Pre-lecture brain teaser

Find the regular expressions for the following languages (if possible)

1. $L_1 = \{0^m 1^n | m, n \geq 0\}$
2. $L_2 = \{0^n 1^n \mid n \geq 0\}$
3. $L_3 = L_1 \cup L_2$
4. $L_4 = L_1 \cap L_2$

CS/ECE-374: Lecture 6 - Non-regularity and closure

Instructor: Nickvash Kani

Febuary 02, 2023

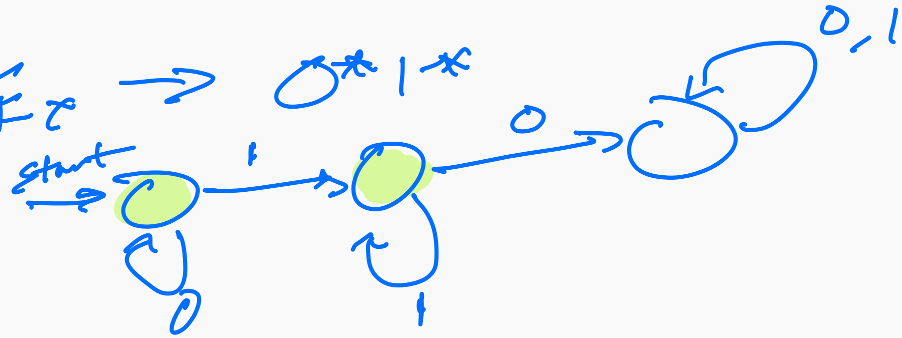
University of Illinois at Urbana-Champaign

Pre-lecture brain teaser

Find the regular expressions for the following languages (if possible)

1. $L_1 = \{0^m 1^n | m, n \geq 0\}$ RegEx → $0^* 1^*$

   DFA

2. $L_2 = \{0^n 1^n \mid n \geq 0\}$

   * non-regular

3. $L_3 = L_1 \cup L_2$ $= L_1$ b/c $L_2 \subset L_1$

4. $L_4 = L_1 \cap L_2$ $= L_2$

   non-regular by 2

Pre-lecture brain teaser

We have a language $L = \{0^n 1^n | n \geq 0\}$

Prove that L is non-regular.

Proving non-regularity: Methods

- Pumping lemma. We will not cover it but it is *sometimes* an easier proof technique to apply, but not as general as the fooling set technique.
- Closure properties. Use existing non-regular languages and regular languages to prove that some new language is non-regular.
- Fooling sets- Method of distinguishing suffixes. To prove that L is non-regular find an infinite fooling set.

Not all languages are regular

Regular Languages, DFAs, NFAs

Theorem
Languages accepted by DFAs, NFAs, and regular expressions are the same.

Question: Is every language a regular language? **No.**

Theorem
Languages accepted by DFAs, NFAs, and regular expressions are the same.

Question: Is every language a regular language? **No.**

- Each DFA M can be represented as a string over a finite alphabet Σ by appropriate encoding
- Hence number of regular languages is <u>countably infinite</u>
- Number of languages is <u>uncountably infinite</u>
- Hence there must be a non-regular language!

A Simple and Canonical Non-regular Language

$$L = \{0^n 1^n \mid n \geq 0\} = \{\epsilon, 01, 0011, 000111, \cdots, \}$$

A Simple and Canonical Non-regular Language

$L = \{0^n 1^n \mid n \geq 0\} = \{\epsilon, 01, 0011, 000111, \cdots, \}$

Theorem
L is not regular.

A Simple and Canonical Non-regular Language

$L = \{0^n 1^n \mid n \geq 0\} = \{\epsilon, 01, 0011, 000111, \cdots, \}$

Theorem
L is not regular.

Question: Proof?

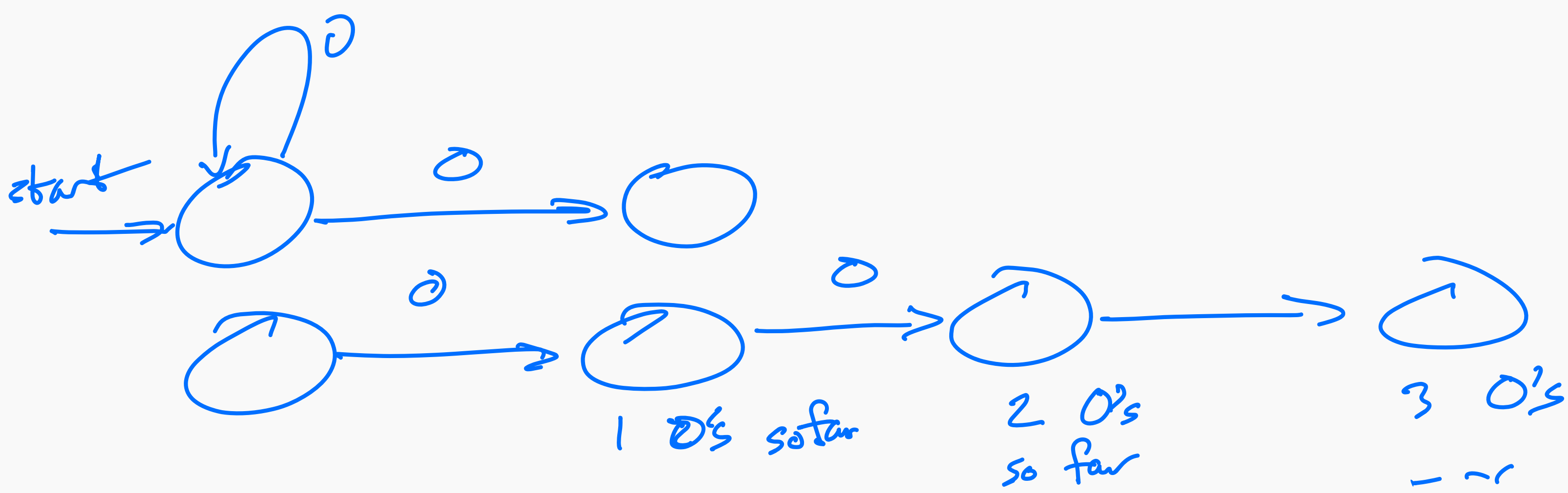
A Simple and Canonical Non-regular Language

$$L = \{0^n 1^n \mid n \geq 0\} = \{\epsilon, 01, 0011, 000111, \cdots, \}$$

Theorem
L is not regular.

Question: Proof?

Intuition: Any program to recognize L seems to require counting number of zeros in input which cannot be done with fixed memory.



A Simple and Canonical Non-regular Language

$L = \{0^n 1^n \mid n \geq 0\} = \{\epsilon, 01, 0011, 000111, \cdots, \}$

Theorem
L is not regular.

Question: Proof?

Intuition: Any program to recognize L seems to require counting number of zeros in input which cannot be done with fixed memory.

How do we formalize intuition and come up with a formal proof?

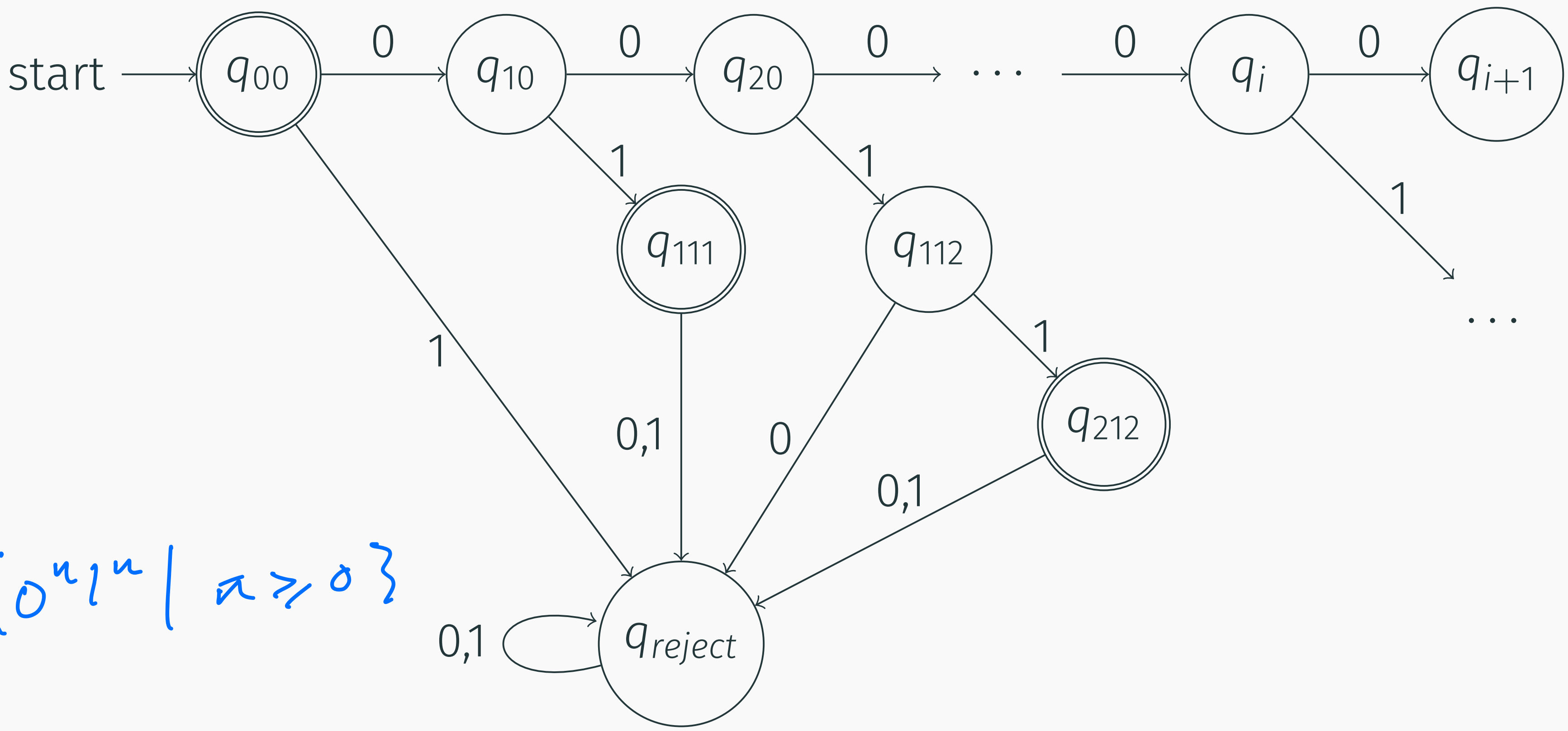
Proof by contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0, 1\}, \delta, s, A)$ where $|Q|$ is finite.

$L = \{ w x w \mid x \in \Sigma^*, |w| \geq 0 \}$

Proof by contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0, 1\}, \delta, s, A)$ where $|Q|$ is finite.



$L = \{0^n 1^n \mid n \geq 0\}$

Proof by Contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0, 1\}, \delta, s, A)$ where $|Q| = n$.

Proof by Contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0,1\}, \delta, s, A)$ where $|Q| = n$.

$L = \{0^n 1^n \mid n \geq 0\}$

Consider strings $\epsilon, 0, 00, 000, \cdots, 0^n$ total of $n+1$ strings.

Proof by Contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0, 1\}, \delta, s, A)$ where $|Q| = n$.

Consider strings $\epsilon, 0, 00, 000, \cdots, 0^n$ total of $n + 1$ strings.

What states does M reach on the above strings? Let $q_i = \delta^*(s, 0^i)$.

By pigeon hole principle $q_i = q_j$ for some $0 \le i < j \le n$. That is, M is in the same state after reading 0^i and 0^j where $i \neq j$.

Proof by Contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0, 1\}, \delta, s, A)$ where $|Q| = n$.

Consider strings $\epsilon, 0, 00, 000, \cdots, 0^n$ total of $n + 1$ strings.

What states does M reach on the above strings? Let $q_i = \delta^*(s, 0^i)$.

By pigeon hole principle $q_i = q_j$ for some $0 \le i < j \le n$. That is, M is in the same state after reading 0^i and 0^j where $i \neq j$.

M should accept 0^i1^i but then it will also accept 0^j1^i where $i \neq j$.

Proof by Contradiction

- Suppose L is regular. Then there is a DFA M such that $L(M) = L$.
- Let $M = (Q, \{0,1\}, \delta, s, A)$ where $|Q| = n$.

Consider strings $\epsilon, 0, 00, 000, \cdots, 0^n$ total of $n+1$ strings.

What states does M reach on the above strings? Let $q_i = \delta^*(s, 0^i)$.

By pigeon hole principle $q_i = q_j$ for some $0 \le i < j \le n$. That is, M is in the same state after reading 0^i and 0^j where $i \neq j$.

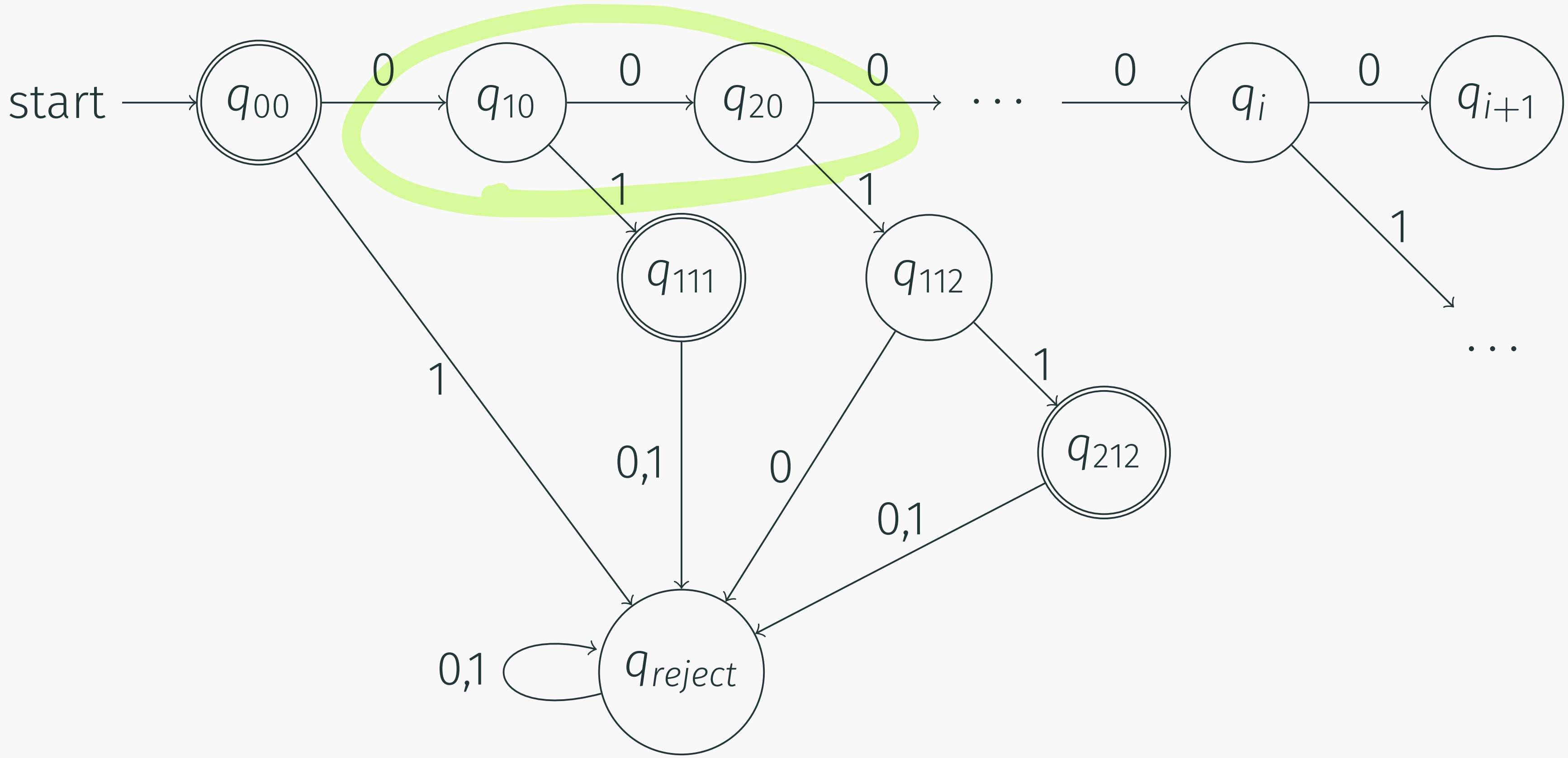
$L = \{0^n 1^n \mid n \geq 0\}$

M should accept $0^i 1^i$ but then it will also accept $0^j 1^i$ where $i \neq j$.

This contradicts the fact that M accepts L. Thus, there is no DFA

When two states are equivalent?

States that cannot be combined?



We concluded that because each 0^i prefix has a unique state.

Are there states that aren't unique?

Can states be combined?

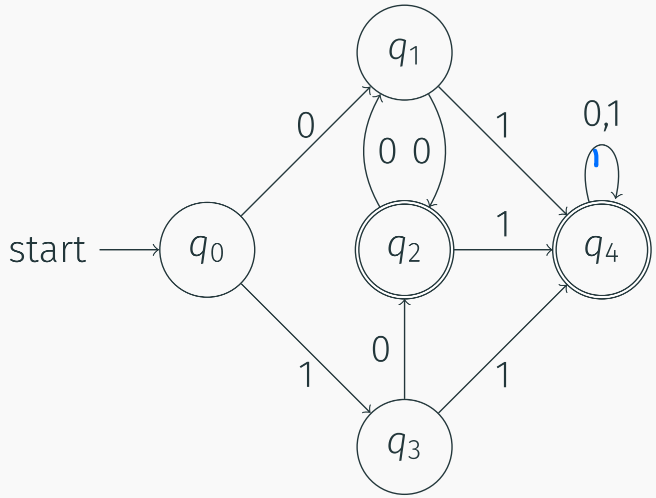
Equivalence between states

Definition
$M = (Q, \Sigma, \delta, s, A)$: DFA.

Two states $p, q \in Q$ are equivalent if for all strings $w \in \Sigma^*$, we have that

$$\delta^*(p, w) \in A \iff \delta^*(q, w) \in A.$$

One can merge any two states that are equivalent into a single state.



q_1 & q_3

$w = 0$

$\delta(q_1, 0) = q_2 \in A$

$\delta(q_3, 0) = q_2 \in A$

$w = 1$

$\delta(q_1, 1) = q_4 \in A$

$\delta(q_3, 1) = q_4 \in A$

Distinguishing between states

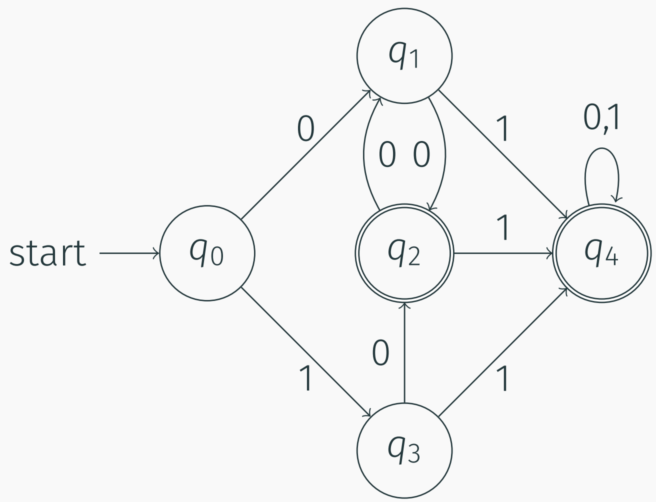
Definition
$M = (Q, \Sigma, \delta, s, A)$: DFA.

Two states $p, q \in Q$ are distinguishable if there exists a string $w \in \Sigma^*$, such that

$$\delta^*(p, w) \in A \qquad \text{and} \qquad \delta^*(q, w) \notin A.$$

or

$$\delta^*(p, w) \notin A \qquad \text{and} \qquad \delta^*(q, w) \in A.$$



$q_0 \not\equiv q_1 \qquad w = 0$

$\delta(q_0, 0) = q_1 \notin A$

$\delta(q_1, 0) = q_2 \in A$

Distinguishable prefixes

$M = (Q, \Sigma, \delta, s, A)$: DFA

Idea: Every string $w \in \Sigma^*$ defines a state $\nabla w = \delta^*(s, w)$.

$M = (Q, \Sigma, \delta, s, A)$: DFA

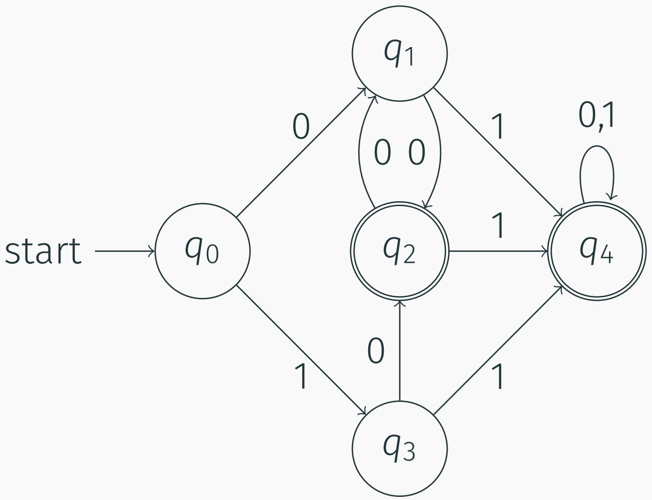
Idea: Every string $w \in \Sigma^*$ defines a state $\nabla w = \delta^*(s, w)$.

Definition
Two strings $u, w \in \Sigma^*$ are distinguishable for M (or $L(M)$) if ∇u and ∇w are distinguishable.

Definition (Direct restatement)
Two prefixes $u, w \in \Sigma^*$ are distinguishable for a language L if there exists a string x, such that $ux \in L$ and $wx \notin L$ (or $ux \notin L$ and $wx \in L$).

accept state

not-accept state



Distinguishable means different states

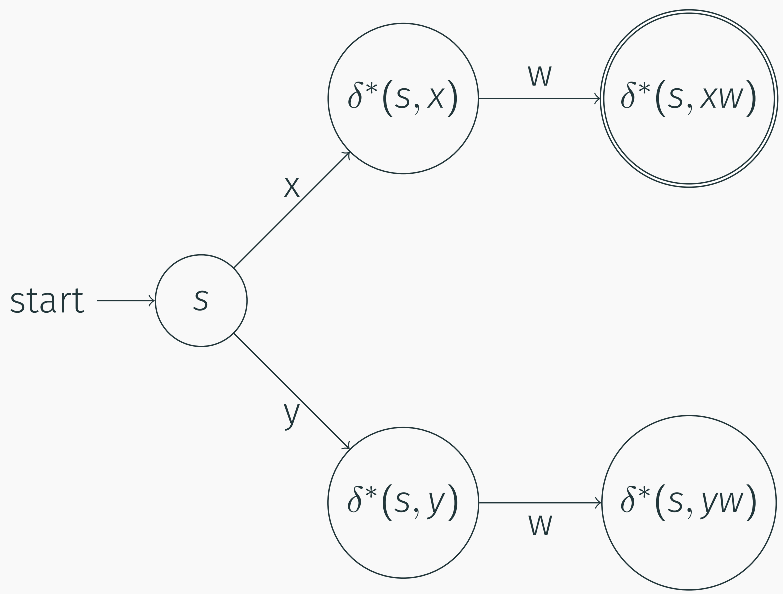
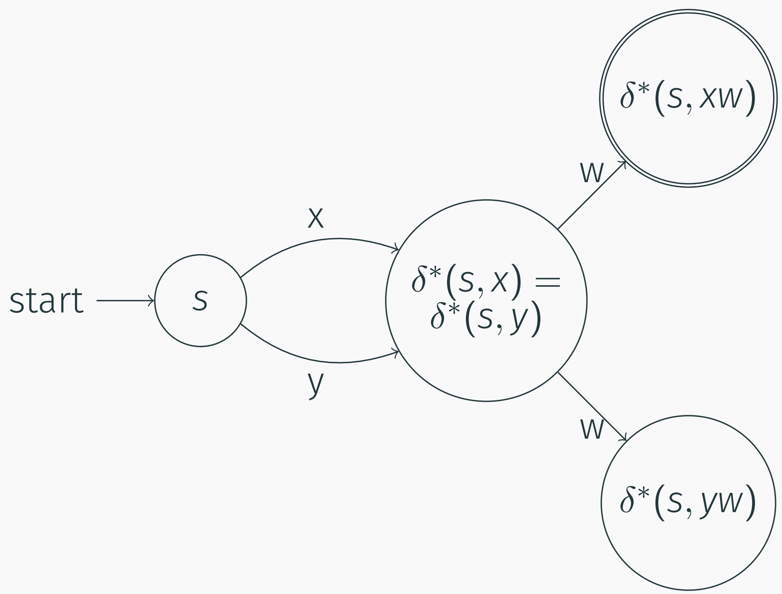
Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Reminder: $\nabla x = \delta^*(s, x) \in Q$ and $\nabla y = \delta^*(s, y) \in Q$

Proof by a figure

Possible	Not possible
	

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

By assumption $\exists w \in \Sigma^*$ such that $\nabla xw \in A$ and $\nabla yw \notin A$.

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

By assumption $\exists w \in \Sigma^*$ such that $\nabla xw \in A$ and $\nabla yw \notin A$.

$\implies A \ni \nabla xw = \delta^*(s, xw) = \delta^*(\nabla x, w)$

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

By assumption $\exists w \in \Sigma^*$ such that $\nabla xw \in A$ and $\nabla yw \notin A$.

$$\implies A \ni \nabla xw = \delta^*(s, xw) = \delta^*(\nabla x, w) = \delta^*(\nabla y, w)$$

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

By assumption $\exists w \in \Sigma^*$ such that $\nabla xw \in A$ and $\nabla yw \notin A$.

$\implies A \ni \nabla xw = \delta^*(s, xw) = \delta^*(\nabla x, w) = \delta^*(\nabla y, w)$
$= \delta^*(s, yw) = \nabla yw \notin A$.

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

By assumption $\exists w \in \Sigma^*$ such that $\nabla xw \in A$ and $\nabla yw \notin A$.

$\implies A \ni \nabla xw = \delta^*(s, xw) = \delta^*(\nabla x, w) = \delta^*(\nabla y, w)$
$= \delta^*(s, yw) = \nabla yw \notin A.$

$\implies A \ni \nabla yw \notin A.$ Impossible!

Distinguishable strings means different states: Proof

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Proof.
Assume for the sake of contradiction that $\nabla x = \nabla y$.

By assumption $\exists w \in \Sigma^*$ such that $\nabla xw \in A$ and $\nabla yw \notin A$.

$\implies A \ni \nabla xw = \delta^*(s, xw) = \delta^*(\nabla x, w) = \delta^*(\nabla y, w)$
$= \delta^*(s, yw) = \nabla yw \notin A$.

$\implies A \ni \nabla yw \notin A$. Impossible!

Assumption that $\nabla x = \nabla y$ is false. □

Review questions...

- Prove for any $i \neq j$ then 0^i and 0^j are distinguishable for the language $\{0^n 1^n \mid n \geq 0\}$.

$L =$

$F = \{0^n \mid n \geq 0\}$

$x = 1^i$

$0^i 1^i \in L$

$0^j 1^i \notin L$

Review questions...

- Prove for any $i \neq j$ then 0^i and 0^j are distinguishable for the language $\{0^n1^n \mid n \geq 0\}$.
- Let L be a regular language, and let $w_1, \ldots, w_k$ be strings that are all pairwise distinguishable for L. Prove any DFA for L must have at least k states.

$\nabla w_i = q_i$ that must exist in the DFA

if $|Q| < k$ the $\nabla w_i = \nabla w_j$

(by pigeon hole principle)

but can't happen b/c $w_i x \in A$ which $w_j x \notin A$

violates distinguishable definition

Review questions...

- Prove for any $i \neq j$ then 0^i and 0^j are distinguishable for the language $\{0^n1^n \mid n \geq 0\}$.
- Let L be a regular language, and let $w_1, \ldots, w_k$ be strings that are all pairwise distinguishable for L. Prove any DFA for L must have at least k states.
- Prove that $\{0^n1^n \mid n \geq 0\}$ is not regular.

$F = \{0^n \mid n \geq 0\} \Rightarrow$ fooling set

0^i & 0^j are distinguishable

$\exists x = 1^i$ where $0^i x \in L$ $0^j x \notin L$

Infinitely many distinguishable states

therefore a DFA can't represent this language

Fooling sets: Proving non-regularity

Fooling Sets

Definition
For a language L over Σ a set of strings F (could be infinite) is a fooling set or distinguishing set for L if every two distinct strings $x, y \in F$ are distinguishable.

Fooling Sets

Definition
For a language L over Σ a set of strings F (could be infinite) is a fooling set or distinguishing set for L if every two distinct strings $x, y \in F$ are distinguishable.

Example: $F = \{0^i \mid i \geq 0\}$ is a fooling set for the language $L = \{0^n 1^n \mid n \geq 0\}$.

$F \{0^i 1 \mid i \geq 0\}$

$x = 1^{i-1}$

$0^i 1 1^{i-1} \in L$

$0^j 1 1^{i-1} \notin L$

Fooling Sets

$L = 0^*$ $F = \{0, 1\}$

Definition
For a language L over Σ a set of strings F (could be infinite) is a fooling set or distinguishing set for L if every two distinct strings $x, y \in F$ are distinguishable.

Example: $F = \{0^i \mid i \geq 0\}$ is a fooling set for the language $L = \{0^n1^n \mid n \geq 0\}$.

$100 \notin L$
$1100 \notin L$

$F = \{0, 00, 000, \ldots;\ 1, 11, 111, \ldots\}$

Theorem
Suppose F is a fooling set for L. If F is finite then there is no DFA M that accepts L with less than $|F|$ states.

$L = \Sigma^*$

$L = \{0^i 1^j \mid i, j \geq 0\}$ $F = \{0, 1\}$

~~$F = \{0^i \mid i \geq 0\}$~~

$x = 00$

$x = 1^i$

$0^i 1^i \in L$

$0^j 1^i \in L$

$000 \in L$

$100 \notin L$

Recall

Already proved the following lemma:

Lemma
L: regular language.

$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

Reminder: $\nabla x = \delta^*(s, x)$.

Proof of theorem

Theorem (Reworded.)
L: A language

F: a fooling set for L.

If F is finite then any DFA M that accepts L has at least |F| states.

Proof.
Let $F = \{w_1, w_2, \ldots, w_m)$ be the fooling set.

Let $M = (Q, \Sigma, \delta, s, A)$ be any DFA that accepts L.

Proof of theorem

Theorem (Reworded.)
L: A language

F: a fooling set for L.

If F is finite then any DFA M that accepts L has at least |F| states.

Proof.
Let $F = \{w_1, w_2, \ldots, w_m)$ be the fooling set.

Let $M = (Q, \Sigma, \delta, s, A)$ be any DFA that accepts L.

Let $q_i = \nabla w_i = \delta^*(s, x_i)$.

Proof of theorem

Theorem (Reworded.)
L: A language

F: a fooling set for L.

If F is finite then any DFA M that accepts L has at least |F| states.

Proof.
Let $F = \{w_1, w_2, \ldots, w_m)$ be the fooling set.

Let $M = (Q, \Sigma, \delta, s, A)$ be any DFA that accepts L.

Let $q_i = \nabla w_i = \delta^*(s, x_i)$.

By lemma $q_i \neq q_j$ for all $i \neq j$.

As such, $|Q| \geq |\{q_1, \ldots, q_m\}| = |\{w_1, \ldots, w_m\}| = |A|$. $\square$

Infinite Fooling Sets

Corollary
If L has an infinite fooling set F then L is not regular.

Proof.
Let $w_1, w_2, \ldots \subseteq F$ be an infinite sequence of strings such that every pair of them are distinguishable.

Assume for contradiction that $\exists$ M a DFA for L.

Corollary
If L has an infinite fooling set F then L is not regular.

Proof.
Let $w_1, w_2, \ldots \subseteq F$ be an infinite sequence of strings such that every pair of them are distinguishable.

Assume for contradiction that $\exists\, M$ a DFA for L.

Let $F_i = \{w_1, \ldots, w_i\}$.

By theorem, $\#$ states of $M \geq |F_i| = i$, for all i.

As such, number of states in M is infinite.

Corollary
If L has an infinite fooling set F then L is not regular.

Proof.
Let $w_1, w_2, \ldots \subseteq F$ be an infinite sequence of strings such that every pair of them are distinguishable.

Assume for contradiction that $\exists$ M a DFA for L.

Let $F_i = \{w_1, \ldots, w_i\}$.

By theorem, $\#$ states of $M \geq |F_i| = i$, for all i.

As such, number of states in M is infinite.

Contradiction: DFA = deterministic finite automata. But M not finite. $\square$

Examples

$L_p \subseteq \Sigma^*$

$L_1 = \{0^n 1^n \mid n \geq 0\}$ $F = \{0^i \mid i \geqslant 0\}$

$L_2 =$ {bitstrings with equal number of 0s and 1s}

$F = \{0^i \mid i \geqslant 0\}$ $x = 1^i$

$0^i 1^i \in L$

$0^j 1^i \notin L$

for some $i \neq j$

$L_3 = \{0^k 1^\ell \mid k \neq \ell\}$

$F = \{0^i \mid i \geqslant 0\}$

$x = 1^i$

$0^i 1^i \notin L_3$

$0^j 1^i \in L_3$

Examples

$$L = \{\text{strings of properly matched open and closing parentheses}\}$$

Examples

$L = \{\text{palindromes over the binary alphabet}\Sigma = \{0, 1\}\}$
A palindrome is a string that is equal to its reversal, e.g. 10001 or 0110.

Closure properties: Proving non-regularity

Non-regularity via closure properties

$H = \{\text{bitstrings with equal number of 0s and 1s}\}$

$H' = \{0^k 1^k \mid k \geq 0\}$

Suppose we have already shown that H' is non-regular. Can we show that H is non-regular without using the fooling set argument from scratch?

Non-regularity via closure properties

$H = \{\text{bitstrings with equal number of 0s and 1s}\}$

$H' = \{0^k 1^k \mid k \geq 0\}$

Suppose we have already shown that L' is non-regular. Can we show that L is non-regular without using the fooling set argument from scratch?

$H' = H \cap L(0^*1^*)$

Claim: The above and the fact that L' is non-regular implies L is non-regular. Why?

Non-regularity via closure properties

$H = \{\text{bitstrings with equal number of 0s and 1s}\}$

$H' = \{0^k 1^k \mid k \geq 0\}$

Suppose we have already shown that L' is non-regular. Can we show that L is non-regular without using the fooling set argument from scratch?

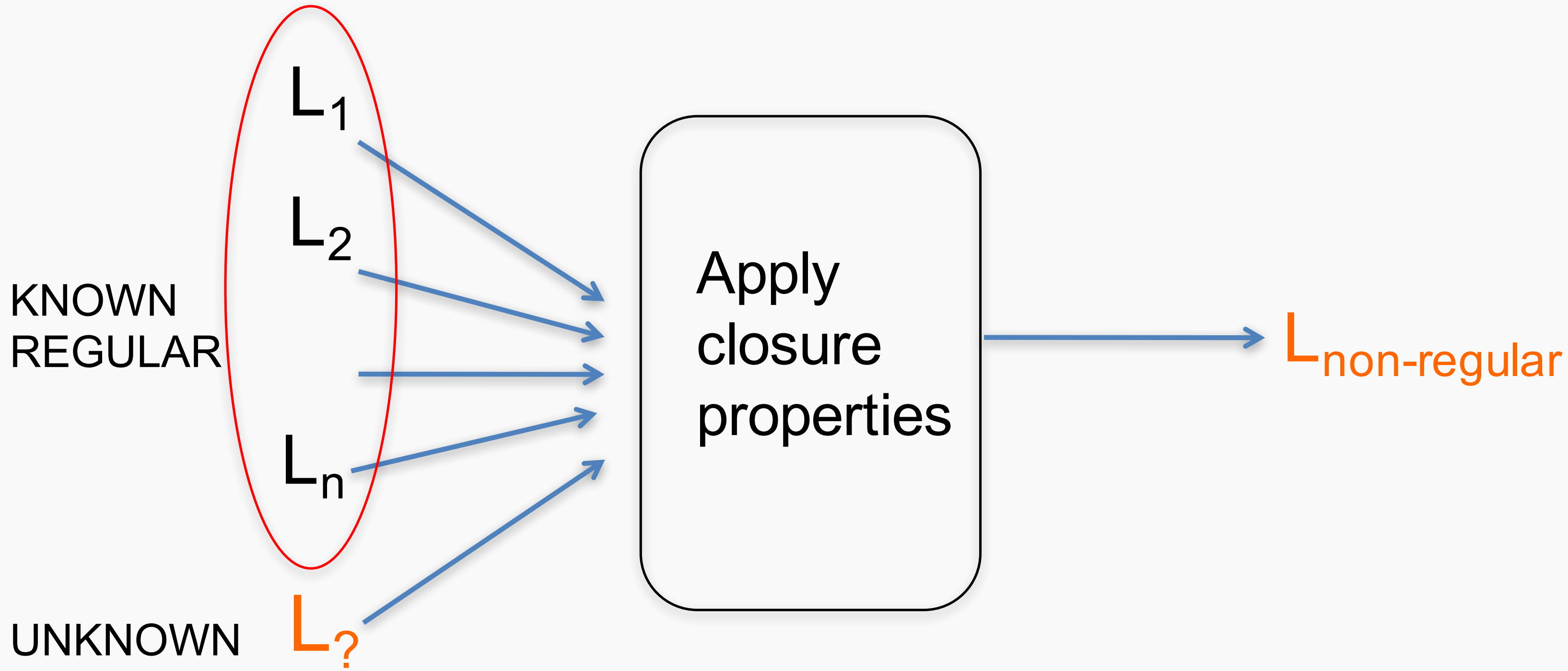
$H' = H \cap L(0^*1^*)$

Claim: The above and the fact that L' is non-regular implies L is non-regular. Why?

Suppose H is regular. Then since $L(0^*1^*)$ is regular, and regular languages are closed under intersection, H' also would be regular. But we know H' is not regular, a contradiction.

Non-regularity via closure properties

General recipe:



Examples

$L = \{0^k 1^k \mid k \geq 1\}$

Careful with closure!

$L' = \{0^k 1^k \mid k \geq 0\}$

Complement of L ($\overline{L}$) is also not regular.

which

But $L \cup \overline{L} = (0+1)^*$ ~~whihc~~ is regular.

In general, always use closure in forward direction, (i.e L and L' are regular, therefore L OP L' is regular.)

In particular, regular languages are not closed under subset/superset relations.

Proving non-regularity: Summary

- Method of distinguishing suffixes. To prove that L is non-regular find an infinite fooling set.
- Closure properties. Use existing non-regular languages and regular languages to prove that some new language is non-regular.
- Pumping lemma. We did not cover it but it is sometimes an easier proof technique to apply, but not as general as the fooling set technique.