Part III. Models for Regular Languages

Regular Expressions (RE): Definition

Gist: Expressions with operators ., +, and * that denote concatenation, union, and iteration, respectively.

Definition: Let Σ be an alphabet. The ***regular expressions*** over Σ and the ***languages they denote*** are defined as follows:

- ∅ is a RE denoting the empty set
- ε is a RE denoting {ε}
- *a*, where $a \in \Sigma$, is a RE denoting $\{a\}$
- Let *r* and *s* be regular expressions denoting the languages L_r and L_s, respectively; then
    - $(r.s)$ is a RE denoting $L = L_r L_s$
    - $(r + s)$ is a RE denoting $L = L_r \cup L_s$
    - (r^*) is a RE denoting $L = L_r^*$

Regular Expressions: Example

Question: Is $(\varepsilon + (a.(b^*)))$ the regular expression over $\Sigma = \{a, b\}$ **?**

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Is a RE over Σ.

ε

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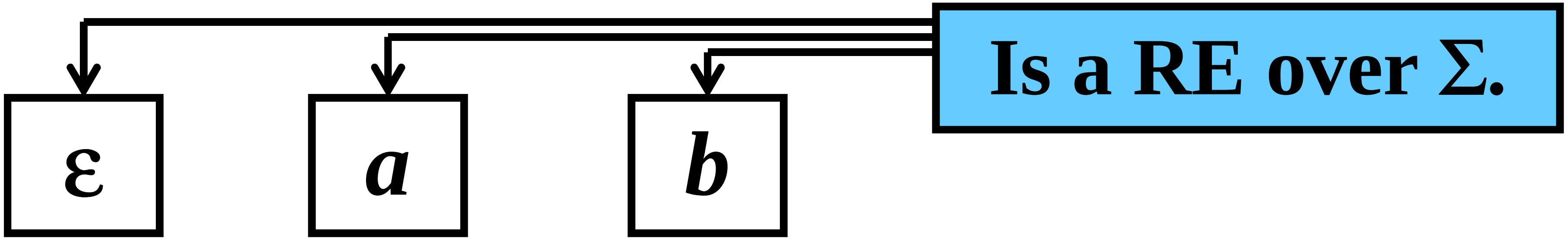

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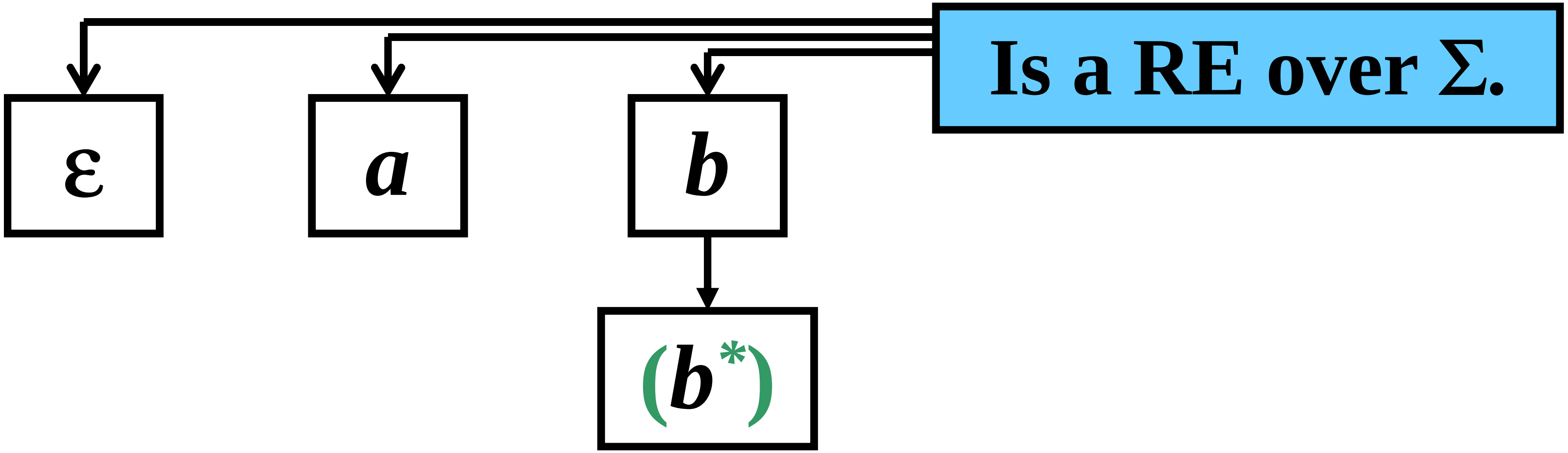

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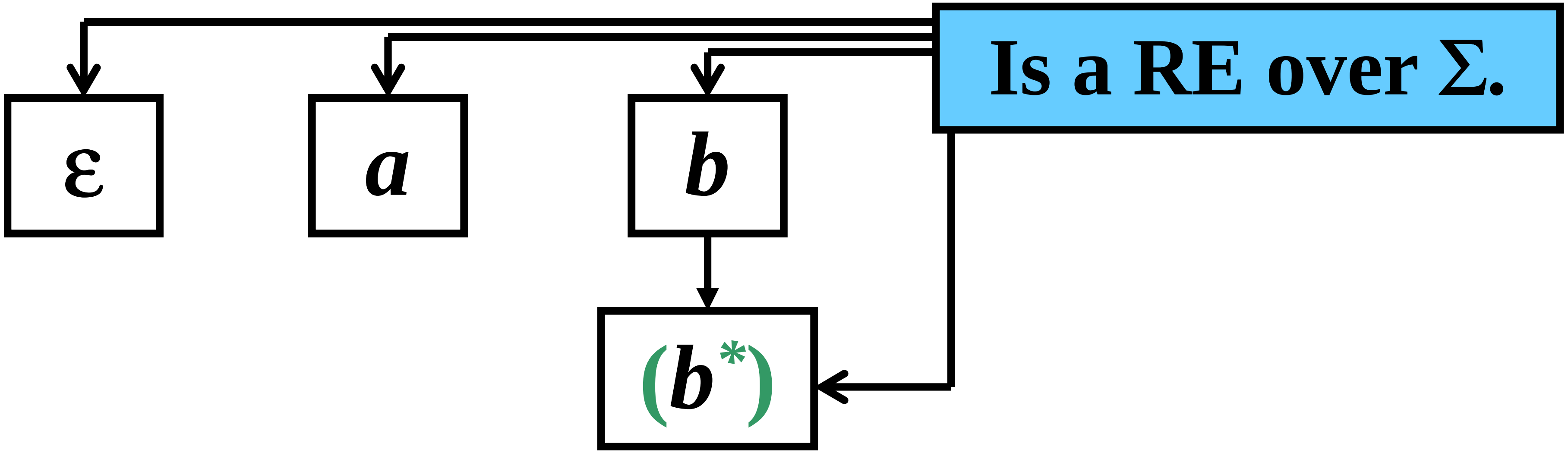

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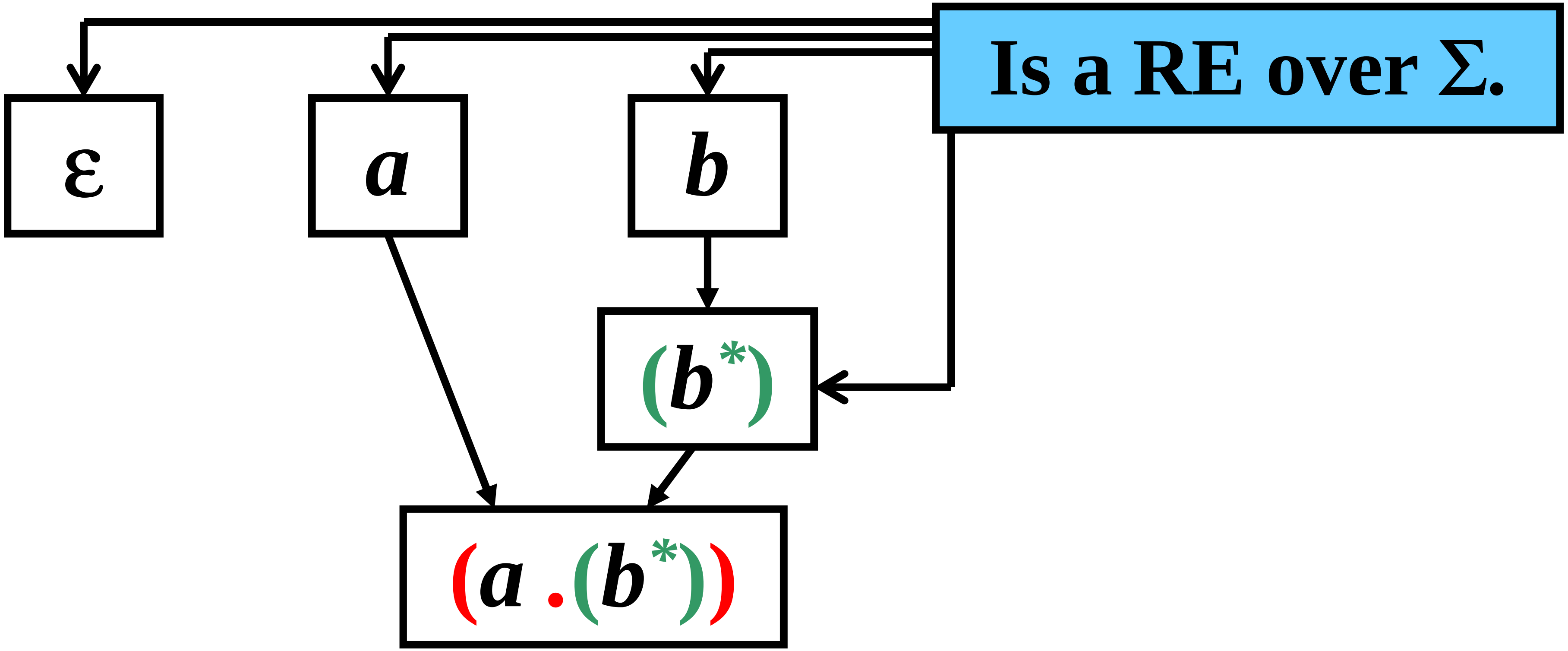

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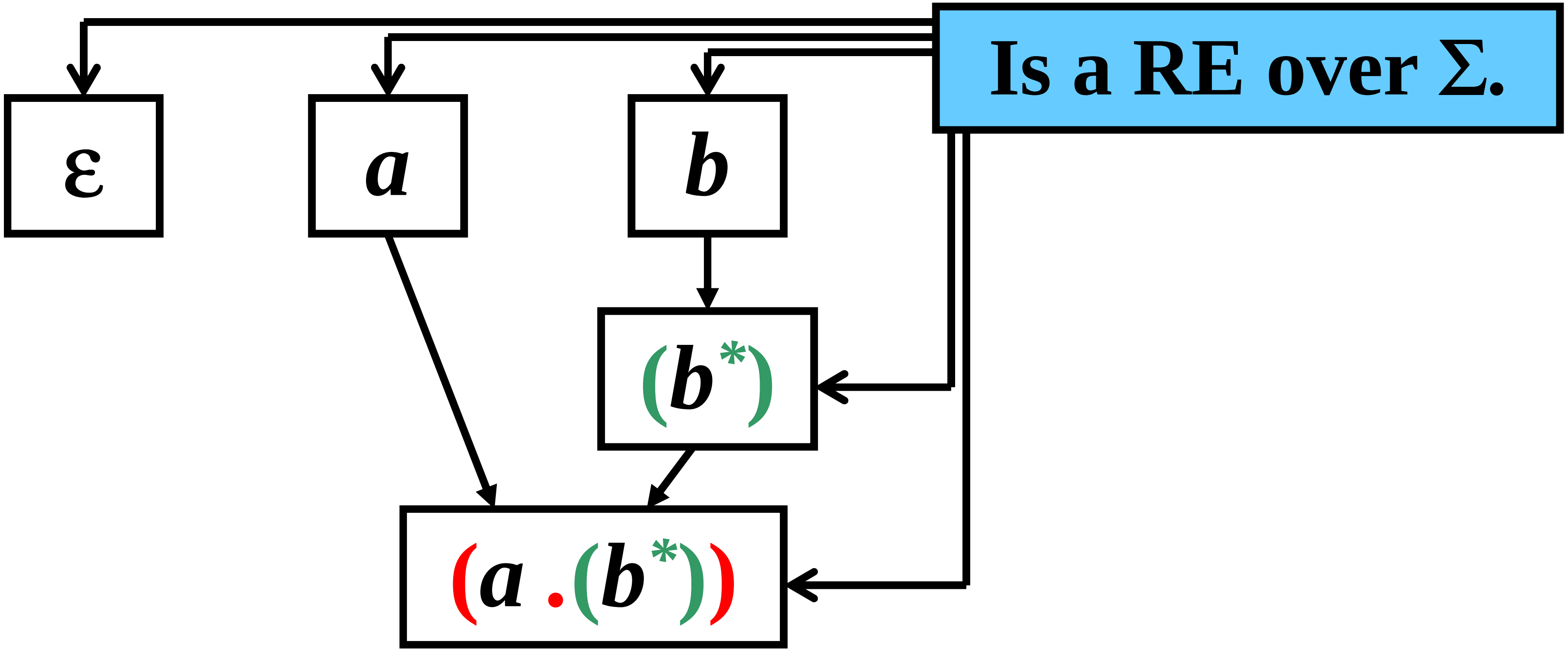

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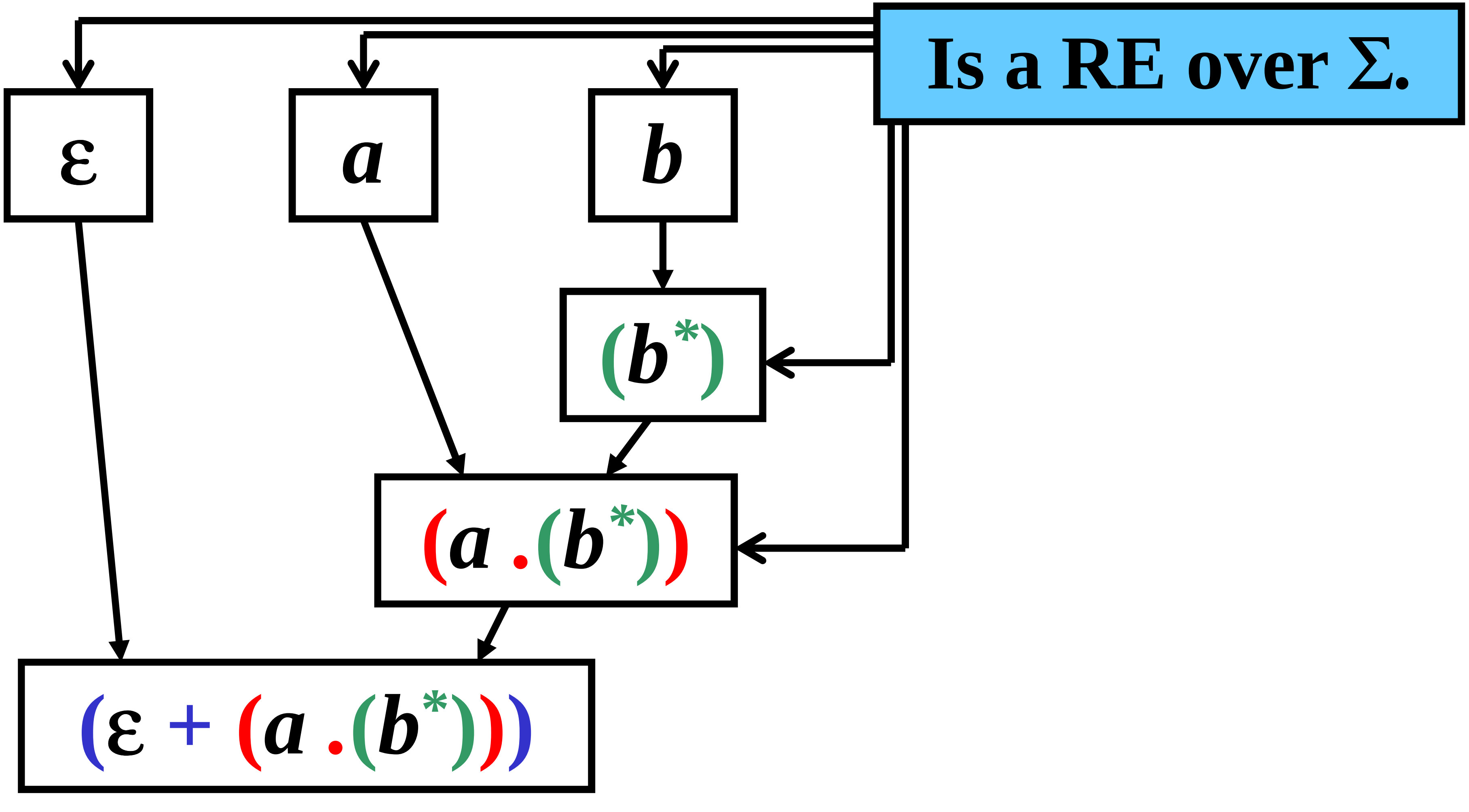

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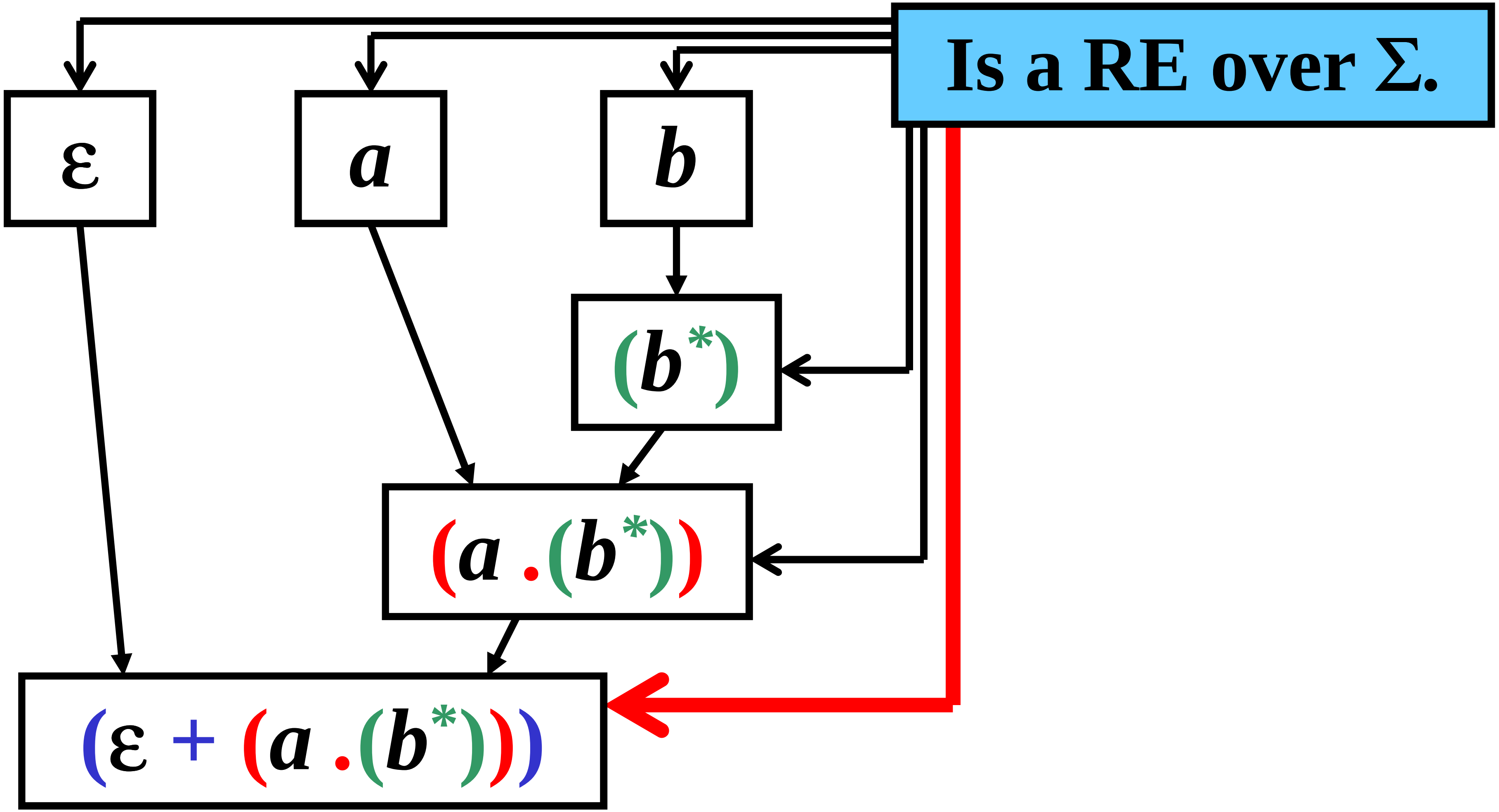

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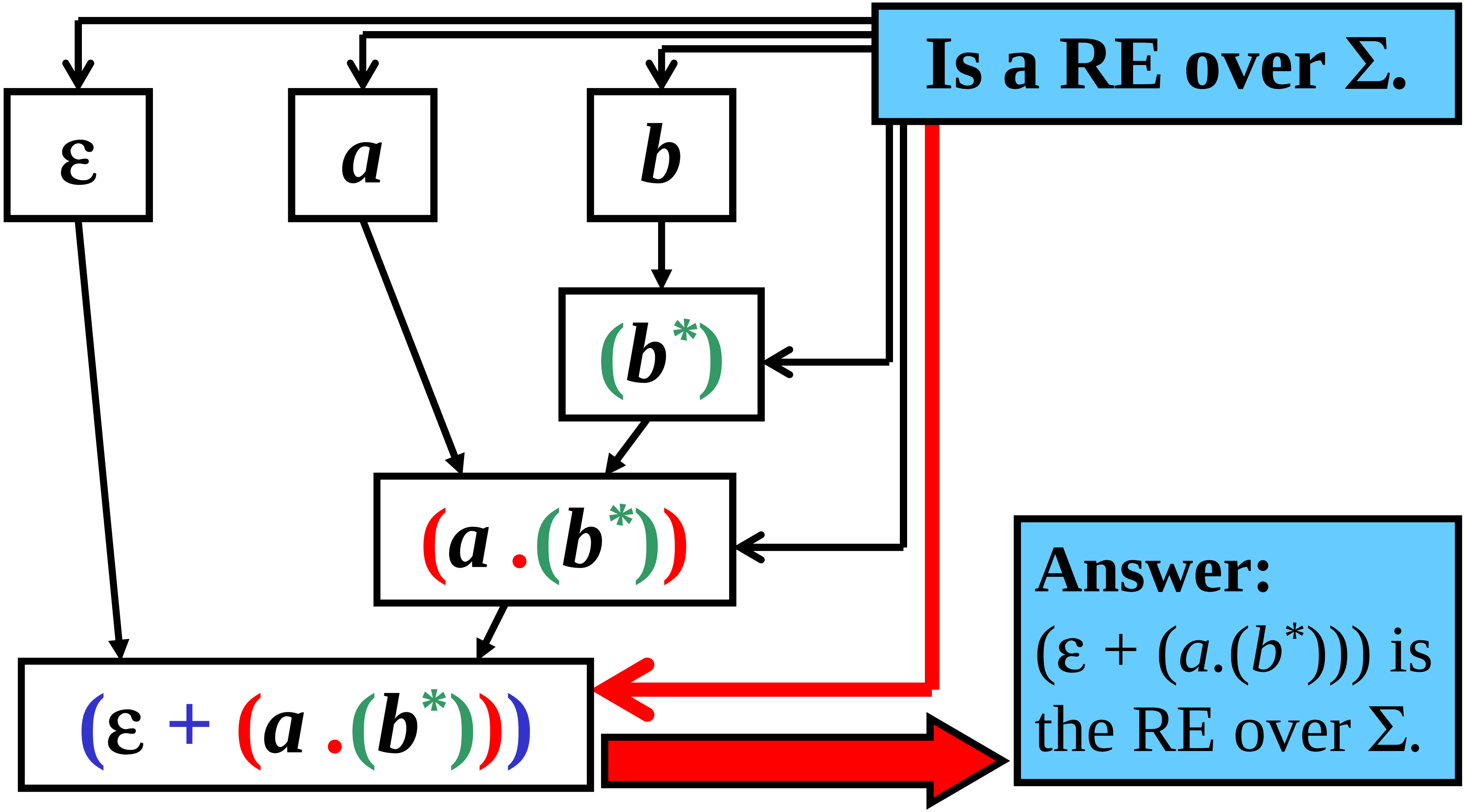


Simplification

1) Reduction of the number of parentheses by

Precedences: $^* > . > +$

2) Expression $r.s$ is simplified to rs

3) Expression rr^* or r^*r is simplified to r^+

Example:

$((\boldsymbol{a}.(\boldsymbol{a}^*)) + ((\boldsymbol{b}^*).\boldsymbol{b}))$ can be written as $\boldsymbol{a}.\boldsymbol{a}^* + \boldsymbol{b}^*.\boldsymbol{b}$,

and $\boldsymbol{a}.\boldsymbol{a}^* + \boldsymbol{b}^*.\boldsymbol{b}$ can be written as $\boldsymbol{a}^+ + \boldsymbol{b}^+$

Regular Language (RL)

Gist: Every RE denotes a regular language

Definition: Let L be a language. L is a *regular language* (RL) if there exists a regular expression r that denotes L.

Denotation: $L(r)$ means the language denoted by r.

Examples:

$r_1 = ab + ba$ denotes $L_1 = \{ab, ba\}$

$r_2 = a^+b^*$ denotes $L_2 = \{a^nb^m: n \geq 1, m \geq 0\}$

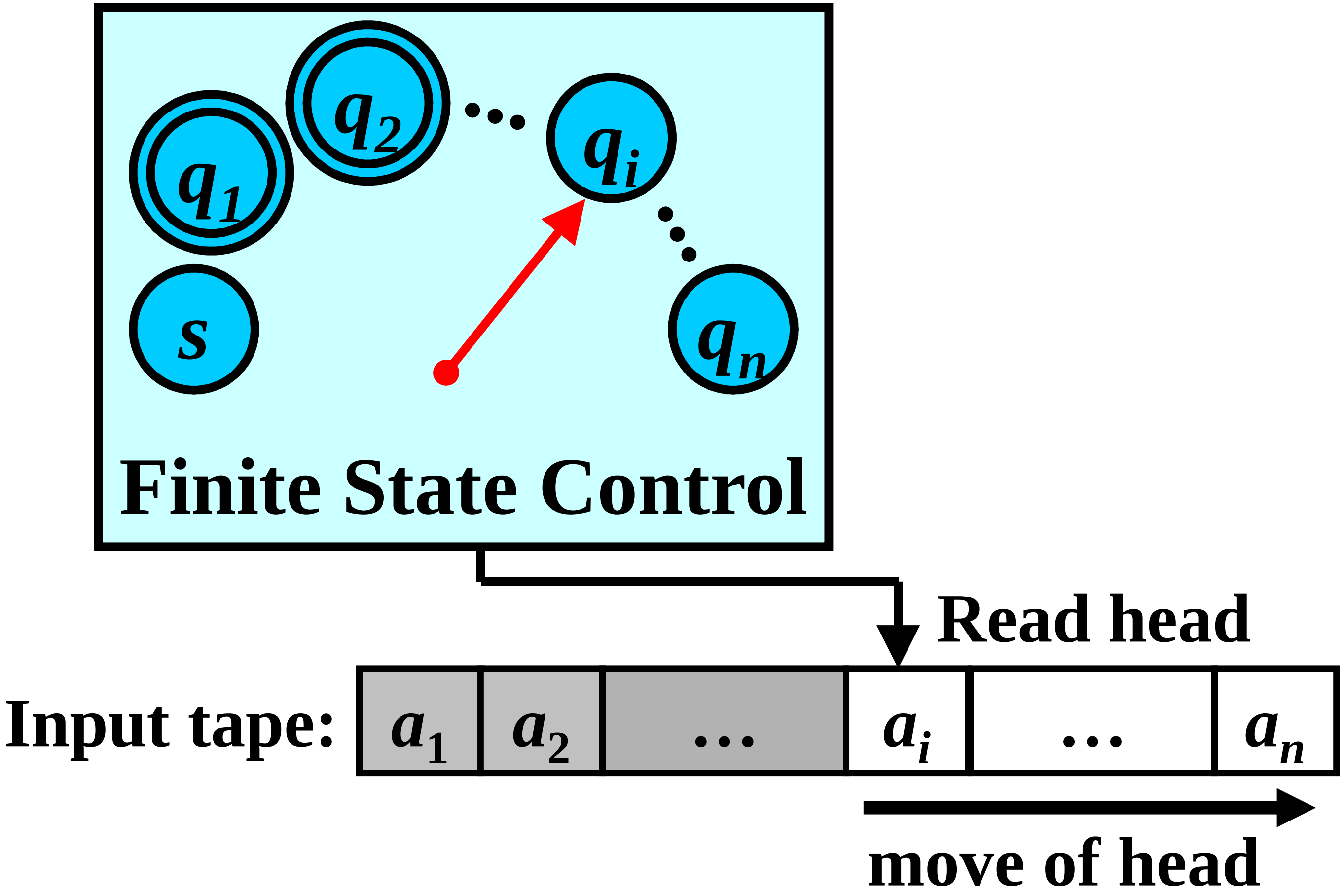
$r_3 = ab(a + b)^*$ denotes $L_3 = \{x: ab$ is prefix of $x\}$

$r_4 = (a + b)^*ab(a + b)^*$ denotes $L_4 = \{x: ab$ is substring of $x\}$

L_1, L_2, L_3, L_4 are regular languages over Σ

Finite Automata (FA)

Gist: The simplest model of computation based on a finite set of states and computational rules.



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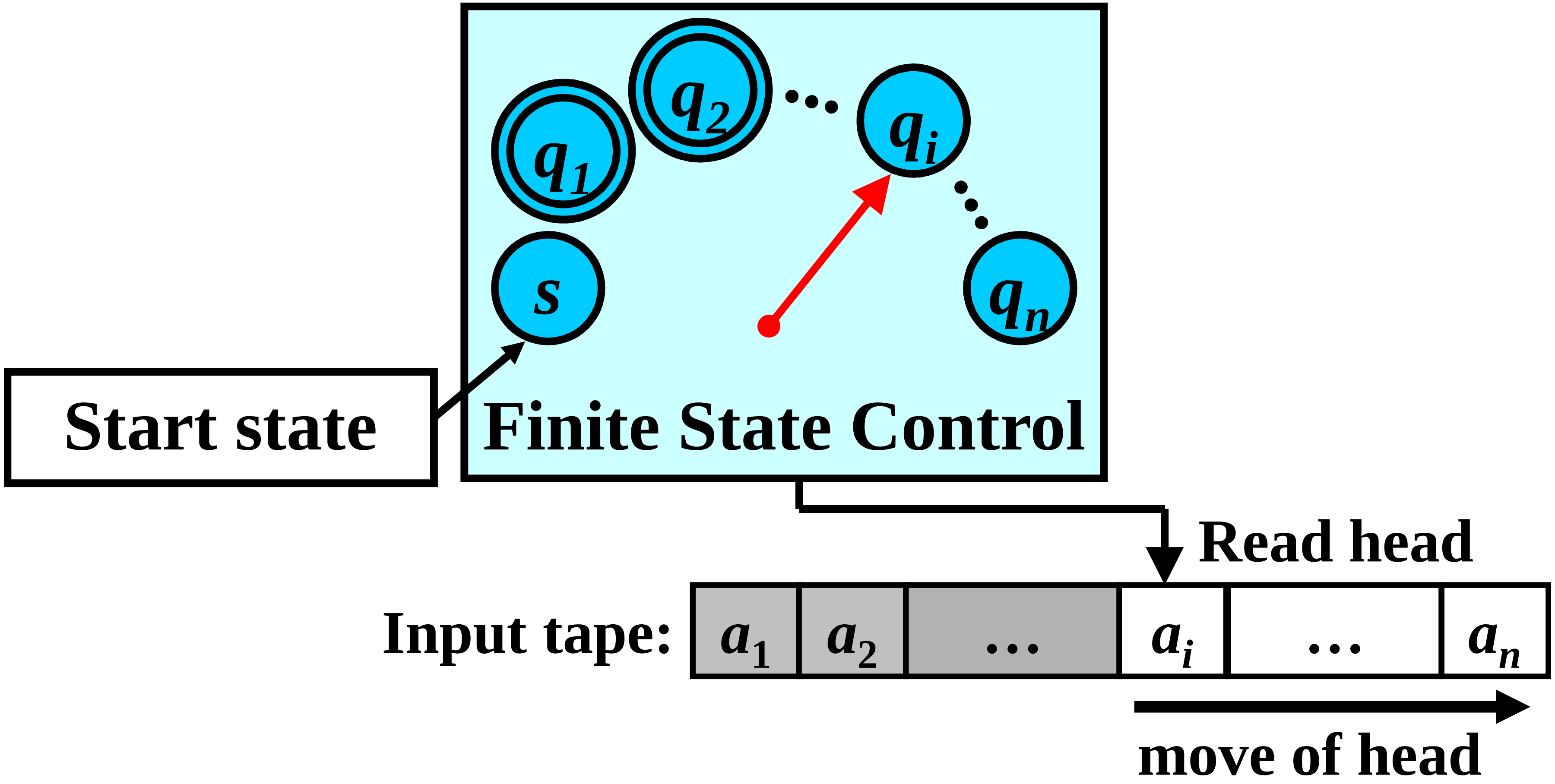

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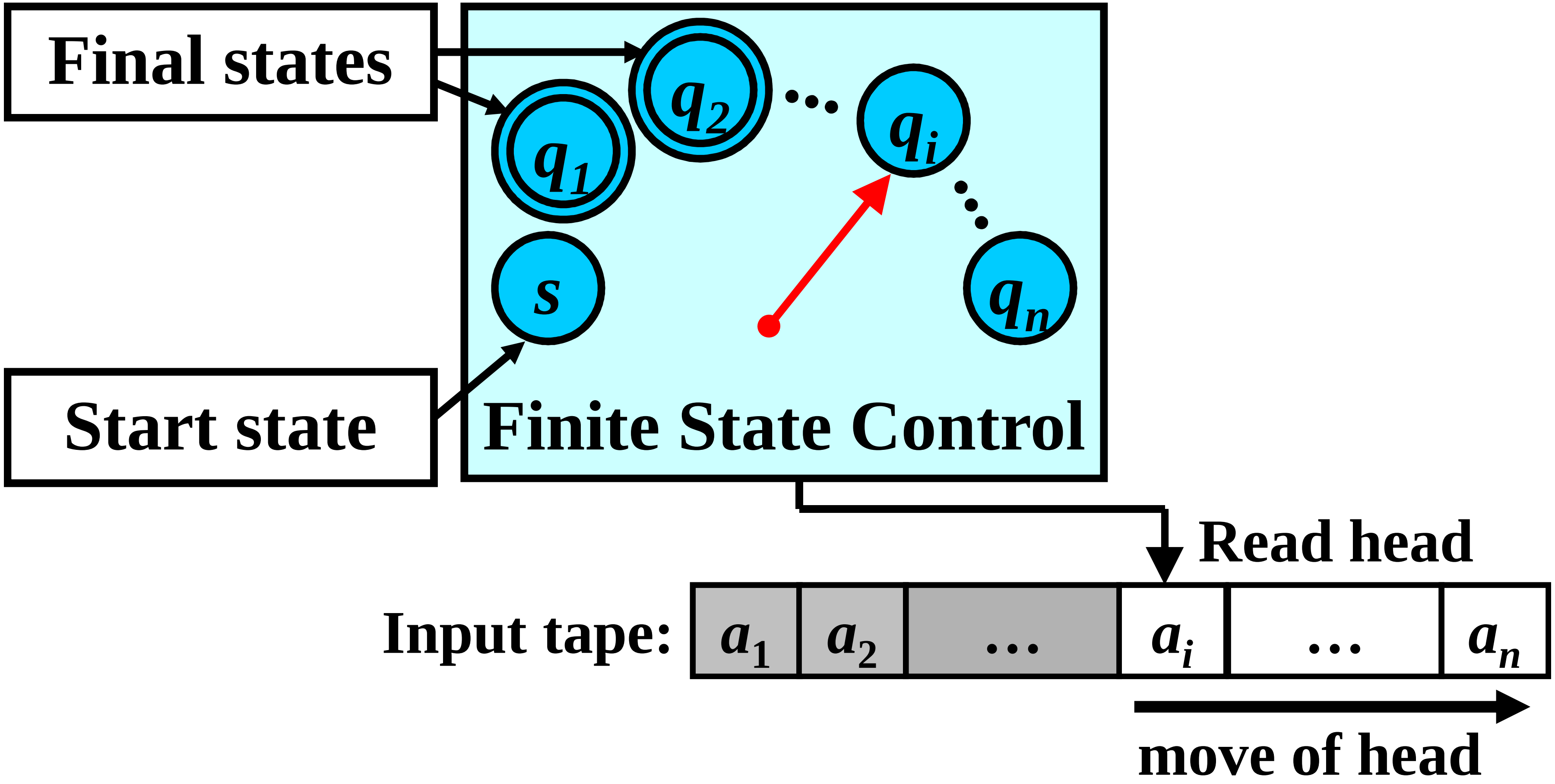

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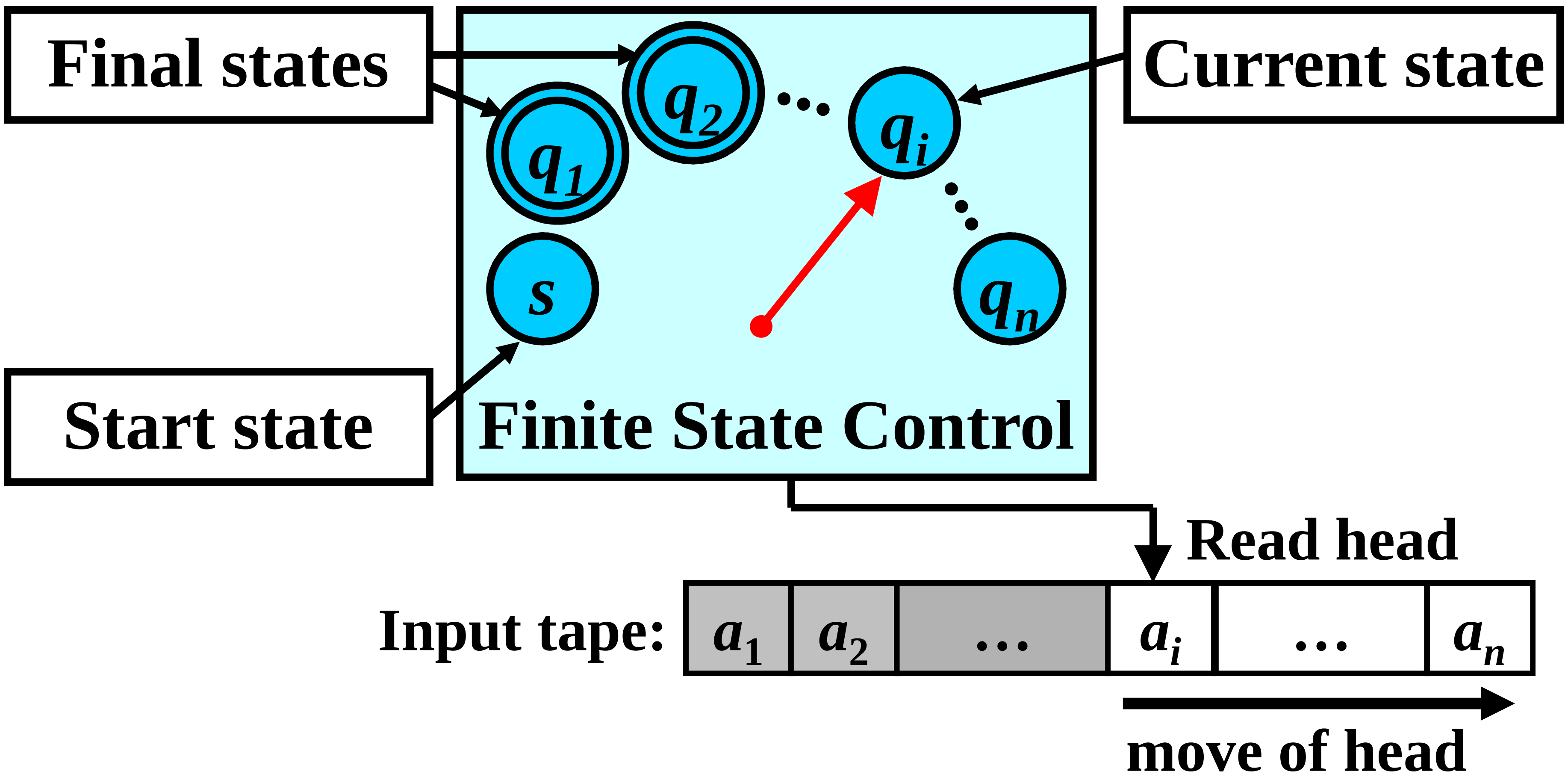


Finite Automata: Definition

Definition: *A finite automaton* (FA) is a 5-tuple:

$$M = (Q, \Sigma, R, s, F)\text{, where}$$

- Q is a *finite set of states*
- Σ is an *input alphabet*
- R is a *finite set of rules* of the form: $pa \rightarrow q$, where $p, q \in Q$, $a \in \Sigma \cup \{\varepsilon\}$
- $s \in Q$ is the *start state*
- $F \subseteq Q$ is a set of *final states*

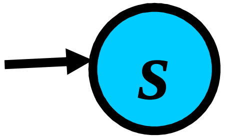
Mathematical note on rules:

- Strictly mathematically, R is a relation from $Q \times (\Sigma \cup \{\varepsilon\})$ to Q
- Instead of $(\boldsymbol{pa}, \boldsymbol{q})$, however, we write the rule as $\boldsymbol{pa} \rightarrow \boldsymbol{q}$

- $\boldsymbol{pa} \rightarrow \boldsymbol{q}$ means that with $\boldsymbol{a}$, M can move from $\boldsymbol{p}$ to $\boldsymbol{q}$
- if $\boldsymbol{a} = \varepsilon$, no symbol is read

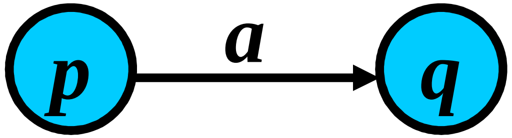
Graphical Representation

denotes a state $q \in Q$



denotes the start state $s \in Q$

denotes a final state $f \in F$



denotes $pa \rightarrow q \in R$

Graphical Representation: Example

$M = (Q, \Sigma, R, s, F)$,
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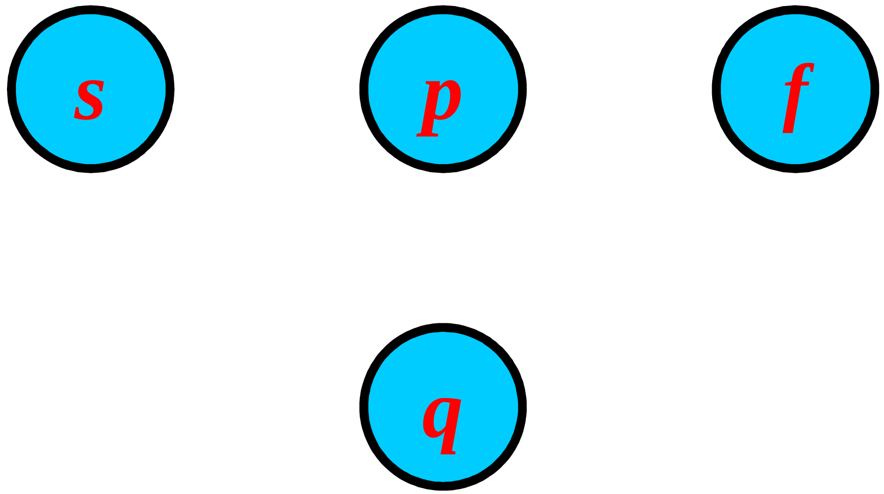

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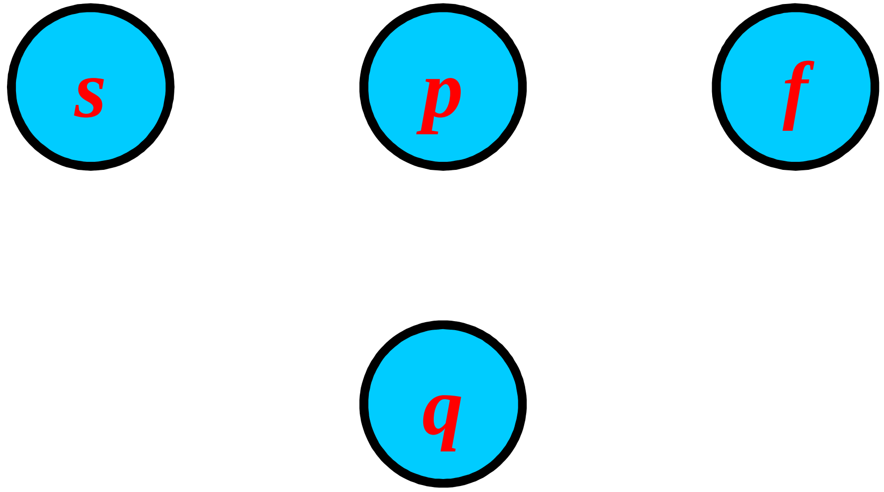

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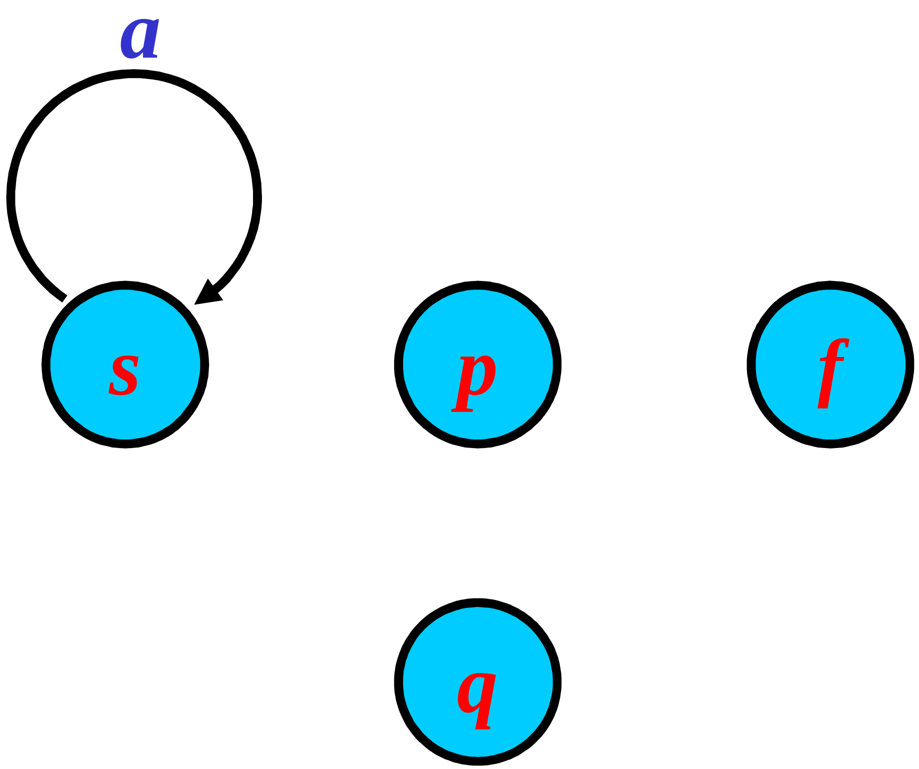

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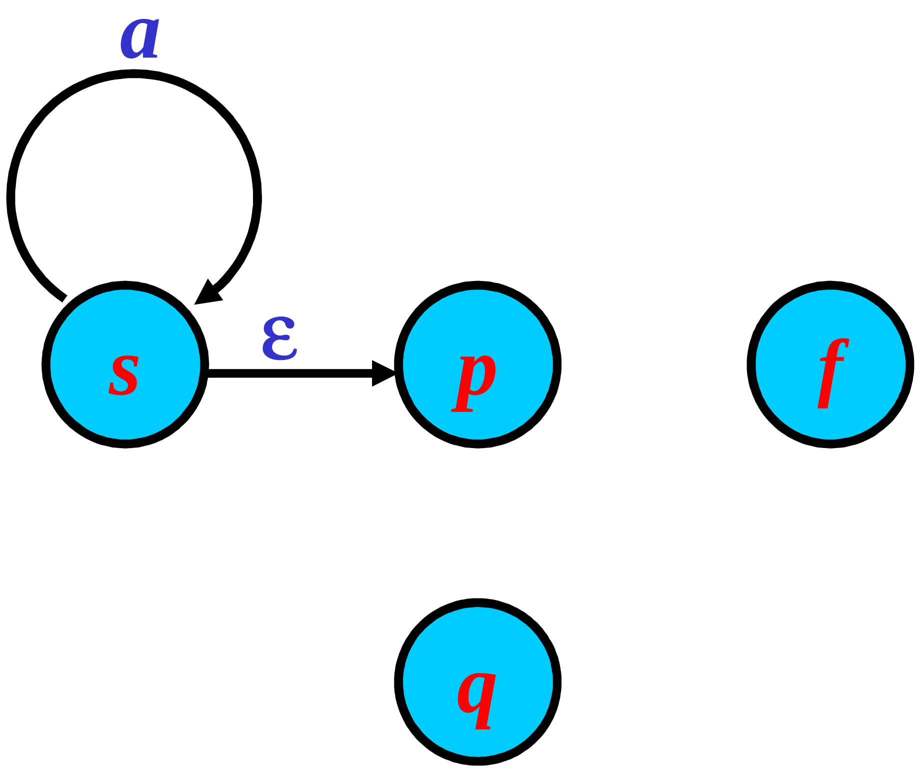

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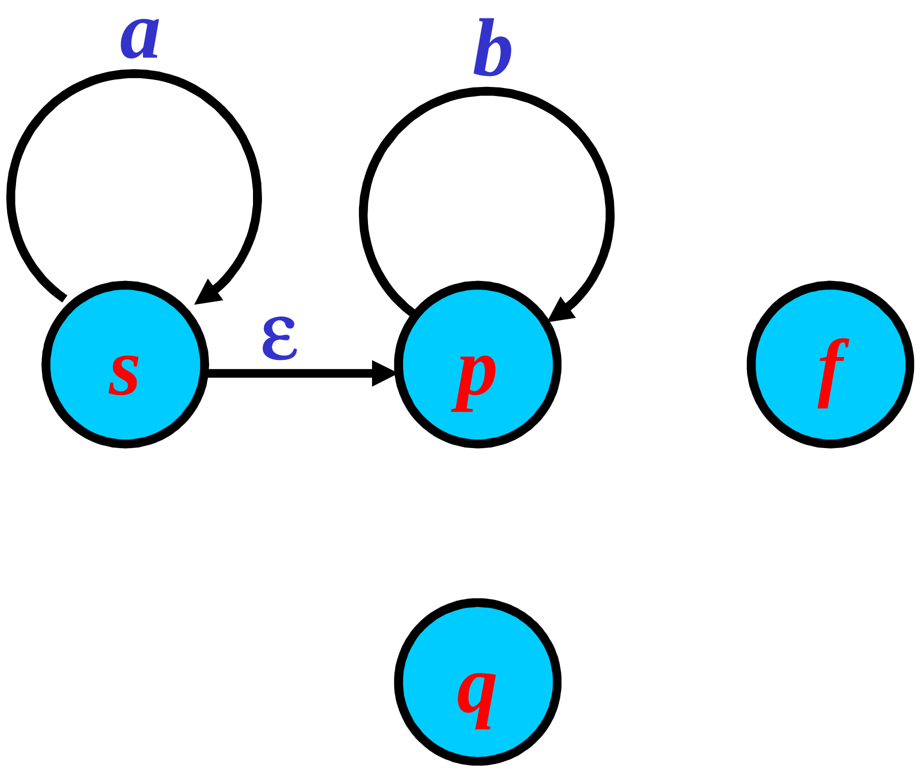

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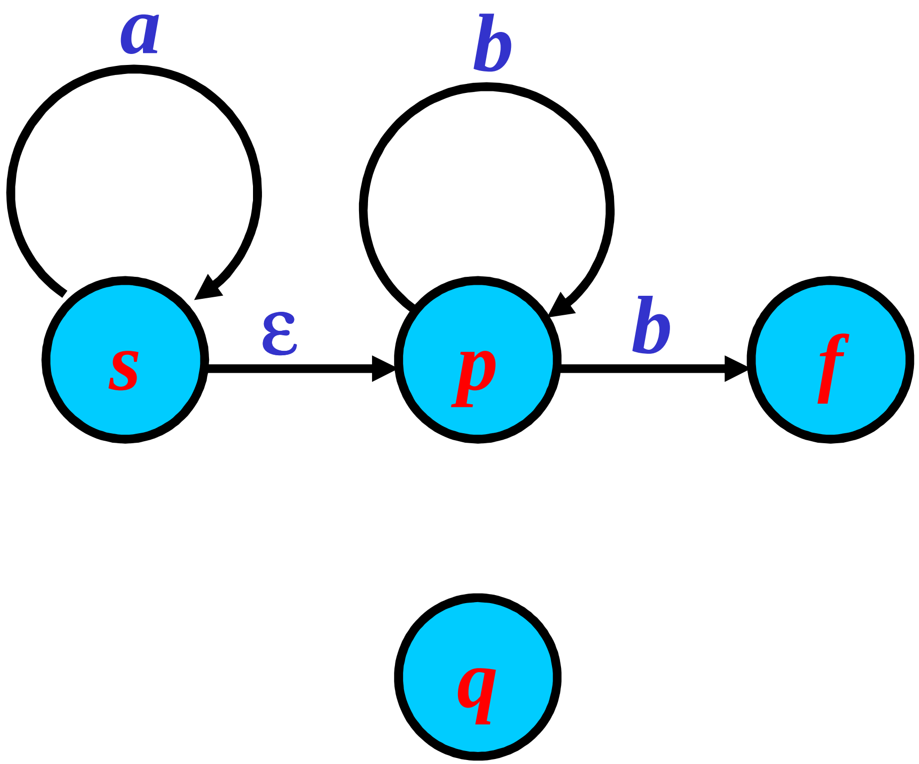

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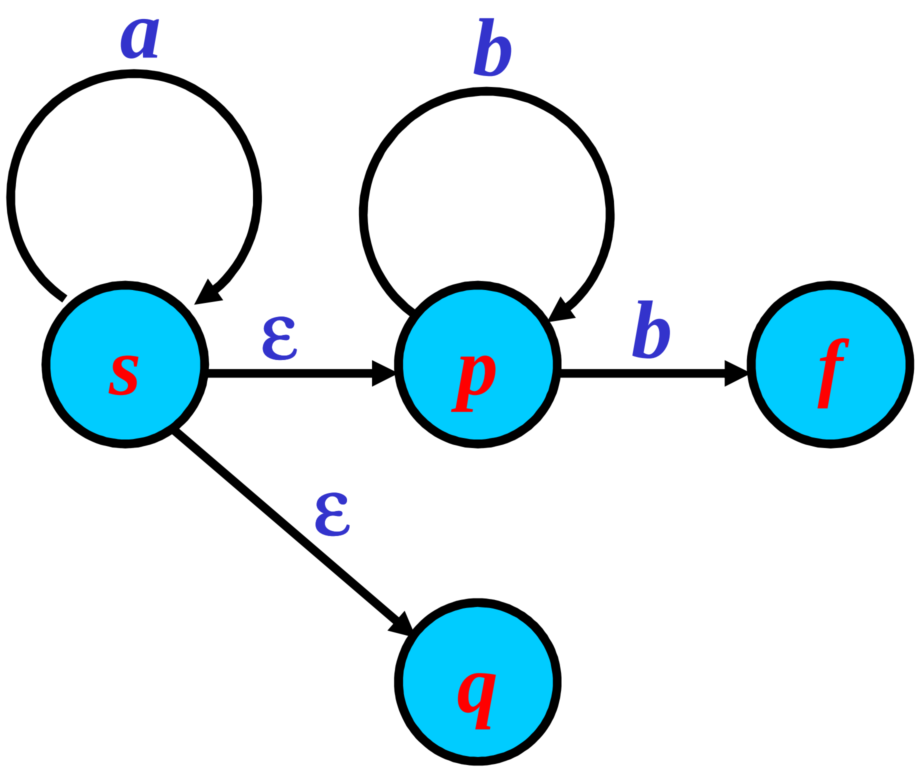

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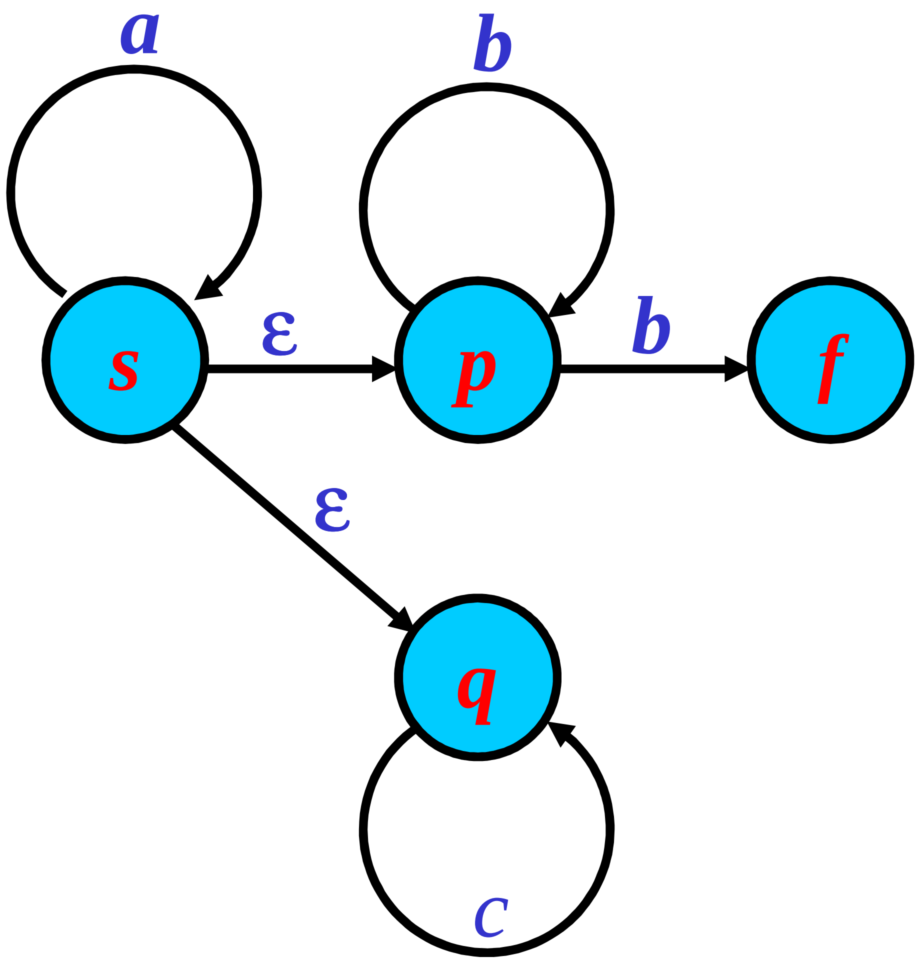

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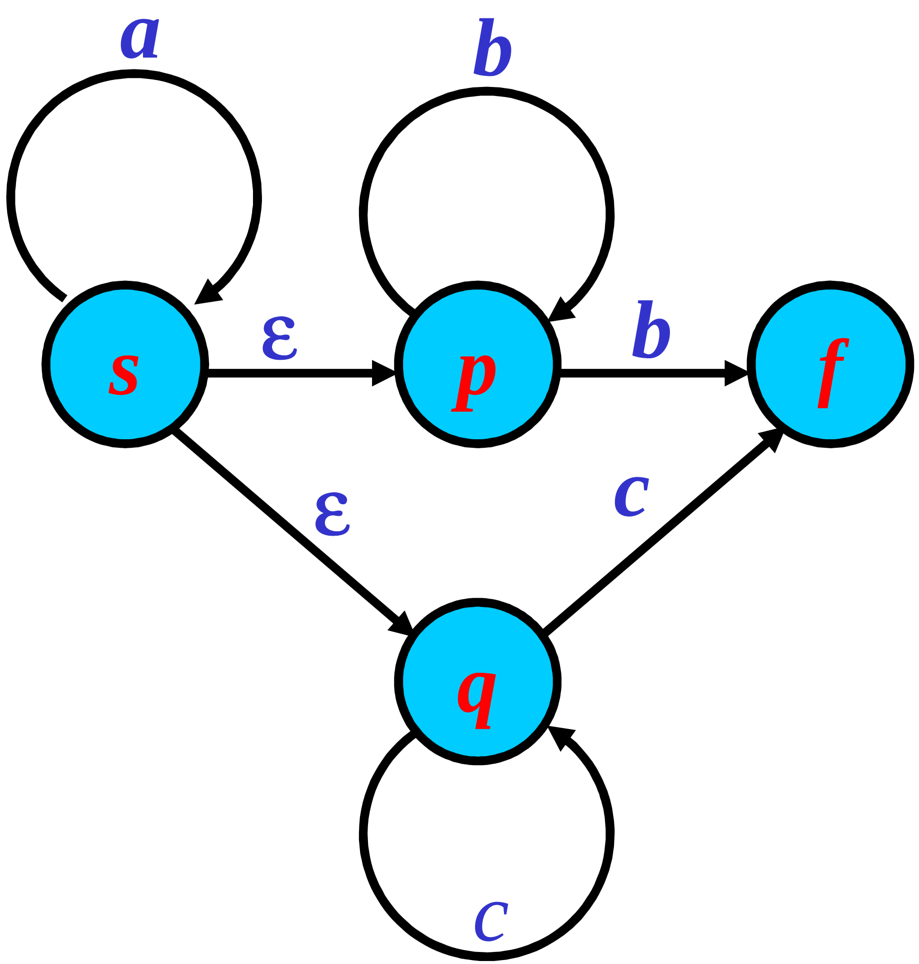

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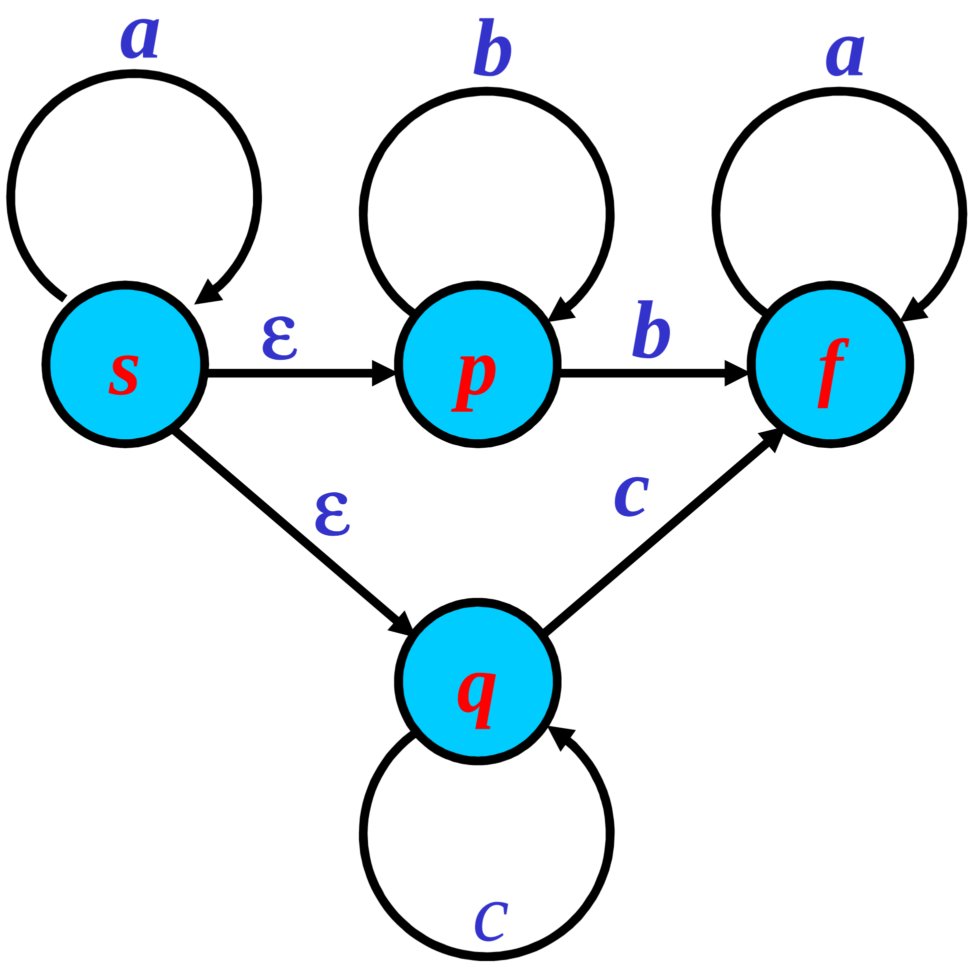

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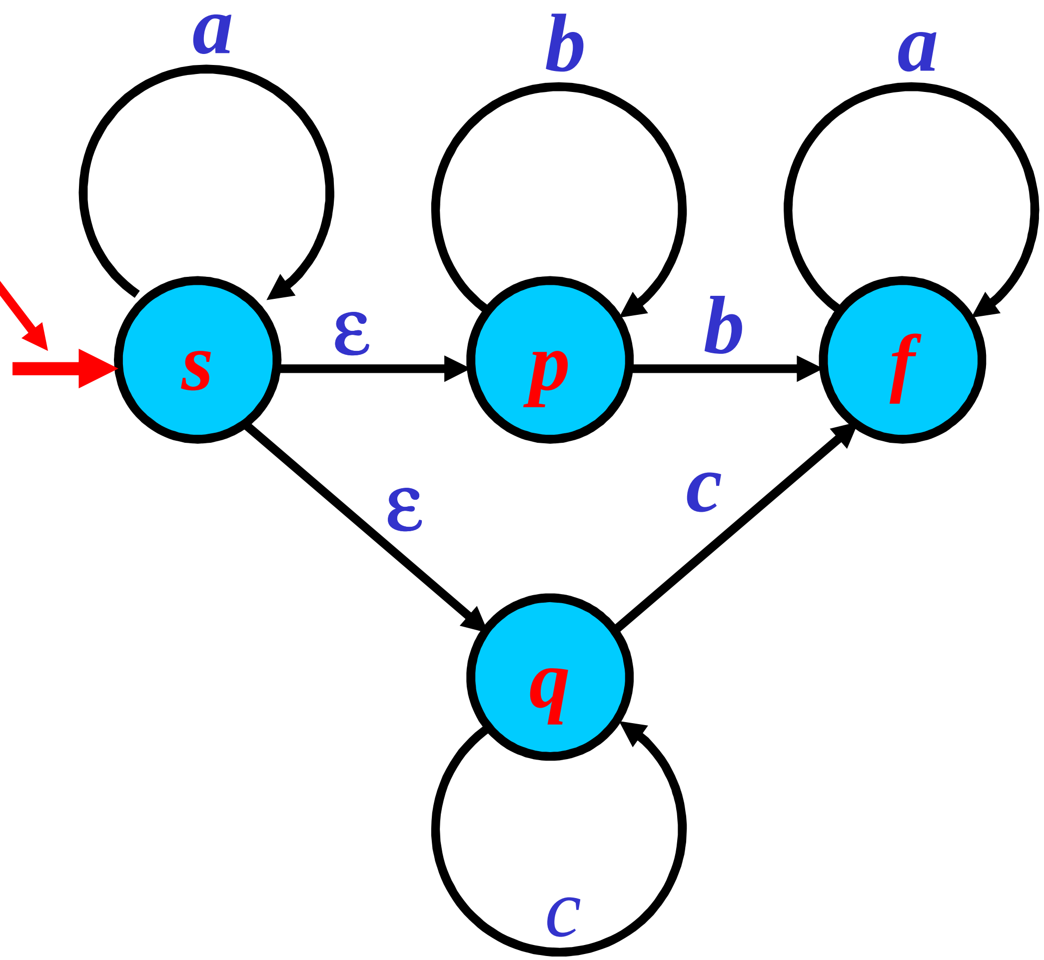

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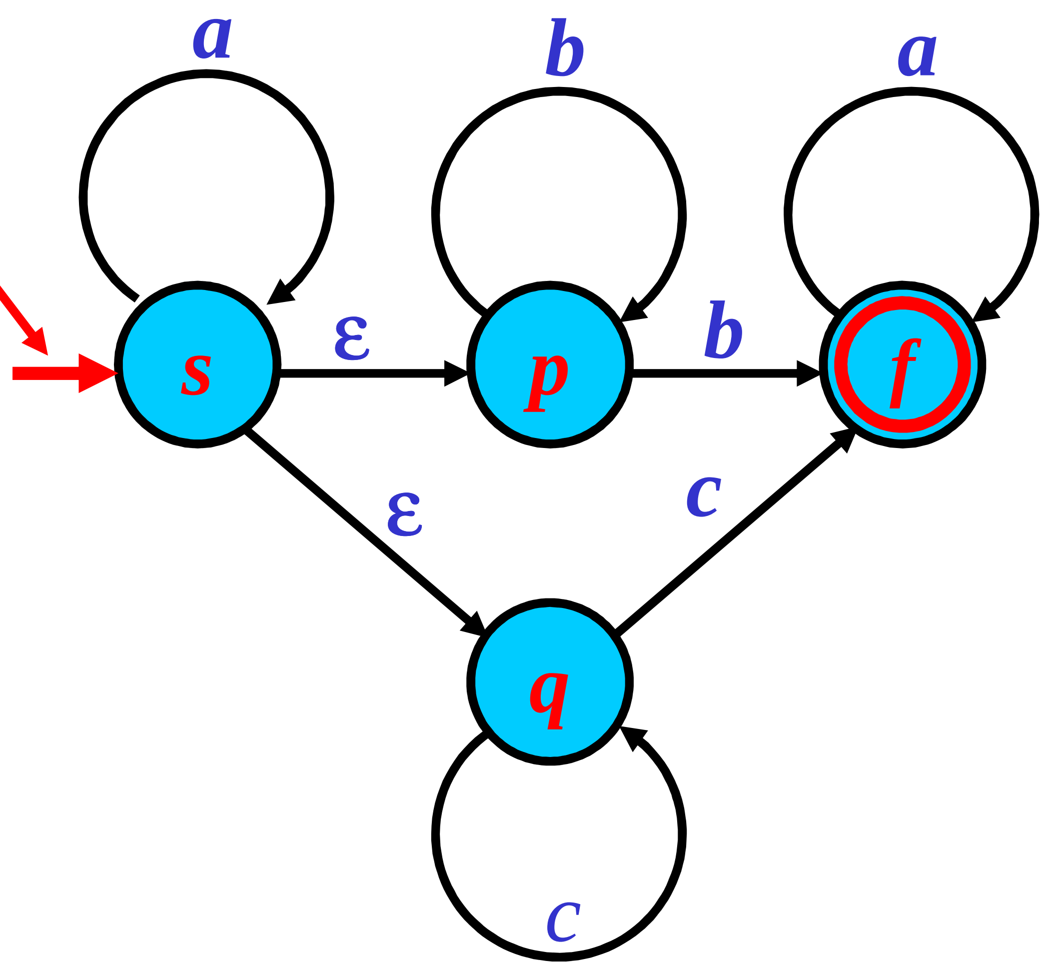
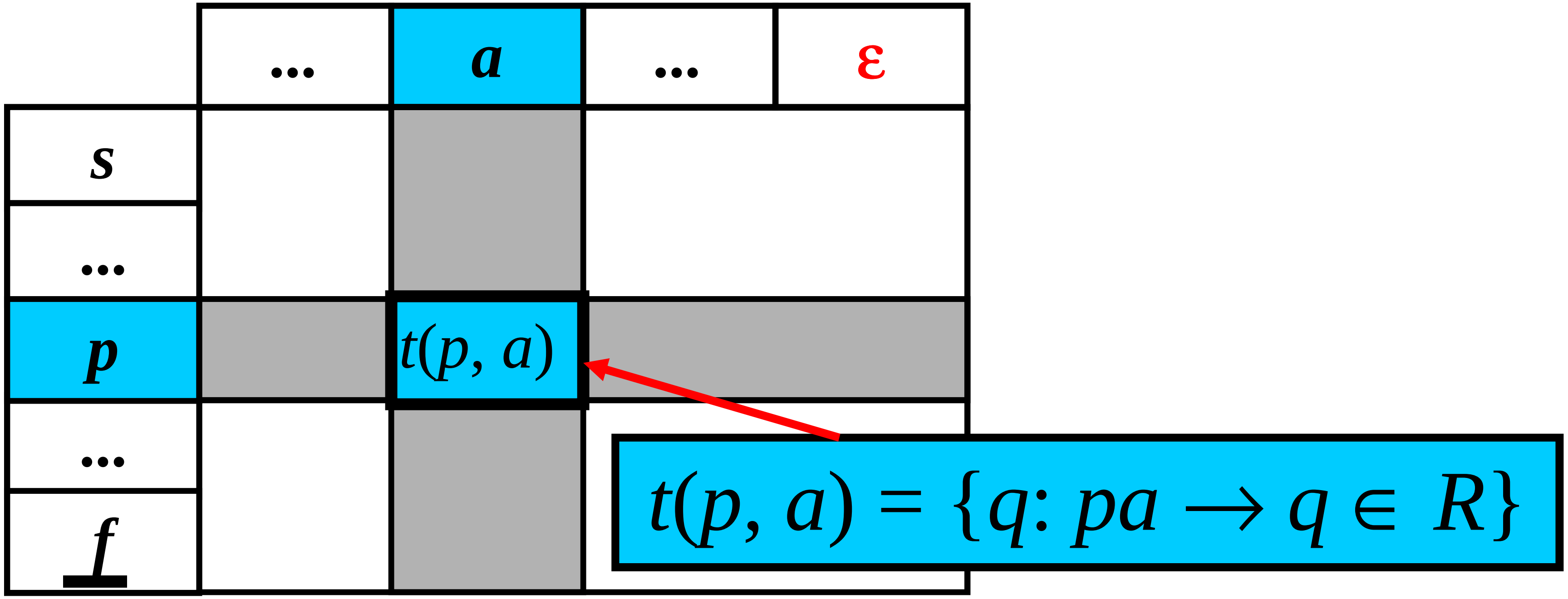
- $F = \{f\}$



Tabular Representation

- **Columns:** Member of $\Sigma \cup \{\varepsilon\}$
- **Rows:** States of Q
- **First row:** The start state
- **Underscored:** Final states



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s
p
q
f

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$M = (Q, \Sigma, R, s, F)$,
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	a	***b***	***c***
s			
p			
q			
f			

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	a	*b*	*c*	ε
s				
p				
q				
f				

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	a	**b**	**c**	**ε**
s	∅	∅	∅	∅
p	∅	∅	∅	∅
q	∅	∅	∅	∅
f	∅	∅	∅	∅

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$M = (Q, \Sigma, R, s, F)$,
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- $\Sigma = \{$***a***, ***b***, ***c***$\}$;
- $R = \{$***sa*** $\rightarrow$ ***s***,

	a	*b*	*c*	ε
s	{*s*}	∅	∅	∅
p	∅	∅	∅	∅
q	∅	∅	∅	∅
f	∅	∅	∅	∅

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$M = (Q, \Sigma, R, s, F)$,
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	a	b	c	ε
s	$\{s\}$	$\emptyset$	$\emptyset$	$\{p\}$
p	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
q	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
f	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$

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	a	b	c	ε
s	{s}	∅	∅	{p}
p	∅	{p}	∅	∅
q	∅	∅	∅	∅
f	∅	∅	∅	∅

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	a	b	c	ε
s	$\{s\}$	$\varnothing$	$\varnothing$	$\{p, q\}$
p	$\varnothing$	$\{p, f\}$	$\varnothing$	$\varnothing$
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  $fa \rightarrow f\}$;

	a	*b*	*c*	ε
s	$\{s\}$	$\emptyset$	$\emptyset$	$\{p, q\}$
p	$\emptyset$	$\{p, f\}$	$\emptyset$	$\emptyset$
q	$\emptyset$	$\emptyset$	$\{q, f\}$	$\emptyset$
f	$\{f\}$	$\emptyset$	$\emptyset$	$\emptyset$

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	a	*b*	*c*	ε
s	$\{s\}$	$\emptyset$	$\emptyset$	$\{p, q\}$
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q	$\emptyset$	$\emptyset$	$\{q, f\}$	$\emptyset$
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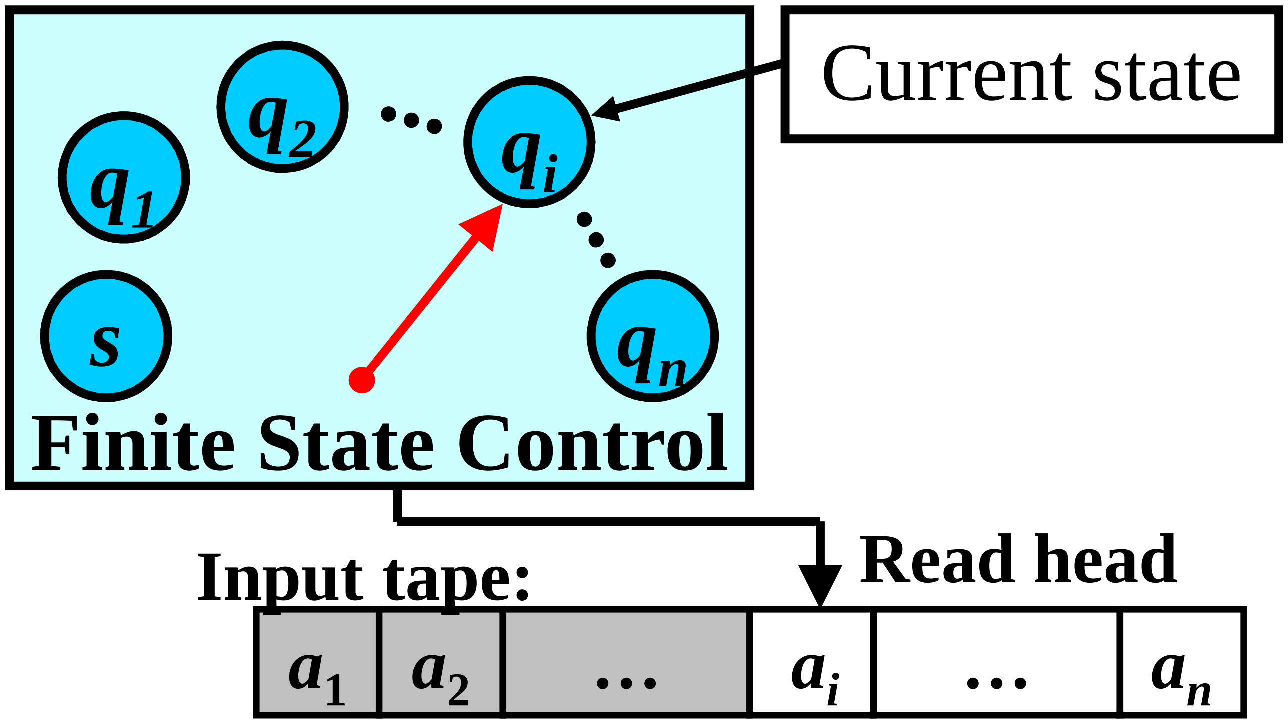
  $qc \to f,$
  $fa \to f\}$;
- $F = \{f\}$

	a	b	c	ε
s	$\{s\}$	$\varnothing$	$\varnothing$	$\{p, q\}$
p	$\varnothing$	$\{p, f\}$	$\varnothing$	$\varnothing$
q	$\varnothing$	$\varnothing$	$\{q, f\}$	$\varnothing$
f	$\{f\}$	$\varnothing$	$\varnothing$	$\varnothing$

Configuration

Gist: Instance description of FA

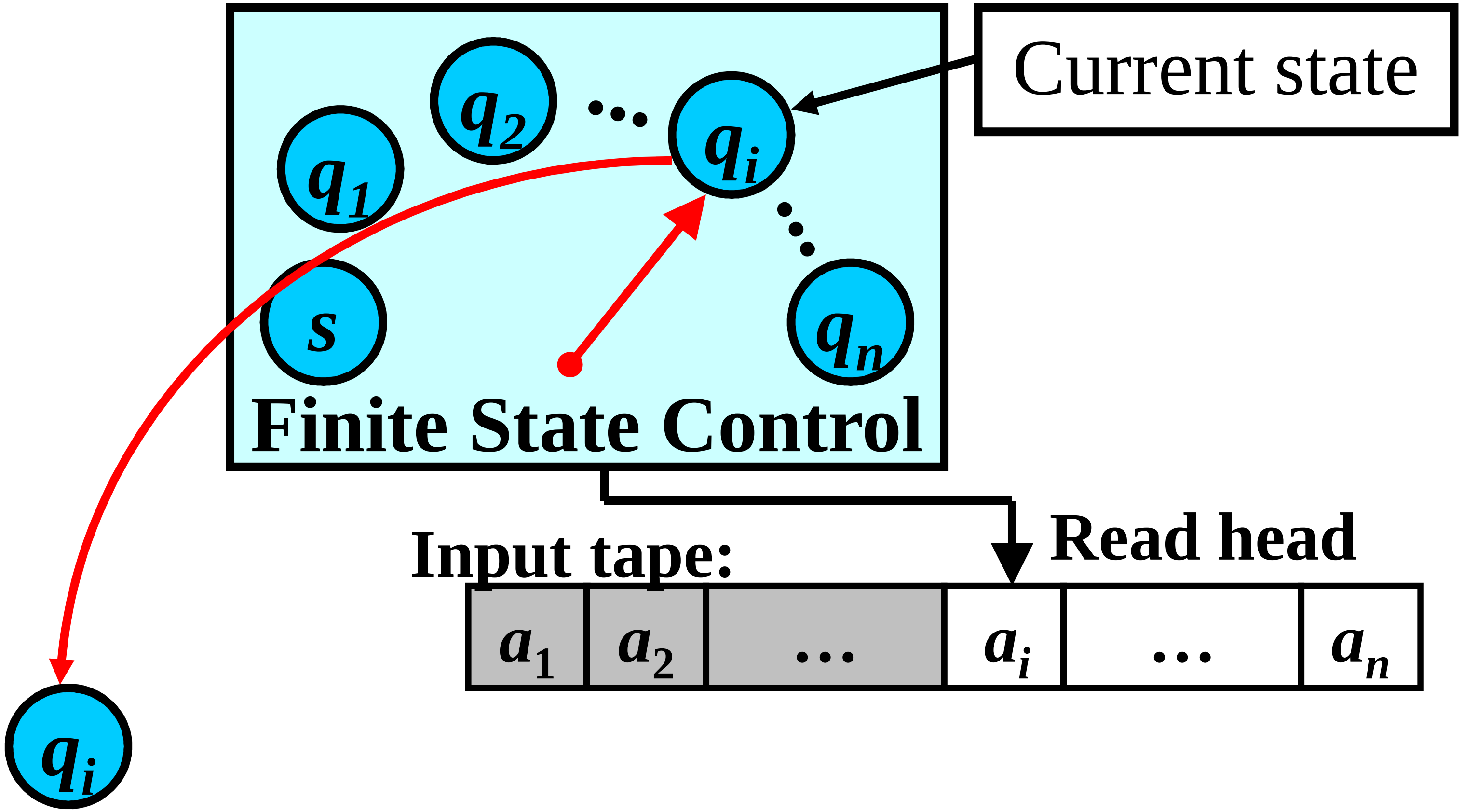
Definition: Let $M = (Q, \Sigma, R, s, F)$ be a FA.
A configuration of M is a string $\chi \in Q\Sigma^*$



Configuration

Gist: Instance description of FA

Definition: Let $M = (Q, \Sigma, R, s, F)$ be a FA.
A configuration of M is a string $\chi \in Q\Sigma^*$



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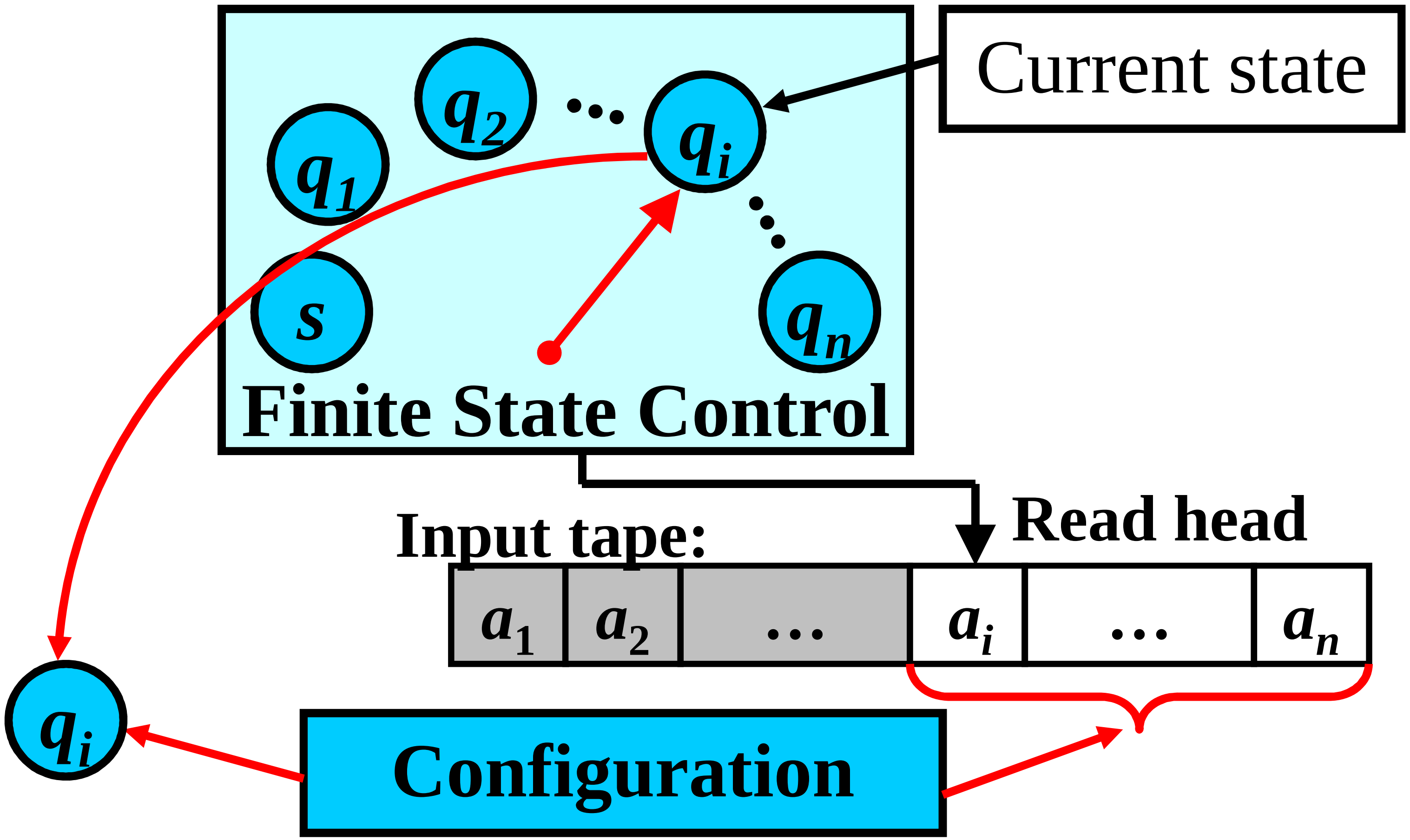

Move

Gist: Computational step of FA

Definition: Let ***p******a***x and ***q***x be two configurations of M, where ***p***, ***q*** $\in Q$, ***a*** $\in \Sigma \cup \{\varepsilon\}$, and $x \in \Sigma^*$. Let ***r*** = ***pa*** $\rightarrow$ ***q*** $\in R$ be a rule. Then M makes a *move* from ***pa***x to ***q***x according to ***r***, written as ***pa***x |– ***q***x [***r***] or, simply, ***pa***x |– ***q***x

Note: if ***a*** = ε, no input symbol is read

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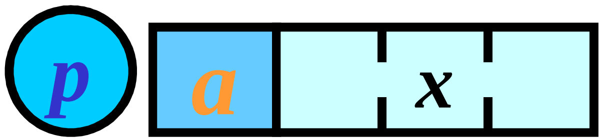

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Definition: Let pax and qx be two configurations of M, where $p, q \in Q$, $a \in \Sigma \cup \{\varepsilon\}$, and $x \in \Sigma^*$. Let $r = pa \to q \in R$ be a rule. Then M makes a *move* from pax to qx according to r, written as $pax \vdash qx\ [r]$ or, simply, $pax \vdash qx$

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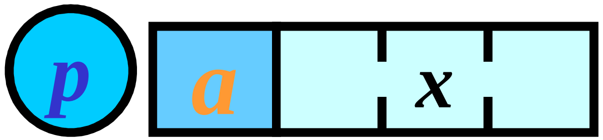

Rule: $pa \to q$

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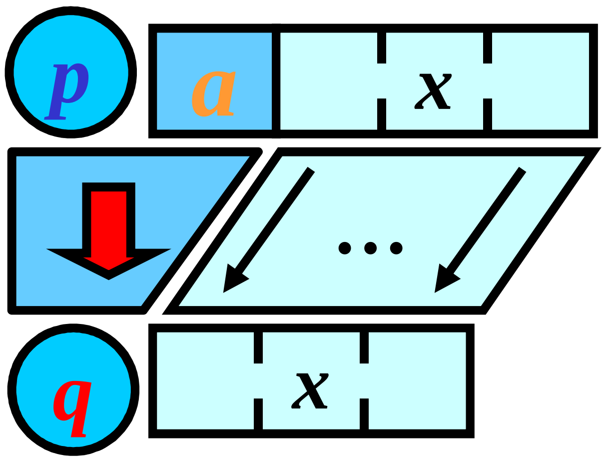
Configuration:

Rule: $pa \rightarrow q$

New configuration:



Sequence of Moves 1/2

Gist: Several consecutive computational steps

Definition: Let χ be a configuration. M makes *zero moves* from χ to χ; in symbols,

$$\chi \vdash^0 \chi \ [\varepsilon] \text{ or, simply, } \chi \vdash^0 \chi$$

Definition: Let $\chi_0, \chi_1, \ldots, \chi_n$ be a sequence of configurations, $n \geq 1$, and $\chi_{i-1} \vdash \chi_i \ [r_i]$, $r_i \in R$, for all $i = 1, \ldots, n$; that is,

$$\chi_0 \vdash \chi_1 \ [r_1] \vdash \chi_2 \ [r_2] \ \ldots \ \vdash \chi_n \ [r_n]$$

Then M makes *n moves* from χ_0 to χ_n:

$$\chi_0 \vdash^n \chi_n \ [r_1 \ldots r_n] \text{ or, simply, } \chi_0 \vdash^n \chi_n$$

Sequence of Moves 2/2

If $\chi_0 \vdash^n \chi_n$ [ρ] for some $n \geq 1$, then

$$\chi_0 \vdash^+ \chi_n [\rho].$$

If $\chi_0 \vdash^n \chi_n$ [ρ] for some $n \geq 0$, then

$$\chi_0 \vdash^* \chi_n [\rho].$$

Example: Consider

pa*bc* |– ***q****bc* [**1**: ***pa*** → ***q***], and ***qb****c* |– ***r****c* [**2**: ***qb*** → ***r***].

Then, ***pab****c* $\vdash^2$ ***r****c* [**1 2**],

pab*c* $\vdash^+$ ***r****c* [**1 2**],

pab*c* $\vdash^*$ ***r****c* [**1 2**]

Accepted Language

Gist: ***M*** **accepts** ***w*** **if it can completely read** ***w*** **by a sequence of moves from** ***s*** **to a final state**

Definition: Let $M = (Q, \Sigma, R, s, F)$ be a FA. The *language accepted by M*, $L(M)$, is defined as:

$$L(M) = \{w: w \in \Sigma^*, sw \vdash^* f,\ f \in F\}$$

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$$\underbrace{s a_1 a_2 \ldots a_n}_{w} \vdash q_1 a_2 \ldots a_n \vdash \ldots \vdash q_{n-1} a_n \vdash q_n$$

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$M = (Q, \Sigma, R, s, F)$:

if $q_n \in F$ then $w \in L(M)$;
otherwise, $w \notin L(M)$

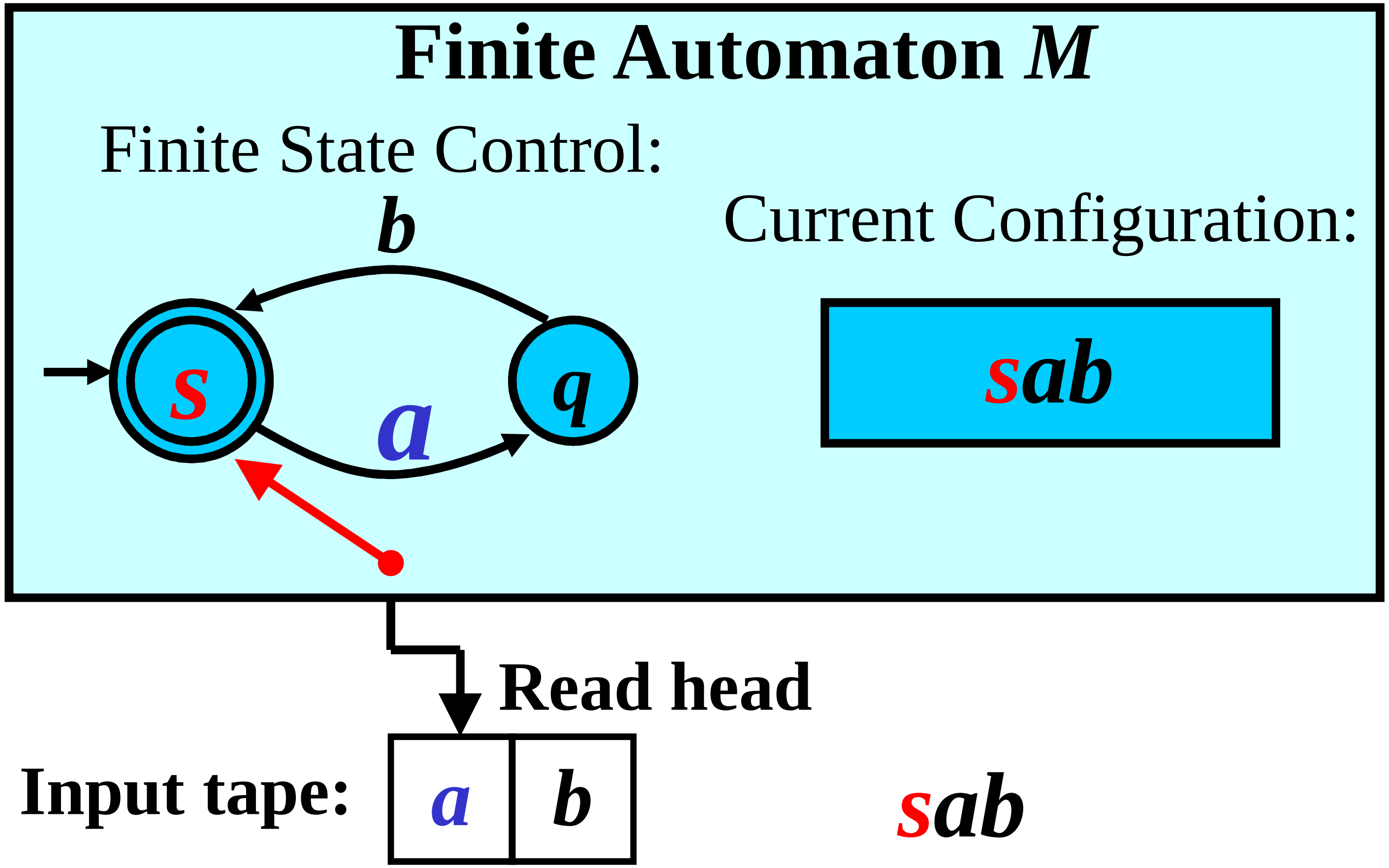
$$\underbrace{s a_1 a_2 \ldots a_n}_{w} \vdash q_1 a_2 \ldots a_n \vdash \ldots \vdash q_{n-1} a_n \vdash q_n$$

FA: Example 1/3

$M = (Q, \Sigma, R, s, F)$, where:

$Q = \{s, q\}$, $\Sigma = \{a, b\}$, $R = \{sa \rightarrow q, qb \rightarrow s\}$, $F = \{s\}$

Question: $ab \in L(M)$ **?**



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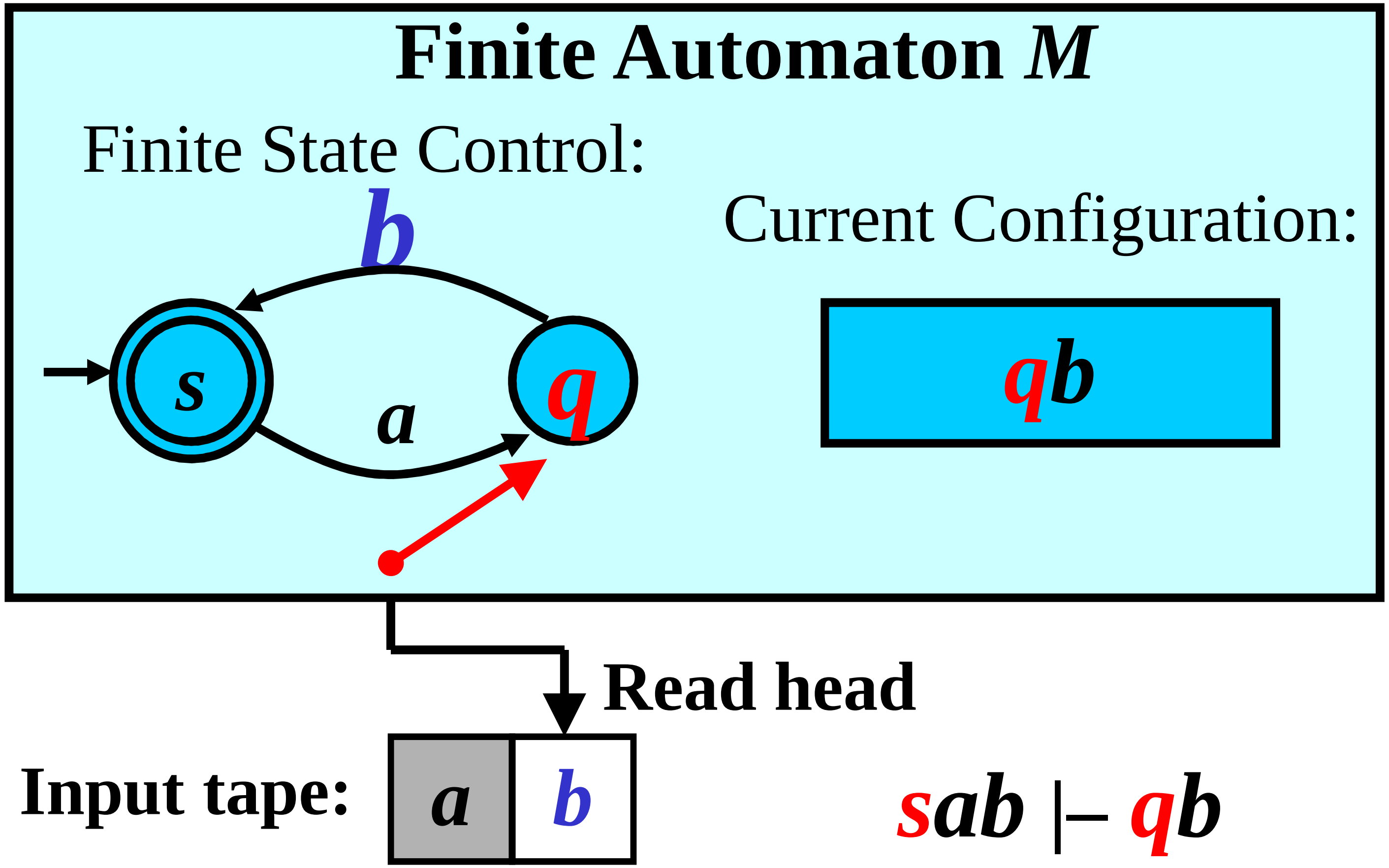

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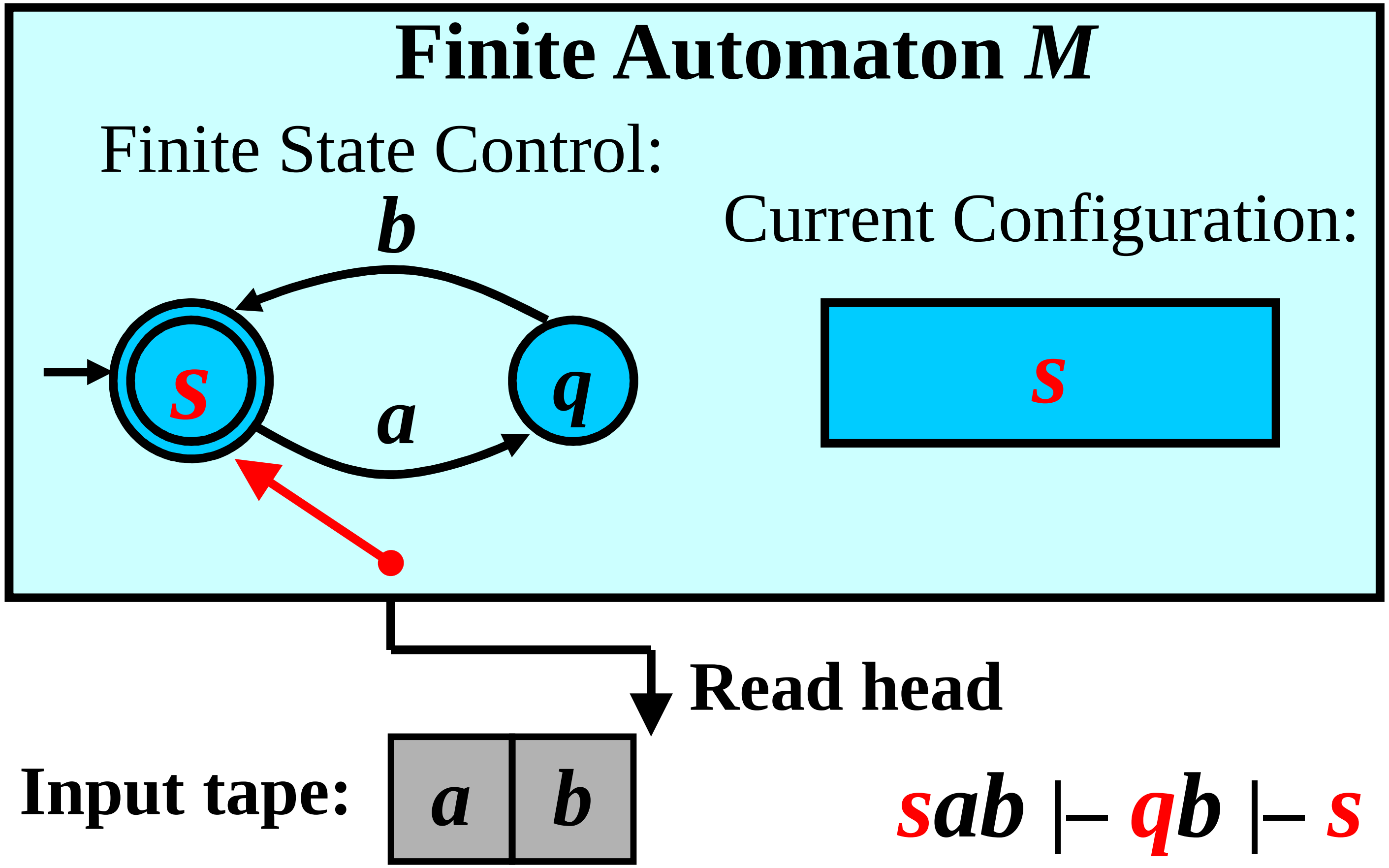

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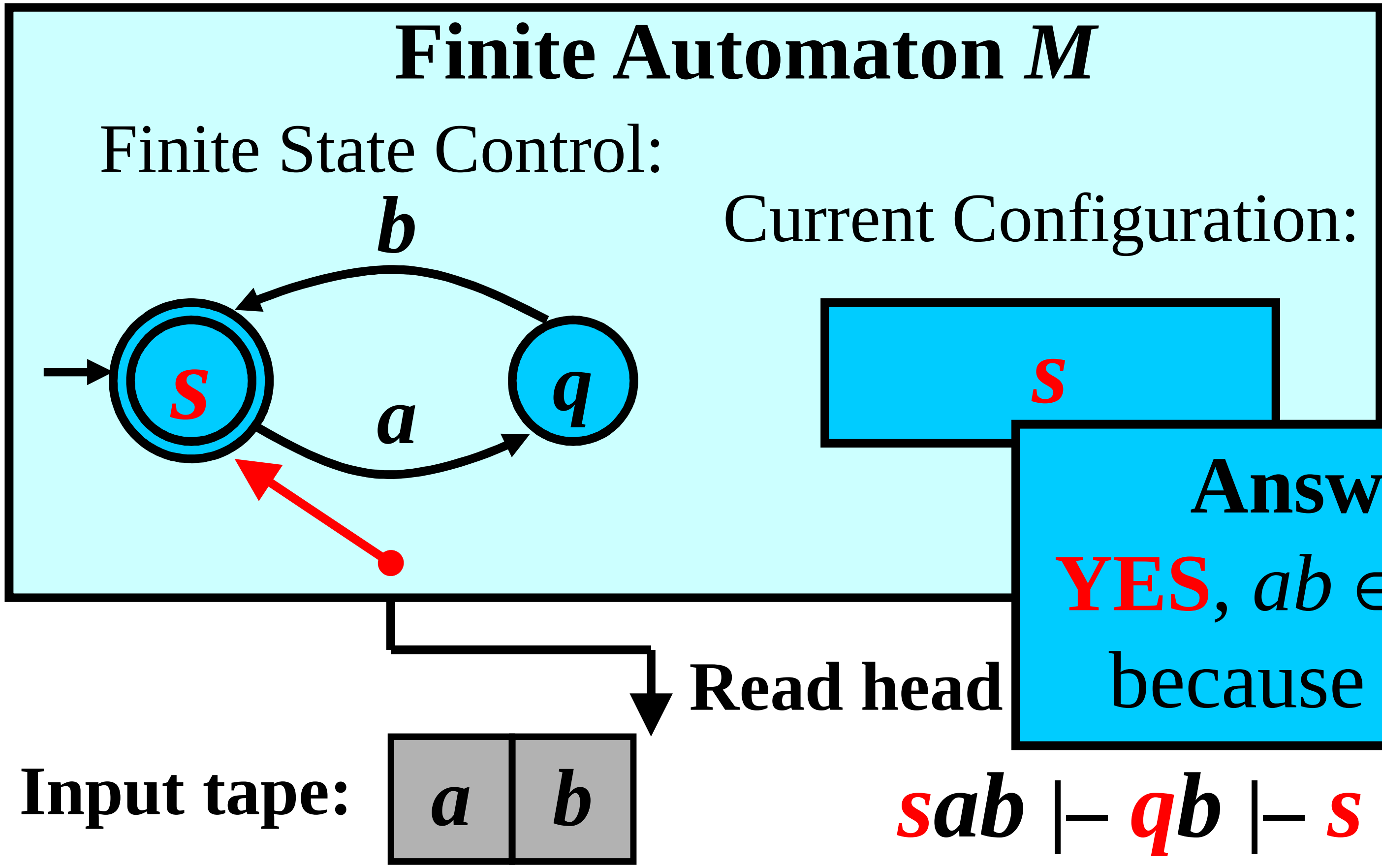


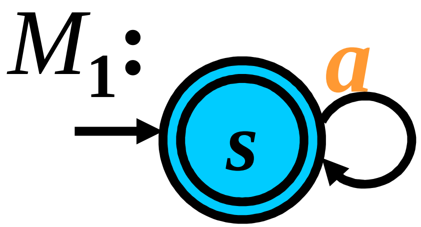
Answer:
YES, $ab \in L(M)$,
because $s \in F$

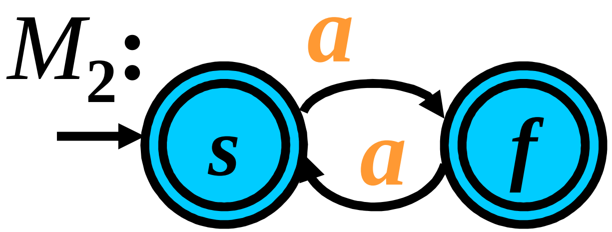
$sab \vdash qb \vdash s$

Equivalent Models

Definition: Two models for languages, such as FAs, are equivalent if they both specify the same language.

Example:





Question: Is M_1 equivalent to M_2 ?

Equivalent Models

Definition: Two models for languages, such as FAs, are equivalent if they both specify the same language.

Example:

Question: Is M_1 equivalent to M_2 ?

Answer: M_1 and M_2 **are equivalent** because

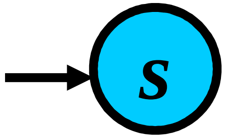
$$\boldsymbol{L(M_1) = L(M_2) = \{a^n : n \geq 0\}}$$

Conversion of RE to FA: Basics 1/5

Gist: Algorithm that converts any RE to an equivalent FA (lex in UNIX).

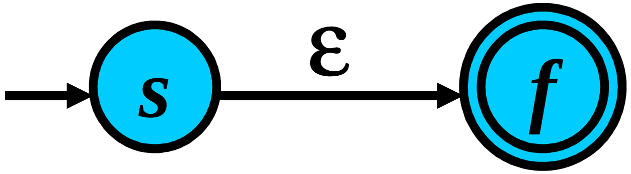
- For a RE $r = \emptyset$, there is an equivalent FA $M_\emptyset$.

Proof: $M_\emptyset$:



- For a RE $r = \varepsilon$, there is an equivalent FA M_ε.

Proof: M_ε:



- For a RE $r = a$, $a \in \Sigma$, there is an equivalent FA M_a .

Proof: M_a :

RE to FA: Concatenation 2/5

- Let $\boldsymbol{r}$ be a RE over Σ and $\boldsymbol{M_r} = (Q_r, \Sigma, R_r, s_r, \{f_r\})$ be an FA such that $L(M_r) = L(r)$.
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- Then, for the RE $\boldsymbol{r.t}$, there exists an equivalent FA $\boldsymbol{M_{r.t}}$

Proof: Let $Q_r \cap Q_t = \emptyset$.

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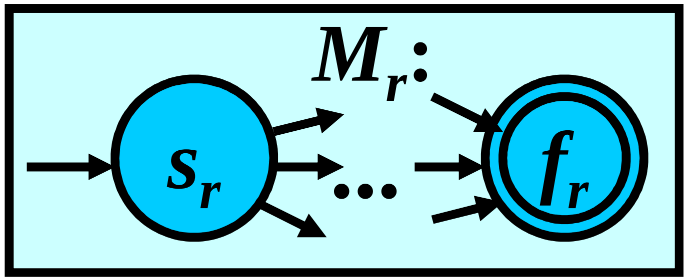

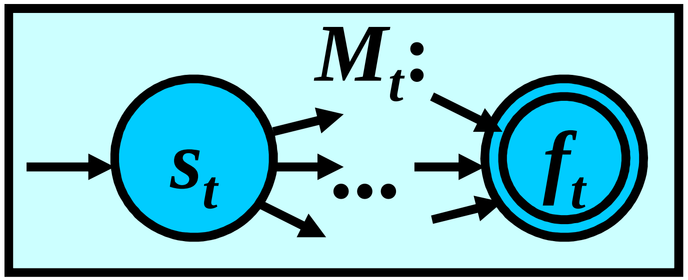

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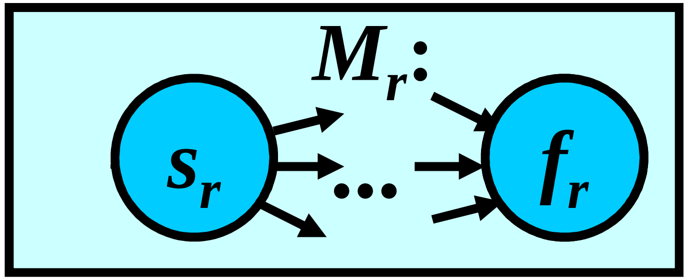

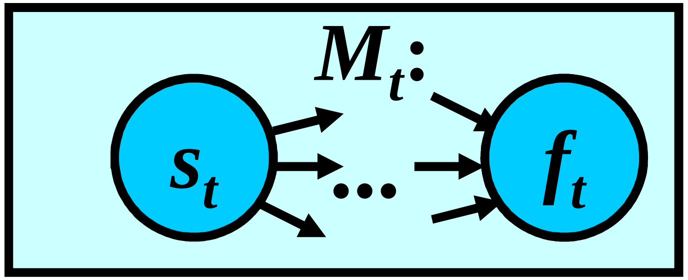

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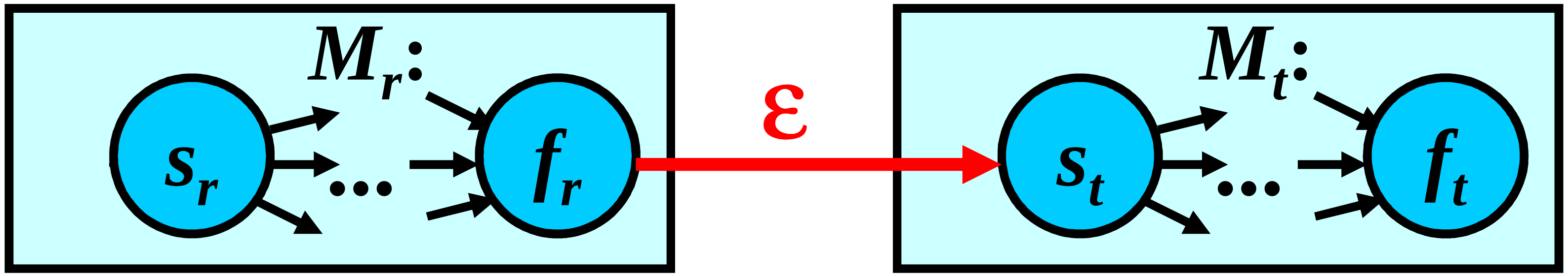

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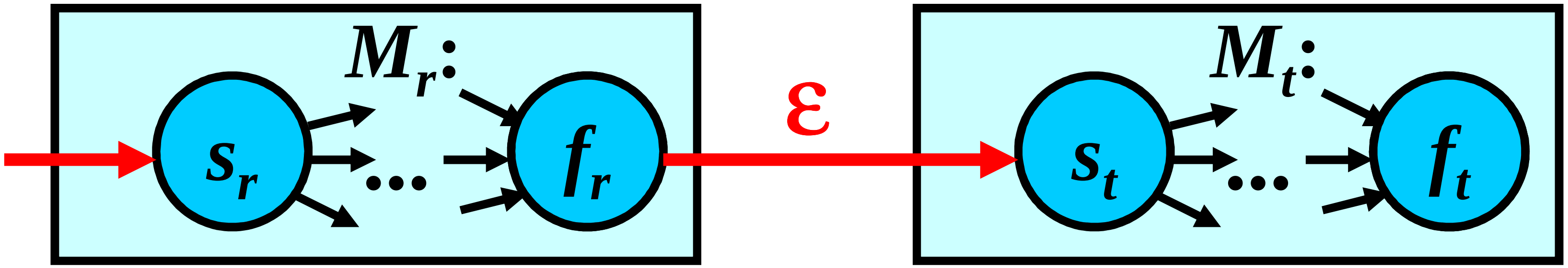

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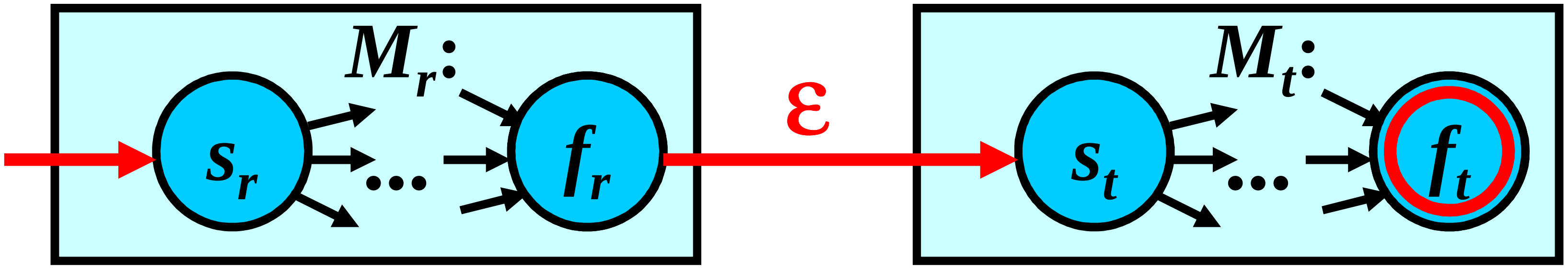

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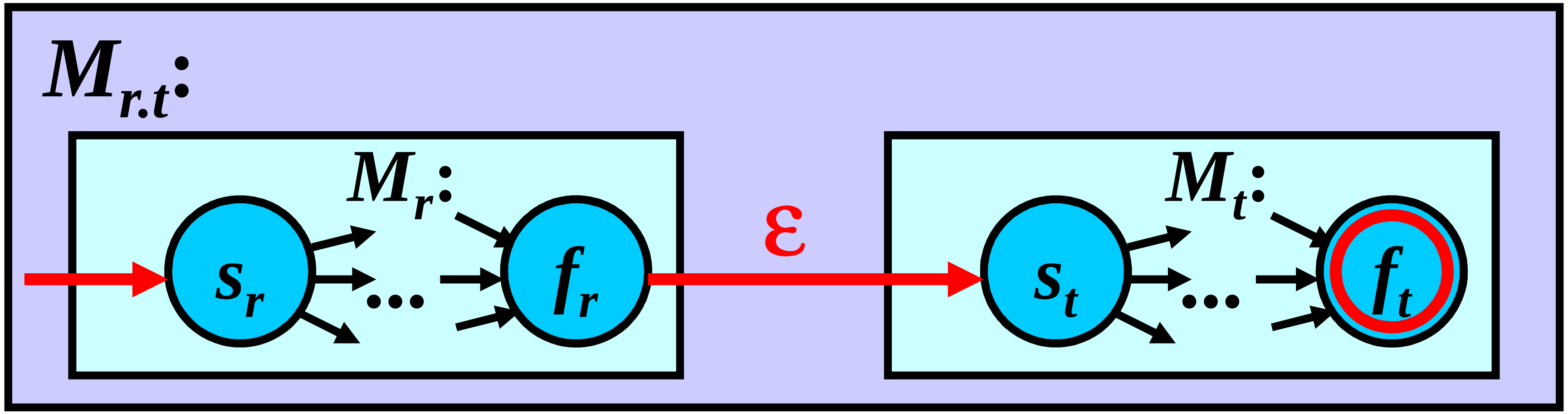

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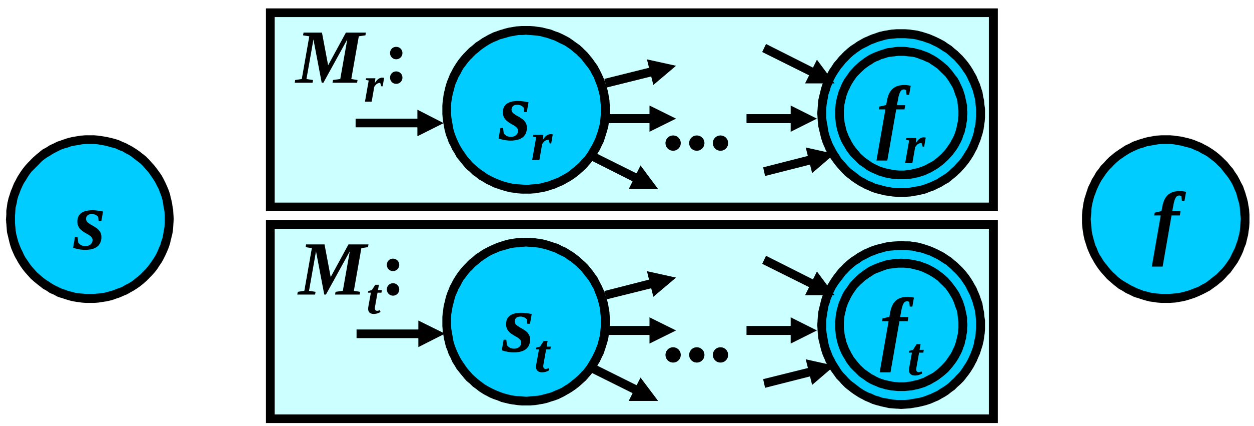

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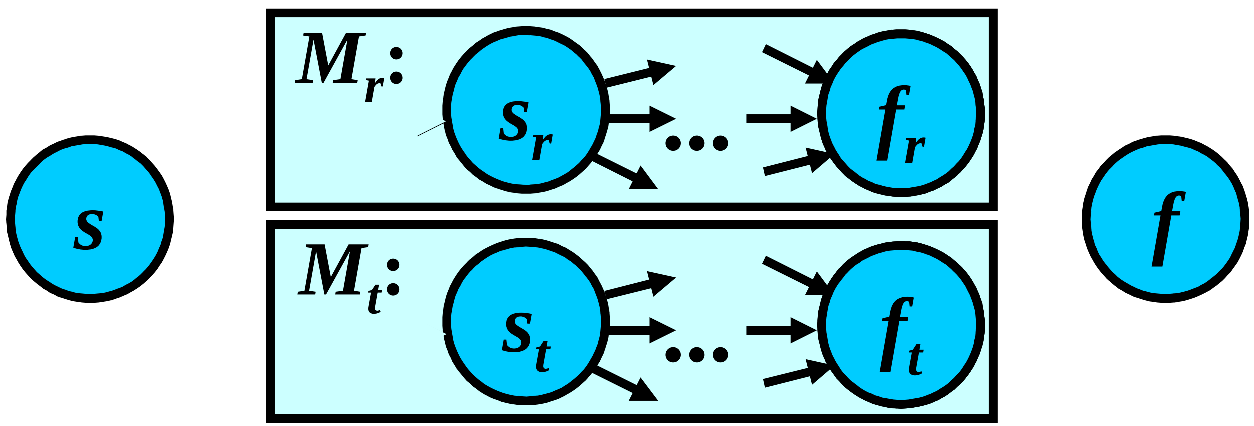

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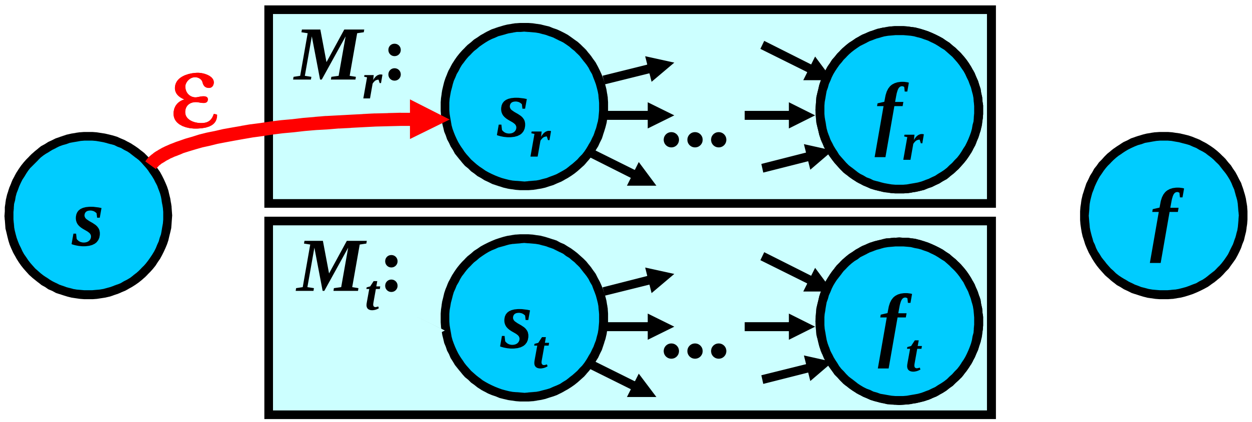

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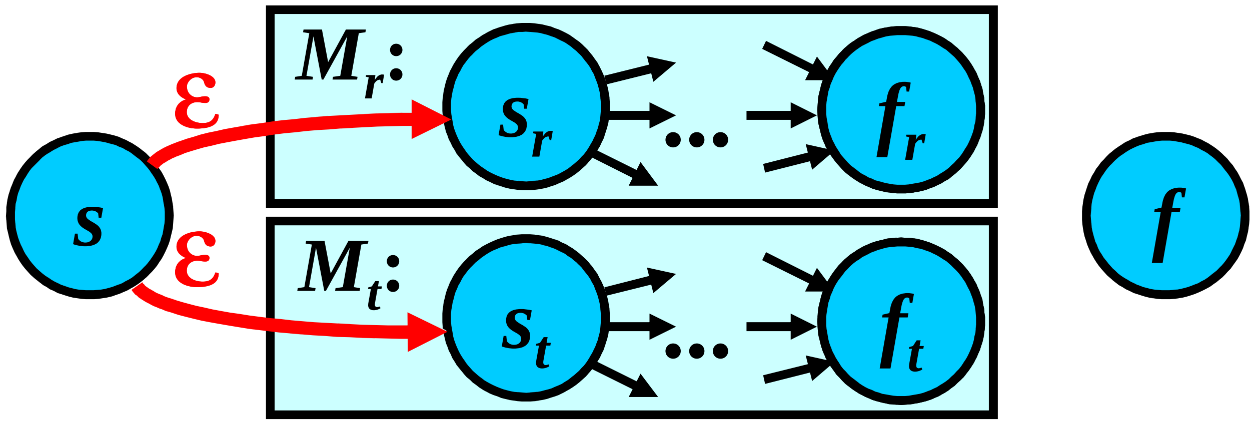

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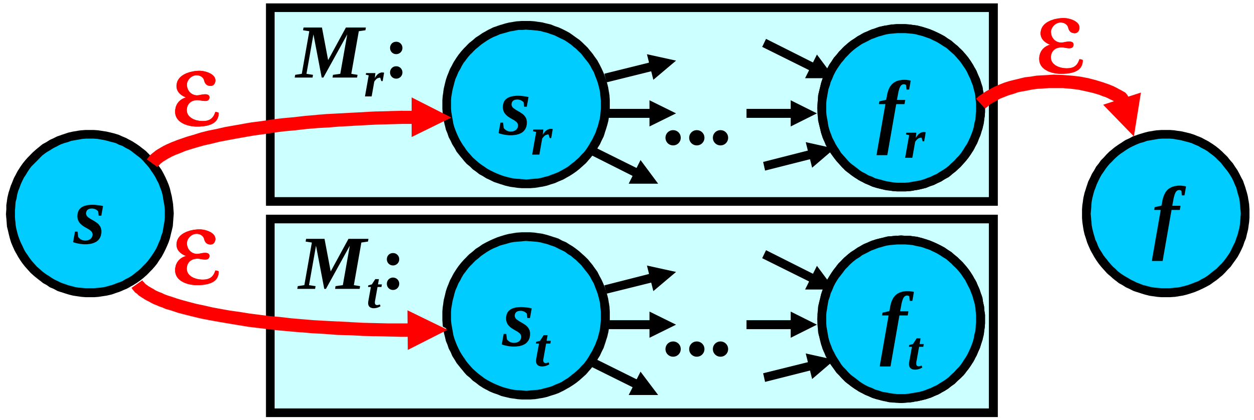


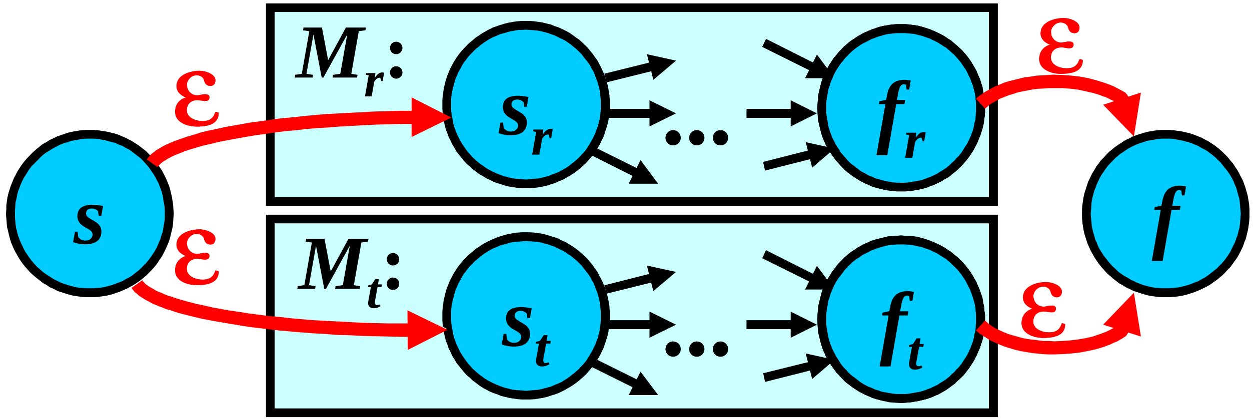
RE to FA: Union 3/5

- Let ***r*** be a RE over Σ and $\boldsymbol{M_r} = (Q_r, \Sigma, R_r, s_r, \{f_r\})$ be an FA such that $L(M_r) = L(r)$.
- Let ***t*** be RE over Σ and $\boldsymbol{M_t} = (Q_t, \Sigma, R_t, s_t, \{f_t\})$ be an FA such that $L(M_t) = L(t)$.
- For a RE ***r* + *t***, there exists an equivalent FA $\boldsymbol{M_{r+t}}$

Proof: Let $Q_r \cap Q_t = \emptyset$, $s, f \notin Q_r \cup Q_t$.

Construction

$M_{r+t} = (Q_r \cup Q_t \cup \{s, f\}, \Sigma, R_r \cup R_t \cup \{s \rightarrow s_r, s \rightarrow s_t, f_r \rightarrow f, f_t \rightarrow f\},$



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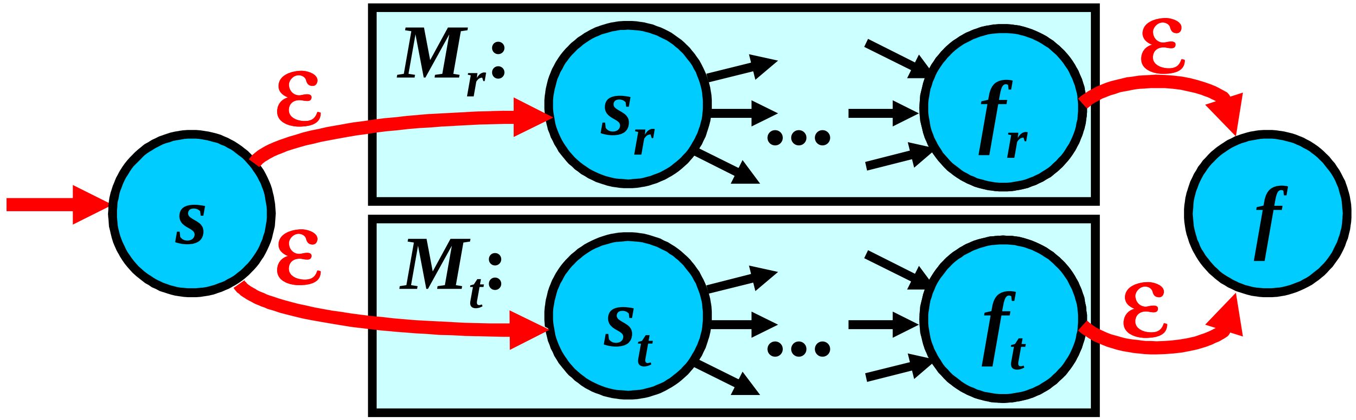

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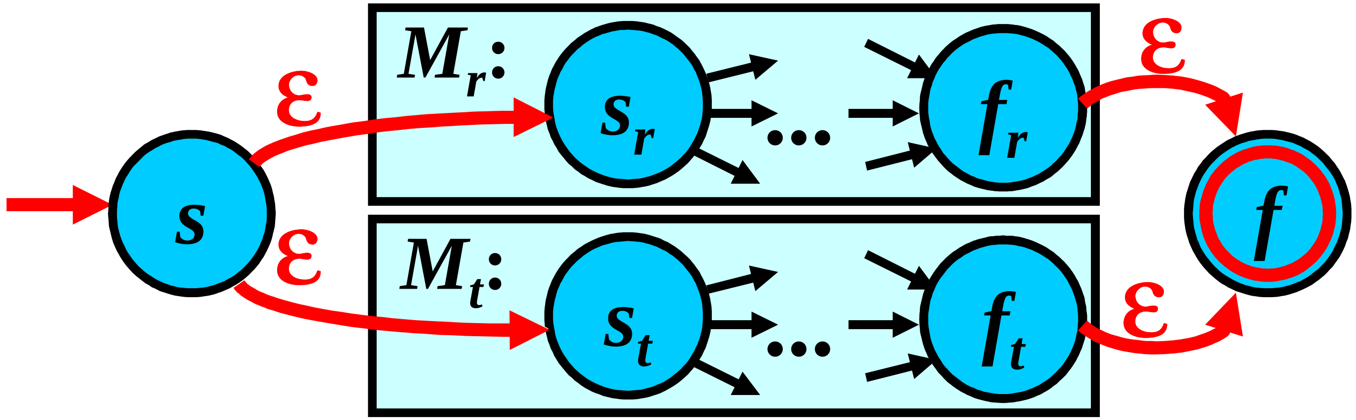

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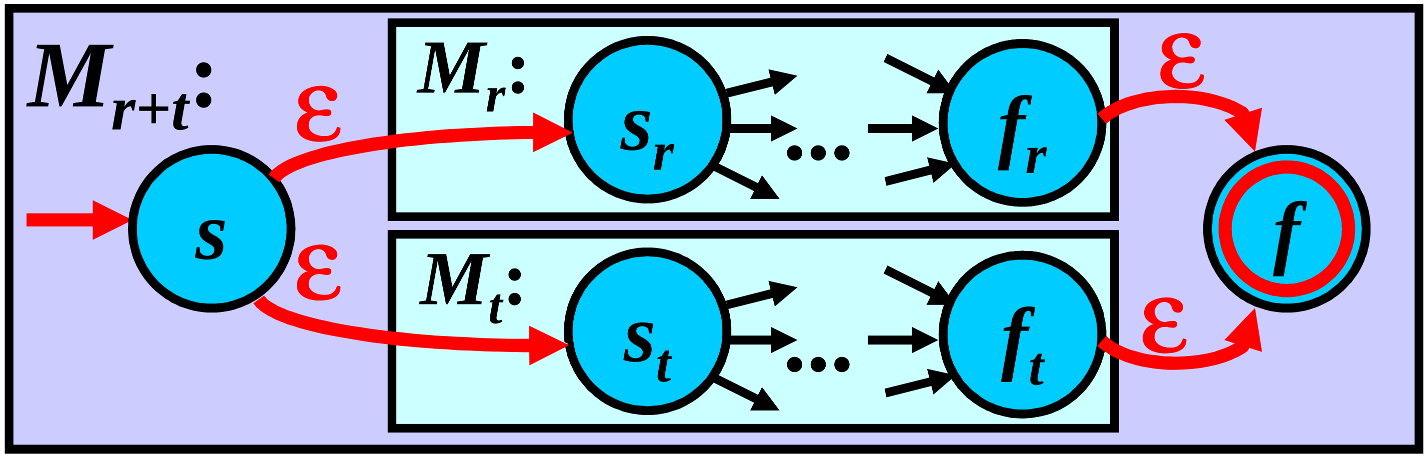

RE to FA: Iteration 4/5

- Let r be a RE over Σ and $M_r = (Q_r, \Sigma, R_r, s_r, \{f_r\})$ be an FA such that $L(M_r) = L(r)$.
- For the RE r^*, there exists an equivalent FA M_{r*}

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Construction:

RE to FA: Iteration 4/5

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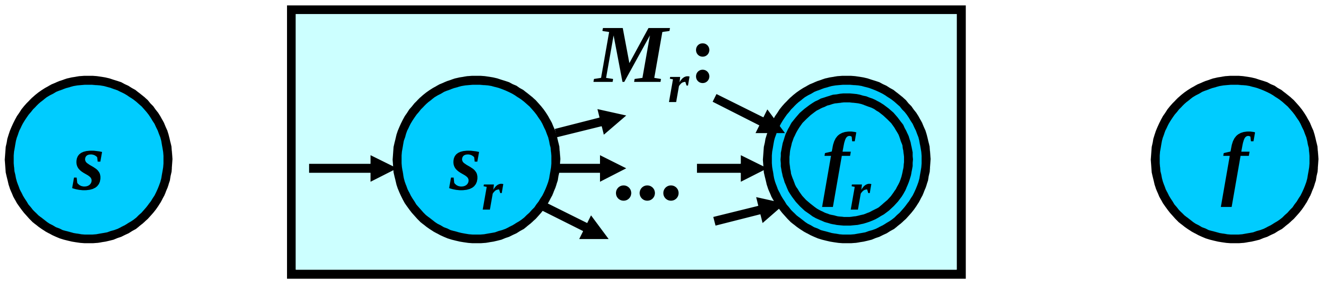

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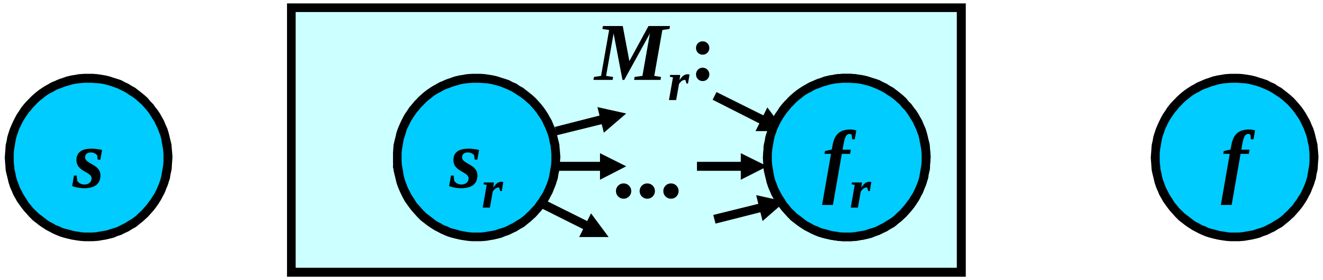

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Proof: Let $s, f \notin Q_r$.

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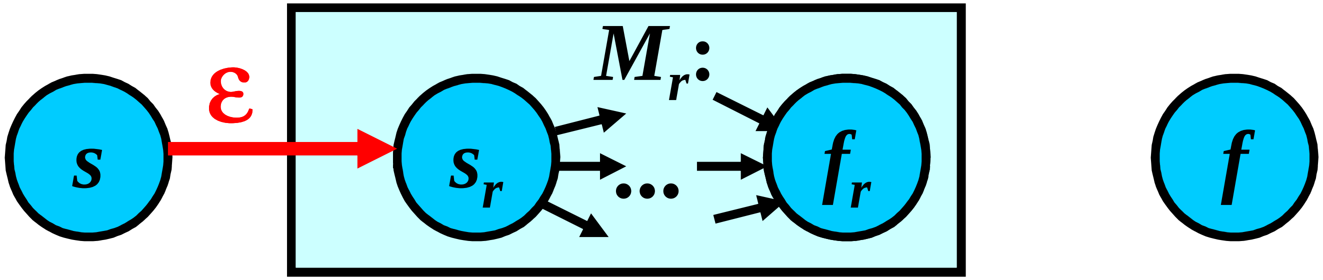

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Proof: Let $s, f \notin Q_r$.

Construction:

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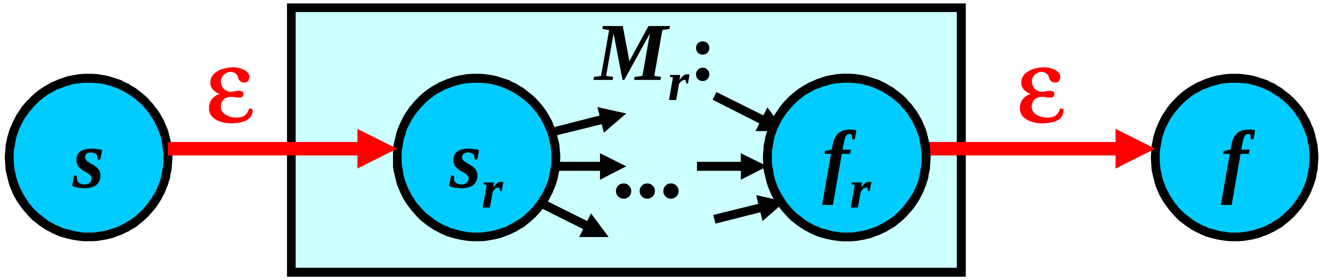

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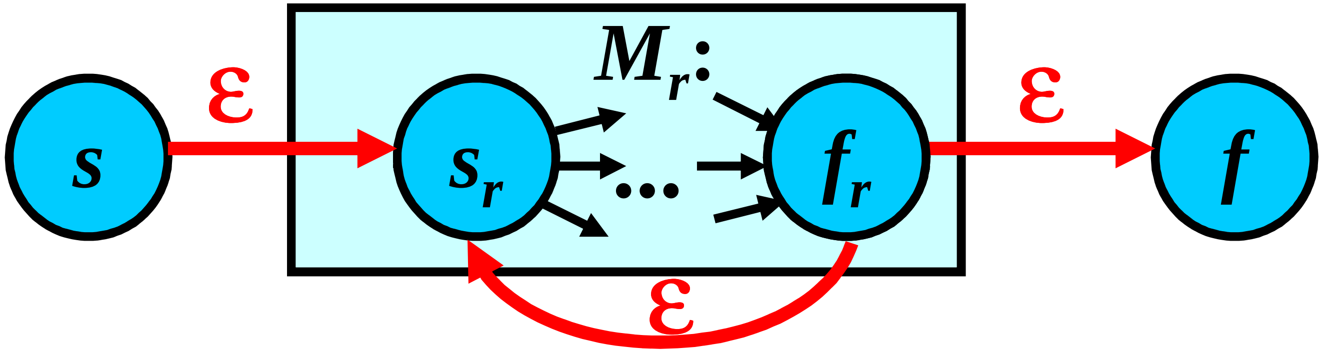

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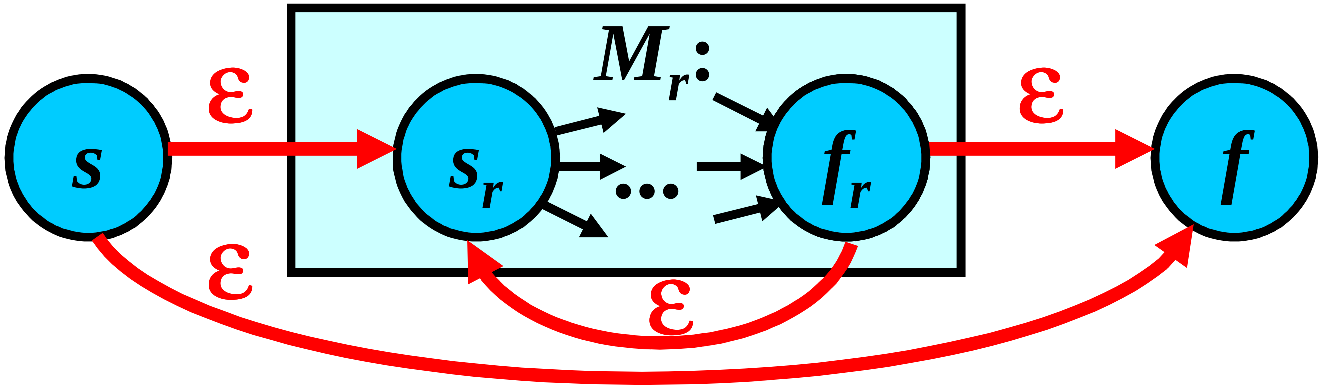

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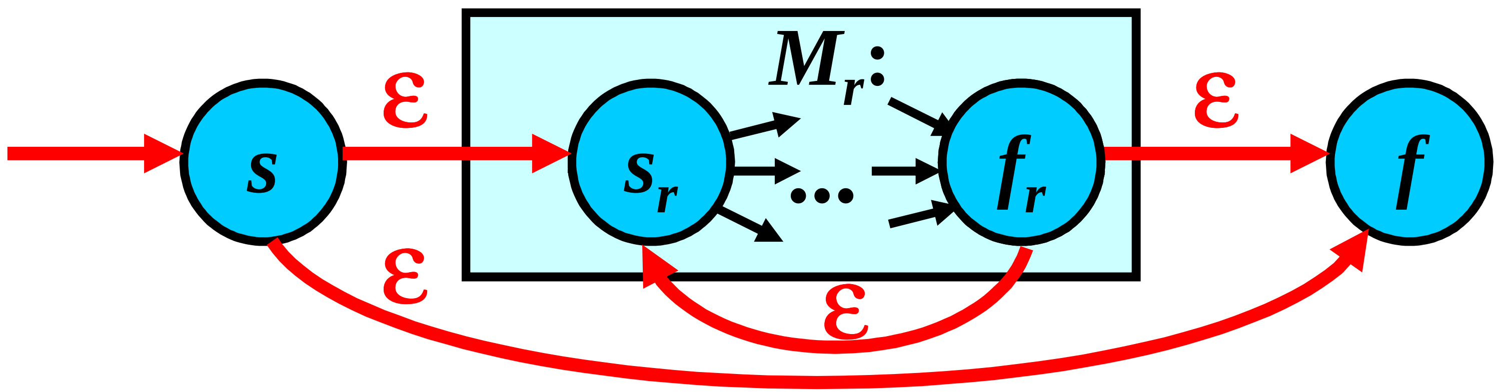

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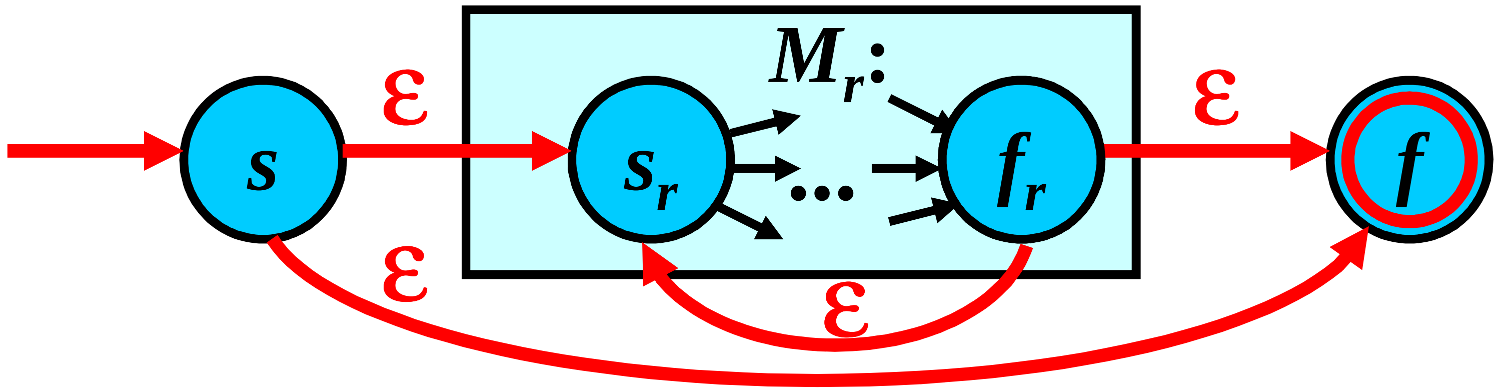

RE to FA: Iteration 4/5

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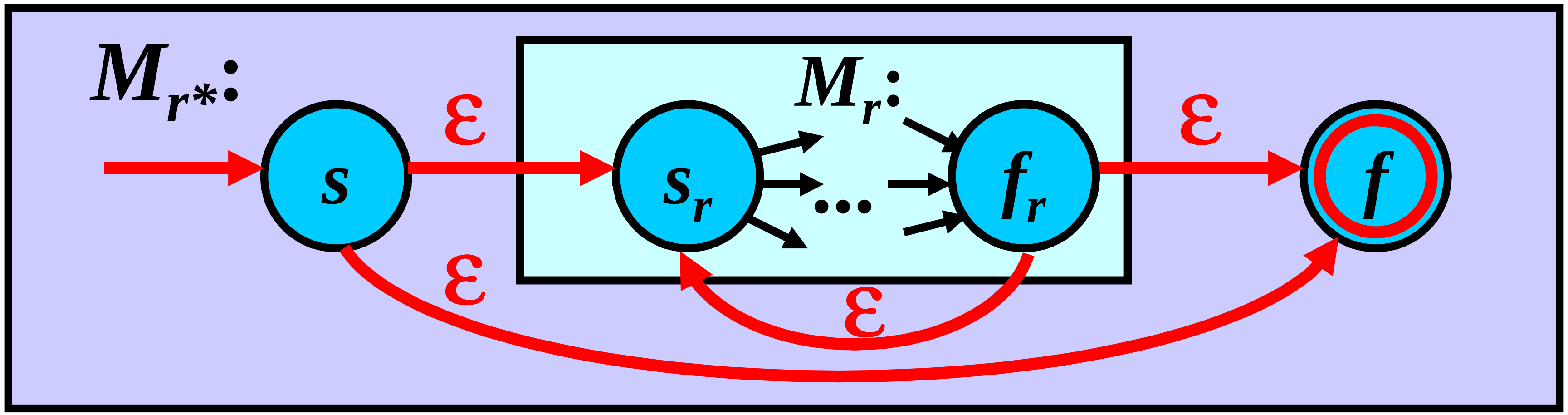


RE to FA: Completion 5/5

- **Input:** RE r over Σ
- **Output:** FA M such that $L(r) = L(M)$

- **Method:**
- **From "inside" of r, repeatedly use the next rules to construct M:**
  - for RE $\emptyset$, construct FA $M_{\emptyset}$
  - for RE ε, construct FA M_{ε}
  - for RE $a \in \Sigma$, construct FA M_a

  → (see 1/5)

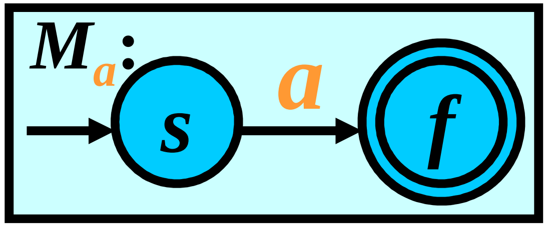
  - **let** for REs r and t, there already exist FAs M_r and M_t, respectively; **then**,
    - for RE $r.t$, construct FA $M_{r.t}$ (see 2/5)
    - for RE $r + t$, construct FA M_{r+t} (see 3/5)
    - for RE r^* construct FA M_{r^*} (see 4/5)

RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M

RE to FA: Example 1/3

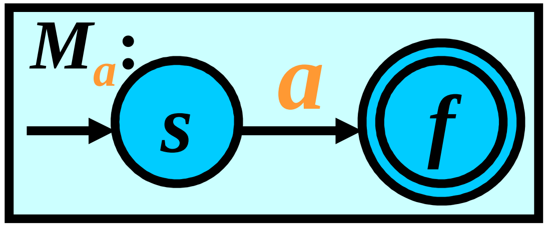
Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M

For RE a: 

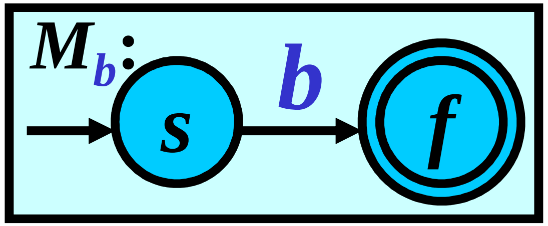
RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M

For RE ***a***:

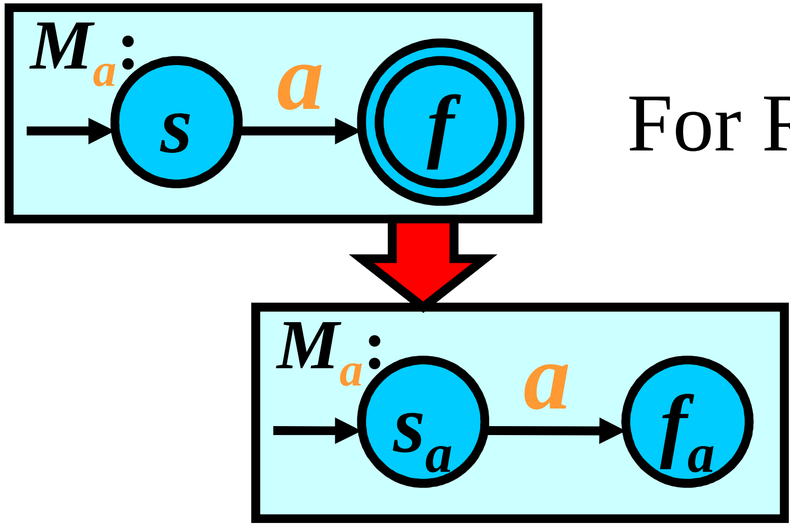


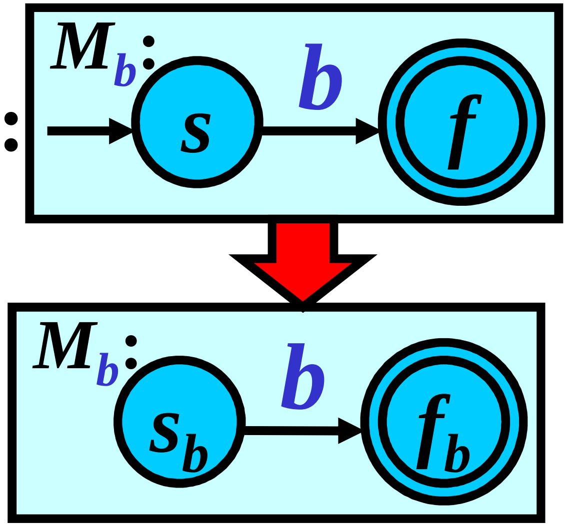
For RE ***b***:



RE to FA: Example 1/3

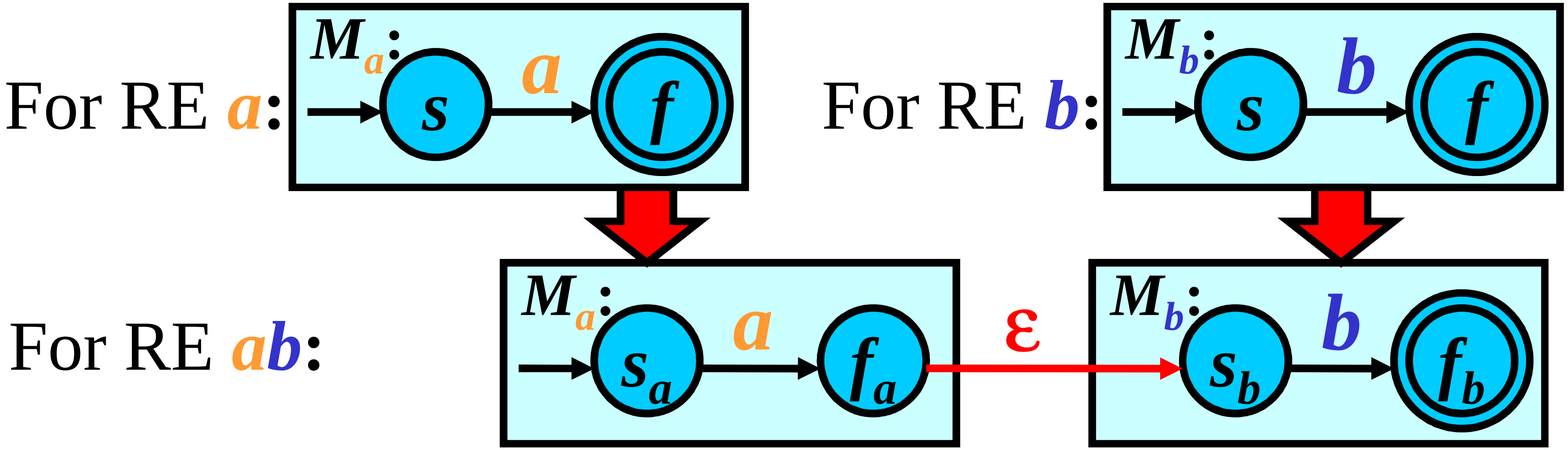
Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M

For RE *a*: 

For RE *b*: 

RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M



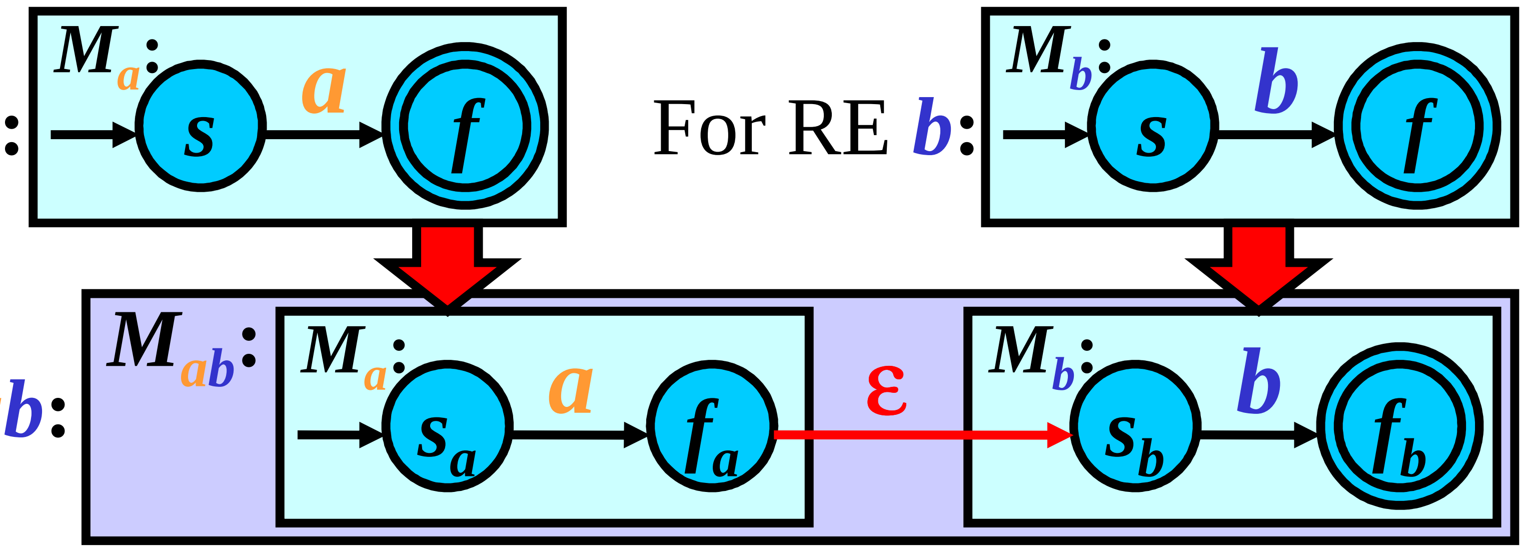
RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M

For RE *a*:

For RE *b*:

For RE *ab*:



RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M

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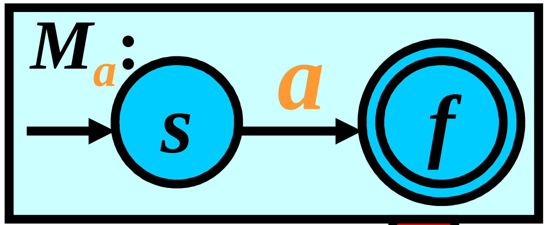
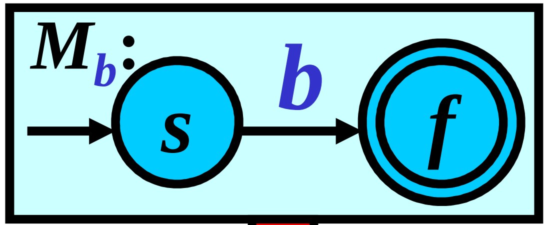
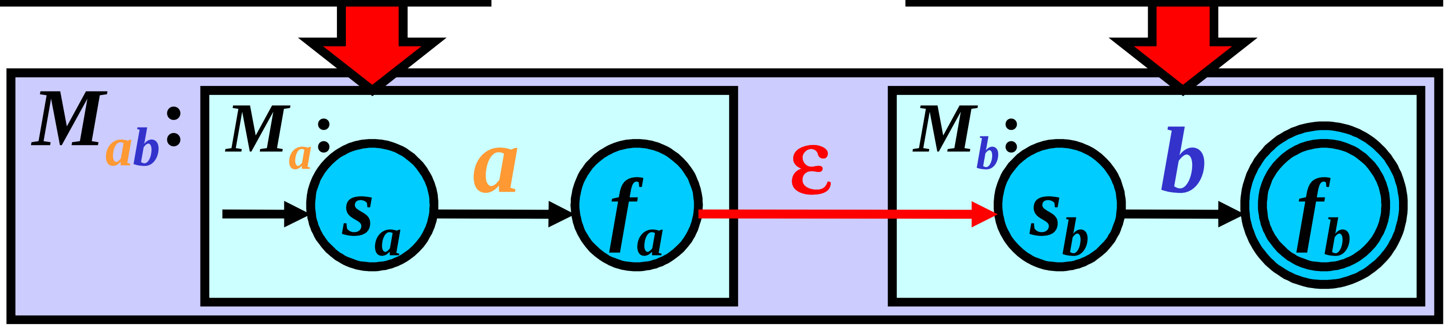


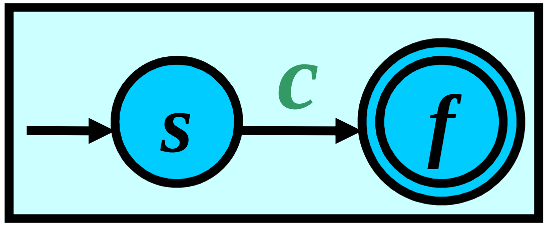
For RE *b*:



For RE *ab*:

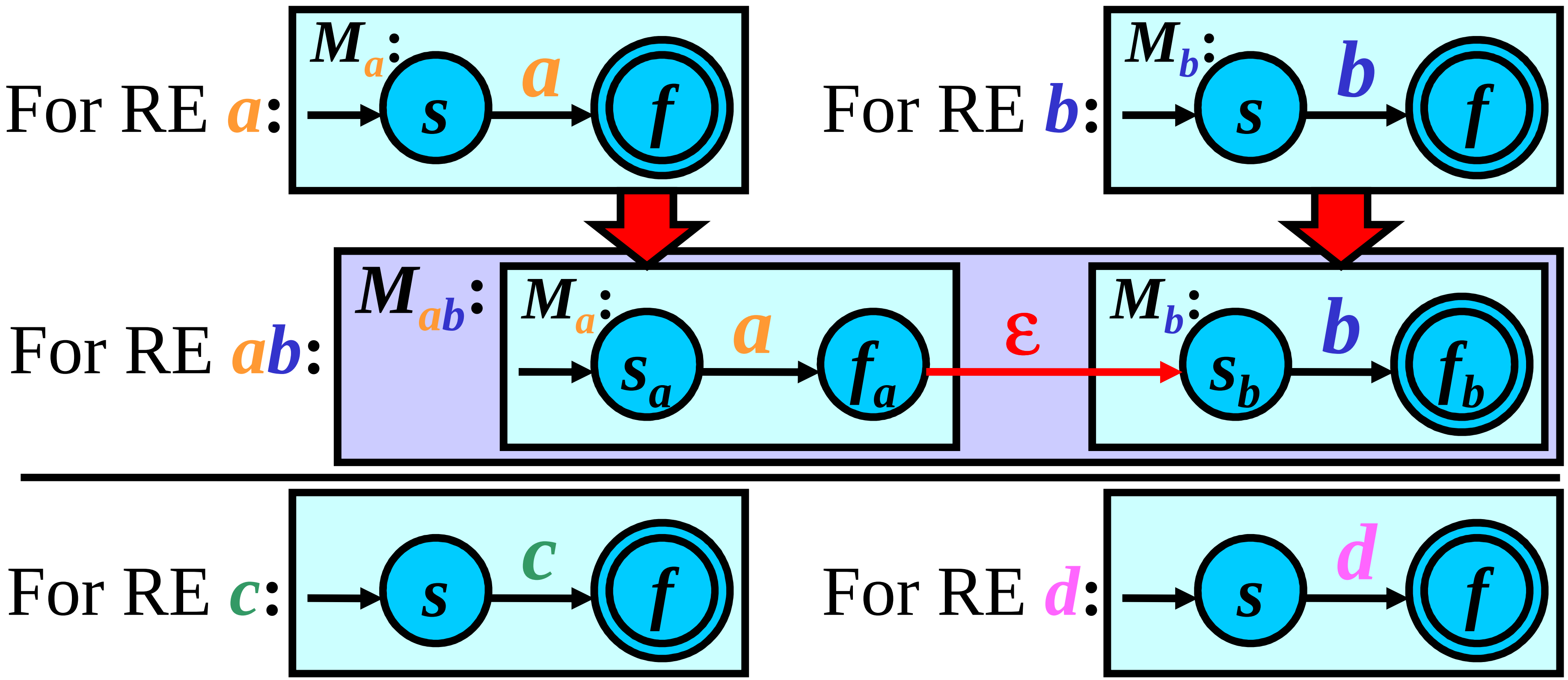


For RE *c*:



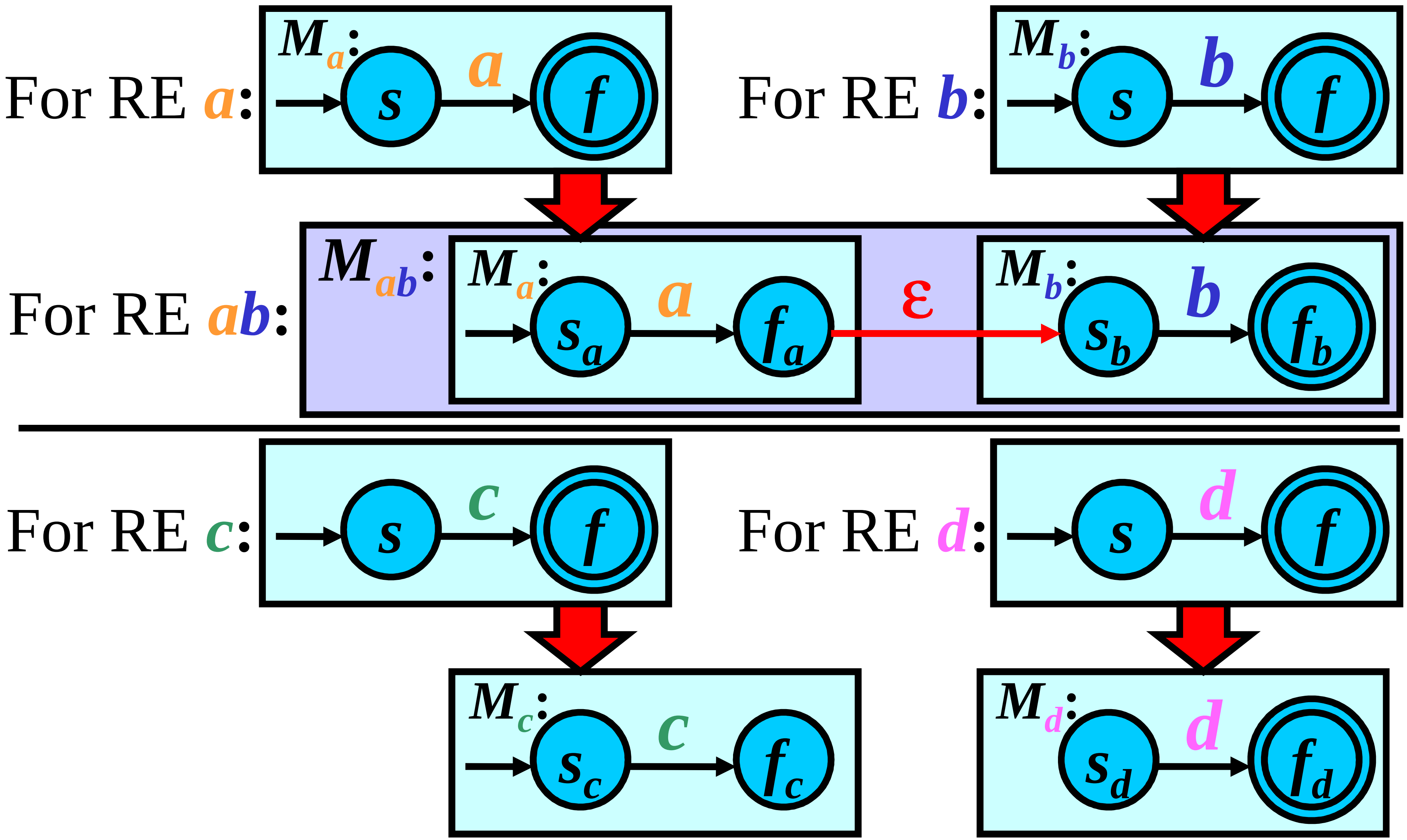
RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M



RE to FA: Example 1/3

Transform RE $r = ((ab) + (cd))^*$ to an equivalent FA M



RE to FA: Example 1/3

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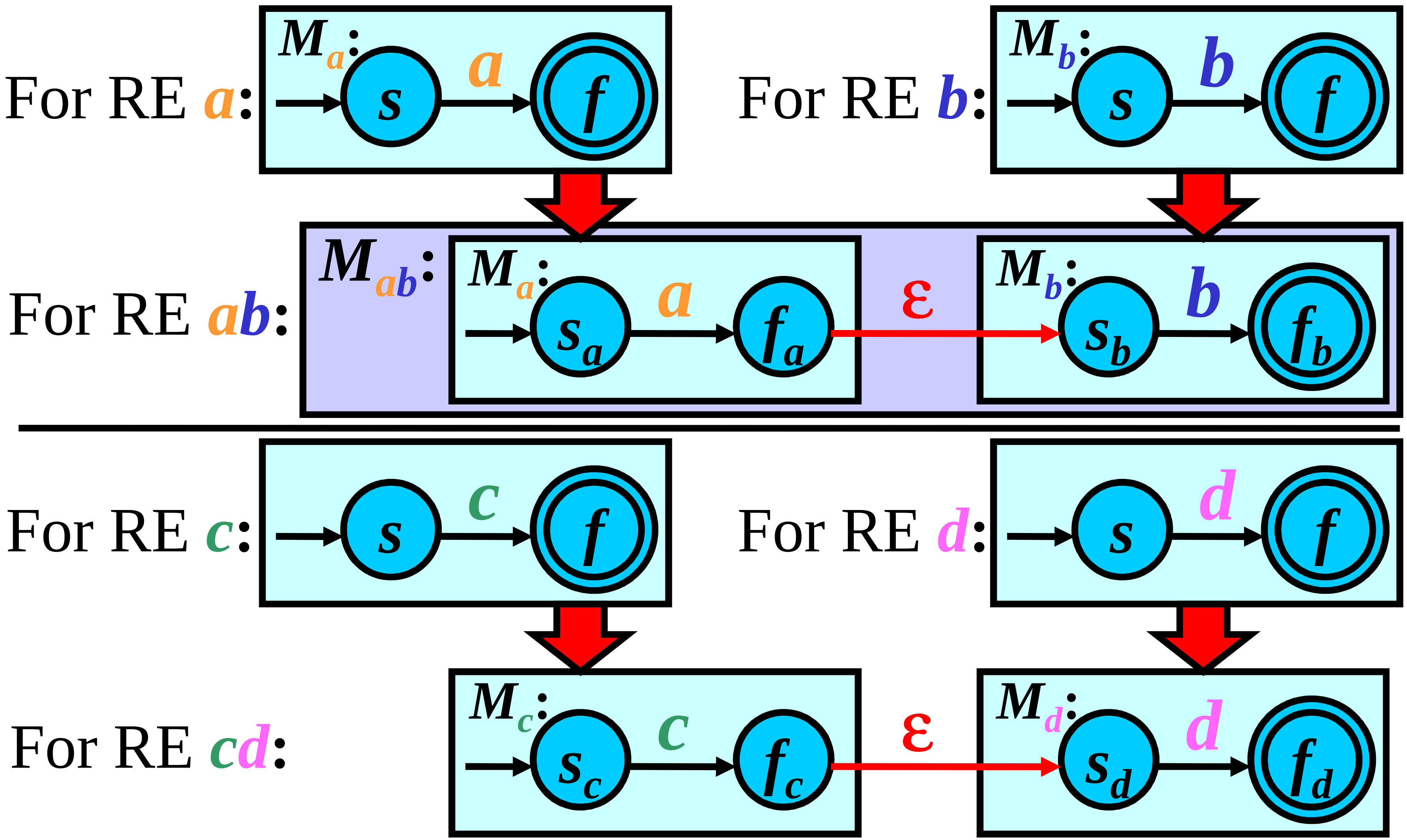

RE to FA: Example 1/3

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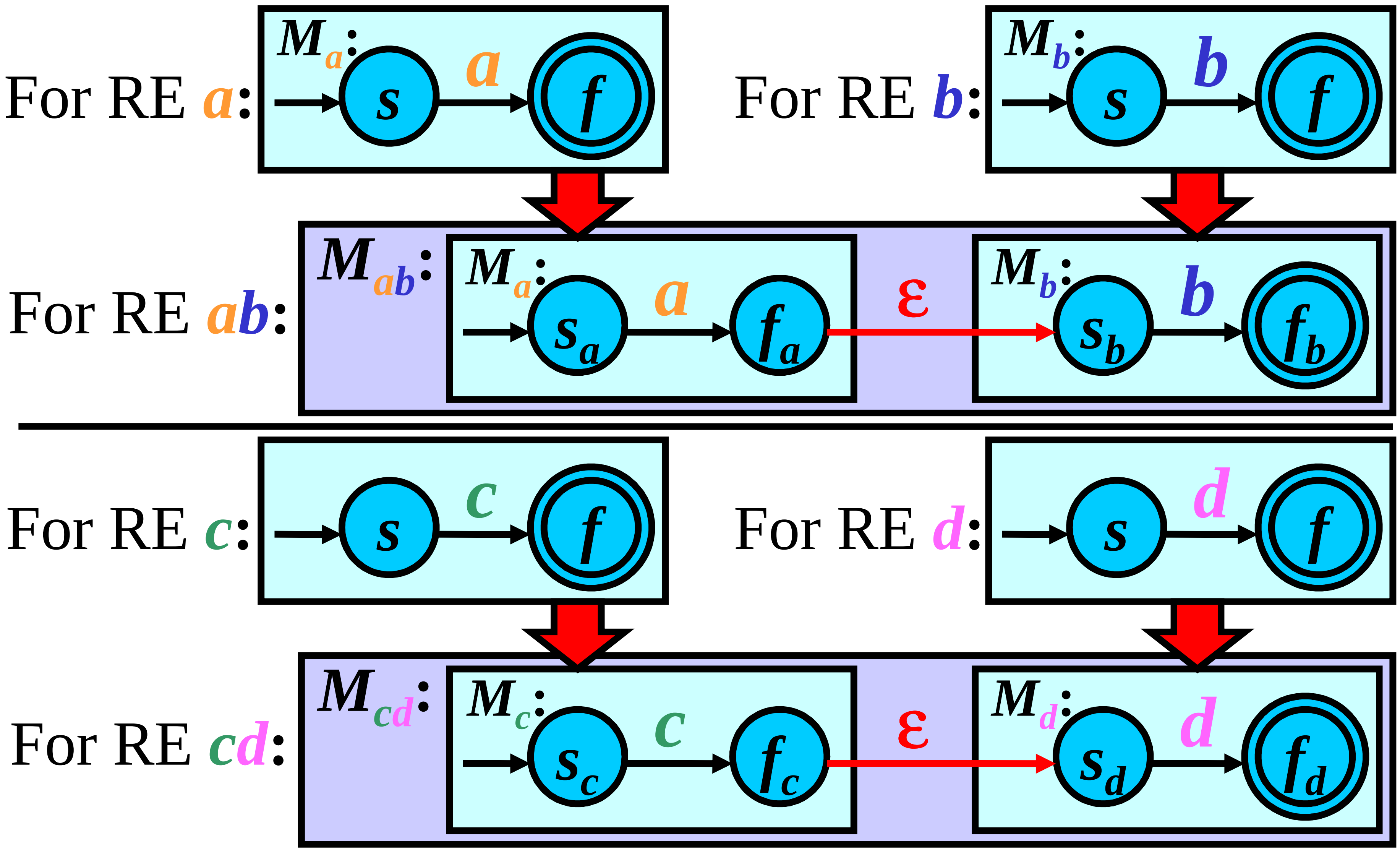
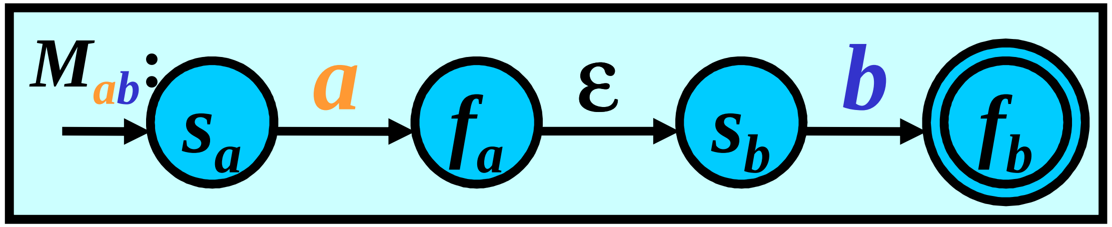


RE to FA: Example 2/3

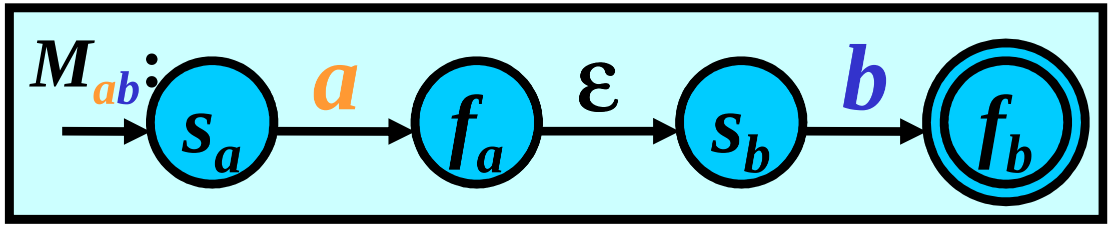
RE to FA: Example 2/3

For RE ***ab***:

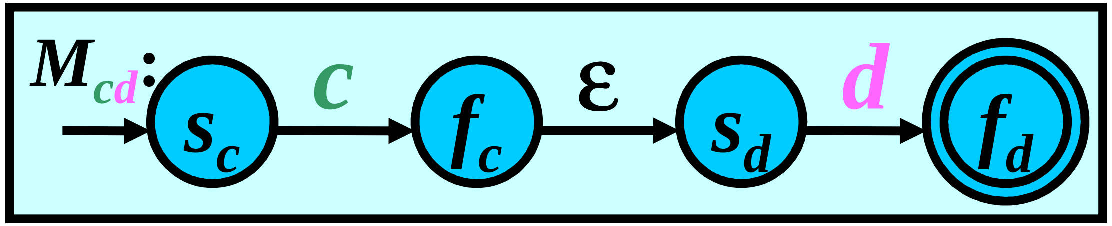


RE to FA: Example 2/3

For RE ***ab***:



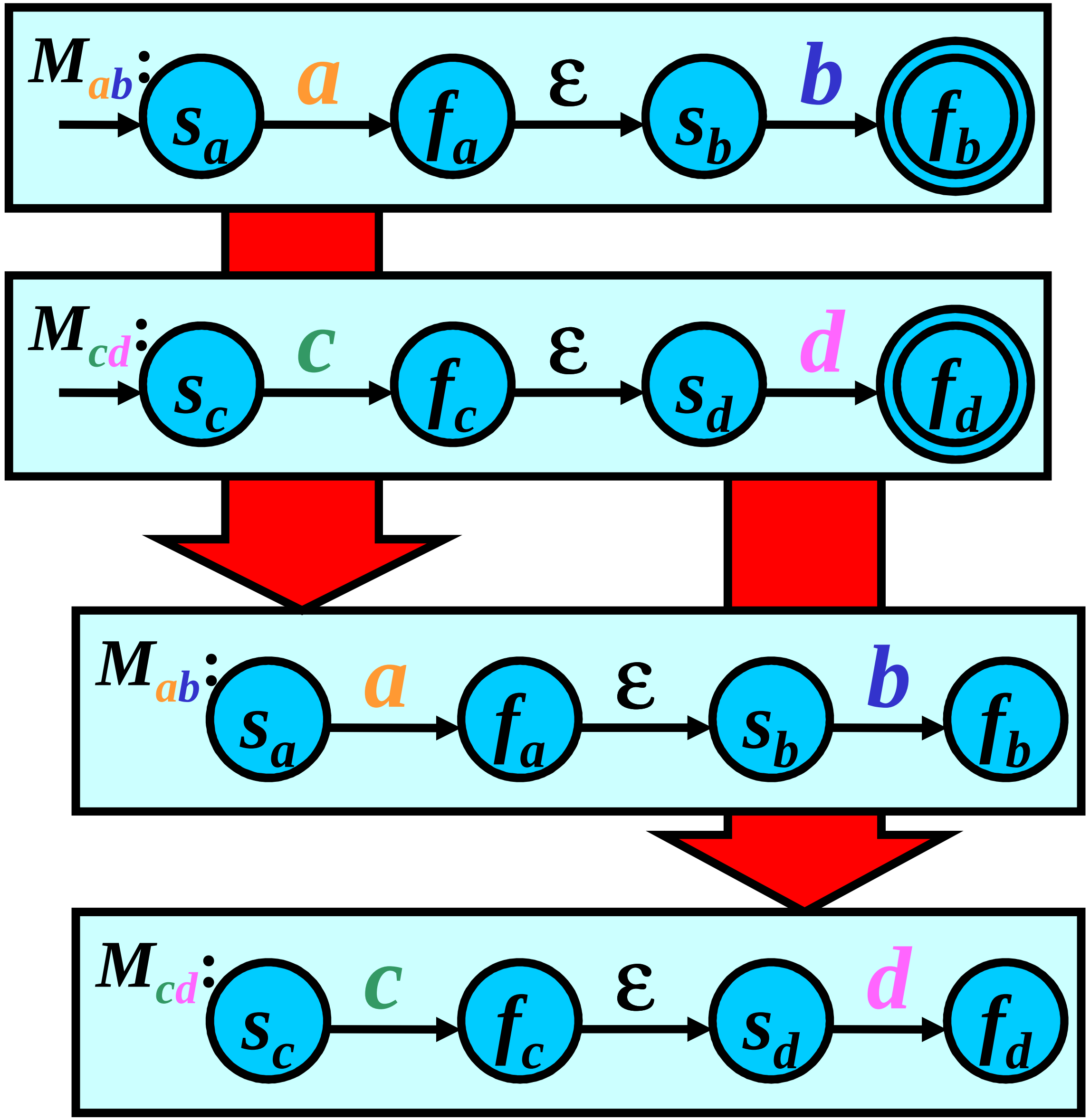
For RE ***cd***:



RE to FA: Example 2/3

For RE ***ab***:

For RE ***cd***:

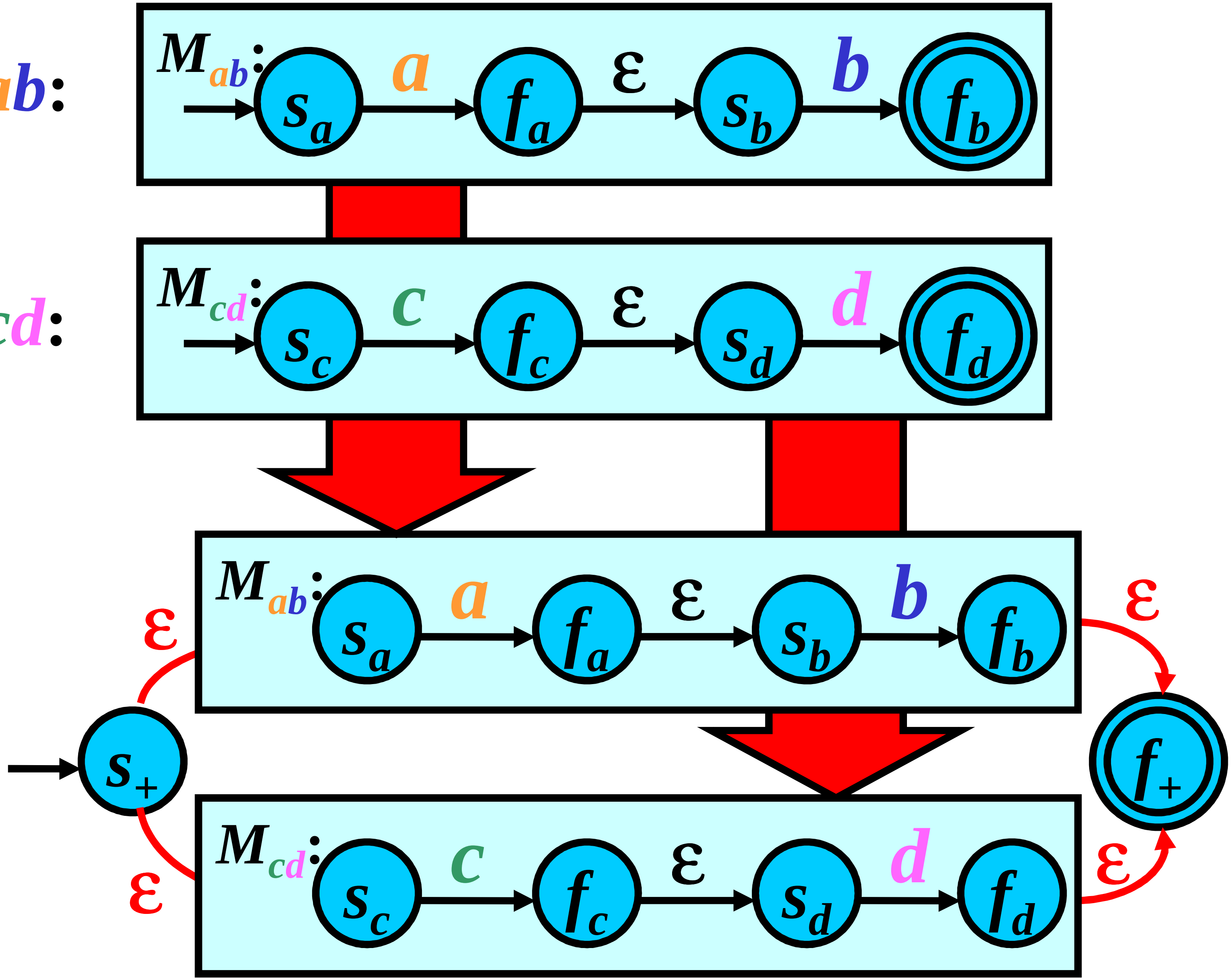


RE to FA: Example 2/3

For RE ***ab***:

For RE ***cd***:

For RE ***ab*** + ***cd***:

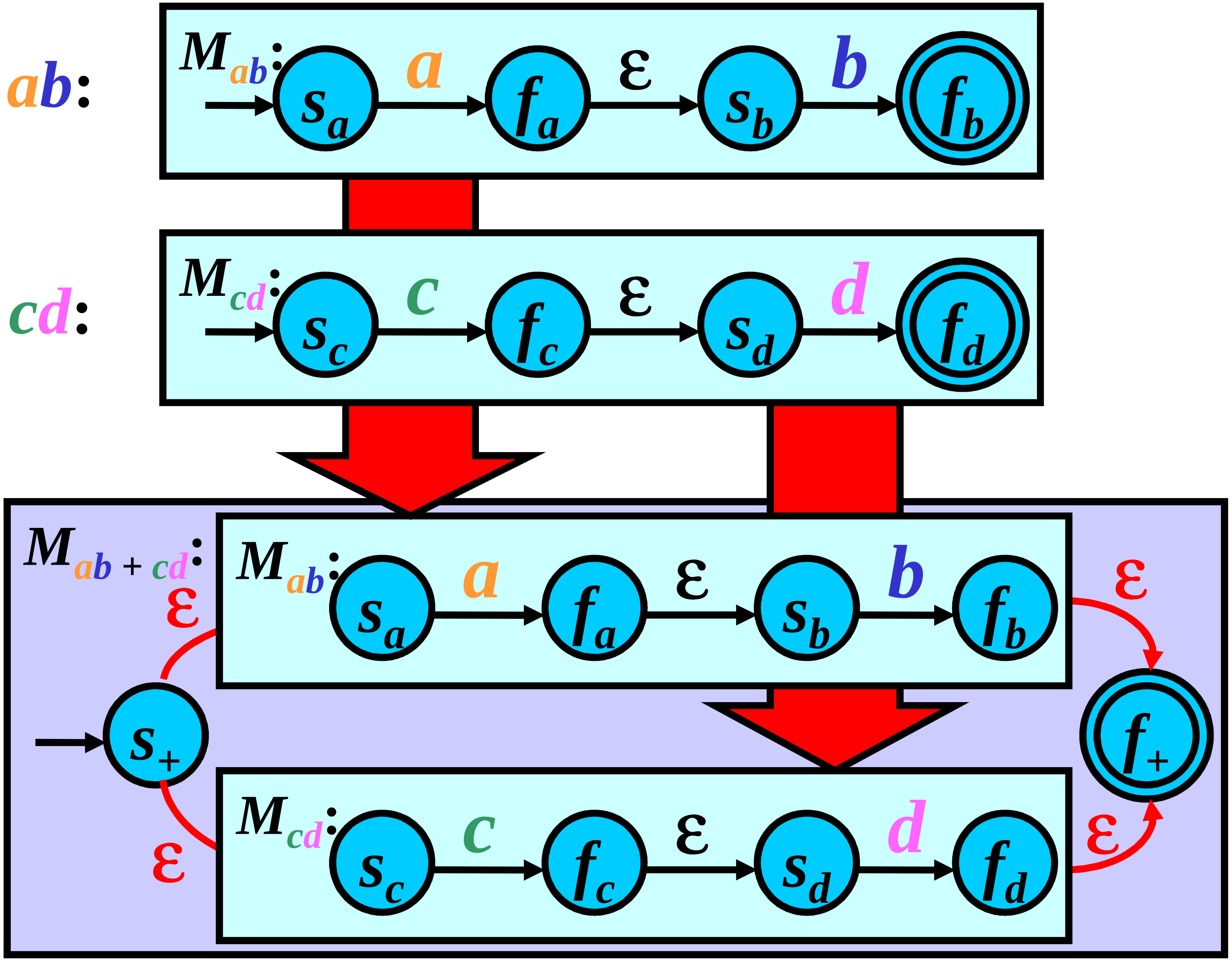


RE to FA: Example 2/3

For RE *ab*:

For RE *cd*:

For RE *ab* + *cd*:

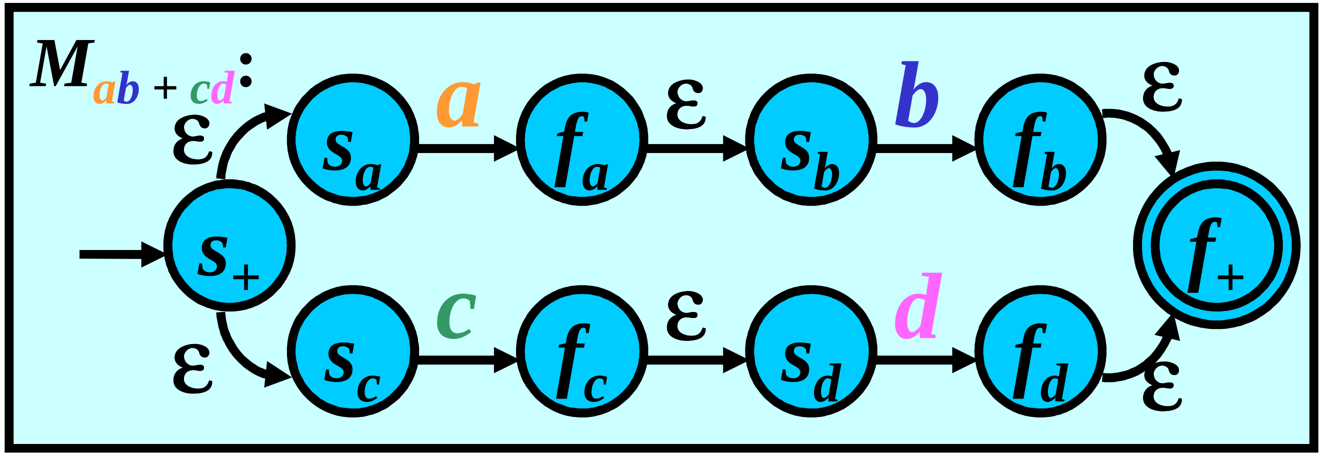


RE to FA: Example 3/3

RE to FA: Example 3/3

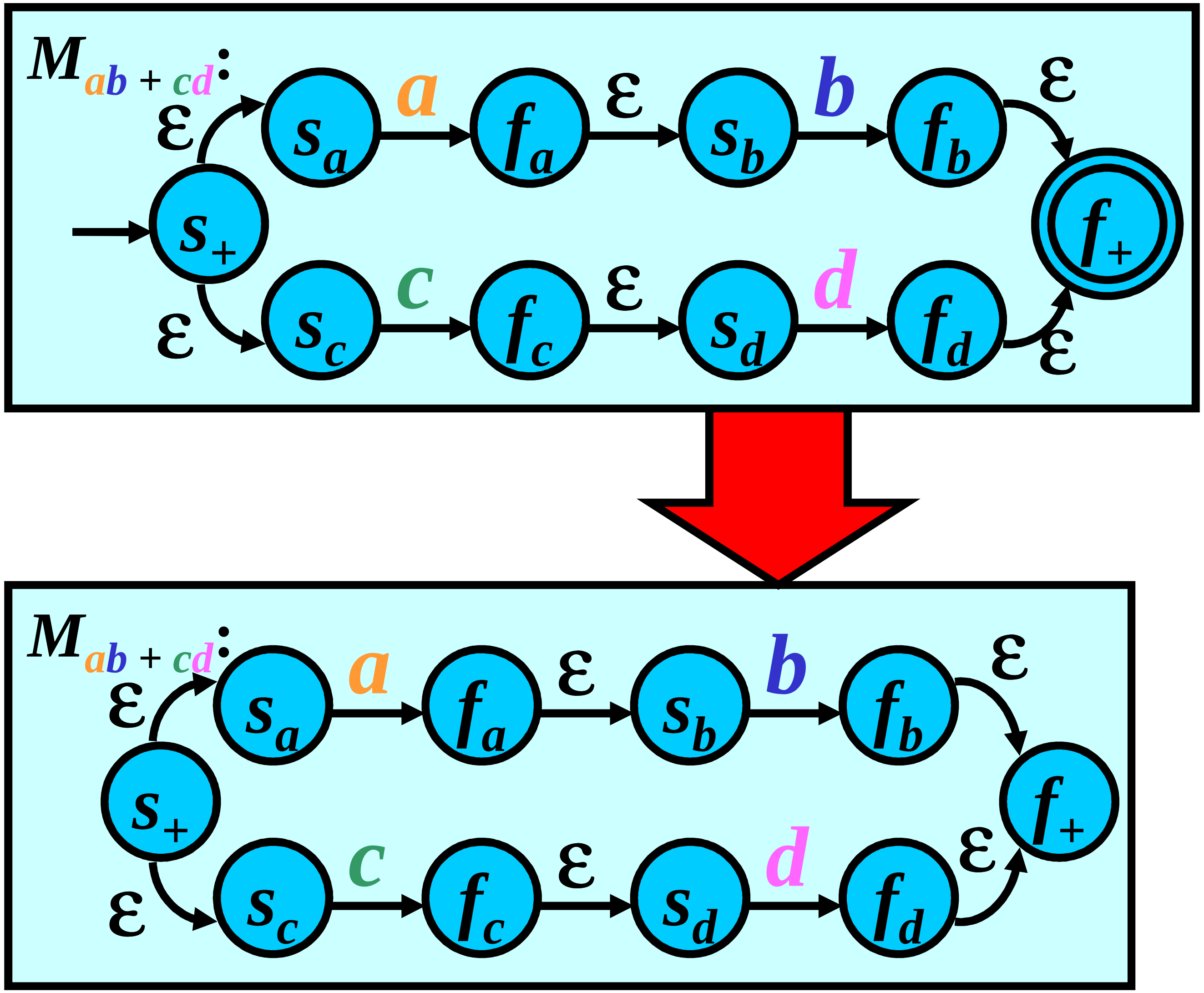
For RE

ab + *cd*:



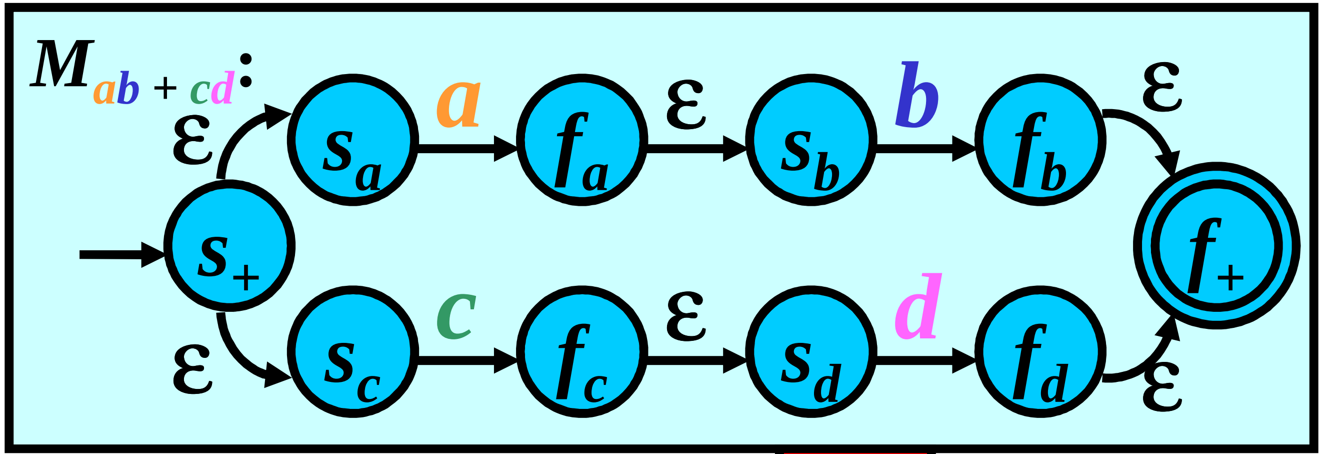
RE to FA: Example 3/3

For RE
$ab + cd$:

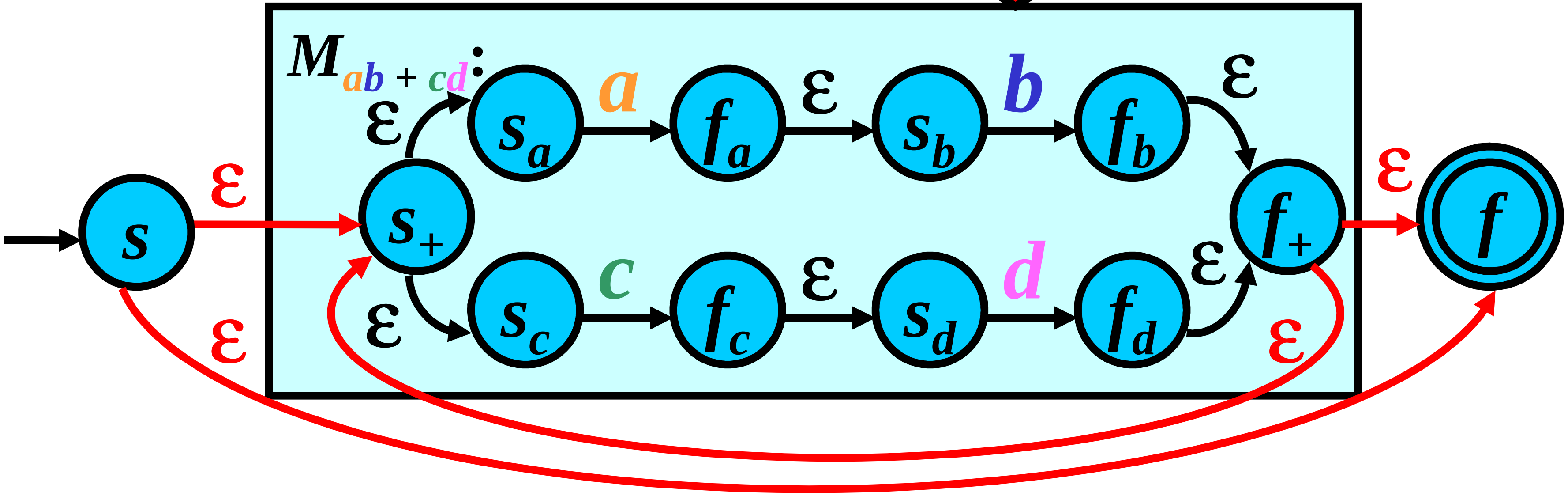


RE to FA: Example 3/3

For RE ***ab*** **+** ***cd*:**

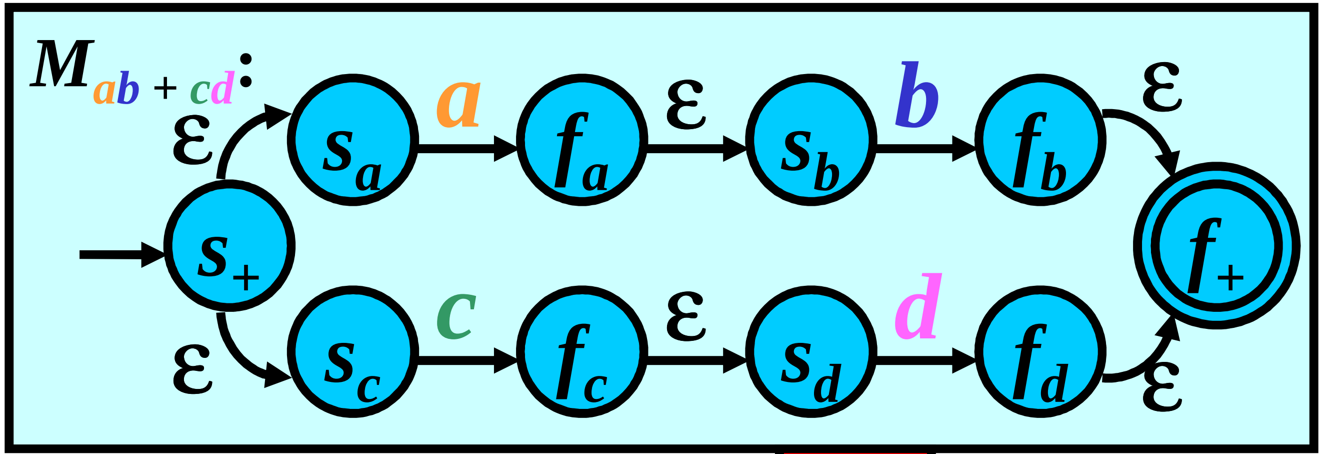


For a final RE **(*ab* + *cd*)*:**

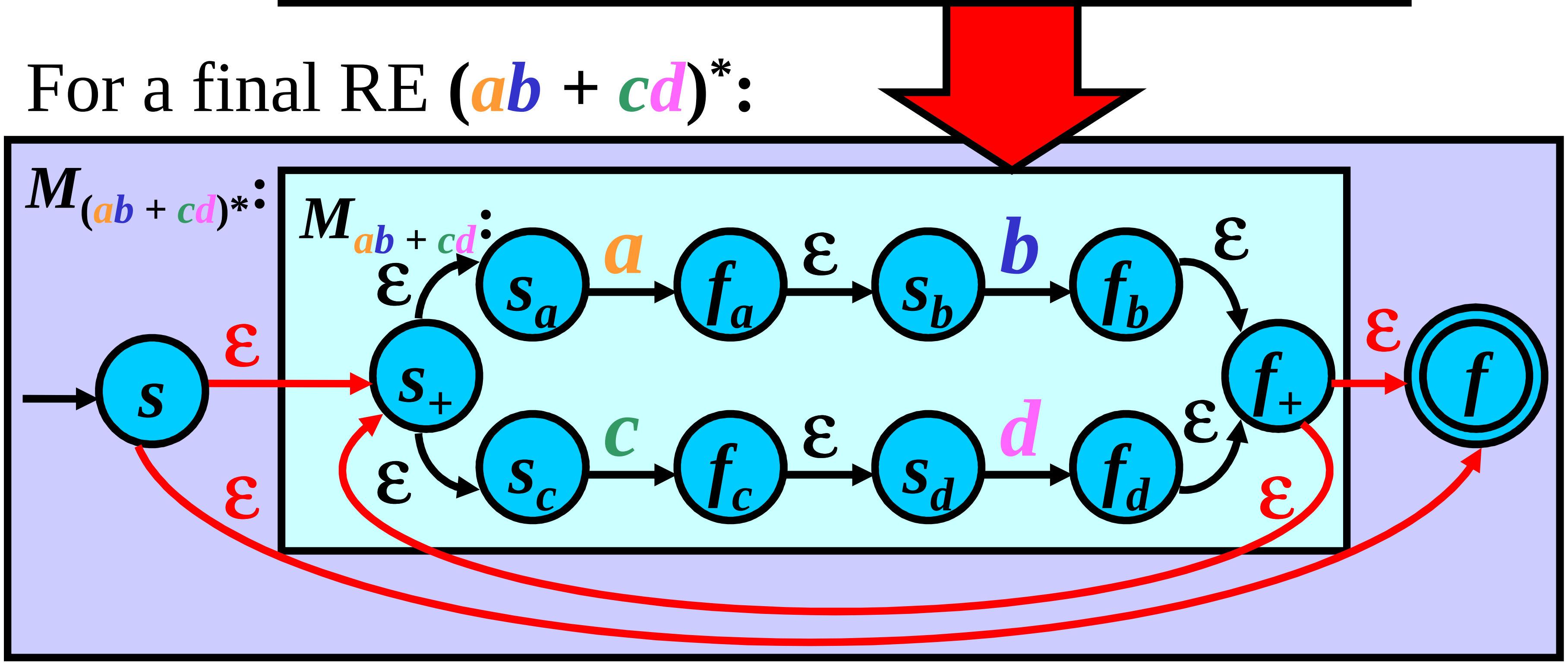


RE to FA: Example 3/3

For RE ***ab*** **+** ***cd*:**



For a final RE **(*ab* + *cd*)*:**



Models for Regular Languages

Theorem: For every RE r, there is an FA M such that $L(r) = L(M)$.

Proof is based on the previous algorithm.

Theorem: For every FA M, there is an RE r such that $L(M) = L(r)$.

Proof: See page 210 in [Meduna: Automata and Languages]

Conclusion: The fundamental models for regular languages are

1) Regular expressions **2) Finite Automata**