DFA Minimization, Pumping Lemma
CSCI 3130 Formal Languages and Automata Theory

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$L = \text{lang. of strings ending in 111}$

Can we do it in 3 states?
Even smaller DFA?

\[ L = \text{lang. of strings ending in 111} \]

Intuitively, needs to remember number of ones recently read

We will show

\[ \varepsilon, 1, 11, 111 \text{ are pairwise distinguishable by } L \]

In other words

\[ (\varepsilon, 1), (\varepsilon, 11), (\varepsilon, 111), (1, 11), (1, 111), (11, 111) \]

are all distinguishable by \( L \)

Then use this result from last lecture:

If strings \( x_1, \ldots, x_n \) are pairwise distinguishable by \( L \), any DFA accepting \( L \)

must have at least \( n \) states
Recap: distinguishable strings

What do we mean by “1 and 11 are distinguishable”?

\((x, y)\) are distinguishable by \(L\) if there is string \(z\) such that \(xz \in L\) and \(yz \notin L\) (or the other way round)

We saw from last lecture

If \(x\) and \(y\) are distinguishable by \(L\), any DFA accepting \(L\) must reach different states upon reading \(x\) and \(y\)
Distinguishable strings

Why are 1 and 11 distinguishable by $L$?

$L = \text{lang. of strings ending in 111}$
Distinguishable strings

Why are 1 and 11 distinguishable by $L$?
$L =$ lang. of strings ending in 111

Take $z = 1$
$11 \notin L \quad 111 \in L$

More generally, why are $1^i$ and $1^j$ distinguishable by $L$?
$(0 \leq i < j \leq 3)$

Take $z = 1^{3-j}$
$1^i1^{3-j} \notin L \quad 1^j1^{3-j} \in L$

$\varepsilon, \; 1, \; 11, \; 111$ are pairwise distinguishable by $L$
Thus our 4-state DFA is minimal
DFA minimization

We now show how to turn any DFA for $L$ into the minimal DFA for $L$. 
Minimal DFA and distinguishability

Distinguishable strings must be in different states
Indistinguishable strings may end up in the same state

DFA minimal ⇔ Every pair of distinct states is distinguishable
Distinguishable states

Two states $q$ and $r$ are distinguishable if on the same continuation string $z = z_1 \ldots z_k$, one accepts, but the other rejects.
Examples of distinguishable states

Which of the following pairs are distinguishable? by which string?

\((q_0, q_3)\)
\((q_1, q_3)\)
\((q_2, q_3)\)
\((q_1, q_2)\)
\((q_0, q_2)\)
\((q_0, q_1)\)
Examples of distinguishable states

Which of the following pairs are distinguishable? by which string?

\[(q_0, q_3)\] distinguishable by \(\varepsilon\)
\[(q_1, q_3)\] distinguishable by \(\varepsilon\)
\[(q_2, q_3)\] distinguishable by \(\varepsilon\)
\[(q_1, q_2)\] distinguishable by \(0\)
\[(q_0, q_2)\] distinguishable by \(0\)
\[(q_0, q_1)\] indistinguishable
Examples of distinguishable states

Which of the following pairs are distinguishable? by which string?

- \((q_0, q_3)\) distinguishable by \(\varepsilon\)
- \((q_1, q_3)\) distinguishable by \(\varepsilon\)
- \((q_2, q_3)\) distinguishable by \(\varepsilon\)
- \((q_1, q_2)\) distinguishable by 0
- \((q_0, q_2)\) distinguishable by 0
- \((q_0, q_1)\) indistinguishable

indistinguishable pairs can be merged
Finding (in)distinguishable states

Phase 1: If $q$ is accepting and $q'$ is rejecting, mark $(q, q')$ as distinguishable ($X$).

Phase 2: If $(q, q')$ are marked, mark $(r, r')$ as distinguishable ($X$).

Phase 3: Unmarked pairs are indistinguishable. Merge them into groups.
Finding (in)distinguishable states

Phase 1: $q \xrightarrow{X} q'$
If $q$ is accepting and $q'$ is rejecting
Mark $(q, q')$ as distinguishable ($X$)

Phase 2: $q \xrightarrow{X} q'$
If $(q, q')$ are marked
Mark $(r, r')$ as distinguishable ($X$)

Phase 3: Unmarked pairs are indistinguishable
Merge them into groups
Finding (in)distinguishable states

Phase 1: If $q$ is accepting and $q'$ is rejecting, mark $(q, q')$ as distinguishable ($\times$).

Phase 2: If $(q, q')$ are marked, mark $(r, r')$ as distinguishable ($\times$).

Phase 3: Unmarked pairs are indistinguishable. Merge them into groups.
DFA minimization: example

(q0, q1, q00, q01, q10, q11)
DFA minimization: example

(Phase 1) \( q_{11} \) is distinguishable from all other states
DFA minimization: example

(Phase 2) Looking at \((r, r') = (q_\varepsilon, q_0)\)
Neither \((q_0, q_{00})\) nor \((q_1, q_{01})\) are distinguishable
DFA minimization: example

(Phase 2) Looking at \((r, r') = (q_\epsilon, q_1)\)

\((q_1, q_{11})\) is distinguishable
DFA minimization: example

(Phase 2) After going through the whole table once
Now we make another pass
DFA minimization: example

(Phase 2) Looking at \((r, r') = (q_\varepsilon, q_0)\)
Neither \((q_0, q_{00})\) nor \((q_1, q_{01})\) are distinguishable
(Phase 2) Looking at \((r, r') = (q_\epsilon, q_{00})\)
Neither \((q_0, q_{00})\) nor \((q_1, q_{01})\) are distinguishable
DFA minimization: example

(Phase 2) Nothing changes in the second pass
Ready to go to Phase 3
DFA minimization: example

(Phase 3) Merge states into **groups** (also called **equivalence classes**)

\[
\begin{array}{c}
q_0 & q_1 & q_00 & q_01 & q_10 & q_11 \\
q_0 & A & X & X & X & X \\
q_1 & X & X & B & X & X \\
q_{00} & A & A & X & A & X \\
q_{01} & X & X & A & X & X \\
q_{10} & A & A & X & X & X \\
q_{11} & X & X & X & X & X \\
q_\varepsilon & \text{X} & \text{X} & \text{X} & \text{X} & \text{X} \\
\end{array}
\]
DFA minimization: example

Minimized DFA:
Why it works

Why have we found all distinguishable pairs?

Because we work backwards
Why it works

Why have we found all distinguishable pairs?

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Why it works

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Why it works

Why have we found all distinguishable pairs?

Because we work backwards
Pumping Lemma
Pumping lemma

Another way to show some language is irregular

Example

$L = \{0^n1^n | n \geq 0\}$ is irregular

We reason by contradiction:
Suppose we have a DFA $M$ for $L$
Something must be wrong with this DFA
$M$ must accept some strings outside $L$
Towards a contradiction

What happens when $M$ gets input $x = 0^{n+1}1^{n+1}$?

$M$ accepts $x$ because $x \in L$
Towards a contradiction

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$M$ accepts $x$ because $x \in L$

Since $M$ has $n$ states, it must revisit one of its states while reading $0^{n+1}$
Towards a contradiction

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The DFA must contain a cycle with 0s
Towards a contradiction

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The DFA must contain a cycle with 0s

The DFA will also accept strings that go around the cycle multiple times

But such strings have more 0s than 1s and cannot be in $L$
Pumping lemma for regular languages

For every regular language $L$ (say accepted by a DFA with $n$ states) for every string $s \in L$ longer than $n$ symbols, we can write $s = uvw$ where

1. $|uv| \leq n$
2. $|v| \geq 1$
3. For every $i \geq 0$, the string $uv^i w$ is in $L$
Proving languages are irregular

For every regular language $L$ (say accepted by a DFA with $n$ states), for every string $s \in L$ longer than $n$ symbols, we can write $s = uvw$ where

1. $|uv| \leq n$
2. $|v| \geq 1$
3. For every $i \geq 0$, the string $uv^i w$ is in $L$

To show that a language $L$ is irregular we need to find arbitrarily long $s$ so that no matter how the lemma splits $s$ into $u$, $v$, $w$ (subject to $|uv| \leq n$ and $|v| \geq 1$) we can find $i \geq 0$ such that $uv^i w \notin L$
$L_2 = \{0^m1^n \mid m > n \geq 0\}$

1. For any $n$ (number of states of an imaginary DFA accepting $L_2$)
2. There is a string $s = 0^{n+1}1^n$
3. Pumping lemma splits $s$ into $uvw$ ($|uv| \leq n$ and $|v| \geq 1$)
4. Choose $i = 0$ so that $uv^iw \notin L_2$

Example: 00000011111