Today's learning goals

- Review what it means for a set to be closed under an operation.
- Define the regular operations on languages
- Prove closure properties of the class of regular languages
Building DFA

Remember

States are our only (computer) memory.

Design and pick states with specific roles / tasks in mind.

"Have not seen any of desired pattern yet"

"Trap state"
Building DFA

New strategy

Express $L$ in terms of simpler languages – use them as building blocks.

Example

$L = \{ w \mid w \text{ does not contain the substring } \text{baba} \}$

$= \text{the complement of the set}$

$\{w \mid w \text{ contains the substring } \text{baba}\}$
Building DFA

1. DFA recognizing \{w \mid w \text{ contains the substring } baba\}

\[ \Sigma = \{a, b\} \]

Example: \text{ababa} or \text{baaababa}

2. DFA recognizing \{w \mid w \text{ doesn't contain the substring baba}\}

Want to accept all strings besides those accepted in first machine.

In first machine

In second machine
Complementation

Claim: If $A$ is a regular language over $\{0,1\}^*$, then so is $\overline{A}$
aka "the class of regular languages is closed under complementation"
Closure of \( \mathbb{Z} \) under addition.

• Set of even ints under multiplication.

• \( \{0\}^* \) under concatenation.

Which of these is true?

A. The set of odd integers is closed under addition.
B. The set of positive integers is closed under subtraction.
C. The set of rational numbers is closed under multiplication.
D. The set of real numbers is closed under division.
E. I don't know.
Complementation

Claim: If $A$ is a regular language over $\{0,1\}^*$, then so is $\overline{A}$
aka "the class of regular languages is closed under complementation"
Complementation

Claim: If $A$ is a regular language over $\{0,1\}$, then so is $\overline{A}$ aka "the class of regular languages is closed under complementation"

Proof: Let $A$ be a regular language. Then there is a DFA $M=(Q, \Sigma, \delta, q_0, F)$ such that $L(M) = A$. We want to build a DFA whose language is $\overline{A}$. Define $M' =$

Claim of Correctness $L(M') = \overline{A}$

Proof of claim…
Correctness: $L(M') = \overline{A}$ sets on each side $L(M) \supseteq \overline{A}$ and $L(M) \subseteq \overline{A}$

1) $w \notin L(M)$ since $L(M) = A$. The computation $M \mathop{\triangleright}^w$ ends in a non-accepting state. Since the accepting states of $M'$ are exactly the non-accepting states of $M^F$ and nothing else changed, the computation of $M'$ on $w$ will end in the same state, which is now an accepting state.

2) $L(M') \subseteq \overline{A}$ if $w \in L(M')$ then $w \in \overline{A}$.

Contrapositive: if $w \in \overline{A}$ then $w \notin L(M')$
Why closure proofs?

- General technique of proving a new language is regular
- Stretch the power of the model
- Puzzle!
The regular operations

For $A$, $B$ languages over same alphabet, define:

$A \cup B = \{ x | x \in A \text{ or } x \in B \}$

$A \circ B = \{ xy | x \in A \text{ and } y \in B \}$

$A^* = \{ x_1x_2 \ldots x_k | k \geq 0 \text{ and each } x_i \in A \}$

These are operations on sets!
Theorem: The class of regular languages over fixed alphabet $\Sigma$ is closed under the union operation.

Proof:

What are we proving here?

A. For any set A, if A is regular then so is A U A.
B. For any sets A and B, if A U B is regular, then so is A.
C. For two DFAs M1 and M2, M1 U M2 is regular.
D. None of the above.
E. I don't know.
Theorem: The class of regular languages over fixed alphabet $\Sigma$ is closed under the union operation.

Proof: Let $A_1, A_2$ be any two regular languages over $\Sigma$. WTS that $A_1 \cup A_2$ is regular.

Goal: build a machine that recognizes $A_1 \cup A_2$. 

Sipser Theorem 1.25 p. 45
**Union**  

**Goal:** build a machine that recognizes $A_1 \cup A_2$.  

**Strategy:** use machines that recognize each of $A_1$, $A_2$.  

*HOW?*
Theorem: The class of regular languages over fixed alphabet \( \Sigma \) is closed under the union operation.

Proof: Let \( A_1, A_2 \) be any two regular languages over \( \Sigma \). Given \( M_1 = (Q_1, \Sigma, \delta_1, q_1, F_1) \) such that \( L(M_1) = A_1 \) and \( M_2 = (Q_2, \Sigma, \delta_2, q_2, F_2) \) such that \( L(M_2) = A_2 \) and WTS that \( A_1 \cup A_2 \) is regular.

Define \( M = (Q, \Sigma, \delta, q, F) \)
Theorem: The class of regular languages over fixed alphabet $\Sigma$ is closed under the union operation.

Proof: Let $A_1, A_2$ be any two regular languages over $\Sigma$. Given $M_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ such that $L(M_1) = A_1$ and $M_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ such that $L(M_2) = A_2$ and WTS that $A_1 \cup A_2$ is regular.

Define $M = (Q_1 \times Q_2, \Sigma, \delta, ?, ?)$

Idea: run in parallel
Theorem: The class of regular languages over fixed alphabet $\Sigma$ is closed under the union operation.

Proof: Let $A_1, A_2$ be any two regular languages over $\Sigma$.

Given $M_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ such that $L(M_1) = A_1$ and $M_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ such that $L(M_2) = A_2$ and WTS that $A_1 \cup A_2$ is regular.

Define $M = (Q_1 \times Q_2, \Sigma, \delta, ?, ?)$

What should be the initial state of $M$?

A. $q_0$
B. $q_1$
C. $q_2$
D. $(q_1, q_2)$
E. I don’t know.
Theorem: The class of regular languages over fixed alphabet $\Sigma$ is closed under the union operation.

Proof: Let $A_1, A_2$ be any two regular languages over $\Sigma$.

Given $M_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ such that $L(M_1) = A_1$ and $M_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ such that $L(M_2) = A_2$ and WTS that $A_1 U A_2$ is regular.

Define $M = (Q_1 \times Q_2, \Sigma, \delta, ?, ?)$

When $r$ is a state in $M_1$, $s$ is a state in $M_2$, and $x$ is in $\Sigma$, then $\delta( (r,s), x ) =$

A. $(r,s)$
B. $(\delta_1(r,x), \delta_2(s,x))$
C. $(\delta_1(r,x), s)$
D. $(\delta_1(r,x), \delta_2(s,x))$
E. I don't know.
Theorem: The class of regular languages over fixed alphabet $\Sigma$ is closed under the union operation.

Proof: Let $A_1$, $A_2$ be any two regular languages over $\Sigma$. Given $M_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ such that $L(M_1) = A_1$ and $M_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ such that $L(M_2) = A_2$ and WTS that $A_1 \cup A_2$ is regular.

Define $M = (Q_1 \times Q_2, \Sigma, \delta, ?, ?)$ where

- The set of accepting states for $M$ is $C. \{ (r, s) \mid r \text{ is in } F_1 \text{ or } s \text{ is in } F_2 \}$.
Proof: Let $A_1, A_2$ be any two regular languages over $\Sigma$. Given $M_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ such that $L(M_1) = A_1$ and $M_2 = (Q_2, \Sigma, \delta_2, q_2, F_2)$ such that $L(M_2) = A_2$.

WTS that $A_1 \cup A_2$ is regular. Define $M = (Q_1 \times Q_2, \Sigma, \delta, (q_1, q_2), \{(r, s) \in Q_1 \times Q_2 \mid r \in F_1 \text{ or } s \in F_2\})$ with $\delta( (r, s), x ) = ( \delta_1(r, x), \delta_2(s, x) )$ for each $(r, s)$ in $Q_1 \times Q_2$ and $x$ in $\Sigma$.

Why does $L(M) = A_1 \cup A_2$?
Intersection

• How would you prove that the class of regular languages is closed under intersection?

• Can you think of more than one proof strategy?

\[ A \cap B = \{ x \mid x \text{ in } A \text{ and } x \text{ in } B \} \]
Payoff

\{ w \mid w \text{ contains neither the substrings aba nor baab}\}

Is this a regular set?
Payoff

\{ w \mid w \text{ contains neither the substrings } aba \text{ nor } baab \}

Is this a regular set?

A = \{ w \mid w \text{ contains } aba \text{ as a substring} \}

B = \{ w \mid w \text{ contains } baab \text{ as a substring} \}

\overline{A \cap B} = \overline{A} \cup \overline{B}
Sample closure proofs

- The class of regular languages over \{0,1\} is closed under the FlipBits operation, where
  \[ \text{FlipBits}(L) = \{ w \mid w \text{ is obtained from some } w' \text{ in } L \text{ by flipping each } 0 \text{ in } w \text{ to } 1, \text{ and each } 1 \text{ to } 0 \} \]

- The class of regular languages of \{a,b,z\} is closed under the DeleteWordsWithZ operation, where
  \[ \text{DeleteWordsWithZ}(L) = \{ w \mid w \text{ is in } L \text{ and } w \text{ doesn't contain } z \} \]
General proof structure/strategy

**Theorem:** For any $L$ over $\Sigma$, if $L$ is regular then [the result of some operation on $L$] is also regular.

**Proof:**

- **Given** name variables for sets, machines assumed to exist.
- **WTS** state goal and outline plan.
- **Construction** using objects previously defined + new tools working towards goal. Give formal definition and explain.
- **Correctness** prove that construction works.
- **Conclusion** recap what you've proved.
The regular operations

For A, B languages over same alphabet, define:

$$A \cup B = \{x \mid x \in A \text{ or } x \in B\}$$

$$A \circ B = \{xy \mid x \in A \text{ and } y \in B\}$$

$$A^* = \{x_1x_2\ldots x_k \mid k \geq 0 \text{ and each } x_i \in A\}$$

How can we prove that the concatenation of two regular languages is a regular language?