BU CS 332 – Theory of Computation

Lecture 6:

- Regexes = NFAs
- Non-regular languages

Reading:
Sipser Ch 1.3
"Myhill-Nerode" note
Sipser Ch 1.4 (optional)

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February 10, 2021

Regular Expressions – Syntax

A regular expression R is defined recursively using the following rules:

1. ε, $\emptyset$, and a are regular expressions for every $a \in \Sigma$

2. If R_1 and R_2 are regular expressions, then so are

   $(R_1 \cup R_2)$, $(R_1 \circ R_2)$, and (R_1^*)

Examples: (over $\Sigma = \{a, b, c\}$) (with simplified notation)

ab $ab^*c \cup (a^*b)^*$ $\emptyset$

Regular Expressions – Semantics

$L(R)$ = the language a regular expression describes

1. $L(\emptyset) = \emptyset$
2. $L(\varepsilon) = \{\varepsilon\}$
3. $L(a) = \{a\}$ for every $a \in \Sigma$
4. $L((R_1 \cup R_2)) = L(R_1) \cup L(R_2)$
5. $L((R_1 \circ R_2)) = L(R_1) \circ L(R_2)$
6. $L\left((R_1^*)\right) = (L(R_1))^*$

Example: $L(a^*b^*) = \{a^m b^n \mid m, n \geq 0\}$

Regular Expressions Describe Regular Languages

Theorem: A language A is regular if and only if it is described by a regular expression

Theorem 1: Every regular expression has an equivalent NFA

Theorem 2: Every NFA has an equivalent regular expression

Regular expression -> NFA

Theorem 1: Every regex has an equivalent NFA

Proof: Induction on size of a regex

Base cases:

$$R = \emptyset$$

$$R = \varepsilon$$

$$R = a$$

Regular expression -> NFA

Theorem 1: Every regex has an equivalent NFA

Proof: Induction on size of a regex

Inductive step:

$$R = (R_1 \cup R_2)$$

$$R = (R_1 R_2)$$

$$R = (R_1^*)$$

Example

Convert $(1(0 \cup 1))^*$ to an NFA

Regular Expressions Describe Regular Languages

Theorem: A language A is regular if and only if it is described by a regular expression

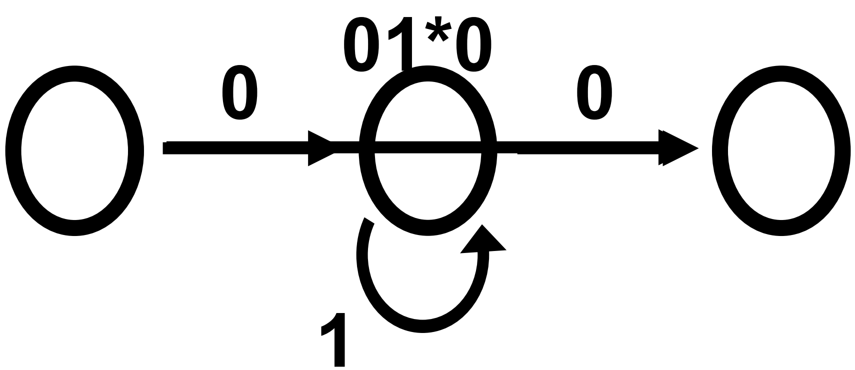
Theorem 1: Every regular expression has an equivalent NFA

Theorem 2: Every NFA has an equivalent regular expression

NFA -> Regular expression

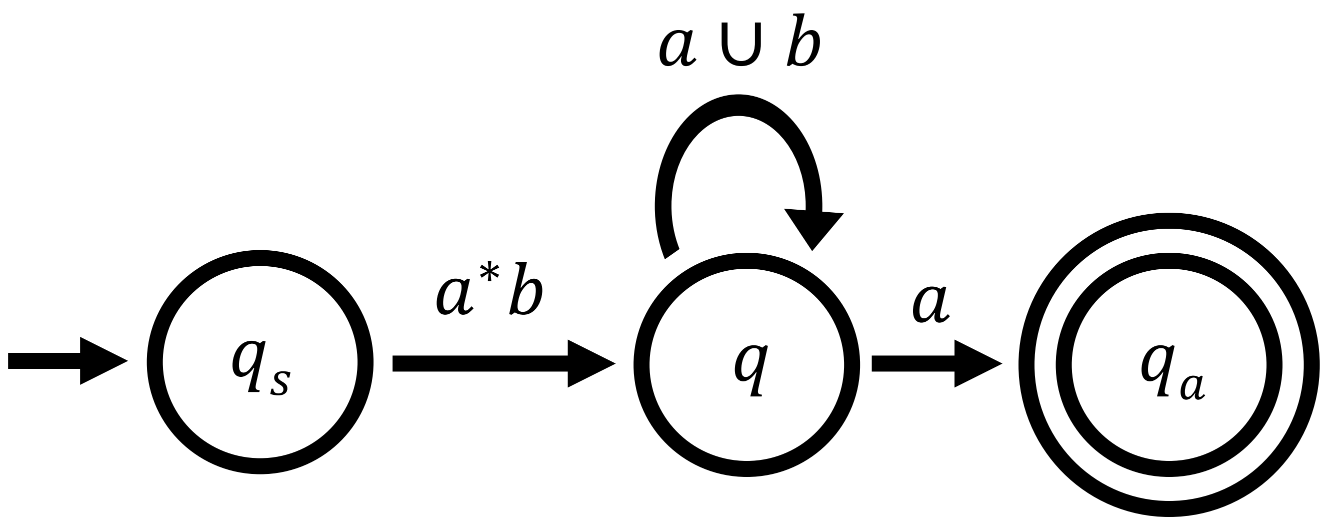
Theorem 2: Every NFA has an equivalent regex

Proof idea: Simplify NFA by "ripping out" states one at a time and replacing with regexes

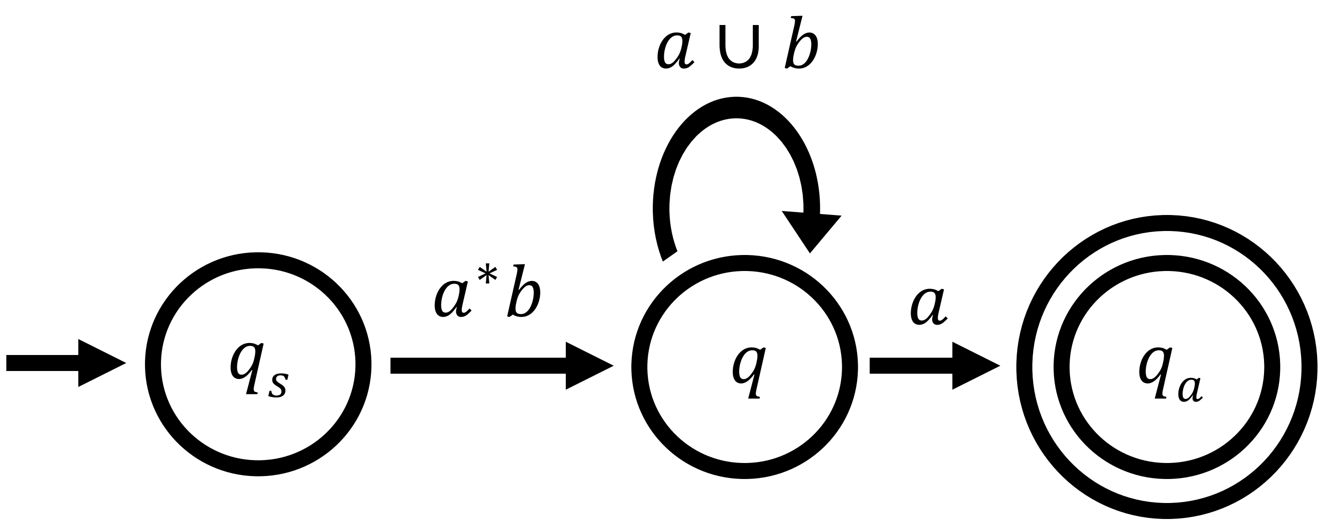


Generalized NFAs

- **Every transition is labeled by a regex**
- One start state with only outgoing transitions
- Only one accept state with only incoming transitions
- Start state and accept state are distinct



Generalized NFA Example



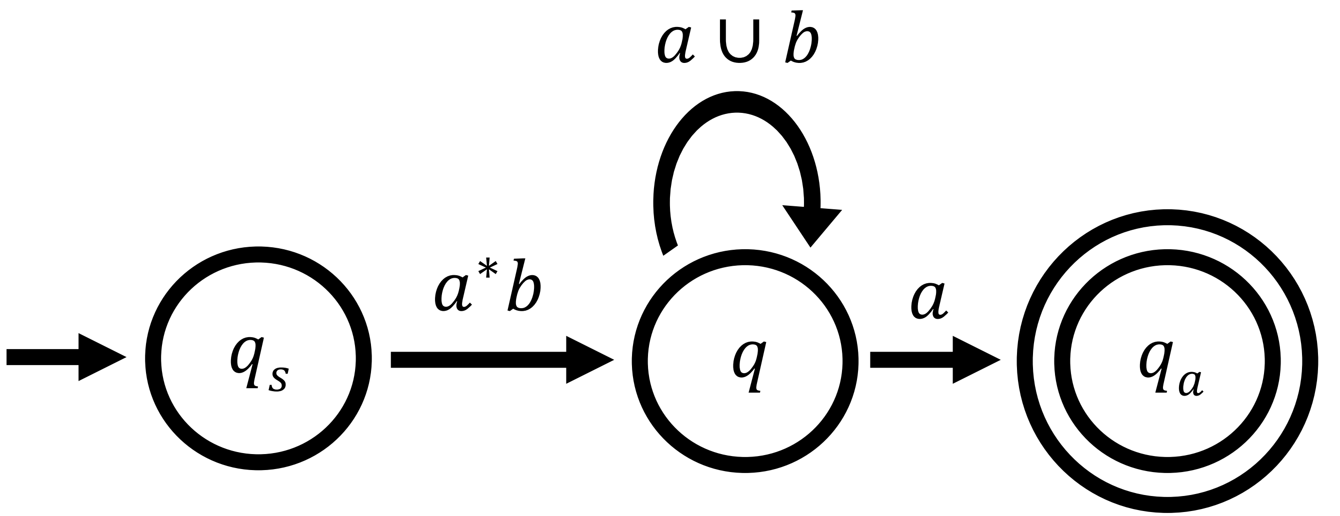
$$R(q_s, q) =$$

$$R(q_a, q) =$$

$$R(q, q_s) =$$

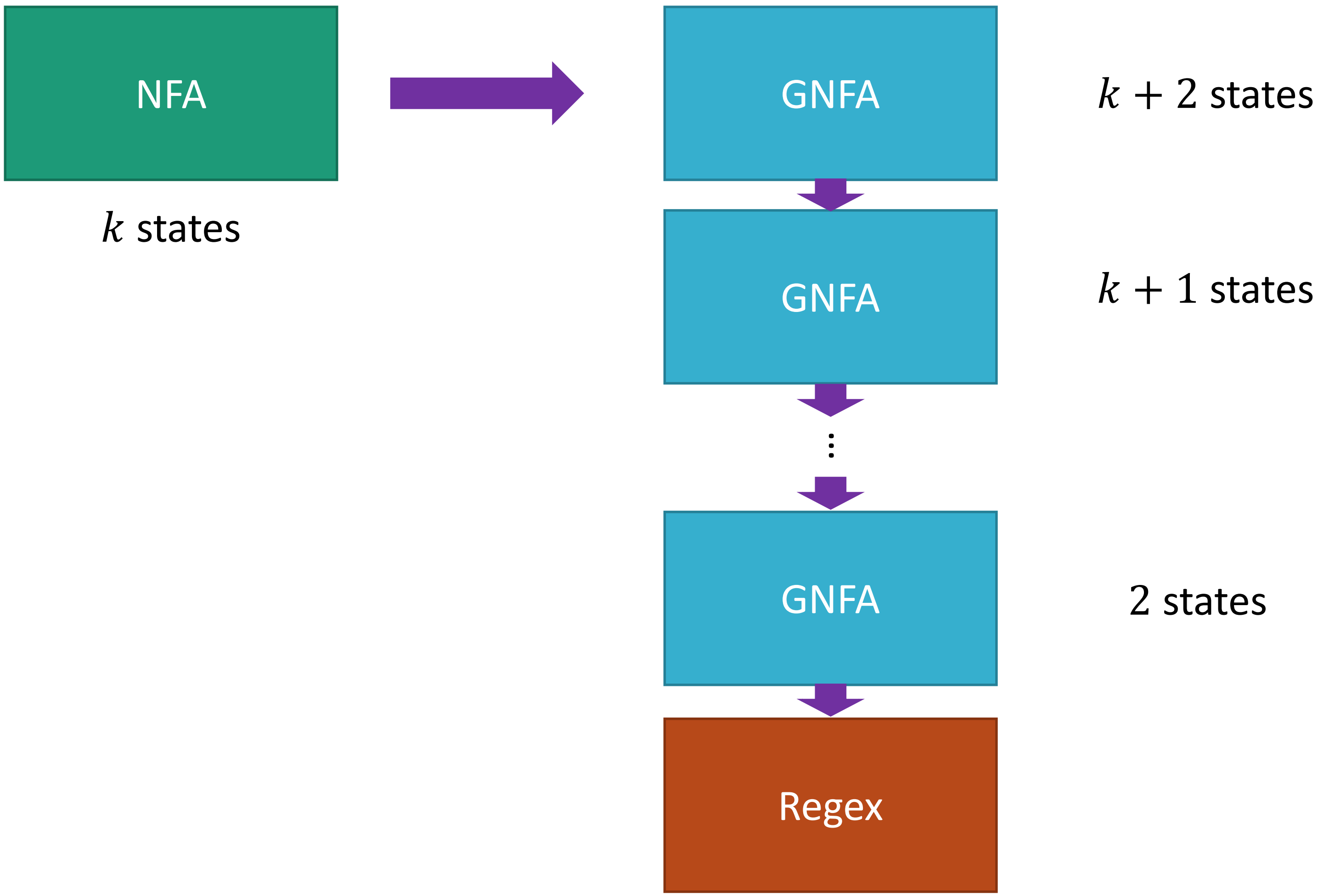
Which of these strings is accepted?

Which of the following strings is accepted by this GNFA?

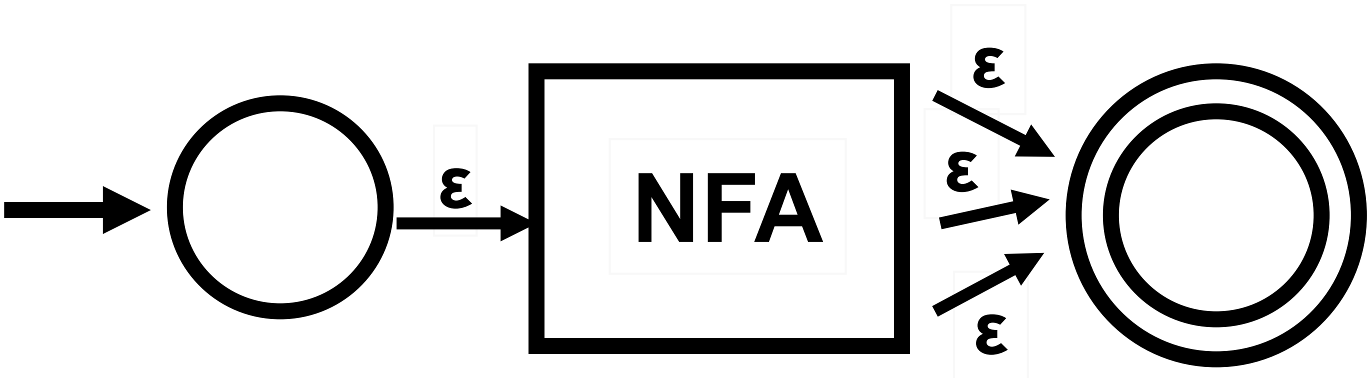


a) aaa
b) $aabb$
c) bbb
d) bba

NFA -> Regular expression



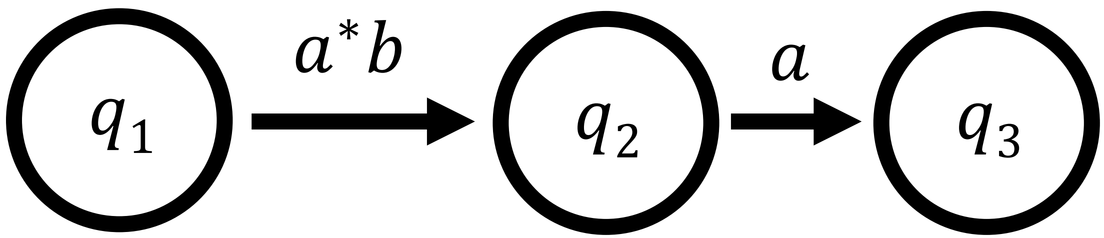
NFA -> GNFA

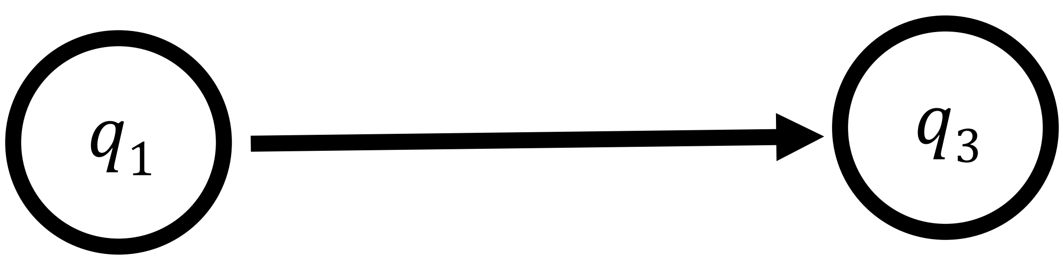


- Add a new start state with no incoming arrows.
- Make a unique accept state with no outgoing arrows.

GNFA -> Regular expression

Idea: While the machine has more than 2 states, rip one out and relabel the arrows with regexes to account for the missing state





GNFA -> Regular expression

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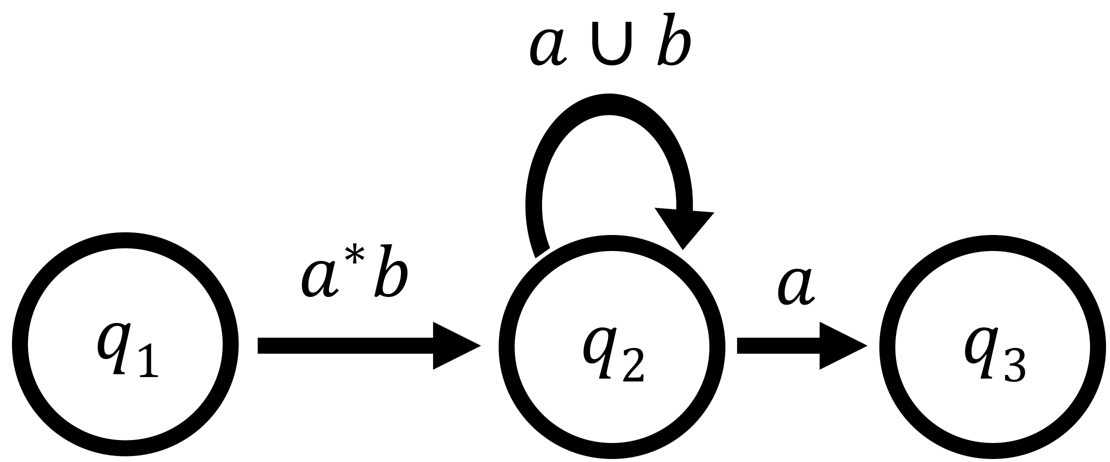

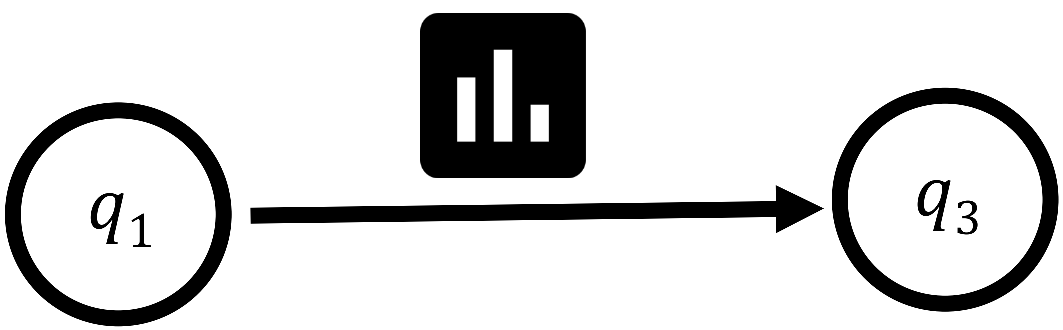

GNFA -> Regular expression

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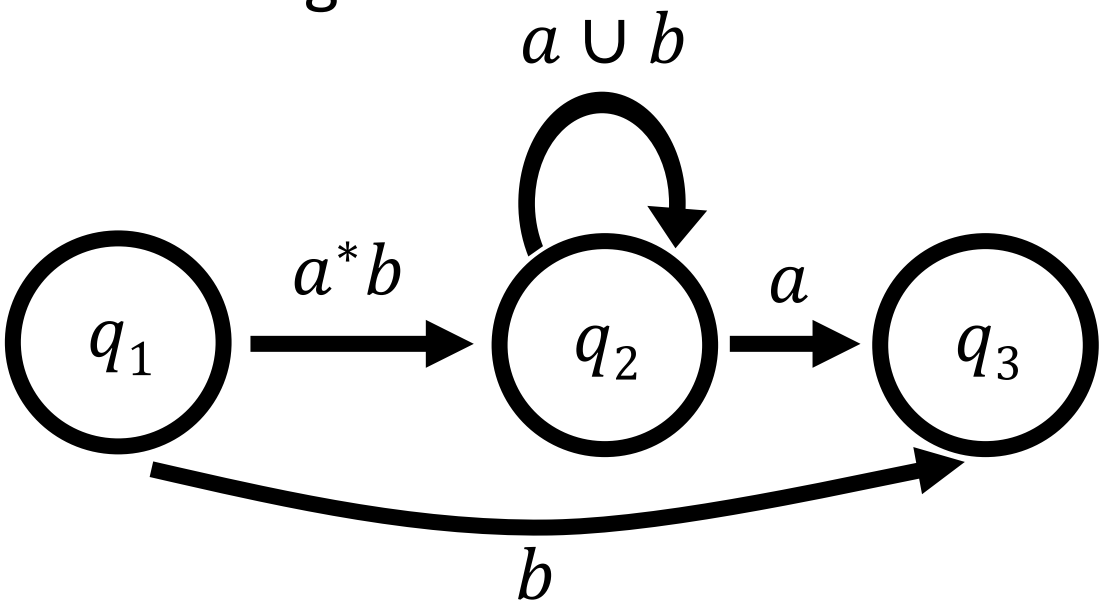
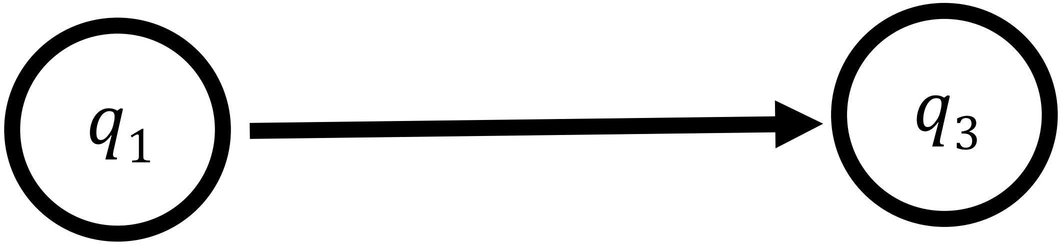
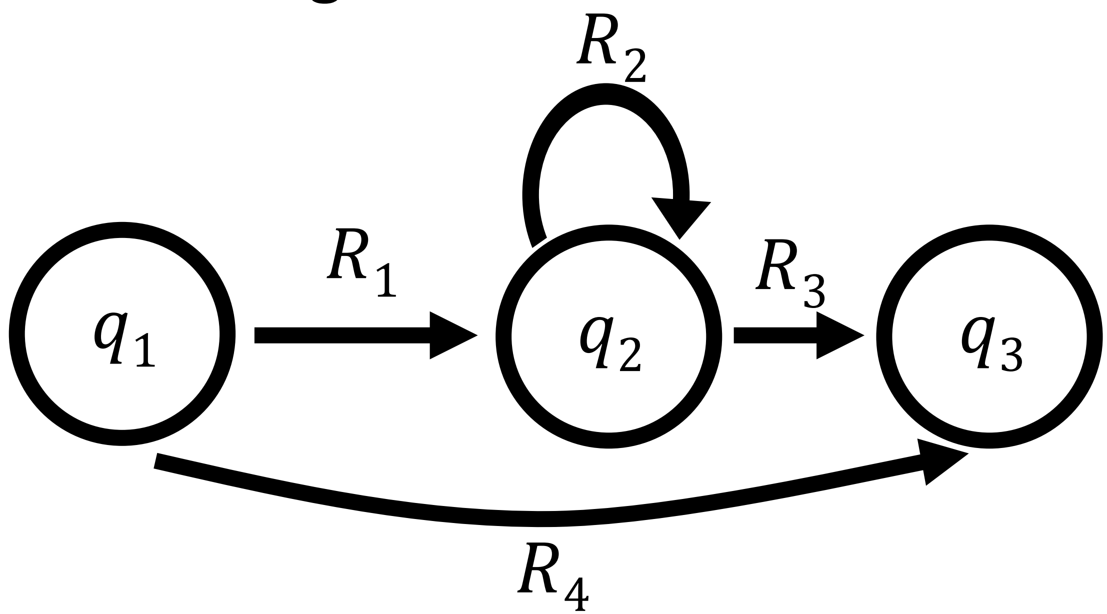
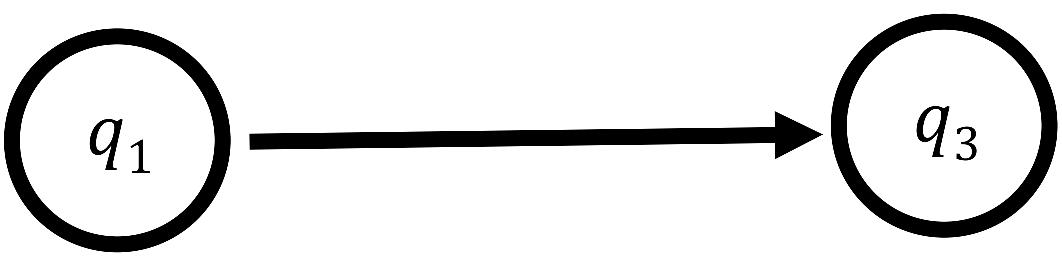


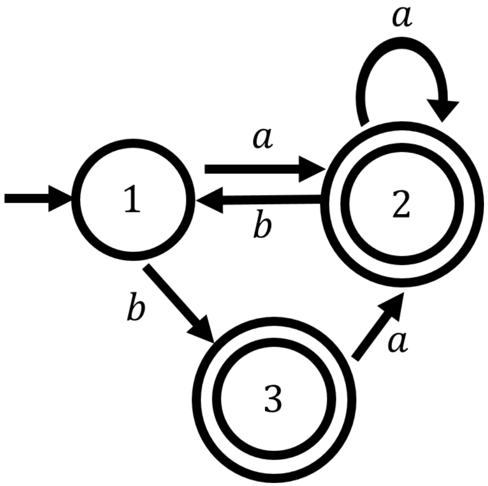


GNFA -> Regular expression

Idea: While the machine has more than 2 states, rip one out and relabel the arrows with regexes to account for the missing state





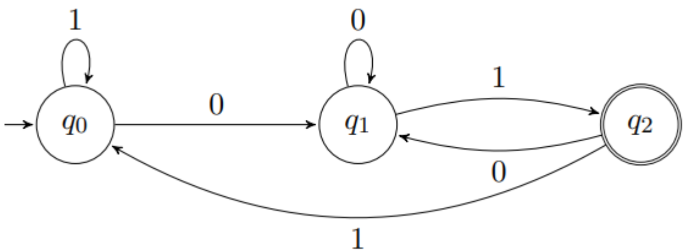

a
a
1
2
b
b
a
3

Non-Regular Languages

Motivating Questions

- We've seen techniques for showing that languages are regular
- How can we tell if we've found the smallest DFA recognizing a language?
- Are all languages regular? How can we prove that a language is not regular?

An Example



$A = \{\, w \in \{0,1\}^* \mid w \text{ ends with } 01 \,\}$

Claim: *Every* DFA recognizing A needs at least 3 states

Proof: Let M be any DFA recognizing A. Consider running M on each of $x = \varepsilon, y = 0, w = 01$

A General Technique

$A = \{ w \in \{0, 1\}^* \mid w \text{ ends with } 01 \}$

Definition: Strings x and y are **distinguishable** by L if there exists z such that exactly one of xz or yz is in L.

Ex. $x = \varepsilon, \quad y = 0$

Definition: A set of strings S is **pairwise distinguishable** by L if every pair of distinct strings $x, y \in S$ is distinguishable by L.

Ex. $S = \{\varepsilon, 0, 01\}$

A General Technique

Theorem: If S is pairwise distinguishable by L, then every DFA recognizing L needs at least $|S|$ states

Proof: Let M be a DFA with $< |S|$ states. By the pigeonhole principle, there are $x, y \in S$ such that M ends up in same state on x and y

Back to Our Example

$A = \{\, w \in \{0, 1\}^* \mid w \text{ ends with } 01 \,\}$

Theorem: If S is pairwise distinguishable by L, then every DFA recognizing L needs at least $|S|$ states

$S = \{\varepsilon, 0, 01\}$

Another Example

$B = \{ w \in \{0,1\}^* \mid |w| = 2 \}$

Theorem: If S is pairwise distinguishable by L, then every DFA recognizing L needs at least $|S|$ states

$S = \{ \qquad \}$

Distinguishing Extension

Which of the following is a distinguishing extension for $x = 0$ and $y = 00$ for language $B = \{ w \in \{0,1\}^* \mid |w| = 2 \}$?

a) $z = \varepsilon$

b) $z = 0$

c) $z = 1$

d) $z = 00$

Non-Regularity

Theorem: If S is pairwise distinguishable by L, then every DFA recognizing L needs at least $|S|$ states

Corollary: If S is an **infinite** set that is pairwise distinguishable by L, then no DFA recognizes L

The Classic Example

Theorem: $A = \{0^n 1^n \mid n \geq 0\}$ is not regular

Proof: Construct an infinite pairwise distinguishable set