Lecture 8 – Closure Properties of Regular Languages

COSE215: Theory of Computation

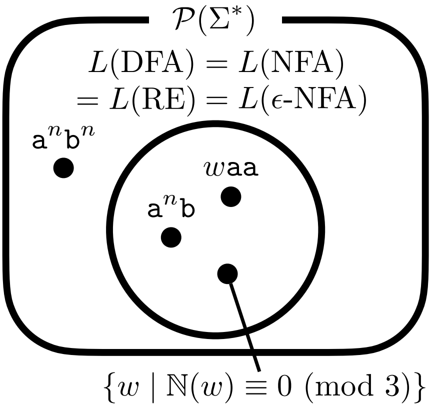
Jihyeok Park

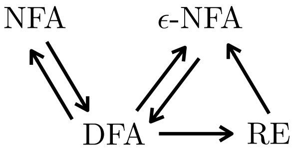
PLRG

2024 Spring

Recall

- Regular Languages





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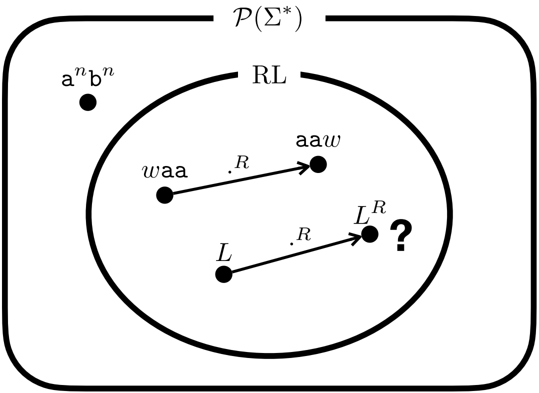
$$L^R = \{\texttt{aa}w \mid w \in \{\texttt{a}, \texttt{b}\}^*\}$$

Yes! We can construct a regular expression whose language is L^R as:

$$L(\texttt{aa(a|b)}^*) = L^R = \{\texttt{aa}w \mid w \in \{\texttt{a}, \texttt{b}\}^*\}$$

Closure Properties of Regular Languages



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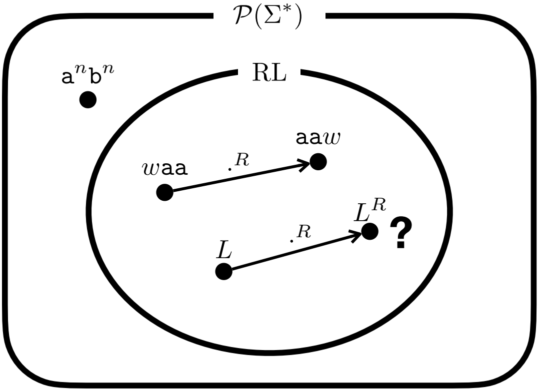

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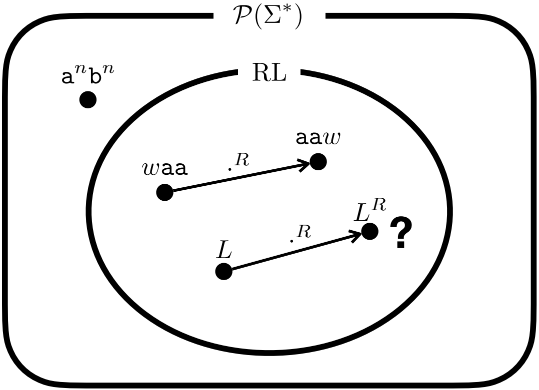

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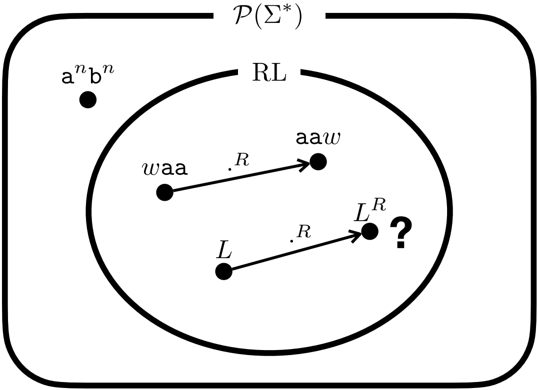

Then, for any regular language L, is L^R always regular? **Yes!**

The class of regular languages is **closed** under the **reversal** operator.

In this lecture, we will discuss and prove the **closure properties** of regular languages for various language operators.

Closure Properties of Regular Languages

Definition (Closure Properties)

The class of regular languages is **closed** under an n-ary operator op if and only if $\mathrm{op}(L_1, \cdots, L_n)$ is regular for any regular languages $L_1, \cdots, L_n$. We say that such properties are **closure properties** of regular languages.

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1. Construct a regular expression R whose language is $L(R) = \text{op}(L(R_1), \cdots, L(R_n))$ for any regular expressions $R_1, \cdots, R_n$.

2. Construct a finite automaton A whose language is $L(A) = \text{op}(L(A_1), \cdots, L(A_n))$ for any finite automata $A_1, \cdots, A_n$.

Closure Properties of Regular Languages

In this lecture, we will prove the closure properties of regular languages for the following operators:

- Union
- Concatenation
- Kleene Star
- Complement
- Intersection
- Difference
- Reversal
- Homomorphism
- Inverse Homomorphism

Theorem (Closure under Union, Concatenation, and Kleene Star)

If L_1 and L_2 are regular languages, then so is $L_1 \cup L_2$, $L_1 L_2$, and L_1^*.

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Consider the following regular expression:

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Then, by the definition of the union ($\cup$), concatenation ($\cdot$), and Kleene star (*) operators for regular expressions,

$$L(R_1 \mid R_2) = L_1 \cup L_2 \qquad\qquad L(R_1 R_2) = L_1 L_2 \qquad\qquad L(R^*) = L^*$$

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So, we proved that the class of regular languages are **closed** under the **union**, **concatenation**, and **Kleene star** operators. $\square$

Closure under Complement

Consider a regular language $L = \{w\texttt{aa} \mid w \in \{\texttt{a}, \texttt{b}\}^*\}$.

Is its **complement** $\overline{L} = \Sigma^* \setminus L$ also regular?

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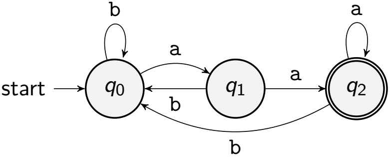
$D =$ 

First, consider the above DFA D accepting the language L.

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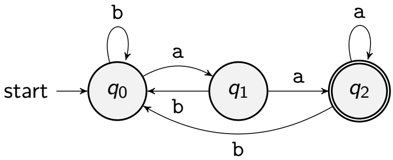
$D =$ 

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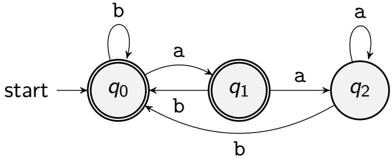
$\overline{D} =$ 

The key idea is to construct a new DFA $\overline{D}$ by **swapping** the **final** and **non-final** states of the original DFA:

Closure under Complement

Theorem (Closure under Complement)

If L is a regular language, then so is $\overline{L}$.

Proof) Let $D = (Q, \Sigma, \delta, q_0, F)$ be the DFA such that $L(D) = L$. Consider the following DFA:

$$\overline{D} = (Q, \Sigma, \delta, q_0, Q \setminus F).$$

Then,

$$\begin{array}{rcl} \forall w \in \Sigma^*,\ w \in L(\overline{D}) & \iff & \delta^*(q_0, w) \in Q \setminus F \\ & \iff & \delta^*(q_0, w) \notin F \\ & \iff & w \notin L(D) \\ & \iff & w \notin L \\ & \iff & w \in \overline{L} \end{array}$$

□

Closure under Intersection

$$L_1 = \{w \in \{0,1\}^* \mid w \text{ has } 0\} \qquad L_2 = \{w \in \{0,1\}^* \mid w \text{ has } 1\}$$

Is the **intersection** of two regular languages $L_1 \cap L_2$ also regular?

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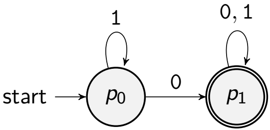
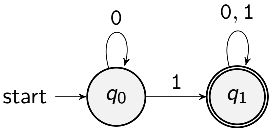
$D_0 =$ 

$D_1 =$ 

First, consider the above DFAs D_0 and D_1 accepting the languages L_1 and L_2, respectively.

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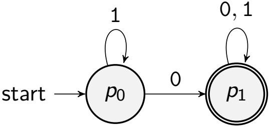
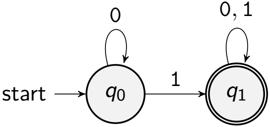
$D_0 =$ 

$D_1 =$ 

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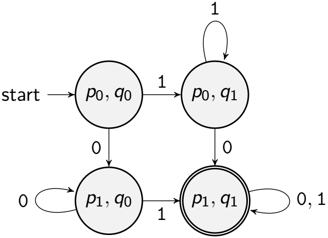
$D =$ 

The key idea is to construct a new DFA D by **combining** them with their **pair of states** as its states.

Closure under Intersection

Theorem (Closure under Intersection)

If L_0 and L_1 are regular languages, then so is $L_0 \cap L_1$.

Proof) Let $D_0 = (Q_0, \Sigma, \delta_0, q_0, F_0)$ and $D_1 = (Q_1, \Sigma, \delta_1, q_1, F_1)$ be the DFA such that $L(D_0) = L_0$ and $L(D_1) = L_1$. Consider the following DFA:

$$D = (Q_0 \times Q_1, \Sigma, \delta, (q_0, q_1), F_0 \times F_1).$$

where $\forall q \in Q_0, q' \in Q_1, \mathtt{a} \in \Sigma.\ \delta((q, q'), \mathtt{a}) = (\delta_0(q, \mathtt{a}), \delta_1(q', \mathtt{a}))$.

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$$\begin{array}{rcl} \forall w \in \Sigma^*,\ w \in L(D) & \iff & \delta^*((q_0, q_1), w) \in F_0 \times F_1 \\ & \iff & \delta^*(q_0, w) \in F_0 \text{ and } \delta^*(q_1, w) \in F_1 \\ & \iff & w \in L(D_0) \text{ and } w \in L(D_1) \\ & \iff & w \in L(D_0) \cap L(D_1) \\ & \iff & w \in L_0 \cap L_1 \end{array}$$

$\square$

Closure under Intersection

Theorem (Closure under Intersection)

If L_0 and L_1 are regular languages, then so is $L_0 \cap L_1$.

Proof) Another proof is to use De Morgan's law:

$$L_0 \cap L_1 = \overline{\overline{L_0} \cup \overline{L_1}}$$

Since we already know that the regular languages are closed under complement and union, we are done. $\square$

Closure under Difference

Theorem (Closure under Difference)

If L_0 and L_1 are regular languages, then so is $L_0 \setminus L_1$.

Proof) Similarly, we can use the following fact:

$$L_0 \setminus L_1 = L_0 \cap \overline{L_1}$$

Since we already know that the regular languages are closed under complement and intersection, we are done. $\square$

Closure under Reversal

$$L = \{w\texttt{a} \text{ or } w\texttt{b} \mid w \in \{\texttt{a}, \texttt{b}, \texttt{c}, \texttt{d}\}^*\}$$

Is the **reversal** L^R of the above regular language L also regular?

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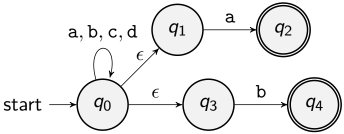

The above ϵ-NFA N^ϵ accepts the language L.

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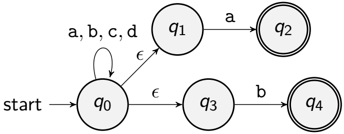

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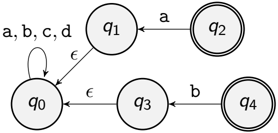

The key idea is to construct a new ϵ-NFA $(N^\epsilon)^R$ by

1. **reversing** the direction of the transitions
2.
3.

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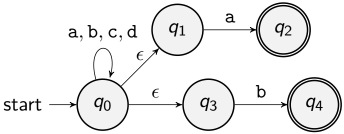

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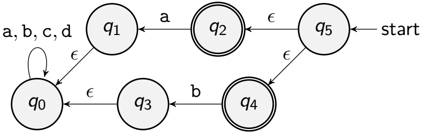

The key idea is to construct a new ϵ-NFA $(N^\epsilon)^R$ by

1. **reversing** the direction of the transitions
2. **adding** new initial state having ϵ-transitions to the original final states
3.

Closure under Reversal

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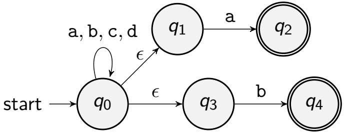
$N^\epsilon =$ 

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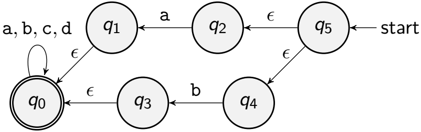
$(N^\epsilon)^R =$ 

The key idea is to construct a new ϵ-NFA $(N^\epsilon)^R$ by

1. **reversing** the direction of the transitions
2. **adding** new initial state having ϵ-transitions to the original final states
3. **change** original initial state to the unique new final state

Theorem (Closure under Reversal)

If L is a regular language, then so is L^R.

Proof) Let $N^\epsilon = (Q, \Sigma, \delta, q_0, F)$ be the ϵ-NFA such that $L(N^\epsilon) = L$. Consider the following

$$(N^\epsilon)^R = (Q \uplus \{q_s\}, \Sigma, \delta^R, q_s, \{q_0\})$$

where

$$\begin{aligned}
\forall q \in Q.\ \forall a \in \Sigma.\ \delta^R(q, \mathrm{a}) &= \{q' \in Q \mid q \in \delta(q', \mathrm{a})\} \\
\forall q \in Q.\ \delta^R(q, \epsilon) &= \{q' \in Q \mid q \in \delta(q', \epsilon)\} \\
\forall a \in \Sigma.\ \delta^R(q_s, \mathrm{a}) &= \varnothing \\
\delta^R(q_s, \epsilon) &= F
\end{aligned}$$

$\square$

Closure under Reversal

Theorem (Closure under Reversal)

If L is a regular language, then so is L^R.

Proof) Another proof is to use the structural induction on the regular expressions. Let R be a regular expression. Then, we can define its reversed regular expression R^R as follows:

- If $R = \varnothing$, then $R^R = \varnothing$.
- If $R = \epsilon$, then $R^R = \epsilon$.
- If $R = \mathtt{a}$, then $R^R = \mathtt{a}$.
- If $R = R_0 \mid R_1$, then $R^R = R_0^R \mid R_1^R$.
- If $R = R_0 R_1$, then $R^R = R_1^R R_0^R$.
- If $R = R_0^*$, then $R^R = (R_0^R)^*$.
- If $R = (R_0)$, then $R^R = (R_0^R)$. $\square$

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- If $R = \epsilon$, then $R^R = \epsilon$.
- If $R = \mathtt{a}$, then $R^R = \mathtt{a}$.
- If $R = R_0 \,|\, R_1$, then $R^R = R_0^R \,|\, R_1^R$.
- If $R = R_0 R_1$, then $R^R = R_1^R R_0^R$.
- If $R = R_0^*$, then $R^R = (R_0^R)^*$.
- If $R = (R_0)$, then $R^R = (R_0^R)$. $\square$

$$R = \mathtt{ab(cd)^*|ef}$$

$$R^R = \mathtt{(dc)^*ba|fe}$$

Closure under Homomorphism

Definition (Homomorphism)

Suppose Σ and Γ are two finite sets of symbols. Then, a function

$$h : \Sigma \to \Gamma^*$$

is called a **homomorphism**. For a given word $w = \mathtt{a}_1\mathtt{a}_2 \cdots \mathtt{a}_n \in \Sigma^*$,

$$h(w) = h(\mathtt{a}_1)h(\mathtt{a}_2) \cdots h(\mathtt{a}_n)$$

For a language $L \subseteq \Sigma^*$,

$$h(L) = \{h(w) \mid w \in L\} \subseteq \Gamma^*$$

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Example

Let $\Sigma = \{0, 1\}$, $\Gamma = \{\mathrm{a}, \mathrm{b}\}$, and $h(0) = \mathrm{ab}$, $h(1) = \mathrm{a}$. Then,

$$h(10) = \mathrm{aab} \qquad h(010) = \mathrm{abaab} \qquad h(1100) = \mathrm{aaabab}$$

Closure under Homomorphism

Theorem (Closure under Homomorphism)

If h is a homomorphism and L is a regular language, then so is $h(L)$.

Proof) Let R be the regular expression such that $L(R) = L$. Then, we can define its homomorphic regular expression $h(R)$ as follows:

- If $R = \varnothing$, then $h(R) = \varnothing$.
- If $R = \epsilon$, then $h(R) = \epsilon$.
- If $R = \mathtt{a}$, then $h(R) = h(\mathtt{a})$.
- If $R = R_0 \mid R_1$, then $h(R) = h(R_0) \mid h(R_1)$.
- If $R = R_0 R_1$, then $h(R) = h(R_0) h(R_1)$.
- If $R = R_0^*$, then $h(R) = (h(R_0))^*$.
- If $R = (R_0)$, then $h(R) = (h(R_0))$. $\square$

Theorem (Closure under Homomorphism)

If h is a homomorphism and L is a regular language, then so is $h(L)$.

Proof) Let R be the regular expression such that $L(R) = L$. Then, we can define its homomorphic regular expression $h(R)$ as follows:

- If $R = \varnothing$, then $h(R) = \varnothing$.
- If $R = \epsilon$, then $h(R) = \epsilon$.
- If $R = \mathtt{a}$, then $h(R) = h(\mathtt{a})$.
- If $R = R_0 \,|\, R_1$, then $h(R) = h(R_0) \,|\, h(R_1)$.
- If $R = R_0 R_1$, then $h(R) = h(R_0) h(R_1)$.
- If $R = R_0^*$, then $h(R) = (h(R_0))^*$.
- If $R = (R_0)$, then $h(R) = (h(R_0))$. $\square$

$$h(\mathtt{0}) = \mathtt{ab}$$
$$h(\mathtt{1}) = \mathtt{a}$$

$$R = \mathtt{0(0|1)^*0^*}$$

$$h(R) = \mathtt{ab(ab|a)^*(ab)^*}$$

Closure under Inverse Homomorphism

Definition (Inverse Homomorphism)

Suppose Σ and Γ are two finite sets of symbols. For a given language $L \subseteq \Gamma^*$ and a homomorphism $h : \Sigma \to \Gamma^*$,

$$h^{-1}(L) = \{w \in \Sigma^* \mid h(w) \in L\} \subseteq \Sigma^*$$

Closure under Inverse Homomorphism

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Example

Let $\Sigma = \{0, 1\}$, $\Gamma = \{\mathtt{a}, \mathtt{b}\}$, and $h(0) = \mathtt{ba}$, $h(1) = \mathtt{a}$. Consider the following language $L \subseteq \Gamma^*$:

$$L = \{w\mathtt{aa} \mid w \in \{\mathtt{a}, \mathtt{b}\}^*\}$$

Then, $01 \in h^{-1}(L)$ because $h(01) = \mathtt{baa} \in L$.

However, $10 \notin h^{-1}(L)$ because $h(10) = \mathtt{aba} \notin L$.

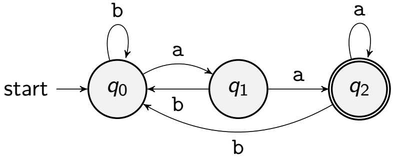
Closure under Inverse Homomorphism

$L = \{w\texttt{aa} \mid w \in \{\texttt{a}, \texttt{b}\}^*\}$ $\qquad$ $h : \Sigma \to \Gamma^*.\ h(\texttt{0}) = \texttt{ba} \wedge h(\texttt{1}) = \texttt{a}$

Is the **inverse homomorphism** $h^{-1}(L)$ of the above regular language L also regular ($\Sigma = \{\texttt{0}, \texttt{1}\}$ and $\Gamma = \{\texttt{a}, \texttt{b}\}$)?

$L = \{w\texttt{aa} \mid w \in \{\texttt{a}, \texttt{b}\}^*\}$ $\qquad$ $h : \Sigma \to \Gamma^*.\ h(0) = \texttt{ba} \wedge h(1) = \texttt{a}$

Is the **inverse homomorphism** $h^{-1}(L)$ of the above regular language L also regular ($\Sigma = \{0, 1\}$ and $\Gamma = \{\texttt{a}, \texttt{b}\}$)? **Yes!**

$D =$ 

The above DFA D accepts the language L.

Closure under Inverse Homomorphism

$$L = \{w\texttt{aa} \mid w \in \{\texttt{a}, \texttt{b}\}^*\} \qquad h : \Sigma \to \Gamma^*.\ h(0) = \texttt{ba} \wedge h(1) = \texttt{a}$$

Is the **inverse homomorphism** $h^{-1}(L)$ of the above regular language L also regular ($\Sigma = \{0, 1\}$ and $\Gamma = \{\texttt{a}, \texttt{b}\}$)? **Yes!**

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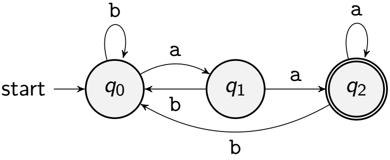
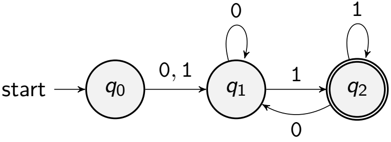


The above DFA D accepts the language L.

$h^{-1}(D) =$



The key idea is to construct a new DFA $h^{-1}(D)$ by **reconstructing** the **transitions** by following the path $h(x)$ for each symbol in $x \in \Sigma$.

Closure under Inverse Homomorphism

Theorem (Closure under Inverse Homomorphism)

If $h : \Sigma \to \Gamma^*$ is a homomorphism and $L \subseteq \Gamma^*$ is a regular language, then so is $h^{-1}(L)$.

Proof) Let $D = (Q, \Gamma, \delta, q_0, F)$ be the DFA such that $L(D) = L$.

Consider the following DFA:

$$h^{-1}(D) = (Q, \Sigma, \delta', q_0, Q).$$

where $\forall q \in Q, x \in \Sigma.\ \delta'(q, x) = \delta^*(q, h(x))$. Then, $\forall w = x_1 \cdots x_n \in \Sigma^*$.

$$\begin{array}{rcl}
w \in L(h^{-1}(D)) & \iff & (\delta')^*(q_0, w) \in F \\
& \iff & \delta'(\ldots(\delta'(\delta'(q_0, x_1), x_2), \ldots, x_n)) \in F \\
& \iff & \delta(\ldots(\delta(\delta(q_0, h(x_1)), h(x_2)), \ldots, h(x_n)) \in F \\
& \iff & \delta^*(q_0, h(x_1) \cdots h(x_n)) \in F \\
& \iff & \delta^*(q_0, h(w)) \in F \\
& \iff & h(w) \in L(D) \\
& \iff & h(w) \in L
\end{array}$$

Summary

1. Closure Properties of Regular Languages
   - Union, Concatenation, and Kleene Star
   - Complement
   - Intersection
   - Difference
   - Reversal
   - Homomorphism
   - Inverse Homomorphism

Exercise #2

- Please see this document for the exercise.

https://github.com/ku-plrg-classroom/docs/tree/main/cose215/rl-closure

- Please implement the following functions in `Implementation.scala`.
  - `complementDFA` for the **complement** of a DFA.
  - `intersectDFA` for the **intersection** of two DFAs.
  - `reverseENFA` for the **reverse** of an ϵ-NFA.
  - `reverseRE` for the **reverse** of a regular expression.
  - `homRE` for the **homomorphism** of a regular expression.
  - `ihomDFA` for the **inverse homomorphism** of a DFA.
- It is just an exercise, and you **don't need to submit** anything.

Next Lecture

- The Pumping Lemma for Regular Languages

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