

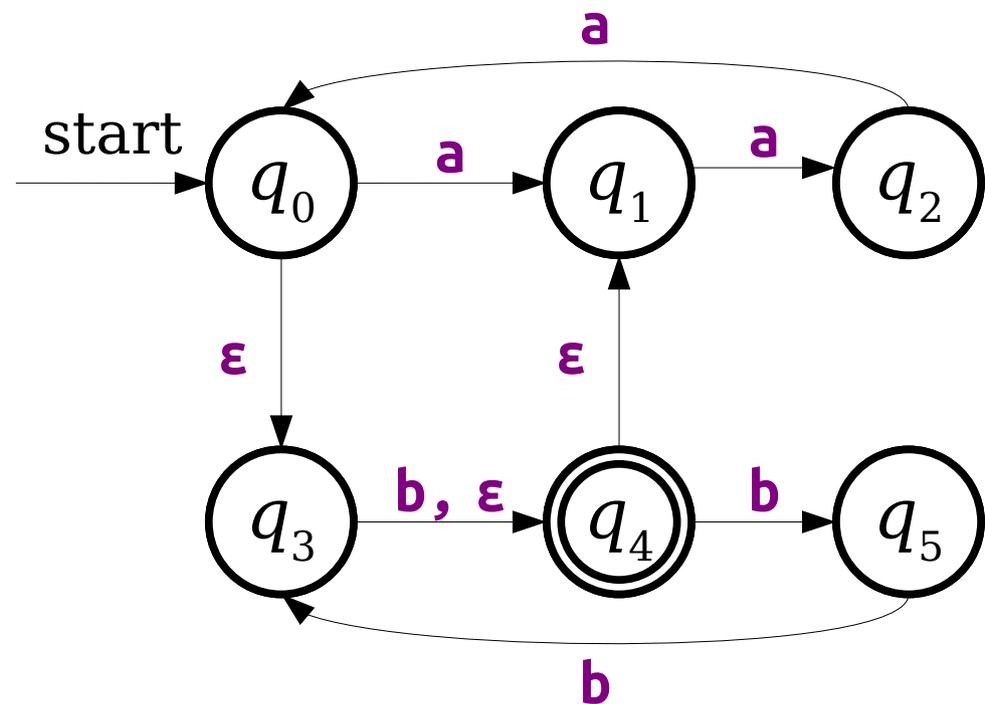
Finite Automata

Part Three

Recap from Last Time

NFAs

- An **NFA** is a
 - **N**ondeterministic
 - **F**inite
 - **A**utomaton
- NFAs have no restrictions on how many transitions are allowed per state.
- They can also use ϵ -transitions.
- An NFA accepts a string w if there is some sequence of choices that leads to an accepting state.



Massive Parallelism

- An NFA can be thought of as a DFA that can be in many states at once.
- At each point in time, when the NFA needs to follow a transition, it tries all the options at the same time.
- The NFA accepts if *any* of the states that are active at the end are accepting states. It rejects otherwise.

New Stuff!

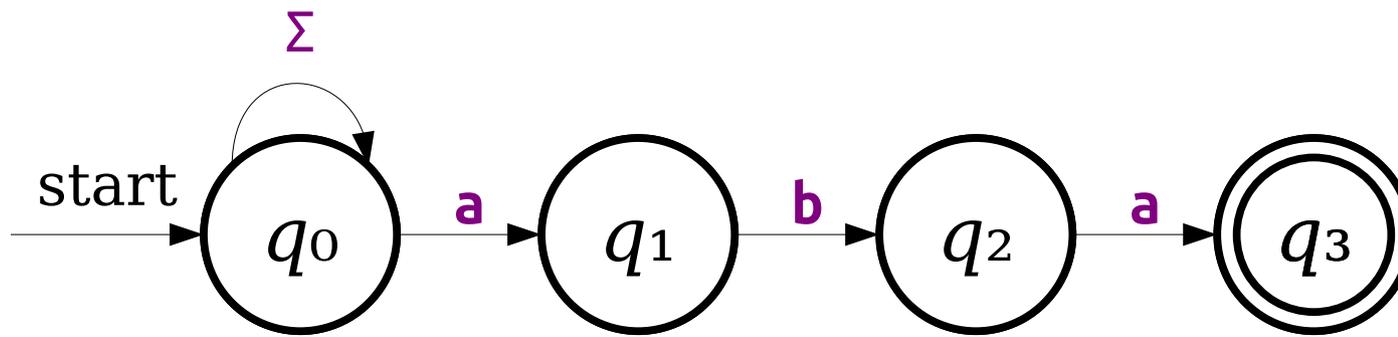
Just how powerful *are* NFAs?

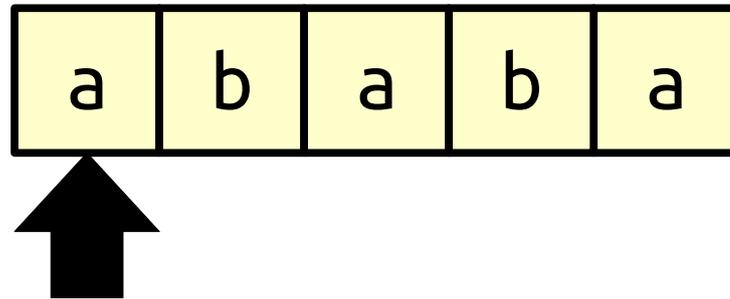
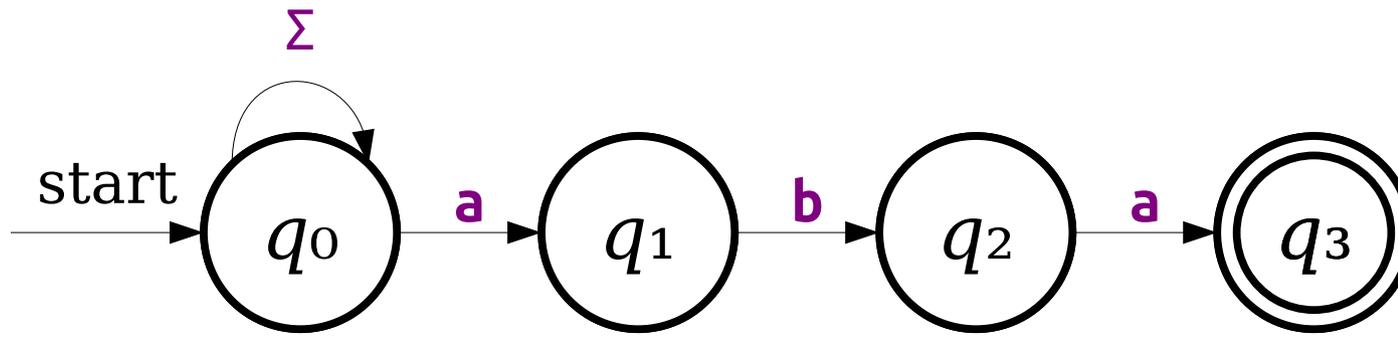
NFAs and DFAs

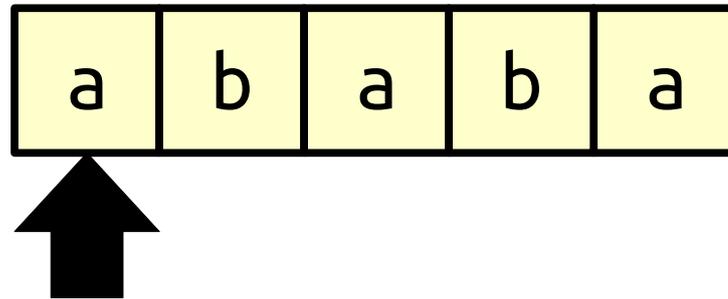
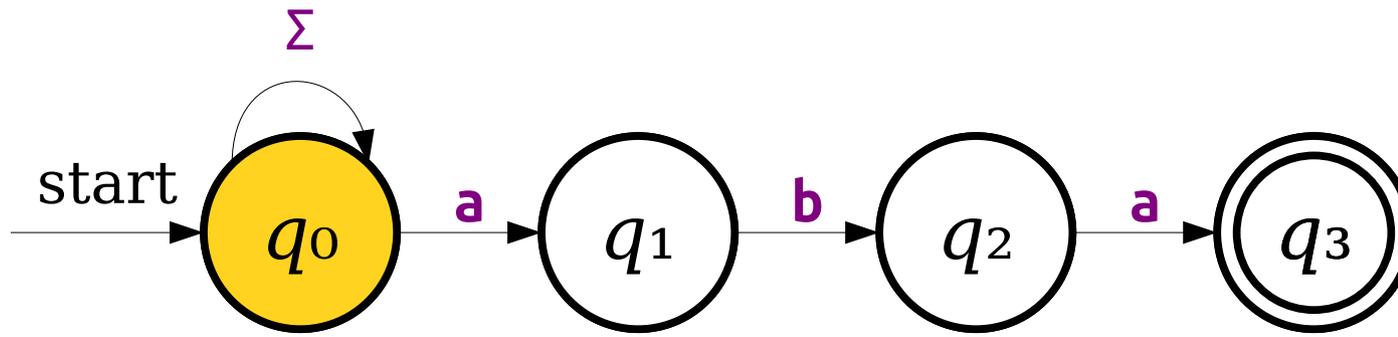
- Any language that can be accepted by a DFA can be accepted by an NFA.
- Why?
 - Every DFA essentially already *is* an NFA!
- **Question:** Can any language accepted by an NFA also be accepted by a DFA?
- Surprisingly, the answer is **yes!**

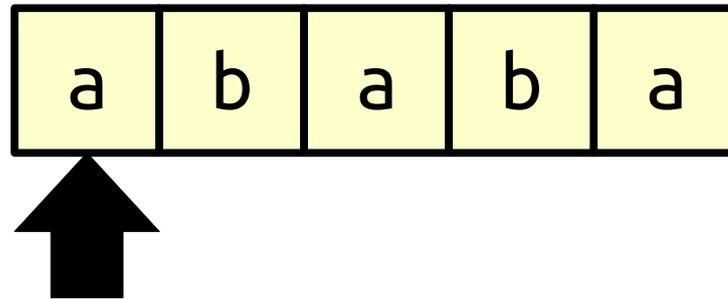
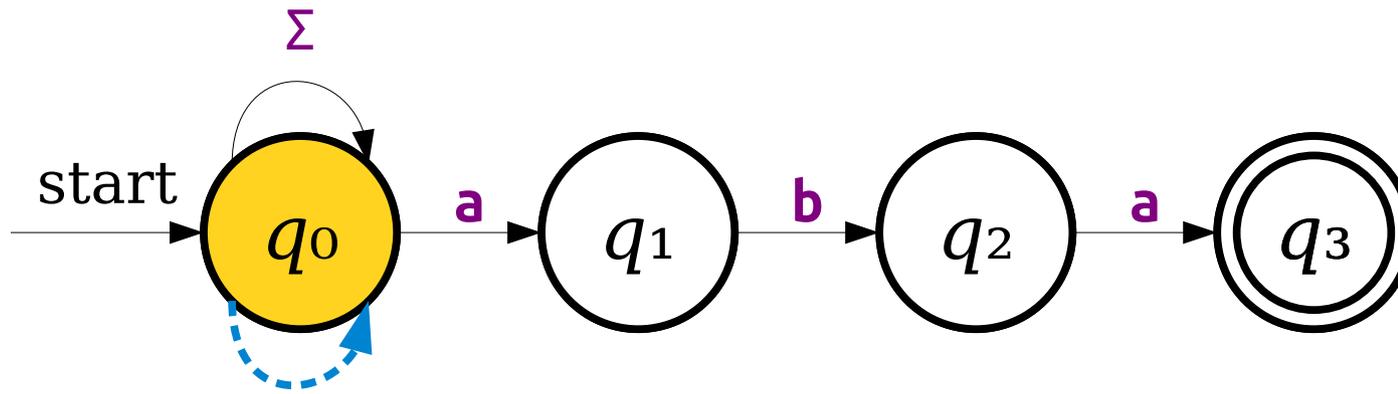
Thought Experiment:

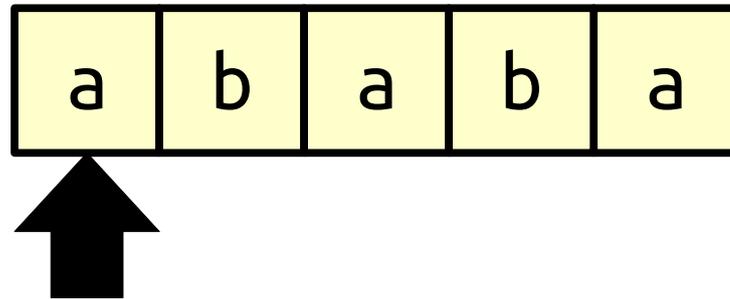
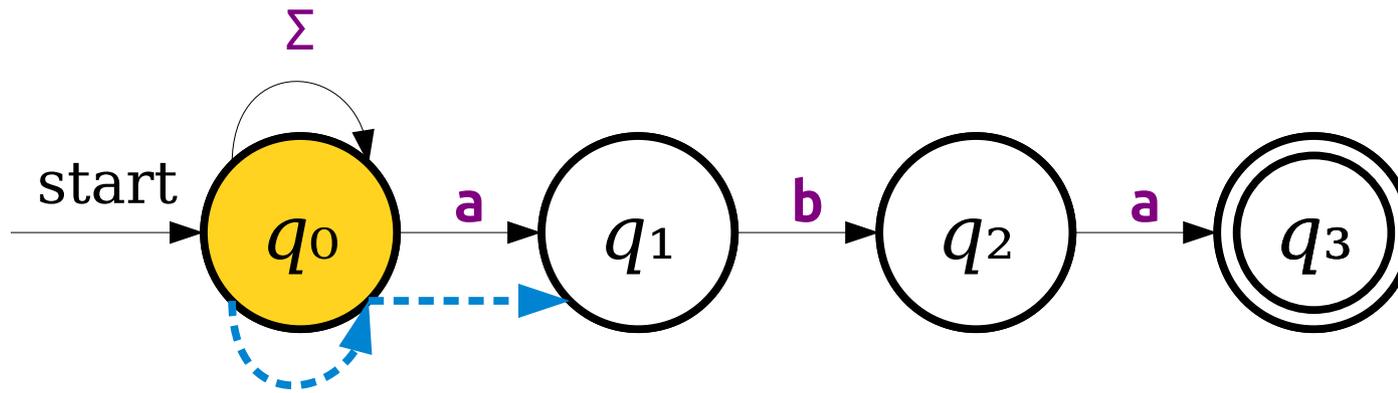
How would you simulate an NFA in software?

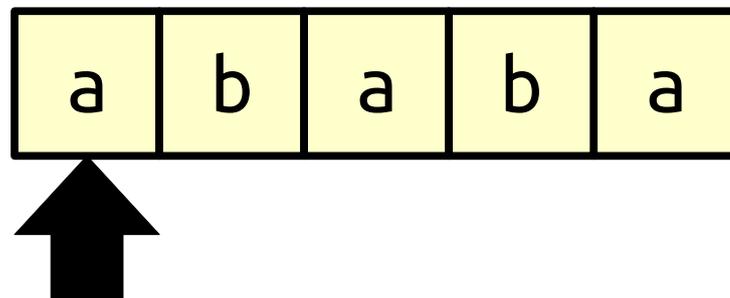
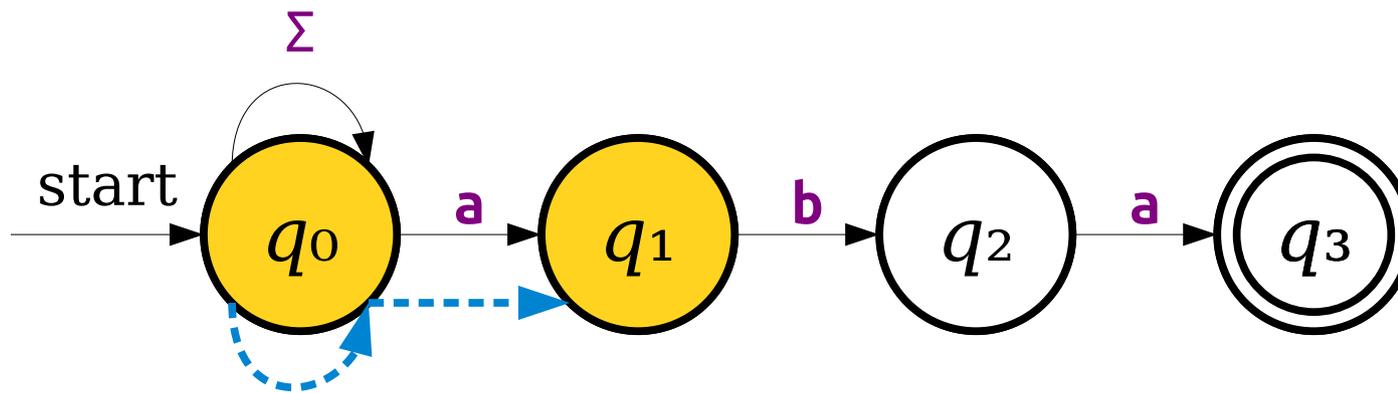


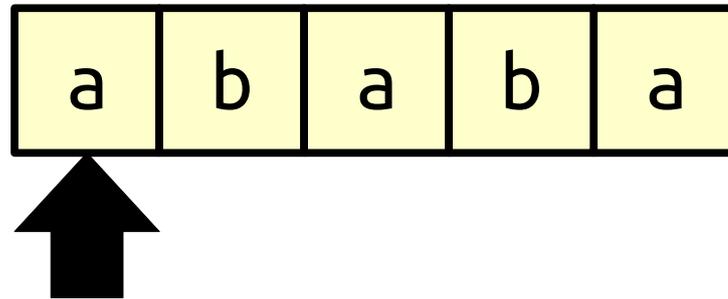
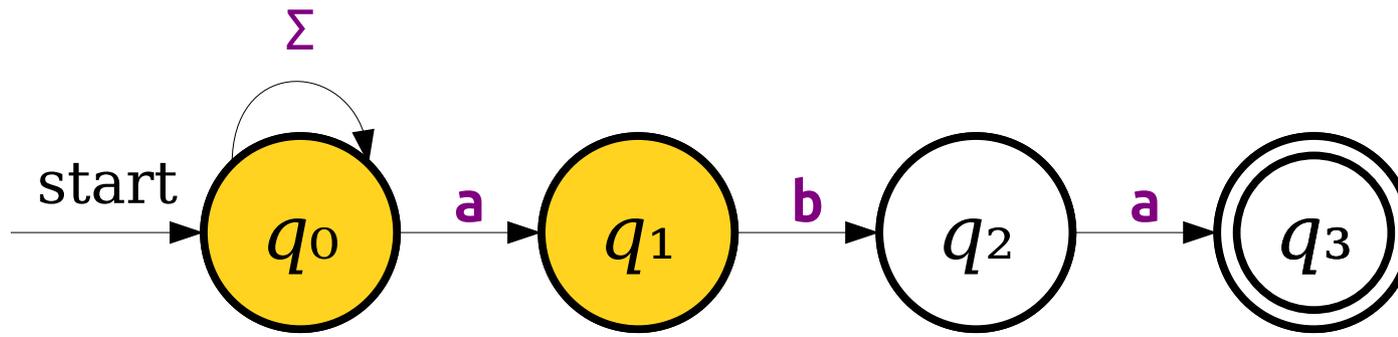


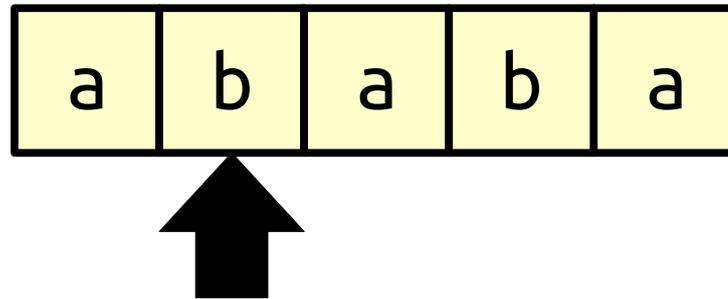
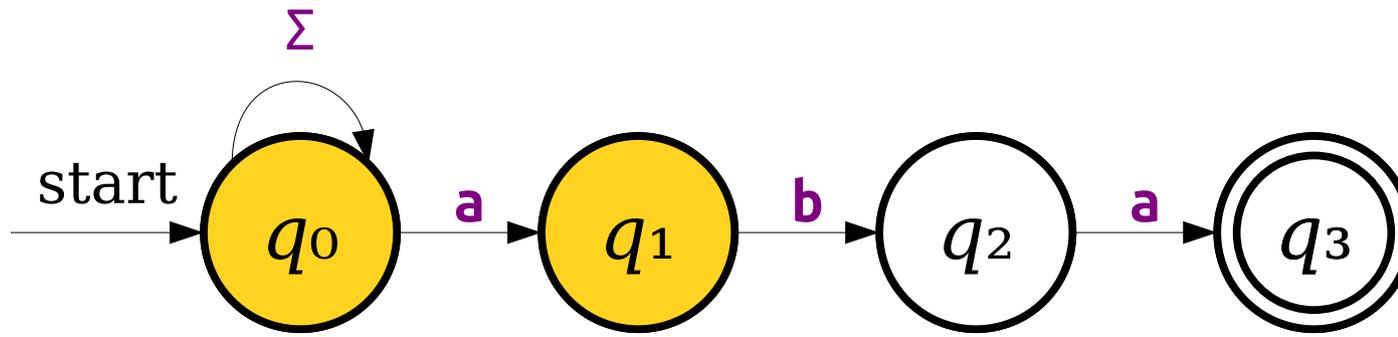


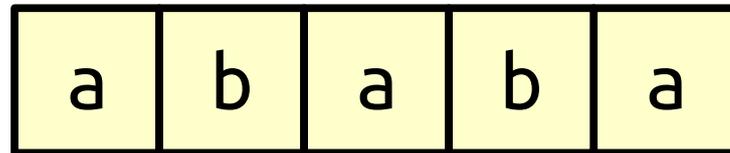
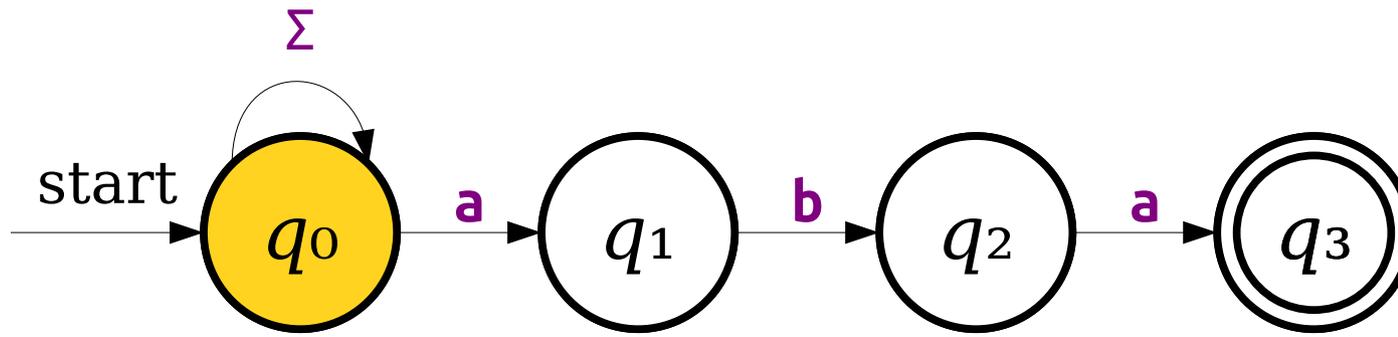


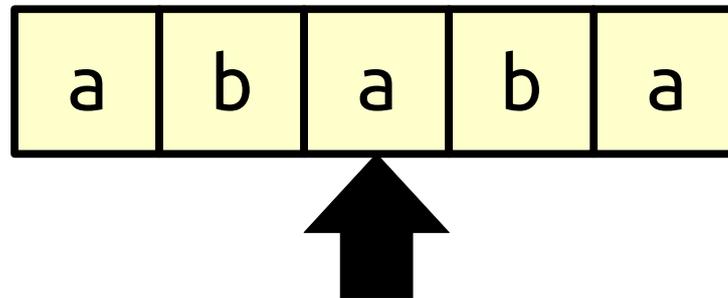
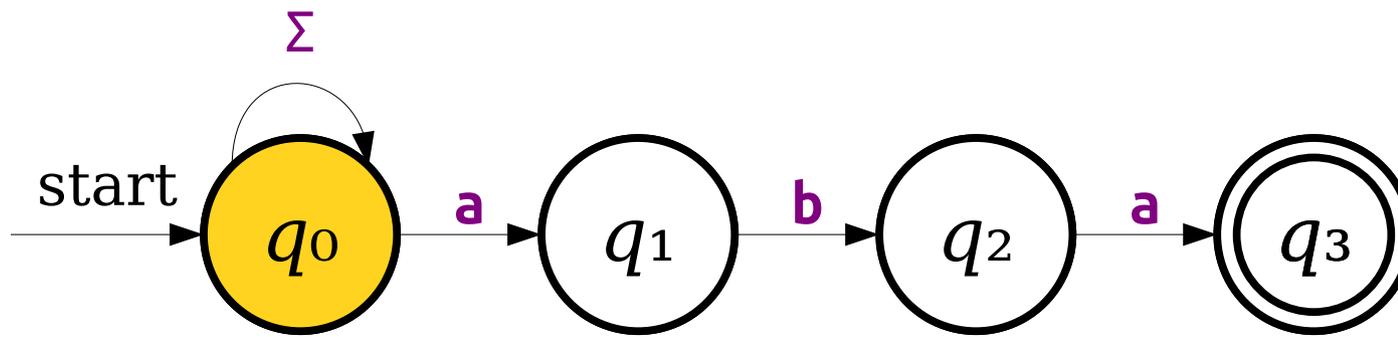


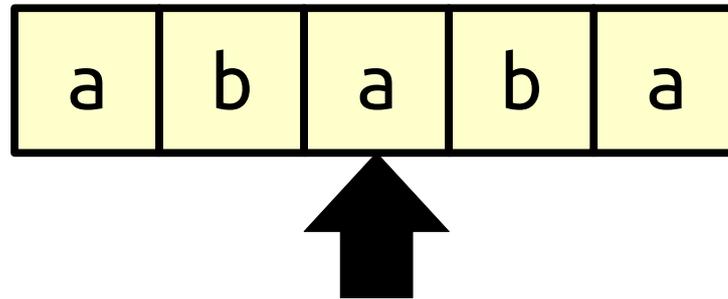
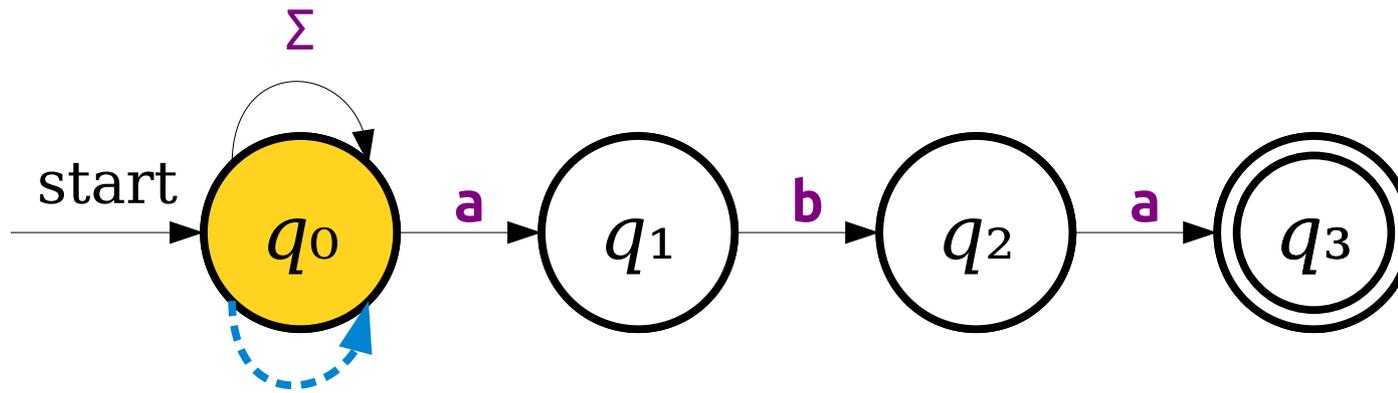


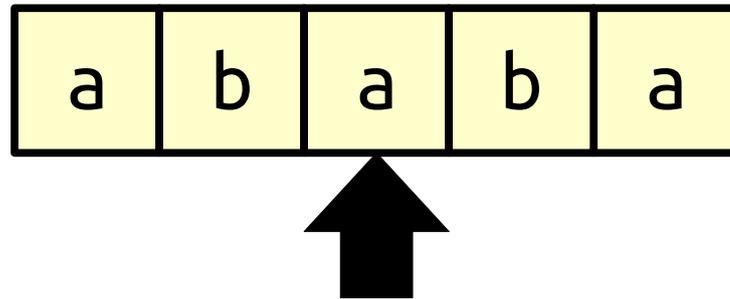
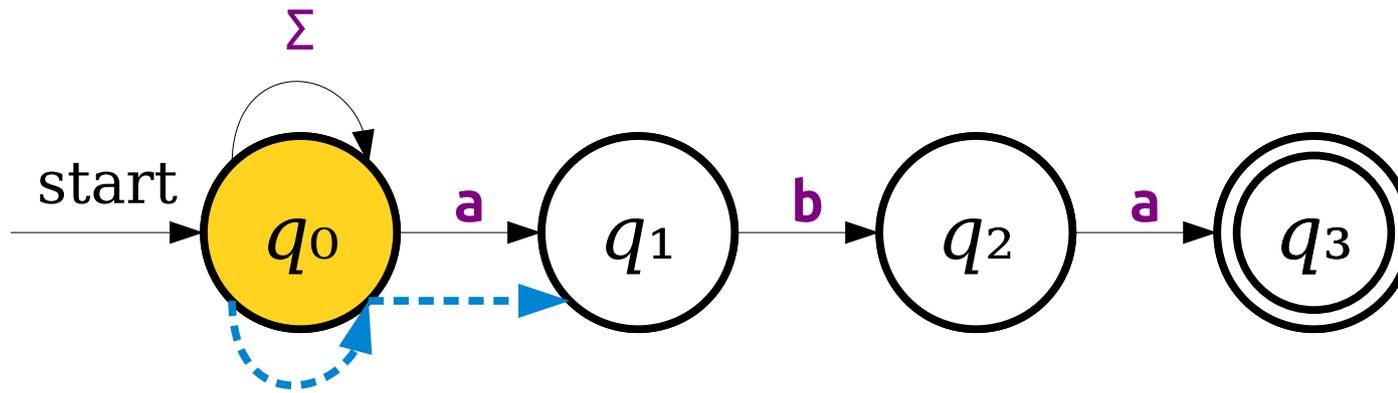


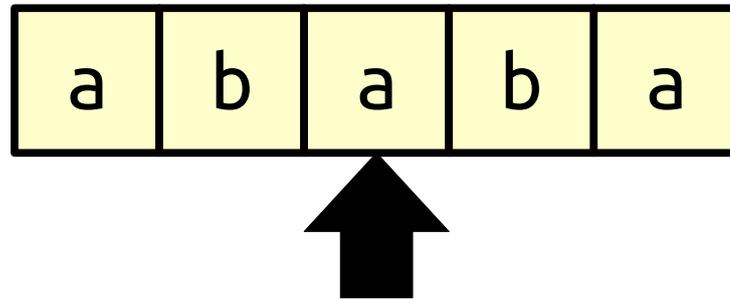
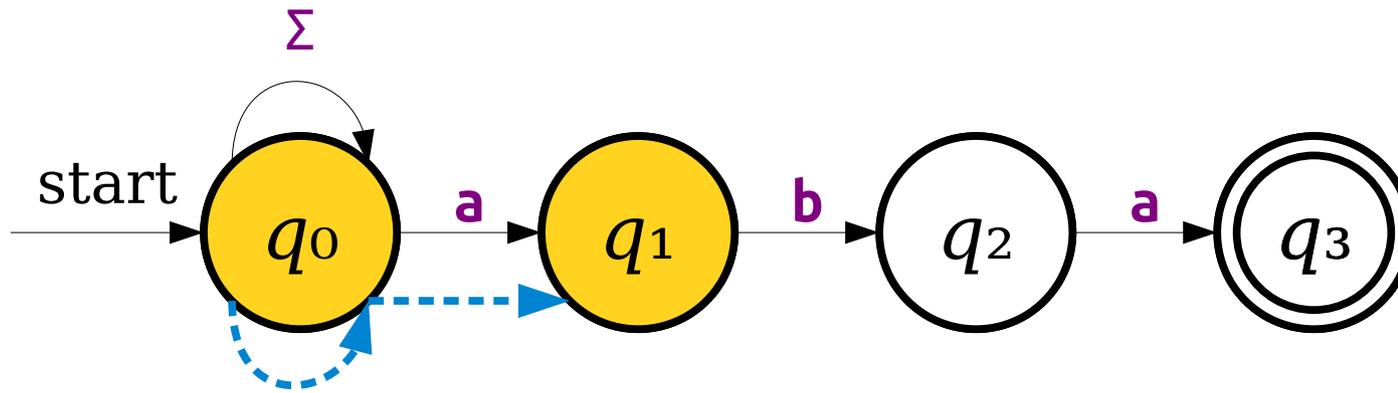


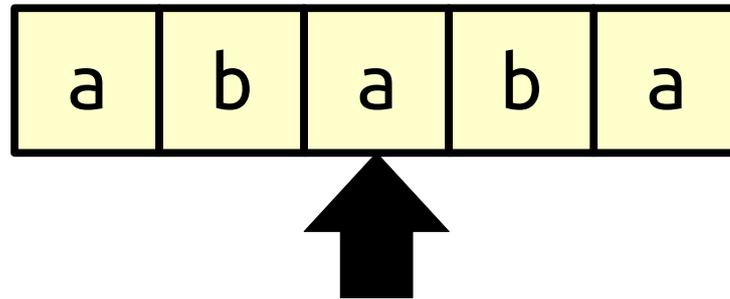
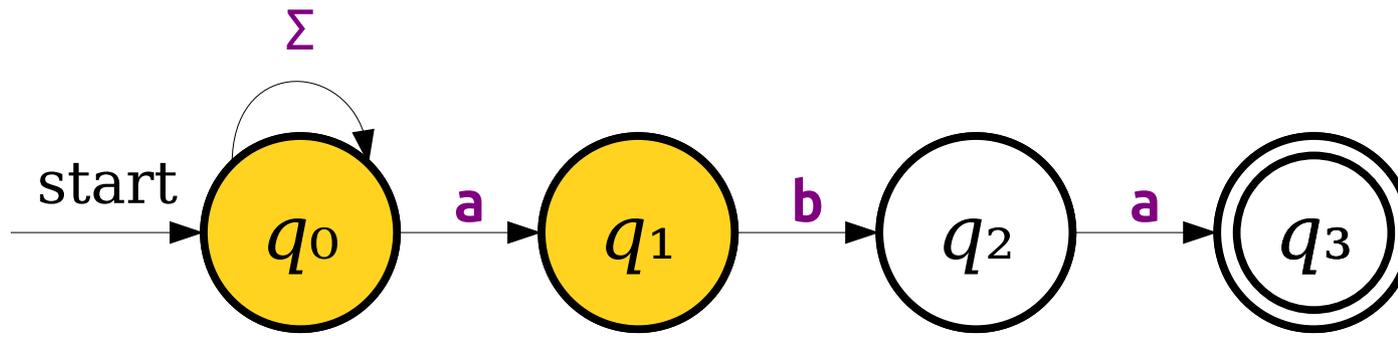


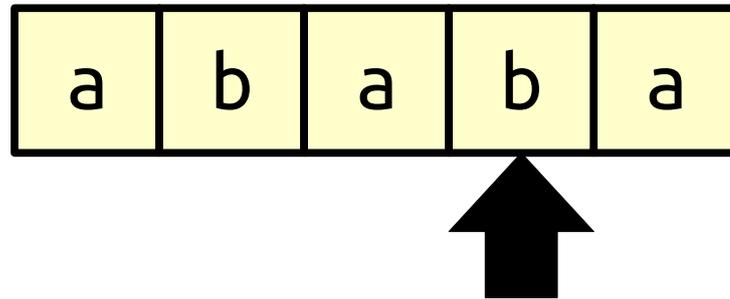
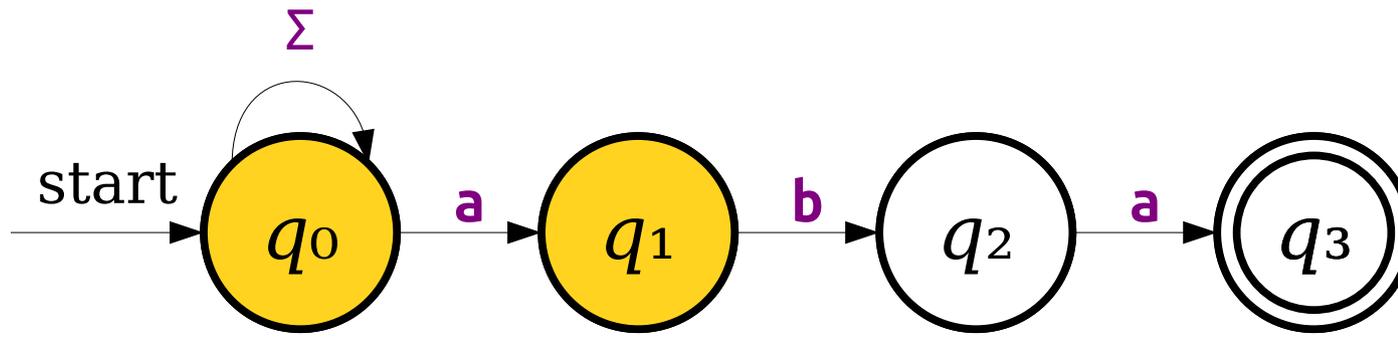


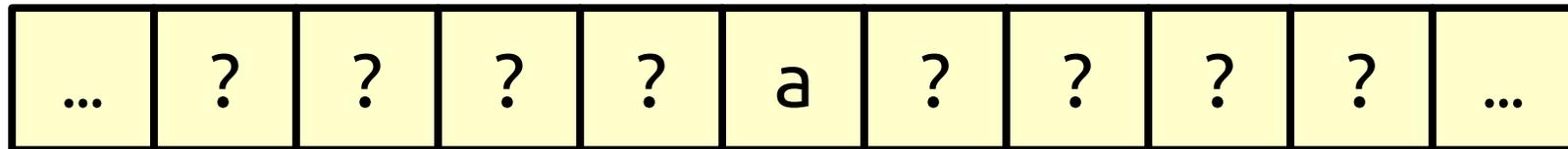
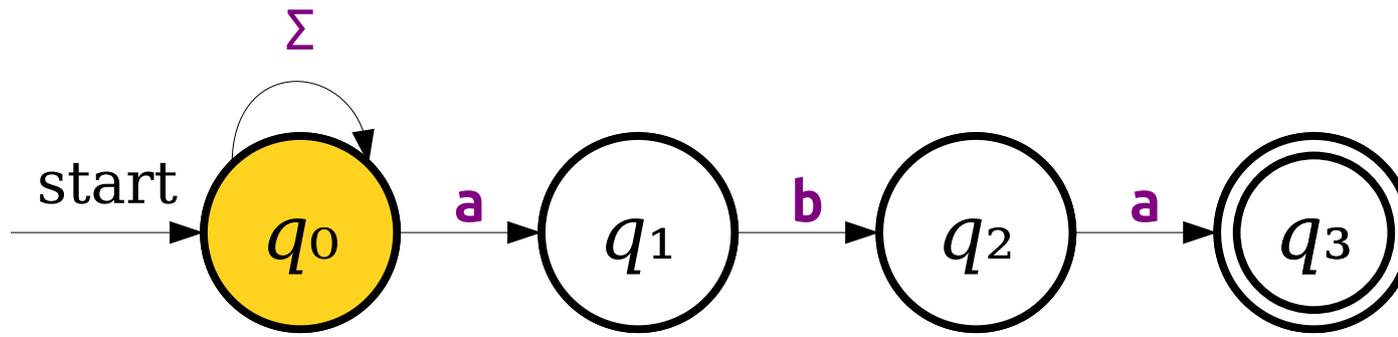


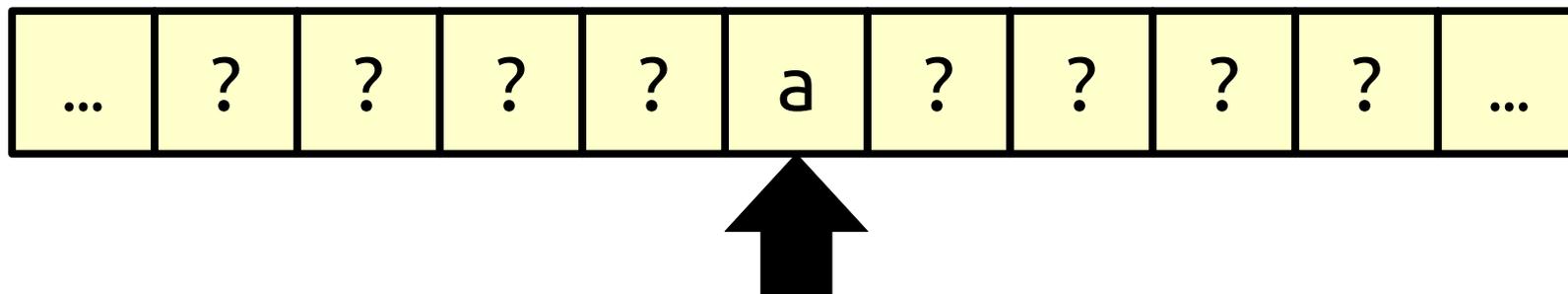
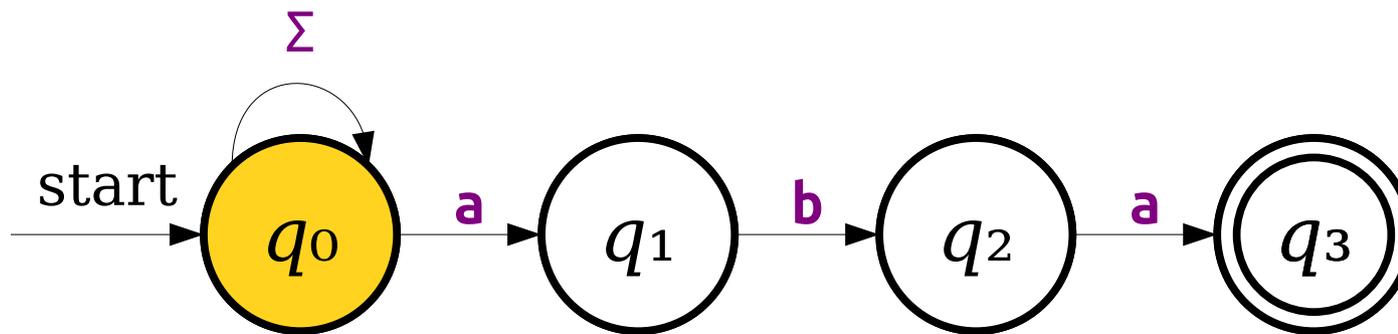


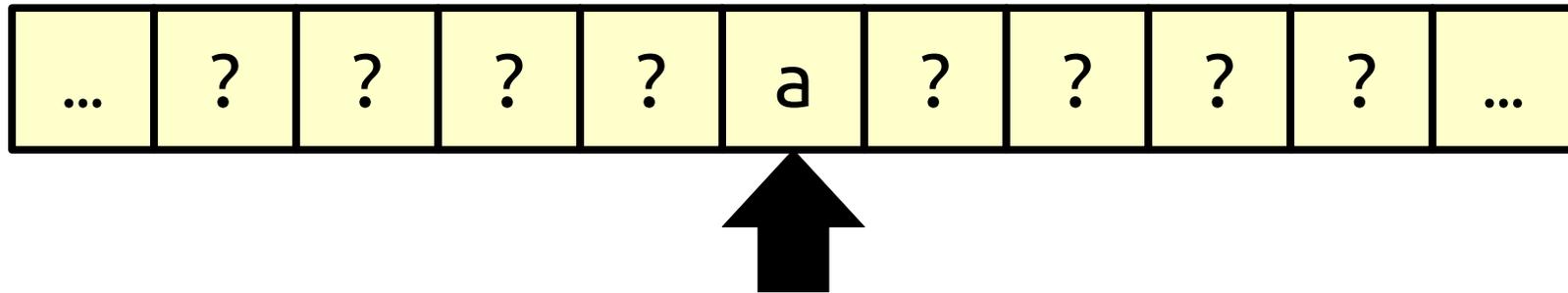
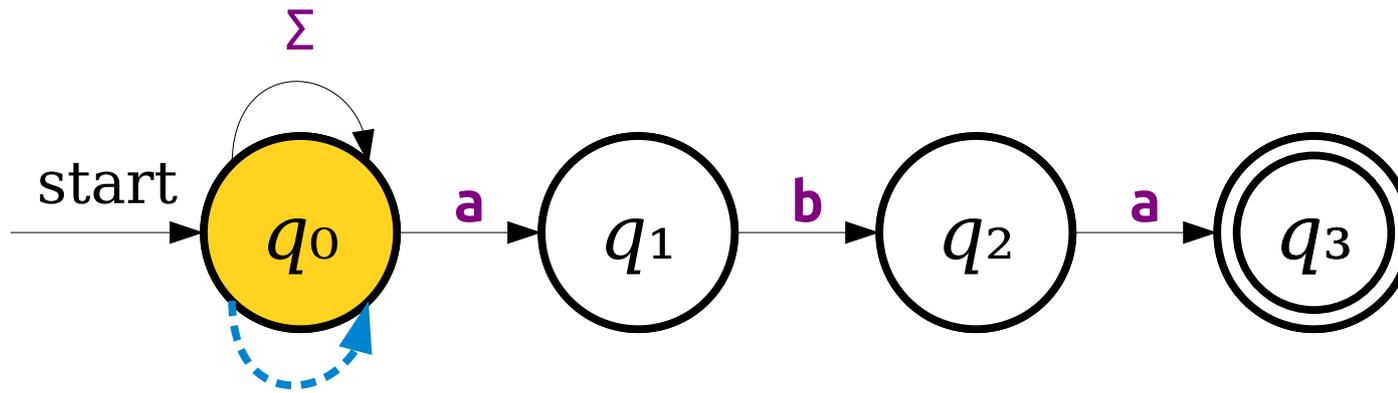


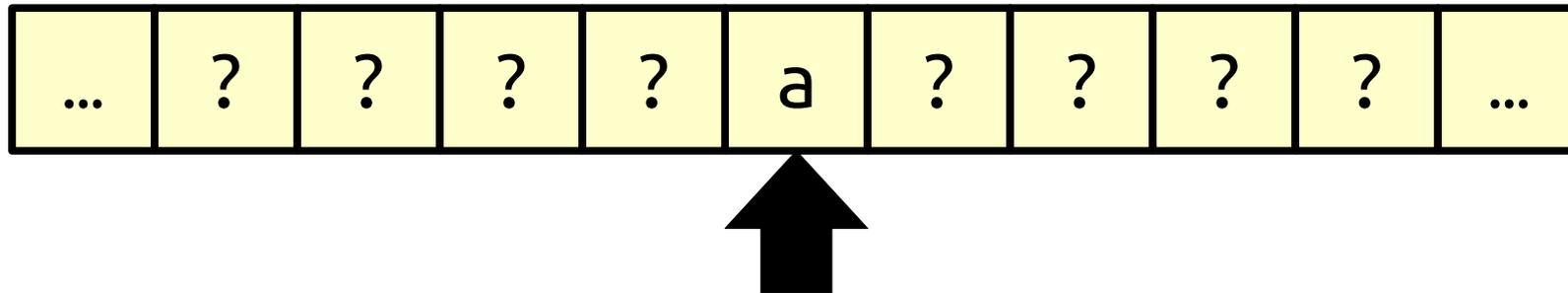
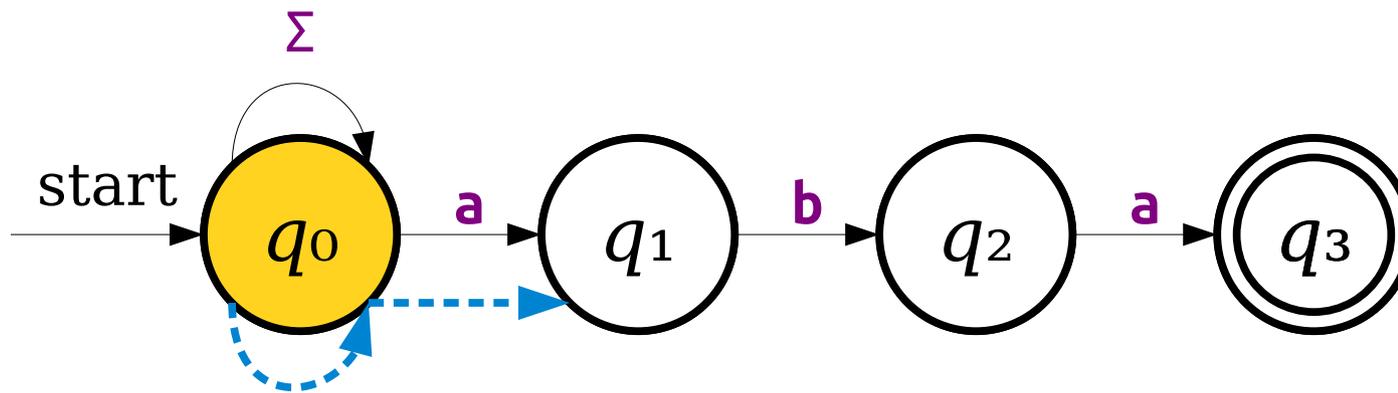


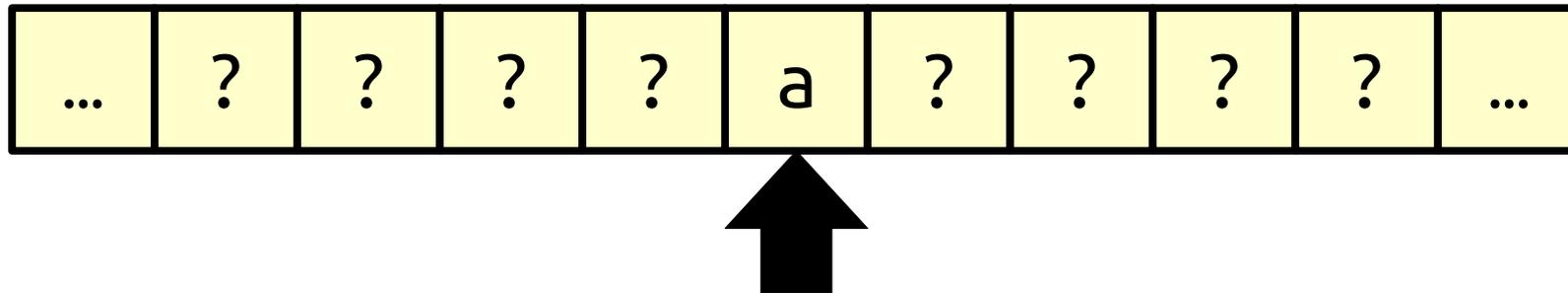
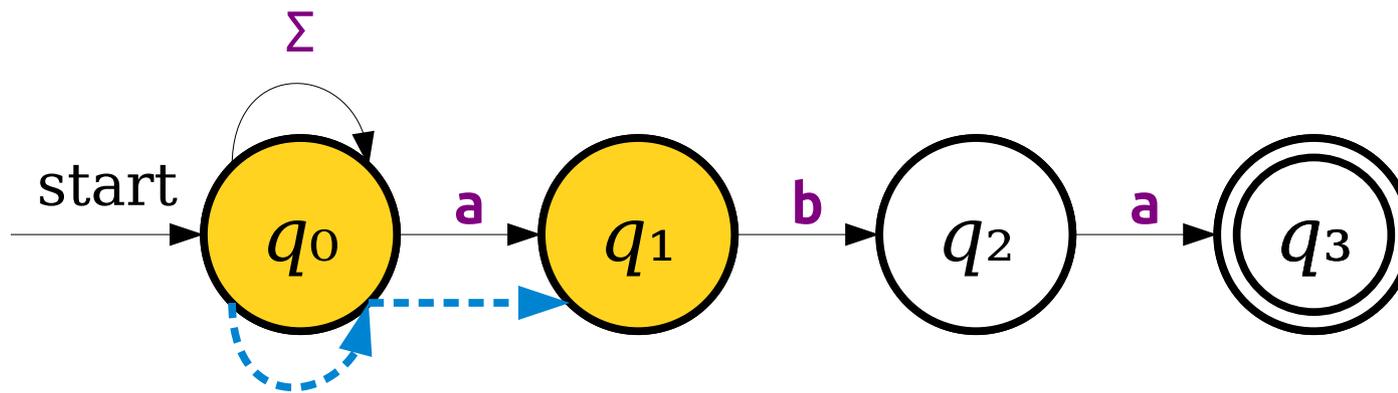


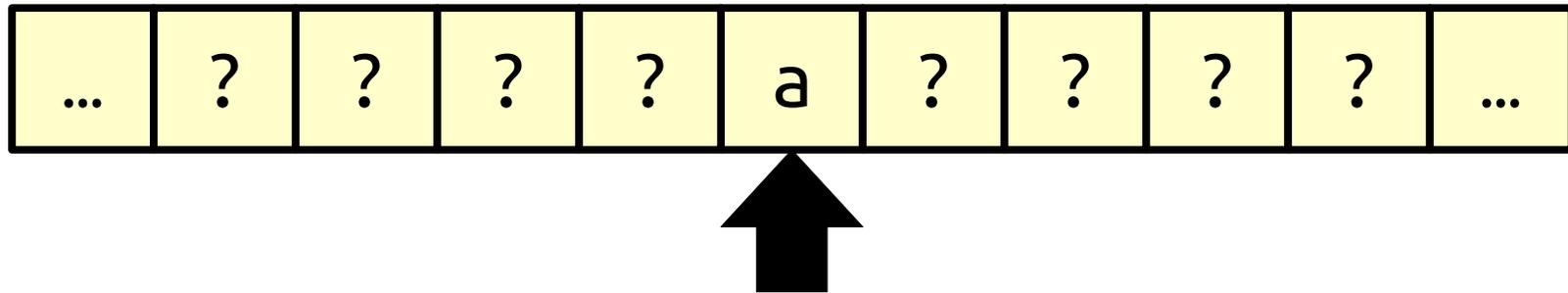
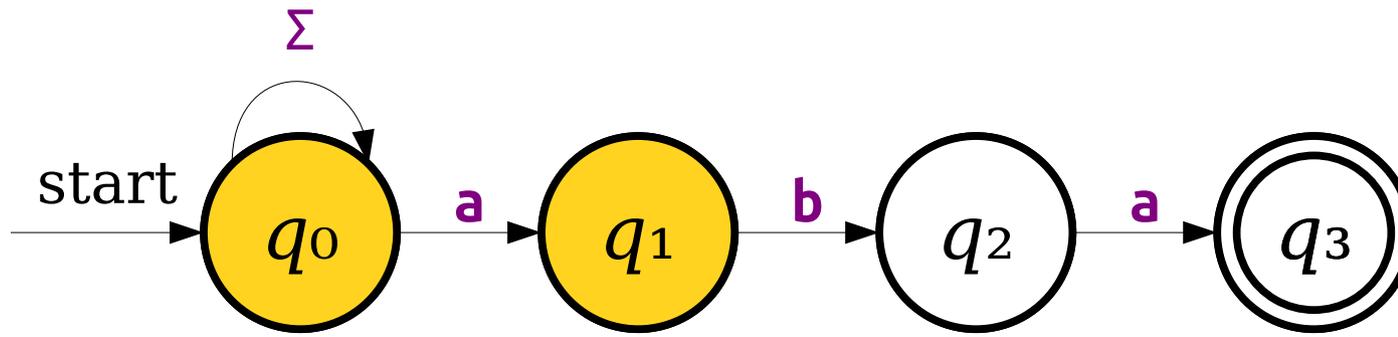


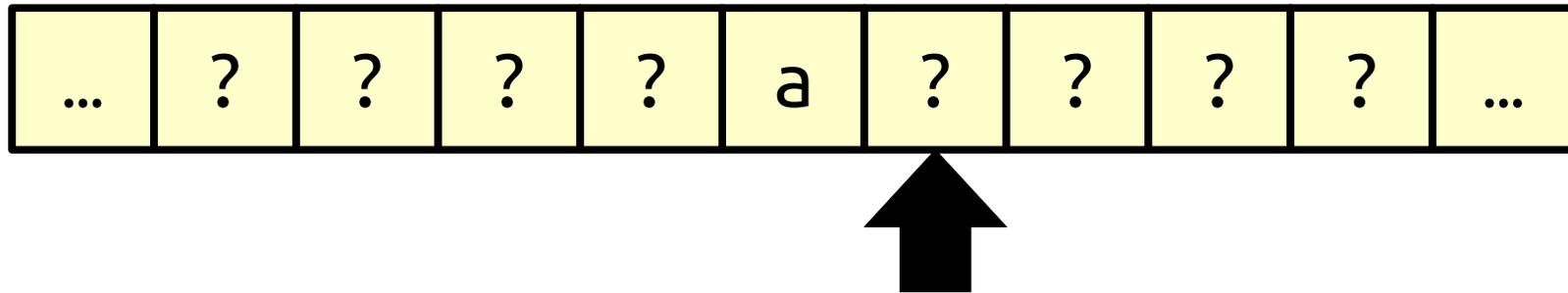
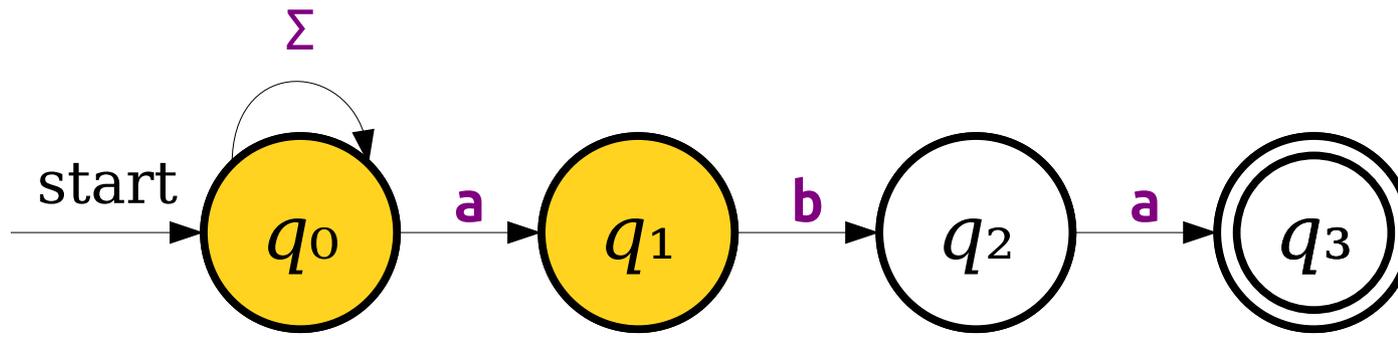


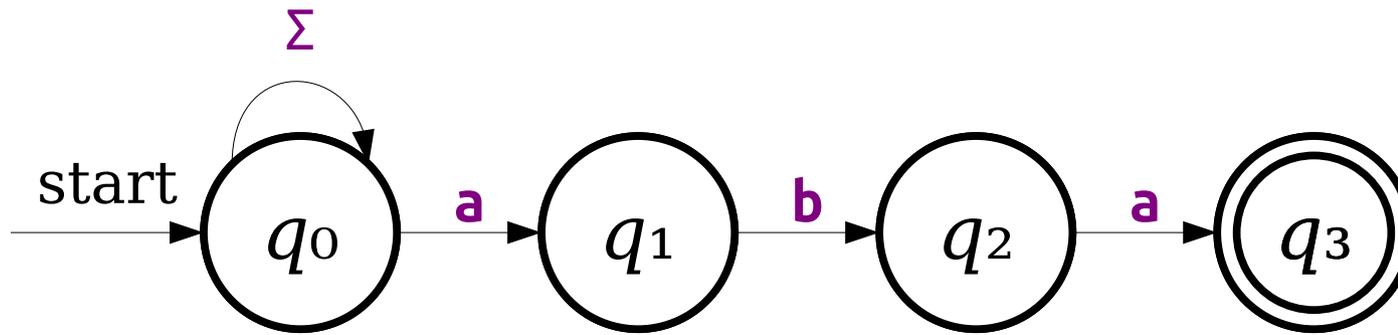




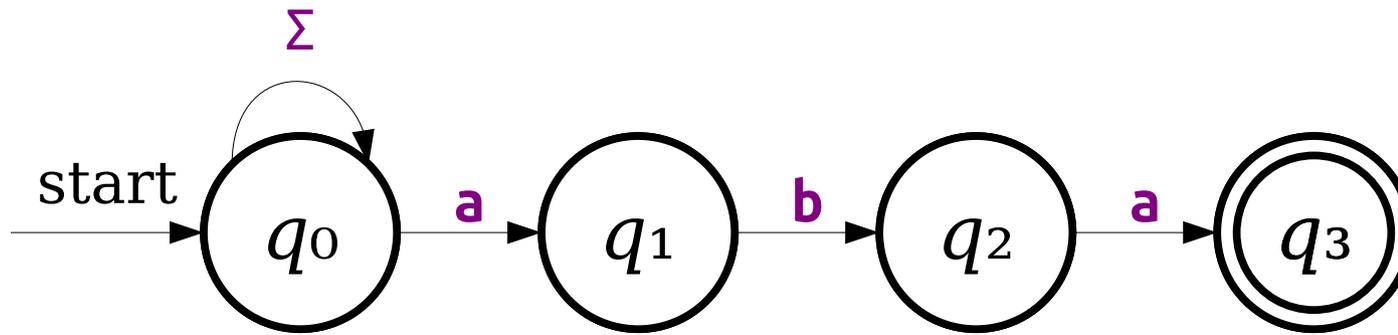




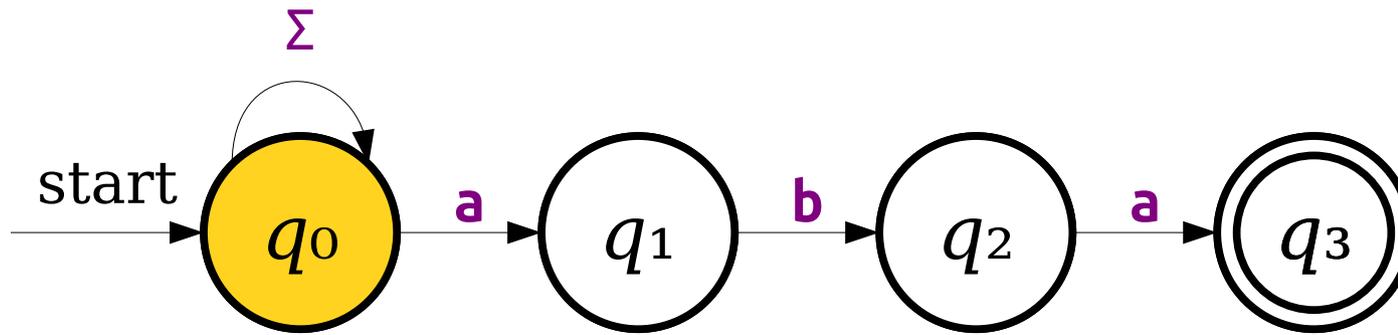




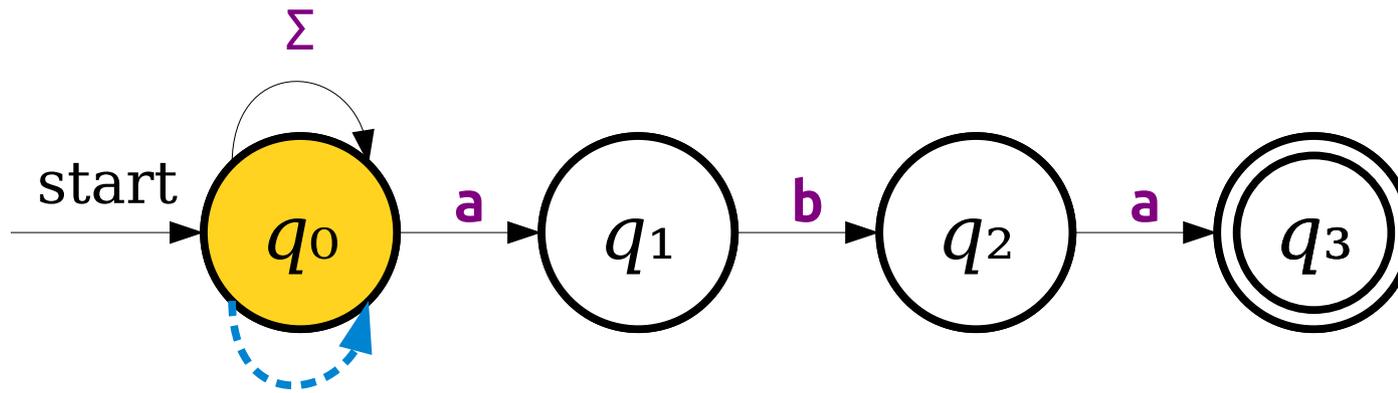
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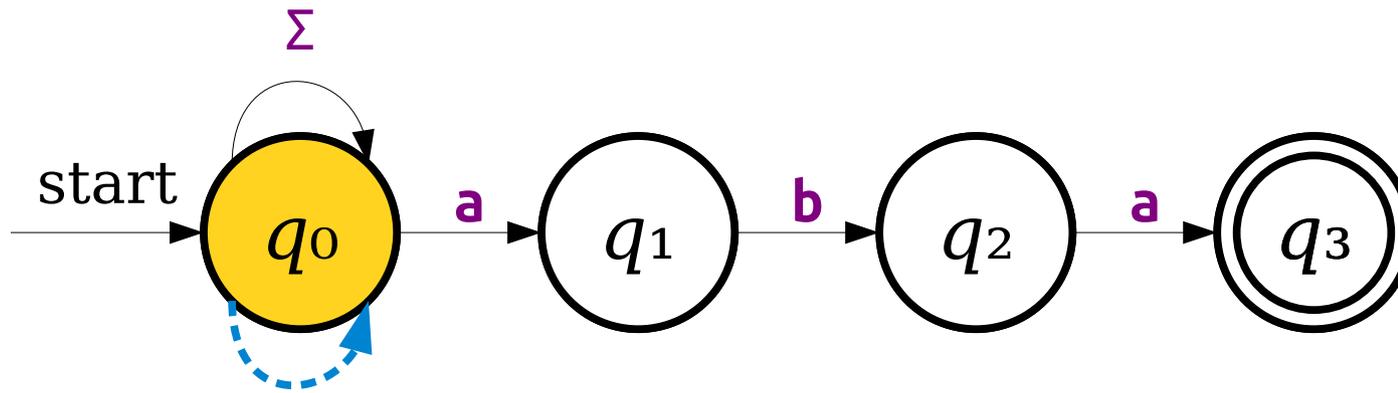
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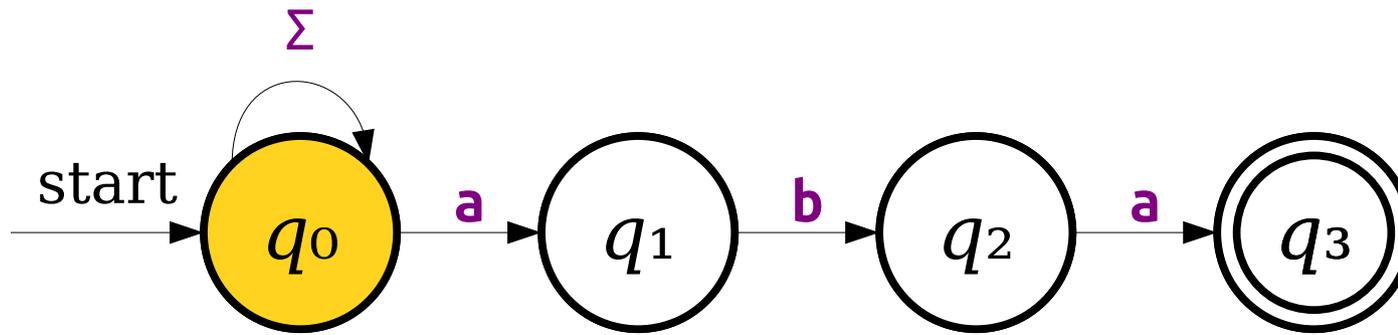
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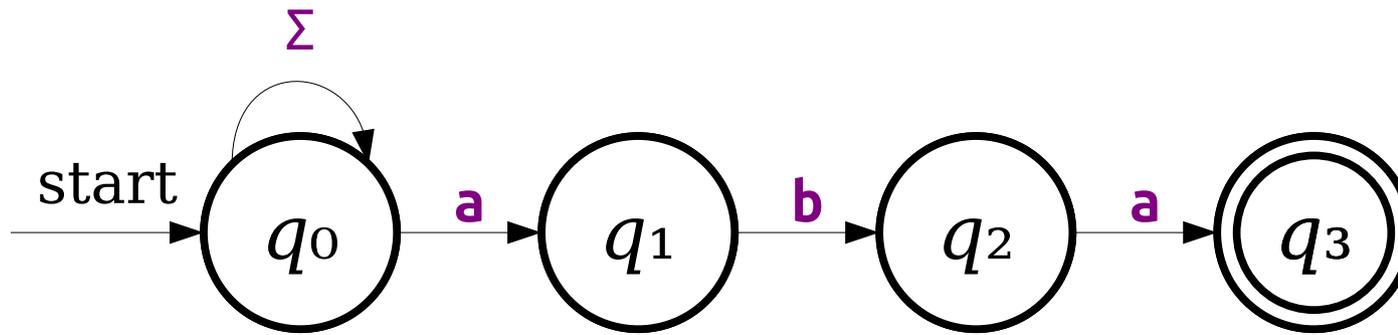
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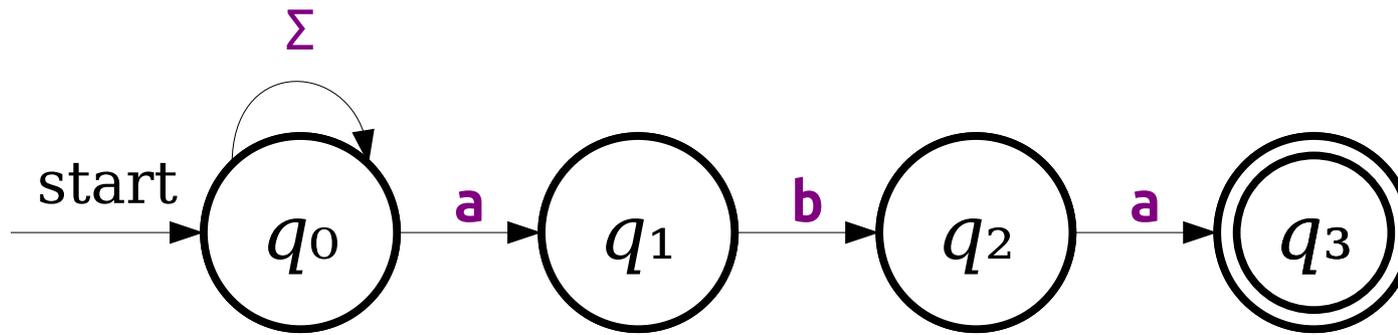
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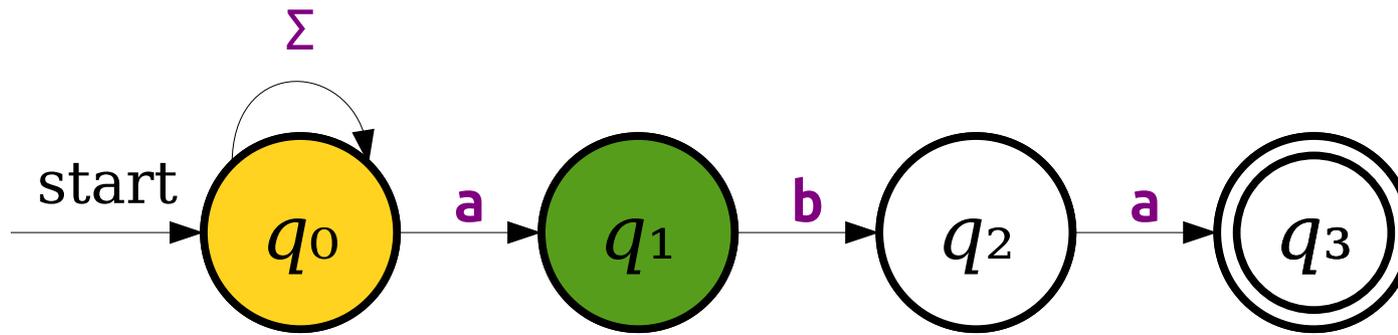
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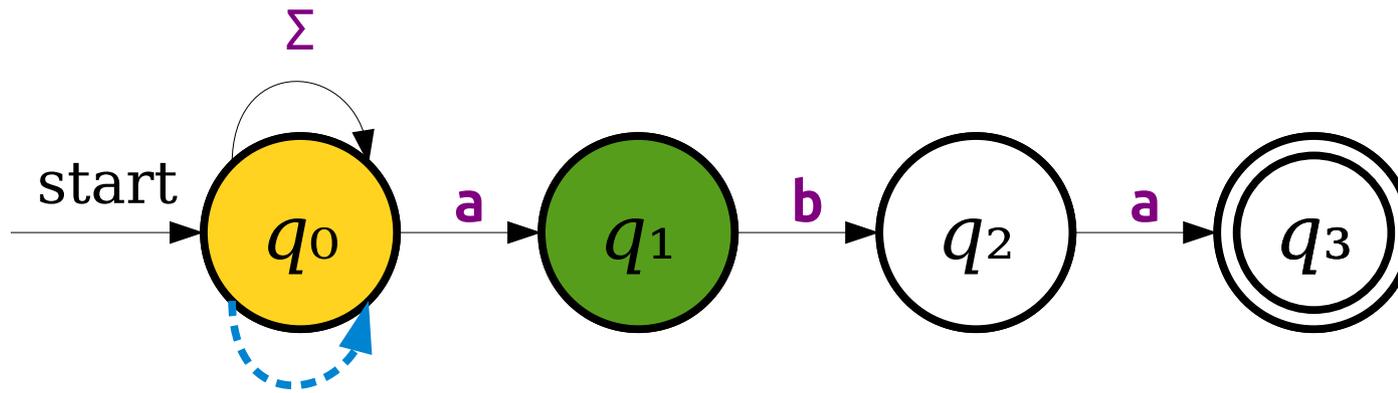
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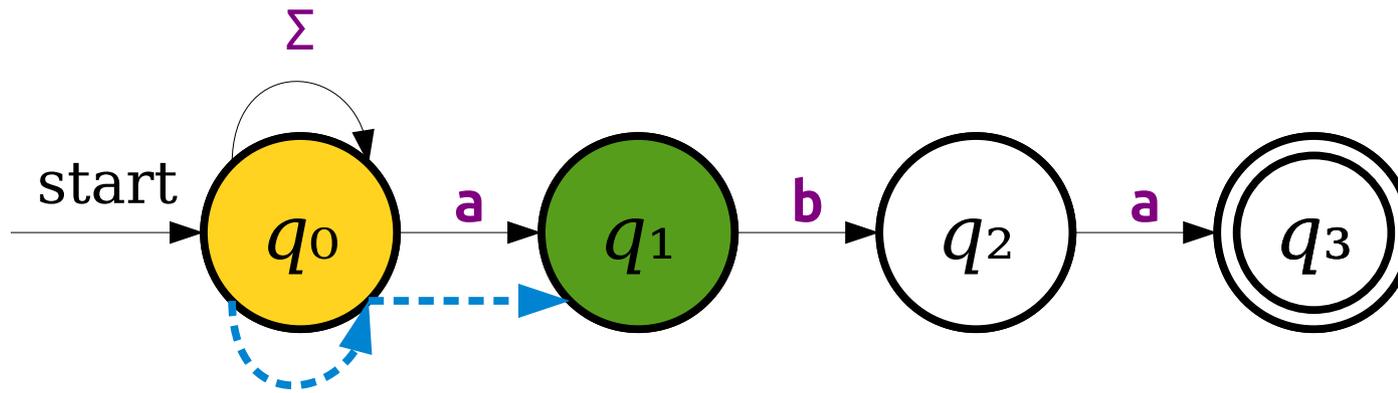
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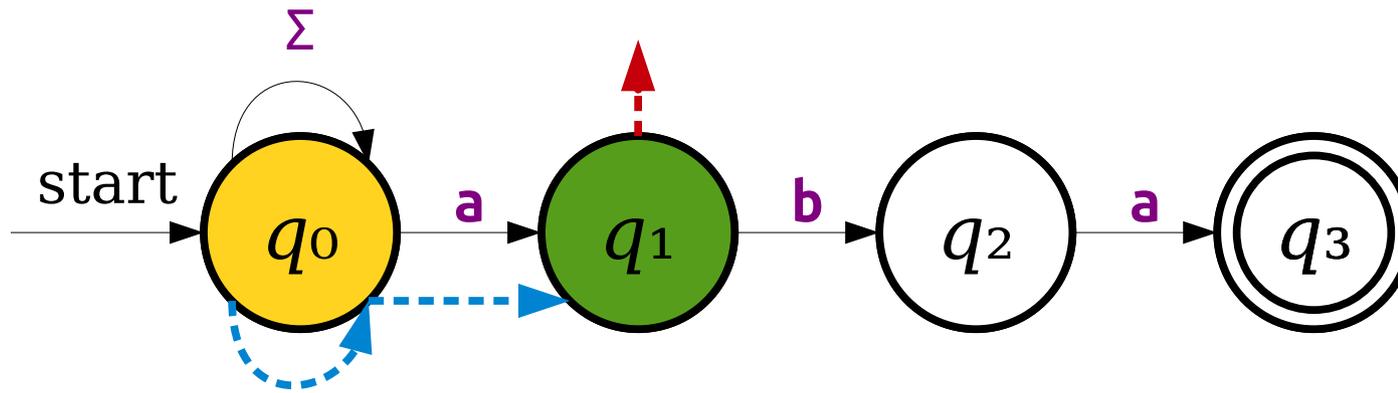
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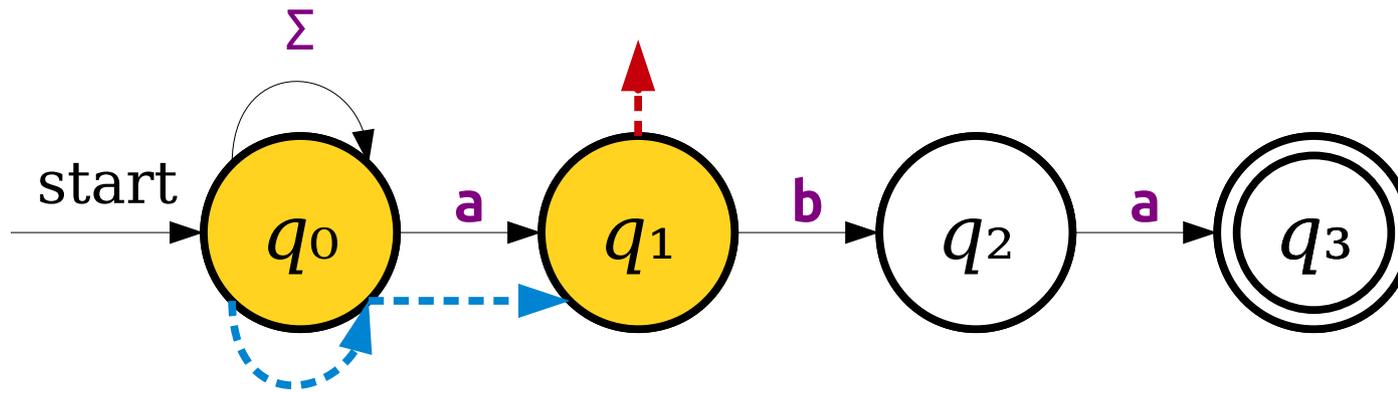
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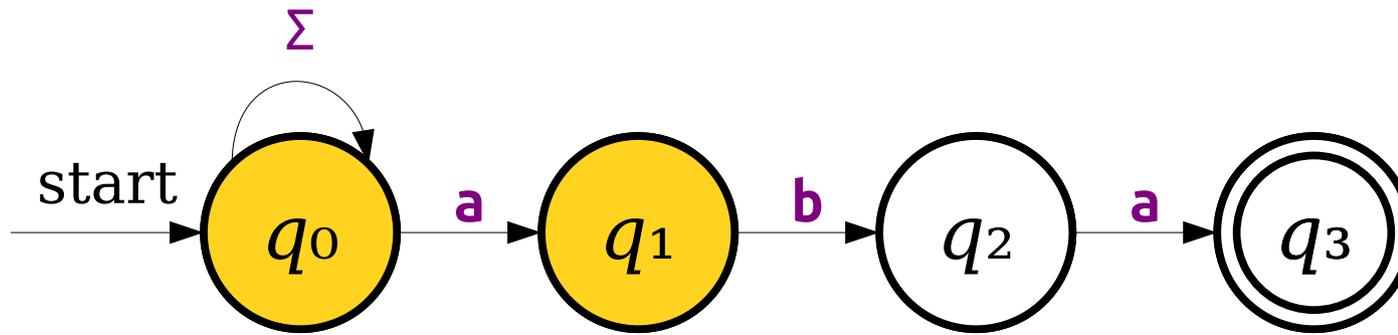
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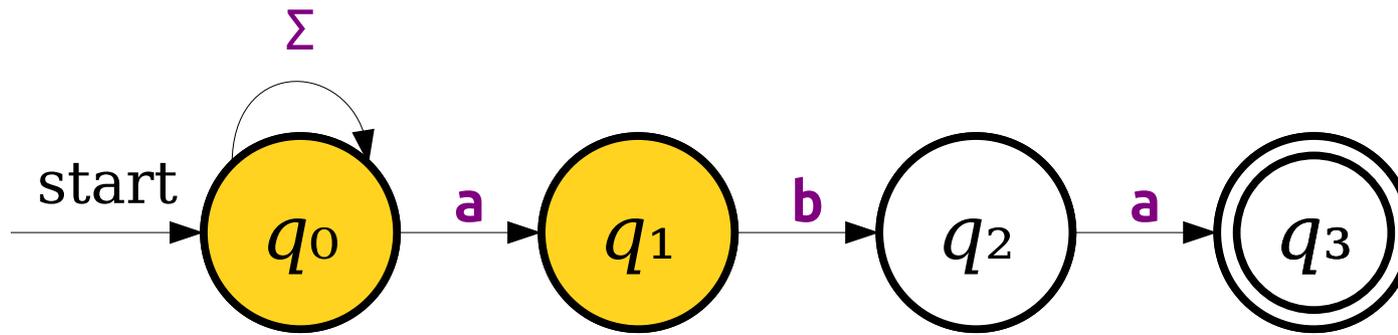
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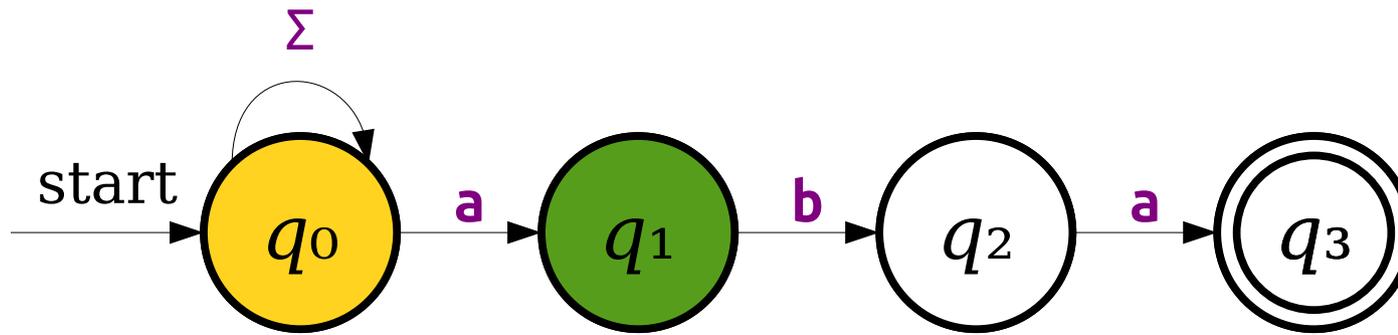
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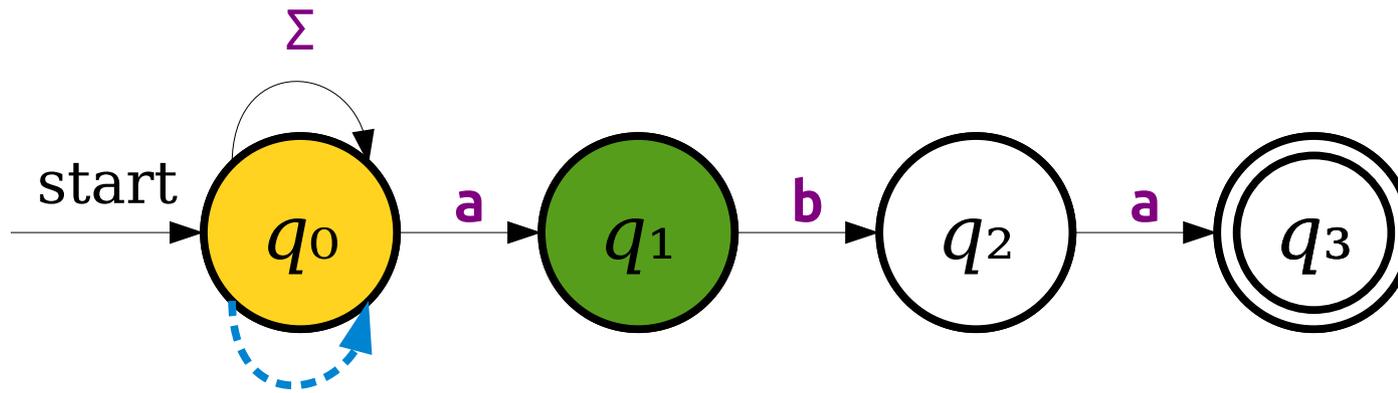
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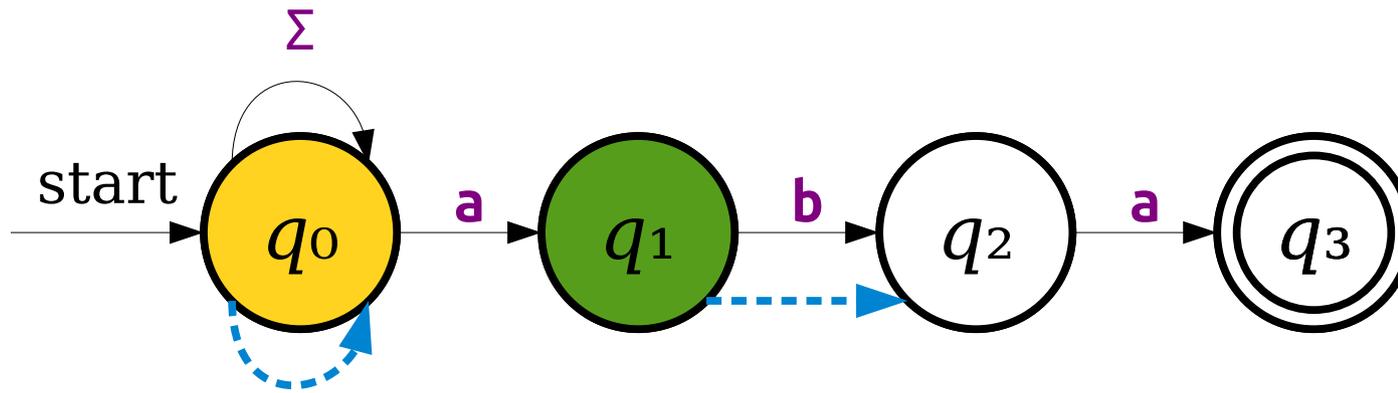
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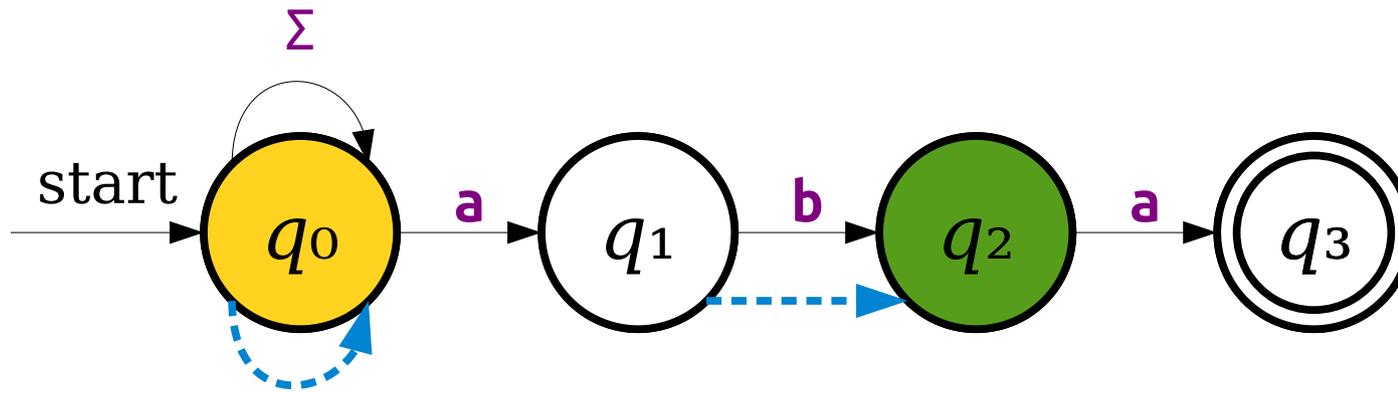
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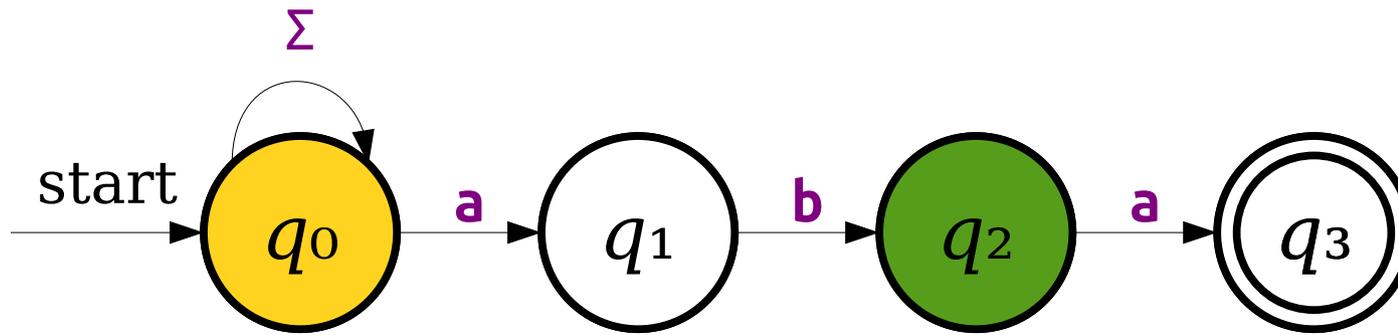
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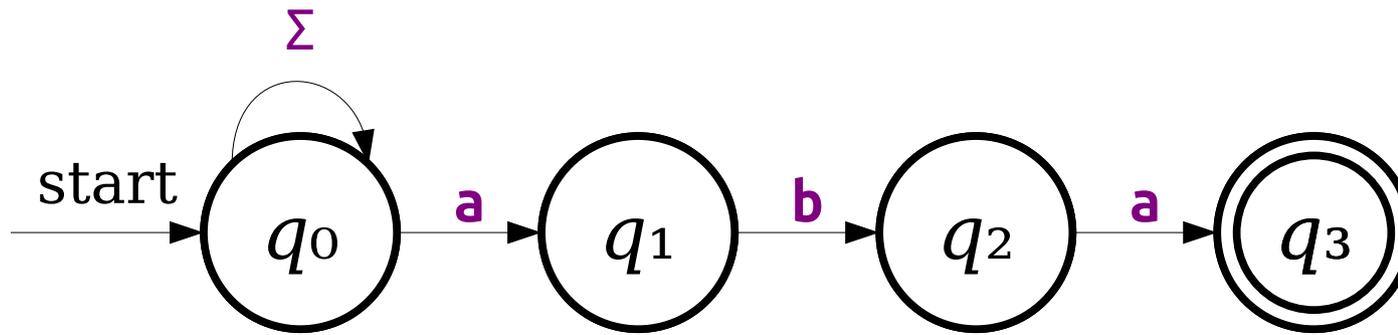
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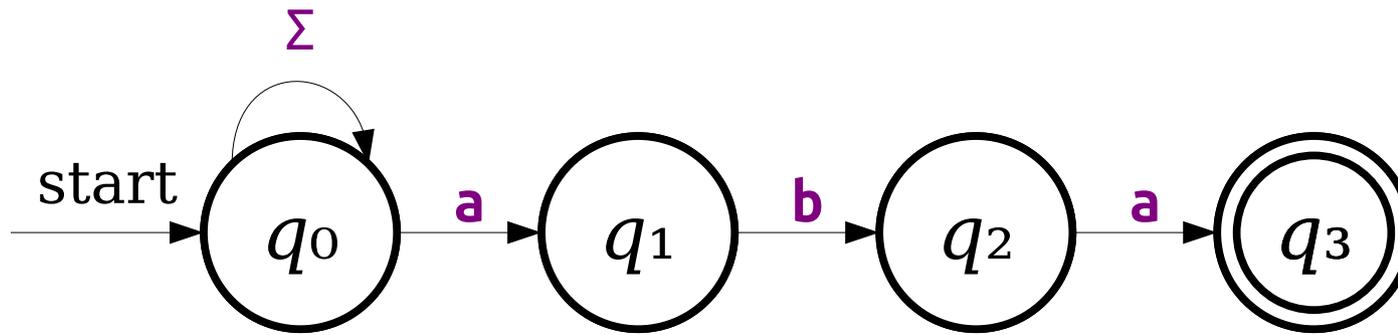
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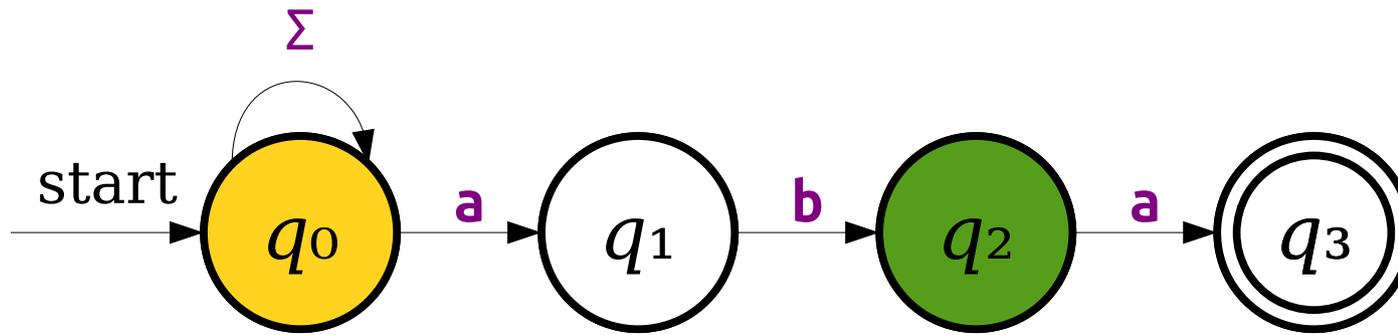
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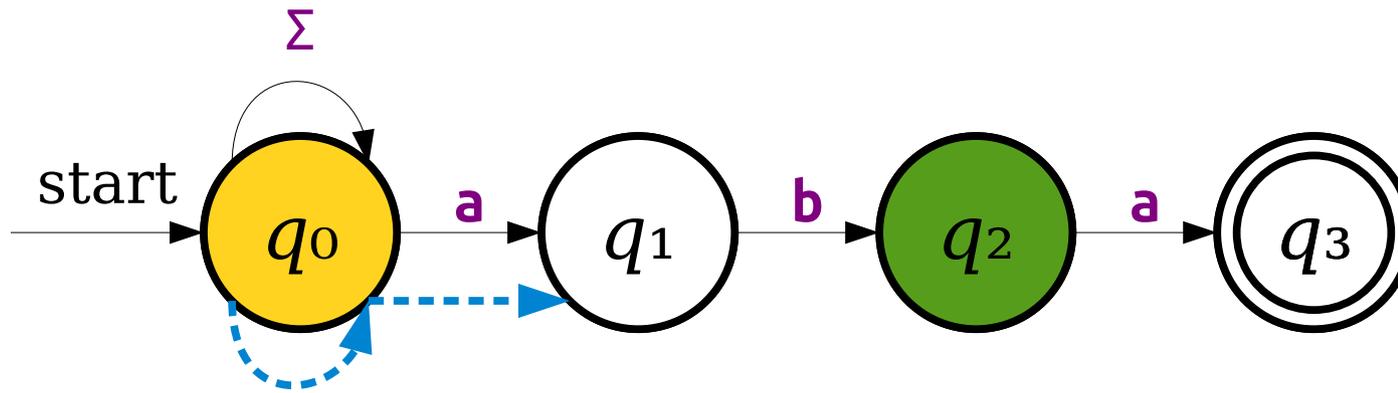
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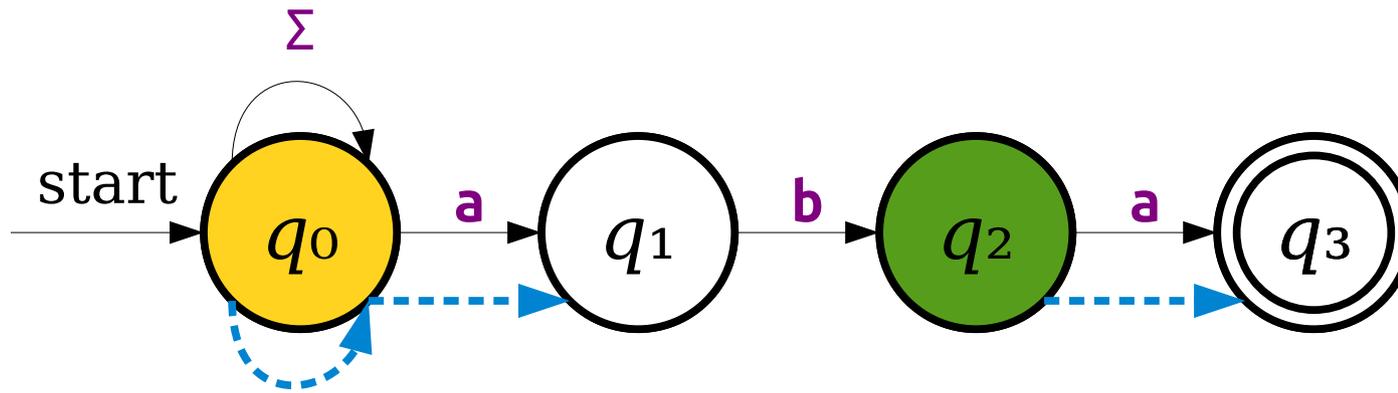
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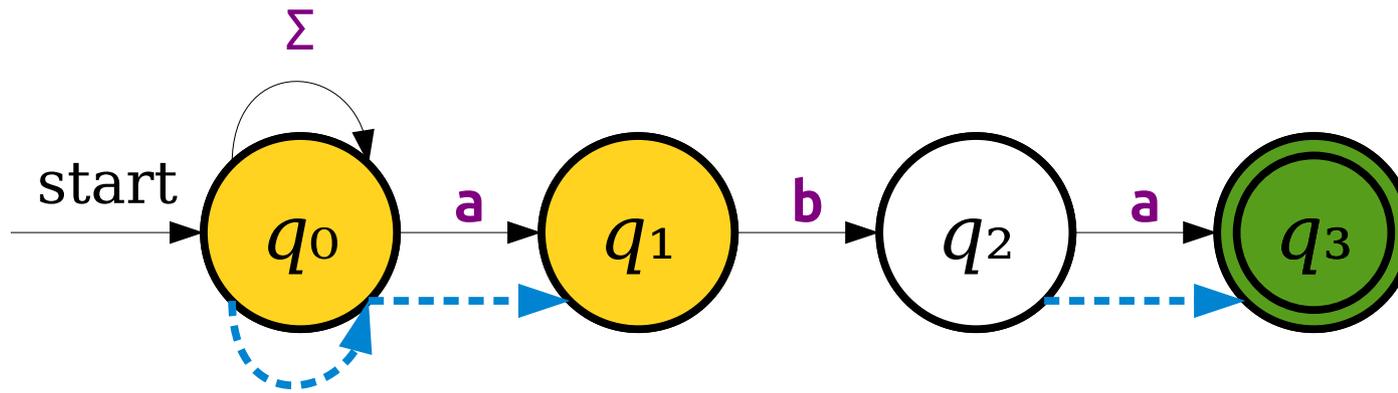
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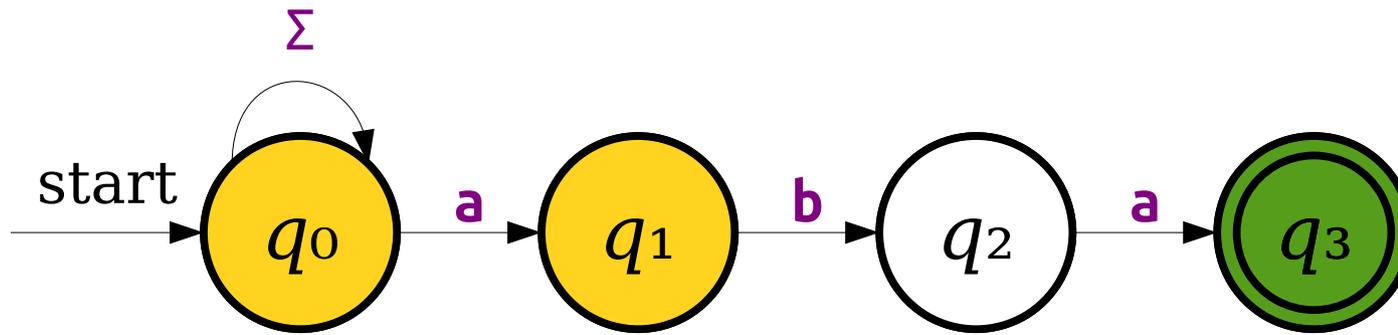
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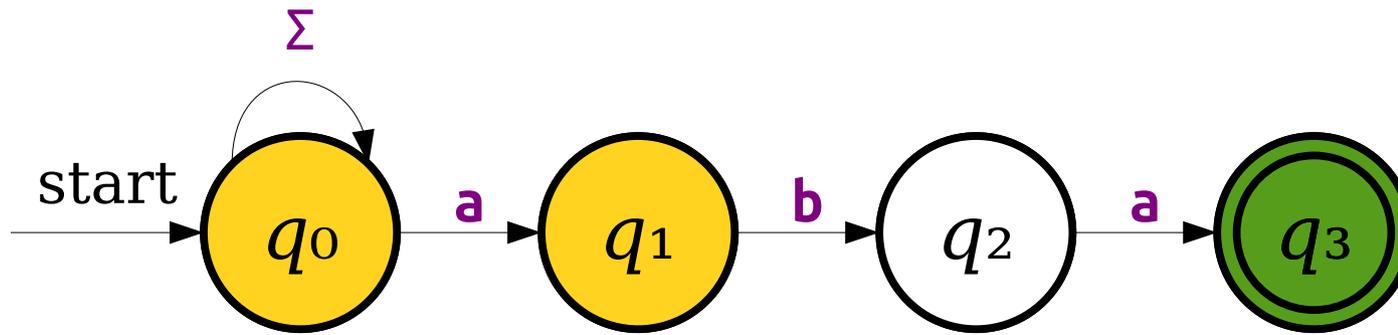
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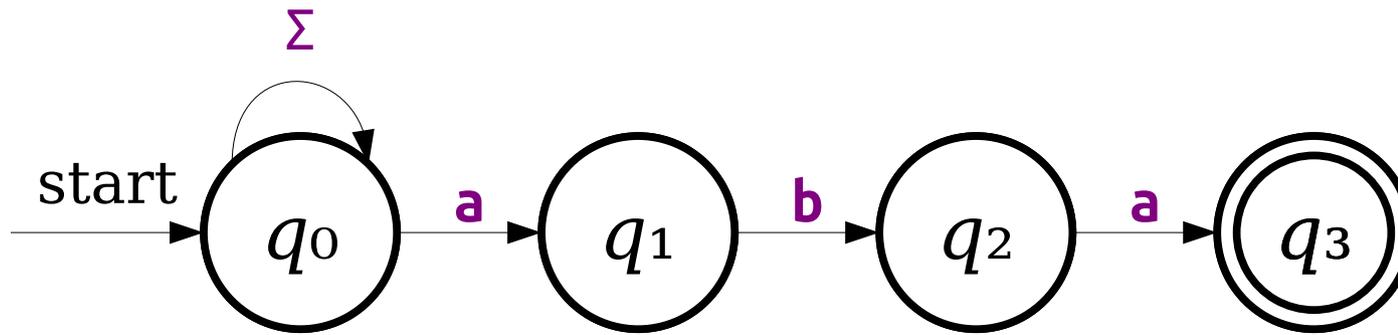
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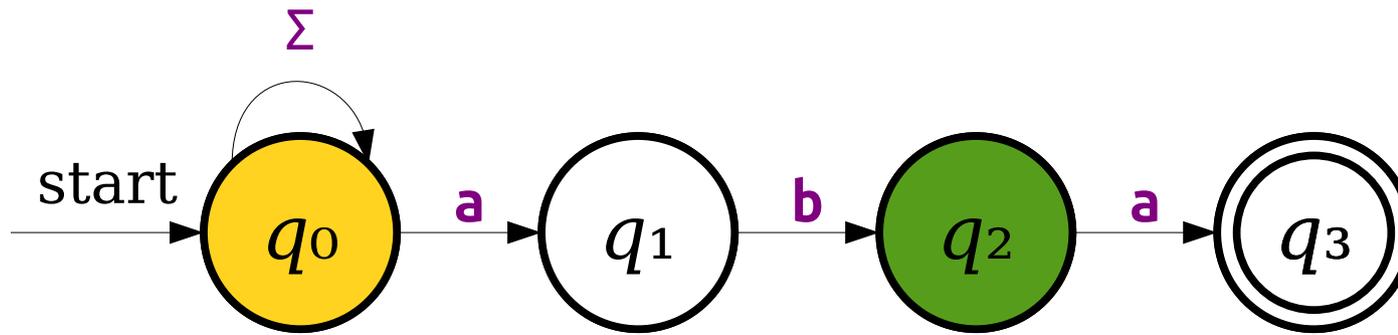
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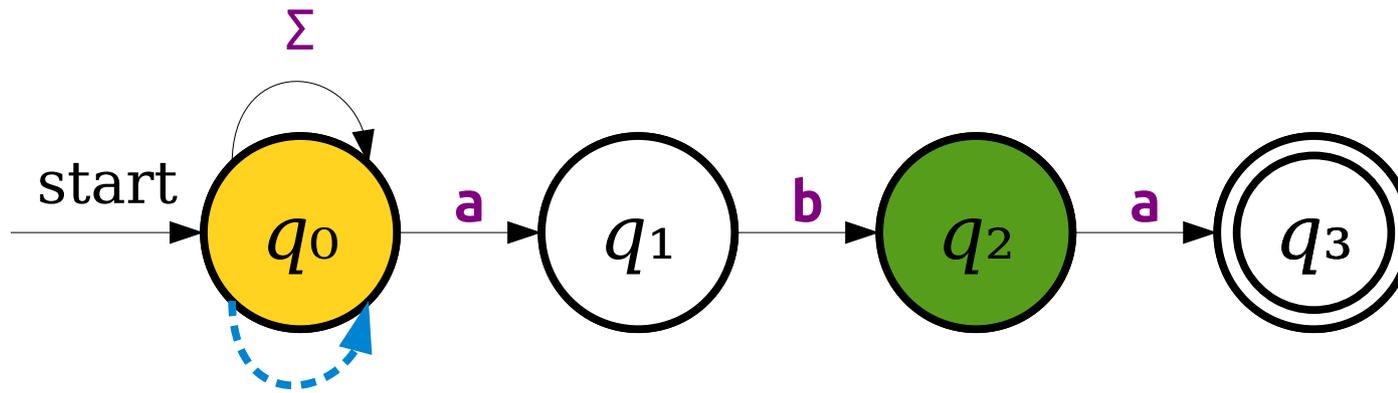
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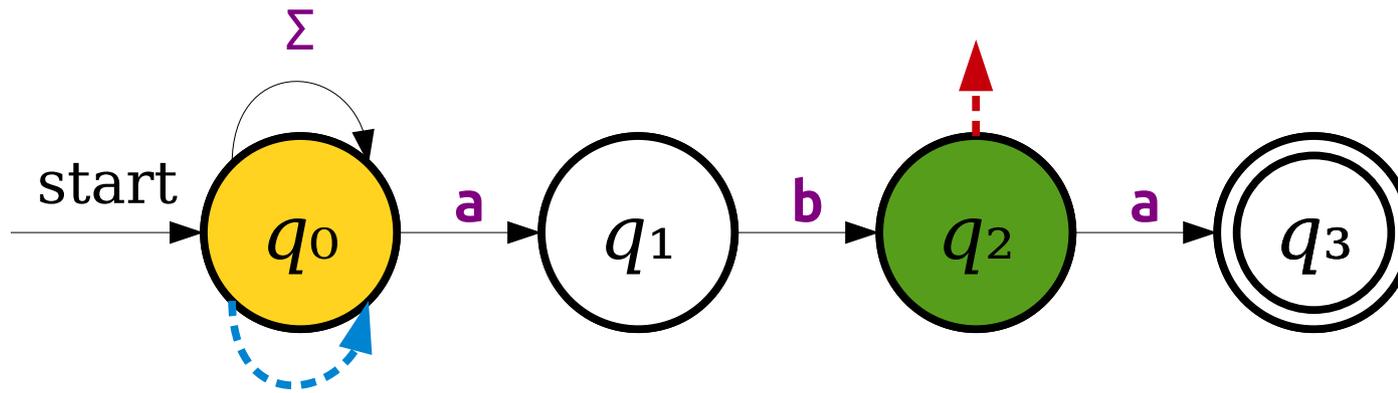
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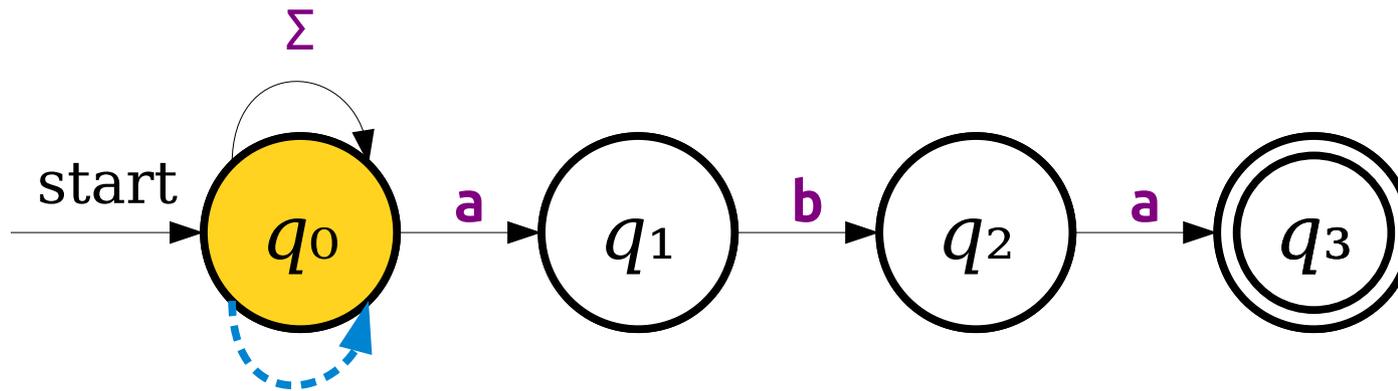
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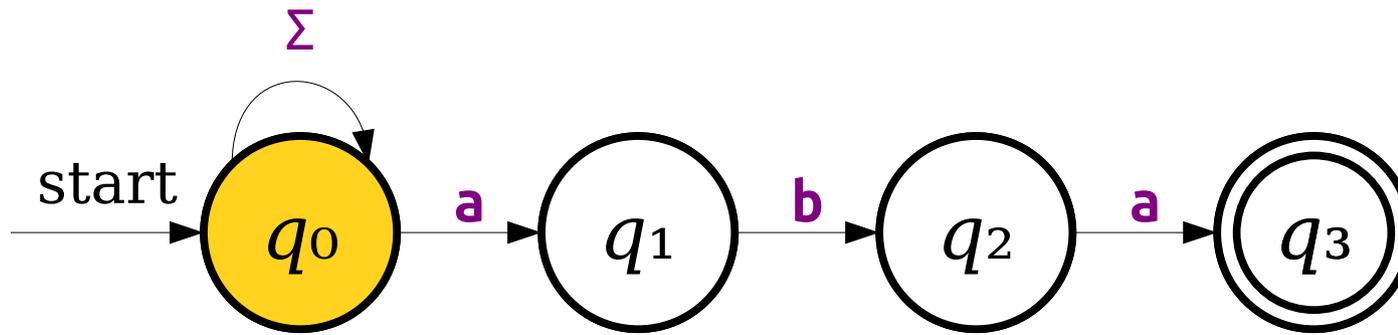
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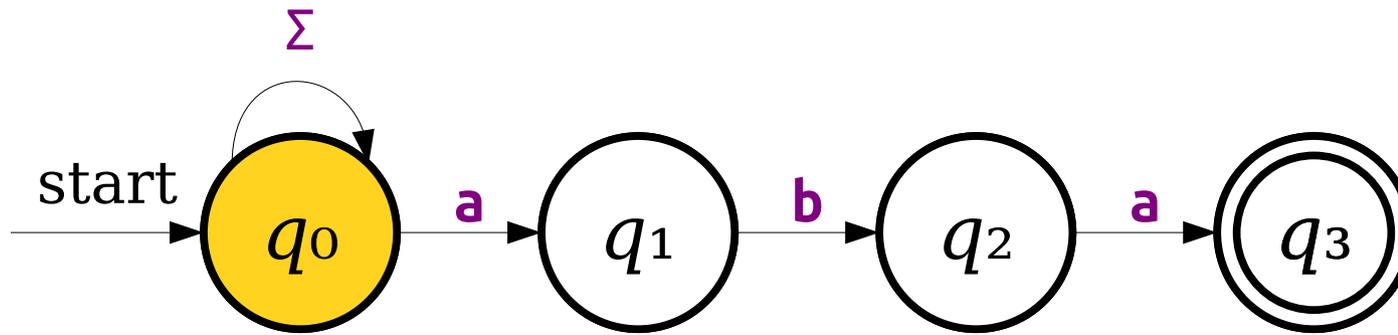
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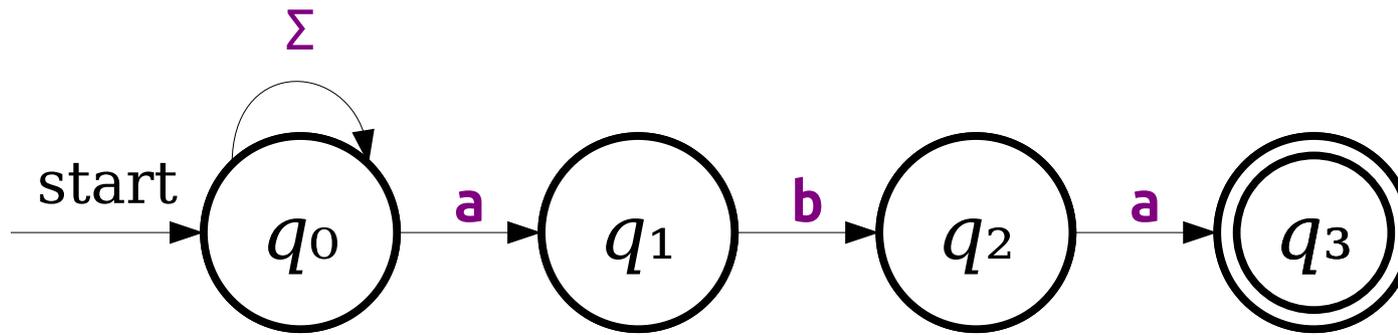
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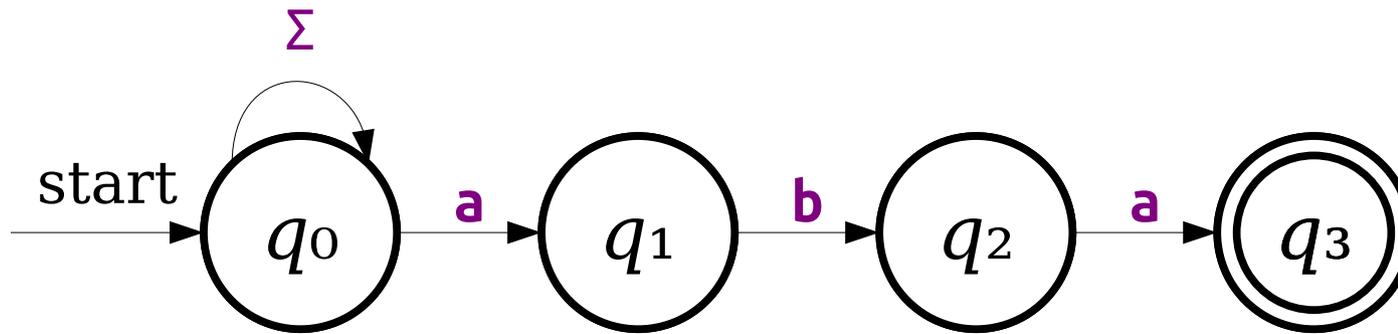
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| $\{q_0, q_2\}$ | $\{q_0, q_1, q_3\}$ | |
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| | a | b |
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| $\{q_0\}$ | $\{q_0, q_1\}$ | $\{q_0\}$ |
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| $\{q_0, q_2\}$ | $\{q_0, q_1, q_3\}$ | $\{q_0\}$ |
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| | <i>a</i> | <i>b</i> |
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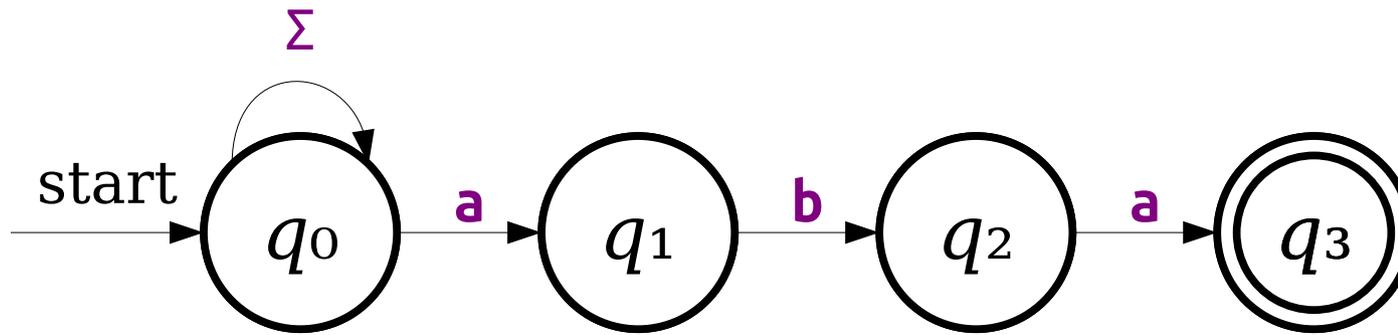


| | <i>a</i> | <i>b</i> |
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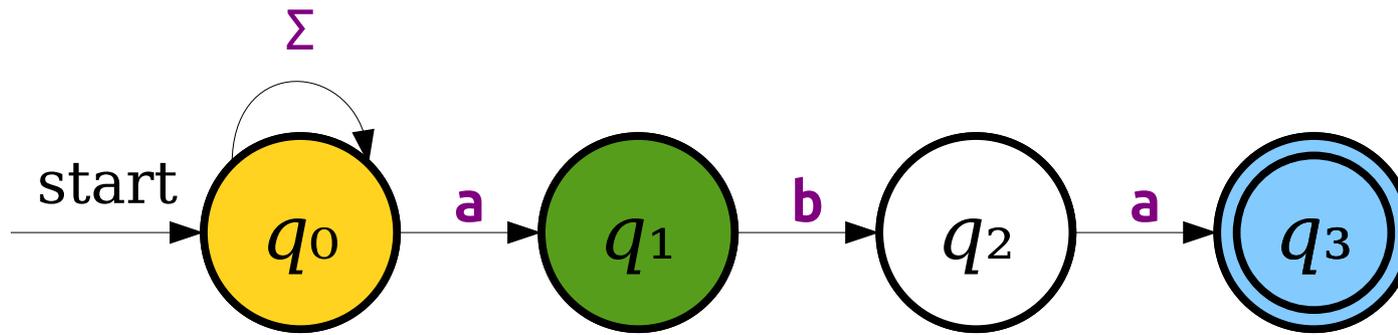
Fill in this row.

Answer at

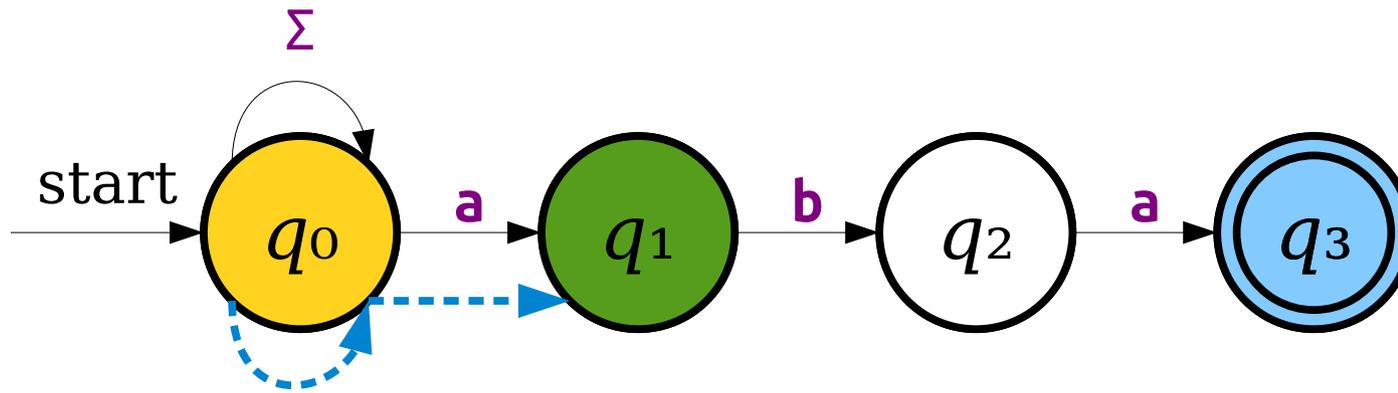
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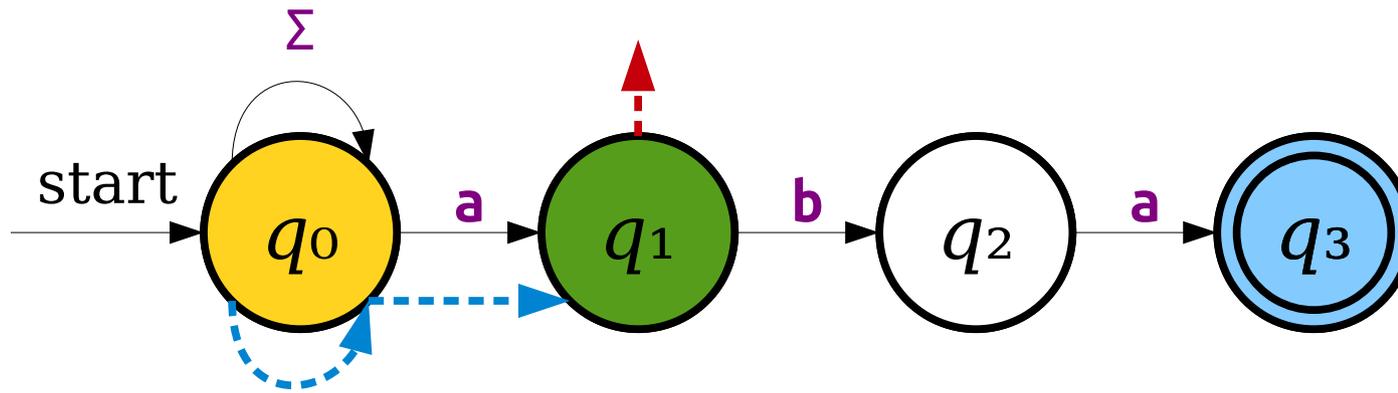
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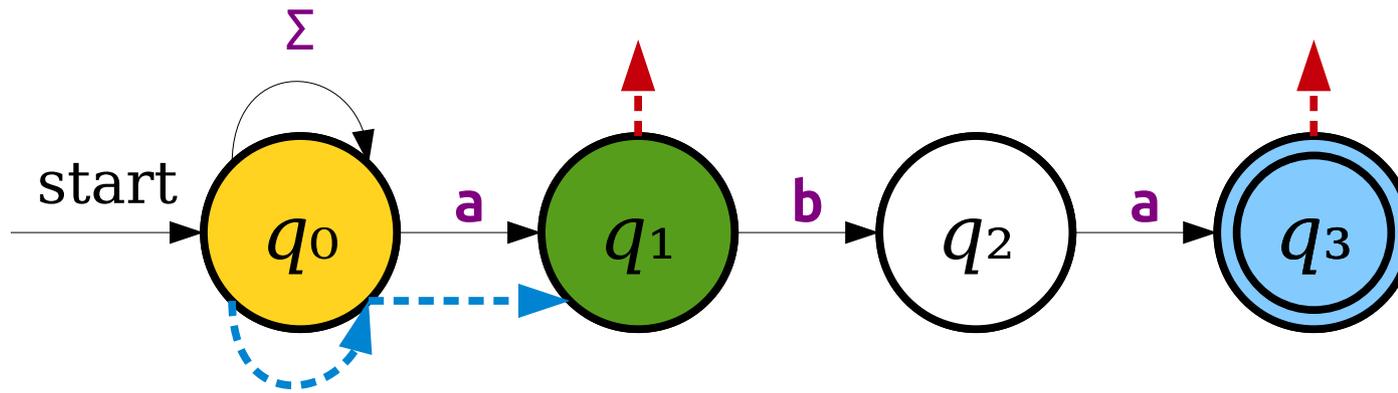
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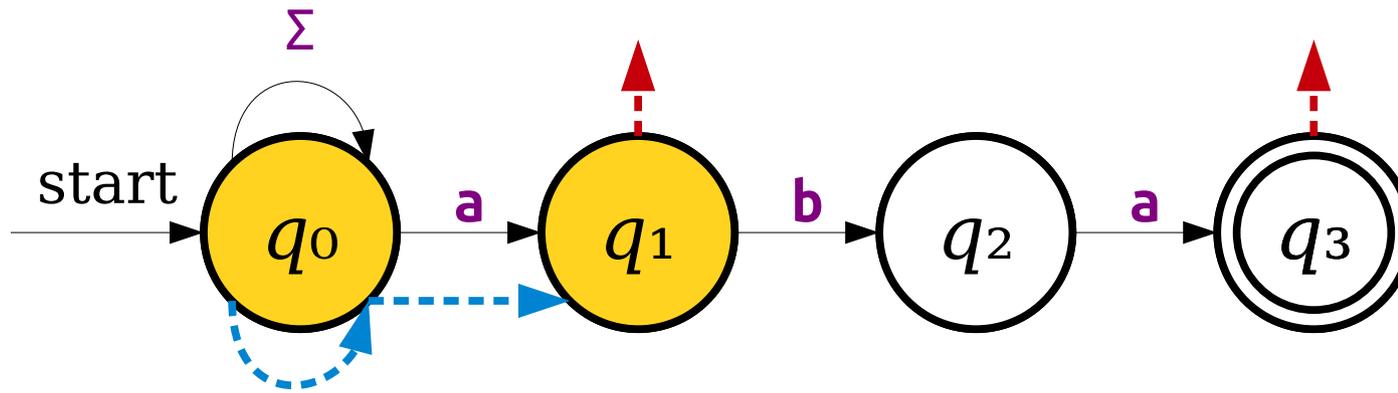
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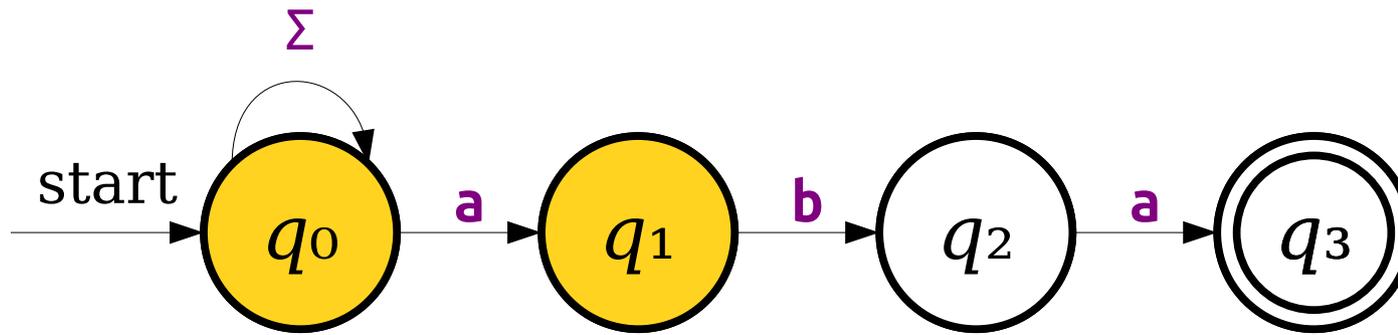
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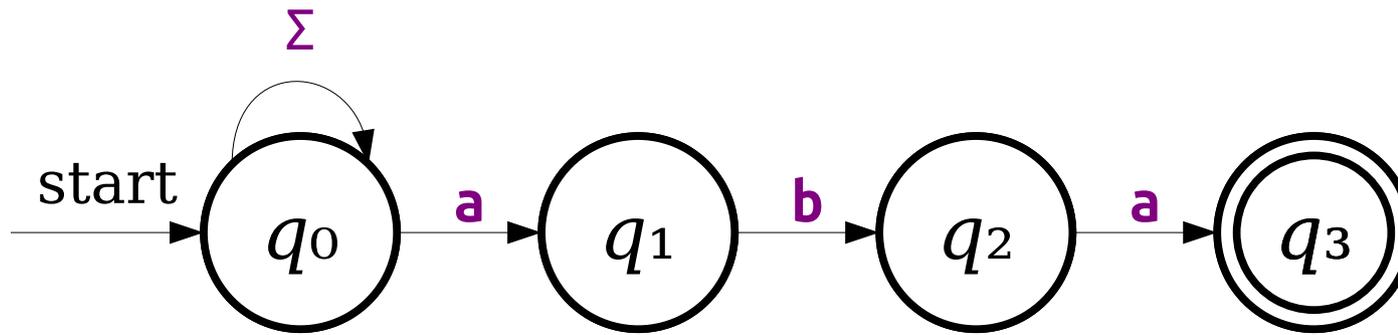
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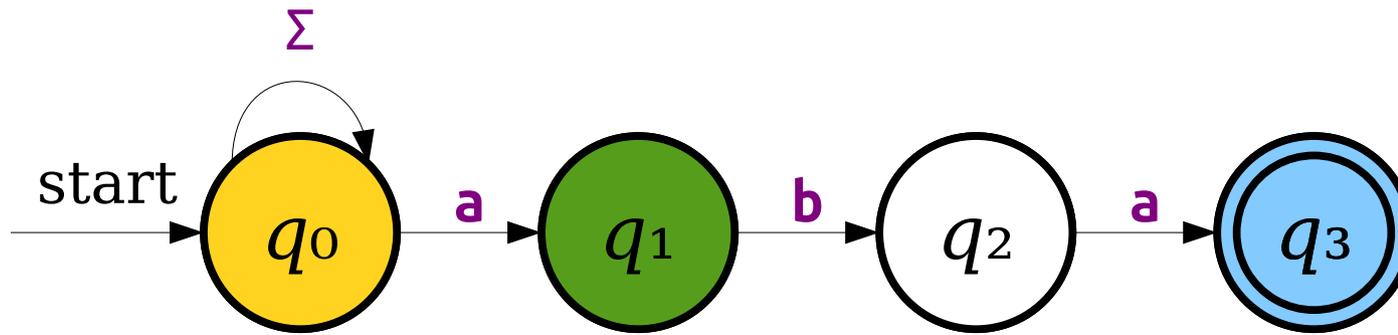
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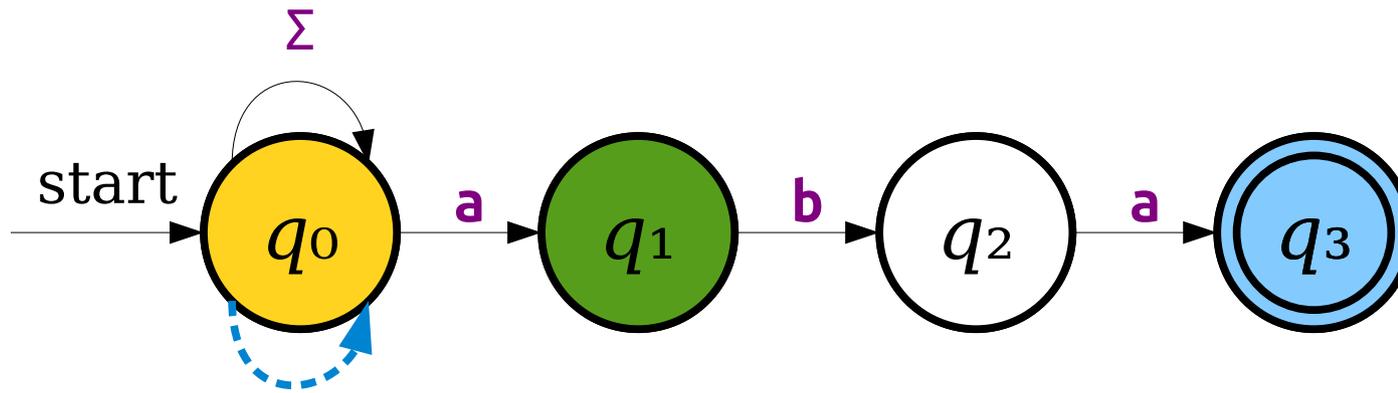
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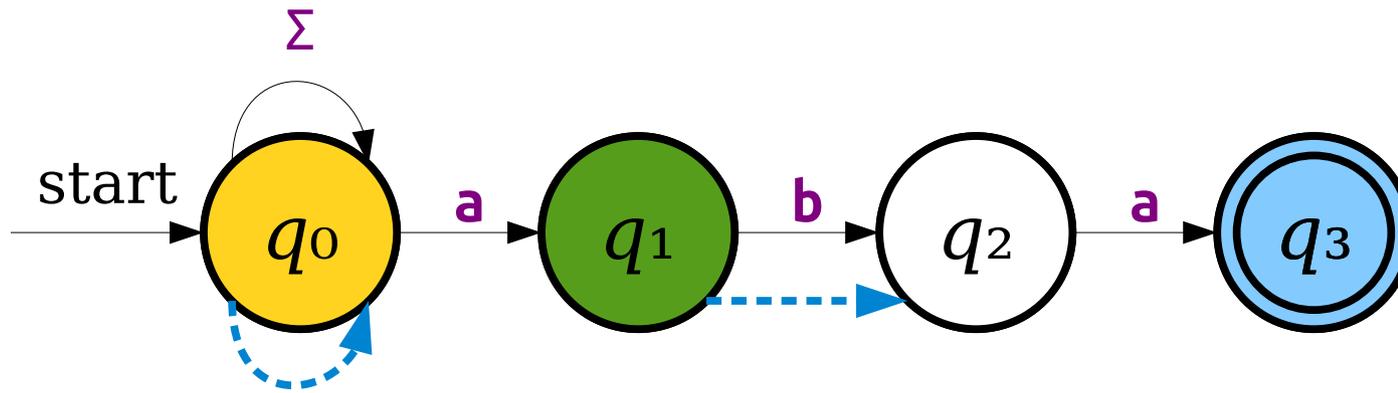
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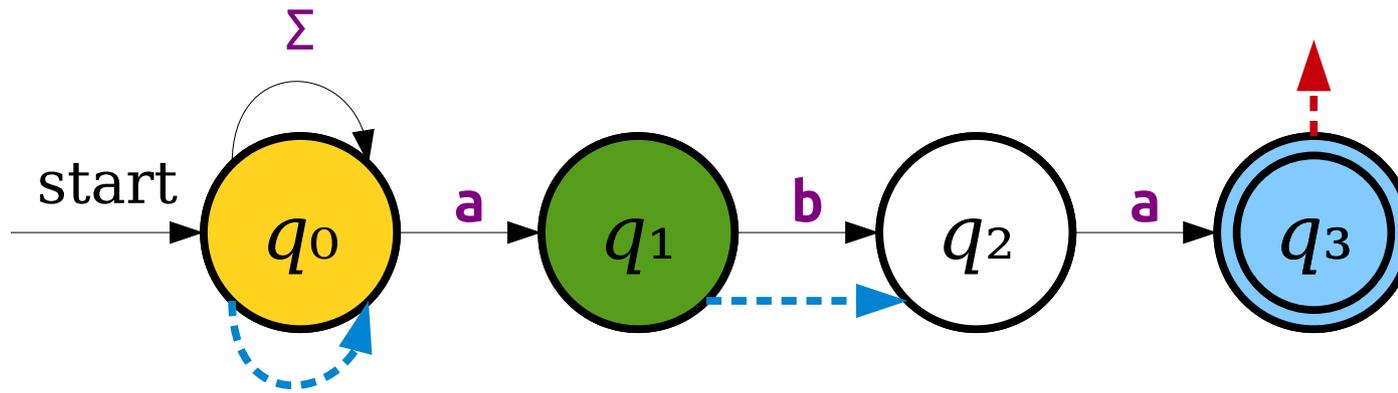
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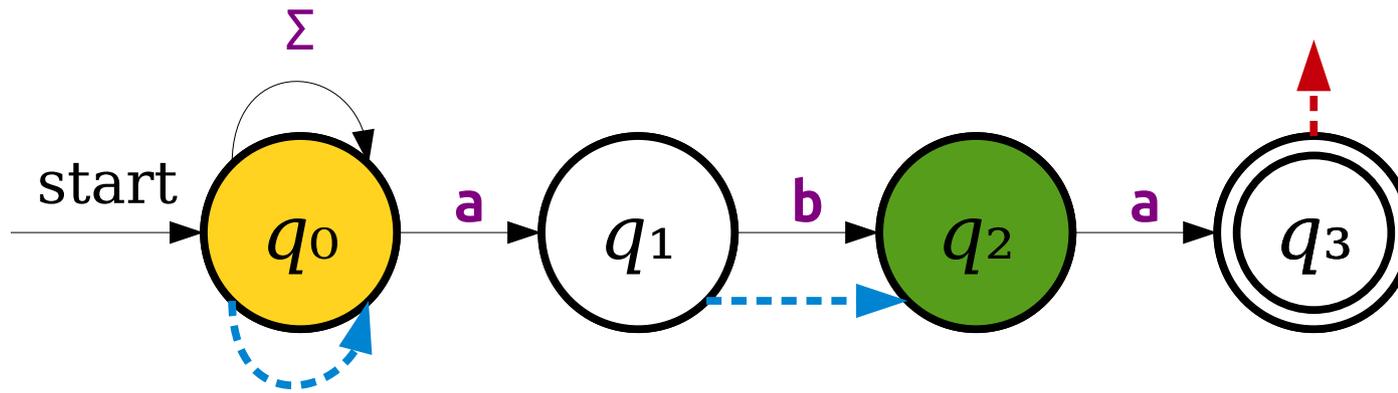
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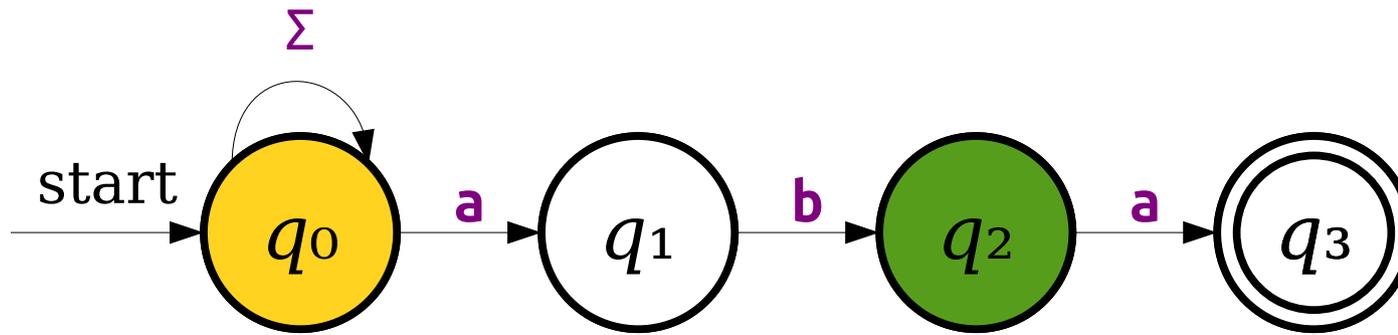
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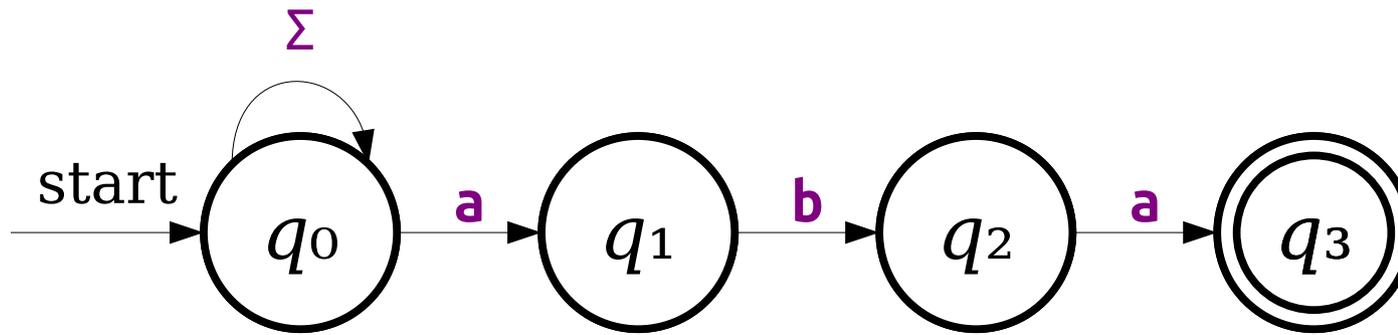
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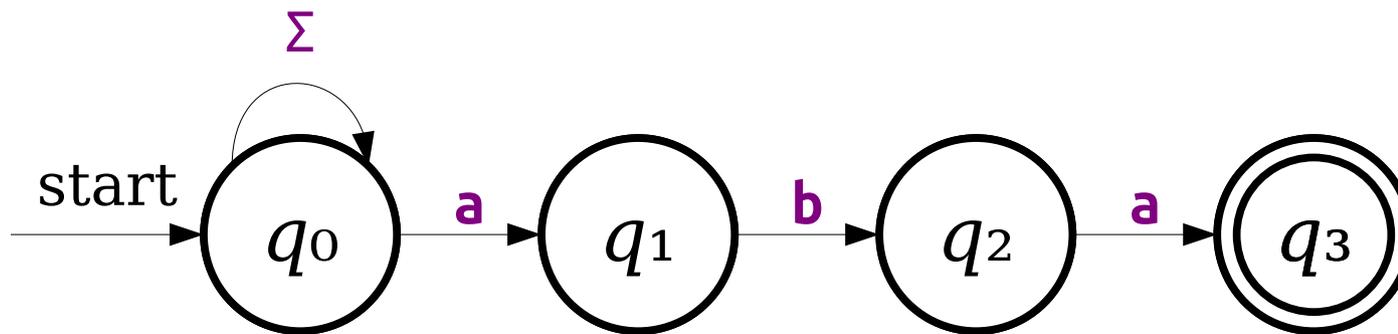
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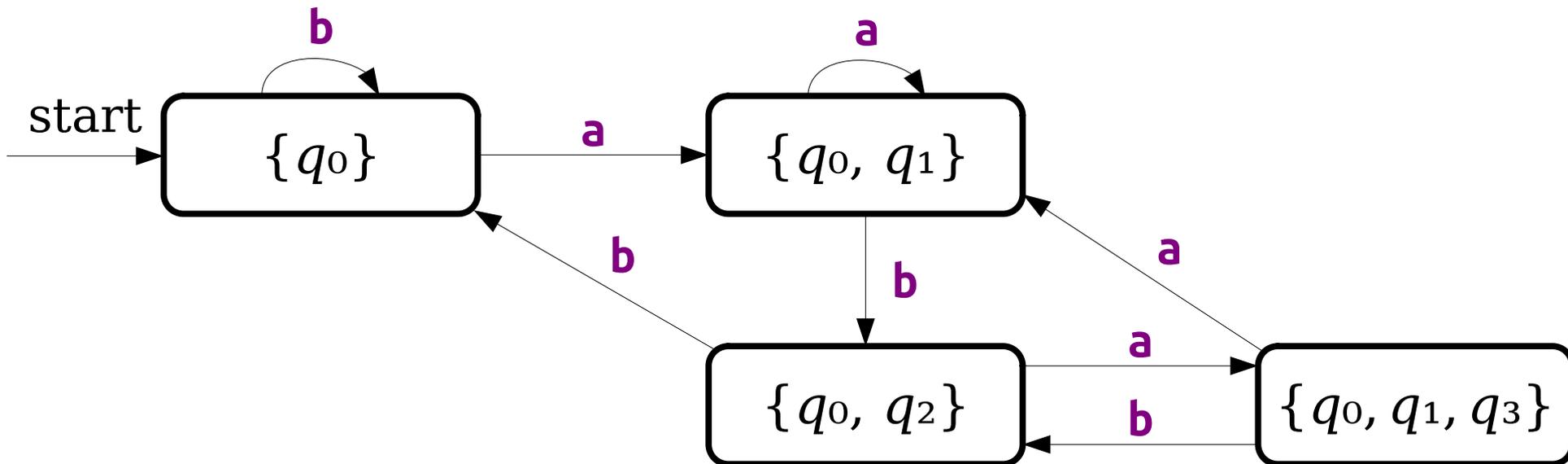
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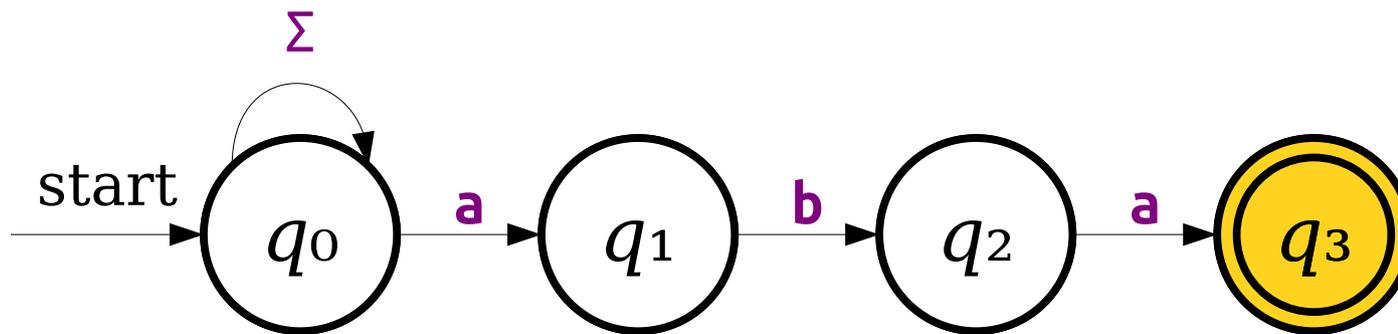


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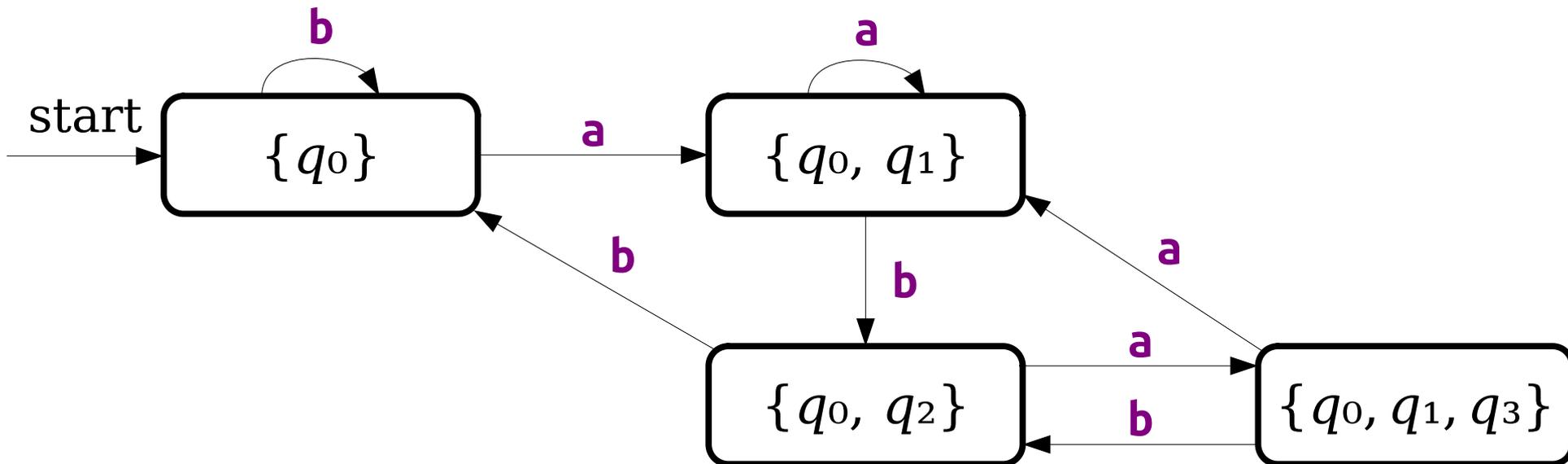


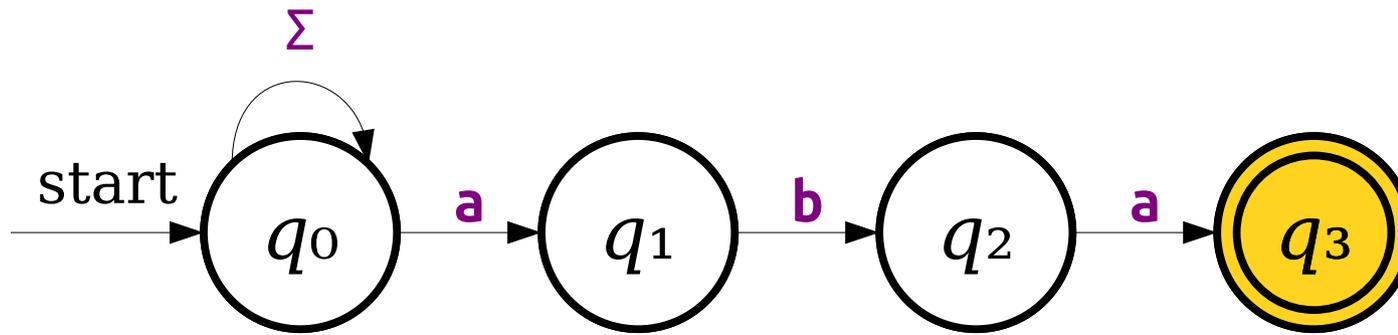
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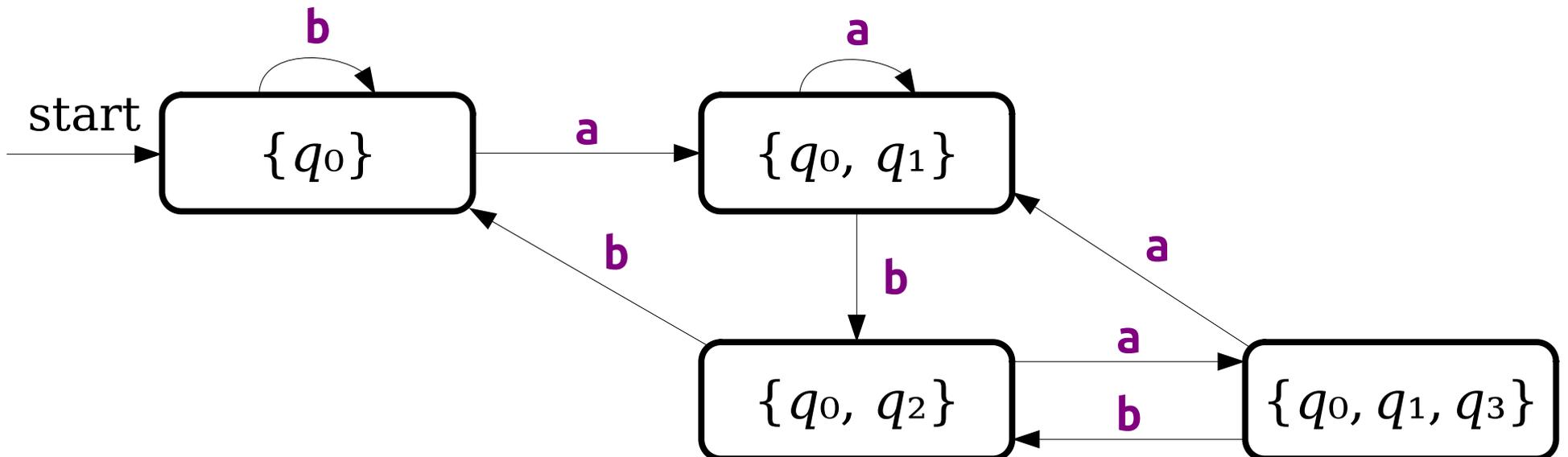


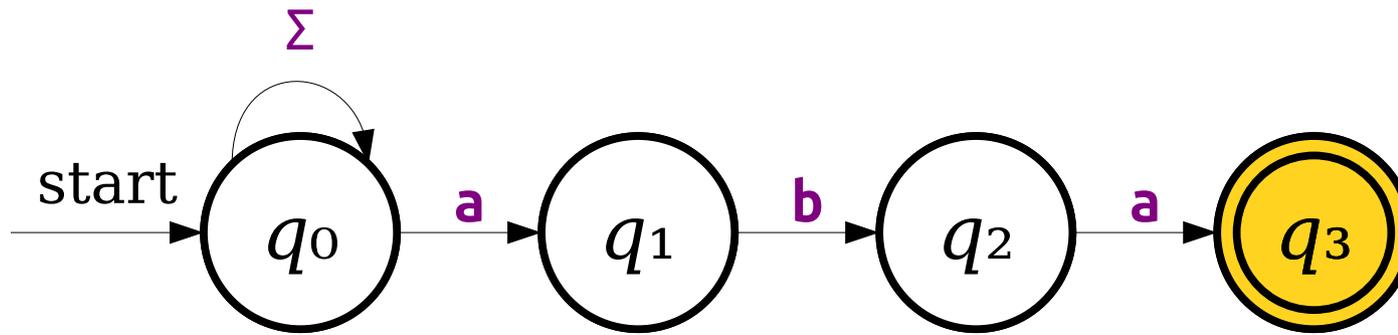
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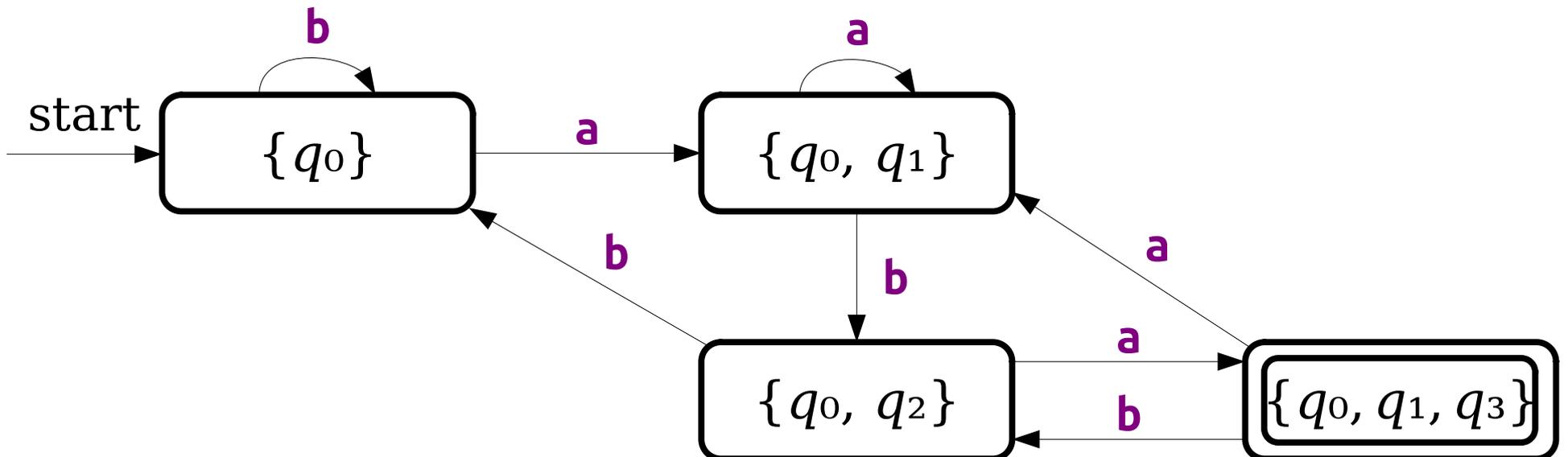


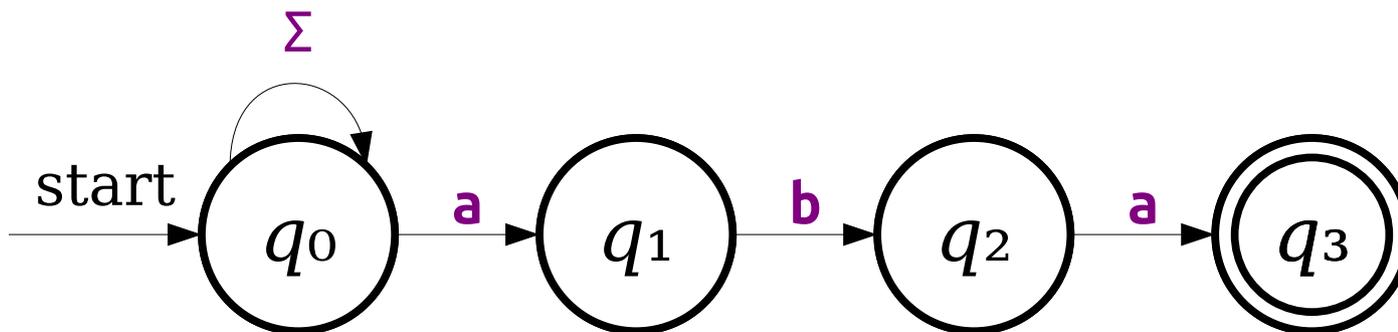
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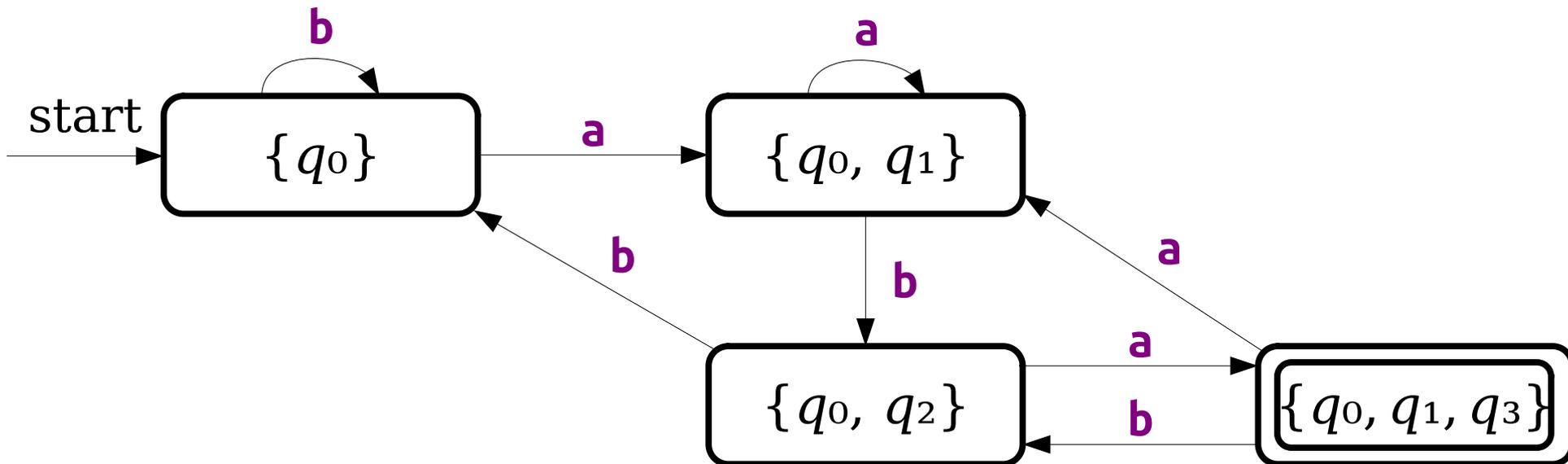


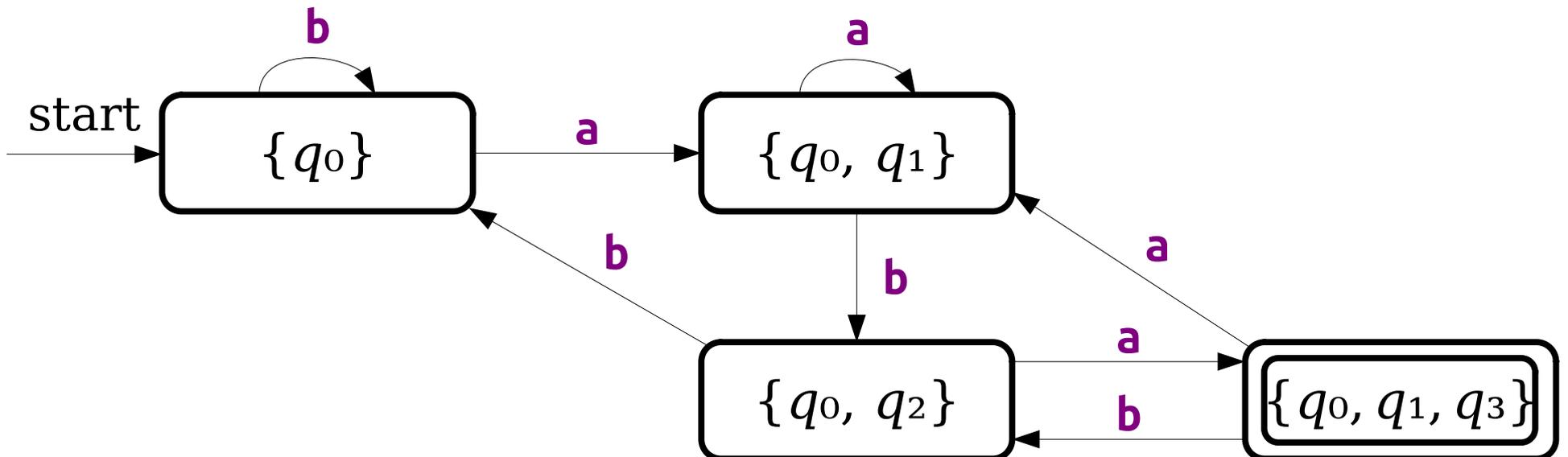
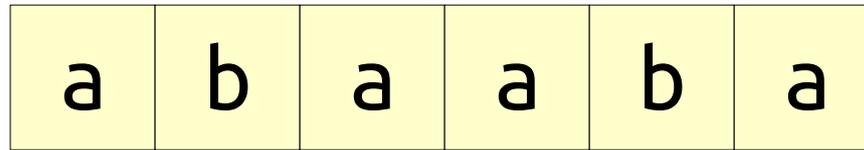
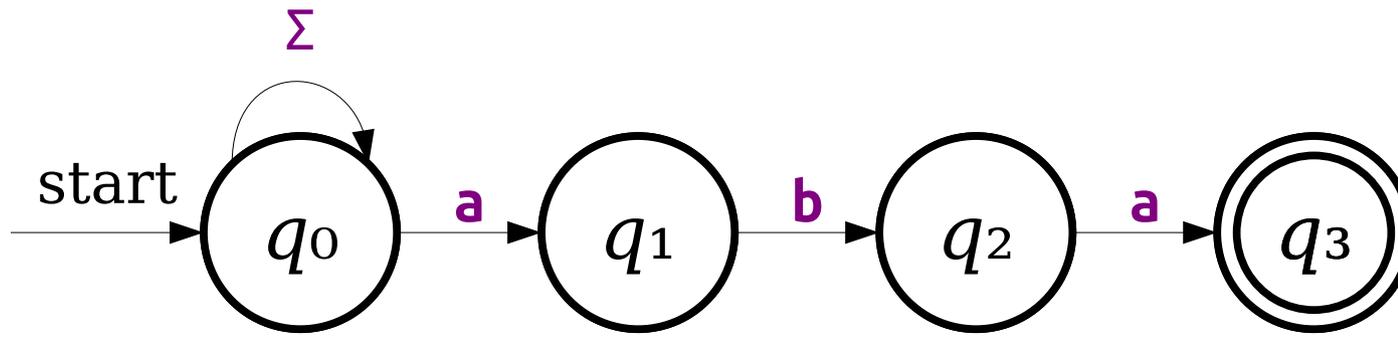
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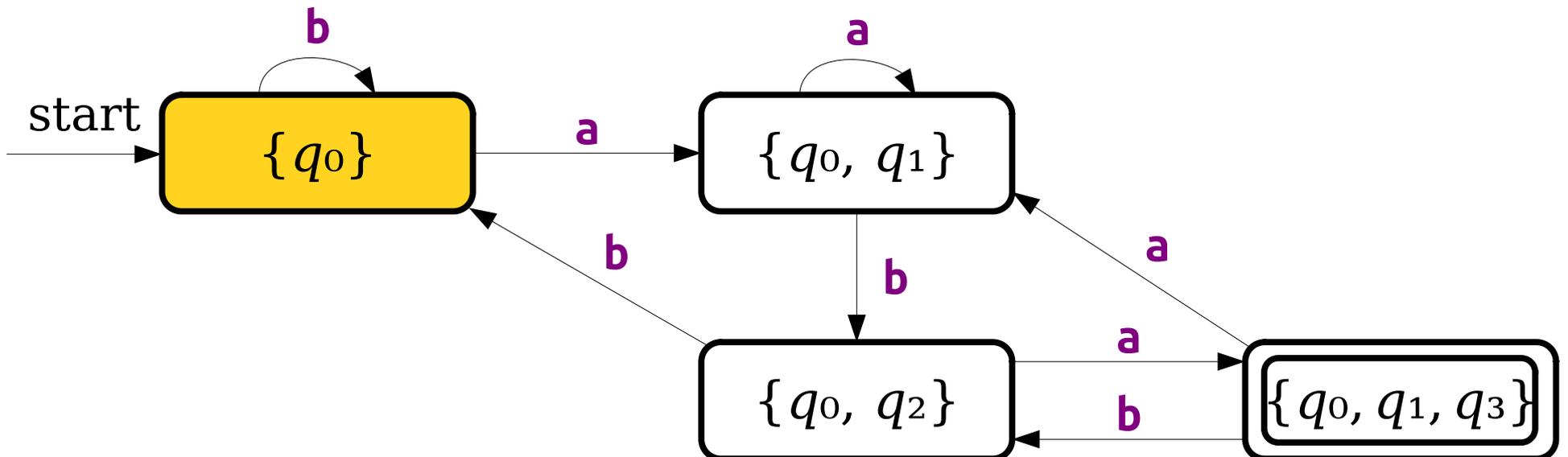
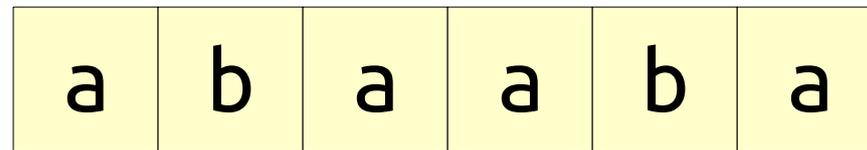
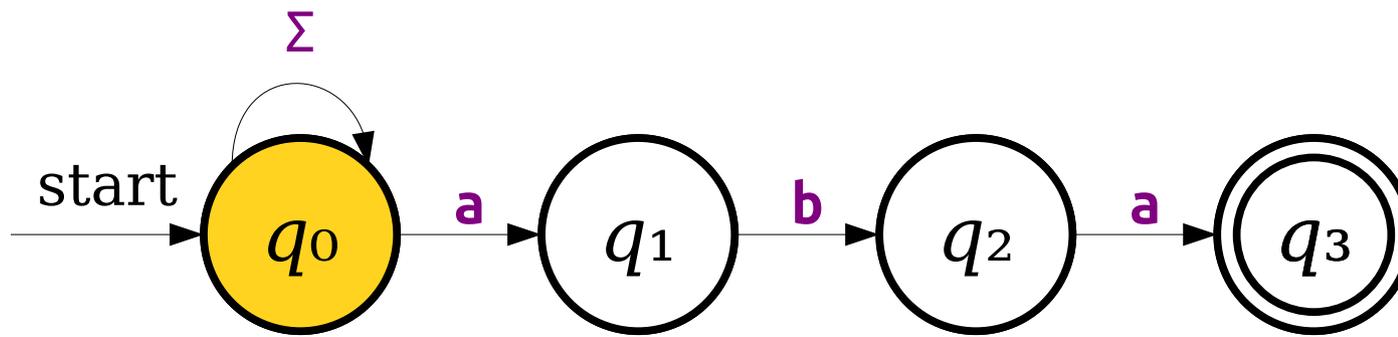


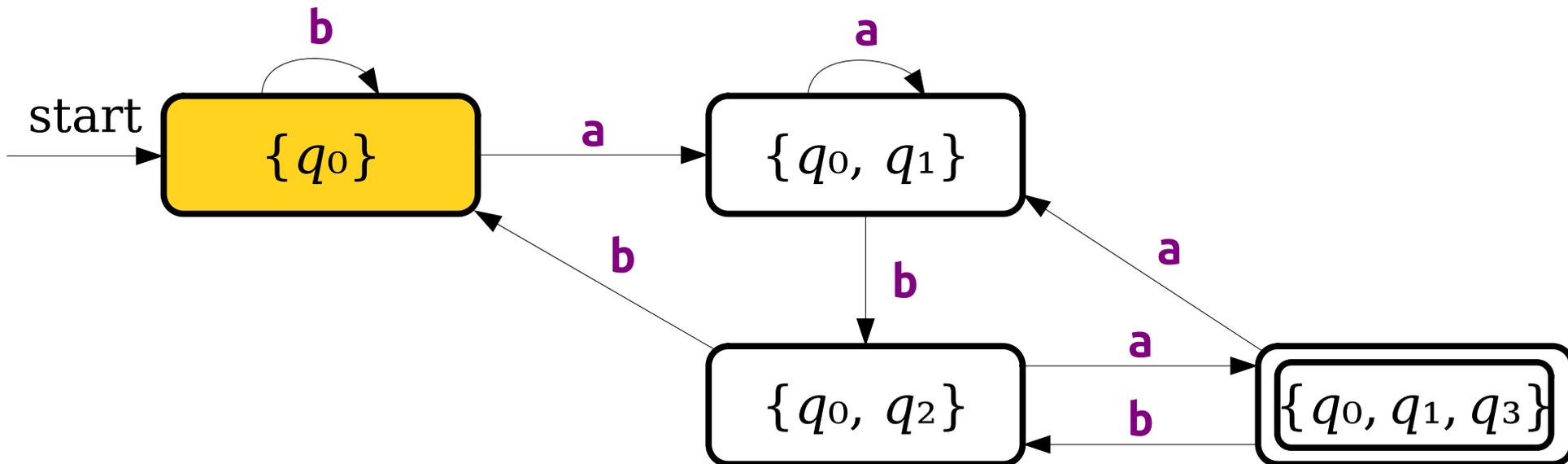
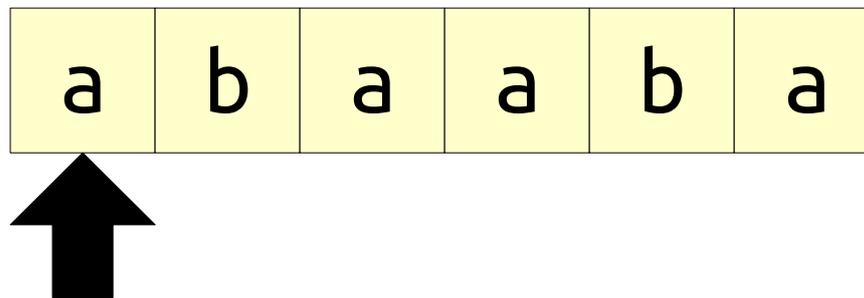
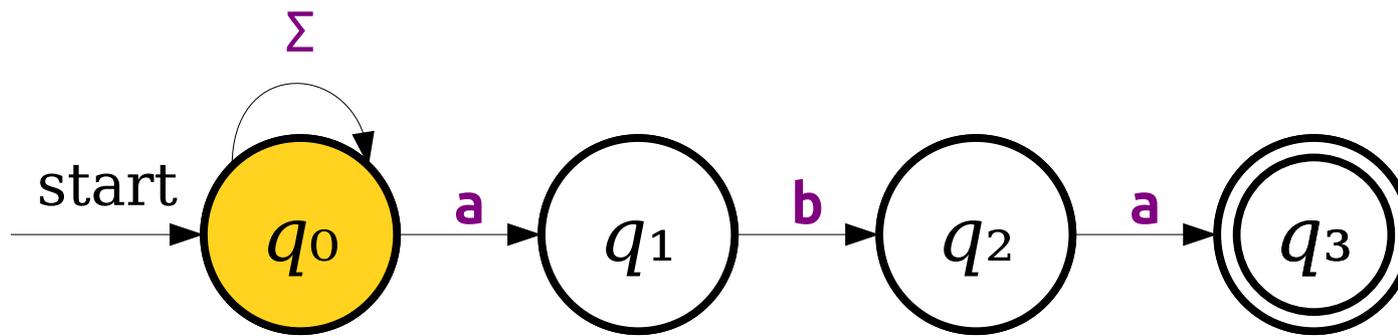


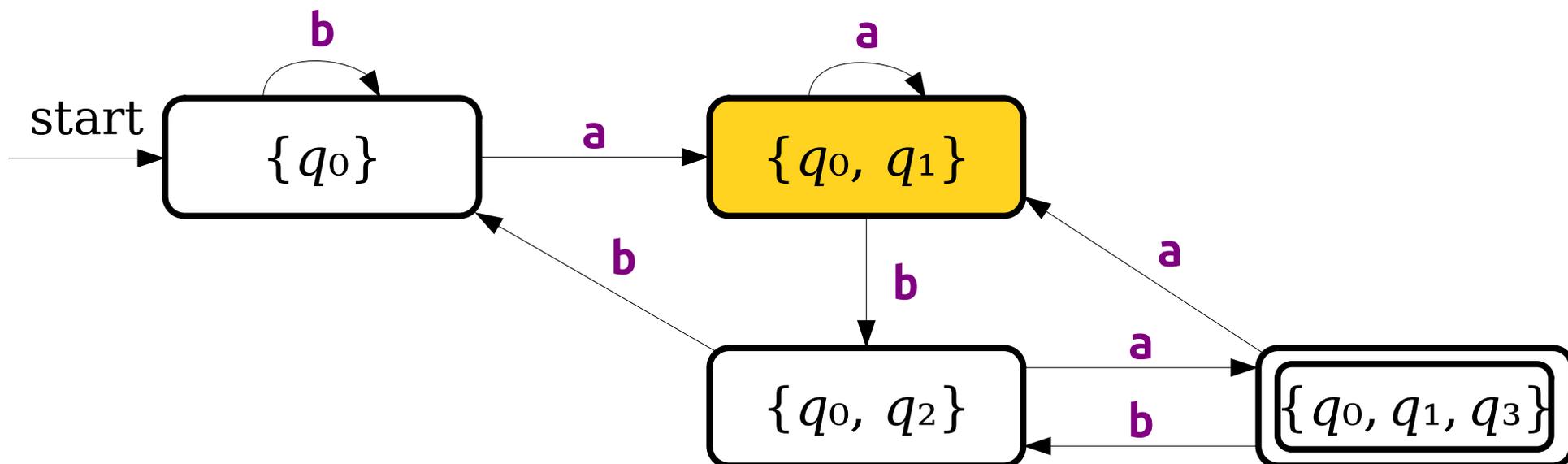
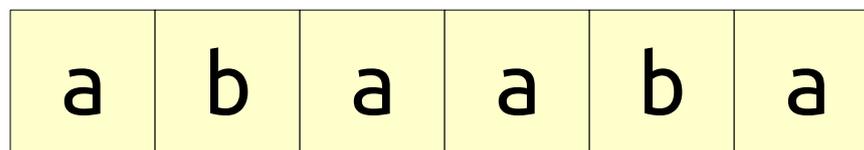
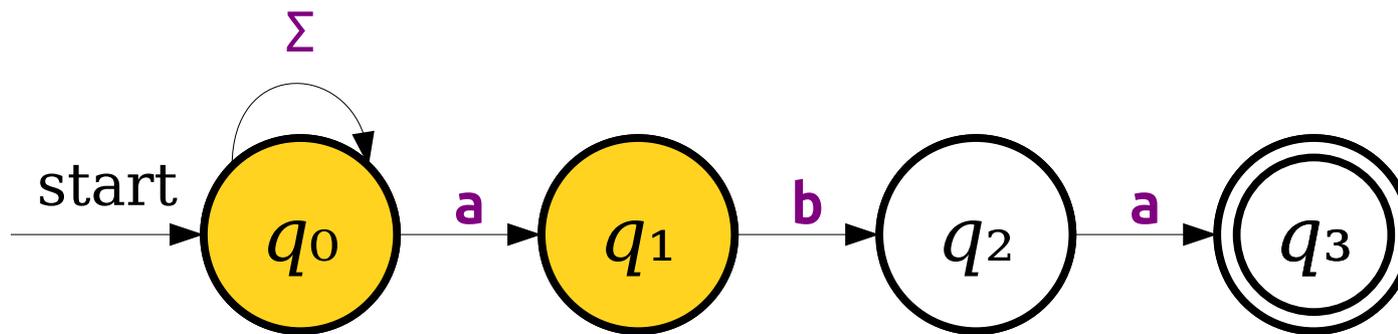
| | <i>a</i> | <i>b</i> |
|----------------------|---------------------|----------------|
| $\{q_0\}$ | $\{q_0, q_1\}$ | $\{q_0\}$ |
| $\{q_0, q_1\}$ | $\{q_0, q_1\}$ | $\{q_0, q_2\}$ |
| $\{q_0, q_2\}$ | $\{q_0, q_1, q_3\}$ | $\{q_0\}$ |
| $*\{q_0, q_1, q_3\}$ | $\{q_0, q_1\}$ | $\{q_0, q_2\}$ |

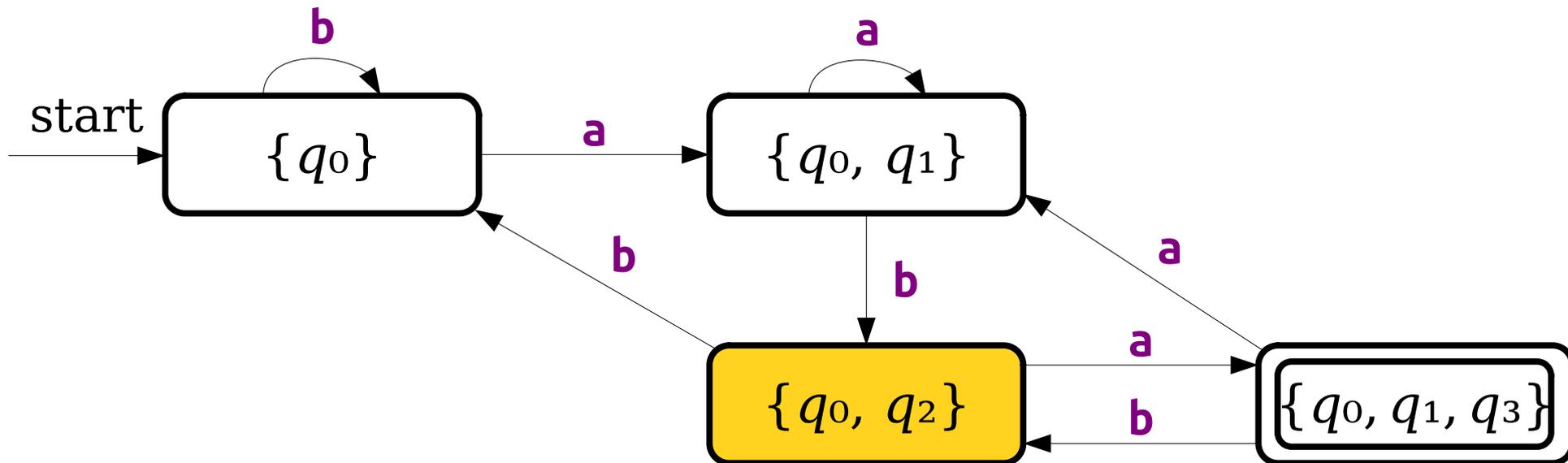
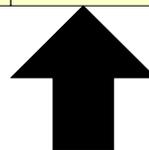
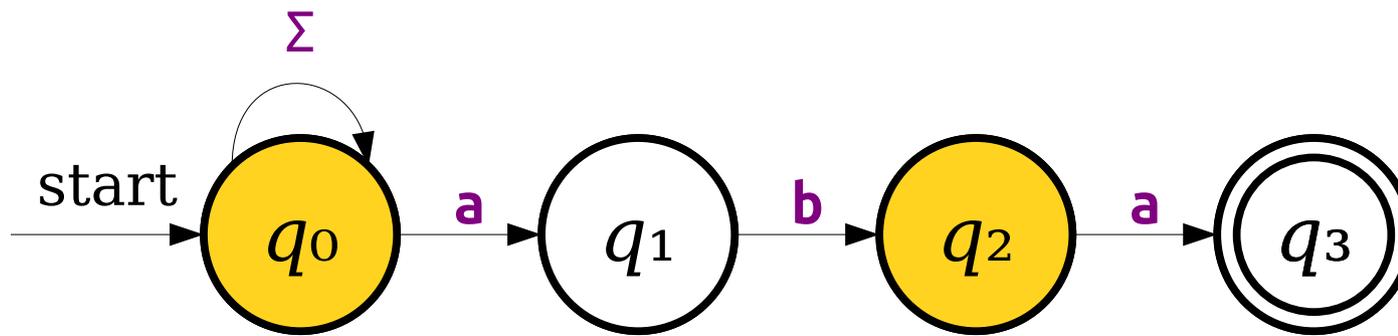


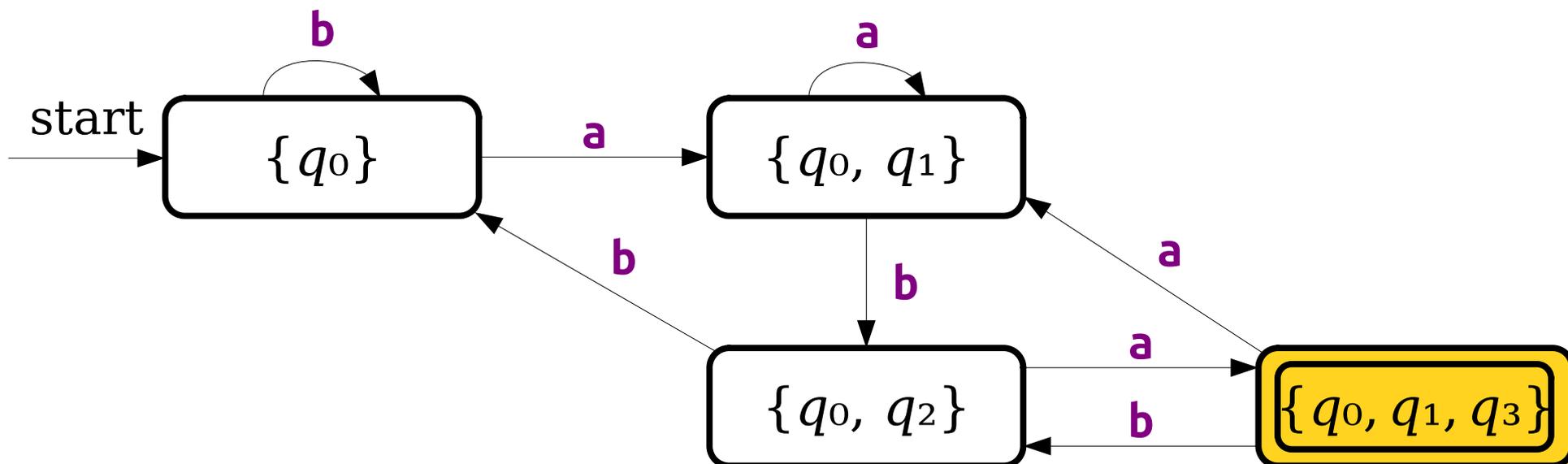
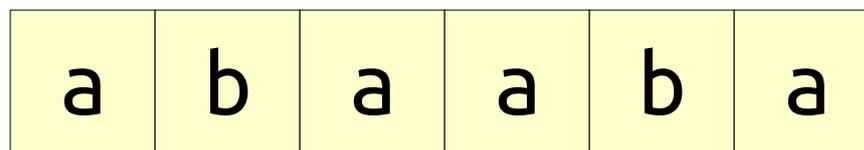
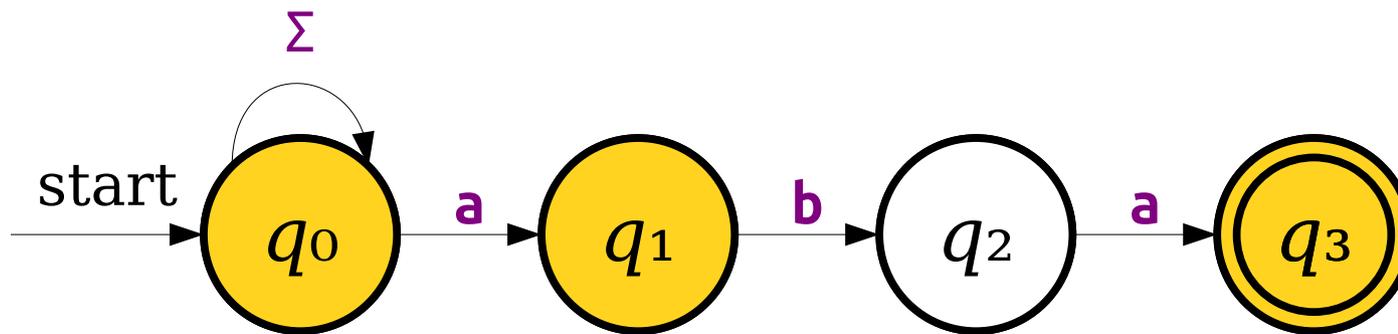


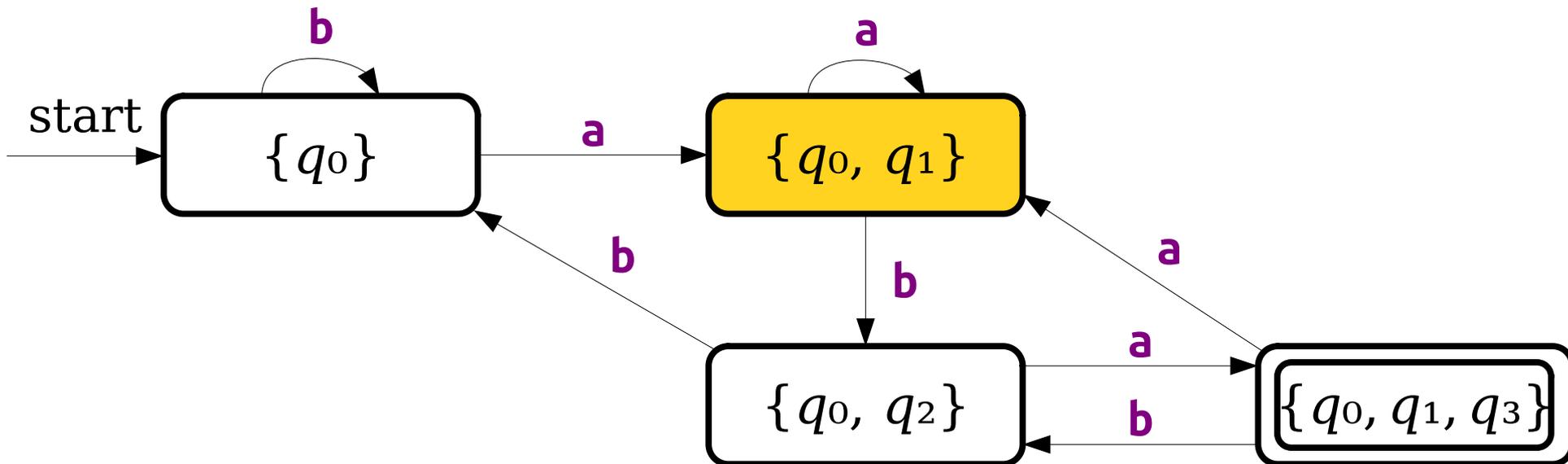
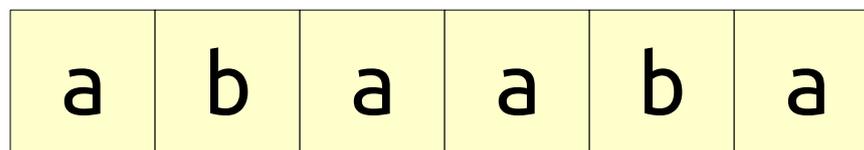
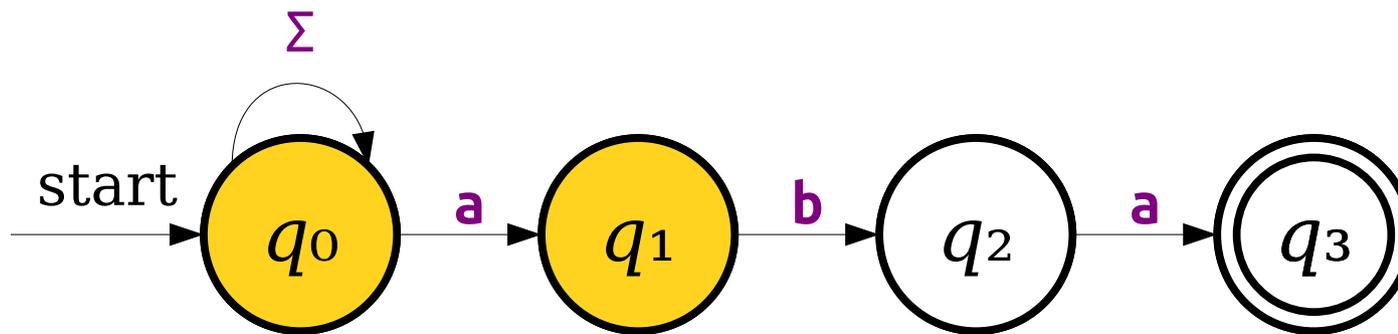


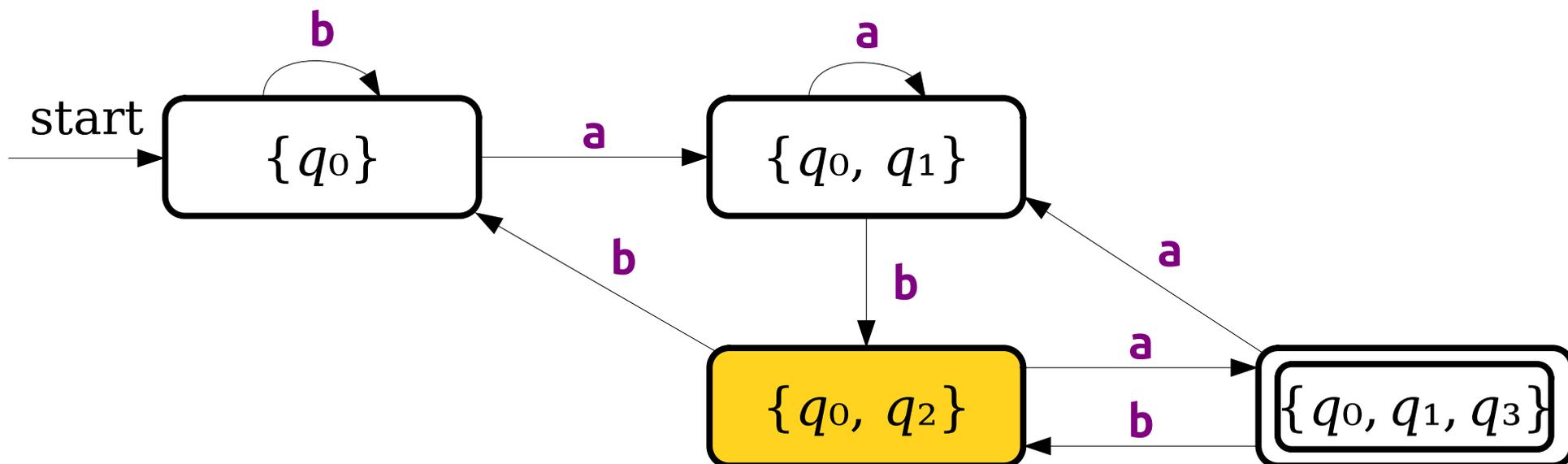
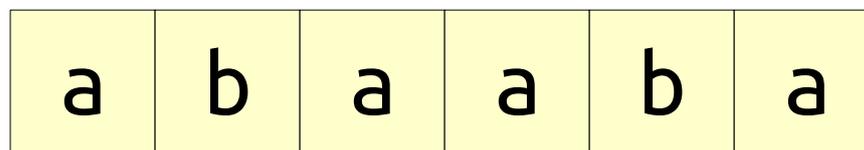
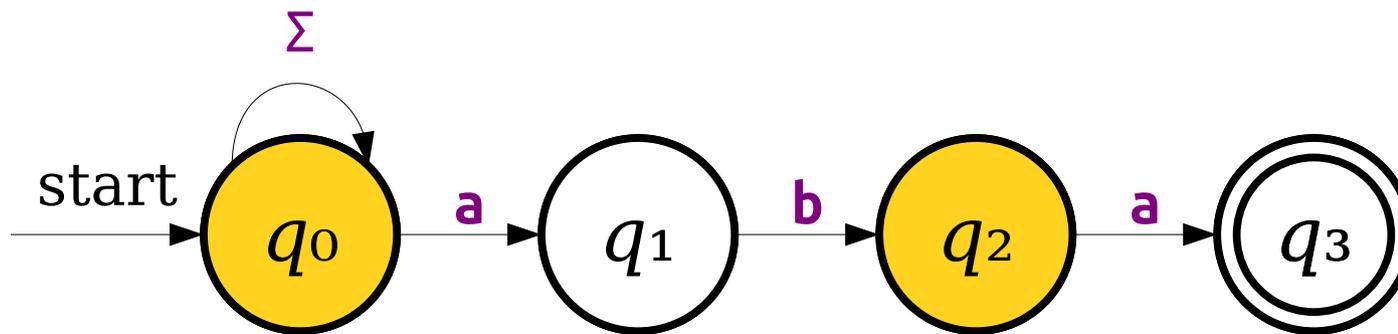


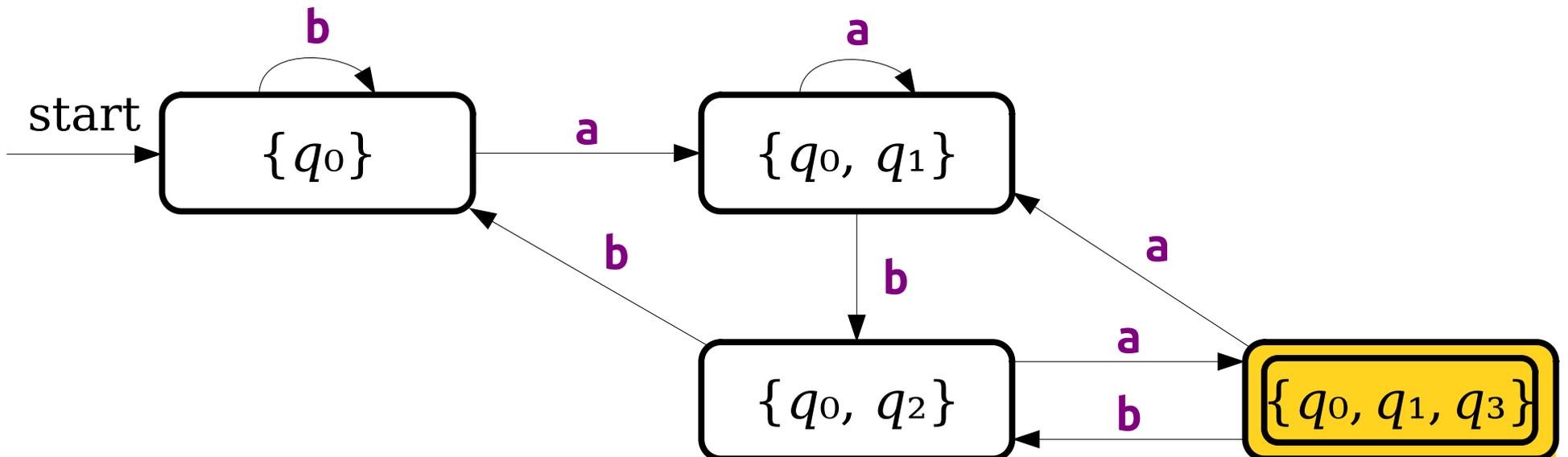
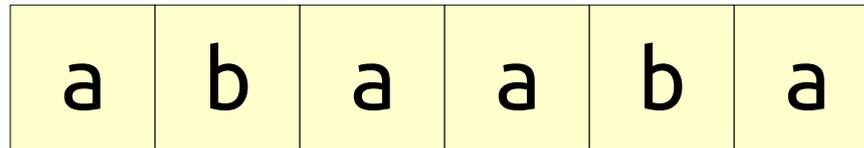
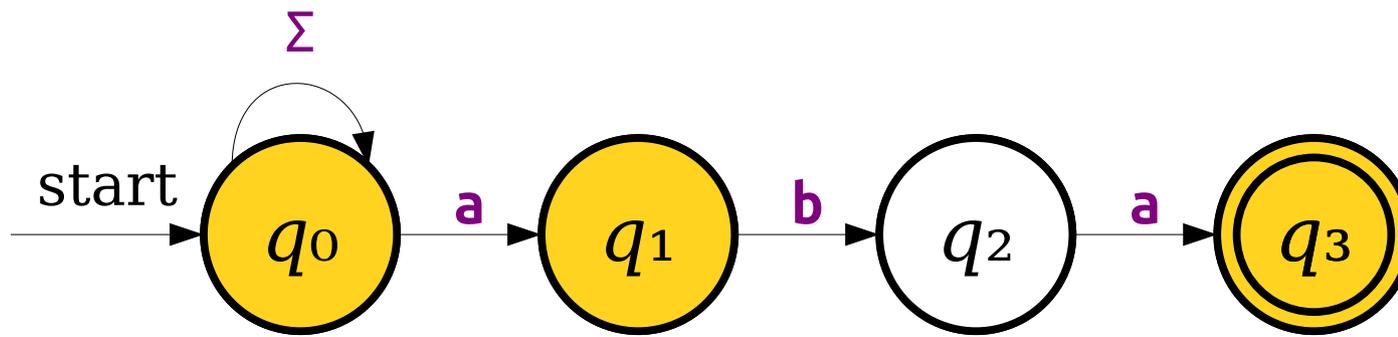












The Subset Construction

- This procedure for turning an NFA for a language L into a DFA for a language L is called the **subset construction**.
 - It's sometimes called the **powerset construction**; it's different names for the same thing!
- Intuitively:
 - Each state in the DFA corresponds to a set of states from the NFA.
 - Each transition in the DFA corresponds to what transitions would be taken in the NFA when using the massive parallel intuition.
 - The accepting states in the DFA correspond to which sets of states would be considered accepting in the NFA when using the massive parallel intuition.
- There's an online **Guide to the Subset Construction** with a more elaborate example involving ϵ -transitions and cases where the NFA dies; check that for more details.

The Subset Construction

- In converting an NFA to a DFA, the DFA's states correspond to sets of NFA states.
- **Useful fact:** $|\wp(S)| = 2^{|S|}$ for any finite set S .
- In the worst-case, the construction can result in a DFA that is *exponentially larger* than the original NFA.
- **Question to ponder:** Can you find a family of languages that have NFAs of size n , but no DFAs of size less than 2^n ?

Regular Languages

- A language L is called **regular** when there's a DFA D that recognizes L (that is, $\mathcal{L}(D) = L$).
- **Theorem:** A language L is regular if and only if there's an NFA N that recognizes it (that is, $\mathcal{L}(N) = L$).
- This fact makes it possible to explore regular languages by considering either DFAs or NFAs.

Time-Out for Announcements!

Problem Set Six

- Problem Set Five was due today at 1:00PM.
 - You can use a late day to extend the deadline to Saturday at 1:00PM.
- Problem Set Six goes out today. It's due next Friday at 1:00PM.
 - Play around with automata!
 - Explore properties of languages!
 - See some cool applications!

Second Midterm Exam

- Our second midterm exam is ***Monday, November 11th*** from ***7PM - 10PM***.
 - Locations TBA.
- Topic focus is Lecture 06 - 13 (functions through induction) and PS3 - PS5. Later topics (automata forward) will not be tested. Earlier material may be covered because course concepts are cumulative.
- We will post a set of practice problems for the second midterm on the course website later today if you want to get a jump on studying.
- More details next Monday.

Back to CS103!

Motivating Example: ***Numbers***

Numbers

- Numbers can be written in many ways:

2718

2,718

2.718×10^3

MMDCCXVIII

二千七百一十八

ב'תשי"ח

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etc.

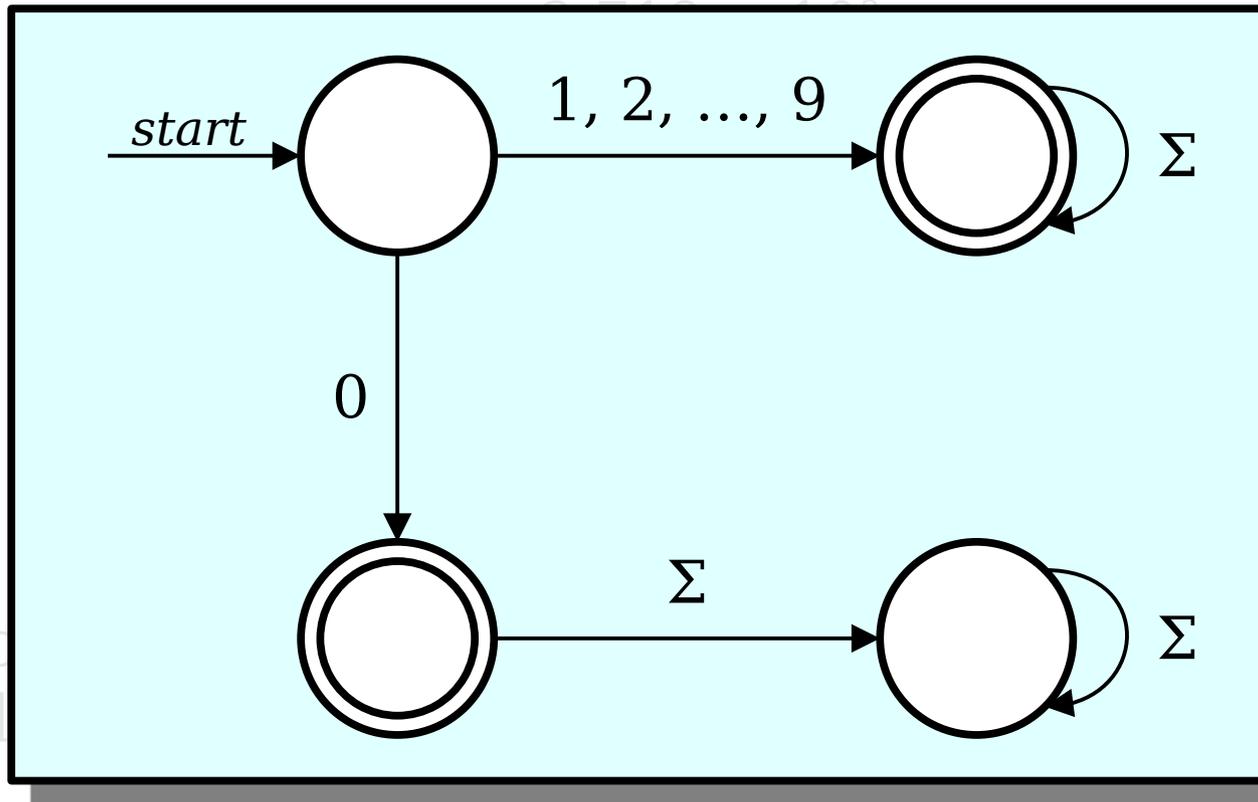
- How would we design a DFA or NFA that checks if a particular string is a number in some numeral system?

Numbers

- Numbers can be written in many ways:

2718

2,718



- How would you represent a particular number in this system?

How would you represent a particular number in this system?

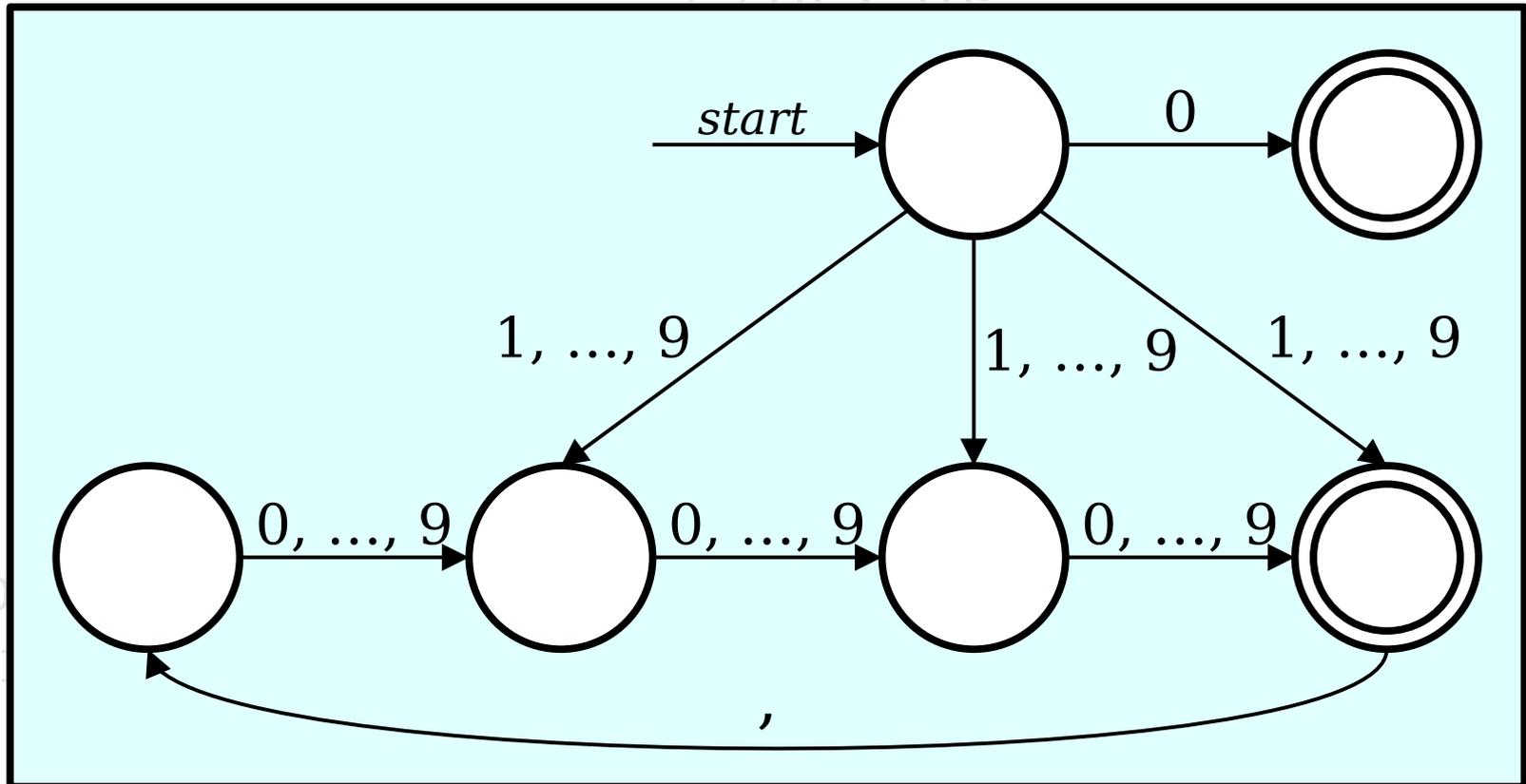
Numbers

- Numbers can be written in many ways:

2718

2,718

$2,718 \times 10^3$



- How
part

...
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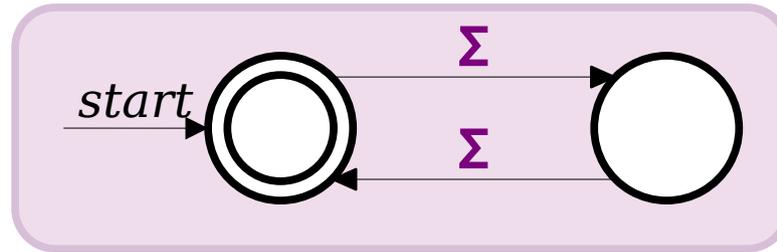
Practical Question: If we can build a bunch of finite automata that all recognize certain patterns, can we build a single finite automaton that recognizes all of those patterns?

Closure Under Union

- If L_1 and L_2 are languages over the alphabet Σ , the language $L_1 \cup L_2$ is the language of all strings in at least one of the two languages.
- Intuitively, if L_1 and L_2 correspond to languages of strings with one of two different patterns, then $L_1 \cup L_2$ is the language of strings with at least one of those patterns.
- **Theorem:** If L_1 and L_2 are regular, so is $L_1 \cup L_2$.

$$L_1 = \{ w \in \{\mathbf{a}, \mathbf{b}\}^* \mid w \text{ has even length} \}$$
$$L_2 = \{ w \in \{\mathbf{a}, \mathbf{b}\}^* \mid w \text{ has length exactly three} \}$$

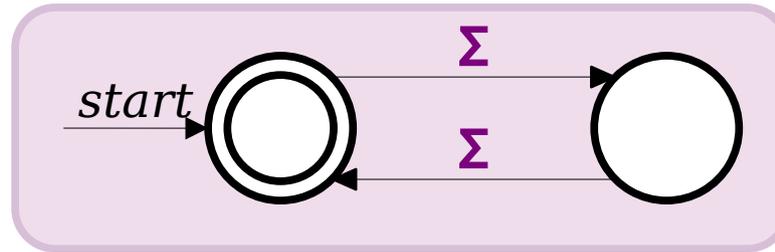
Construct an NFA for $L_1 \cup L_2$.



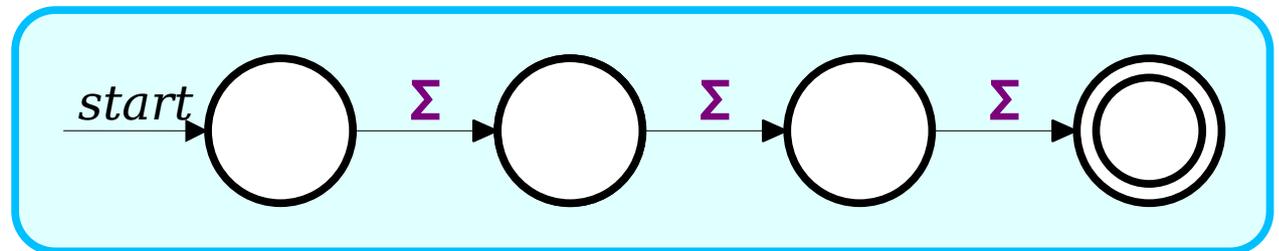
DFA for L_1

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Construct an NFA for $L_1 \cup L_2$.



DFA for L_1

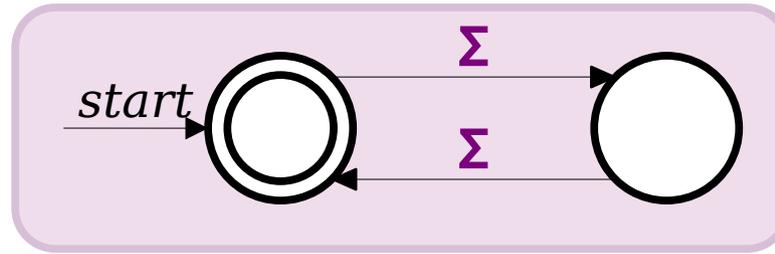


NFA for L_2

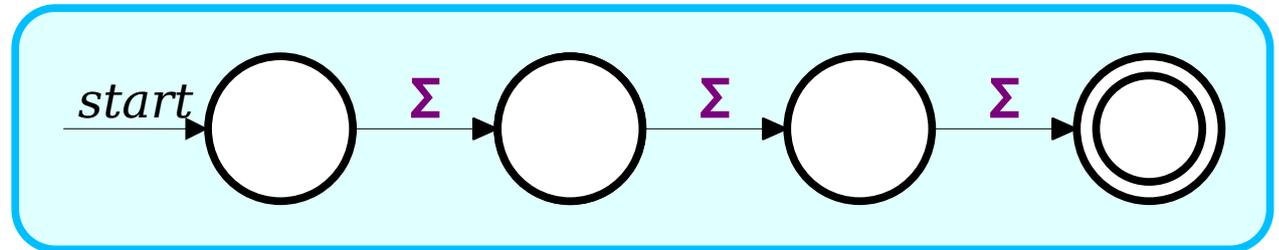
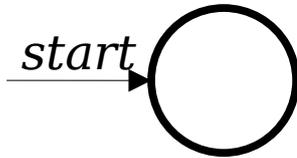
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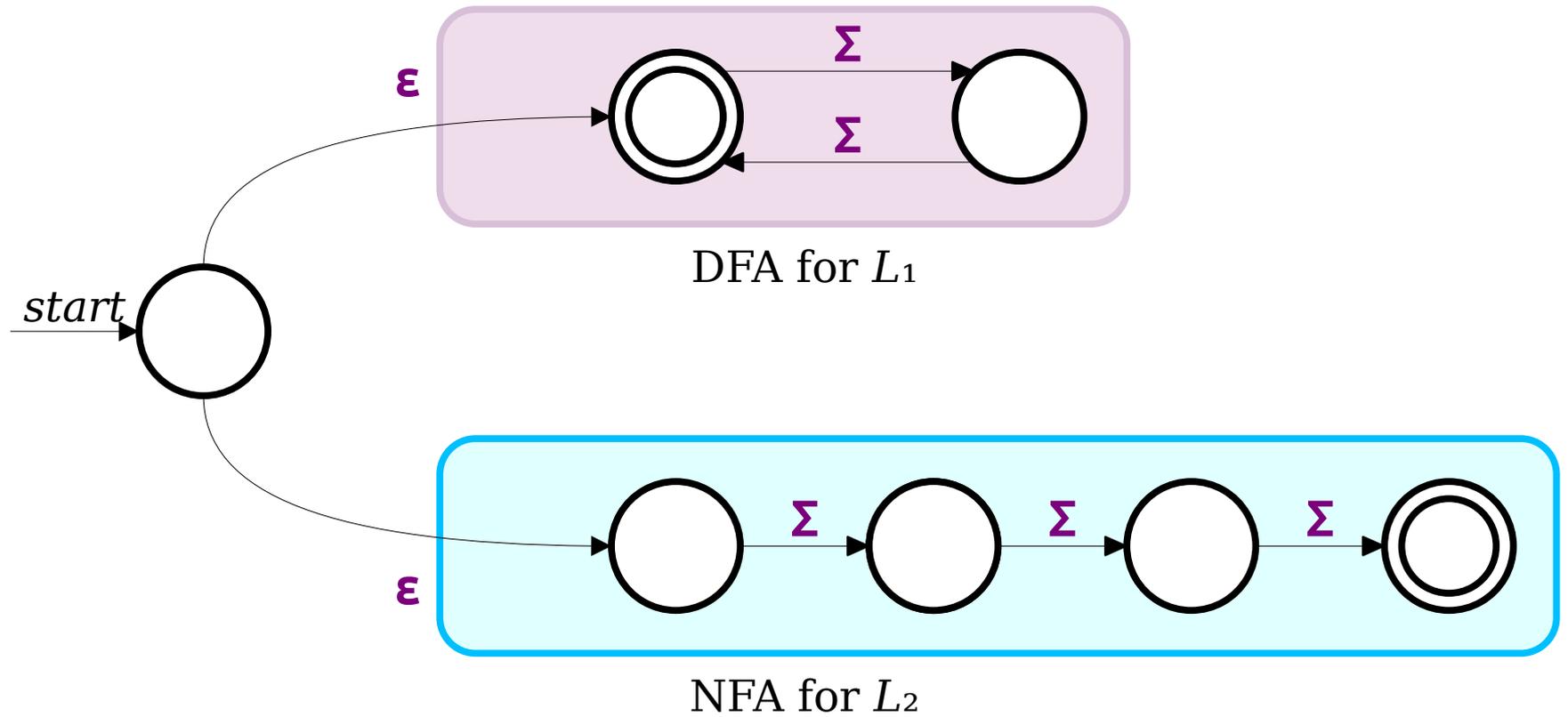


NFA for L_2

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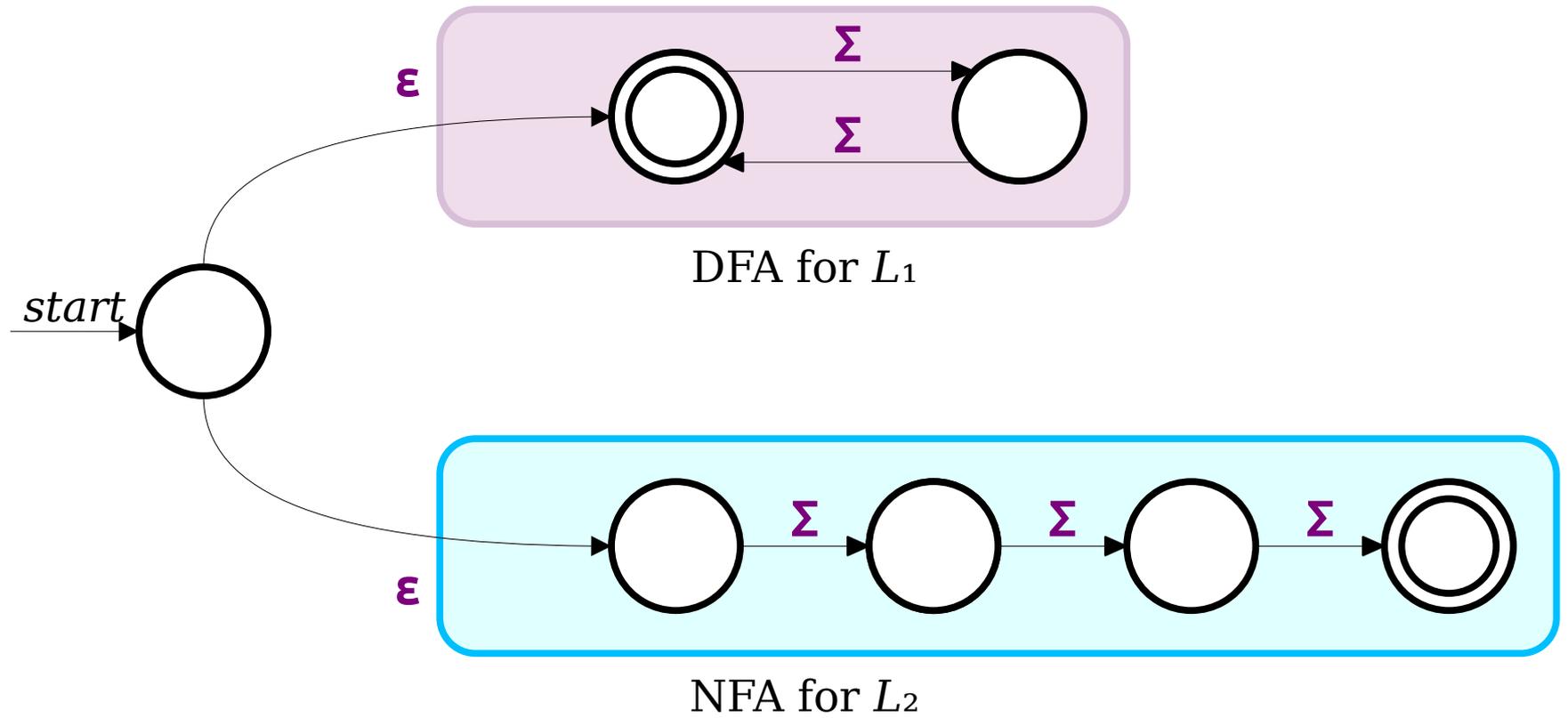
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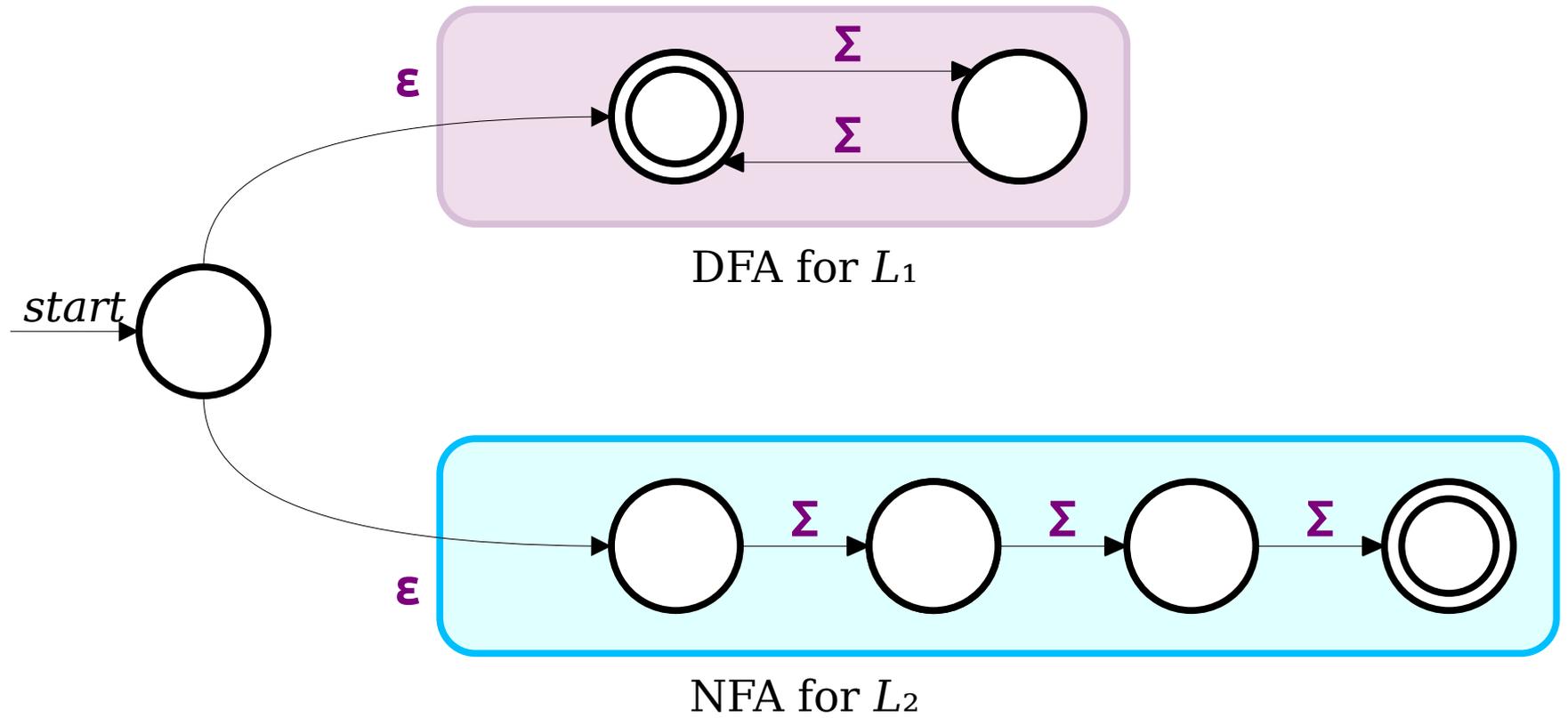
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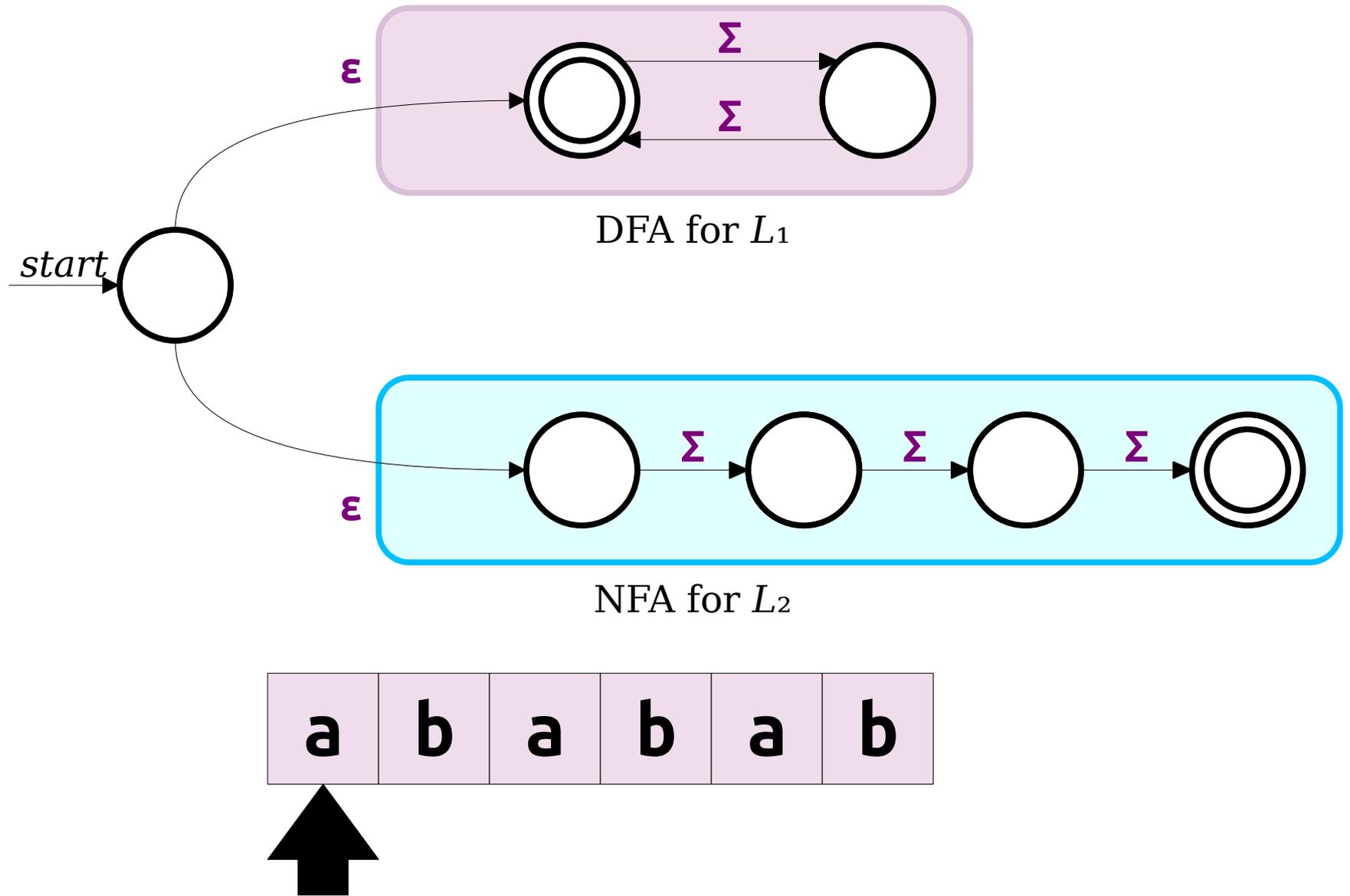
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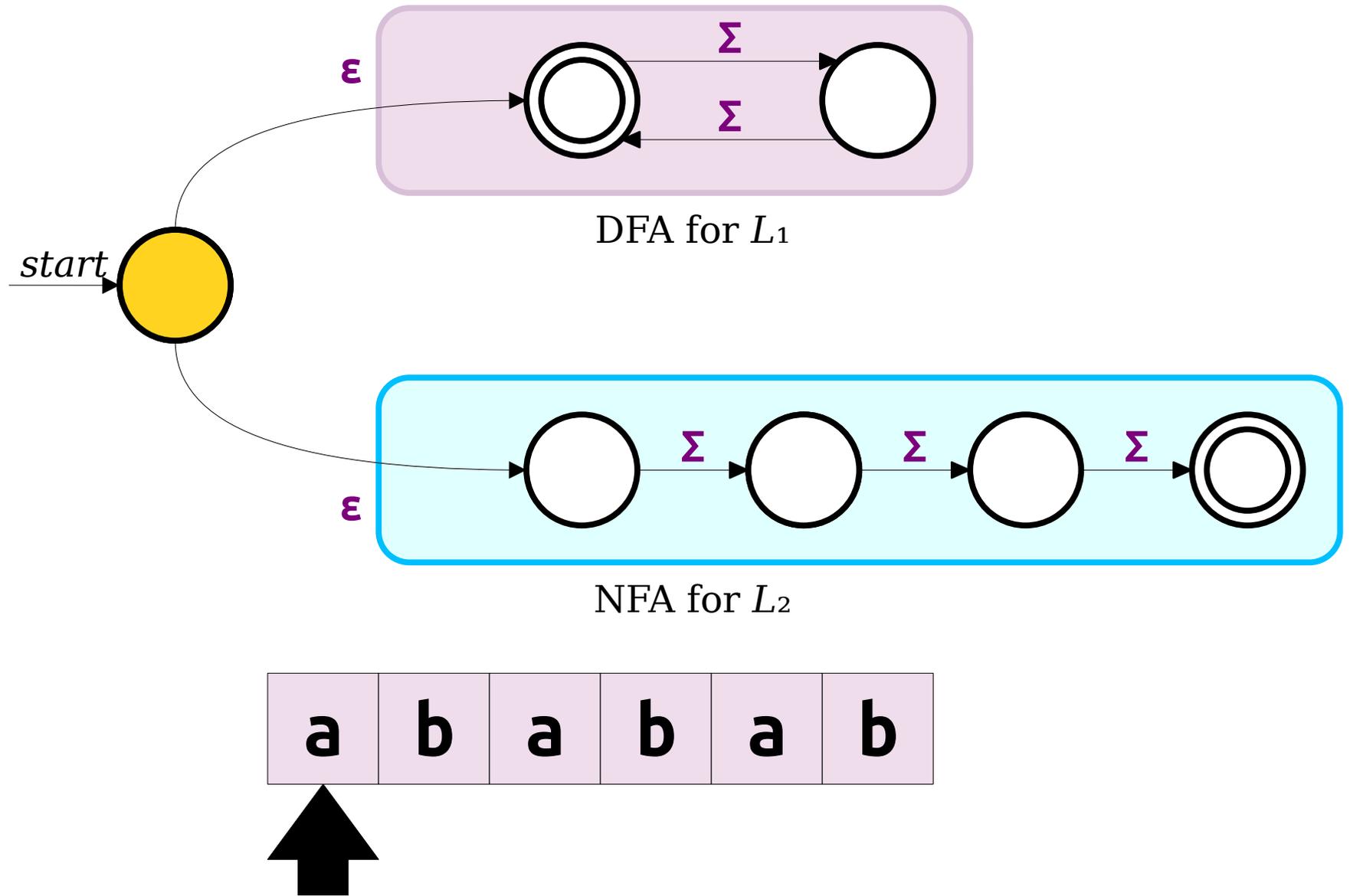
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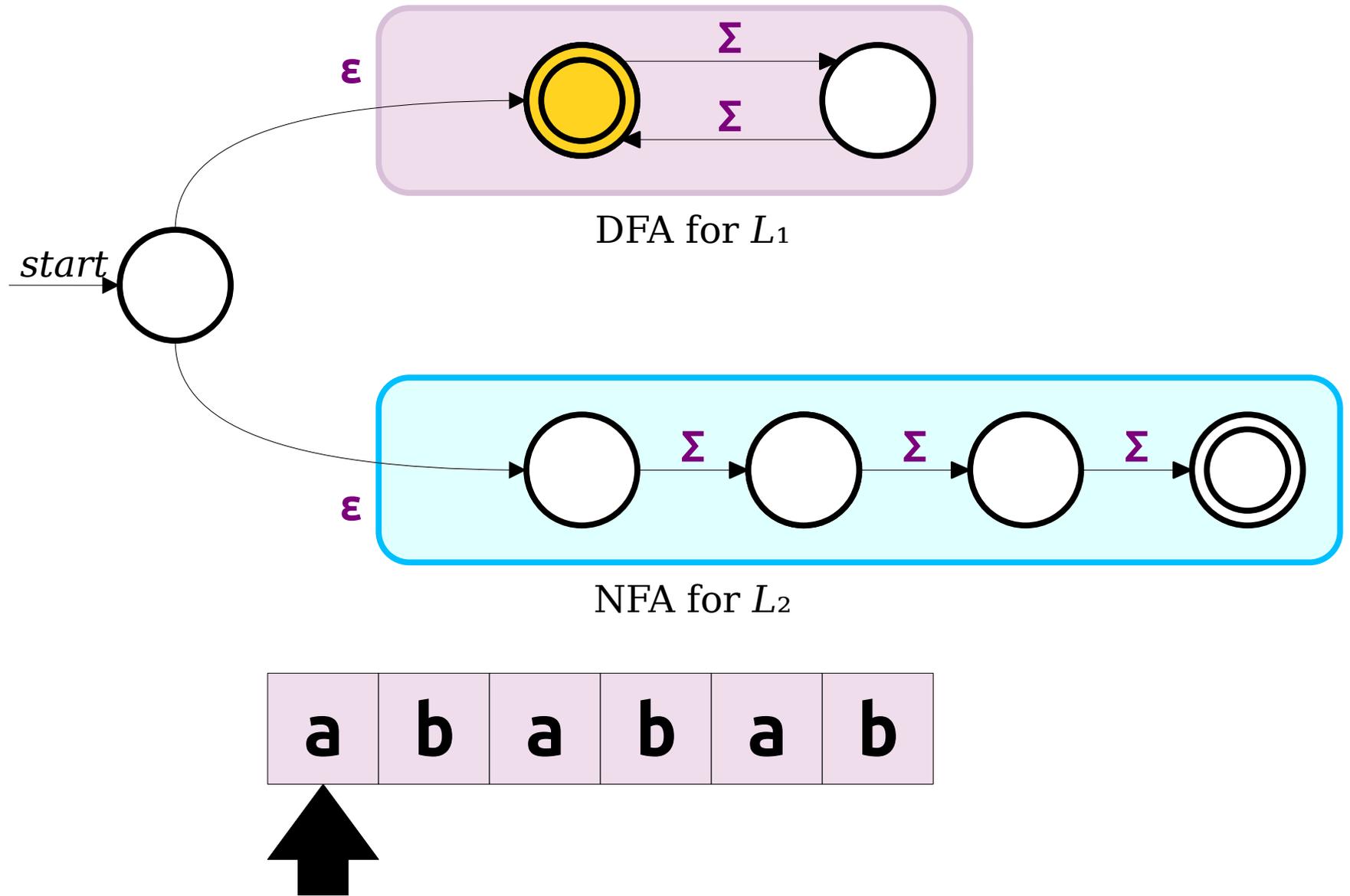
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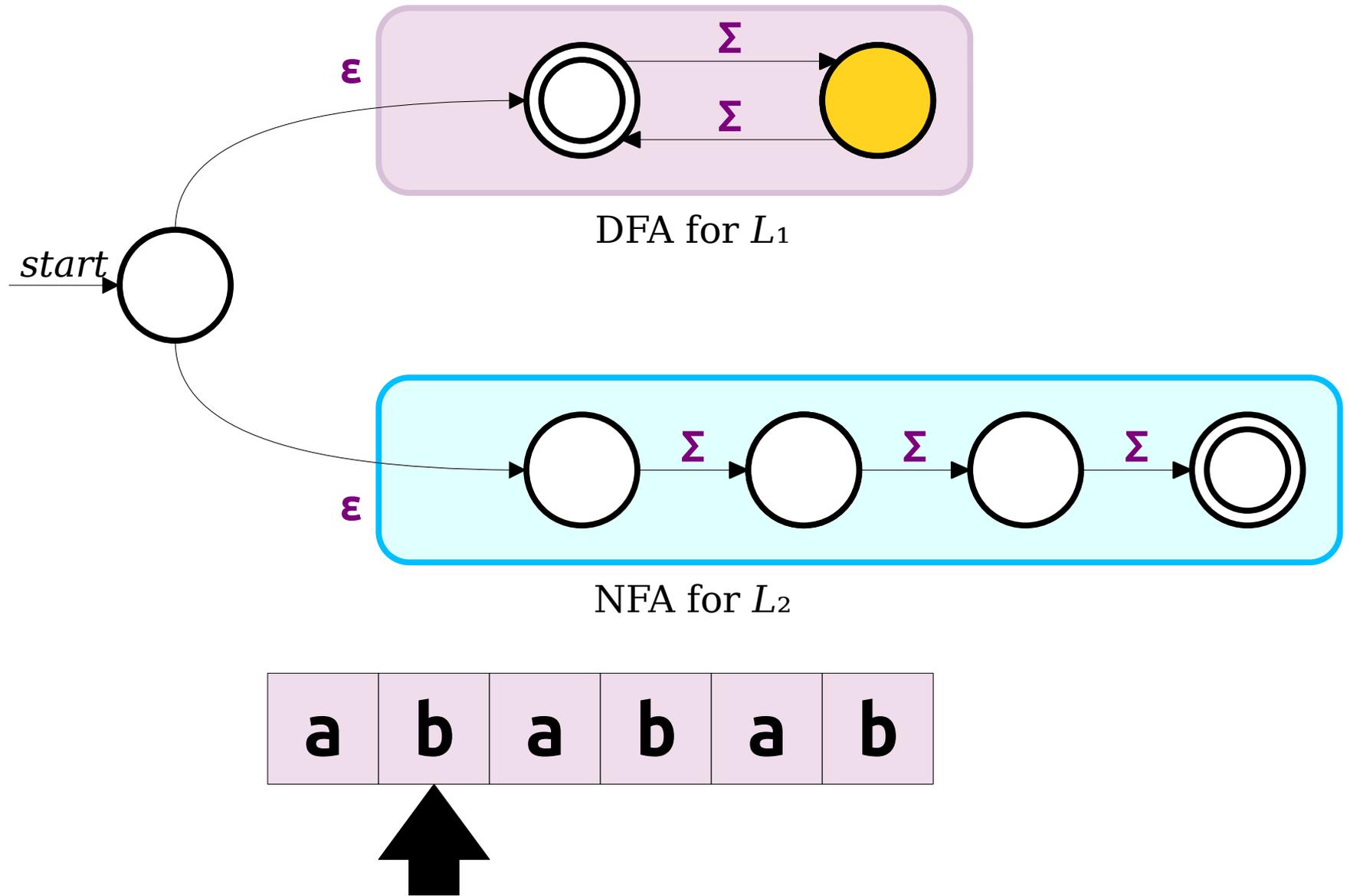
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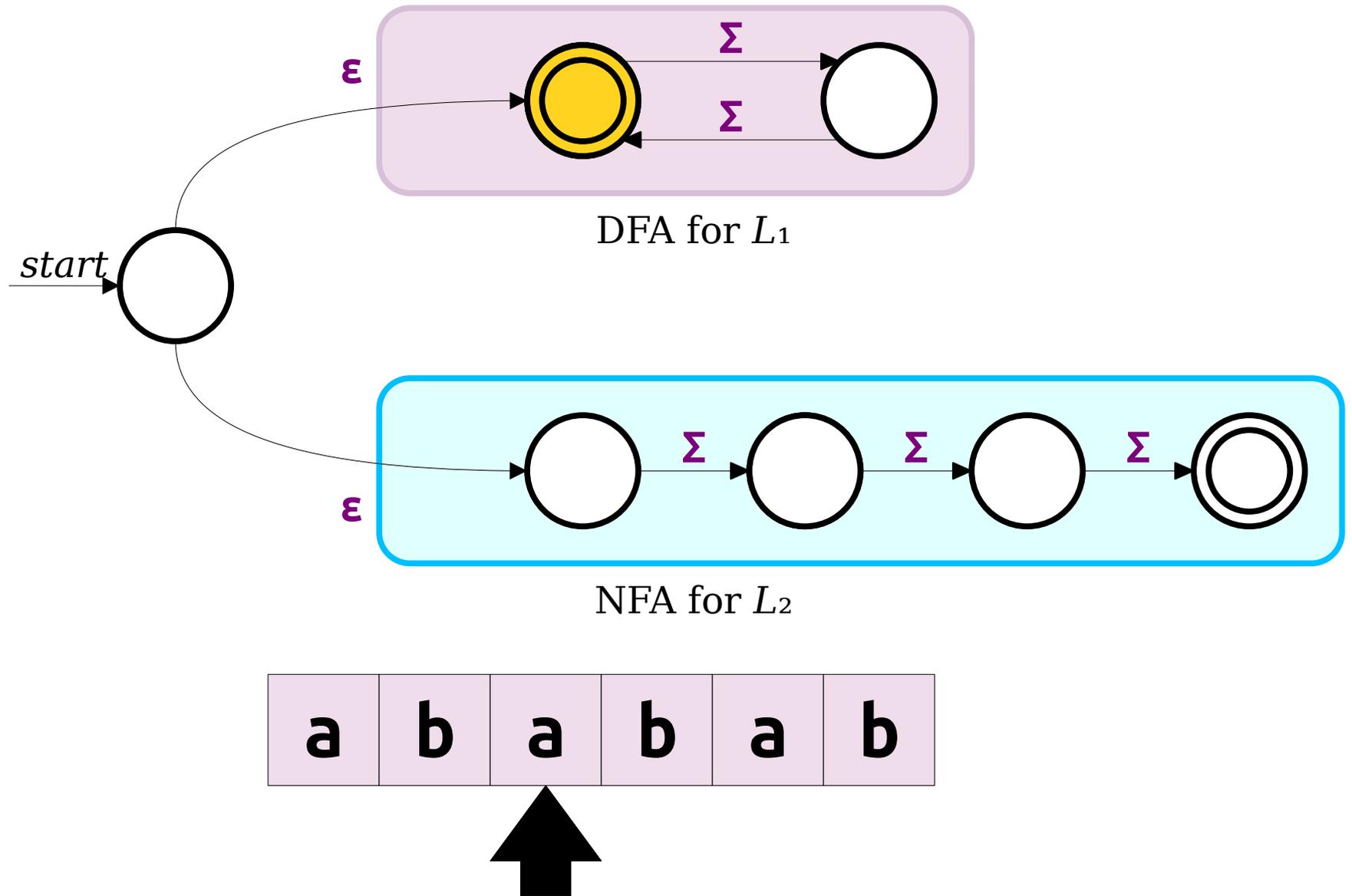
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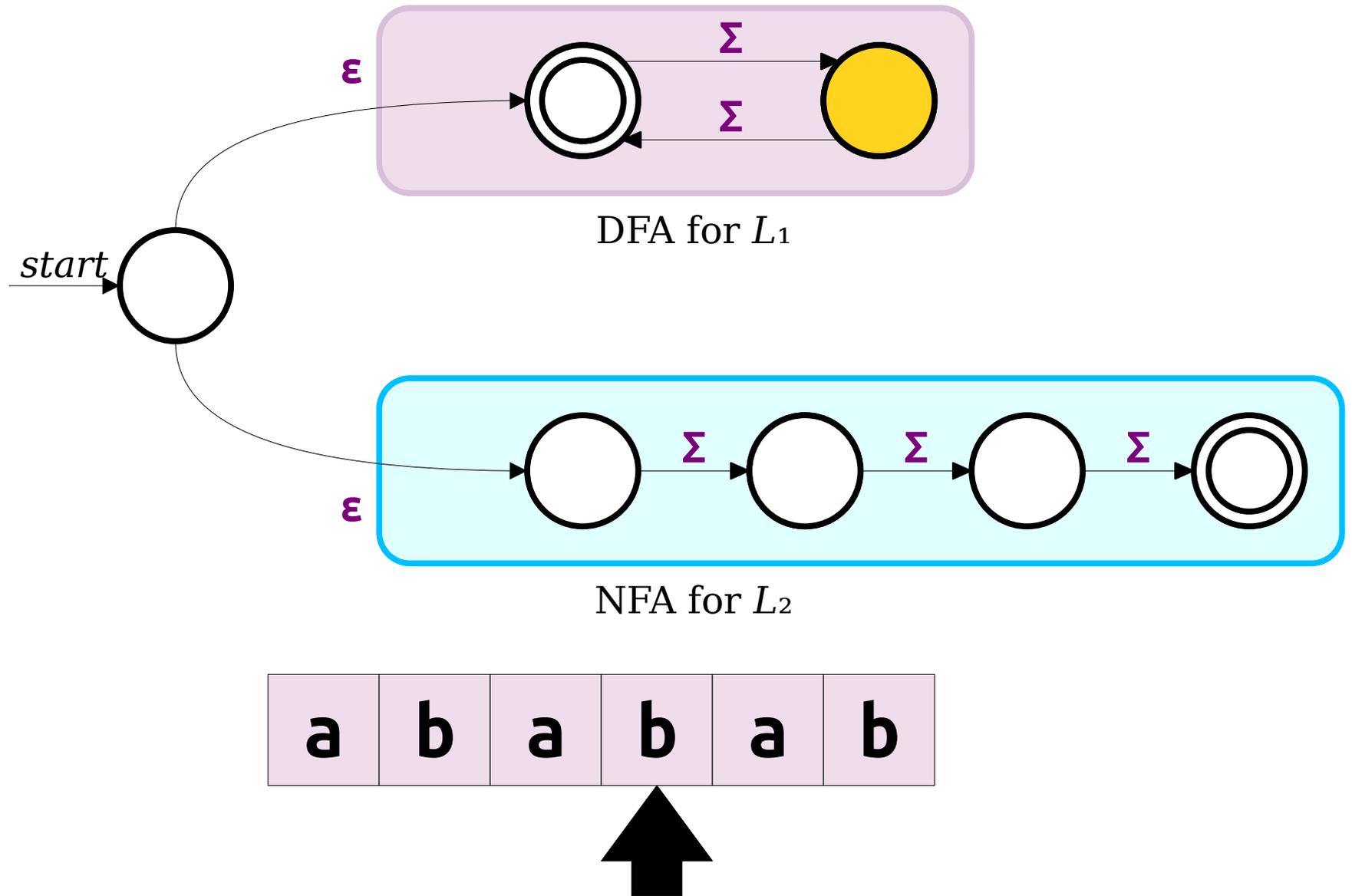
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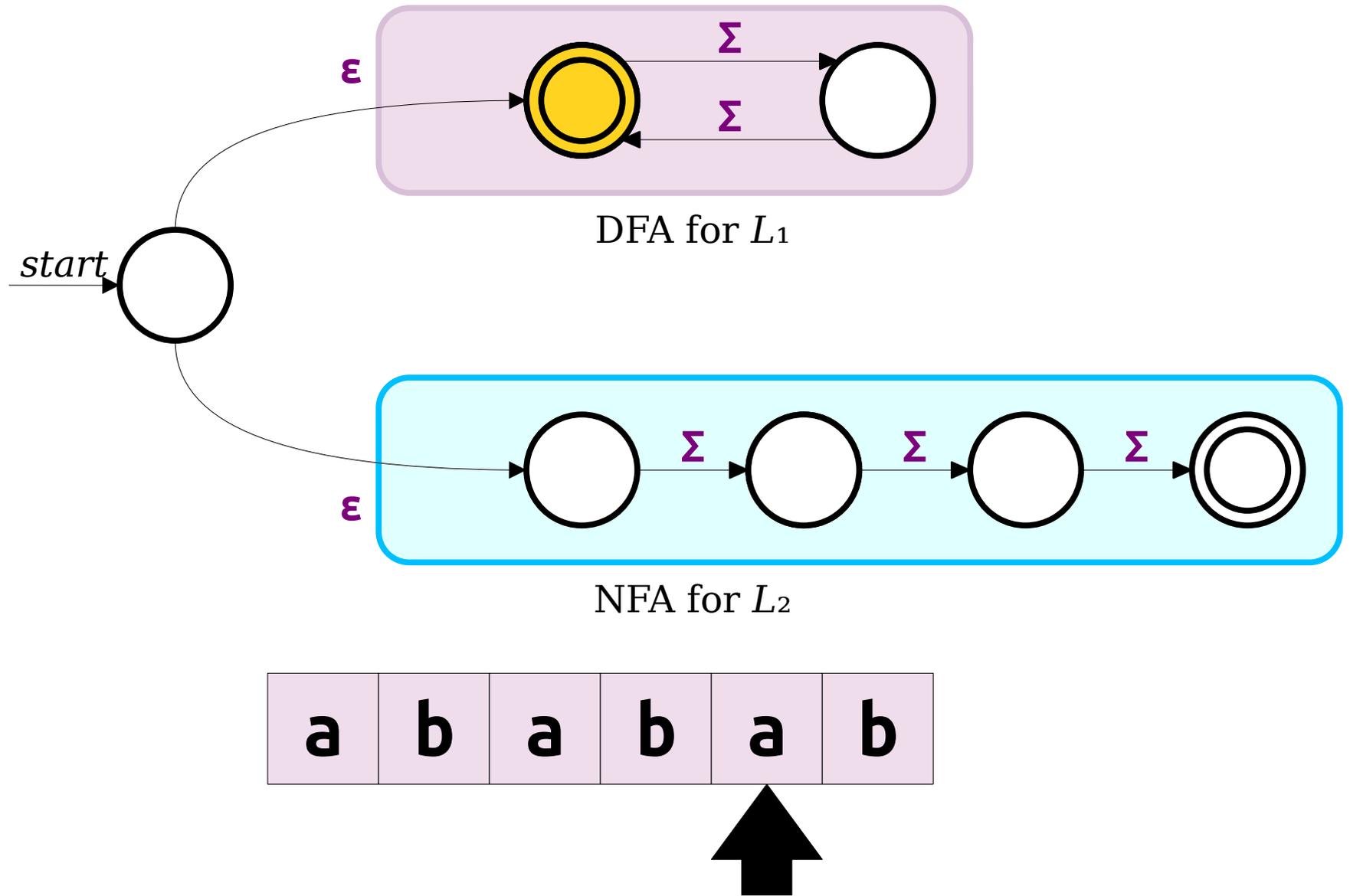
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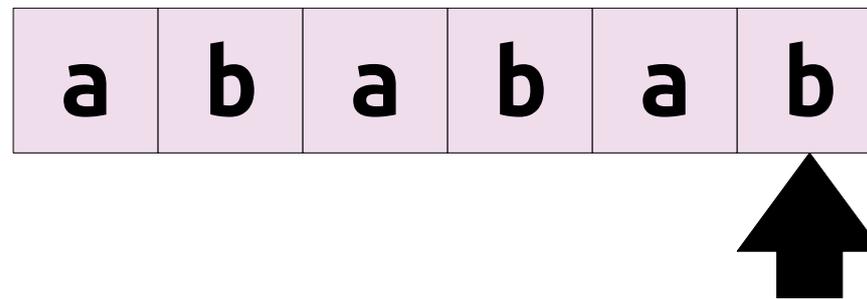
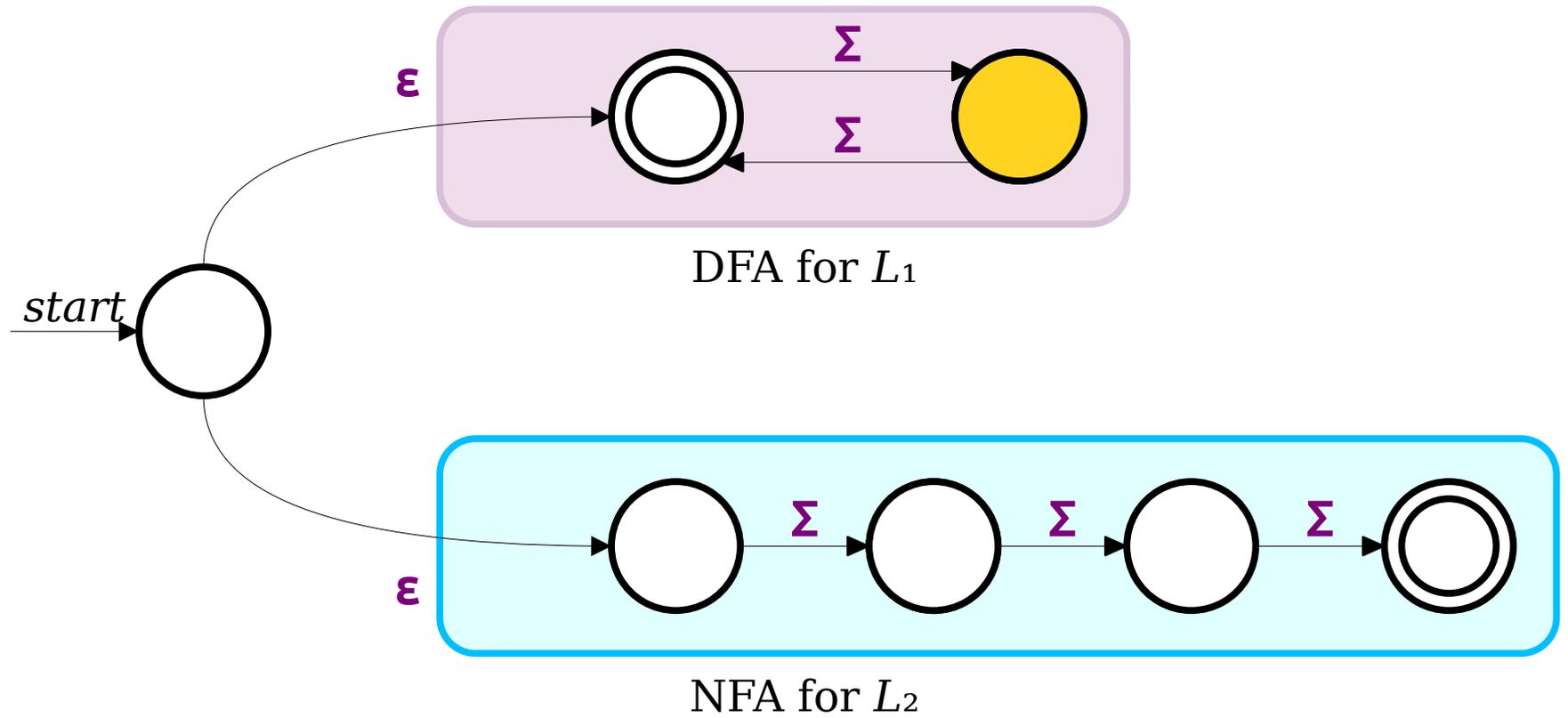
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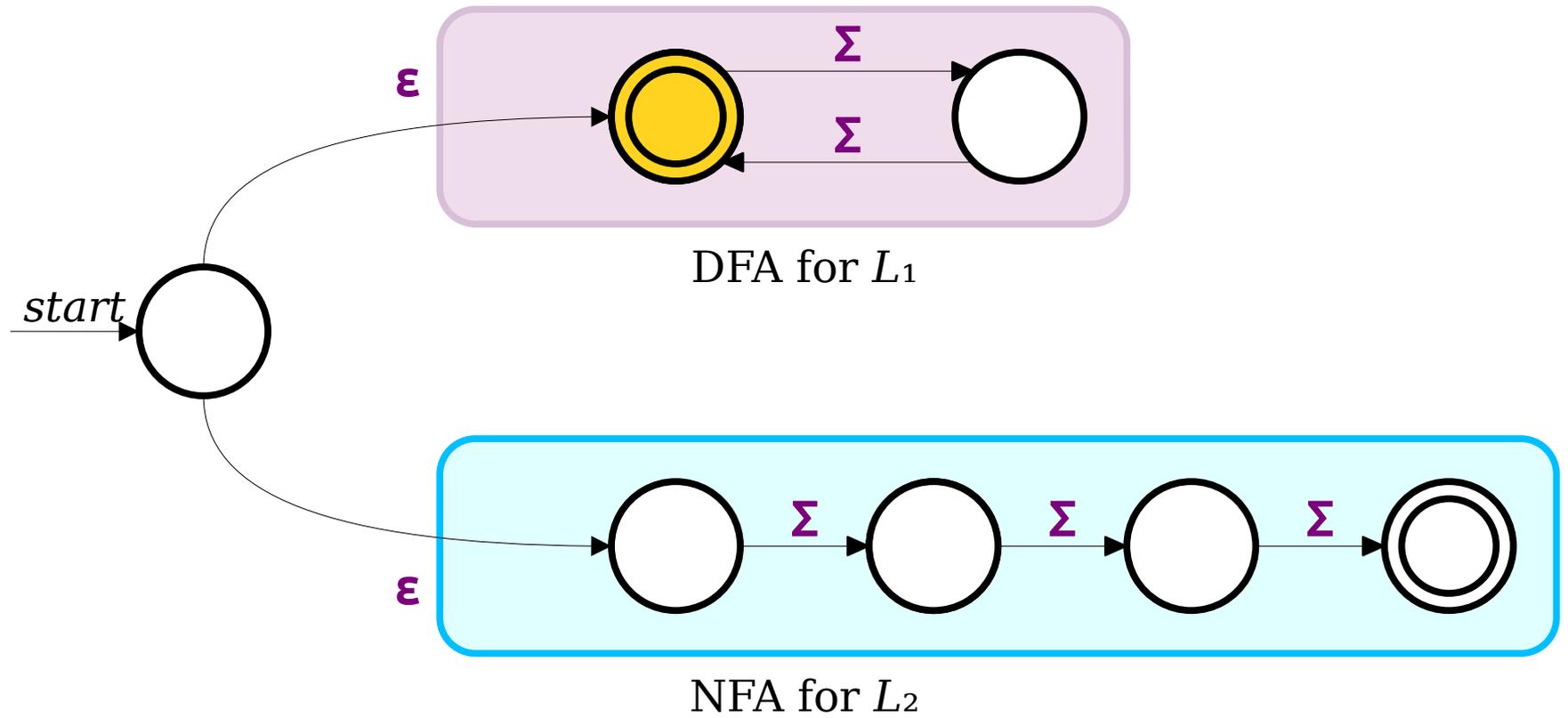
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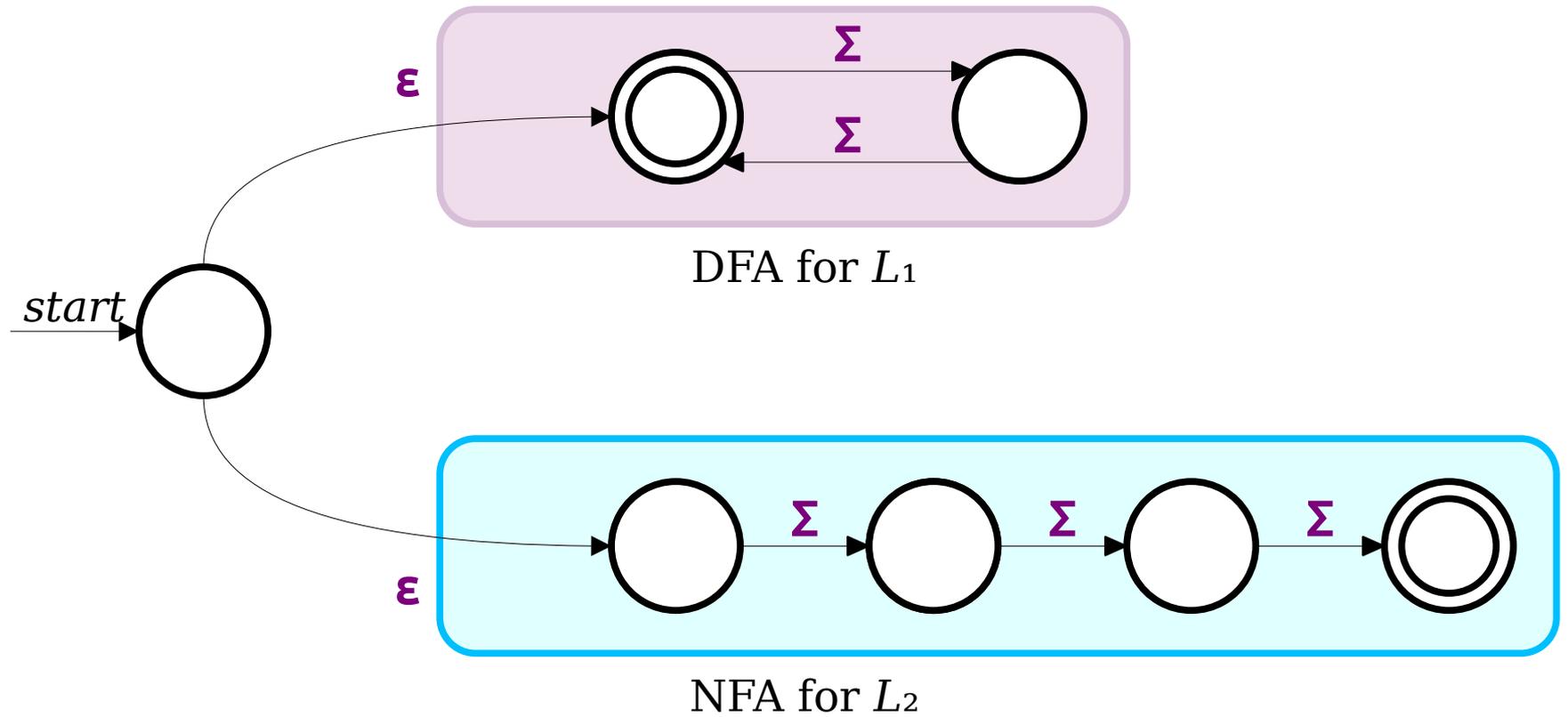
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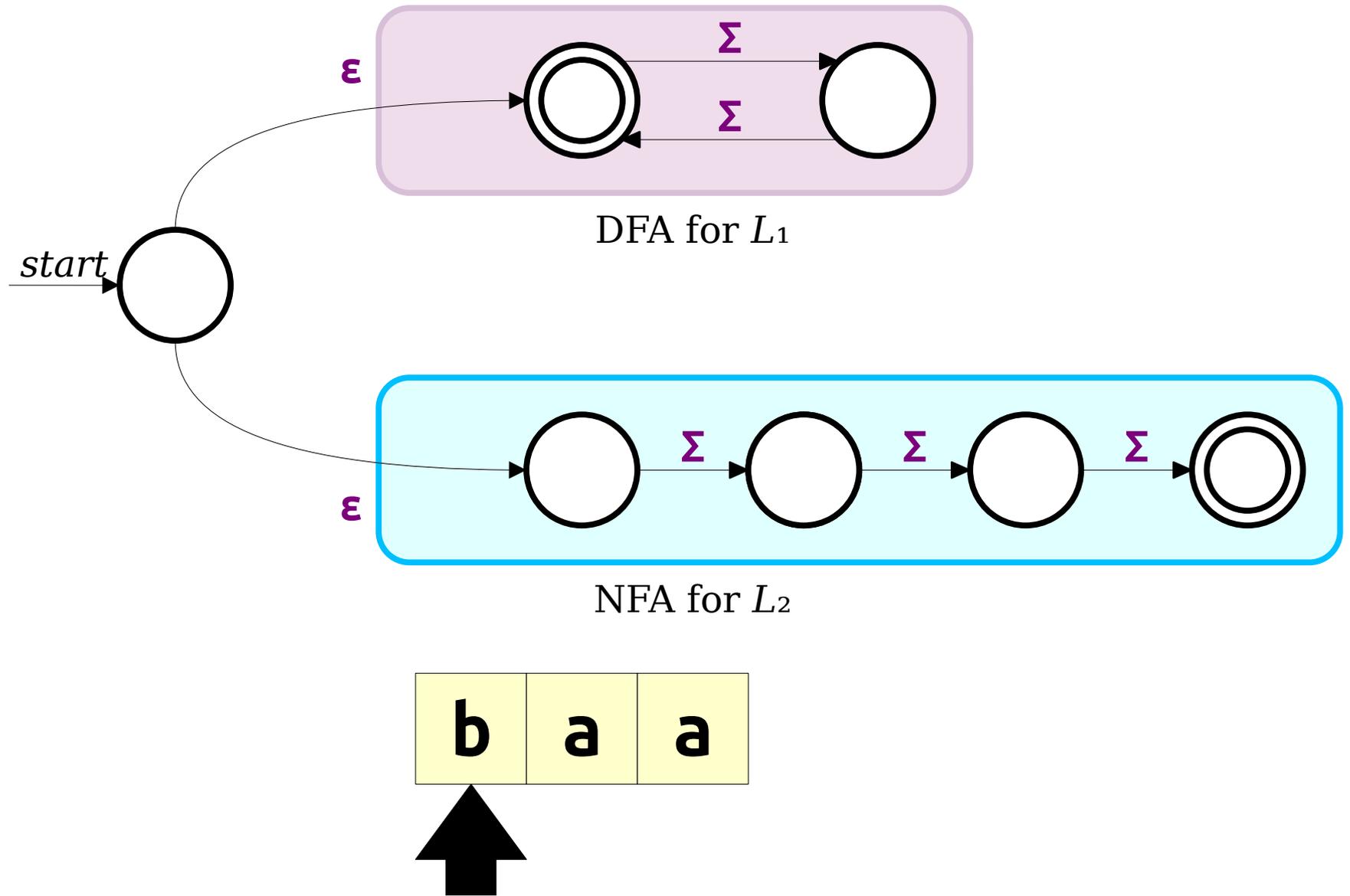
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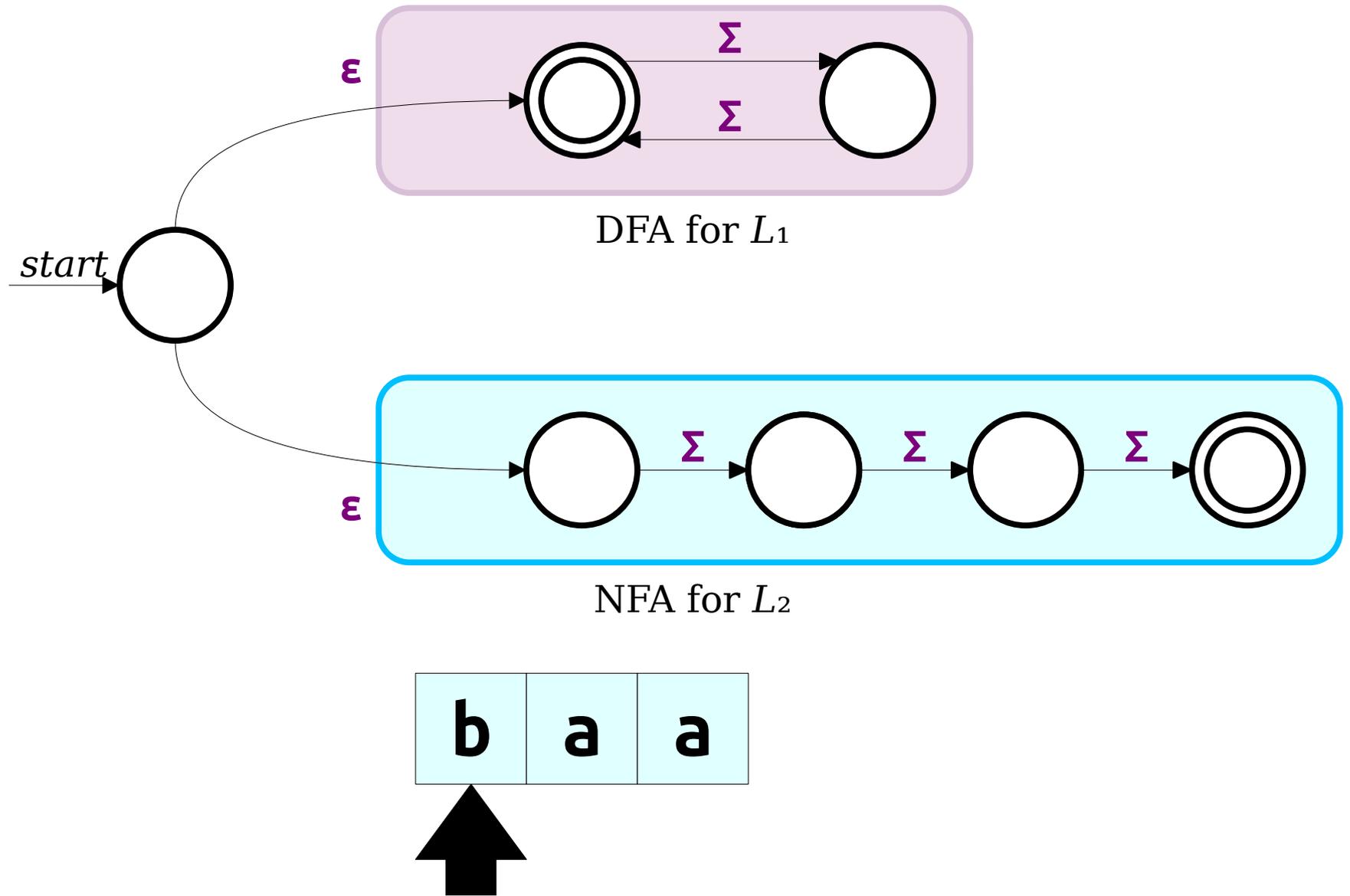
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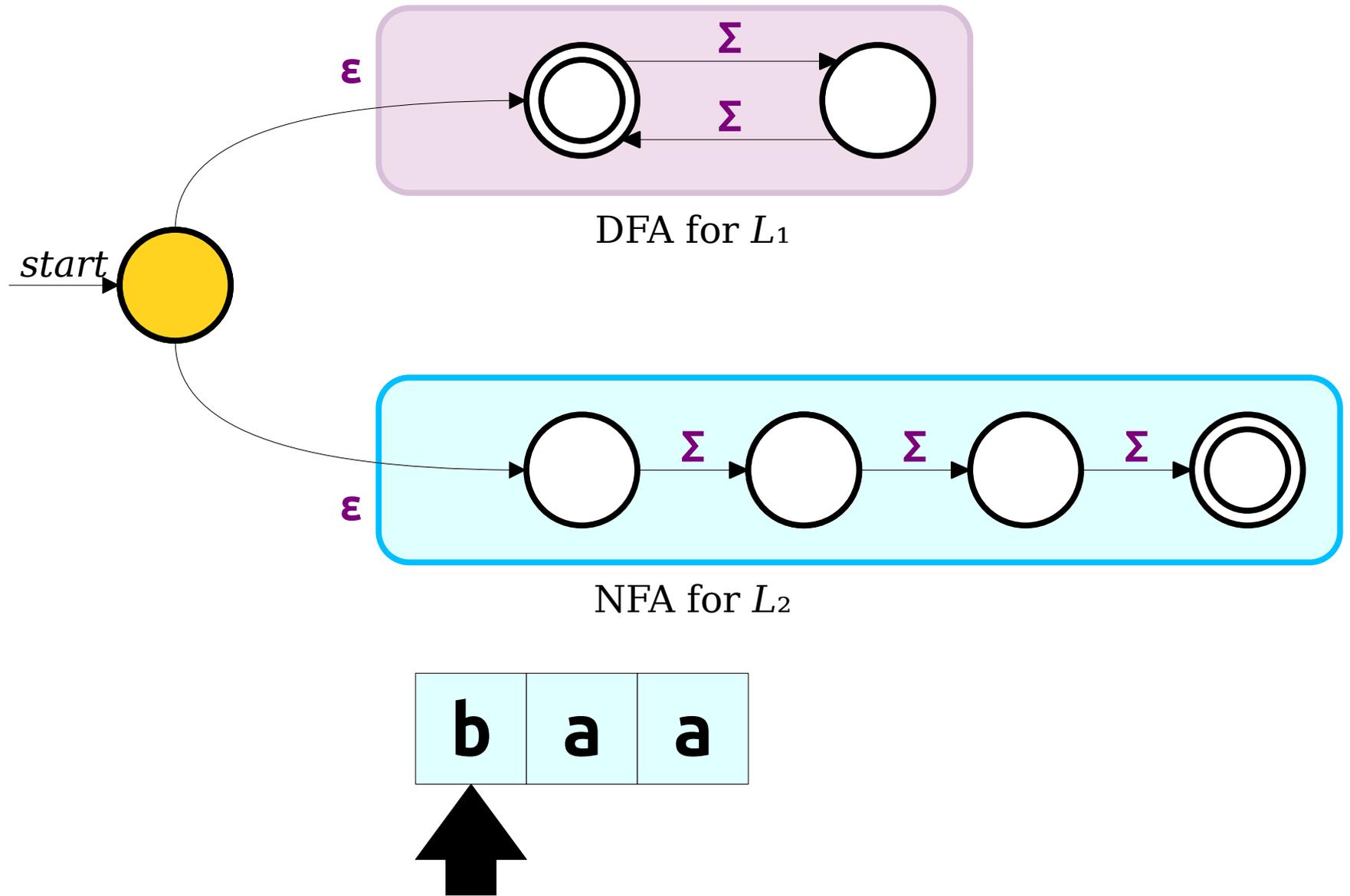
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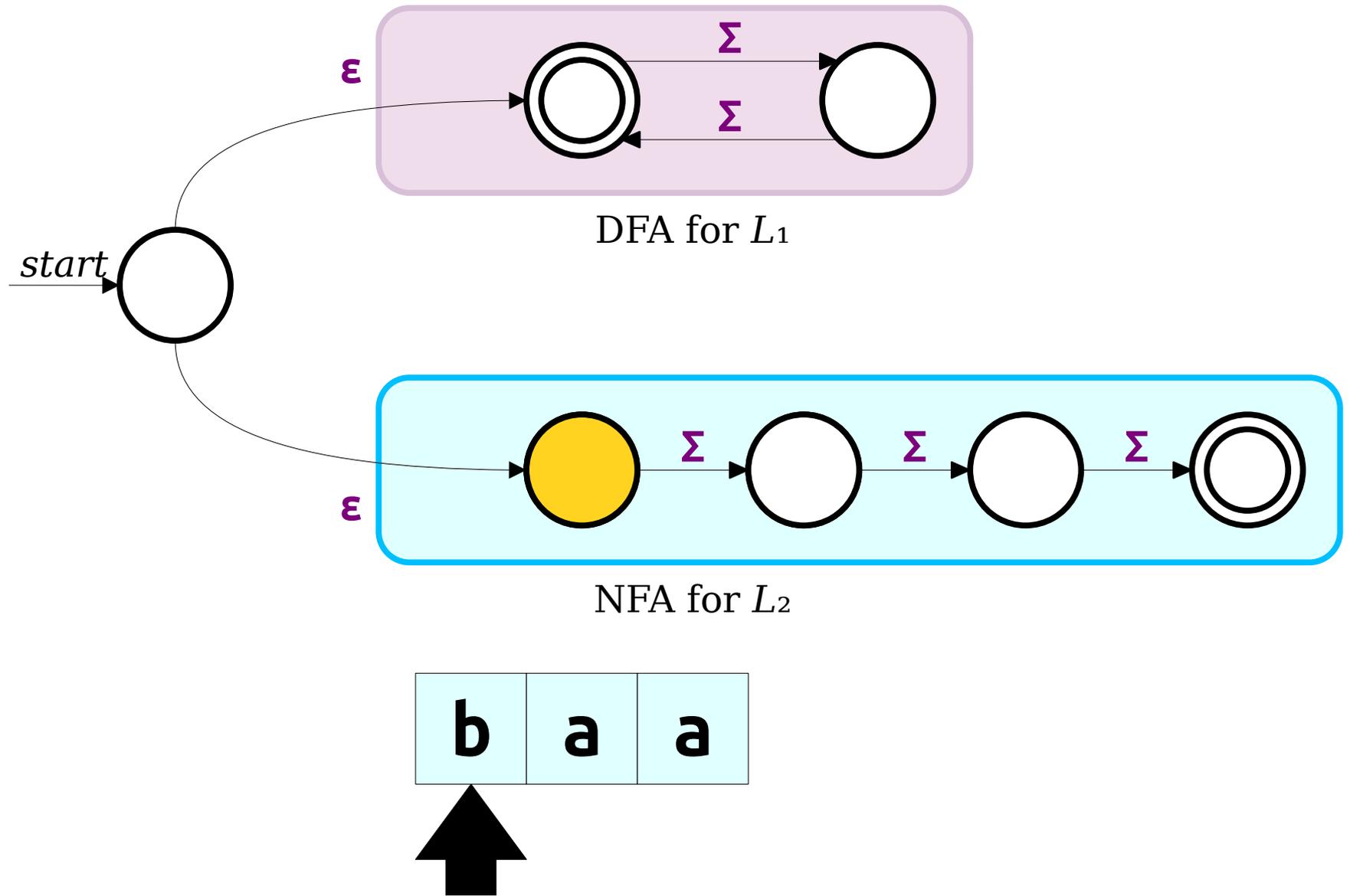
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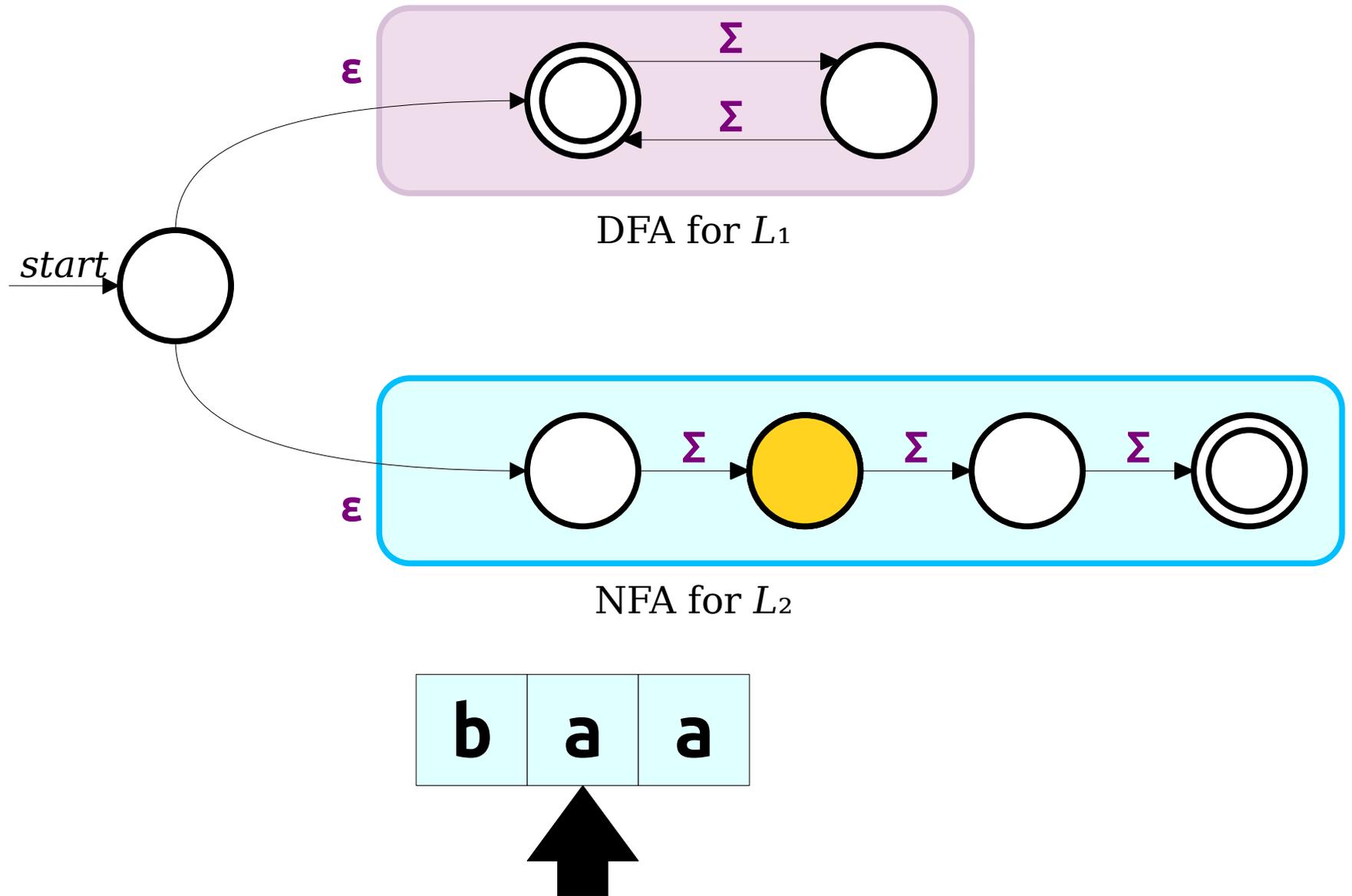
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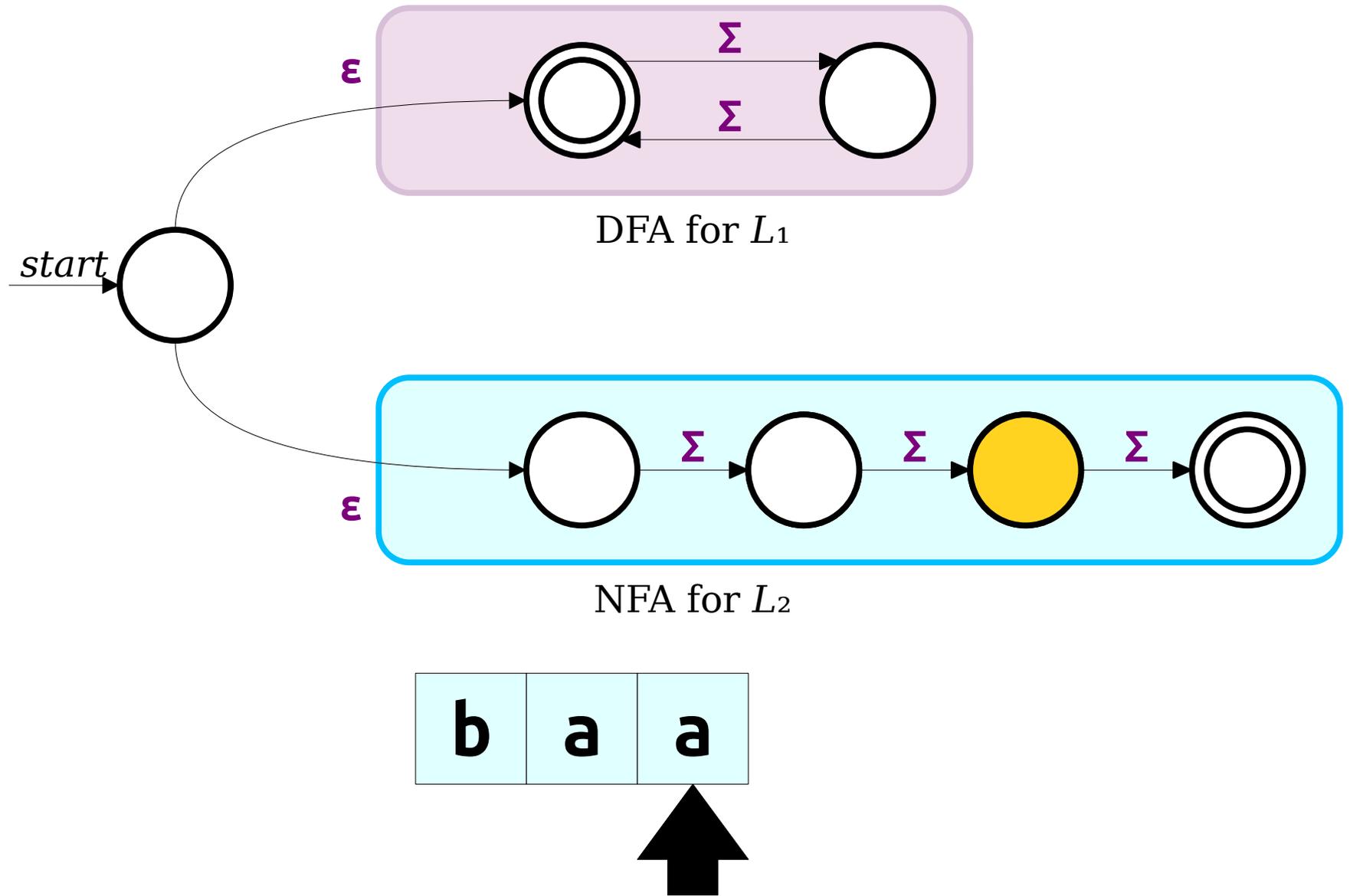
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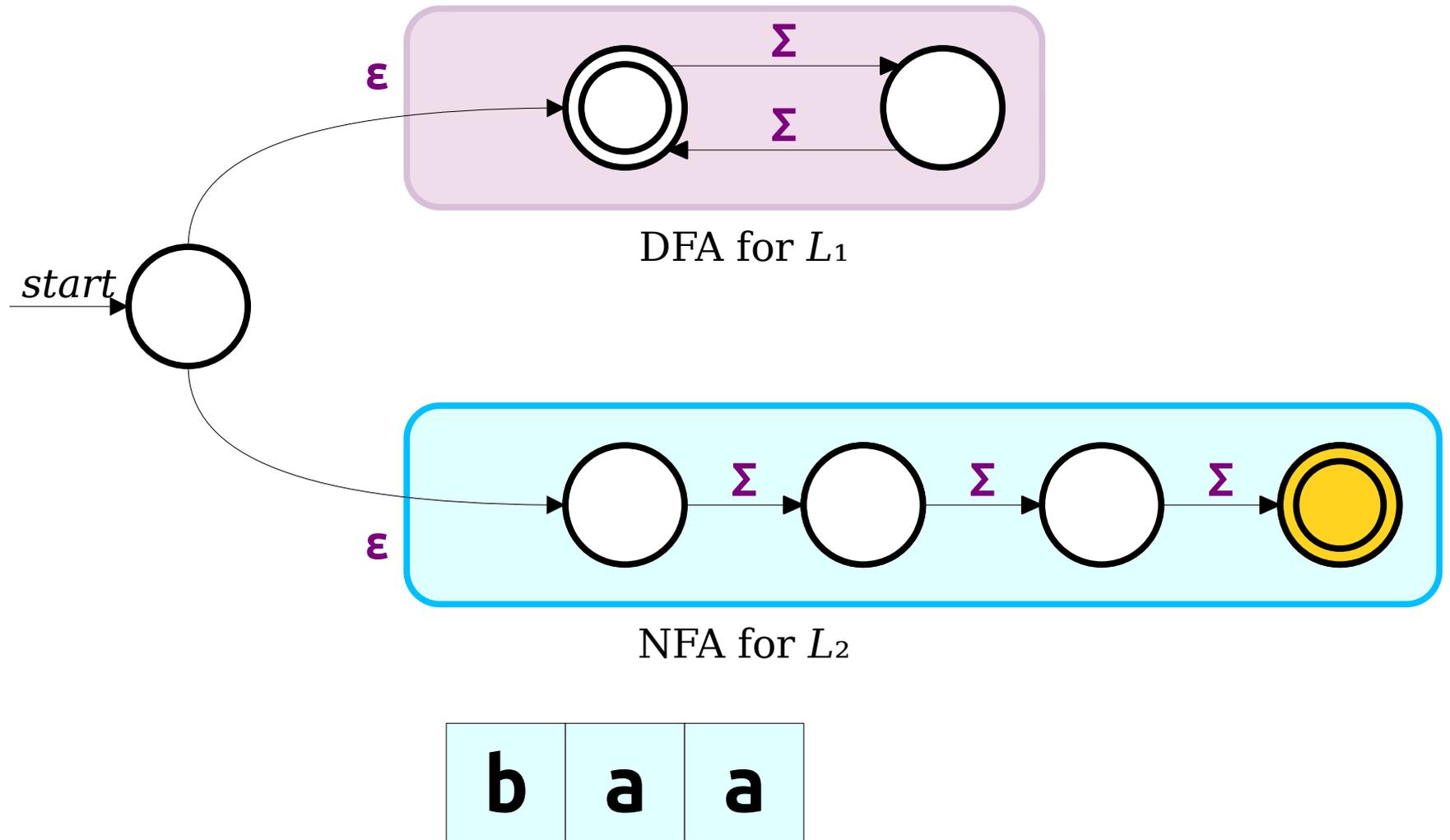
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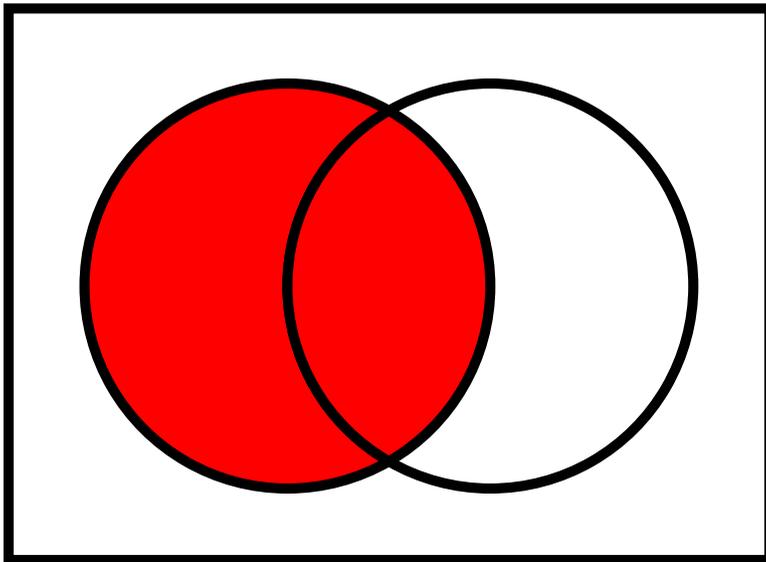
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Closure Under Intersection

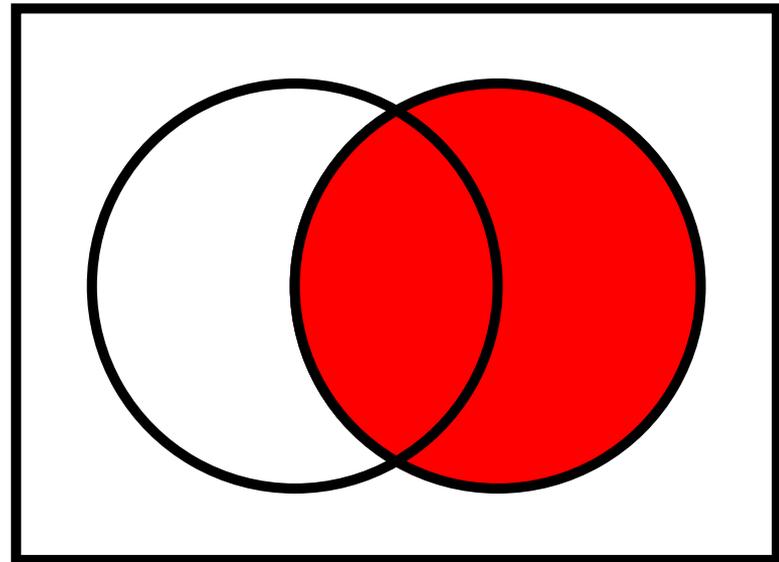
- If L_1 and L_2 are languages over Σ , then $L_1 \cap L_2$ is the language of strings in both L_1 and L_2 .
- Intuitively, $L_1 \cap L_2$ is the set of strings meeting the requirements of each language.
- **Theorem:** If L_1 and L_2 are regular, so is $L_1 \cap L_2$.

Closure Under Intersection

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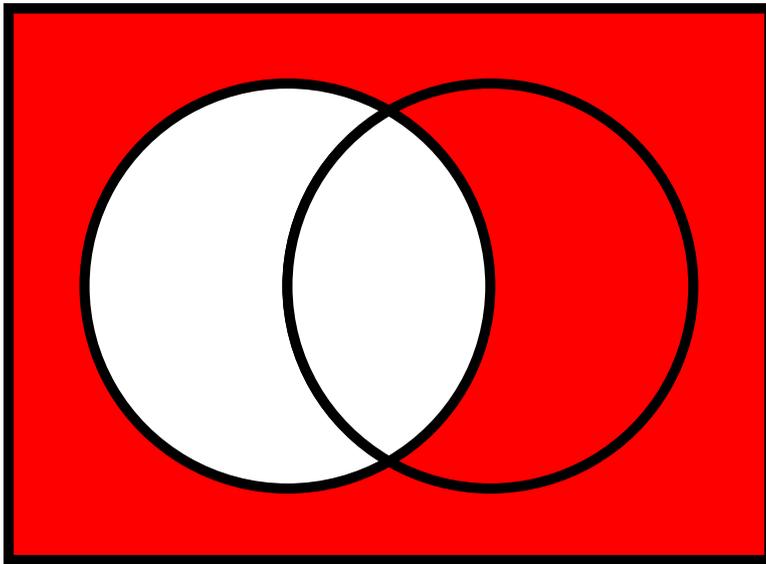
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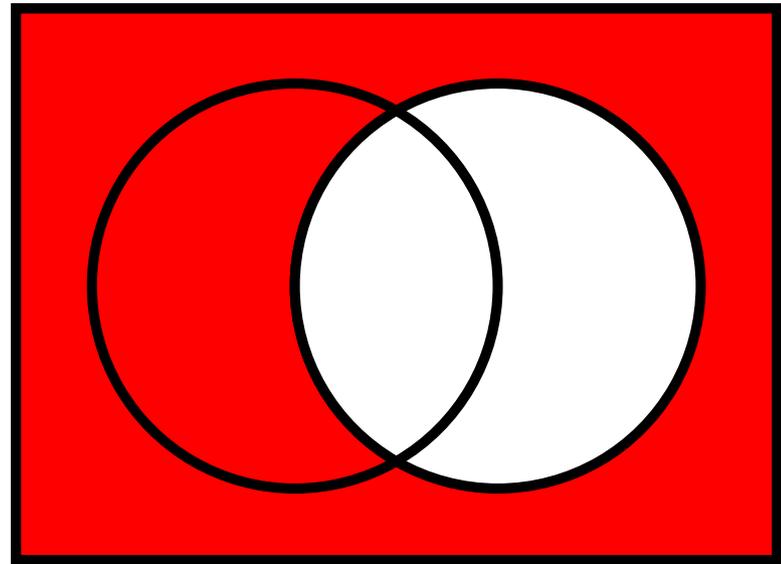
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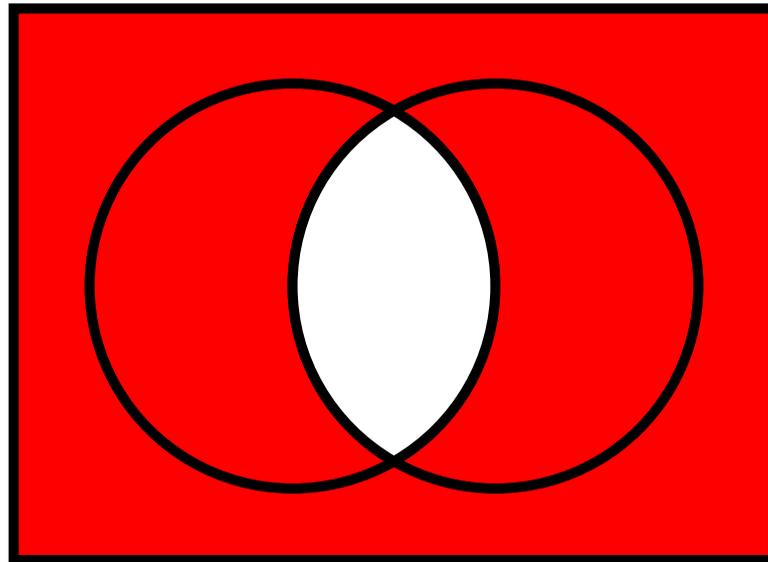
\bar{L}_1



\bar{L}_2

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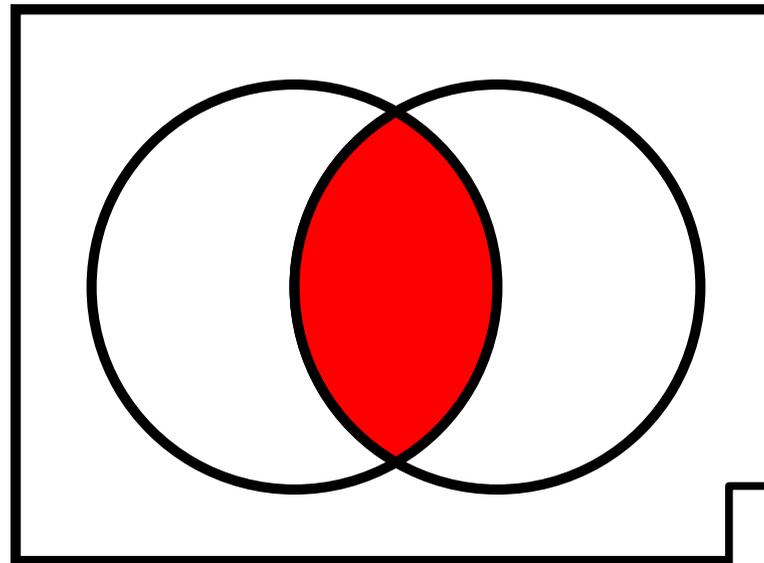
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Hey, it's De Morgan's laws!

Concatenation

Numbers

- Numbers can be written in many ways:

2718

2,718

2.718×10^3

MMDCCXVIII

二千七百一十八

ב'תשי"ח

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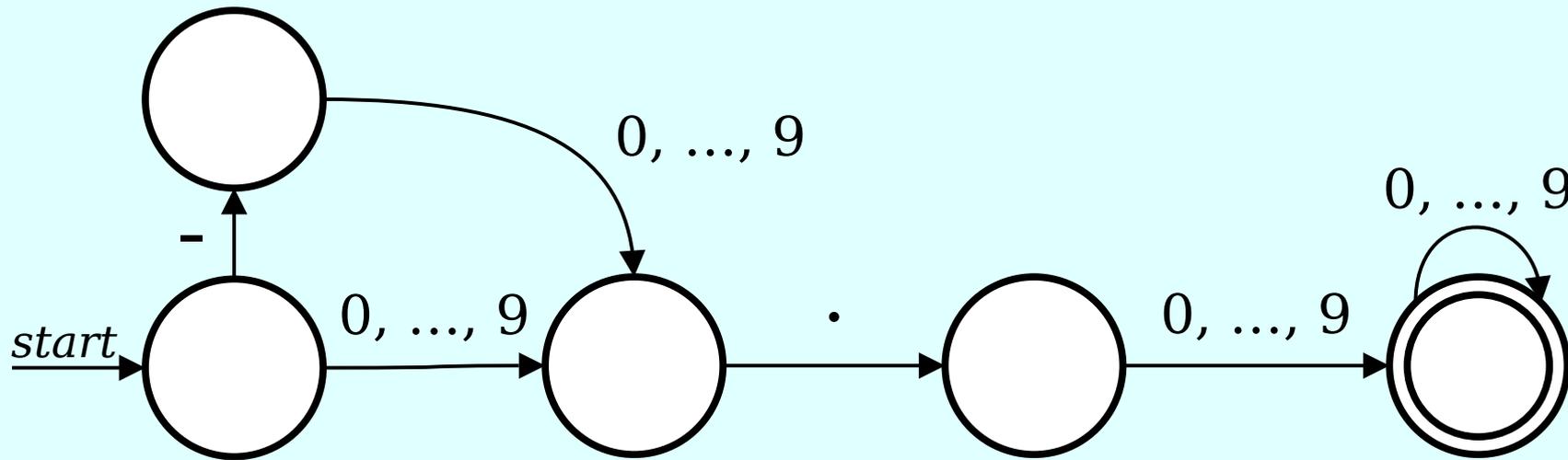
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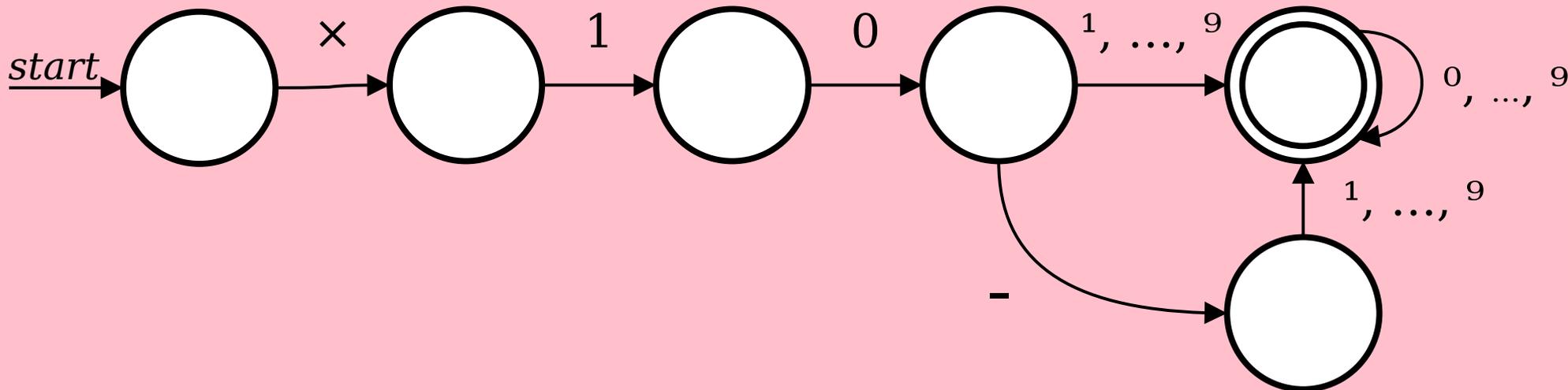
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Question: If you can build finite automata to match the first and second halves of a pattern, can you build a single finite automaton that matches the full pattern?

String Concatenation

- If $w \in \Sigma^*$ and $x \in \Sigma^*$, the **concatenation** of w and x , denoted **wx** , is the string formed by tacking all the characters of x onto the end of w .
- Example: if $w = \mathbf{quo}$ and $x = \mathbf{kka}$, the concatenation $wx = \mathbf{quokka}$.
- This is analogous to the $+$ operator for strings in many programming languages.
- Some facts about concatenation:
 - The empty string ε is the **identity element** for concatenation:

$$w\varepsilon = \varepsilon w = w$$

- Concatenation is **associative**:

$$wxy = w(xy) = (wx)y$$

Concatenation

- The **concatenation** of two languages L_1 and L_2 over the alphabet Σ is the language

$$L_1L_2 = \{ x \mid \exists w_1 \in L_1. \exists w_2 \in L_2. x = w_1w_2 \}$$

- Let $L_1 = \{ ab, ba \}$ and $L_2 = \{ aa, bb \}$. What is L_1L_2 ?

Answer at

<https://cs103.stanford.edu/pollev>

Concatenation Example

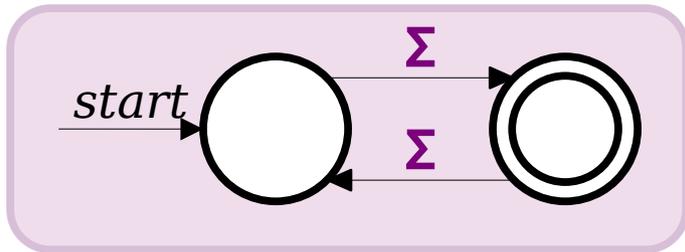
- Let $\Sigma = \{ a, b, \dots, z, A, B, \dots, Z \}$ and consider these languages over Σ :
 - ***Noun*** = { **Puppy, Rainbow, Whale, ...** }
 - ***Verb*** = { **Hugs, Juggles, Loves, ...** }
 - ***The*** = { **The** }
- The language ***TheNounVerbTheNoun*** is
 - { **ThePuppyHugsTheWhale,**
TheWhaleLovesTheRainbow,
TheRainbowJugglesTheRainbow, ... }

Concatenation

- The **concatenation** of two languages L_1 and L_2 over the alphabet Σ is the language
$$L_1L_2 = \{ x \mid \exists w_1 \in L_1. \exists w_2 \in L_2. x = w_1w_2 \}$$
- Two views of L_1L_2 :
 - The set of all strings that can be made by concatenating a string in L_1 with a string in L_2 .
 - The set of strings that can be split into two pieces: a piece from L_1 and a piece from L_2 .
- **Theorem:** If L_1 and L_2 are regular languages, then so is L_1L_2 .

$L_1 = \{ w \in \{\mathbf{a}, \mathbf{b}\}^* \mid w \text{ has } \textit{odd} \text{ length} \}$
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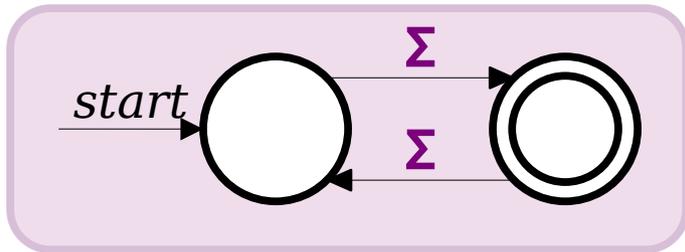
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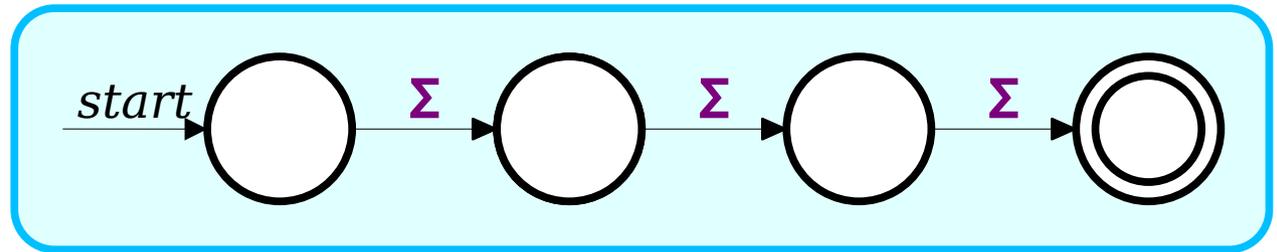
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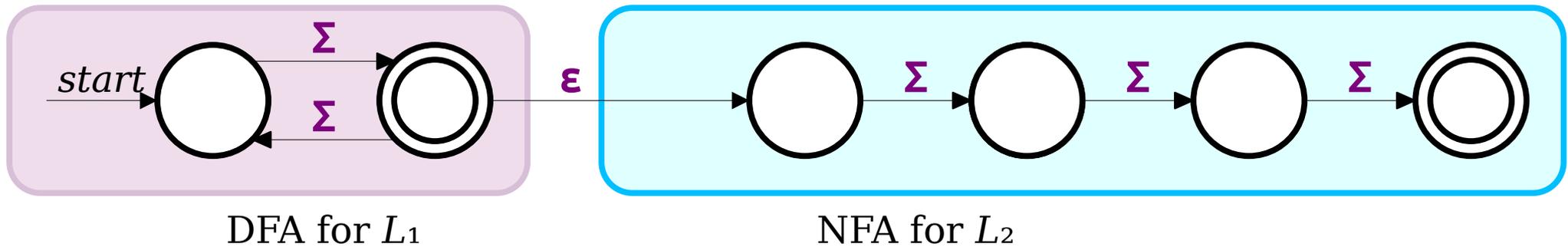


NFA for L_2

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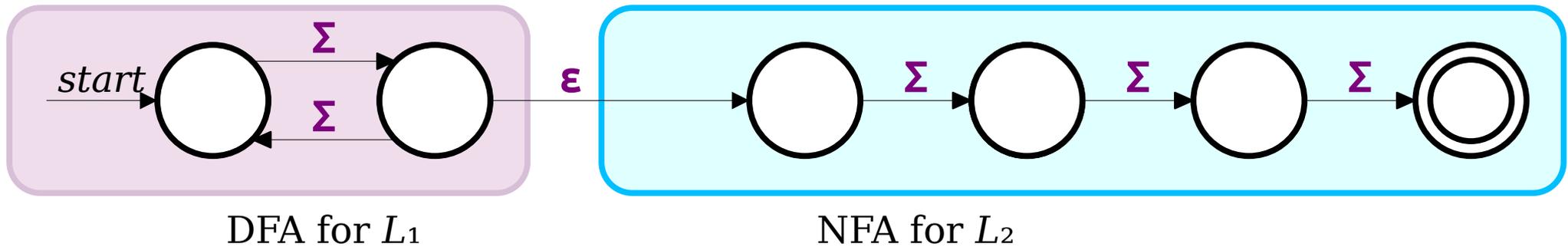
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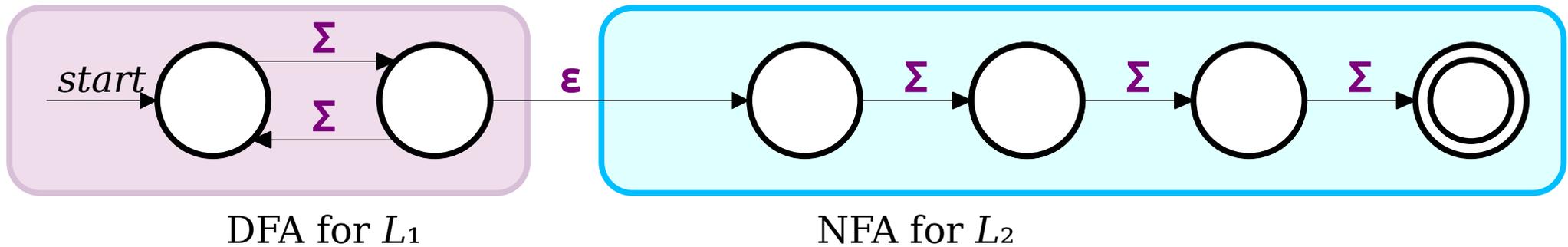
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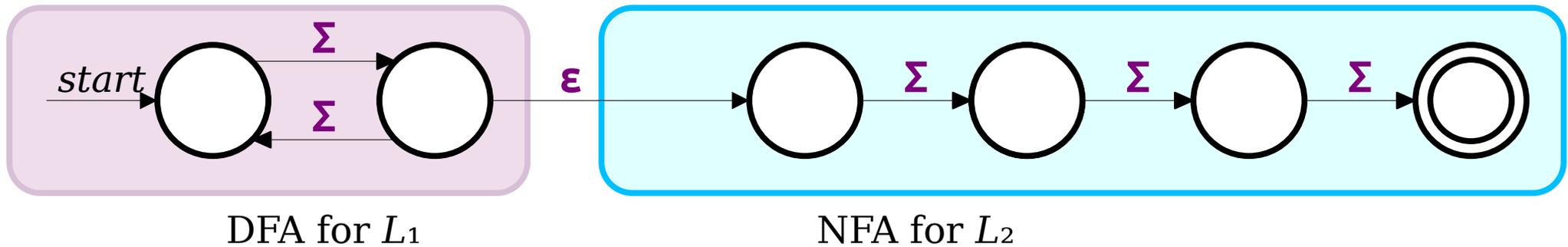
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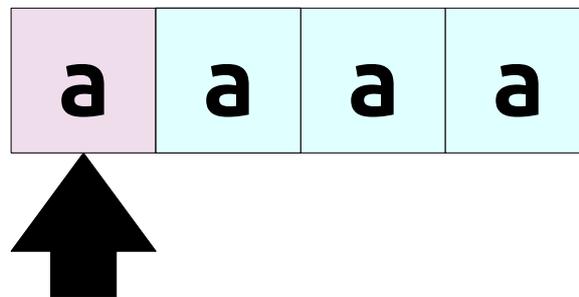
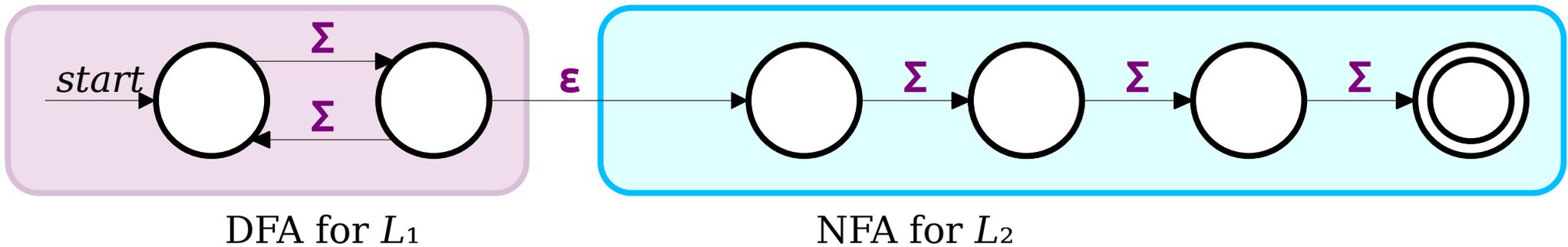
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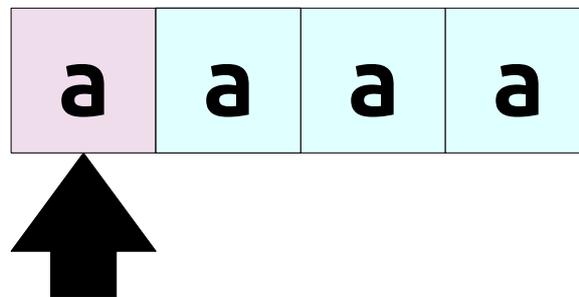
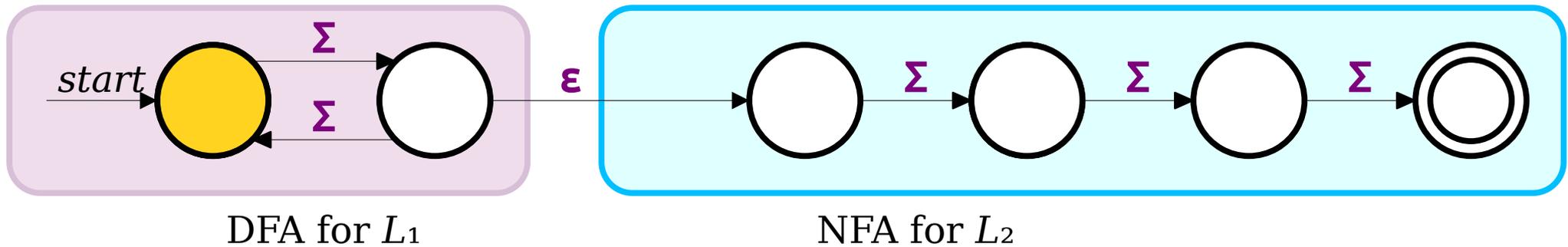
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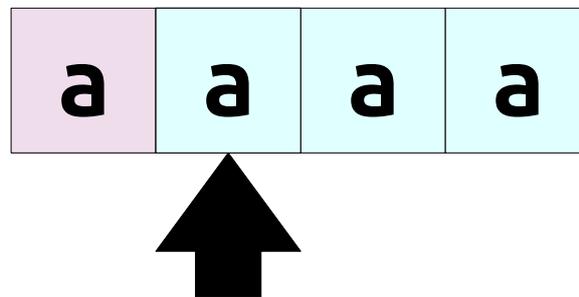
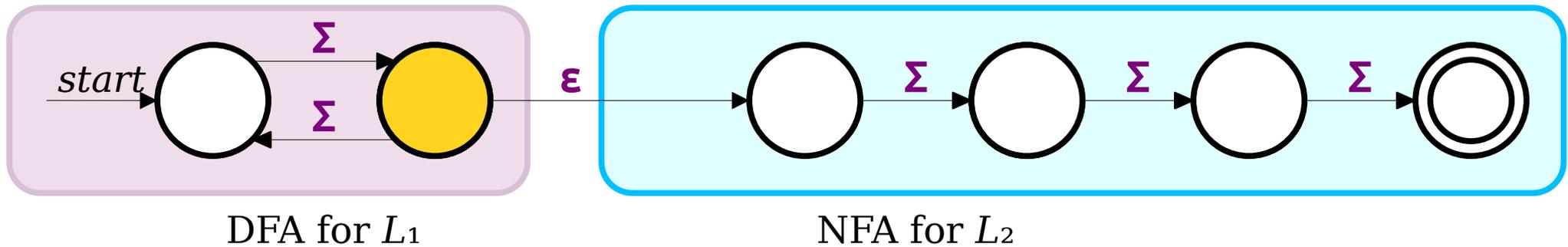
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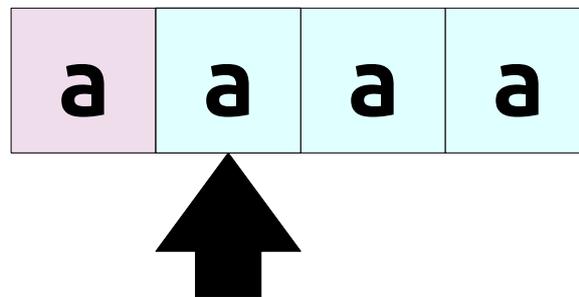
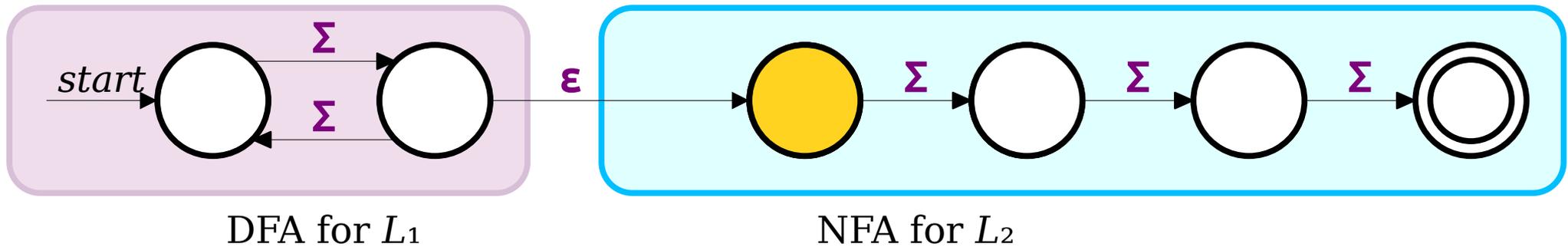


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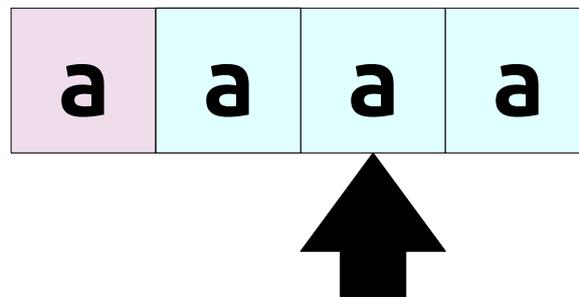
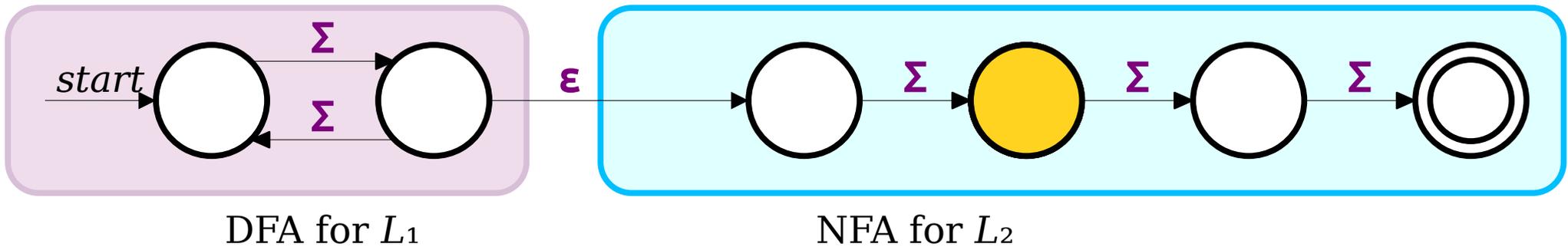
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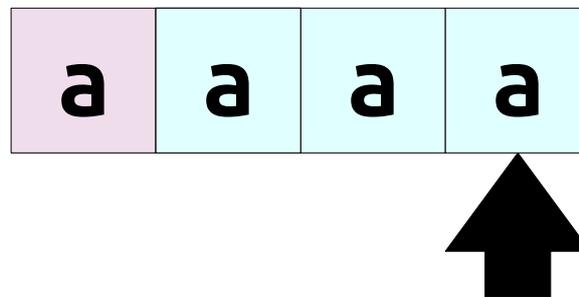
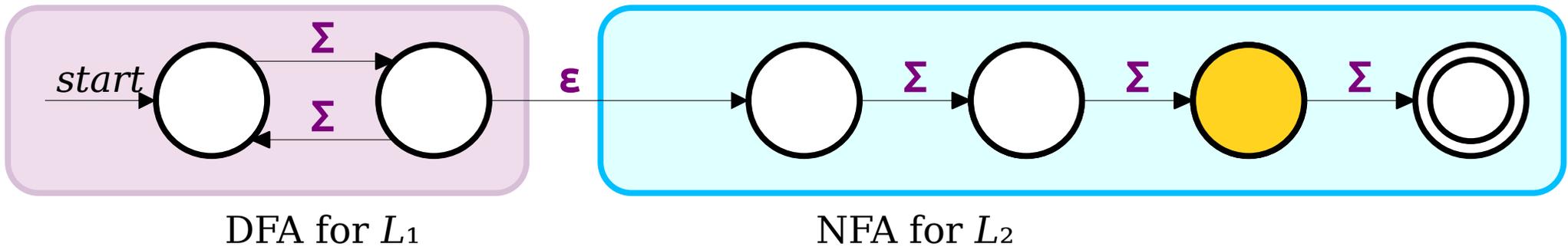
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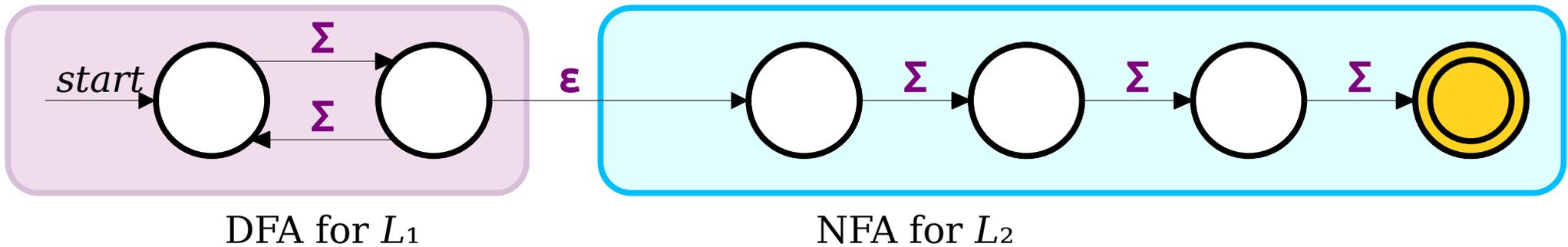
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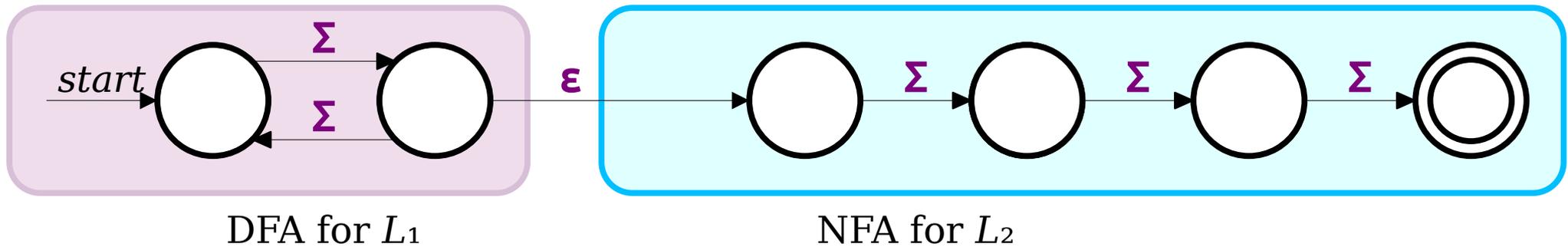


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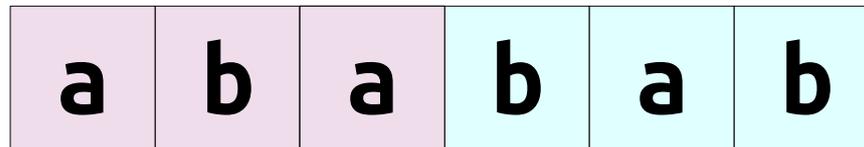
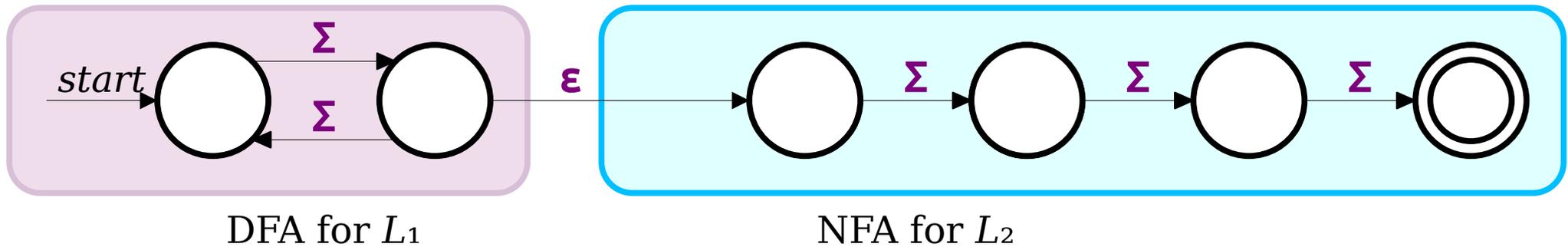


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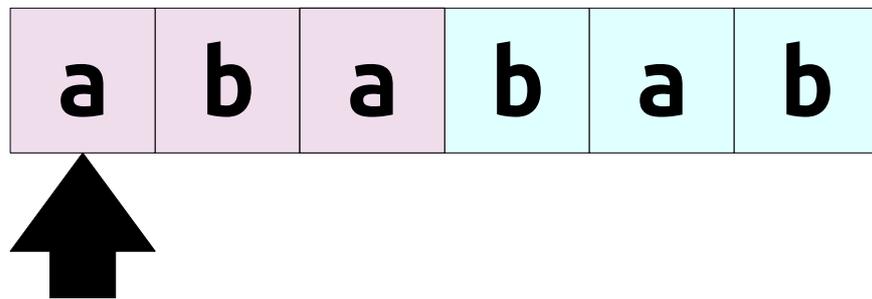
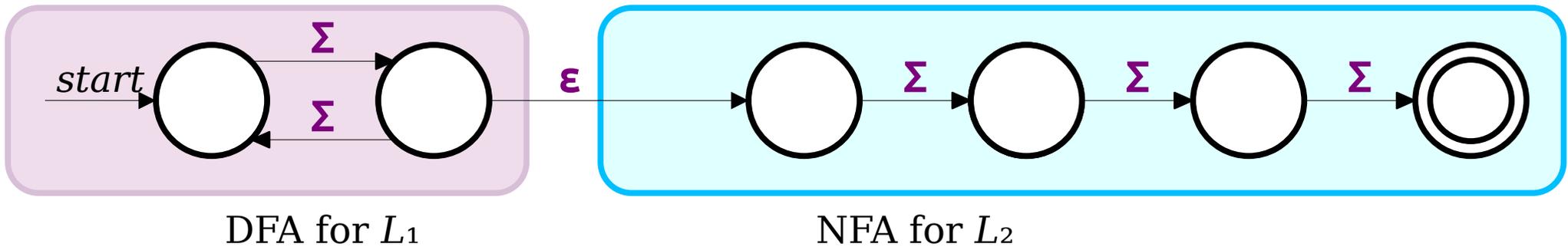
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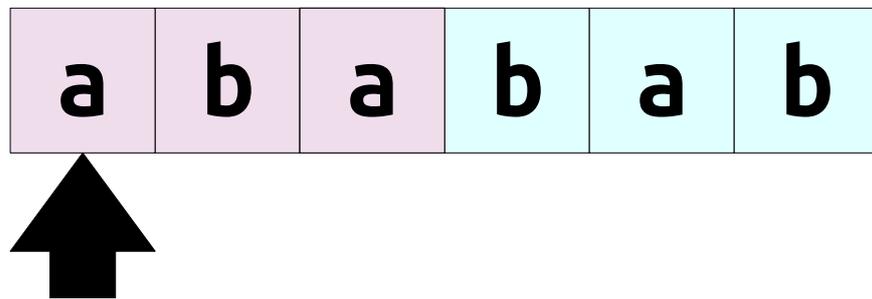
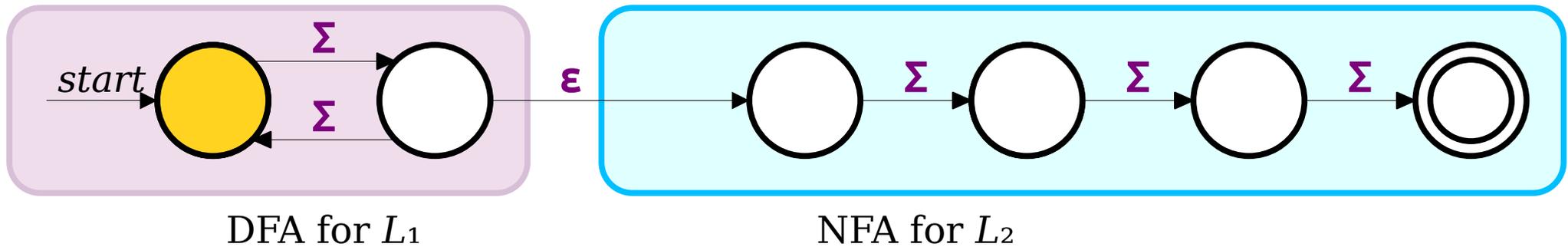
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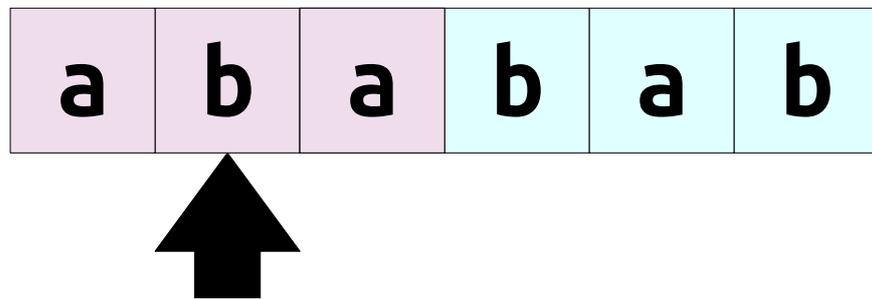
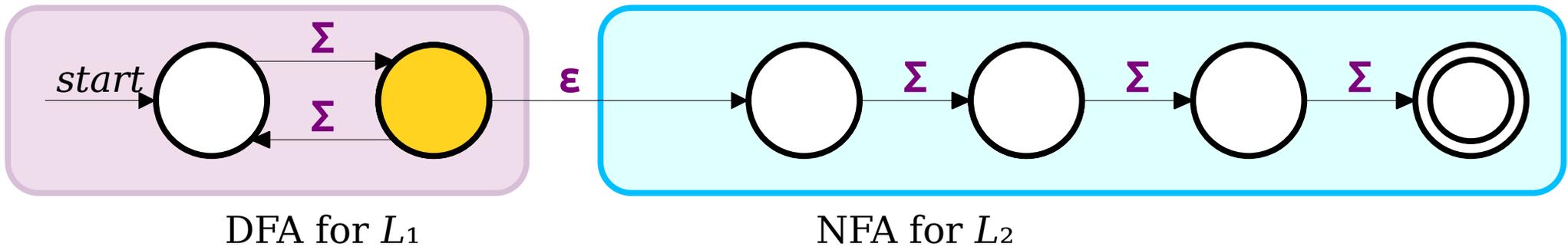
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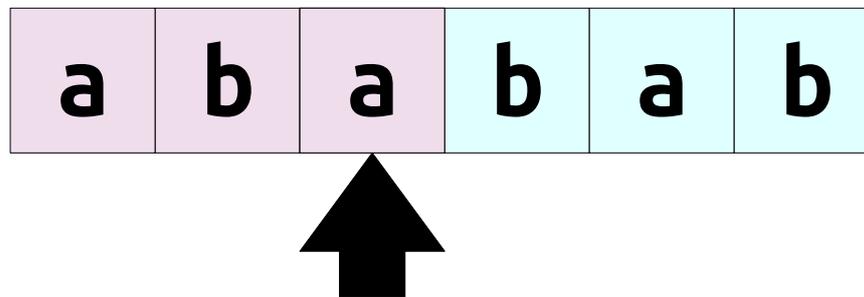
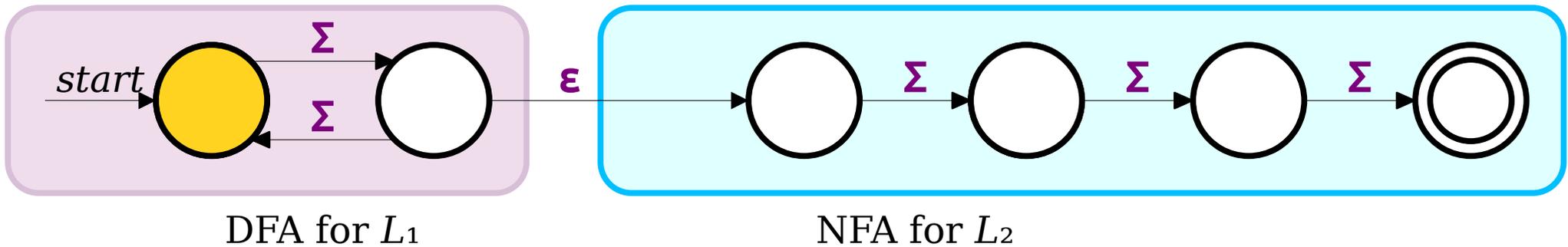
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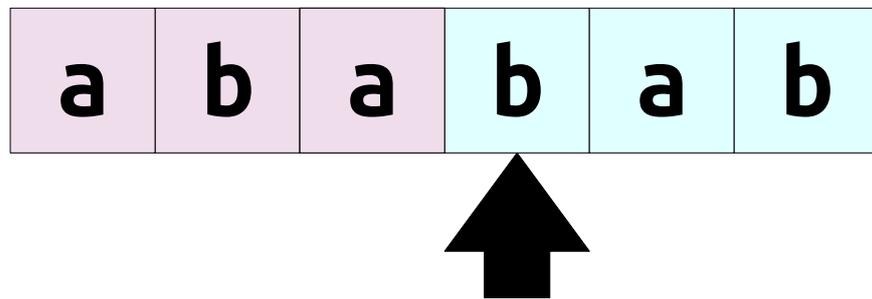
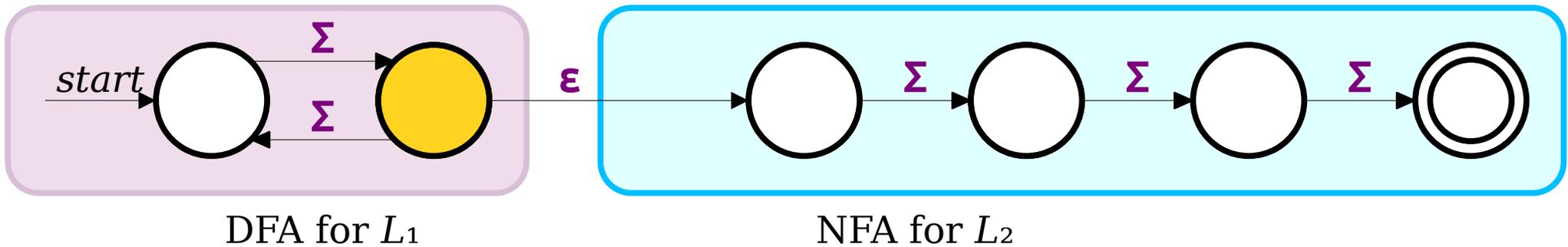
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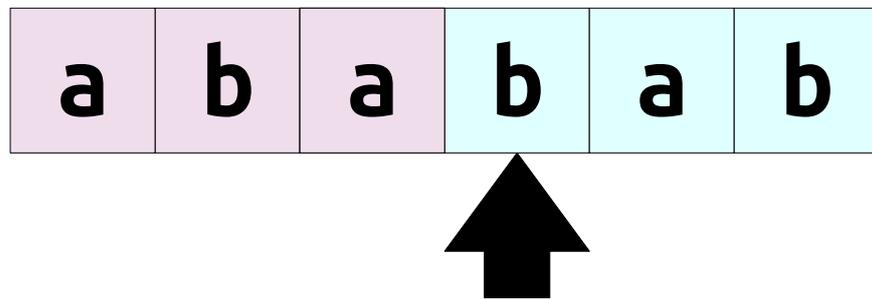
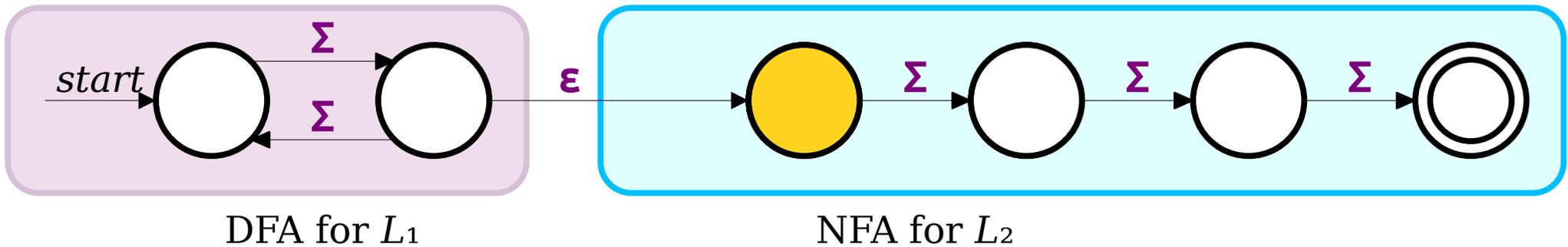
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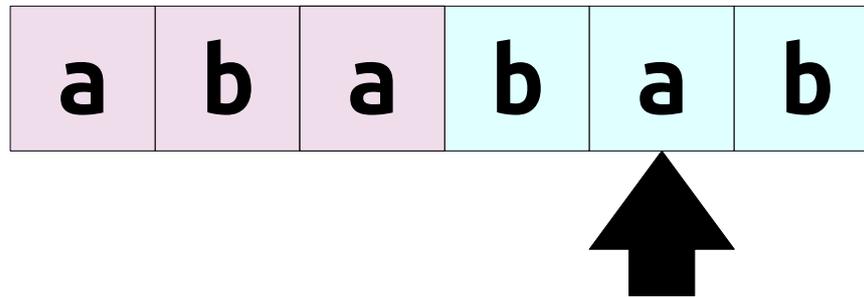
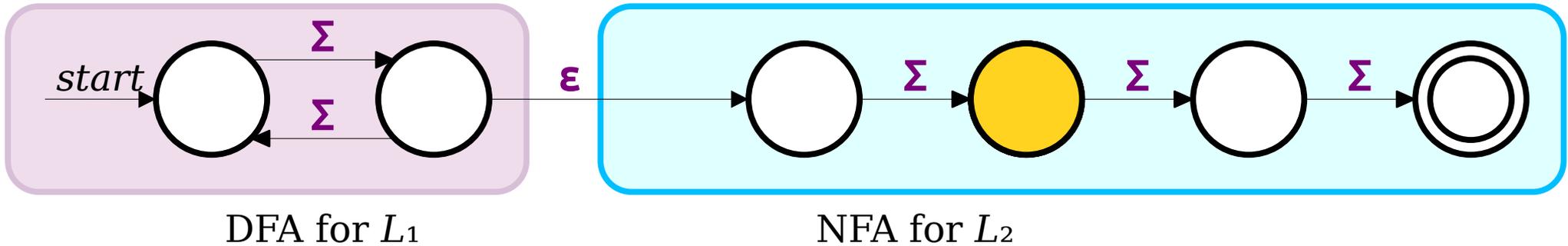
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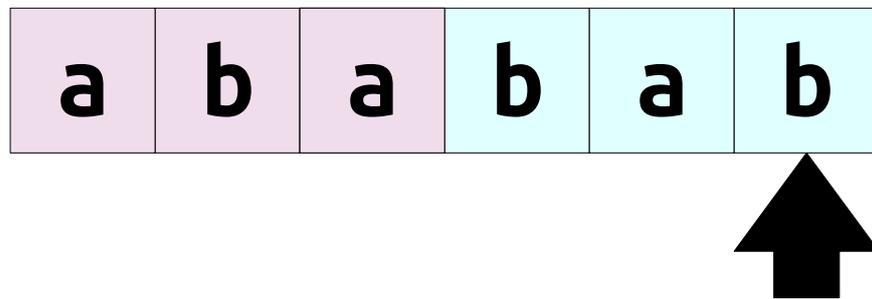
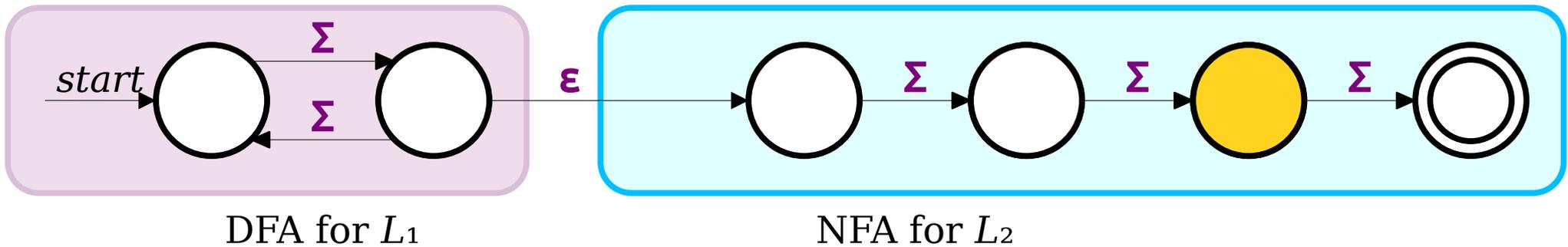
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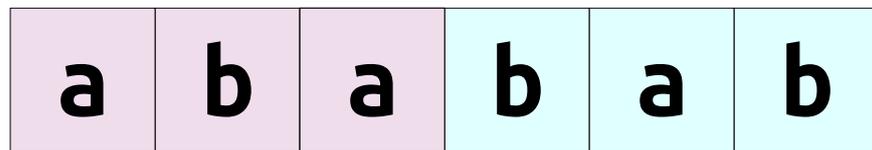
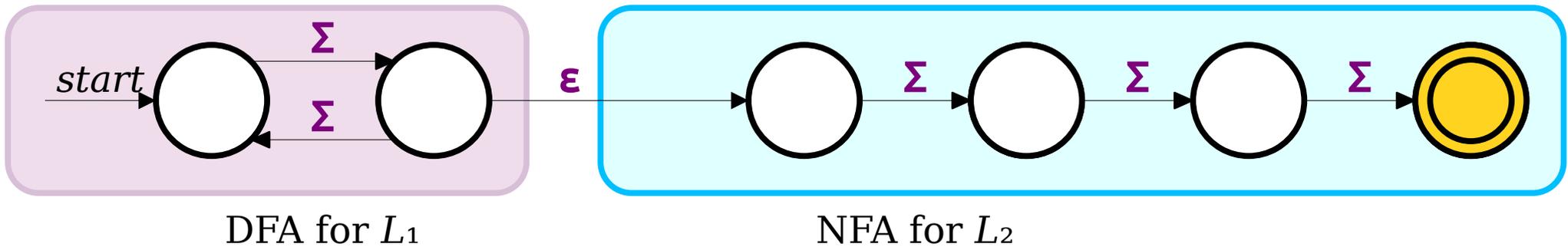
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Numbers

- Suppose we successfully build a finite automaton that checks if a string is a numbers.
- Now, we want to make a new automaton that checks if a string consists of a *series* of numbers.
 - Perhaps we're parsing a data file, for example.
- Do we have to start from scratch? Or could we reuse what we have?

The Kleene Star

Lots and Lots of Concatenation

- Consider the language $L = \{ \mathbf{aa}, \mathbf{b} \}$
- LL is the set of strings formed by concatenating pairs of strings in L .

$\{ \mathbf{aaaa}, \mathbf{aab}, \mathbf{baa}, \mathbf{bb} \}$

- LLL is the set of strings formed by concatenating triples of strings in L .

$\{ \mathbf{aaaaaa}, \mathbf{aaaab}, \mathbf{aabaa}, \mathbf{aabb}, \mathbf{baaaa}, \mathbf{baab}, \mathbf{bbaa}, \mathbf{bbb} \}$

- $LLLL$ is the set of strings formed by concatenating quadruples of strings in L .

$\{ \mathbf{aaaaaaaa}, \mathbf{aaaaaab}, \mathbf{aaaabaa}, \mathbf{aaaabb}, \mathbf{aabaaaa}, \mathbf{aabaab}, \mathbf{aabbaa}, \mathbf{aabbb}, \mathbf{baaaaaa}, \mathbf{baaaab}, \mathbf{baabaa}, \mathbf{baabb}, \mathbf{bbaaaa}, \mathbf{bbaab}, \mathbf{bbbaa}, \mathbf{bbbb} \}$

Language Exponentiation

- We can define what it means to “exponentiate” a language as follows:
- $L^0 = \{\varepsilon\}$
 - Intuition: The only string you can form by gluing no strings together is the empty string.
 - Notice that $\{\varepsilon\} \neq \emptyset$. Can you explain why?
- $L^{n+1} = LL^n$
 - Idea: Concatenating $(n+1)$ strings together works by concatenating n strings, then concatenating one more.
- **Question to ponder:** Why define $L^0 = \{\varepsilon\}$?
- **Question to ponder:** What is \emptyset^0 ?

The Kleene Closure

- An important operation on languages is the ***Kleene closure***, or ***Kleene star***, which is defined as

$$L^* = \{ w \in \Sigma^* \mid \exists n \in \mathbb{N}. w \in L^n \}$$

- Mathematically:

$$w \in L^* \quad \leftrightarrow \quad \exists n \in \mathbb{N}. w \in L^n$$

- Intuitively, L^* is the language all possible ways of concatenating zero or more strings in L together, possibly with repetition.
- ***Question to ponder:*** What is \emptyset^* ?

The Kleene Closure

If $L = \{ \mathbf{a}, \mathbf{bb} \}$, then $L^* = \{$

$\epsilon,$

$\mathbf{a}, \mathbf{bb},$

$\mathbf{aa}, \mathbf{abb}, \mathbf{bba}, \mathbf{bbbb},$

$\mathbf{aaa}, \mathbf{aabb}, \mathbf{abba}, \mathbf{abbbb}, \mathbf{bbaa}, \mathbf{bbabb}, \mathbf{bbbba}, \mathbf{bbbbbb},$

\dots

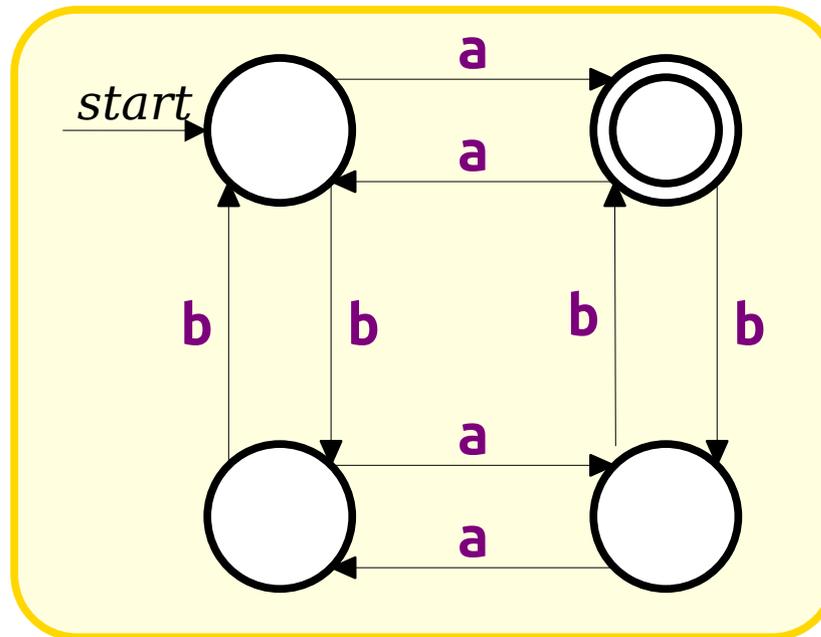
$\}$

Think of L^* as the set of strings you can make if you have a collection of stamps – one for each string in L – and you form every possible string that can be made from those stamps.

Theorem: If L is a regular language, so is L^* .

$L = \{ w \in \{a, b\}^* \mid w \text{ has an odd number of } a\text{'s and an even number of } b\text{'s} \}$

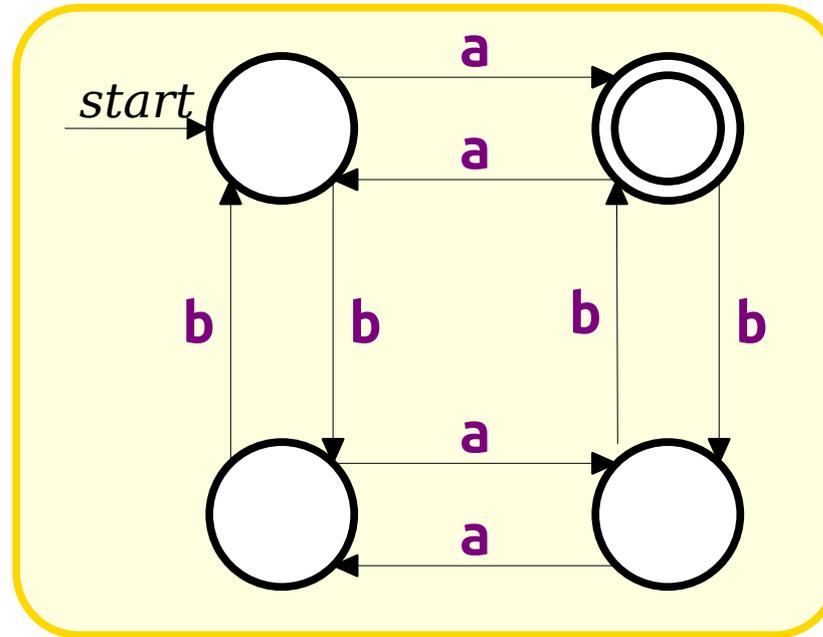
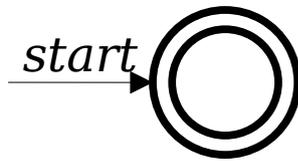
Construct an NFA for L^* .



DFA for L

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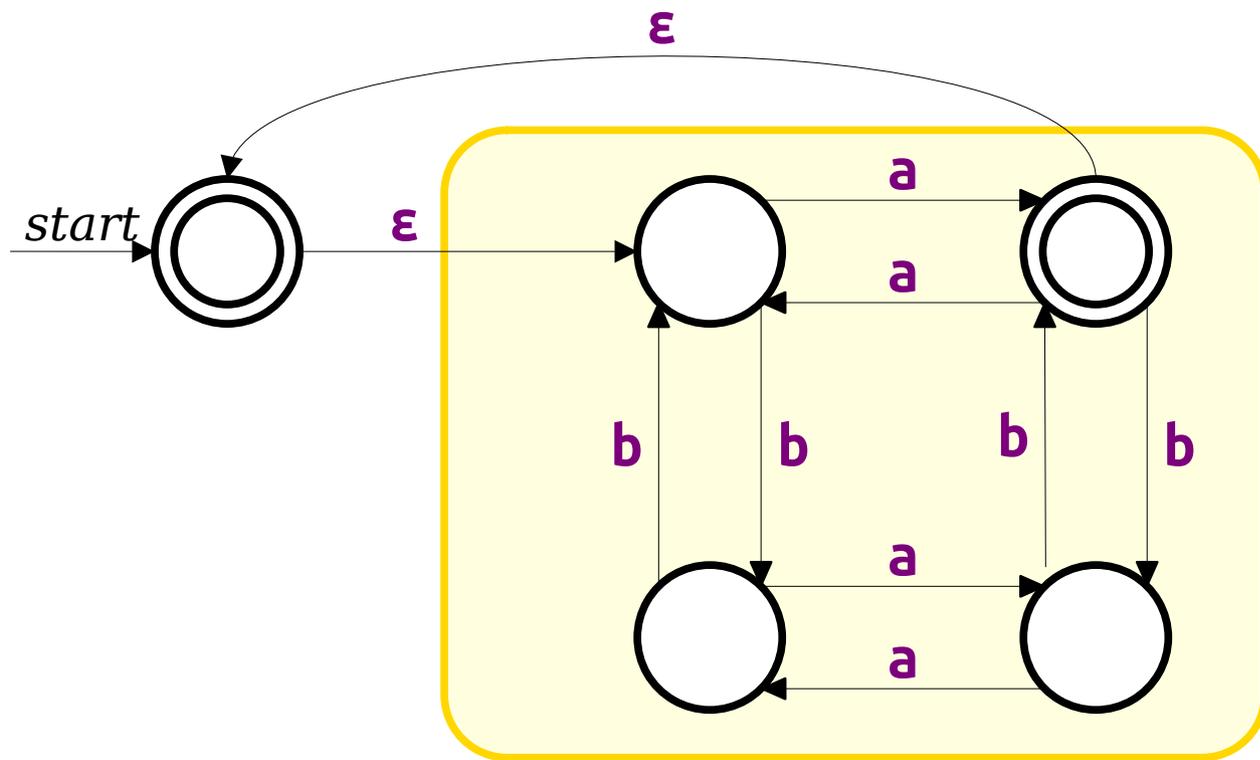
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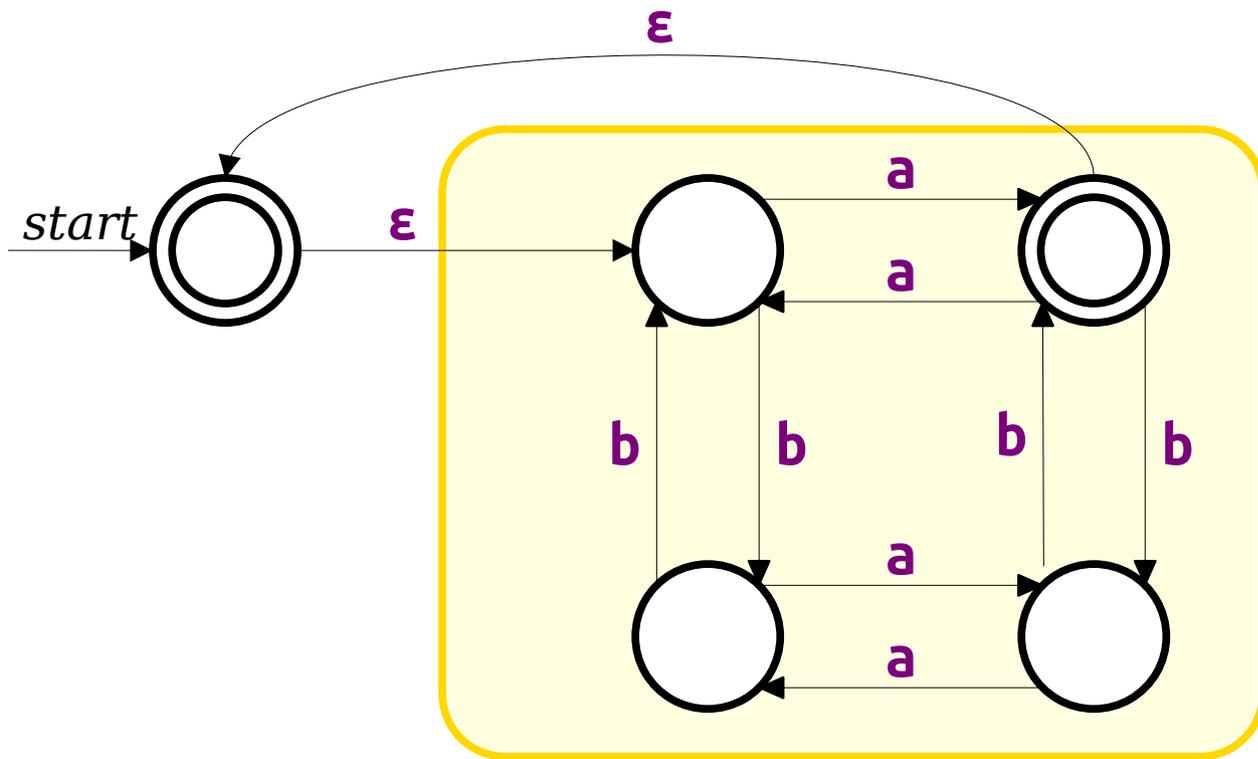
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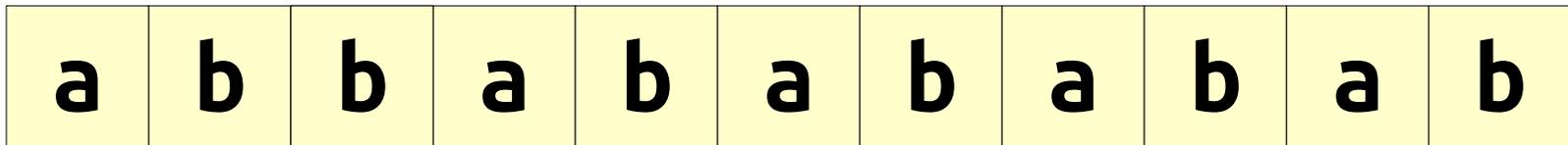
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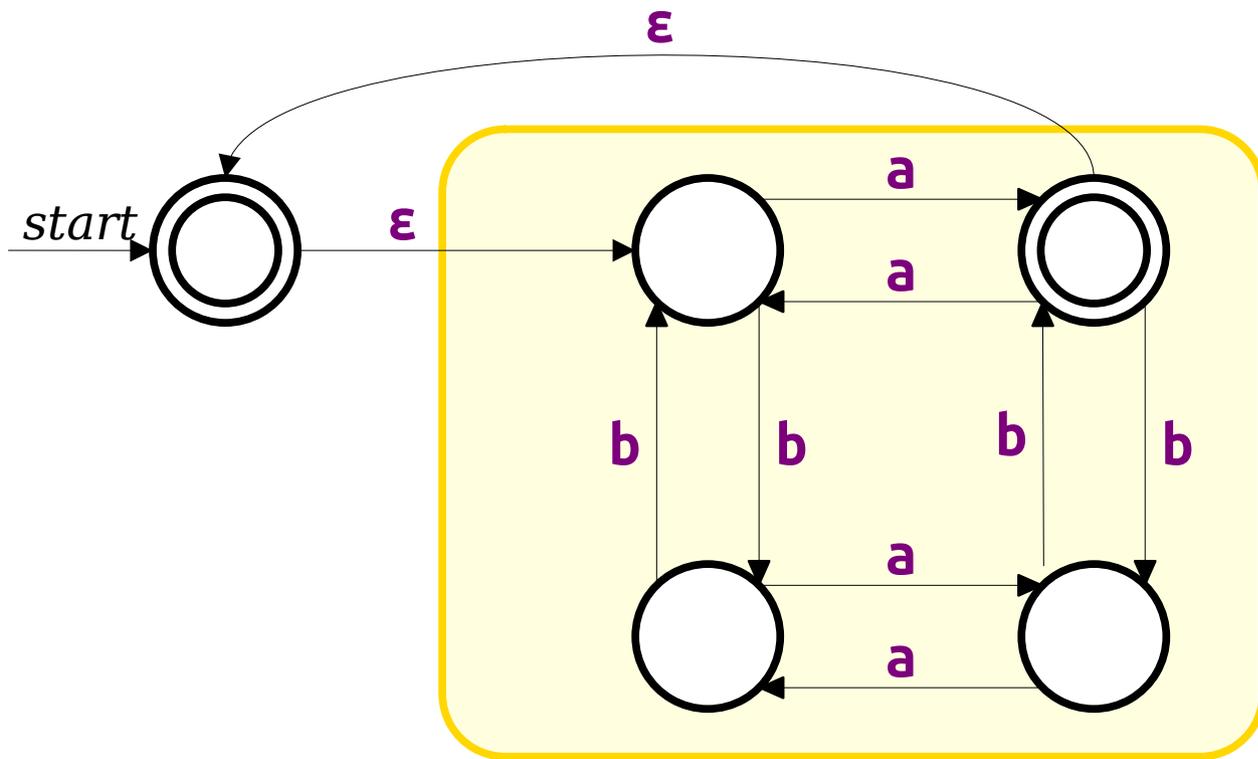


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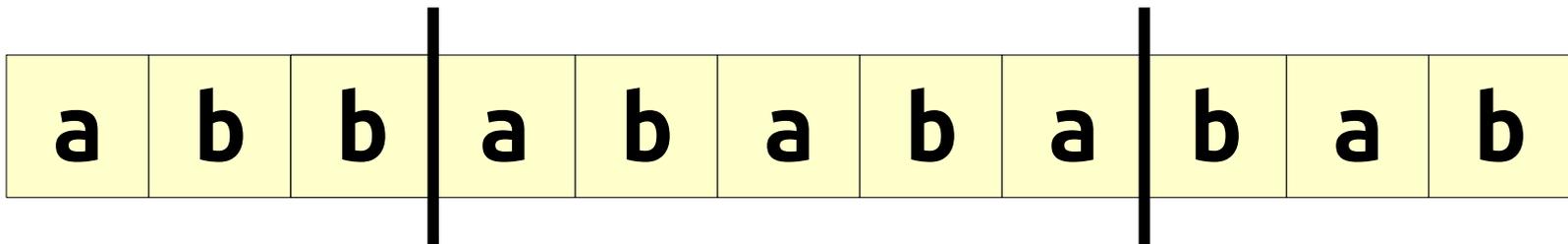


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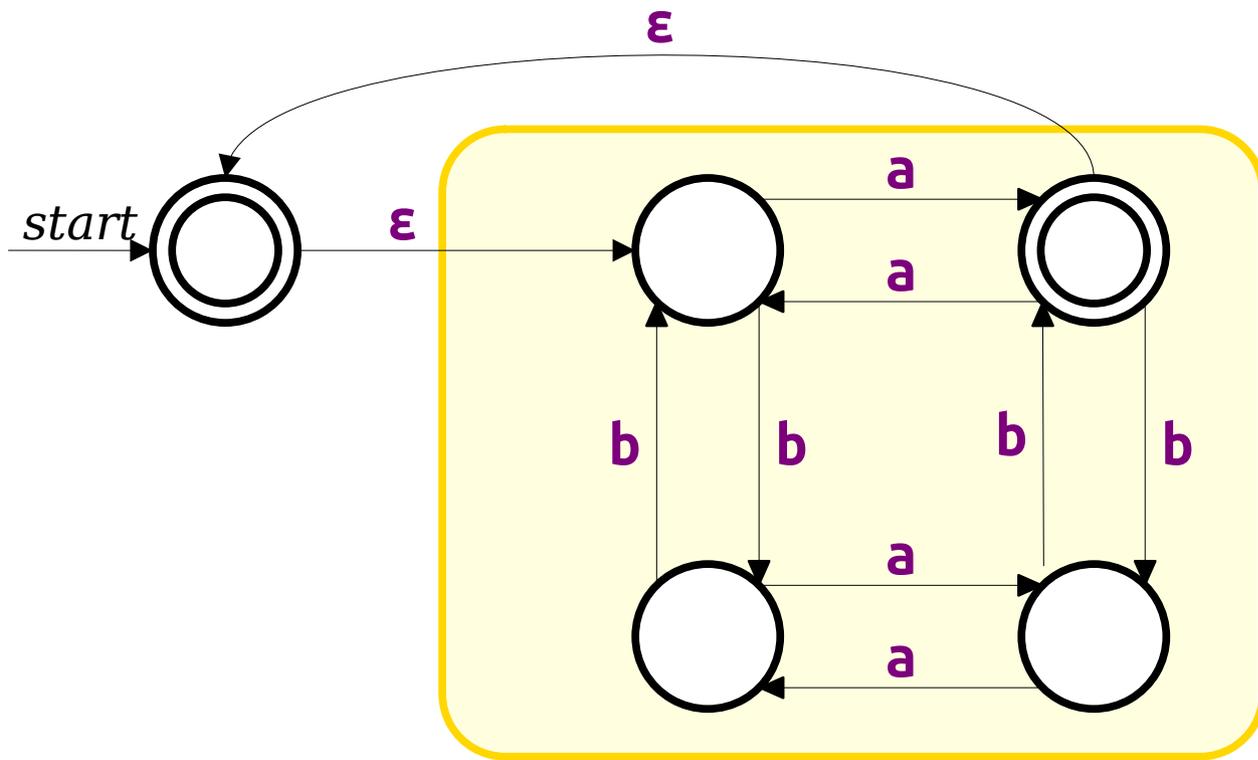


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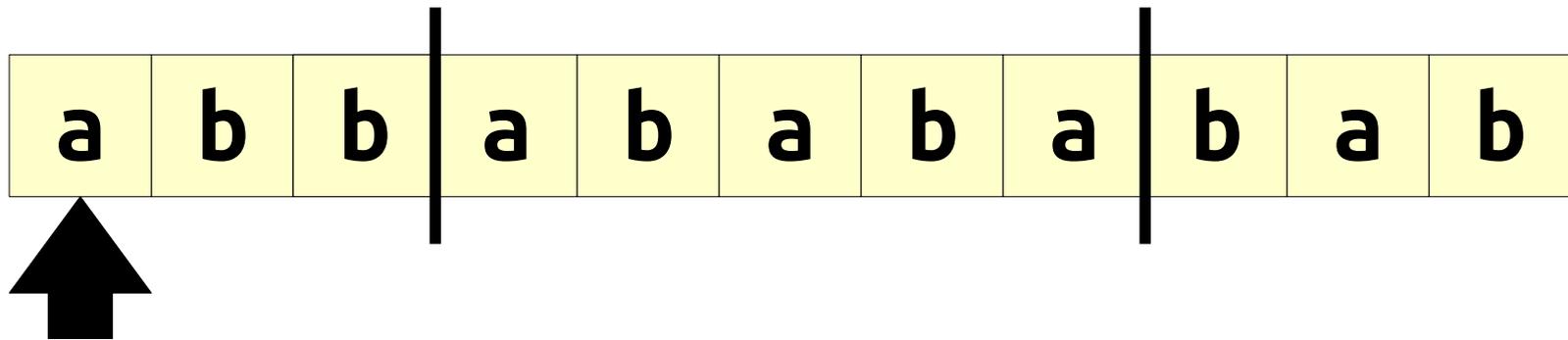


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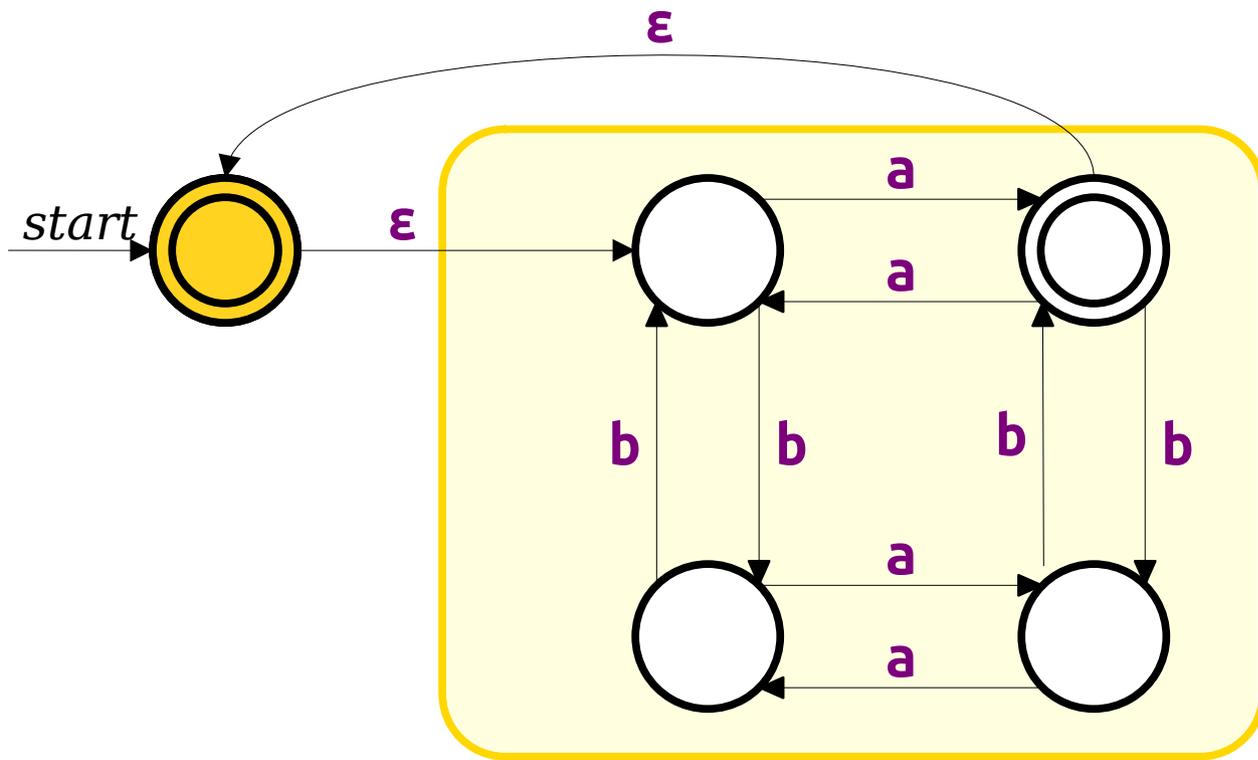


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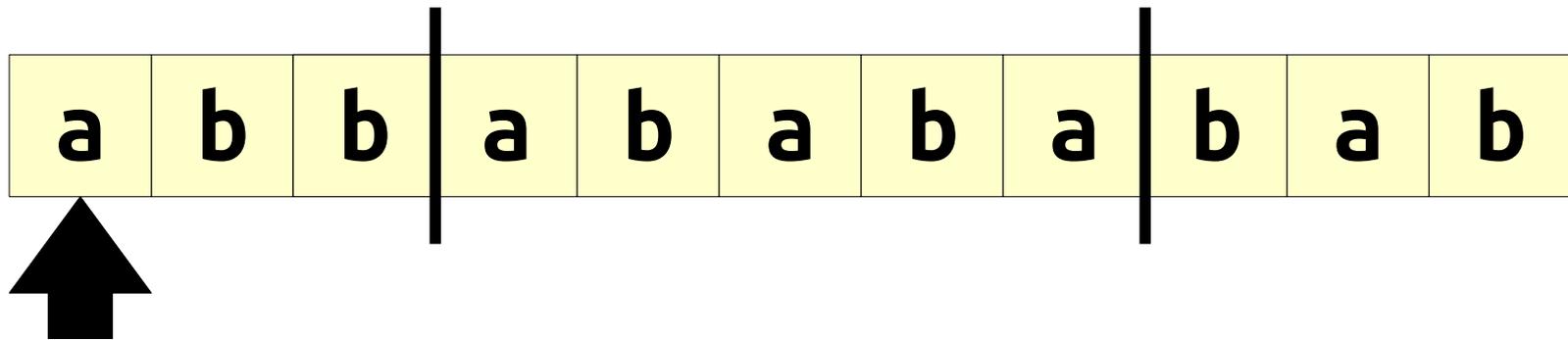


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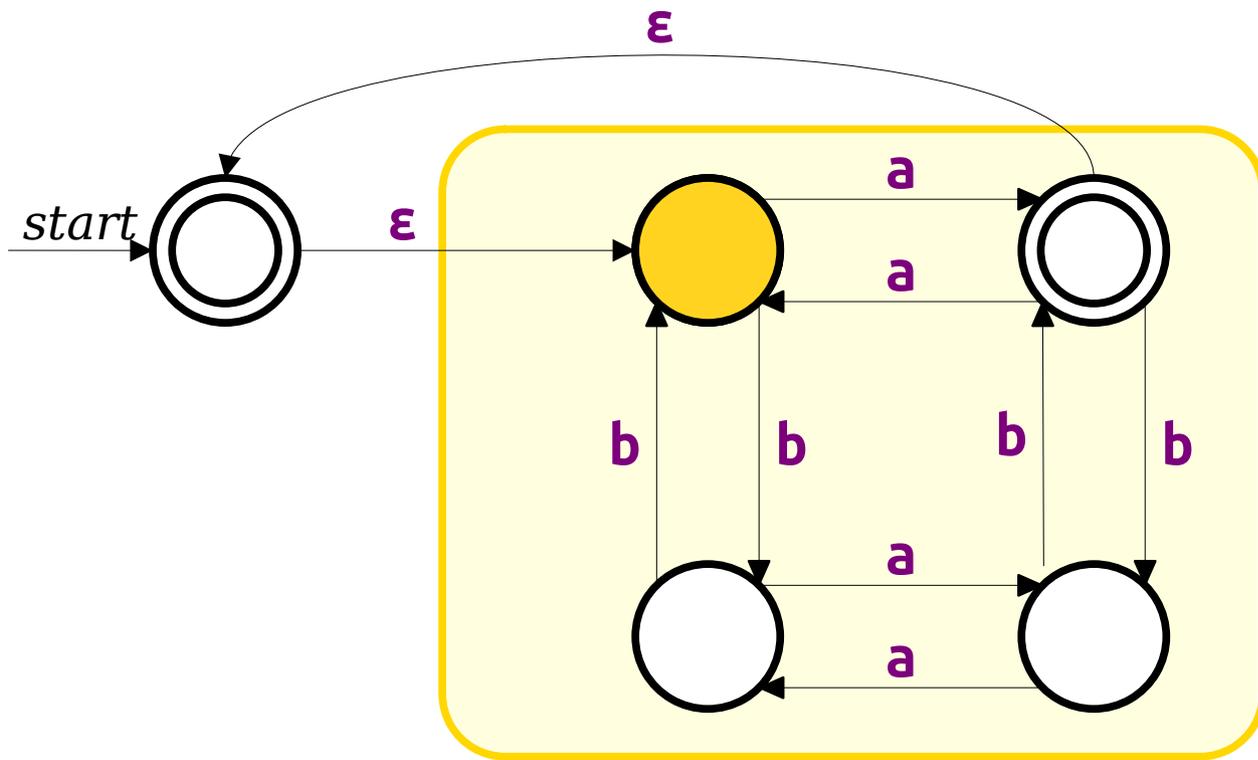


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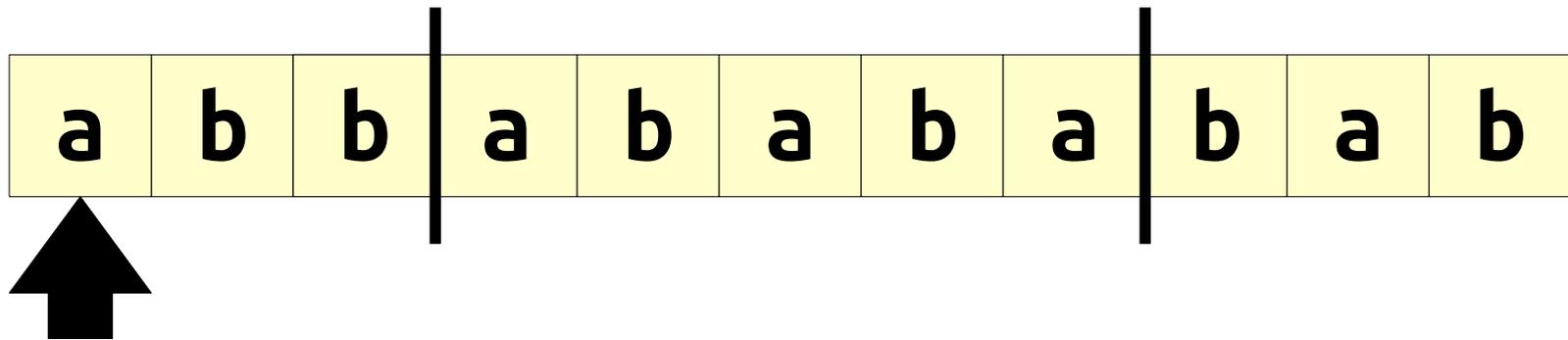


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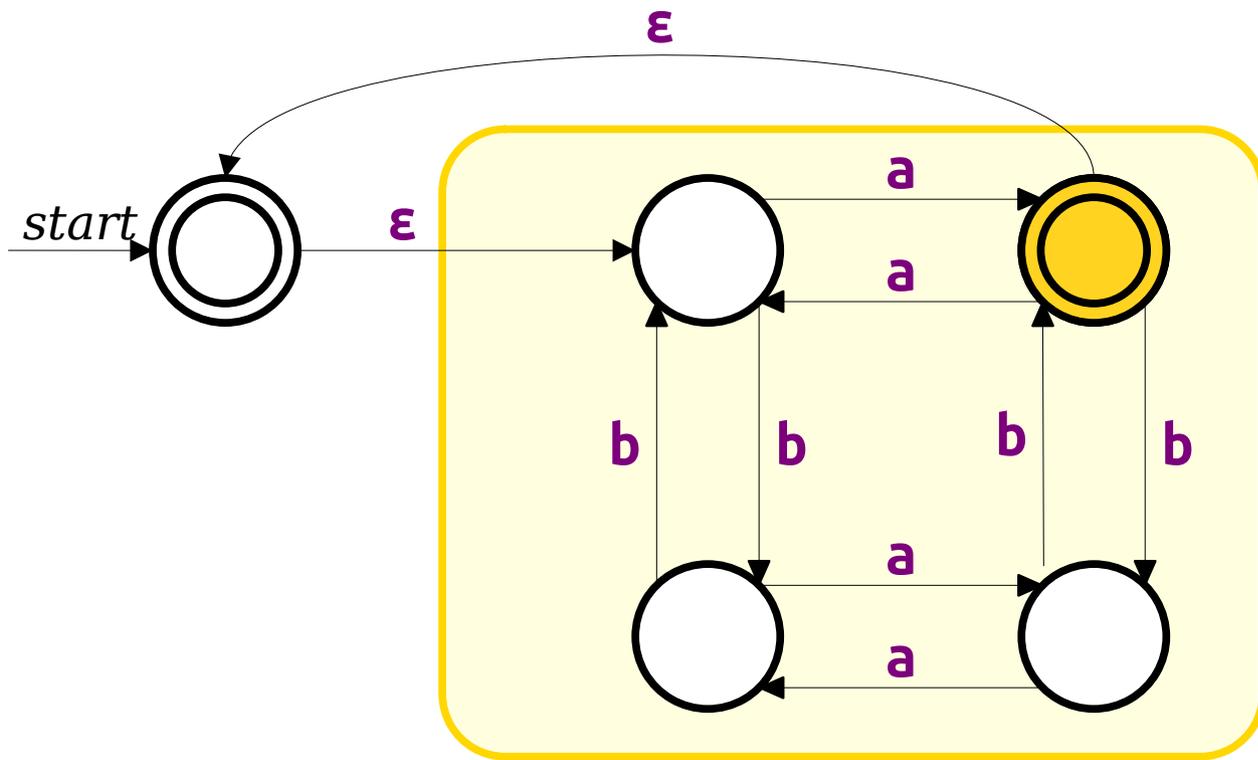


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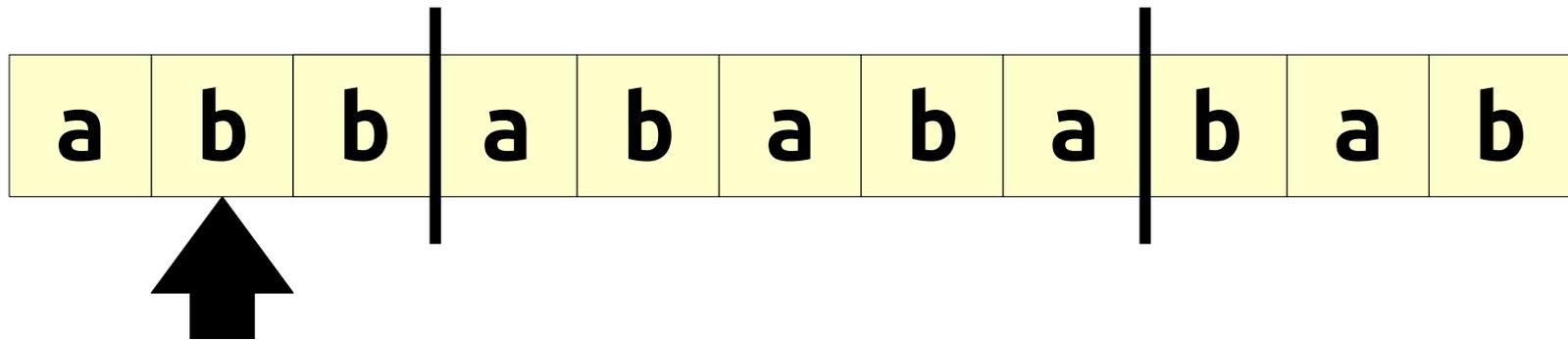


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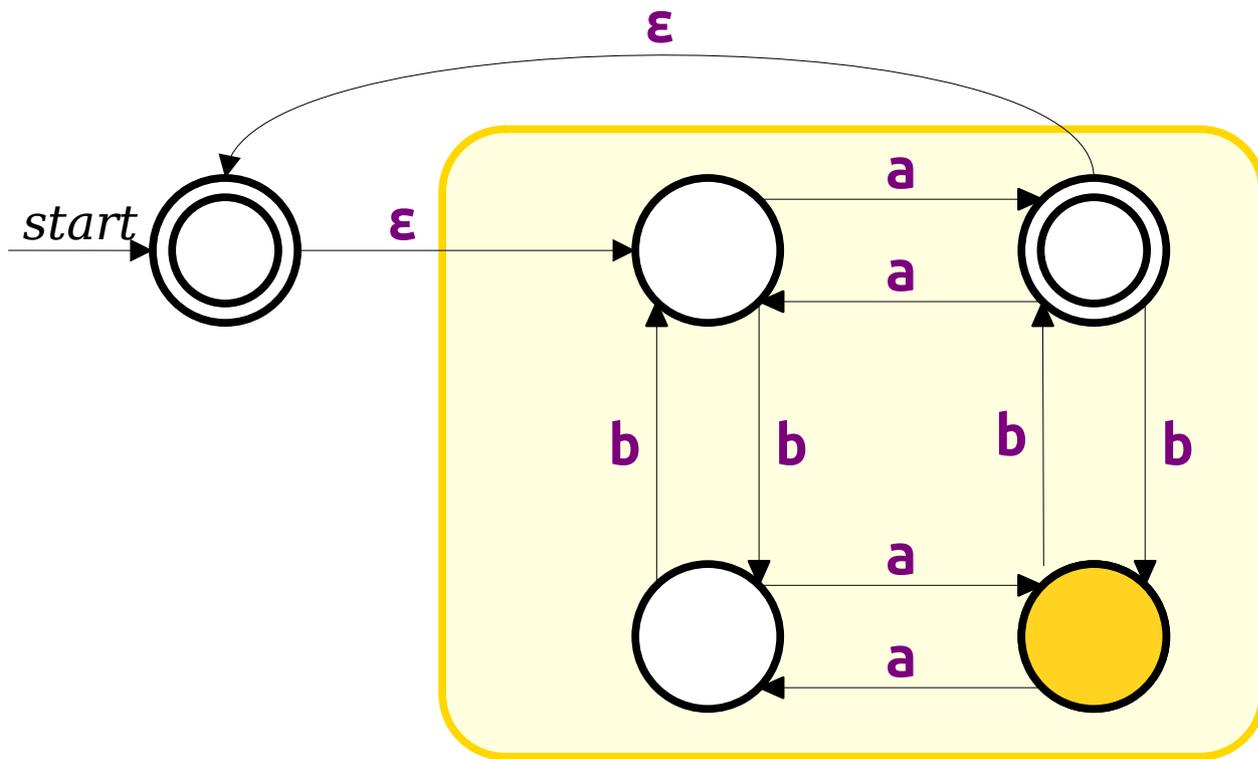


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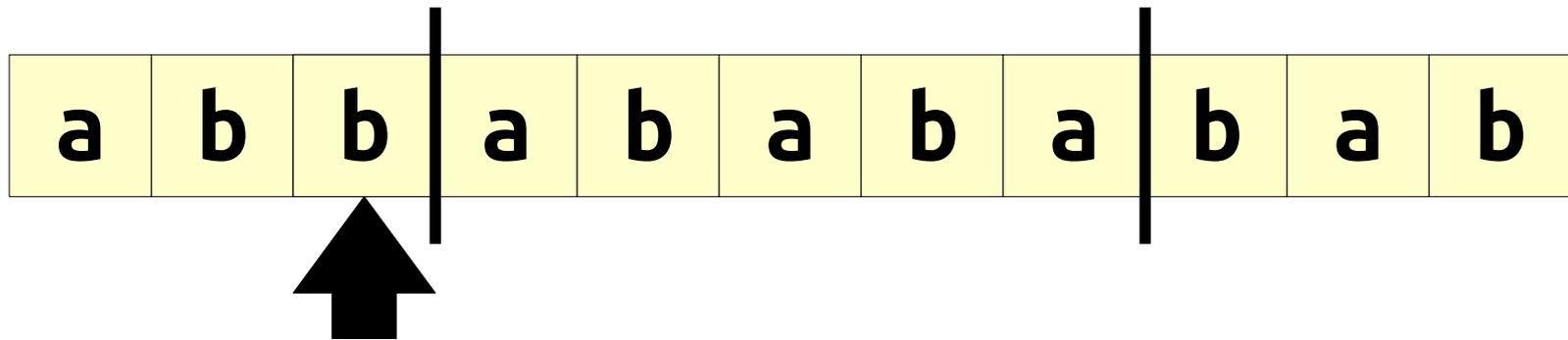


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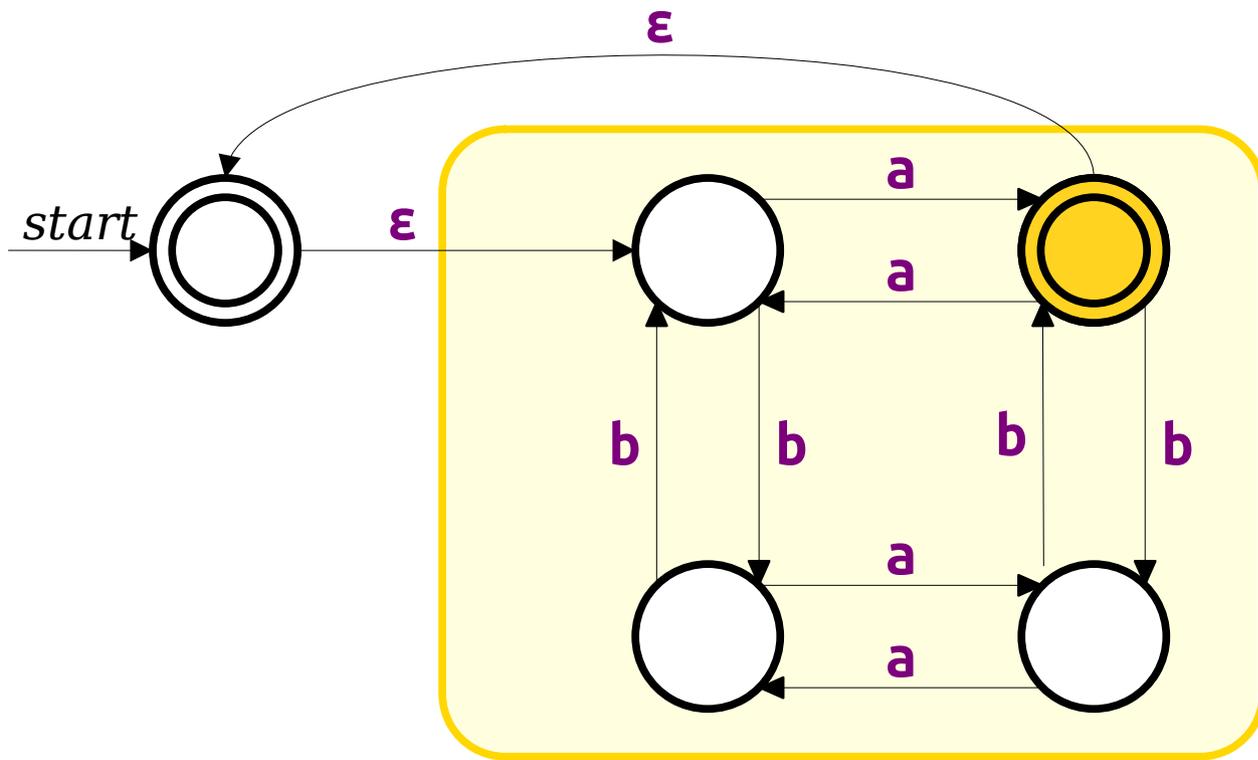


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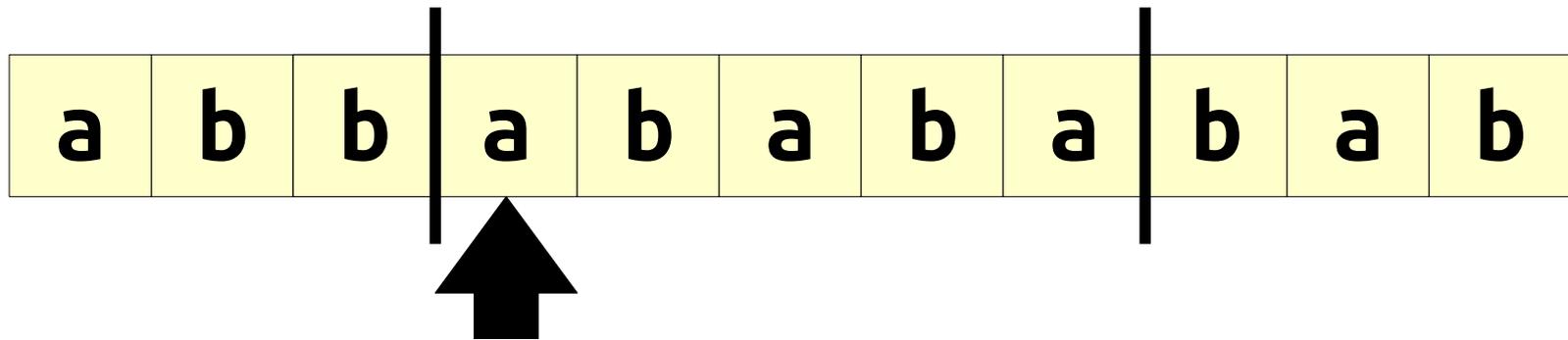


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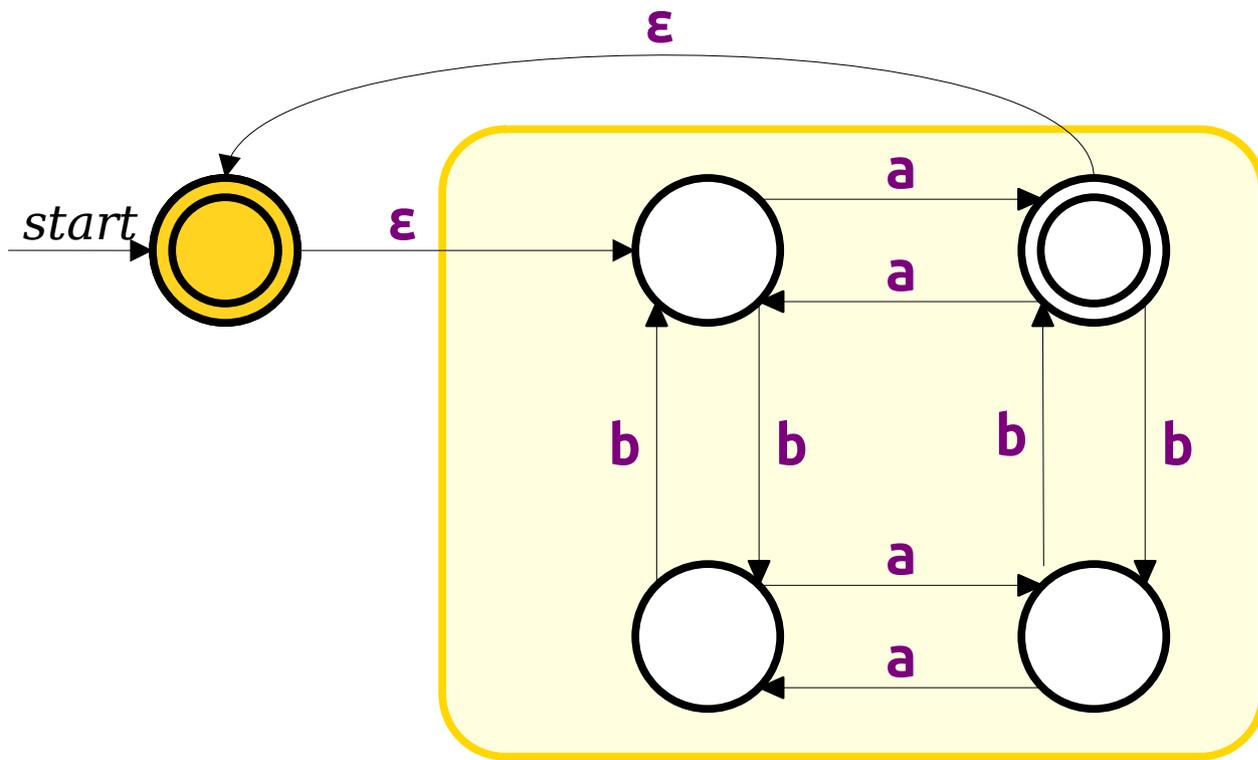


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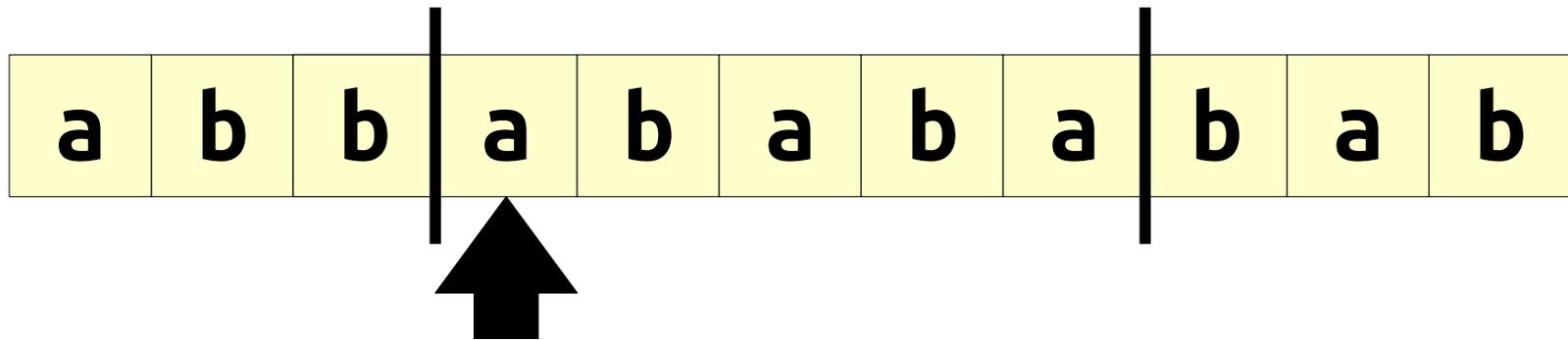


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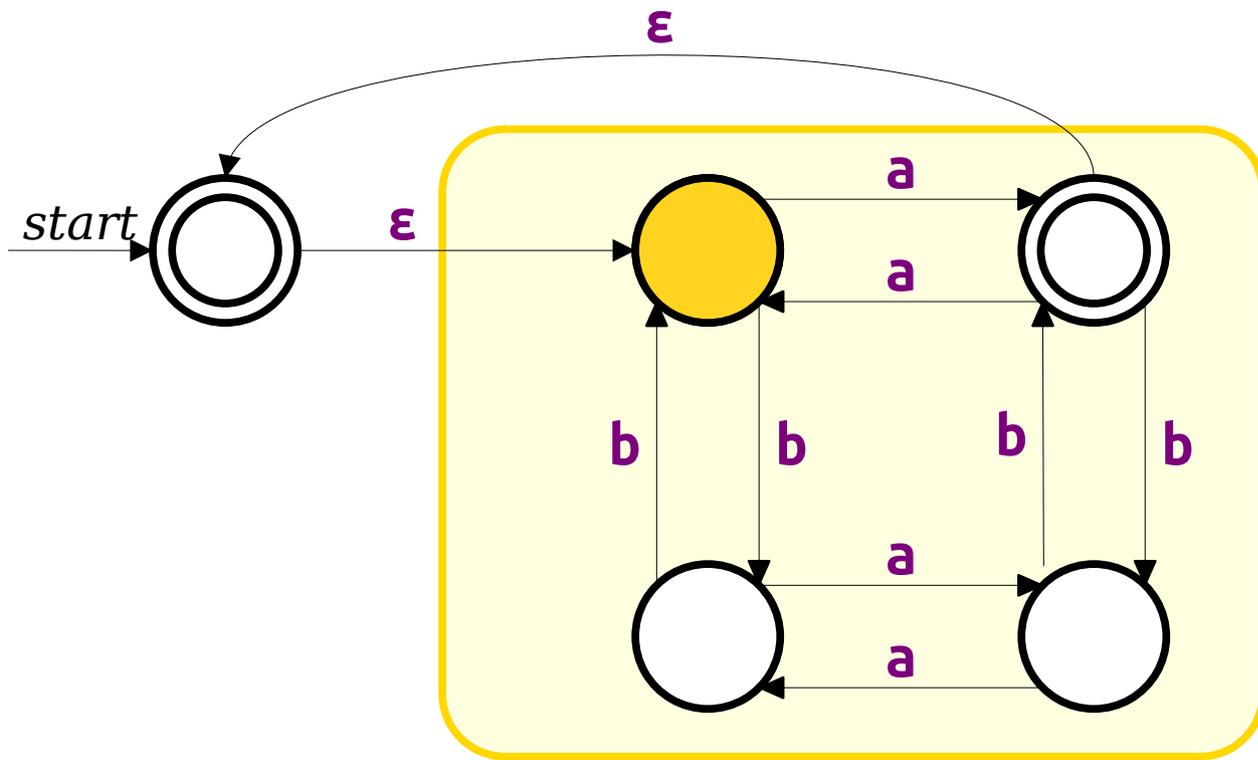


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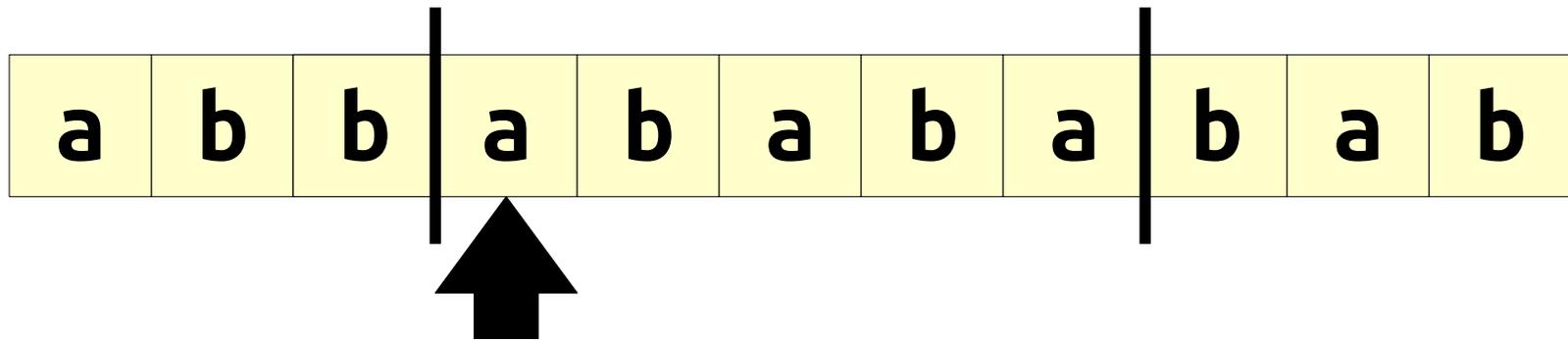


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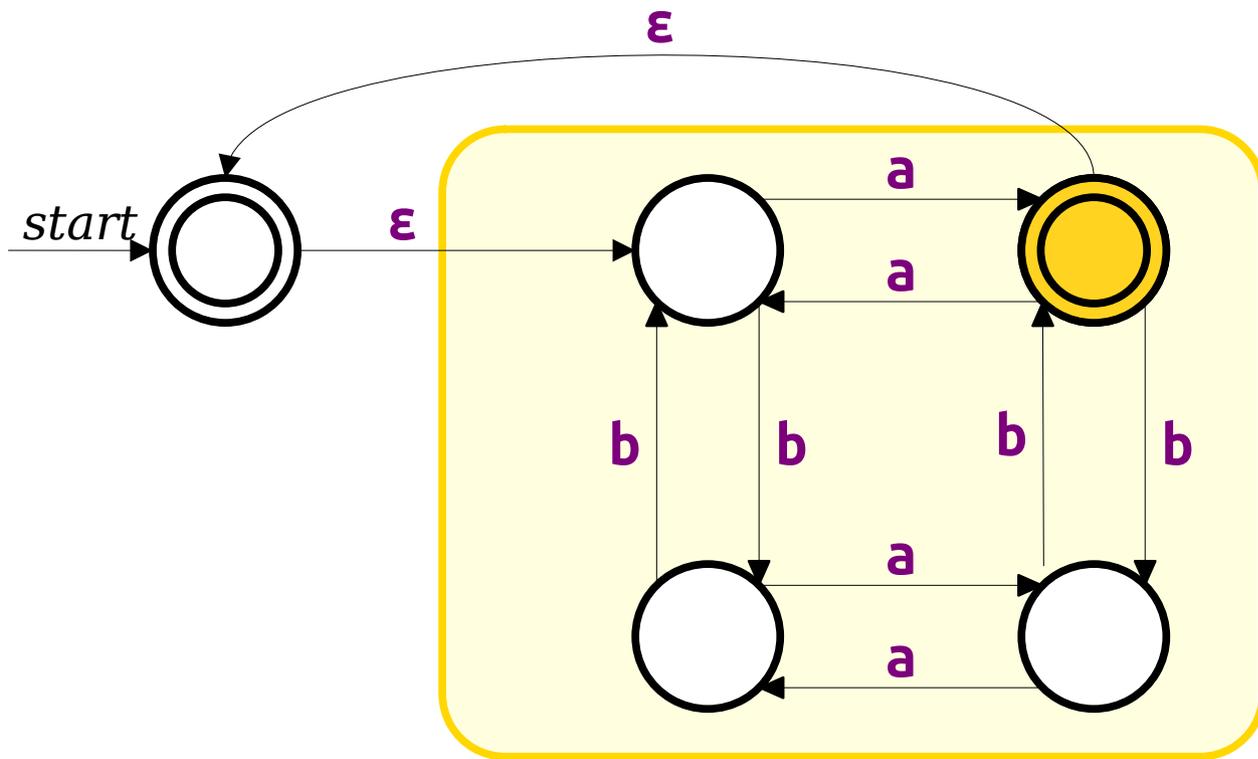


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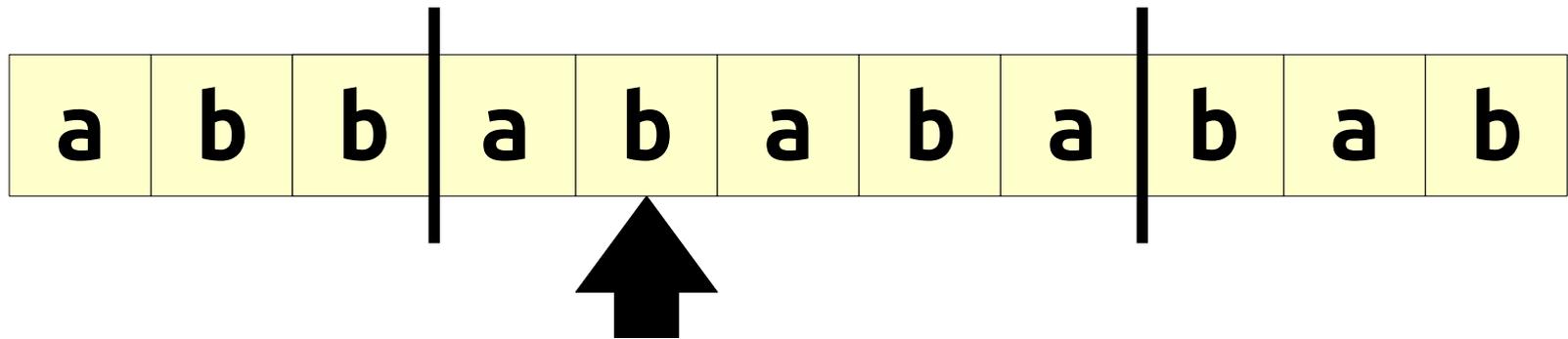


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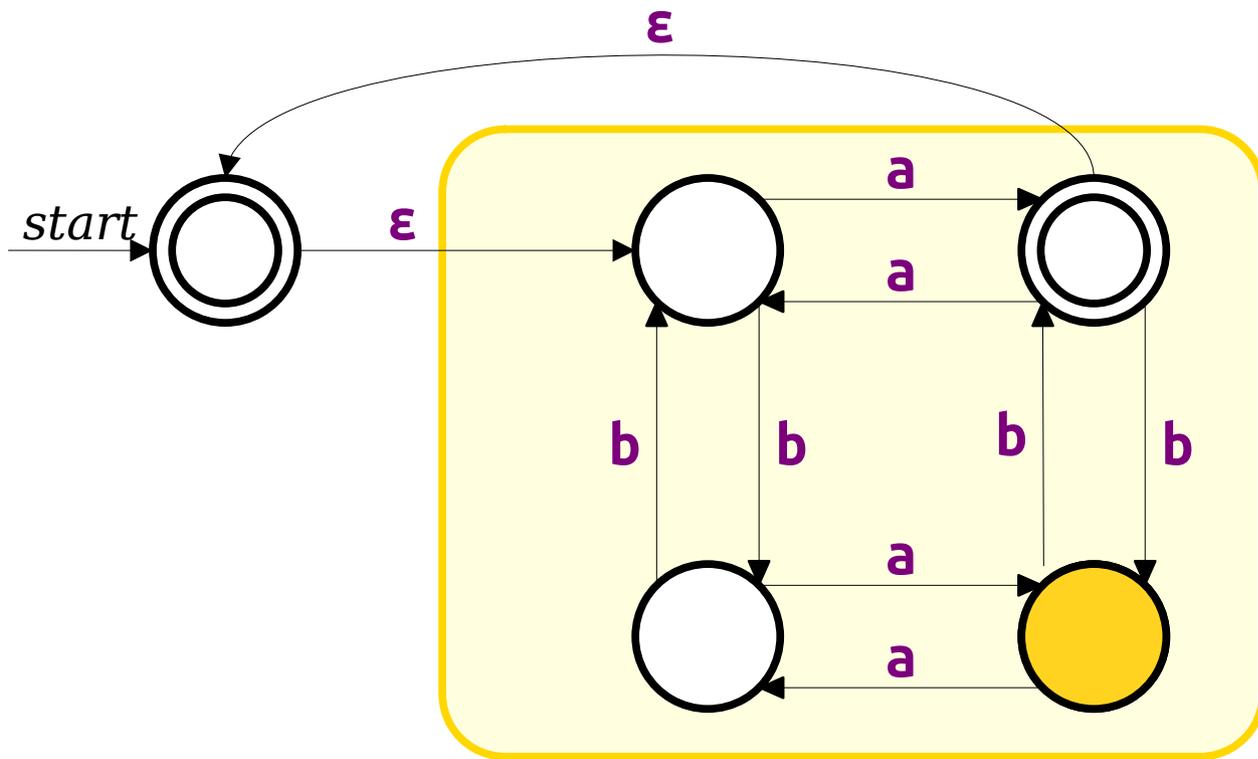


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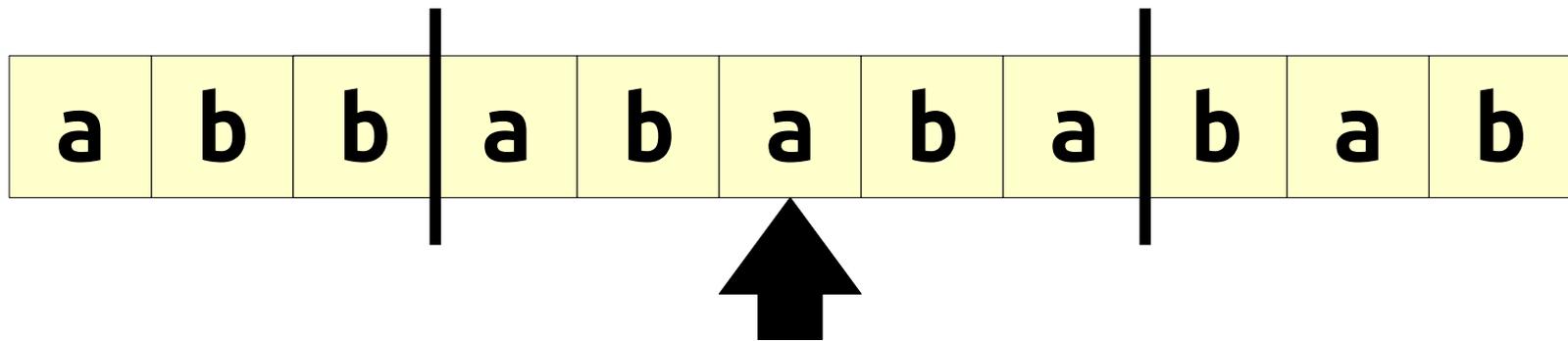


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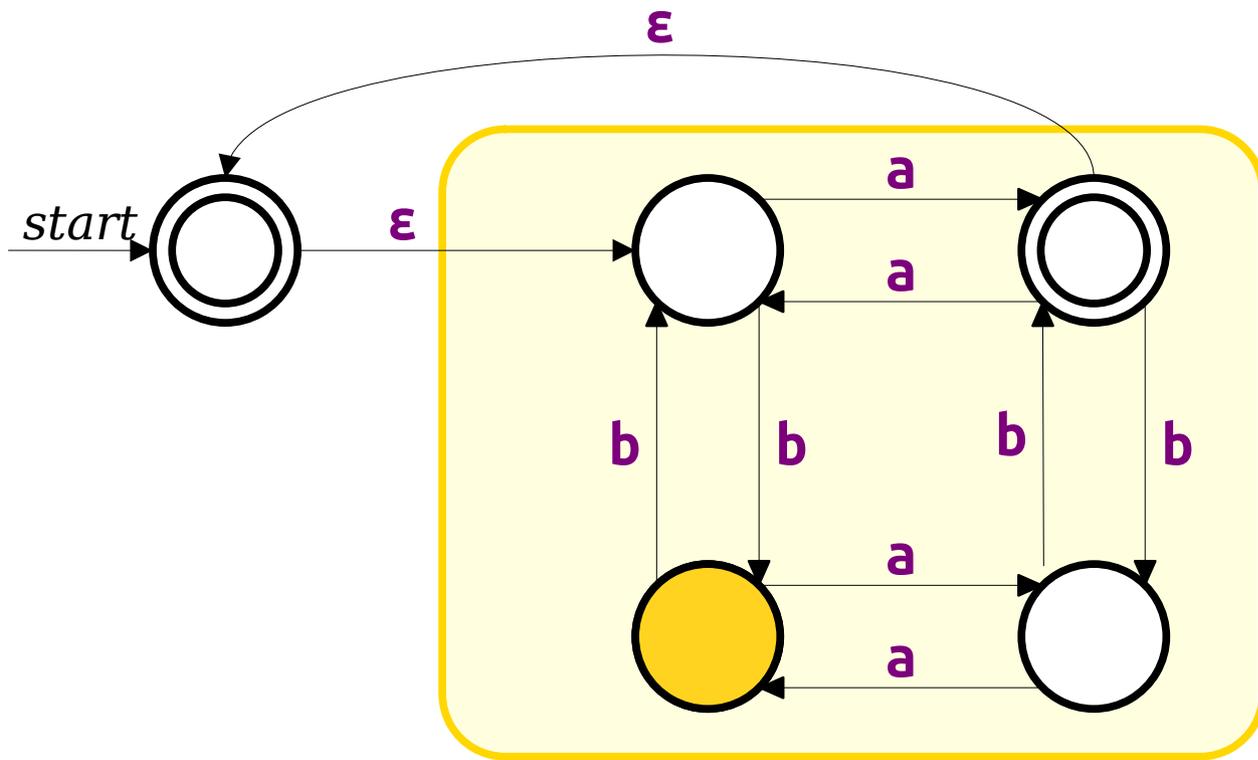


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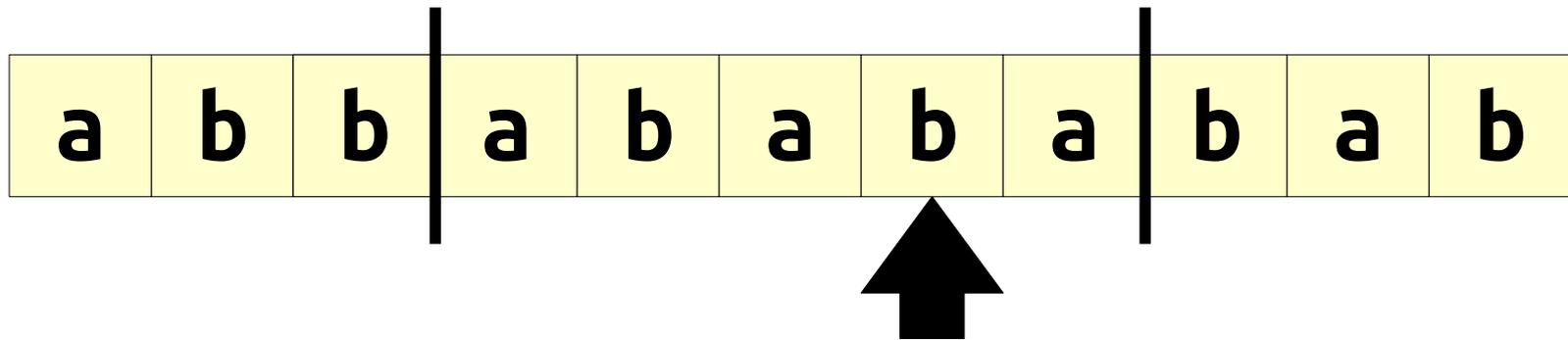


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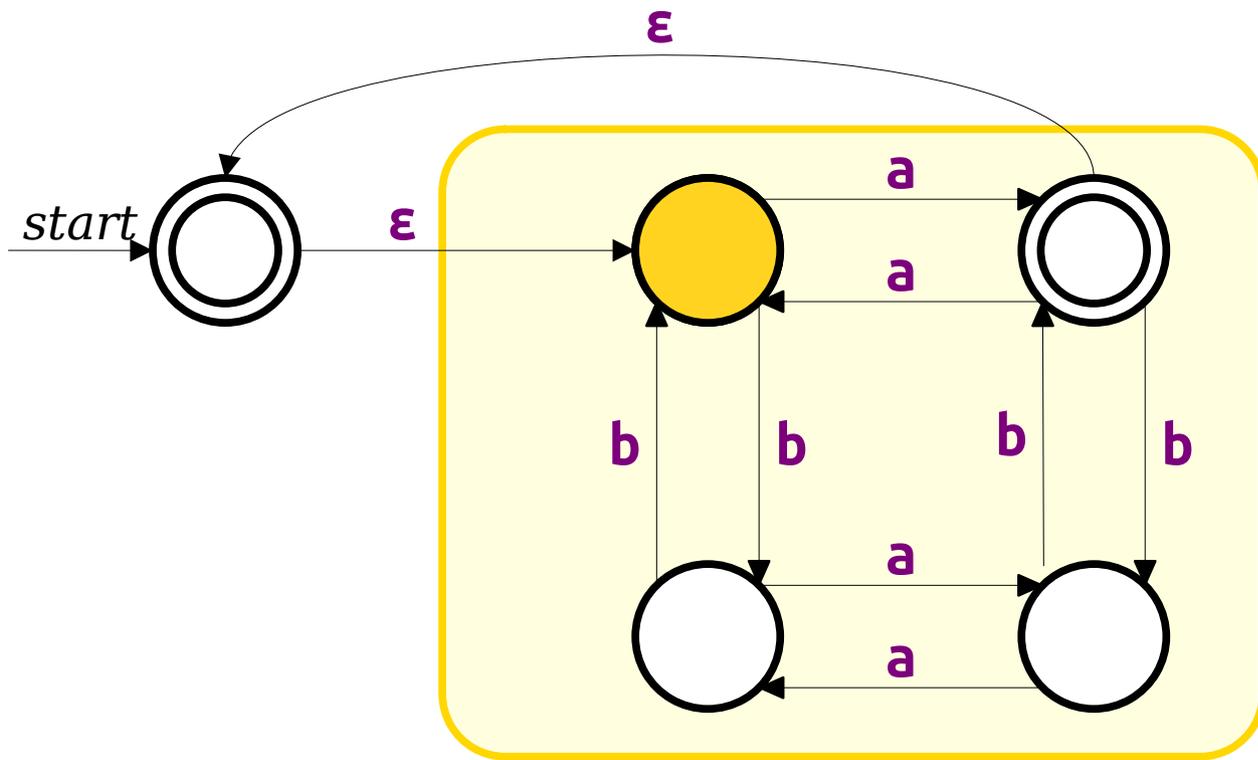


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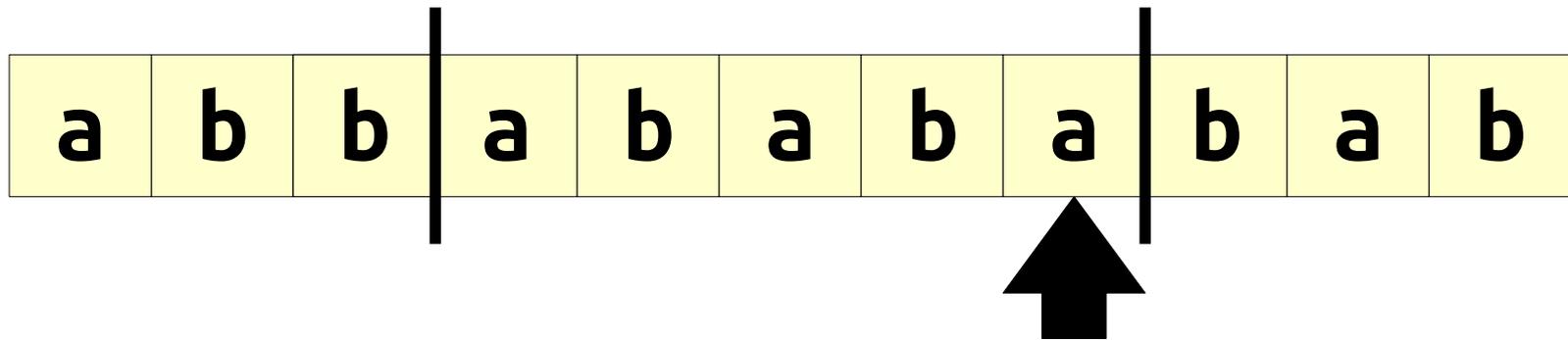


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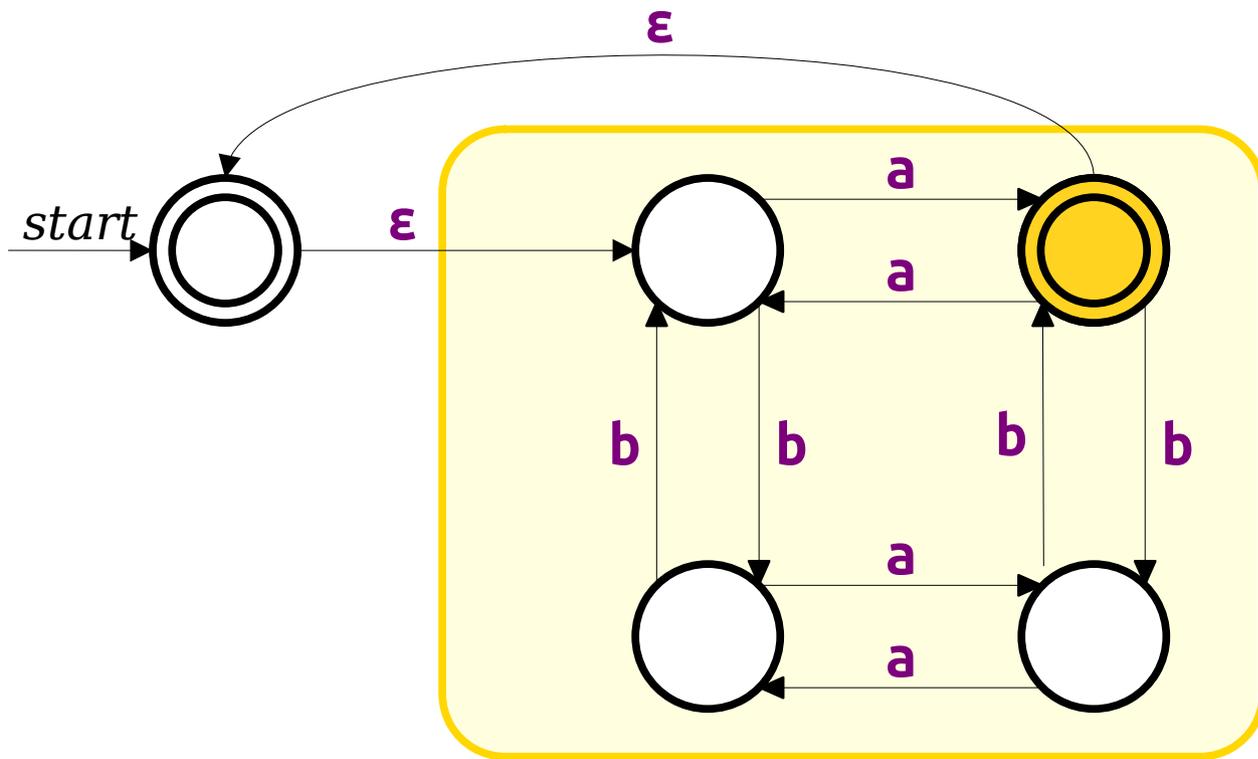


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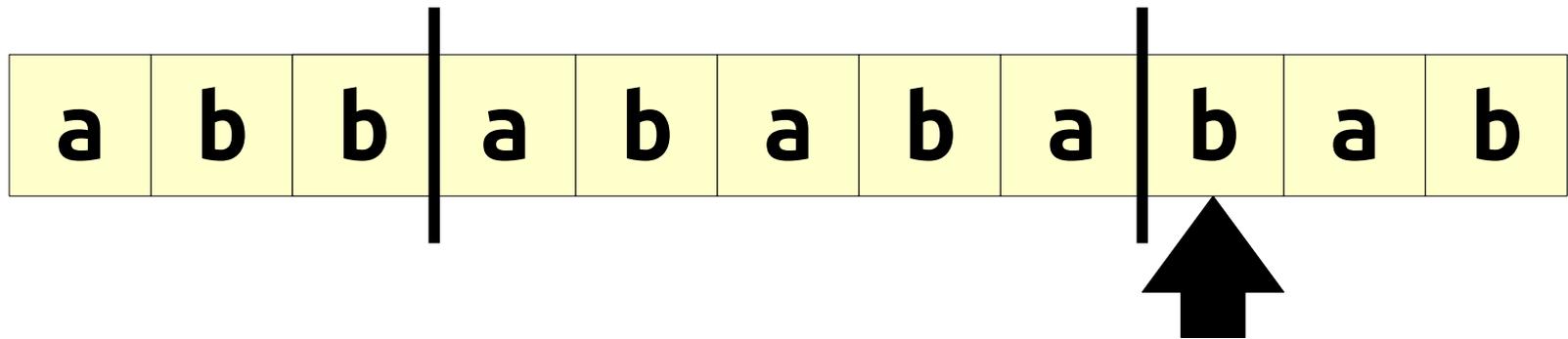


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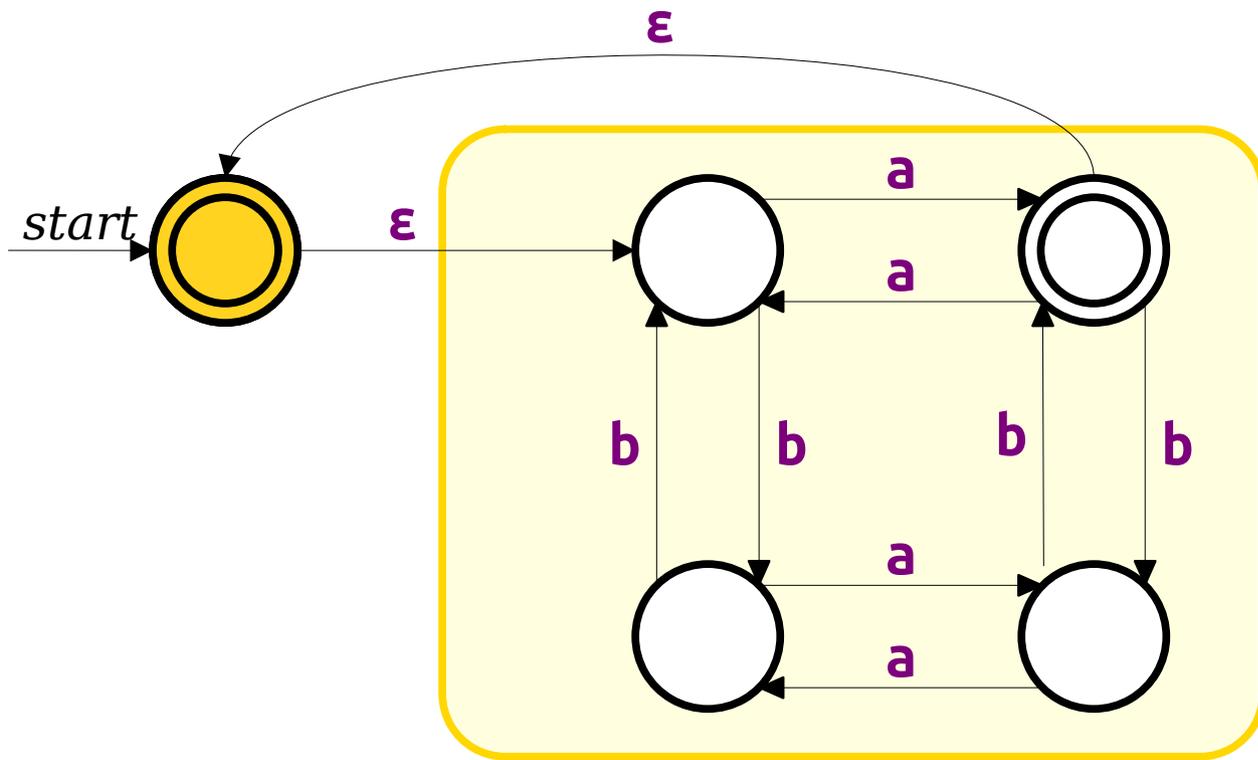


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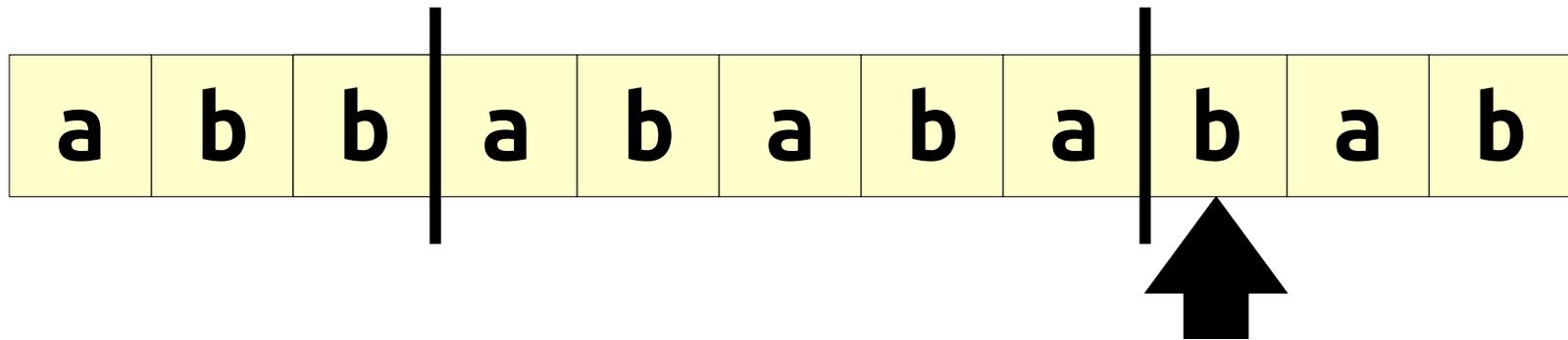


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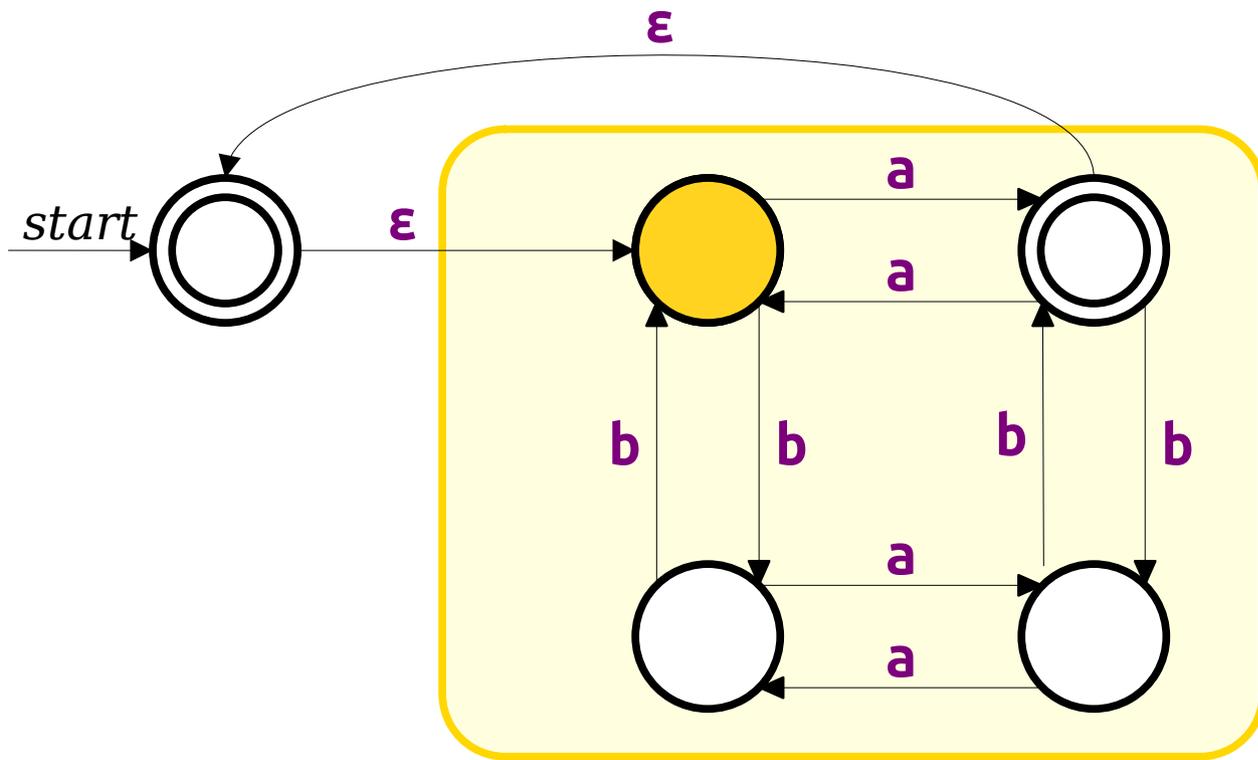


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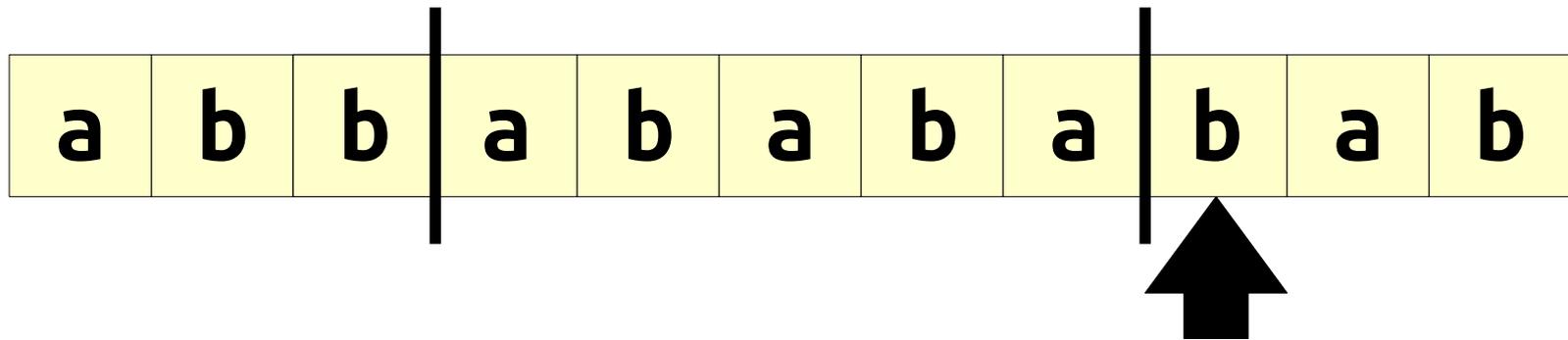


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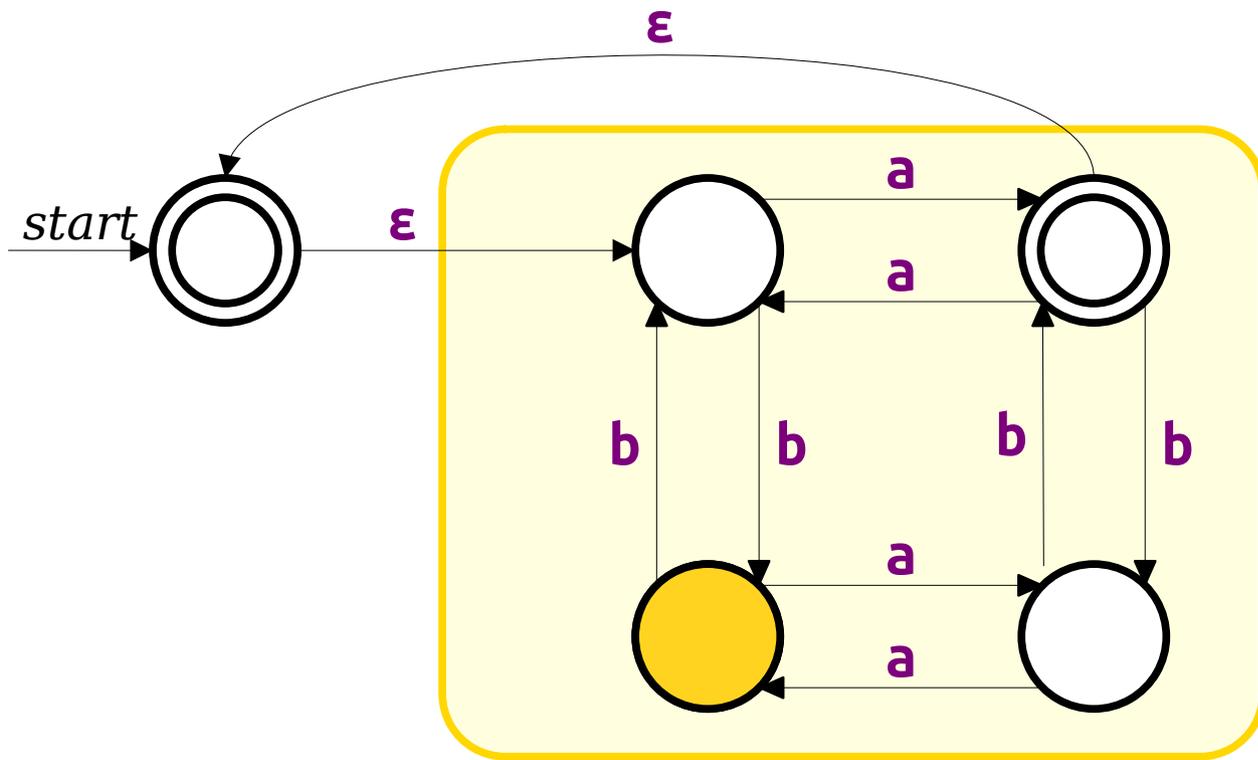


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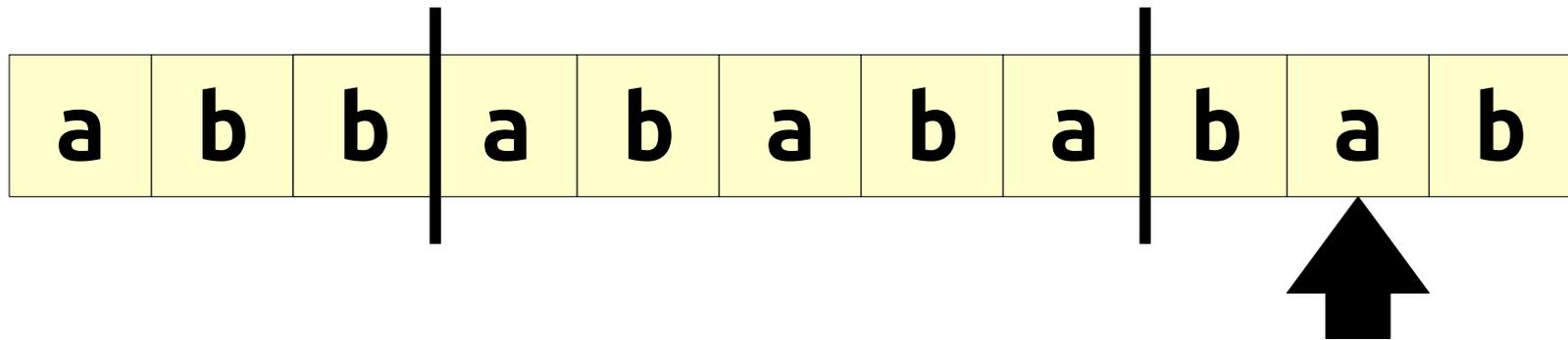


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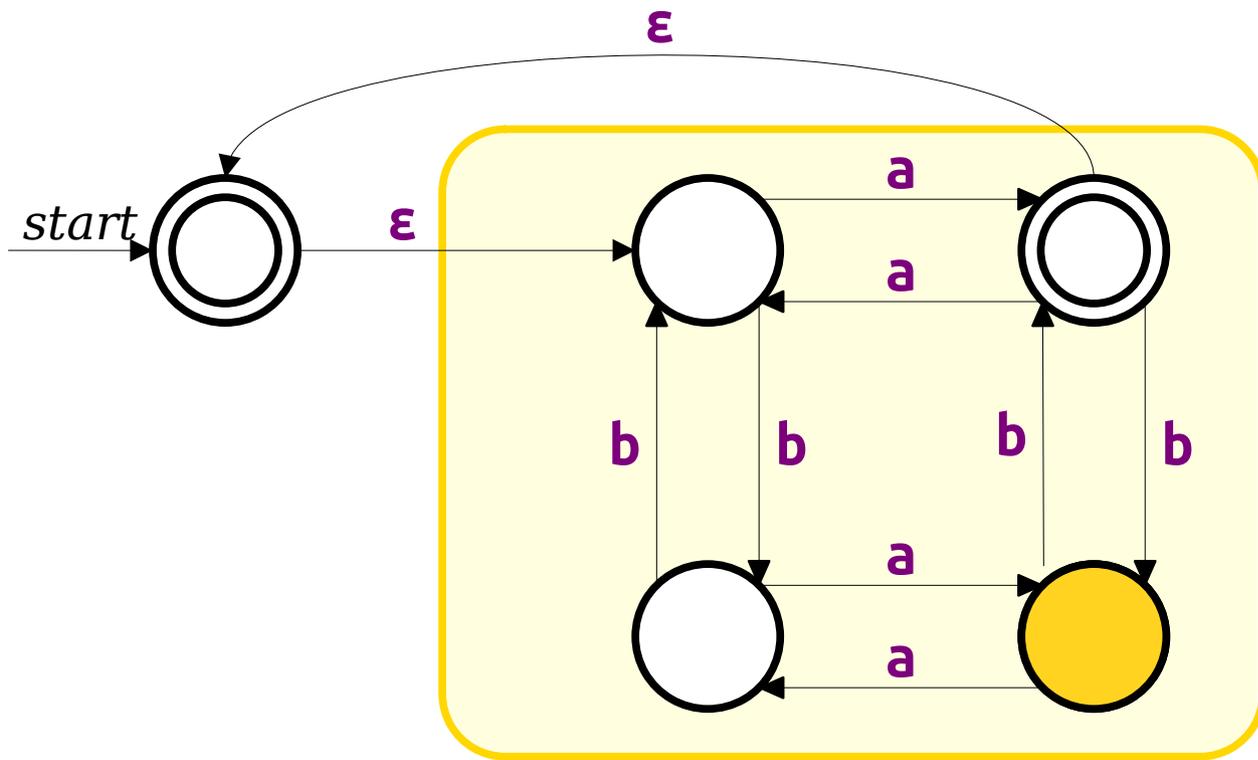


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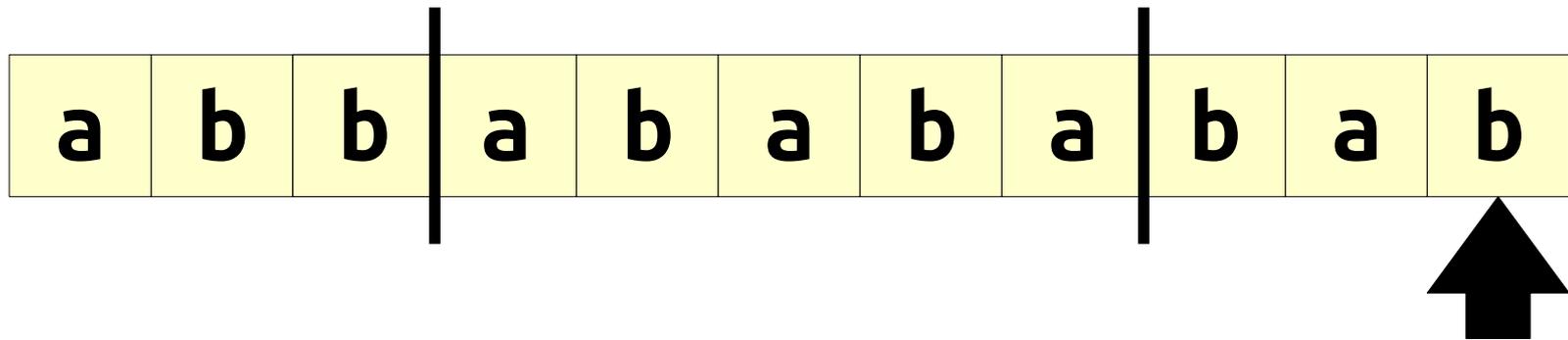


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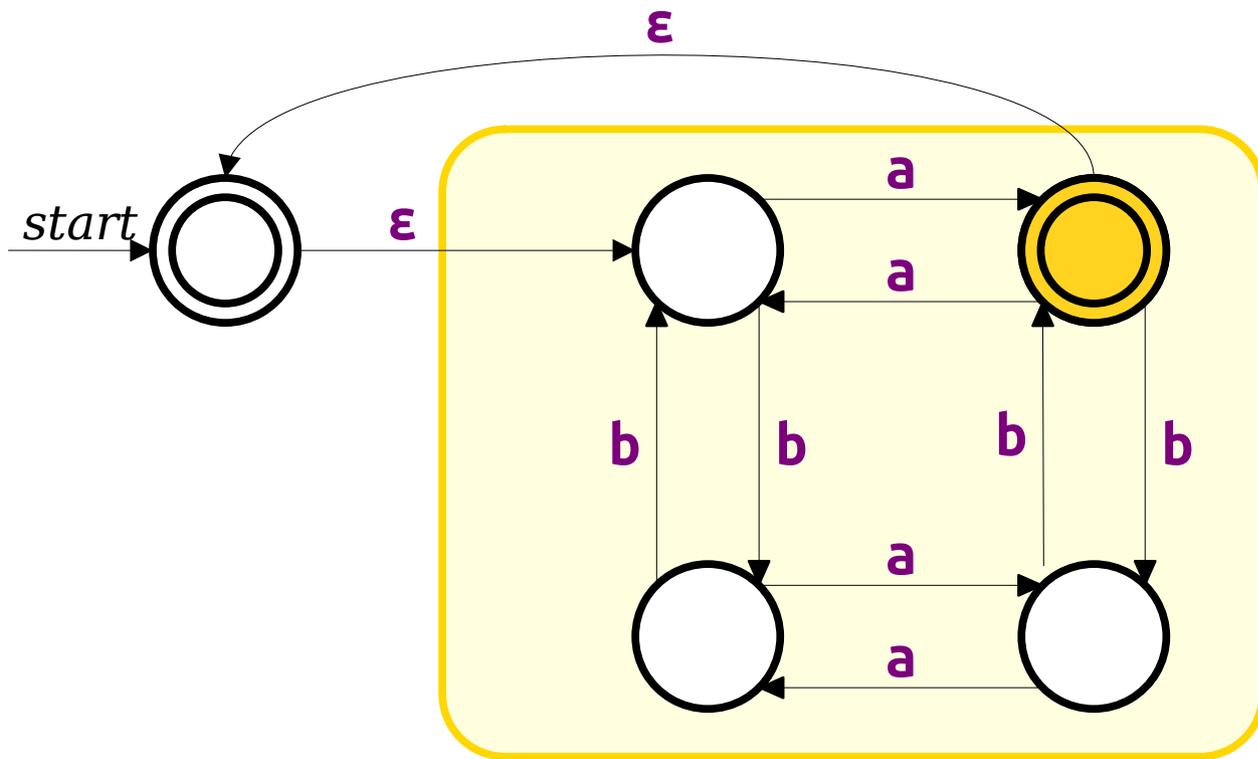


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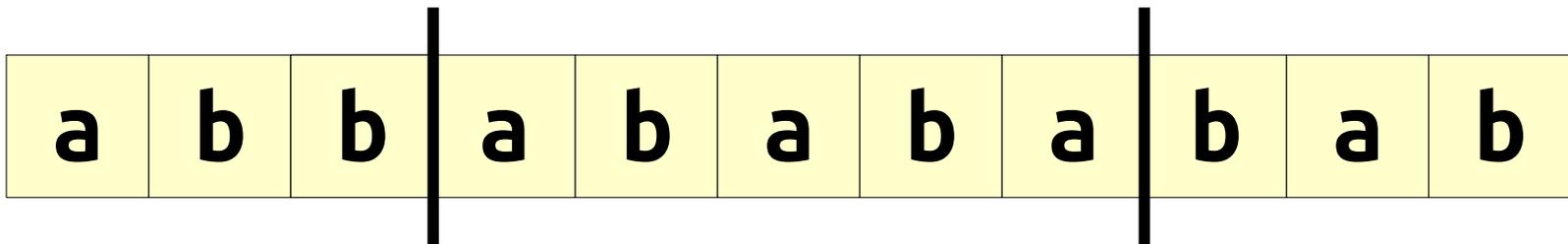


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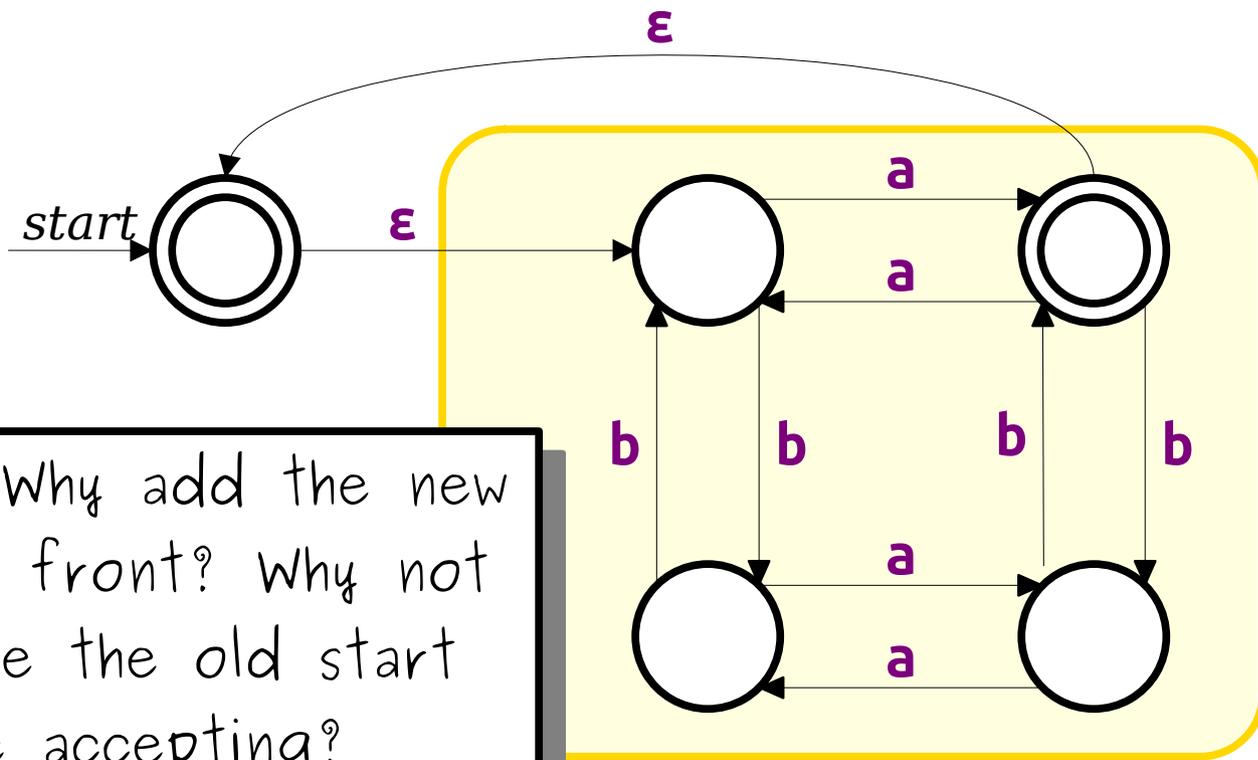


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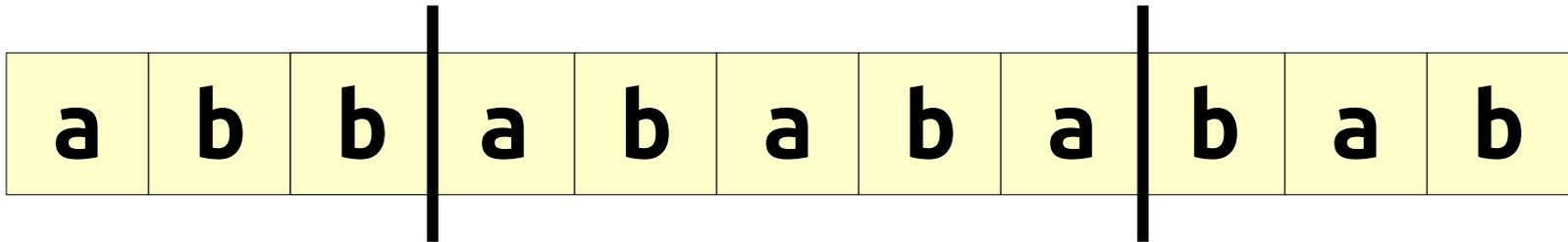
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Construct an NFA for L^* .



Question: Why add the new state out front? Why not just make the old start state accepting?

DFA for L



$$L = \{ w \in \{a, b\}^* \mid w \text{ has an odd number of } a\text{'s and an even number of } b\text{'s} \}$$

Construct an NFA for L^* .

Closure Properties

- ***Theorem:*** If L_1 and L_2 are regular languages over an alphabet Σ , then so are the following languages:
 - $L_1 \cup L_2$
 - $L_1 \cap L_2$
 - L_1L_2
 - L_1^*
- These are some of the ***closure properties of the regular languages.***

Next Time

- ***Regular Expressions***
 - Building languages from the ground up!
- ***Thompson's Algorithm***
 - A UNIX Programmer in Theoryland.
- ***Kleene's Theorem***
 - From machines to programs!