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. $L_4 = L_1 \cap L_2$

Fix tablet view after hours

CS/ECE-374: Lecture 5 - Non-regularity and closure

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September 07, 2023

University of Illinois at Urbana-Champaign

Pre-lecture brain teaser

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

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

2. $L_2 = \{0^n 1^n \mid n \geq 0\}$ $\cancel{(01)^* \to \varepsilon + (01) + (01)(01)}$
   $\cancel{+ (01)(01)(01) + \cdots}$

3. $L_3 = L_1 \cup L_2 \equiv L_1$ $0^* 1^*$

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

Pre-lecture brain teaser

We have a language $\boxed{L_2 = \{0^n 1^n | n \geq 0\}}$

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.**

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

A Simple and Canonical Non-regular Language

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

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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.

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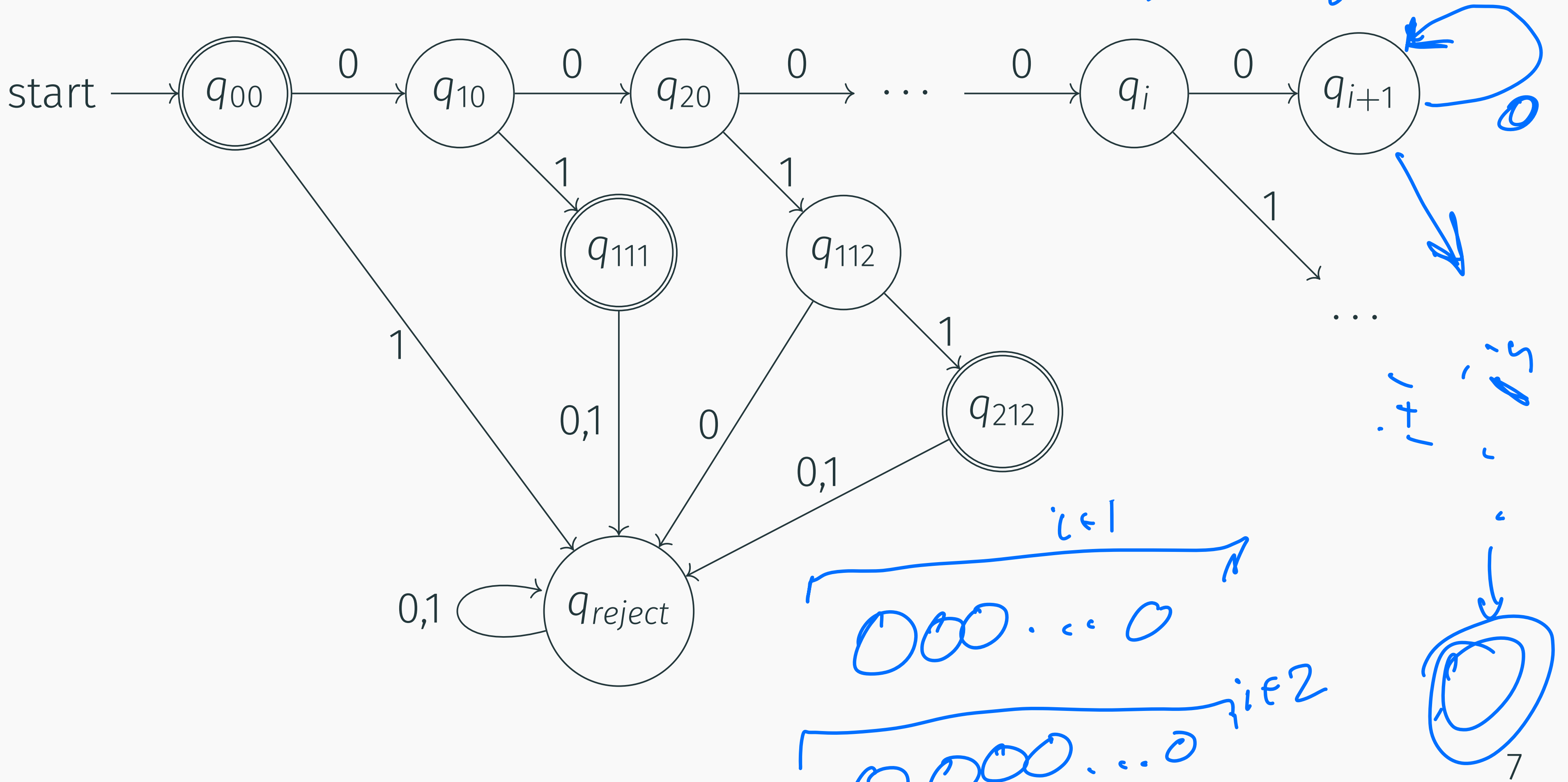
$L = \{0^n 1^n \mid n \geq 0\}$

$\{\varepsilon \quad 01 \quad 0011 \quad 000111$

$i+1$



$\overbrace{000\cdots0}^{i+1}$

$\overbrace{0000\cdots0}^{i+2}$

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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 $0 \leq i < j \leq n$. That is, M is in the same state after reading 0^i and 0^j where $i \neq j$.

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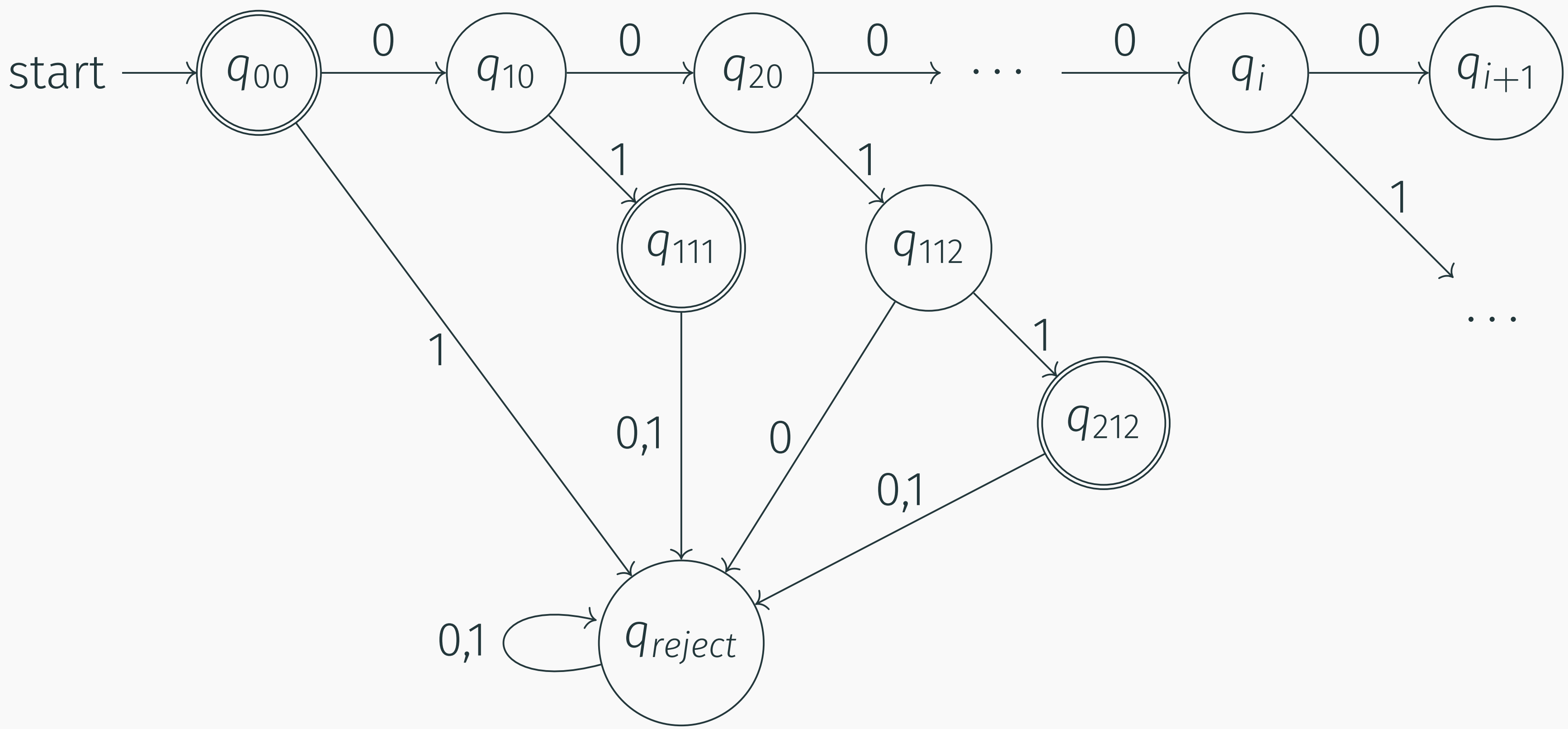
M should accept $0^i 1^i$ but then it will also accept $0^j 1^i$ where $i \neq j$.

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?

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

prefix

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.

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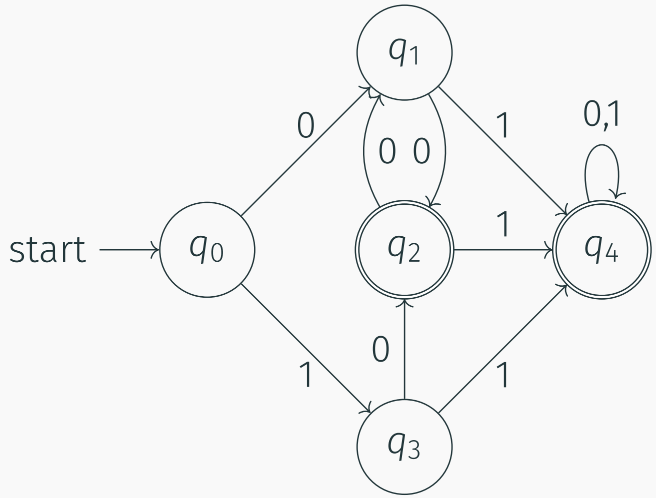


$\delta(q_1, 0) = q_2 \in A$

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

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

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

Distinguishing between states

$\delta(q_1, \varepsilon) = q_1 \notin A$

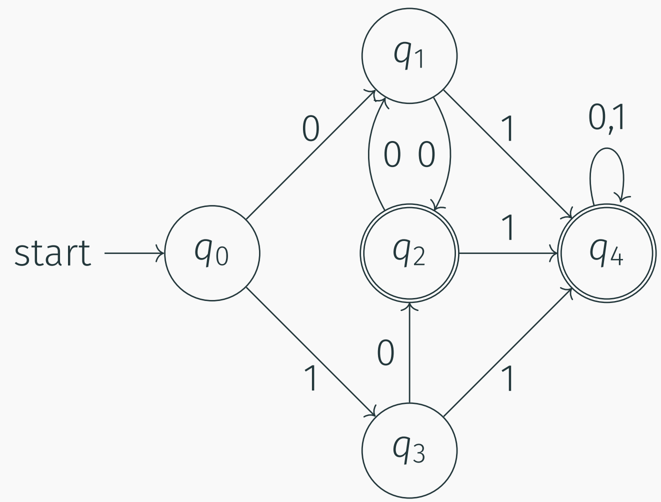
$\delta(q_2, \varepsilon) = q_2 \in A$

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

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

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



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

or

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

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

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

Distinguishable prefixes

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

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

Distinguishable prefixes

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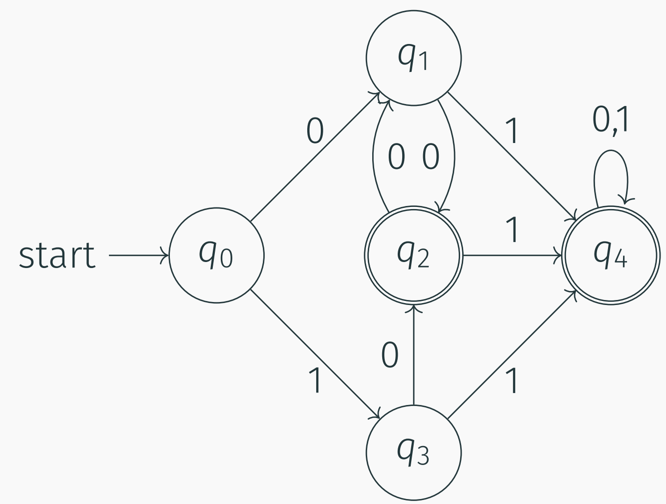
Idea: Every string $w \in \Sigma^*$ defines a state $\nabla w = \delta^*(s, w)$.

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 $wx \in L$).



Distinguishable means different states

Lemma
L: regular language.

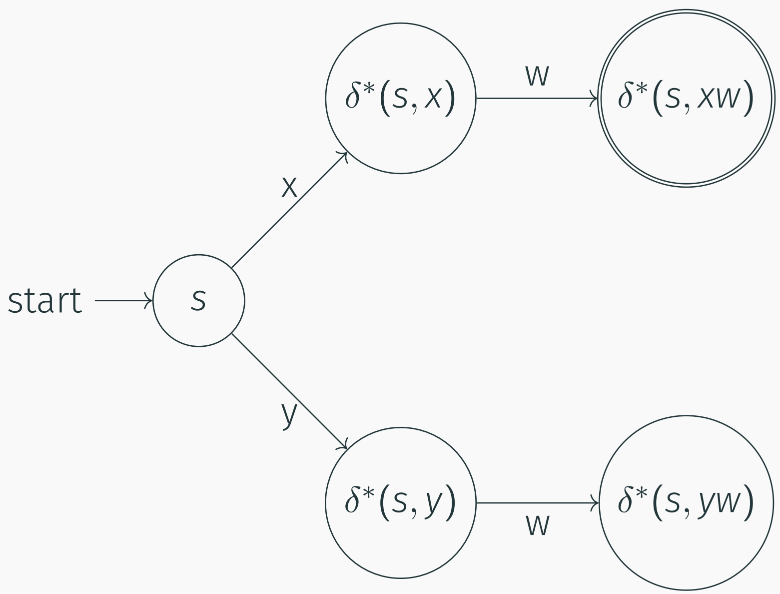
$M = (Q, \Sigma, \delta, s, A)$: DFA for L.

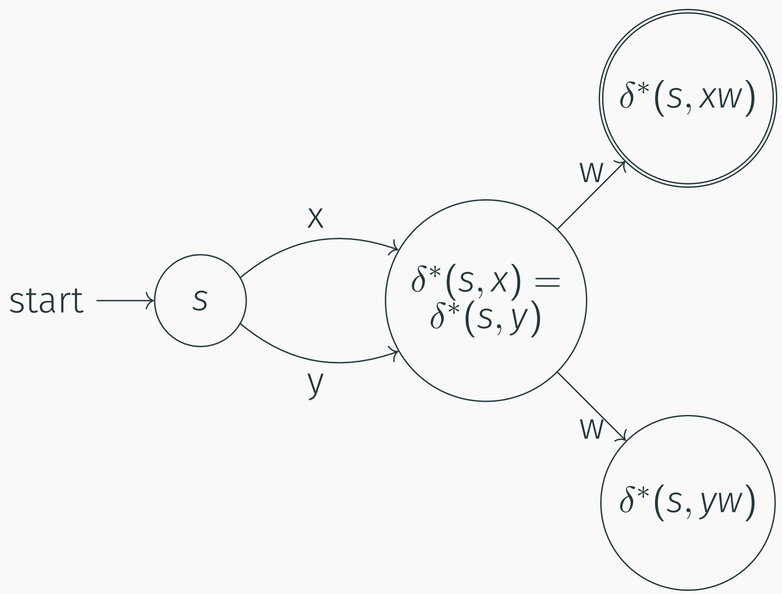
If $x, y \in \Sigma^*$ are distinguishable, then $\nabla x \neq \nabla y$.

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

Proof by a figure

Possible	Not possible





Review questions...

- Are $\nabla 0^i$ and $\nabla 0^j$ are distinguishable for the language $\{0^n 1^n \mid n \geq 0\}$.

$i \neq j$

$\exists\ w = 1^i$

$0^i 1^i \in L$

$0^j 1^i \notin L$

Review questions...

- Are $\nabla 0^i$ and $\nabla 0^j$ are distinguishable for the language $\{0^n 1^n \mid n \geq 0\}$.
- Let L be a regular language, and let $w_1, \ldots, w_k$ be strings that are all pairwise distinguishable for L. How many states must the DFA for L have? $k \leq |Q|$

Review questions...

- Are $\nabla 0^i$ and $\nabla 0^j$ 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. How many states must the DFA for L have?
- Prove that $\{0^n1^n \mid n \geq 0\}$ is not regular.

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.

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

0^i, 0^j distinguishable

(goes to an accept

$\exists\, x = 1^i$ $\quad 0^i 1^i \in L$

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

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.

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.

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.

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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.

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

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

Examples

- $\{0^n1^n \mid n \geq 0\}$ $= L_1$

Assume L_1 is regular

know $\exists\, M = \langle Q, \Sigma, \delta, s, A \rangle$ that represents L $(L(M) = L_1)$

L has fooling set $F = \{0^i \mid i > 0\}$

F is a fooling b/c for every 2 prefixes in F $0^i, 0^j$ $\exists$ suffix $w = 1^i$ where $0^i1^i \in L_1$ but $0^j1^i \notin L_1$

Therefore M must have $|Q| \geq |F|$ but F is infinite, contradiction

Examples

- $\{0^n 1^n \mid n \geq 0\}$

$(0+1)^*$

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

010101 . . . 110011 00

Assume L_2 is regular Assume M_2

$F = \{0^i \mid i > 0\}$ $\exists\, w = 1^i$

$0^i 1^i \in L_2$

$0^j 1^i \notin L_2$

$|Q_2|$ is infinite . . . contradiction

Examples

- $\{0^n1^n \mid n \geq 0\}$

- {bitstrings with equal number of 0s and 1s}

- $\{0^k1^\ell \mid k \neq \ell\} = L_3$

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

$w = 1^i$

$0^i1^i \notin L$

$0^j1^i \in L$

Examples

$L_4 = \{\text{strings of properly matched open and closing parentheses}\}$

$F = \{ (^i \mid i > 0 \}$ $\qquad \Sigma = \{ (,) \}$

$(^i)^i \in L$

$(^j)^i \notin L$

Examples

$L_5 = \{\text{palindromes over the binary alphabet} \Sigma = \{0, 1\}\}$

A palindrome is a string that is equal to its reversal, e.g. 10001 or 0110.

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

$0^i 1 0^i \in L$

$0^j 1 0^i \notin L$

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

$0^i 0^i \in L_5$

? $0^j 0^i \in L_5$ As long as $j > i + 1$

Closure properties: Proving non-regularity

Non-regularity via closure properties

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

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

Suppose we have already shown that L' is non-regular. Can we show that $\cancel{L'}\,H$ 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?

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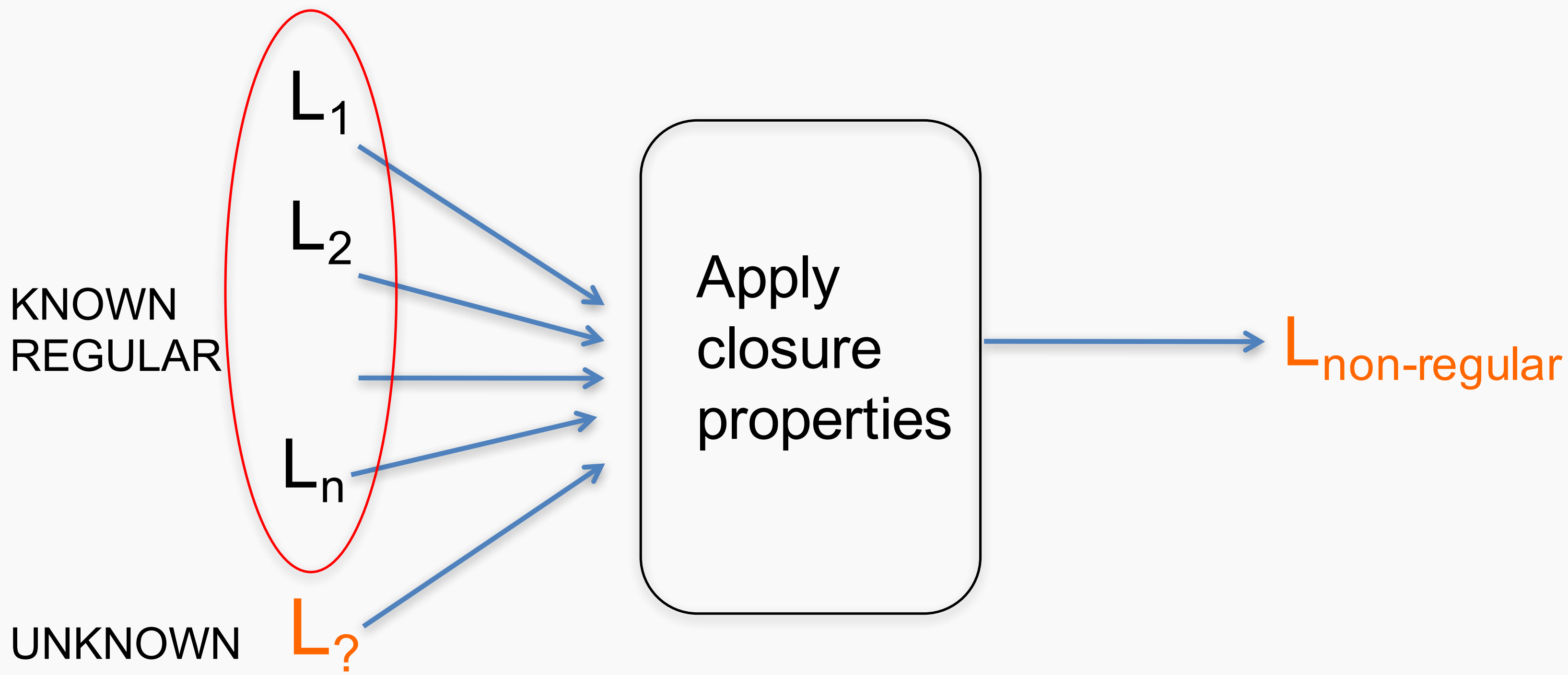
Suppose H is regular. Then since $L(0^*1^*)$ is regular, and regular languages are closed under intersection, H' also would be regular. But we know H' is not regular, a contradiction.

General recipe:



Examples

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

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

non-regular

Assume L is regular

$\{0^k 1^k \mid k \geq 1\} \cup \underbrace{\{\varepsilon\}} = 0^n 1^n$

Careful with closure!

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

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

But $L \cup \overline{L} = (0+1)^*$ which 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.