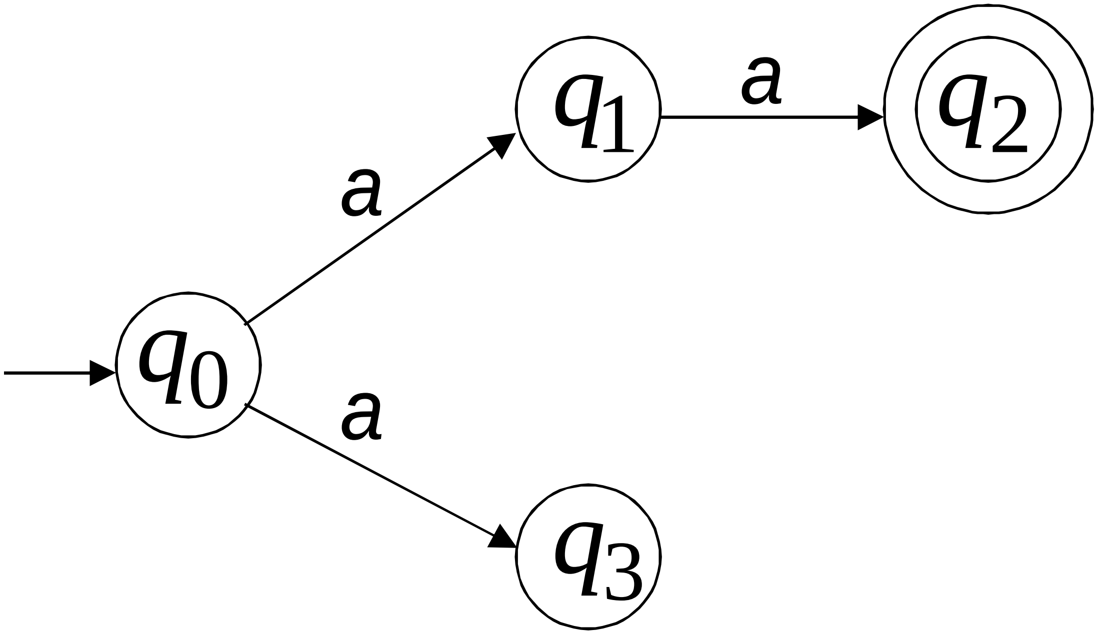
Non Deterministic Automata

Nondeterministic Finite Accepter (NFA)

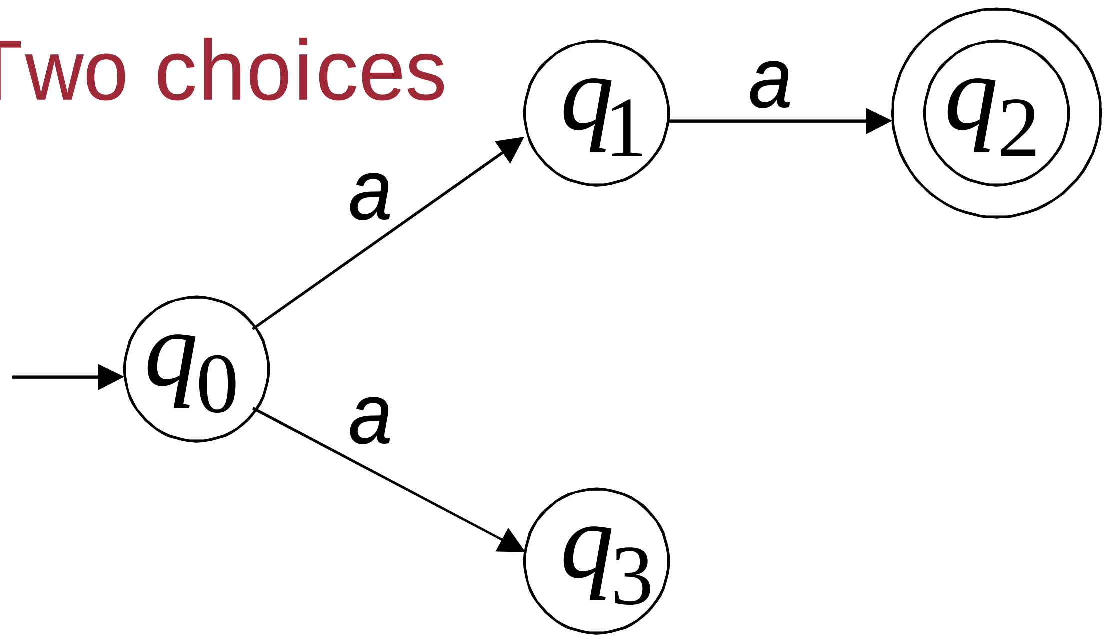
Alphabet = $\{a\}$



Nondeterministic Finite Accepter (NFA)

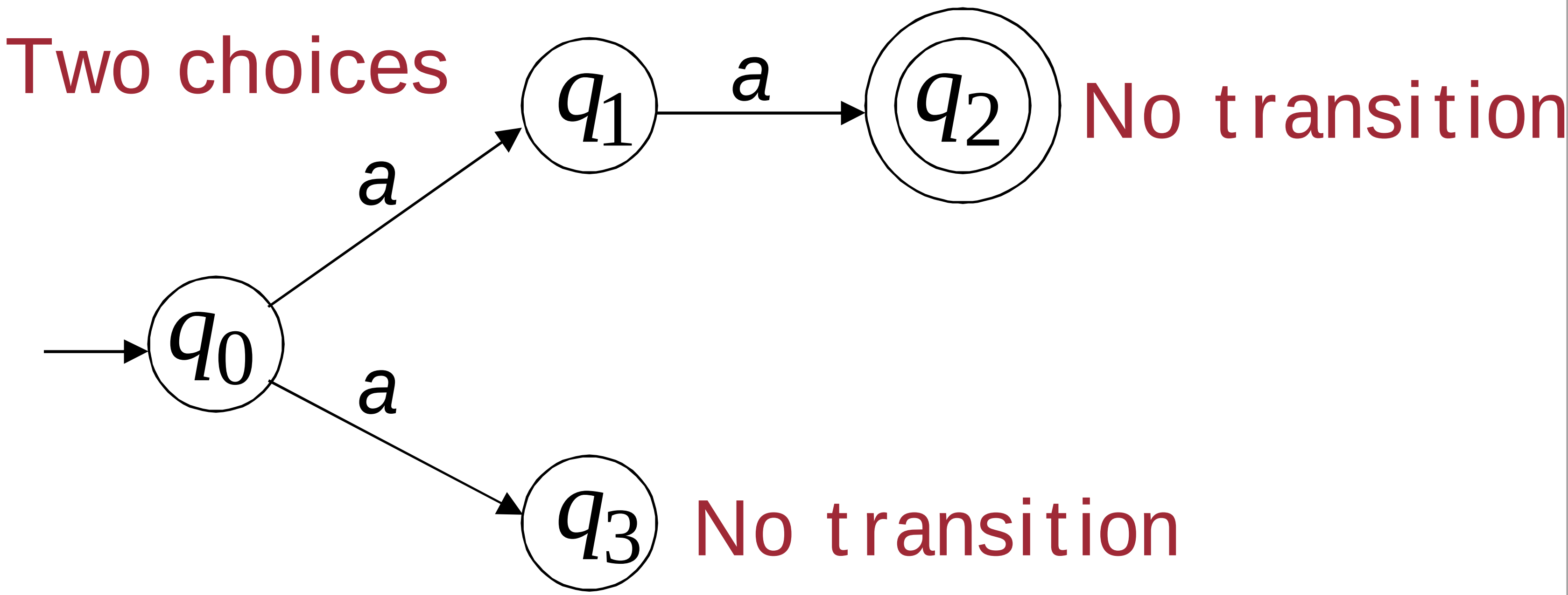
Alphabet = $\{a\}$

Two choices

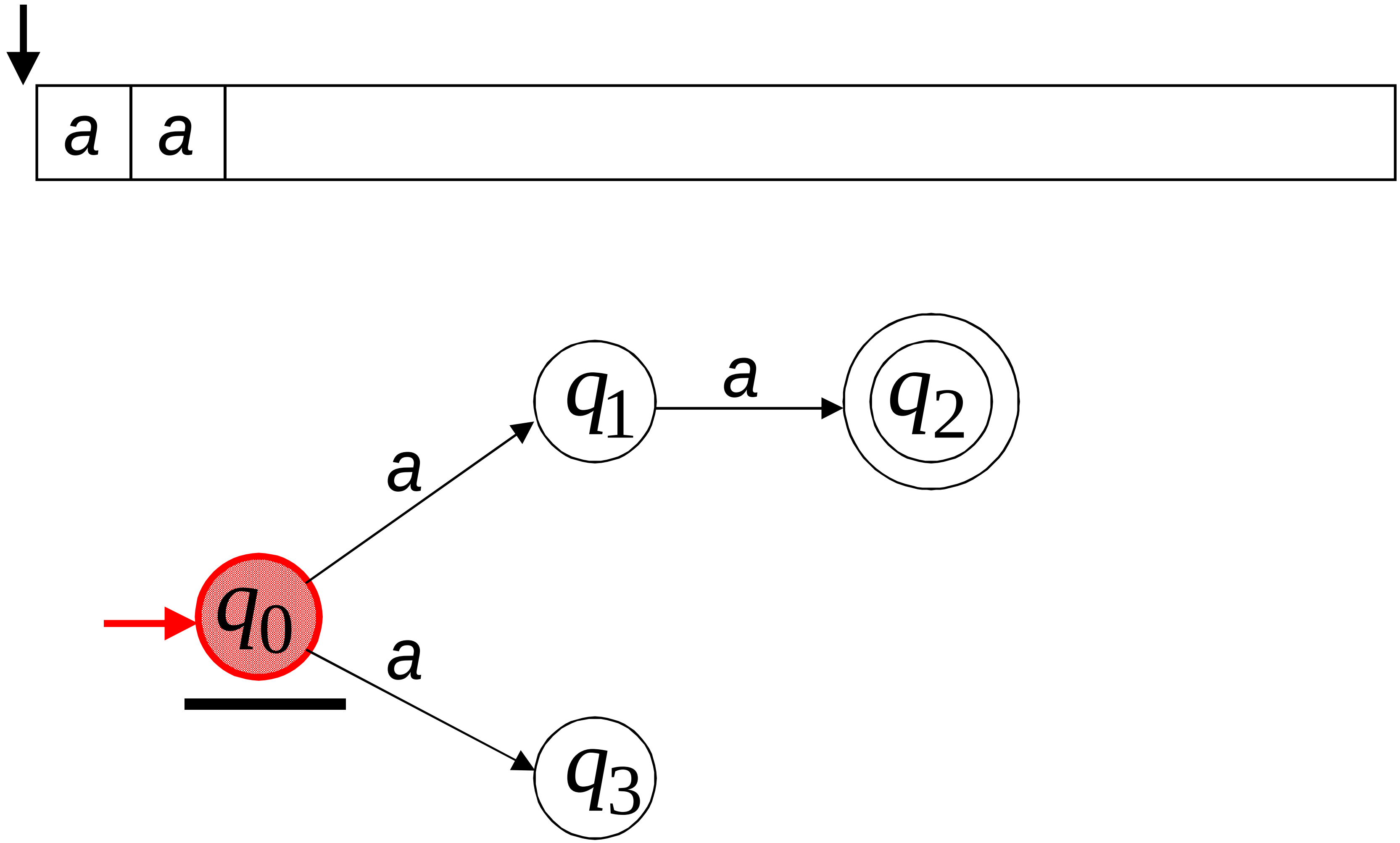


Nondeterministic Finite Accepter (NFA)

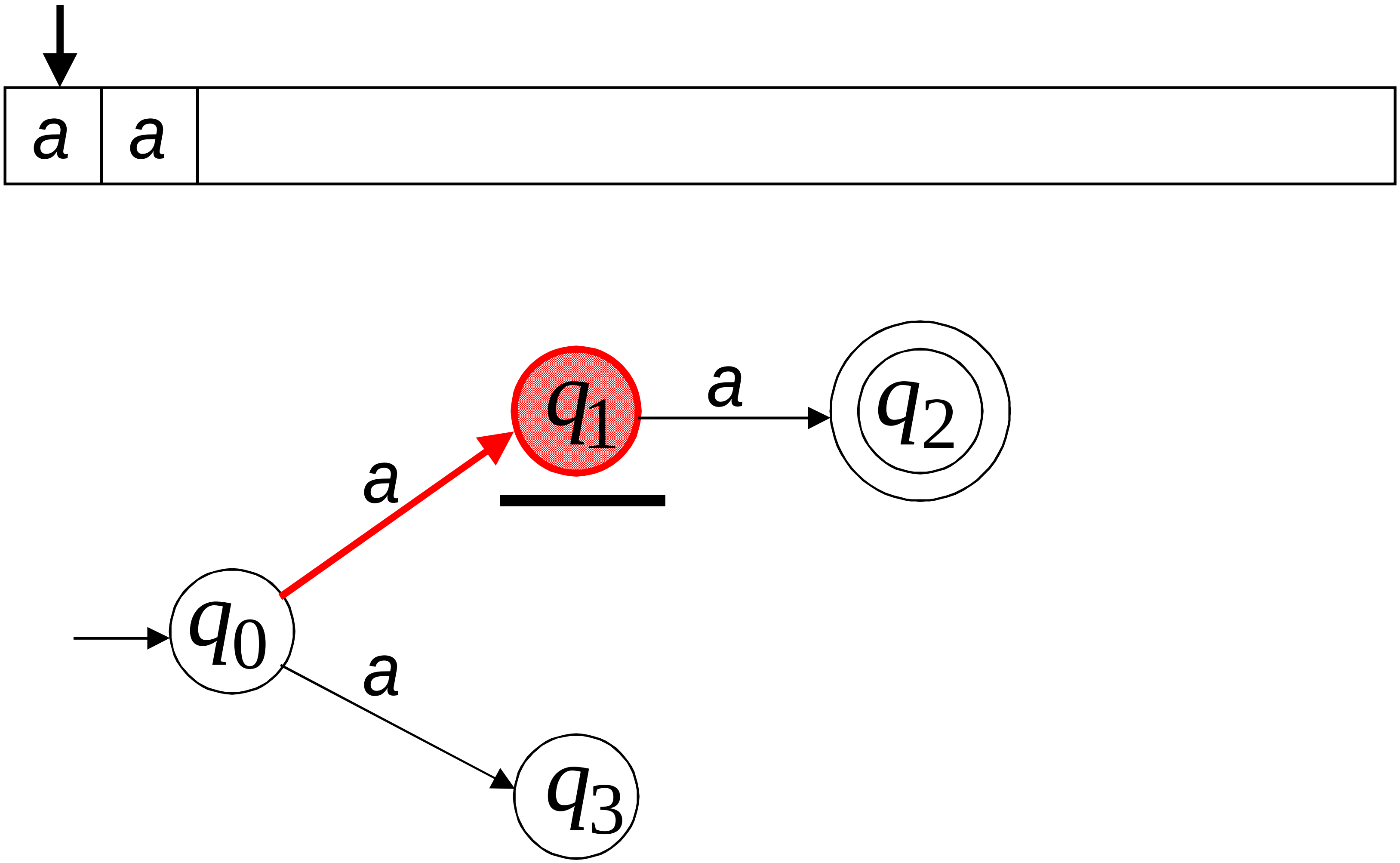
Alphabet = $\{a\}$



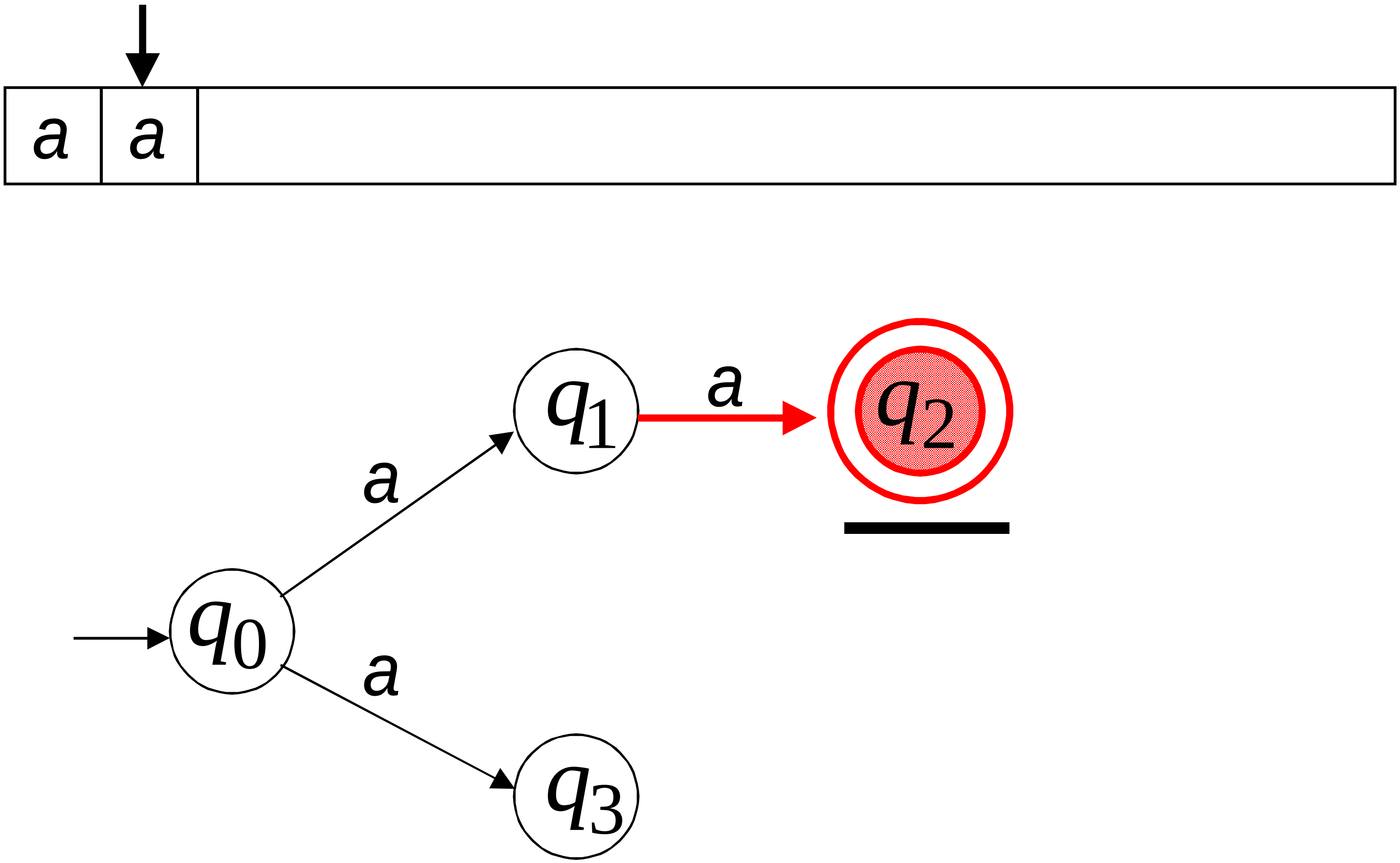
First Choice



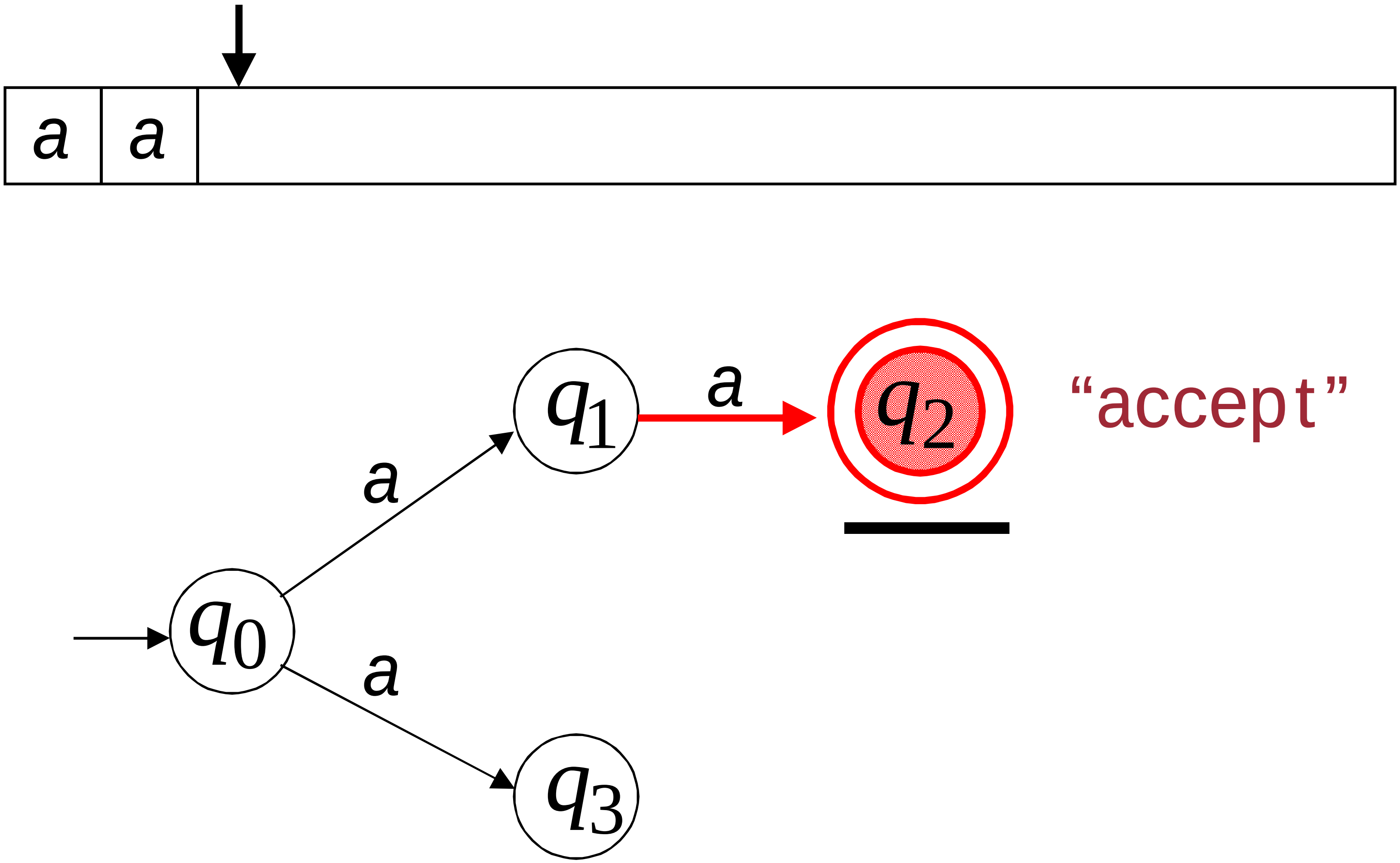
First Choice



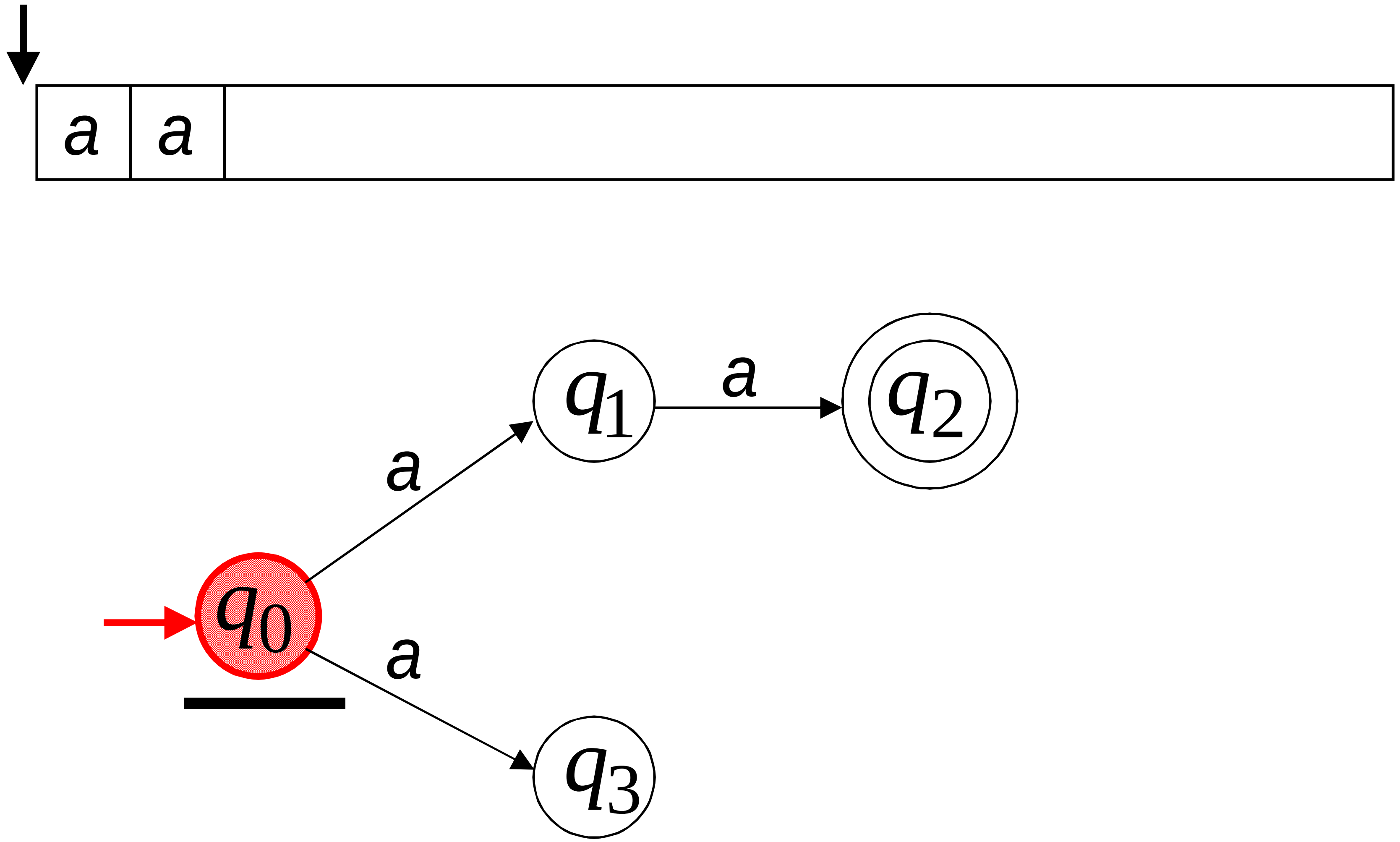
First Choice



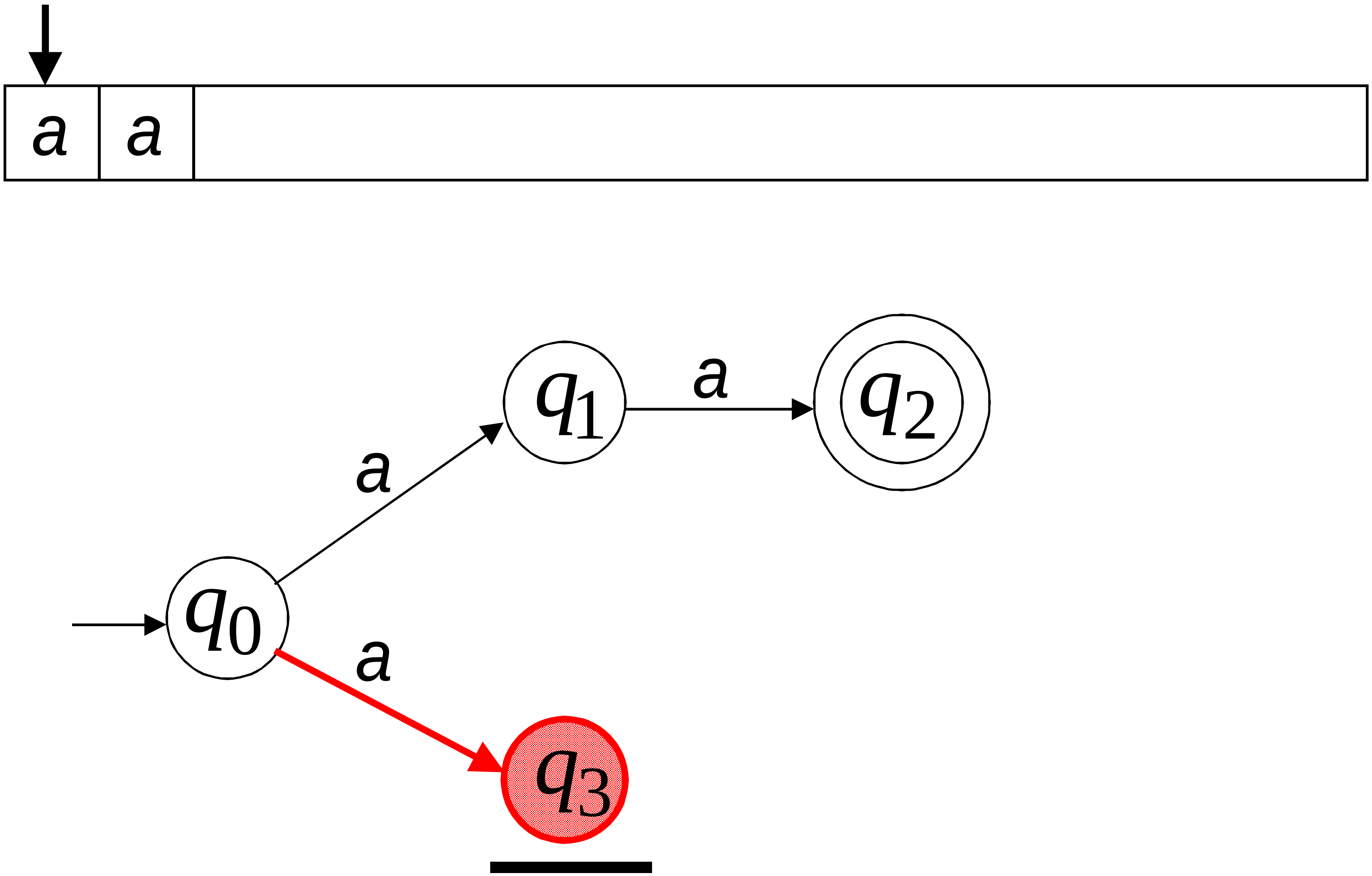
First Choice



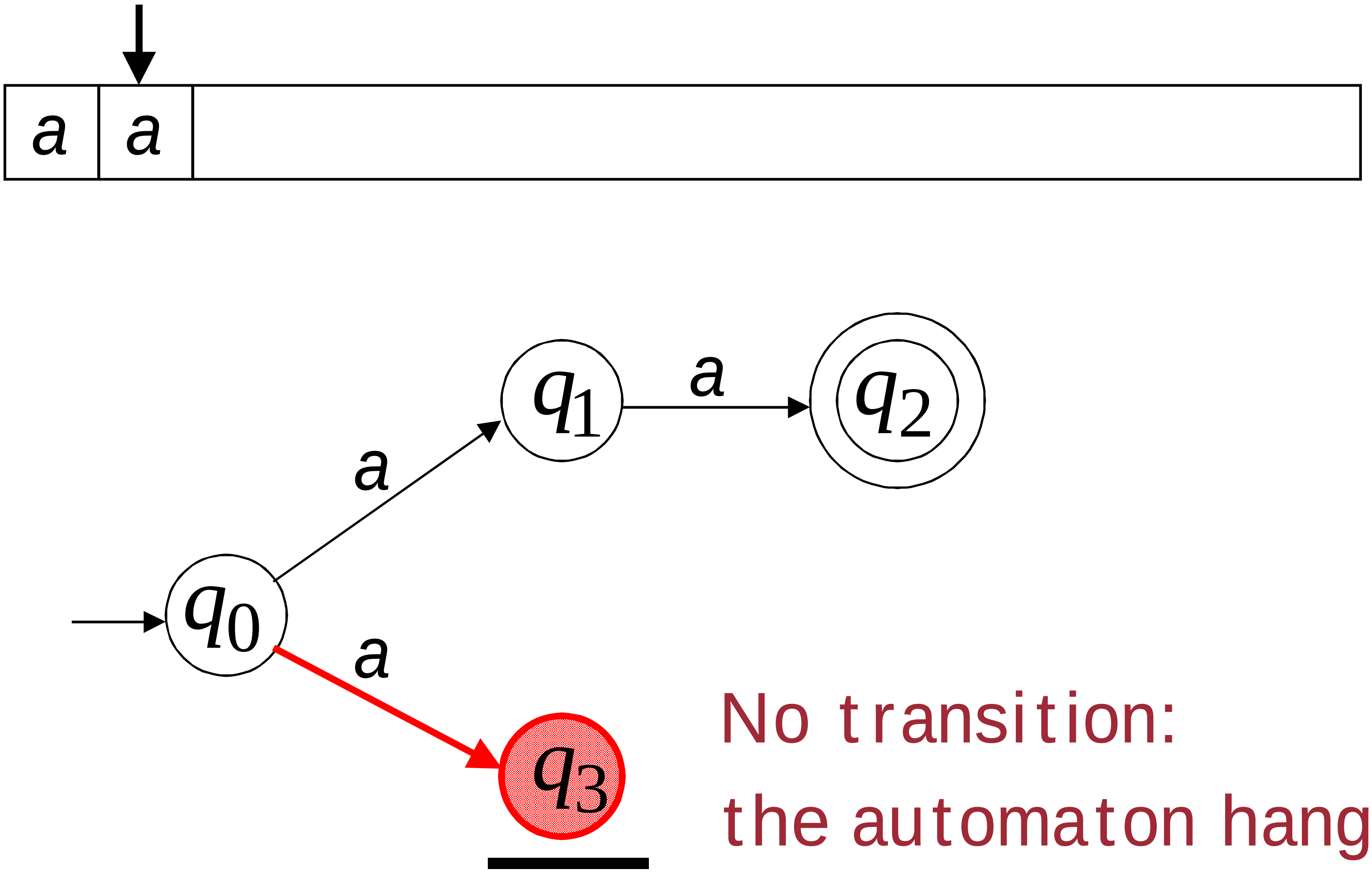
Second Choice



Second Choice

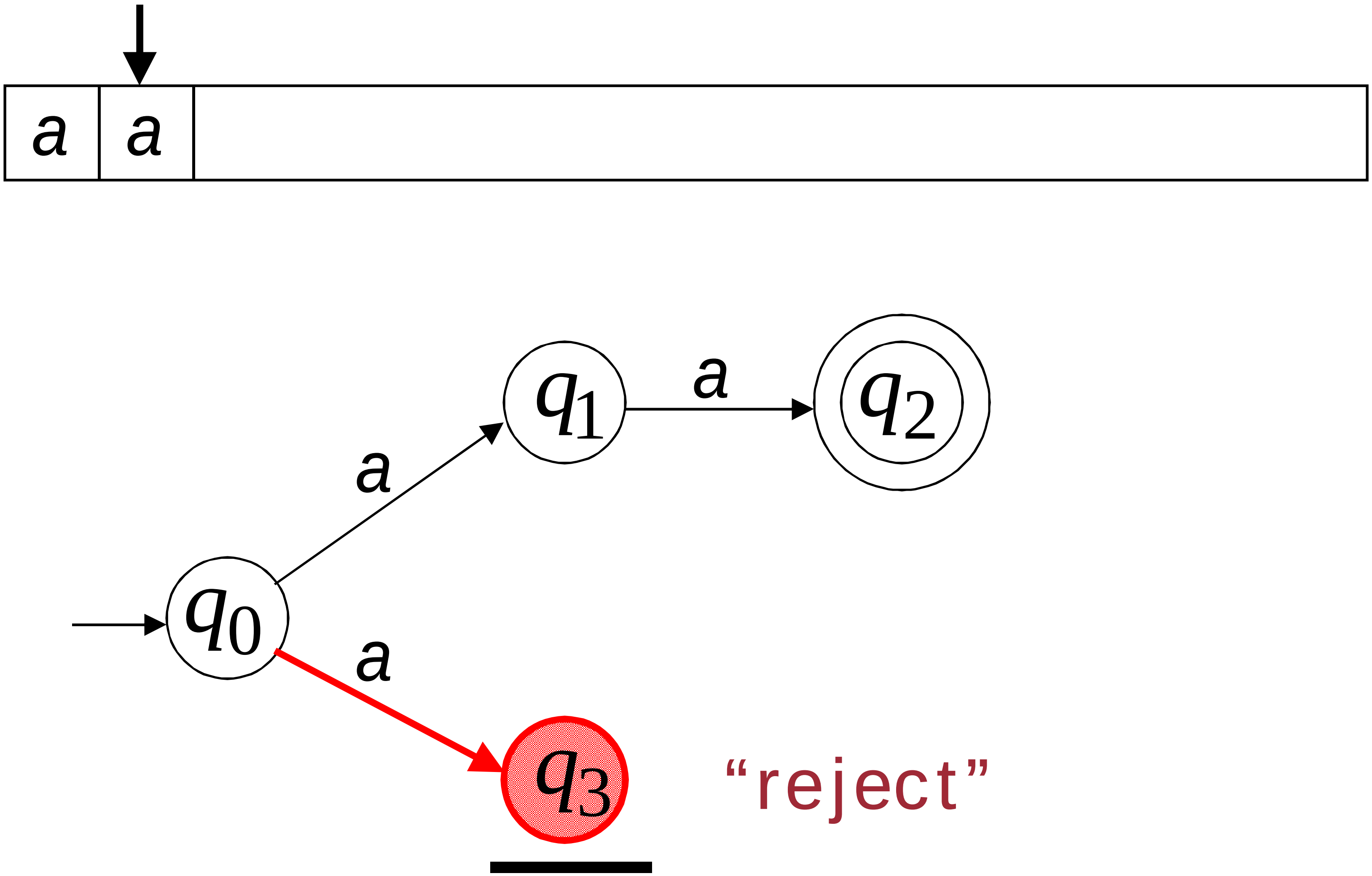


Second Choice



No transition:
the automaton hangs

Second Choice



"reject"

Observation

An NFA accepts a string

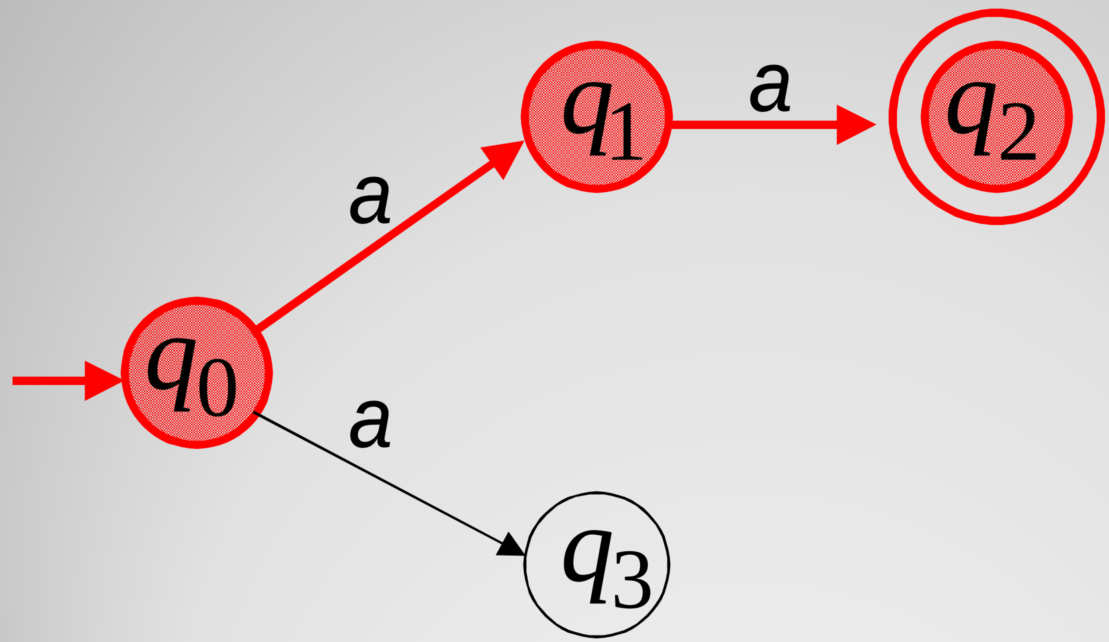
if

there is a computation of the NFA

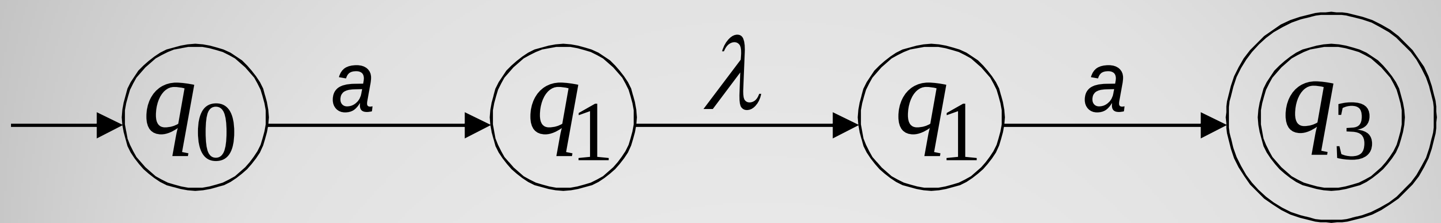
that accepts the string

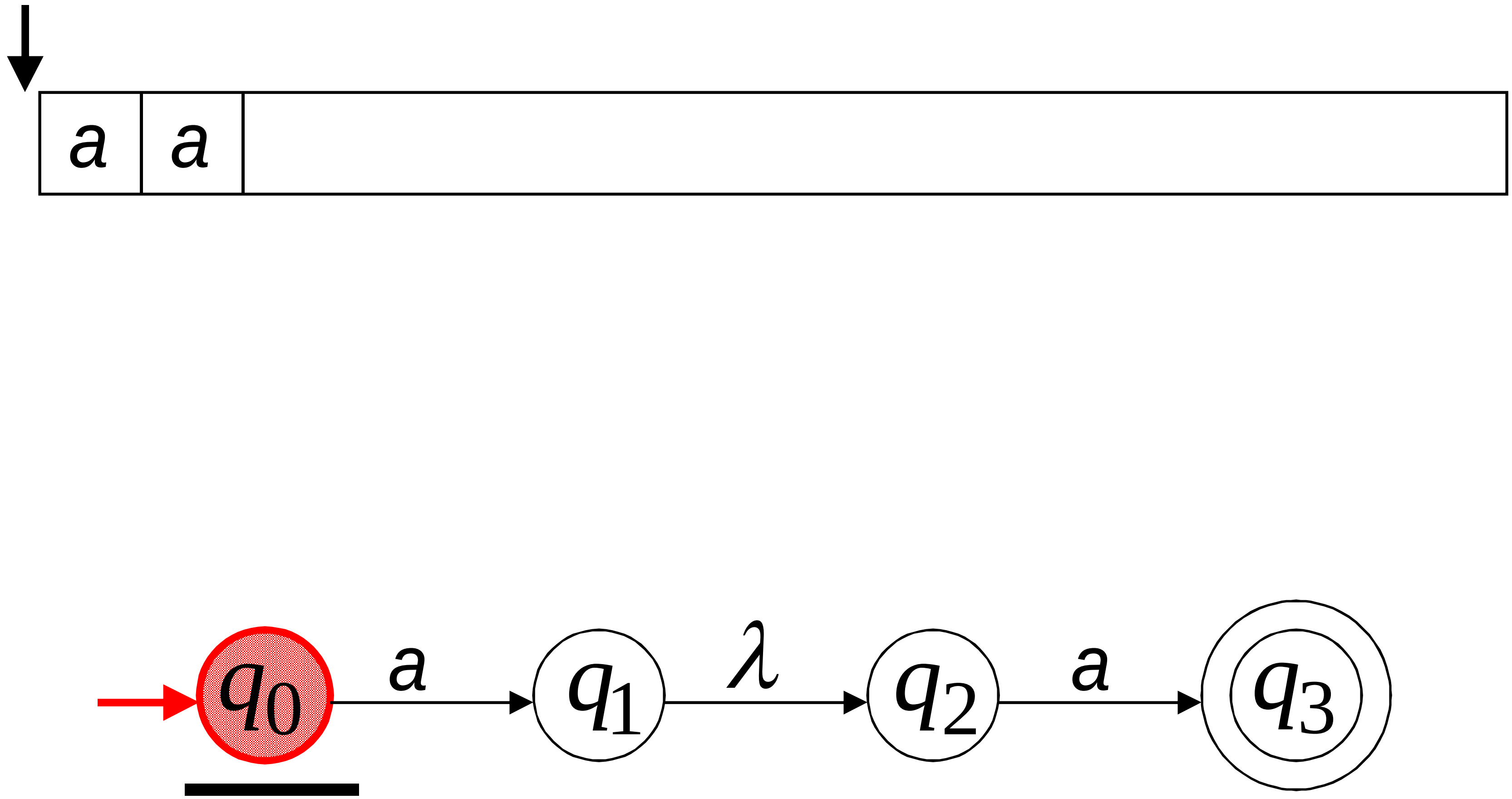
Example

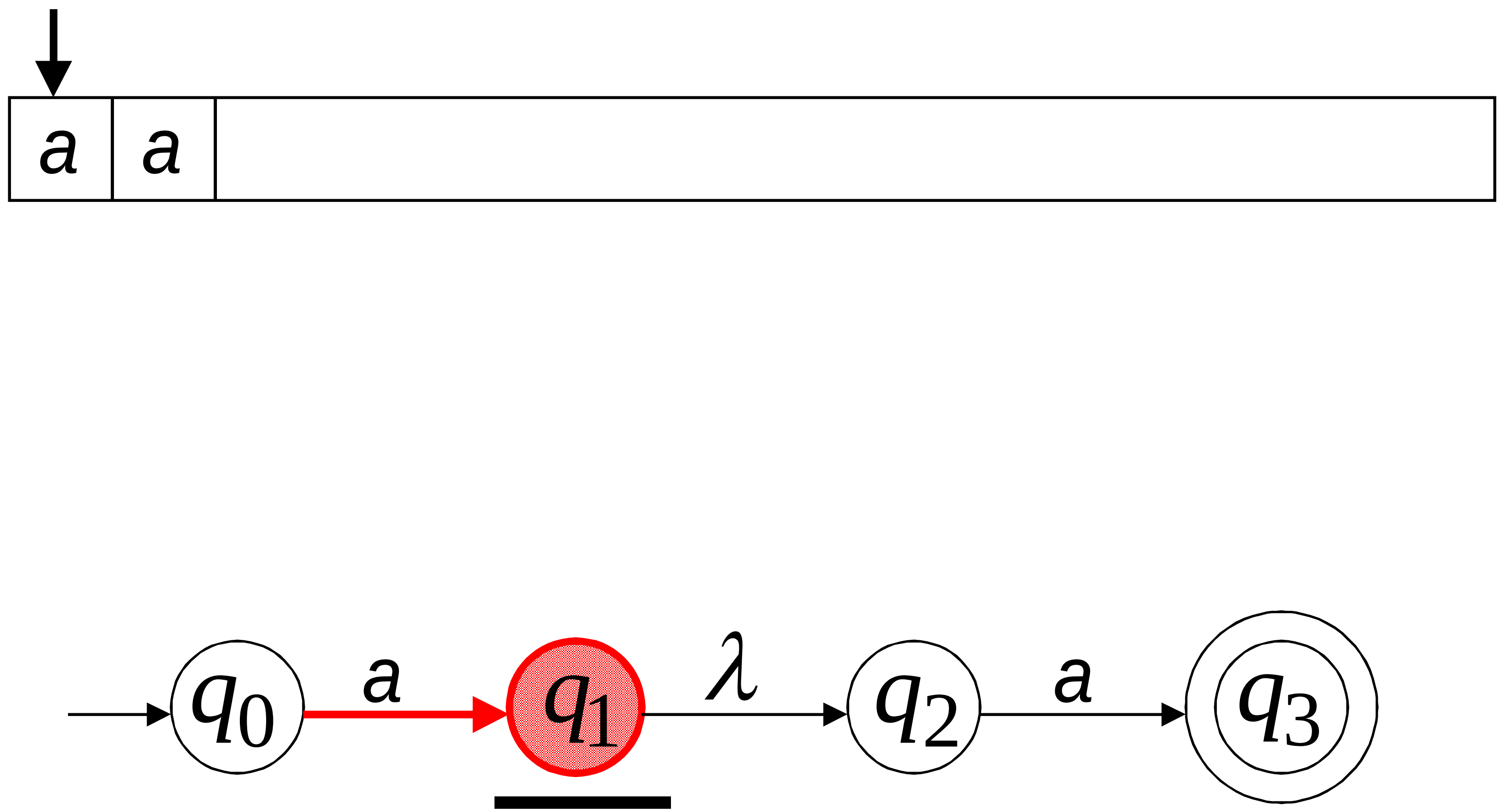
aa is accepted by the NFA:



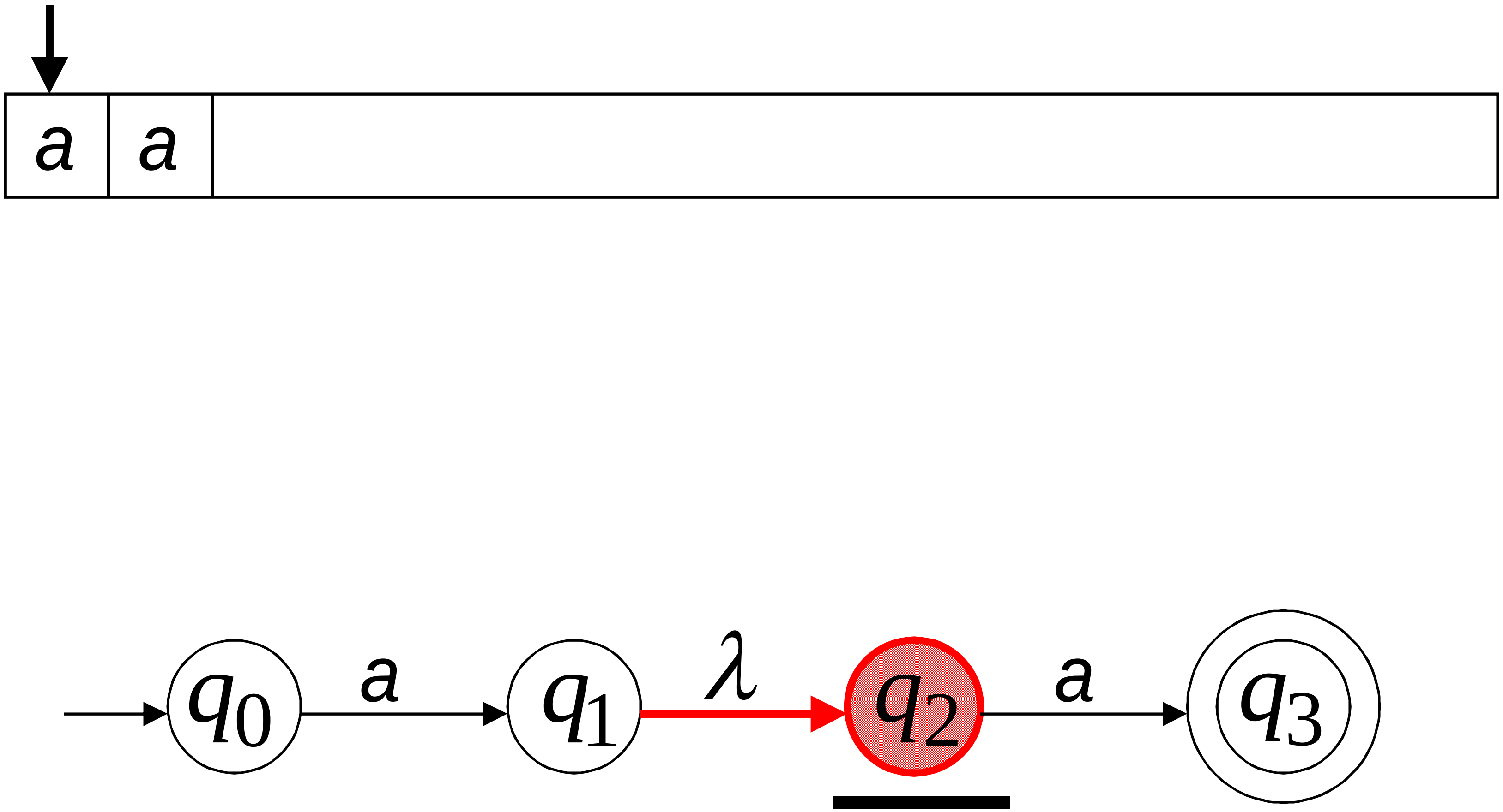
Lambda Transitions

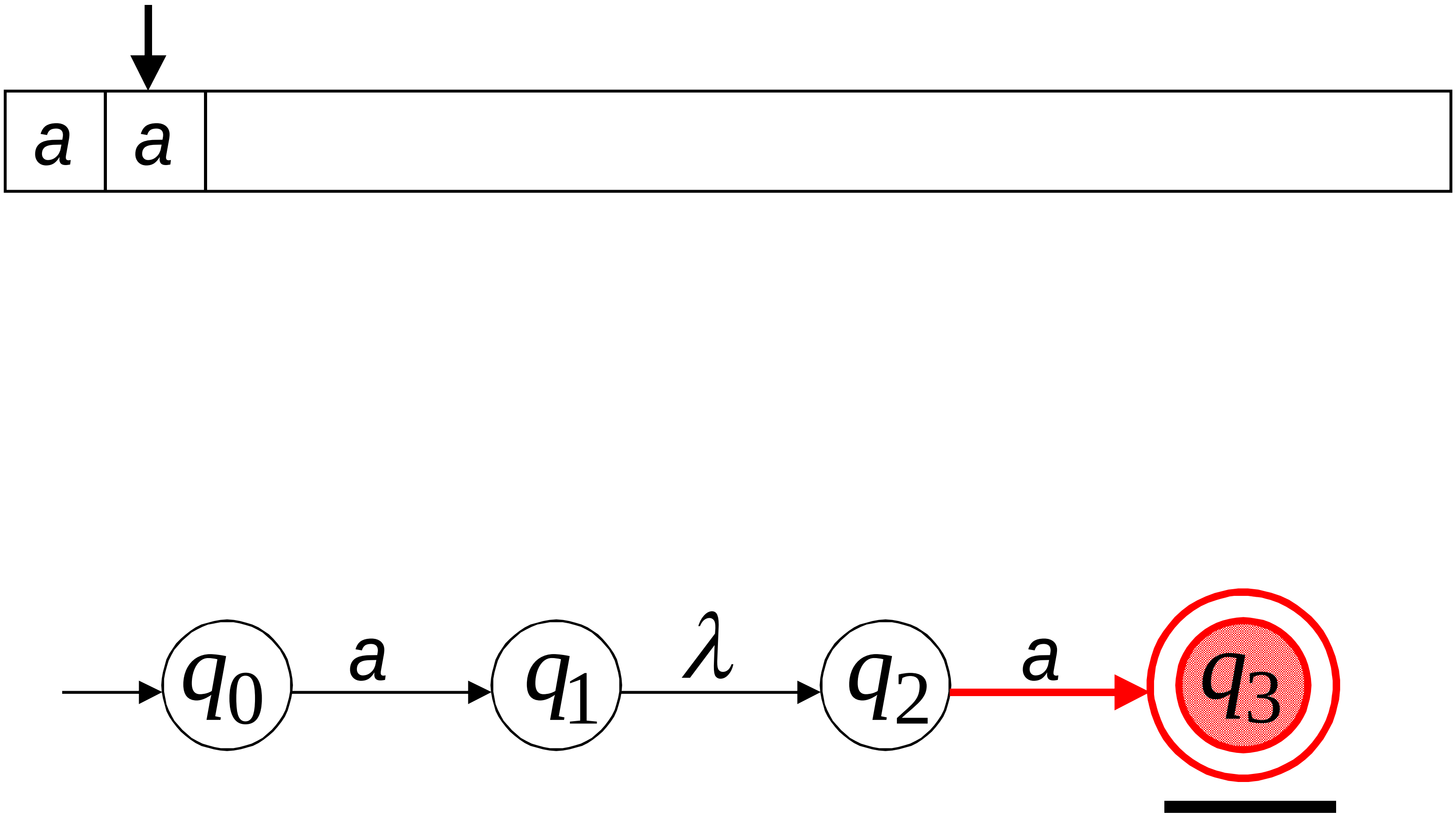



a
a
q0
a
q1
λ
q2
a
q3

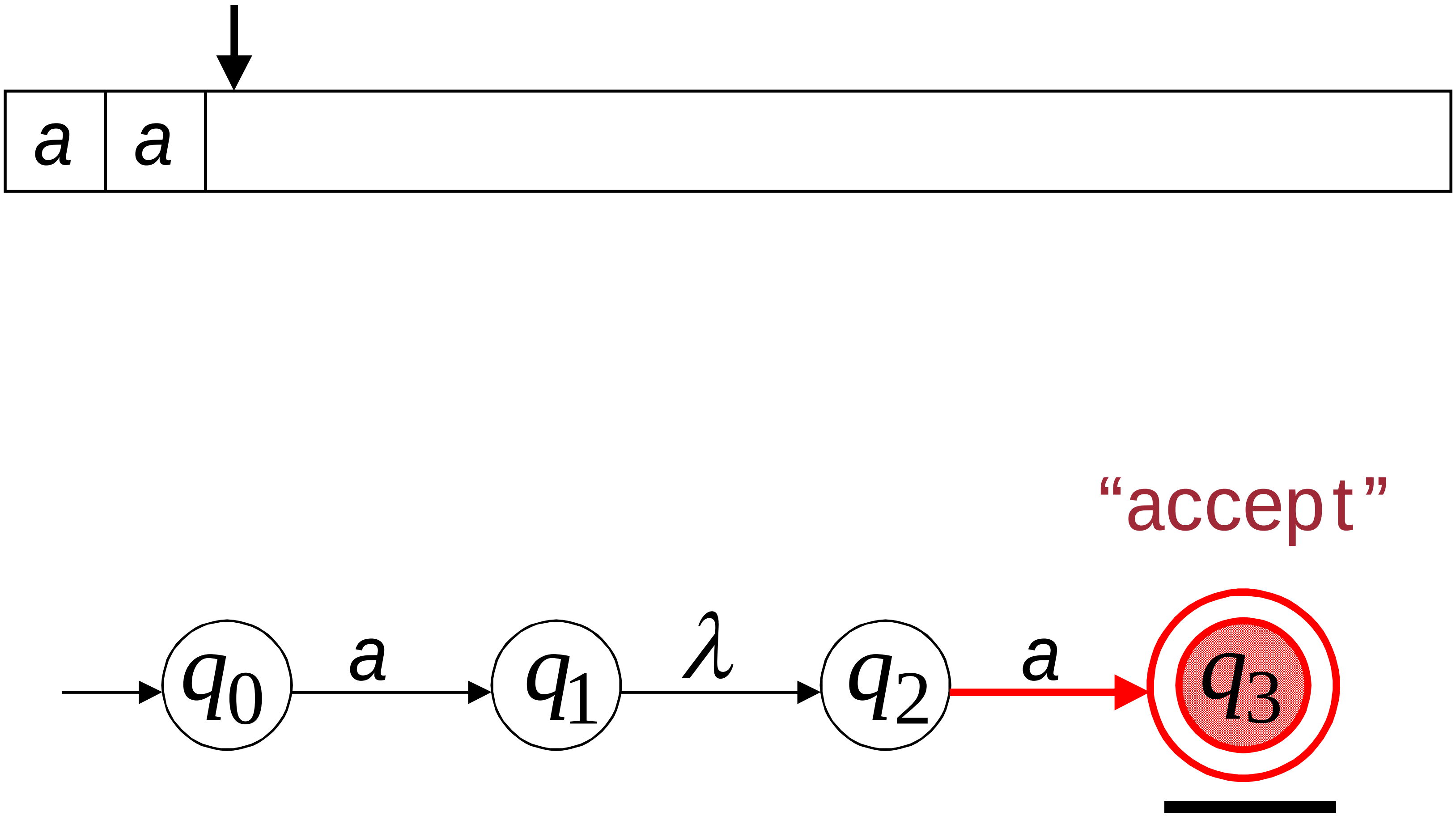

a
a
q_0
a
q_1
λ
q_2
a
q_3

(read head doesn't move)



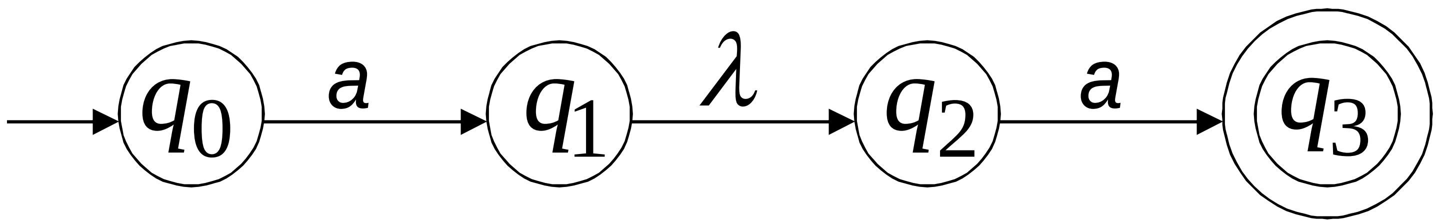


a
a
q_0
a
q_1
λ
q_2
a
q_3

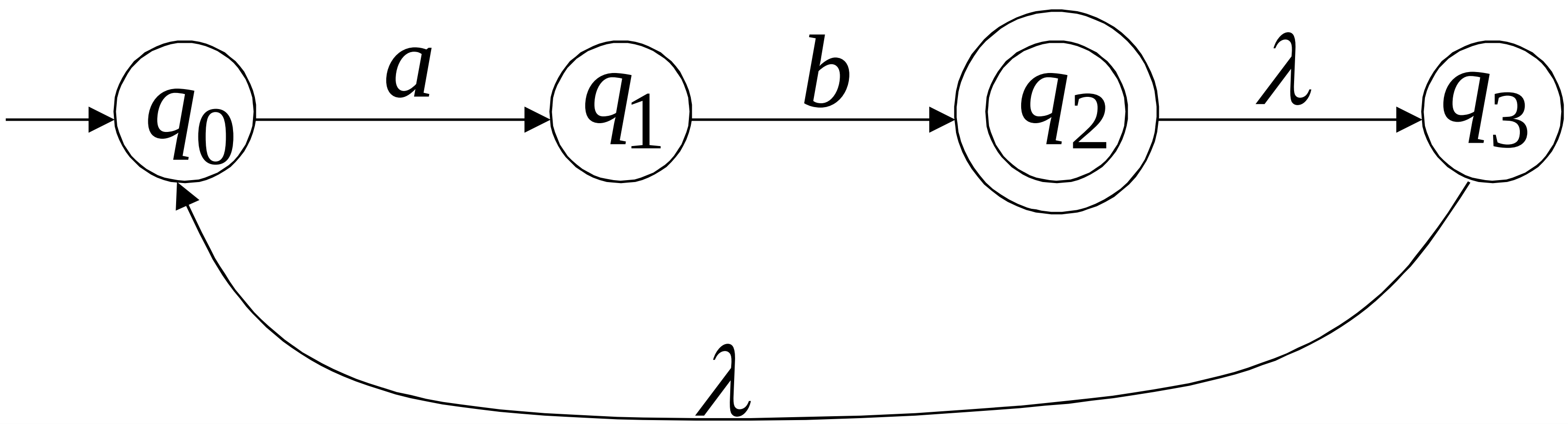


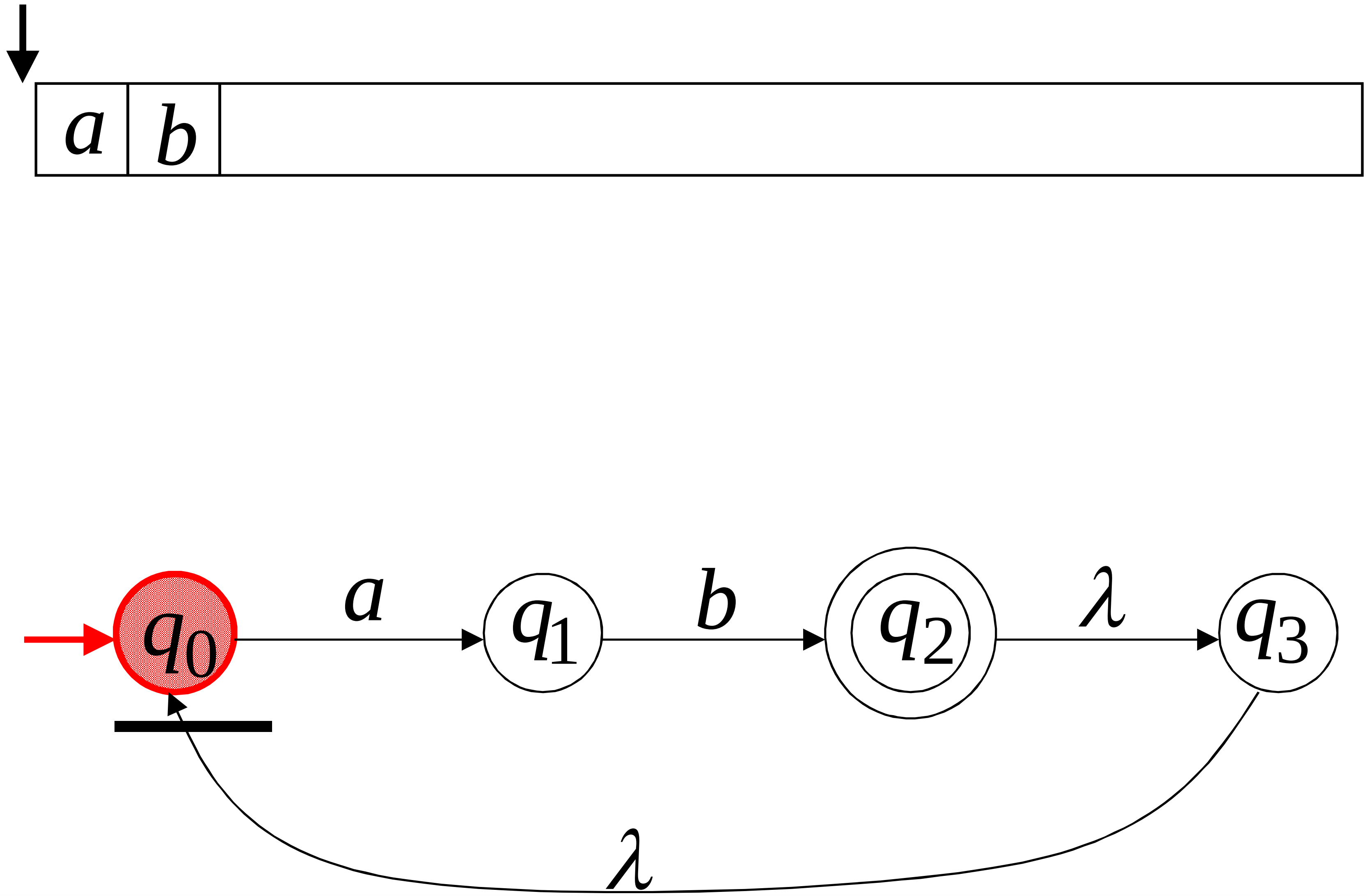
String aa is accepted

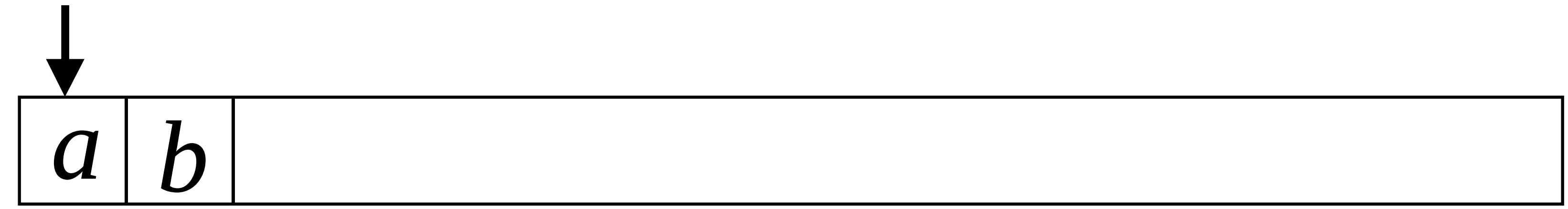
Language accepted: $L = \{aa\}$

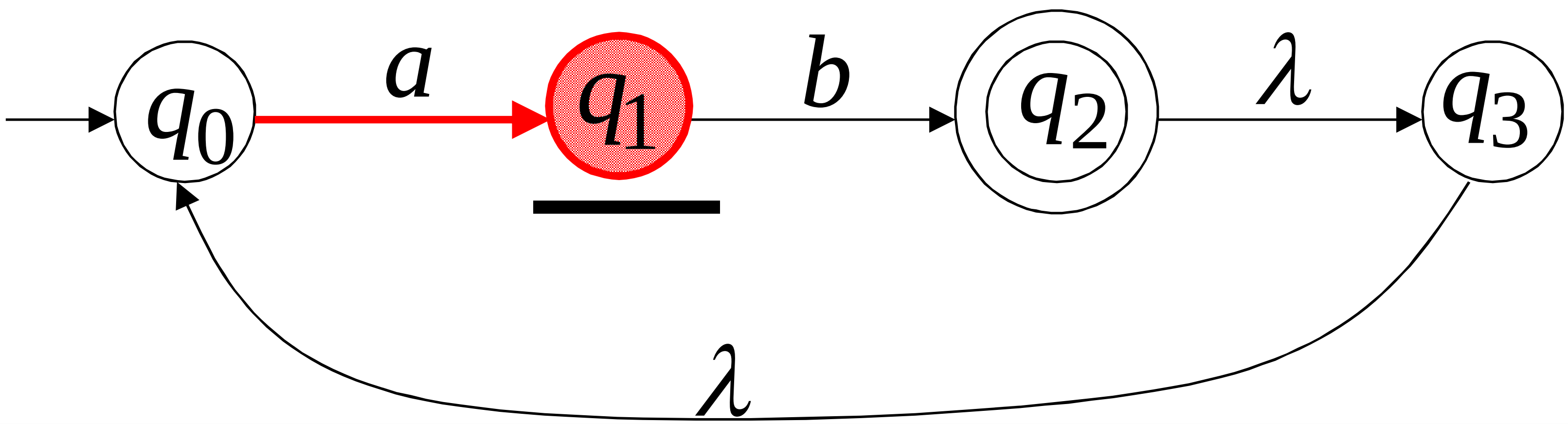


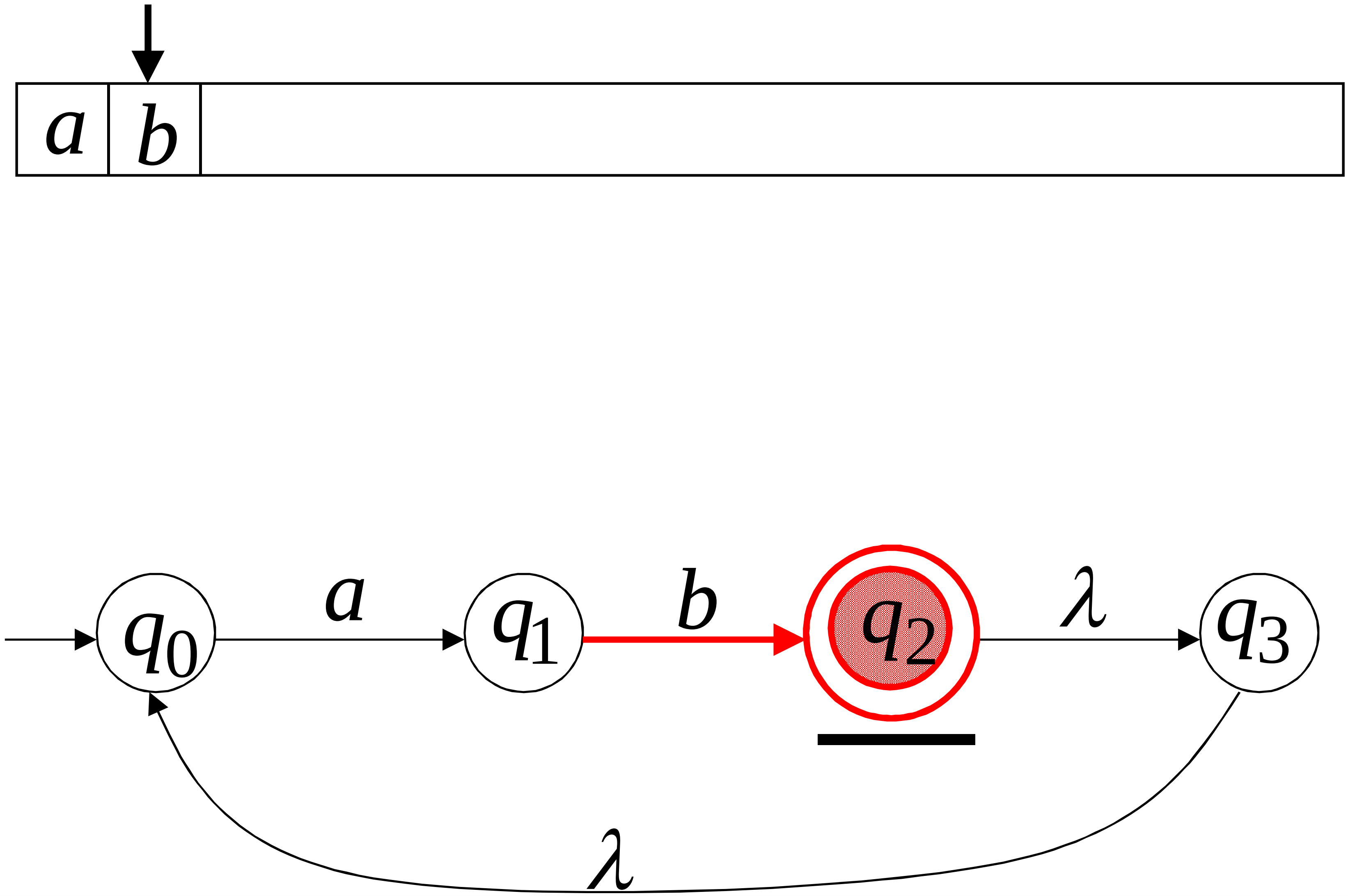
Another NFA Example

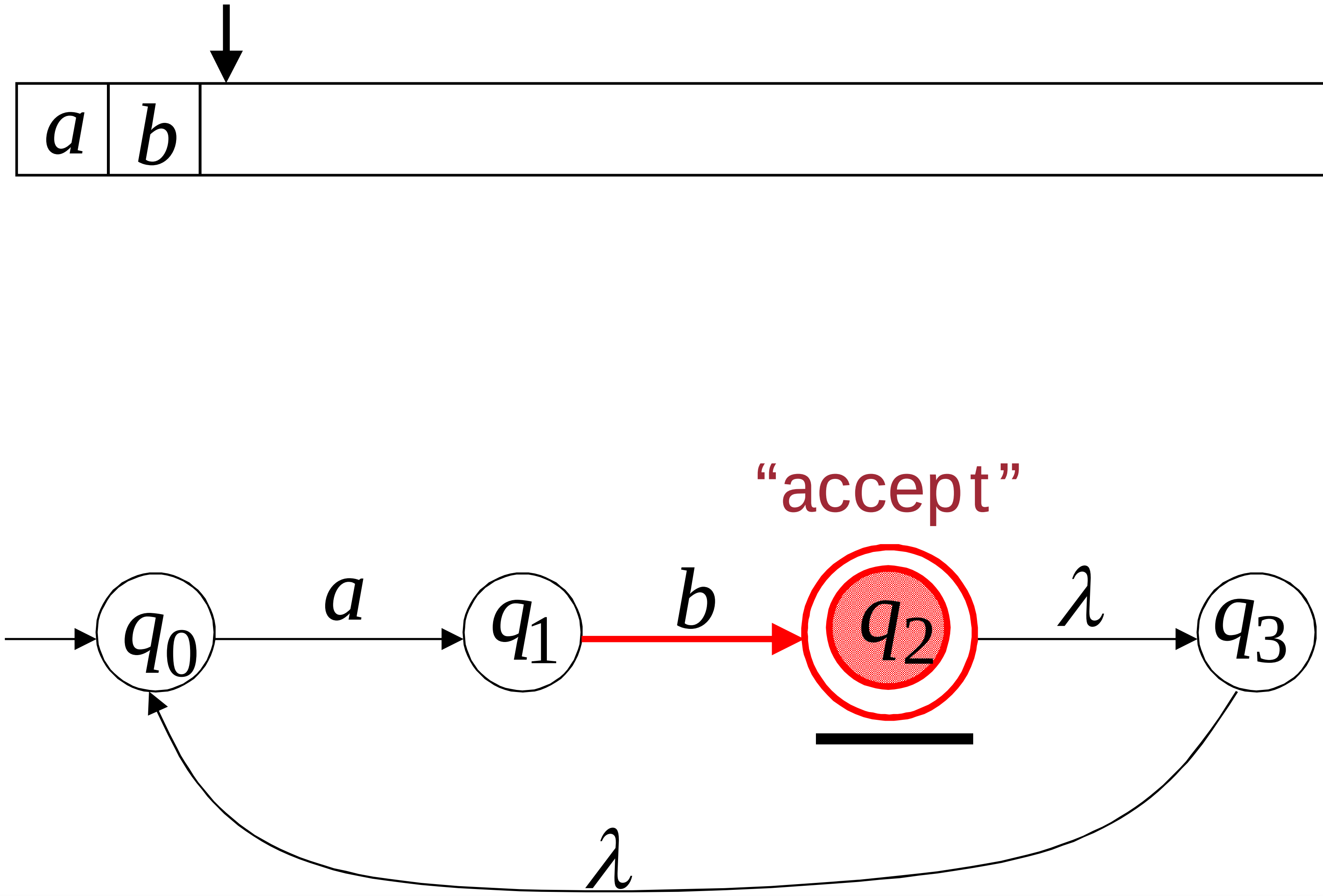



a
b
a
q0
b
q1
q2
λ
q3
λ

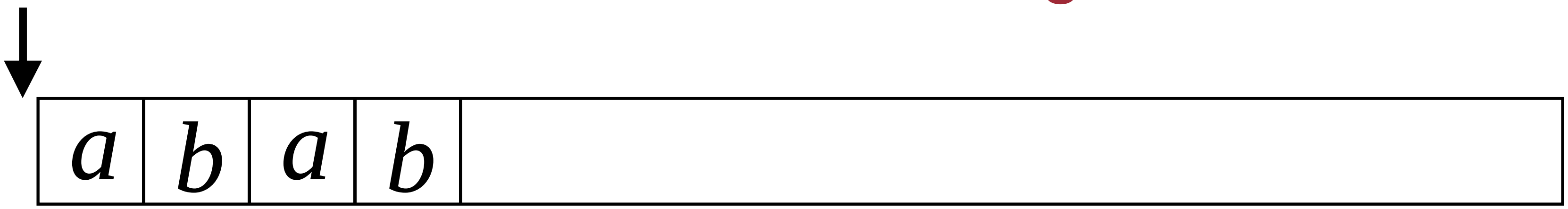

a
b
a
b
λ
λ

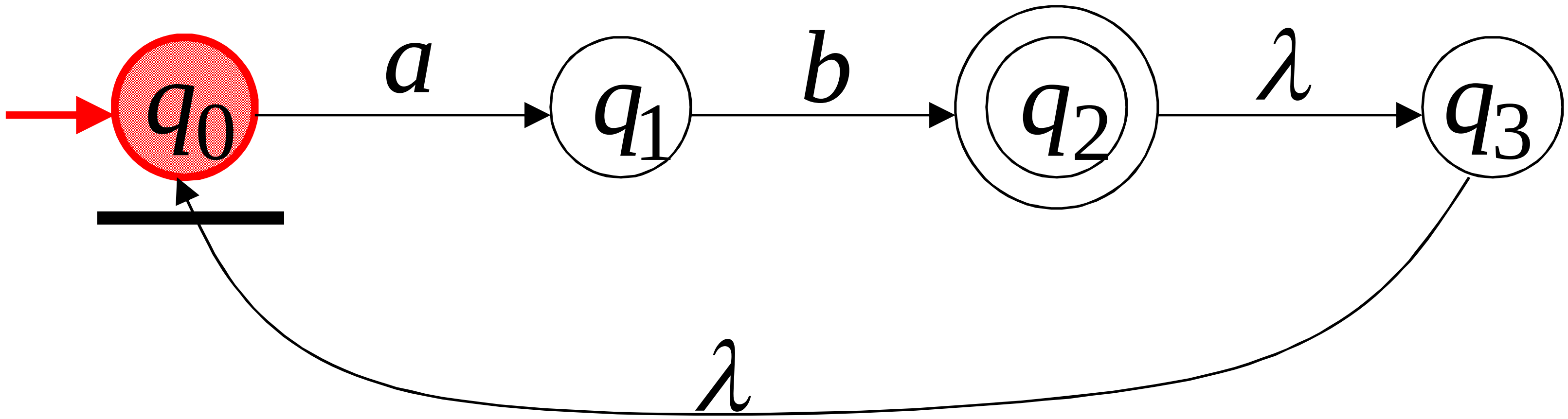

q_0
q_1
q_2
q_3

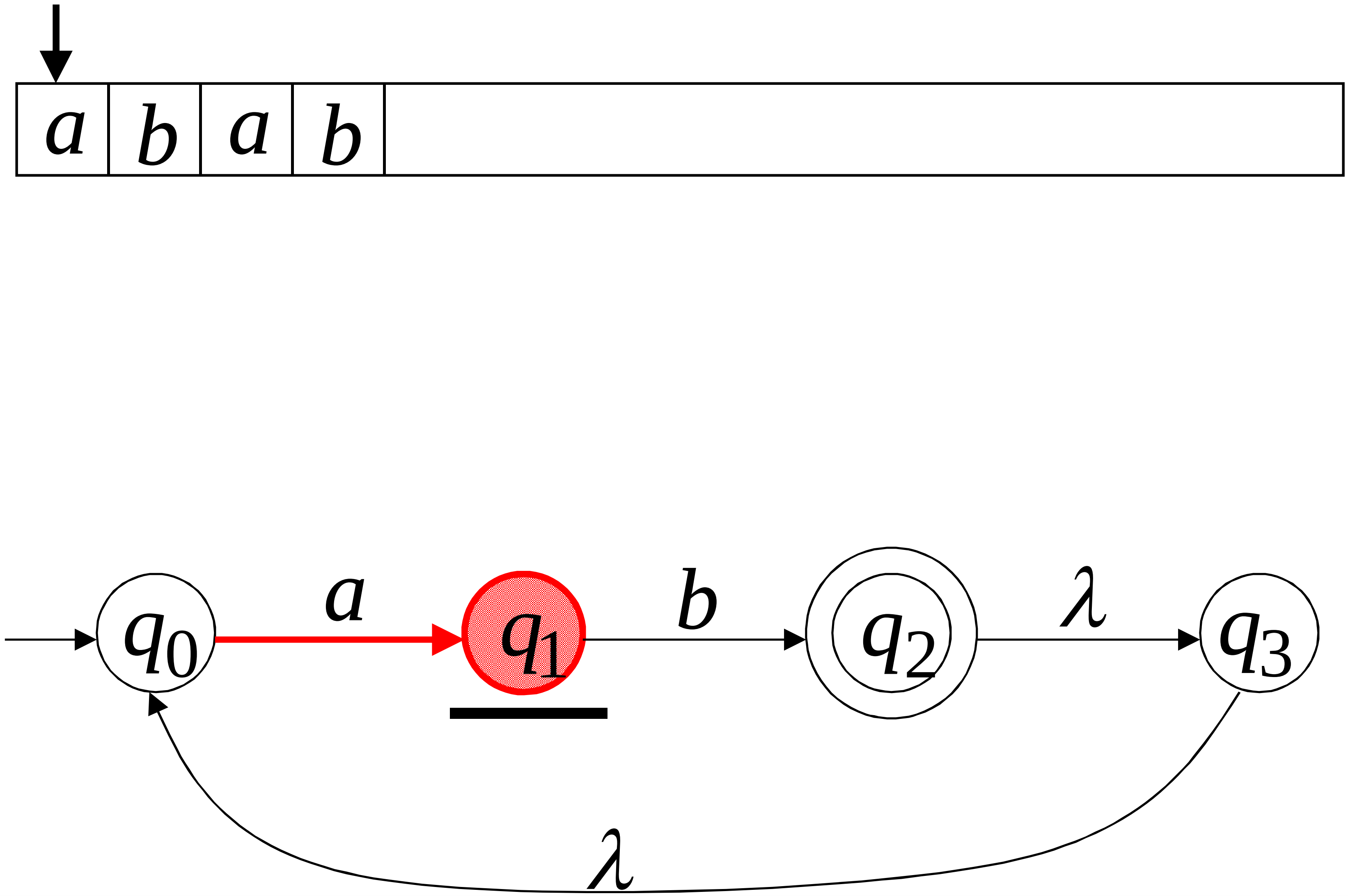

a
b
a
b
λ
λ
q0
q1
q2
q3

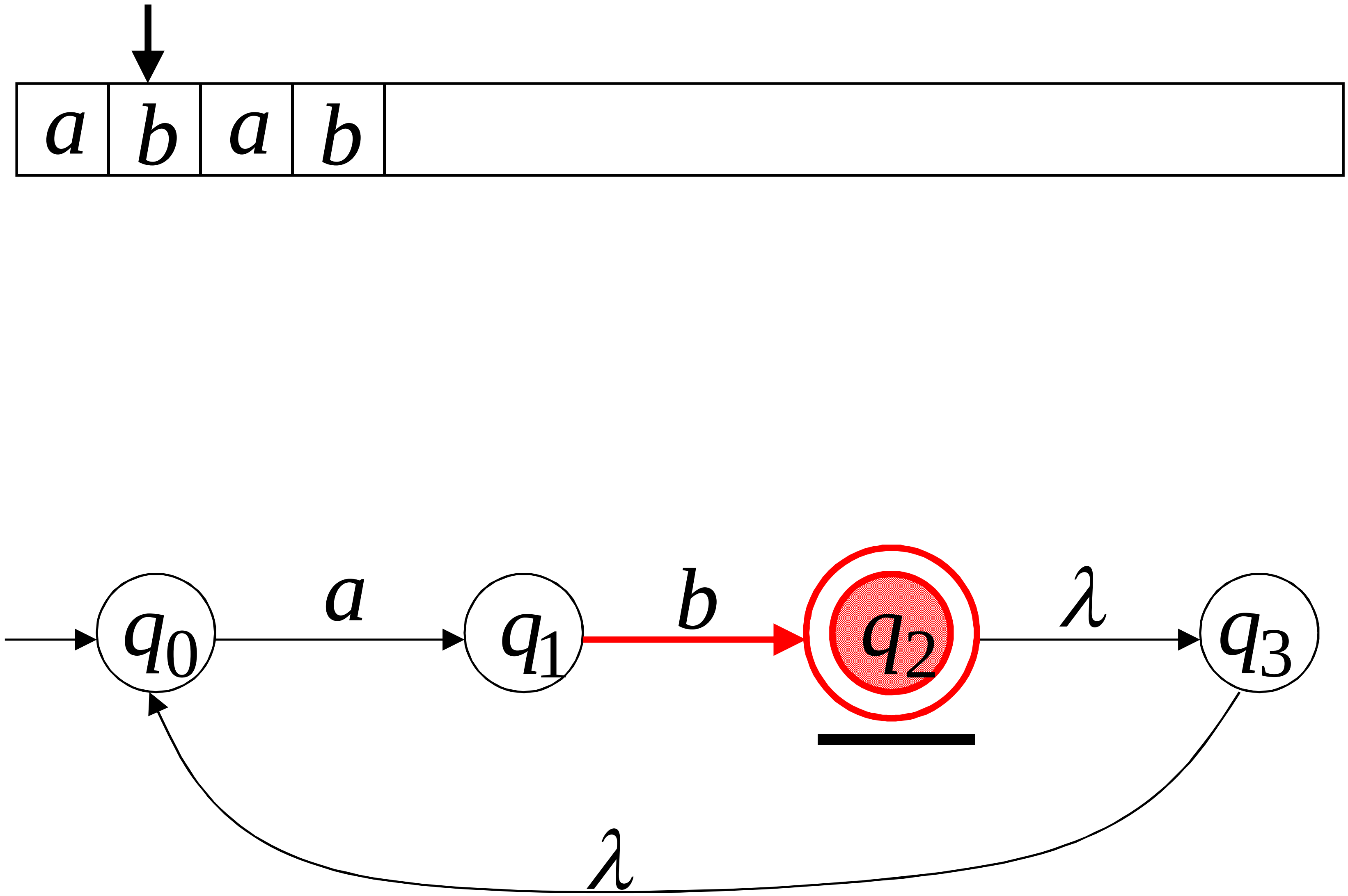

a
b
"accept"
a
b
λ
λ
q0
q1
q2
q3

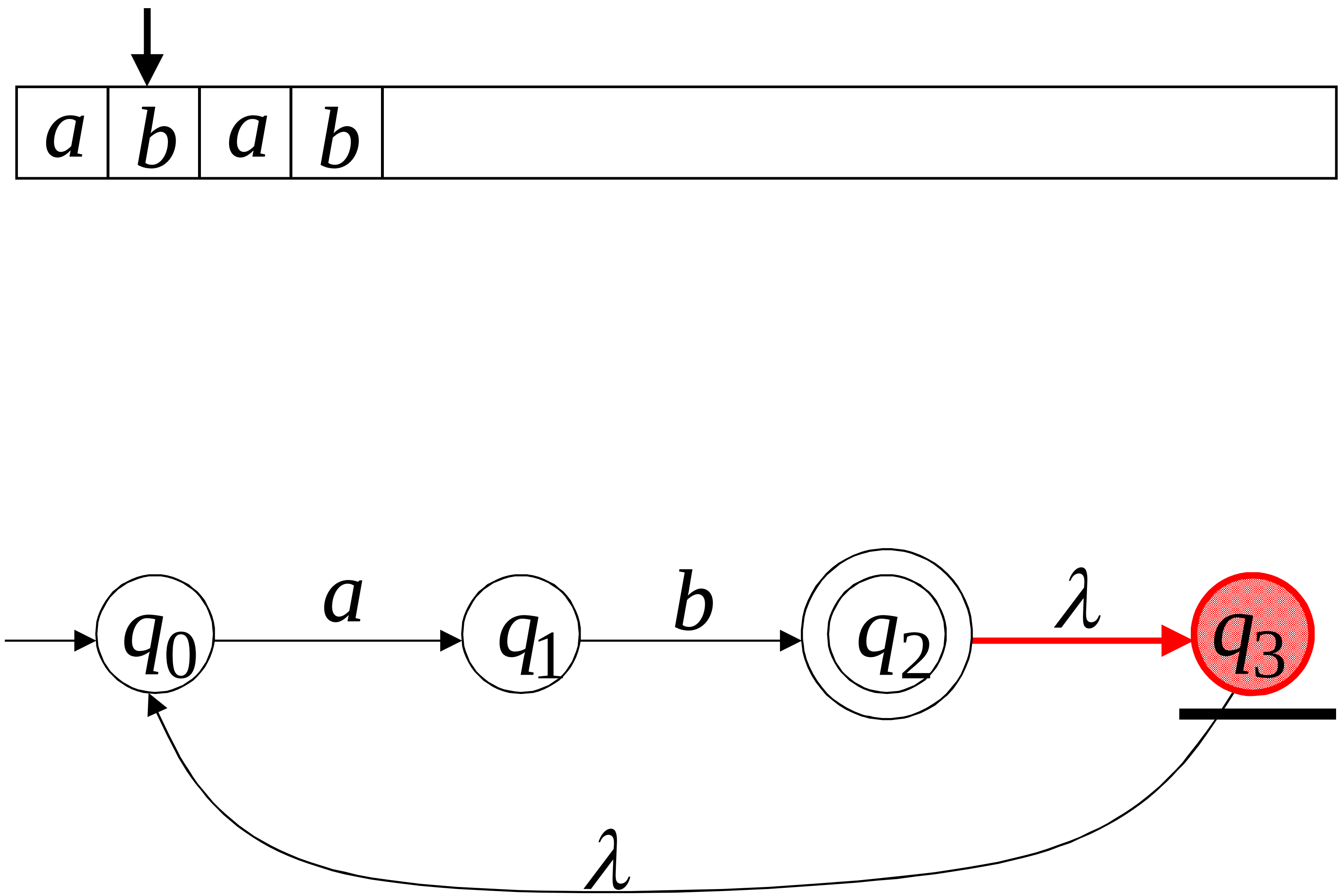
Another String



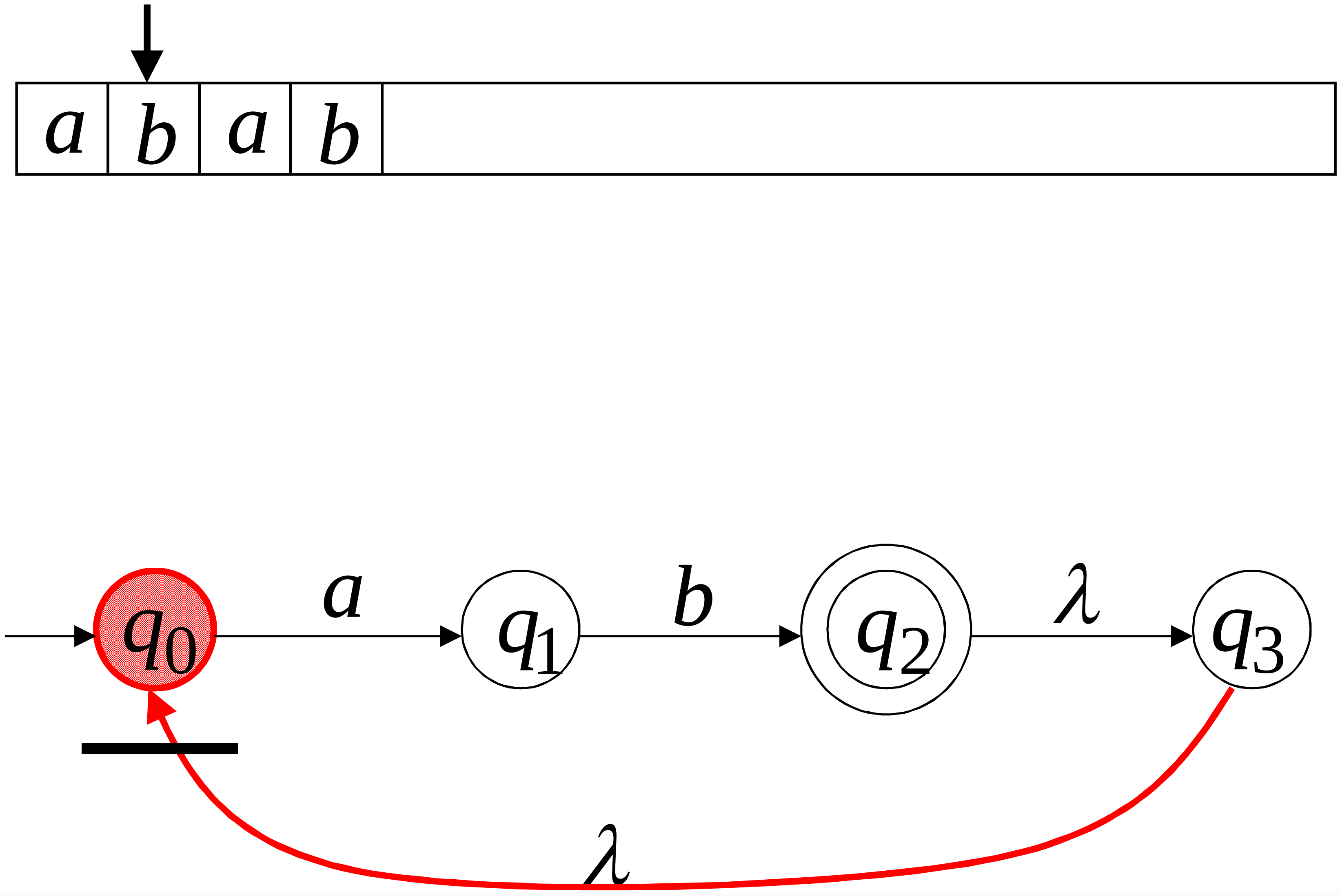



a b a b
a
b
λ
q0 q1 q2 q3
λ

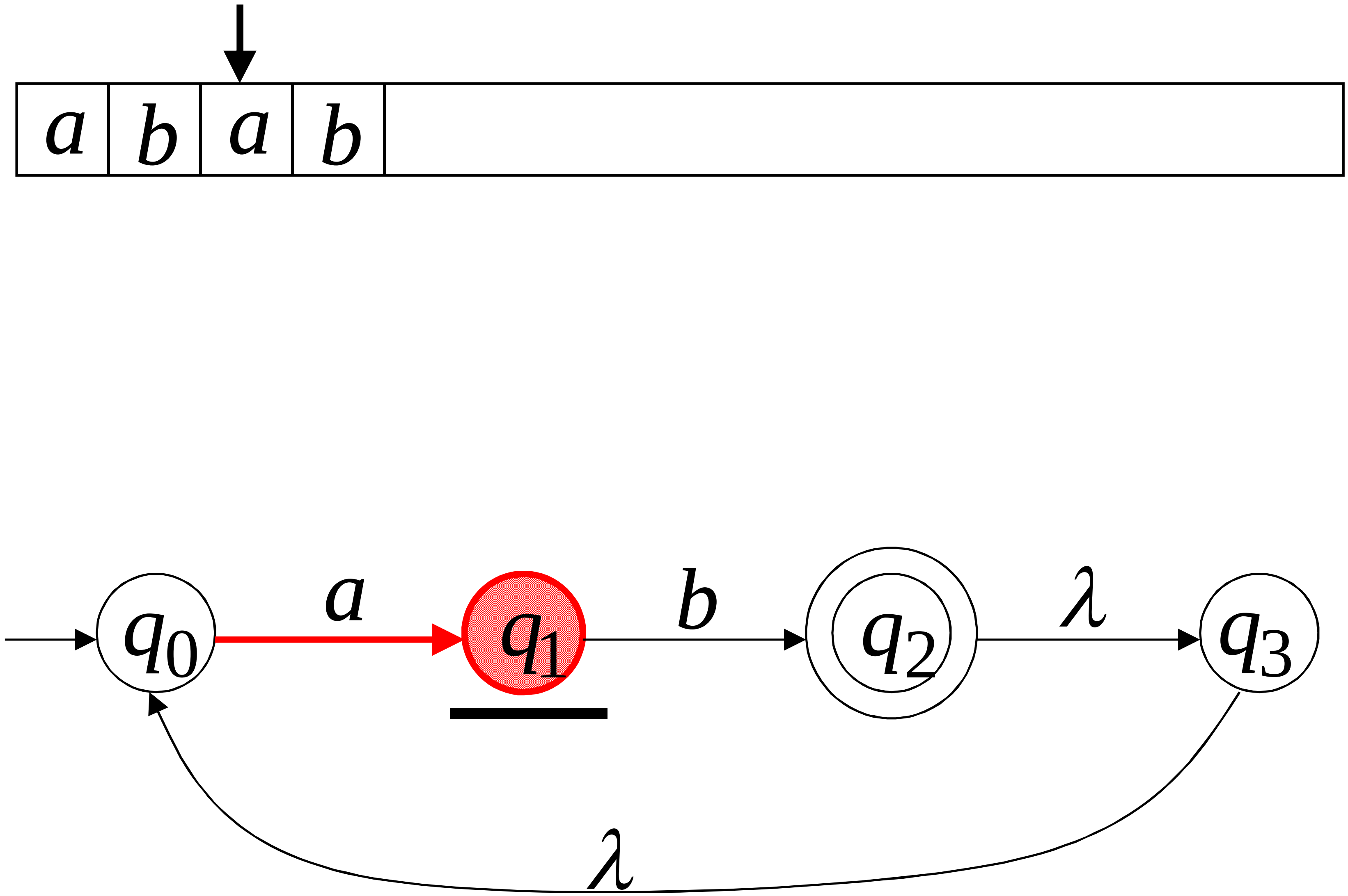

a b a b
q_0
a
q_1
b
q_2
λ
q_3
λ

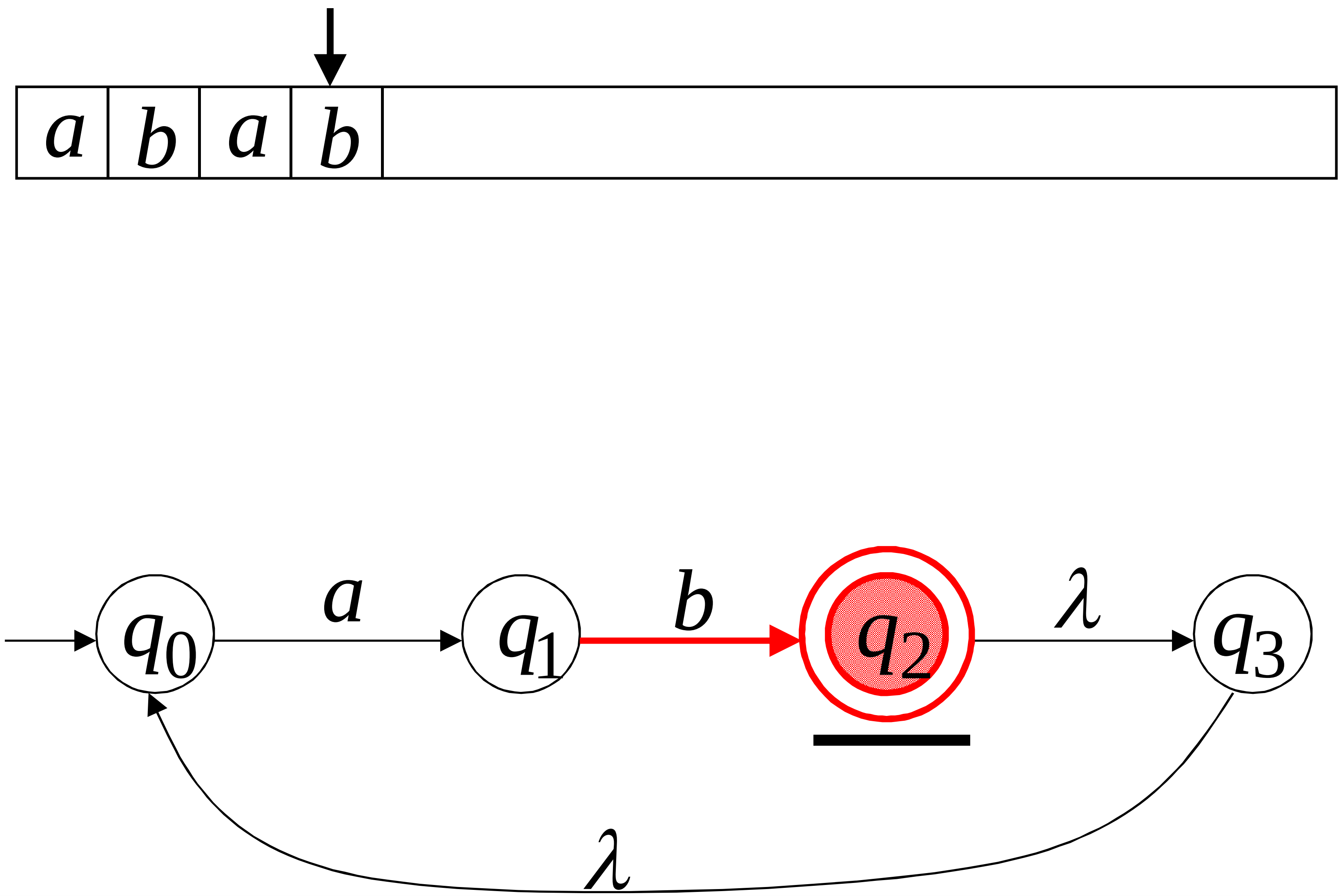


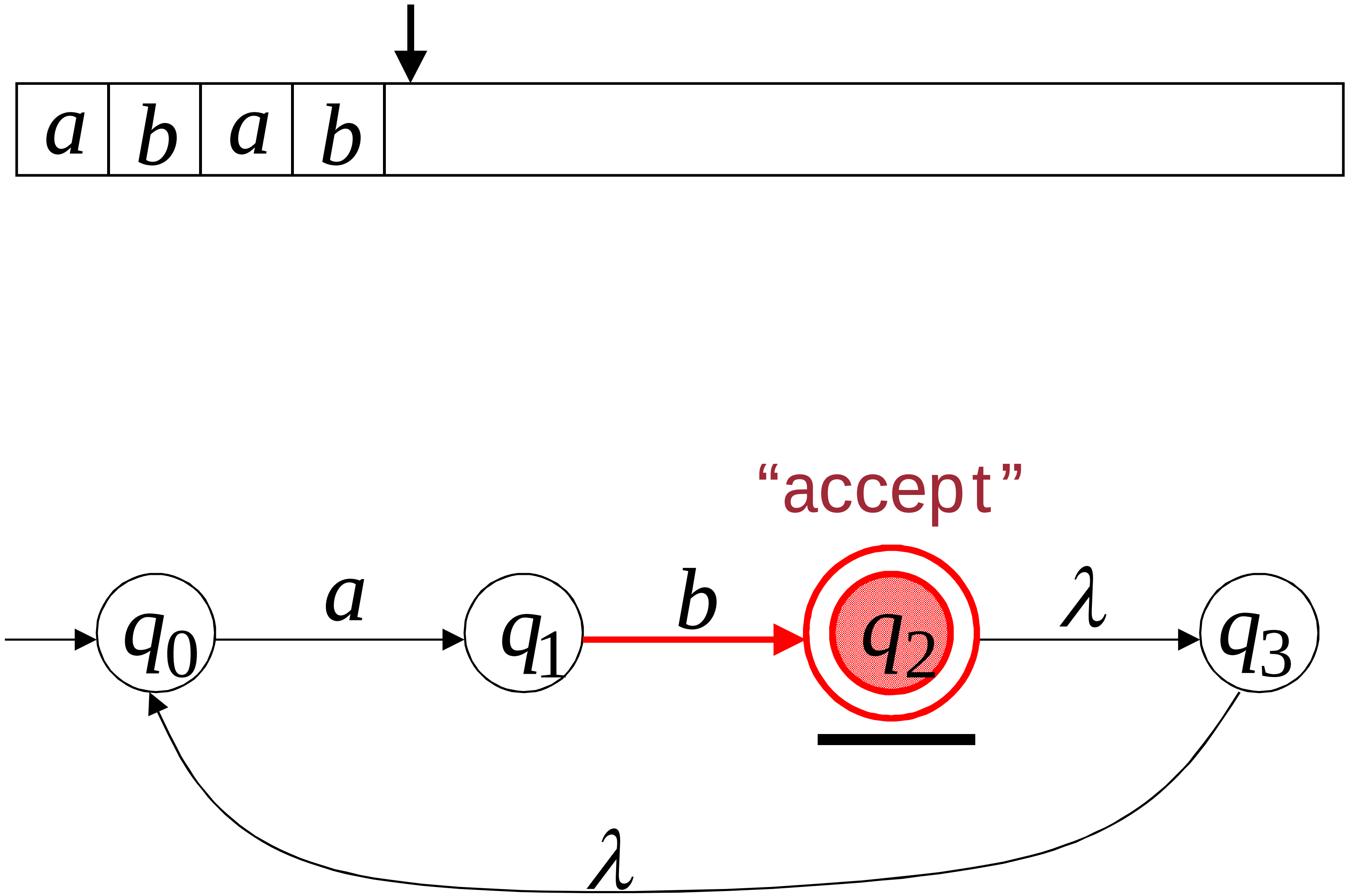
a
b
a
b
a
b
λ
λ
q_0
q_1
q_2
q_3



a
b
a
b
a
b
λ
λ
q0
q1
q2
q3


a
b
a
b
q0
a
q1
b
q2
λ
q3
λ

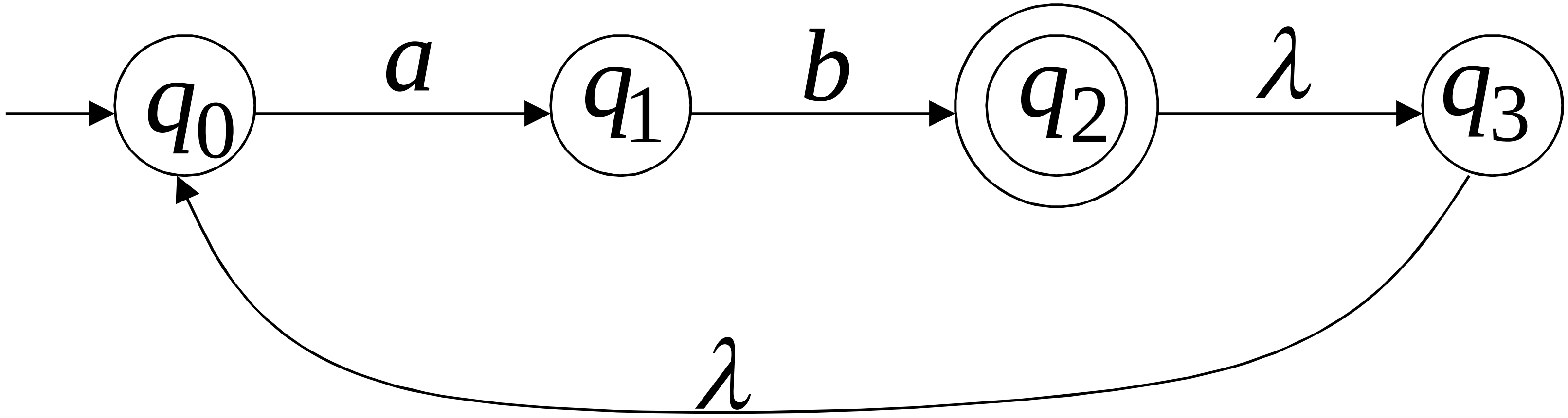

a
b
a
b
q_0
a
q_1
b
q_2
λ
q_3
λ


a b a b
“accept”
a
b
λ
q_0
q_1
q_2
q_3
λ

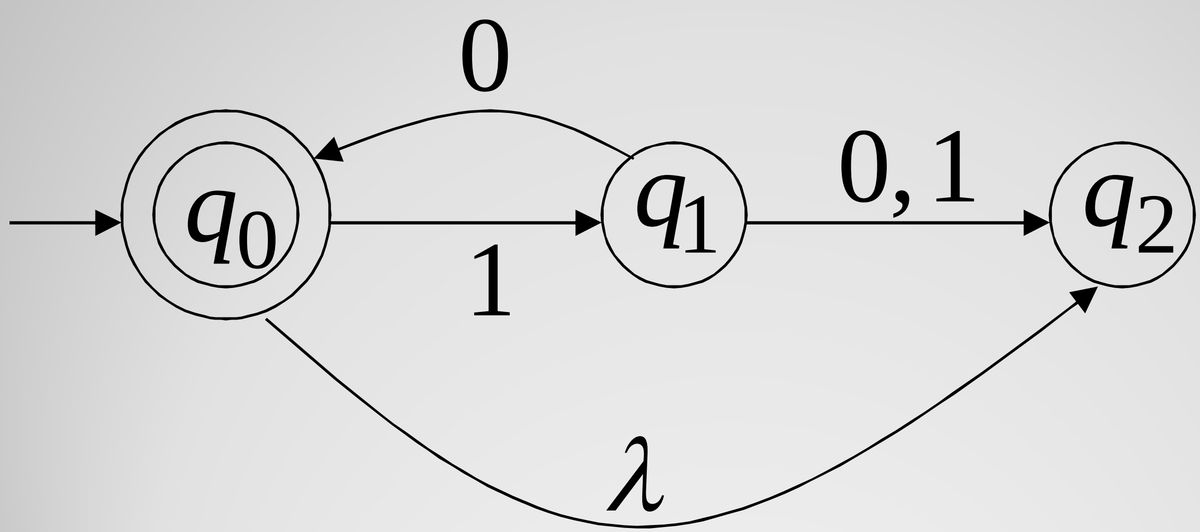
Language accepted

$$L = \{ab,\ abab,\ ababab,\ \ldots\}$$

$$= \{ab\}^{+}$$

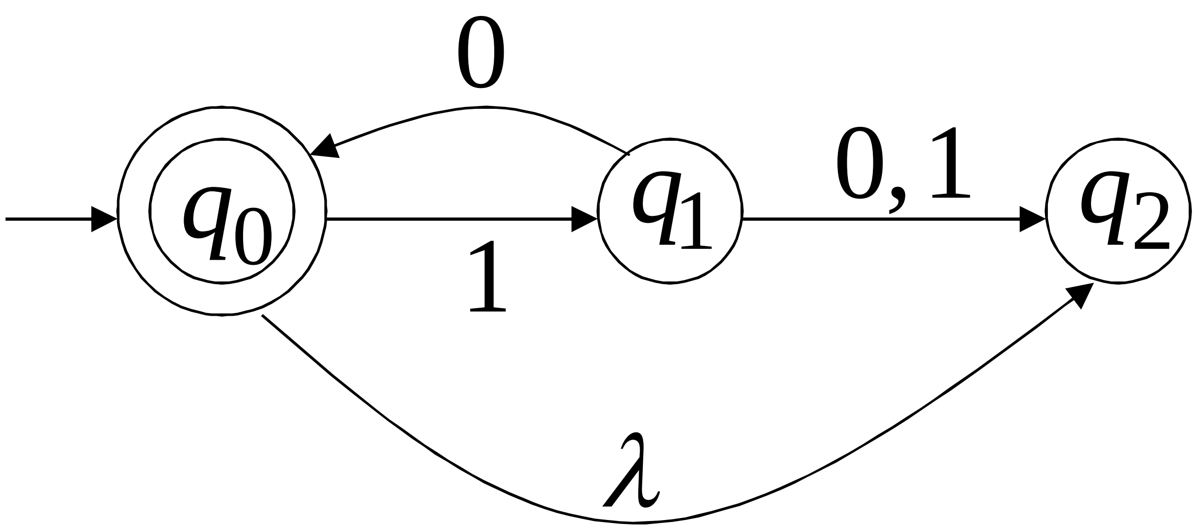


Another NFA Example



Language accepted

$$L = \{\lambda,\ 10,\ 1010,\ 101010,\ \ldots\}$$
$$= \{10\}^*$$



Formal Definition of NFAs

- $$M = (Q,\ \Sigma,\ \delta,\ q_0,\ F)$$

Q : Set of states, i.e. $\{q_0, q_1, q_2\}$

Σ : Input aplhabet, i.e. $\{a, b\}$

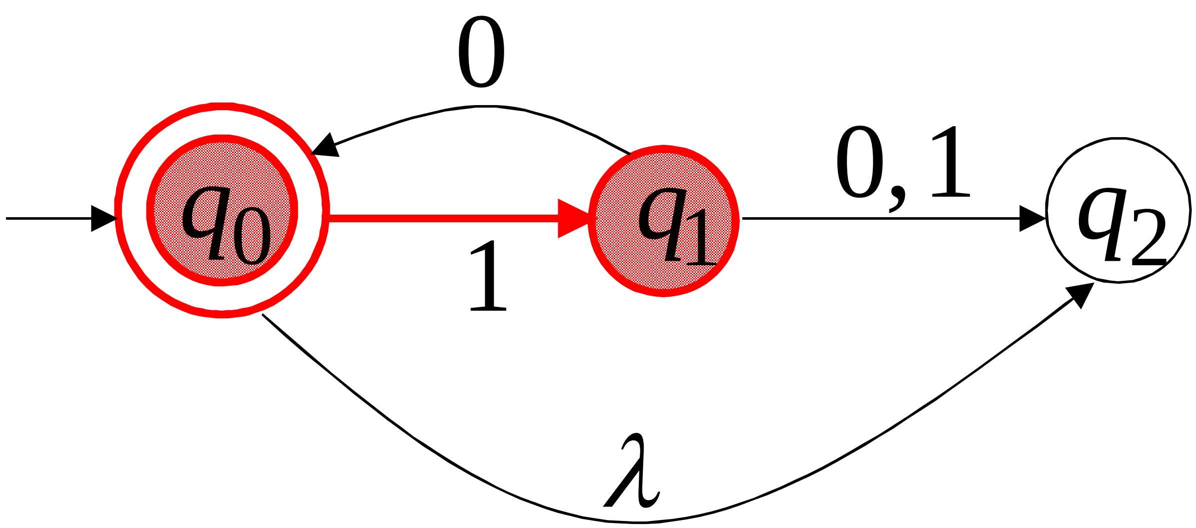
δ : Transition function

q_0 : Initial state

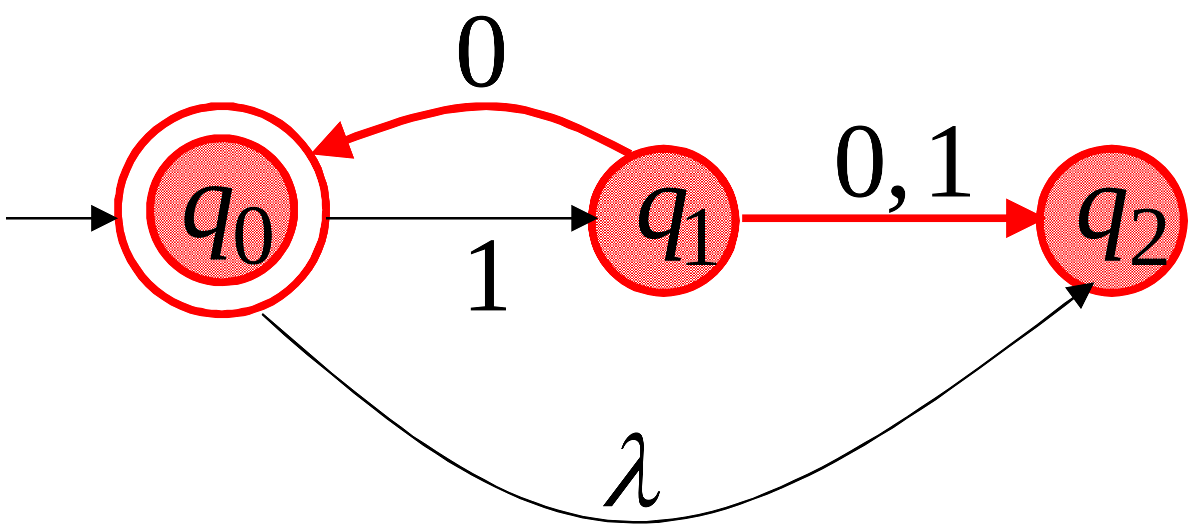
F : Final states

Transition Function δ

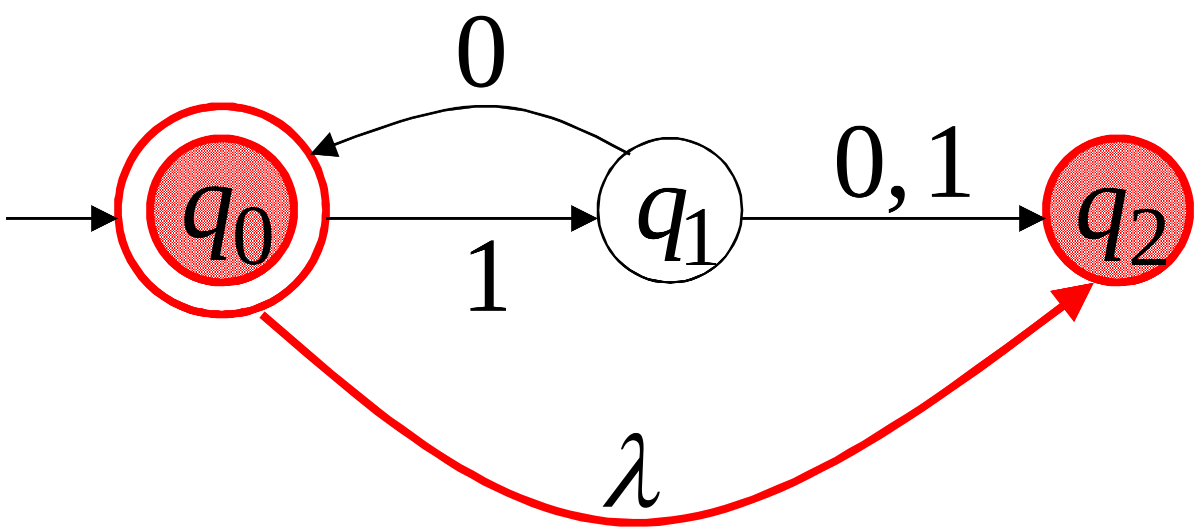
$$\delta(q_0, 1) = \{q_1\}$$



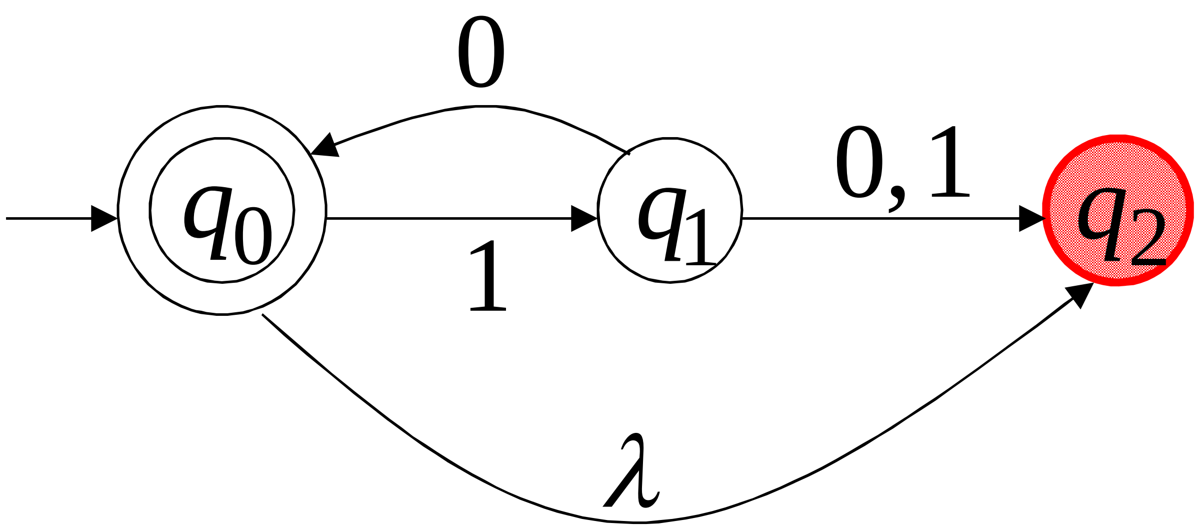
$$\delta(q_1,0)=\{q_0,q_2\}$$



$$\delta(q_0, \lambda) = \{q_0, q_2\}$$

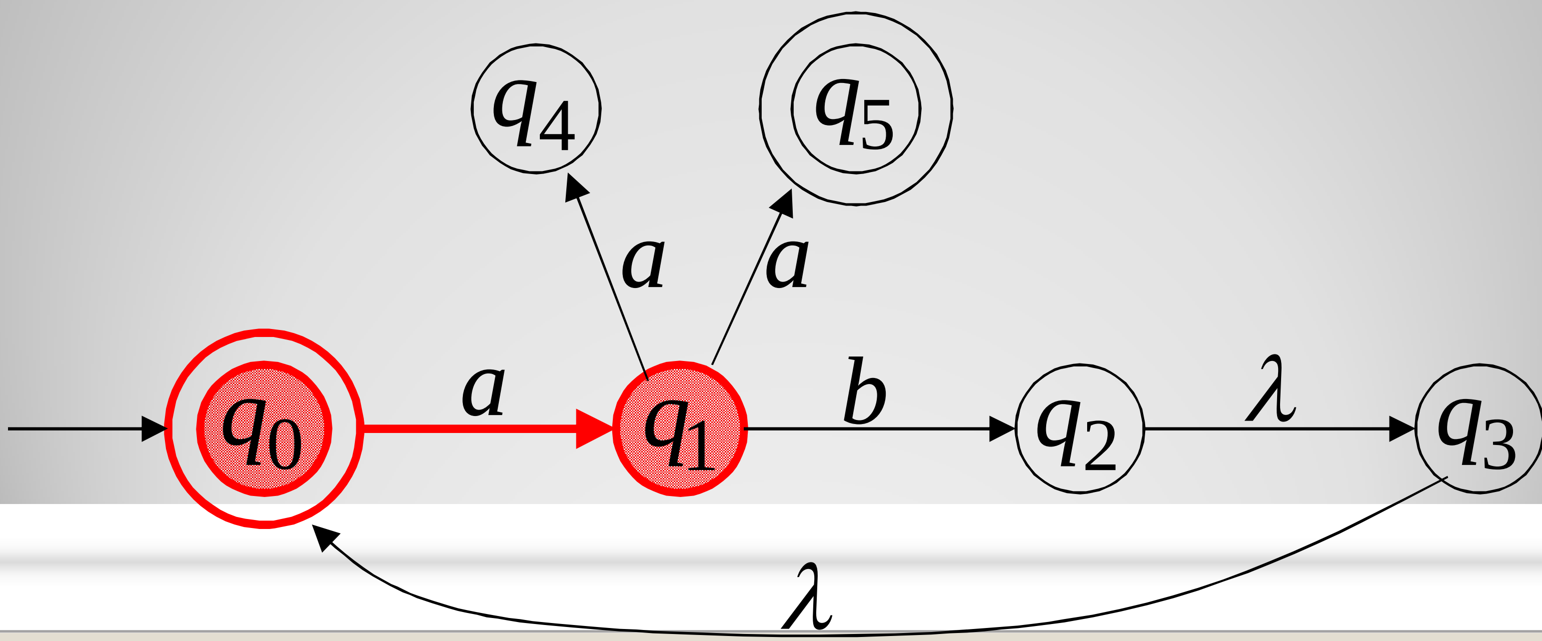


$$\delta(q_2, 1) = \emptyset$$

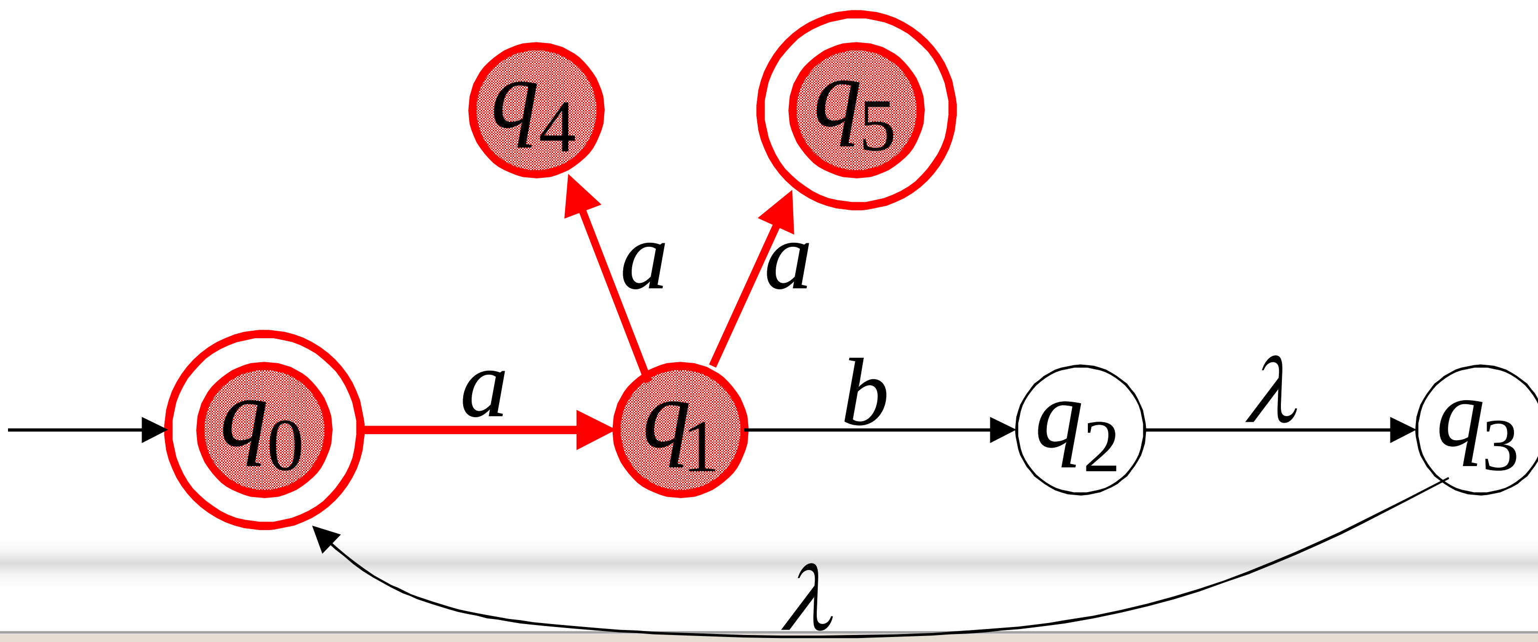


Extended Transition Function δ^*

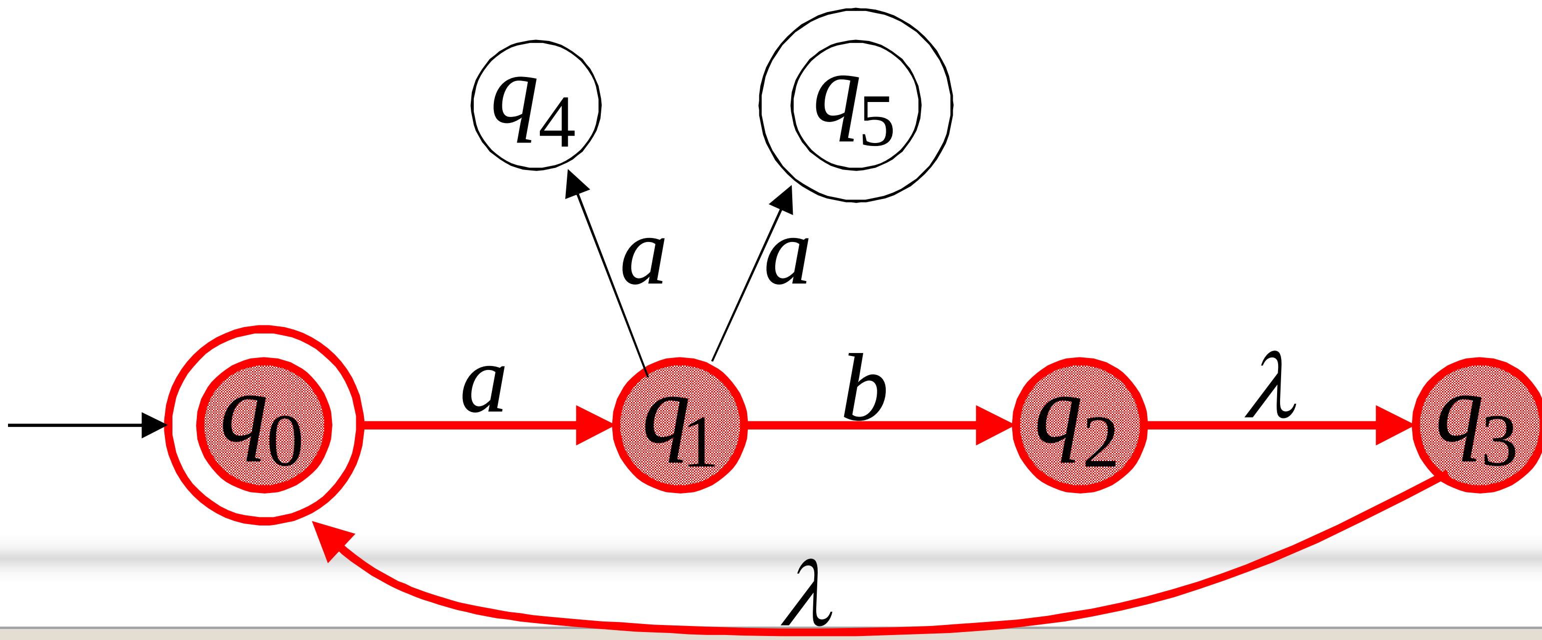
$$\delta^*(q_0, a) = \{q_1\}$$



$$\delta^*(q_0, aa) = \{q_4, q_5\}$$



$$\delta^*(q_0, ab) = \{q_2, q_3, q_0\}$$



Formally

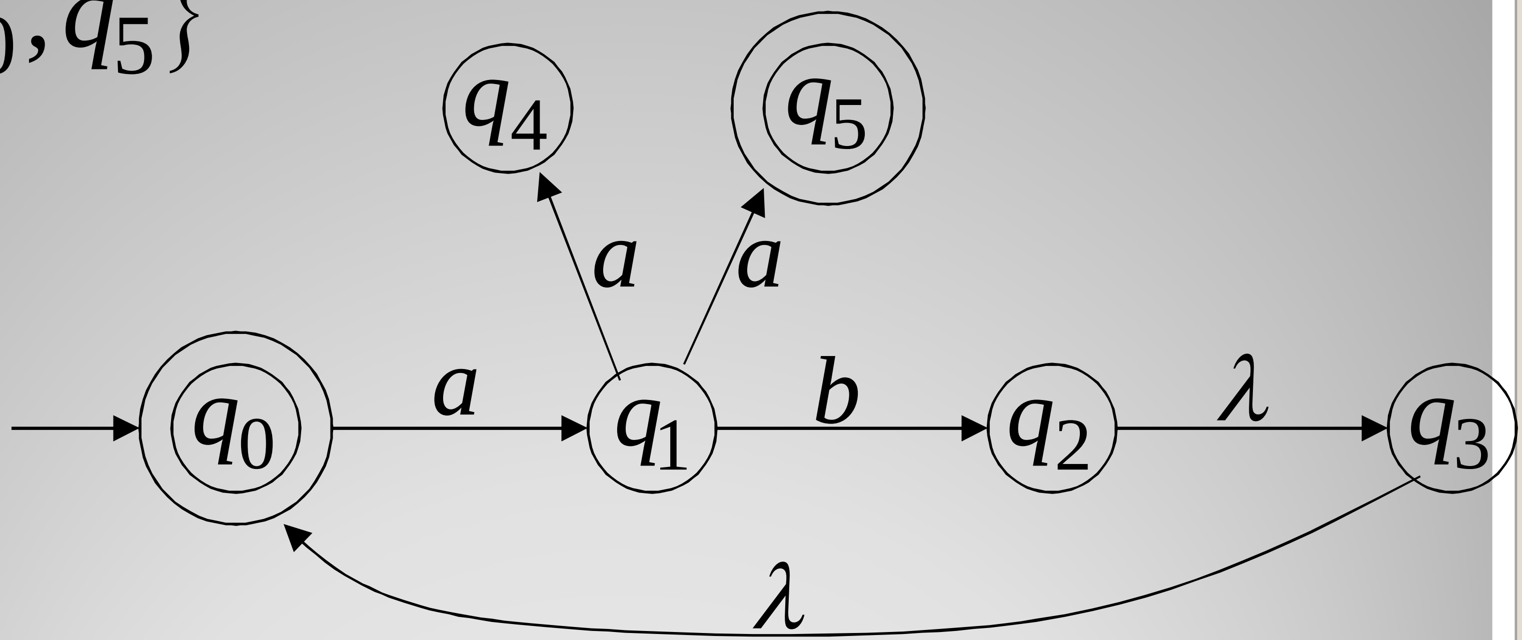
It holds $q_j \in \delta^*(q_i, w)$

if and only if

there is a walk from q_i to q_j with label w

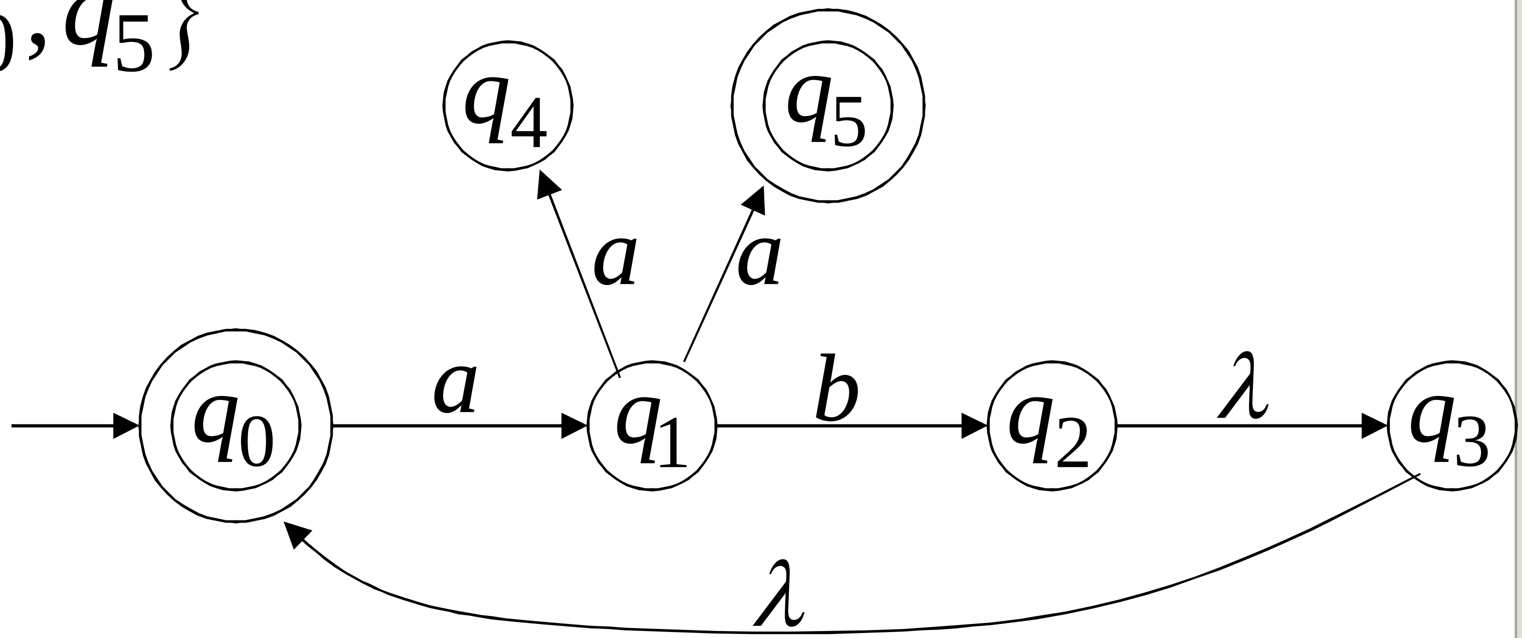
The Language of an NFA

$F = \{q_0, q_5\}$



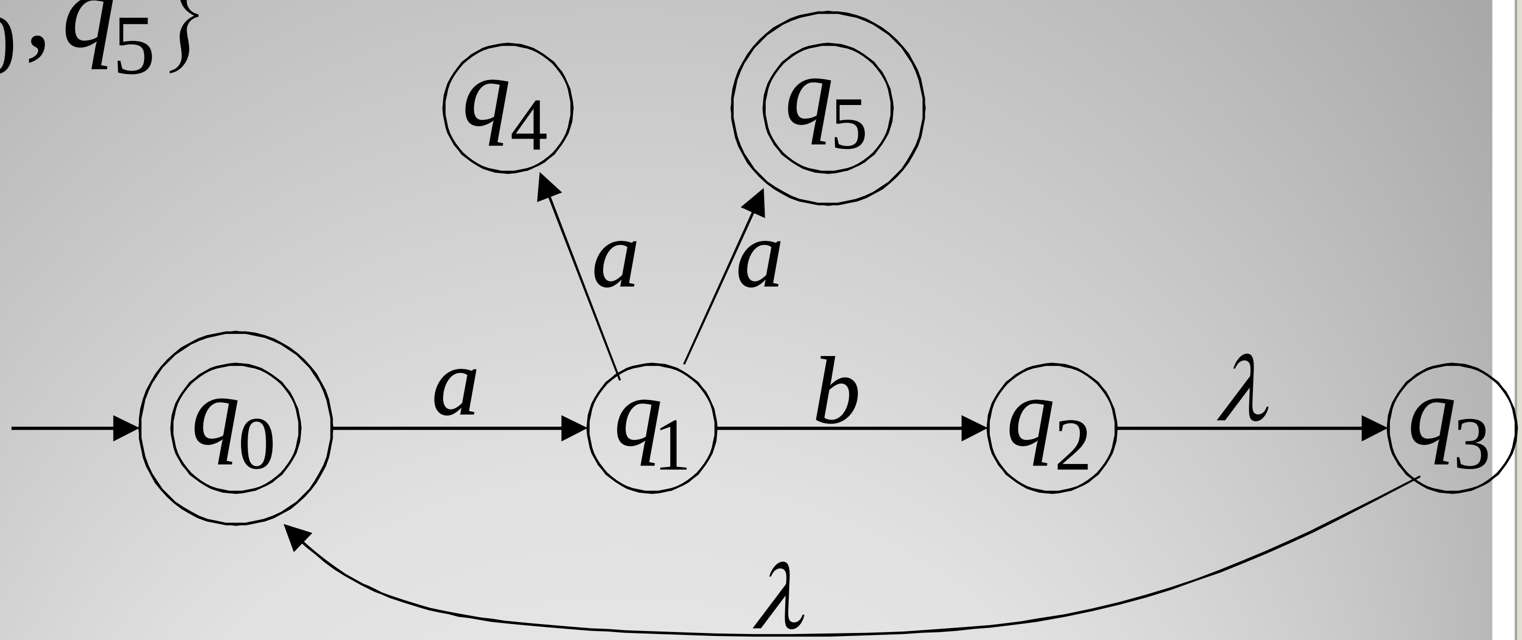
$\delta^*(q_0, aa) = \{q_4, \underline{q_5}\}$ $\quad aa \in L(M)$

$$F = \{q_0, q_5\}$$



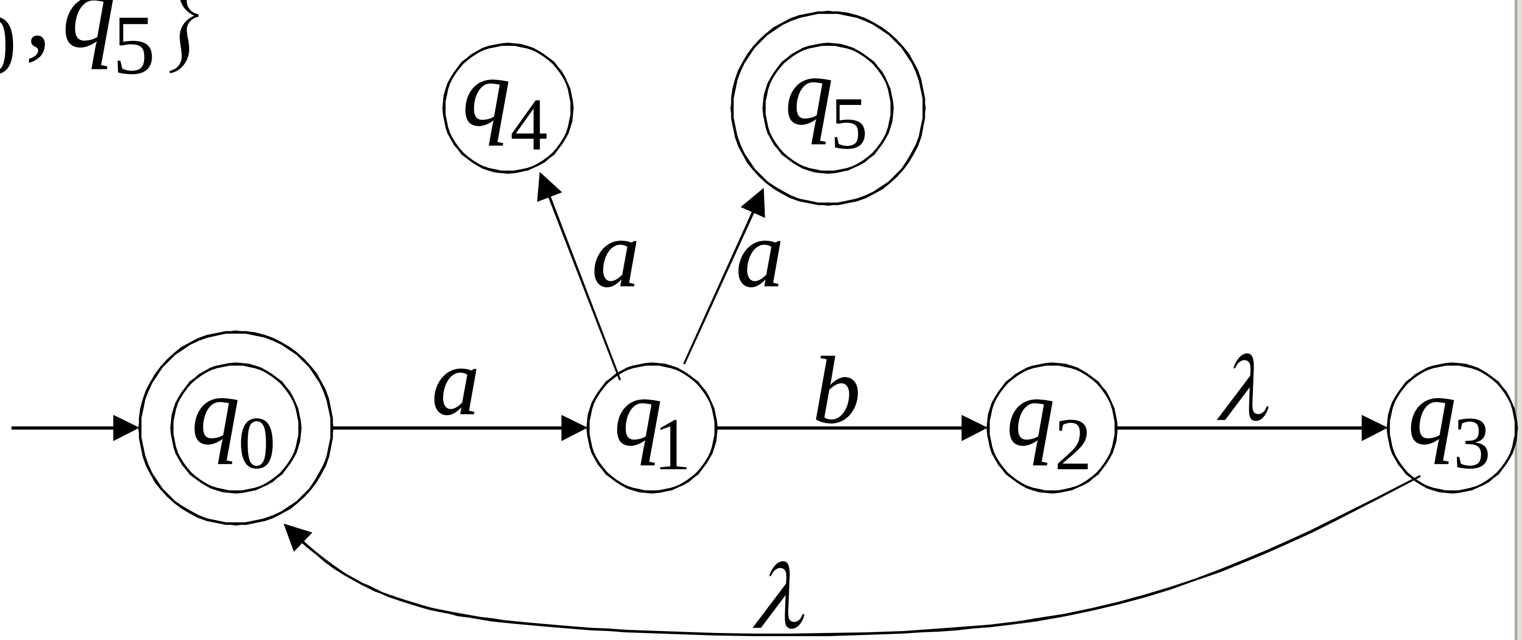
$$\delta^*(q_0, ab) = \{q_2, q_3, \underline{q_0}\} \qquad ab \in L(M)$$

$F = \{q_0, q_5\}$



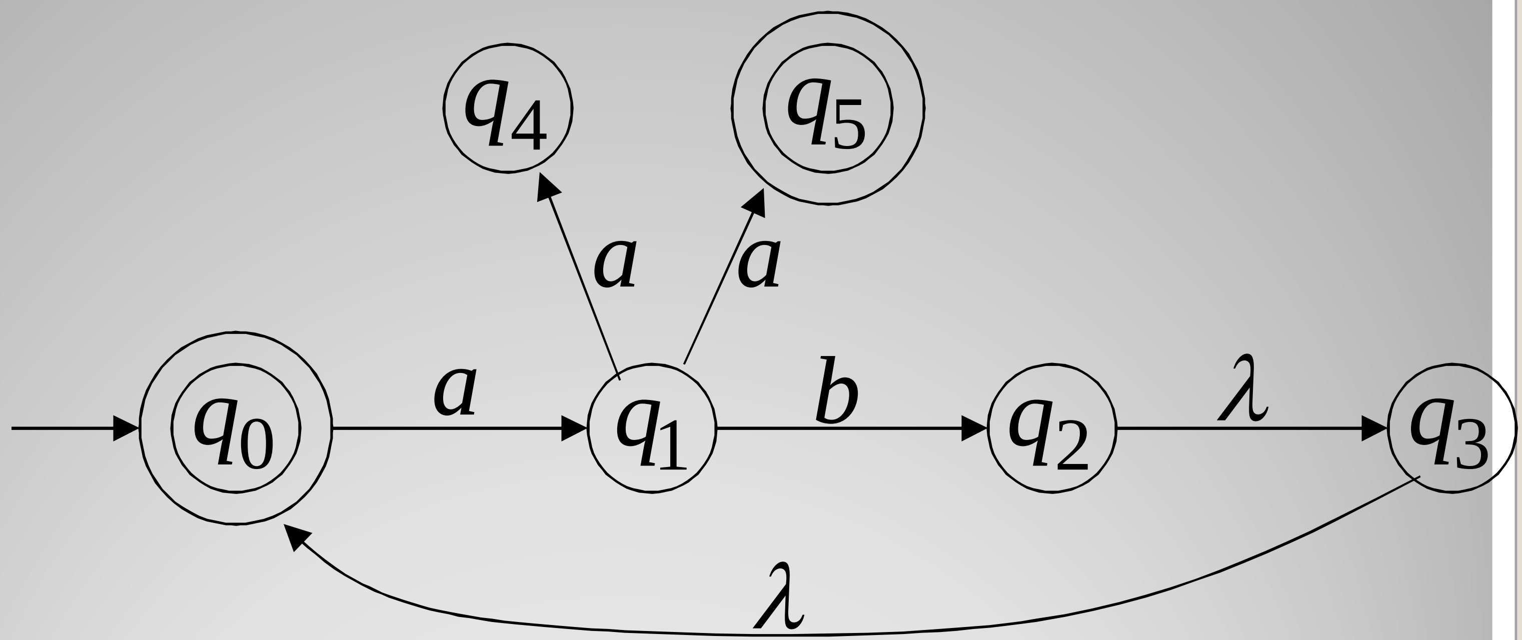
$\delta^*(q_0, abaa) = \{q_4, \underline{q_5}\}$ $\quad$ $aaba \in L(M)$

$$F = \{q_0, q_5\}$$



$$\delta^*(q_0, aba) = \{q_1\}$$

$$aba \notin L(M)$$



$$L(M) = \{aa\} \cup \{ab\}^* \cup \{ab\}^+\{aa\}$$

Formally

- The language accepted by NFA M is:

$$L(M) = \{w_1, w_2, w_3, ...\}$$

- where

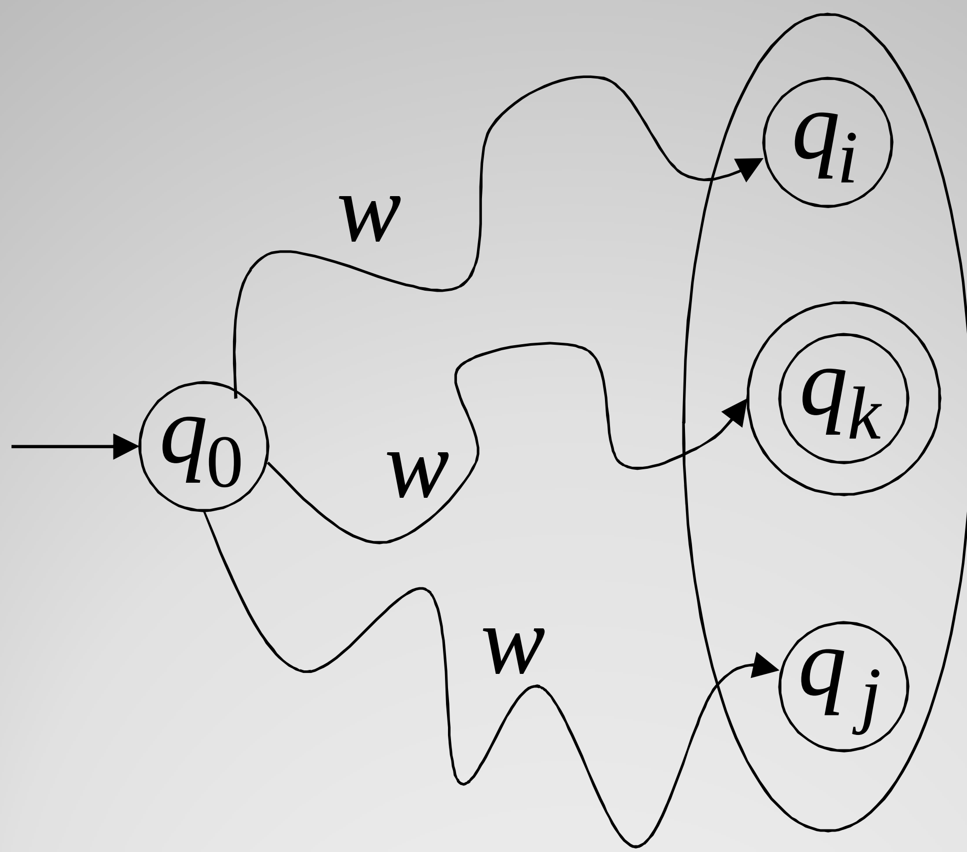
$$\delta^*(q_0, w_m) = \{q_i, q_j, ...\}$$

- and there is some

$$q_k \in F \qquad \text{(final state)}$$

- $w \in L(M)$

$\delta^*(q_0, w)$



$q_k \in F$

Equivalence of NFAs and DFAs

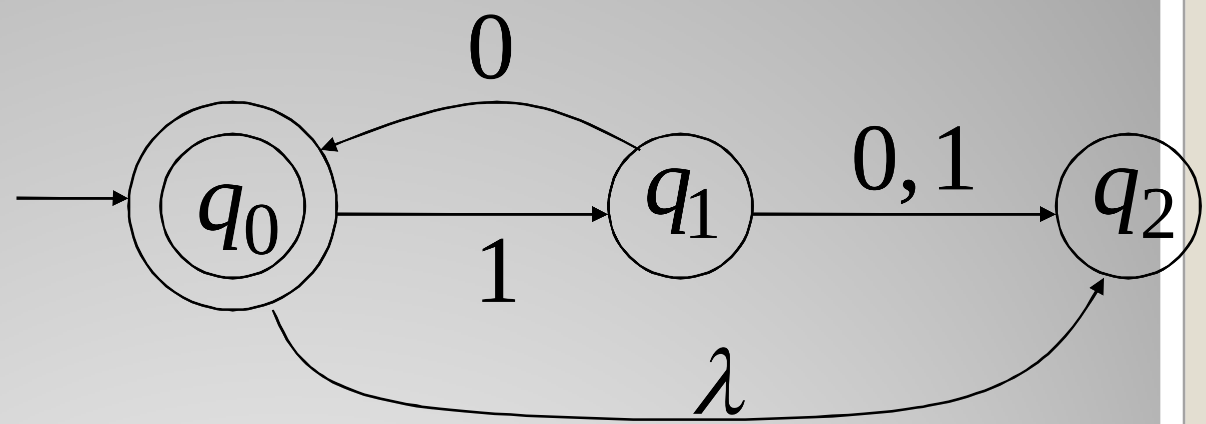
Equivalence of Machines

- For DFAs or NFAs:
- Machine M_1 is equivalent to machine M_2
- if
$$L(M_1) = L(M_2)$$
-

Example

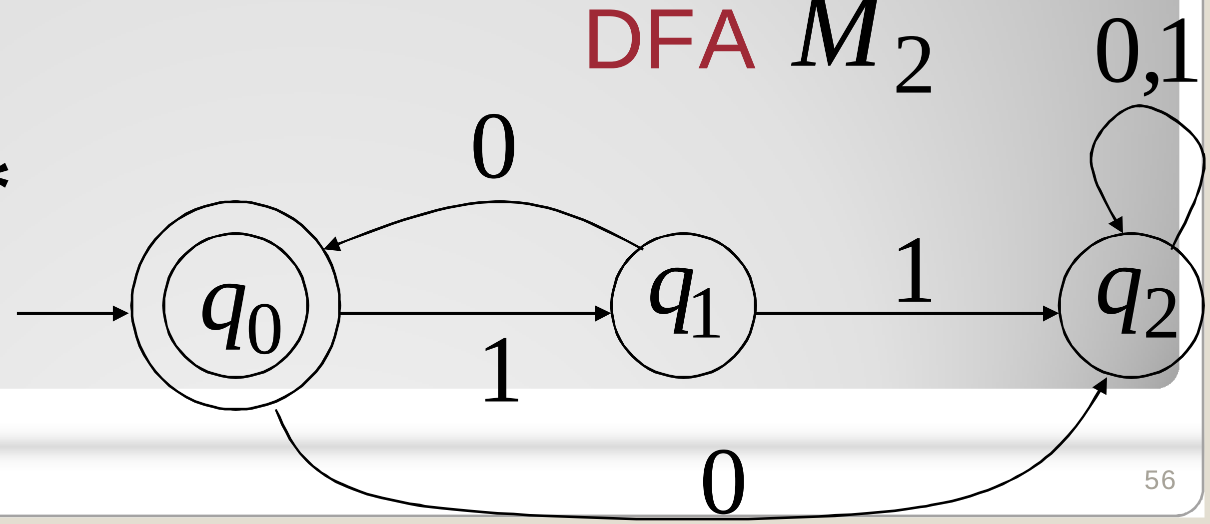
NFA M_1

$$L(M_1) = \{10\}^*$$



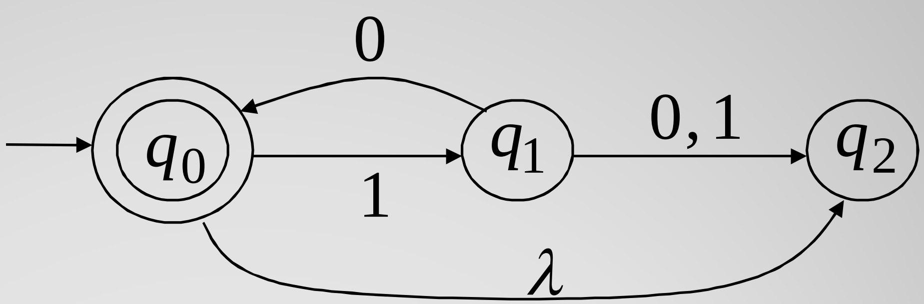
DFA M_2

$$L(M_2) = \{10\}^*$$

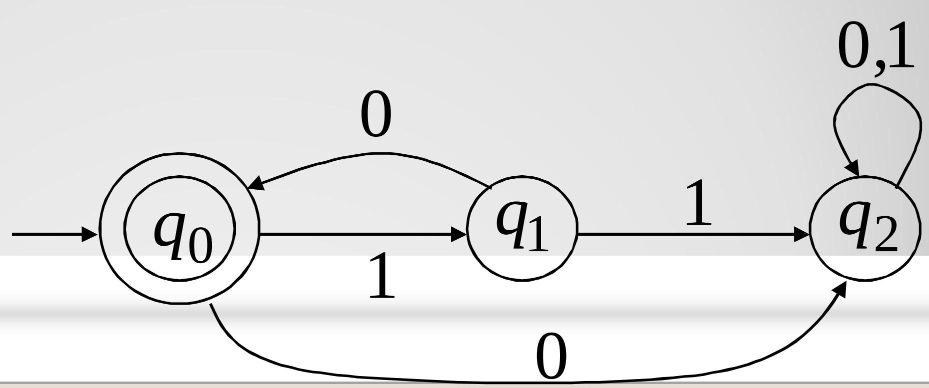


- Since $L(M_1) = L(M_2) = \{10\}^*$
- machines M_1 and M_2 are equivalent

NFA M_1



DFA M_2



Equivalence of NFAs and DFAs

Question: NFAs = DFAs ?

Same power?

Accept the same languages?

Equivalence of NFAs and DFAs

Question: NFAs = DFAs ? **YES!**

↑

Same power?

Accept the same languages?

We will prove:

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} = \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

We will prove:

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} = \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

NFAs and DFAs have the same computation power

Step 1

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} \supseteq \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

Step 1

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} \supseteq \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

Proof: Every DFA is also an NFA

Step 1

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} \supseteq \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

Proof: Every DFA is also an NFA

A language accepted by a DFA is also accepted by an NFA

Step 2

$$\left\{\begin{array}{l}\text{Languages}\\ \text{accepted}\\ \text{by NFAs}\end{array}\right\} \subseteq \left\{\begin{array}{l}\text{Languages}\\ \text{accepted}\\ \text{by DFAs}\end{array}\right\}$$

Step 2

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} \subseteq \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

Proof: Any NFA can be converted to an equivalent DFA

Step 2

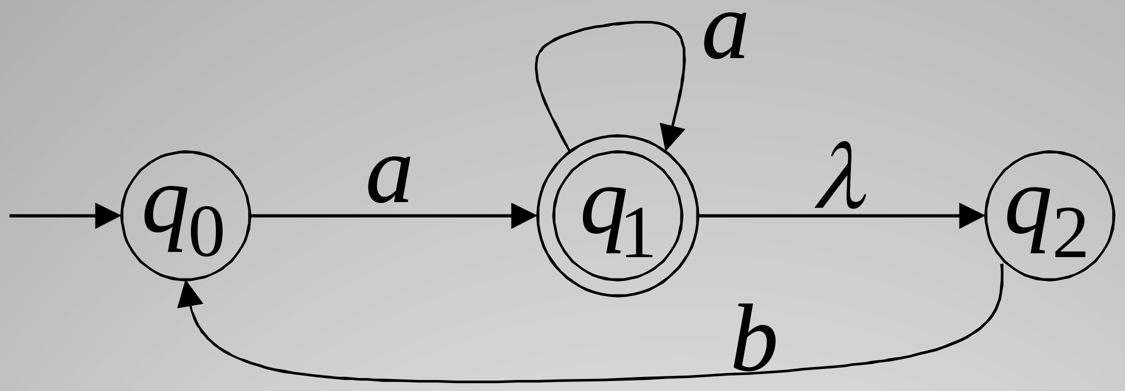
$$\left\{\begin{array}{l}\text{Languages}\\\text{accepted}\\\text{by NFAs}\end{array}\right\} \subseteq \left\{\begin{array}{l}\text{Languages}\\\text{accepted}\\\text{by DFAs}\end{array}\right\}$$

Proof: Any NFA can be converted to an equivalent DFA

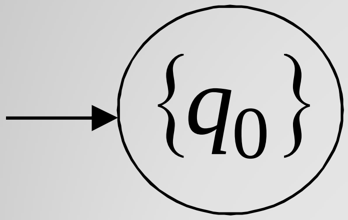
A language accepted by an NFA is also accepted by a DFA

NFA to DFA

NFA

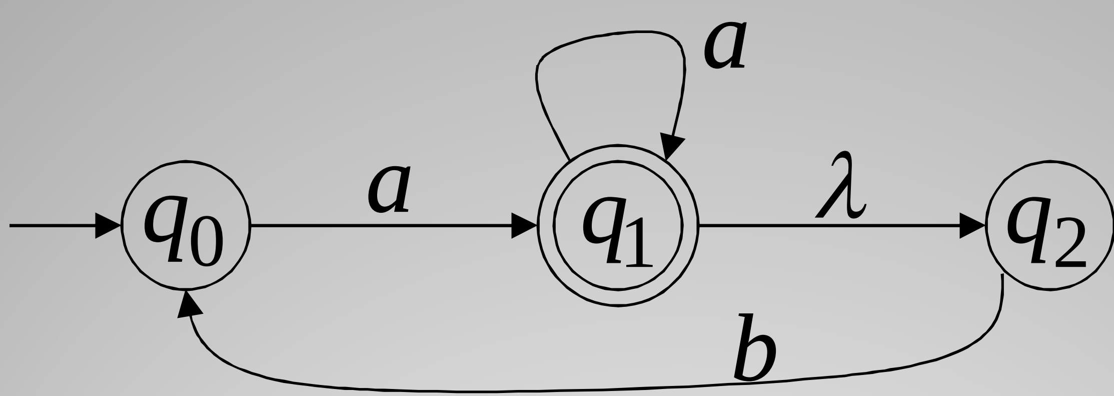


DFA

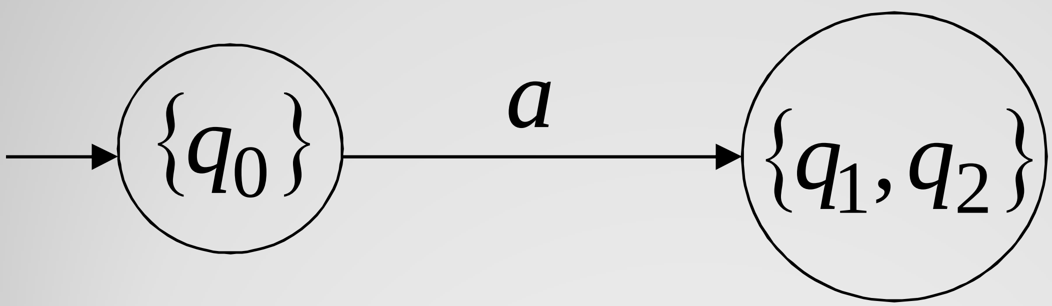


NFA to DFA

NFA

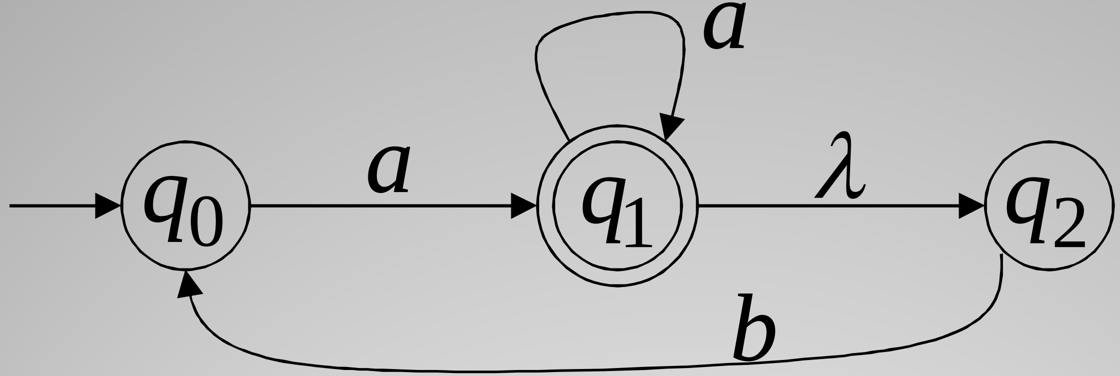


DFA

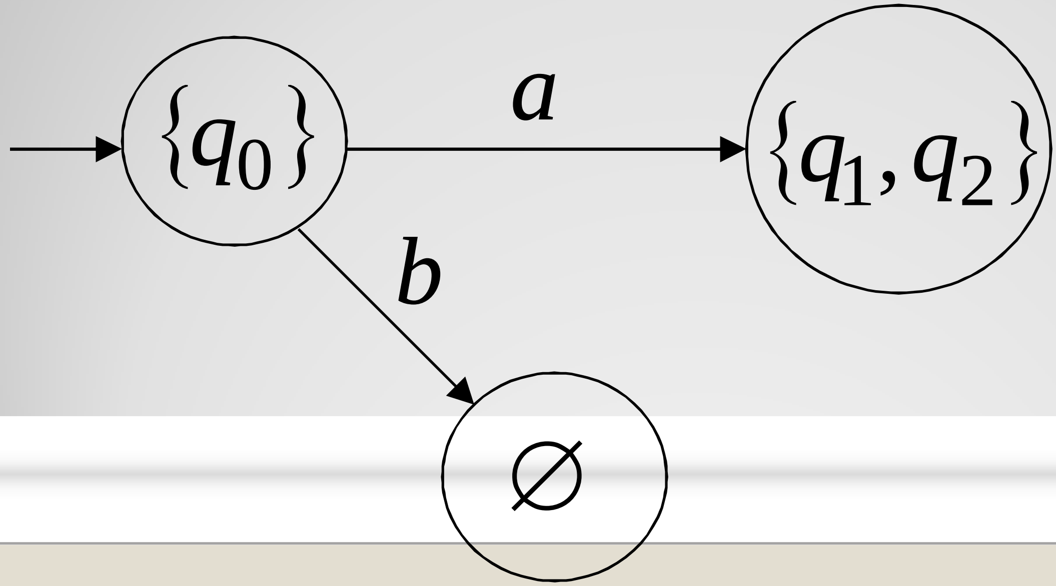


NFA to DFA

- NFA

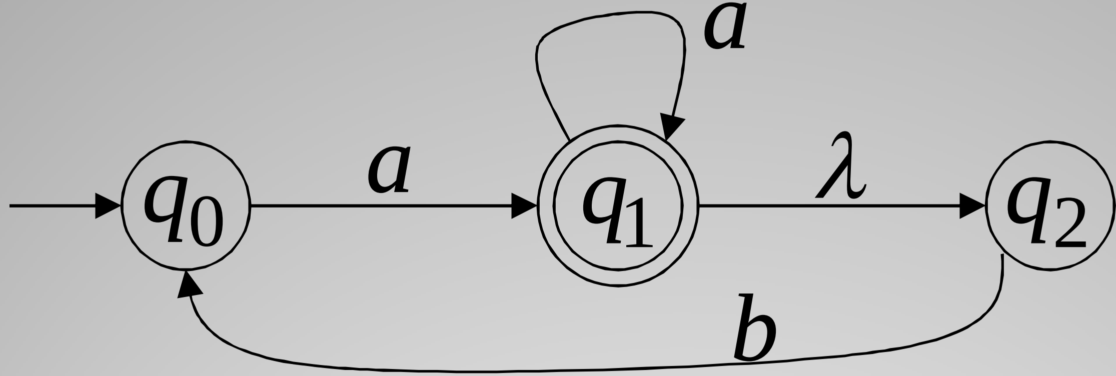


DFA

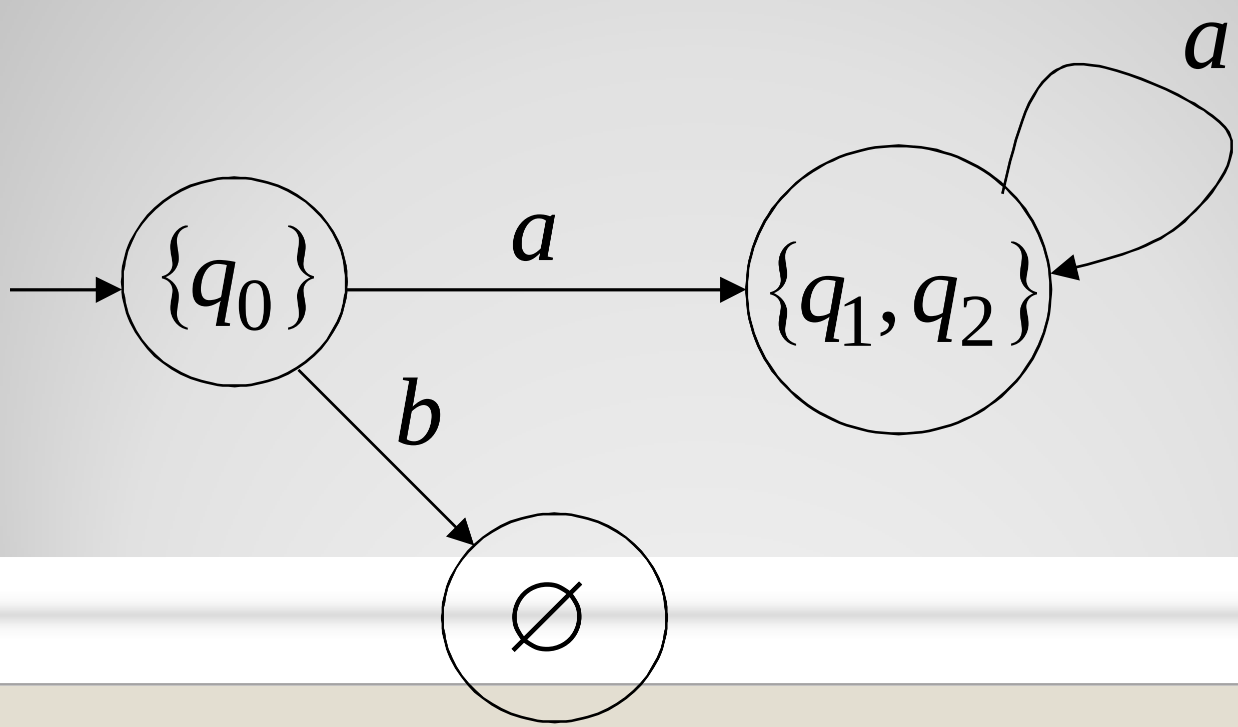


NFA to DFA

- NFA

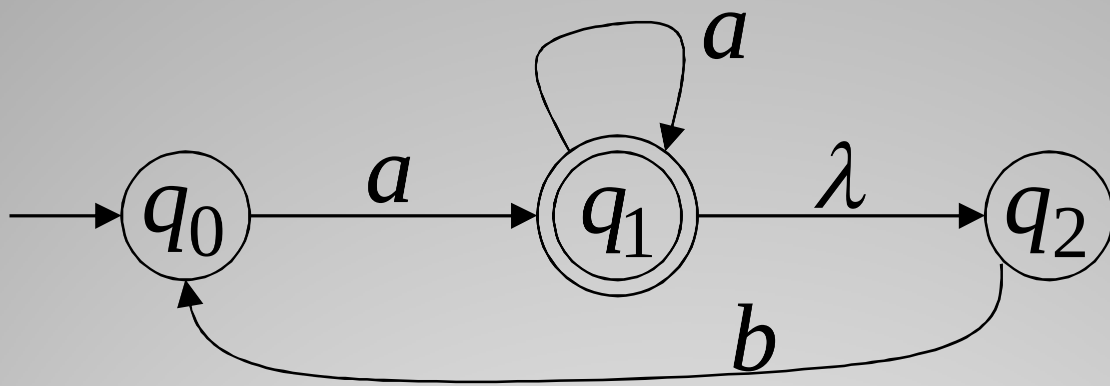


DFA

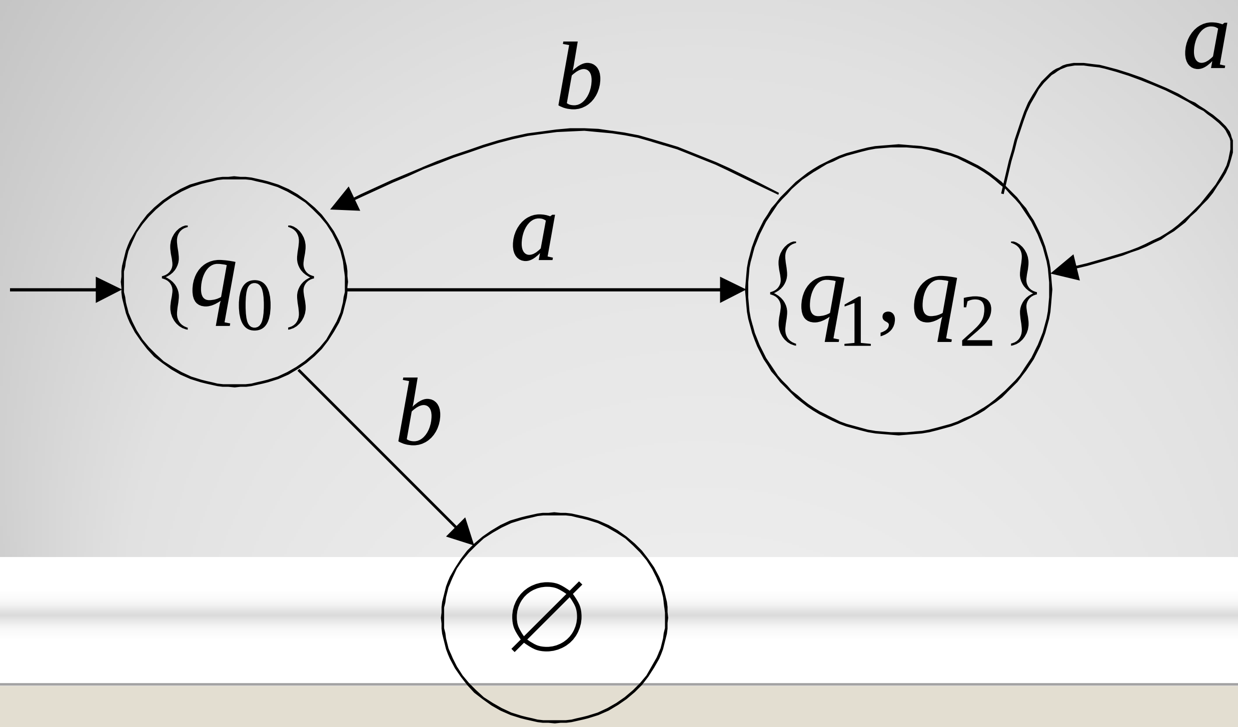


NFA to DFA

- NFA

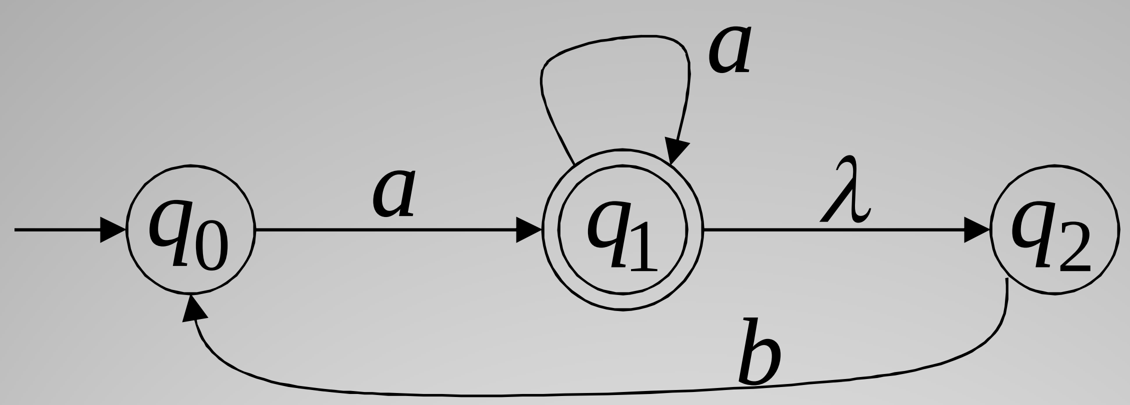


DFA

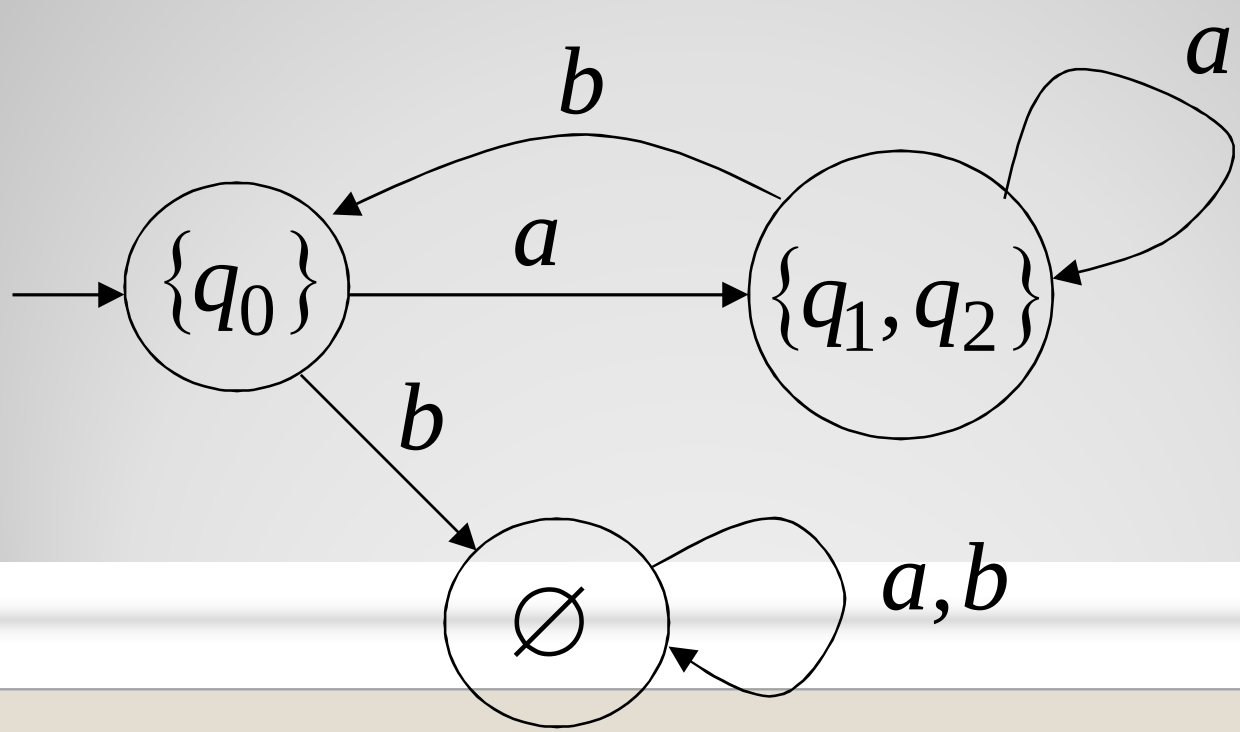


NFA to DFA

- NFA

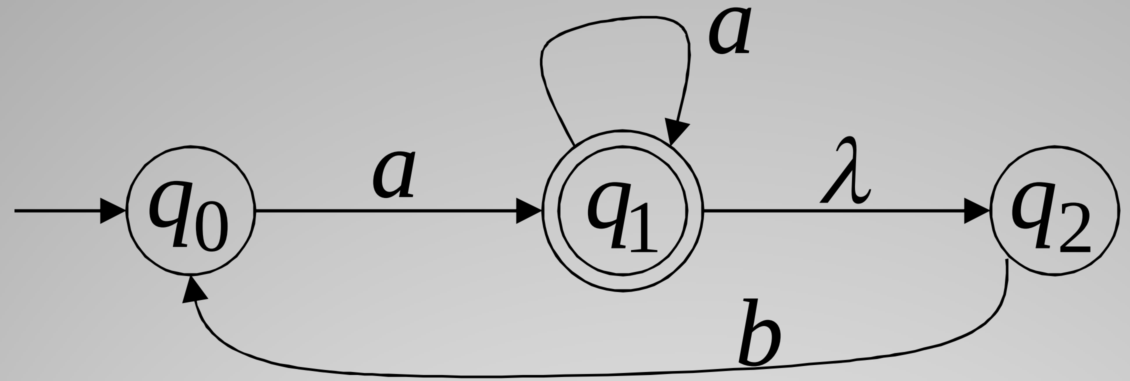


DFA

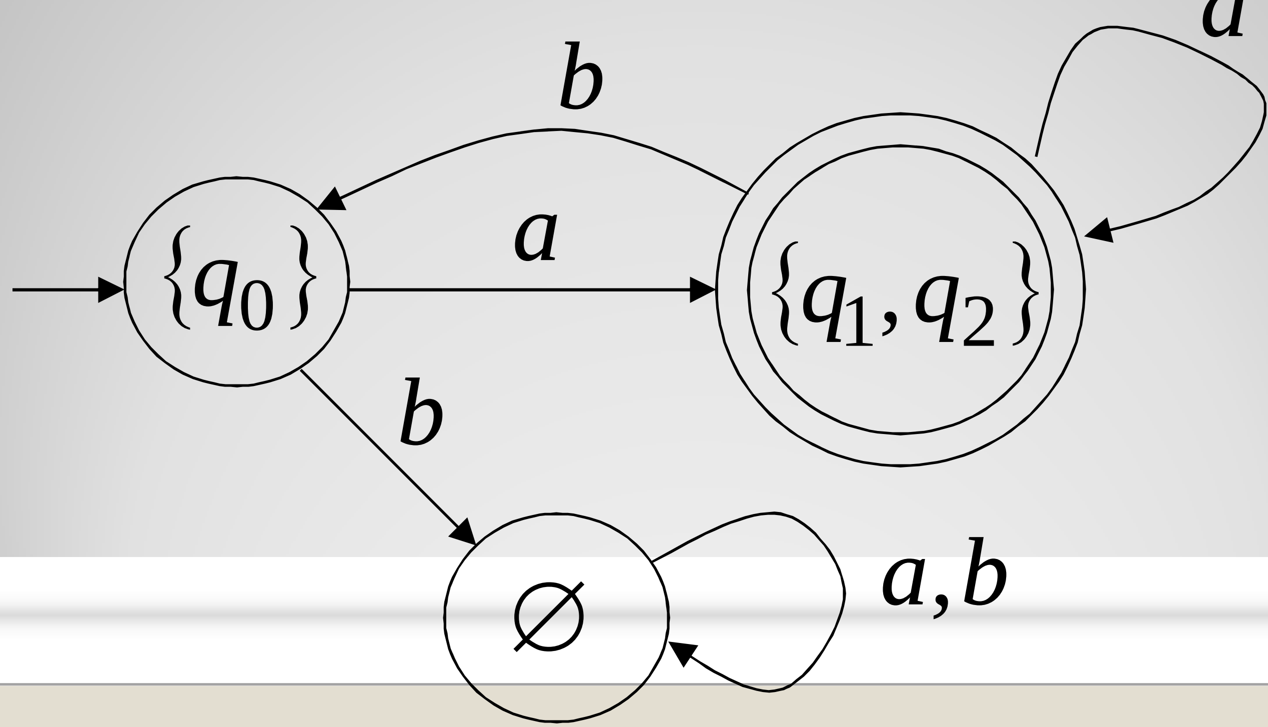


NFA to DFA

- **NFA**



DFA



NFA to DFA: Remarks

- We are given an NFA
$$M$$
- We want to convert it
- to an equivalent DFA
$$M'$$
- With
$$L(M) = L(M')$$

- If the NFA has states

$$q_0, q_1, q_2, \ldots$$

- the DFA has states in the powerset
-

$$\emptyset, \{q_0\}, \{q_1\}, \{q_1, q_2\}, \{q_3, q_4, q_7\}, \ldots.$$

Procedure NFA to DFA

- **1.** Initial state of NFA:

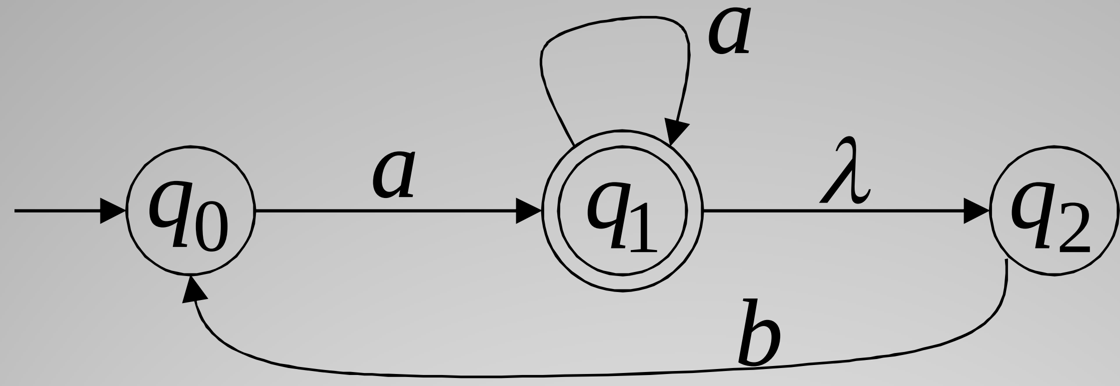
$$q_0$$

- Initial state of DFA:

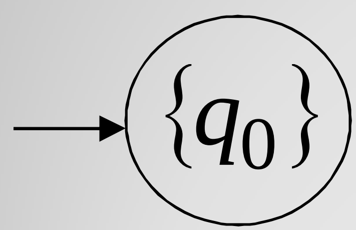
$$\{q_0\}$$

Example

NFA



DFA



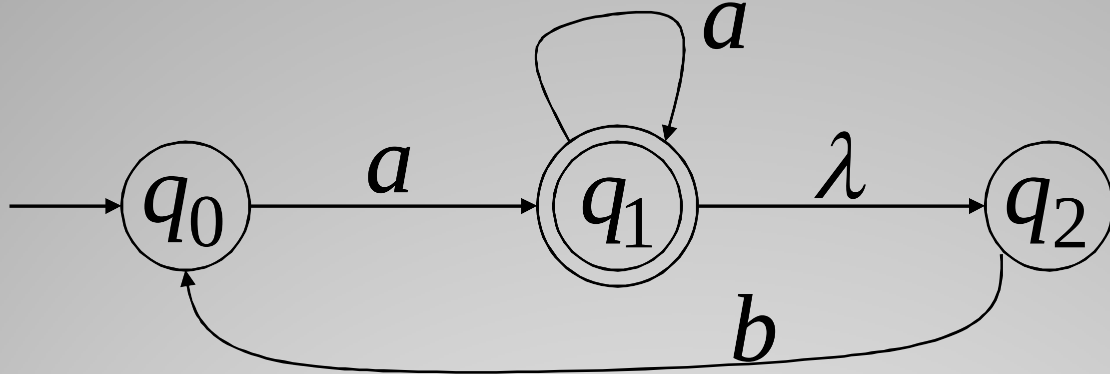
Procedure NFA to DFA

- **2.** For every DFA's state $\{q_i, q_j, \ldots, q_m\}$
- Compute in the NFA
  $$\left.\begin{array}{l}\delta^*(q_i, a), \\ \delta^*(q_j, a), \\ \ldots\end{array}\right\} = \{q'_i, q'_j, \ldots, q'_m\}$$
- Add transition

$$\delta(\{q_i, q_j, \ldots, q_m\},\ a) = \{q'_i, q'_j, \ldots, q'_m\}$$

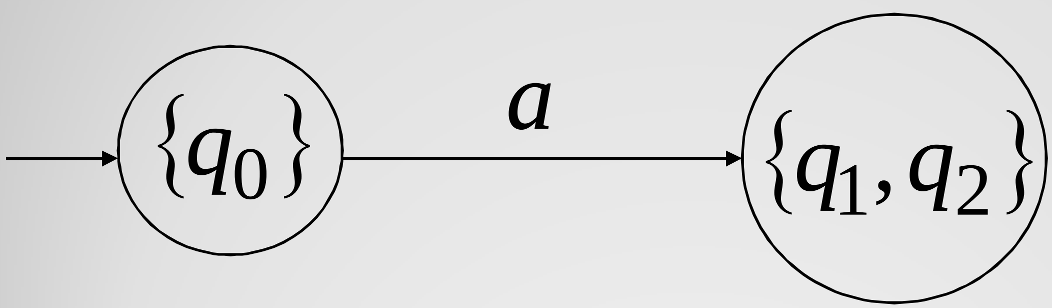
Example

- **NFA**



$$\delta^*(q_0, a) = \{q_1, q_2\}$$

DFA



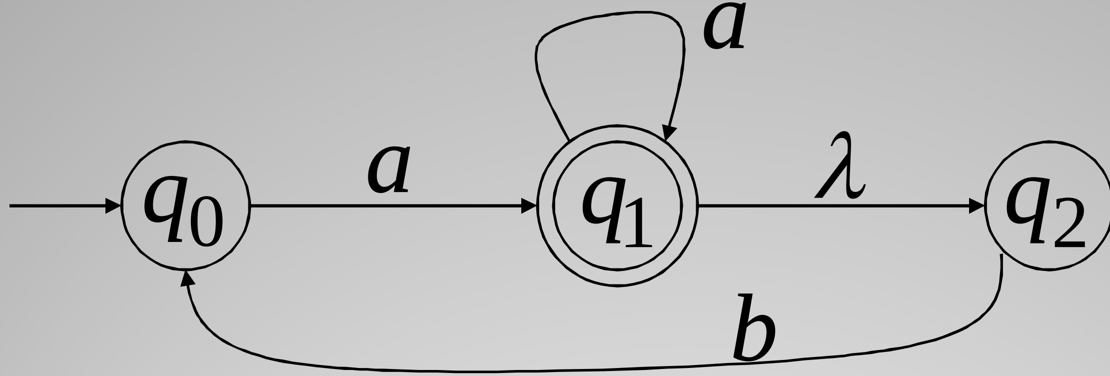
$$\delta(\{q_0\}, a) = \{q_1, q_2\}$$

Procedure NFA to DFA

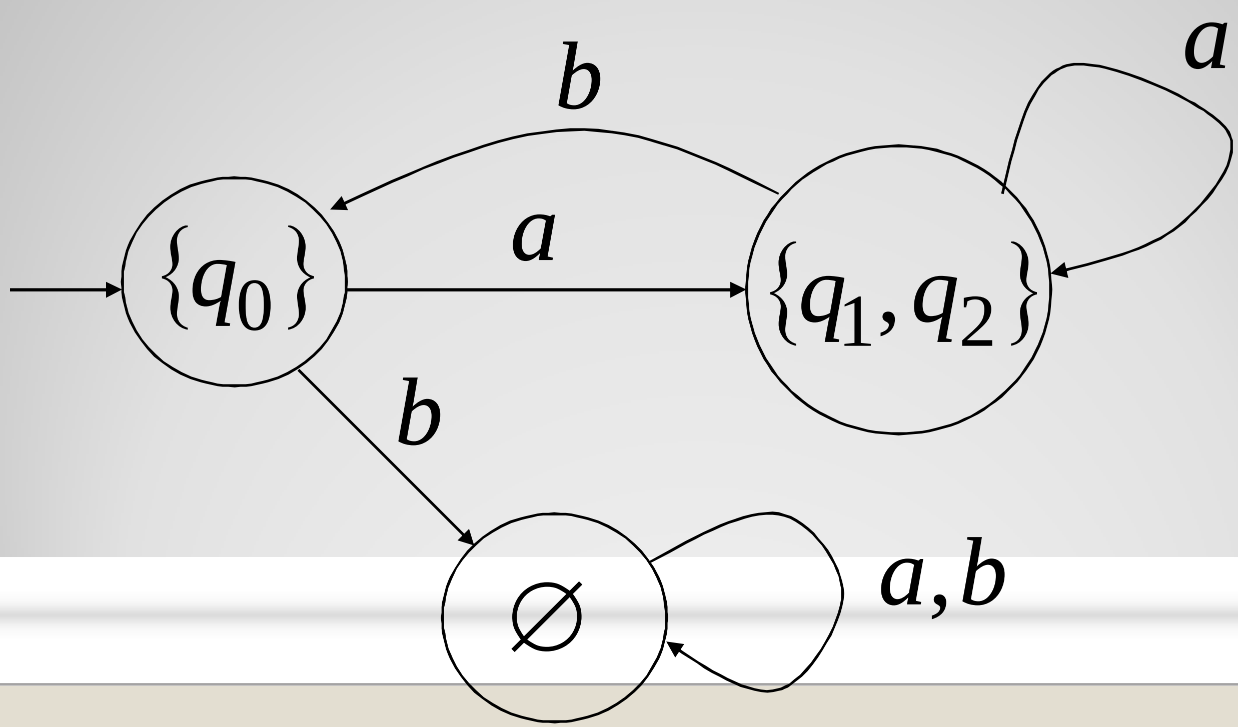
- Repeat Step 2 for all letters in alphabet,
- until
- no more transitions can be added.

Example

NFA



DFA

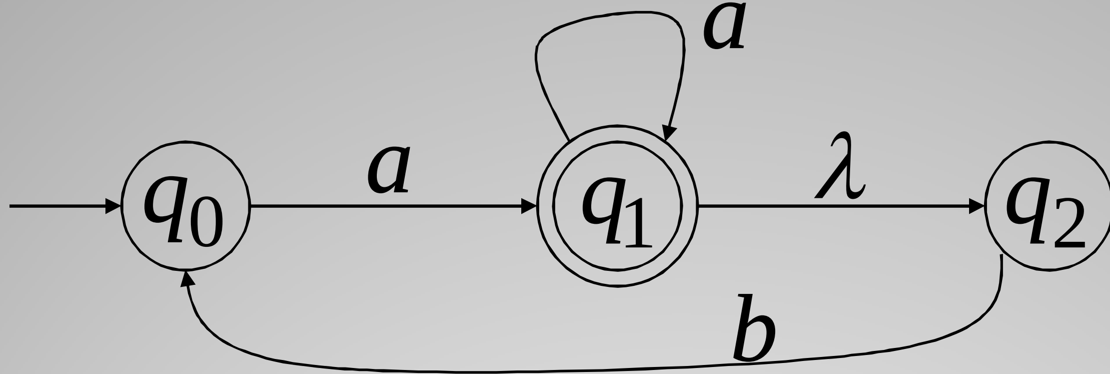


Procedure NFA to DFA

- **3.** For any DFA state $\{q_i, q_j, \ldots, q_m\}$
- If some q_j is a final state in the NFA
- Then, $\{q_i, q_j, \ldots, q_m\}$
-
- is a final state in the DFA
-

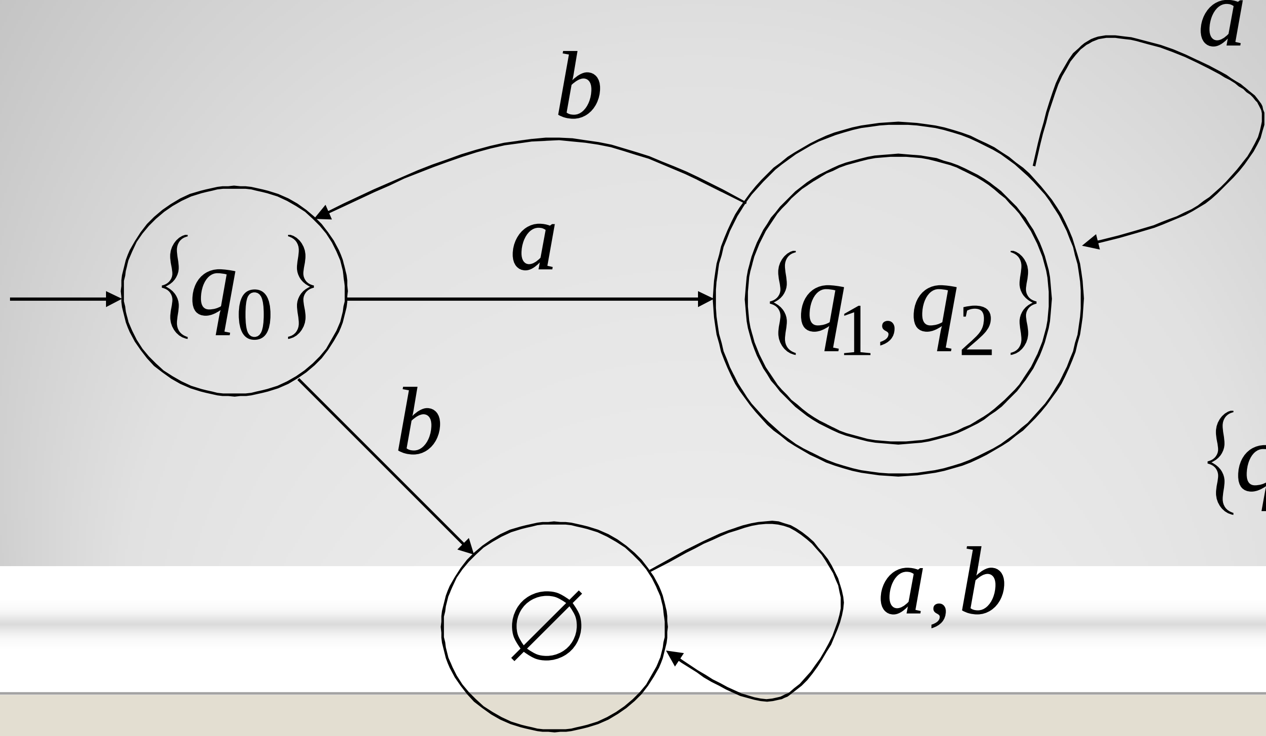
Example

NFA



$q_1 \in F$

DFA



$\{q_1, q_2\} \in F'$

Theorem

- Take NFA M

Apply procedure to obtain DFA M'

Then M and M' are equivalent :

$$L(M) = L(M')$$

Finally

We have proven

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} = \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

We have proven

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} = \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

Regular Languages

We have proven

$$\left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by NFAs} \end{array} \right\} = \left\{ \begin{array}{l} \text{Languages} \\ \text{accepted} \\ \text{by DFAs} \end{array} \right\}$$

Regular Languages

Regular Languages