CS 154, Lecture 4: Limitations on DFAs (I), Pumping Lemma, Minimizing DFAs
Non-Regular Languages

Regular or Not?

\[ \text{D} = \{ w \mid \text{w has equal number of occurrences of 01 and 10} \} \]

\text{REGULAR!}

\[ \text{C} = \{ w \mid \text{w has equal number of 1s and 0s} \} \]

\text{NOT REGULAR!}

How can we prove that there is no DFA for a particular language?

- Surprising Algorithms (even in restricted models) are routinely being discovered
The Pumping Lemma: Structure in Regular Languages

Let $L$ be a regular language

Then there is a positive integer $P$ s.t.

for all strings $w \in L$ with $|w| \geq P$ there is a way to write $w = xyz$, where:

1. $|y| > 0$ (that is, $y \neq \varepsilon$)
2. $|xy| \leq P$
3. For all $i \geq 0$, $xy^iz \in L$

Why is it called the *pumping lemma*?
The word $w$ gets *pumped* into longer and longer strings...
Let $P$ be the number of states in $M$

Let $w$ be a string where $w \in L$ and $|w| \geq P$

We show: $w = xyz$

1. $|y| > 0$
2. $|xy| \leq P$
3. $xy^iz \in L$ for all $i \geq 0$

Claim: There must exist $j$ and $k$ such that $0 \leq j < k \leq P$, and $q_j = q_k$
Let’s prove that \( \text{EQ}=\{w | \#1s = \#0s\} \) is not regular.

By contradiction. Assume \( \text{EQ} \) is regular. Let \( P \) be as in pumping lemma. Let \( w = 0^P1^P \in \text{EQ} \).

\[ \Rightarrow \text{Can write } w = xyz, \text{ with } |y| > 0, |xy| \leq P, \text{ such that for all } i \geq 0, xy^iz \text{ is also in EQ} \]

Claim: The string \( y \) must be all zeroes.

Why? Because \( |xy| \leq P \) and \( w = xyz = 0^P1^P \)

But then \( xyyz \) has more 0s than 1s \( \Rightarrow \text{Contradiction!} \)
Applying the Pumping Lemma

Prove: \( SQ = \{0^n^2 \mid n \geq 0\} \) is not regular

Assume \( SQ \) is regular. Let \( w = 0^{P^2} \)

\[ \Rightarrow \text{Can write } w = xyz, \text{ with } |y| > 0, \ |xy| \leq P, \] such that for all \( i \geq 0 \), \( xy^i z \) is also in \( EQ \)

So \( xyyz \in SQ \). Note that \( xyyz = 0^{P^2 + |y|} \)

Note that \( 0 < |y| \leq P \)

So \( |xyyz| = P^2 + |y| \leq P^2 + P < P^2 + 2P + 1 = (P+1)^2 \)

and \( P^2 < |xyyz| < (P+1)^2 \)

Therefore \( |xyyz| \) is not a perfect square!

Hence \( 0^{P^2 + |y|} = xyyz \notin SQ \), so our assumption must be false.

\[ \Rightarrow SQ \text{ is not regular!} \]
Does this DFA have a minimal number of states?
Is this minimal?

How can we tell in general?
Theorem:

For every regular language $L$, there is a unique (up to re-labeling of the states) minimal-state DFA $M^*$ such that $L = L(M^*)$.

Furthermore, there is an efficient algorithm which, given any DFA $M$, will output this unique $M^*$.

If these were true for more general models of computation, that would be an engineering breakthrough.
Note: There isn’t a uniquely minimal NFA
Extending transition function $\delta$ to strings

Given DFA $M = (Q, \Sigma, \delta, q_0, F)$, we extend $\delta$ to a function $\Delta : Q \times \Sigma^* \rightarrow Q$ as follows:

$$\Delta(q, \varepsilon) = q$$

$$\Delta(q, \sigma) = \delta(q, \sigma)$$

$$\Delta(q, \sigma_1...\sigma_{k+1}) = \delta(\Delta(q, \sigma_1...\sigma_k), \sigma_{k+1})$$

$\Delta(q, w) =$ the state of $M$ reached after reading in $w$, starting from state $q$

Note: $\Delta(q_0, w) \in F \iff M$ accepts $w$

**Def.** $w \in \Sigma^*$ distinguishes states $q_1$ and $q_2$ if exactly one of $\Delta(q_1, w), \Delta(q_2, w)$ is a final state
Distinguishing two states

Def. \( w \in \Sigma^* \) distinguishes states \( q_1 \) and \( q_2 \) if exactly one of \( \Delta(q_1, w) \), \( \Delta(q_2, w) \) is a final state

I’m in \( q_1 \) or \( q_2 \), but which? How can I tell?

Ok, I’m accepting! Must have been \( q_1 \)
Fix $M = (Q, \Sigma, \delta, q_0, F)$ and let $p, q \in Q$

Definitions:

State $p$ is *distinguishable* from state $q$
if there is $w \in \Sigma^*$ that distinguishes $p$ and $q$
($\iff$ there is $w \in \Sigma^*$ so that
exactly one of $\Delta(p, w), \Delta(q, w)$ is a final state)

State $p$ is *indistinguishable* from state $q$
if $p$ is not distinguishable from $q$
($\iff$ for all $w \in \Sigma^*$, $\Delta(p, w) \in F \iff \Delta(q, w) \in F$)

*Pairs of indistinguishable states are redundant...*
ε distinguishes all final states from non-final states

Which pairs of states are distinguishable here?
Which pairs of states are distinguishable here?

The string 10 distinguishes $q_0$ and $q_3$. 
Which pairs of states are distinguishable here?

The string 0 distinguishes $q_1$ and $q_2$. The string 0,1 distinguishes $q_0$ and $q_2$. The string 0,1 distinguishes $q_0$ and $q_3$. The string 0,1 distinguishes $q_1$ and $q_3$.
Fix $M = (Q, \Sigma, \delta, q_0, F)$ and let $p, q, r \in Q$

Define a binary relation $\sim$ on the states of $M$:

$p \sim q$ iff $p$ is indistinguishable from $q$

$p \not\sim q$ iff $p$ is distinguishable from $q$

Proposition: $\sim$ is an equivalence relation

$p \sim p$ (reflexive)

$p \sim q \Rightarrow q \sim p$ (symmetric)

$p \sim q$ and $q \sim r \Rightarrow p \sim r$ (transitive)

Proof?
Fix $M = (Q, \Sigma, \delta, q_0, F)$ and let $p, q, r \in Q$

Therefore, the relation $\sim$ partitions $Q$ into disjoint equivalence classes.

Proposition: $\sim$ is an equivalence relation

$$[q] := \{ p \mid p \sim q \}$$
Algorithm: MINIMIZE-DFA

Input: DFA M

Output: DFA $M_{\text{MIN}}$ such that:

$L(M) = L(M_{\text{MIN}})$

$M_{\text{MIN}}$ has no inaccessible states

$M_{\text{MIN}}$ is irreducible

For all states $p \neq q$ of $M_{\text{MIN}}$, $p$ and $q$ are distinguishable

Theorem: $M_{\text{MIN}}$ is the unique minimal DFA that is equivalent to $M$
Intuition:
The states of $M_{\text{MIN}}$ will be the equivalence classes of states of $M$

We’ll uncover these equivalent states with a dynamic programming algorithm
The Table-Filling Algorithm

Input: DFA $M = (Q, \Sigma, \delta, q_0, F)$

Output:  
1. $D_M = \{(p, q) \mid p, q \in Q \text{ and } p \sim q\}$
2. $\text{EQUIV}_M = \{[q] \mid q \in Q\}$

High-Level Idea:

- We know how to find those pairs of states that the string $\epsilon$ distinguishes...
- Use this and iteration to find those pairs distinguishable with longer strings
- The pairs of states left over will be indistinguishable
The Table-Filling Algorithm

Input: DFA $M = (Q, \Sigma, \delta, q_0, F)$

Output:  
1. $D_M = \{(p, q) \mid p, q \in Q \text{ and } p \not\sim q\}$
2. $\text{EQUIV}_M = \{[q] \mid q \in Q\}$

Base Case: For all $(p, q)$ such that $p$ accepts and $q$ rejects $\Rightarrow p \not\sim q$
The Table-Filling Algorithm

Input: DFA $M = (Q, \Sigma, \delta, q_0, F)$

Output:
1. $D_M = \{ (p, q) \mid p, q \in Q \text{ and } p \sim q \}$
2. $\text{EQUIV}_M = \{ [q] \mid q \in Q \}$

Base Case: For all $(p, q)$ such that $p$ accepts and $q$ rejects $\Rightarrow p \not\sim q$

Iterate: If there are states $p, q$ and symbol $\sigma \in \Sigma$ satisfying:

\[
\delta (p, \sigma) = p' \quad \text{mark} \\
\not\sim \Rightarrow p \not\sim q
\]

\[
\delta (q, \sigma) = q' \\
\not\sim \Rightarrow p \not\sim q
\]

Repeat until no more $D$'s can be added
Claim: If \((p, q)\) is marked \(D\) by the Table-Filling algorithm, then \(p \not\sim q\)

Proof: By induction on the number of steps in the algorithm before \((p, q)\) is marked \(D\)

If \((p, q)\) is marked \(D\) at the start, then one state’s in \(F\) and the other isn’t, so \(\varepsilon\) distinguishes \(p\) and \(q\)

Suppose \((p, q)\) is marked \(D\) at a later point.

Then there are states \(p', q'\) such that:
1. \((p', q')\) are marked \(D\) \(\Rightarrow\) \(p' \not\sim q'\) (by induction)

So there’s a string \(w\) s.t. \(\Delta(p', w) \in F \iff \Delta(q', w) \notin F\)

2. \(p' = \delta(p, \sigma)\) and \(q' = \delta(q, \sigma)\), where \(\sigma \in \Sigma\)

The string \(\sigma w\) distinguishes \(p\) and \(q\)!
Claim: If \((p, q)\) is not marked D by the Table-Filling algorithm, then \(p \sim q\)

Proof (by contradiction):

Suppose the pair \((p, q)\) is not marked D by the algorithm, yet \(p \sim q\) (call this a “bad pair”)

Then there is a string \(w\) such that \(|w| > 0\) and:

\[ \Delta(p, w) \in F \text{ and } \Delta(q, w) \not\in F \]  \quad (Why is \(|w| > 0|?)

We have a bad pair, let \(p, q\) be a pair with the shortest distinguishing string \(w\).

Let \(p' = \delta(p, \sigma)\) and \(q' = \delta(q, \sigma)\)

Then \((p', q')\) is also a bad pair, but with a SHORTER distinguishing string, \(w'\)!
Algorithm MINIMIZE

Input: DFA M

Output: Equivalent minimal-state DFA $M_{\text{MIN}}$

1. Remove all inaccessible states from M

2. Run Table-Filling algorithm on M to get:
   $\text{EQUIV}_M = \{ [q] | q \text{ is an accessible state of } M \}$

3. Define: $M_{\text{MIN}} = (Q_{\text{MIN}}, \Sigma, \delta_{\text{MIN}}, q_{0 \text{MIN}}, F_{\text{MIN}})$
   
   $Q_{\text{MIN}} = \text{EQUIV}_M, \ q_{0 \text{MIN}} = [q_0], \ F_{\text{MIN}} = \{ [q] | q \in F \}$
   
   $\delta_{\text{MIN}}( [q], \sigma ) = [ \delta( q, \sigma ) ]$

Claim: $L(M_{\text{MIN}}) = L(M)$
Suppose for now the Claim is true.

If $M'$ is a minimal DFA, then $M'$ has no inaccessible states and is irreducible $\Rightarrow$ there is an isomorphism between $M'$ and $M_{\text{MIN}}$.

Claim: If $L(M')=L(M_{\text{MIN}})$ and $M'$ has no inaccessible states and $M'$ is irreducible $\Rightarrow$ there is an isomorphism between $M'$ and $M_{\text{MIN}}$.

Thm: $M_{\text{MIN}}$ is the unique minimal DFA equivalent to $M$.
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Claim: If $L(M')=L(M_{\text{MIN}})$ and $M'$ has no inaccessible states and $M'$ is irreducible $\Rightarrow$ there is an isomorphism between $M'$ and $M_{\text{MIN}}$

Proof: We recursively construct a map from the states of $M_{\text{MIN}}$ to the states of $M'$

Base Case: $q_{0 \text{MIN}} \mapsto q_{0'}$

Recursive Step: If $p \mapsto p'$
\[\begin{align*}
\downarrow \sigma & \quad \downarrow \sigma \\
q & \quad q' \\
\end{align*}\] Then $q \mapsto q'$
Base Case: $q_{0\text{MIN}} \mapsto q_0'$

Recursive Step: If $p \mapsto p'$

Then $q \mapsto q'$
Base Case: $q_{0 \text{ MIN}} \mapsto q_{0'}$

Recursive Step: If $p \mapsto p'$

\[
\begin{array}{c}
p \\
\downarrow \sigma \\
q
\end{array} \quad \begin{array}{c}
p' \\
\downarrow \sigma \\
 q'
\end{array}
\]

Then $q \mapsto q'$

We need to prove:

- The map is defined everywhere
- The map is well defined
- The map is a bijection
- The map preserves all transitions:
  If $p \mapsto p'$ then $\delta_{\text{MIN}}(p, \sigma) \mapsto \delta'(p', \sigma)$

*(this follows from the definition of the map!)*
Base Case: $q_0^{\text{MIN}} \mapsto q_0'$

Recursive Step: If $p \mapsto p'$

\[ \downarrow \sigma \] \[ \downarrow \sigma \]

Then $q \mapsto q'$

The map is defined everywhere

That is, for all states $q$ of $M_{\text{MIN}}$ there is a state $q'$ of $M'$ such that $q \mapsto q'$

If $q \in M_{\text{MIN}}$, there is a string $w$ such that $\Delta_{\text{MIN}}(q_0^{\text{MIN}}, w) = q$

Let $q' = \Delta'(q_0', w)$. Then $q \mapsto q'$
The map is well defined

Proof by contradiction.
Suppose there are states \( q' \) and \( q'' \) such that \( q \mapsto q' \) and \( q \mapsto q'' \)

We show that \( q' \) and \( q'' \) are indistinguishable, so it must be that \( q' = q'' \)

Base Case: \( q_{0MIN} \mapsto q'_0 \)
Recursive Step: If \( p \mapsto p' \)
\[ \downarrow \sigma \downarrow \sigma \]
\[ q \mapsto q' \] Then \( q \mapsto q' \)
Suppose there are states $q'$ and $q''$ such that $q \rightarrow q'$ and $q \rightarrow q''$

Suppose $q'$ and $q''$ are distinguishable

Contradiction!
Base Case: $q_{0\text{MIN}} \mapsto q_0'$

Recursive Step: If $p \mapsto p'$

\[ \begin{array}{c}
\sigma \\
q
\end{array} \quad \begin{array}{c}
\sigma \\
q'
\end{array} \quad \rightarrow 

\text{Then } q \mapsto q'

The map is onto

Want to show: For all states $q'$ of $M'$ there is a state $q$ of $M_{\text{MIN}}$ such that $q \mapsto q'$

For every $q'$ there is a string $w$ such that $M'$ reaches state $q'$ after reading in $w$

Let $q$ be the state of $M_{\text{MIN}}$ after reading in $w$

Claim: $q \mapsto q'$
Proof by contradiction. Suppose there are states $p \neq q$ such that $p \mapsto q'$ and $q \mapsto q'$.

If $p \neq q$, then $p$ and $q$ are distinguishable.

The map is one-to-one.

Contradiction!
How can we prove that two regular expressions are equivalent?
Parting thoughts:
Pumping for contradictions
DFAs can’t count
DFAs can be optimized
Later: Can DFAs be learned?

Questions?