

# Lecture 4 – Nondeterministic Finite Automata (NFA)

## COSE215: Theory of Computation

Jihyeok Park



2023 Spring

## ① Deterministic Finite Automata (DFA)

- Definition
- Transition Diagram and Transition Table
- Extended Transition Function
- Acceptance of a Word
- Language of DFA (Regular Language)
- Examples

## 1. Nondeterministic Finite Automata (NFA)

- Definition

- Transition Diagram and Transition Table

- Extended Transition Function

- Language of NFA

- Equivalence of DFA and NFA

  - $\text{DFA} \rightarrow \text{NFA}$

  - $\text{DFA} \leftarrow \text{NFA}$  (Subset Construction)

## Definition (Nondeterministic Finite Automaton (NFA))

A **nondeterministic finite automaton** is a 5-tuple:

$$N = (Q, \Sigma, \delta, q_0, F)$$

- $Q$  is a finite set of **states**
- $\Sigma$  is a finite set of **symbols**
- $\delta : Q \times \Sigma \rightarrow \mathcal{P}(Q)$  is the **transition function**
- $q_0 \in Q$  is the **initial state**
- $F \subseteq Q$  is the set of **final states**

$$N = (\{q_0, q_1, q_2\}, \{0, 1\}, \delta, q_0, \{q_2\})$$

$$\delta(q_0, 0) = \{q_0, q_1\}$$

$$\delta(q_1, 0) = \{q_2\}$$

$$\delta(q_2, 0) = \emptyset$$

$$\delta(q_0, 1) = \{q_0\}$$

$$\delta(q_1, 1) = \emptyset$$

$$\delta(q_2, 1) = \emptyset$$

```
// The type definitions of states and symbols
type State = Int
type Symbol = Char
// The definition of NFA
case class NFA(
  states: Set[State],
  symbols: Set[Symbol],
  trans: Map[(State, Symbol), Set[State]],
  initState: State,
  finalStates: Set[State],
)
// An example of NFA
val nfa: NFA = NFA(
  states = Set(0, 1, 2),
  symbols = Set('0', '1'),
  trans = Map(
    (0, '0') -> Set(0, 1), (1, '0') -> Set(2), (2, '0') -> Set(),
    (0, '1') -> Set(0), (1, '1') -> Set(), (2, '1') -> Set(),
  ),
  initState = 0,
  finalStates = Set(2),
)
```

$$N = (\{q_0, q_1, q_2\}, \{0, 1\}, \delta, q_0, \{q_2\})$$

$$\delta(q_0, 0) = \{q_0, q_1\}$$

$$\delta(q_1, 0) = \{q_2\}$$

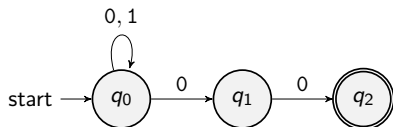
$$\delta(q_2, 0) = \emptyset$$

$$\delta(q_0, 1) = \{q_0\}$$

$$\delta(q_1, 1) = \emptyset$$

$$\delta(q_2, 1) = \emptyset$$

**Transition Diagram**



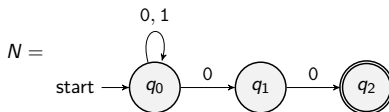
**Transition Table**

q	0	1
$\rightarrow q_0$	$\{q_0, q_1\}$	$\{q_0\}$
$q_1$	$\{q_2\}$	$\emptyset$
$*q_2$	$\emptyset$	$\emptyset$

## Definition (Extended Transition Function)

For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ , the **extended transition function**  $\delta^* : Q \times \Sigma^* \rightarrow \mathcal{P}(Q)$  is defined as follows:

- **(Basis Case)**  $\delta^*(q, \epsilon) = \{q\}$
- **(Induction Case)**  $\delta^*(q, aw) = \bigcup_{q' \in \delta(q, a)} \delta^*(q', w)$

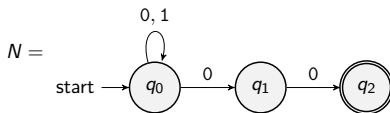


$$\delta^*(q_0, 100)$$

## Definition (Extended Transition Function)

For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ , the **extended transition function**  $\delta^* : Q \times \Sigma^* \rightarrow \mathcal{P}(Q)$  is defined as follows:

- **(Basis Case)**  $\delta^*(q, \epsilon) = \{q\}$
- **(Induction Case)**  $\delta^*(q, aw) = \bigcup_{q' \in \delta(q, a)} \delta^*(q', w)$



$$\begin{aligned}
 \delta^*(q_0, 100) &= \bigcup_{q' \in \delta(q_0, 1)} \delta^*(q', 00) &&= \delta^*(q_0, 00) \\
 &= \bigcup_{q' \in \delta(q_0, 0)} \delta^*(q', 0) &&= \delta^*(q_0, 0) \cup \delta^*(q_1, 0) \\
 &= \bigcup_{q' \in \delta(q_0, 0)} \delta^*(q', \epsilon) \cup \bigcup_{q' \in \delta(q_1, 0)} \delta^*(q', \epsilon) &&= \delta^*(q_0, \epsilon) \cup \delta^*(q_1, \epsilon) \cup \delta^*(q_2, \epsilon) \\
 &= \{q_0, q_1, q_2\}
 \end{aligned}$$

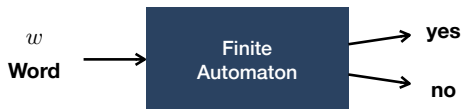


```
// The type definition of words
type Word = String

// A helper function to extract first symbol and rest of word
object `<|` { def unapply(w: Word) = w.headOption.map((_, w.drop(1))) }

// The extended transition function of NFA
def extTrans(nfa: NFA)(q: State, w: Word): Set[State] = w match
  case "" => Set(q)
  case a <| x => for {
    p <- nfa.trans(q, a)
    r <- extTrans(nfa)(p, x)
  } yield r

// An example transition for a word "100"
extTrans(nfa)(0, "100") // Set(0, 1, 2)
```



## Definition (Acceptance of a Word)

For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ , we say that  $N$  **accepts** a word  $w \in \Sigma^*$  if and only if  $\delta^*(q_0, w) \cap F \neq \emptyset$

```
// The acceptance of a word by NFA
def accept(nfa: NFA)(w: Word): Boolean =
  val curStates: Set[State] = extTrans(nfa)(nfa.initState, w)
  curStates.intersect(nfa.finalStates).nonEmpty

// An example acceptance of a word "100"
accept(nfa)("100") // true
```

## Definition (Language of NFA)

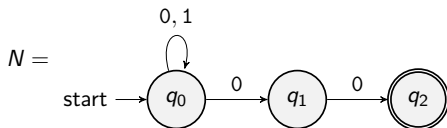
For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ , the **language** of  $N$  is defined as follows:

$$L(N) = \{w \in \Sigma^* \mid N \text{ accepts } w\}$$

## Definition (Language of NFA)

For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ , the **language** of  $N$  is defined as follows:

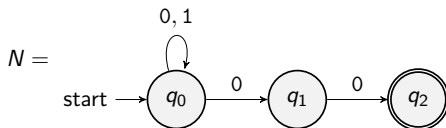
$$L(N) = \{w \in \Sigma^* \mid N \text{ accepts } w\}$$



## Definition (Language of NFA)

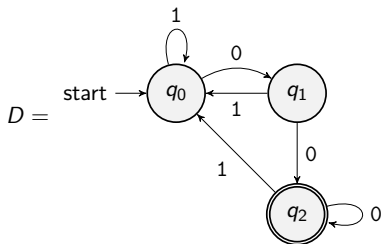
For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ , the **language** of  $N$  is defined as follows:

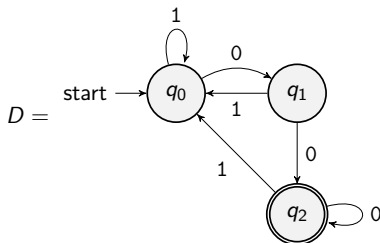
$$L(N) = \{w \in \Sigma^* \mid N \text{ accepts } w\}$$



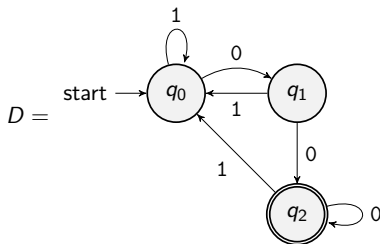
$$L(N) = \{w00 \mid w \in \Sigma^*\}$$

# Equivalence of DFA and NFA

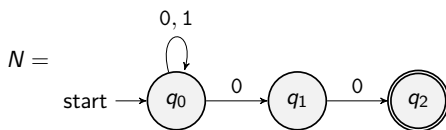




$$L(D) = \{w00 \mid w \in \Sigma^*\}$$



$$L(D) = \{w00 \mid w \in \Sigma^*\}$$





## Theorem (Equivalence of DFA and NFA)

*A language  $L$  is the language  $L(D)$  of a DFA  $D$  if and only if  $L$  is the language  $L(N)$  of an NFA  $N$ .*

**Proof)** By the following two theorems.

## Theorem (DFA to NFA)

*For a given DFA  $D = (Q, \Sigma, \delta, q, F)$ ,  $\exists$  NFA  $N$ .  $L(D) = L(N)$ .*

## Theorem (NFA to DFA – Subset Construction)

*For a given NFA  $N = (Q, \Sigma, \delta, q_0, F)$ ,  $\exists$  DFA  $D$ .  $L(D) = L(N)$ .*

## Theorem (DFA to NFA)

*For a given DFA  $D = (Q, \Sigma, \delta_D, q_0, F)$ ,  $\exists$  NFA  $N$ .  $L(D) = L(N)$ .*

**Proof)** Define an NFA

$$N = (Q, \Sigma, \delta_N, q_0, F)$$

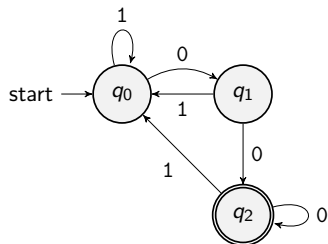
where

- $\forall q \in Q. \forall a \in \Sigma.$

$$\delta_N(q, a) = \{\delta_D(q, a)\}$$

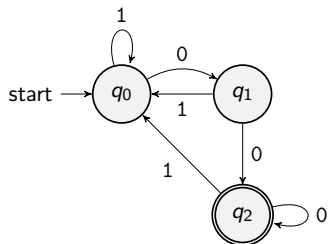
# DFA $\rightarrow$ NFA – Example

DFA  $D$



q	0	1
$\rightarrow q_0$	$q_1$	$q_0$
$q_1$	$q_2$	$q_0$
$*q_2$	$q_2$	$q_0$

NFA  $N$



q	0	1
$\rightarrow q_0$	$\{q_1\}$	$\{q_0\}$
$q_1$	$\{q_2\}$	$\{q_0\}$
$*q_2$	$\{q_2\}$	$\{q_0\}$



### Lemma

$\forall q \in Q. \forall w \in \Sigma^*. \delta_N^*(q, w) = \{\delta_D^*(q, w)\}.$

**Proof)** By induction on the **length of word**.

- **(Base Case)**  $\delta_N^*(q, \epsilon) = \{q\} = \{\delta_D^*(q, \epsilon)\}.$
- **(Inductive Case)** Assume it holds for  $w$  (I.H.).

$$\begin{aligned}
 \delta_N^*(q, aw) &= \bigcup_{q' \in \delta_N(q, a)} \delta_N^*(q', w) && (\because \text{definition of } \delta_N^*) \\
 &= \bigcup_{q' \in \{\delta_D(q, a)\}} \delta_N^*(q', w) && (\because \text{definition of } \delta_N) \\
 &= \delta_N^*(\delta_D(q, a), w) \\
 &= \{\delta_D^*(\delta_D(q, a), w)\} && (\because \text{I.H.}) \\
 &= \{\delta_D^*(q, aw)\} && (\because \text{definition of } \delta^*) \quad \square
 \end{aligned}$$

$$\begin{aligned}
 \text{Then, } w \in L(D) &\iff \delta_D^*(q_0, w) \in F && (\because \text{definition of } L(D)) \\
 &\iff \{\delta_D^*(q_0, w)\} \cap F \neq \emptyset && (\because \text{set theory}) \\
 &\iff \delta_N^*(q_0, w) \cap F \neq \emptyset && (\because \text{above lemma}) \\
 &\iff w \in L(N) && (\because \text{definition of } L(N)) \quad \square
 \end{aligned}$$

## Theorem (NFA to DFA – Subset Construction)

*For a given NFA  $N = (Q, \Sigma, \delta_N, q_0, F)$ ,  $\exists$  DFA  $D$ .  $L(D) = L(N)$ .*

**Proof)** Define a DFA

$$D = (Q_D, \Sigma, \delta_D, \{q_0\}, F_D)$$

where

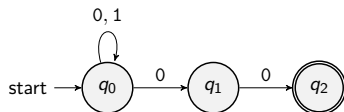
- $Q_D = \mathcal{P}(Q)$
- $\forall S \in Q_D. \forall a \in \Sigma.$

$$\delta_D(S, a) = \bigcup_{q \in S} \delta_N(q, a)$$

- $F_D = \{S \in Q_D \mid S \cap F \neq \emptyset\}$

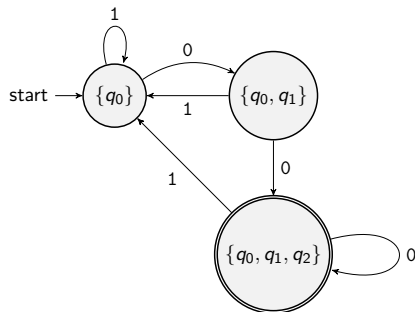
DFA  $D$ 

q	0	1
$\emptyset$	$\emptyset$	$\emptyset$
$\rightarrow \{q_0\}$	$\{q_0, q_1\}$	$\{q_0\}$
$\{q_1\}$	$\{q_2\}$	$\emptyset$
$*\{q_2\}$	$\emptyset$	$\emptyset$
$\{q_0, q_1\}$	$\{q_0, q_1, q_2\}$	$\{q_0\}$
$*\{q_0, q_2\}$	$\{q_0, q_1\}$	$\{q_0\}$
$*\{q_1, q_2\}$	$\{q_2\}$	$\emptyset$
$*\{q_0, q_1, q_2\}$	$\{q_0, q_1, q_2\}$	$\{q_0\}$

NFA  $N$ 

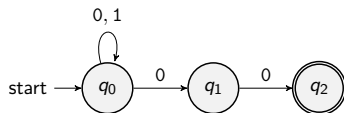
q	0	1
$\rightarrow q_0$	$\{q_0, q_1\}$	$\{q_0\}$
$q_1$	$\{q_2\}$	$\emptyset$
$*q_2$	$\emptyset$	$\emptyset$

DFA  $D$



q	0	1
$\rightarrow \{q_0\}$	$\{q_0, q_1\}$	$\{q_0\}$
$\{q_0, q_1\}$	$\{q_0, q_1, q_2\}$	$\{q_0\}$
$*\{q_0, q_1, q_2\}$	$\{q_0, q_1, q_2\}$	$\{q_0\}$

NFA  $N$



q	0	1
$\rightarrow q_0$	$\{q_0, q_1\}$	$\{q_0\}$
$q_1$	$\{q_2\}$	$\emptyset$
$*q_2$	$\emptyset$	$\emptyset$

### Lemma

$$\forall S \in Q_D. \forall w \in \Sigma^*. \delta_D^*(S, w) = \bigcup_{q \in S} \delta_N^*(q, w)$$

**Proof)** By induction on the **length of word**.

- **(Base Case)**  $\delta_N^*(S, \epsilon) = S = \bigcup_{q \in S} \delta_N^*(q, \epsilon)$ .
- **(Inductive Case)** Assume it holds for  $w$  (I.H.).

$$\begin{aligned}
 \delta_D^*(S, aw) &= \delta_D^*(\delta_D(S, a), w) && (\because \text{definition of } \delta_D^*) \\
 &= \delta_D^*(\bigcup_{q \in S} \delta_N(q, a), w) && (\because \text{definition of } \delta_D) \\
 &= \bigcup_{q \in S} \bigcup_{q' \in \delta_N(q, a)} \delta_N^*(q', w) && (\because \text{I.H.}) \\
 &= \bigcup_{q \in S} \delta_N^*(q, aw) && (\because \text{definition of } \delta_N^*)
 \end{aligned}$$

$$\begin{aligned}
 \text{Then, } w \in L(D) &\iff \delta_D^*({q_0}, w) \in F_D && (\because \text{definition of } L(D)) \\
 &\iff \delta_D^*({q_0}, w) \cap F_N \neq \emptyset && (\because \text{definition of } F_D) \\
 &\iff \delta_N^*({q_0}, w) \cap F \neq \emptyset && (\because \text{above lemma}) \\
 &\iff w \in L(N) && (\because \text{definition of } L(N)) \quad \square
 \end{aligned}$$



## 1. Nondeterministic Finite Automata (NFA)

- Definition

- Transition Diagram and Transition Table

- Extended Transition Function

- Language of NFA

- Equivalence of DFA and NFA

  - $\text{DFA} \rightarrow \text{NFA}$

  - $\text{DFA} \leftarrow \text{NFA}$  (Subset Construction)

- $\epsilon$ -Nondeterministic Finite Automata ( $\epsilon$ -NFA)

Jihyeok Park

[jihyeok\\_park@korea.ac.kr](mailto:jihyeok_park@korea.ac.kr)

<https://plrg.korea.ac.kr>