15-453

FORMAL LANGUAGES, AUTOMATA AND COMPUTABILITY

NON-DETERMINISM and REGULAR OPERATIONS

THURSDAY JAN 16

UNION THEOREM

The union of two regular languages is also a regular language

“Regular Languages Are Closed Under Union”

INTERSECTION THEOREM

The intersection of two regular languages is also a regular language

Complement THEOREM

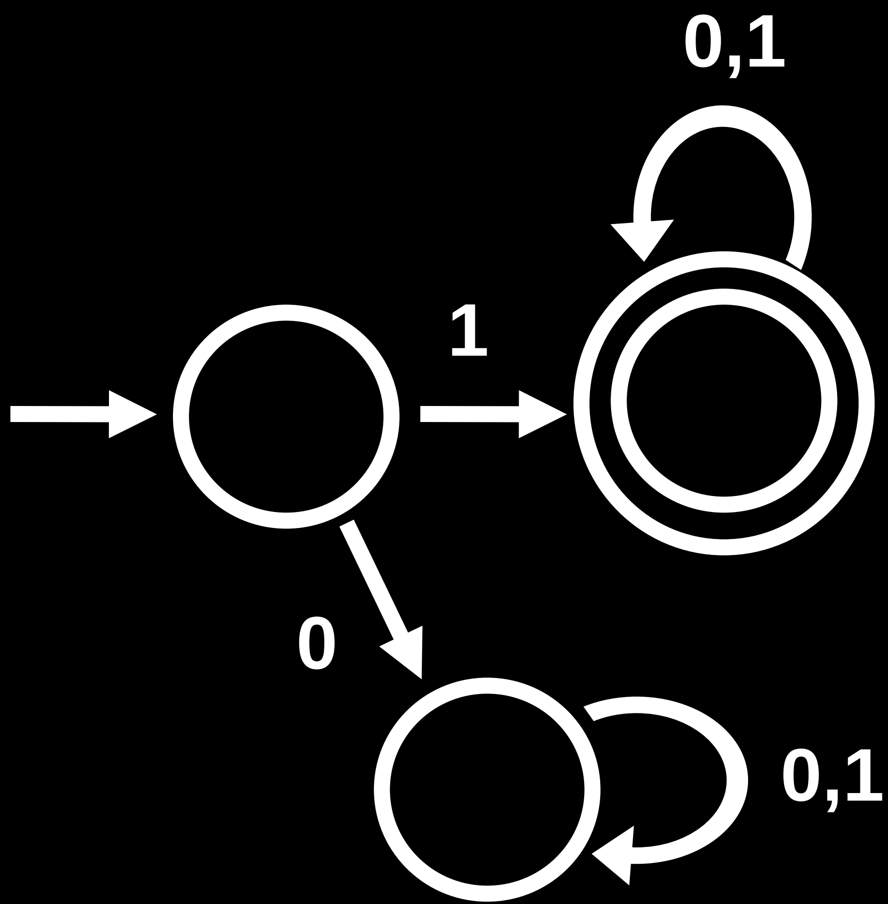
The complement of a regular language is also a regular language

In other words,

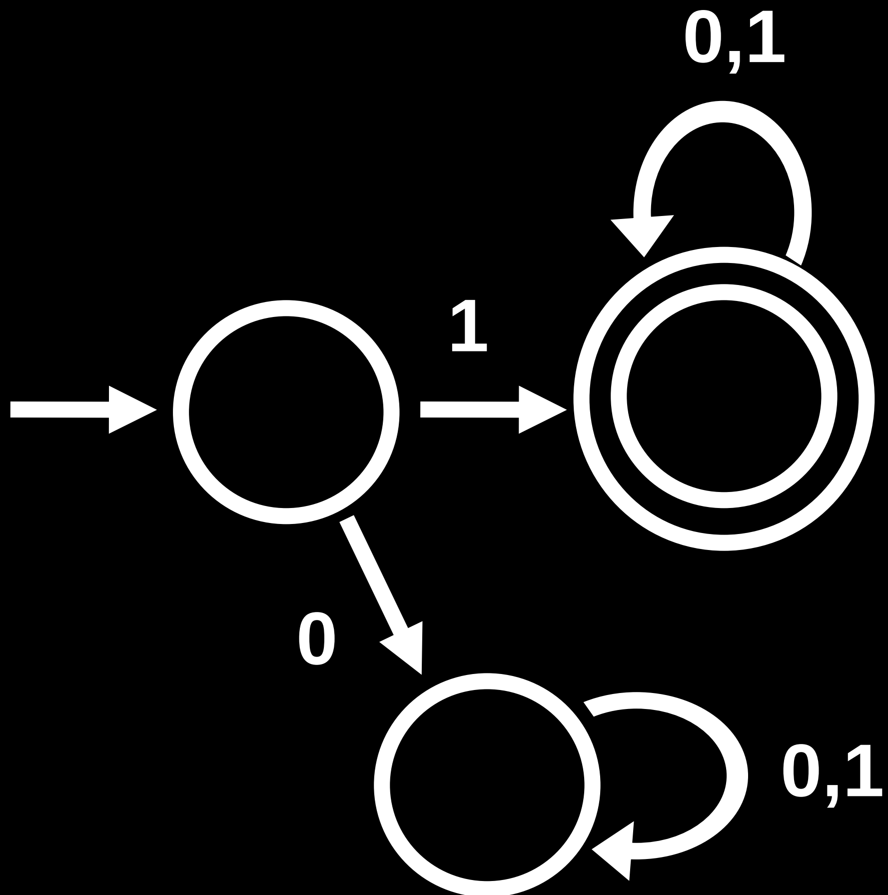
if L is regular than so is $\neg L$,

where $\neg L = \{ w \in \Sigma^* \mid w \notin L \}$

Proof ?

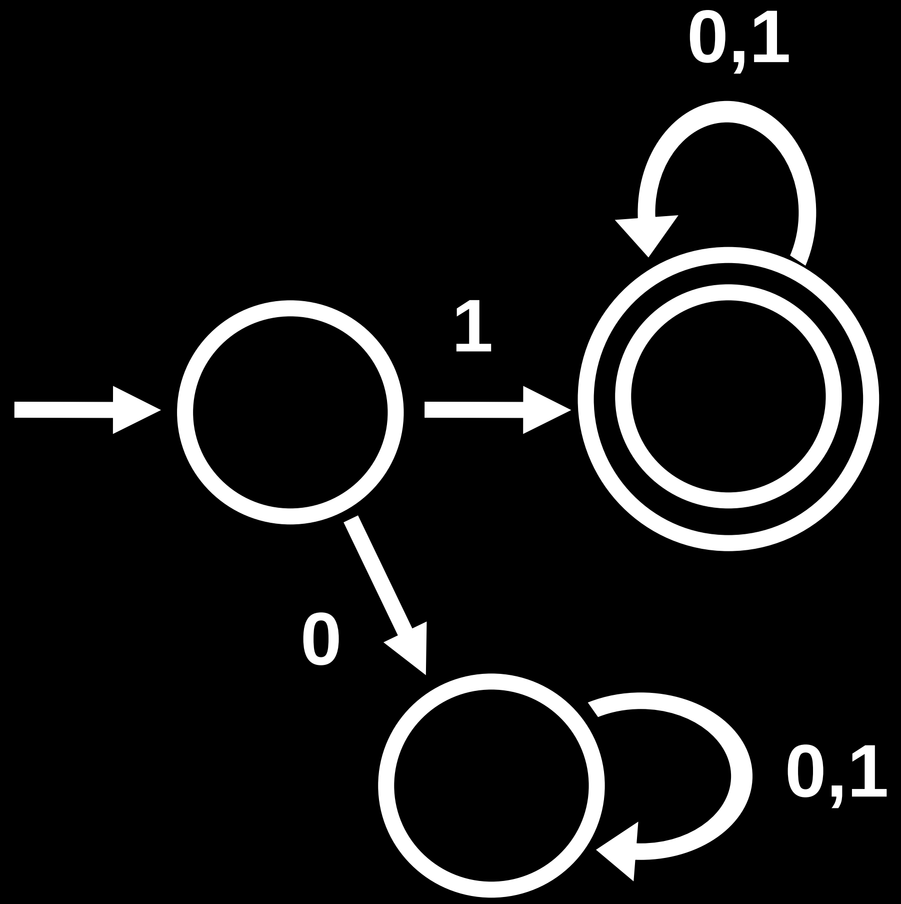


L(M) = { w | w begins with 1}



L(M) = { w | w begins with 1}

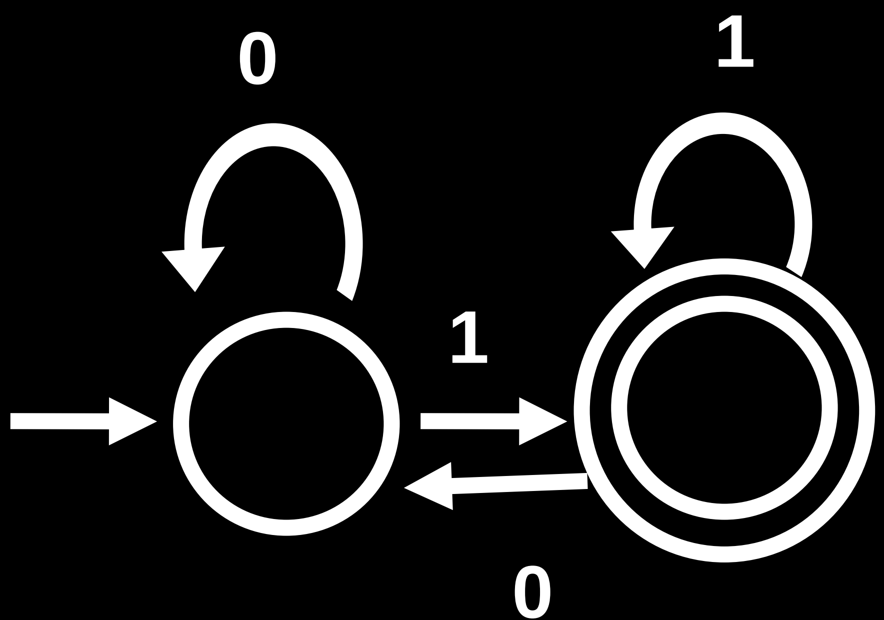
Suppose our machine reads strings from *right to left*…
What language would be recognized then?



L(M) = { w | w begins with 1}

Suppose our machine reads strings from *right to left*…
What language would be recognized then?

L(M) = { w | w ends with 1} Is L(M) regular?



L(M) = { w | w ends with 1} Is L(M) regular?

THE REVERSE OF A LANGUAGE

Reverse: $L^R = \{ w_1 \ldots w_k \mid w_k \ldots w_1 \in L, w_i \in \Sigma \}$

If L is recognized by a normal DFA,
Then L^R is recognized by a DFA reading from right to left!

Can every “Right-to-Left DFA” be replaced by a normal DFA??

REVERSE THEOREM

The reverse of a regular language is also a regular language

``Regular Languages Are Closed Under Reverse”

If a language can be recognized by a DFA that reads strings from *right* to *left*, **then** there is an “normal” DFA that accepts the same language

REVERSING DFAs

Assume L is a regular language.
Let M be a DFA that recognizes L

Task: Build a DFA M^R that accepts L^R

If M accepts w, then w describes a directed path in M from *start* to an *accept* state.

REVERSING DFAs

Assume L is a regular language.
Let M be a DFA that recognizes L

Task: Build a DFA M^R that accepts L^R

If M accepts w, then w describes a directed path in M from *start* to an *accept* state.

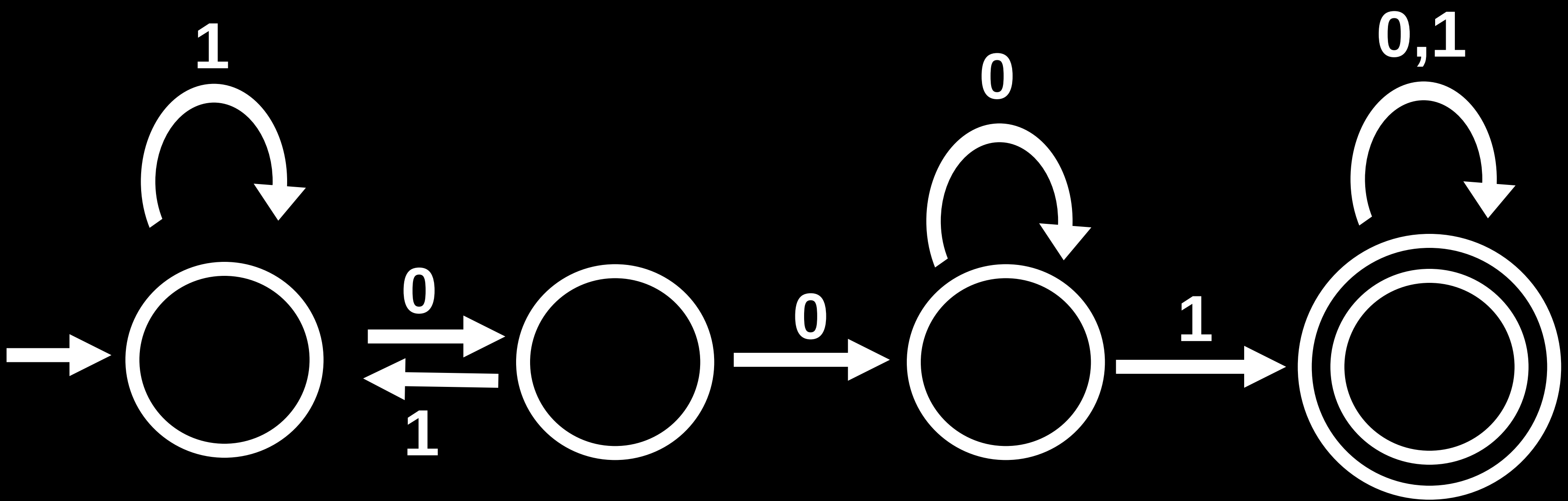
First Attempt:
Try to define M^R as M with the arrows reversed.
Turn start state into a final state.
Turn final states into start states.

M^R IS NOT ALWAYS A DFA!

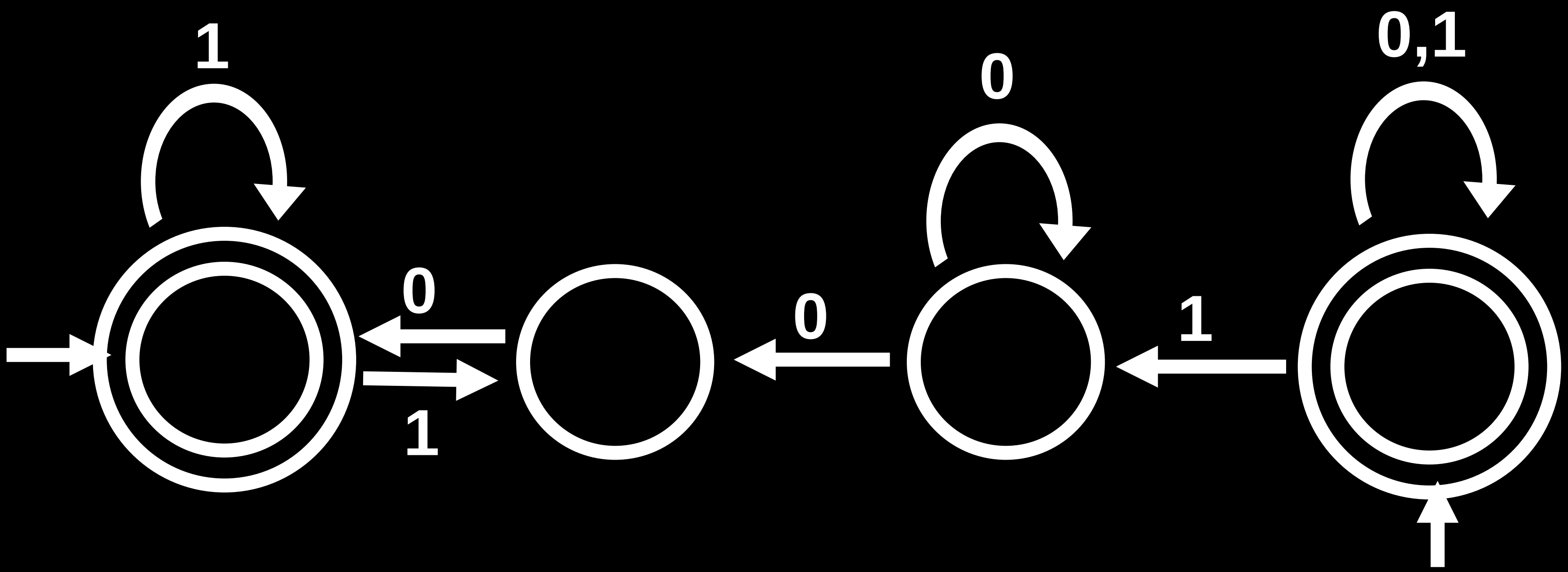
It could have many start states

Some states may have too many outgoing edges,

or none at all!

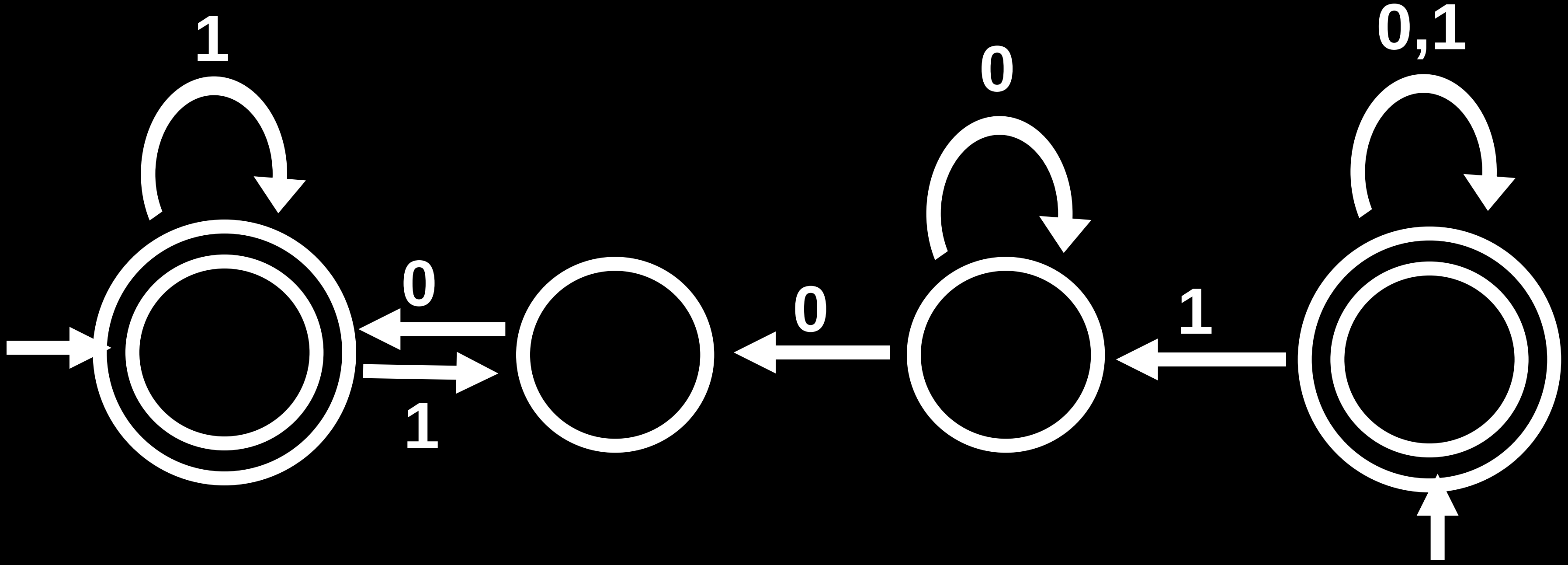

1
0
1
0
0
1
0,1

REVERSE



What happens with 100?

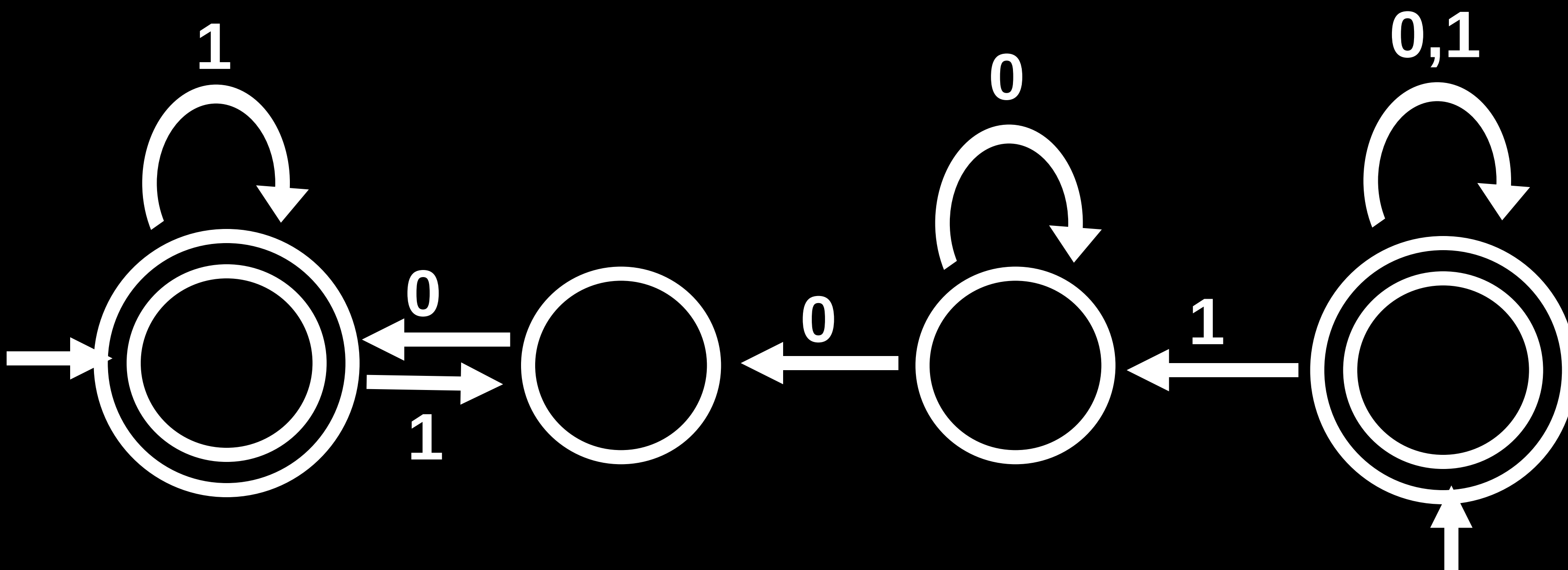
REVERSE



What happens with 100?

We will say that this machine accepts a string if there is *some path* that reaches an accept state from a start state.

NONDETERMINISM is BORN!



What happens with 100?

We will say that this machine accepts a string if there is *some path* that reaches an accept state from a start state.

***IBM JOURNAL* APRIL** 1959

Turing Award winning paper

M. O. Rabin*

D. Scott†

Finite Automata and Their Decision Problems‡

Abstract: Finite automata are considered in this paper as instruments for classifying finite tapes. Each one-tape automaton defines a set of tapes, a two-tape automaton defines a set of pairs of tapes, et cetera. The structure of the defined sets is studied. Various generalizations of the notion of an automaton are introduced and their relation to the classical automata is determined. Some decision problems concerning automata are shown to be solvable by effective algorithms; others turn out to be unsolvable by algorithms.

Introduction

Turing machines are widely considered to be the abstract prototype of digital computers; workers in the field, however, have felt more and more that the notion of a Turing machine is too general to serve as an accurate model of actual computers. It is well known that even for simple calculations it is impossible to give an *a priori* upper bound on the amount of tape a Turing machine will need for any given computation. It is precisely this feature that renders Turing's concept unrealistic.

In the last few years the idea of a *finite automaton* has appeared in the literature. These are machines having

a method of viewing automata but have retained throughout a machine-like formalism that permits direct comparison with Turing machines. A neat form of the definition of automata has been used by Burks and Wang[1] and by E. F. Moore,[4] and our point of view is closer to theirs than it is to the formalism of nerve-nets. However, we have adopted an even simpler form of the definition by doing away with a complicated output function and having our machines simply give "yes" or "no" answers. This was also used by Myhill, but our generalizations to the "nondeterministic," "two-way," and "many-tape"

he construction of $\mathfrak{A}$ and we shall
etail.

ces of words $S_1=(a_1,a_2, \ldots, a_n)$
$b_n)$ then $P(a_1,a_2, \ldots, a_n) \cap P(b_1,$
d only if the Post correspondence
$_2$ has a solution. Since the corre-
not effectively solvable it follows
ther

$$T_2(\mathfrak{A}(b_1, \ldots, b_n)) \neq \phi$$

able.

tape automata

-way, two-tape automata we find
constructive decision processes is
sible to decide, by a constructive
icable to all automata, whether a
chine accepts any tapes. To prove
ourse, necessary to give the explicit
y machine. We shall not give the
y are long and not very much dif-
al definitions needed for two-way,
he main point is that, as with the
omaton, the table of moves of a
itomaton sometimes requires the
om the scanned square. However
should clarify the method.
that there is no constructive deci-

Theorem 19. *There is no effective method of deciding whether the set of tapes definable by a two-tape, two-way automaton is empty or not.*

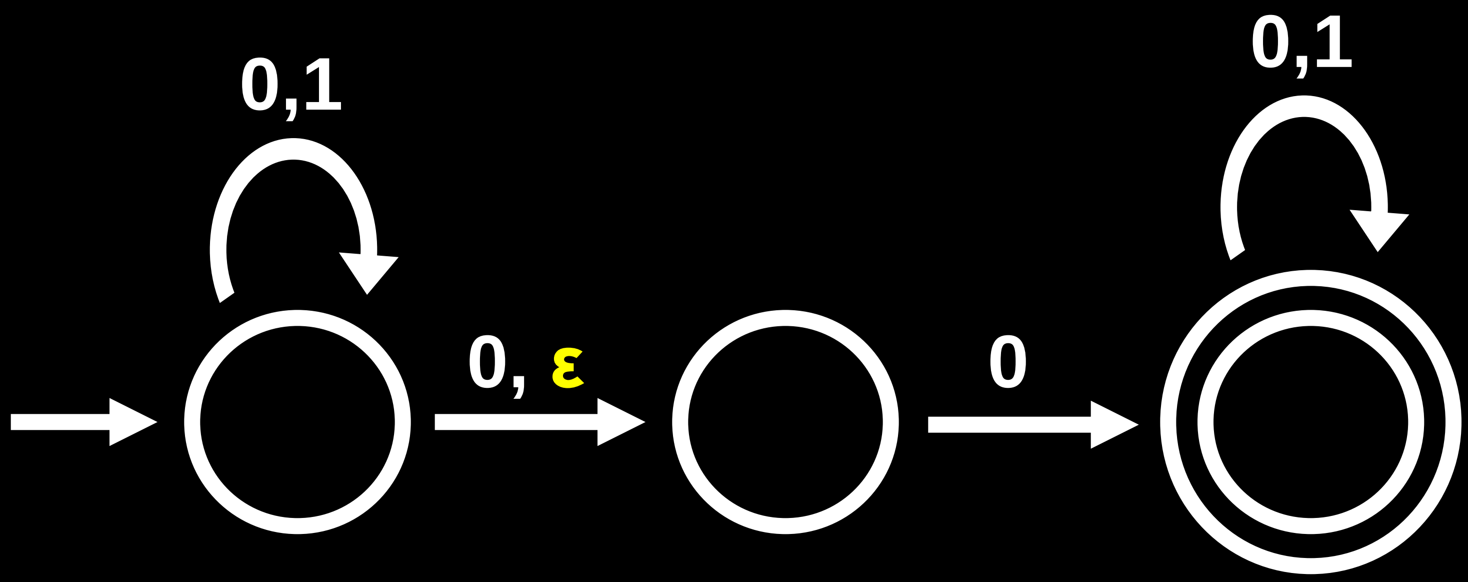
An argument similar to the above one will show that the class of sets of pairs of tapes definable by two-way, two-tape automata is closed under Boolean operations. In view of Theorem 17, this implies that there are sets definable by two-way automata which are not definable by any one-way automaton; thus no analogue to Theorem 15 holds.

References

1. A. W. Burks and Hao Wang, "The logic of automata," *Journal of the Association for Computing Machinery*, **4**, 193-218 and 279-297 (1957).
2. S. C. Kleene, "Representation of events in nerve nets and finite automata," *Automata Studies*, Princeton, pp. 3-41, (1956).
3. W. S. McCulloch and E. Pitts, "A logical calculus of the ideas imminent in nervous activity," *Bulletin of Mathematical Biophysics*, **5**, 115-133 (1943).
4. E. F. Moore, "Gedanken-experiments on sequential machines," *Automata Studies*, Princeton, pp. 129-153 (1956).
5. A. Nerode, "Linear automaton transformations," *Proceedings of the American Mathematical Society*, **9**, 541-544 (1958).
6. E. Post, "A variant of a recursively unsolvable problem," *Bulletin of the American Mathematical Society*, **52**, 264-268 (1946).
7. J. C. Shepherdson, "The reduction of two-way automata to one-way automata," *IBM Journal*, **3**, 198-200 (1959).

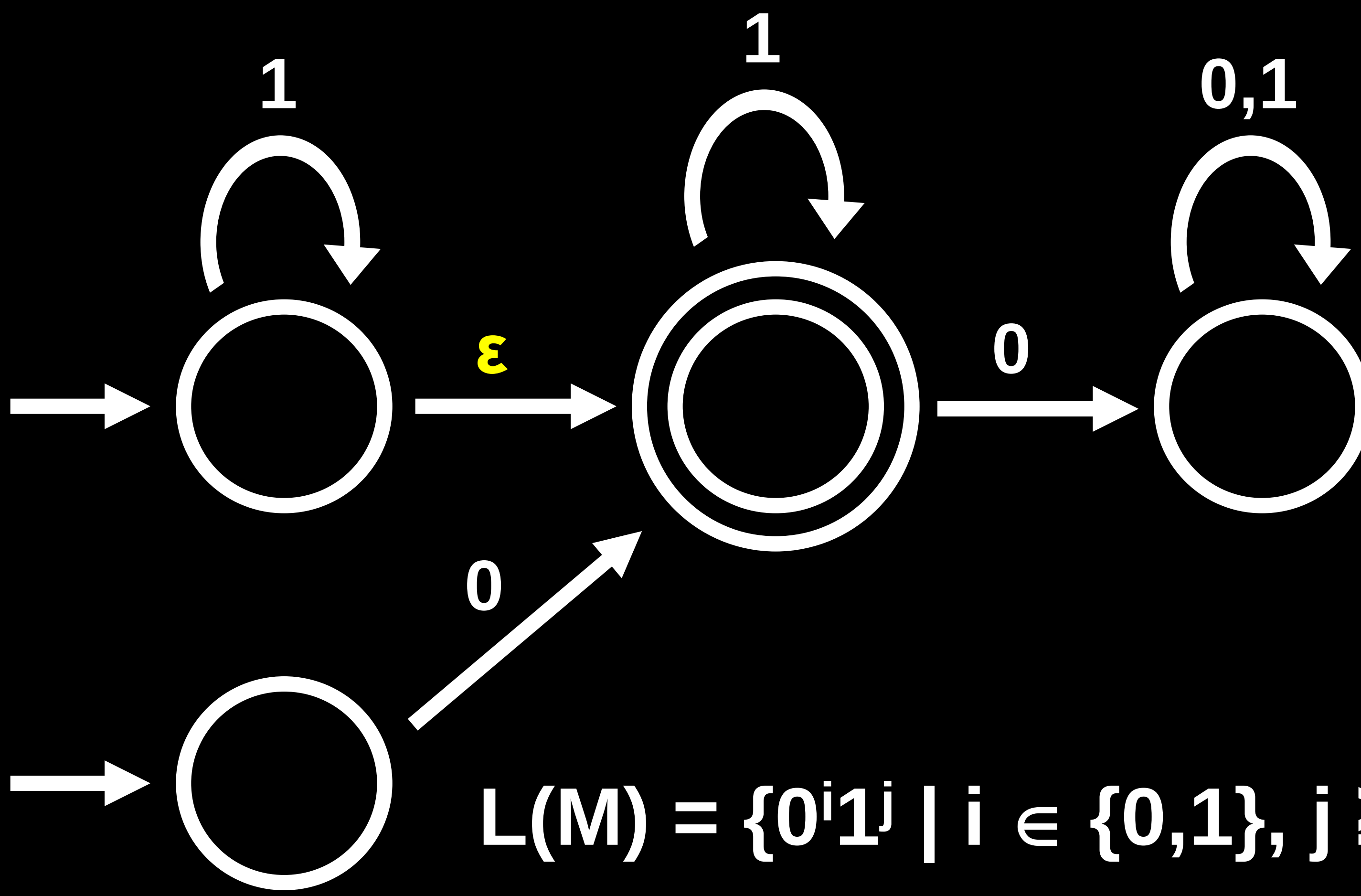
Revised manuscript received August 8, 1958

NFA EXAMPLES



At each state, we can have ***any*** number of out arrows for each letter $\sigma \in \Sigma_\varepsilon = \Sigma \cup \{\varepsilon\}$

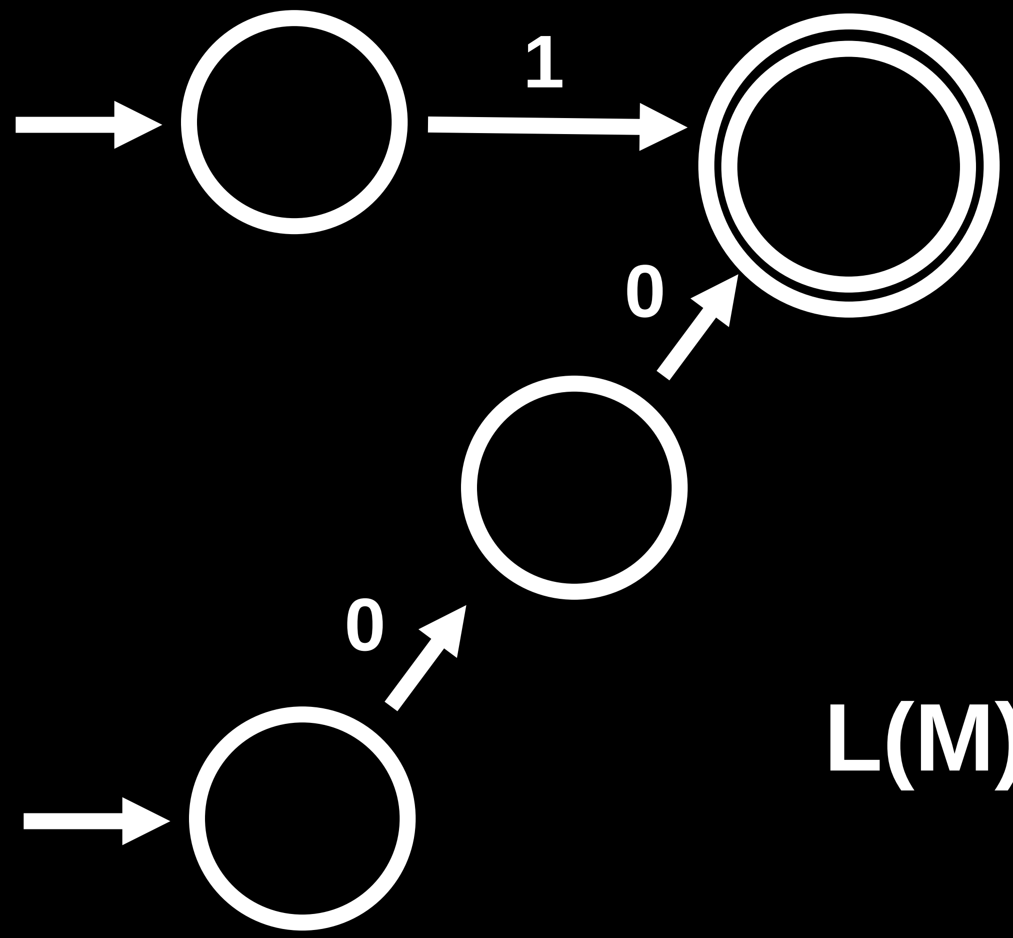
NFA EXAMPLES



$L(M) = \{0^i 1^j \mid i \in \{0,1\}, j \geq 0\}$

Possibly many start states

NFA EXAMPLES



L(M)={1,00}

A *non-deterministic* finite automaton (NFA) is a 5-tuple $N = (Q, \Sigma, \delta, Q_0, F)$

Q is the set of states

Σ is the alphabet

$\delta : Q \times \Sigma_\varepsilon \rightarrow 2^Q$ is the transition function

$Q_0 \subseteq Q$ is the set of start states

$F \subseteq Q$ is the set of accept states

2^Q is the set of all possible subsets of Q

$\Sigma_\varepsilon = \Sigma \cup \{\varepsilon\}$

Let $w \in \Sigma^*$ and suppose w can be written as $w_1 \ldots w_n$ where $w_i \in \Sigma_\varepsilon$ (ε = empty string)

Then N **accepts** w if there are $r_0, r_1, \ldots, r_n \in Q$ such that

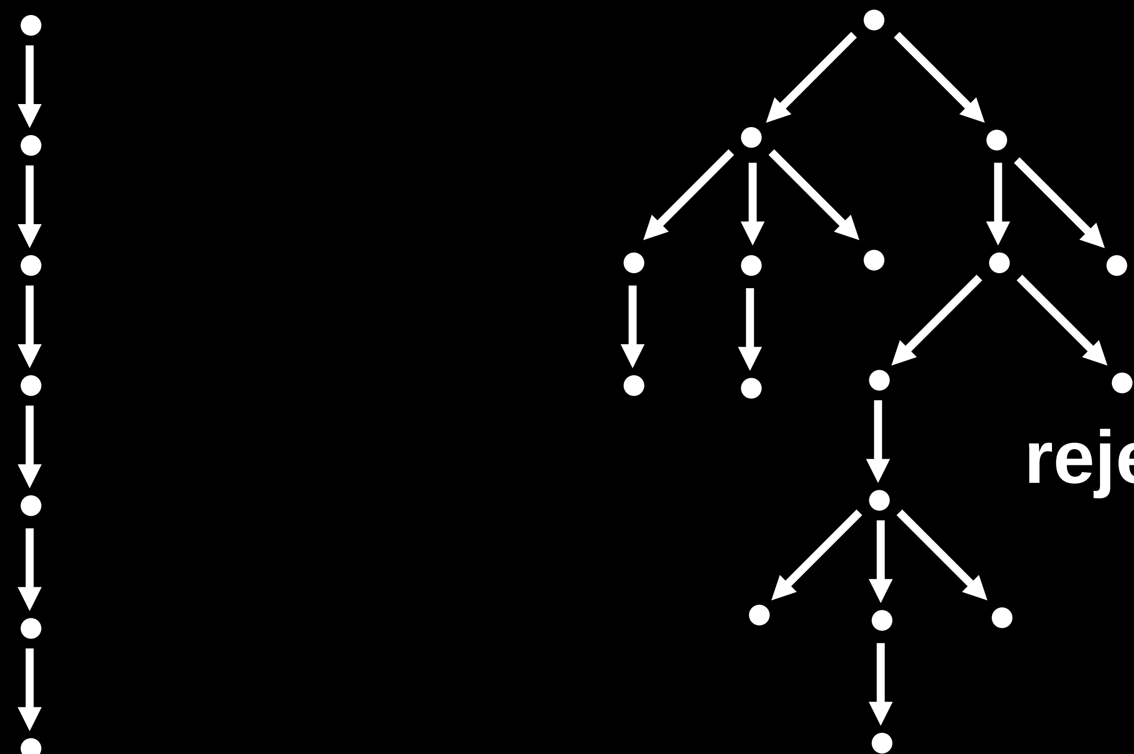
1. $r_0 \in Q_0$
2. $r_{i+1} \in \delta(r_i, w_{i+1})$ for $i = 0, \ldots, n-1$, and
3. $r_n \in F$

$L(N)$ = the language recognized by N
= set of all strings machine N accepts

A language L is **recognized** by an NFA N if $L = L(N)$.

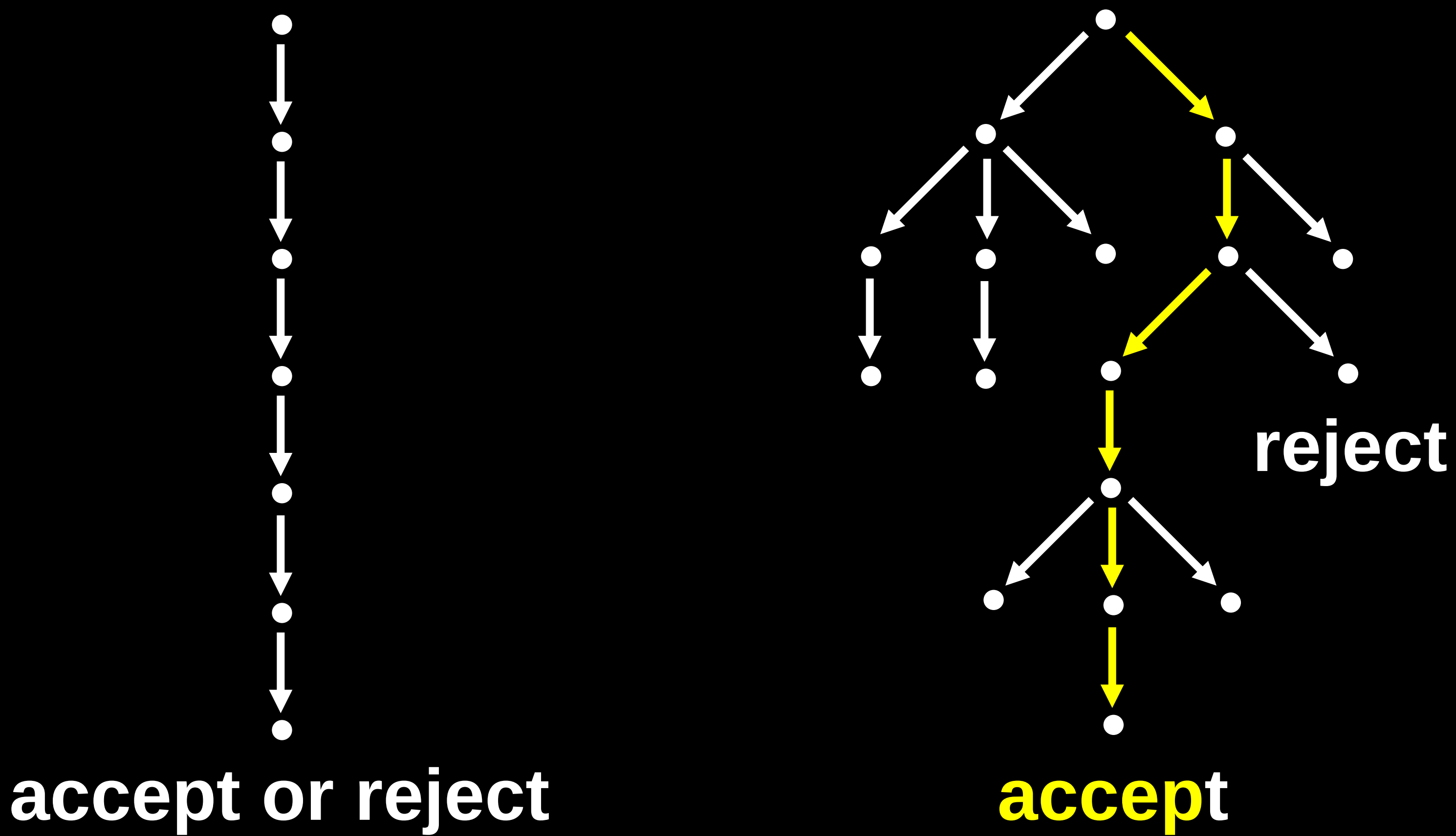
Deterministic Computation

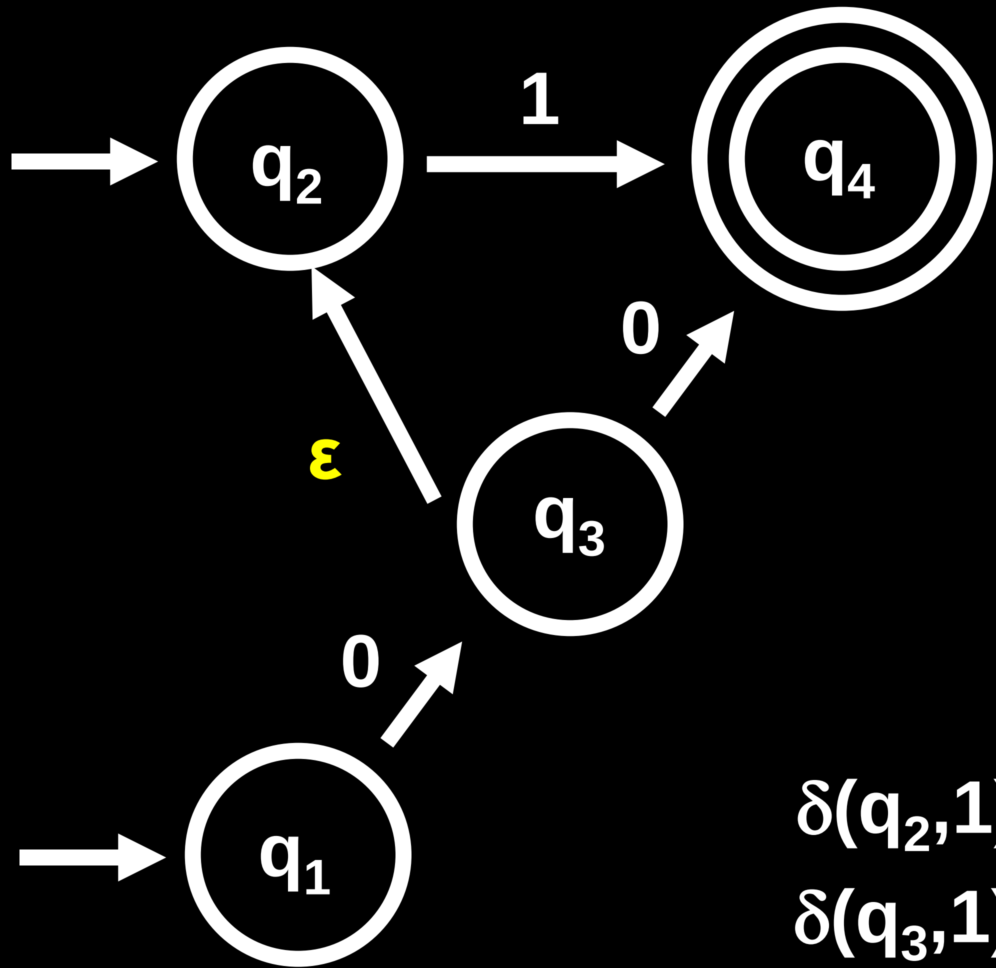
Non-Deterministic Computation



Deterministic Computation

Non-Deterministic Computation





$N = (Q, \Sigma, \delta, Q_0, F)$

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

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

$Q_0 = \{q_1, q_2\}$

$F = \{q_4\} \subseteq Q$

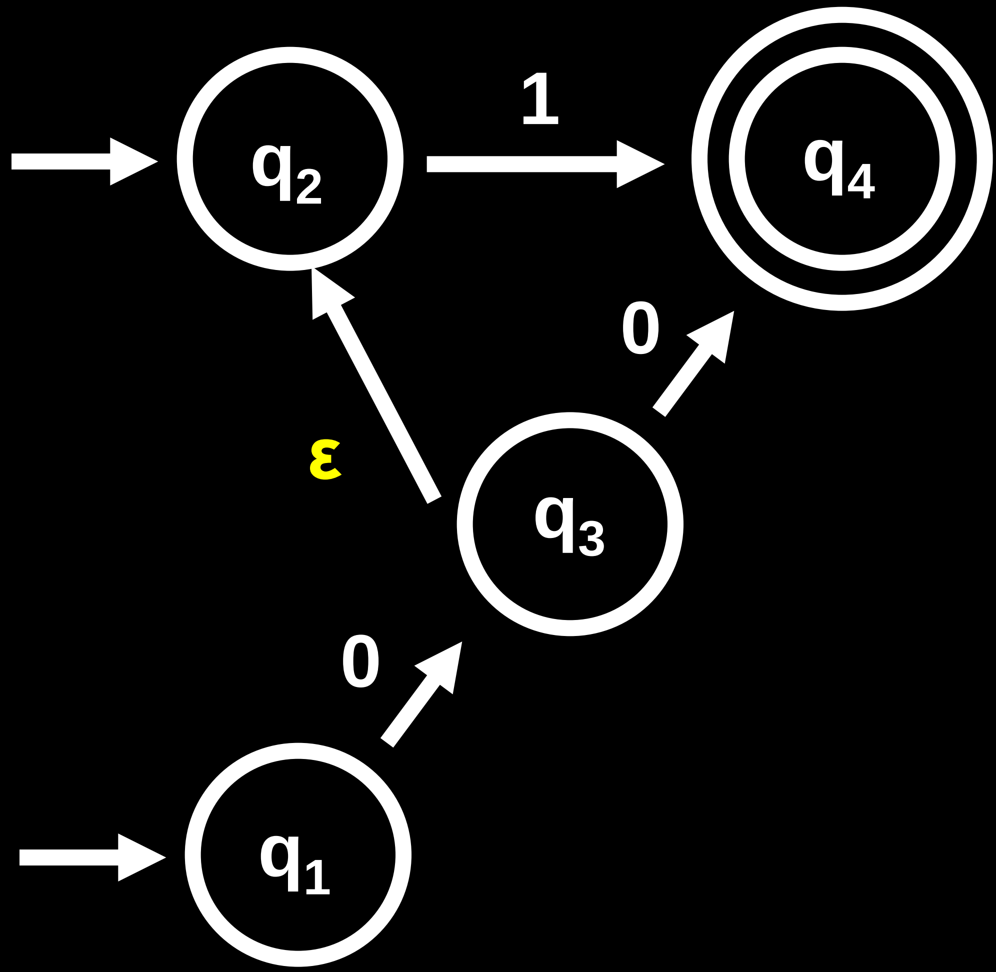
$\delta(q_2,1) = \{q_4\}$

$\delta(q_3,1) = \emptyset \quad \delta(q_3, \varepsilon) = \{ q_2\}$

$\delta(q_1,0) = \{ q_3\}$

$00 \in L(N)$?

$01 \in L(N)$?



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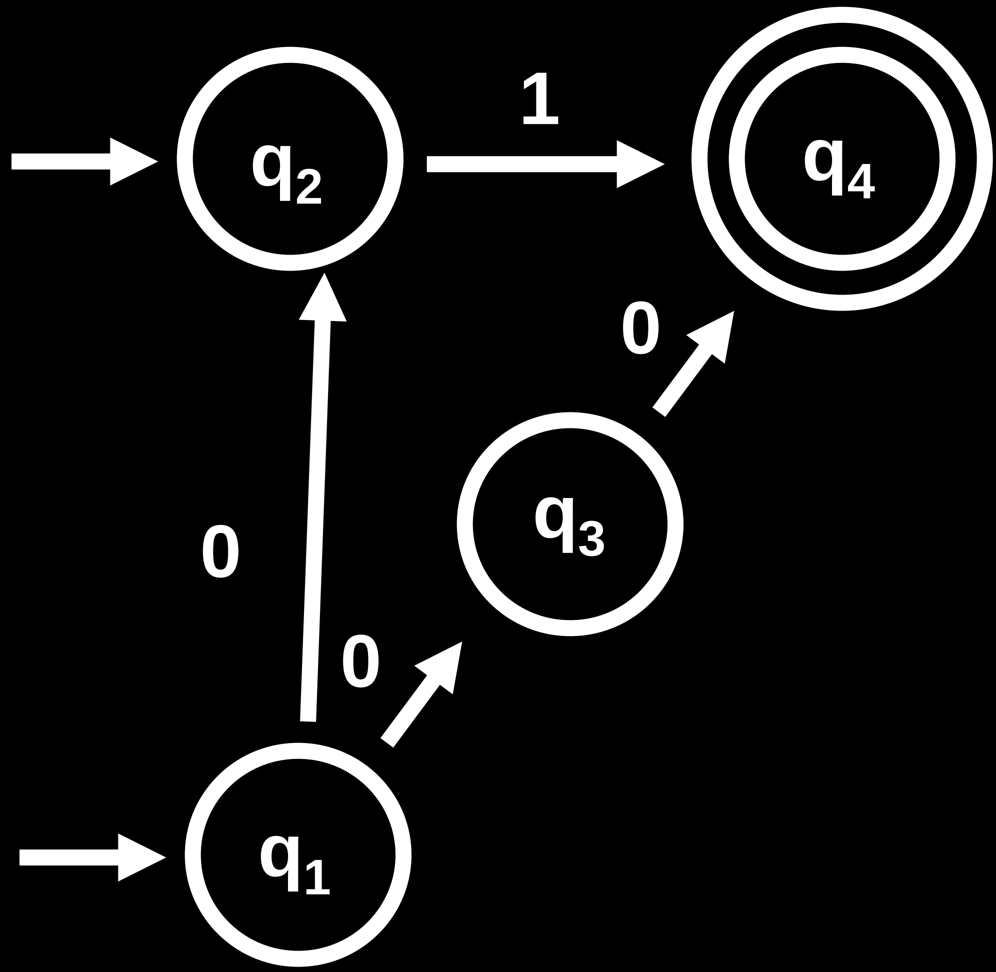
$F = \{q_4\} \subseteq Q$

δ	0	1	ε
q_1	$\{q_3\}$	$\varnothing$	$\varnothing$
q_2	$\varnothing$	$\{q_4\}$	$\varnothing$
q_3	$\{q_4\}$	$\varnothing$	$\{q_2\}$
q_4	$\varnothing$	$\varnothing$	$\varnothing$



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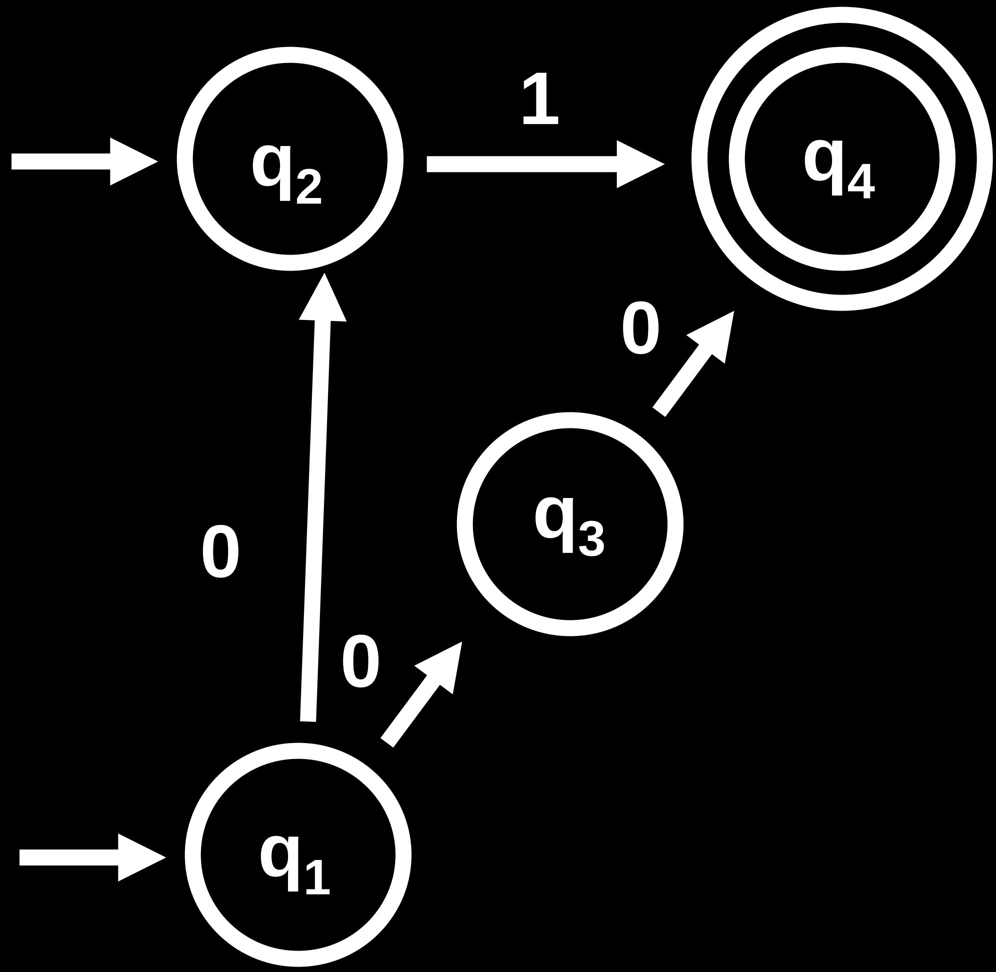
q_1	$\{q_2, q_3\}$	$\emptyset$	$\emptyset$
q_2	$\emptyset$	$\{q_4\}$	$\emptyset$
q_3	$\{q_4\}$	$\emptyset$	$\emptyset$
q_4	$\emptyset$	$\emptyset$	$\emptyset$



$N = (Q, \Sigma, \delta, Q_0, F)$

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

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

$Q_0 = \{q_1, q_2\}$

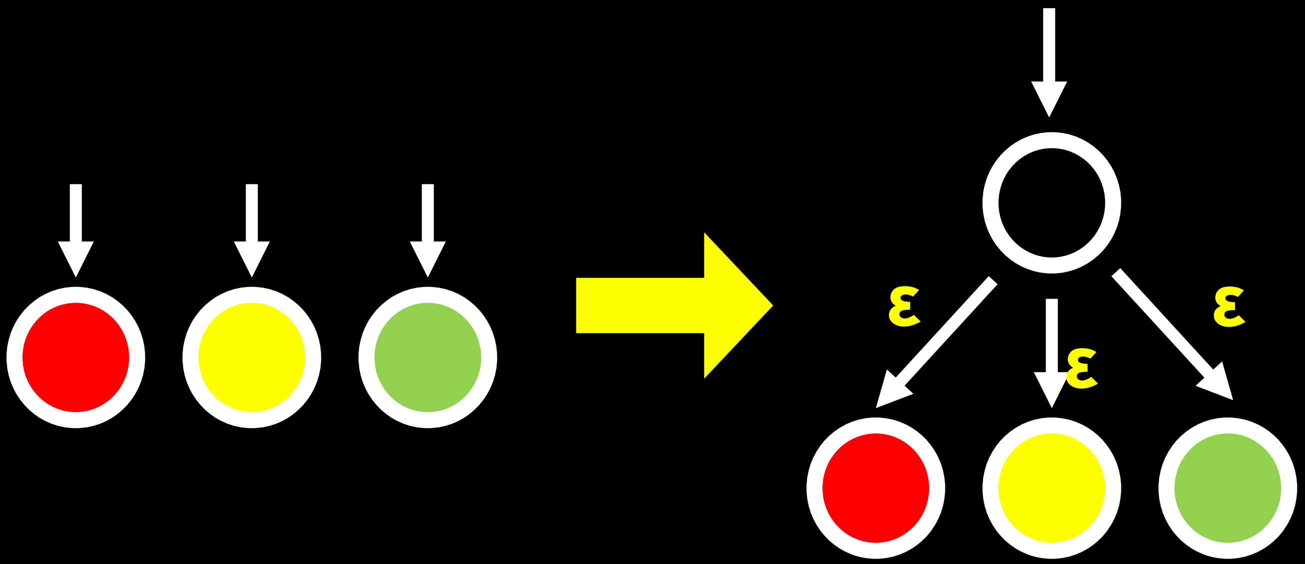
$F = \{q_4\} \subseteq Q$

δ	0	1
q_1	$\{q_2, q_3\}$	$\emptyset$
q_2	$\emptyset$	$\{q_4\}$
q_3	$\{q_4\}$	$\emptyset$
q_4	$\emptyset$	$\emptyset$

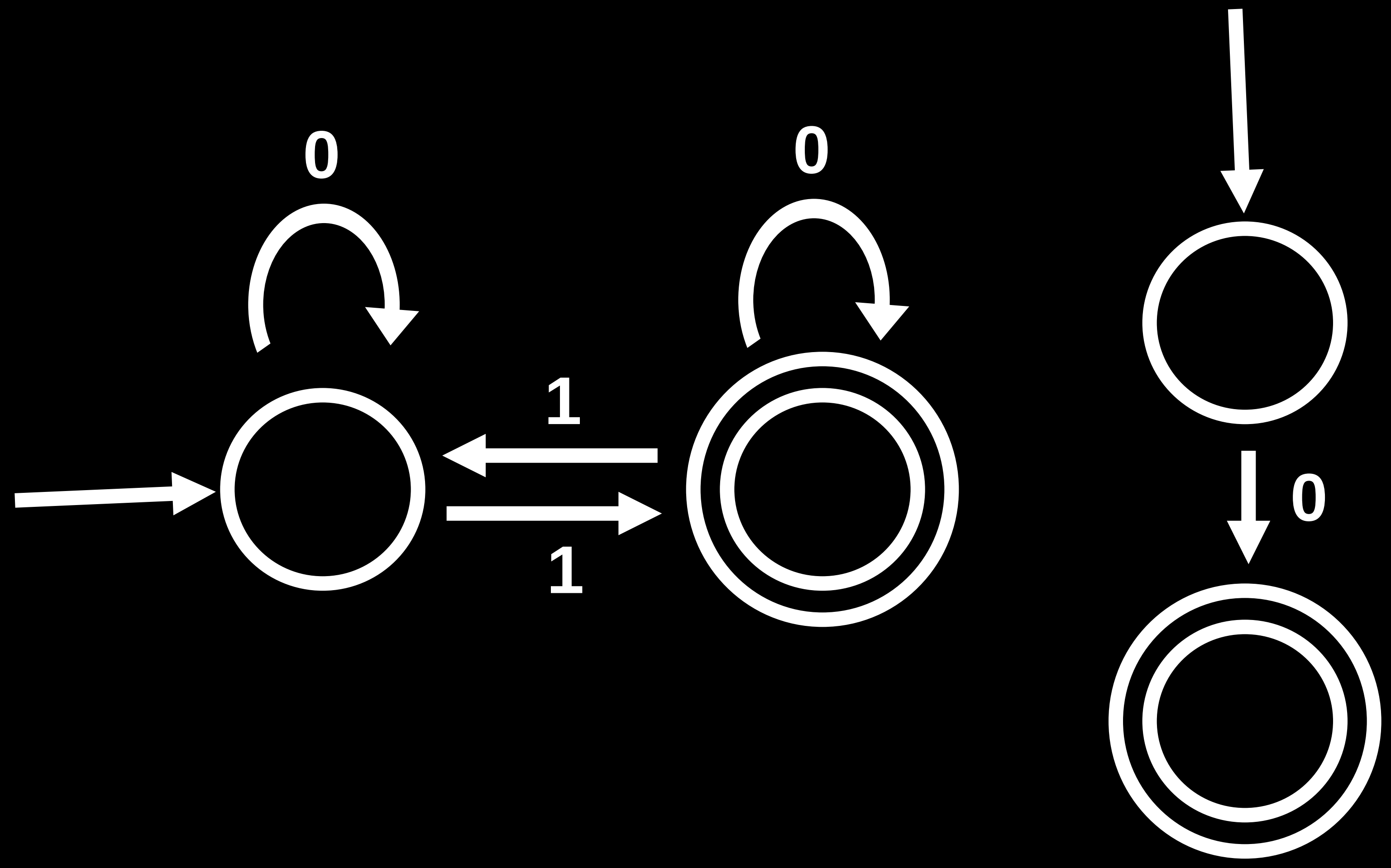
MULTIPLE START STATES

We allow *multiple* start states for NFAs, and Sipser allows only one

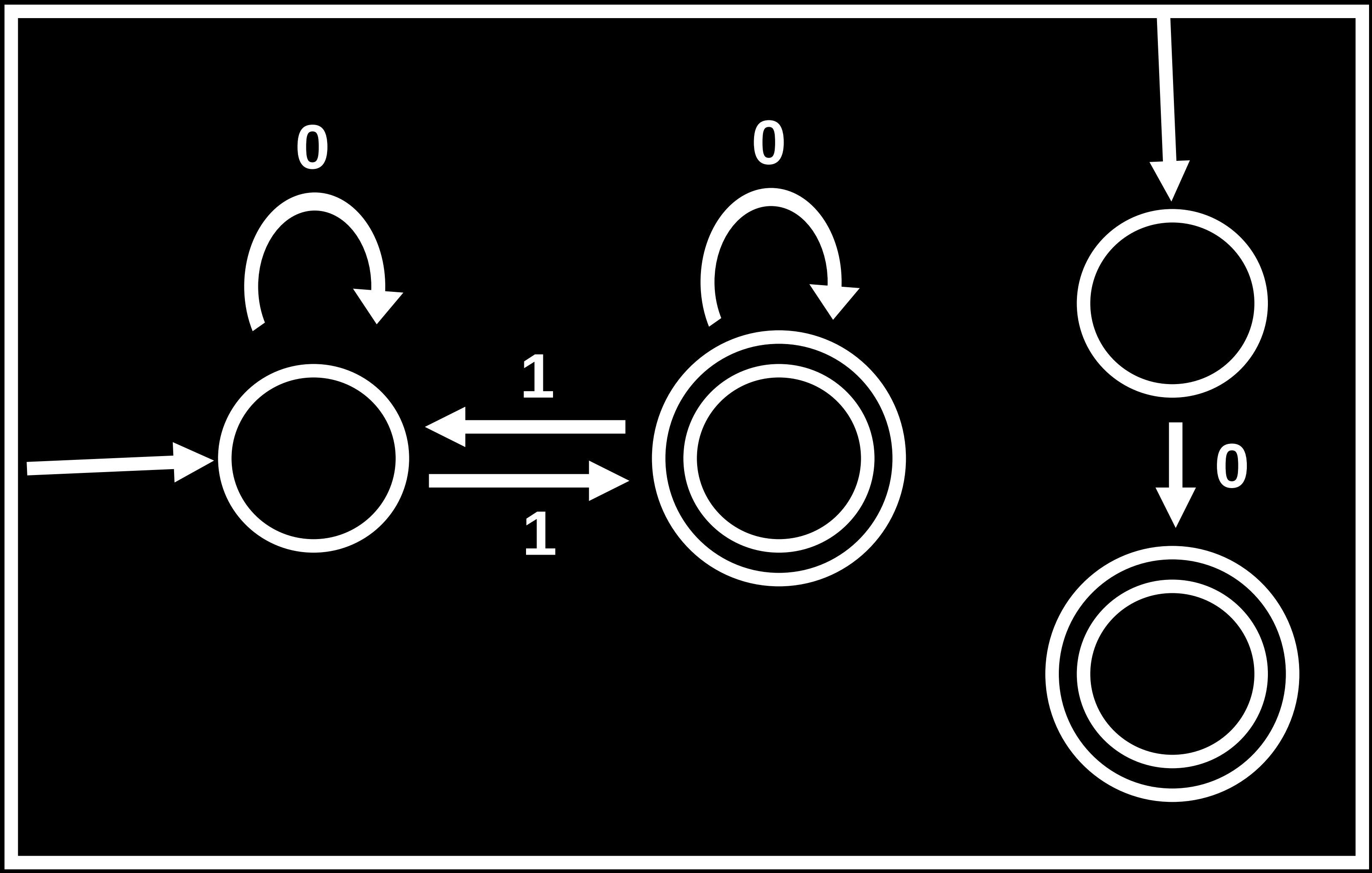
Can easily convert NFA with many start states into one with a single start state:



UNION THEOREM FOR NFAs?

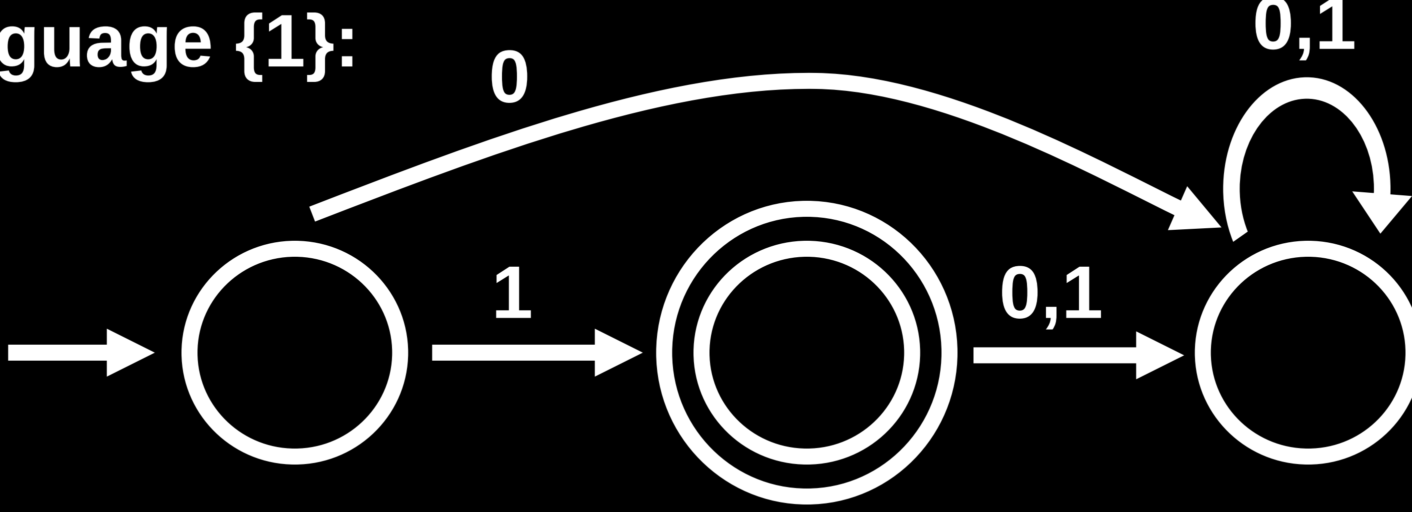


UNION THEOREM FOR NFAs?



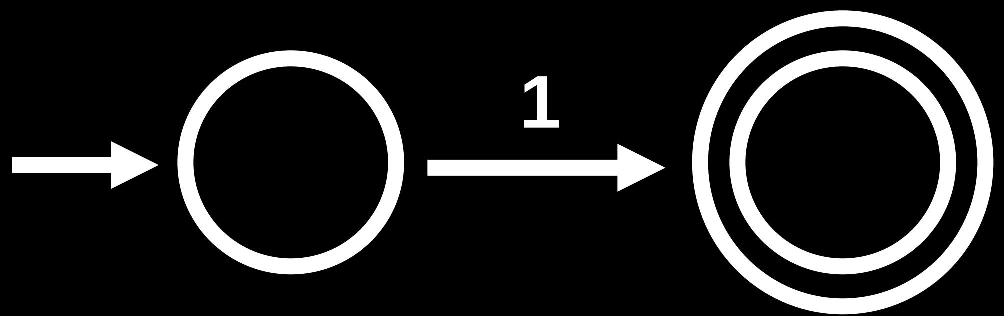
NFAs ARE SIMPLER THAN DFAs

A DFA that recognizes the language {1}:

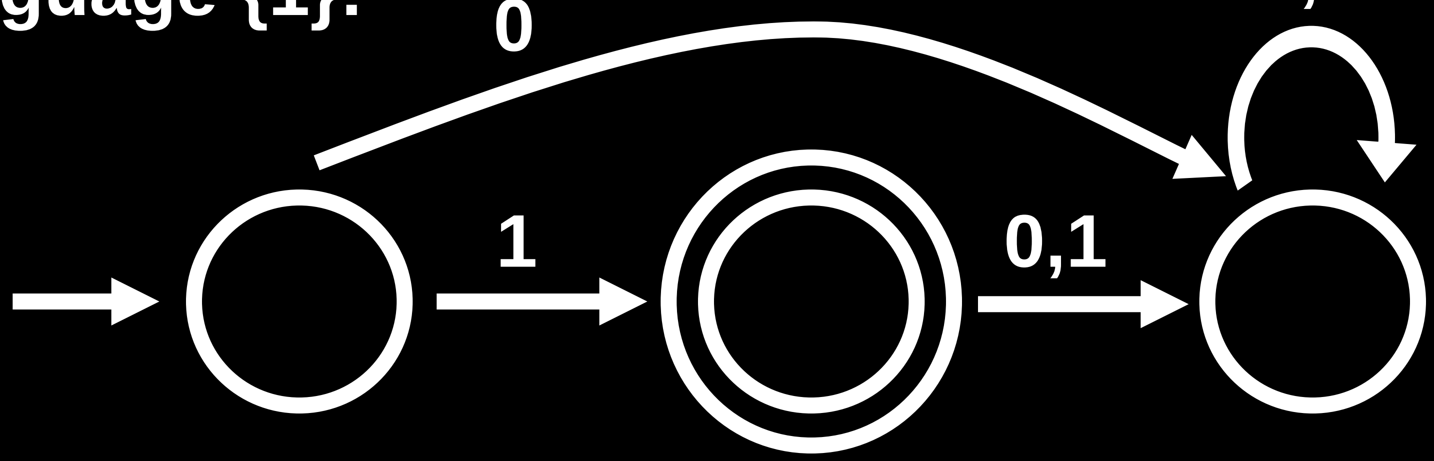


NFAs ARE SIMPLER THAN DFAs

An NFA that recognizes the language {1}:



A DFA that recognizes the language {1}:



BUT DFAs CAN SIMULATE NFAs!

Theorem: **Every NFA has an equivalent* DFA**

Corollary: A language is regular iff it is recognized by an NFA

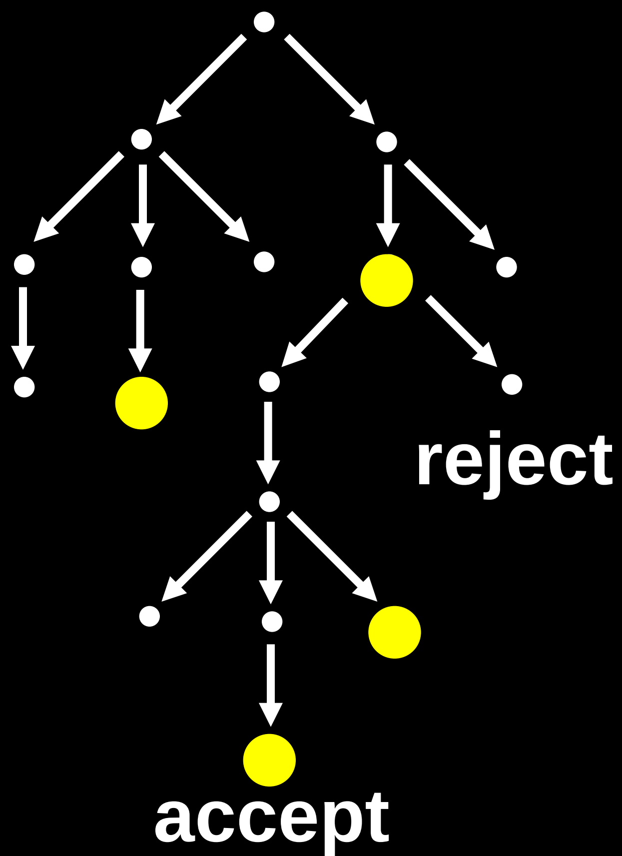
Corollary: L is regular iff L^R is regular

*** N is equivalent to M if L(N) = L (M)**

FROM NFA TO DFA

Input: NFA N = (Q, Σ, δ, Q_0, F)

Output: DFA M = (Q′, Σ, δ′, q_0′, F′)



To learn if NFA accepts, we could do the computation in parallel, maintaining the set of all possible states that can be reached

Idea:

$$Q' = 2^Q$$

FROM NFA TO DFA

Input: NFA N = $(Q, \Sigma, \delta, Q_0, F)$

Output: DFA M = $(Q', \Sigma, \delta', q_0', F')$

$$Q' = 2^Q$$

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

$$\delta'(R,\sigma) = \bigcup_{r \in R} \varepsilon(\ \delta(r,\sigma)\ )$$ *

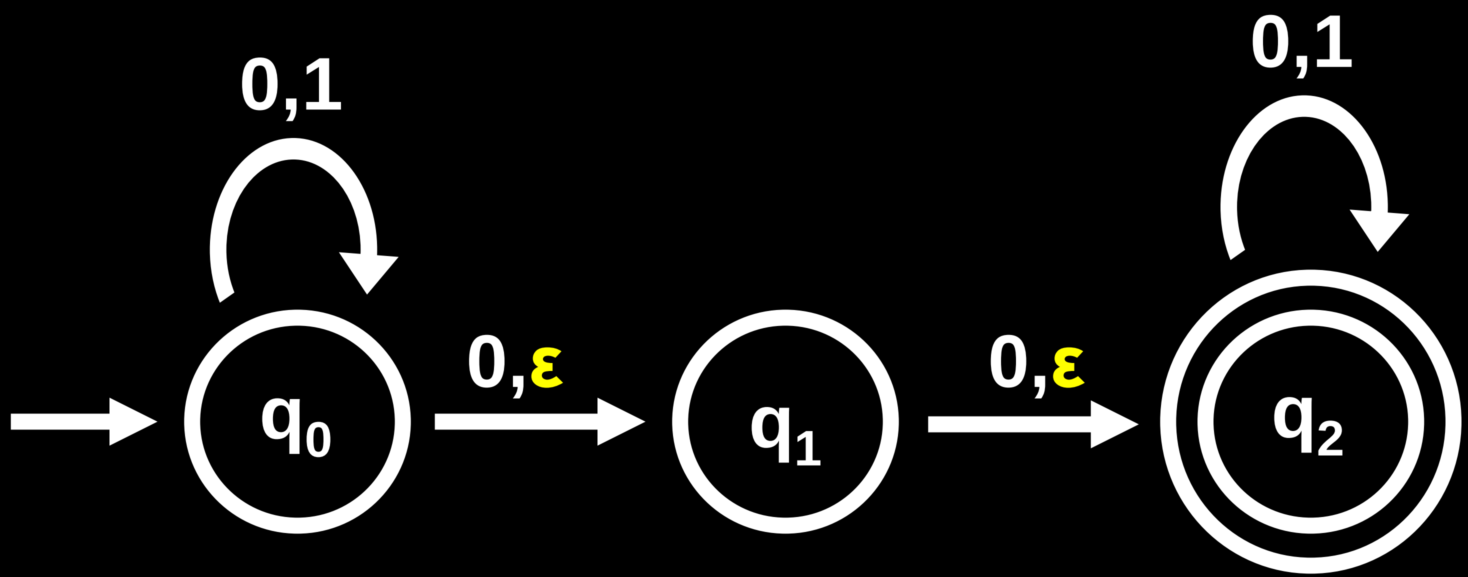
$$q_0' = \varepsilon(Q_0)$$

$$F' = \{\ R \in Q' \mid f \in R \text{ for some } f \in F\ \}$$

*

For **R** $\subseteq$ **Q,** the **ε-closure of R, ε(R)** = **{q** that can be reached from some r $\in$ **R** by traveling along zero or more **ε** arrows}

EXAMPLE OF ε-CLOSURE

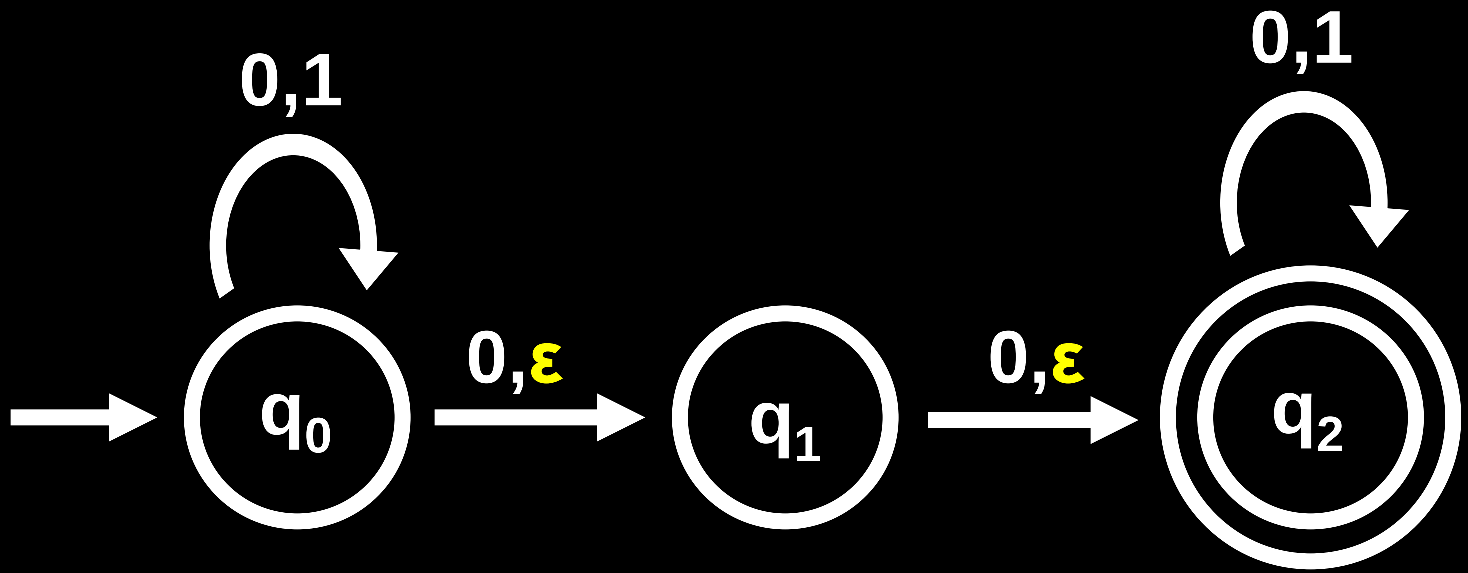


$\varepsilon(\{q_0\}) =$

$\varepsilon(\{q_1\}) =$

$\varepsilon(\{q_2\}) =$

EXAMPLE OF ε-CLOSURE



$\varepsilon(\{q_0\}) = \{q_0, q_1, q_2\}$

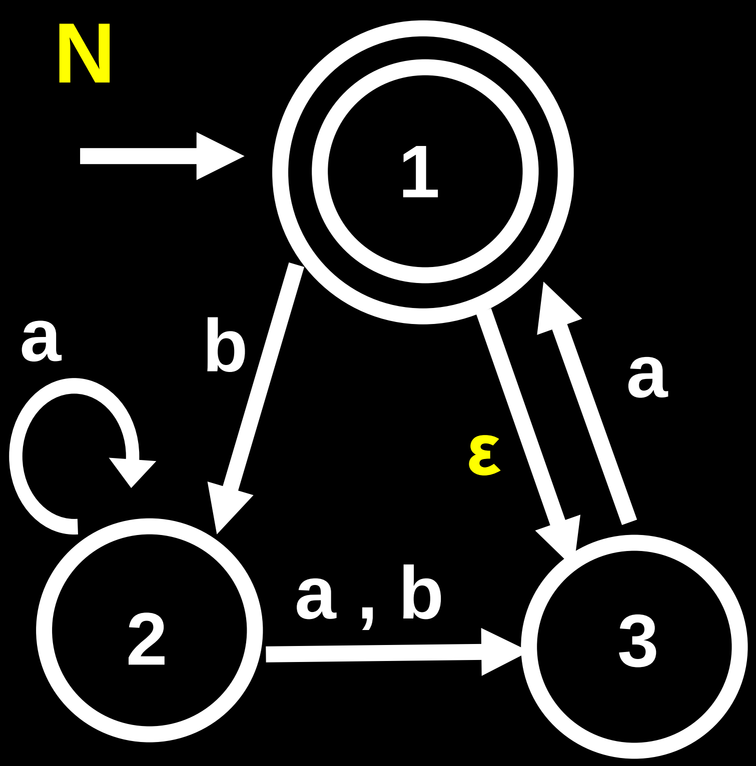
$\varepsilon(\{q_1\}) = \{q_1, q_2\}$

$\varepsilon(\{q_2\}) = \{q_2\}$

Given: NFA N = ({1,2,3}, {a,b}, δ , {1}, {1})

Construct: Equivalent DFA M

M = ($2^{\{1,2,3\}}$, {a,b}, δ', {1,3}, …)



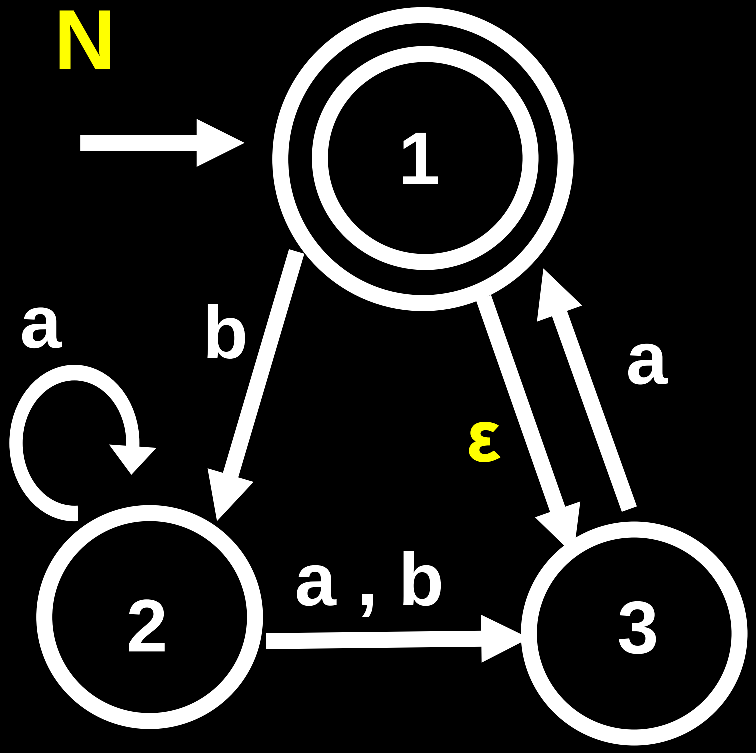
ε({1}) = {1,3}

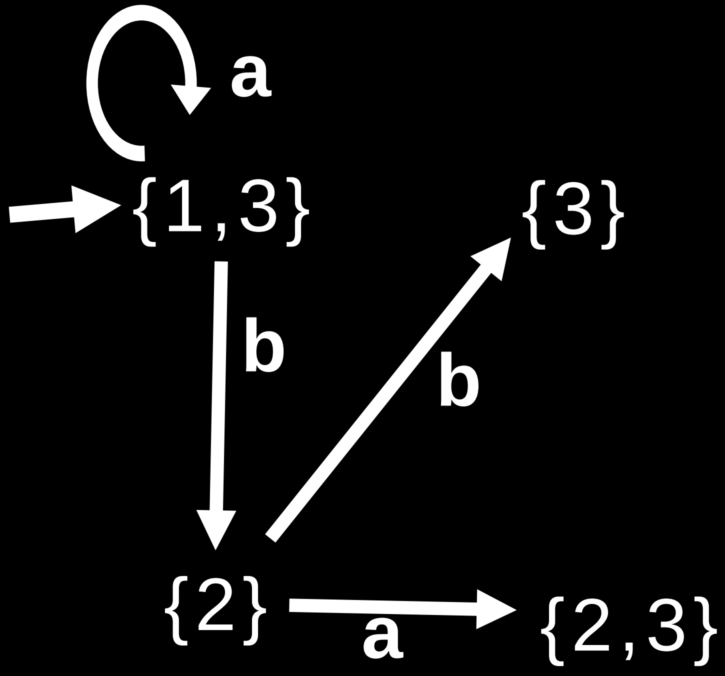
Given: NFA N = ({1,2,3}, {a,b}, δ , {1}, {1})

Construct: Equivalent DFA M

M = ($2^{\{1,2,3\}}$, {a,b}, δ', {1,3}, …)

N





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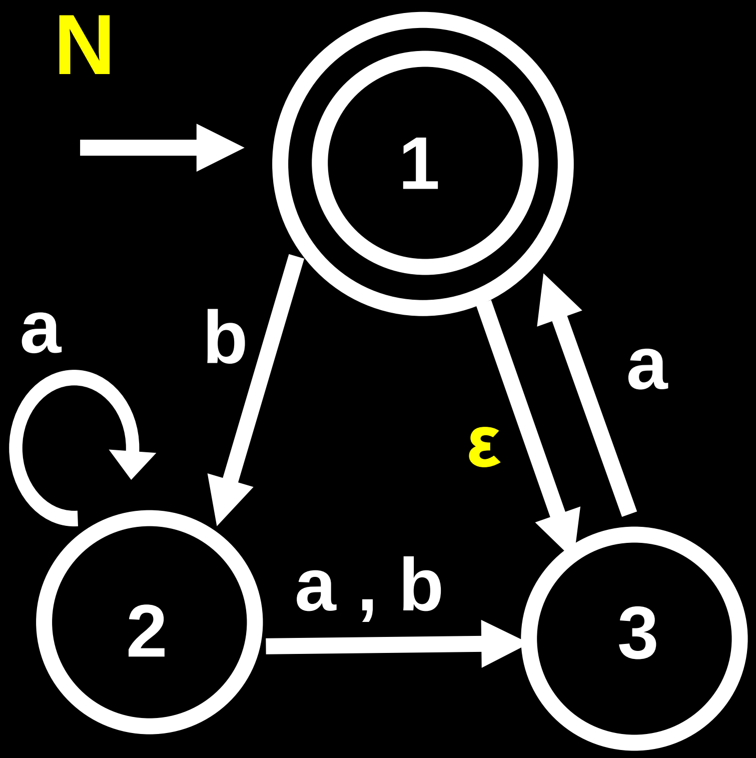
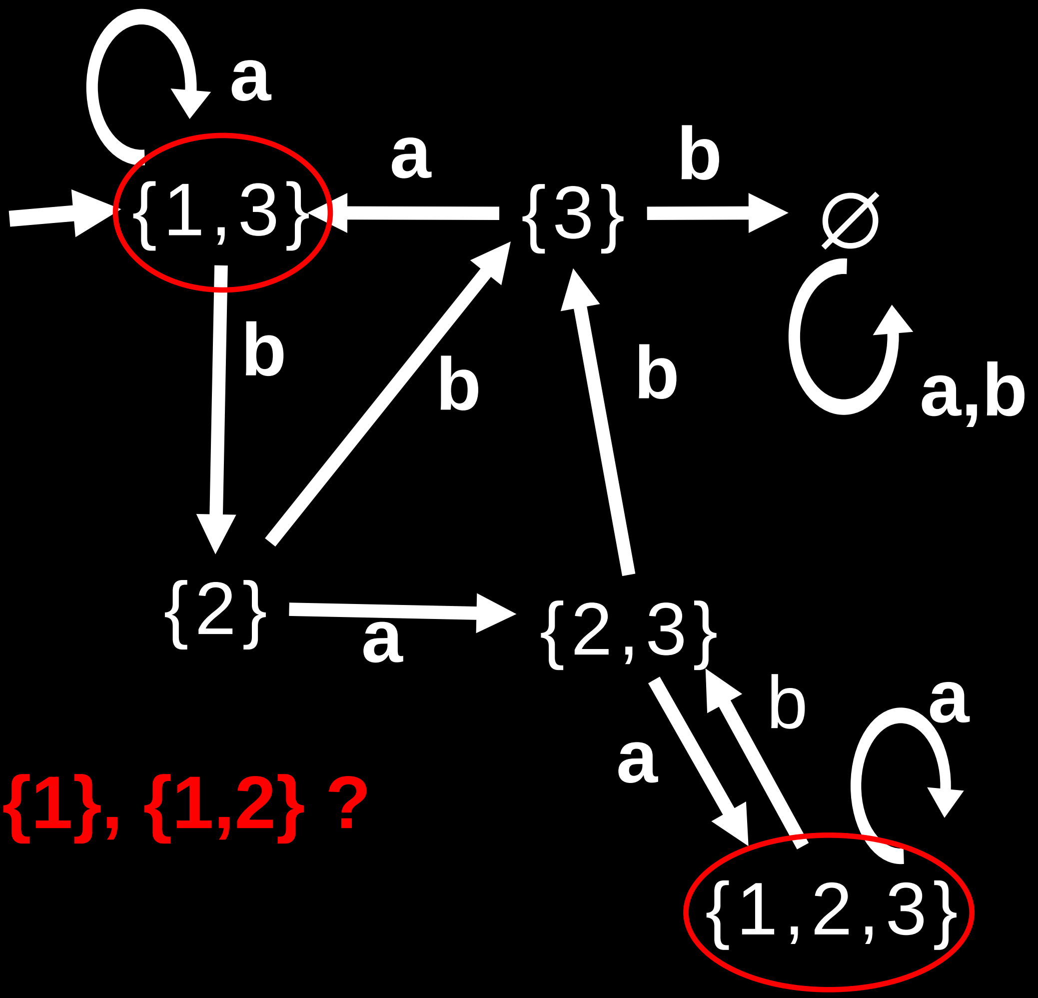
Given: NFA **N** = ({1,2,3}, {a,b}, δ , {1}, {1})

Construct: Equivalent DFA **M**

M = ($2^{\{1,2,3\}}$, {a,b}, δ′, {1,3}, …)



ε({1}) = {1,3}

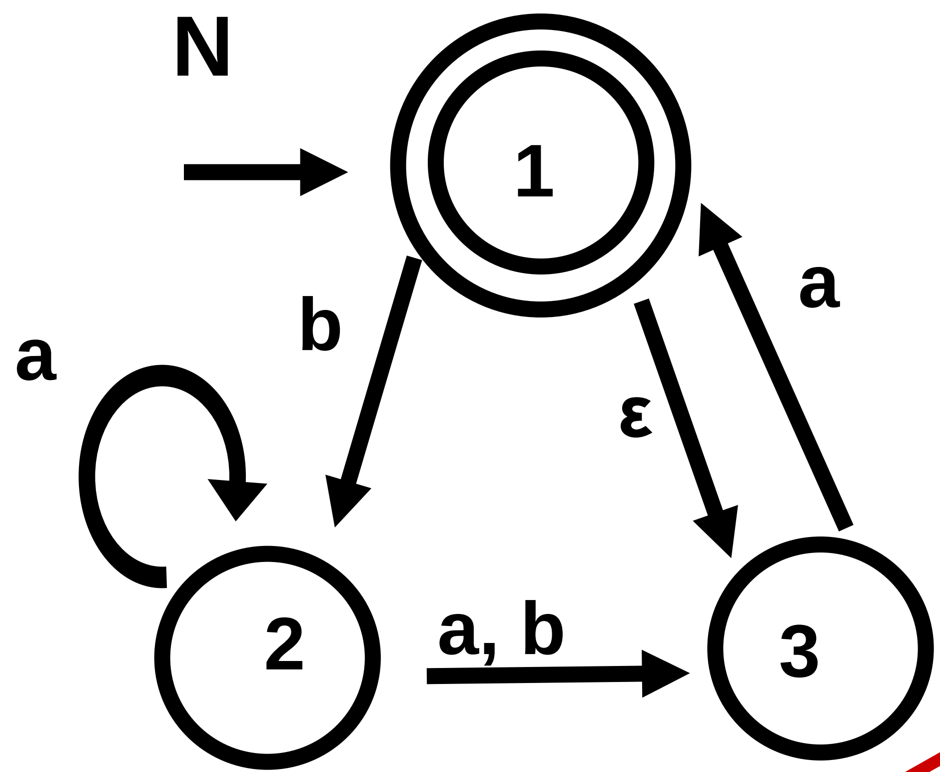


{1}, {1,2} ?

$N = (Q, \Sigma, \delta, Q_0, F)$

Given: NFA $N = (\{1,2,3\}, \{a,b\}, \delta, \{1\}, \{1\})$

Construct: equivalent DFA $M = (Q', \Sigma, \delta', q_0', F')$



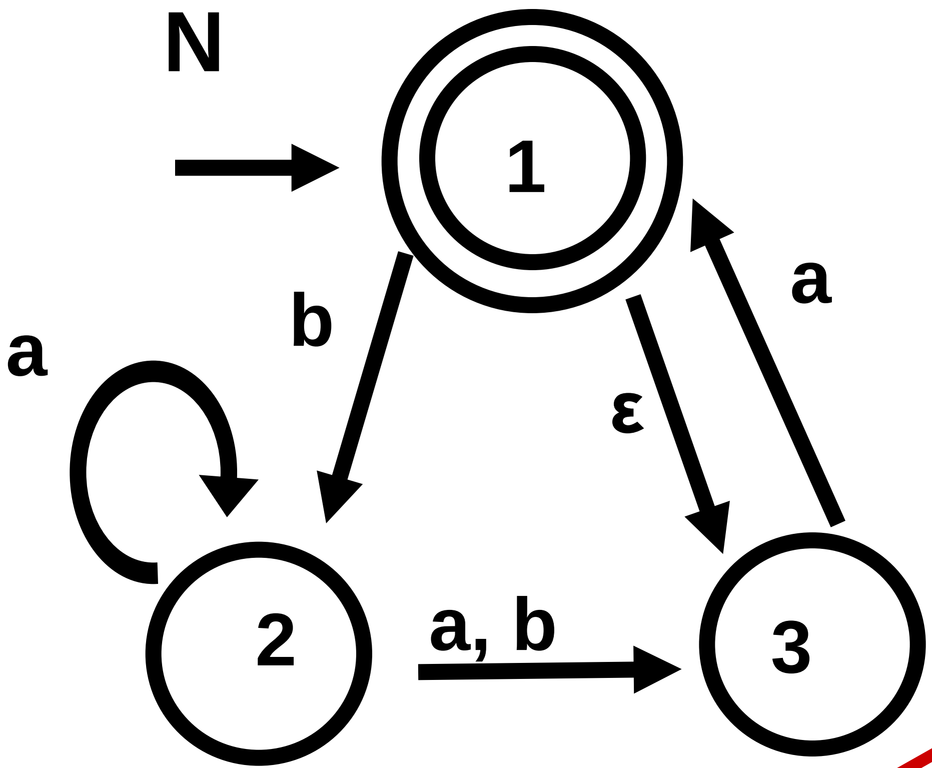
$q_0' = \varepsilon(\{1\}) = \{1,3\}$

δ′	a	b
∅		
{1}		
{2}		
{3}		
{1,2}		
{1,3}		
{2,3}		
{1,2,3}		

$N = (Q, \Sigma, \delta, Q_0, F)$

Given: NFA $N = (\{1,2,3\}, \{a,b\}, \delta, \{1\}, \{1\})$

Construct: equivalent DFA $M = (Q', \Sigma, \delta', q_0', F')$



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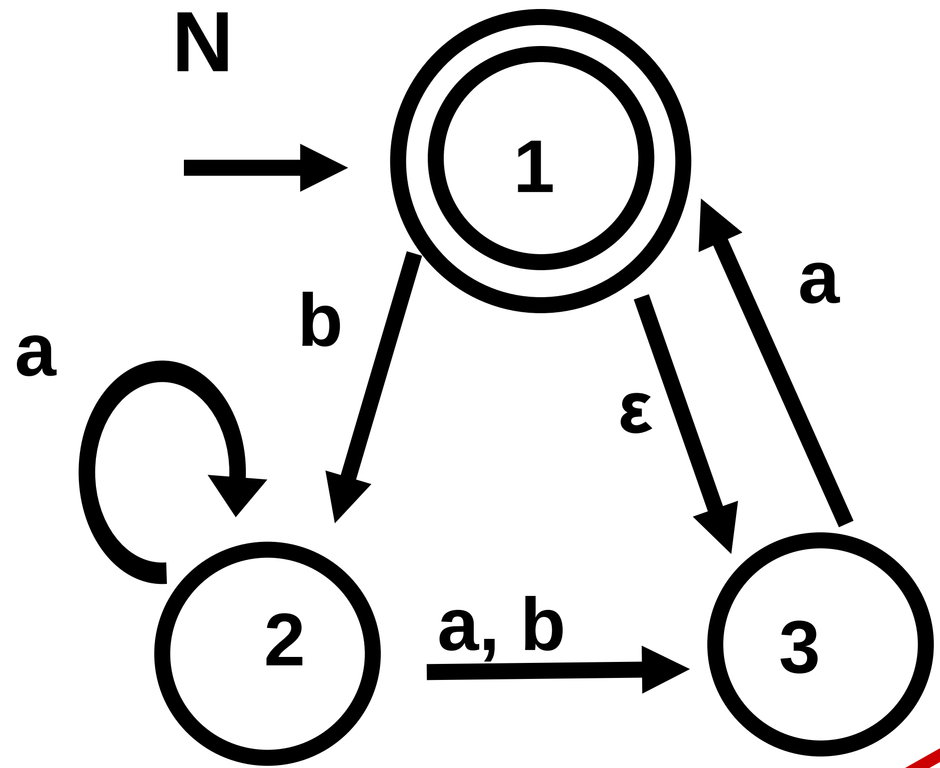
δ′	a	b
∅		
{1}		
{2}		
{3}		
{1,2}		
{1,3}		
{2,3}		
{1,2,3}		

$N = (Q, \Sigma, \delta, Q_0, F)$

<u>Given</u>: NFA $N = (\{1,2,3\}, \{a,b\}, \delta, \{1\}, \{1\})$

<u>Construct</u>: equivalent DFA $M = (Q', \Sigma, \delta', q_0', F')$



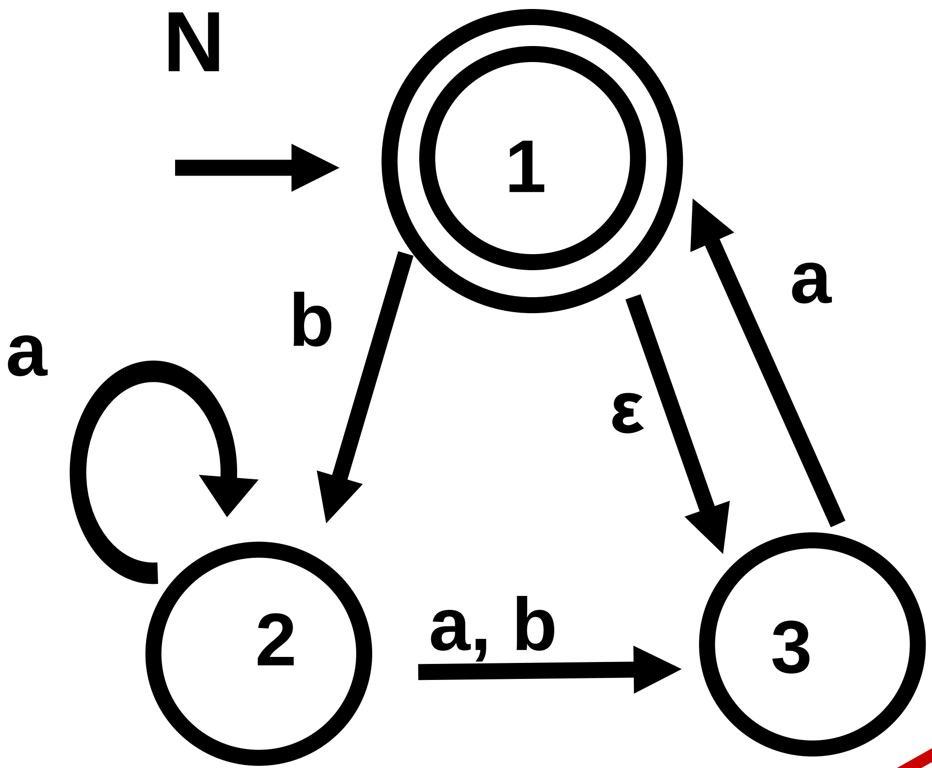
$q_0' = \varepsilon(\{1\}) = \{1,3\}$

δ'	a	b
∅	∅	∅
{1}	∅	{2}
{2}	{2,3}	{3}
{3}	{1,3}	∅
{1,2}	{2,3}	{2,3}
{1,3}	{1,3}	{2}
{2,3}	{1,2,3}	{3}
{1,2,3}	{1,2,3}	{2,3}

$N = (Q, \Sigma, \delta, Q_0, F)$

Given: NFA $N = (\{1,2,3\}, \{a,b\}, \delta, \{1\}, \{1\})$

Construct: equivalent DFA $M = (Q', \Sigma, \delta', q_0', F')$



$q_0' = \varepsilon(\{1\}) = \{1,3\}$

δ'	a	b
∅	∅	∅
{1}	∅	{2}
{2}	{2,3}	{3}
{3}	{1,3}	∅
{1,2}	{2,3}	{2,3}
{1,3}	{1,3}	{2}
{2,3}	{1,2,3}	{3}
{1,2,3}	{1,2,3}	{2,3}

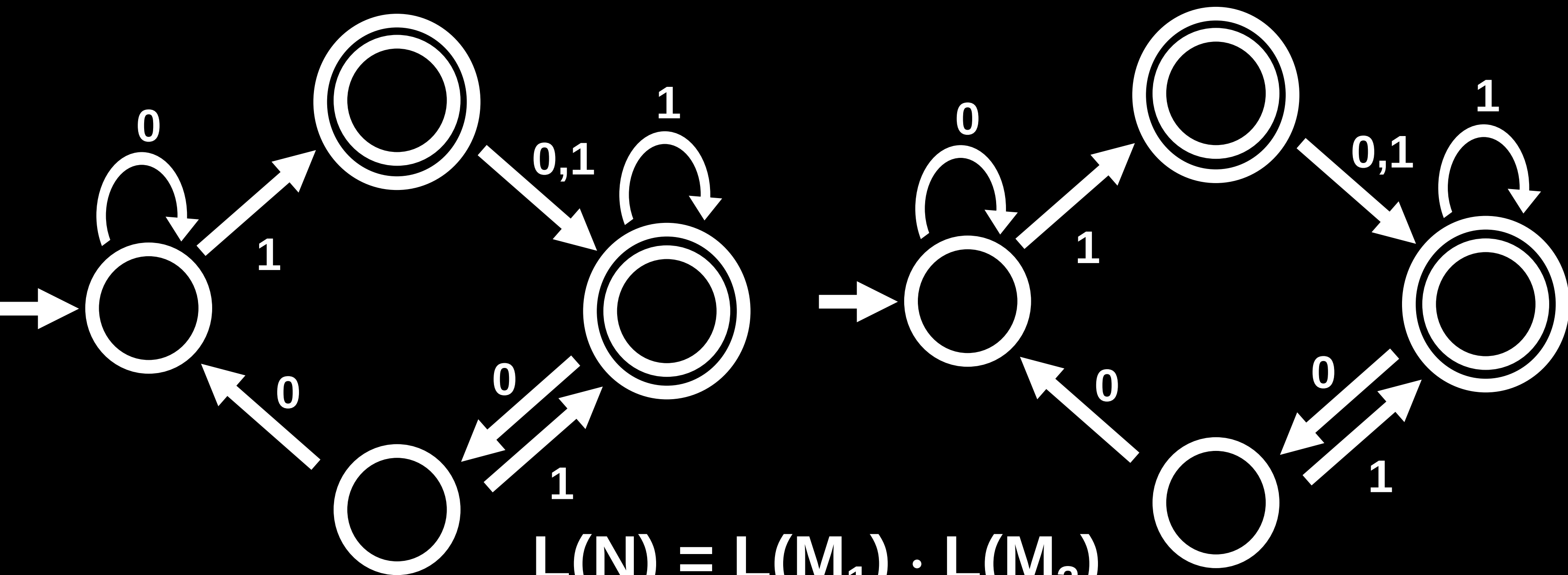
NFAs CAN MAKE PROOFS MUCH EASIER!

Remember this on your Homework!

REGULAR LANGUAGES CLOSED UNDER CONCATENATION

Concatenation: $A \cdot B = \{ vw \mid v \in A \text{ and } w \in B \}$

Given DFAs M_1 and M_2, connect accept states in M_1 to start states in M_2



$$L(N) = L(M_1) \cdot L(M_2)$$

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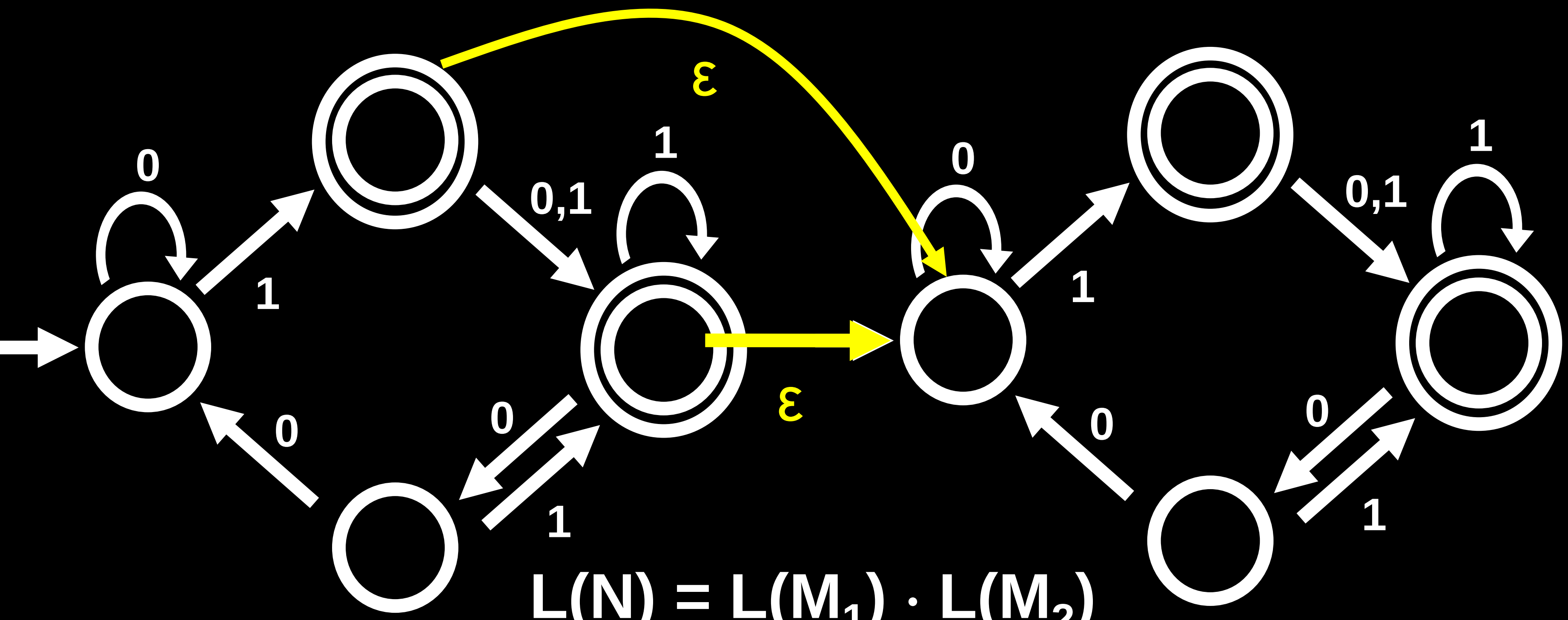

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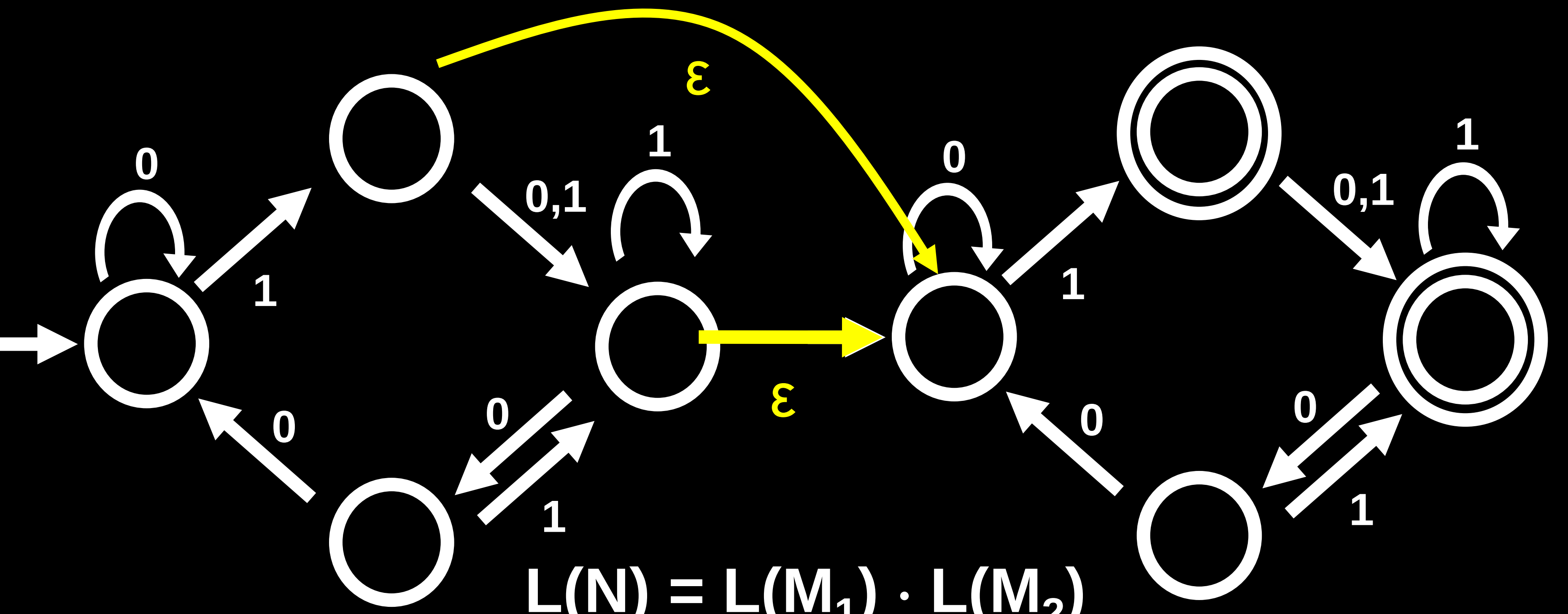


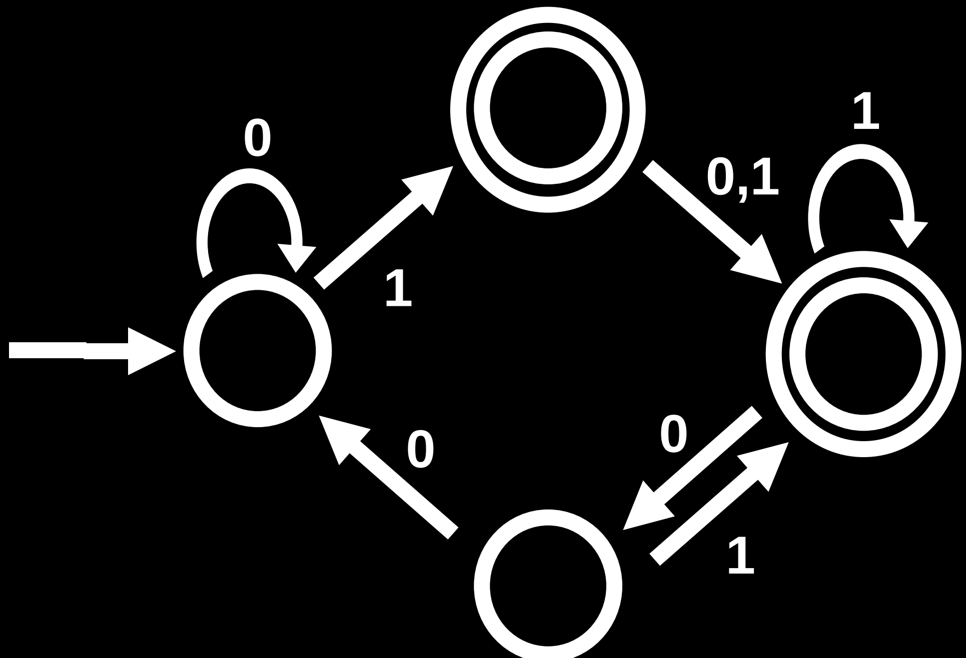
$L(N) = L(M_1) \cdot L(M_2)$

RLs ARE CLOSED UNDER STAR

Star: $A^* = \{ s_1 \ldots s_k \mid k \geq 0 \text{ and each } s_i \in A \}$

Let M be a DFA, and let L = L(M)

Can construct an NFA N that recognizes L*



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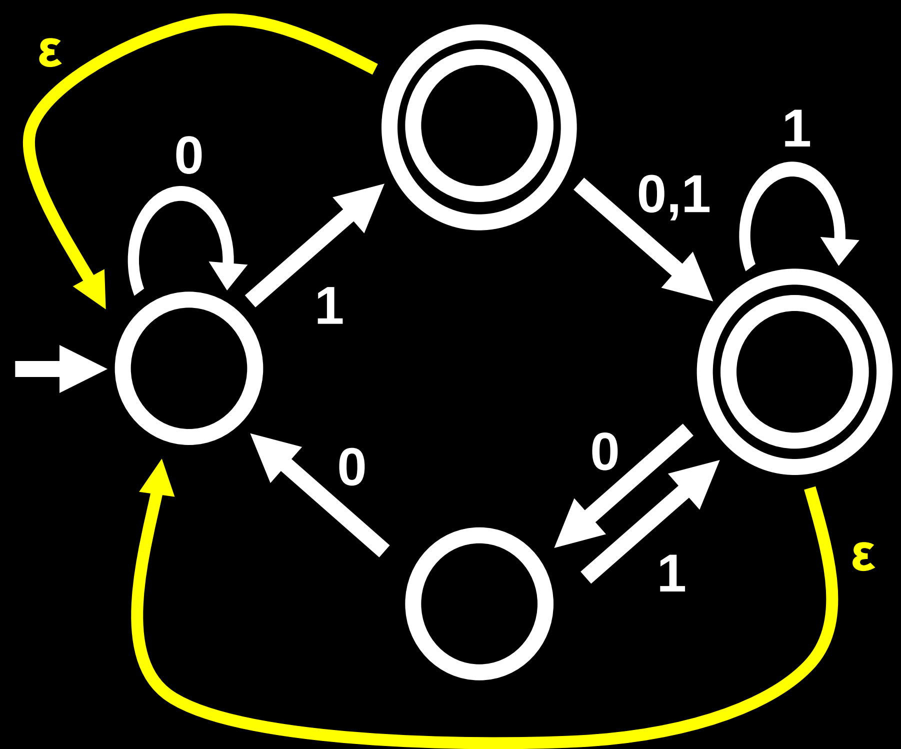

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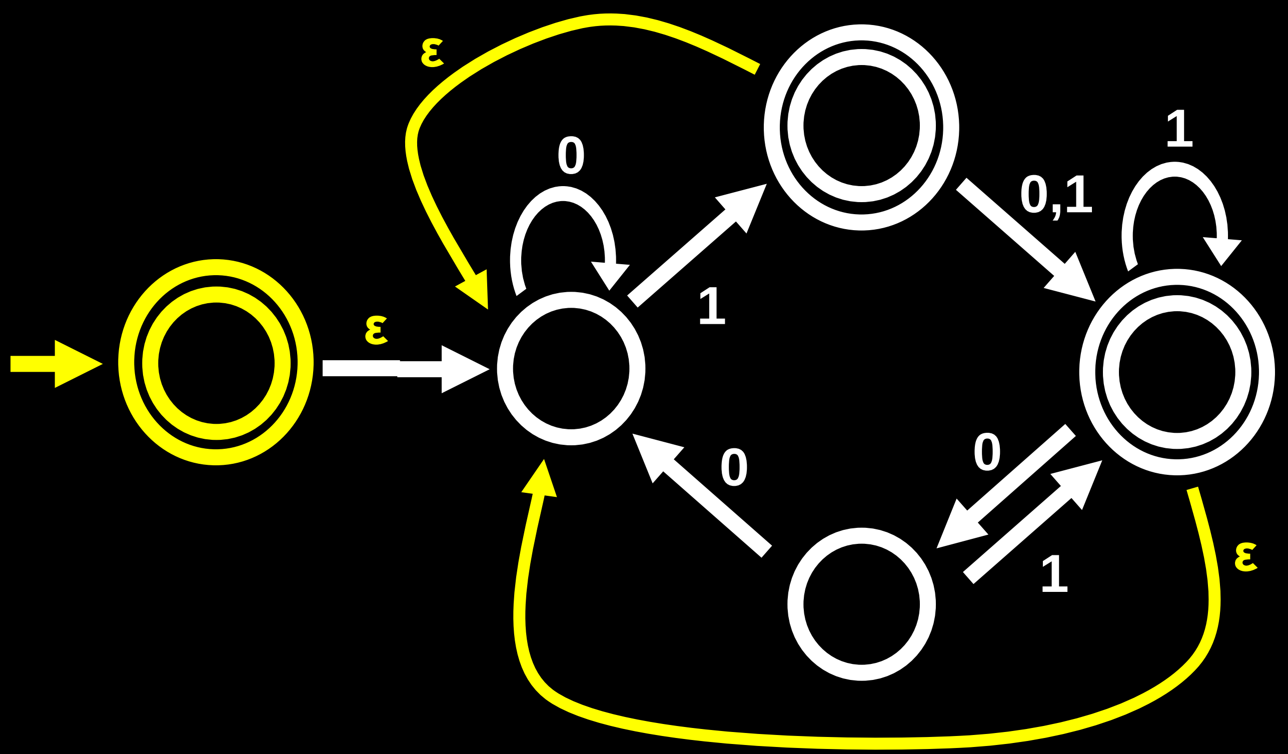

Formally:

Input: **M** $= (Q, \Sigma, \delta, q_1, F)$

Output: **N** $= (Q', \Sigma, \delta', \{q_0\}, F')$

$Q' = Q \cup \{q_0\}$

$F' = F \cup \{q_0\}$

$$\delta'(q,a) = \begin{cases} \{\delta(q,a)\} & \text{if } q \in Q \text{ and } a \neq \varepsilon \\ \{q_1\} & \text{if } q \in F \text{ and } a = \varepsilon \\ \{q_1\} & \text{if } q = q_0 \text{ and } a = \varepsilon \\ \emptyset & \text{if } q = q_0 \text{ and } a \neq \varepsilon \\ \emptyset & \text{else} \end{cases}$$

Show: $L(N) = L^*$ where $L = L(M)$

1. $L(N) \supseteq L^*$

2. $L(N) \subseteq L^*$

1. $L(N) \supseteq L^*$ (where $L = L(M)$)

Assume $w = w_1 \ldots w_k$ is in L^*, where $w_1, \ldots, w_k \in L$

We show N accepts w by induction on k

Base Cases:

- ✓ $k = 0$ ($w = \varepsilon$)
- ✓ $k = 1$ ($w \in L$)

1. L(N) $\supseteq$ L* (where L = L(M))

Assume w = $w_1 \ldots w_k$ is in L*, where $w_1, \ldots, w_k \in$ L

We show N accepts w by induction on k

Base Cases:

- ✓ k = 0 (w = ε)
- ✓ k = 1 (w $\in$ L)

Inductive Step:

Assume N accepts all strings v = $v_1 \ldots v_k \in$ L*, $v_i \in$ L
and let v = $v_1 \ldots v_k \, v_{k+1} \in$ L* , $u_j \in$ L

Since N accepts $v_1 \ldots v_k$ (by induction) and
M accepts v_{k+1}, N must accept v

2. $L(N) \subseteq L^*$ (where $L = L(M)$)

Assume w is accepted by N, we show $w \in L^*$

If $w = \varepsilon$ or $w \in L$, then $w \in L^*$

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write w as $w=uv$,

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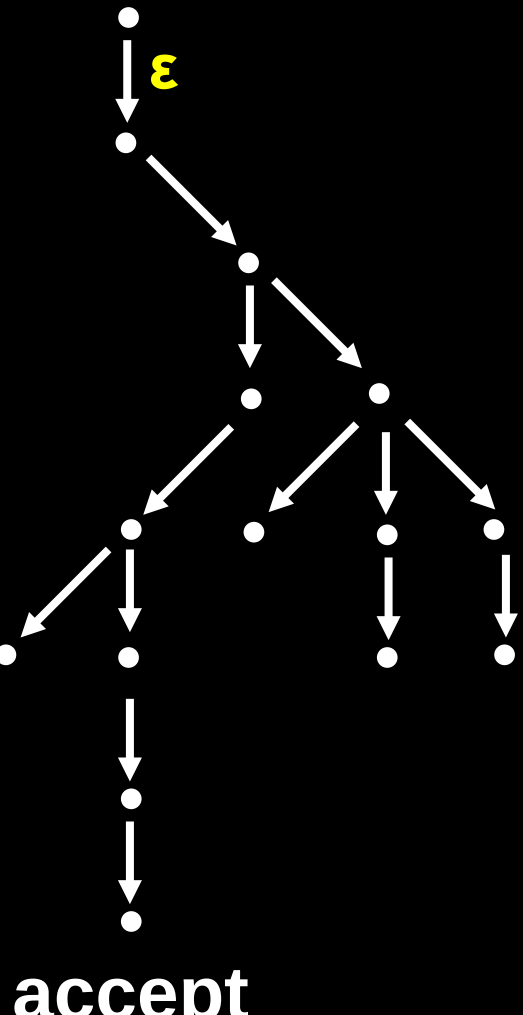

2. L(N) $\subseteq$ L* (where L = L(M))

Assume w is accepted by N, we show w $\in$ L*

If w = ε or w $\in$ L, then w $\in$ L*

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write w as w=uv,
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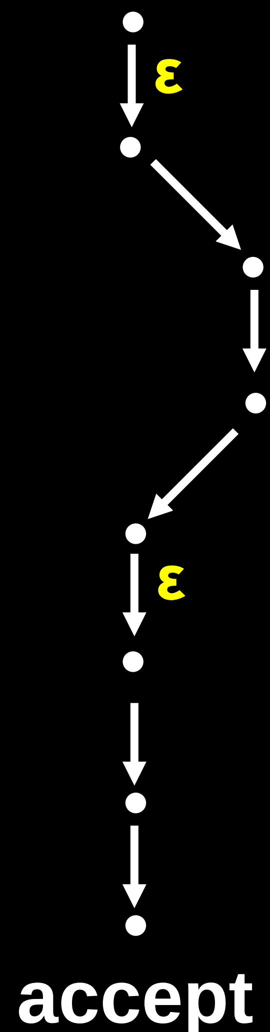

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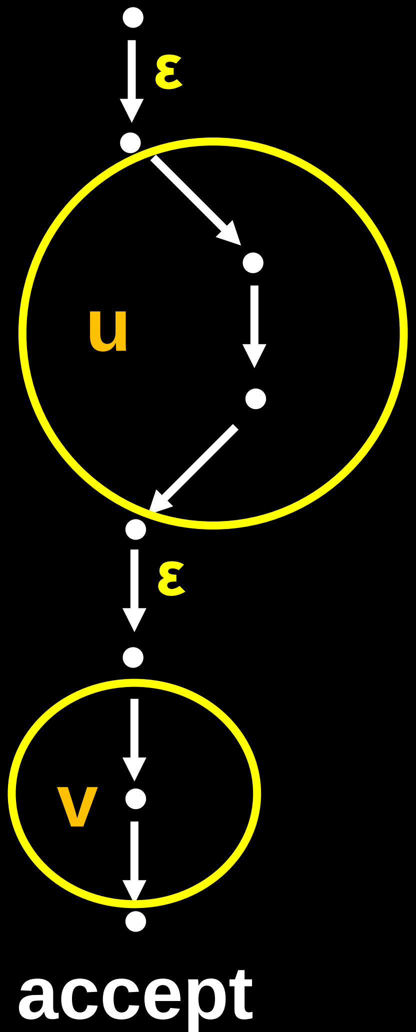

2. L(N) ⊆ L* (where L = L(M))

Assume w is accepted by N, we show w ∈ L*

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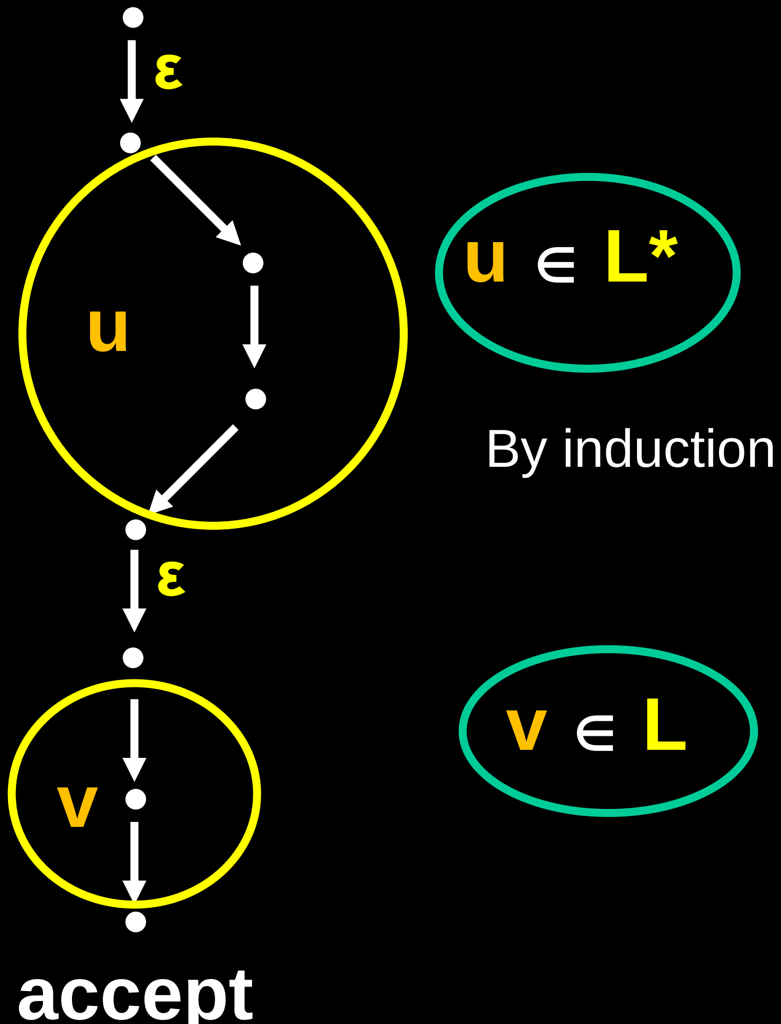
If w ≠ ε or w ∉ L write w as w=uv, where v is the substring read after the *last* ε-transition



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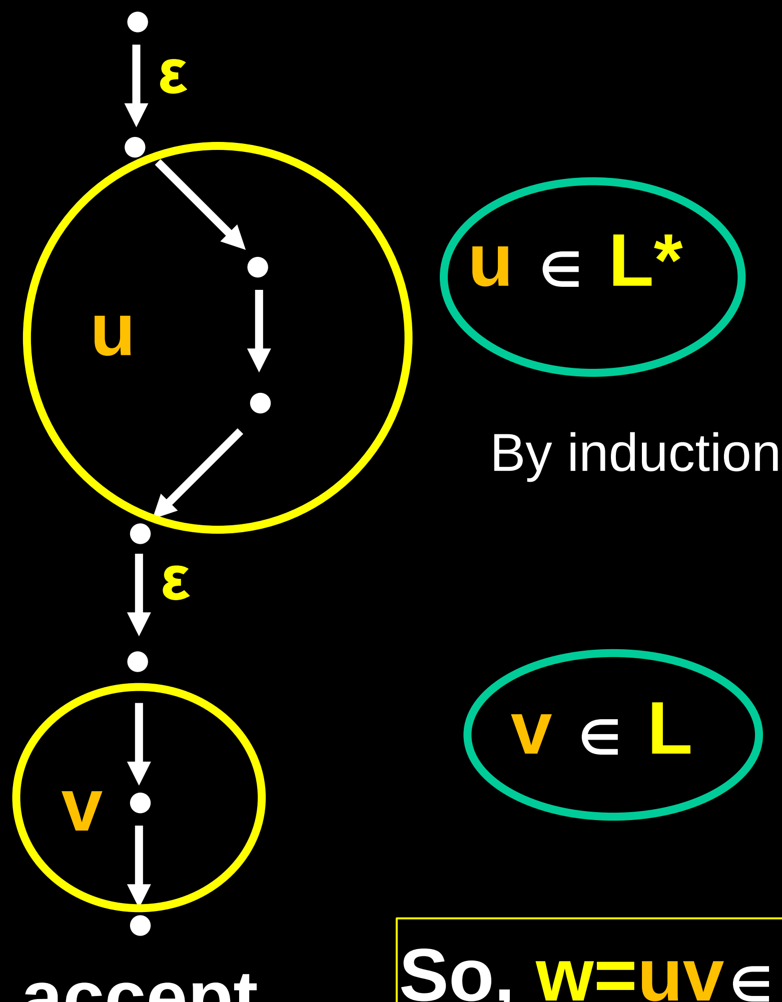

So, w=uv$\in$ L*

REGULAR LANGUAGES ARE CLOSED UNDER THE REGULAR OPERATIONS

- **Union:** $A \cup B = \{ w \mid w \in A \text{ or } w \in B \}$
- **Intersection:** $A \cap B = \{ w \mid w \in A \text{ and } w \in B \}$
- **Negation:** $\neg A = \{ w \in \Sigma^* \mid w \notin A \}$
- **Reverse:** $A^R = \{ w_1 \ldots w_k \mid w_k \ldots w_1 \in A \}$
- **Concatenation:** $A \cdot B = \{ vw \mid v \in A \text{ and } w \in B \}$
- **Star:** $A^* = \{ w_1 \ldots w_k \mid k \geq 0 \text{ and each } w_i \in A \}$

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Read Chapters 1.3 and 1.4 of the book for next time