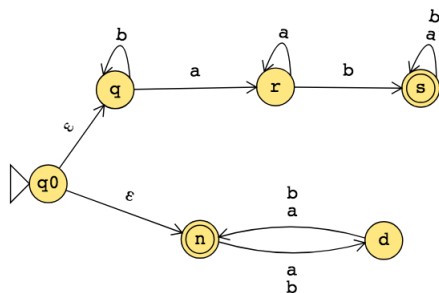


Week3 monday

The state diagram of an NFA over $\{a, b\}$ is below. The formal definition of this NFA is:



The language recognized by this NFA is:

Suppose A_1, A_2 are languages over an alphabet Σ . **Claim:** if there is a NFA N_1 such that $L(N_1) = A_1$ and NFA N_2 such that $L(N_2) = A_2$, then there is another NFA, let's call it N , such that $L(N) = A_1 \cup A_2$.

Proof idea: Use nondeterminism to choose which of N_1, N_2 to run.

Formal construction: Let $N_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ and $N_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ and assume $Q_1 \cap Q_2 = \emptyset$ and that $q_0 \notin Q_1 \cup Q_2$. Construct $N = (Q, \Sigma, \delta, q_0, F_1 \cup F_2)$ where

- $Q =$
- $\delta : Q \times \Sigma_\epsilon \rightarrow \mathcal{P}(Q)$ is defined by, for $q \in Q$ and $a \in \Sigma_\epsilon$:

Proof of correctness would prove that $L(N) = A_1 \cup A_2$ by considering an arbitrary string accepted by N , tracing an accepting computation of N on it, and using that trace to prove the string is in at least one of A_1, A_2 ; then, taking an arbitrary string in $A_1 \cup A_2$ and proving that it is accepted by N . Details left for extra practice.

Over the alphabet $\{a, b\}$, the language L described by the regular expression $\Sigma^*a\Sigma^*b$

includes the strings

and excludes the strings

The state diagram of a NFA recognizing L is:

Suppose A_1, A_2 are languages over an alphabet Σ . **Claim:** if there is a NFA N_1 such that $L(N_1) = A_1$ and NFA N_2 such that $L(N_2) = A_2$, then there is another NFA, let's call it N , such that $L(N) = A_1 \circ A_2$.

Proof idea: Allow computation to move between N_1 and N_2 “spontaneously” when reach an accepting state of N_1 , guessing that we’ve reached the point where the two parts of the string in the set-wise concatenation are glued together.

Formal construction: Let $N_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ and $N_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ and assume $Q_1 \cap Q_2 = \emptyset$. Construct $N = (Q, \Sigma, \delta, q_0, F)$ where

- $Q =$
- $q_0 =$
- $F =$
- $\delta : Q \times \Sigma_\varepsilon \rightarrow \mathcal{P}(Q)$ is defined by, for $q \in Q$ and $a \in \Sigma_\varepsilon$:

$$\delta((q, a)) = \begin{cases} \delta_1((q, a)) & \text{if } q \in Q_1 \text{ and } q \notin F_1 \\ \delta_1((q, a)) & \text{if } q \in F_1 \text{ and } a \in \Sigma \\ \delta_1((q, a)) \cup \{q_2\} & \text{if } q \in F_1 \text{ and } a = \varepsilon \\ \delta_2((q, a)) & \text{if } q \in Q_2 \end{cases}$$

Proof of correctness would prove that $L(N) = A_1 \circ A_2$ by considering an arbitrary string accepted by N , tracing an accepting computation of N on it, and using that trace to prove the string can be written as the result of concatenating two strings, the first in A_1 and the second in A_2 ; then, taking an arbitrary string in $A_1 \circ A_2$ and proving that it is accepted by N . Details left for extra practice.

Suppose A is a language over an alphabet Σ . **Claim:** if there is a NFA N such that $L(N) = A$, then there is another NFA, let's call it N' , such that $L(N') = A^*$.

Proof idea: Add a fresh start state, which is an accept state. Add spontaneous moves from each (old) accept state to the old start state.

Formal construction: Let $N = (Q, \Sigma, \delta, q_1, F)$ and assume $q_0 \notin Q$. Construct $N' = (Q', \Sigma, \delta', q_0, F')$ where

- $Q' = Q \cup \{q_0\}$
- $F' = F \cup \{q_0\}$
- $\delta' : Q' \times \Sigma_\varepsilon \rightarrow \mathcal{P}(Q')$ is defined by, for $q \in Q'$ and $a \in \Sigma_\varepsilon$:

$$\delta'((q, a)) = \begin{cases} \delta((q, a)) & \text{if } q \in Q \text{ and } q \notin F \\ \delta((q, a)) & \text{if } q \in F \text{ and } a \in \Sigma \\ \delta((q, a)) \cup \{q_1\} & \text{if } q \in F \text{ and } a = \varepsilon \\ \{q_1\} & \text{if } q = q_0 \text{ and } a = \varepsilon \\ \emptyset & \text{if } q = q_0 \text{ and } a \in \Sigma \end{cases}$$

Proof of correctness would prove that $L(N') = A^$ by considering an arbitrary string accepted by N' , tracing an accepting computation of N' on it, and using that trace to prove the string can be written as the result of concatenating some number of strings, each of which is in A ; then, taking an arbitrary string in A^* and proving that it is accepted by N' . Details left for extra practice.*

Application: A state diagram for a NFA over $\Sigma = \{a, b\}$ that recognizes $L((\Sigma^*b)^*)$:

True or False: The state diagram of any DFA is also the state diagram of a NFA.

True or False: The state diagram of any NFA is also the state diagram of a DFA.

True or False: The formal definition $(Q, \Sigma, \delta, q_0, F)$ of any DFA is also the formal definition of a NFA.

True or False: The formal definition $(Q, \Sigma, \delta, q_0, F)$ of any NFA is also the formal definition of a DFA.

Week3 wednesday

Consider the state diagram of an NFA over $\{a, b\}$:



The language recognized by this NFA is

The state diagram of a DFA recognizing this same language is:

Suppose A is a language over an alphabet Σ . **Claim:** if there is a NFA N such that $L(N) = A$ then there is a DFA M such that $L(M) = A$.

Proof idea: States in M are “macro-states” – collections of states from N – that represent the set of possible states a computation of N might be in.

Formal construction: Let $N = (Q, \Sigma, \delta, q_0, F)$. Define

$$M = (\mathcal{P}(Q), \Sigma, \delta', q', \{X \subseteq Q \mid X \cap F \neq \emptyset\})$$

where $q' = \{q \in Q \mid q = q_0 \text{ or is accessible from } q_0 \text{ by spontaneous moves in } N\}$ and

$\delta'((X, x)) = \{q \in Q \mid q \in \delta(r, x) \text{ for some } r \in X \text{ or is accessible from such an } r \text{ by spontaneous moves in } N\}$

Consider the state diagram of an NFA over $\{0, 1\}$. Use the “macro-state” construction to find an equivalent DFA.



Prune this diagram to get an equivalent DFA with only the “macro-states” reachable from the start state.

Suppose A is a language over an alphabet Σ . **Claim:** if there is a regular expression R such that $L(R) = A$, then there is a NFA, let's call it N , such that $L(N) = A$.

Structural induction: Regular expression is built from basis regular expressions using inductive steps (union, concatenation, Kleene star symbols). Use constructions to mirror these in NFAs.

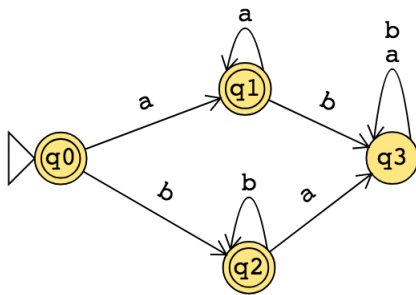
Application: A state diagram for a NFA over $\{a, b\}$ that recognizes $L(a^*(ab)^*)$:

Suppose A is a language over an alphabet Σ . **Claim:** if there is a DFA M such that $L(M) = A$, then there is a regular expression, let's call it R , such that $L(R) = A$.

Proof idea: Trace all possible paths from start state to accept state. Express labels of these paths as regular expressions, and union them all.

1. Add new start state with ε arrow to old start state.
2. Add new accept state with ε arrow from old accept states. Make old accept states non-accept.
3. Remove one (of the old) states at a time: modify regular expressions on arrows that went through removed state to restore language recognized by machine.

Application: Find a regular expression describing the language recognized by the DFA with state diagram



Conclusion: For each language L ,

There is a DFA that recognizes L $\iff \exists M$ (M is a DFA and $L(M) = L$)
if and only if

There is a NFA that recognizes L $\iff \exists N$ (N is a NFA and $L(N) = L$)
if and only if

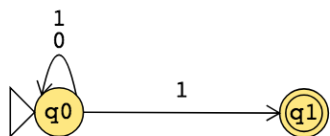
There is a regular expression that describes L $\iff \exists R$ (R is a regular expression and $L(R) = L$)

A language is called **regular** when any (hence all) of the above three conditions are met.

Week2 friday

Nondeterministic finite automaton $M = (Q, \Sigma, \delta, q_0, F)$	
Finite set of states Q	Can be labelled by any collection of distinct names. Default: q_0, q_1, \dots
Alphabet Σ	Each input to the automaton is a string over Σ .
Arrow labels Σ_ϵ	$\Sigma_\epsilon = \Sigma \cup \{\epsilon\}$.
Transition function δ	Arrows in the state diagram are labelled either by symbols from Σ or by ϵ $\delta : Q \times \Sigma_\epsilon \rightarrow \mathcal{P}(Q)$ gives the set of possible next states for a transition from the current state upon reading a symbol or spontaneously moving.
Start state q_0	Element of Q . Each computation of the machine starts at the start state.
Accept (final) states F	$F \subseteq Q$.
M accepts the input string	if and only if there is a computation of M on the input string that processes the whole string and ends in an accept state.
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The formal definition of the NFA over $\{0, 1\}$ given by this state diagram is:



The language over $\{0, 1\}$ recognized by this NFA is:

Change the transition function to get a different NFA which accepts the empty string.

The state diagram of an NFA over $\{a, b\}$ is below. The formal definition of this NFA is:



The language recognized by this NFA is: