CSE 135: Introduction to Theory of Computation
Equivalence of DFA and NFA

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Expressive Power of NFAs and DFAs

- Is there a language that is recognized by a DFA but not by any NFAs?

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In other words:

- *For any DFA D, there is an NFA N such that $L(N) = L(D)$, and*
- *for any NFA N, there is a DFA D such that $L(D) = L(N)$.*

Converting DFAs to NFAs

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Is a DFA an NFA? Essentially yes! Syntactically, not quite. The formal definition of DFA has $\delta_{\mathsf{DFA}} : Q \times \Sigma \to Q$ whereas $\delta_{\mathsf{NFA}} : Q \times (\Sigma \cup \{\epsilon\}) \to \mathcal{P}(Q)$.

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For DFA $D = (Q, \Sigma, \delta_D, q_0, F)$, define an "equivalent" NFA $N = (Q, \Sigma, \delta_N, q_0, F)$ that has the exact same set of states, initial state and final states. Only difference is in the transition function.

$$\delta_N(q, a) = \{\delta_D(q, a)\}$$

for $a \in \Sigma$ and $\delta_N(q, \epsilon) = \emptyset$ for all $q \in Q$. $\square$

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How do we write a computer program to solve the NFA Acceptance problem?

Two Views of Nondeterminsm

Guessing View

At each step, the NFA "guesses" one of the choices available; the NFA will guess an "accepting sequence of choices" if such a one exists.

Parallel View

At each step the machine "forks" threads corresponding to each of the possible next states.

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Very useful in reasoning about NFAs and in designing NFAs.

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Parallel View

At each step the machine "forks" threads corresponding to each of the possible next states.

Very useful in simulating/running NFA on inputs.

Algorithm for Simulating an NFA

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Keep track of the current state of each of the active threads.

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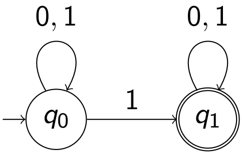
Example



Example NFA N

Consider the input $w = 111$. The execution (listing only the states of currently active threads) is

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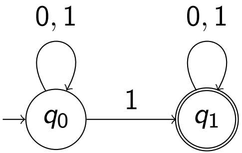

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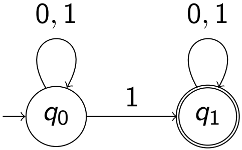

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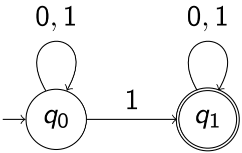

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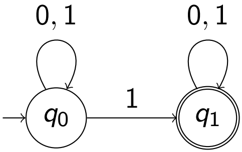
- If two threads are in the same state, then we can ignore one of the threads
  - Threads in the same state will "behave" identically; either one of the descendent threads of both will reach a final state, or none of the descendent threads of both will reach a final state

Parsimonious Algorithm in Action

Example



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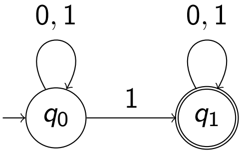

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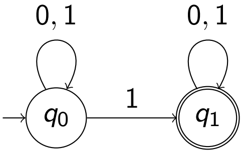

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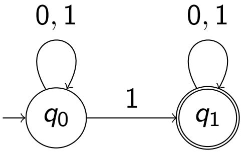

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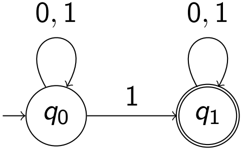

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Revisiting NFA Simulation Algorithm

- Need to keep track of the states of the active threads
  - Unordered: Without worrying about exactly which thread is in what state
  - No Duplicates: Keeping only one copy if there are multiple threads in same state
- How much memory is needed?
  - If Q is the set of states of the NFA N, then we need to keep a subset of Q!
  - Can be done in $|Q|$ bits of memory (i.e., $2^{|Q|}$ states), which is finite!!

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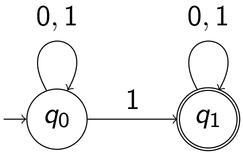
- The DFA runs the simulation algorithm
- DFA remembers the current states of active threads without duplicates, i.e., maintains a subset of states of the NFA
- When a new symbol is read, it updates the states of the active threads
- Accepts whenever one of the threads is in a final state

Example of Equivalent DFA (1)



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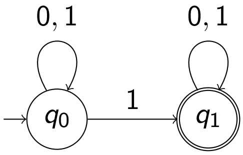

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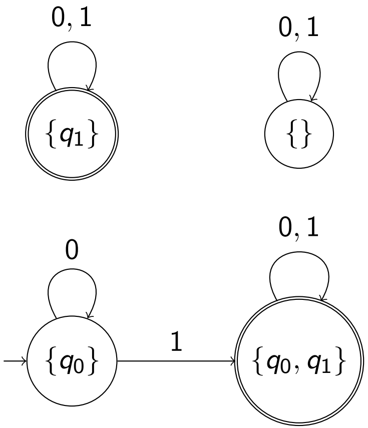

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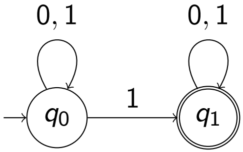

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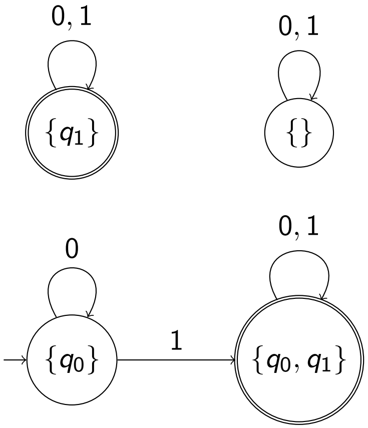

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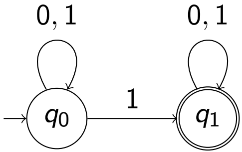

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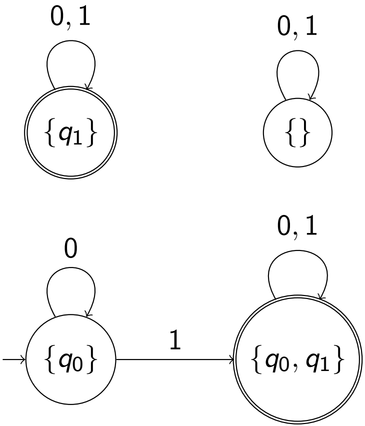

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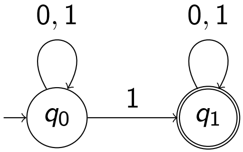

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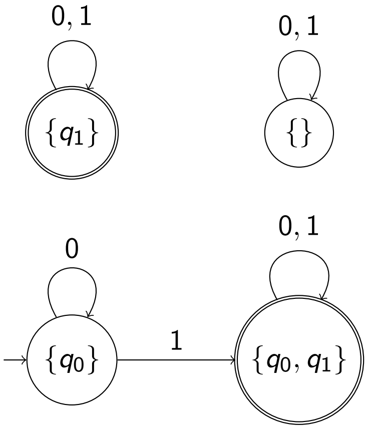

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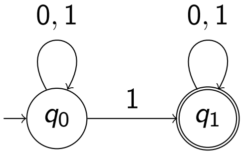

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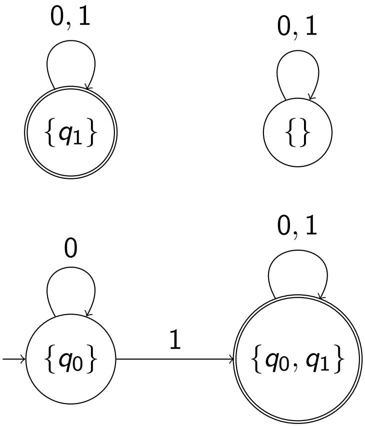

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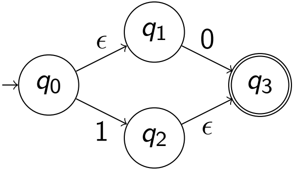
We can remove states unreachable from the initial state. How to find such states? Use DFS or BFS!

Example of Equivalent DFA (2)



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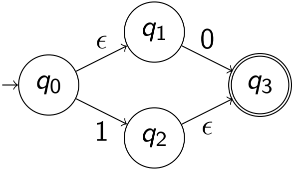

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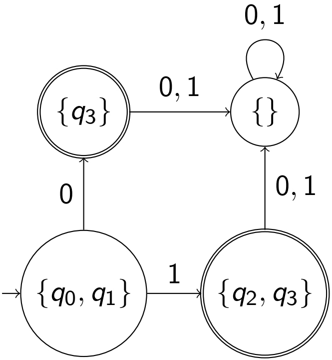
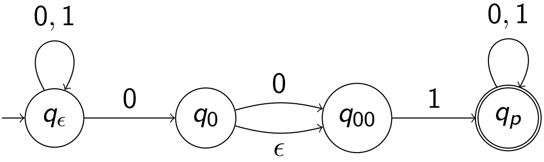


DFA D'_ϵ for N_ϵ (only relevant states)

Example of Equivalent DFA (3)



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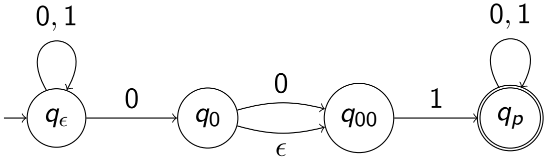

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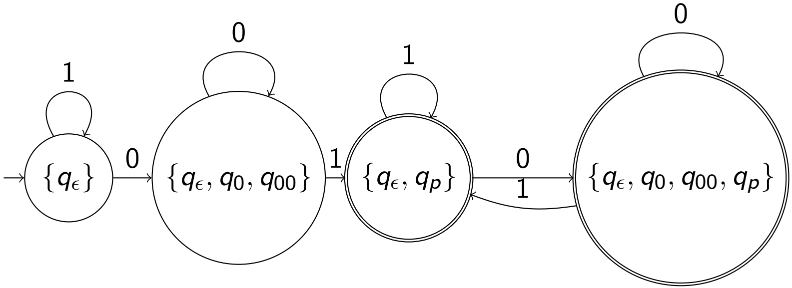

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Formal Construction

Given NFA $N = (Q, \Sigma, \delta, q_0, F)$, construct DFA $\det(N) = (Q', \Sigma, \delta', q_0', F')$ as follows.

- $Q' =$
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$$\delta'(A, a) = \bigcup_{q \in A} \hat{\Delta}(q, a)$$

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For any NFA N, the DFA $\mathrm{det}(N)$ is equivalent to it, i.e., $L(N) = L(\mathrm{det}(N))$.

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We will instead prove the stronger claim $\forall w \in \Sigma^*.\ \hat{\delta}(q_0', w) = A$ iff $\hat{\Delta}(q_0, w) = A$.

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- Induction Hypothesis: Assume inductively that the statement holds $\forall w.\ |w| = n$

$\cdots\!\longrightarrow$

Correctness Proof

Induction Step

Proof (contd).

- Induction Step: If $|w| = n + 1$ then $w = ua$ with $|u| = n$ and $a \in \Sigma$.

$$\hat{\delta}(q_0', ua) = \delta(\hat{\delta}(q_0', u), a) \qquad \text{defn. of } \hat{\delta}$$

$\square$

Correctness Proof

Induction Step

Proof (contd).

- Induction Step: If $|w| = n + 1$ then $w = ua$ with $|u| = n$ and $a \in \Sigma$.

$$
\begin{aligned}
\hat{\delta}(q_0', ua) &= \delta(\hat{\delta}(q_0', u), a) && \text{defn. of } \hat{\delta} \\
&= \delta(\hat{\Delta}(q_0, u), a) && \text{ind. hyp.}
\end{aligned}
$$

$\square$

Correctness Proof

Induction Step

Proof (contd).

- Induction Step: If $|w| = n + 1$ then $w = ua$ with $|u| = n$ and $a \in \Sigma$.

$$\begin{aligned}
\hat{\delta}(q'_0, ua) &= \delta(\hat{\delta}(q'_0, u), a) && \text{defn. of } \hat{\delta} \\
&= \delta(\hat{\Delta}(q_0, u), a) && \text{ind. hyp.} \\
&= \bigcup_{q \in \hat{\Delta}(q_0, u)} \hat{\Delta}(q, a) && \text{defn. of } \delta
\end{aligned}$$

$\square$

Correctness Proof

Induction Step

Proof (contd).

- Induction Step: If $|w| = n + 1$ then $w = ua$ with $|u| = n$ and $a \in \Sigma$.

$$
\begin{aligned}
\hat{\delta}(q'_0, ua) &= \delta(\hat{\delta}(q'_0, u), a) && \text{defn. of } \hat{\delta} \\
&= \delta(\hat{\Delta}(q_0, u), a) && \text{ind. hyp.} \\
&= \bigcup_{q \in \hat{\Delta}(q_0, u)} \hat{\Delta}(q, a) && \text{defn. of } \delta \\
&= \hat{\Delta}(q_0, ua) && \text{prop. about } \hat{\Delta}
\end{aligned}
$$

$\square$