2019

Theory of Computation

Kun-Ta Chuang
Department of Computer Science and Information Engineering
National Cheng Kung University

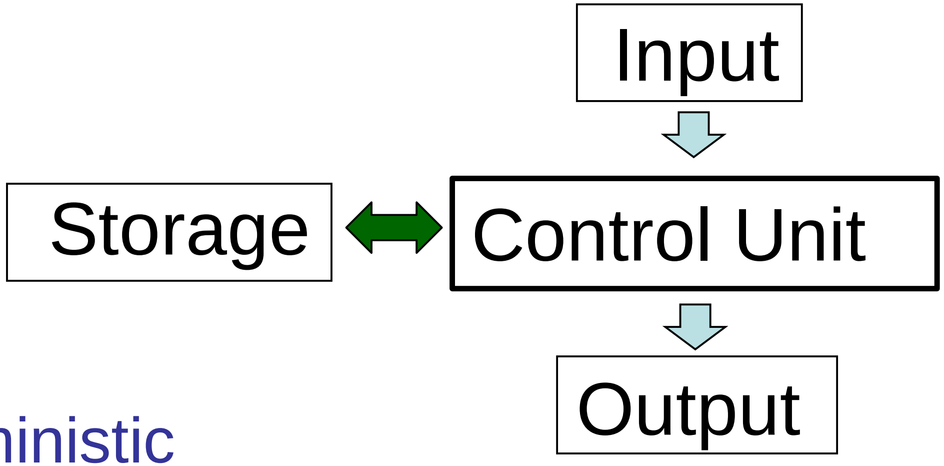
Outline

1. Deterministic Finite Accepters (DFA)
2. Nondeterministic Finite Accepters (NFA)
3. Equivalence of DFA and NFA
4. Reduction of the Number of States in FA*

Automata

Automaton: 模擬一台電腦的特定行為的model為automata

An abstract model of a digital computer



•Deterministic V.S. Nondeterministic

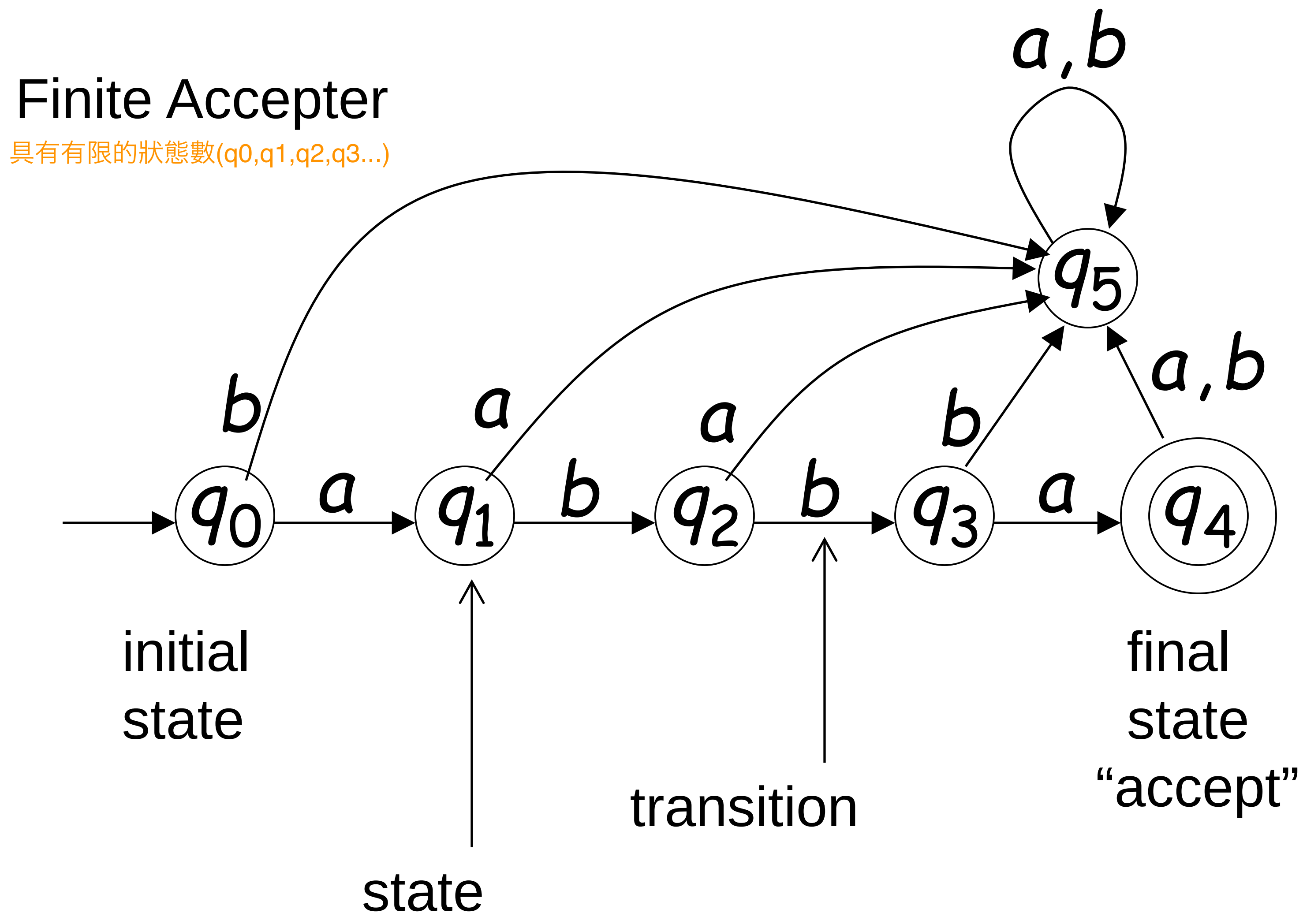
•An automaton whose output is YES or NO

Accepter

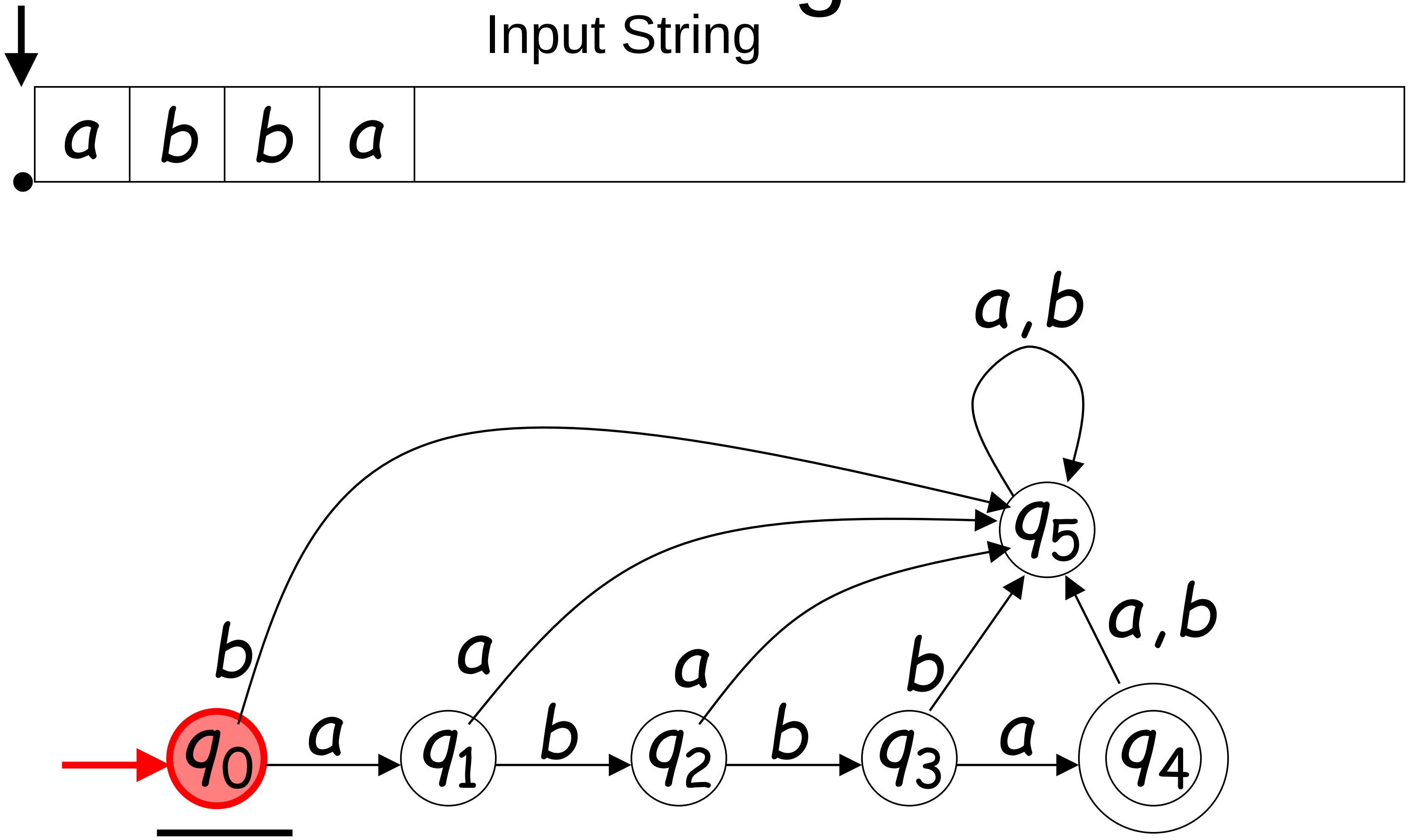
•An automaton whose output are strings of symbols

Transducer

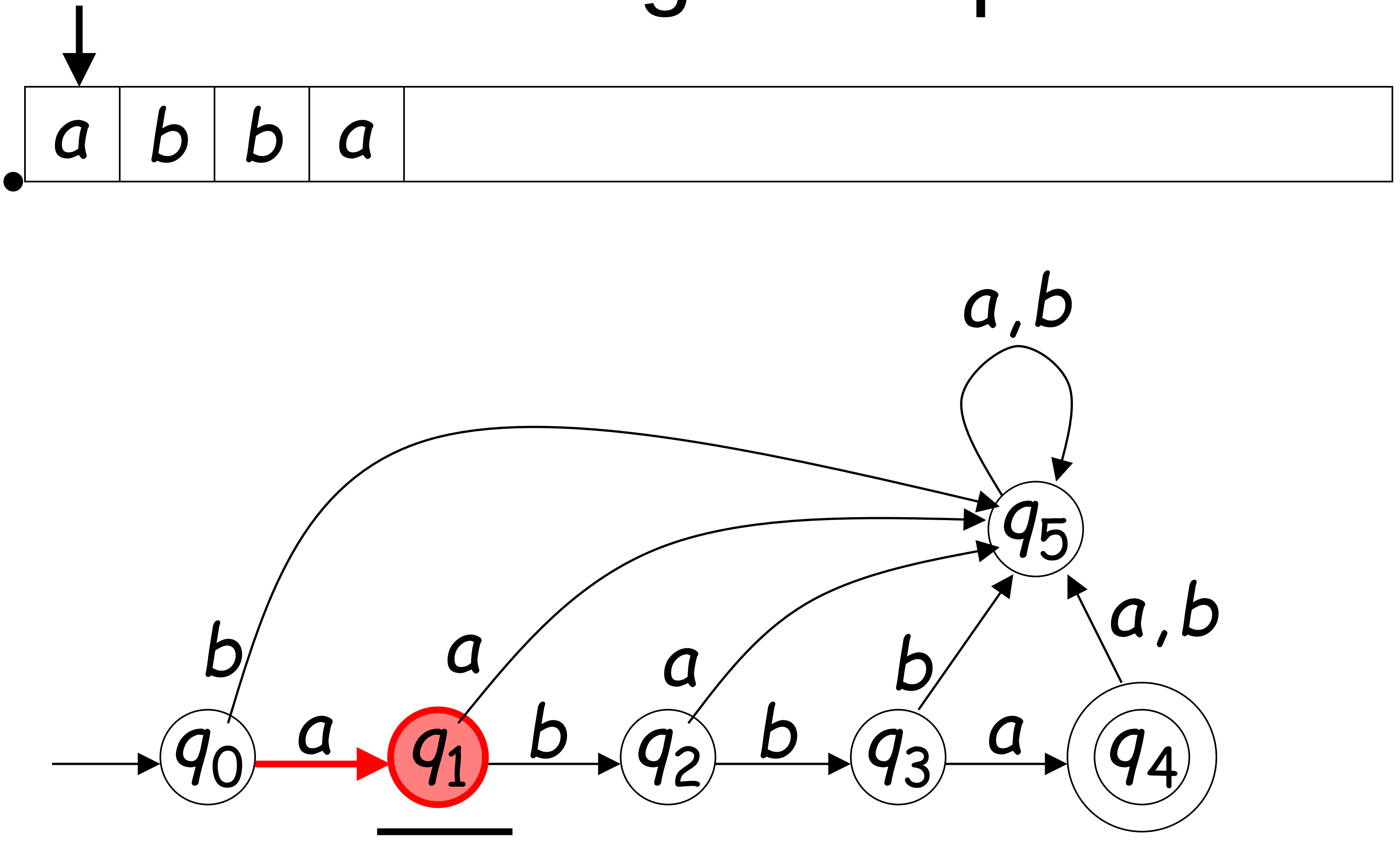
Transition Graph

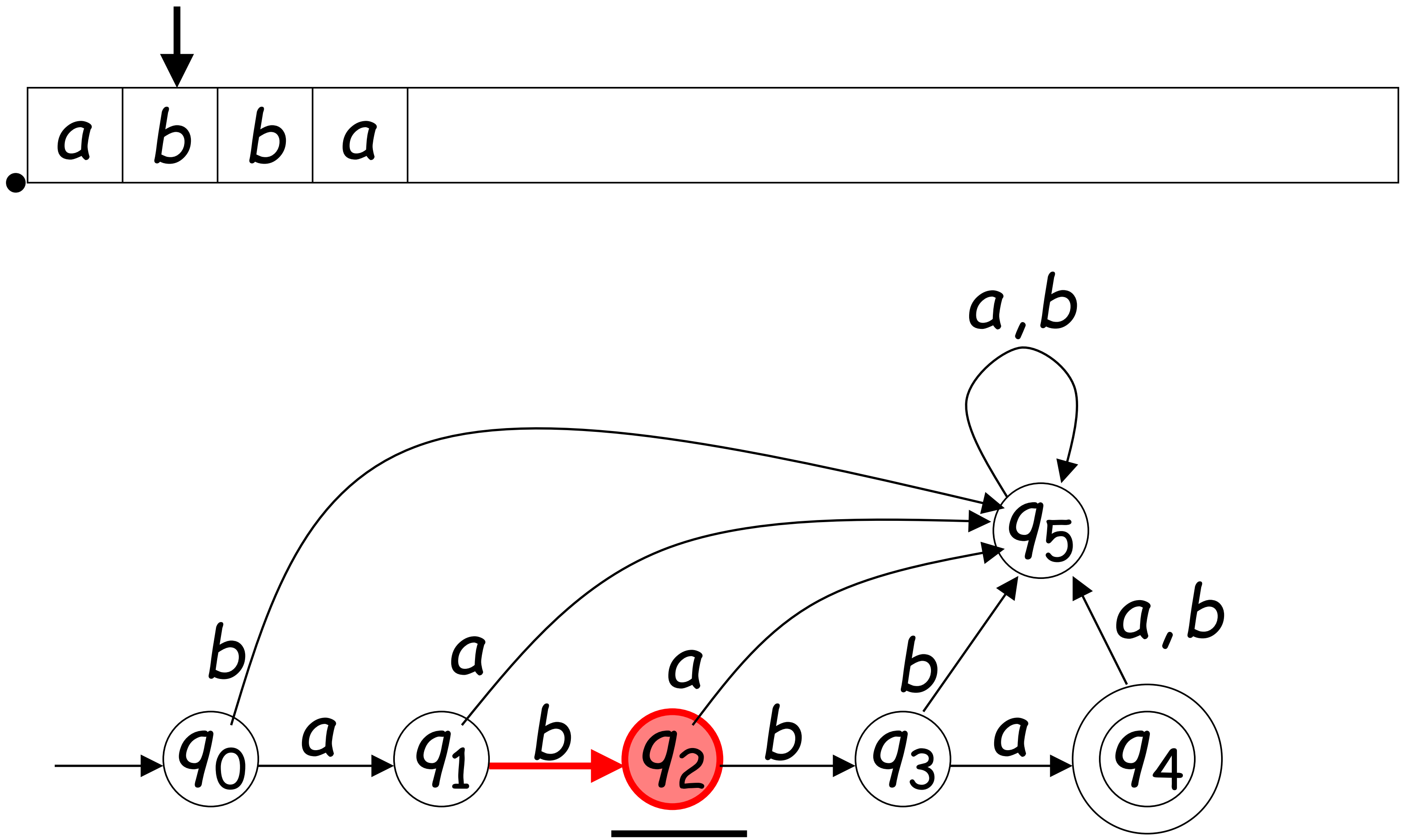


Initial Configuration

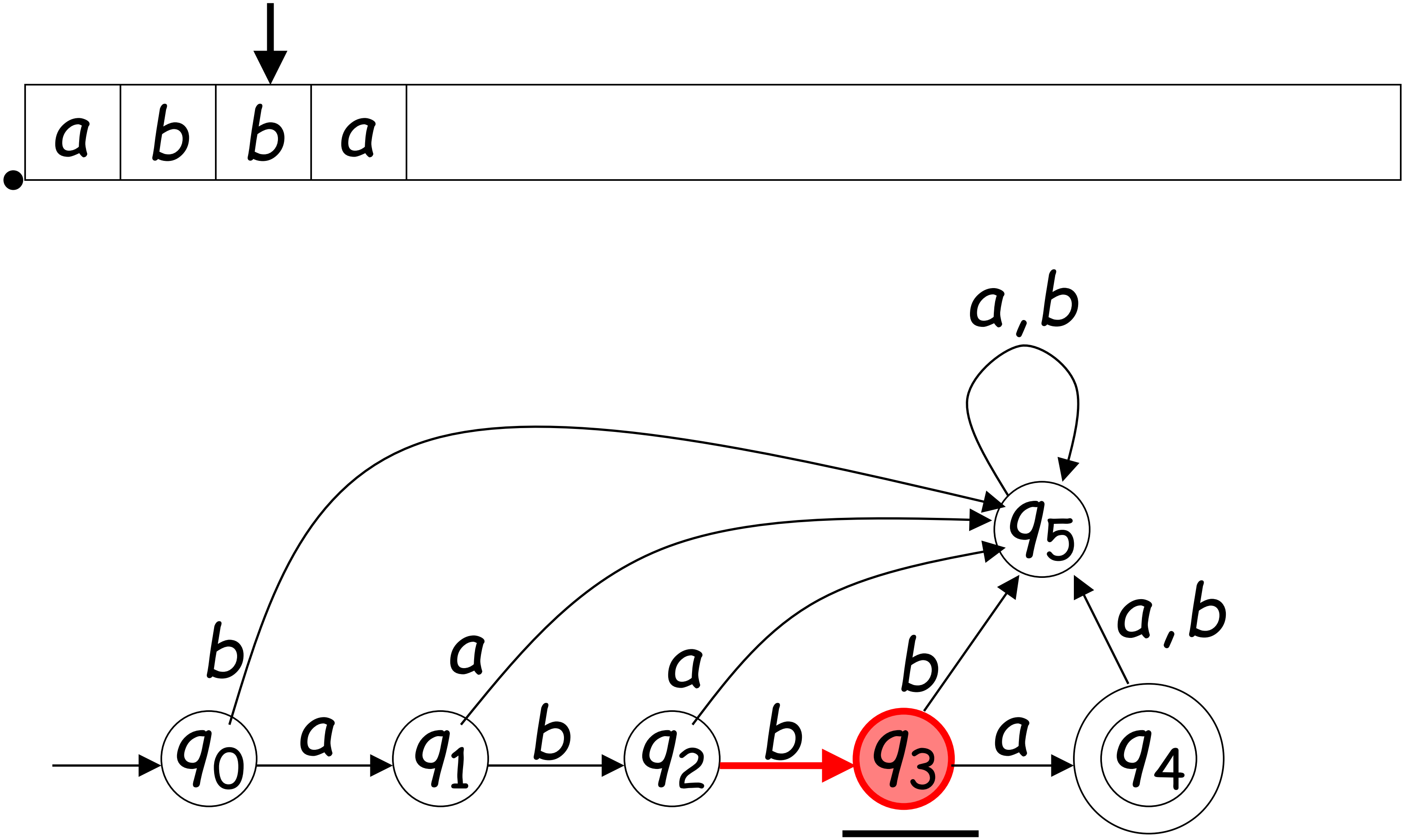


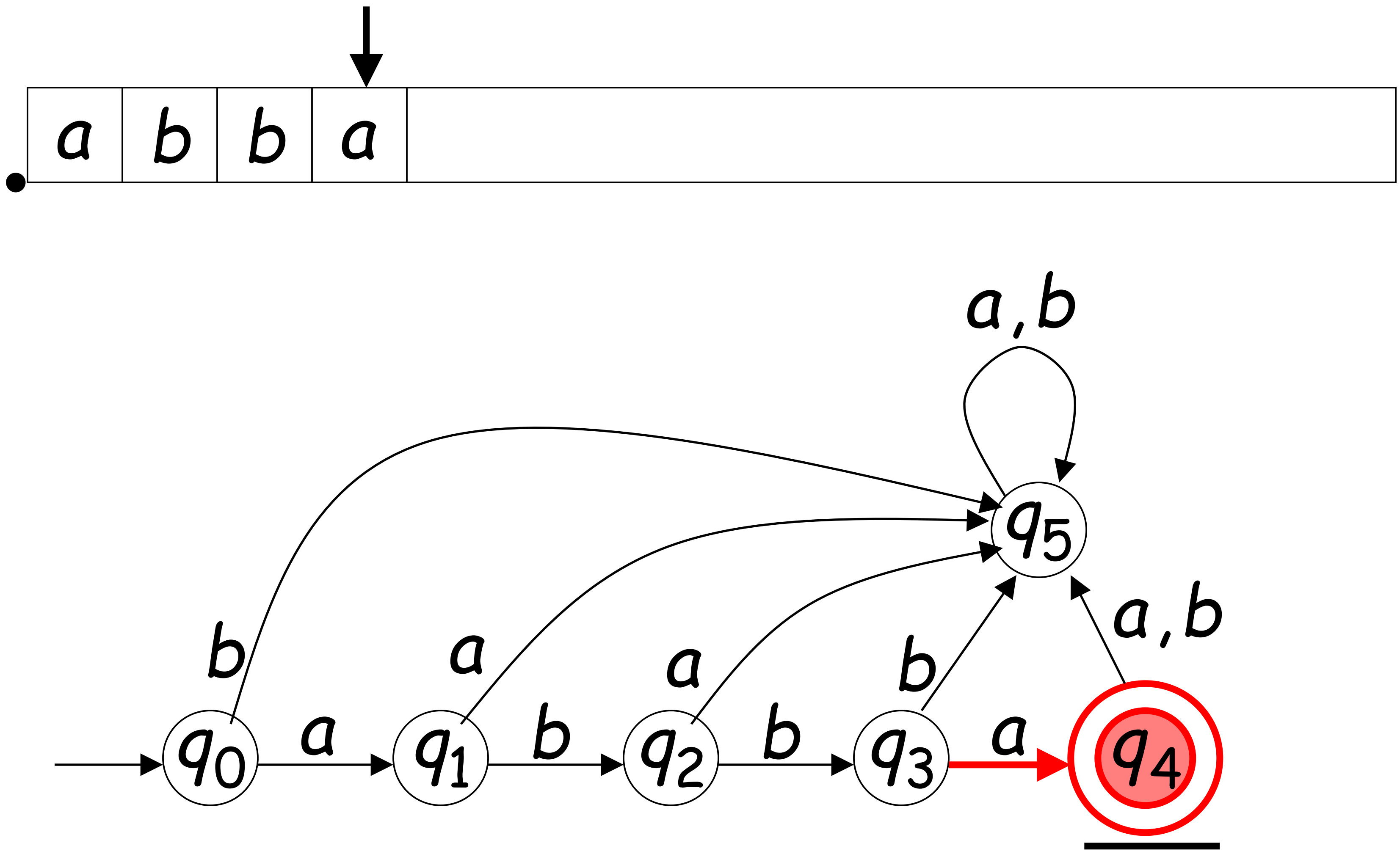
Reading the Input



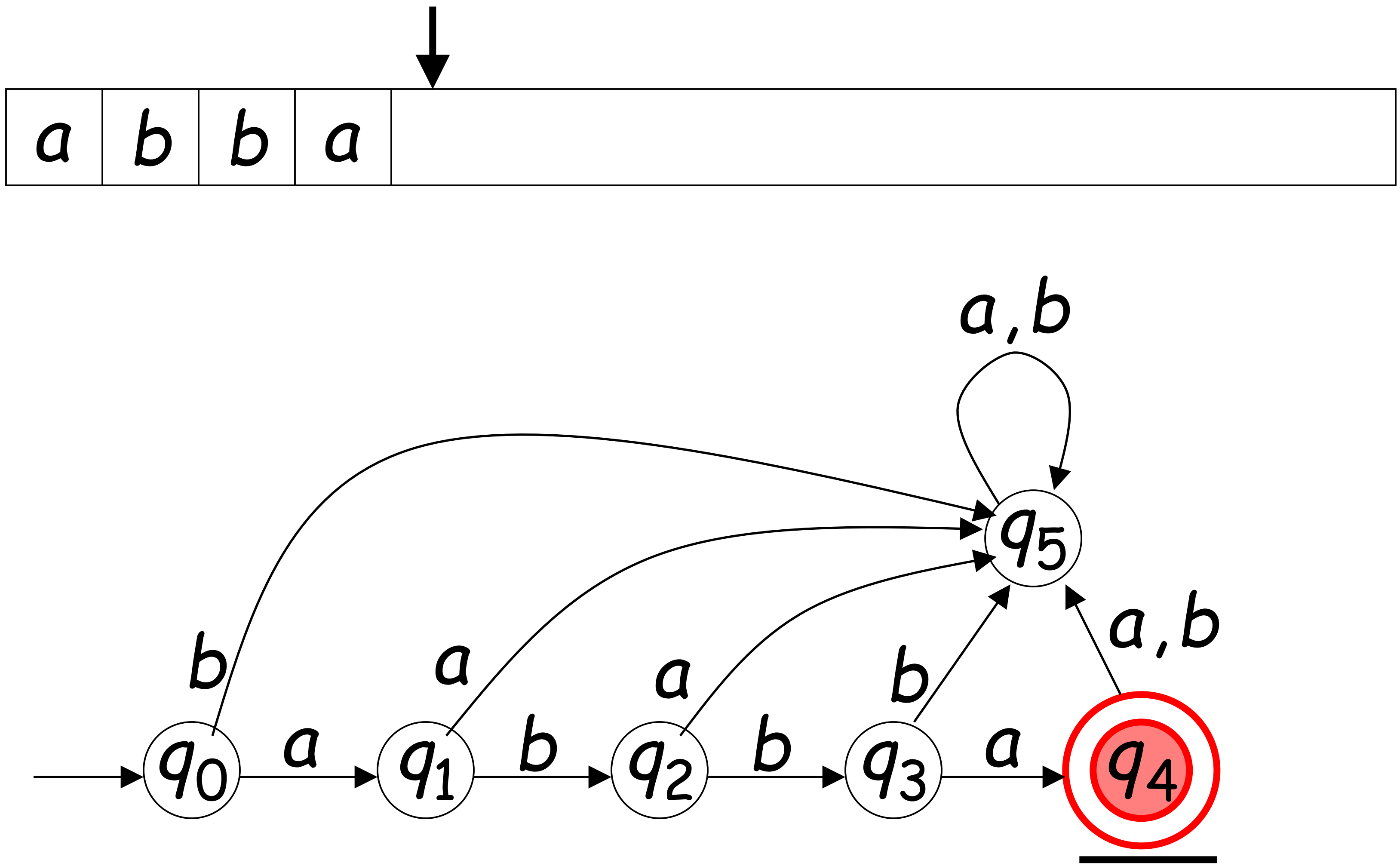


a
b
b
a
a,b
q5
b
a
a
b
a,b
q0
a
q1
b
q2
b
q3
a
q4


a
b
b
a
a,b
a,b
b
a
a
b
a
b
b
a
q0
q1
q2
q3
q4
q5

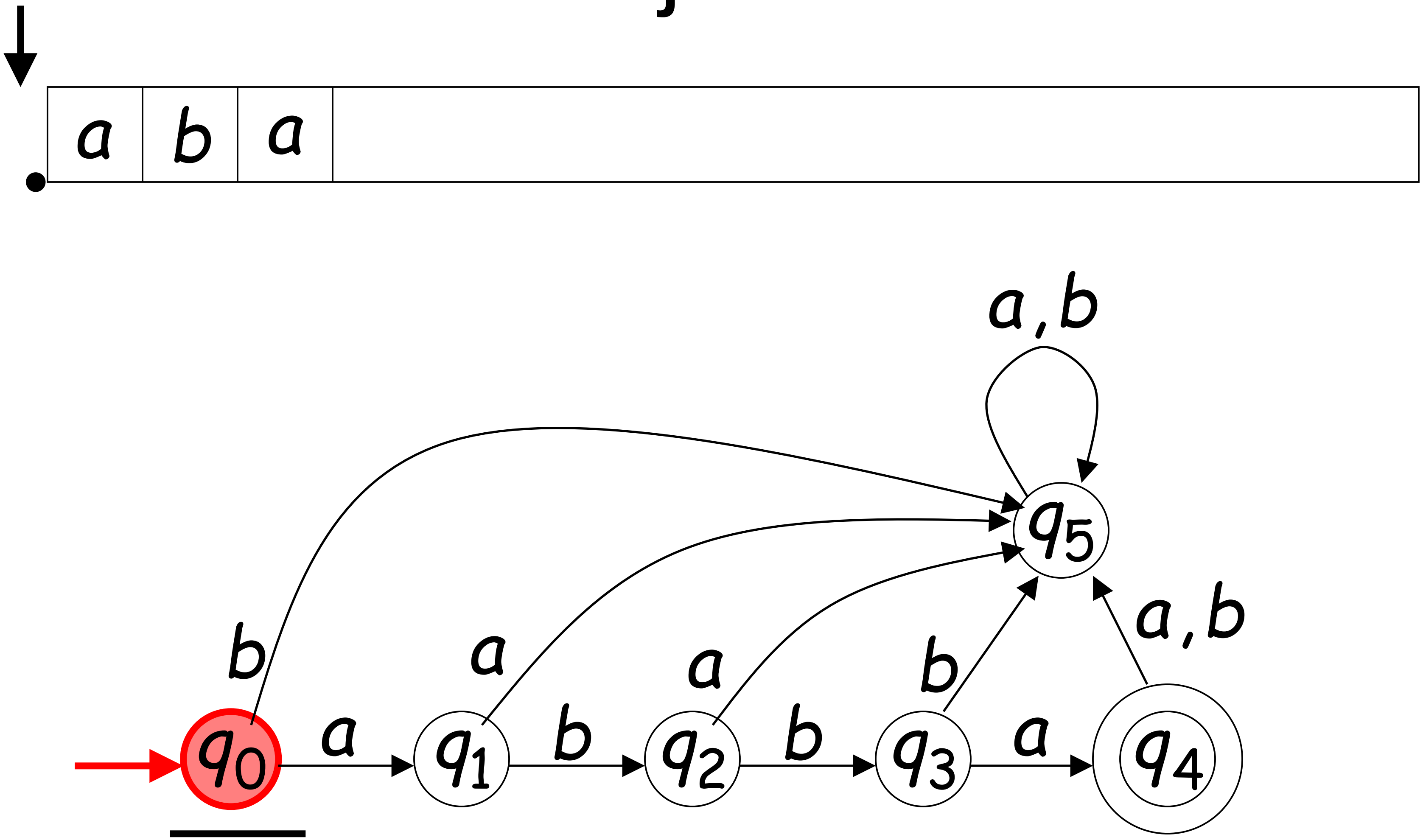

a
b
b
a
a,b
a,b
b
a
a
b
a
b
b
a
q_0
q_1
q_2
q_3
q_4
q_5

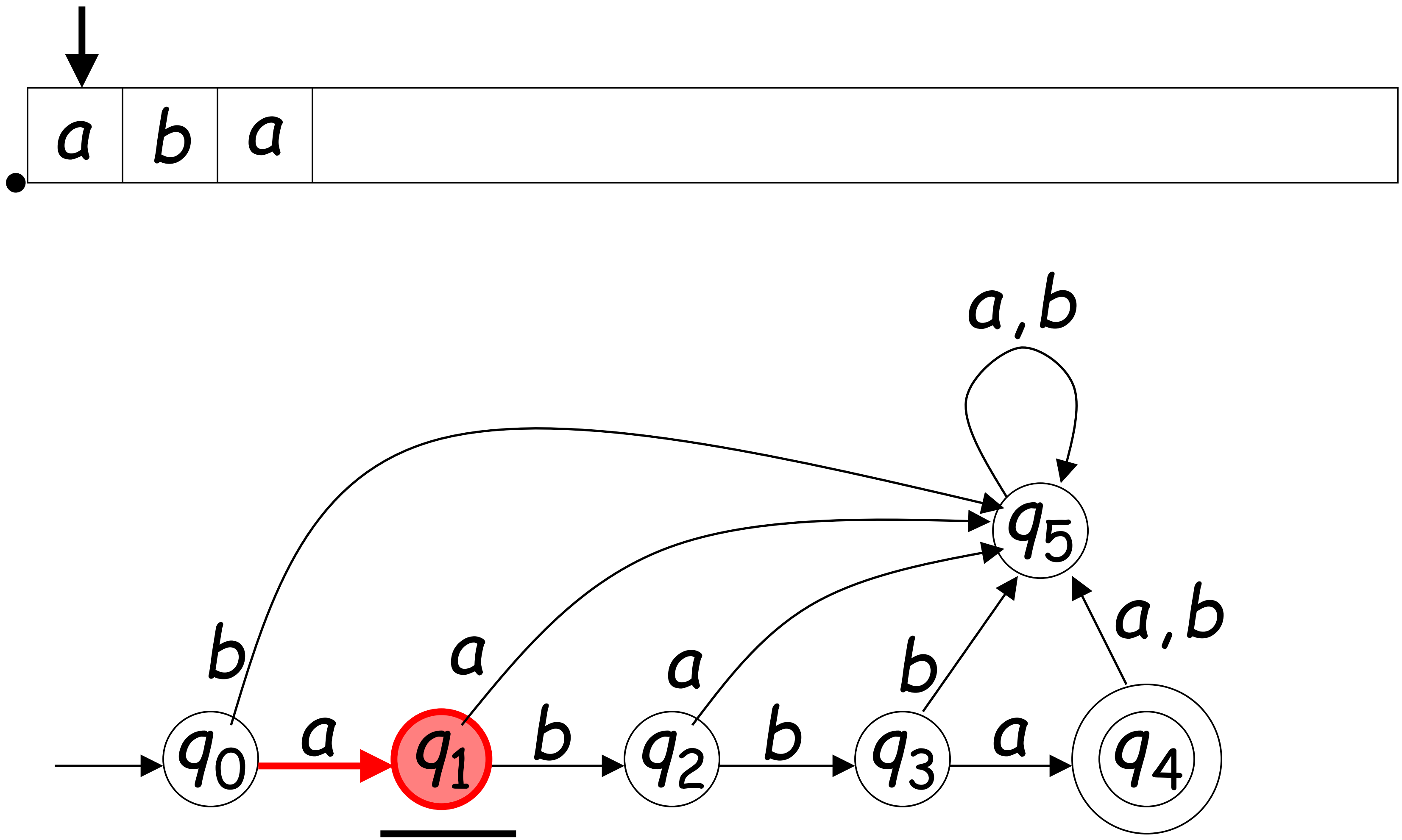
Input finished

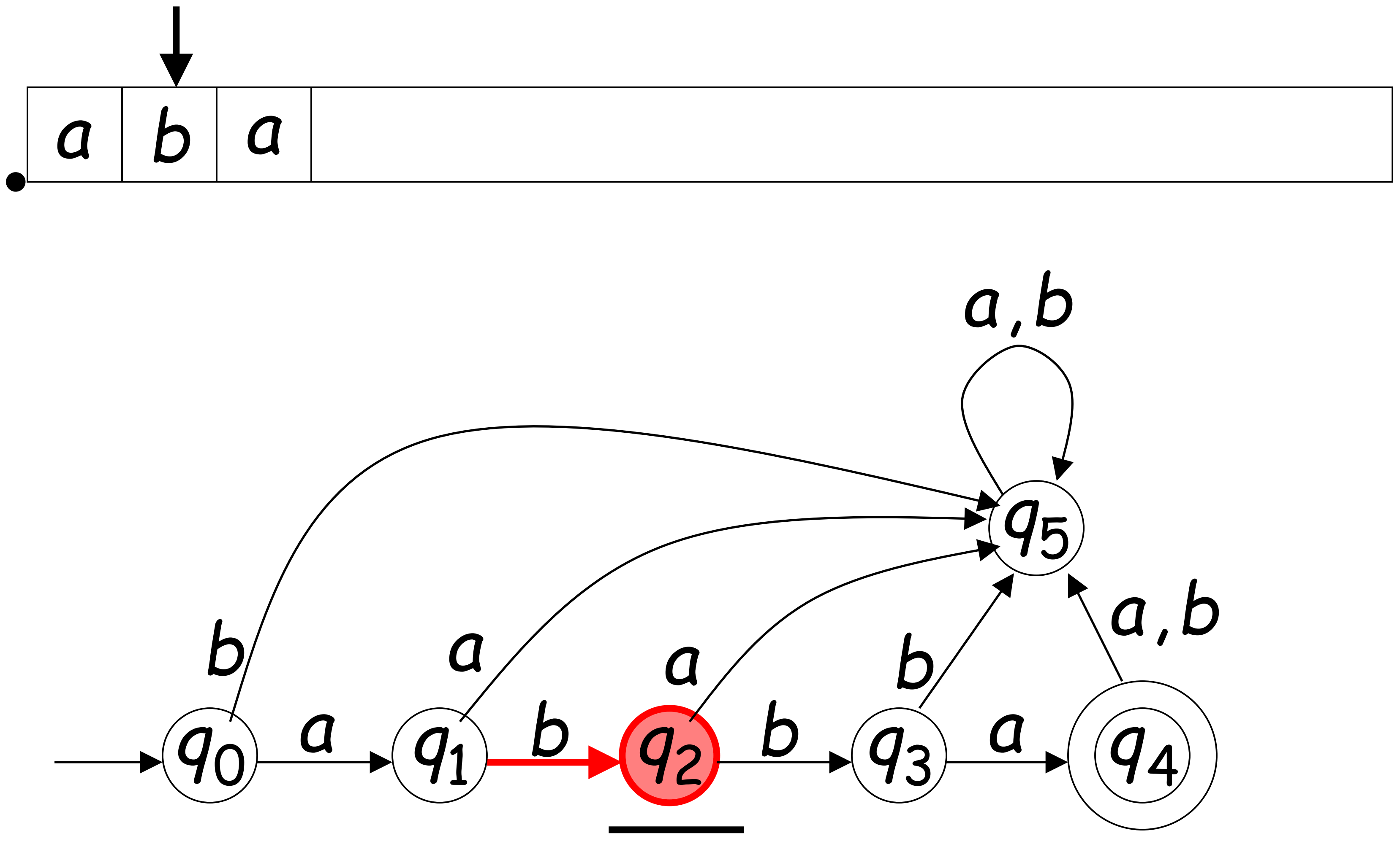


Output: “accept”

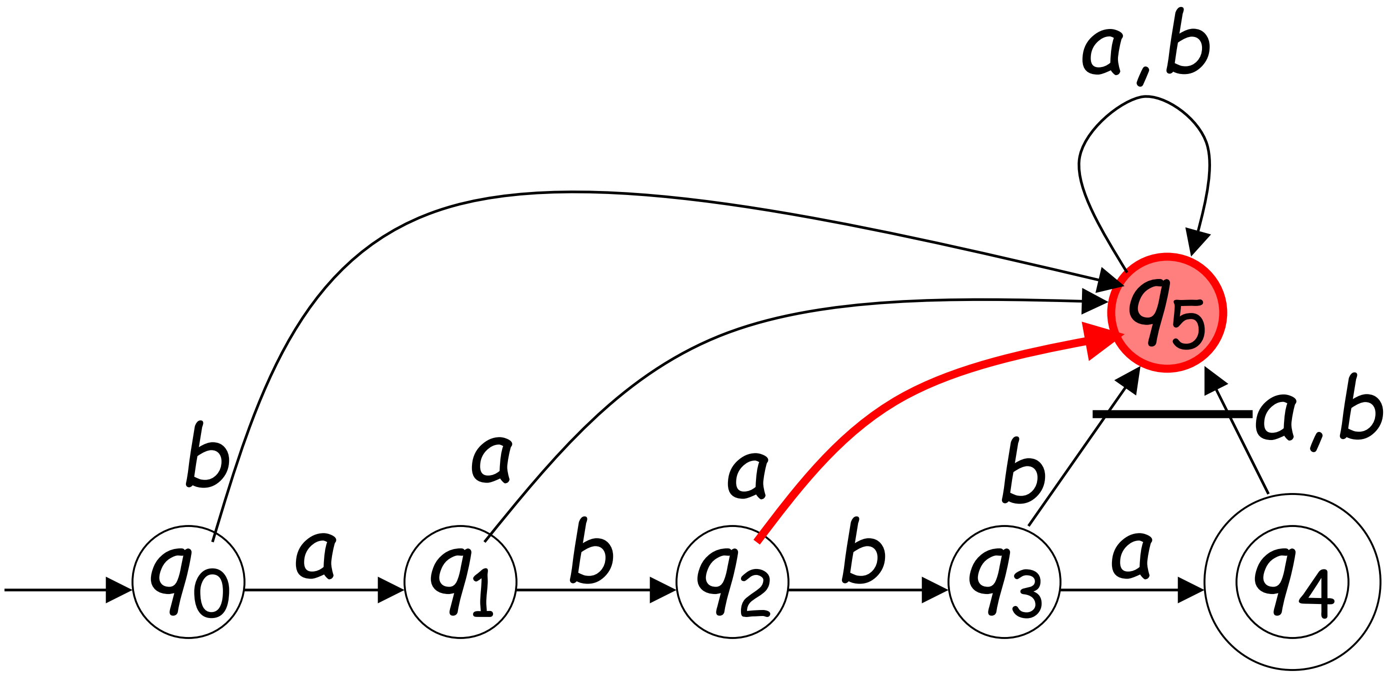
Rejection



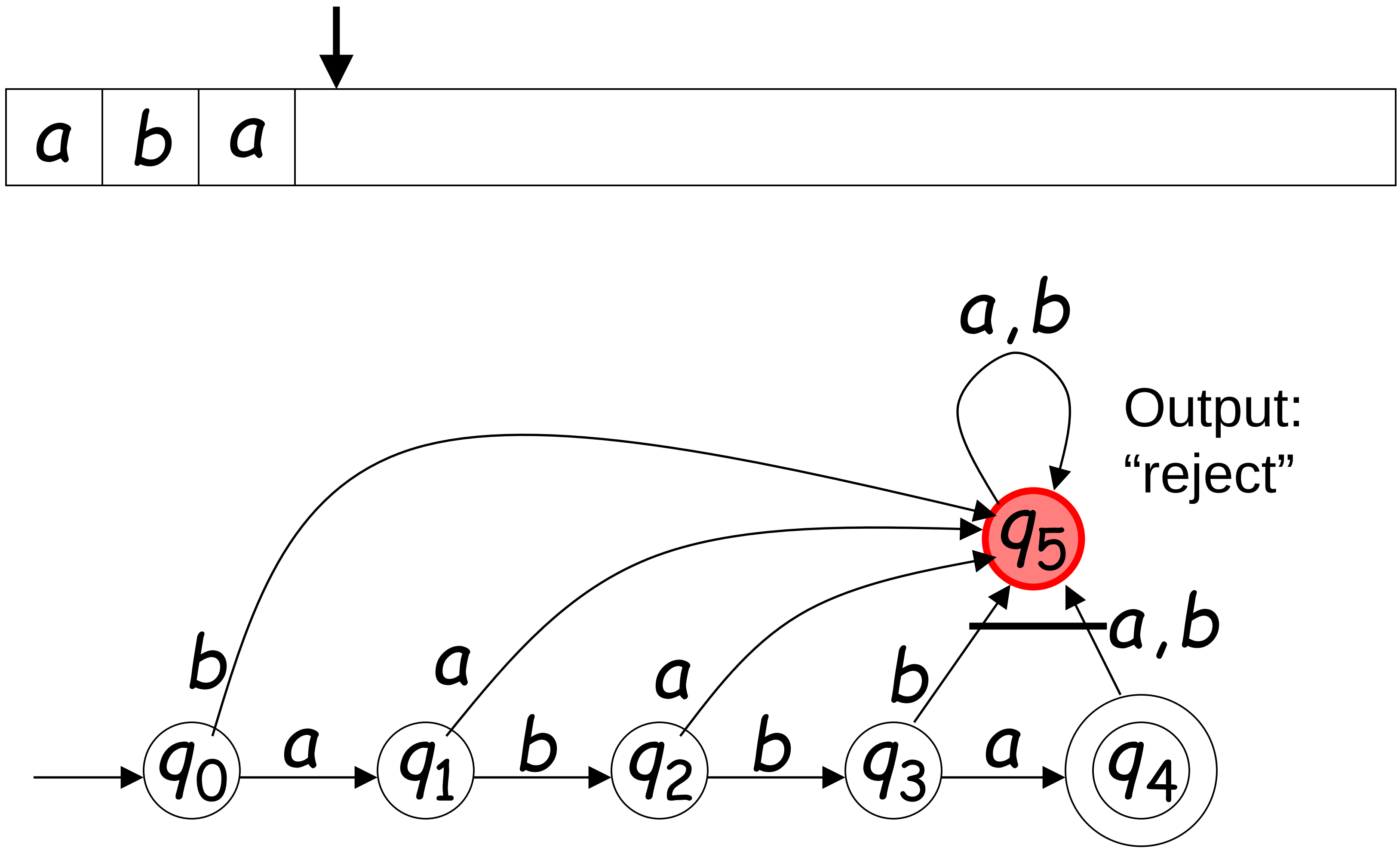

a
b
a
a,b
q5
a,b
b
a
a
b
q0
a
q1
b
q2
b
q3
a
q4


a
b
a
a,b
q5
b
a
a
b
a,b
a
b
b
a
q0
q1
q2
q3
q4


a
b
a


a,b
q5
b
a
a
b
a,b
q0
a
q1
b
q2
b
q3
a
q4

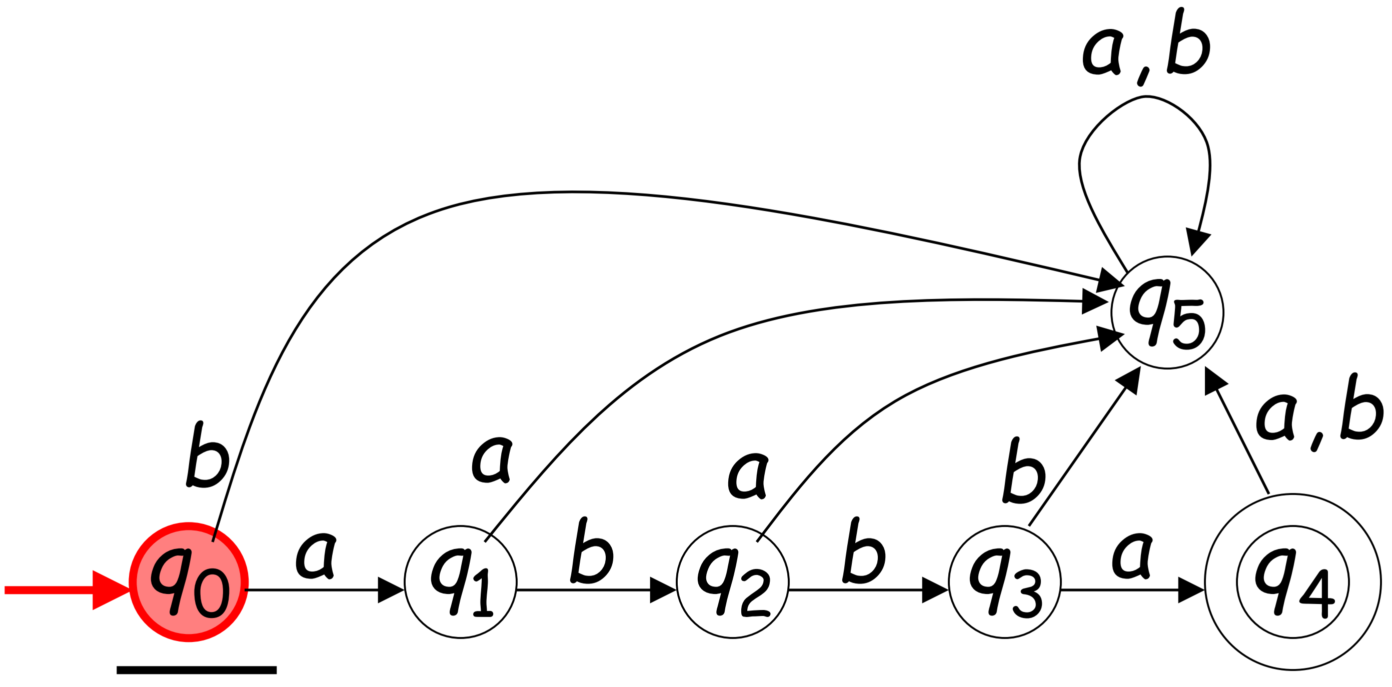
Input finished

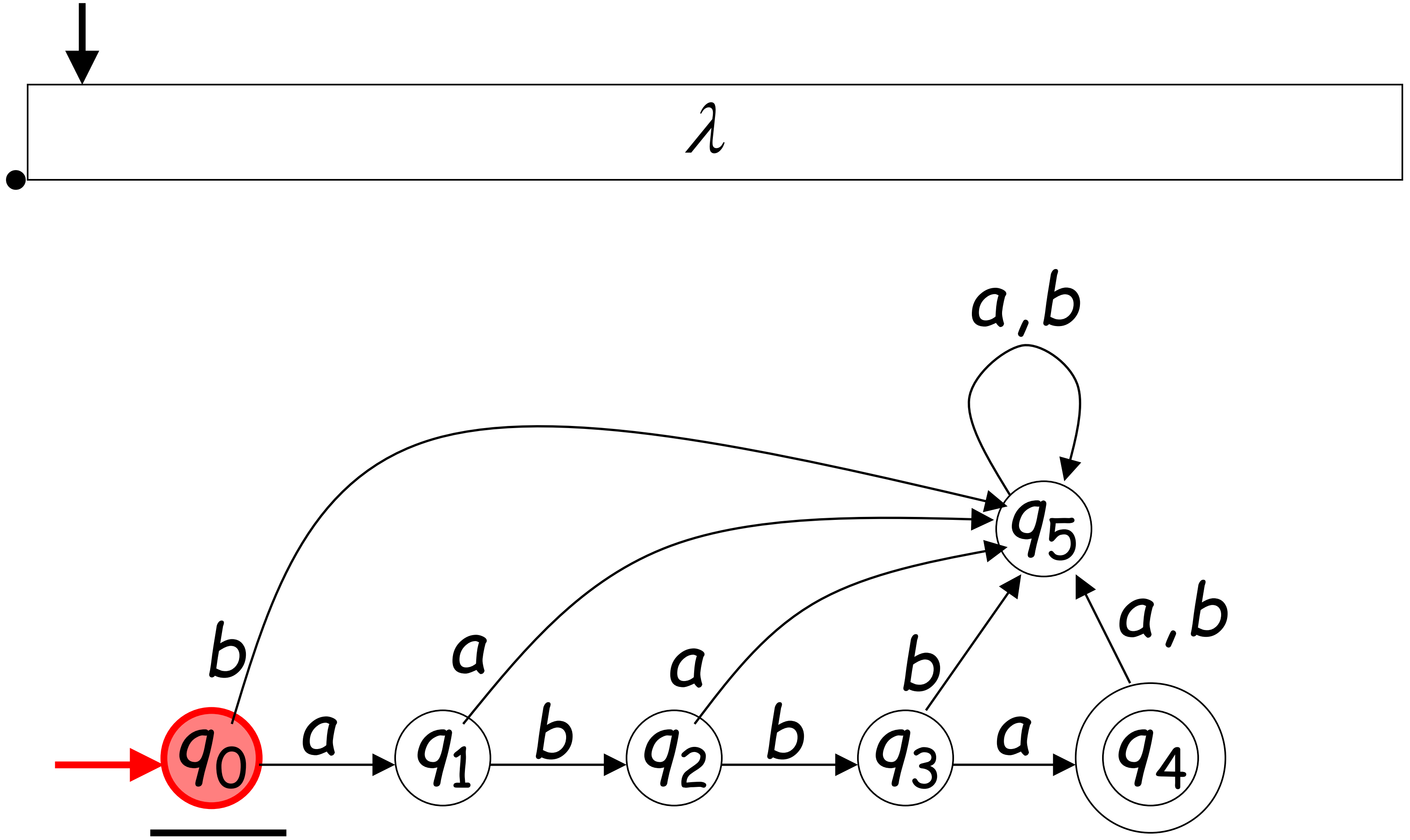


Another Rejection

λ

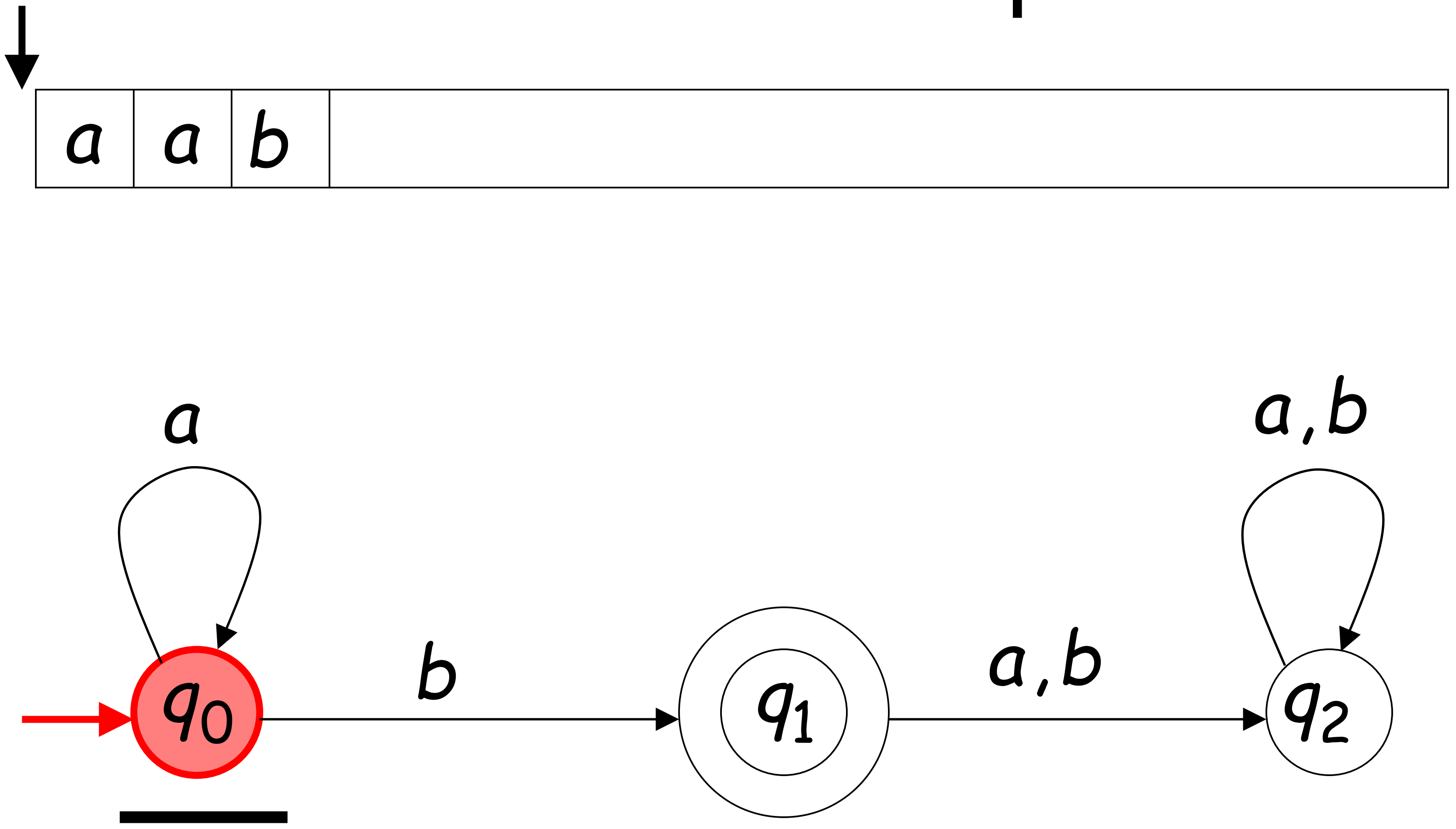
看到lambda不屬於a,b所以看到它不用動作，停在q0就沒了，所以結果為reject

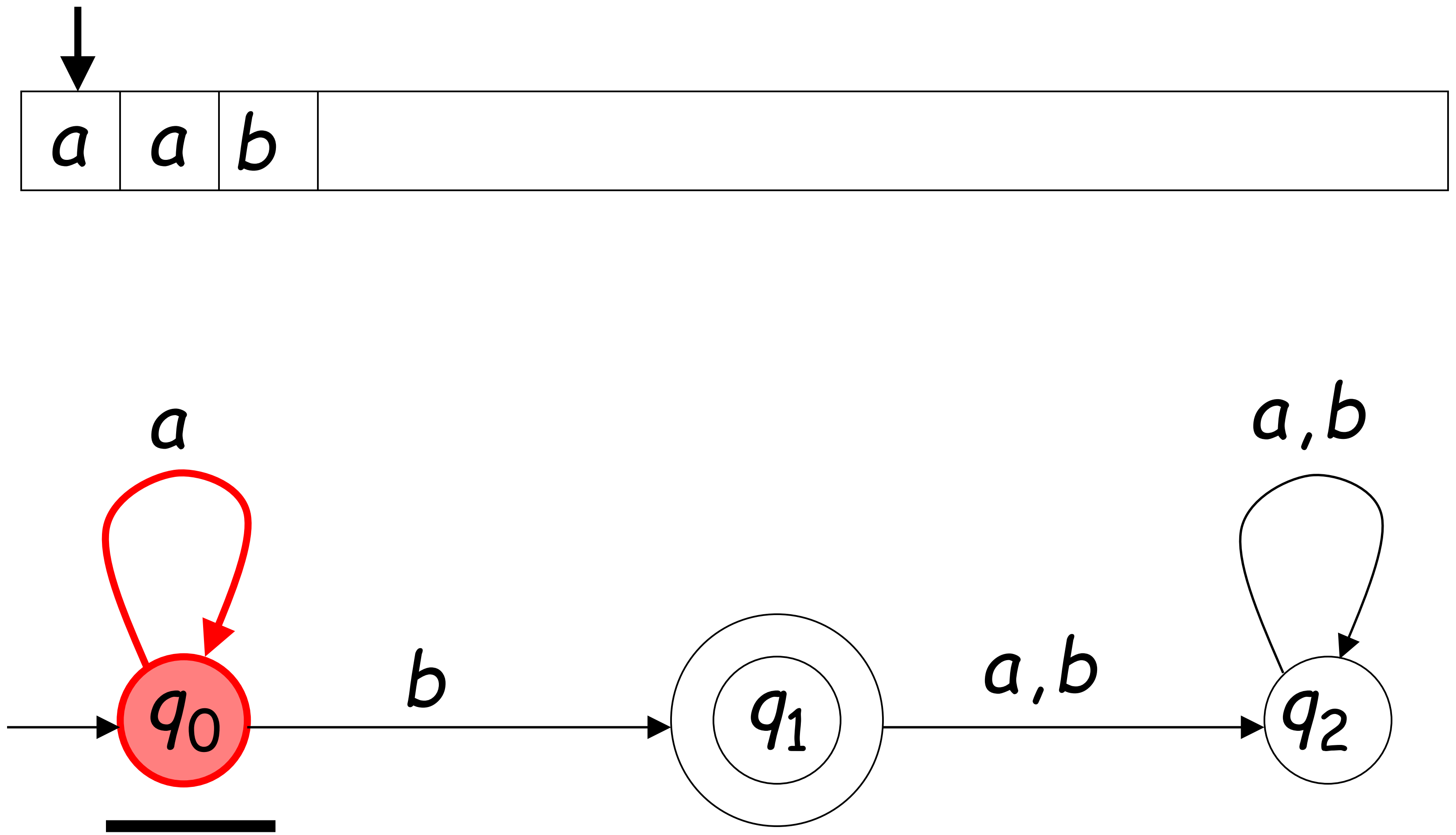


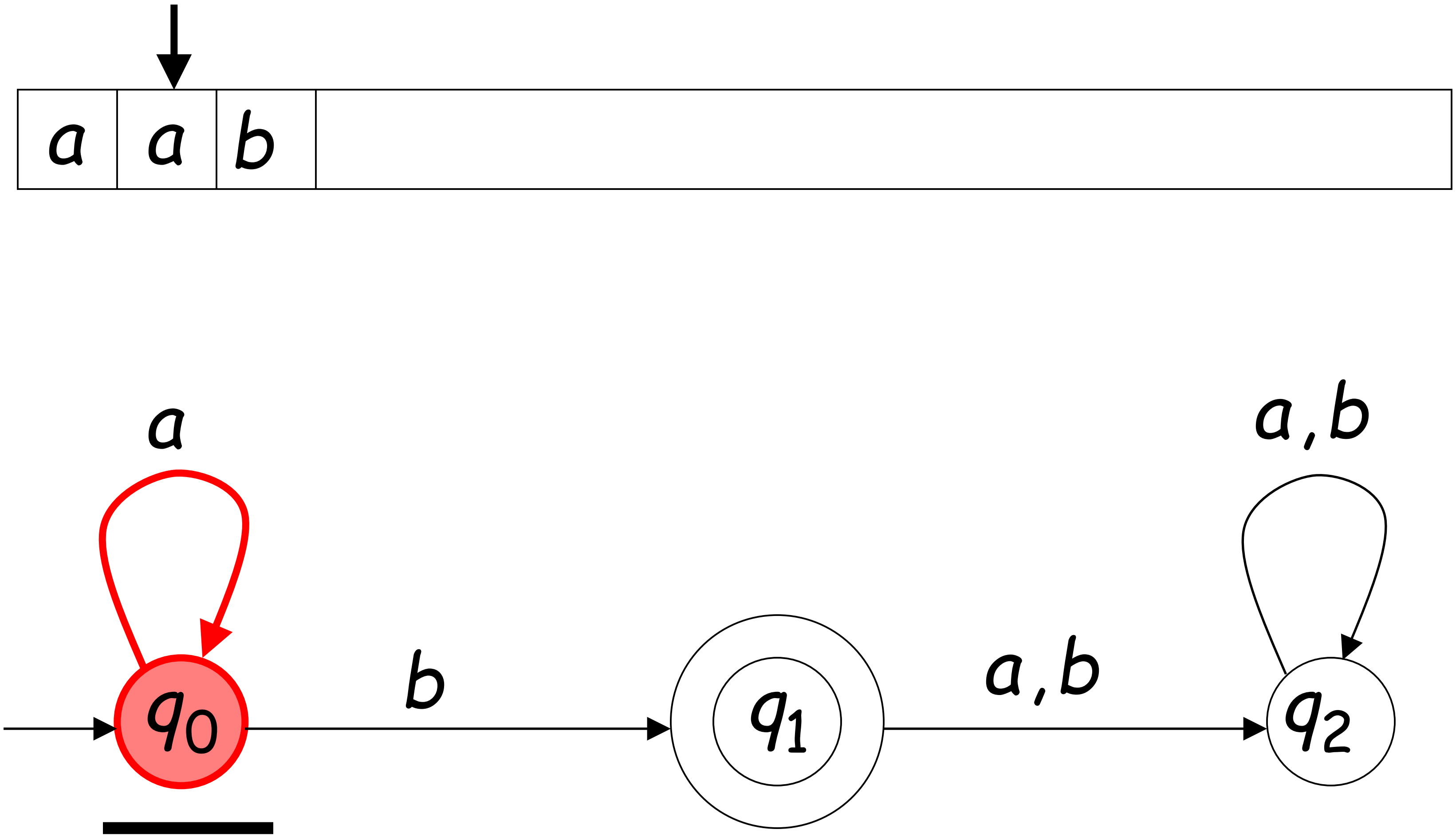


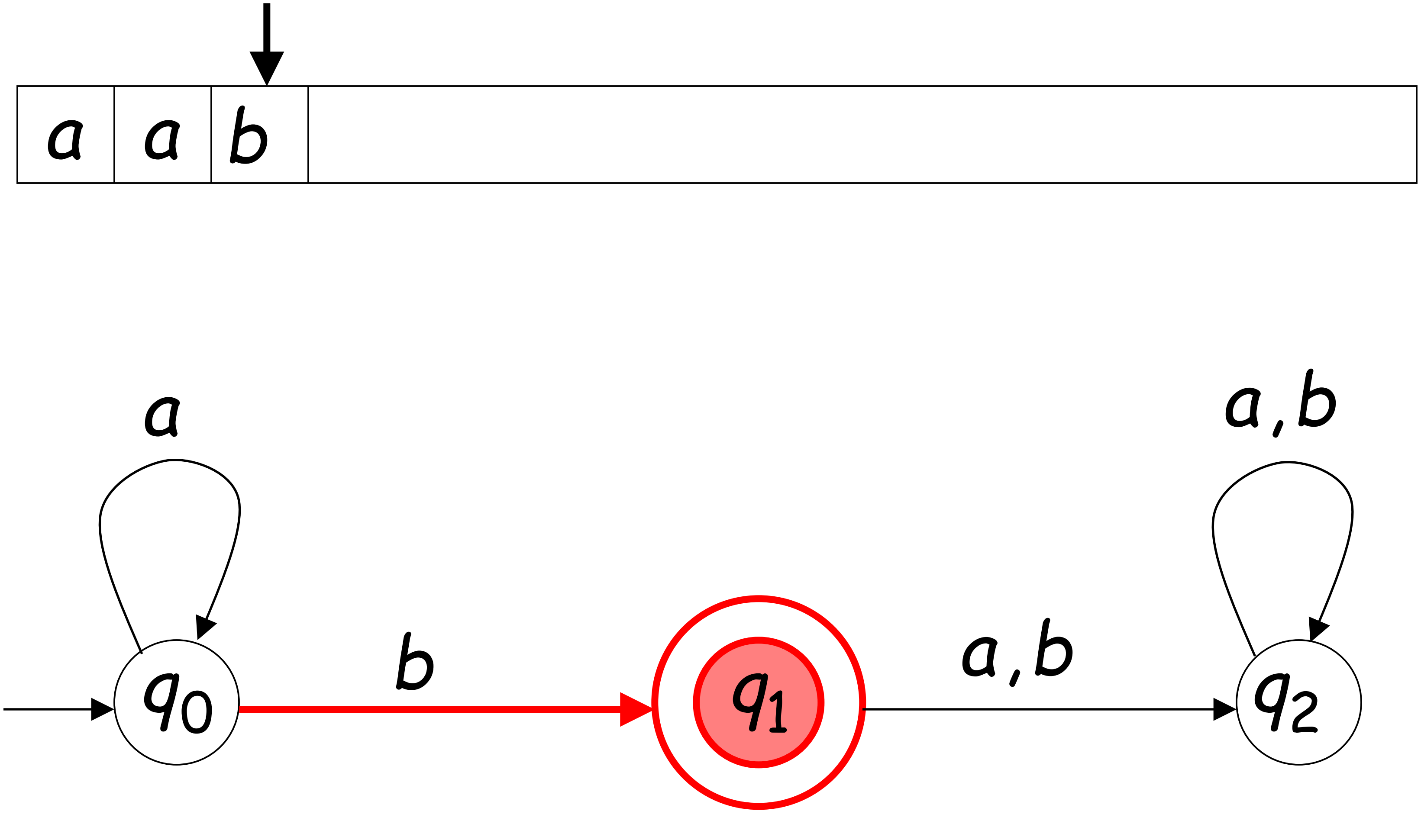
Output:
"reject"

Another Example



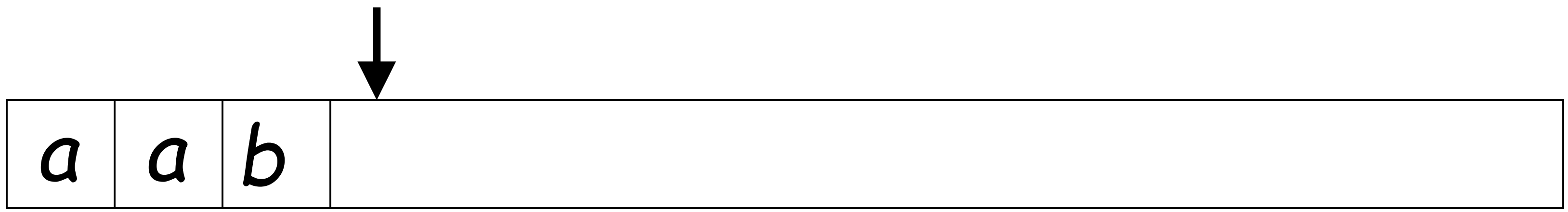

a
a
b
a
b
a,b
a,b
q_0
q_1
q_2

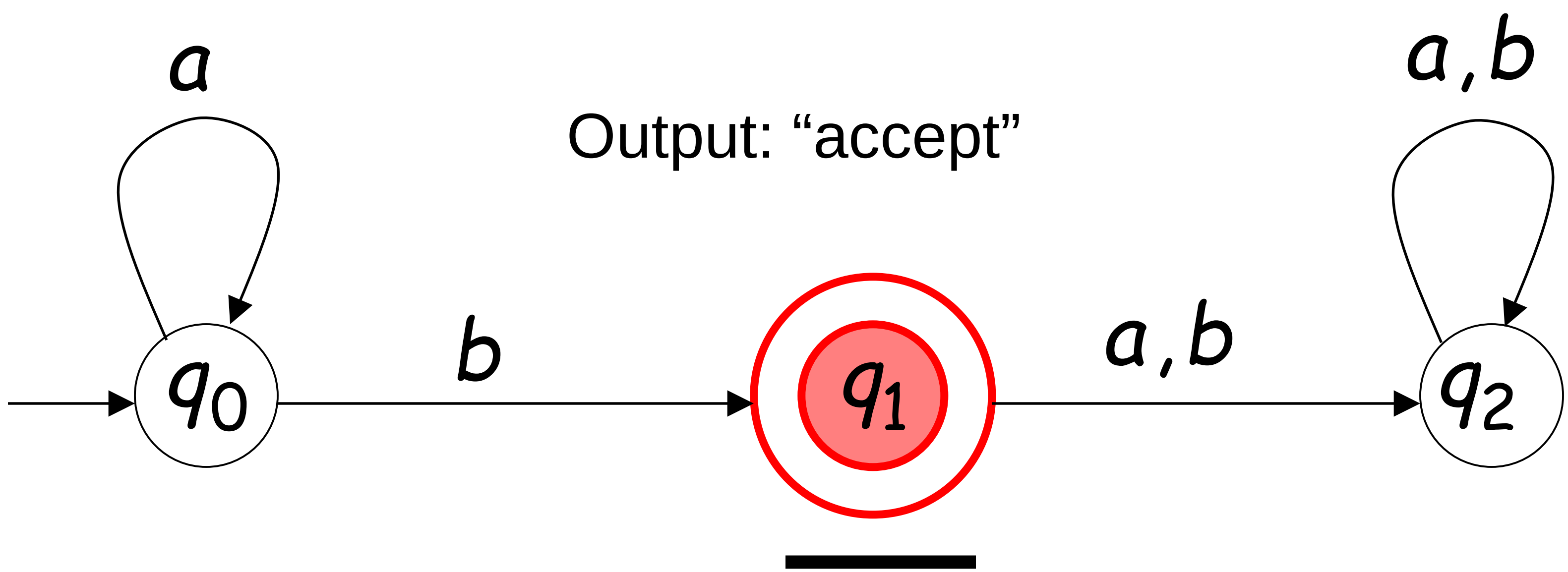

a
a
b
a
b
a, b
a, b
q_0
q_1
q_2



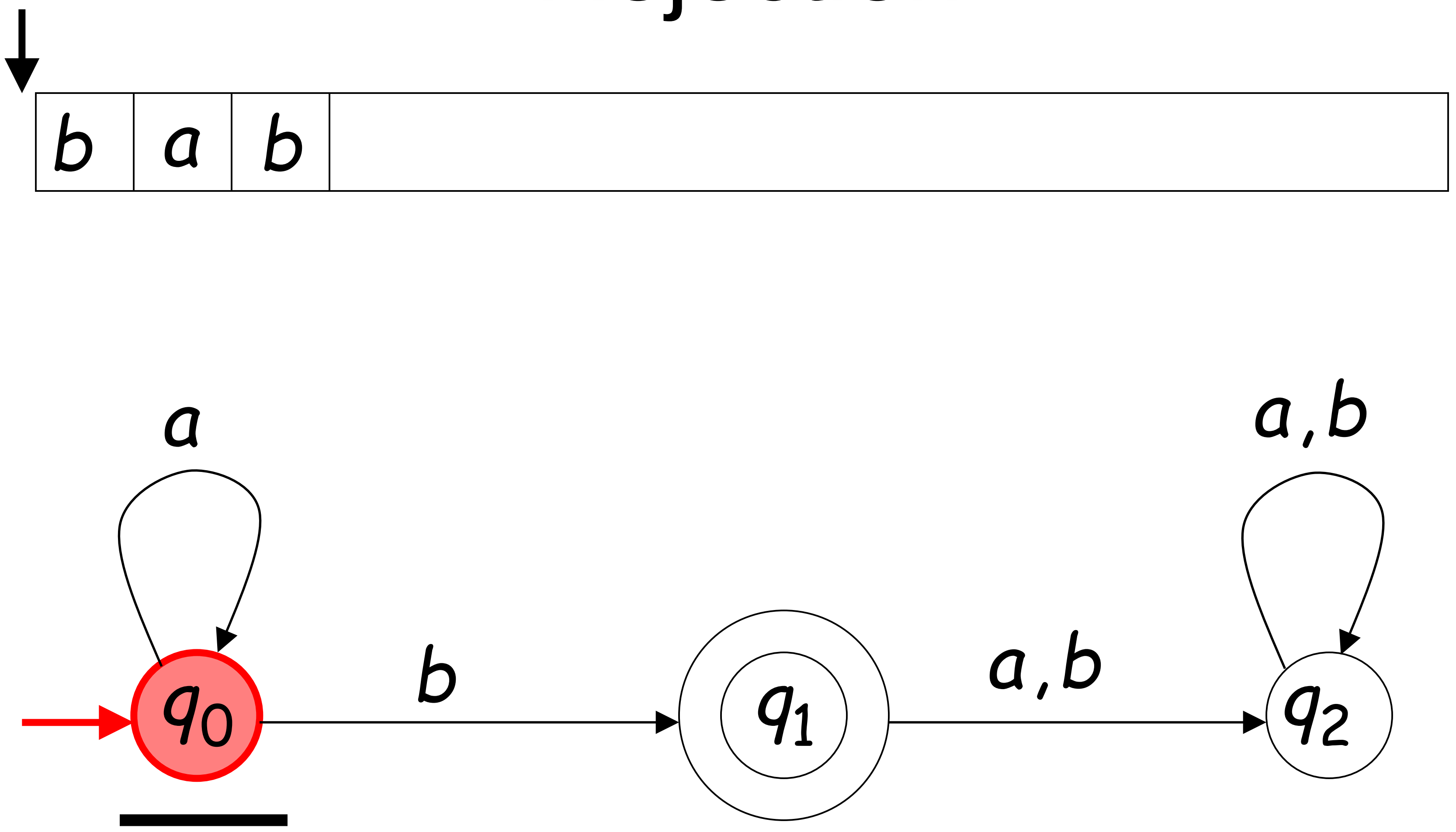
a
a
b
a
a,b
b
a,b
q0
q1
q2

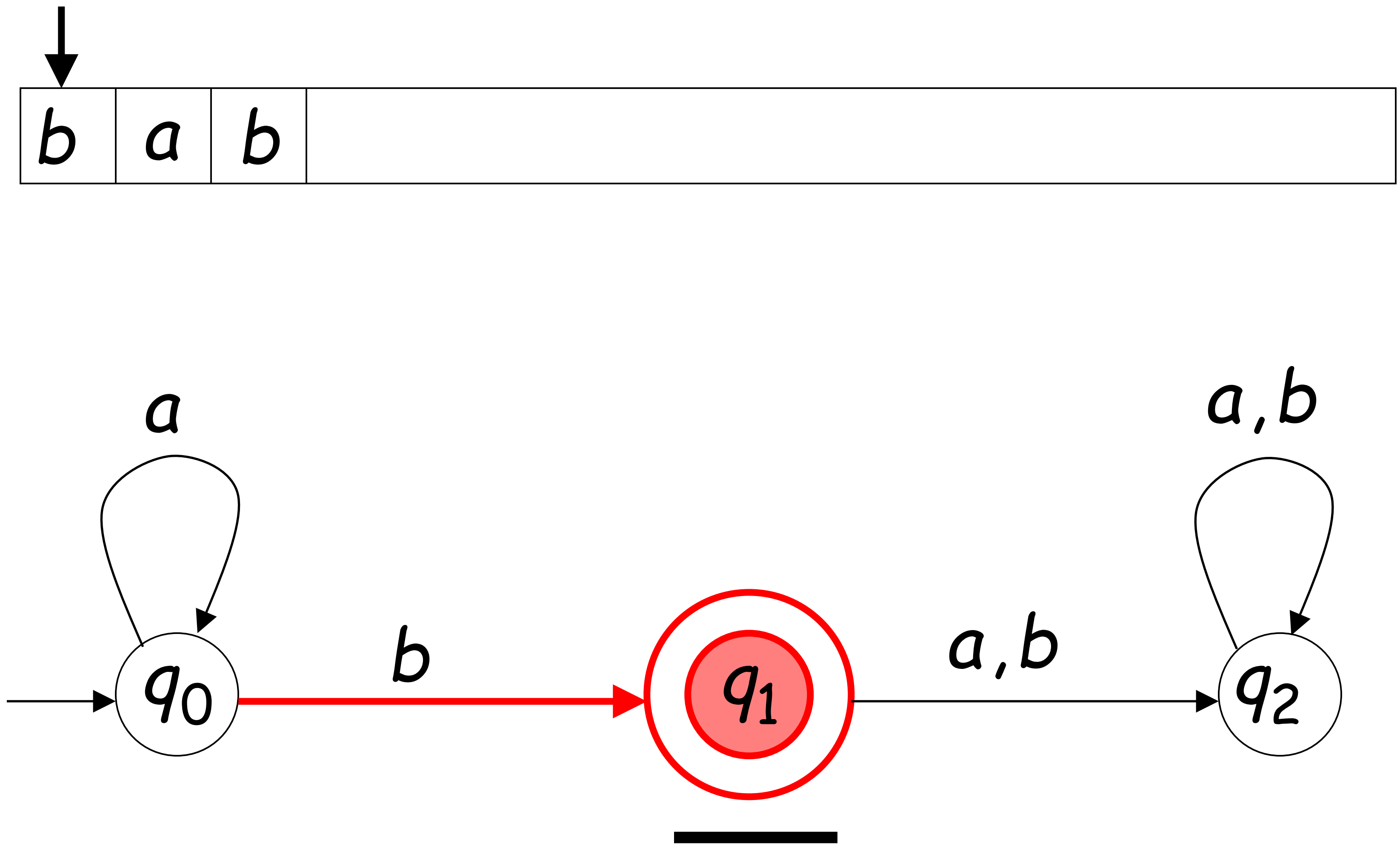
Input finished

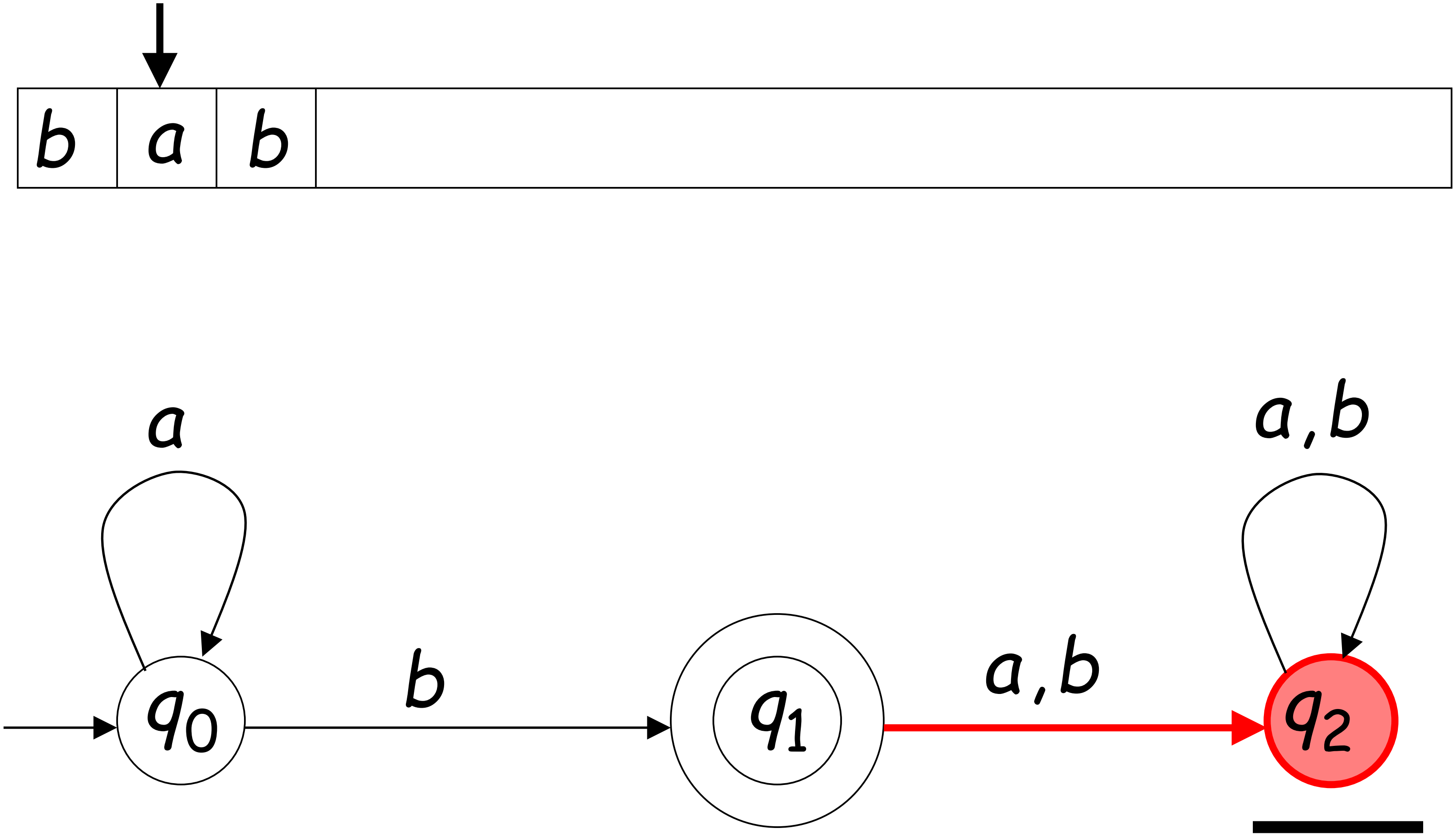




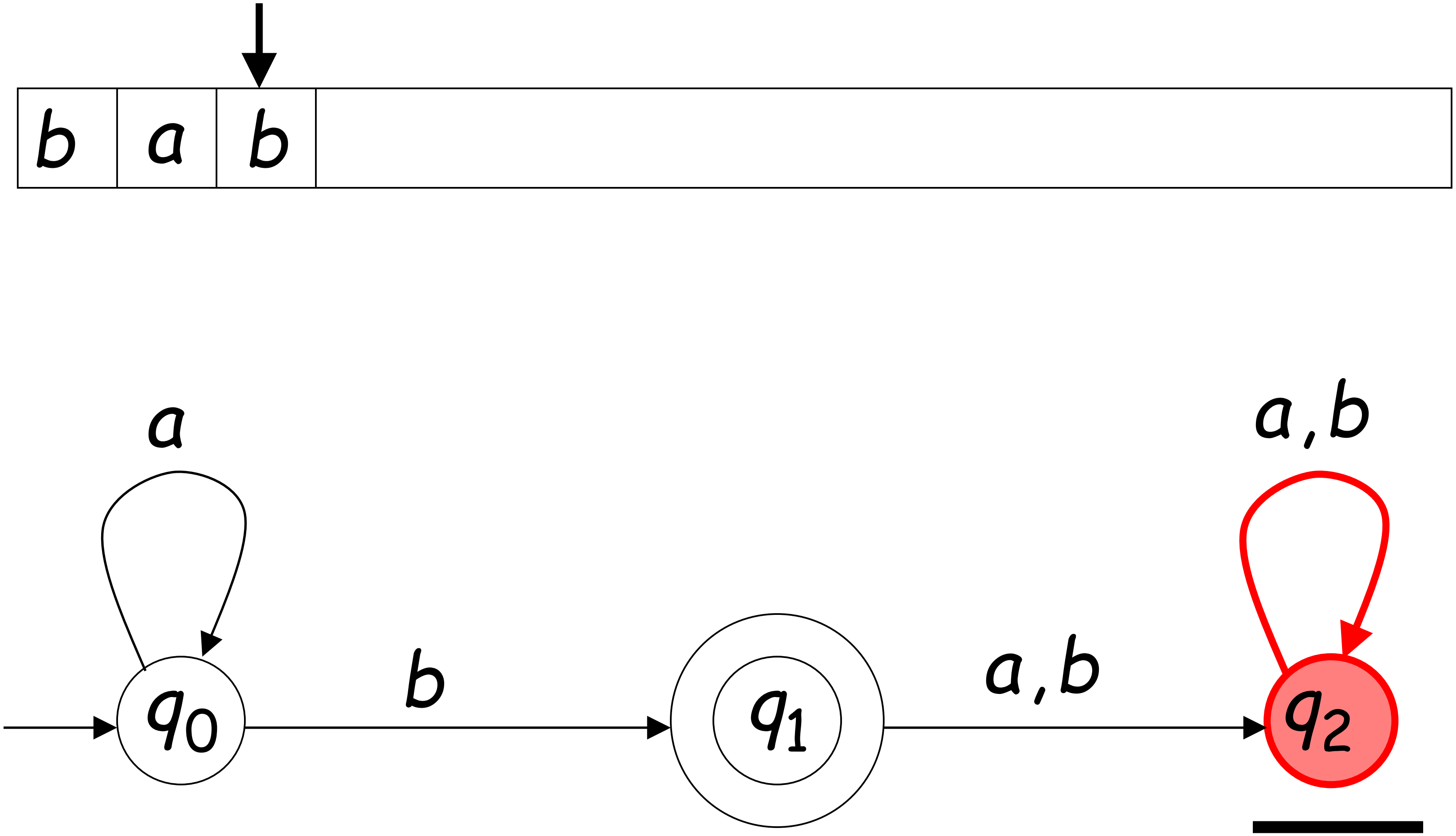
Rejection



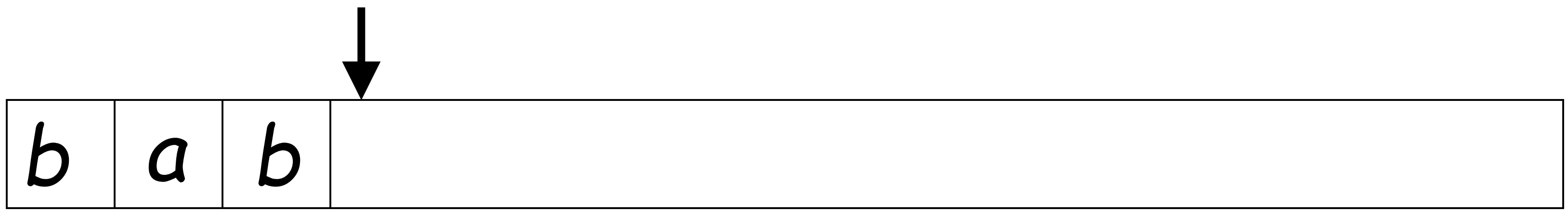

b
a
b
a
a,b
b
a,b
q_0
q_1
q_2

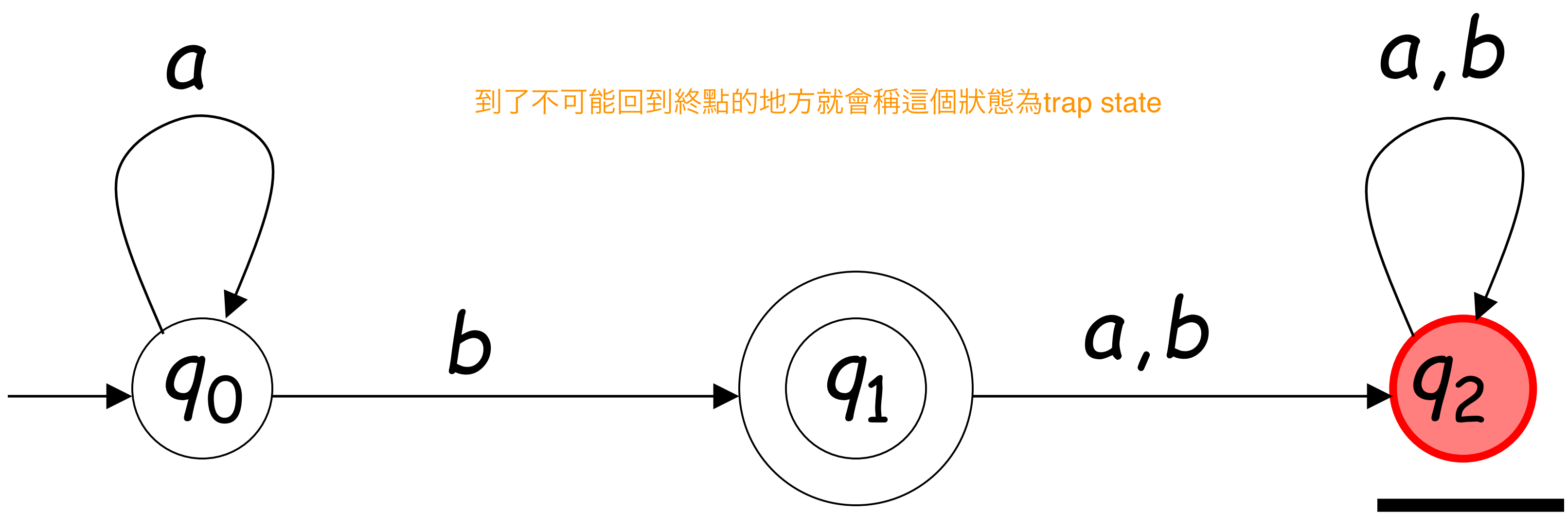


b
a
b
a
a,b
b
a,b
q_0
q_1
q_2


b a b
a
a,b
b
a,b
q0
q1
q2

Input finished





Output: “reject”

Trap state

Definition 2.1

Deterministic Finite Accepter (DFA) is define by the 5-tuple

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

Q : a finite set of **internal states**

Σ : a finite set of symbols called **input alphabet**

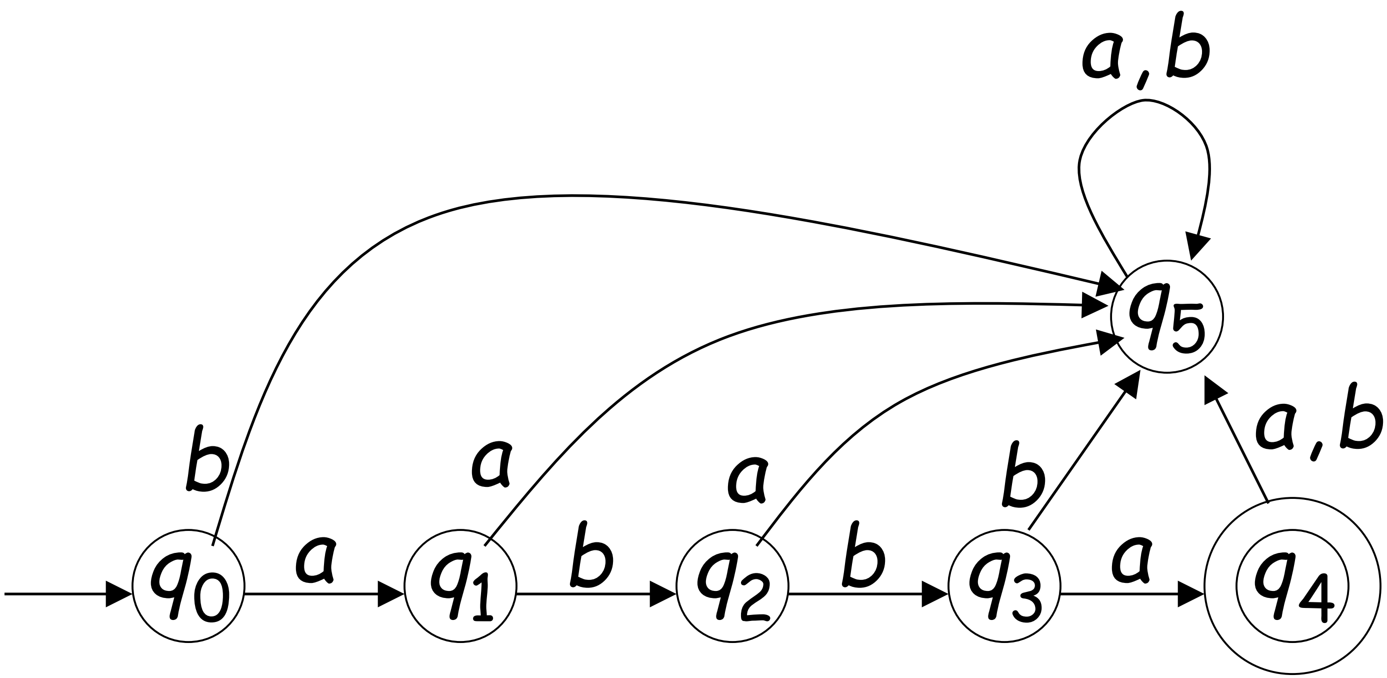
δ : $Q \times \Sigma \rightarrow Q$ called **transition function** (Total function)

q_0 : $q_0 \in Q$ is the **initial state**

F : $F \subseteq Q$ is a set of **final states**

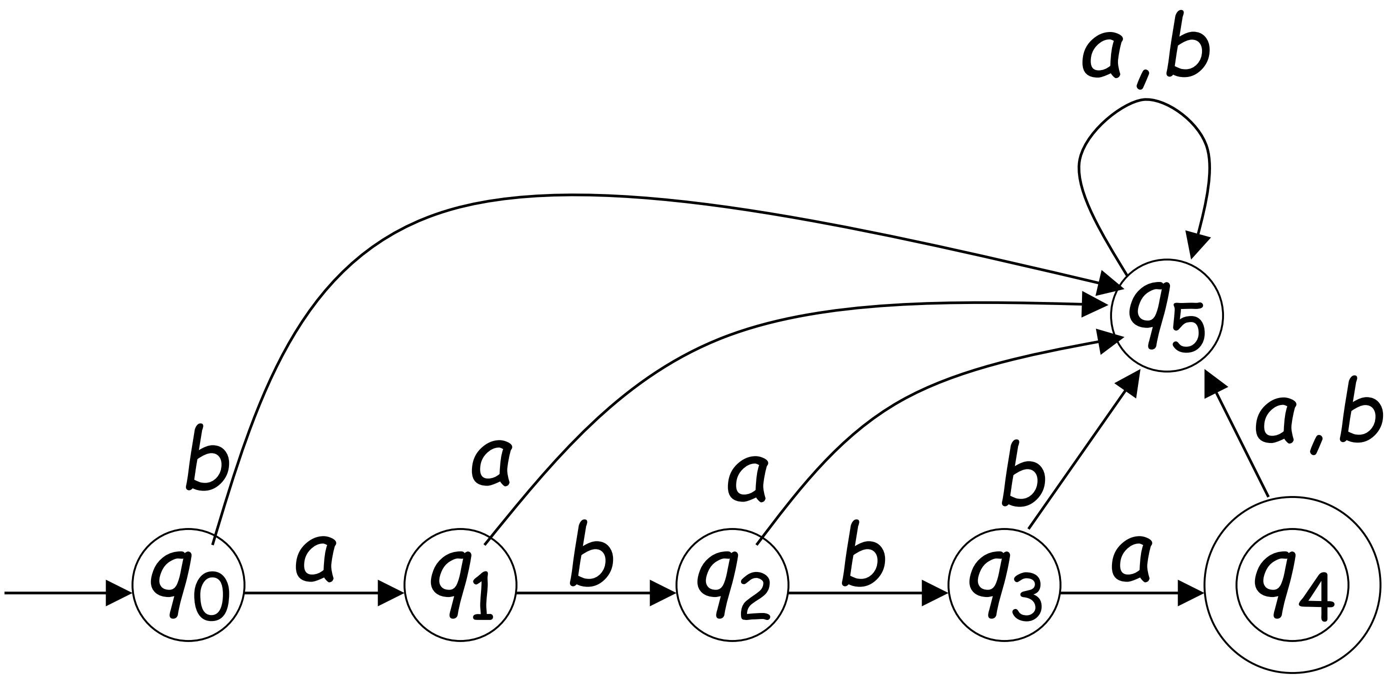
Input Alphabet Σ

$$\Sigma = \{a, b\}$$

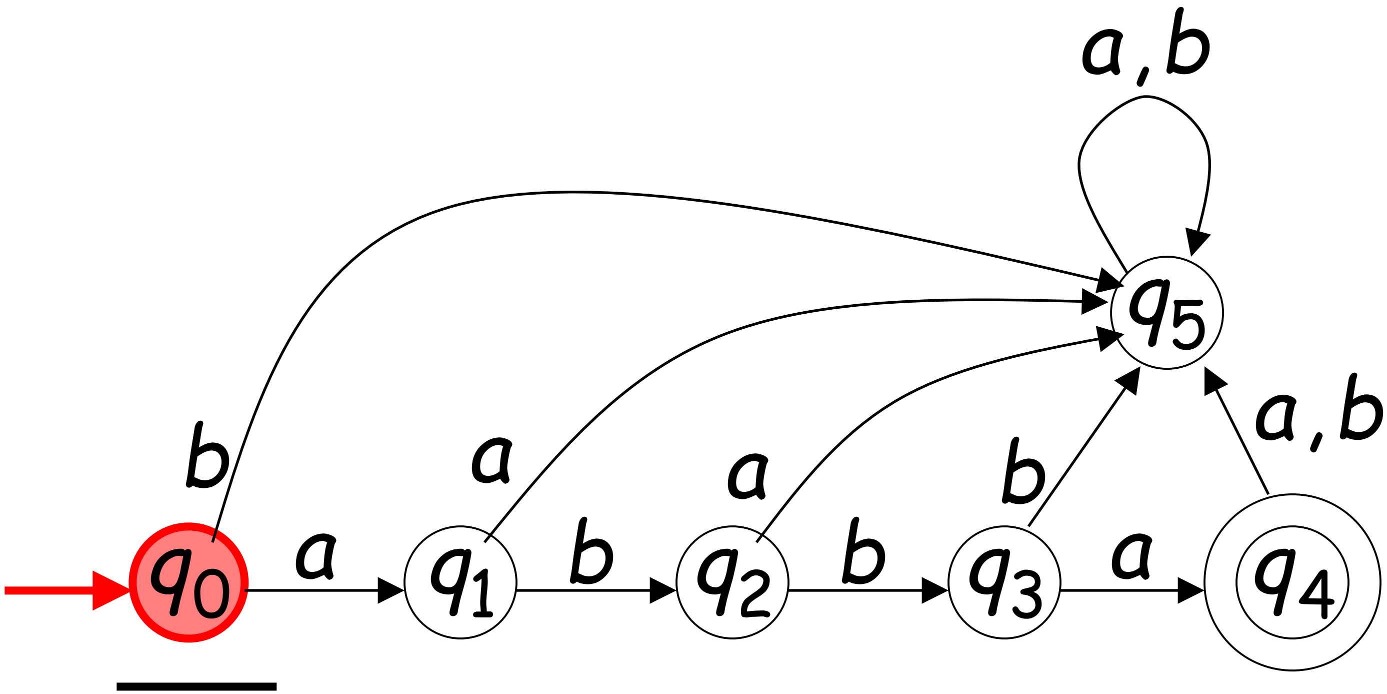


Set of States Q

$$Q = \{q_0, q_1, q_2, q_3, q_4, q_5\}$$

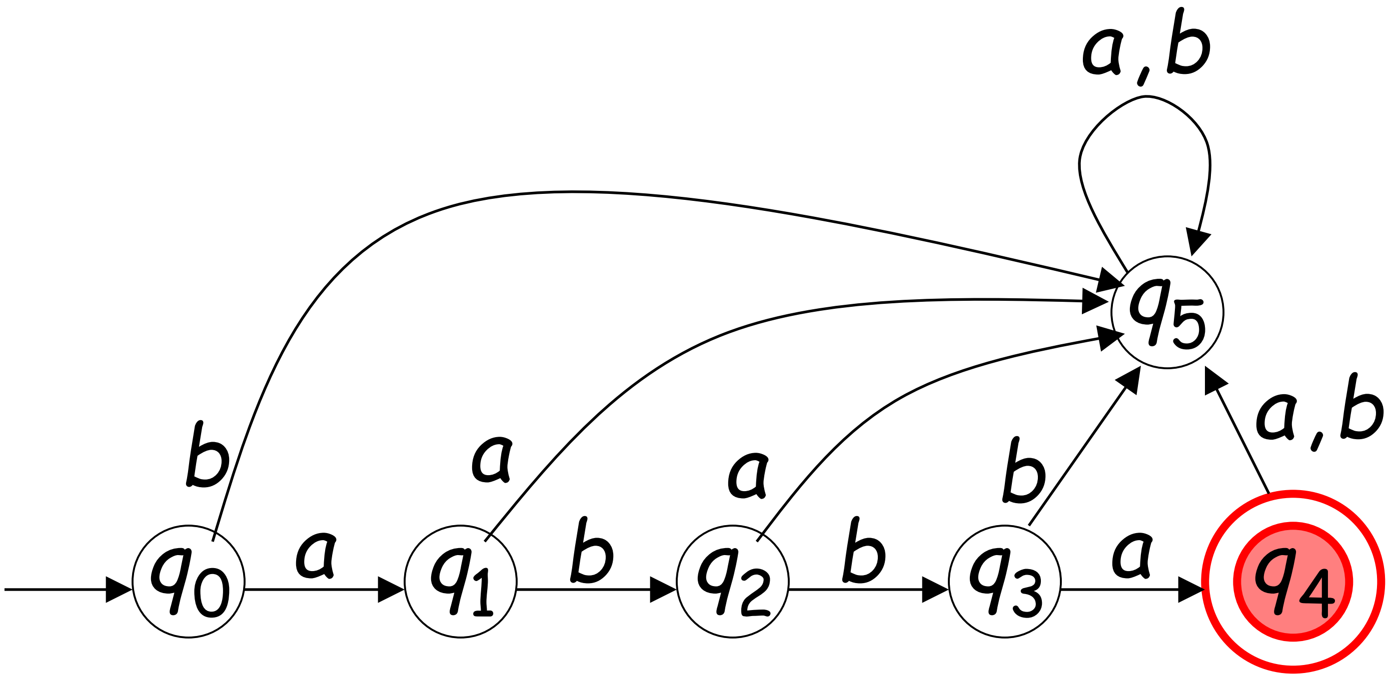


Initial State q_0



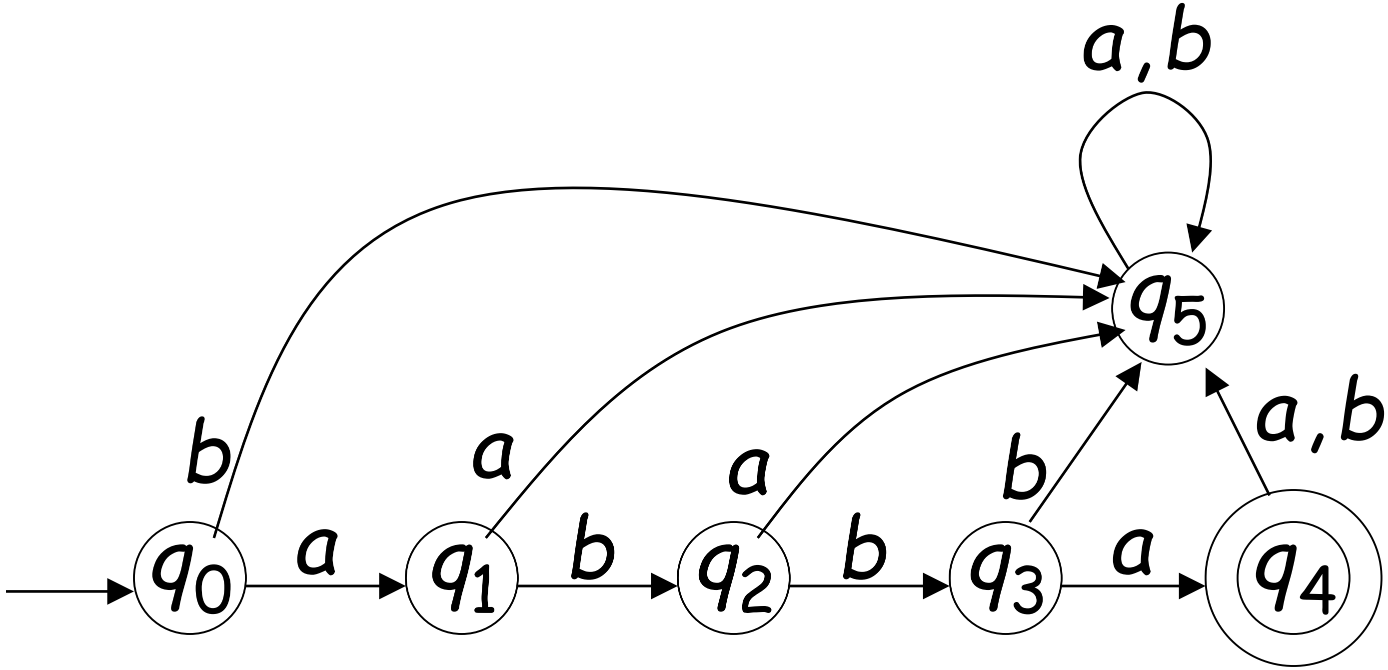
Set of Final States F

$$F = \{q_4\}$$

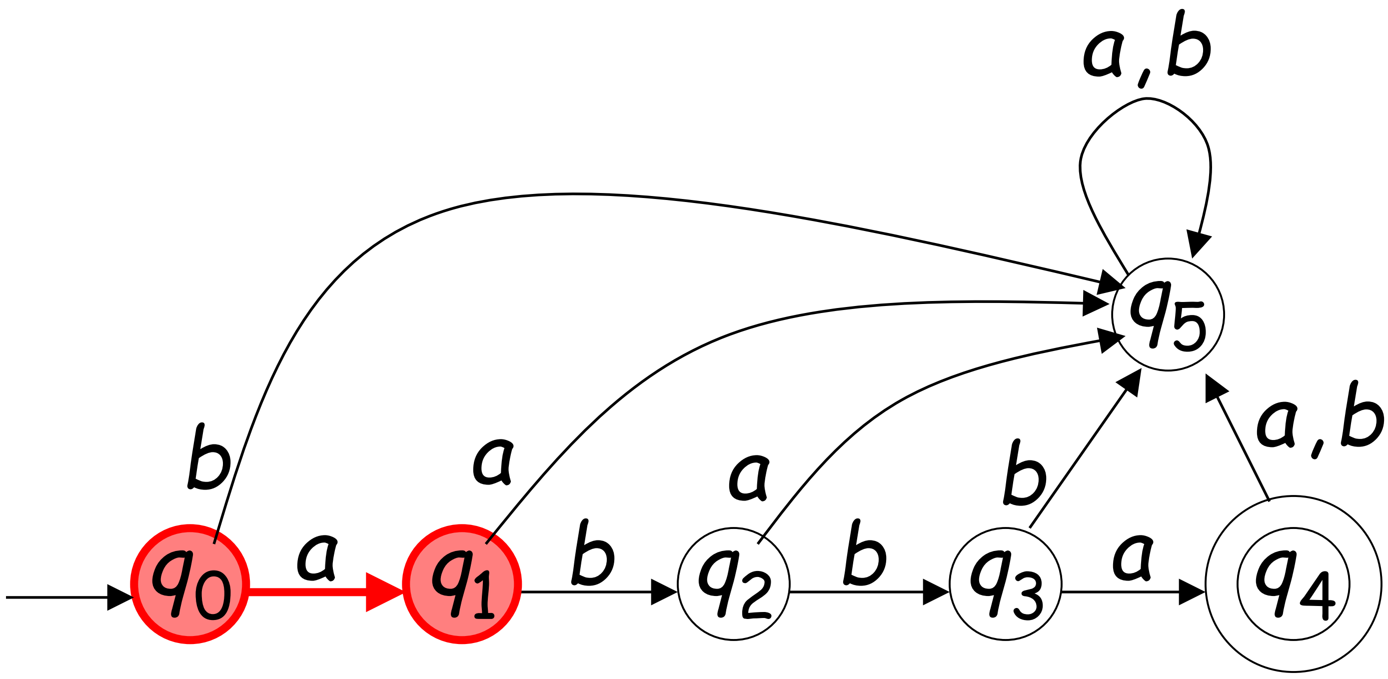


Transition Function δ

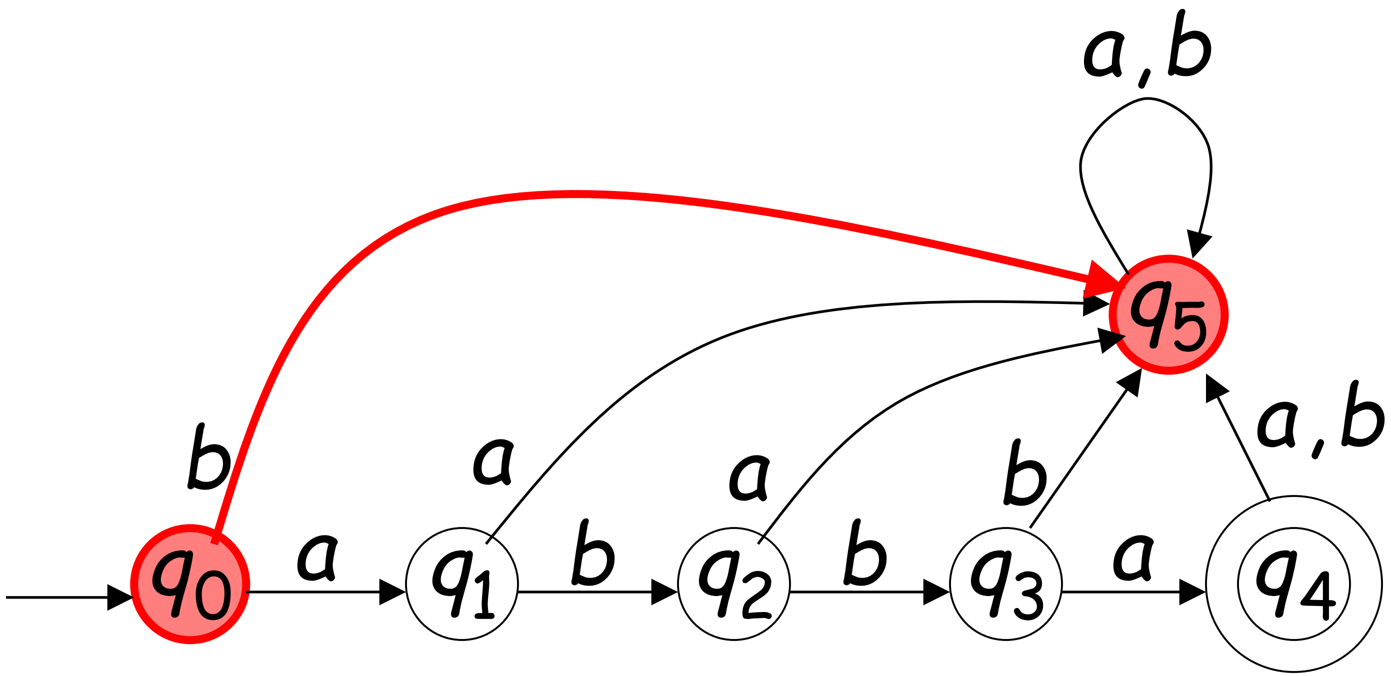
$$\delta : Q \times \Sigma \rightarrow Q$$



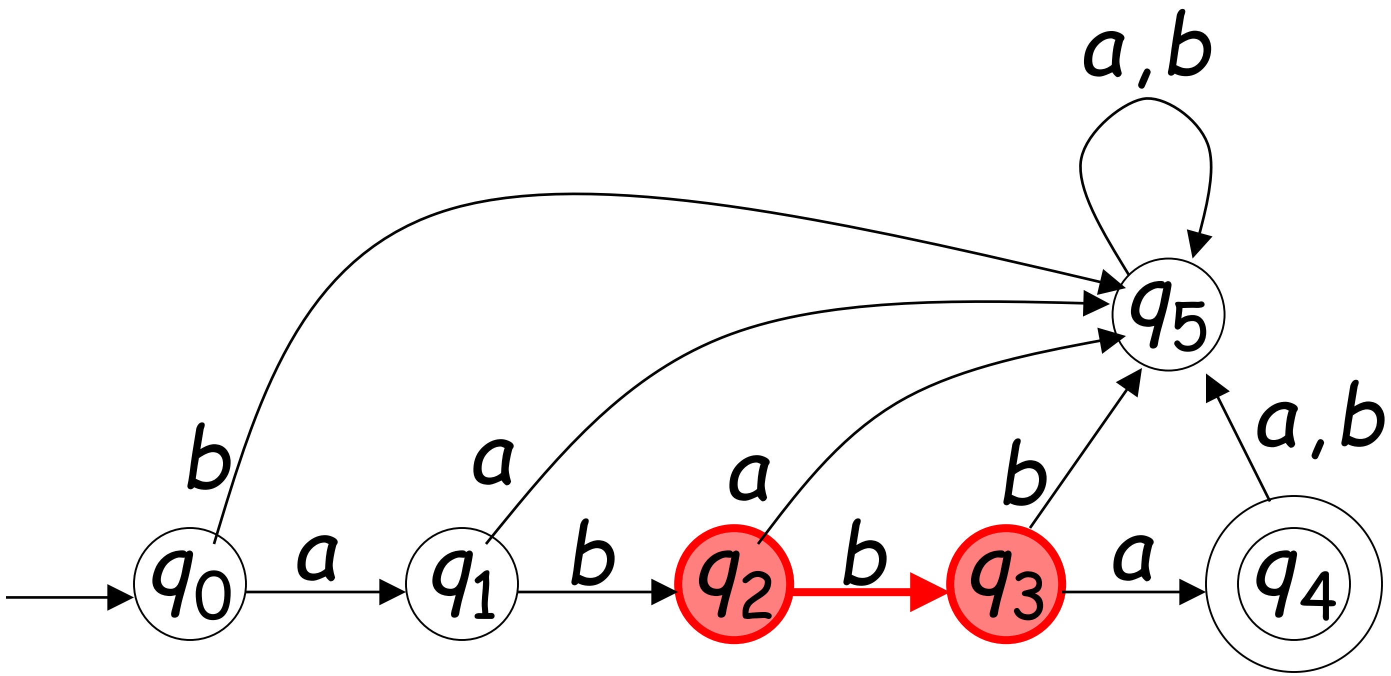
$$\delta(q_0, a) = q_1$$



$$\delta(q_0, b) = q_5$$



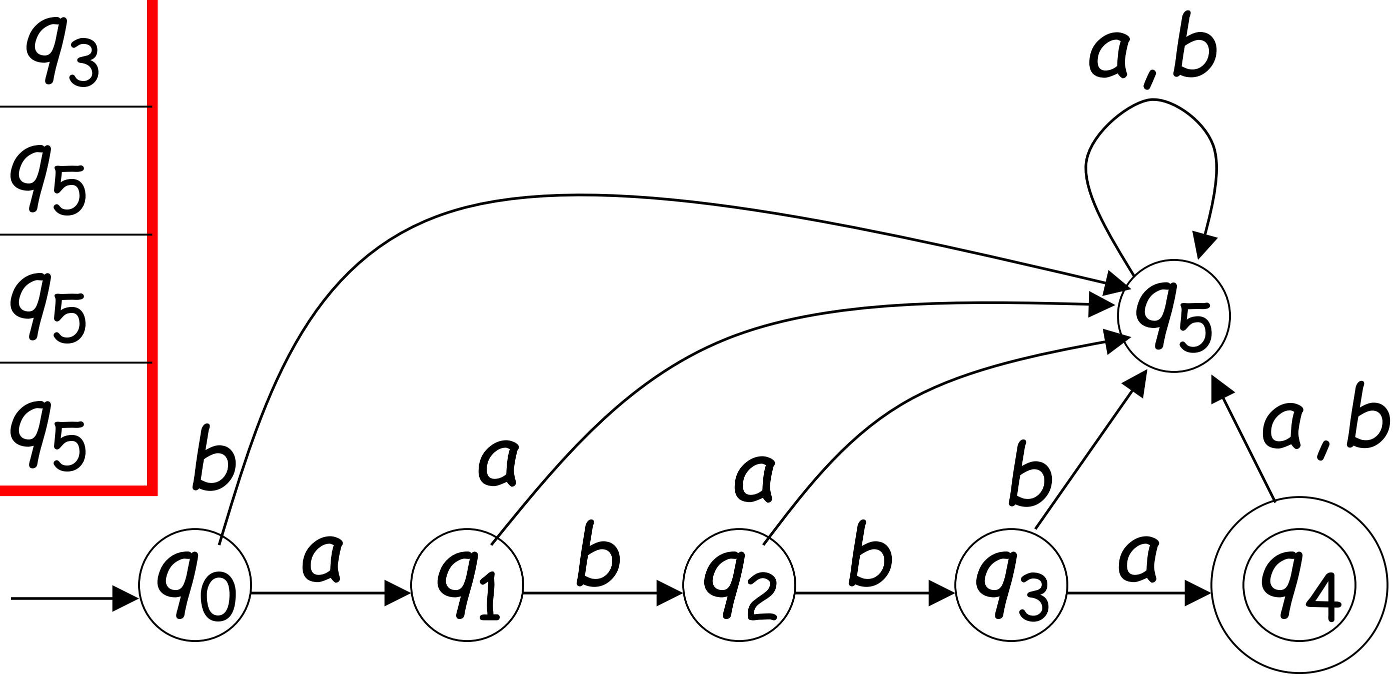
$$\delta(q_2, b) = q_3$$



Transition Function δ

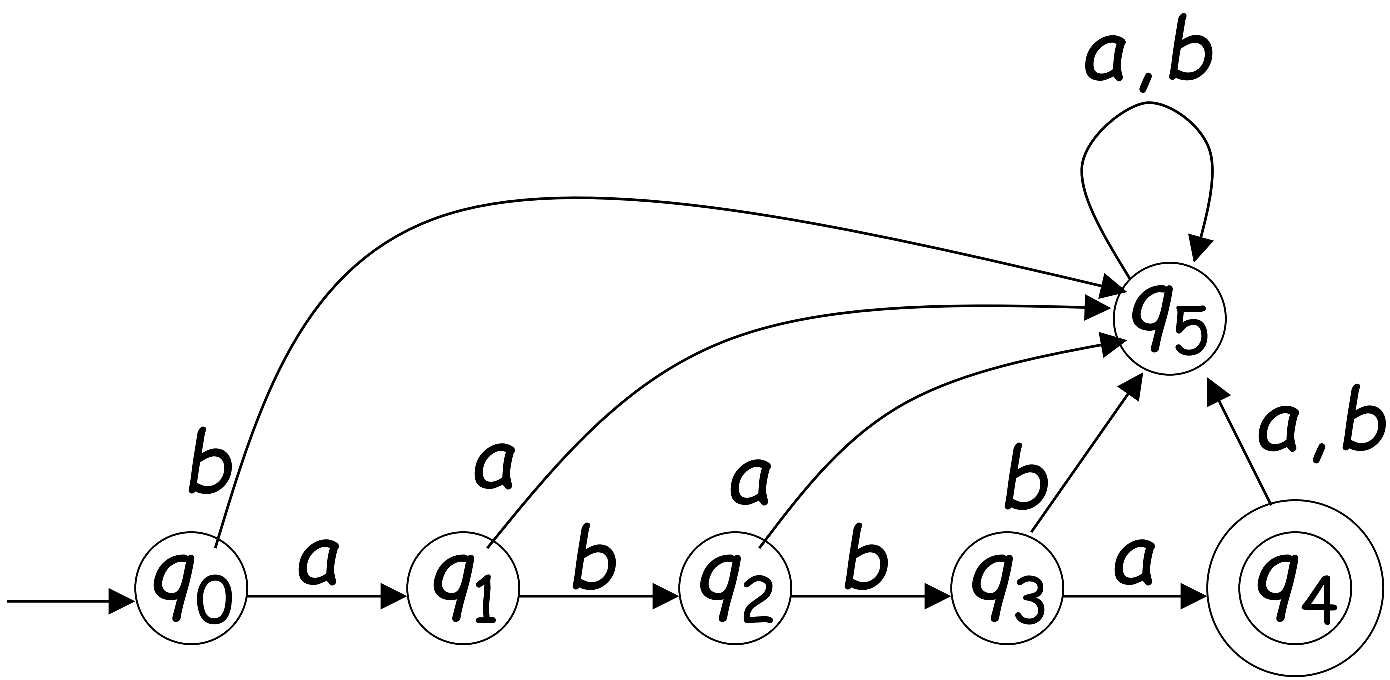
δ	a	b
q_0	q_1	q_5
q_1	q_5	q_2
q_2	q_5	q_3
q_3	q_4	q_5
q_4	q_5	q_5
q_5	q_5	q_5

在transition table, transition function中每一個格子都必須有state
不能空著或是有2個state以上

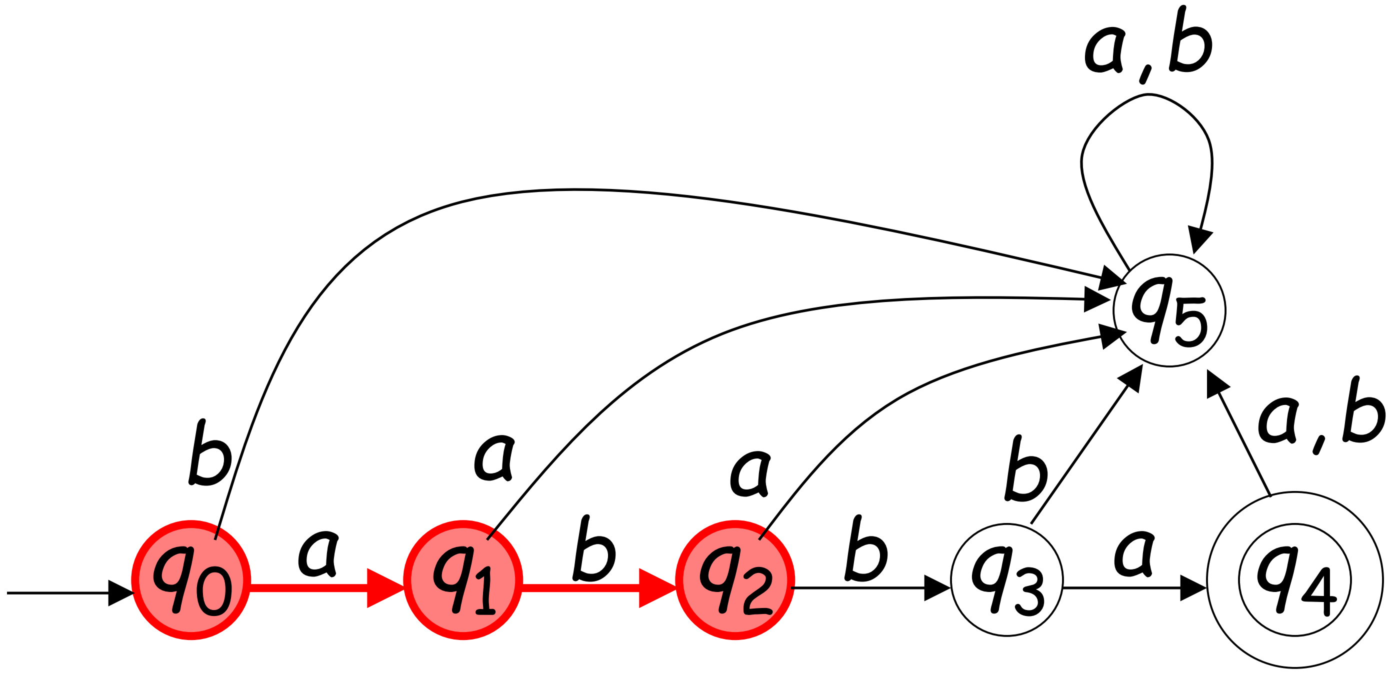


Extended Transition Function δ^*

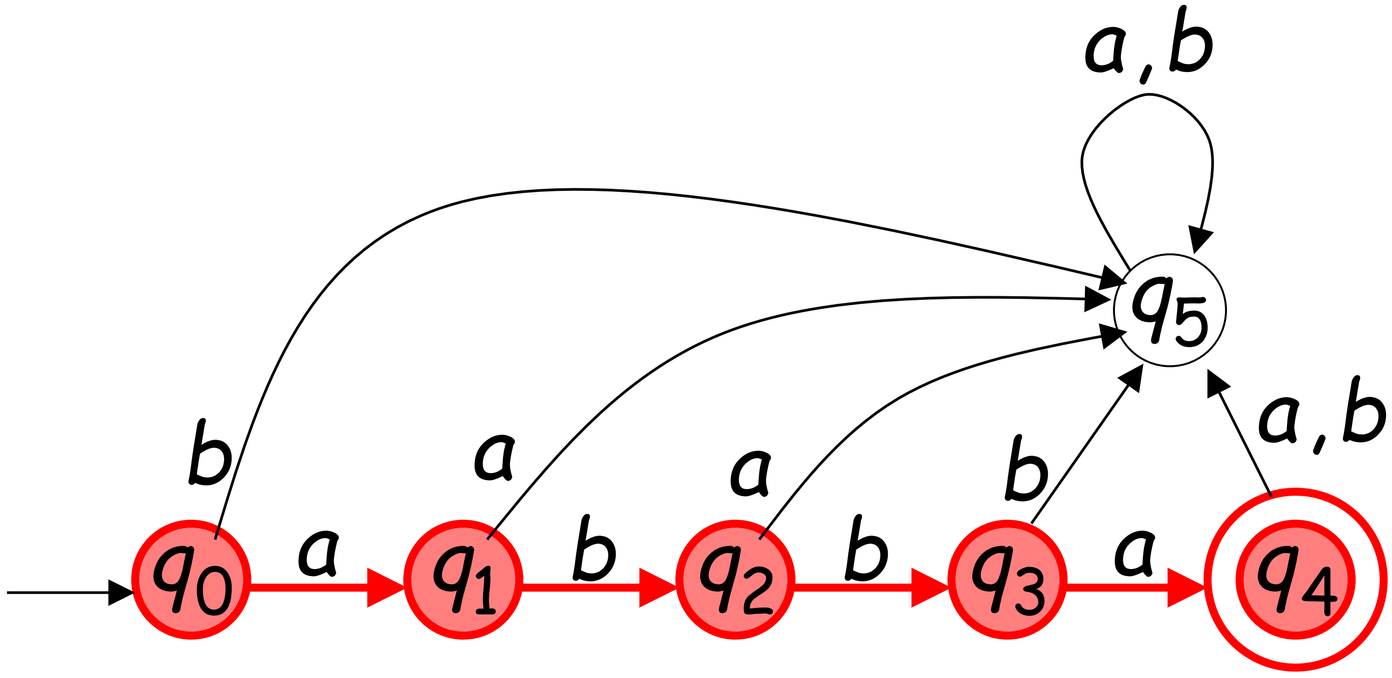
$$\delta^* : Q \times \Sigma^* \rightarrow Q$$



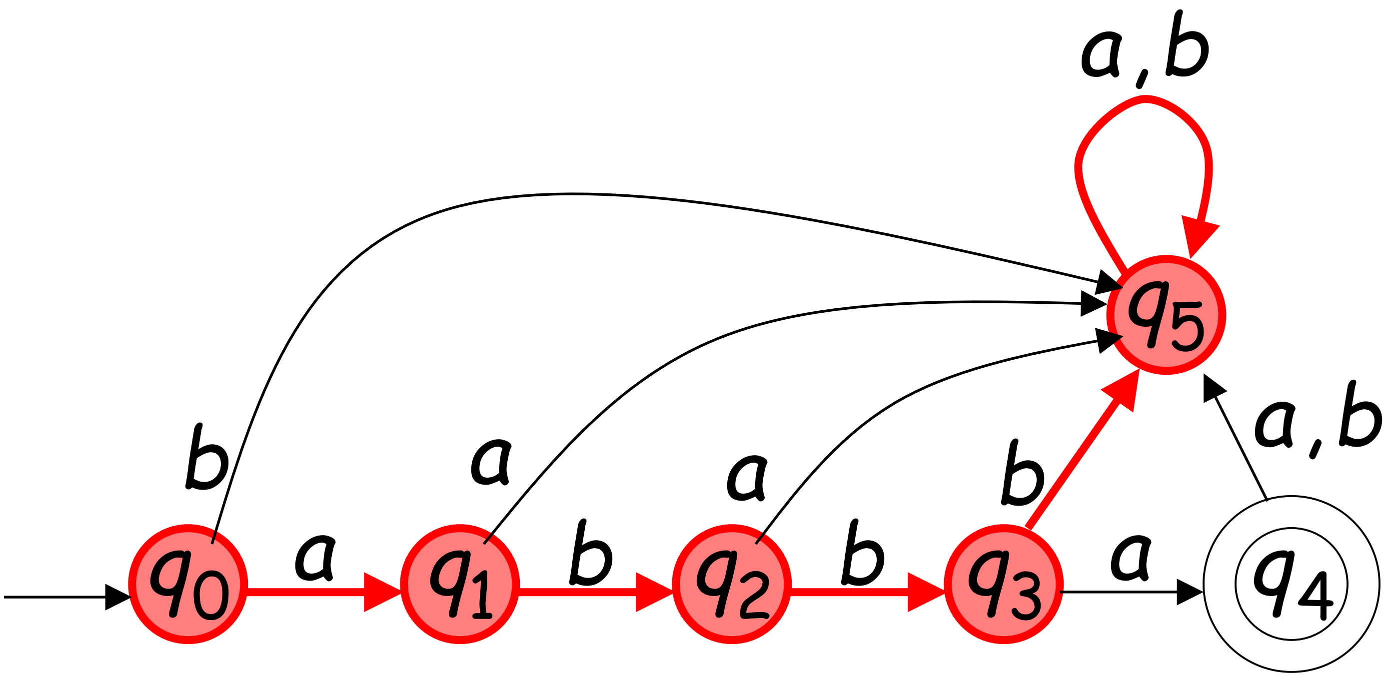
$$\delta^*(q_0, ab) = q_2$$



$$\delta^*(q_0, abba) = q_4$$



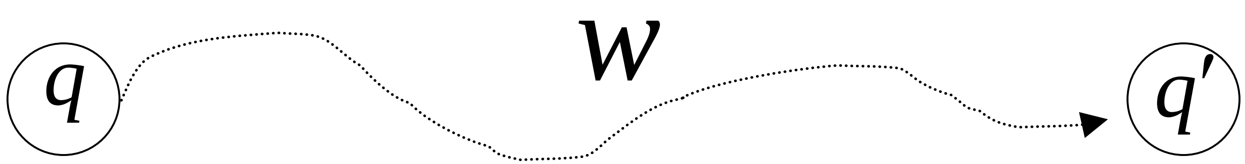
$$\delta^*(q_0, abbbaa) = q_5$$



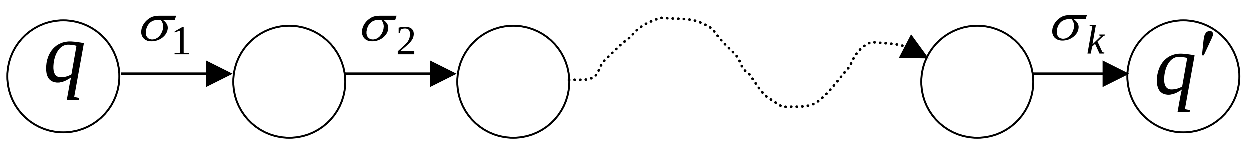
Observation: If there is a walk from q to q' with label w

Theorem 2.1

iff $\delta^*(q, w) = q'$

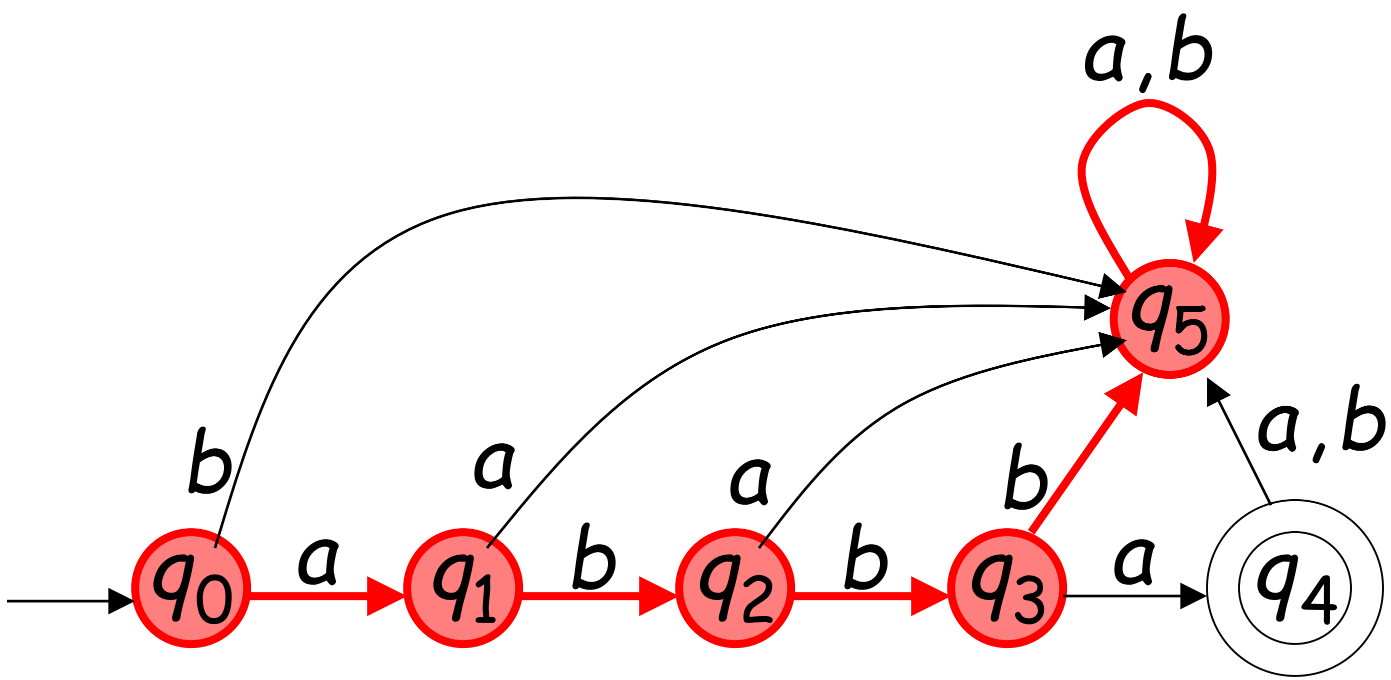


$$w = \sigma_1 \sigma_2 \cdots \sigma_k$$



Example: There is a walk from q_0 to q_5 with label $abbbaa$

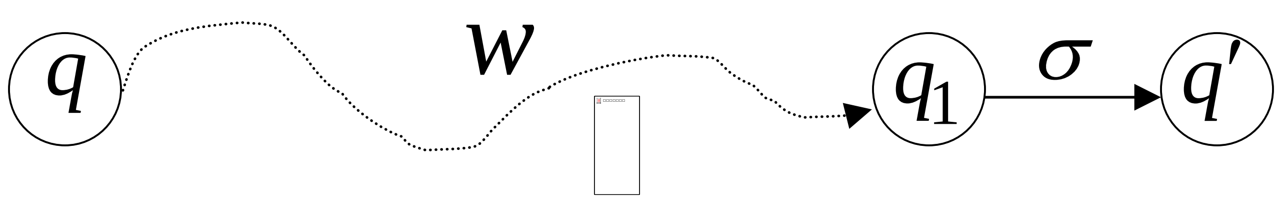
$$\delta^*(q_0, abbbaa) = q_5$$



Recursive Definition

$$\delta^*(q,\lambda)=q$$

$$\delta^*(q,w\sigma)=\delta(\delta^*(q,w),\sigma)$$



$$\left.\begin{array}{l}\left.\begin{array}{l}\delta^*(q,w\sigma)=q' \\ \delta(q_1,\sigma)=q'\end{array}\right\} \Rightarrow \delta^*(q,w\sigma)=\delta(q_1,\sigma) \\ \delta^*(q,w)=q_1\end{array}\right\} \Rightarrow \delta^*(q,w\sigma)=\delta(\delta^*(q,w),\sigma)$$

$$\delta^*(q_0, ab) =$$

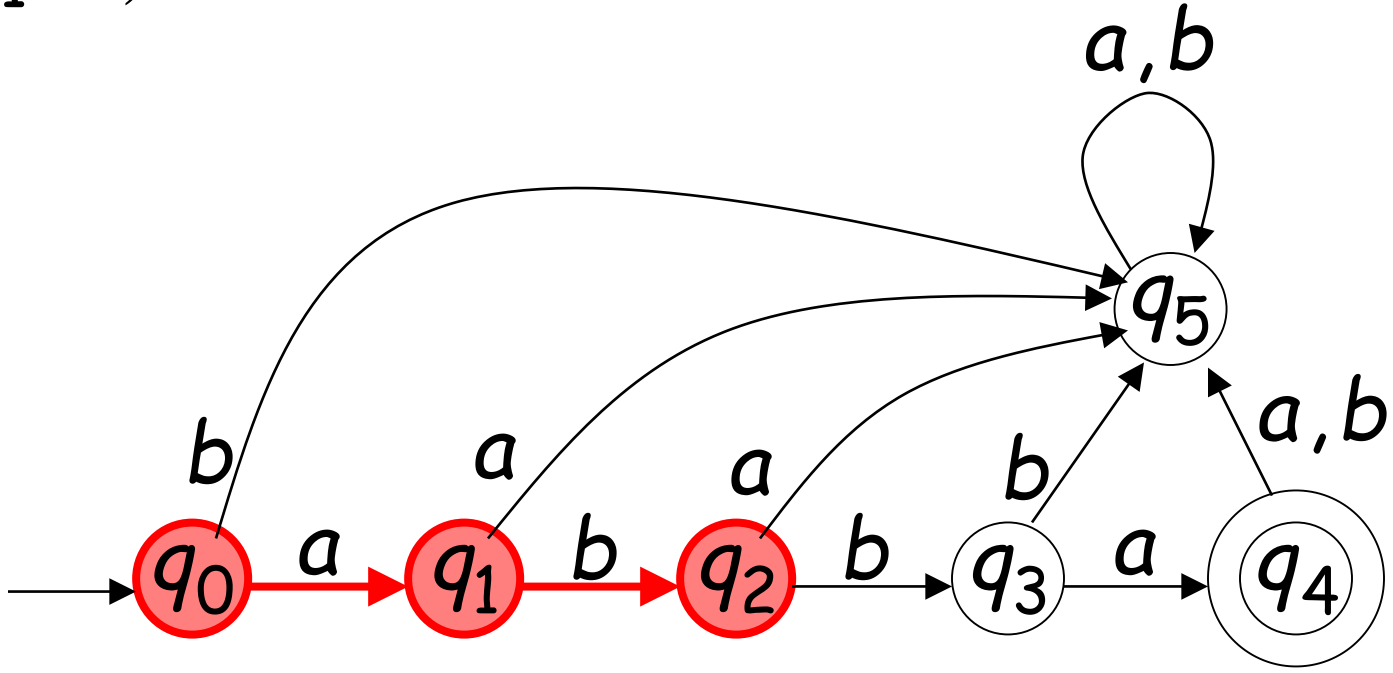
$$\delta(\delta^*(q_0, a), b) =$$

$$\delta(\delta(\delta^*(q_0, \lambda), a), b) =$$

$$\delta(\delta(q_0, a), b) =$$

$$\delta(q_1, b) =$$

$$q_2$$



Languages Accepted by DFAs

Take DFA M

一個DFA都會對應到一個Language

Definition:

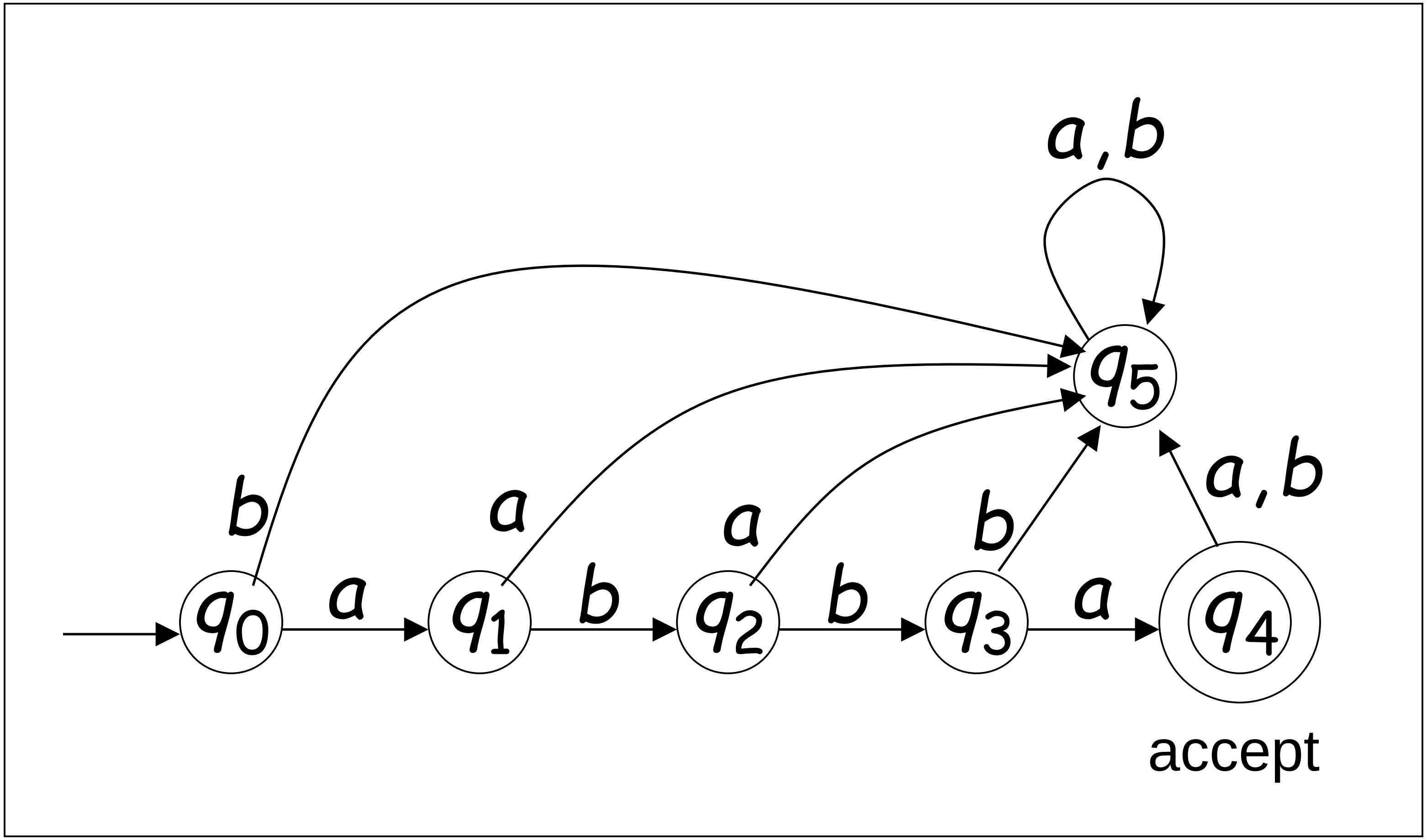
– The language $L(M)$ contains all input strings accepted by M

– $L(M)$= { strings that drive M to a final state}

Example

$$L(M) = \{abba\}$$

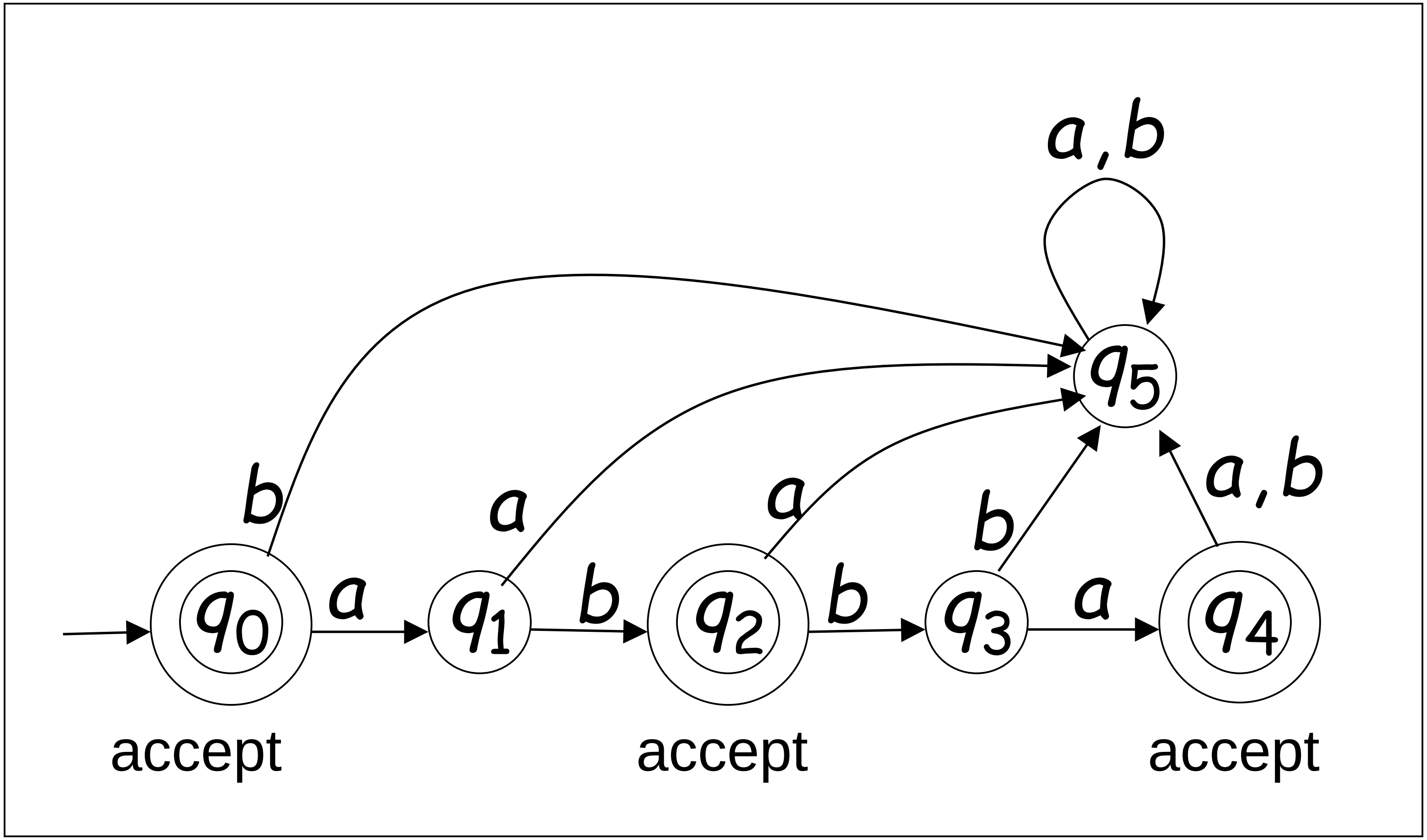
M



Another Example

$$L(M)=\{\lambda, ab, abba\}$$

M



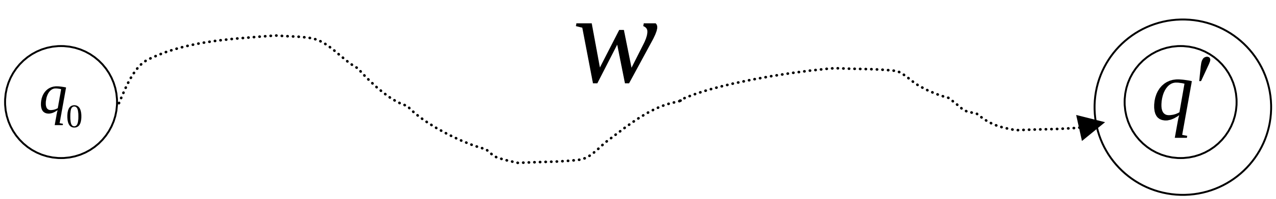
Formally

For a DFA $M = (Q, \Sigma, \delta, q_0, F)$

Language accepted by M :

$$L(M) = \{ w \in \Sigma^* : \delta^*(q_0, w) \in F \}$$

$q' \in F$



Observation

- Language rejected by M :

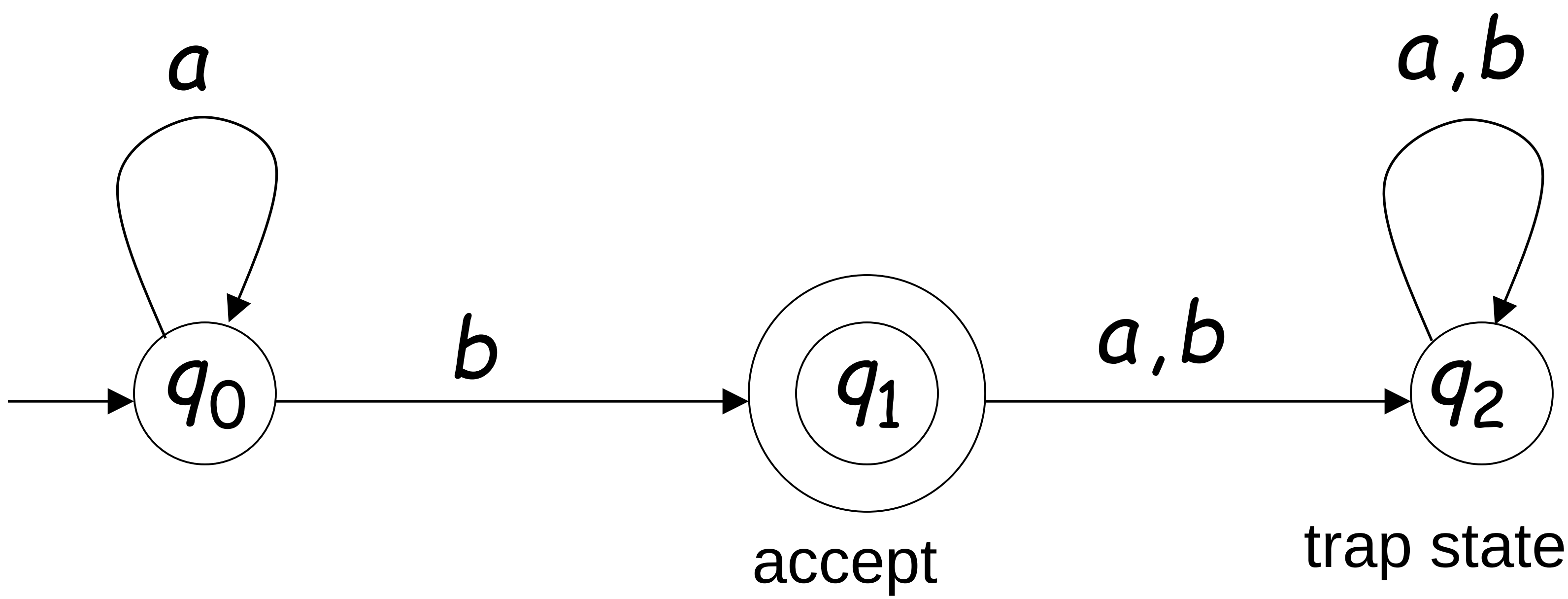
$$\overline{L(M)} = \{ w \in \Sigma^* : \delta^*(q_0, w) \notin F \}$$

$$q_0 \xrightarrow{w} q' \qquad q' \notin F$$

Example 2.2

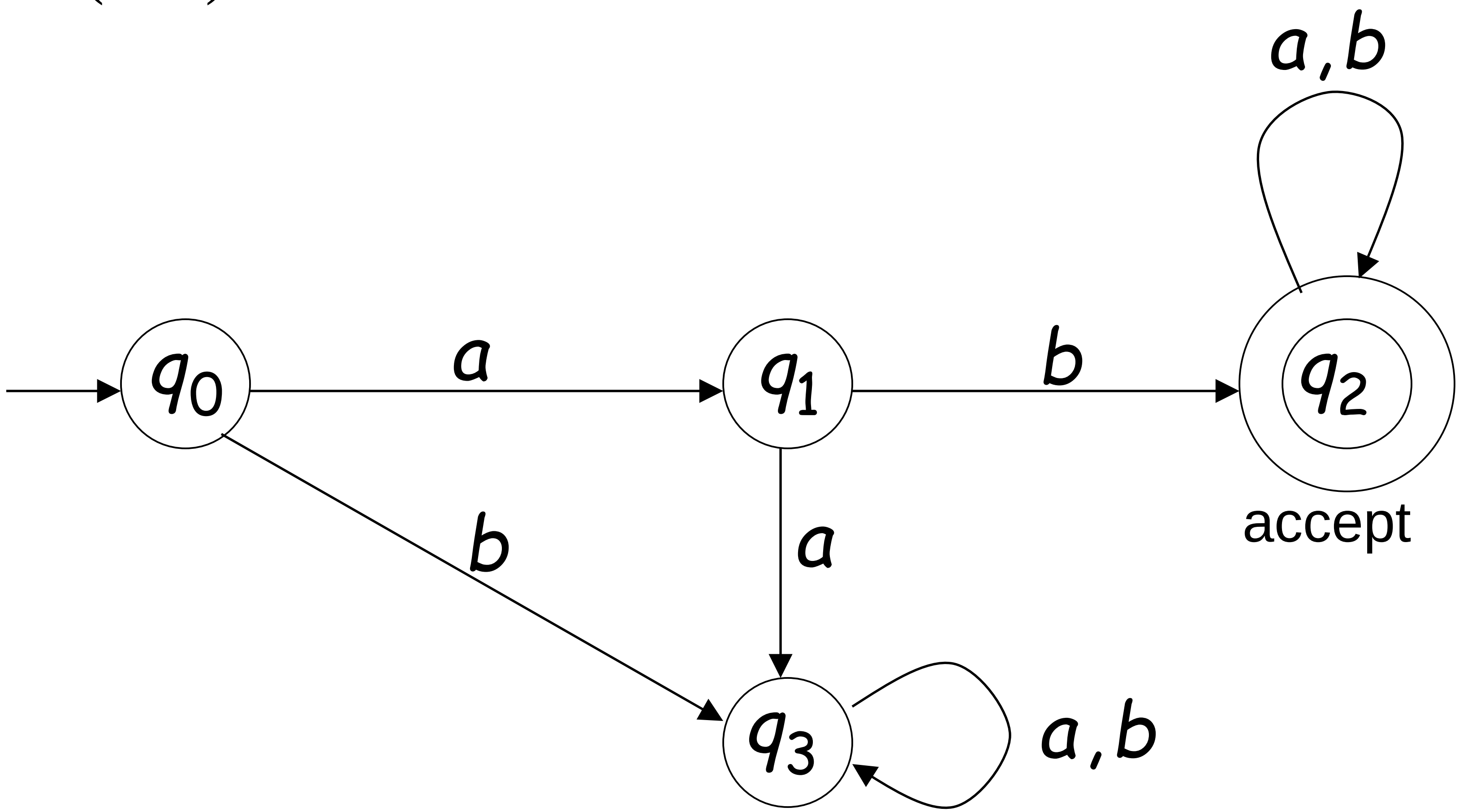
$$M = (Q, \Sigma, \delta, q_0, F)$$

$$L(M) = \{a^n b : n \geq 0\}$$



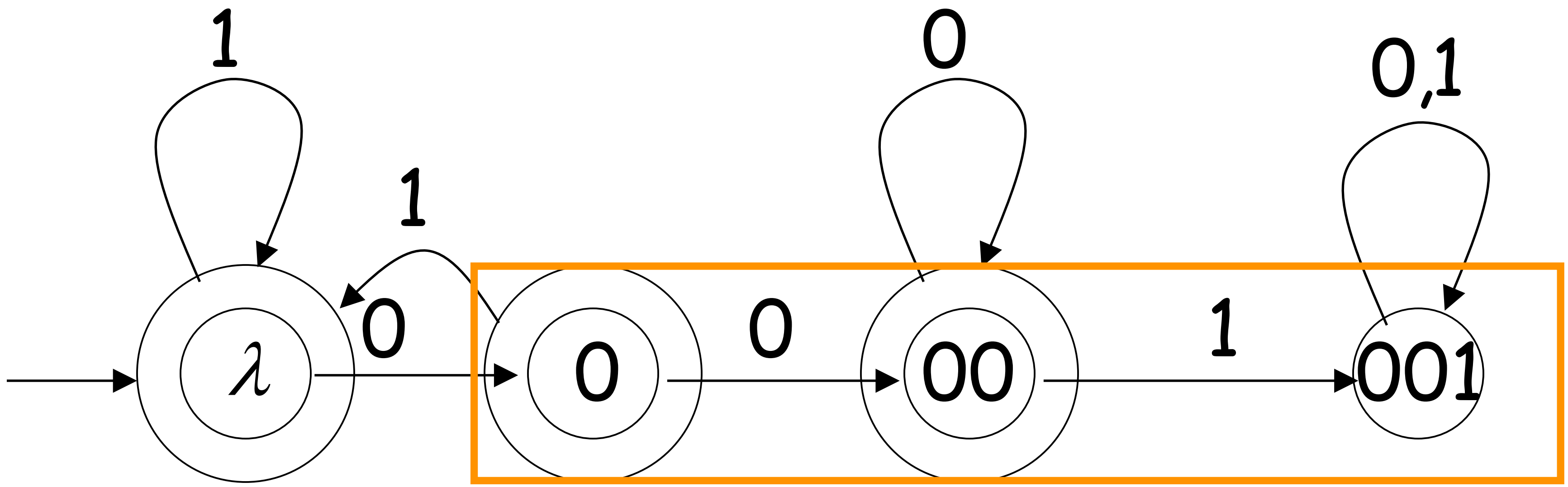
Example 2.3

$L(M)$ = { all strings with prefix ab }



Example 2.4

$L(M) =$ { all strings without substring 001 }



可以先把最基本的一條會出現001的路徑畫出來

Regular Languages

A language L is regular iff there exists some DFA M such that $L = L(M)$

All regular languages form a language family

Examples of regular languages:

$$\{abba\} \qquad \{\lambda, ab, abba\} \qquad \{a^n b : n \geq 0\}$$

{ all strings with prefix ab }

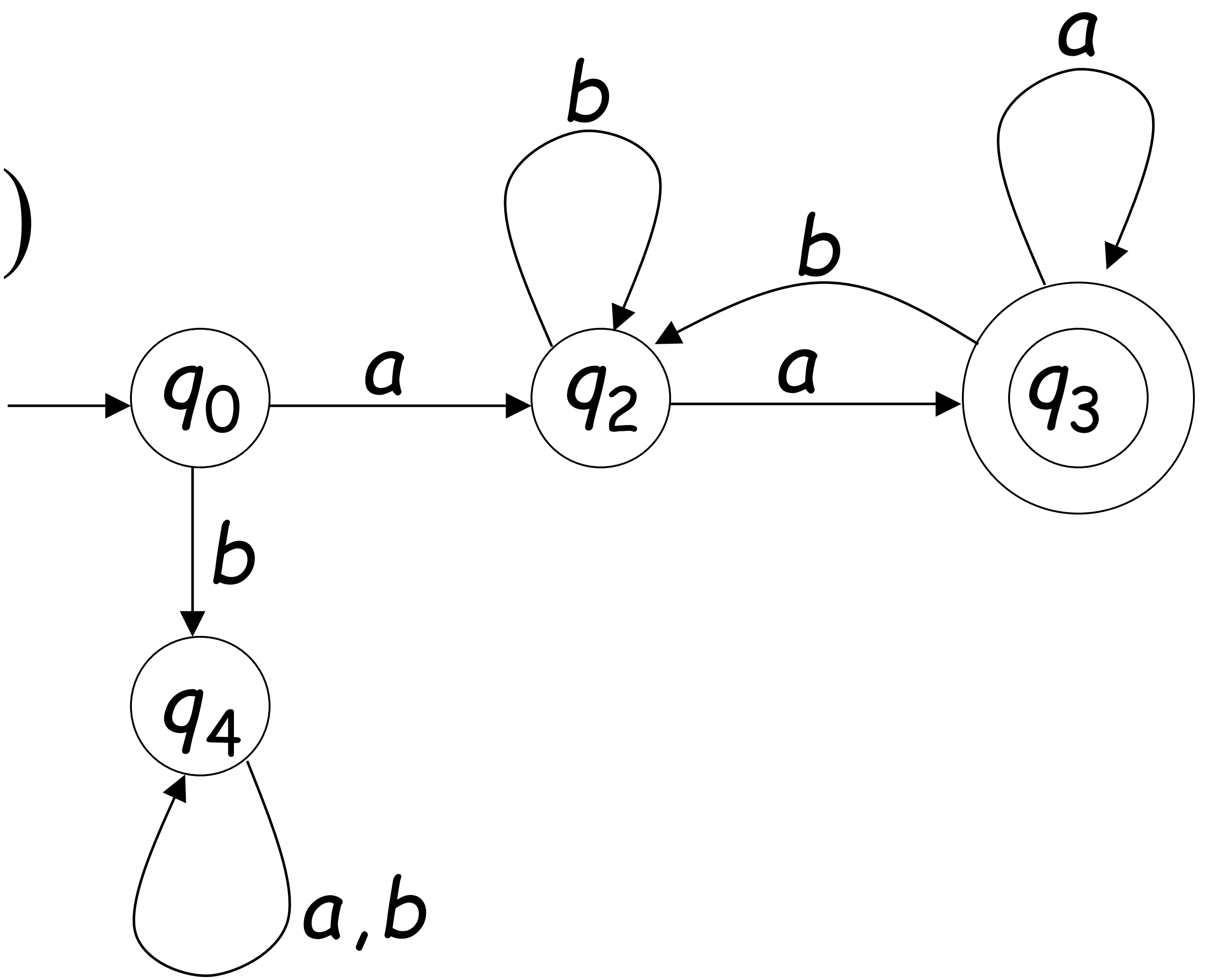
{ all strings without substring 001 }

There exists DFA that accept these Languages

Example 2.5

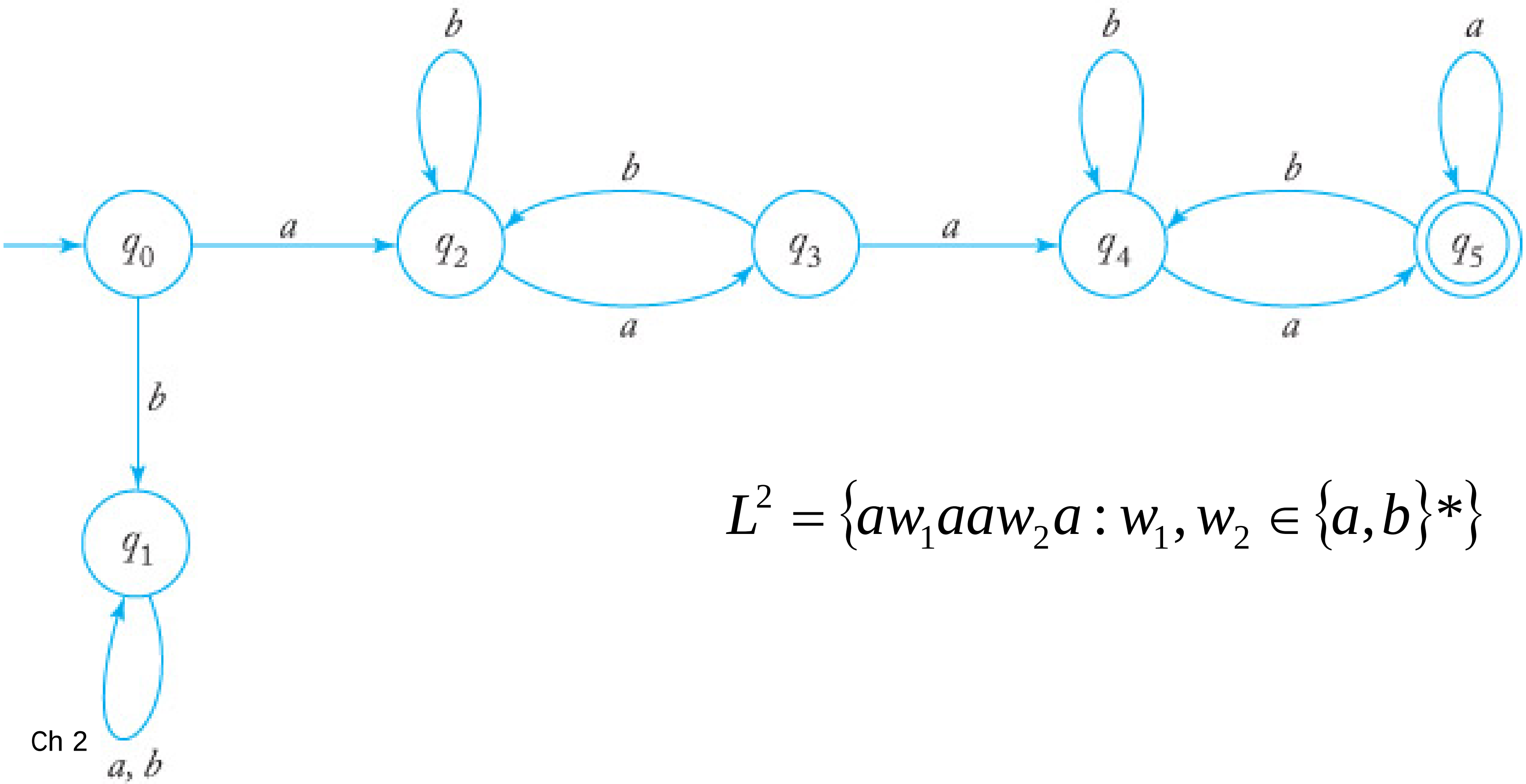
The language $L = \{awa : w \in \{a,b\}^*\}$ is regular:

$$L = L(M)$$



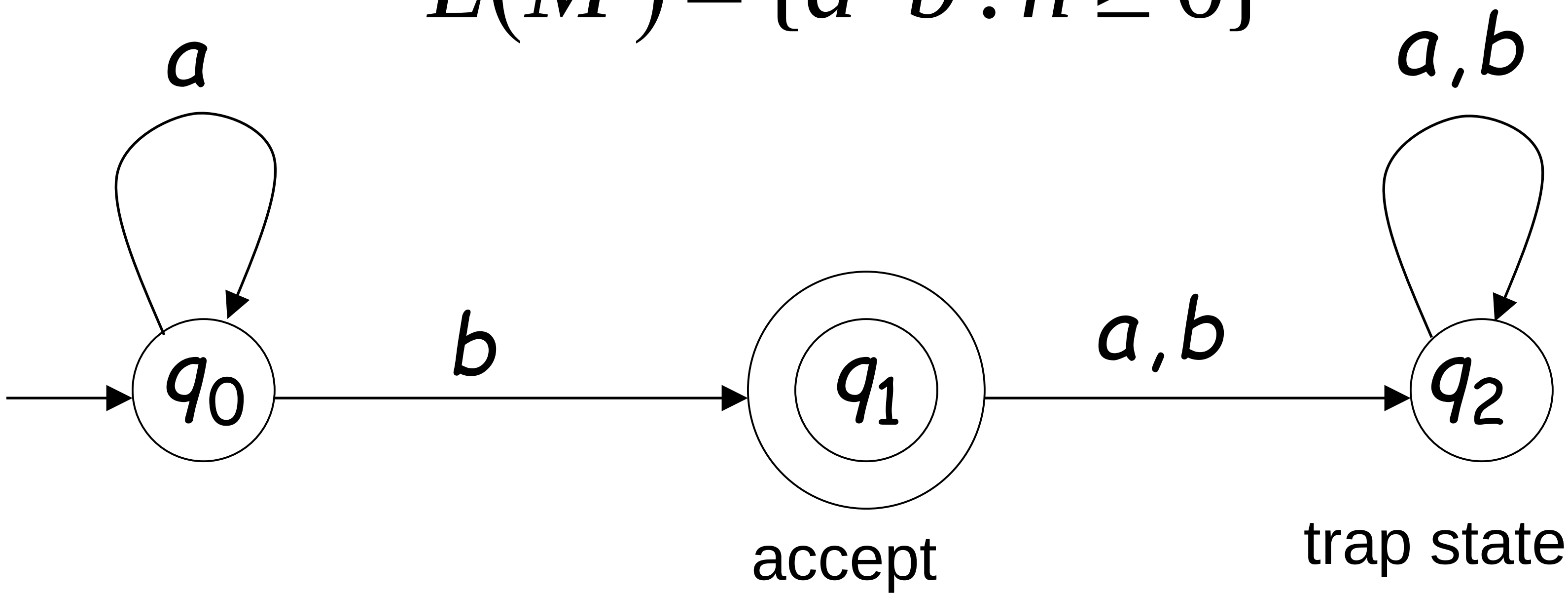
Example 2.6

The language $L = \{awa : w \in \{a,b\}^*\}$
is regular, how about L^2?



$$L^2 = \{aw_1aaw_2a : w_1, w_2 \in \{a,b\}^*\}$$

$$L(M)=\{a^n b : n \geq 0\}$$



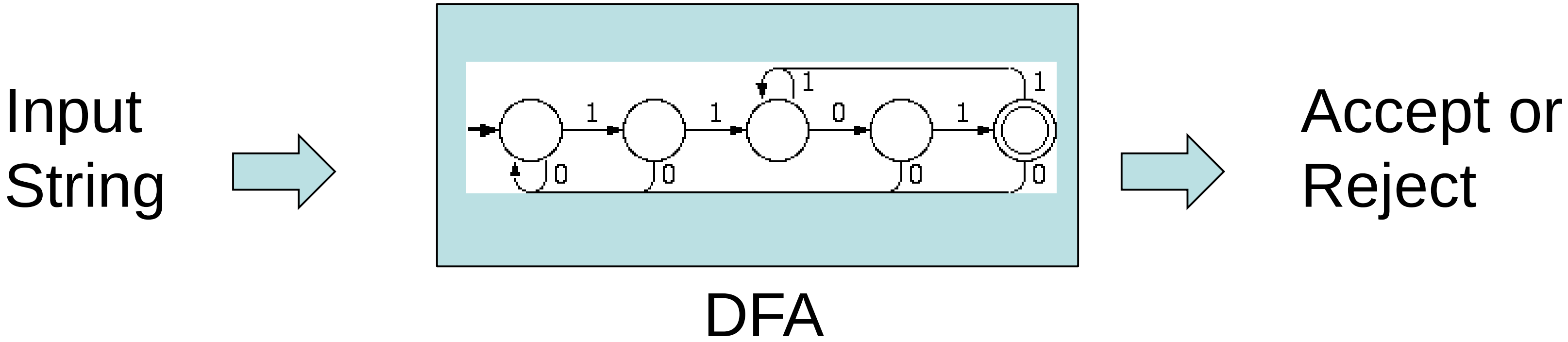
$$\boxed{L=\{a^n b^n : n \geq 0\}} \text{ ?}$$

無法將此Language畫出DFA，因為dfa沒有記憶性

There exist languages which are <u>not</u> Regular:

There is no DFA that accepts such a language
(we will prove this later in the class)

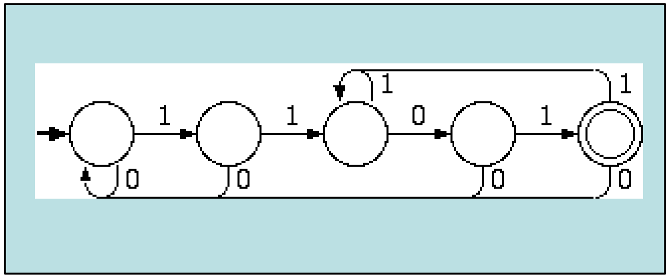
DFA Recap



- A machine with finite number of states, some states are accepting states, others are rejecting states
- At any time, it is in one of the states
- It reads an input string, one character at a time

DFA Recap

Input String



DFA

Accept or Reject

- After reading each character, it moves to another state depending on what is read and what is the current state
- If reading all characters, the DFA is in an accepting state, the input string is accepted.
- Otherwise, the input string is rejected.

Definition 2.1

Deterministic Finite Accepter (DFA) is define by the 5-tuple

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

Q : a finite set of **internal states**

Σ : a finite set of symbols called **input alphabet**

δ : $Q \times \Sigma \rightarrow Q$ called **transition function**

q_0 : $q_0 \in Q$ is the **initial state**

F : $F \subseteq Q$ is a set of **final states**

Regular Languages

A language L is regular iff there exists some DFA M such that $L = L(M)$

Definition:

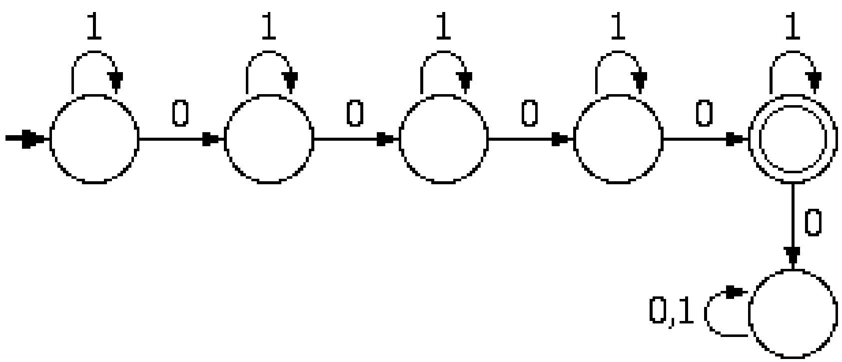
– The language $L(M)$ contains all input strings accepted by a DFA M

– $L(M)$ = { strings that drive M to a final state} p.63~68注意，一定會考

More Examples

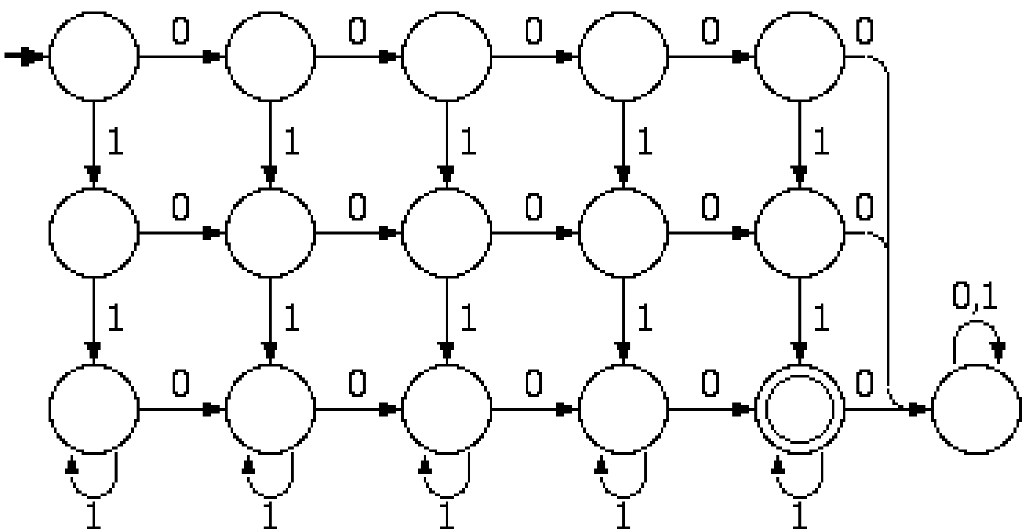
- All strings that contain exactly 4 "0"s.
- All strings containing exactly 4 "0" s and at least 2 "1" s.
- All strings of length at most five.
- All strings ending in "1101".
- All strings whose binary interpretation is divisible by 5.
- All strings that contain the substring 0101.
- All strings that don’t contain the substring 110.

一開始在畫DFA時都先將對的路徑畫出來



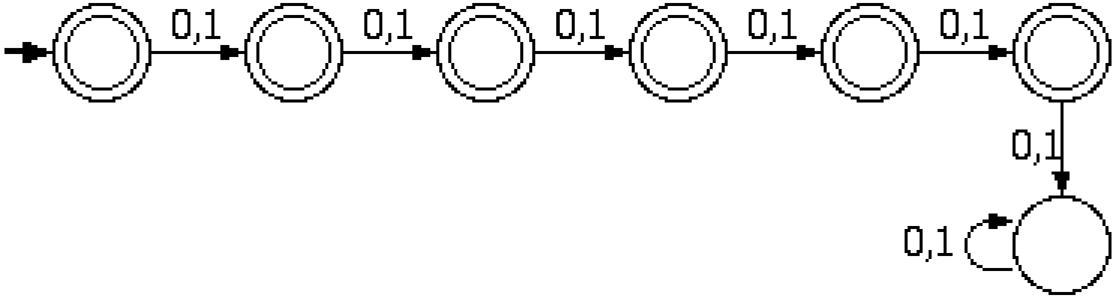
More Examples

- All strings that contain exactly 4 "0"s.
- All strings containing exactly 4 "0" s and at least 2 "1" s.
- All strings of length at most five.
- All strings ending in "1101".
- All strings whose binary interpretation is divisible by 5.
- All strings that contain the substring 0101.
- All strings that don’t contain the substring 110.



More Examples

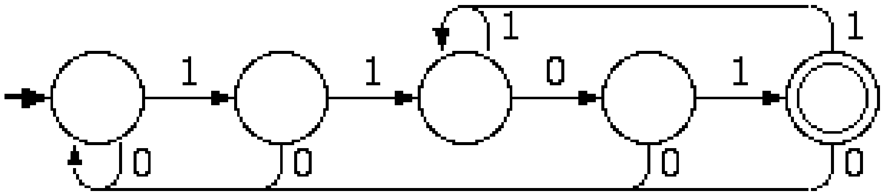
- All strings that contain exactly 4 "0"s.
- All strings containing exactly 4 "0" s and at least 2 "1" s.
- All strings of length at most five.
- All strings ending in "1101".
- All strings whose binary interpretation is divisible by 5.
- All strings that contain the substring 0101.
- All strings that don’t contain the substring 110.



More Examples

- All strings that contain exactly 4 "0"s.
- All strings containing exactly 4 "0" s and at least 2 "1" s.
- All strings of length at most five.
- All strings ending in "1101". 必考
- All strings whose binary interpretation is divisible by 5.
- All strings that contain the substring 0101.
- All strings that don’t contain the substring 110.

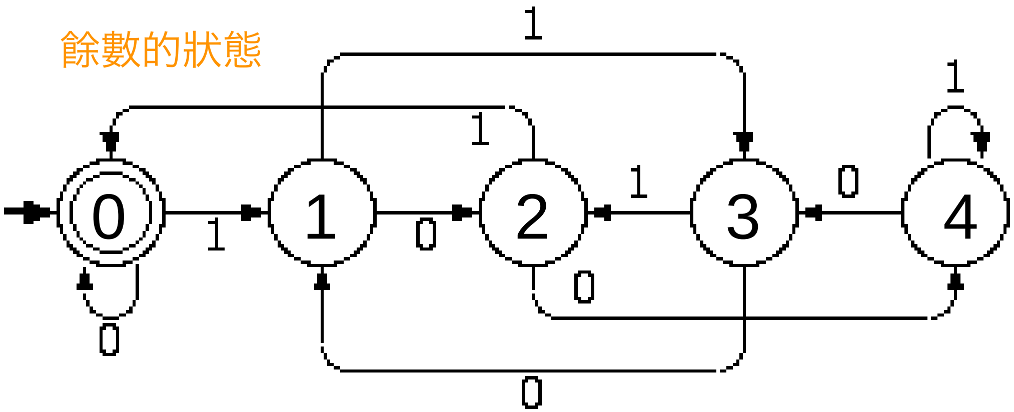
連續2個1以上一樣等同於看到2個1的狀態



More Examples

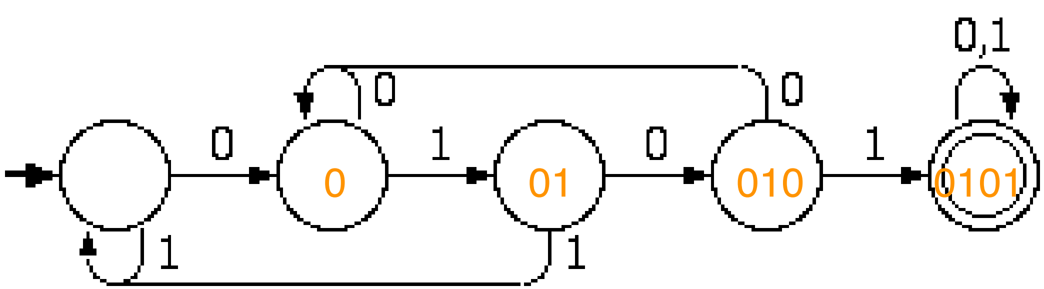
– All strings that contain exactly 4 "0"s.
– All strings containing exactly 4 "0" s and at least 2 "1" s.
– All strings of length at most five.
– All strings ending in "1101".
可能會考 – All strings whose binary interpretation is divisible by 5.
– All strings that contain the substring 0101.
– All strings that don’t contain the substring 110.

餘數的狀態



More Examples

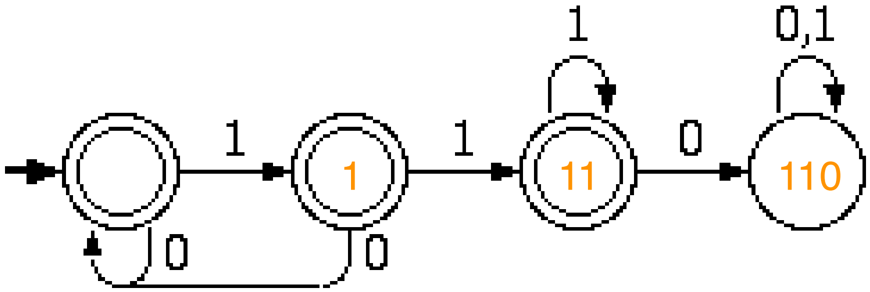
- All strings that contain exactly 4 "0"s.
- All strings containing exactly 4 "0" s and at least 2 "1" s.
- All strings of length at most five.
- All strings ending in "1101".
- All strings whose binary interpretation is divisible by 5.
- All strings that contain the substring 0101.
- All strings that don’t contain the substring 110.



Hint:直接在狀態上面標記已經可以看到的pattern,可以幫助把圖畫出來

More Examples

- All strings that contain exactly 4 "0"s.
- All strings containing exactly 4 "0" s and at least 2 "1" s.
- All strings of length at most five.
- All strings ending in "1101".
- All strings whose binary interpretation is divisible by 5.
- All strings that contain the substring 0101.
- All strings that don’t contain the substring 110.

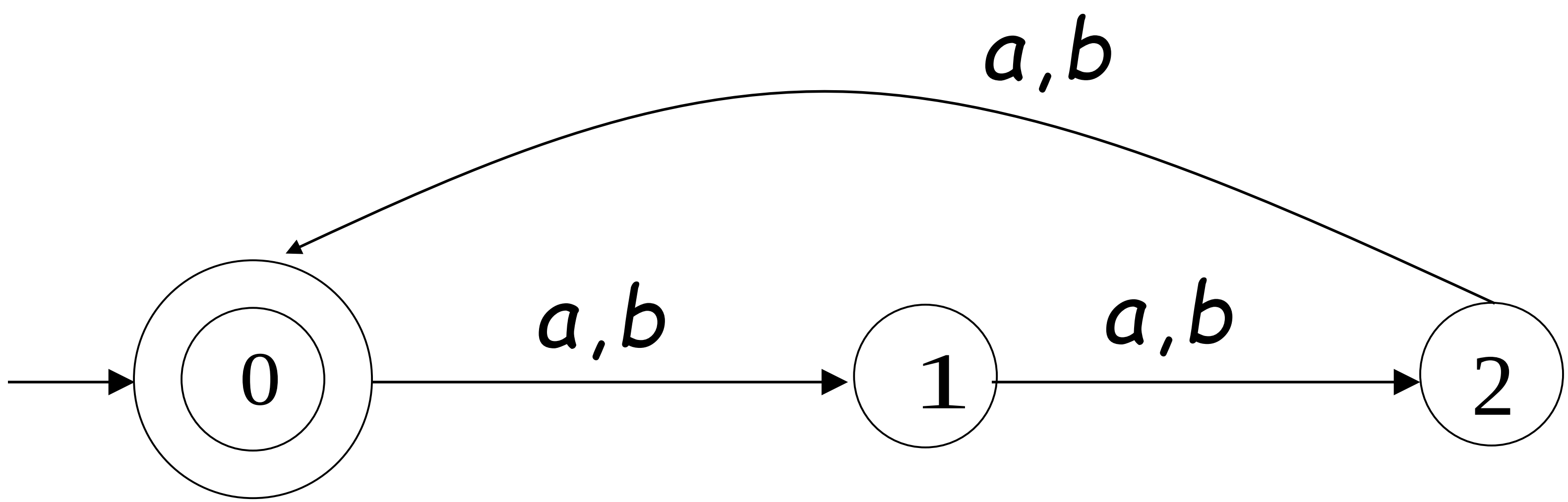


Exercise 2.1.7

Find DFAs for the following languages on $\Sigma=\{a,b\}$

(a) $L = \{w: |w| \bmod 3 = 0\}$

(b) $L = \{w: n_a(w) \bmod 3 > n_b(w) \bmod 3\}$

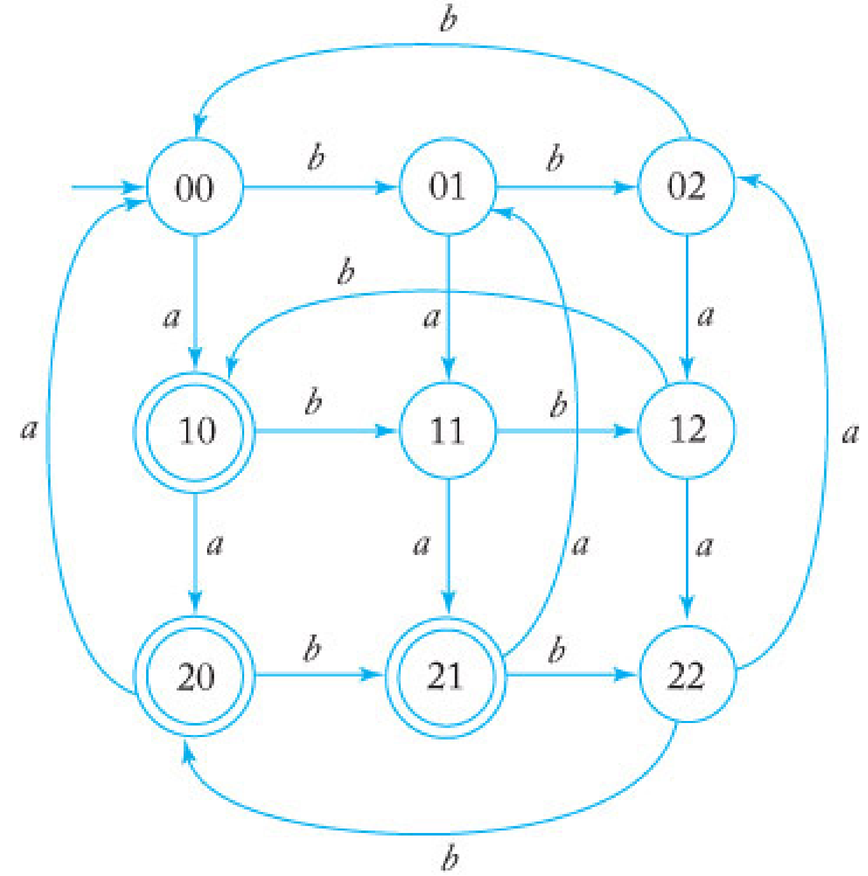


Exercise 2.1.7

Find DFAs for the following languages on ∑={a,b}

(a) L = {w: |w| mod 3 = 0}

(b) L = {w: $n_a(w)$ mod 3 > $n_b(w)$ mod 3}



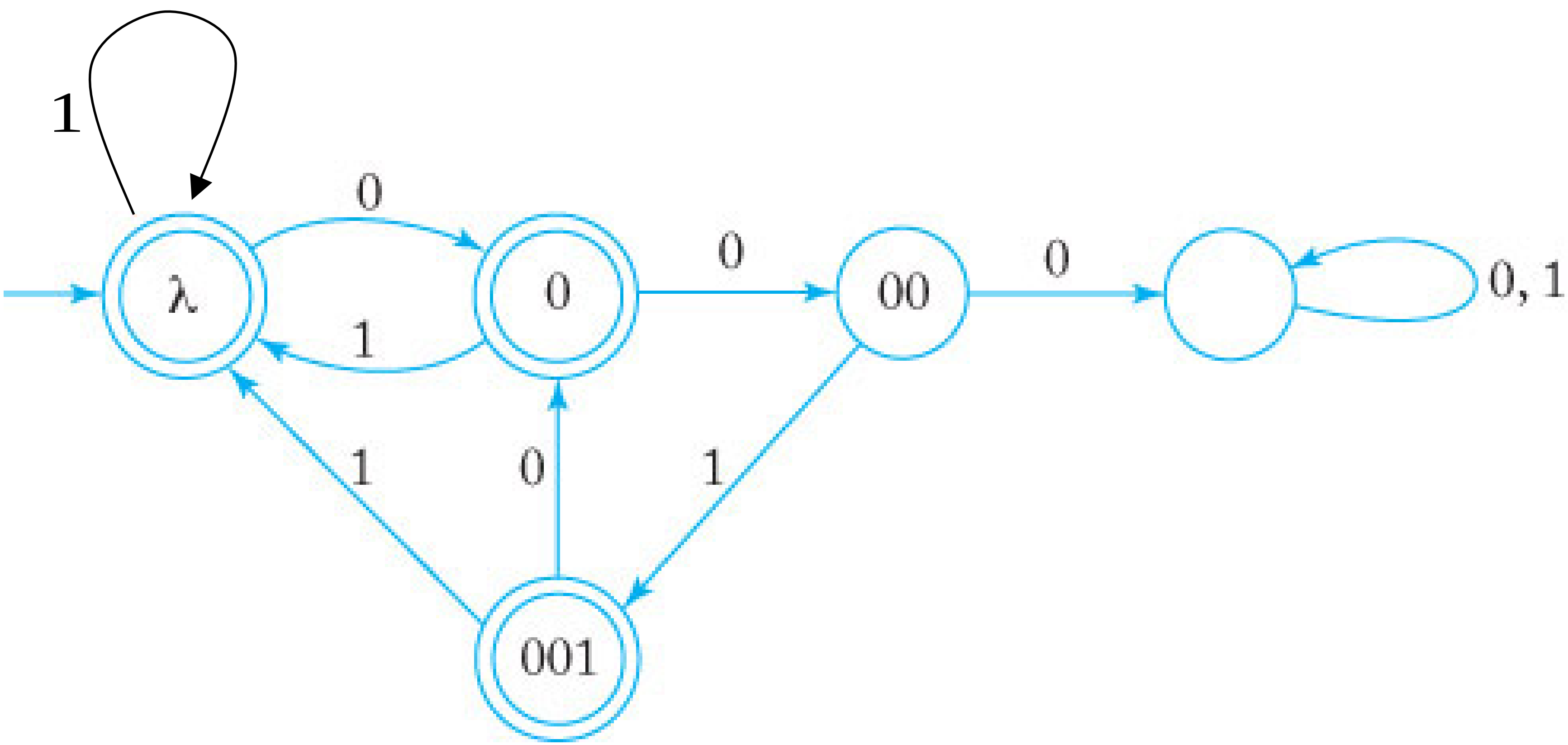
Exercise 2.1.9

(a) Every 00 is followed immediately by a 1.

Ex: 101, 0010,0010011001 ϵ L

0001 and 00100 ∉ L

$\Sigma = \{0,1\}$



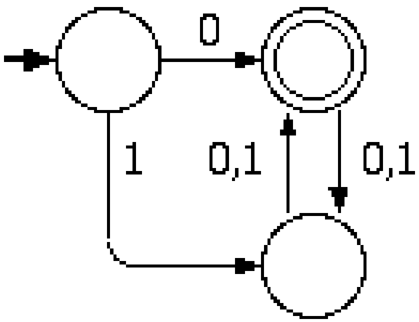
Questions?

Short Quiz

- All strings that start with 0 and have odd length or start with 1 and have even length.
- All strings where every odd position is a 1.

Short Quiz

- All strings that start with 0 and have odd length or start with 1 and have even length.



- All strings where every odd position is a 1.