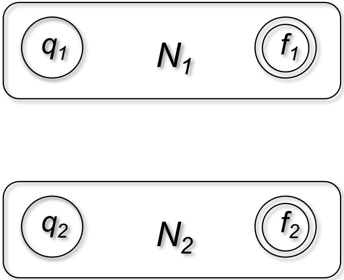
Are the class of languages accepted by NFAs closed under the following operations?

- union
- intersection
- concatenation
- Kleene star
- complement

Closure under union

Theorem 4.1.

For any two NFA*s* N_1 *and* N_2 *there is a* NFA N *such that* $L(N) = L(N_1) \cup L(N_2)$.



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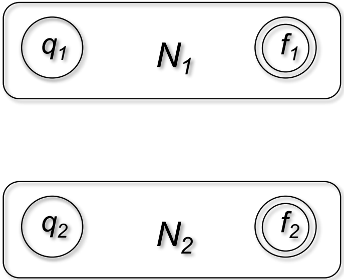

Closure under concatenation

Theorem 4.2.

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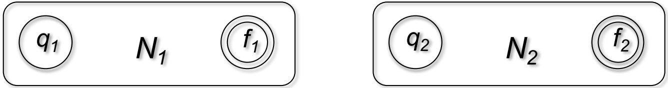

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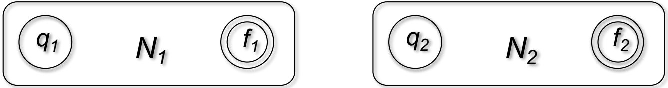
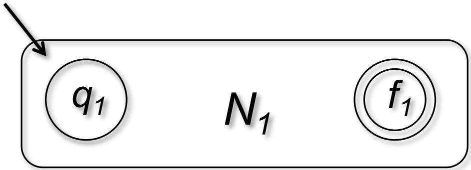


Closure under Kleene star

Theorem 4.3.

For any NFA N_1 *there is a* NFA N *such that* $L(N) = (L(N_1))^*$.



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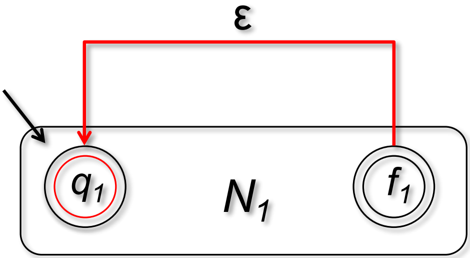

Does not work! Why?

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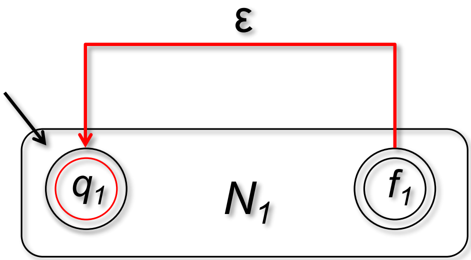

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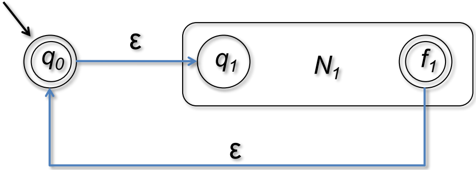

4.4
NFAs capture Regular Languages

Regular Languages Recap

Regular Languages	**Regular Expressions**
$\emptyset$ regular	$\emptyset$ denotes $\emptyset$
$\{\epsilon\}$ regular	ϵ denotes $\{\epsilon\}$
$\{a\}$ regular for $a \in \Sigma$	$\mathbf{a}$ denote $\{a\}$
$R_1 \cup R_2$ regular if both are	$\mathbf{r}_1 + \mathbf{r}_2$ denotes $R_1 \cup R_2$
$R_1 R_2$ regular if both are	$\mathbf{r}_1\mathbf{r}_2$ denotes $R_1 R_2$
R^* is regular if R is	$\mathbf{r}^*$ denote R^*

Regular expressions denote regular languages — they explicitly show the operations that were used to form the language

NFAs and Regular Language

Theorem 4.1.

For every regular language L there is an NFA N such that $L = L(N)$.

Proof strategy:

- For every regular expression r show that there is a NFA N such that $L(r) = L(N)$
- Induction on length of r

NFAs and Regular Language

- For every regular expression r show that there is a NFA N such that $L(r) = L(N)$
- Induction on length of r

Base cases: $\emptyset$, $\{\varepsilon\}$, $\{a\}$ for $a \in \Sigma$.

NFAs and Regular Language

- For every regular expression r show that there is a NFA N such that $L(r) = L(N)$
- Induction on length of r

Inductive cases:

- r_1, r_2 regular expressions and $r = r_1 + r_2$.
  By induction there are NFAs N_1, N_2 s.t
  $L(N_1) = L(r_1)$ and $L(N_2) = L(r_2)$. We have already seen that there is NFA N s.t $L(N) = L(N_1) \cup L(N_2)$, hence $L(N) = L(r)$
- $r = r_1 \bullet r_2$. Use closure of NFA languages under concatenation
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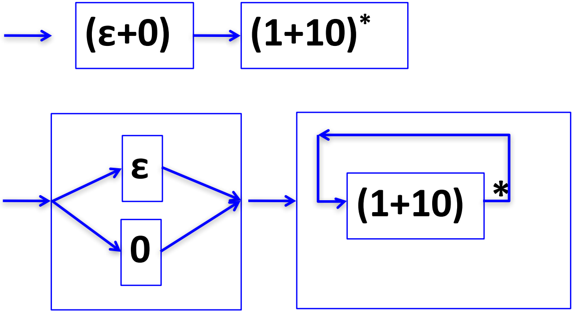
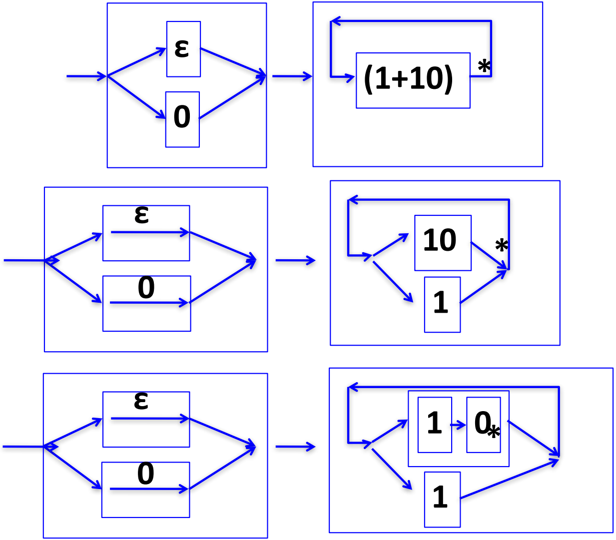
- r_1, r_2 regular expressions and $r = r_1 + r_2$.
  By induction there are NFAs N_1, N_2 s.t
  $L(N_1) = L(r_1)$ and $L(N_2) = L(r_2)$. We have already seen that there is NFA N s.t $L(N) = L(N_1) \cup L(N_2)$, hence $L(N) = L(r)$
- $r = r_1 \bullet r_2$. Use closure of NFA languages under concatenation
- $r = (r_1)^*$. Use closure of NFA languages under Kleene star

Example

$(\varepsilon+0)(1+10)^*$



Example



Example

Final NFA simplified slightly to reduce states