

Finite Automata

Part Two

Outline for Today

- ***Recap from Last Time***
 - Where are we, again?
- ***Designing a DFA***
 - How to think about finite memory.
- ***Regular Languages***
 - A fundamental class of languages.
- ***NFAs***
 - Automata with Magic Superpowers.
- ***Designing NFAs***
 - Harnessing an awesome power.

Recap from Last Time

Formal Language Theory

- An **alphabet** is a set, usually denoted Σ , consisting of elements called **characters**.
 - $a \in \Sigma$ means “ a is a single character.”
- A **string over Σ** is a finite sequence of zero or more characters taken from Σ .
- The **empty string** has no characters and is denoted ε .
- A **language over Σ** is a set of strings over Σ .
- The language Σ^* is the set of all strings over Σ .
 - $w \in \Sigma^*$ means “ w is a string of characters from Σ .”

The Language of an Automaton

- If A is an automaton that processes strings over Σ , the ***language of A*** , denoted $\mathcal{L}(A)$, is the set of all strings A accepts.
- Formally:

$$\mathcal{L}(A) = \{ w \in \Sigma^* \mid A \text{ accepts } w \}$$

DFAs

- A ***DFA*** is a
 - ***D***eterministic
 - ***F***inite
 - ***A***utomaton
- DFAs are the simplest type of automaton that we will see in this course.

DFA's

- A DFA is defined relative to some alphabet Σ .
- For each state in the DFA, there must be *exactly one* transition defined for each symbol in Σ .
 - This is the “deterministic” part of DFA.
- There is a unique start state.
- There are zero or more accepting states.

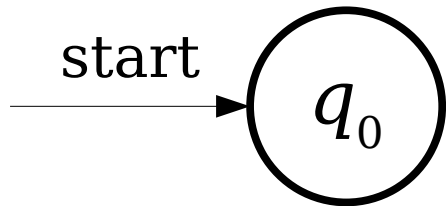
New Stuff!

Recognizing Languages with DFAs

$L = \{ w \in \{a, b\}^* \mid w \text{ contains } aa \text{ as a substring} \}$

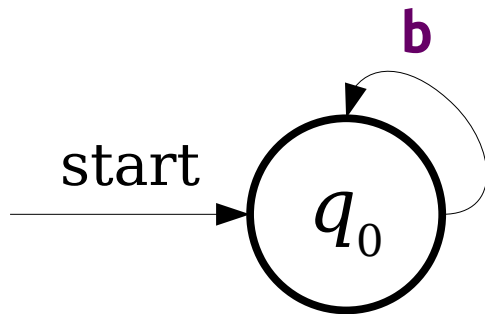
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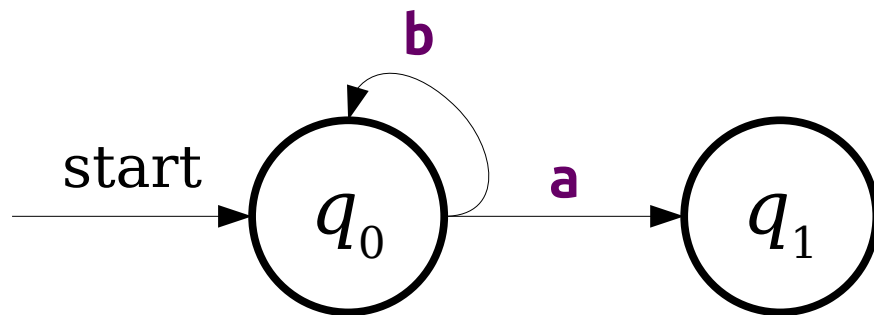
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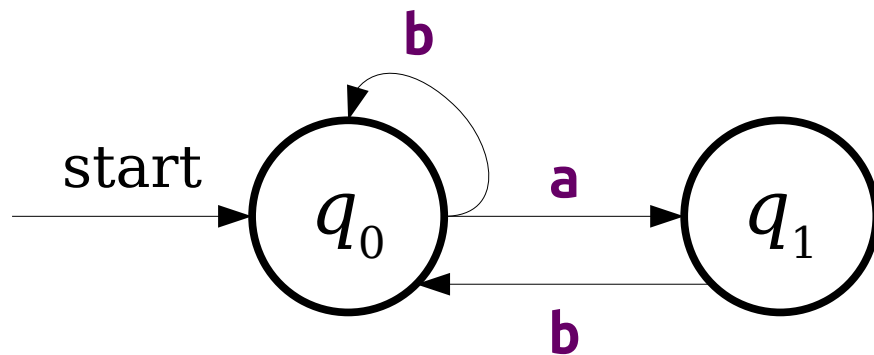
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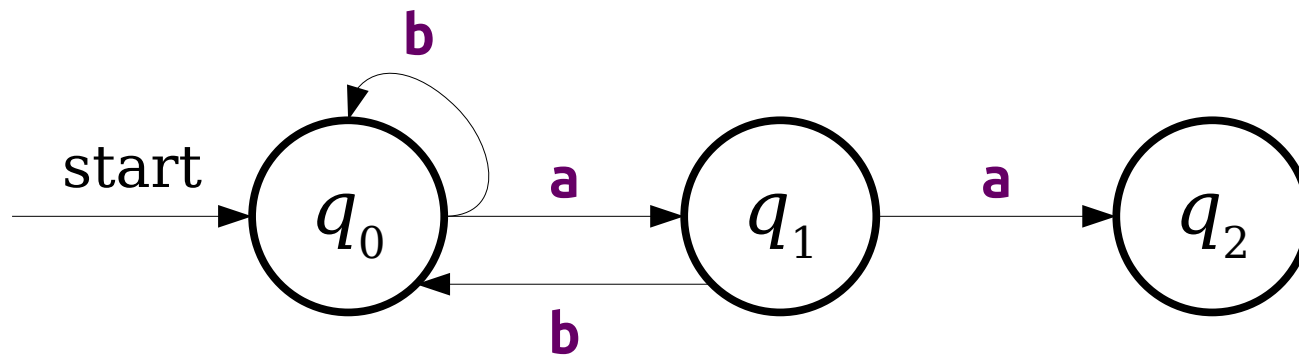
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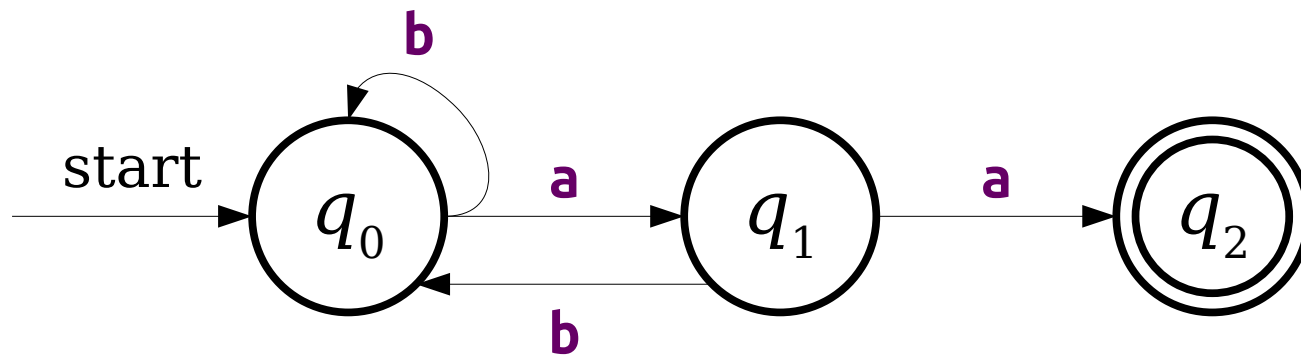
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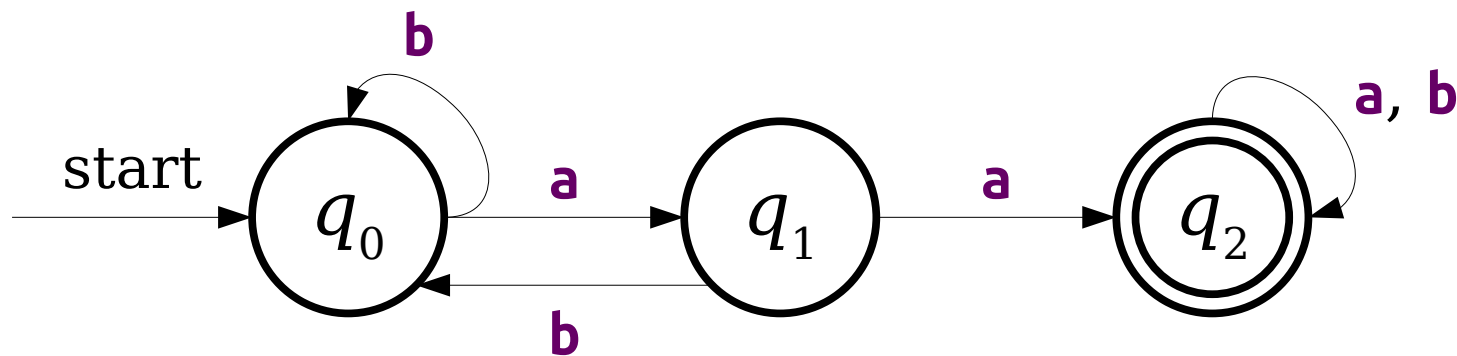
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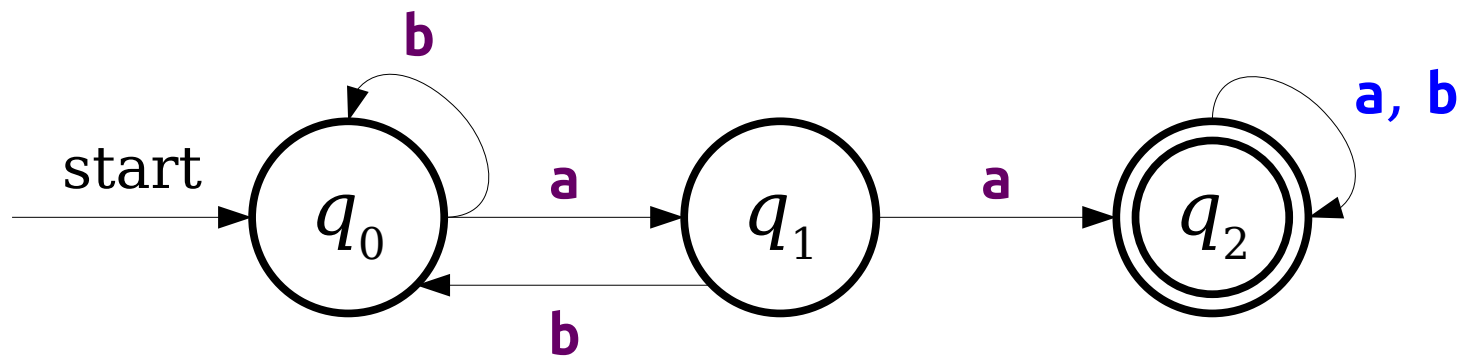
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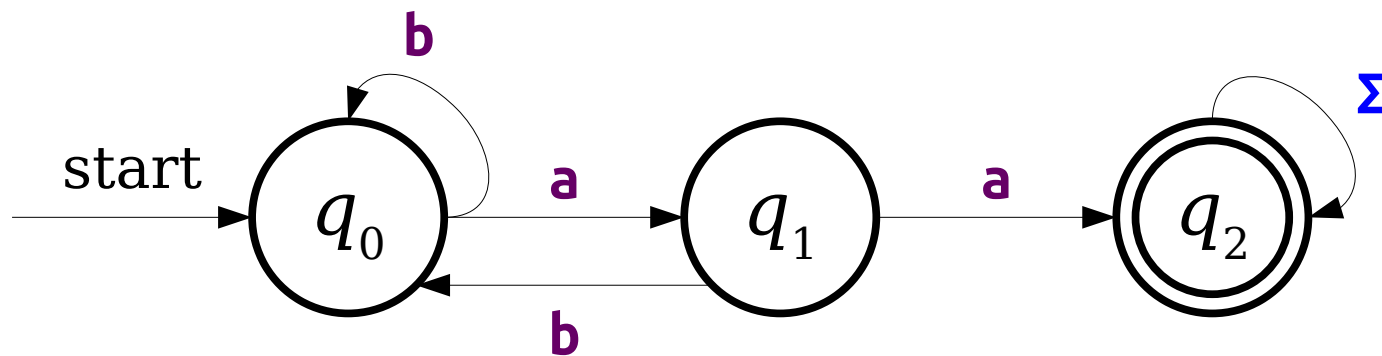
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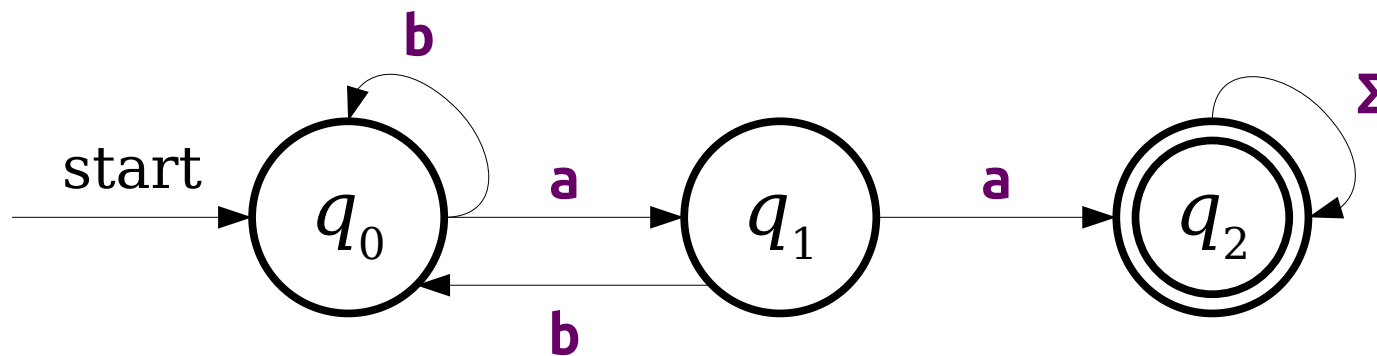
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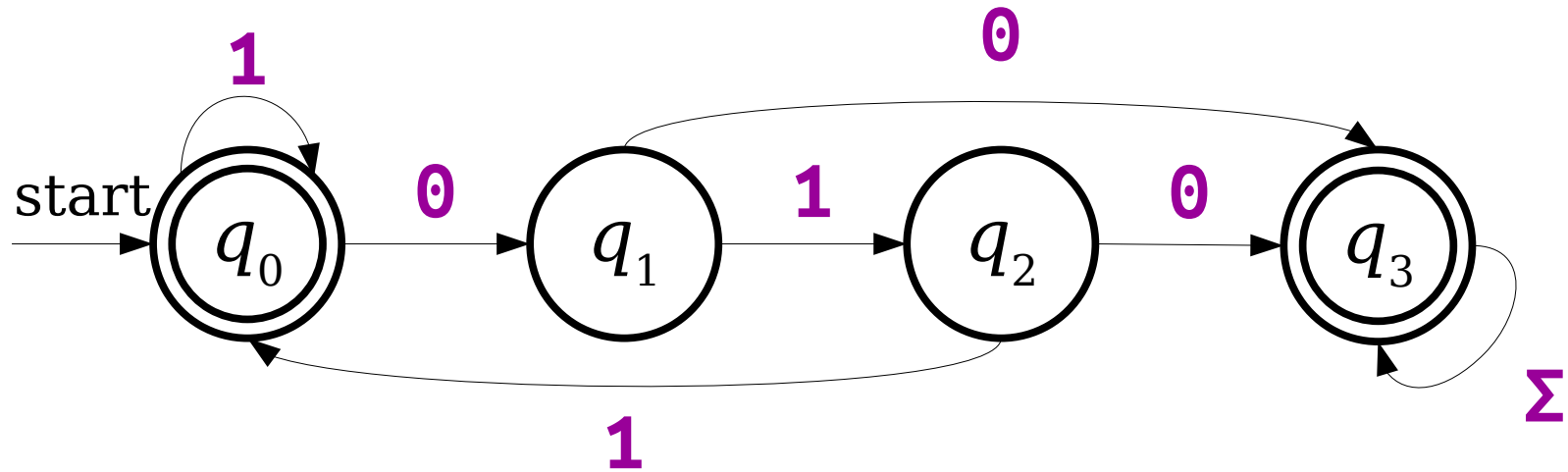
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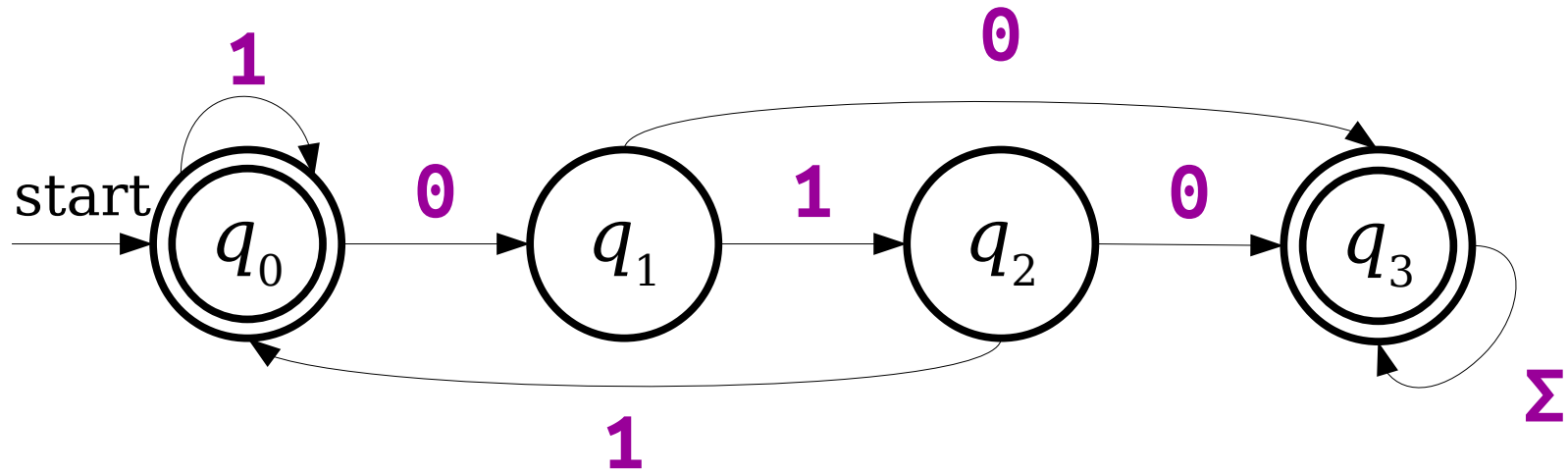
Tabular DFAs

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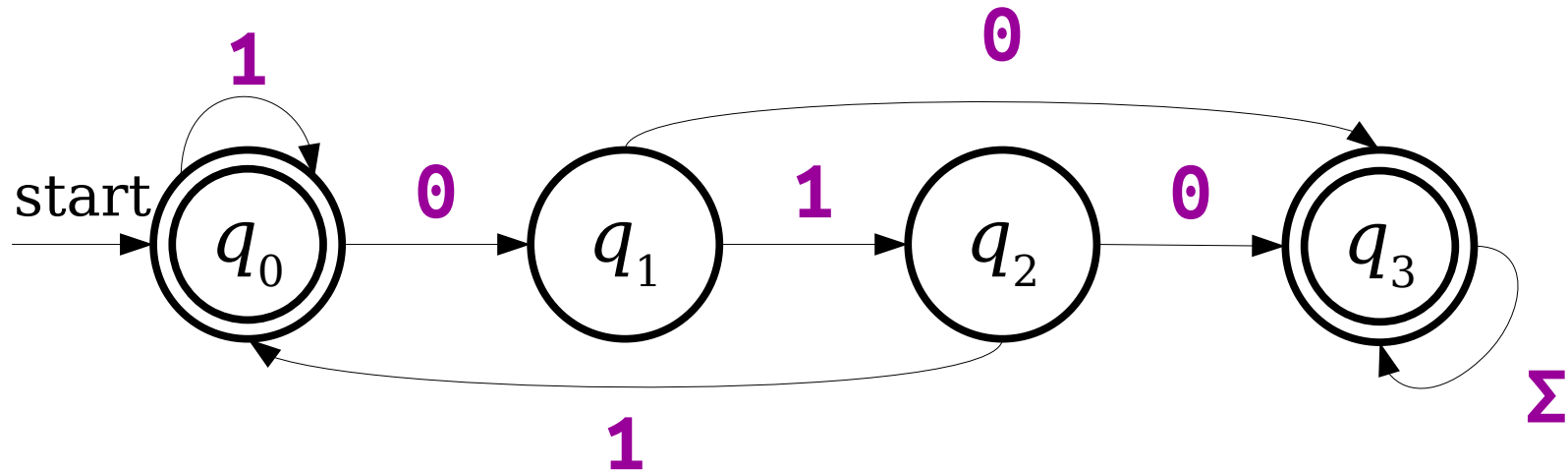
	0	1
q_0		
q_1		
q_2		
q_3		

Tabular DFAs



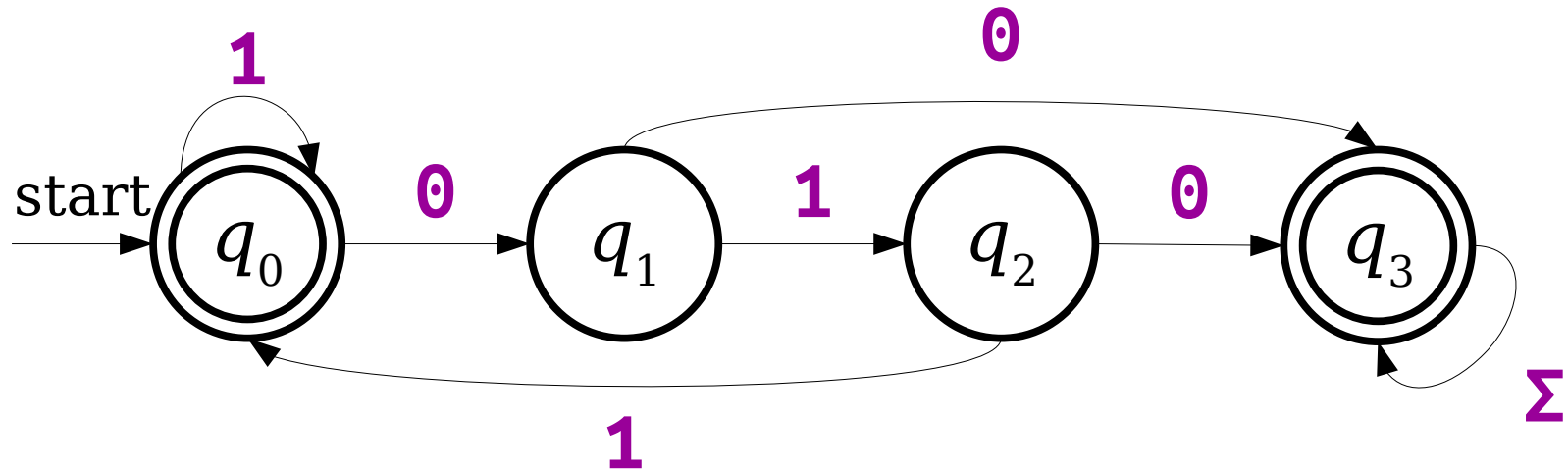
	0	1
q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
q_3	q_3	q_3

Tabular DFAs



	0	1
* q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
* q_3	q_3	q_3

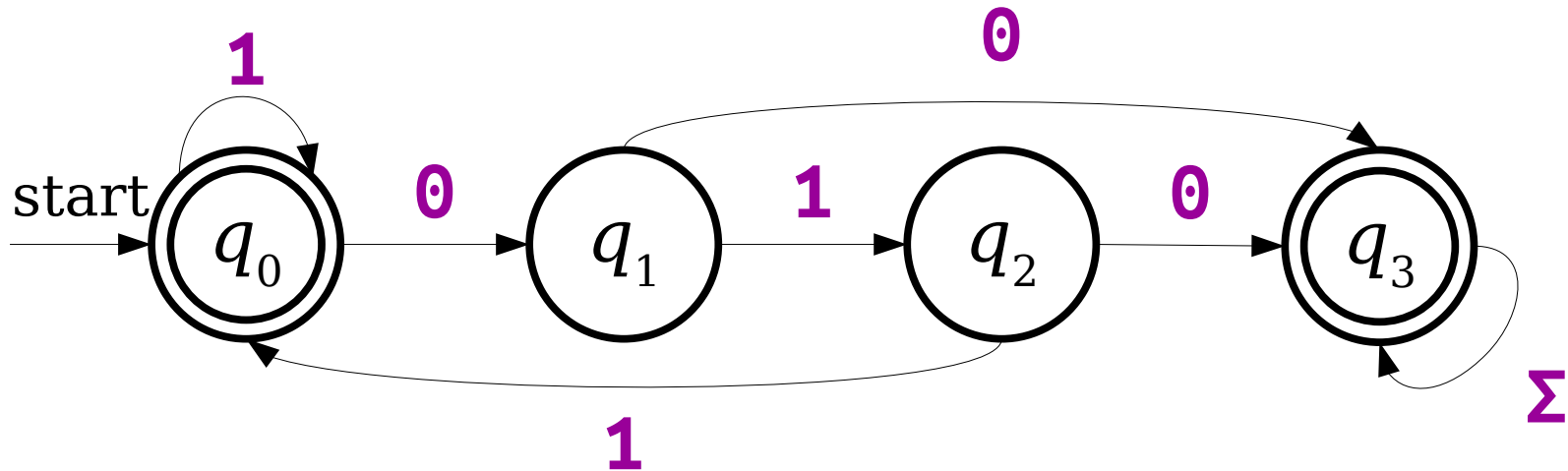
Tabular DFAs



	0	1
* q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
* q_3	q_3	q_3

These stars indicate accepting states.

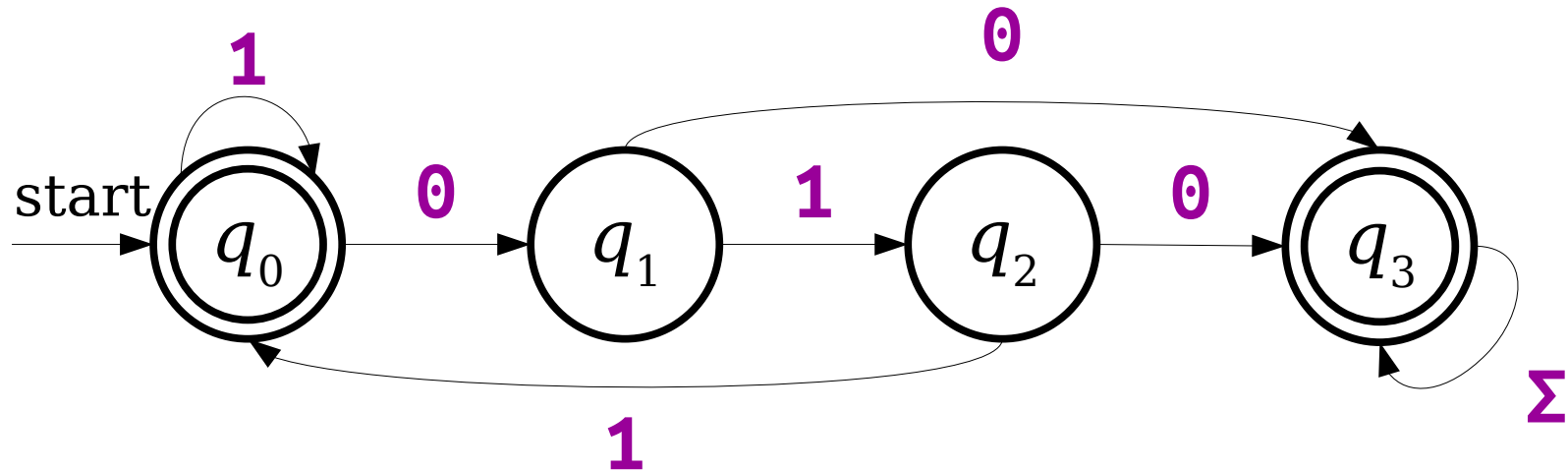
Tabular DFAs



	0	1
* q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
* q_3	q_3	q_3

Since this is the first row, it's the start state.

Tabular DFAs



	0	1
* q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
* q_3	q_3	q_3

Why isn't there a column here for Σ ?

Answer at
pollev.com/cs103aut23

My Turn to Code Things Up!

```
int kTransitionTable[kNumStates][kNumSymbols] = {  
    {0, 0, 1, 3, 7, 1, ...},  
    ...  
};  
bool kAcceptTable[kNumStates] = {  
    false,  
    true,  
    true,  
    ...  
};  
bool doesAccept(string input) {  
    int state = 0;  
    for (char ch: input) {  
        state = kTransitionTable[state][ch];  
    }  
    return kAcceptTable[state];  
}
```

The Regular Languages

A language L is called a ***regular language*** if there exists a DFA D such that $\mathcal{L}(D) = L$.

If L is a language and $\mathcal{L}(D) = L$, we say that D ***recognizes*** the language L .

The Complement of a Language

- Given a language $L \subseteq \Sigma^*$, the **complement** of that language (denoted \bar{L}) is the language of all strings in Σ^* that aren't in L .
- Formally:

$$\bar{L} = \Sigma^* - L$$

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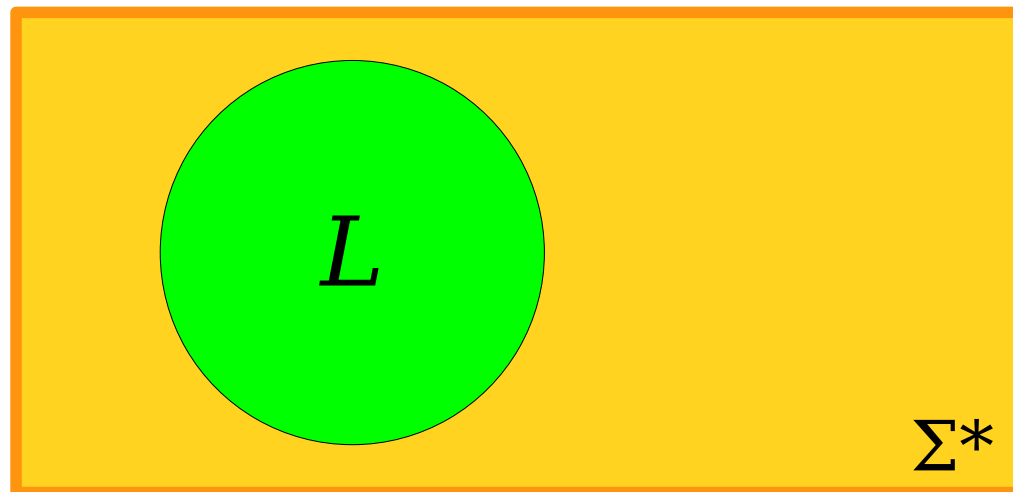
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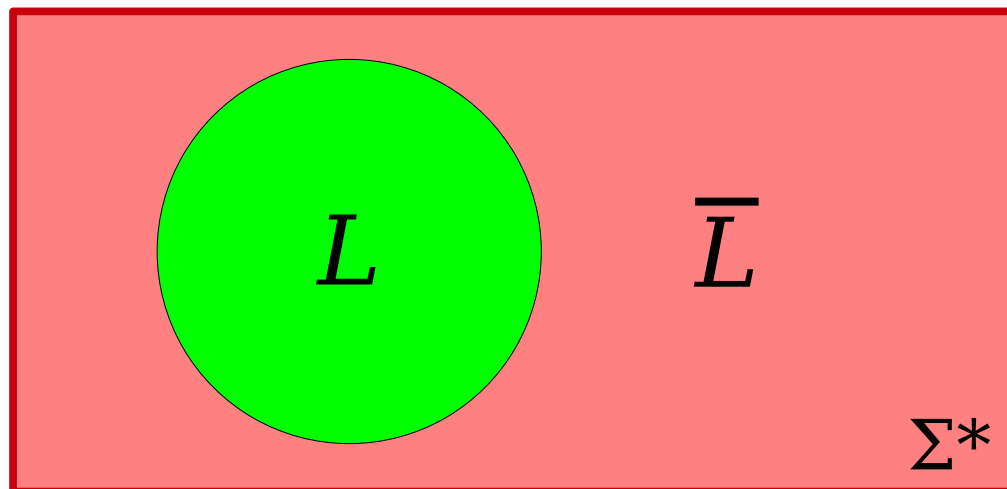
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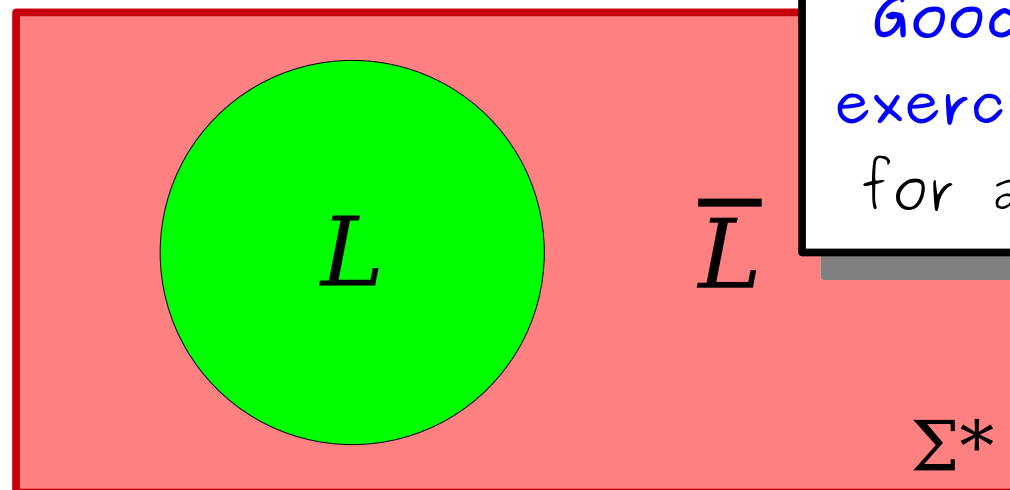
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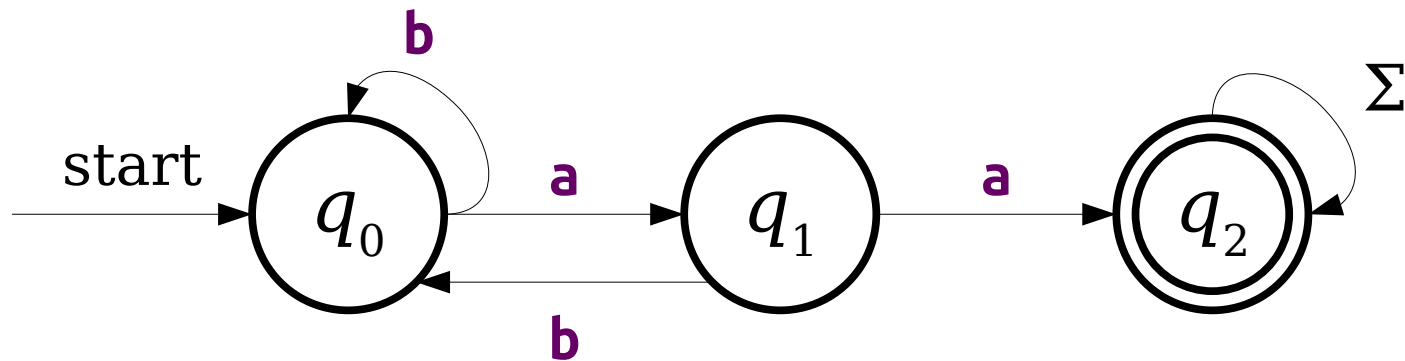
$$\bar{L} = \Sigma^* - L$$



Good proofwriting
exercise: prove $\bar{\bar{L}} = L$
for any language L .

Complementing Regular Languages

$L = \{ w \in \{a, b\}^* \mid w \text{ contains } aa \text{ as a substring} \}$



$\bar{L} = \{ w \in \{a, b\}^* \mid w \text{ **does not** contain } aa \text{ as a substring} \}$

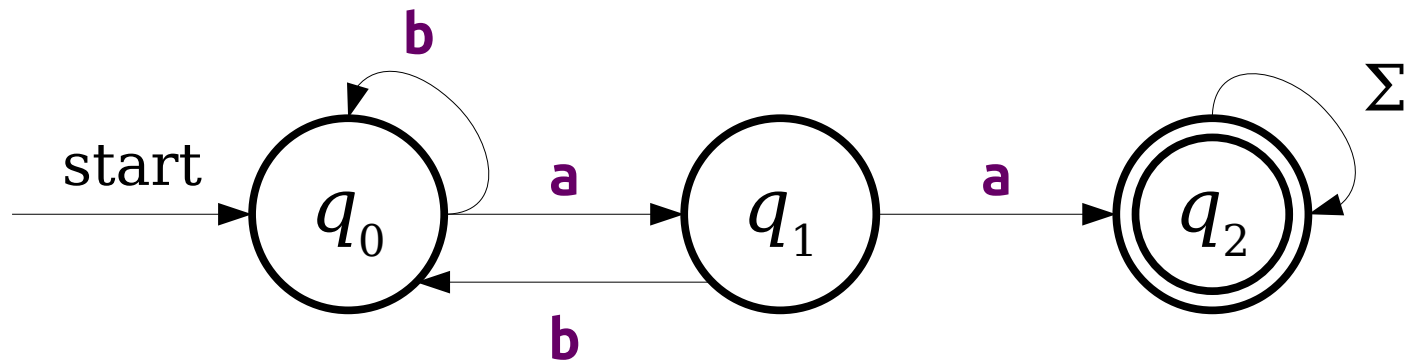
How do we turn the DFA above into a DFA for \bar{L} ?

Answer at

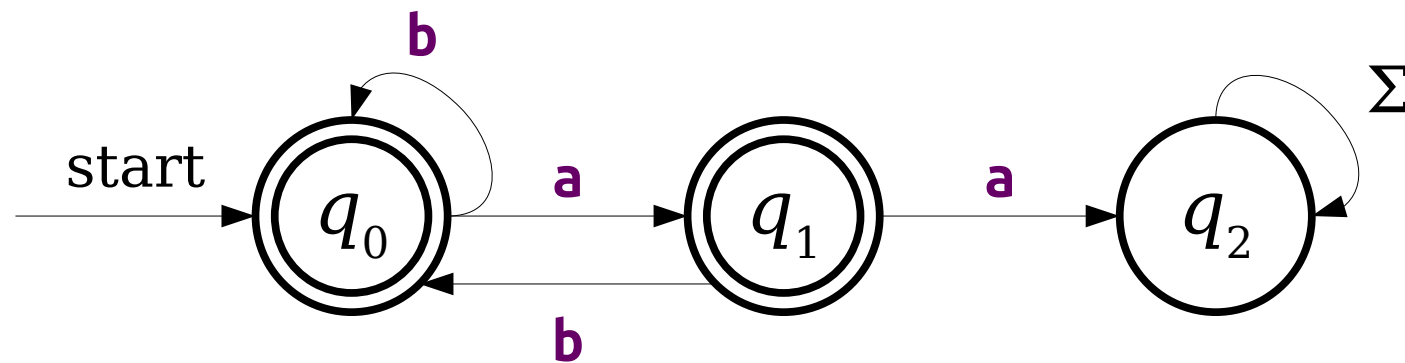
<https://pollev.com/cs103aut23>

Complementing Regular Languages

$$L = \{ w \in \{a, b\}^* \mid w \text{ contains } \mathbf{aa} \text{ as a substring} \}$$

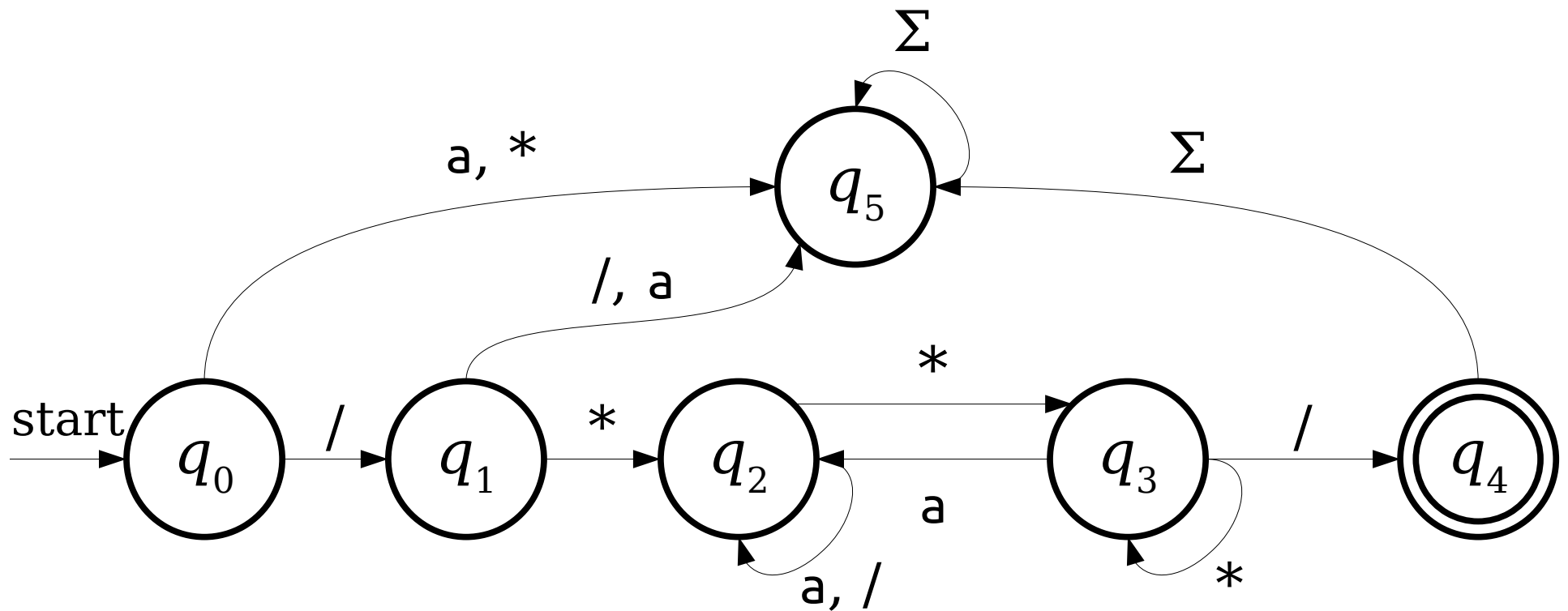


$$\bar{L} = \{ w \in \{a, b\}^* \mid w \text{ **does not** contain } \mathbf{aa} \text{ as a substring} \}$$



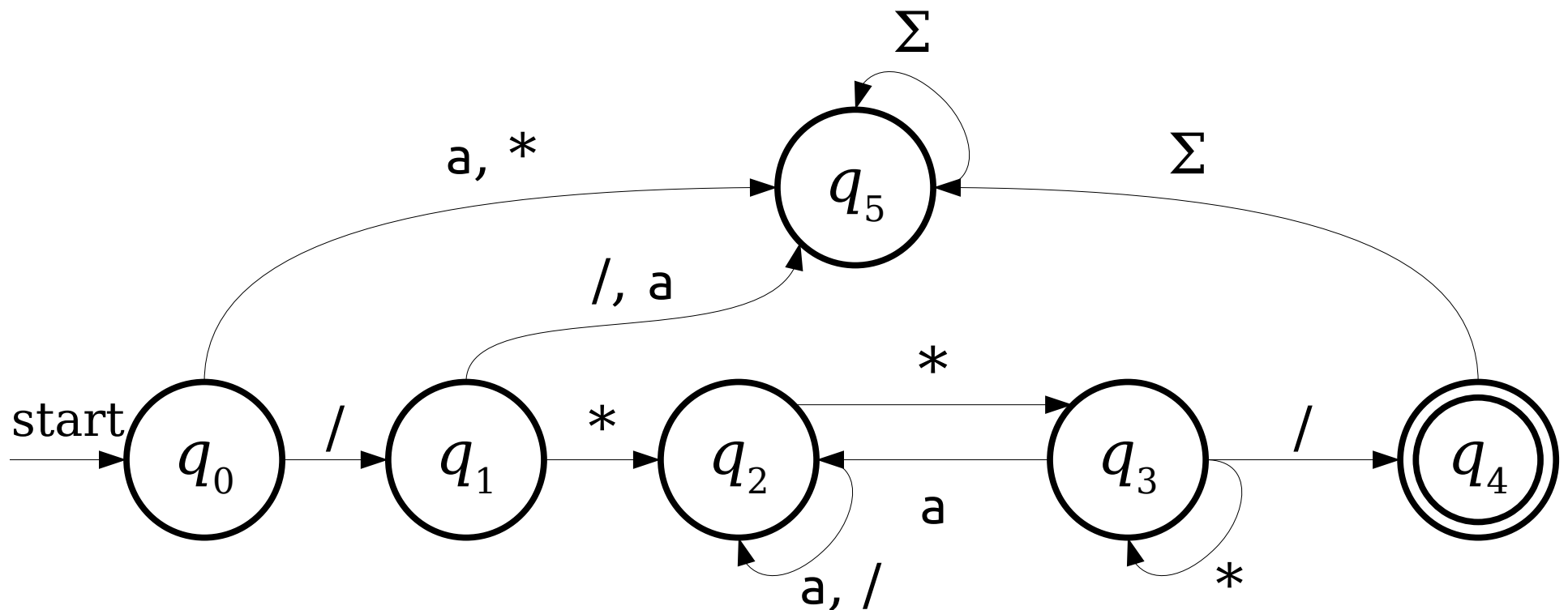
Complementing Regular Languages

$L = \{ w \in \{a, *, /\}^* \mid w \text{ represents a C-style comment} \}$



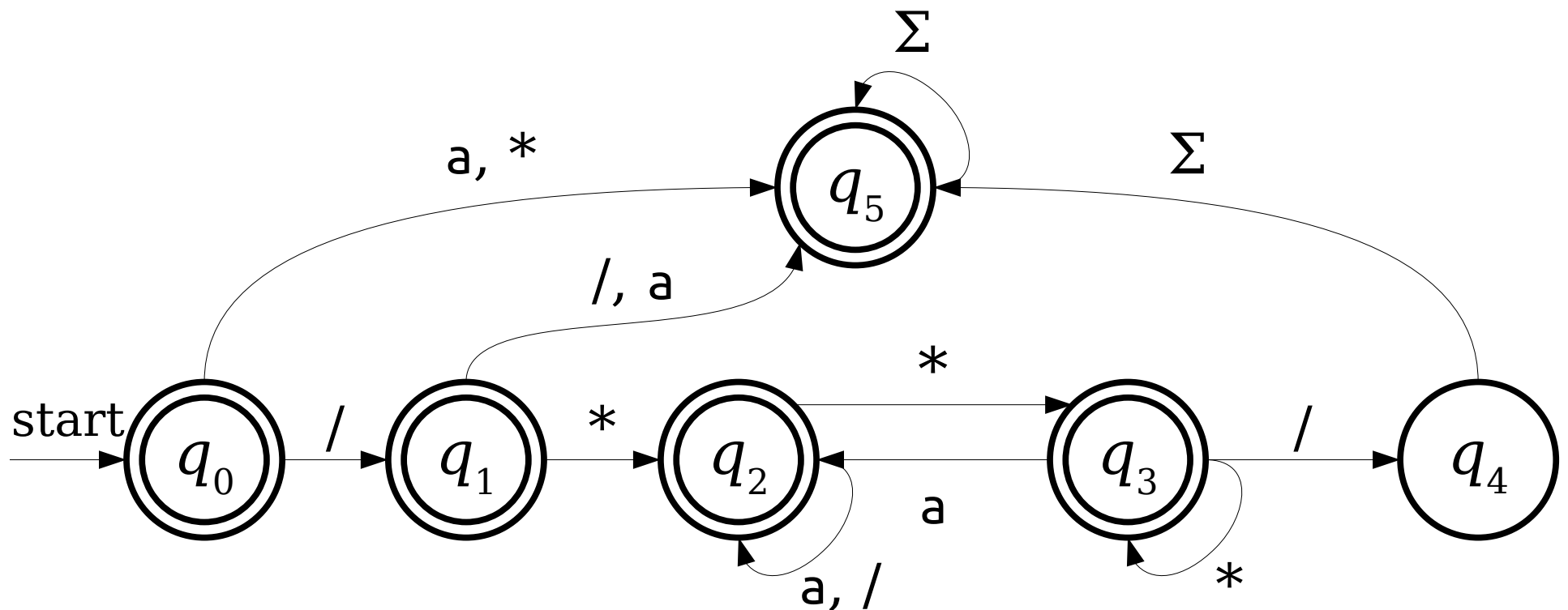
Complementing Regular Languages

$\bar{L} = \{ w \in \{a, *, /\}^* \mid w \text{ *doesn't* represent a C-style comment} \}$



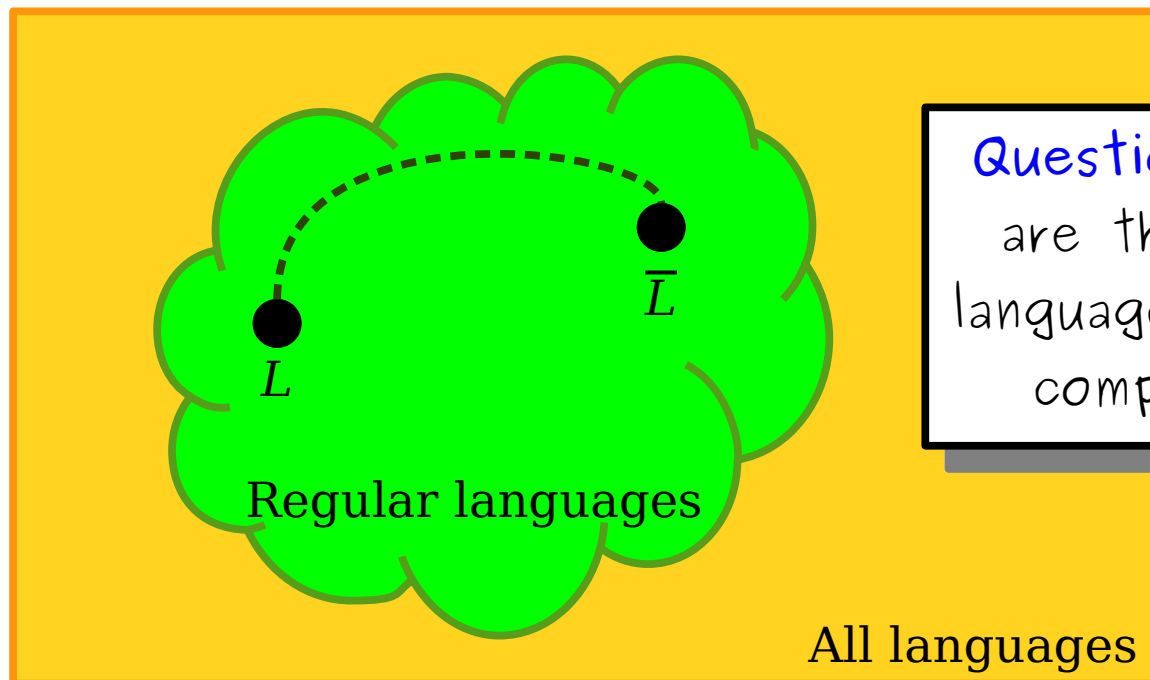
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Closure Properties

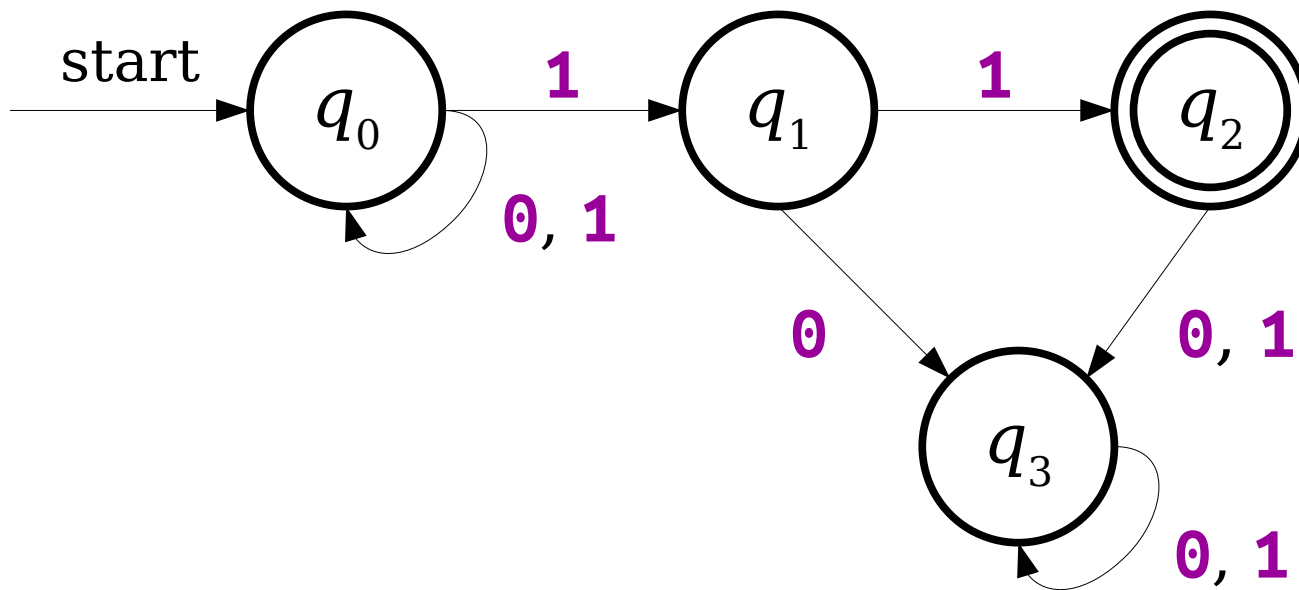
- **Theorem:** If L is a regular language, then \bar{L} is also a regular language.
- As a result, we say that the regular languages are **closed under complementation**.



Question to ponder:
are the *nonregular*
languages closed under
complementation?

NFAS

The Motivation



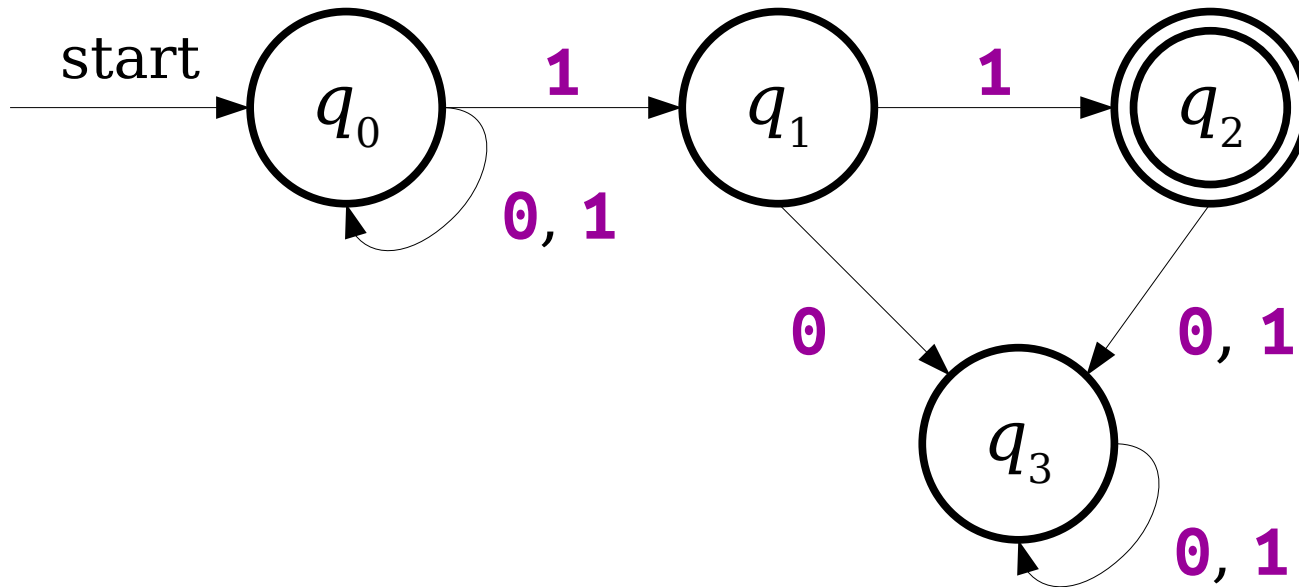
NFAs

- An *NFA* is a
 - *N*ondeterministic
 - *F*inite
 - *A*utomaton
- Structurally similar to a DFA, but represents a fundamental shift in how we'll think about computation.

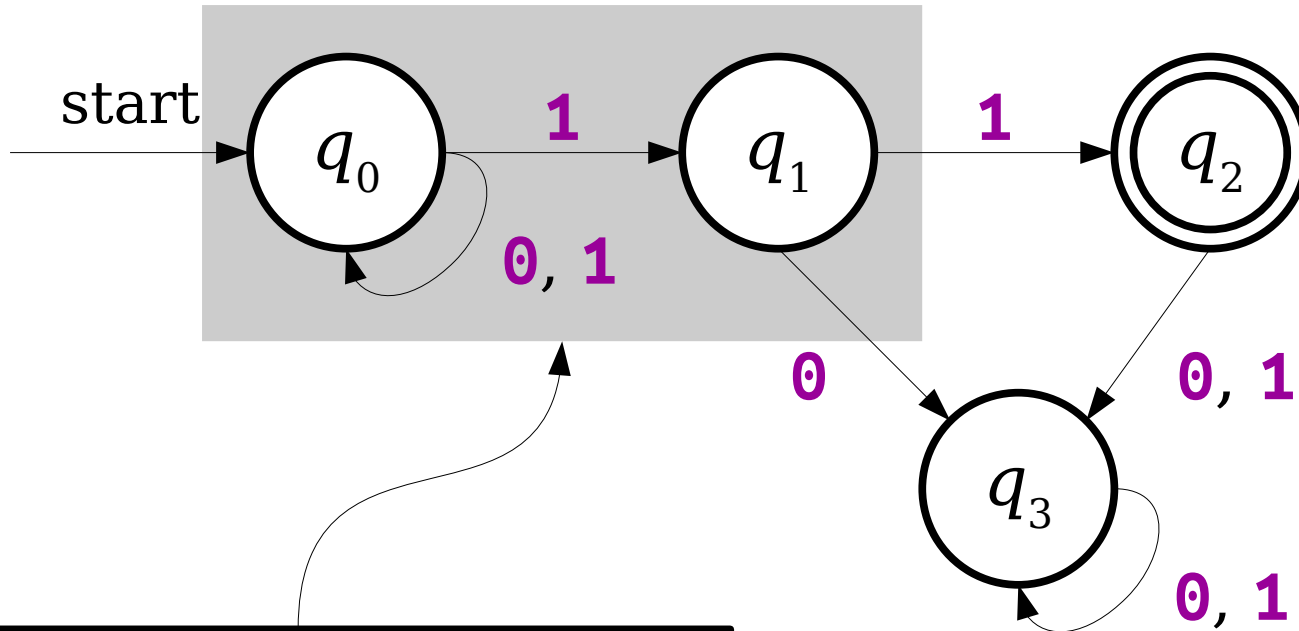
(Non)determinism

- A model of computation is **deterministic** if at every point in the computation, there is exactly one choice that can make.
 - The machine accepts if that series of choices leads to an accepting state.
- A model of computation is **nondeterministic** if the computing machine has a finite number of choices available to make at each point, possibly including zero.
- The machine accepts if **any** series of choices leads to an accepting state.
 - (This sort of nondeterminism is technically called **existential nondeterminism**, the most philosophical-sounding term we'll introduce all quarter.)

A Simple NFA

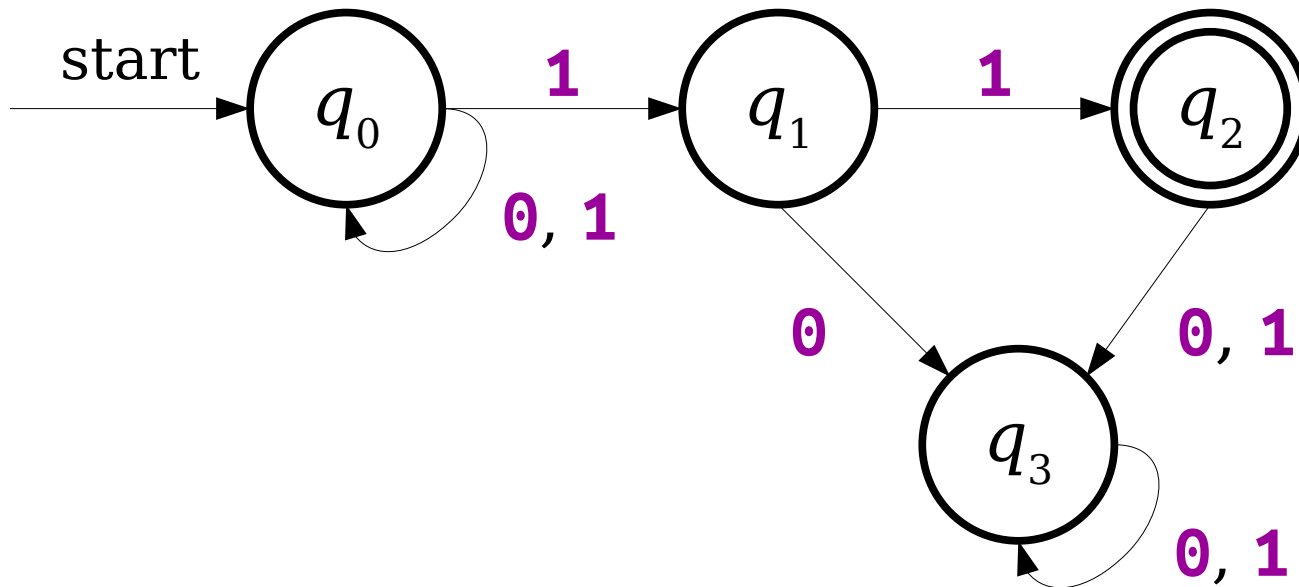


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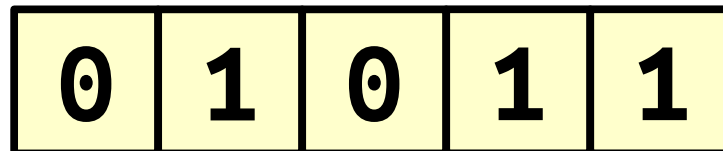
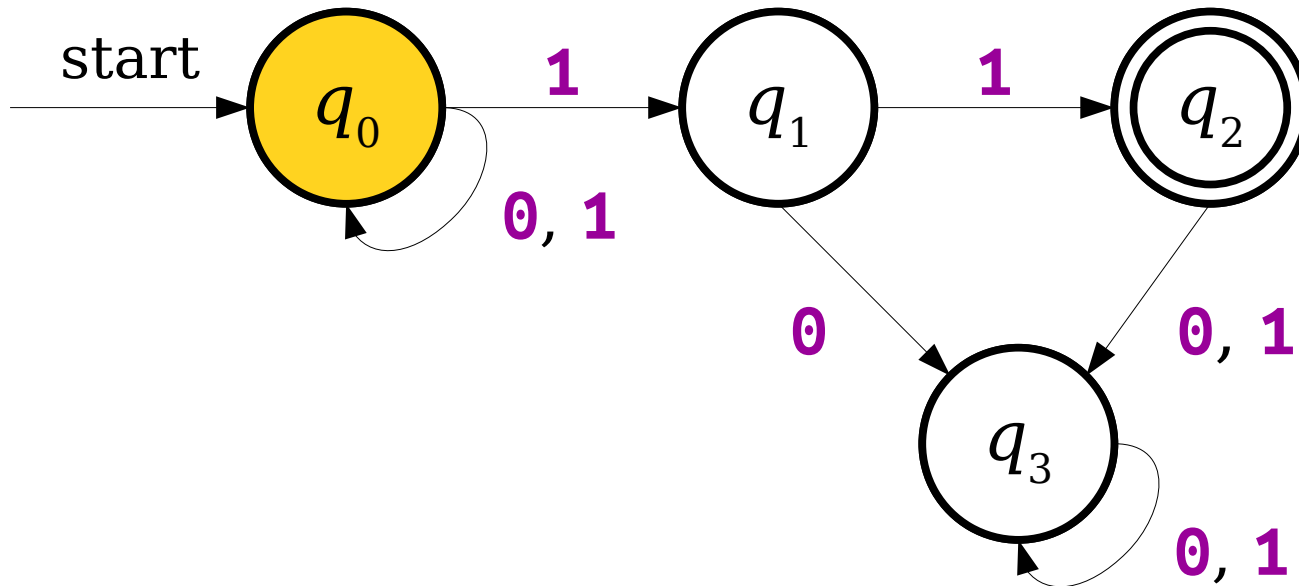
q_0 has two transitions defined on 1!

A Simple NFA

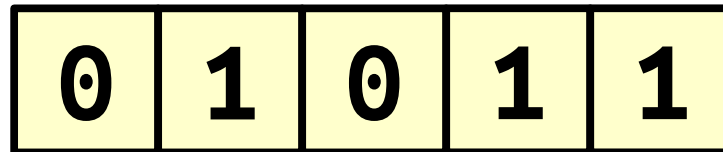
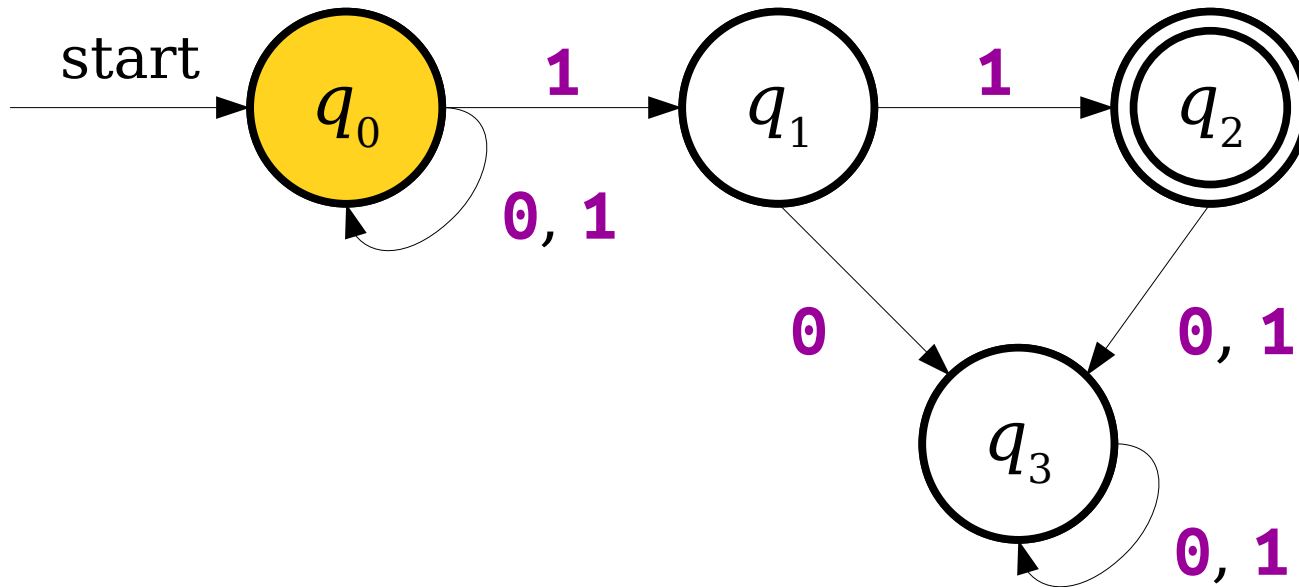


0	1	0	1	1
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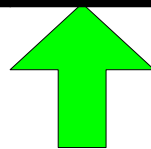
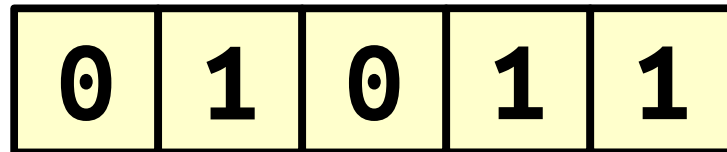
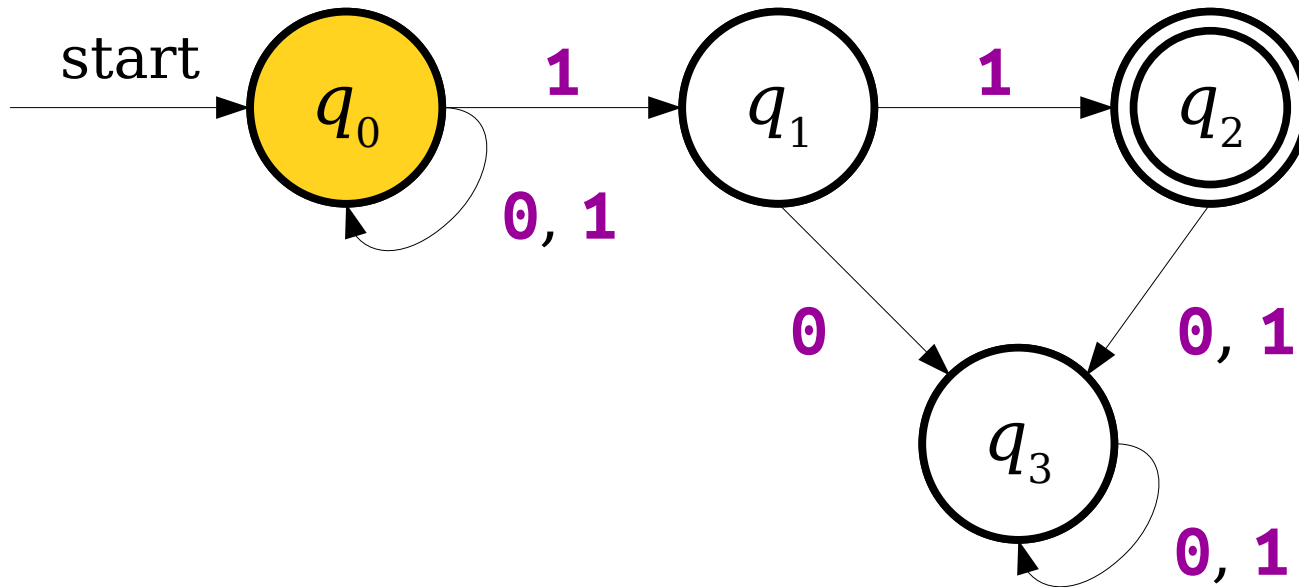
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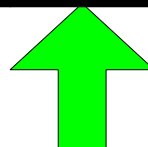
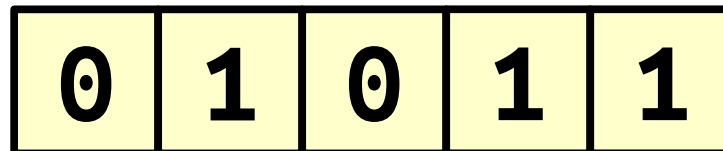
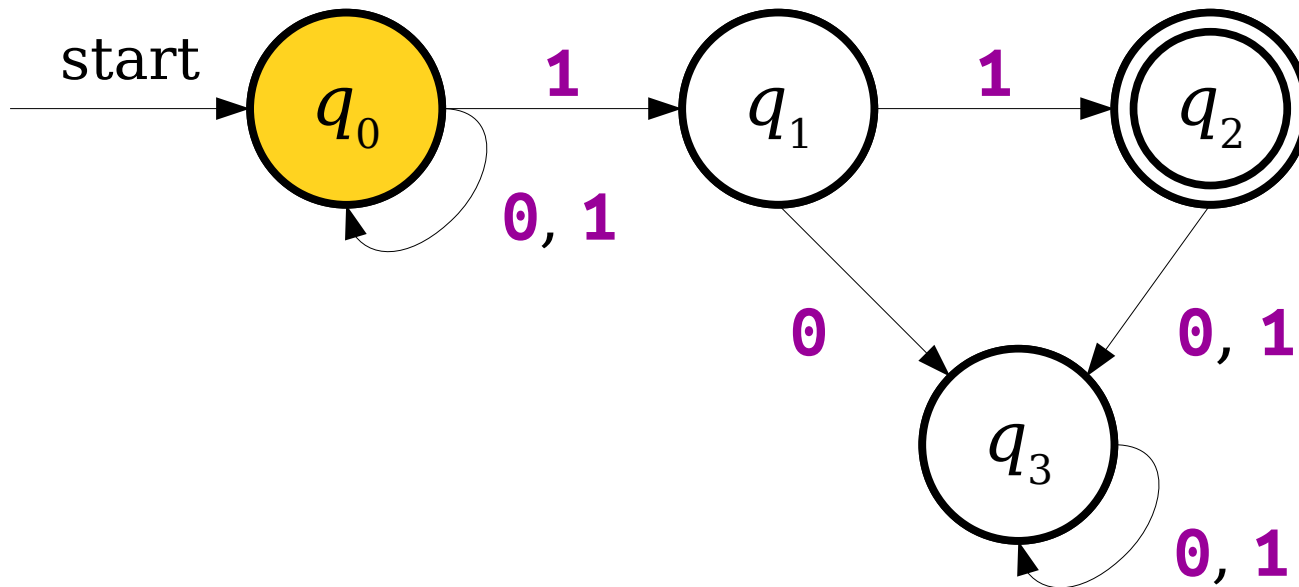
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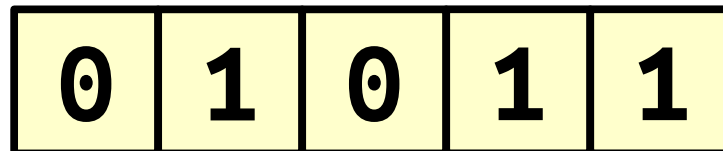
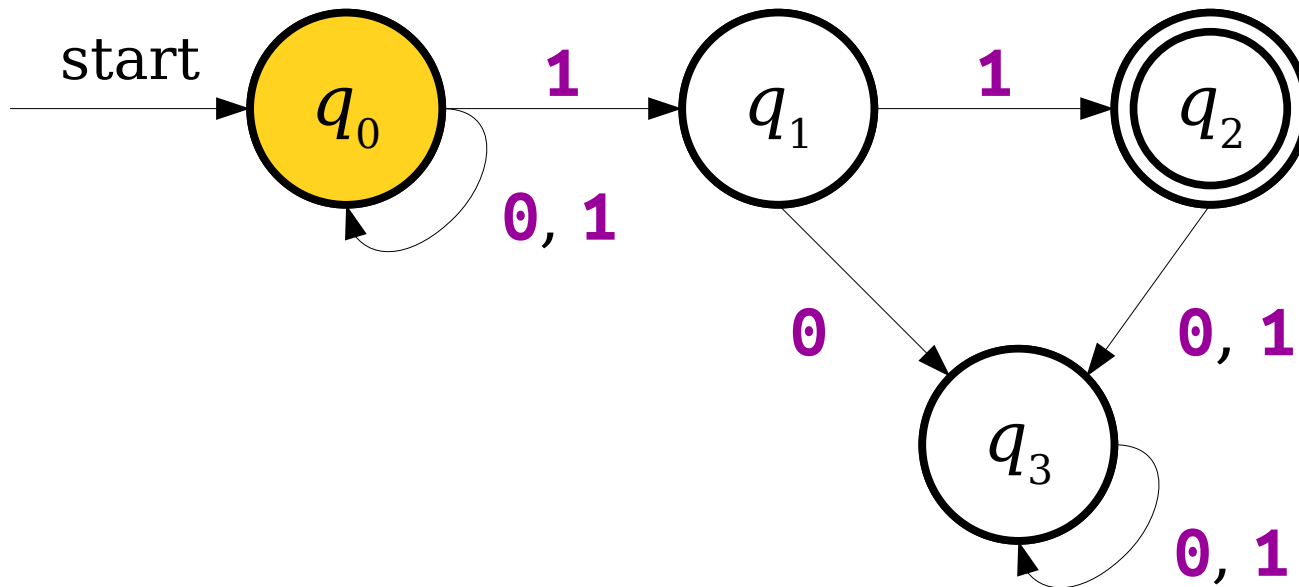
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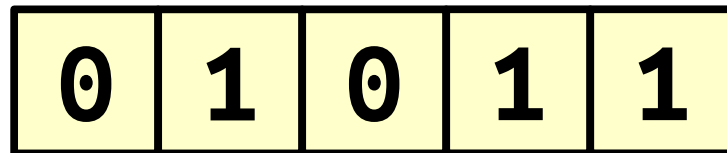
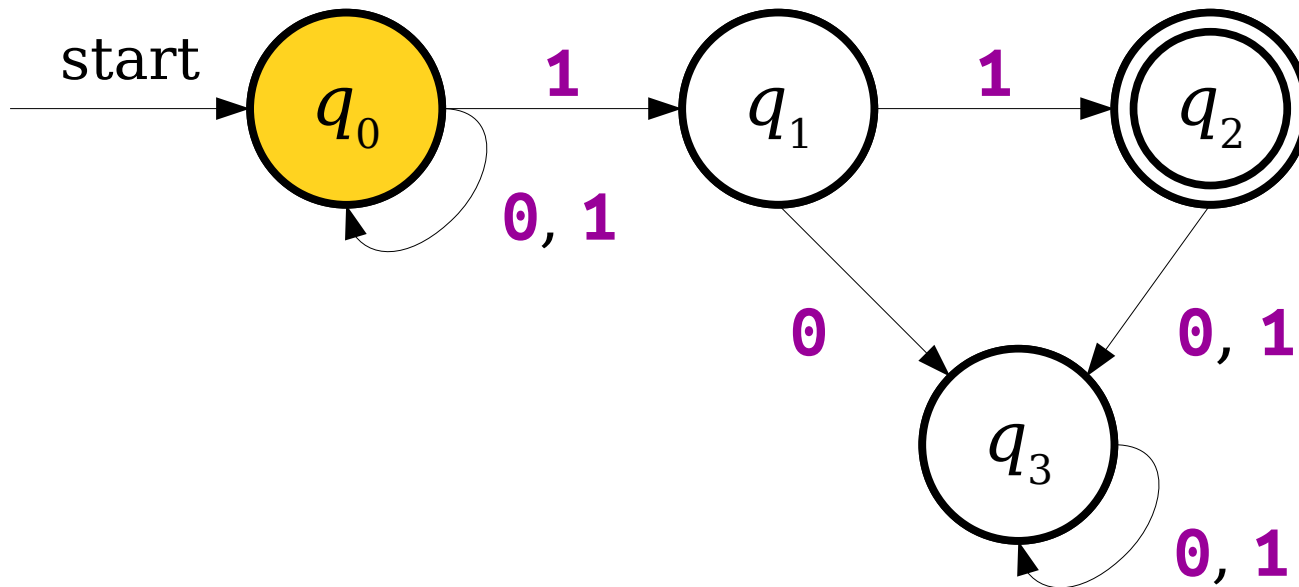
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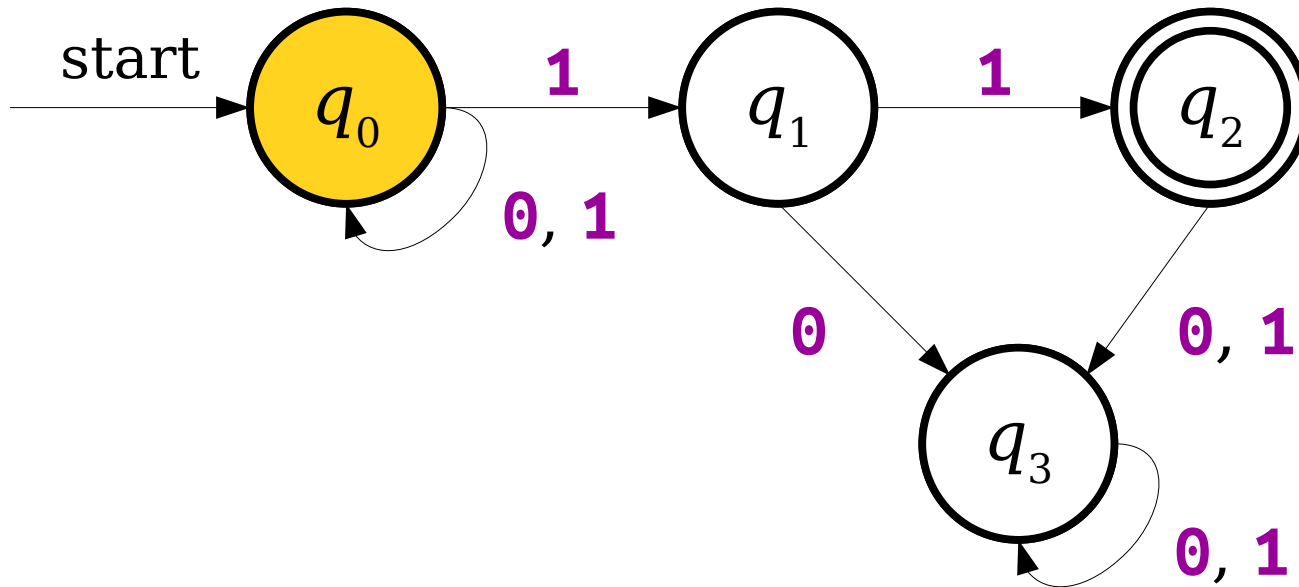
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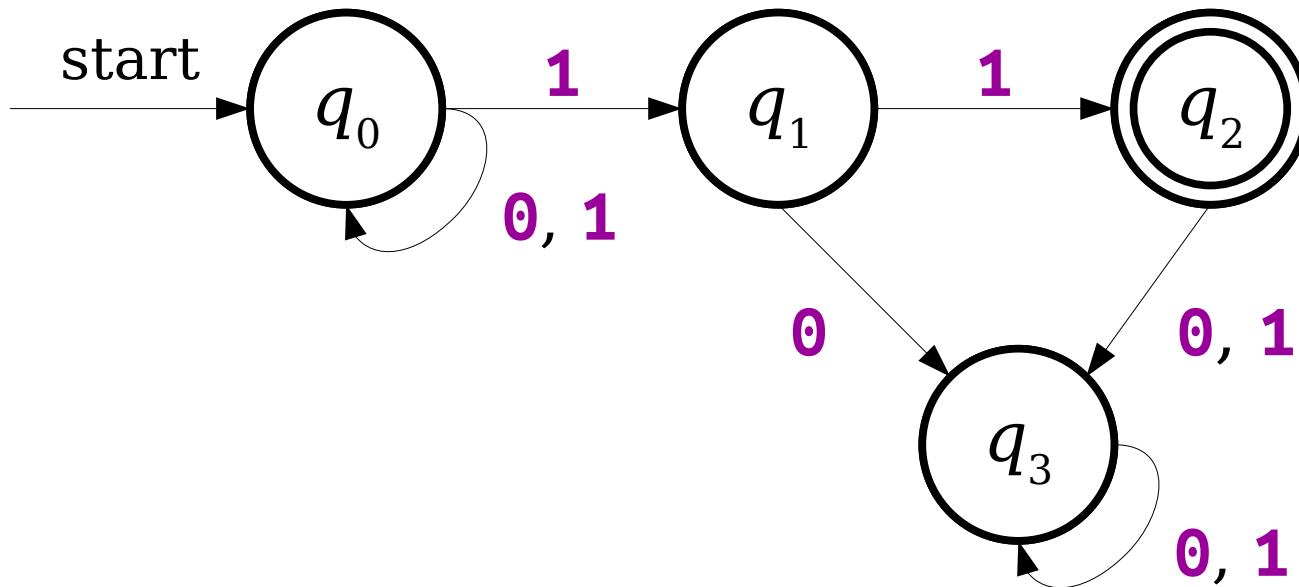


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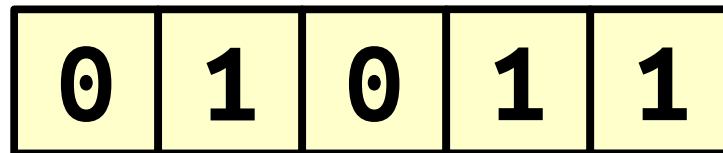
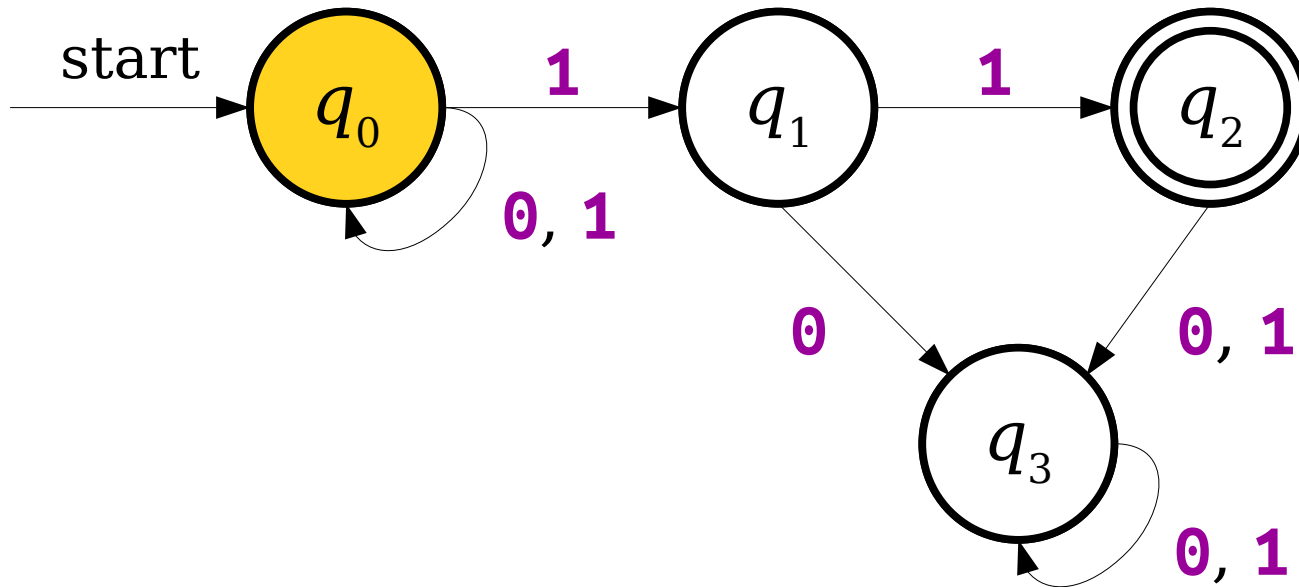
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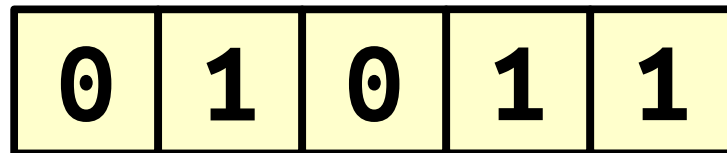
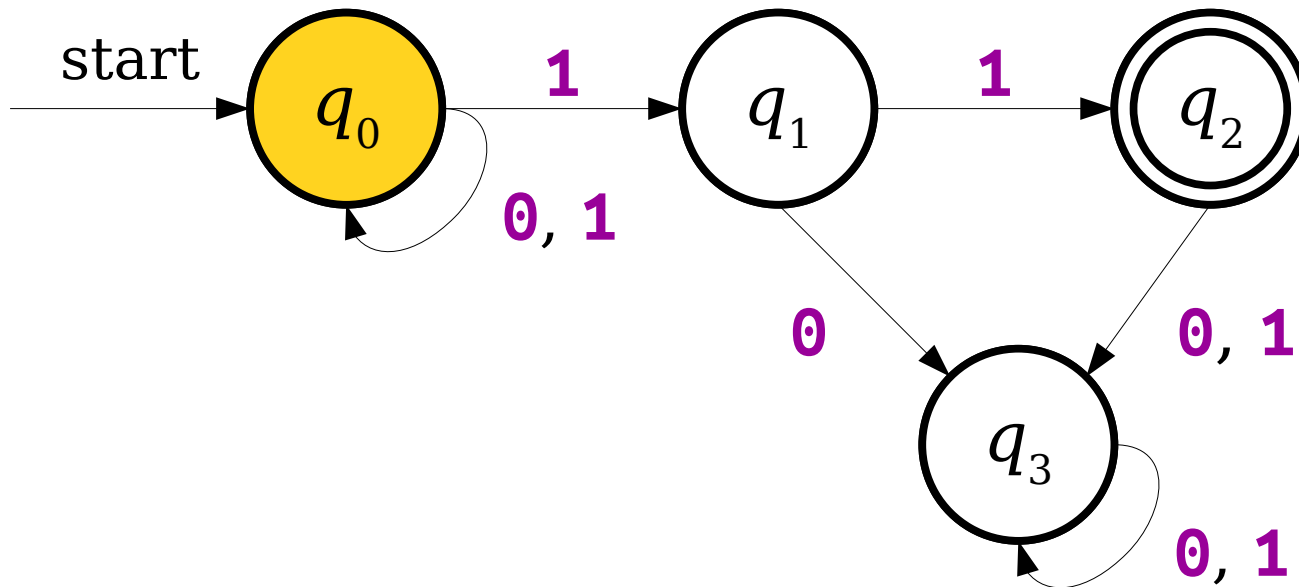


0	1	0	1	1
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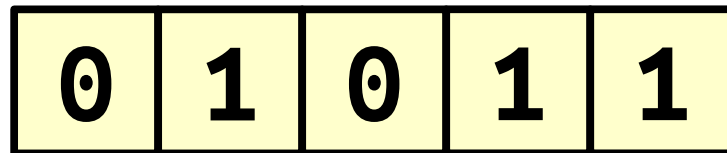
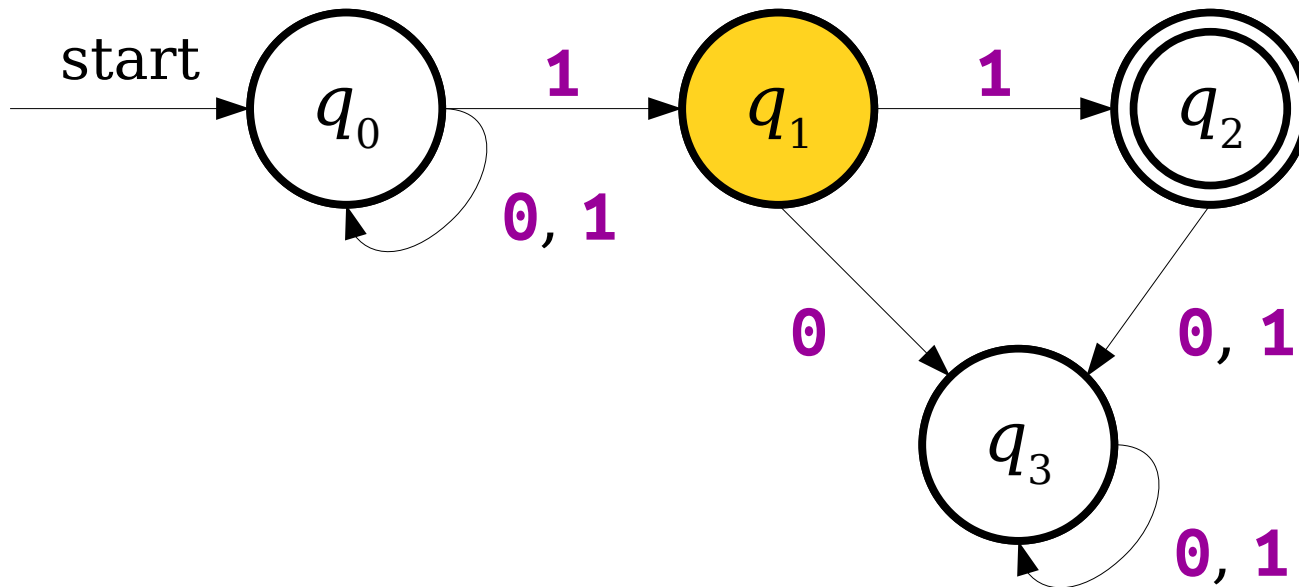
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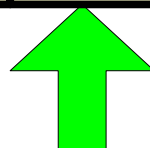
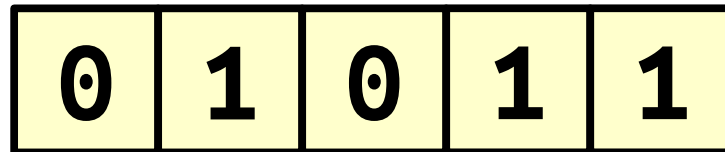
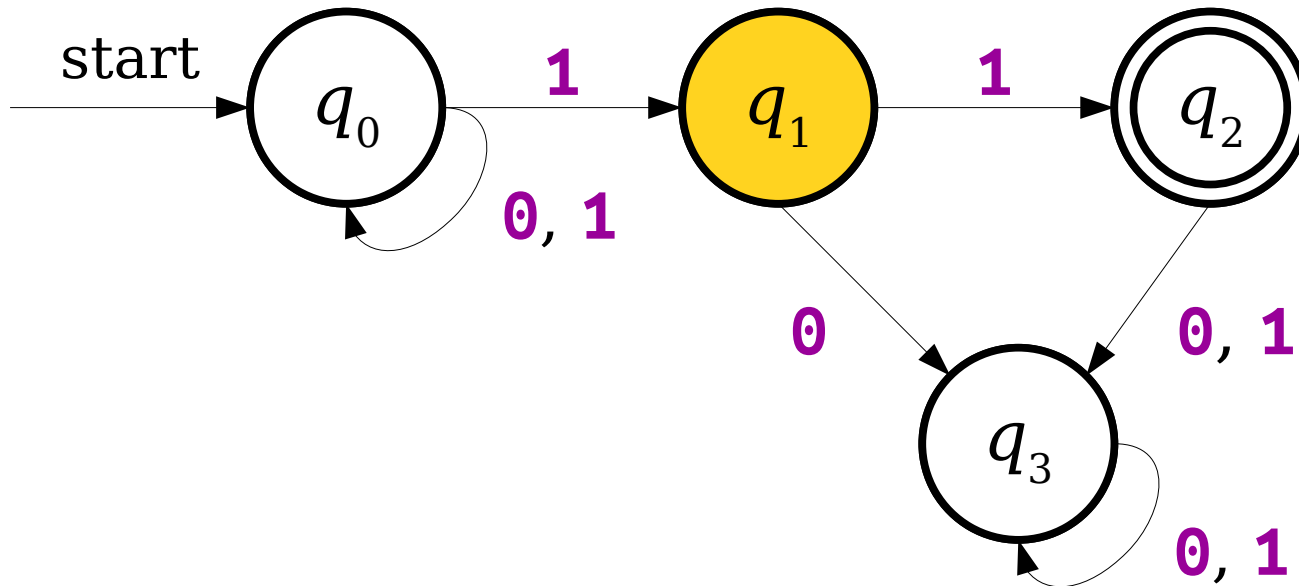
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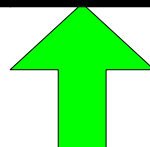
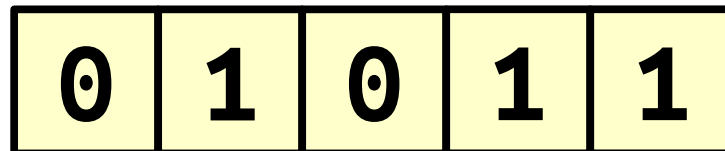
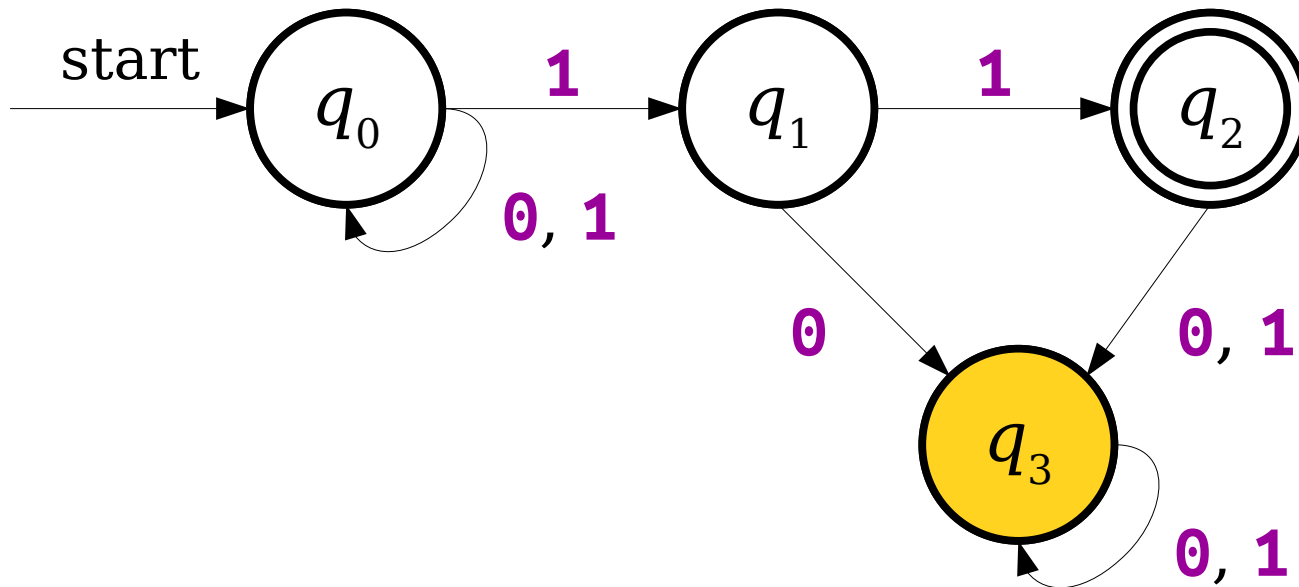
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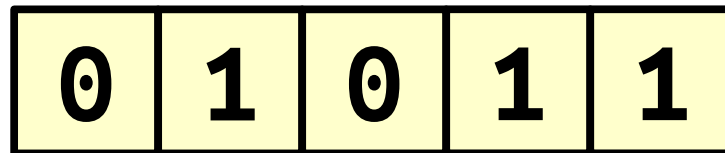
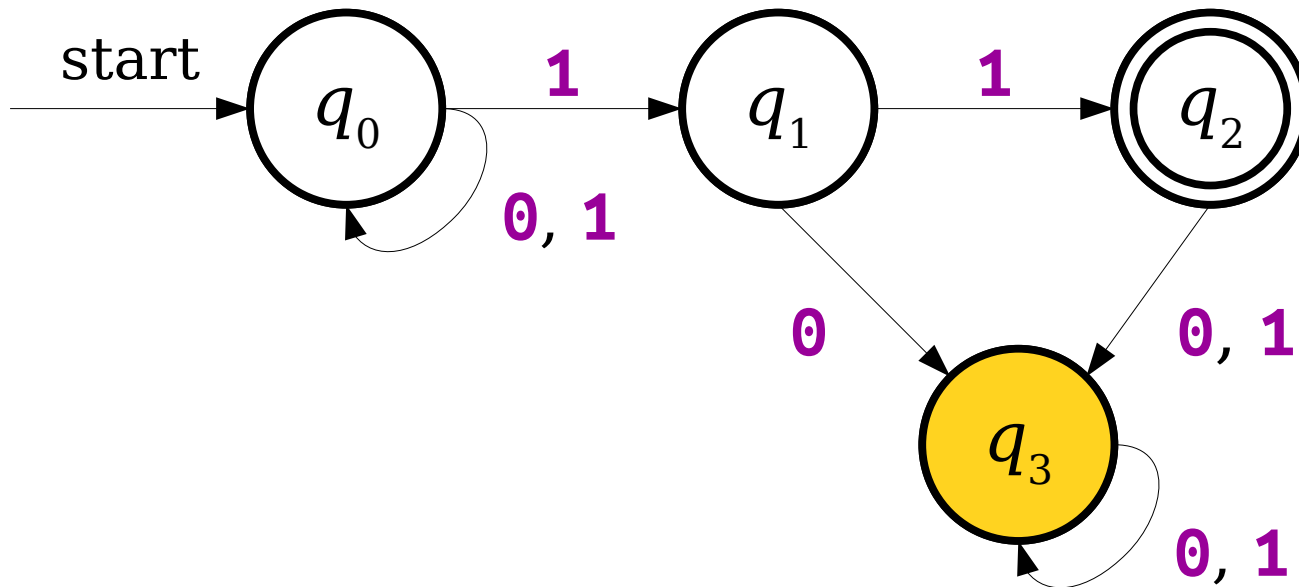
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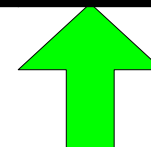
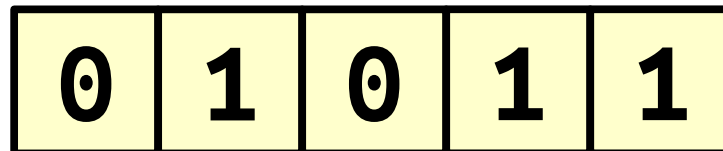
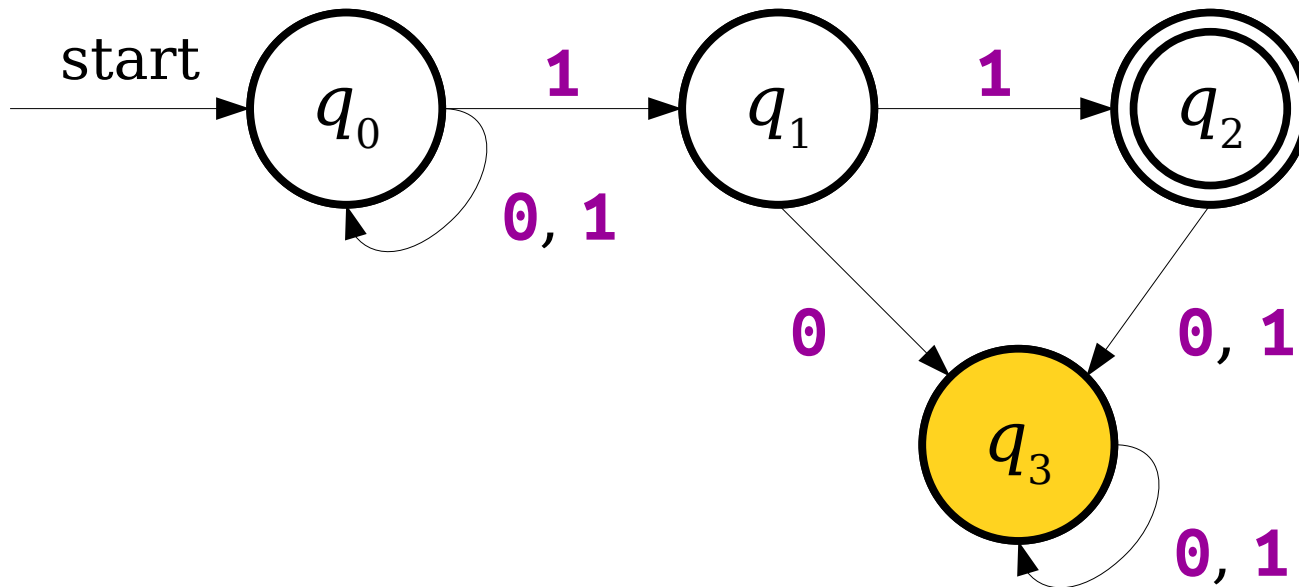
A Simple NFA



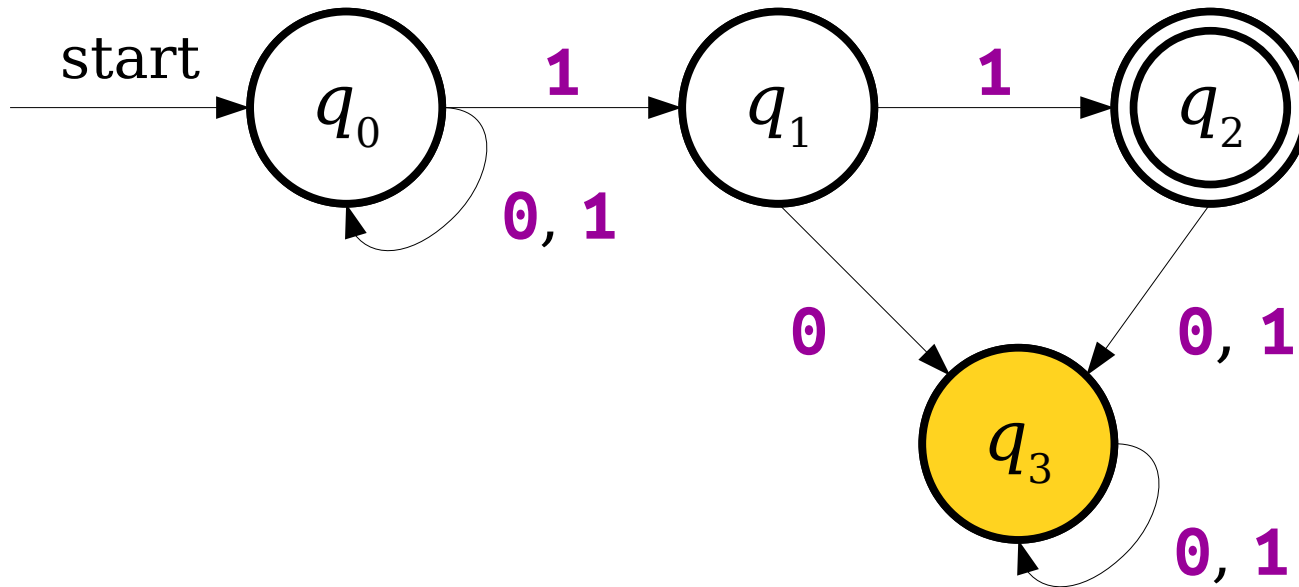
A Simple NFA



A Simple NFA

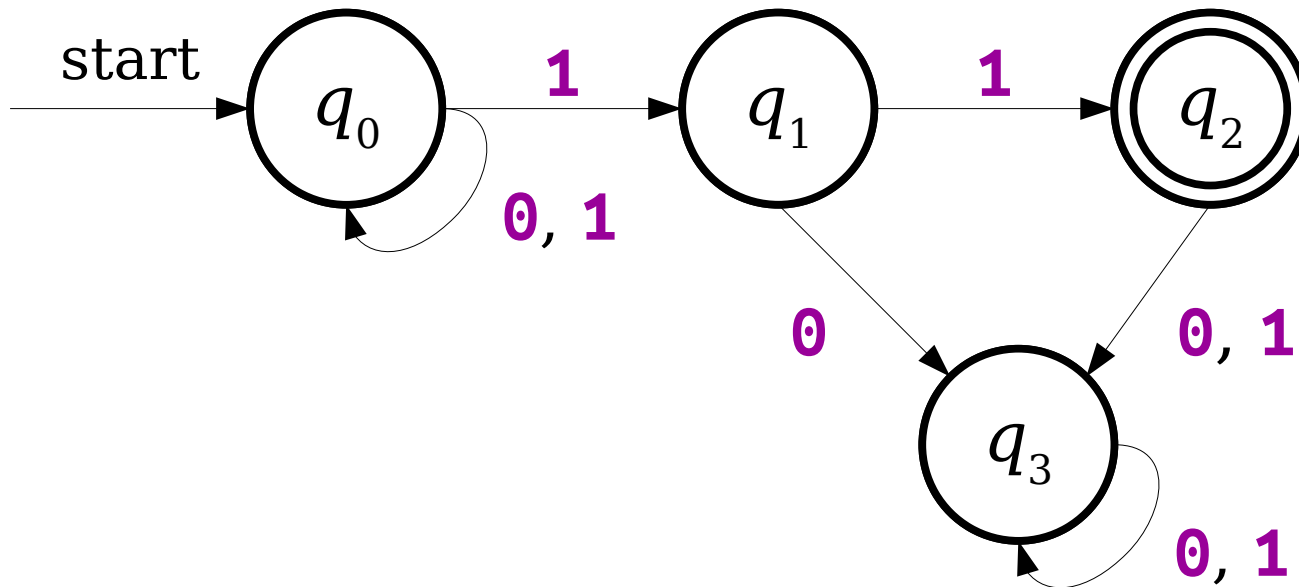


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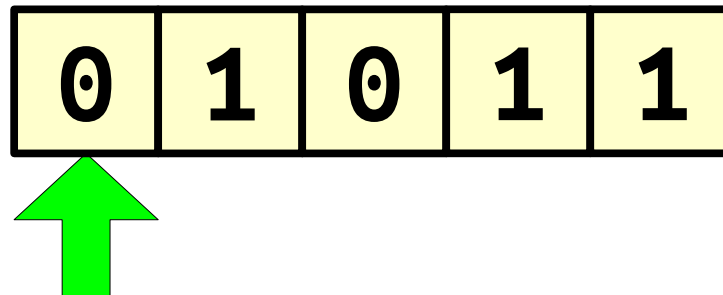
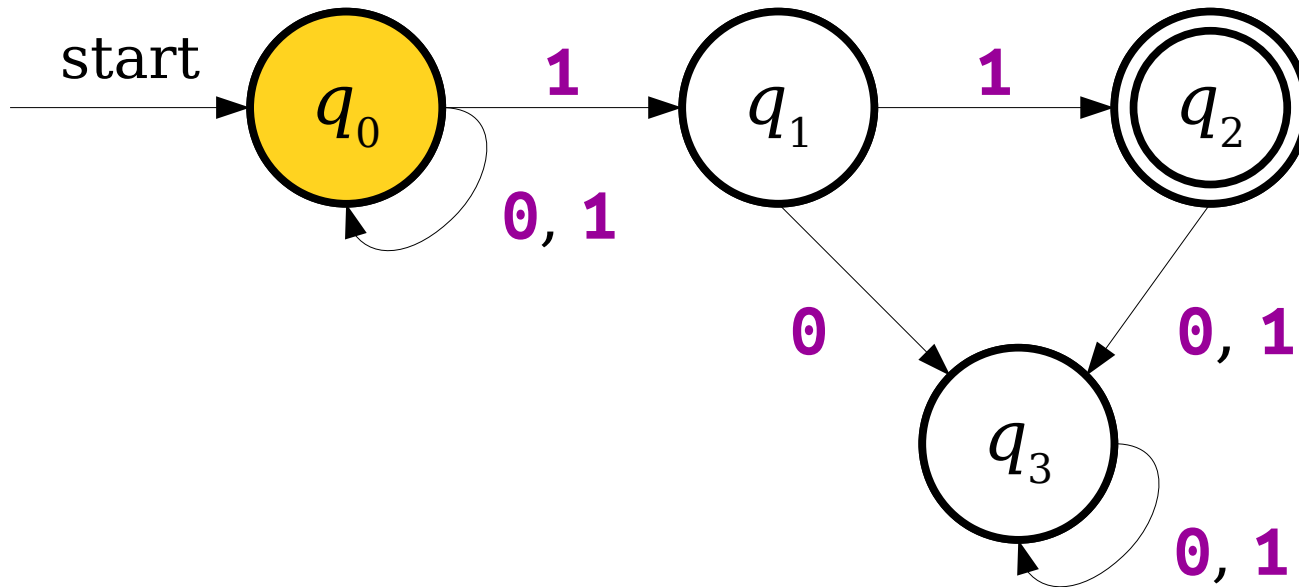
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A Simple NFA

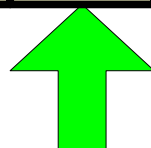
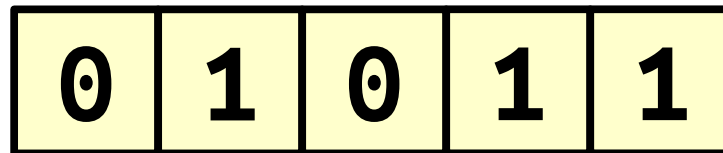
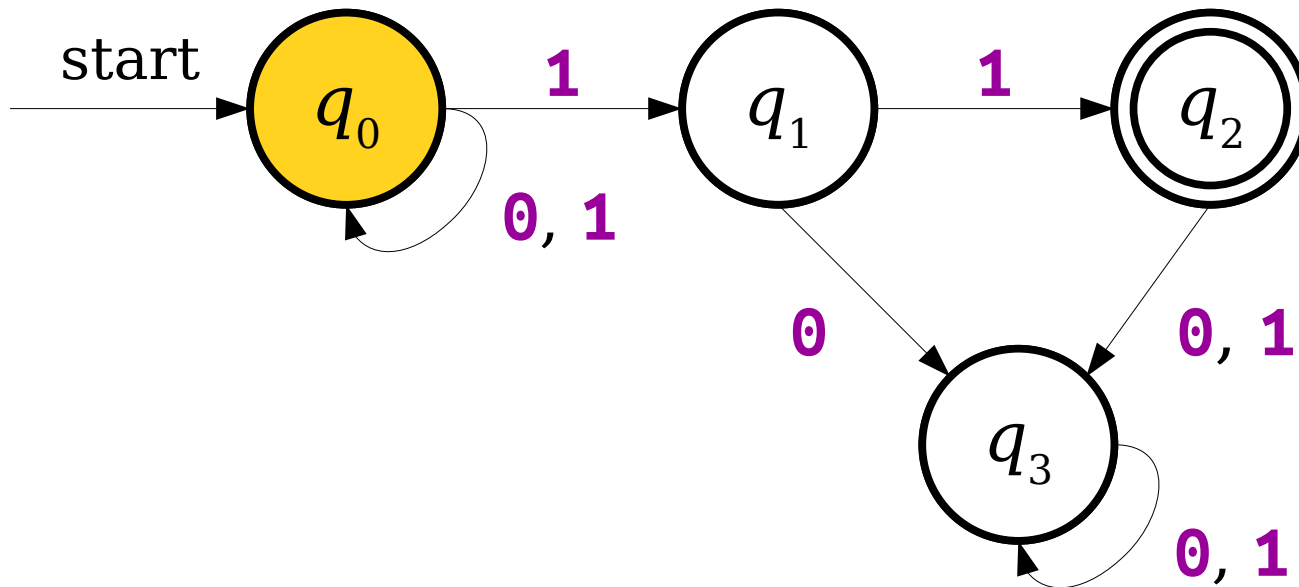


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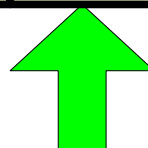
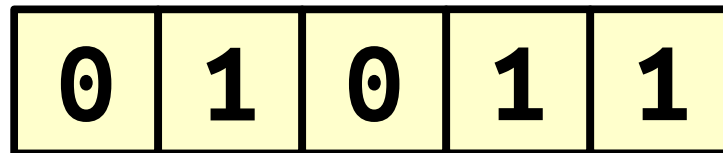
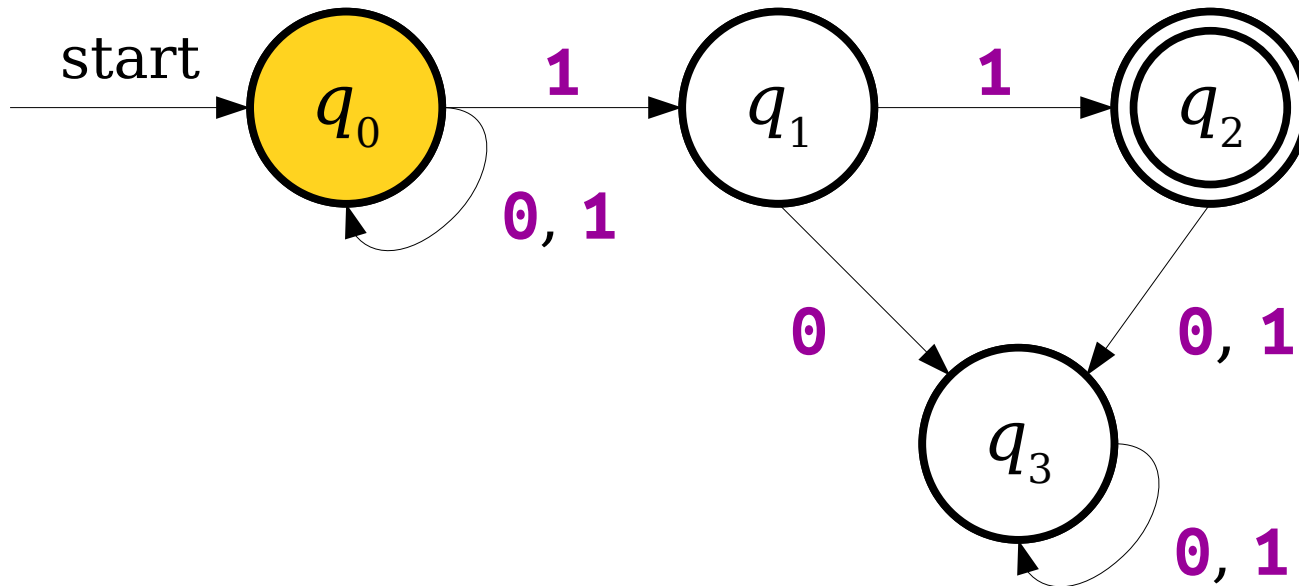
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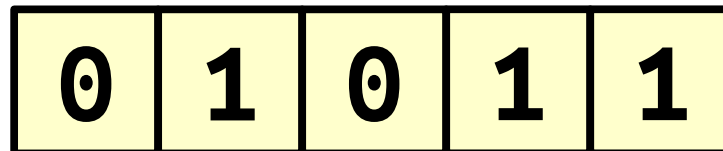
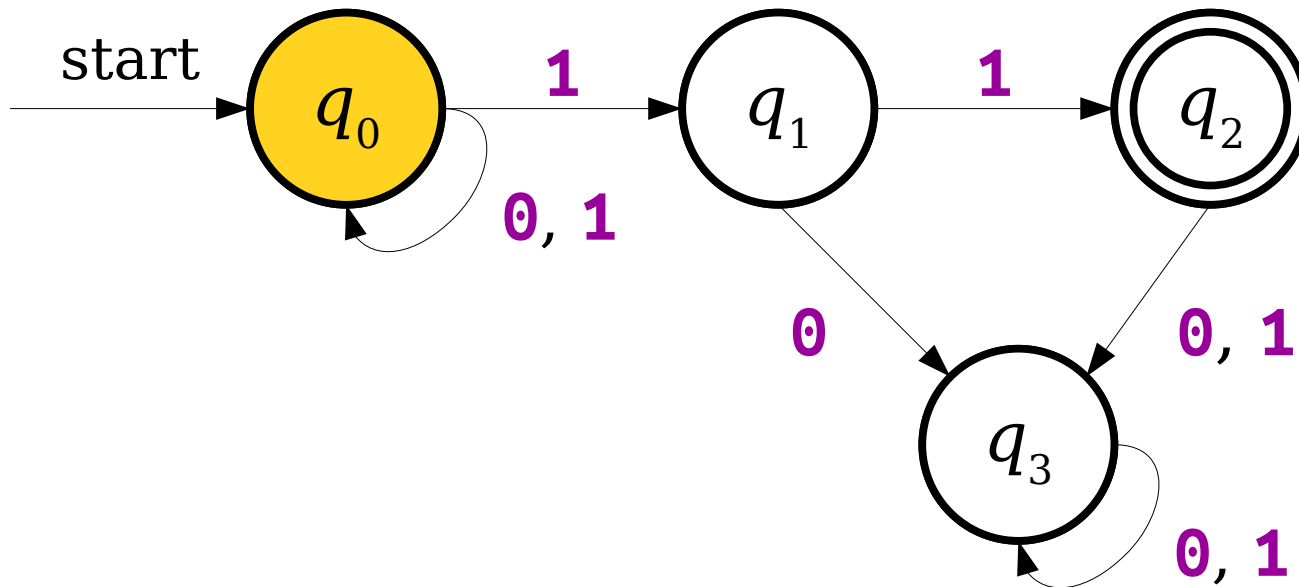
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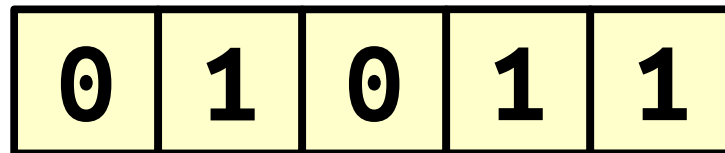
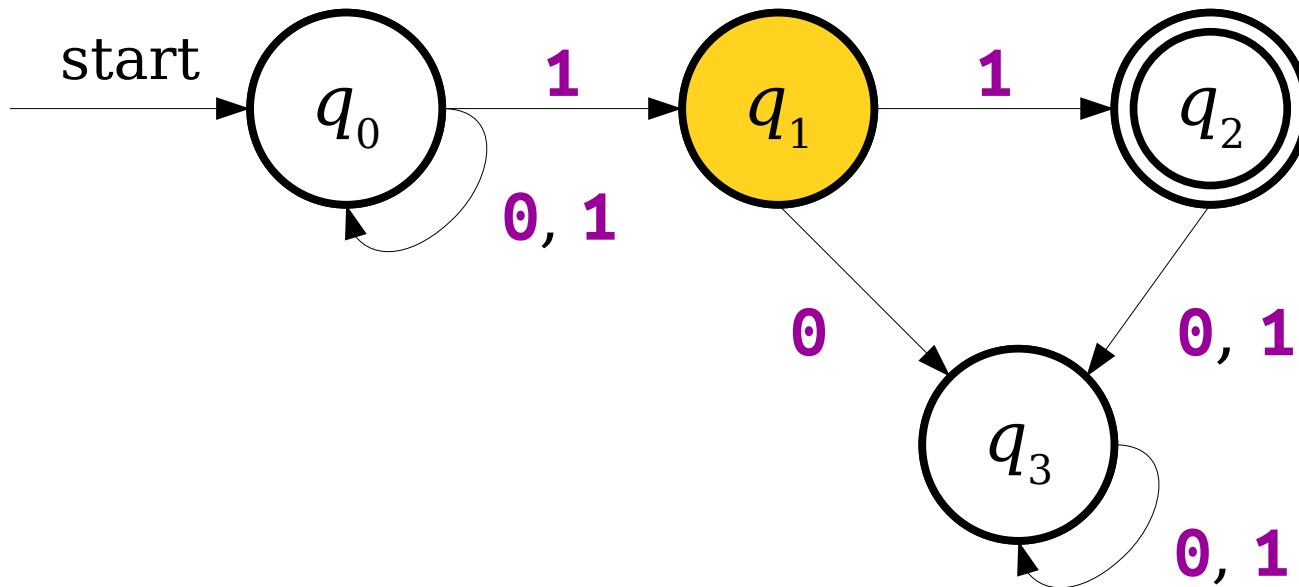
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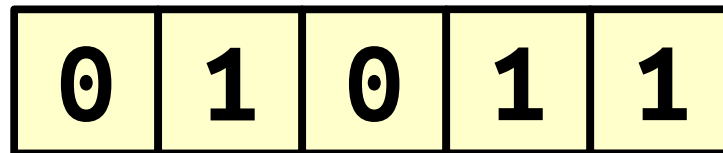
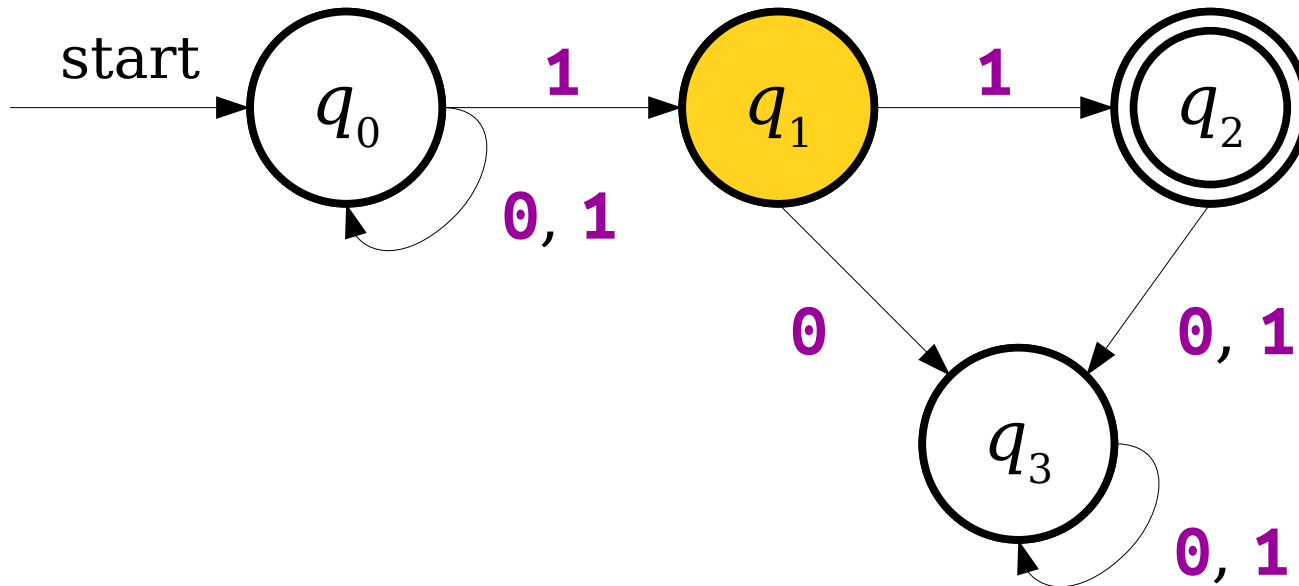
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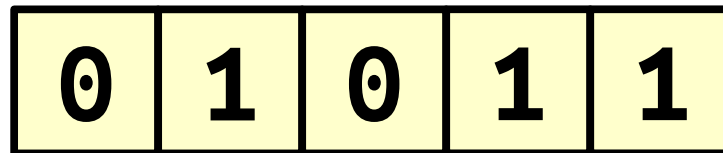
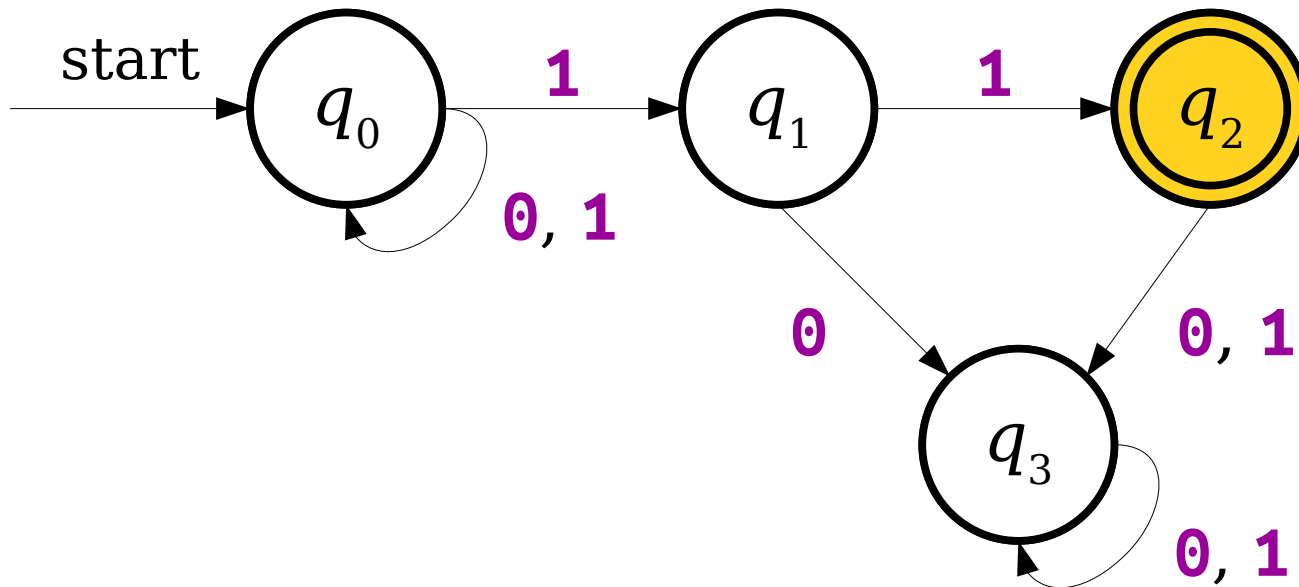
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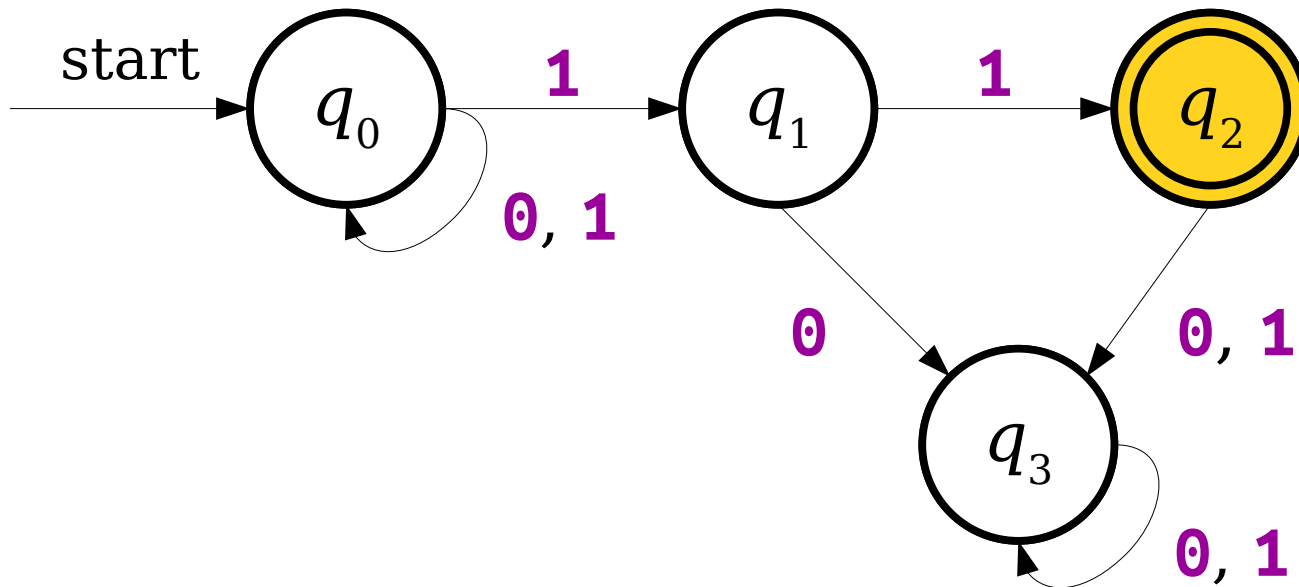
A Simple NFA



A Simple NFA

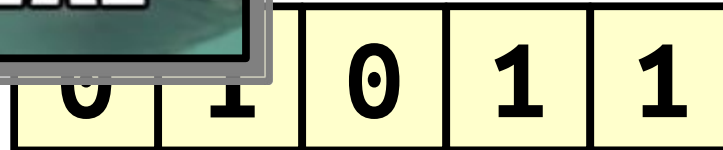
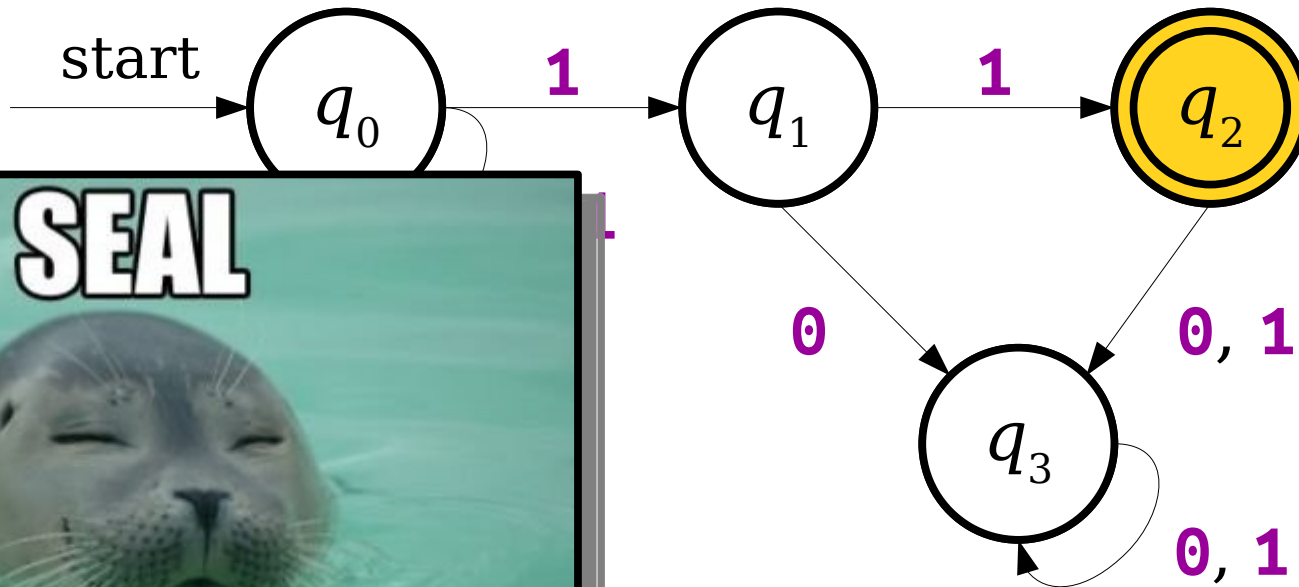


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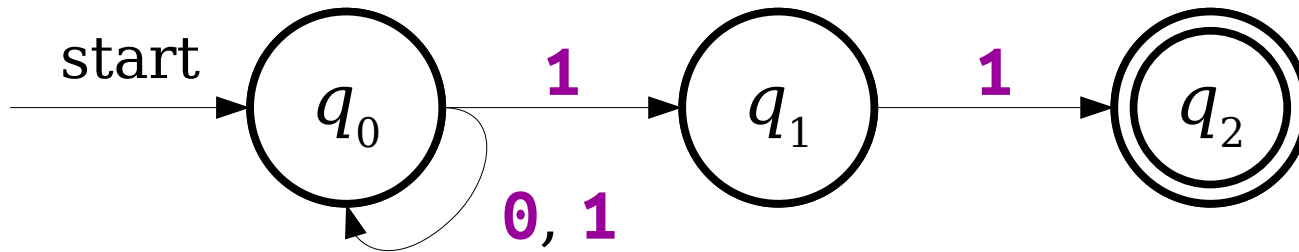


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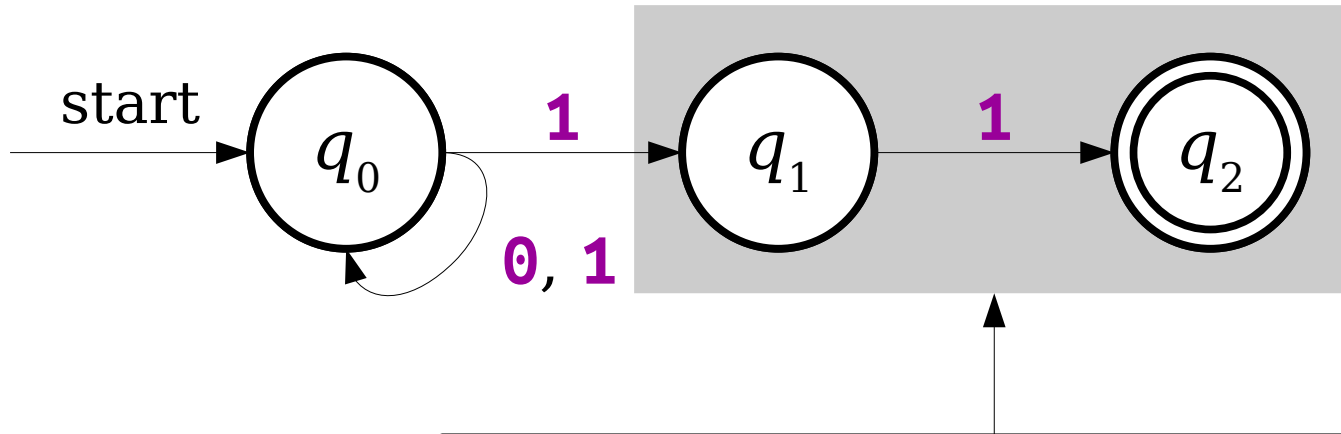
A Simple NFA



A More Complex NFA

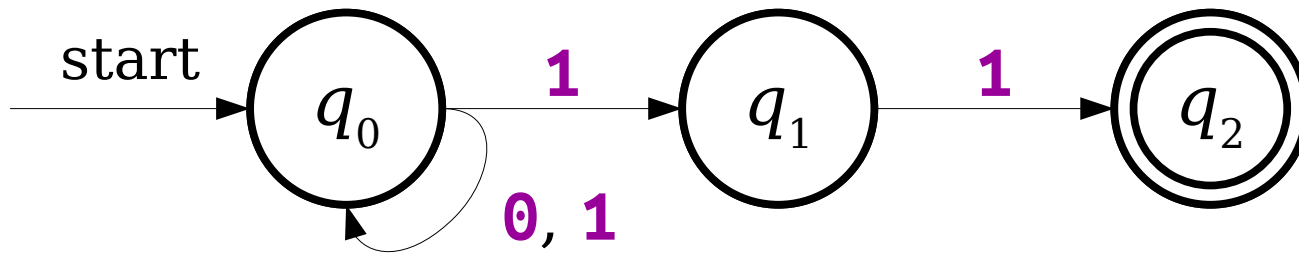


A More Complex NFA



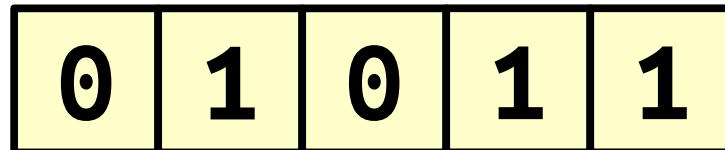
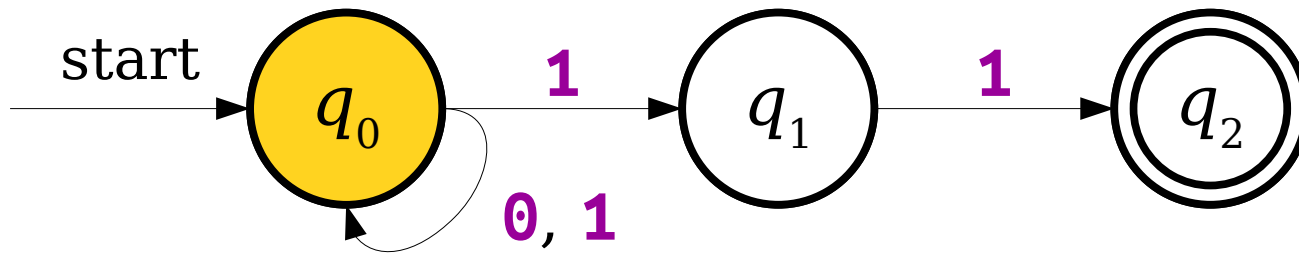
If a NFA needs to make a transition when no transition exists, the automaton **dies** and that particular path does not accept.

A More Complex NFA

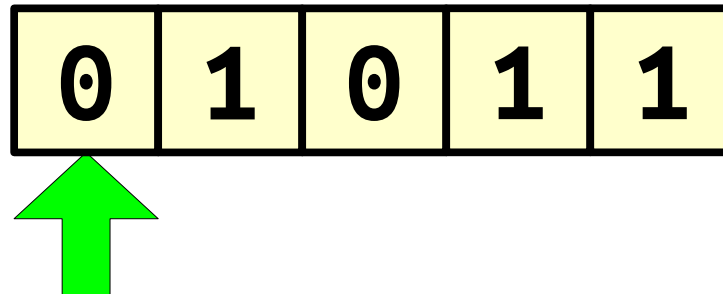
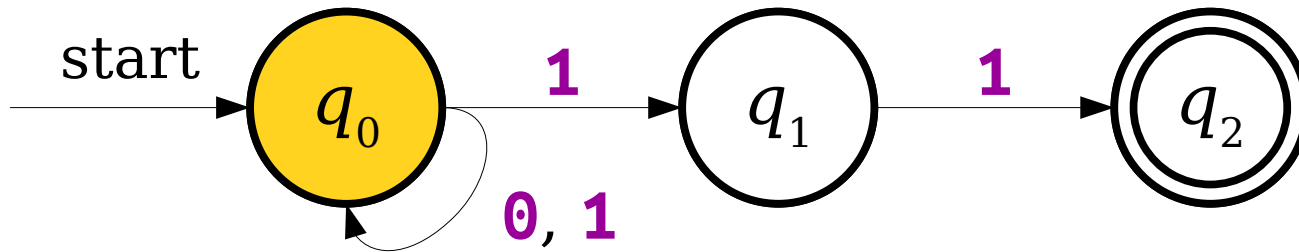


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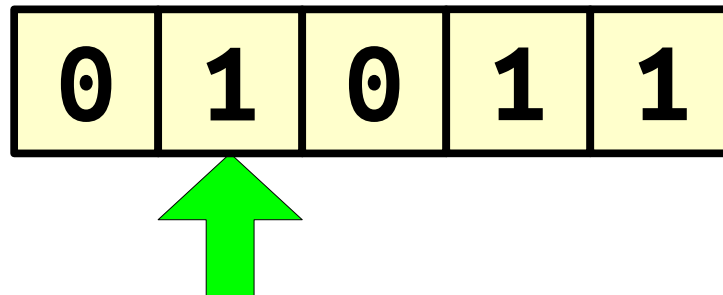
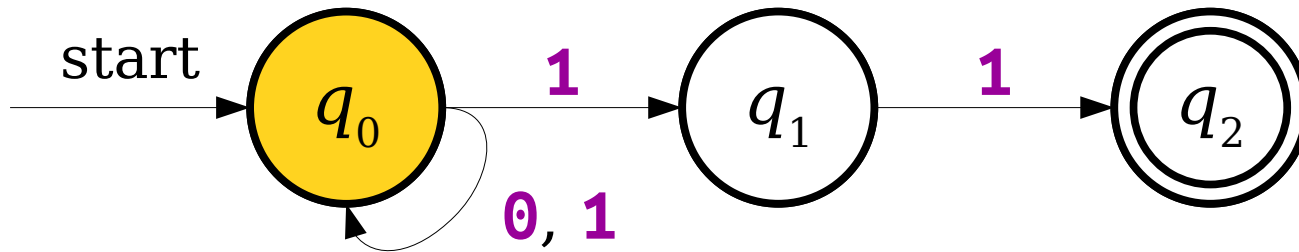
A More Complex NFA



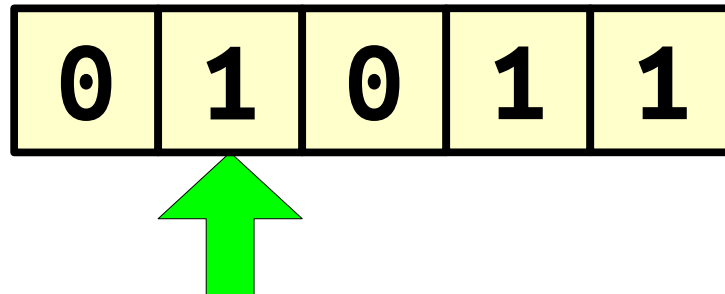
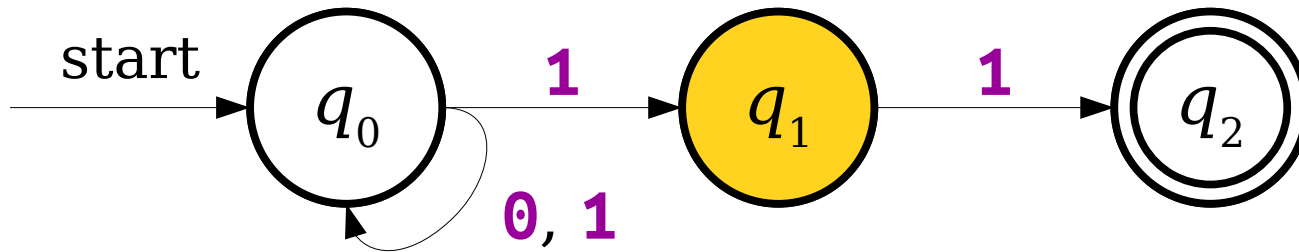
A More Complex NFA



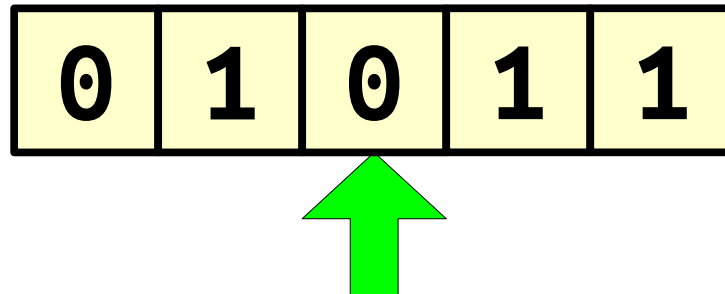
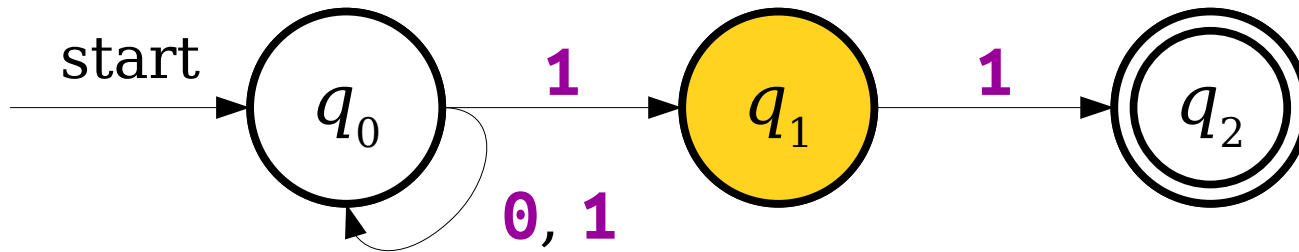
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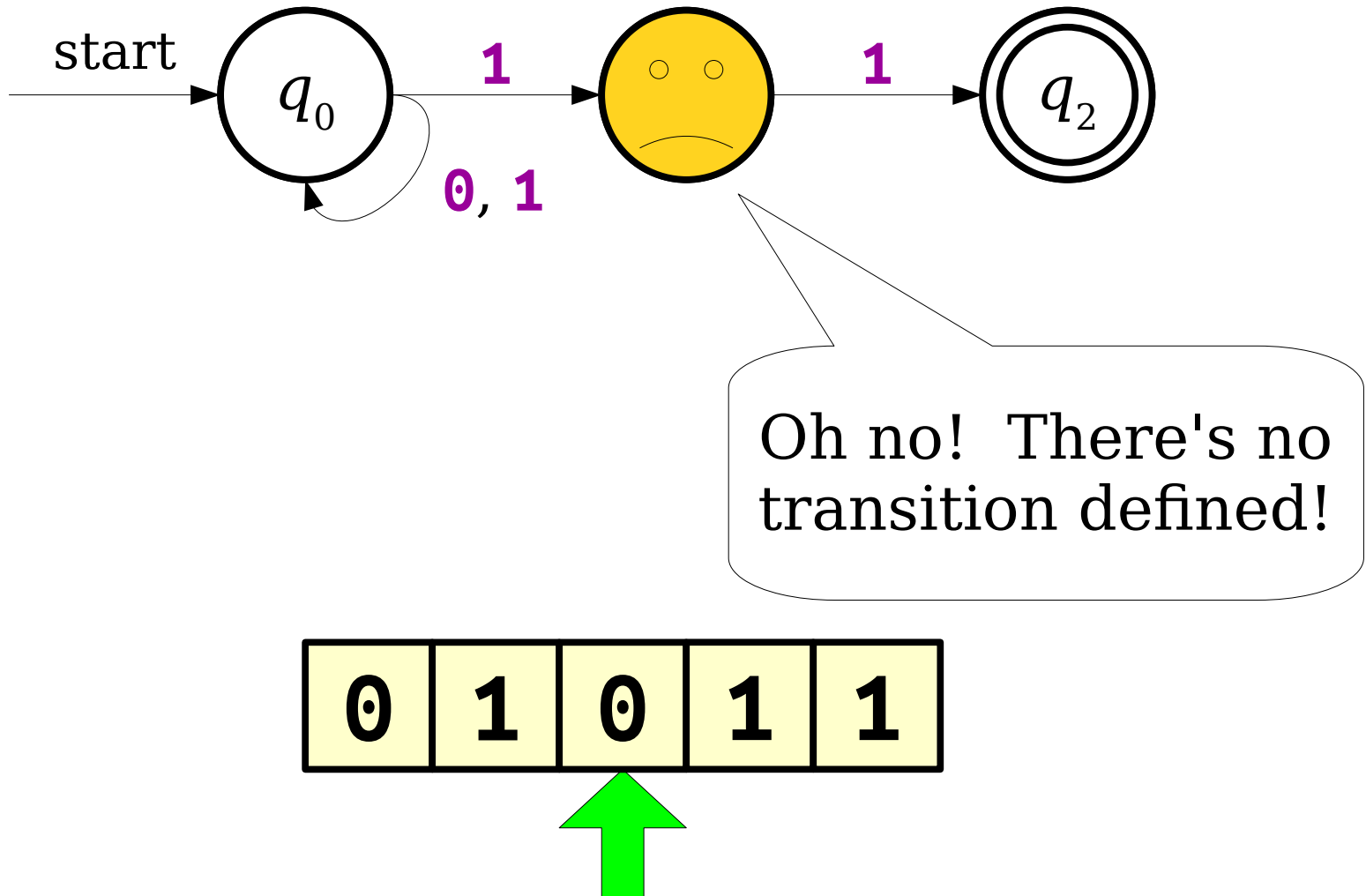
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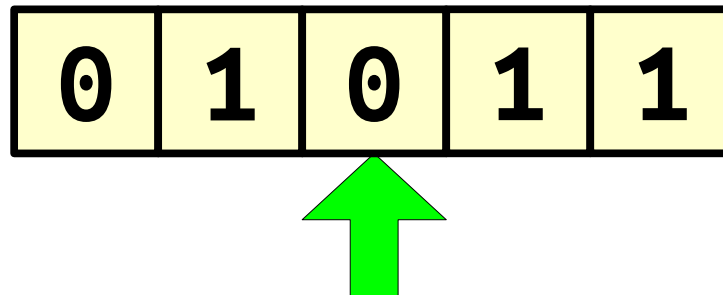
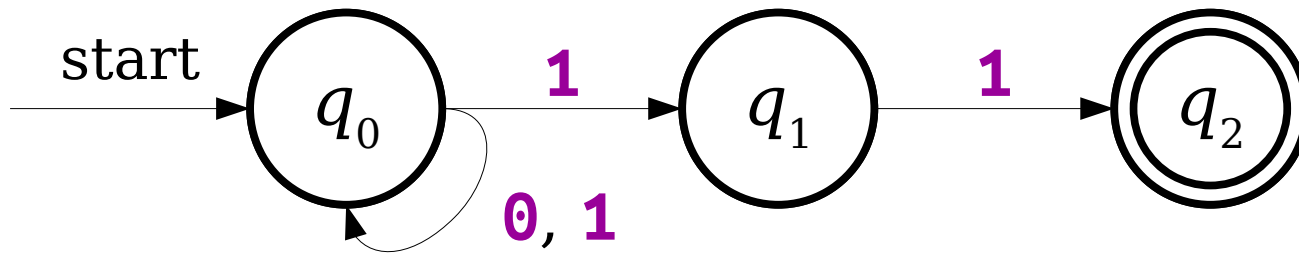
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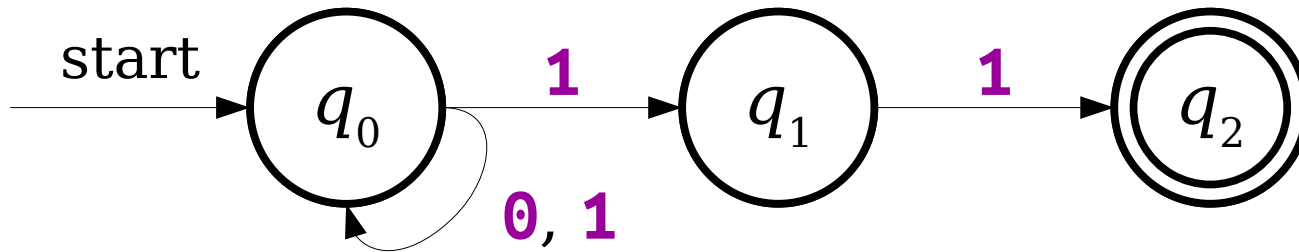
A More Complex NFA



A More Complex NFA

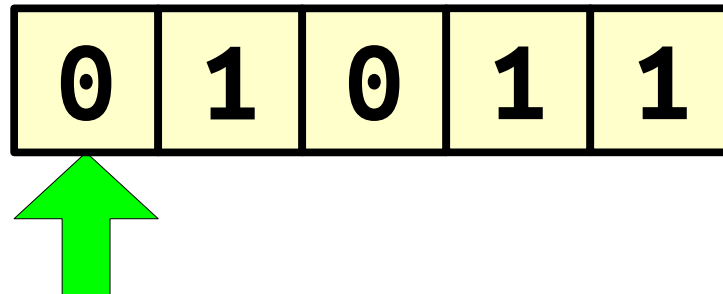
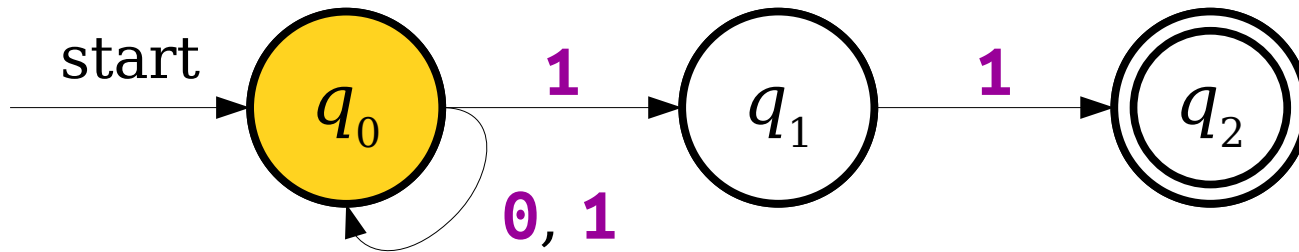


A More Complex NFA

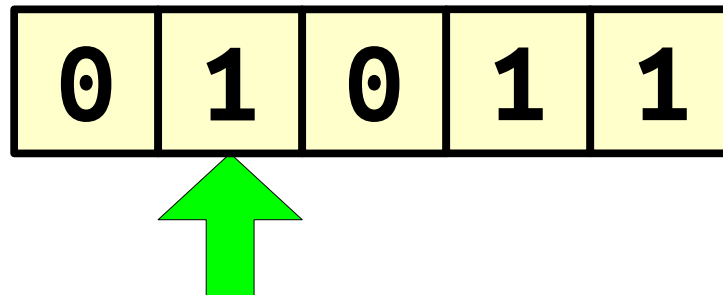
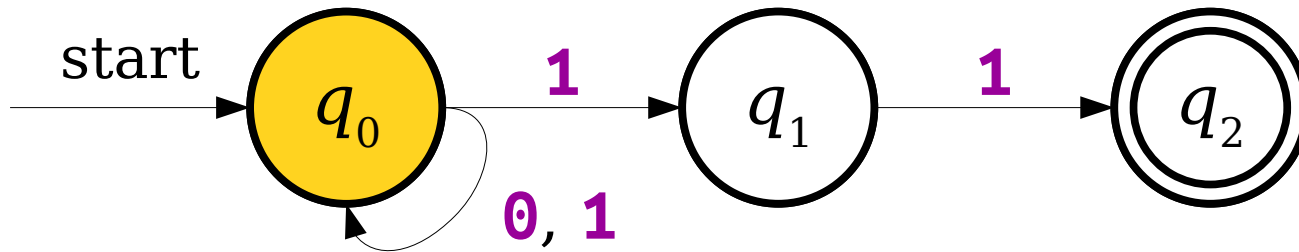


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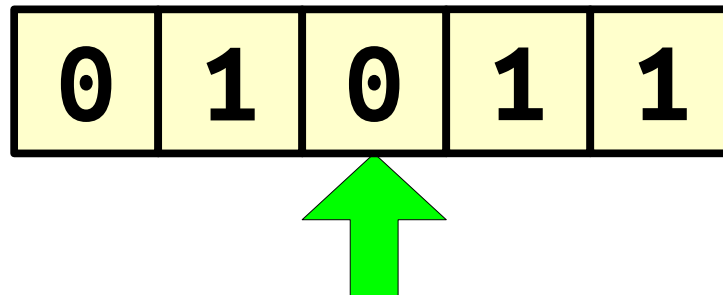
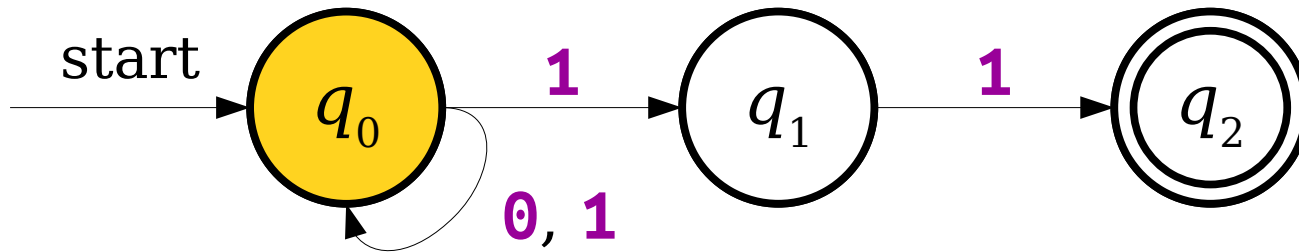
A More Complex NFA



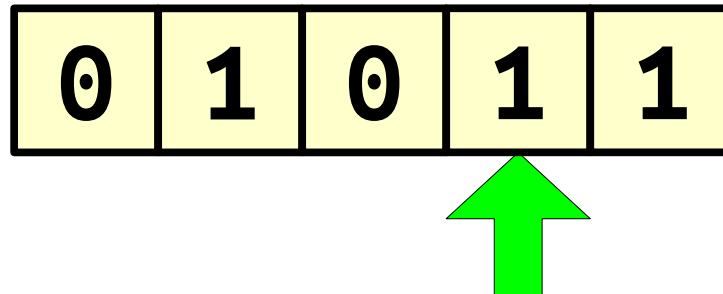
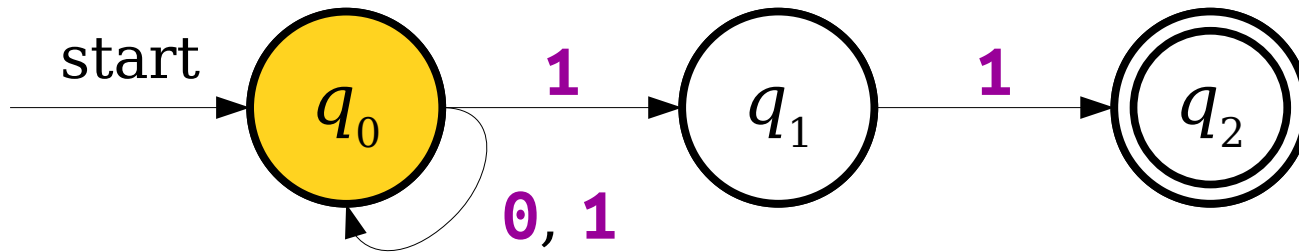
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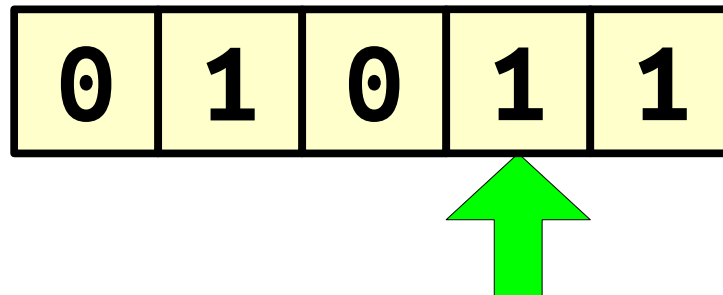
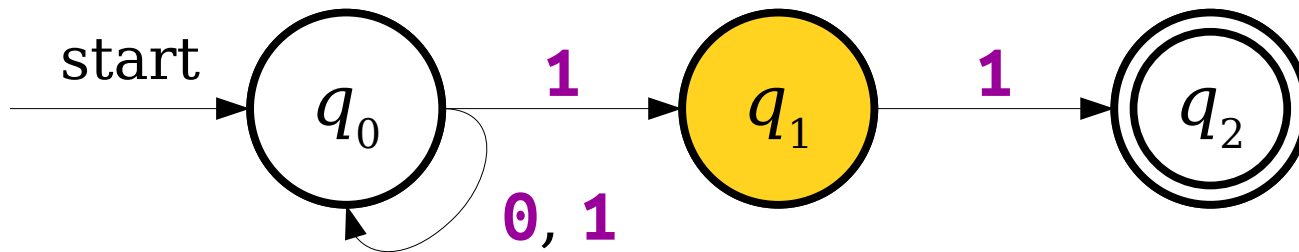
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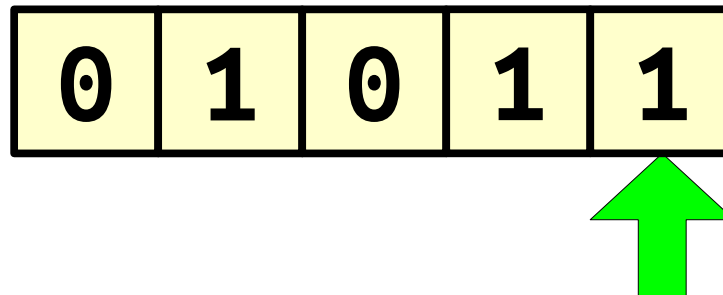
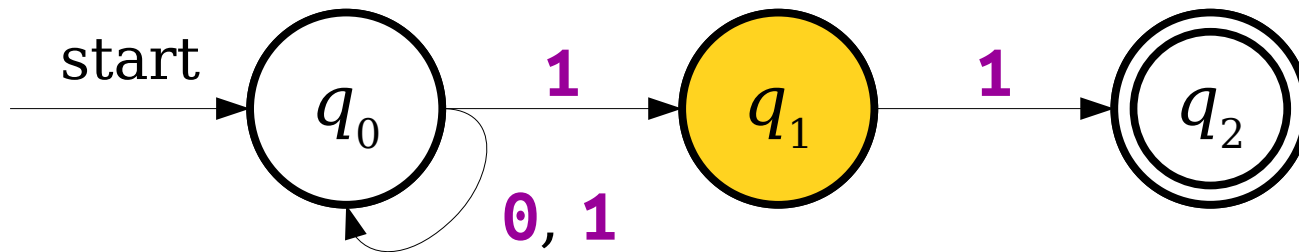
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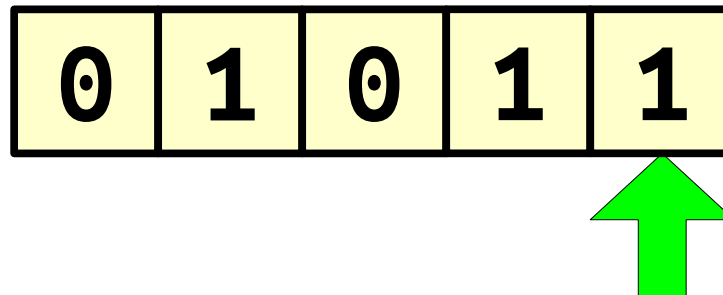
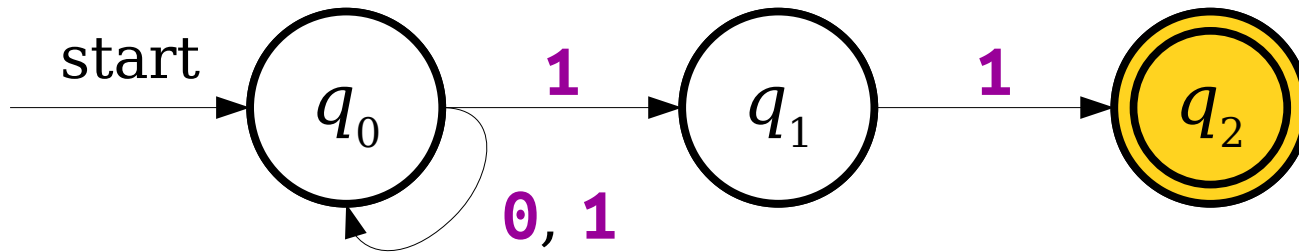
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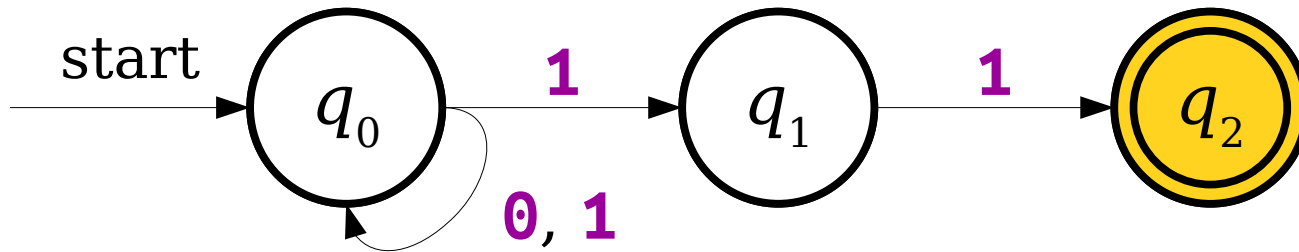
A More Complex NFA



A More Complex NFA

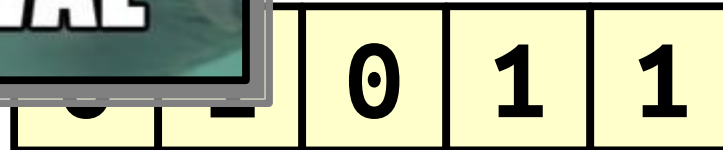
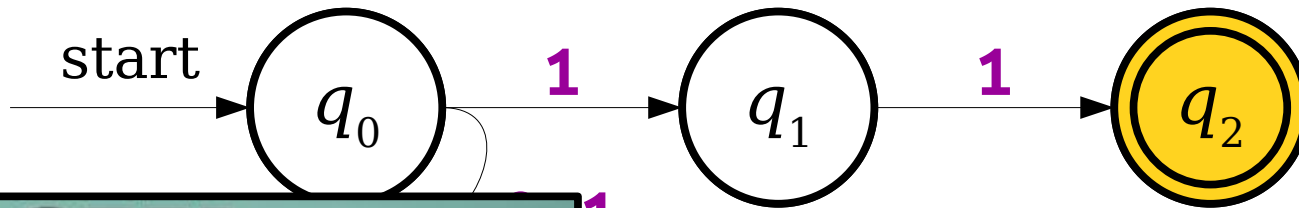


A More Complex NFA

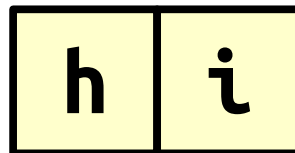
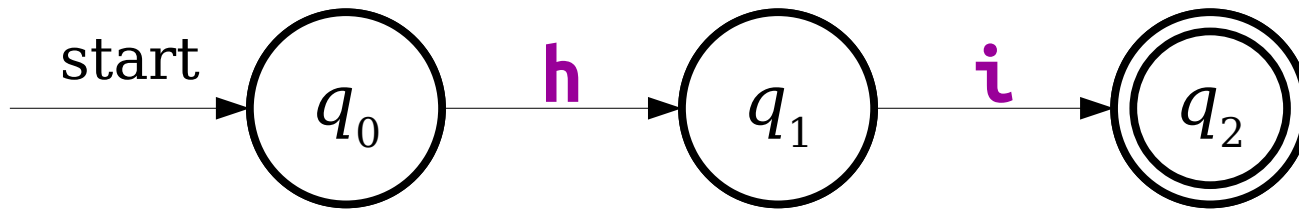


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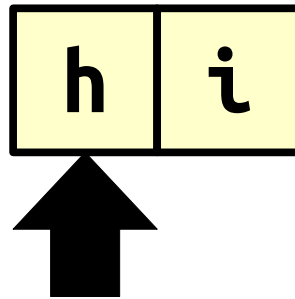
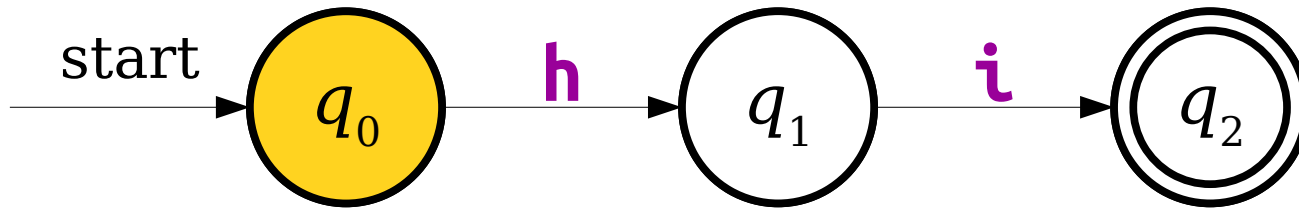
A More Complex NFA



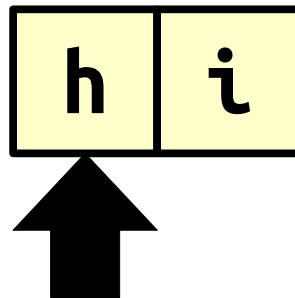
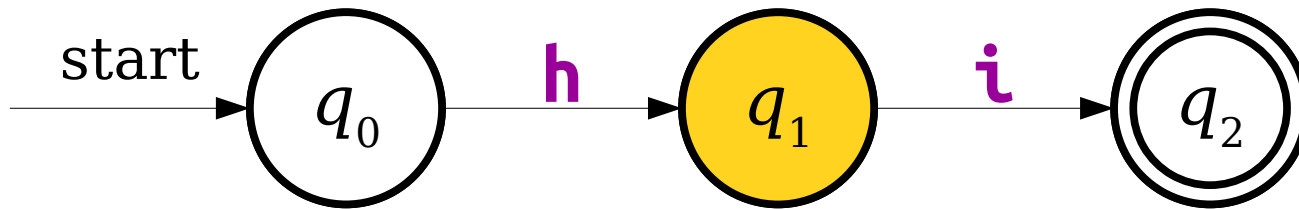
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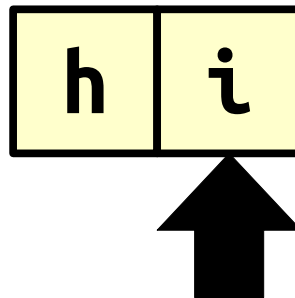
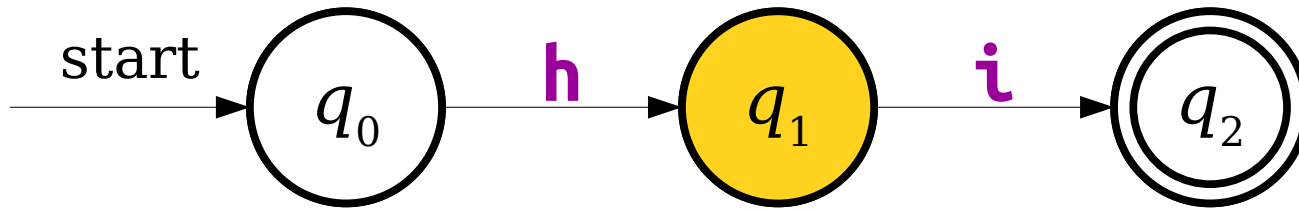
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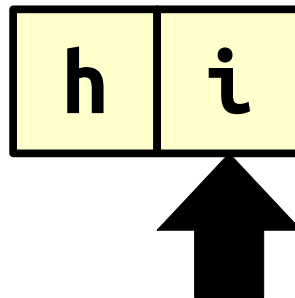
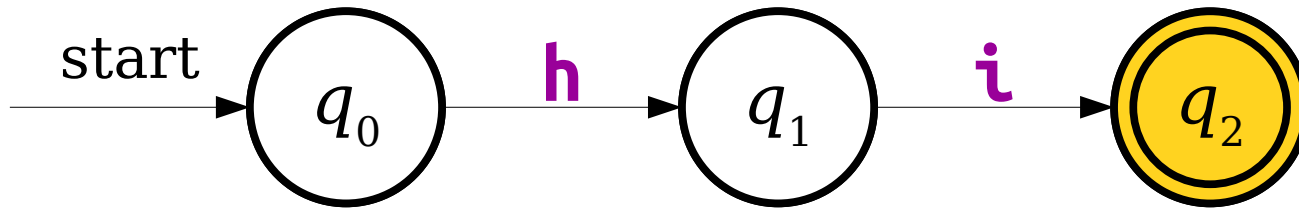
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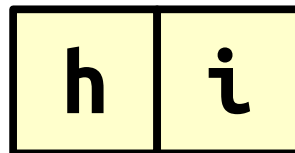
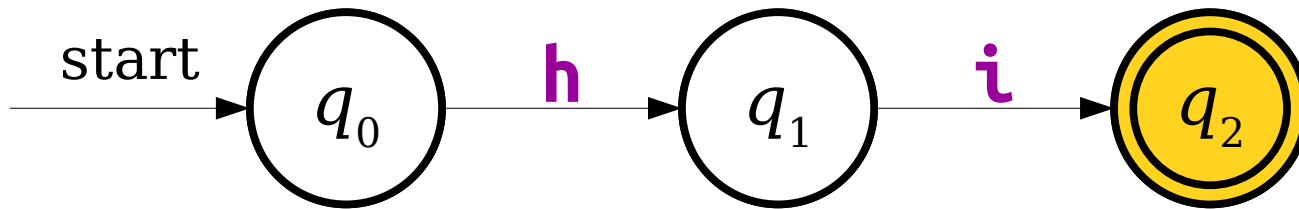
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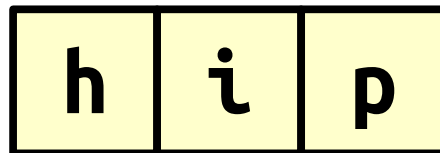
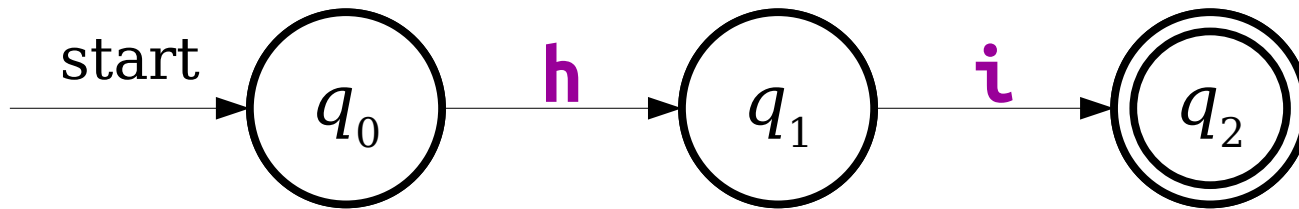
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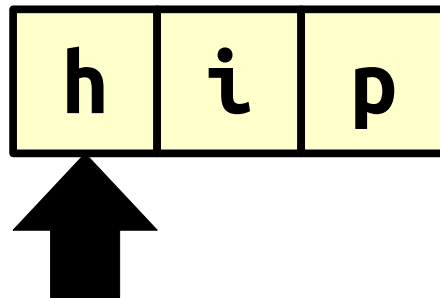
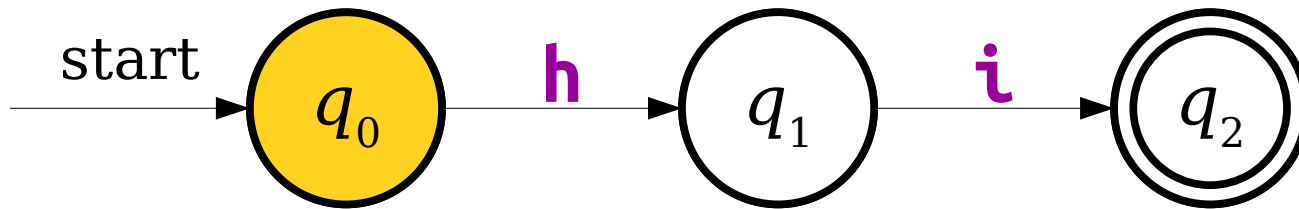
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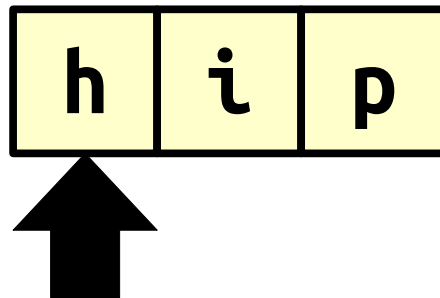
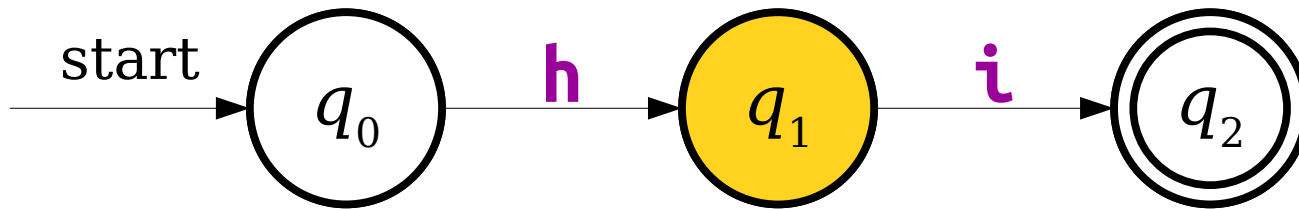
Tragedy in Paradise



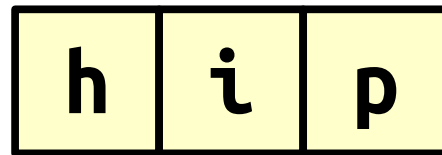
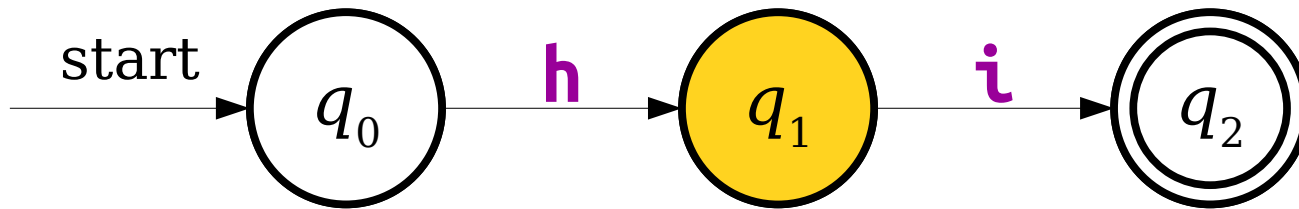
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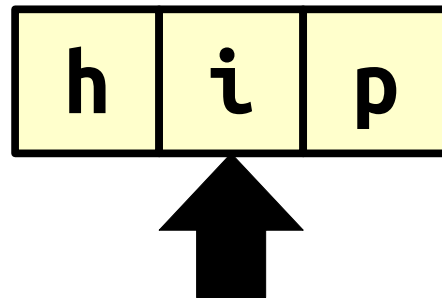
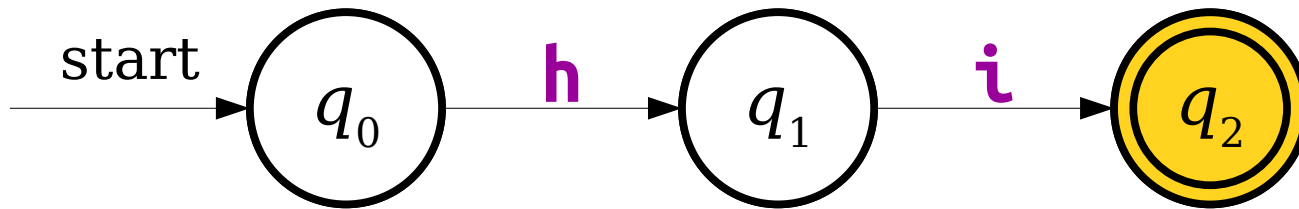
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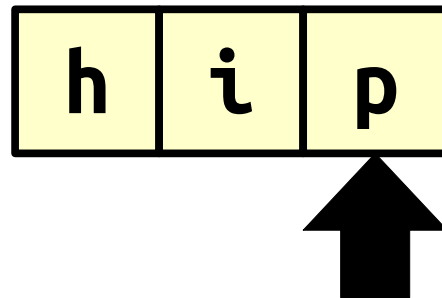
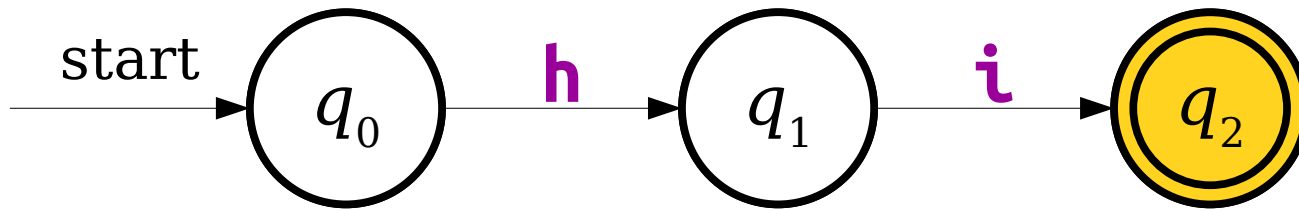
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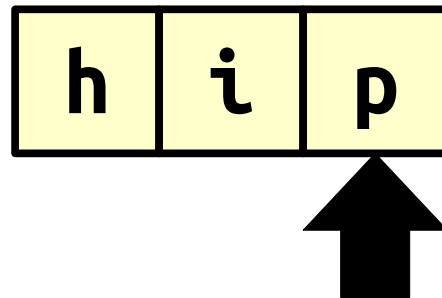
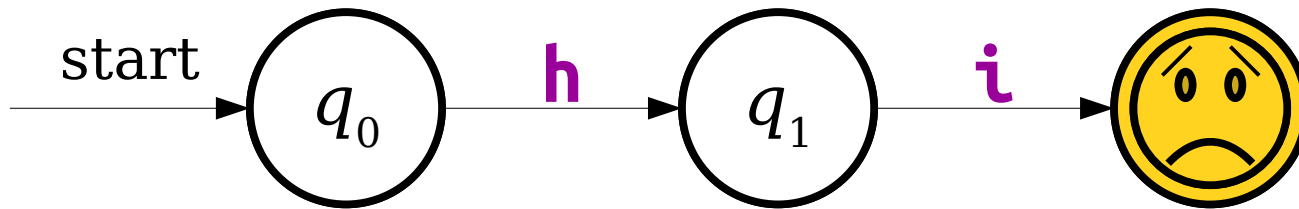
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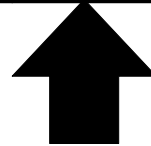
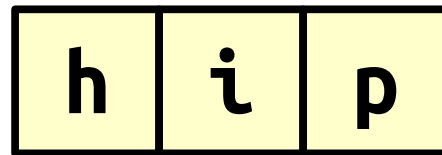
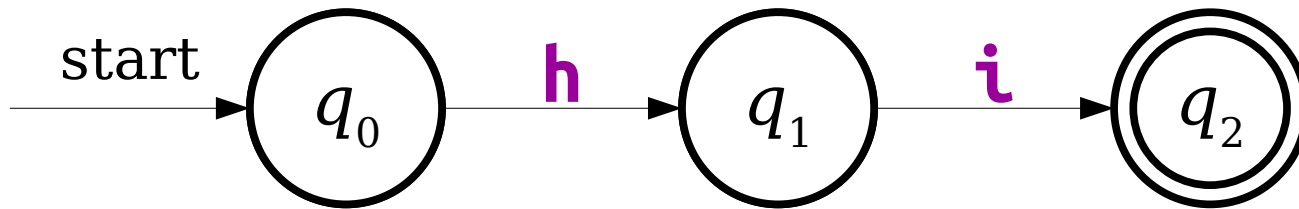
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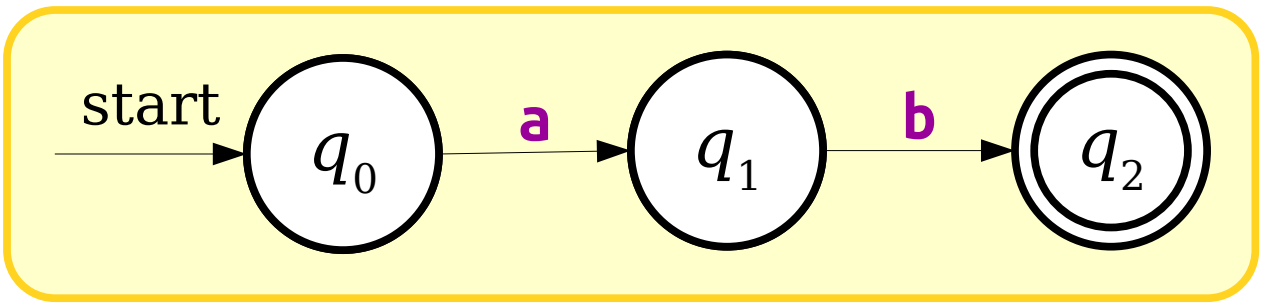


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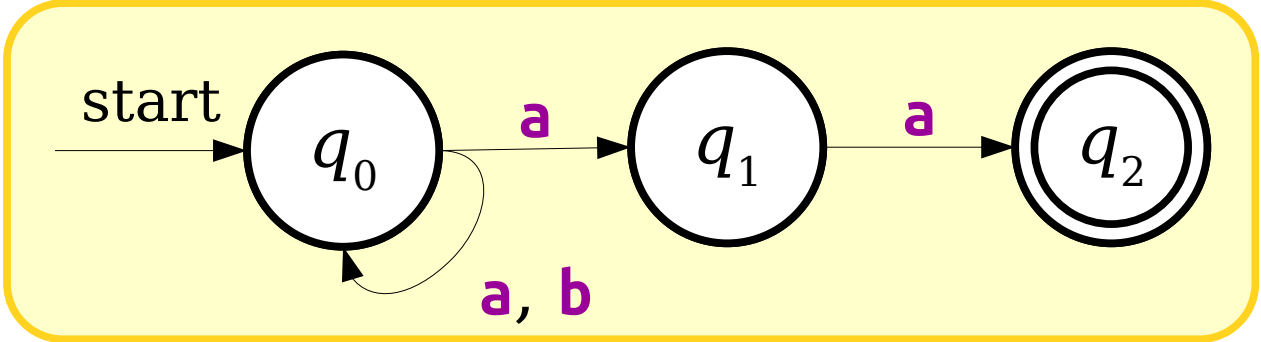
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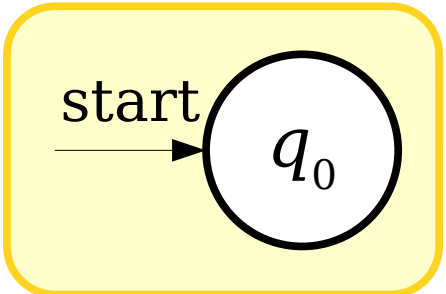


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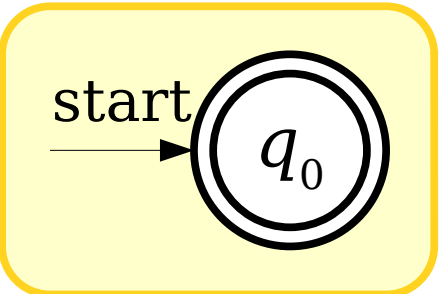
Question to ponder:
 Why is the answer
 $\{ w \in \Sigma^* \mid w \text{ ends in } \mathbf{aaa} \}$
 not correct?



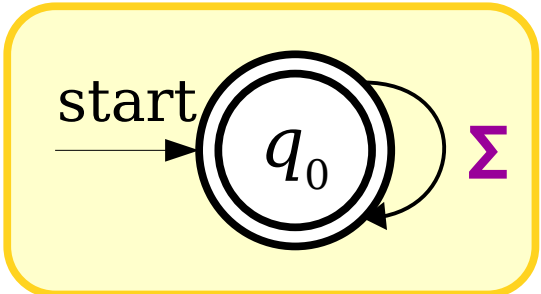
$\{ w \in \Sigma^* \mid w \text{ ends in } \mathbf{aa} \}$



\emptyset



{ε}



Σ^*

The **language of an NFA** is

$$\mathcal{L}(N) = \{ w \in \Sigma^* \mid N \text{ accepts } w \}.$$

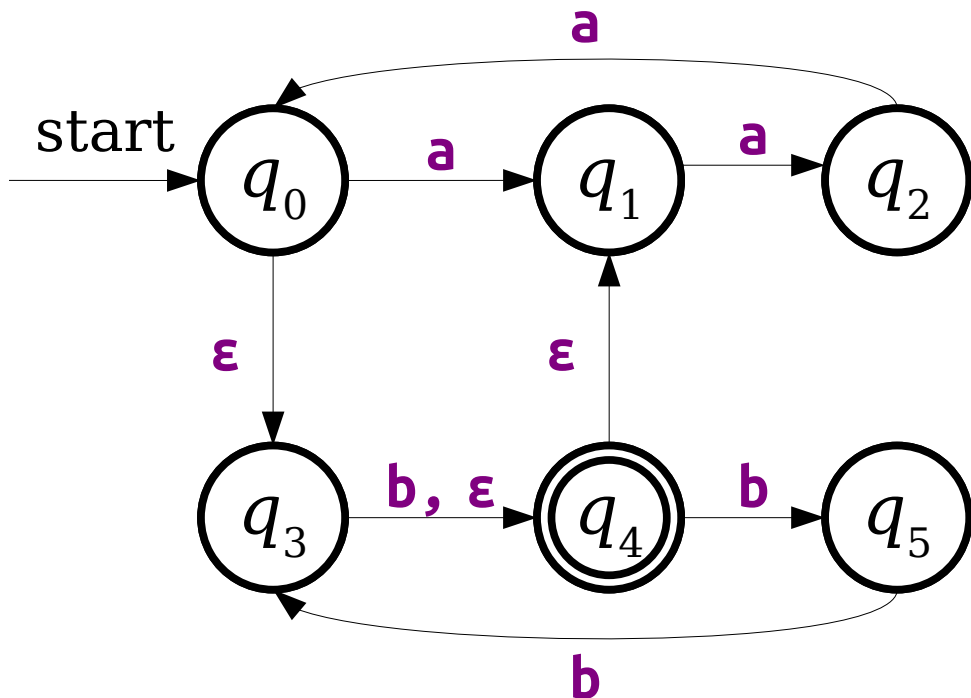
What is the language of each NFA? (Assume $\Sigma = \{ \mathbf{a}, \mathbf{b} \}$.)
 Answer at <https://pollev.com/cs103aut23>

ϵ -Transitions

- NFAs have a special type of transition called the **ϵ -transition**.
- An NFA may follow any number of ϵ -transitions at any time without consuming any input.

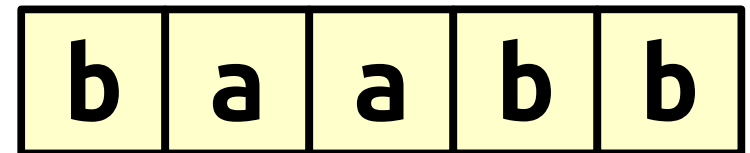
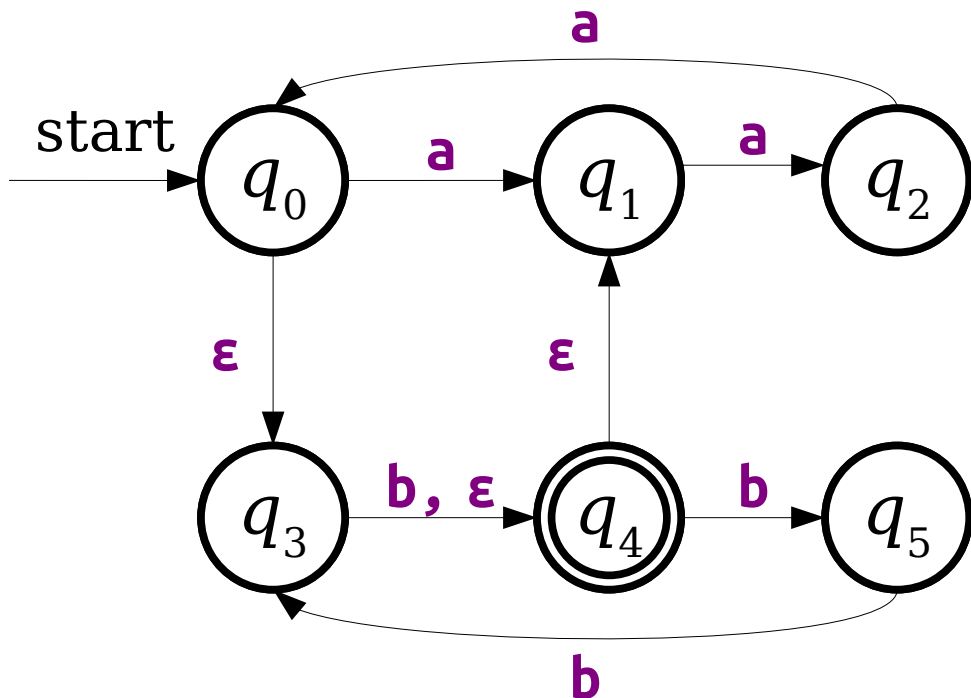
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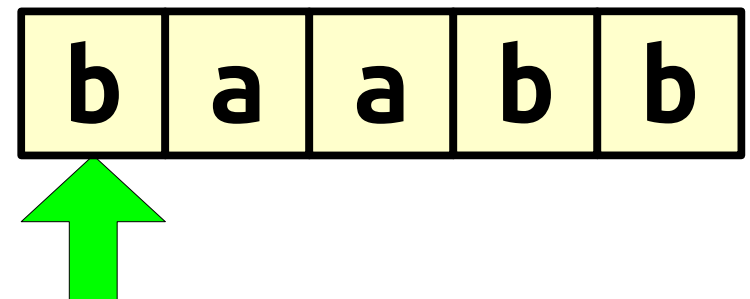
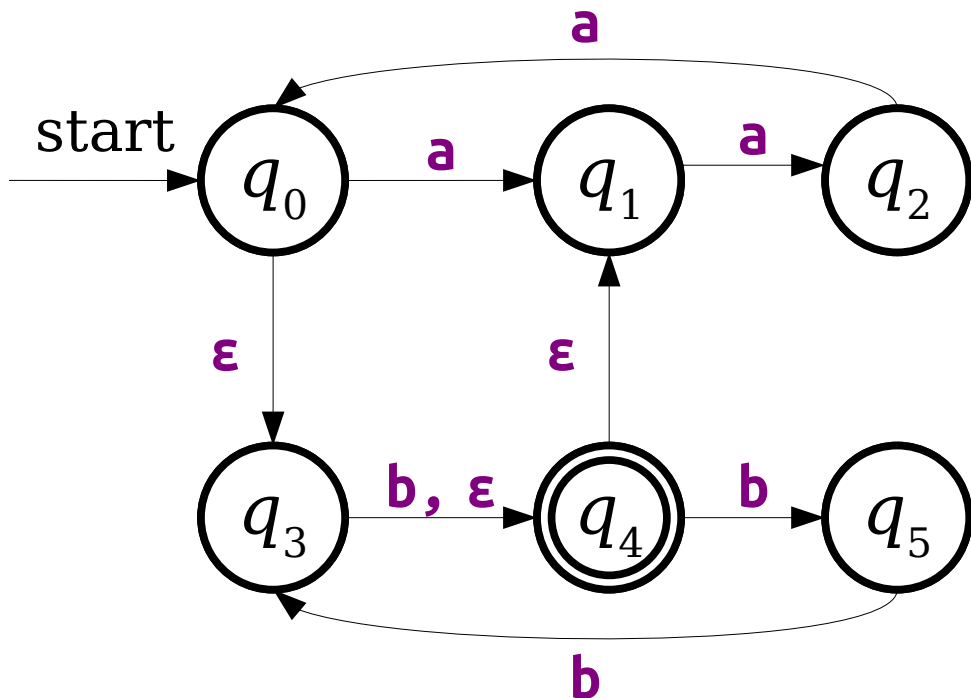
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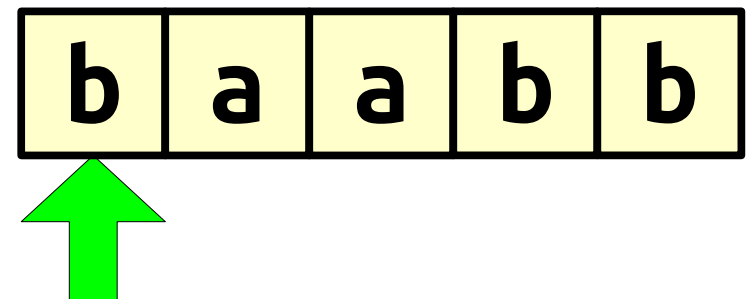
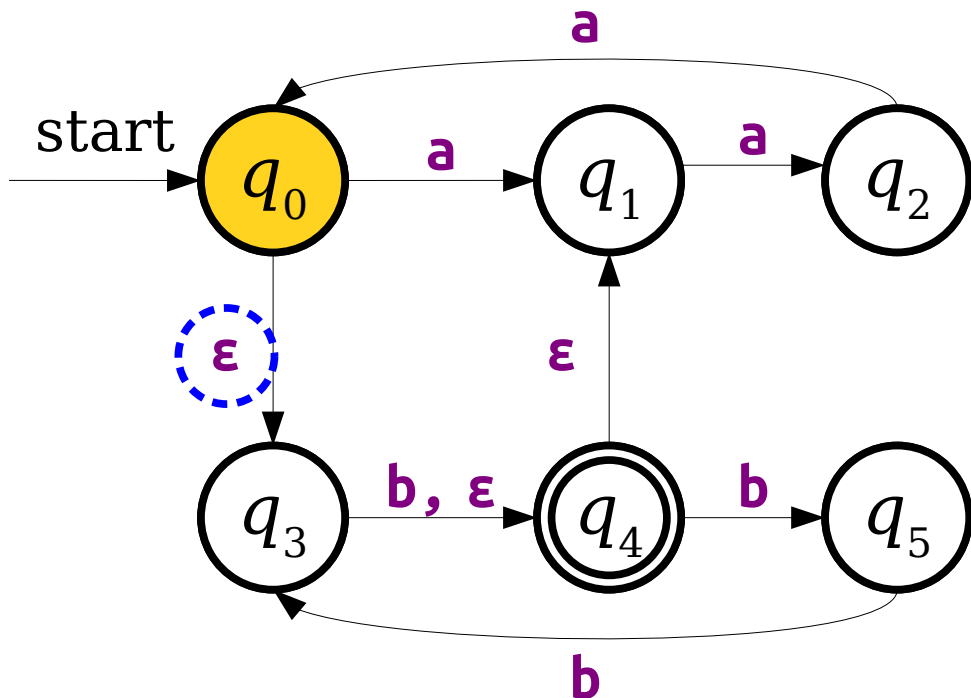
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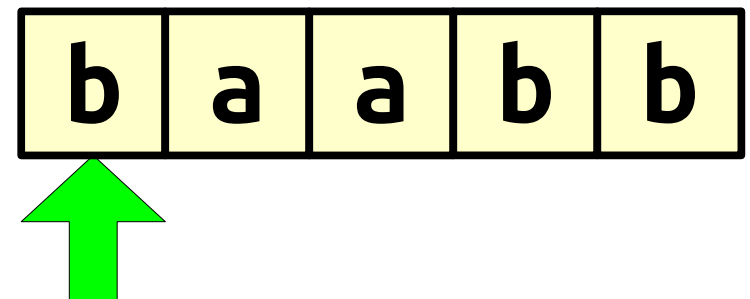
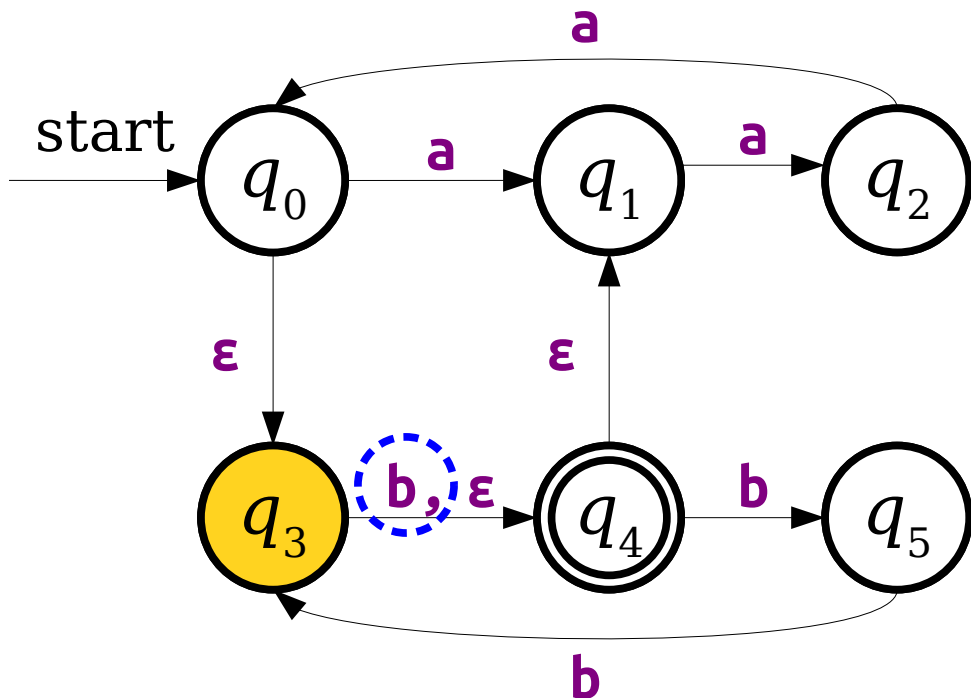
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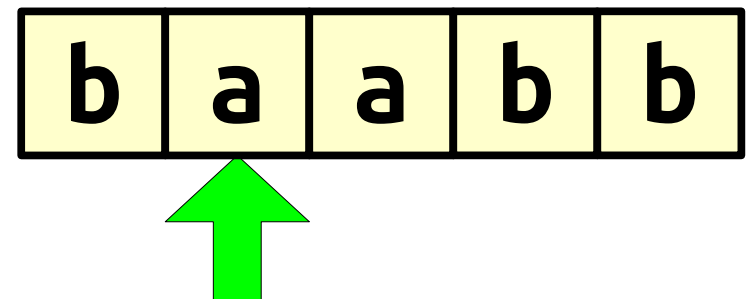
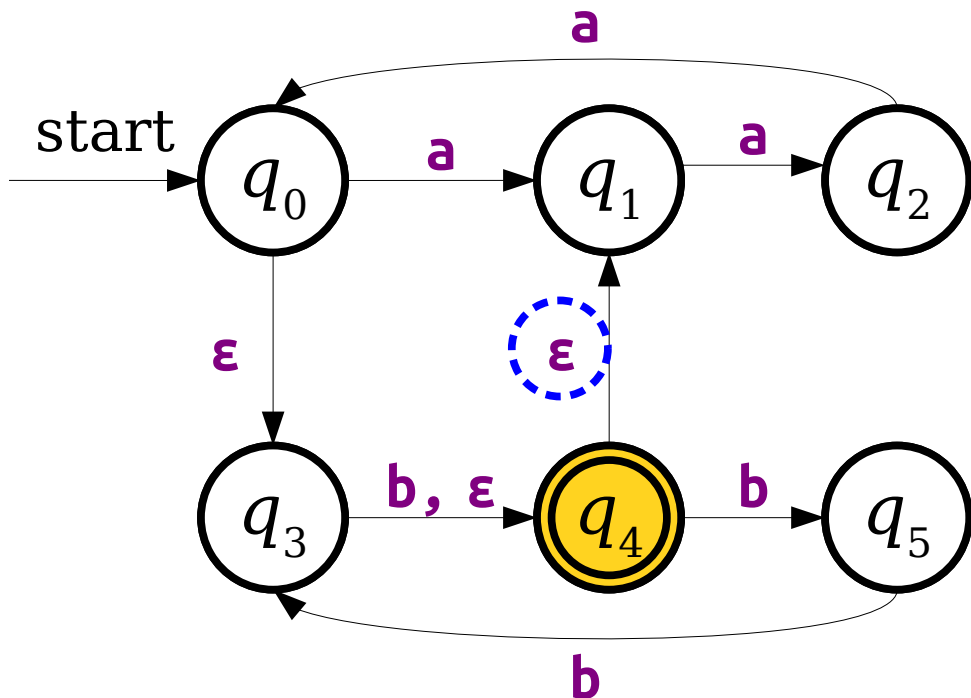
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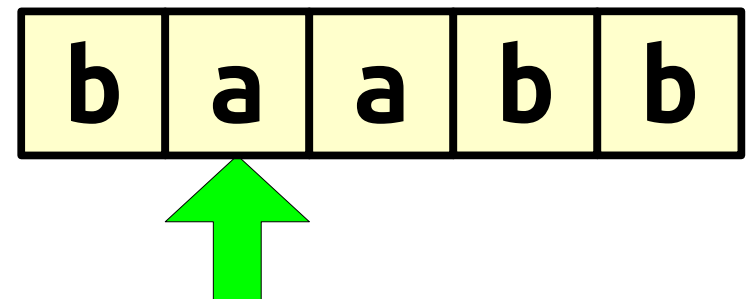
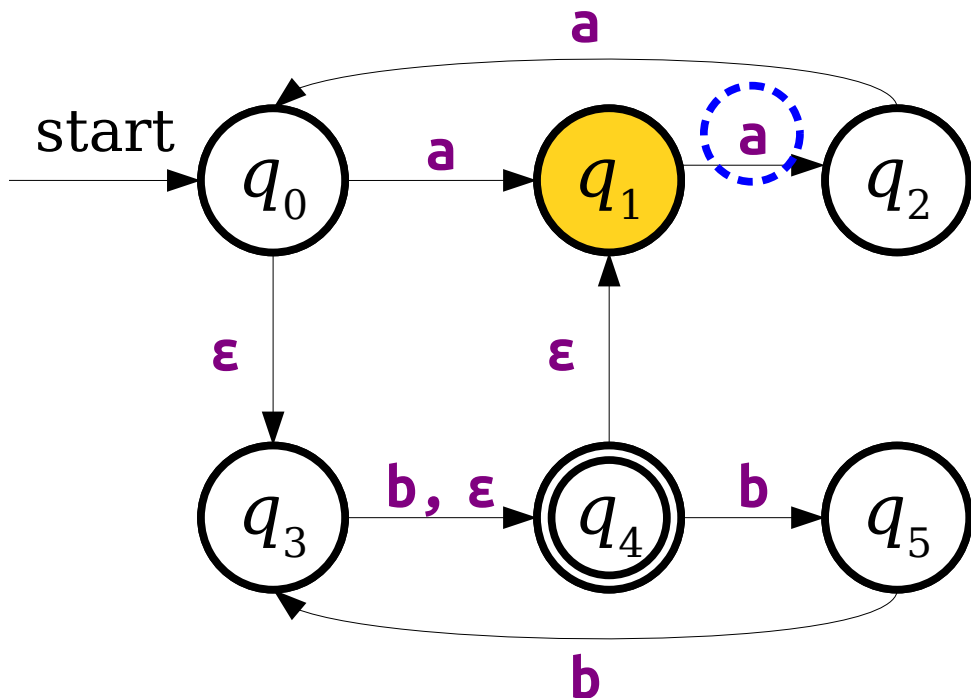
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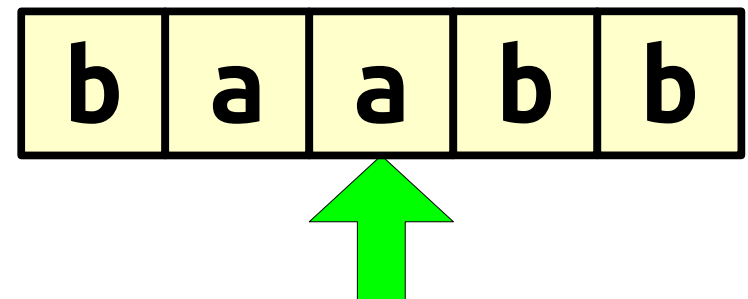
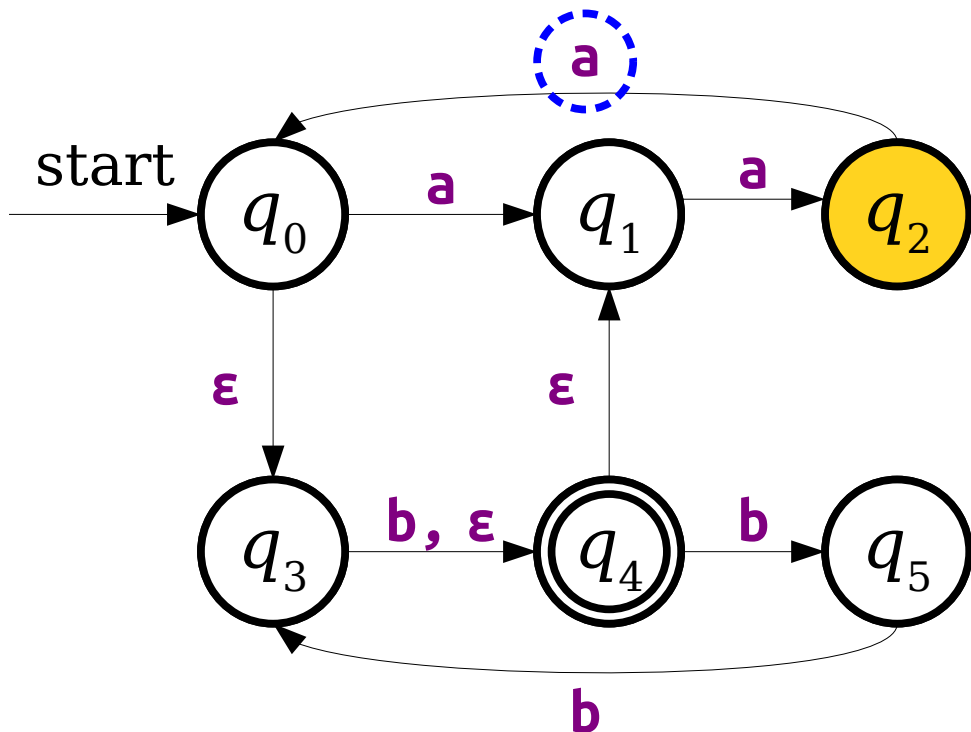
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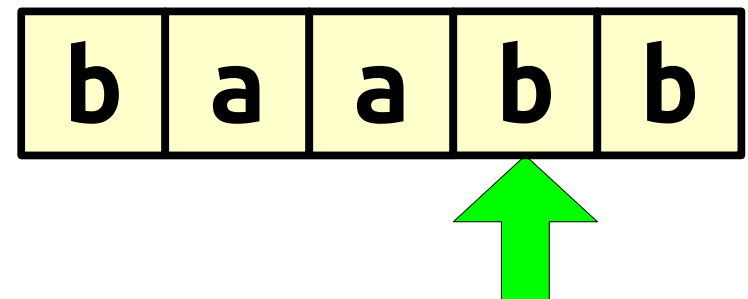
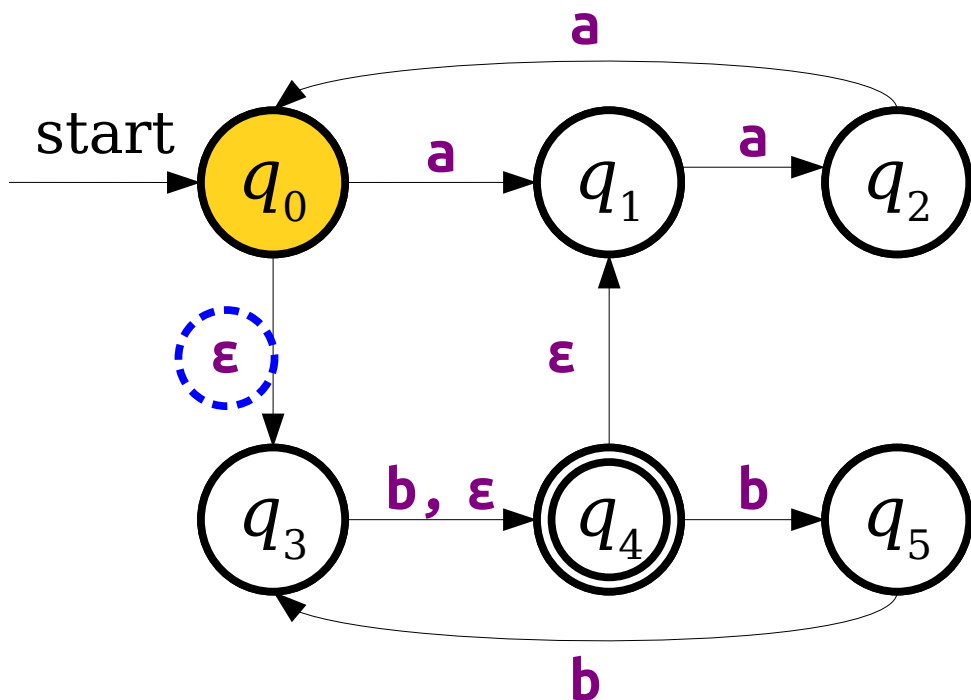
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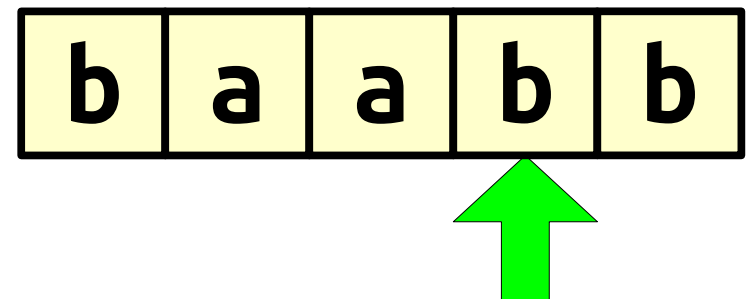
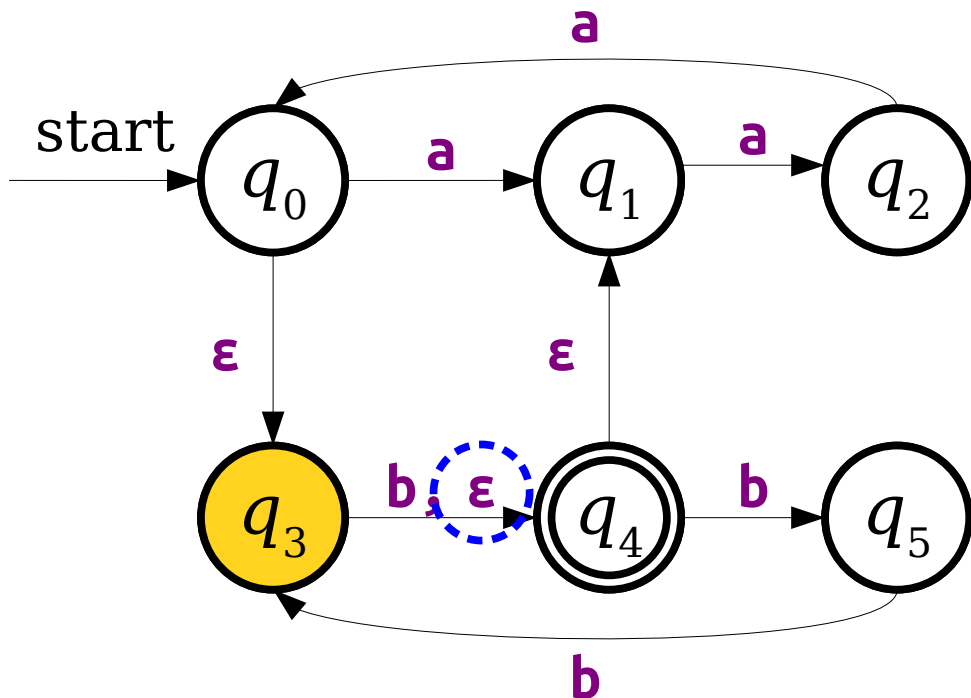
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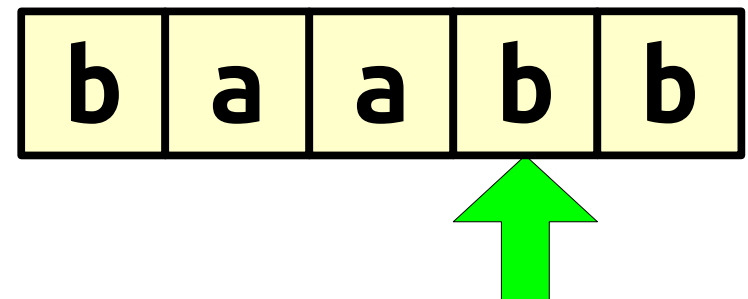
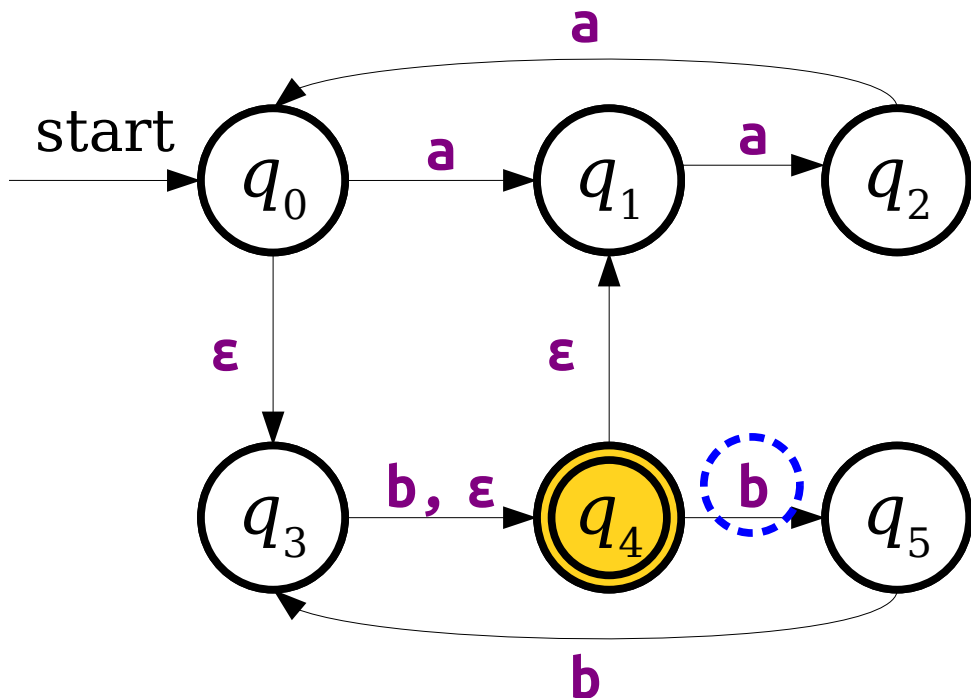
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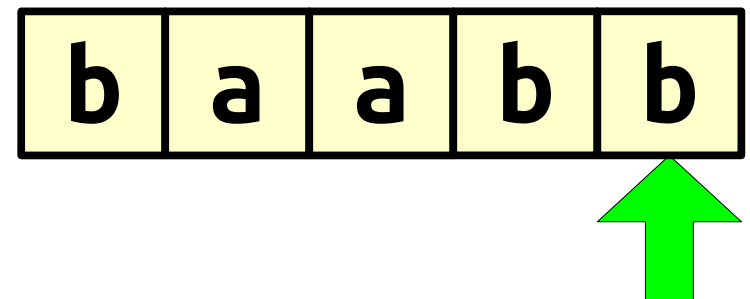
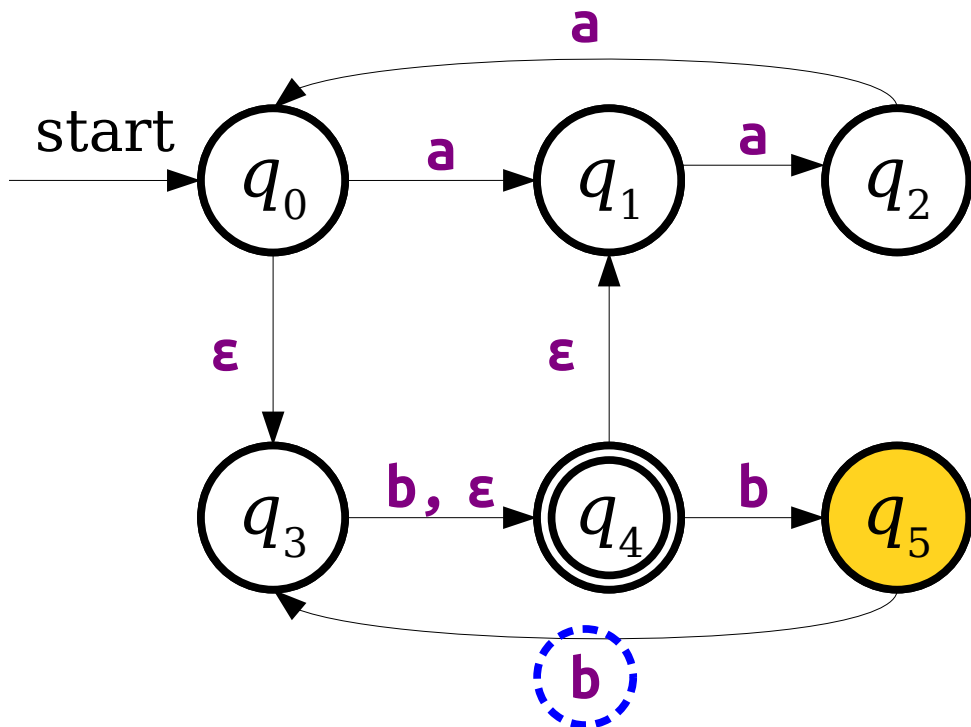
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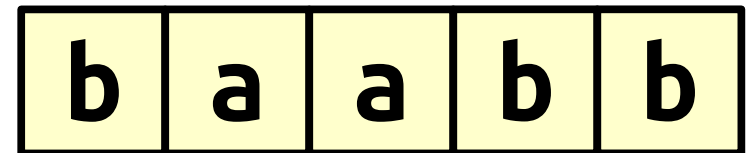
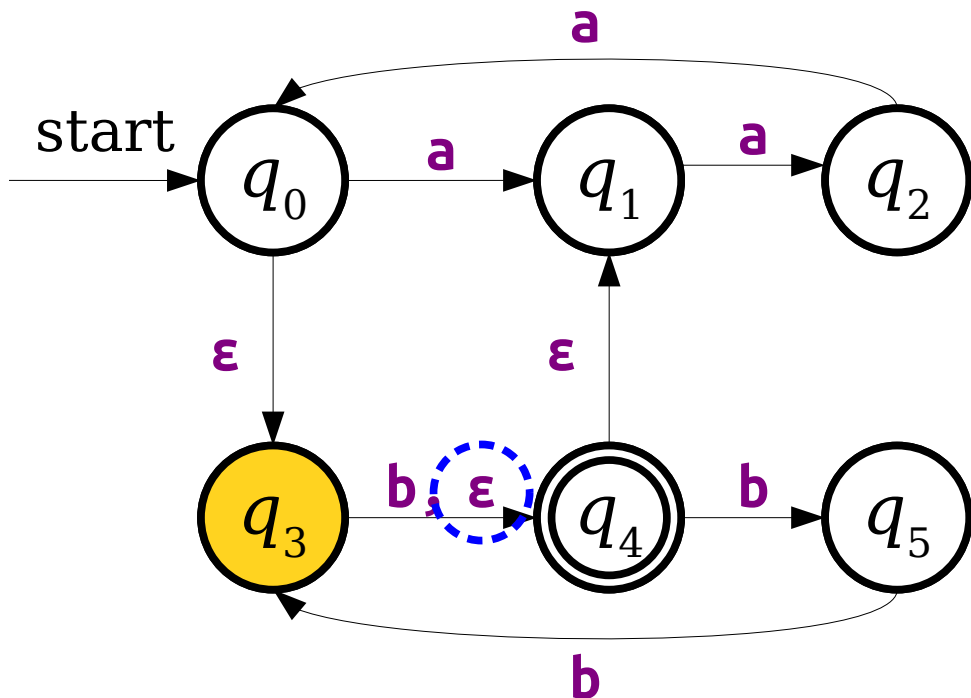
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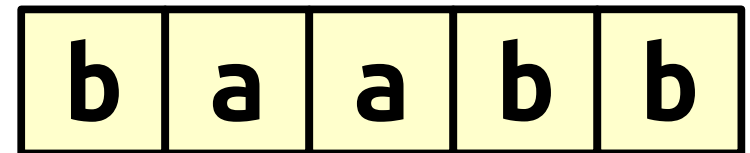
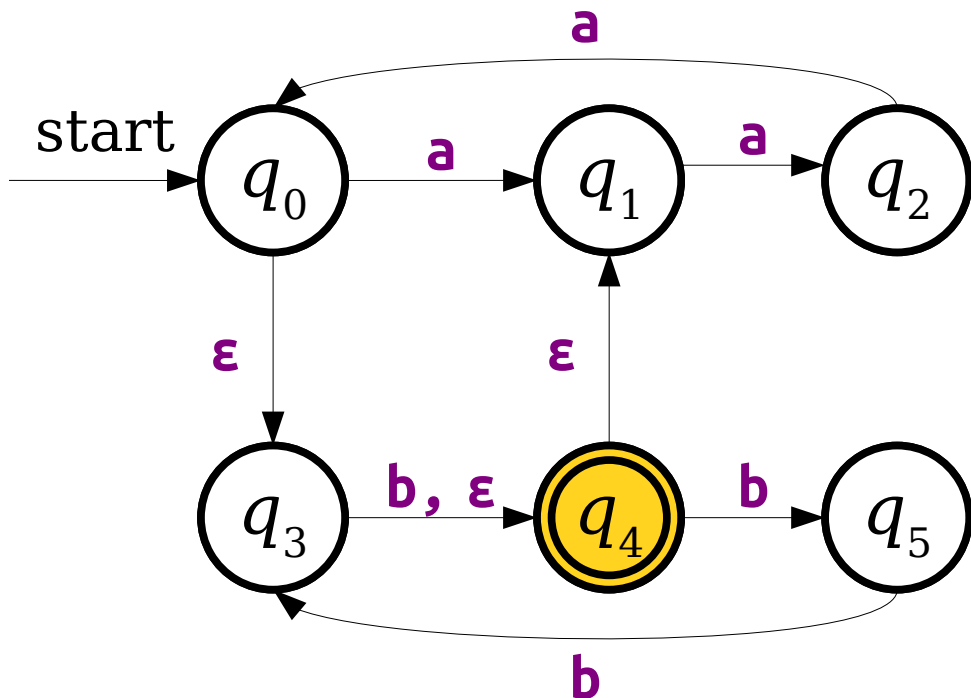
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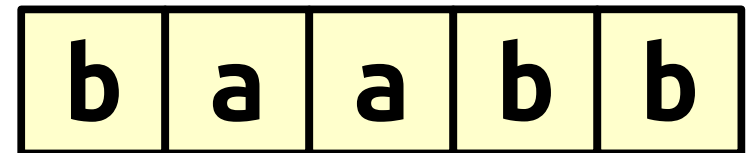
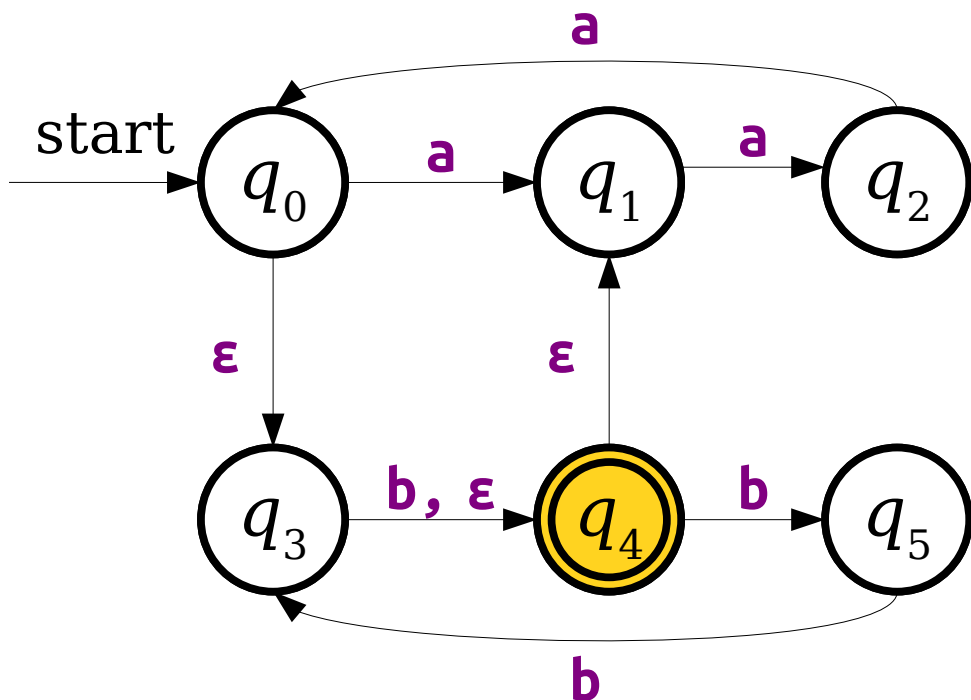
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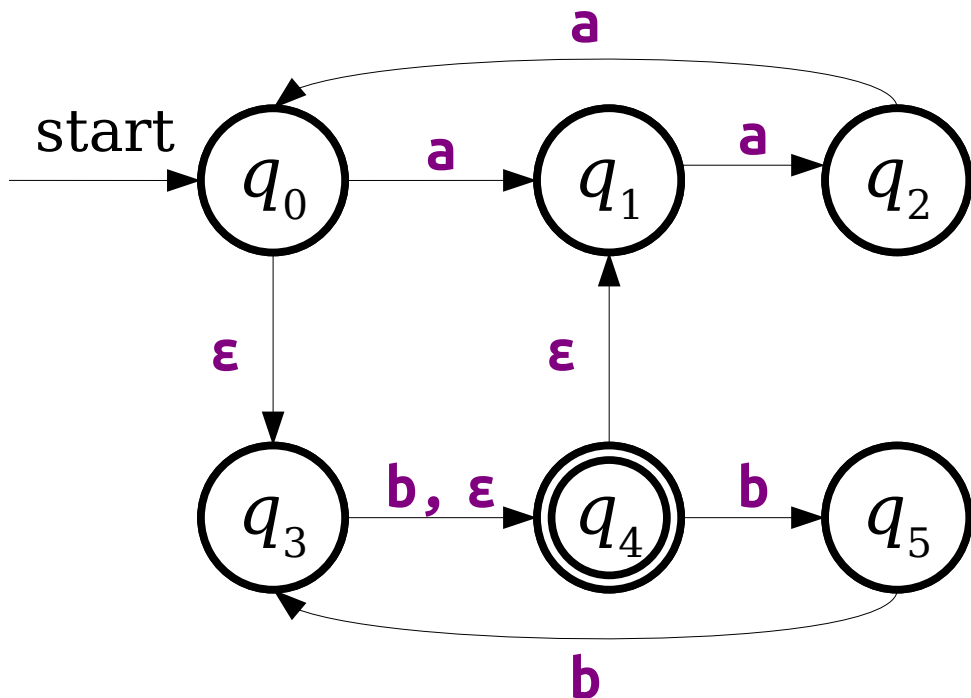
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Not at all fun or rewarding exercise:
what is the language of this NFA?

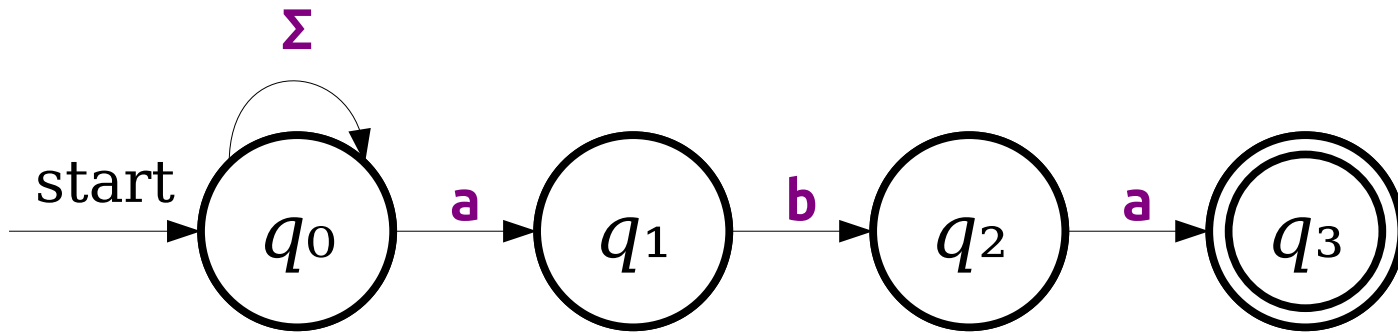
ϵ -Transitions

- NFAs have a special type of transition called the **ϵ -transition**.
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- NFAs are not *required* to follow ϵ -transitions. It's simply another option at the machine's disposal.

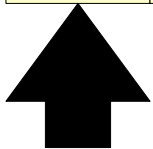
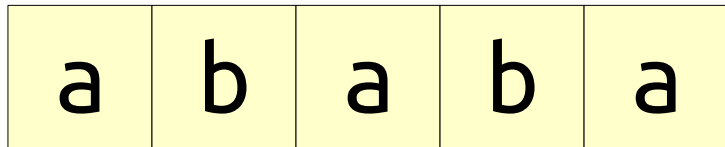
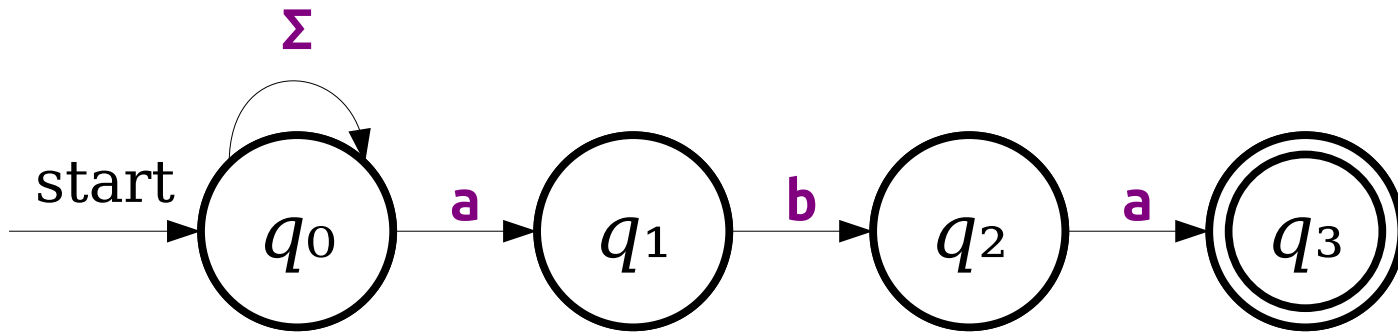
Intuiting Nondeterminism

- Nondeterministic machines are a serious departure from physical computers. How can we build up an intuition for them?
- There are two particularly useful frameworks for interpreting nondeterminism:
 - ***Perfect positive guessing***
 - ***Massive parallelism***

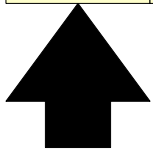
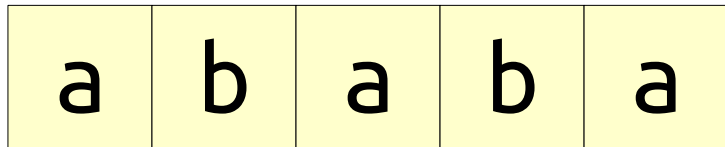
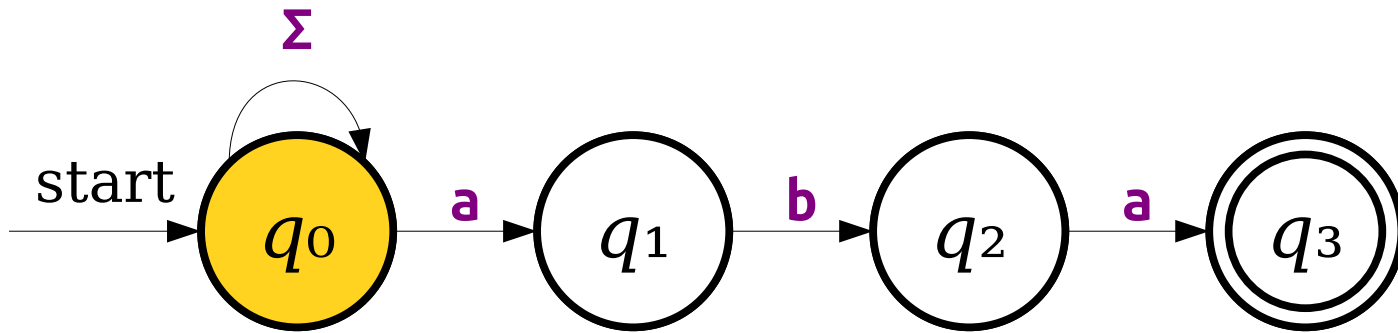
Perfect Positive Guessing



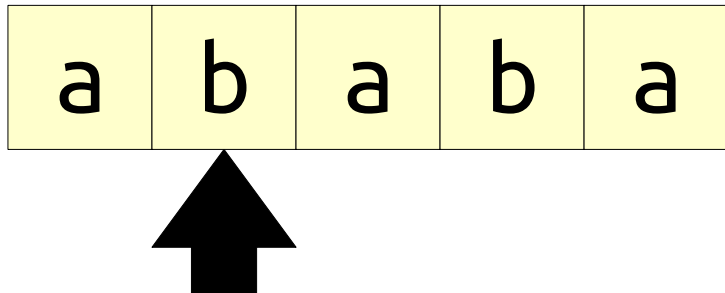
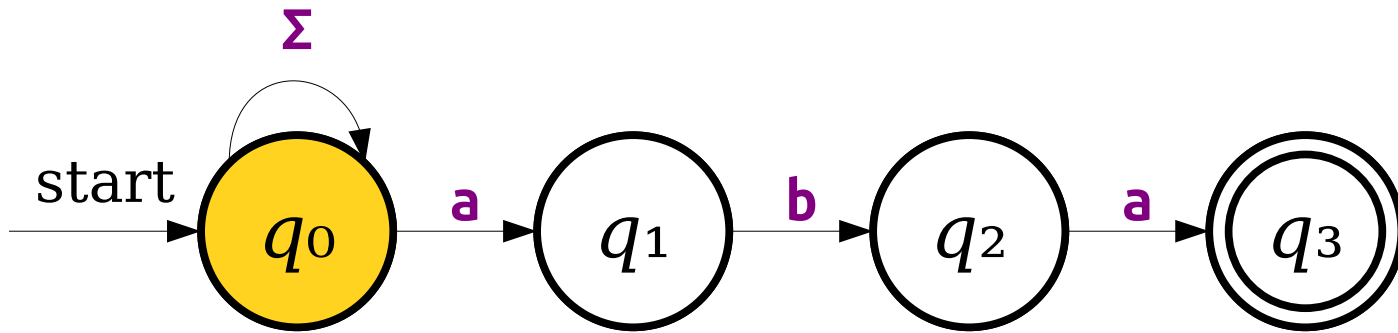
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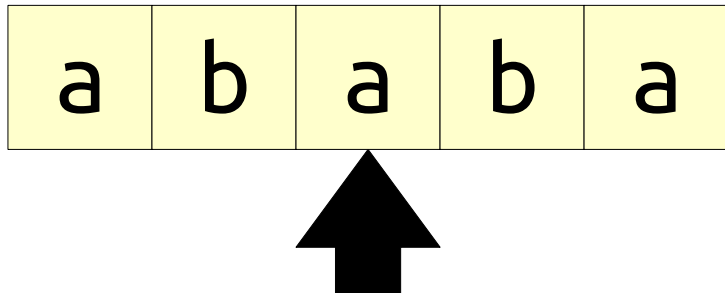
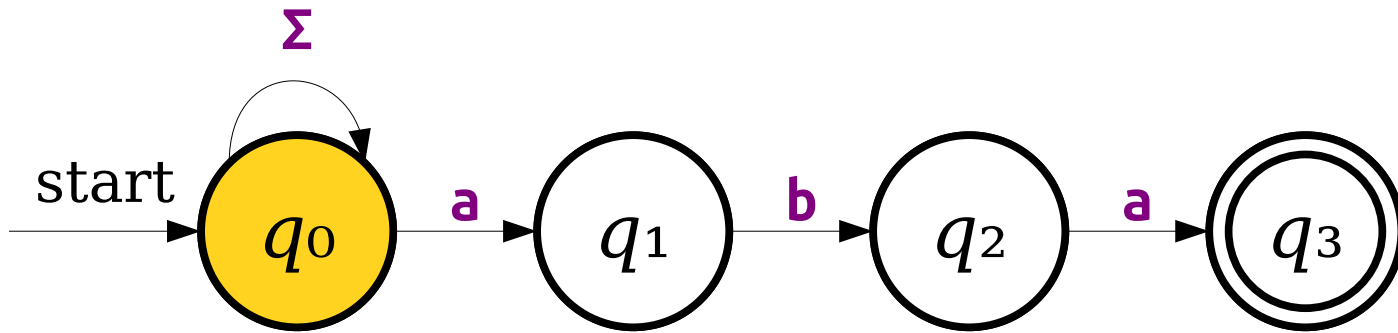
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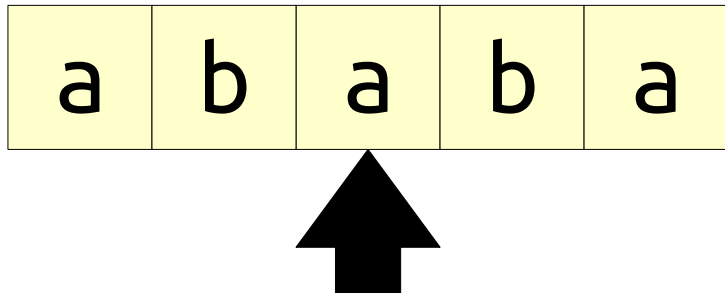
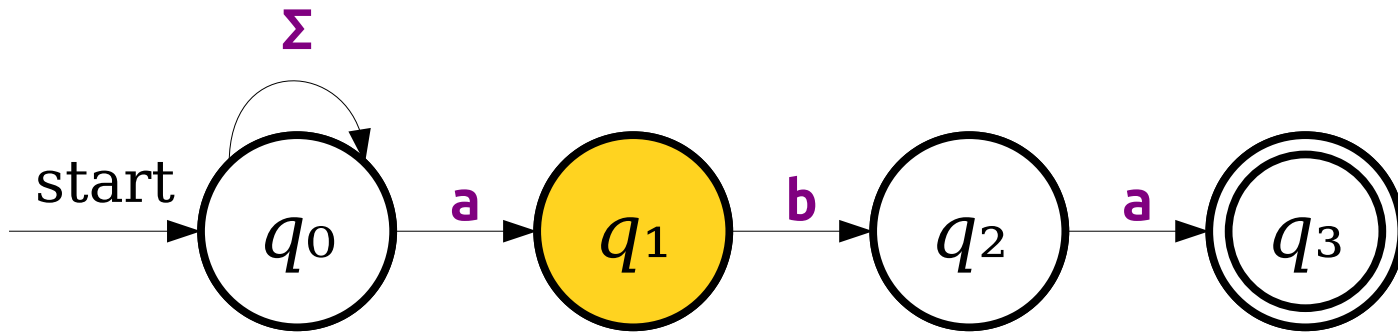
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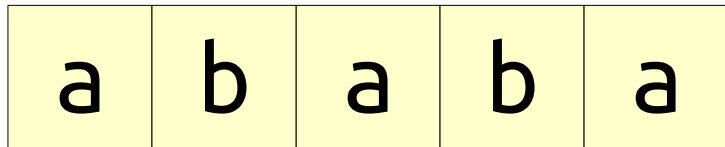
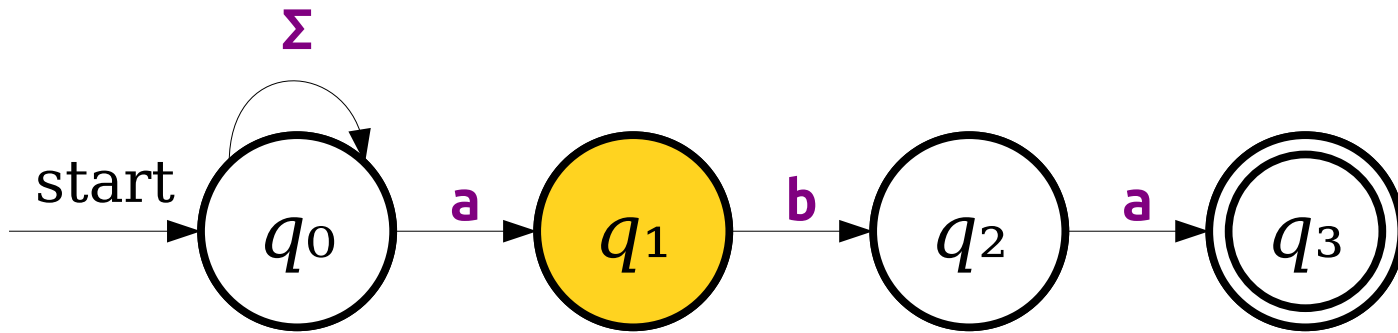
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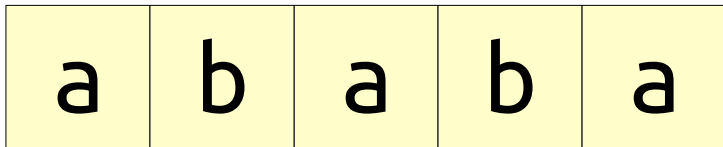
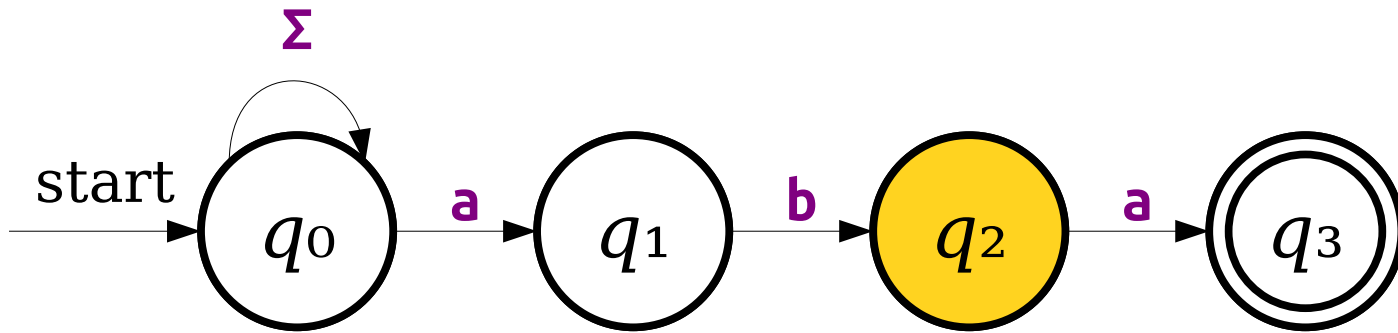
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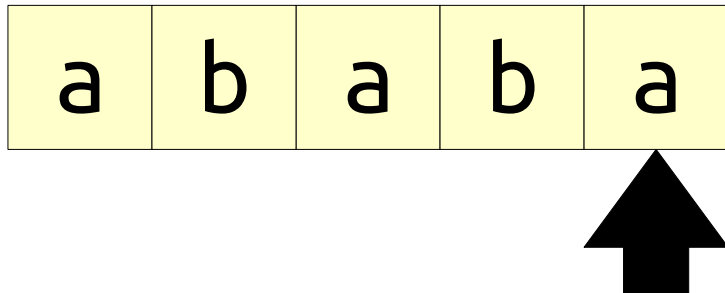
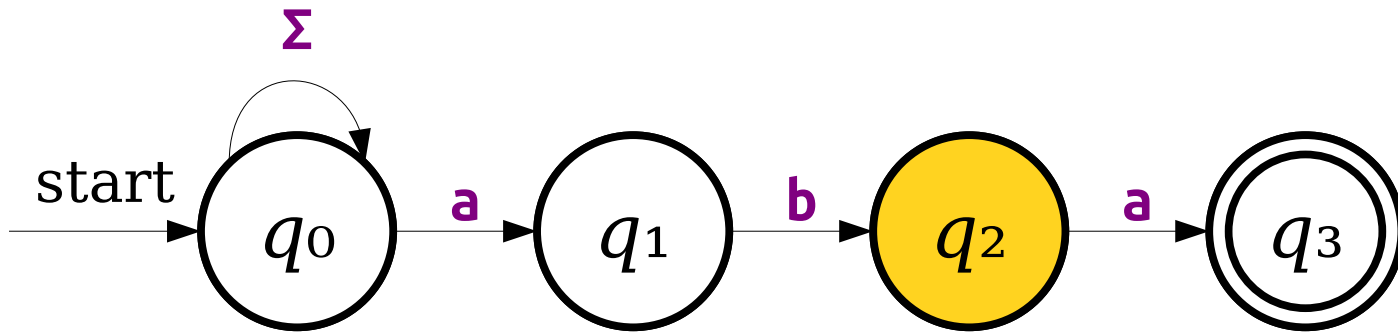
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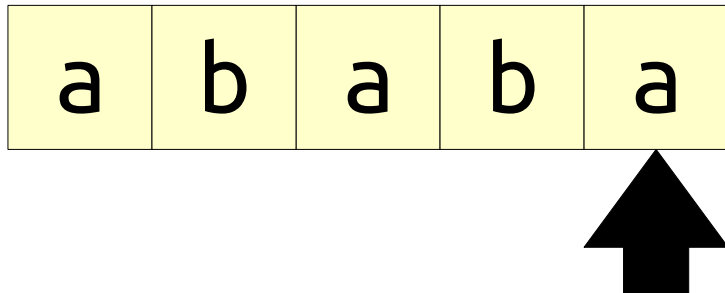
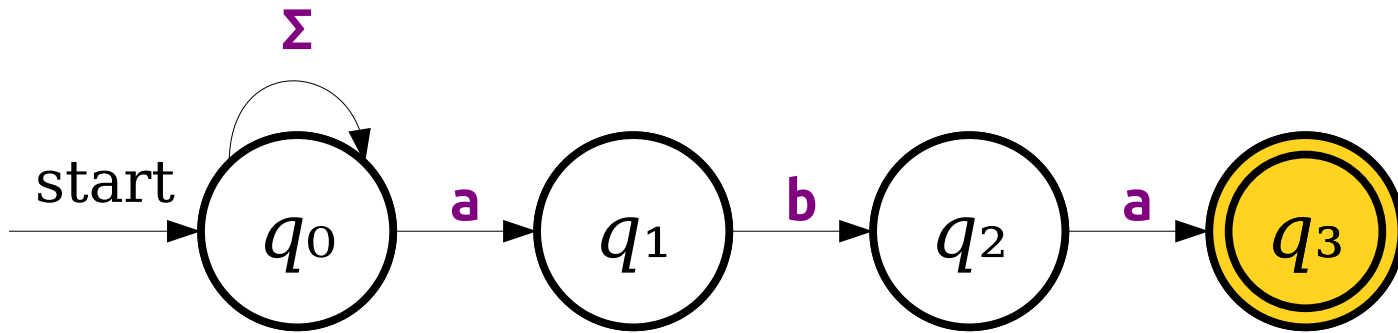
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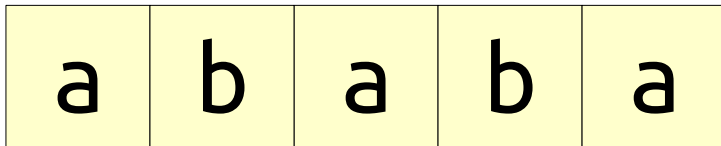
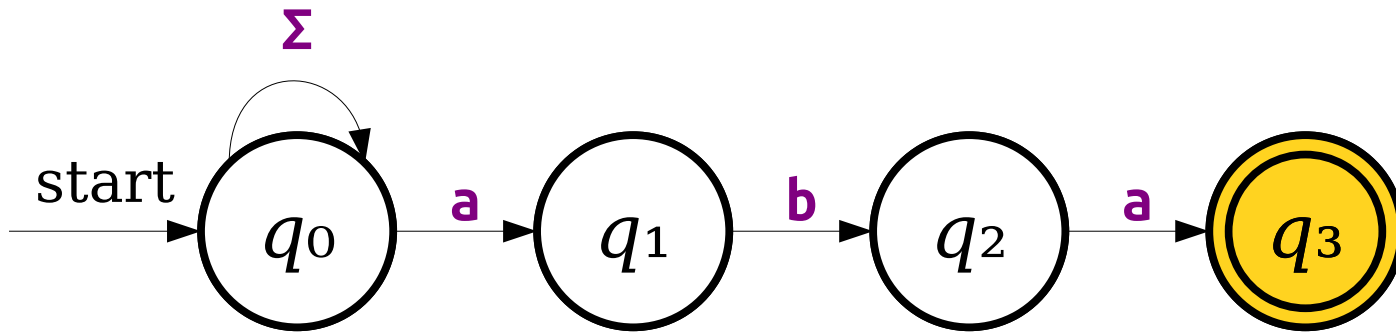
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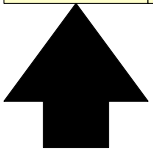
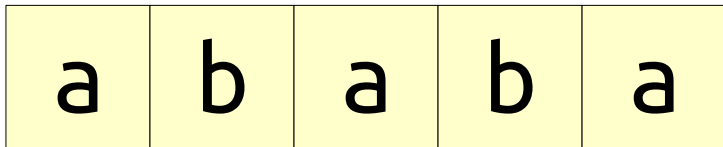
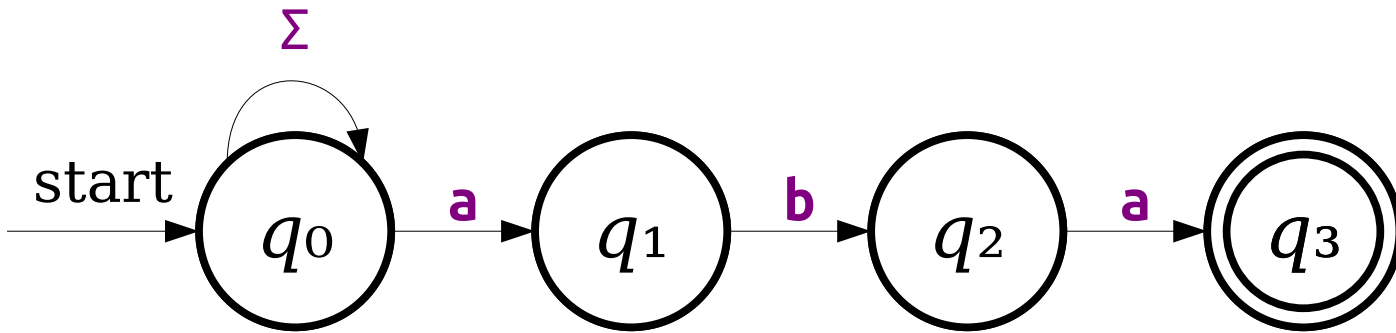
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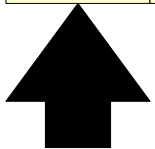
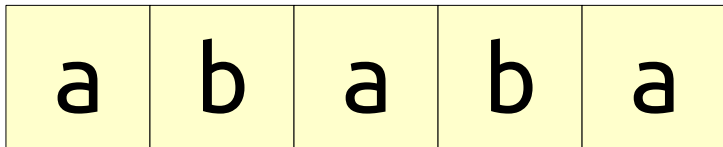
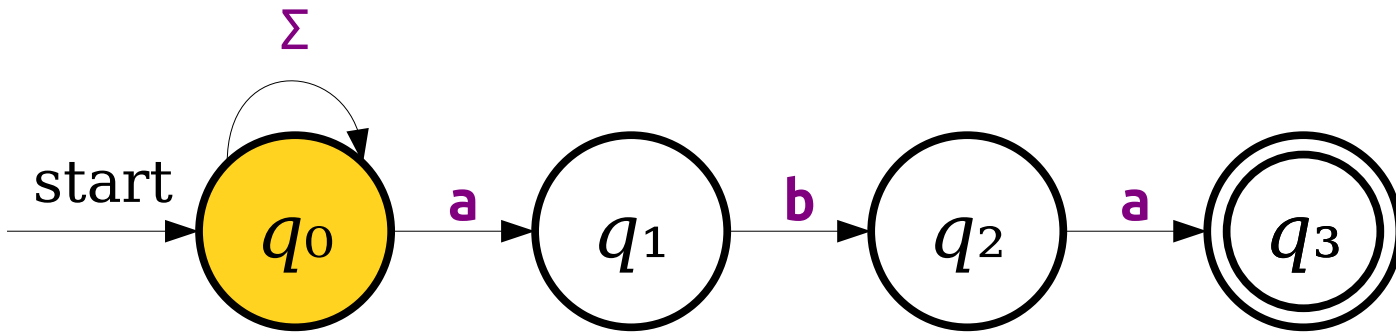
Perfect Positive Guessing

- We can view nondeterministic machines as having *Magic Superpowers* that enable them to guess choices that lead to an accepting state.
 - If there is at least one choice that leads to an accepting state, the machine will guess it.
 - If there are no choices, the machine guesses any one of the wrong guesses.
- There is no known way to physically model this intuition of nondeterminism – this is quite a departure from reality!

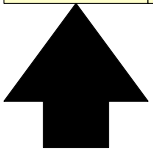
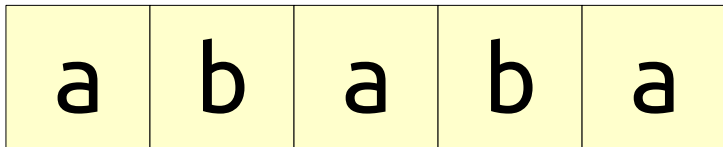
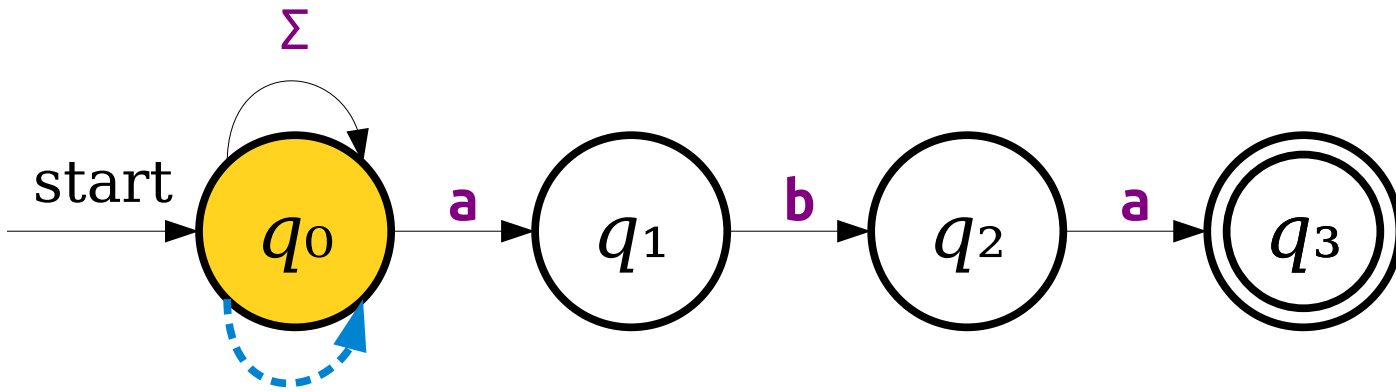
Massive Parallelism



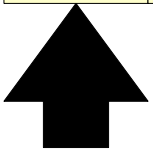
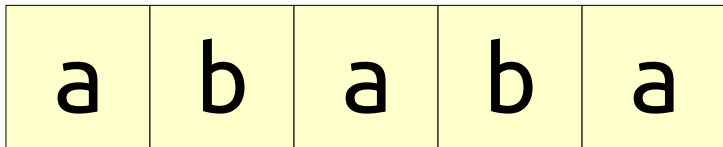
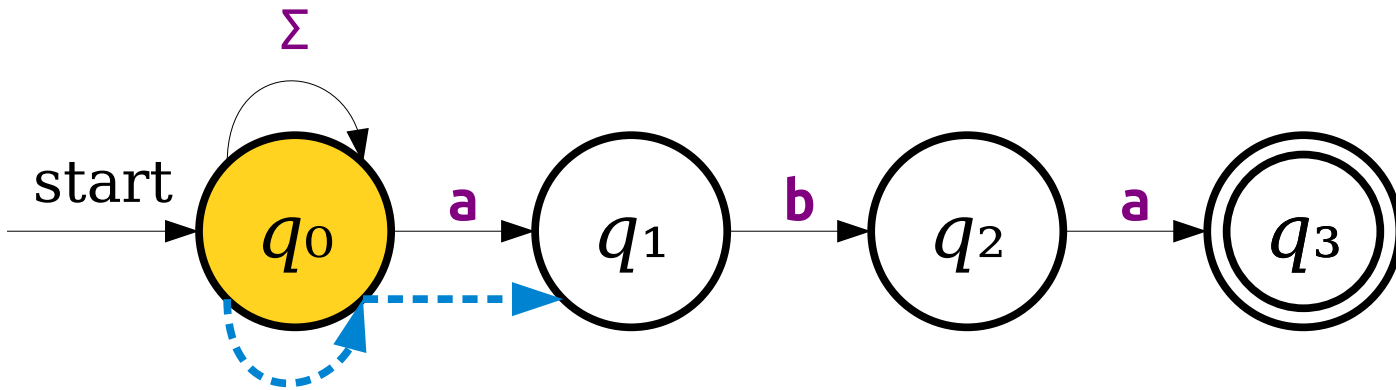
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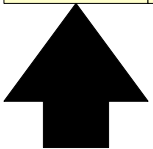
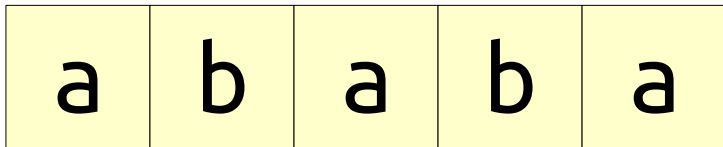
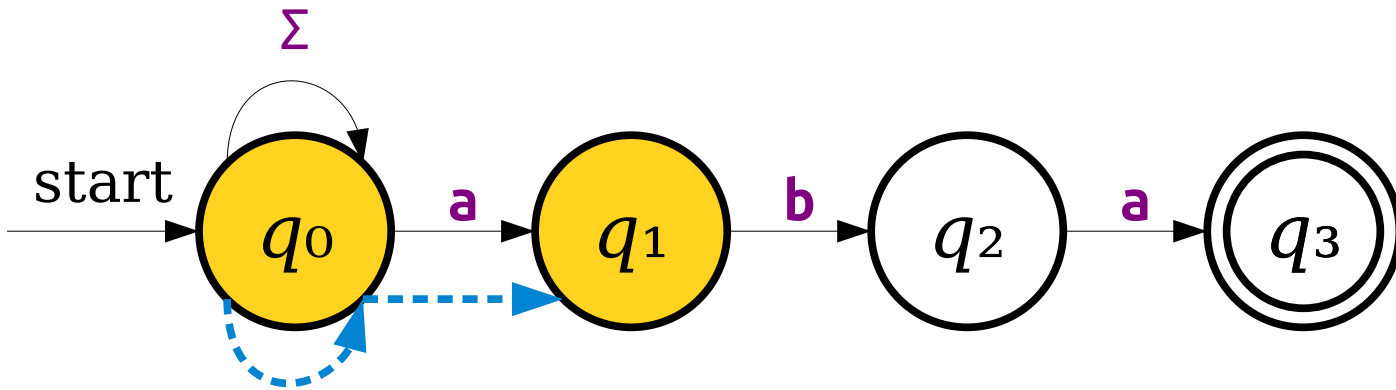
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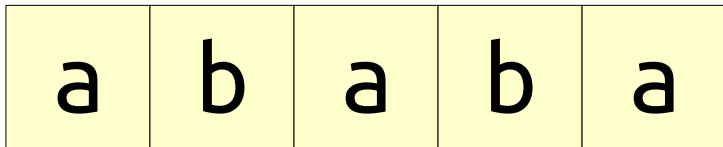
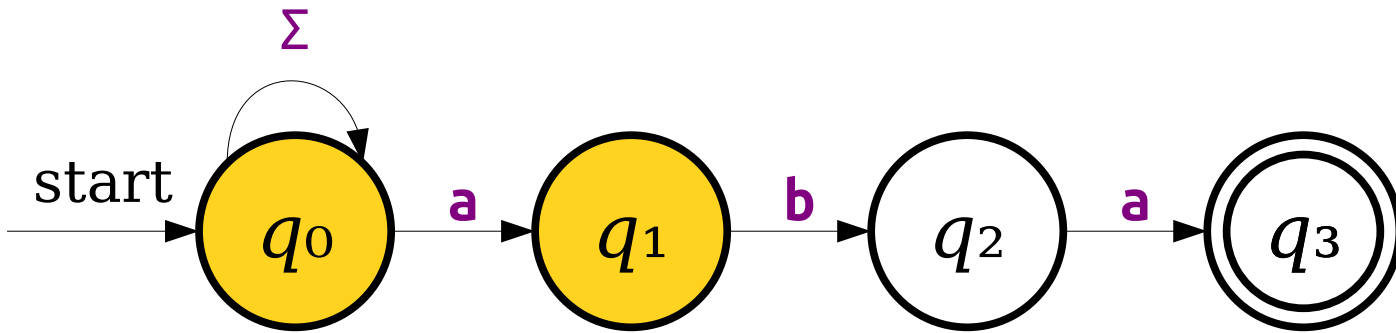
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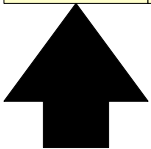
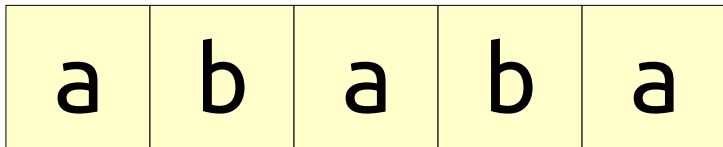
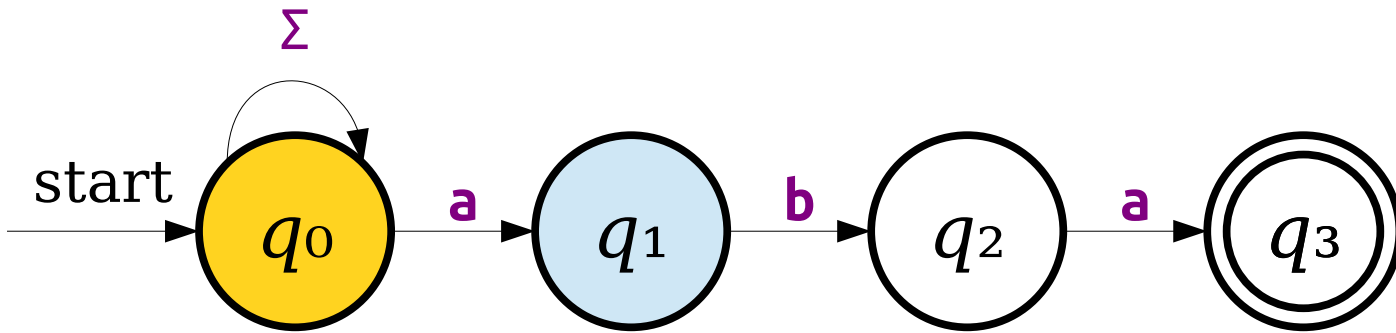
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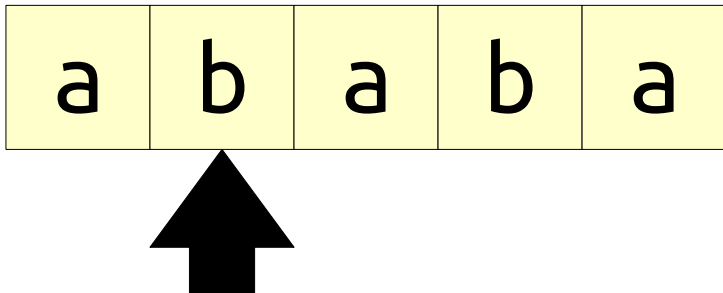
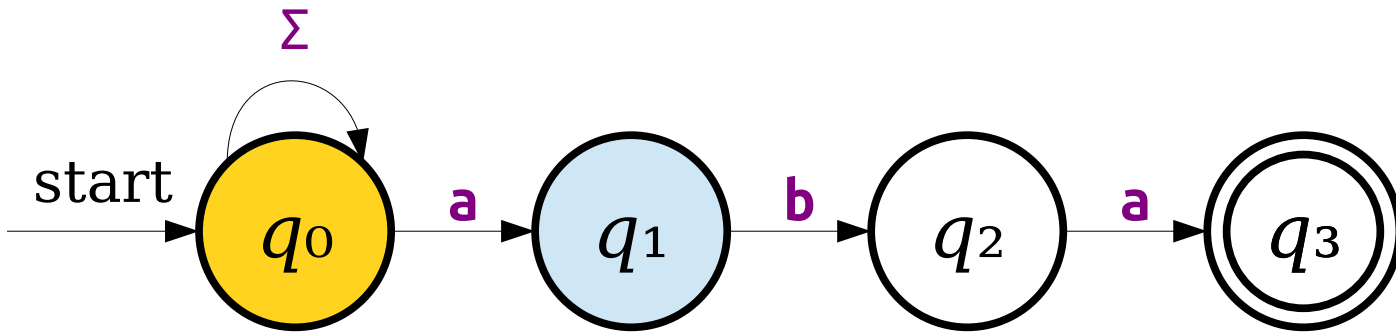
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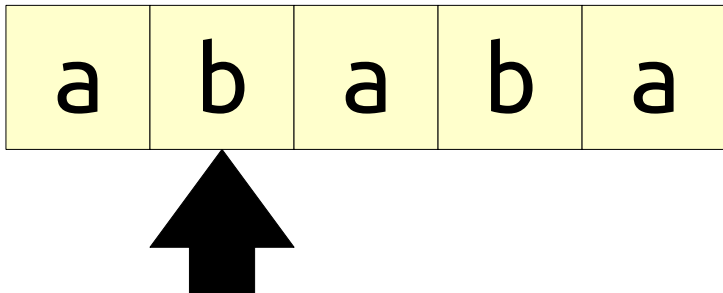
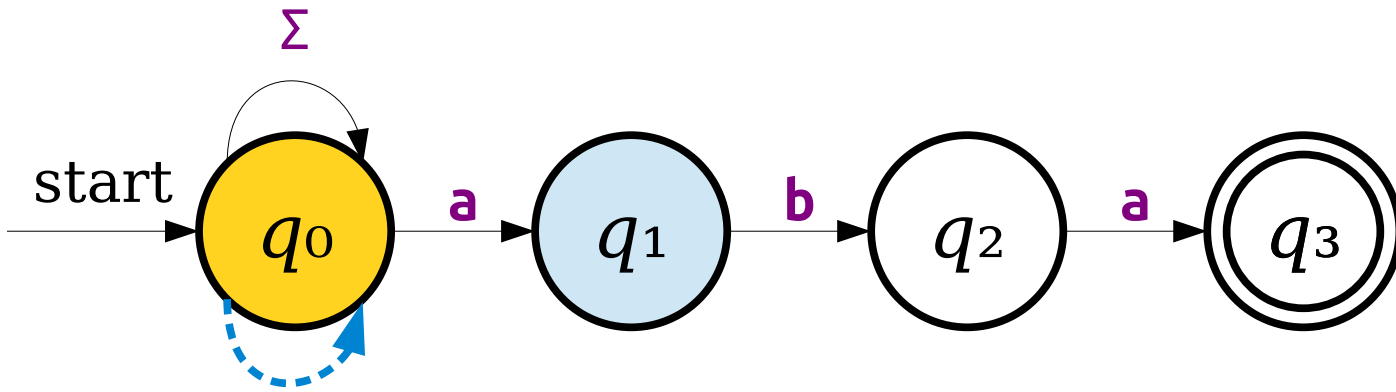
Massive Parallelism



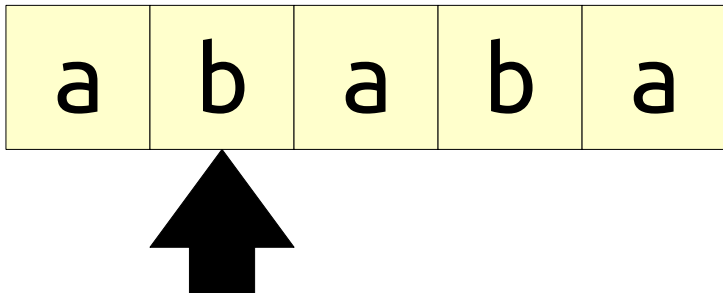
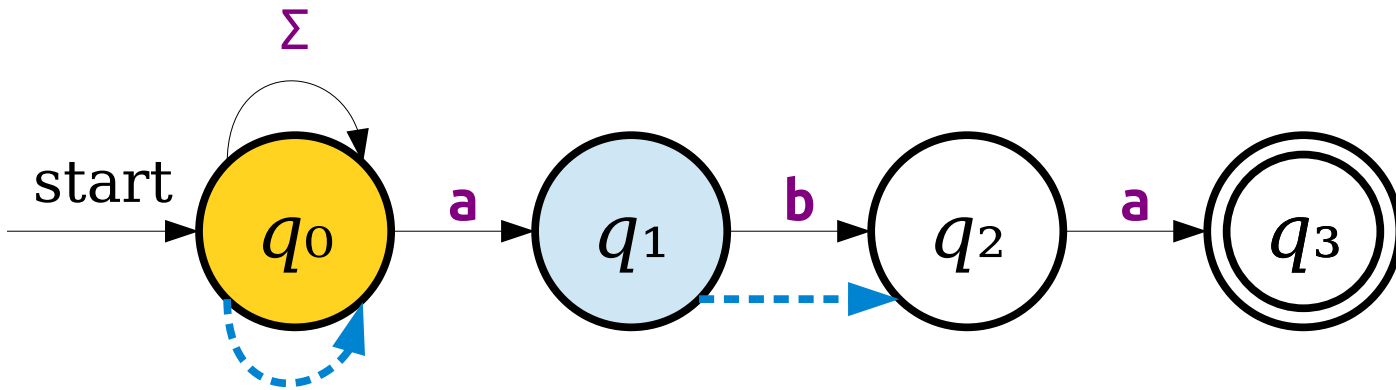
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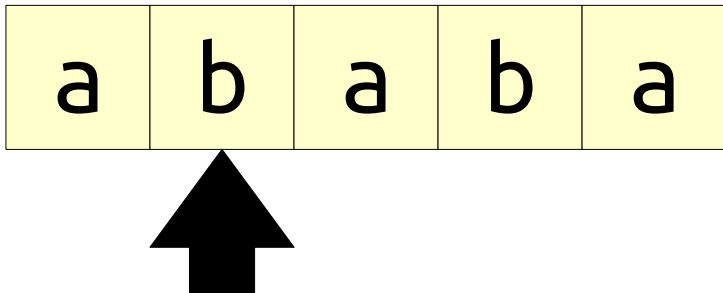
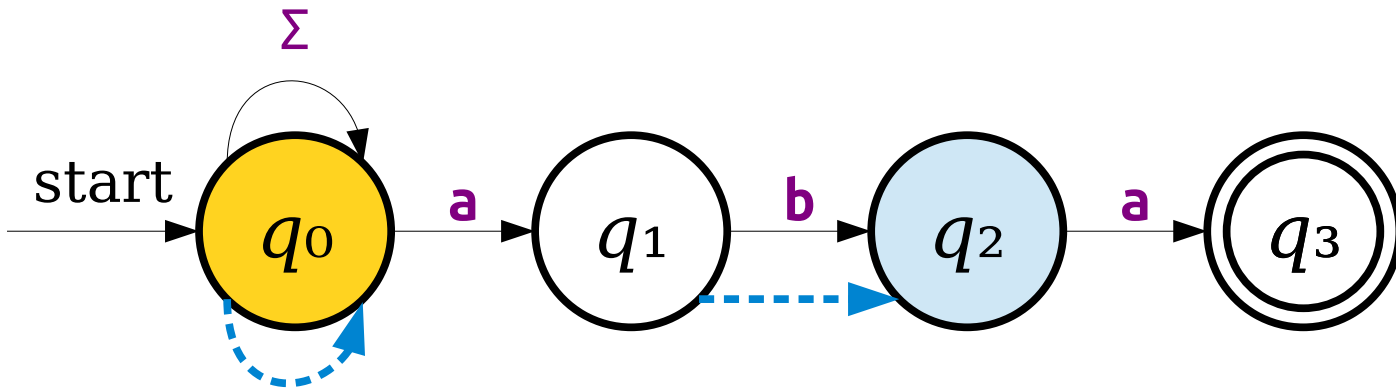
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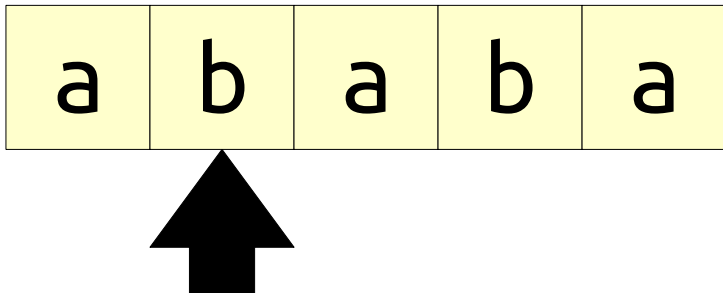
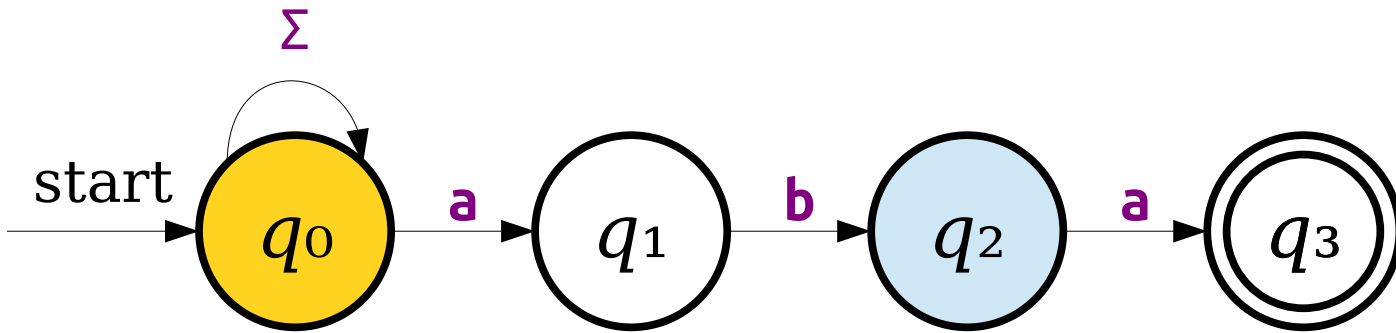
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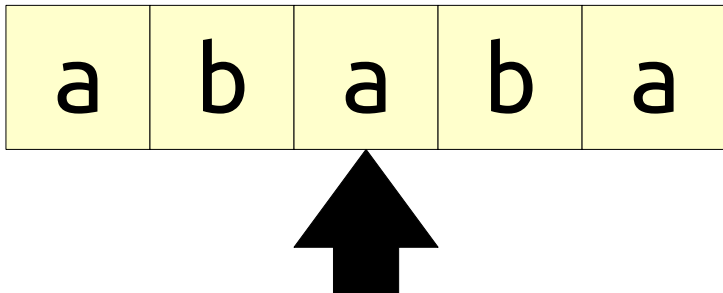
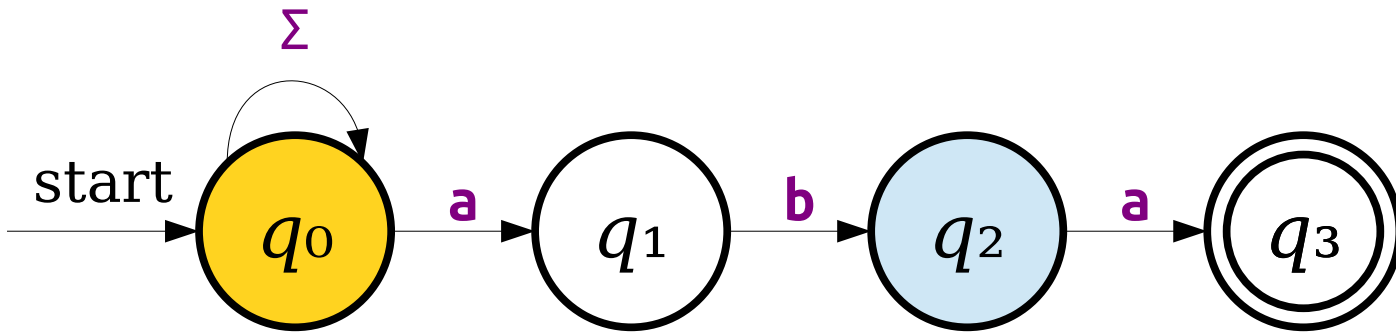
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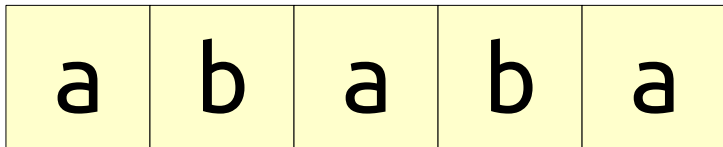
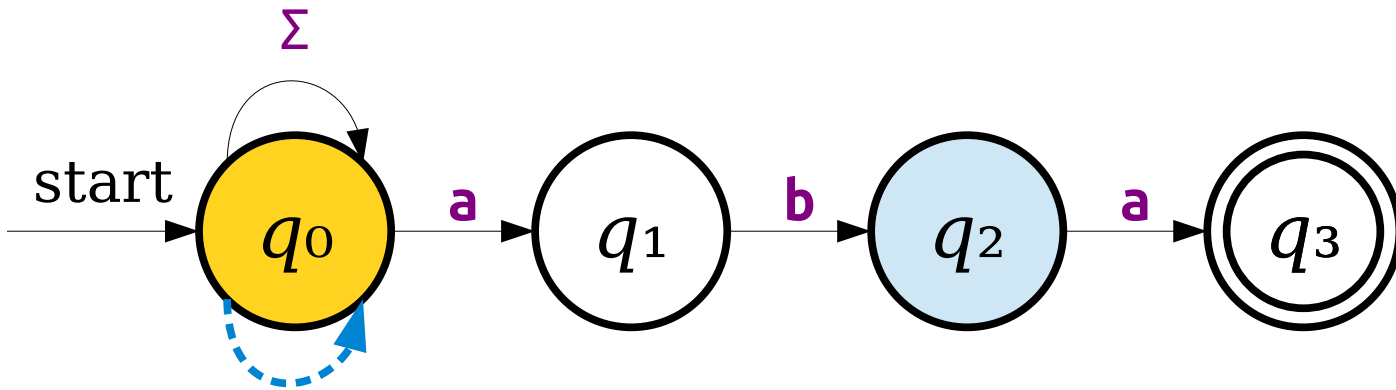
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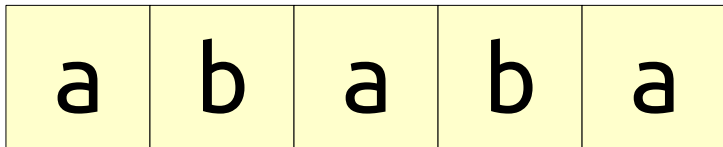
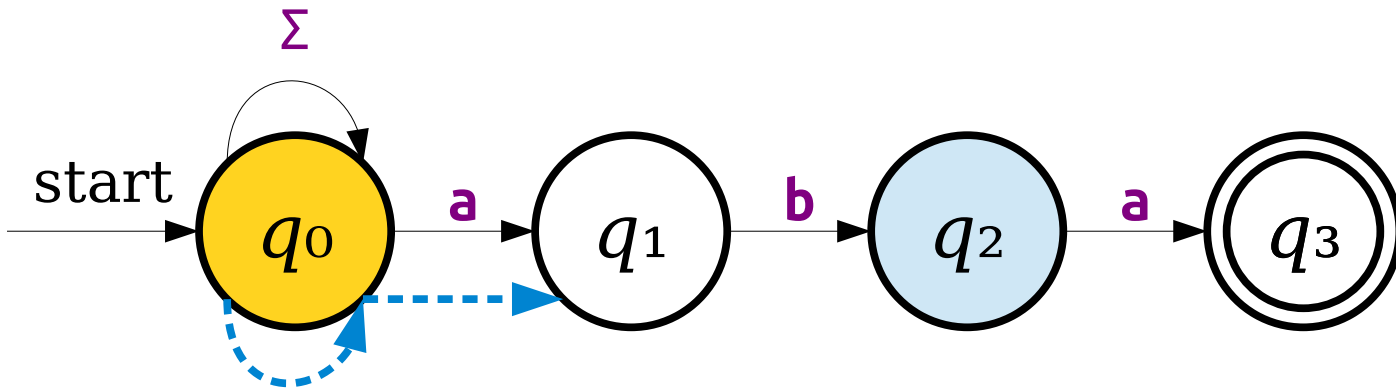
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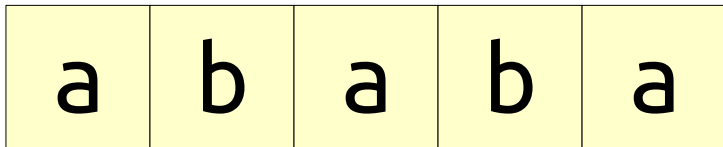
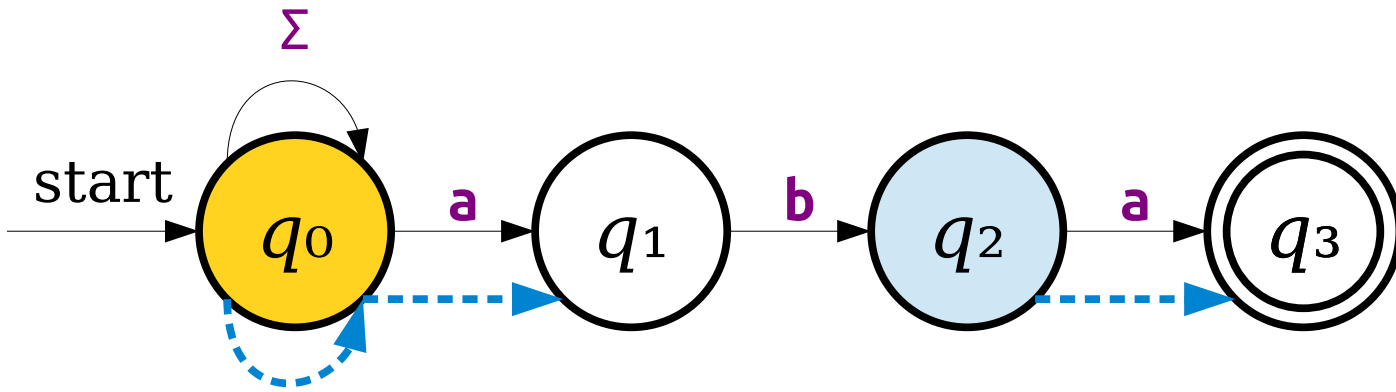
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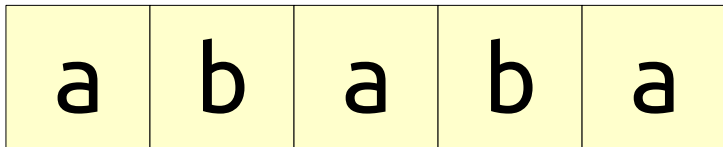
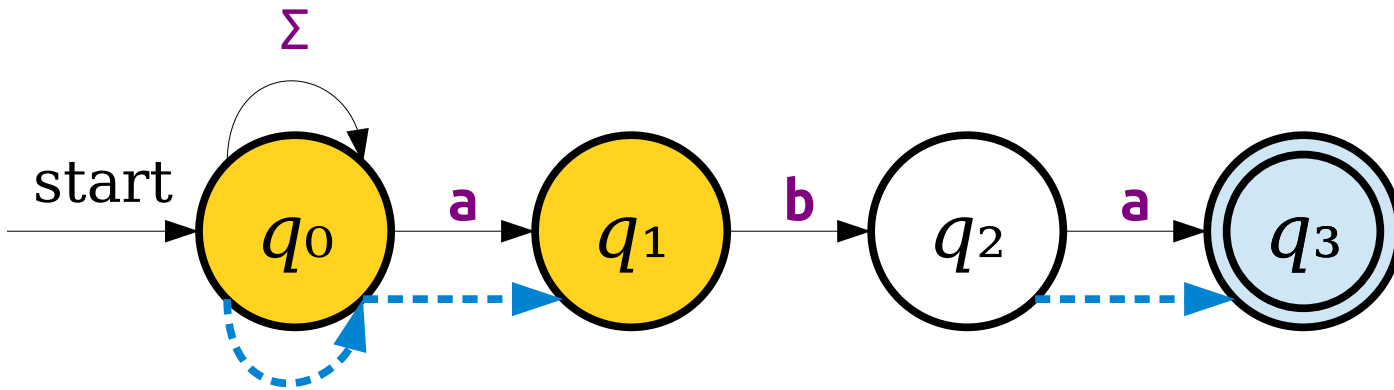
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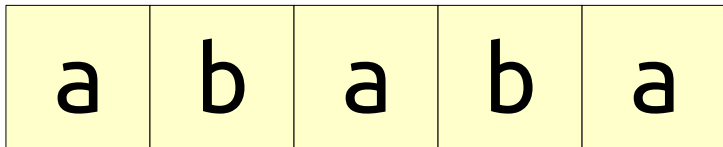
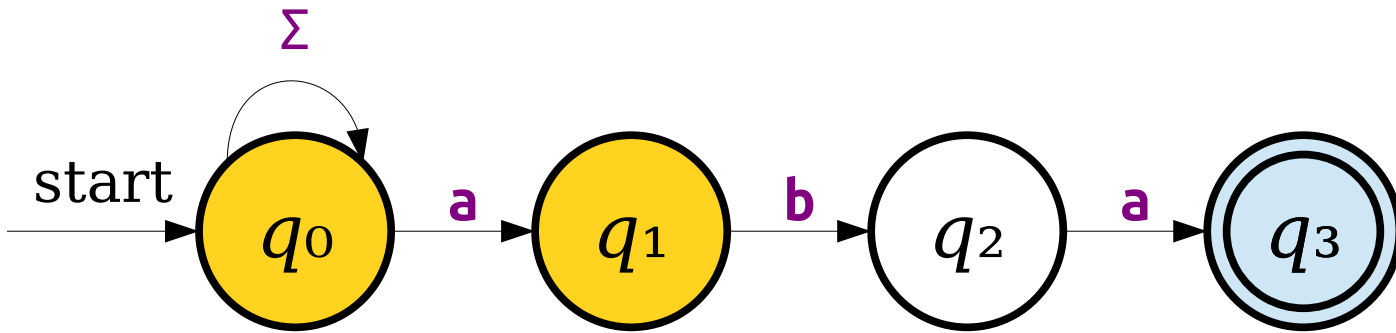
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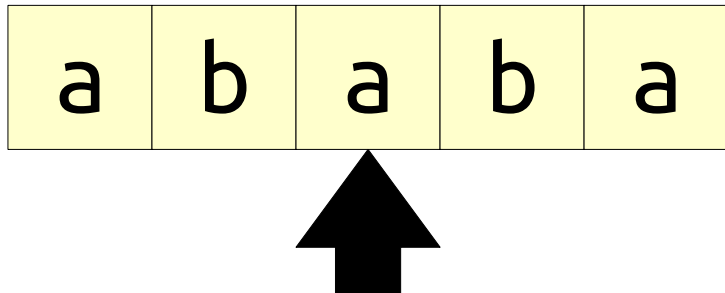
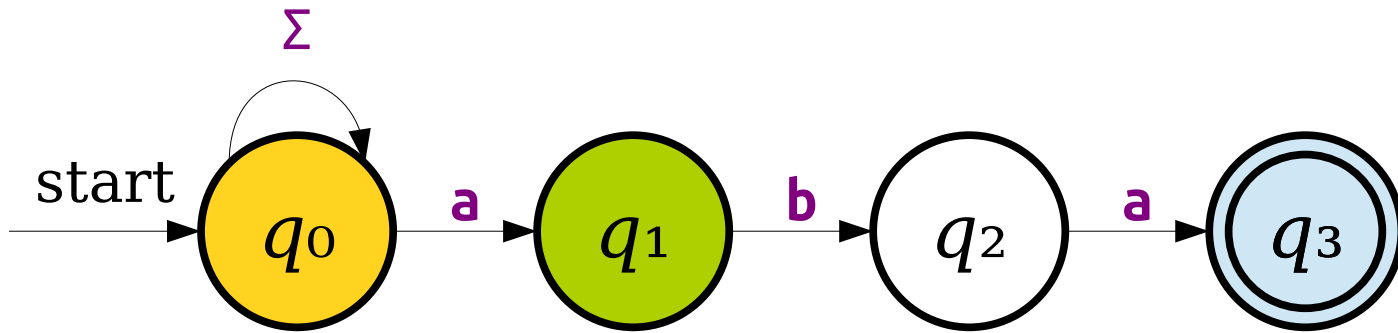
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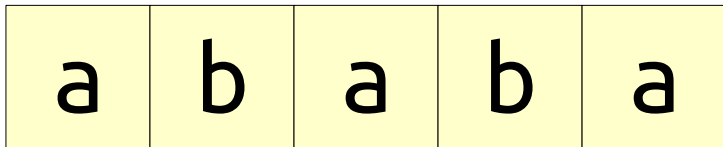
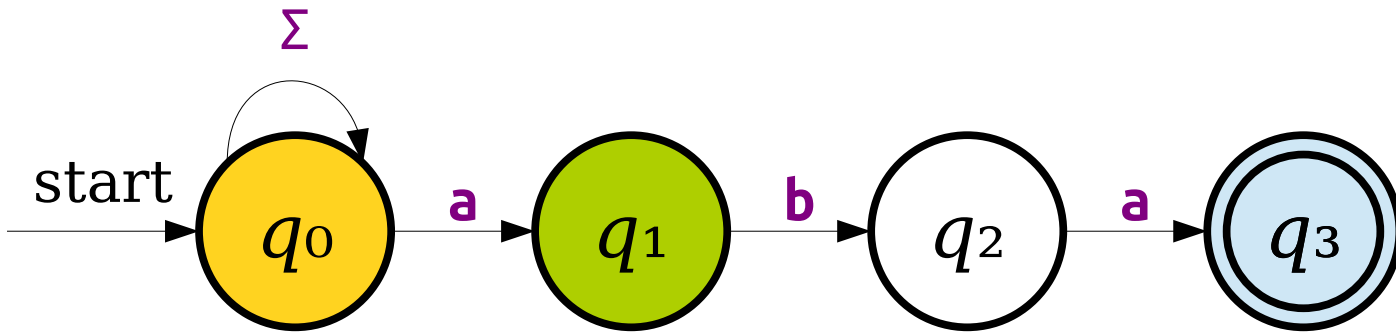
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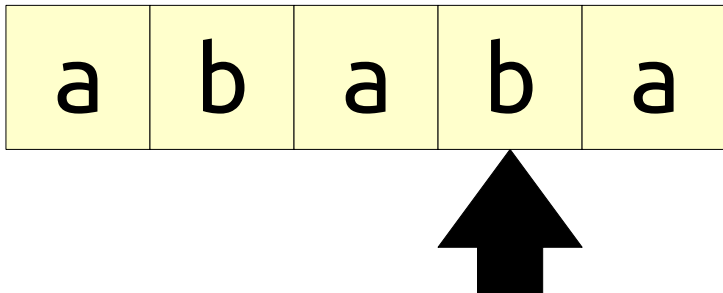
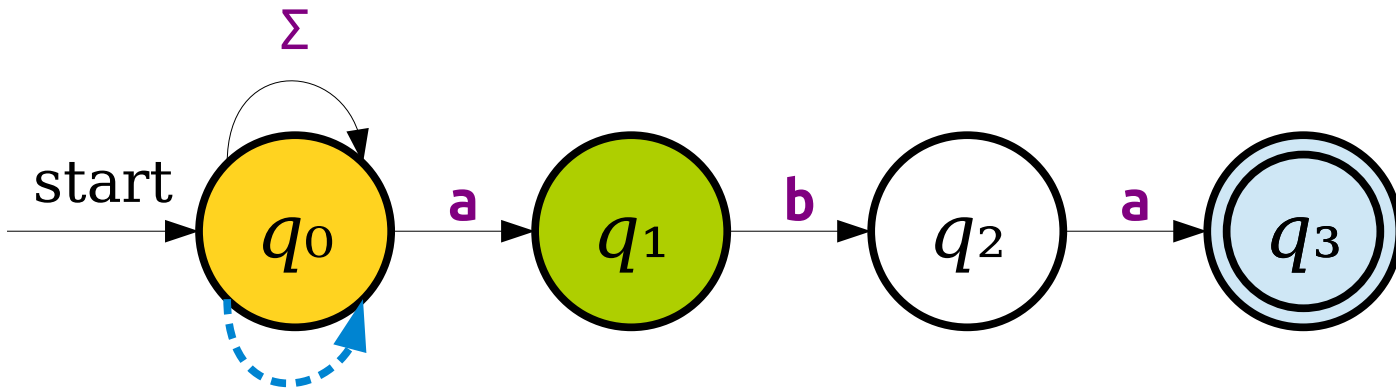
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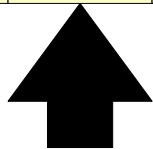
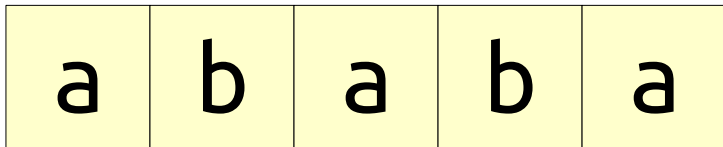
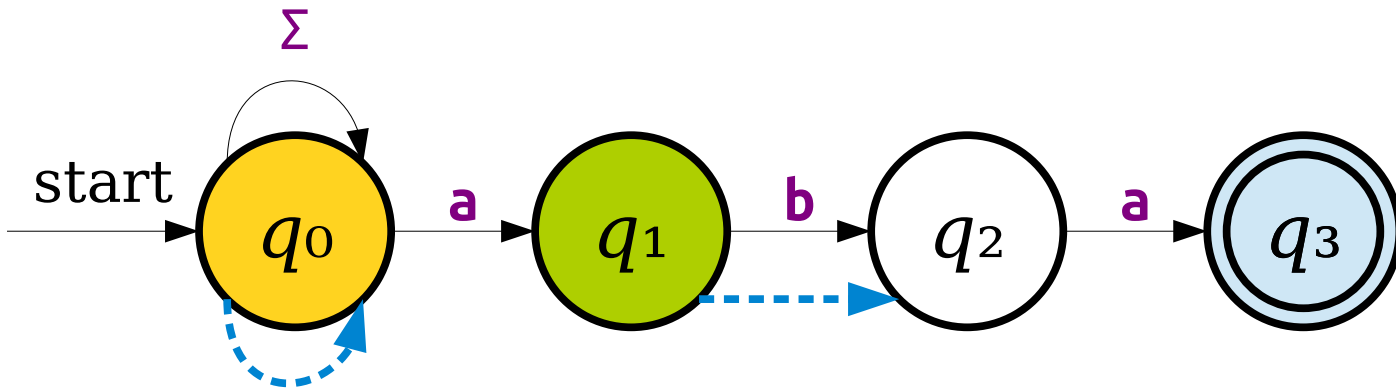
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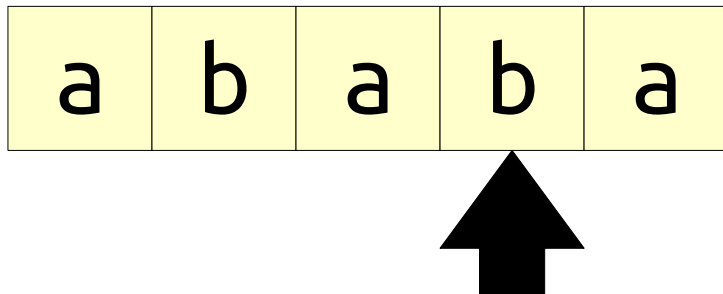
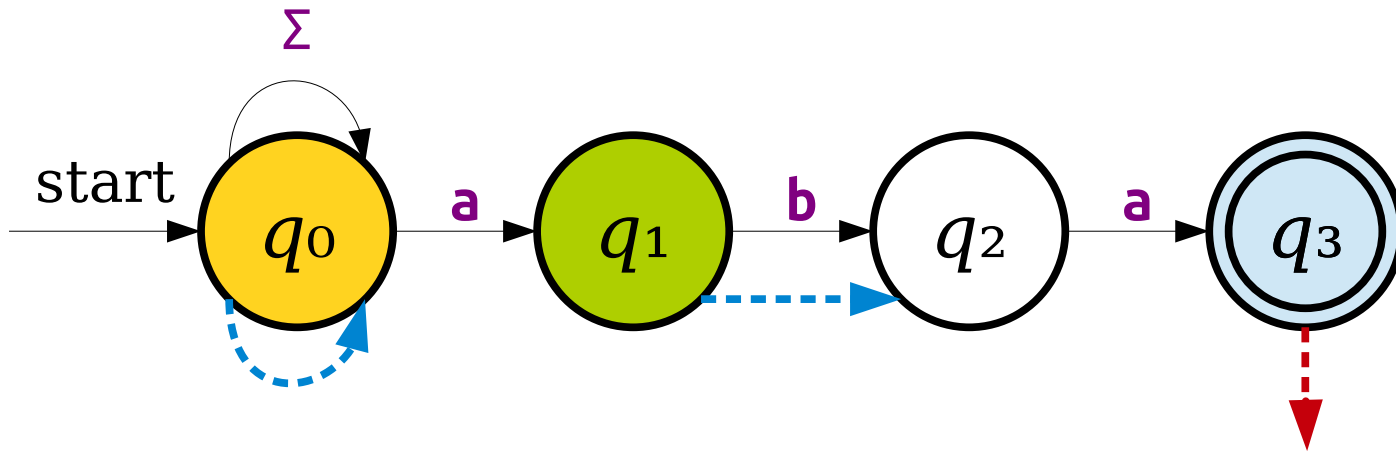
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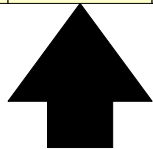
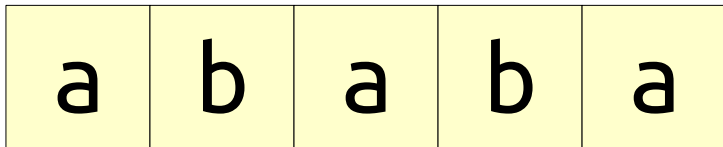
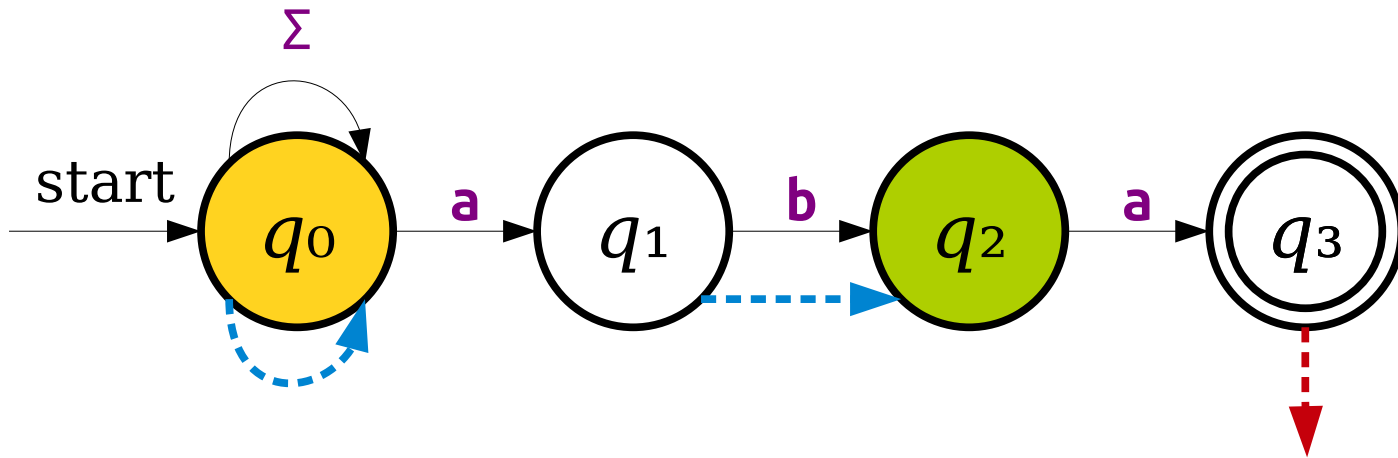
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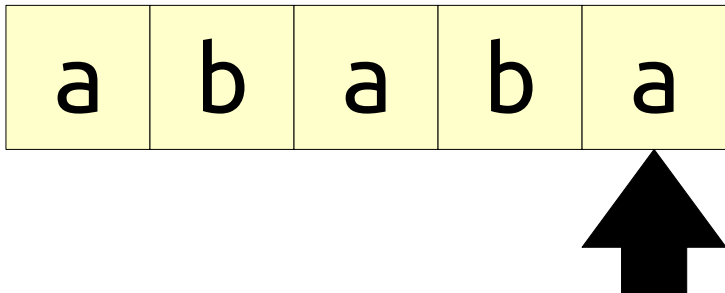
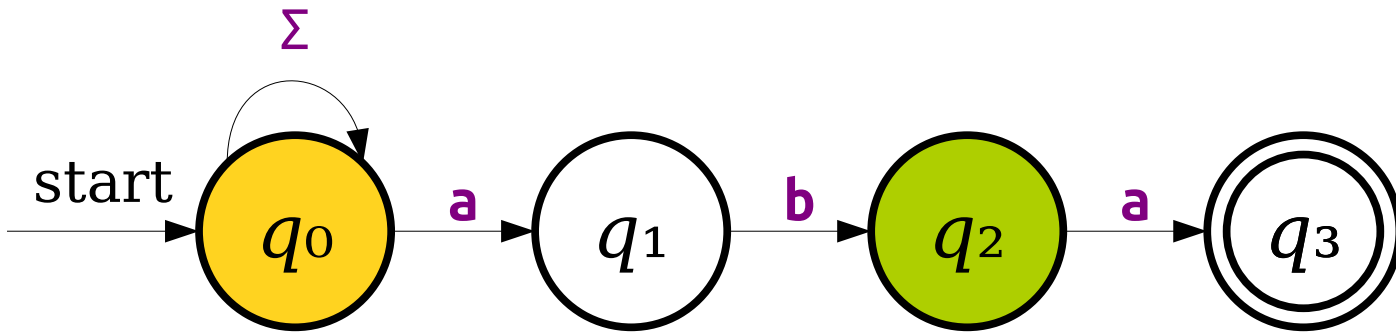
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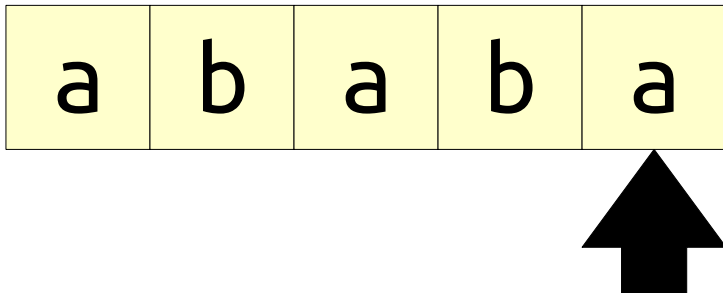
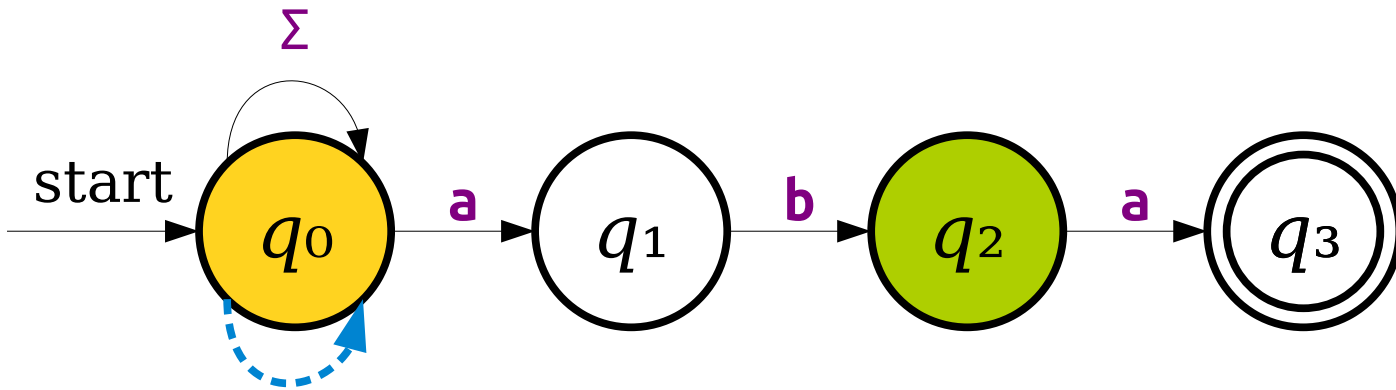
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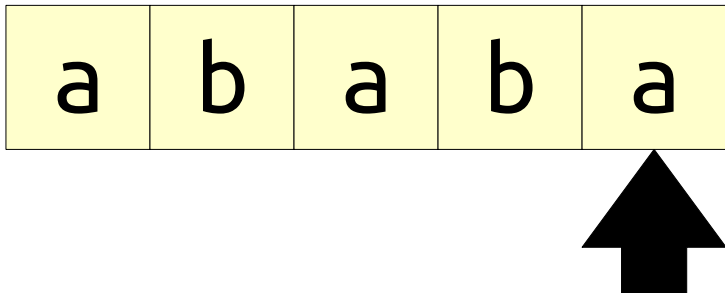
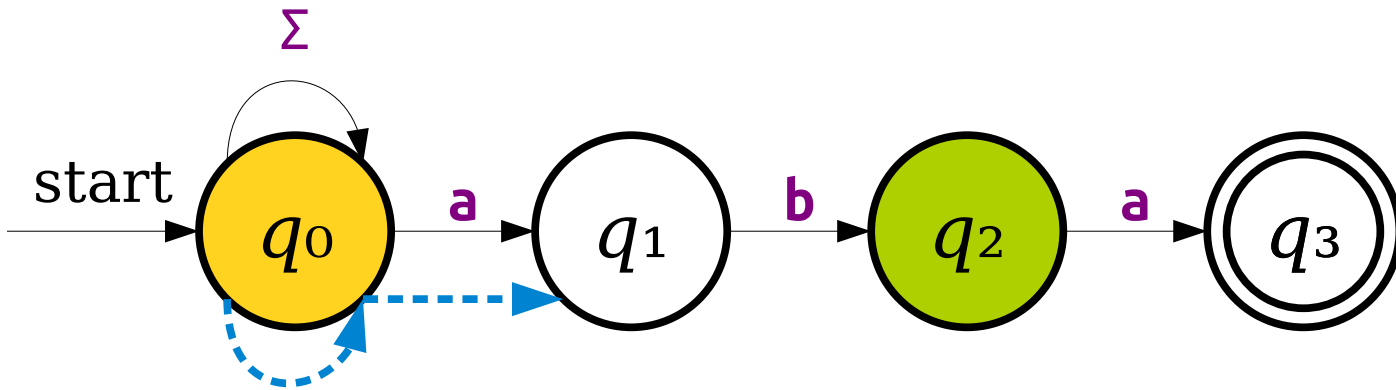
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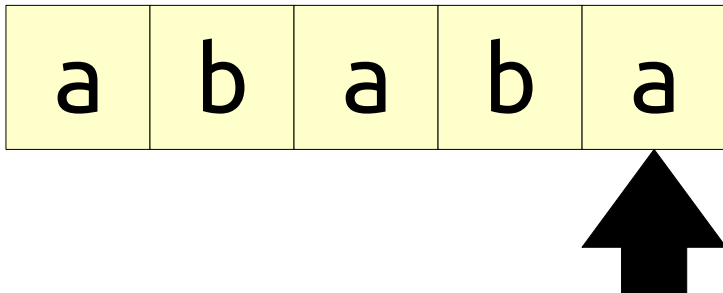
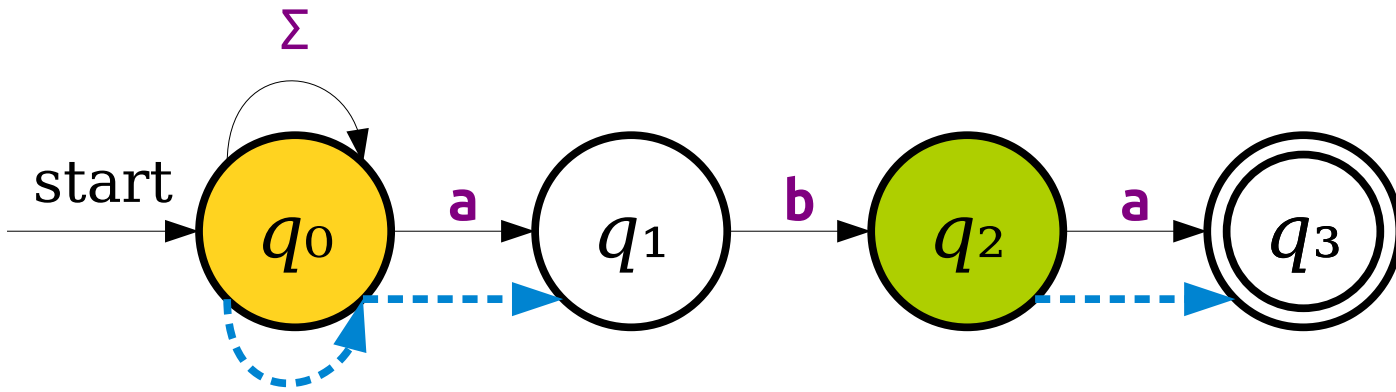
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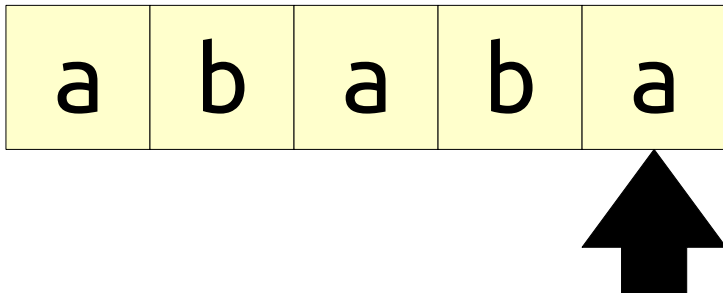
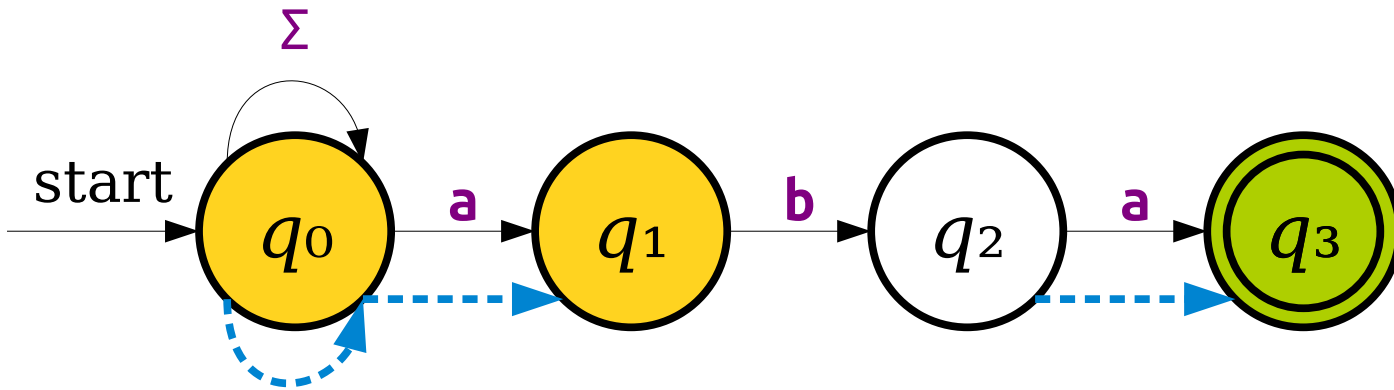
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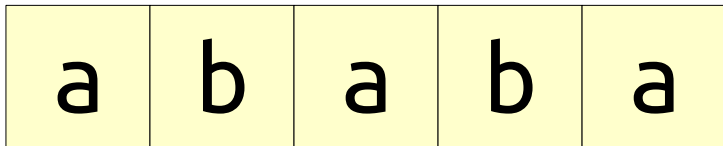
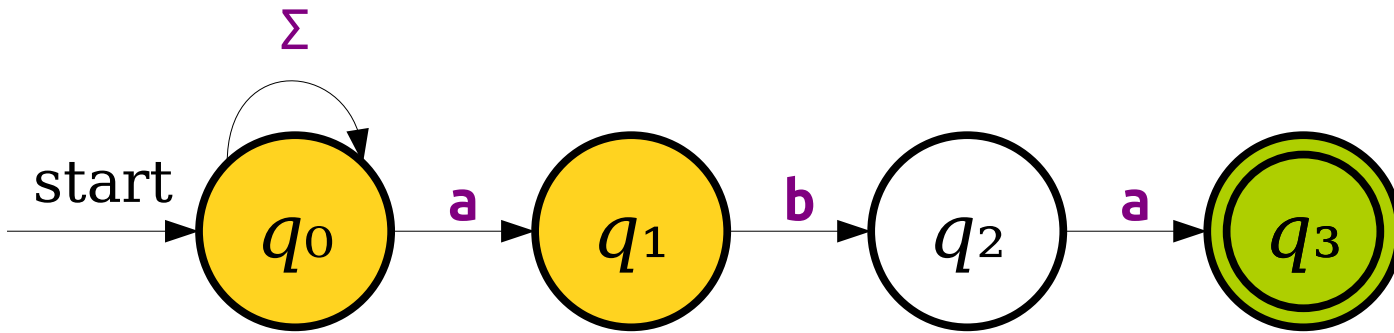
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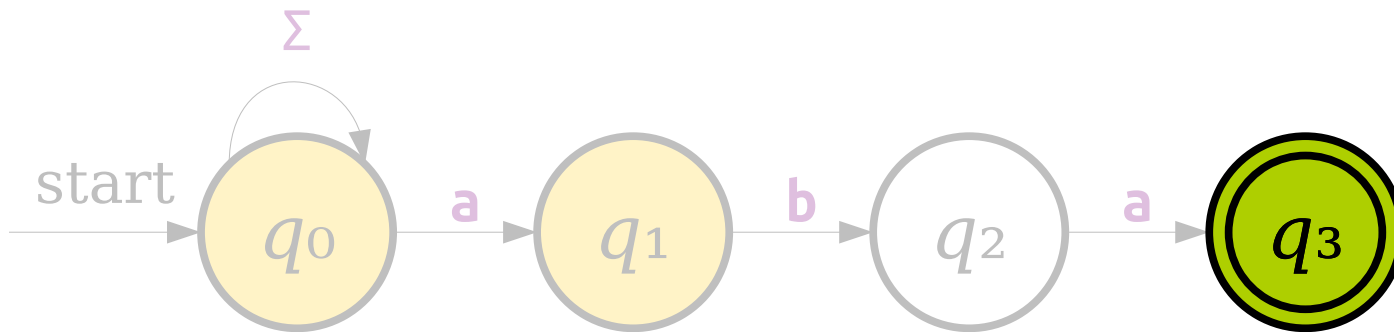
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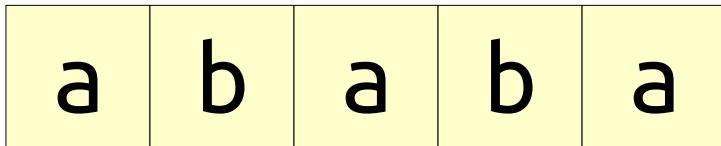
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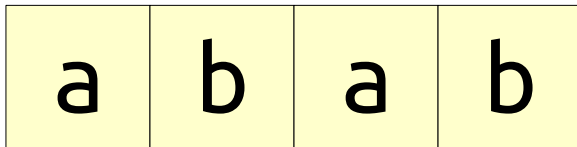
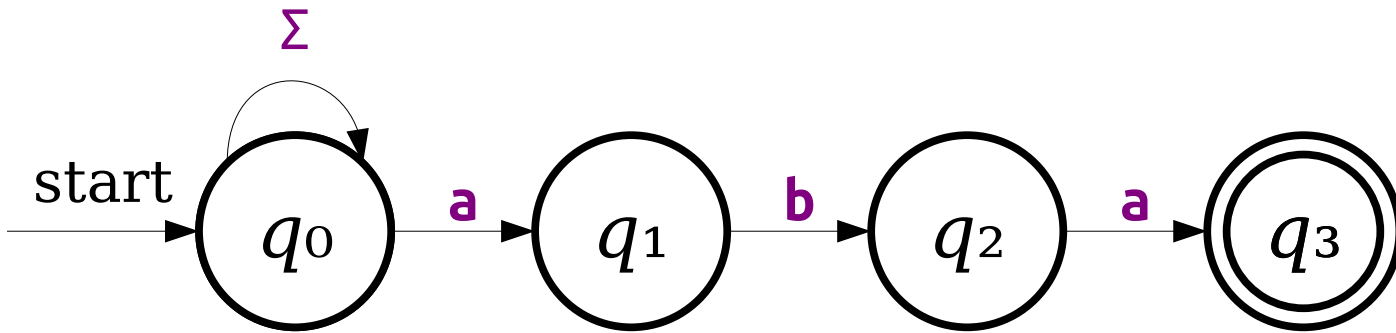
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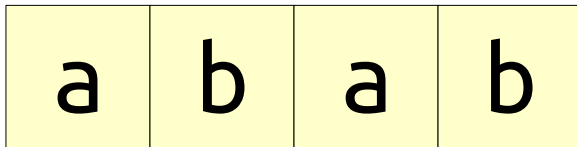
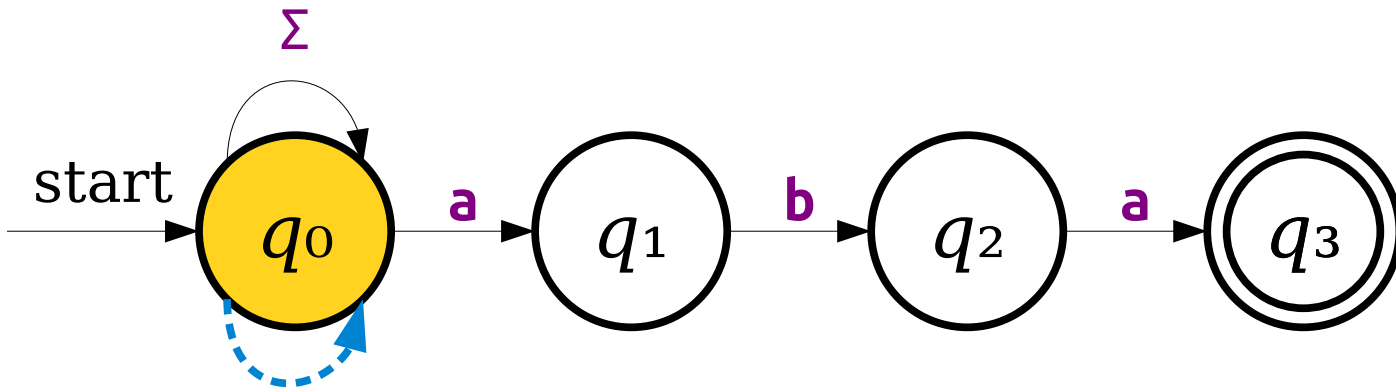
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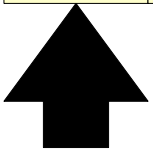
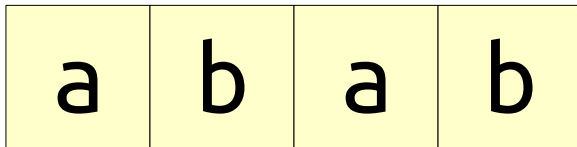
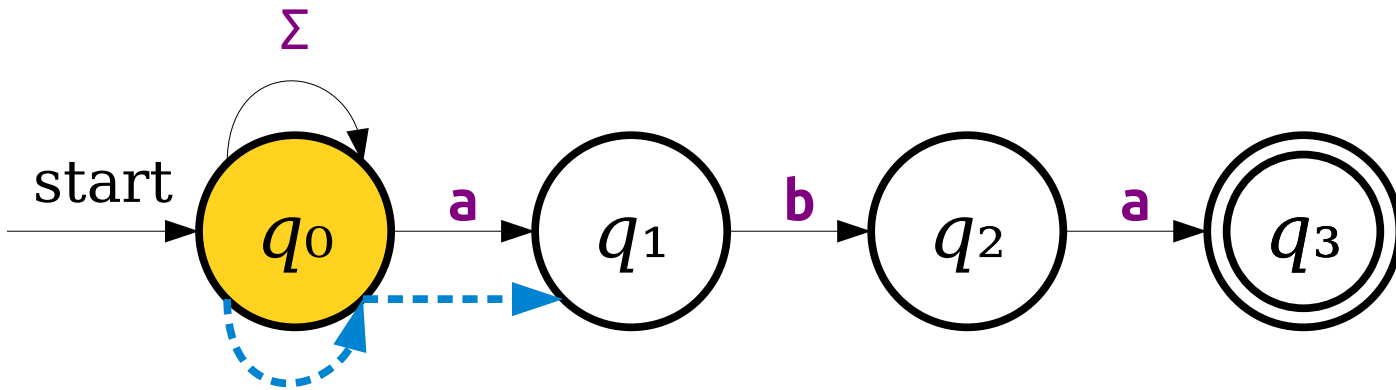
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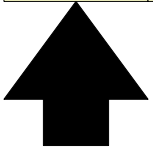
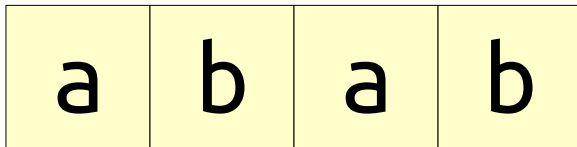
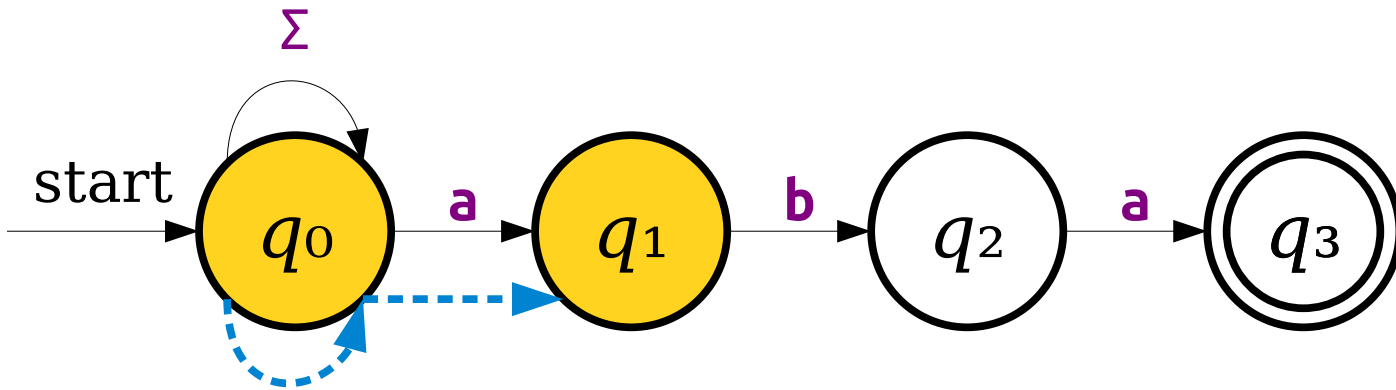
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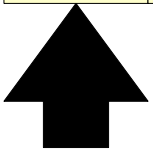
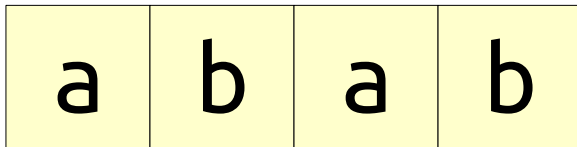
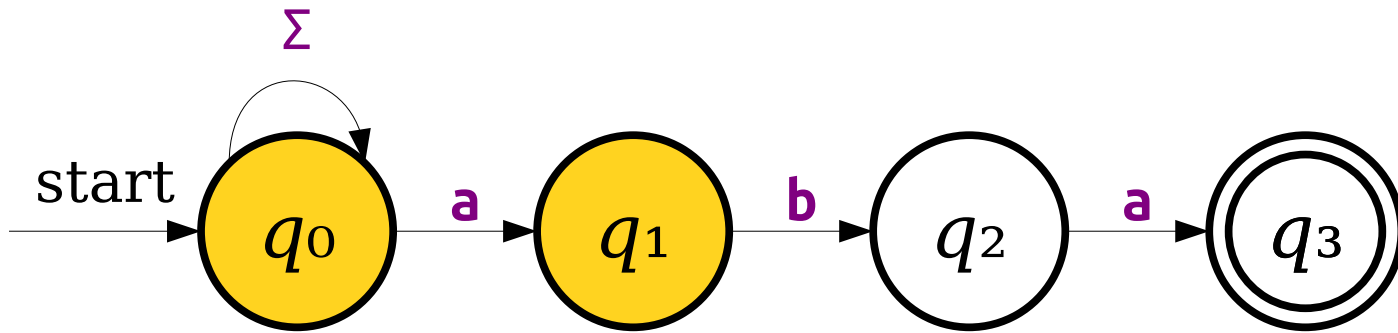
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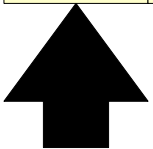
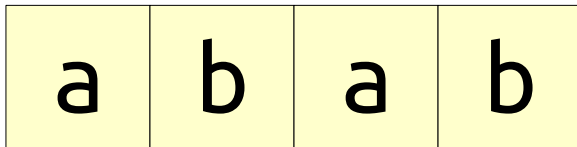
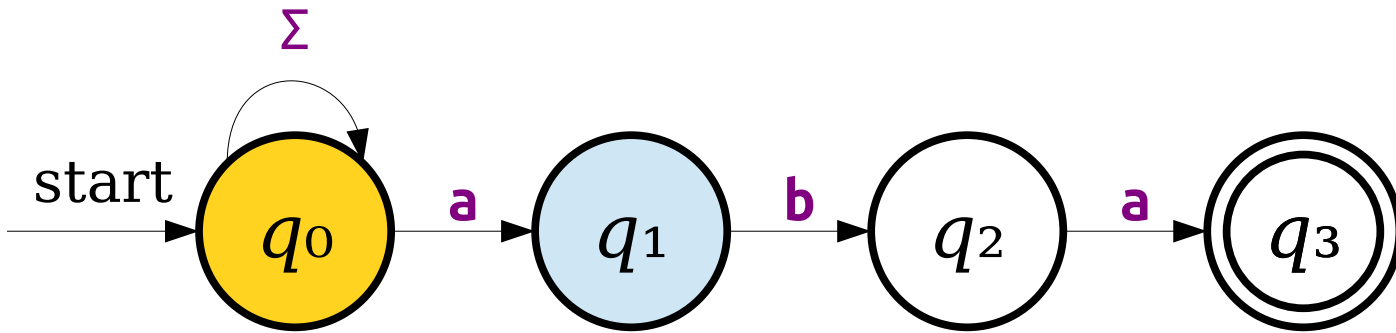
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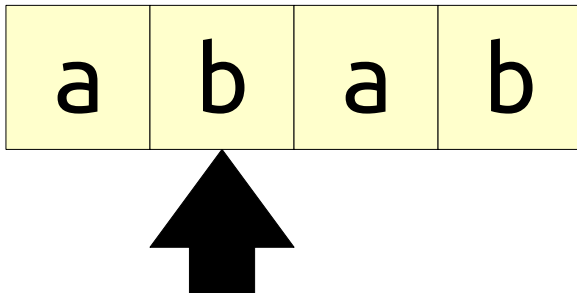
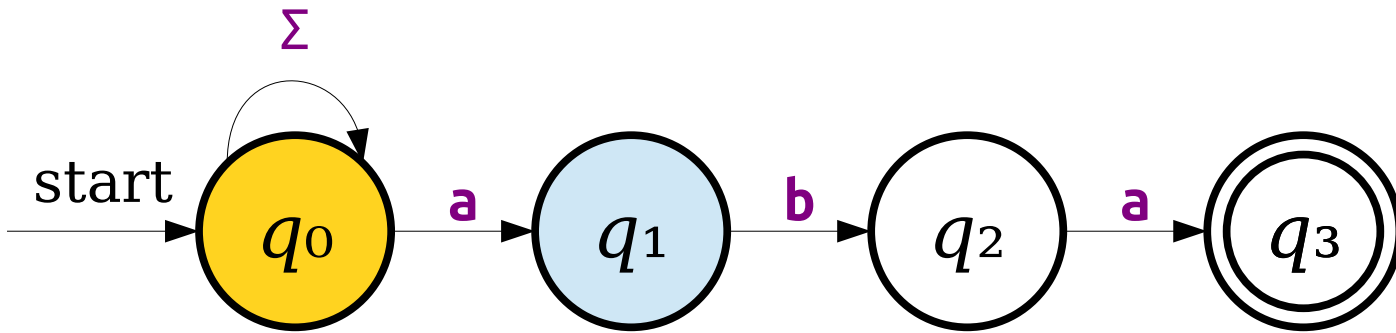
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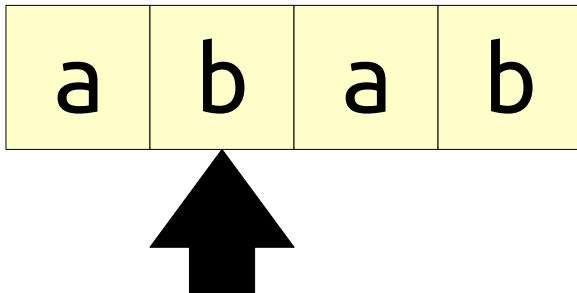
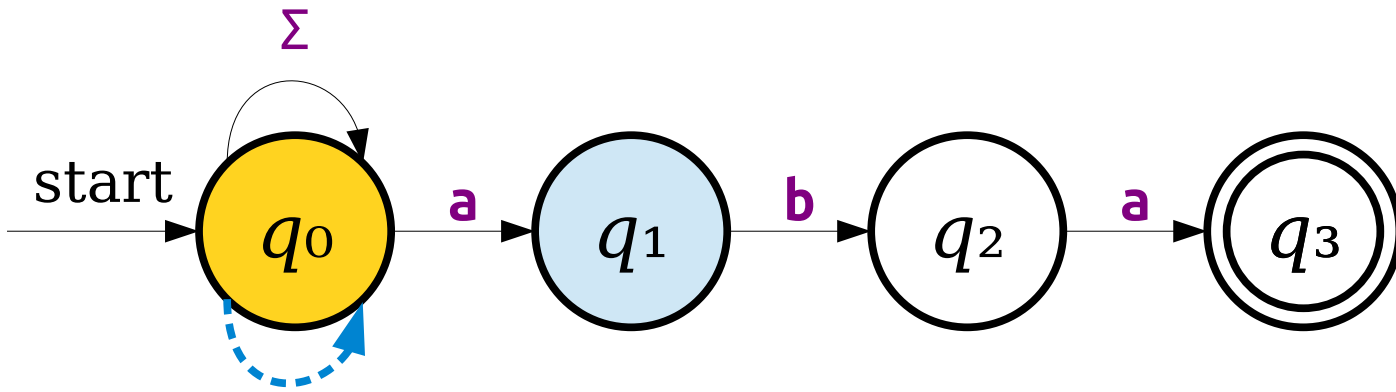
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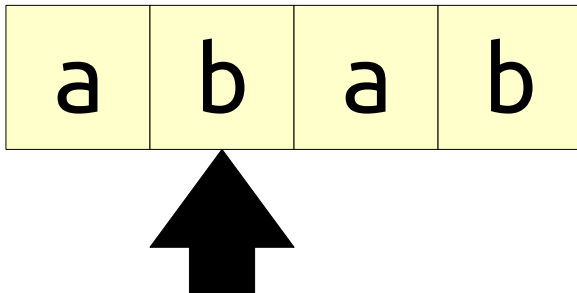
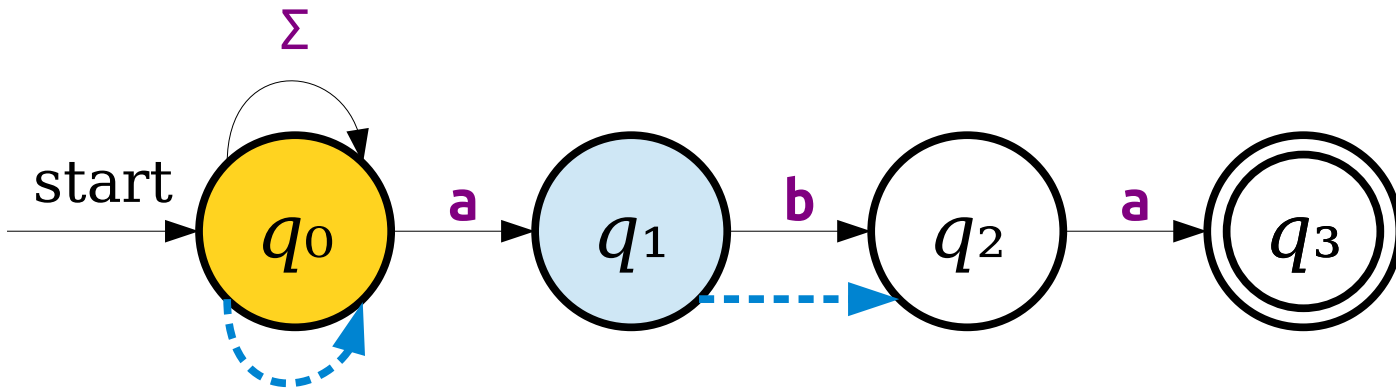
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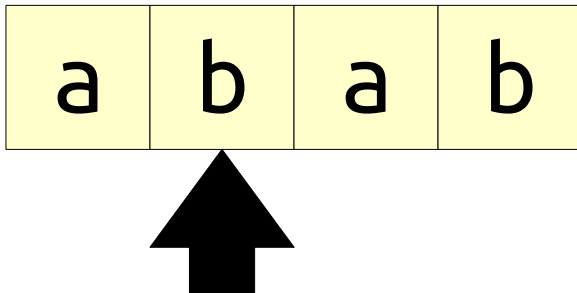
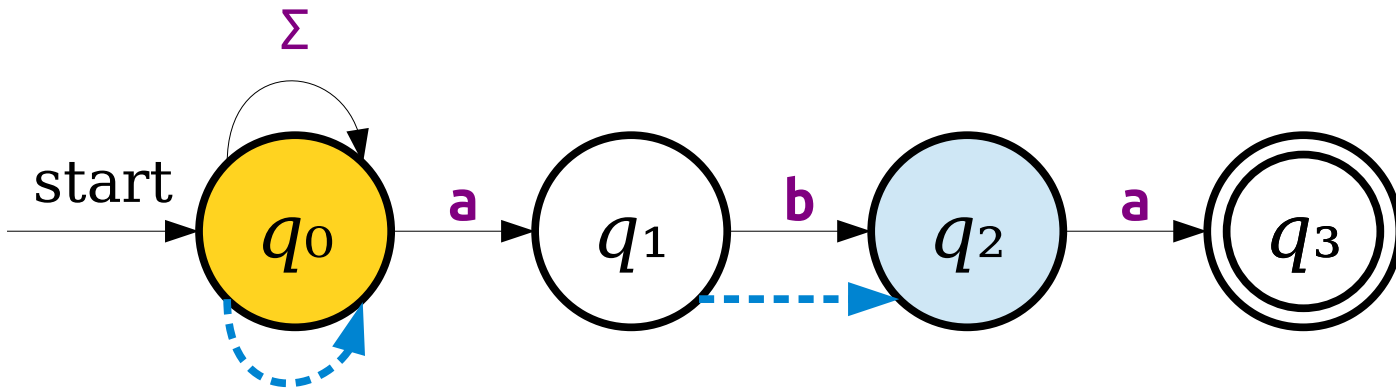
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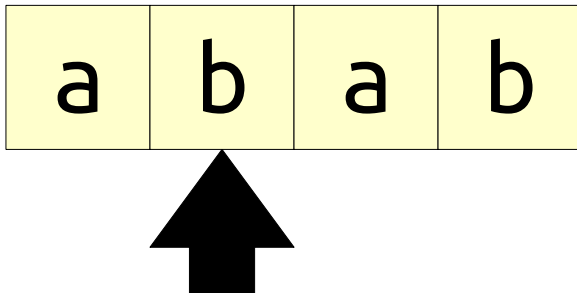
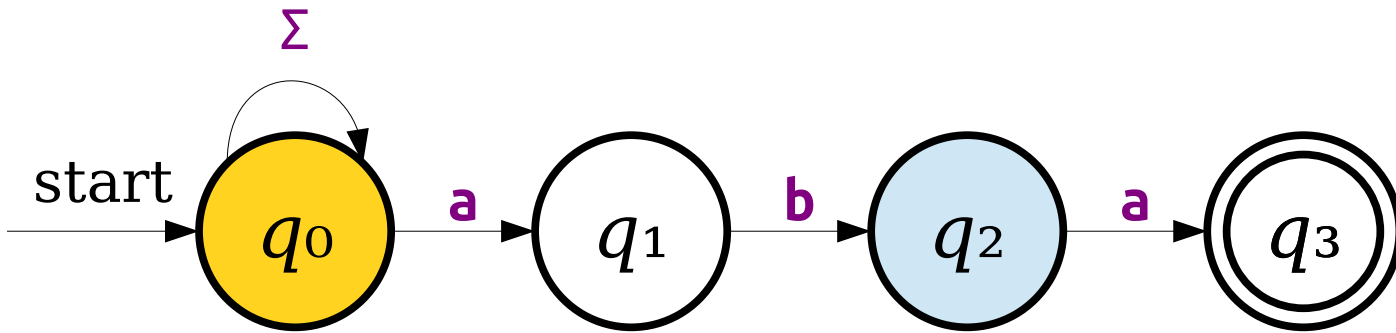
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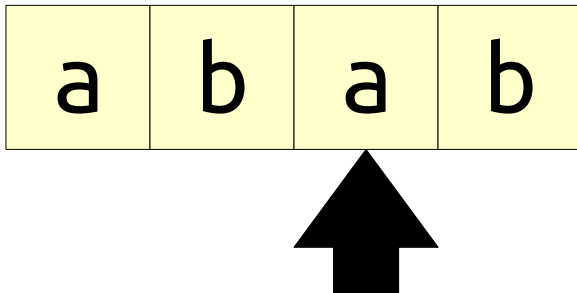
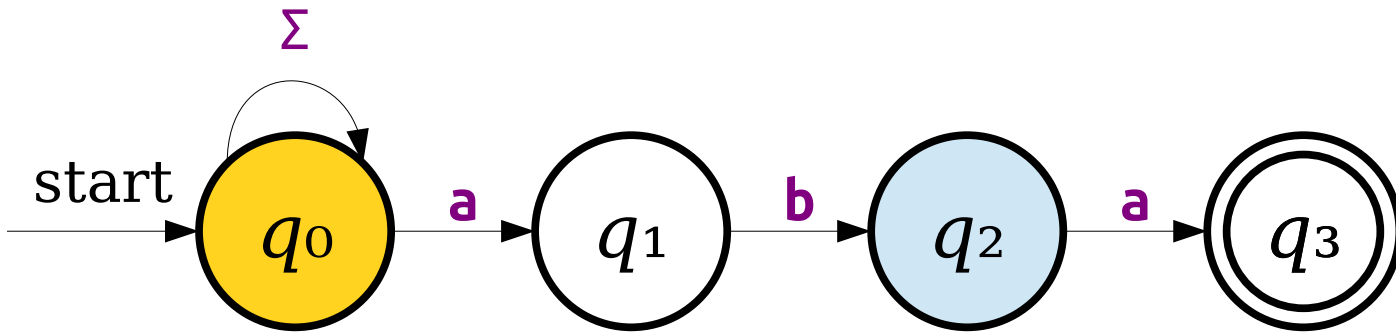
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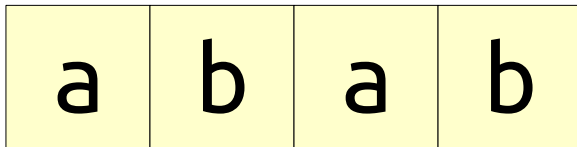
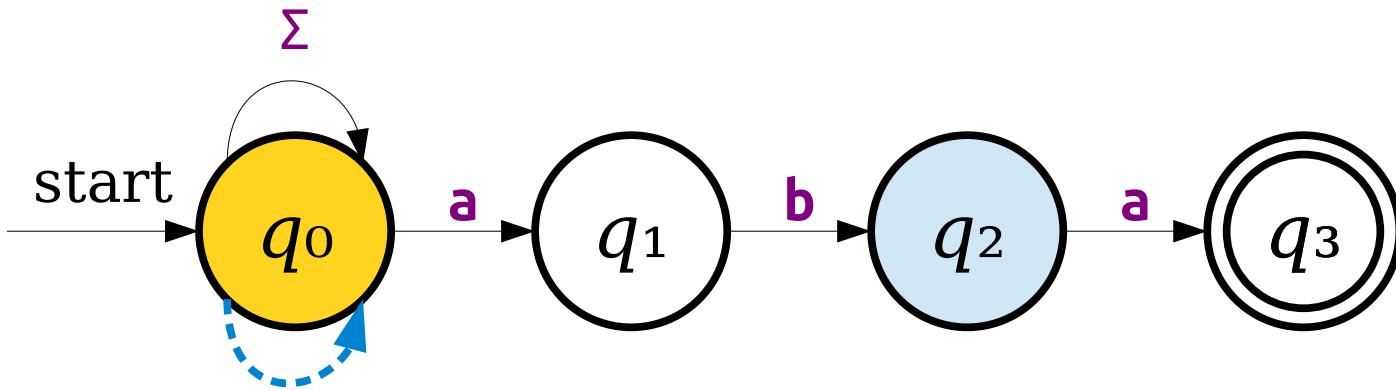
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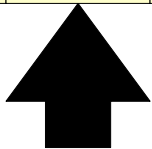
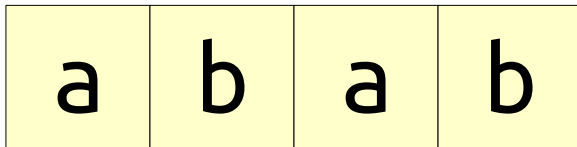
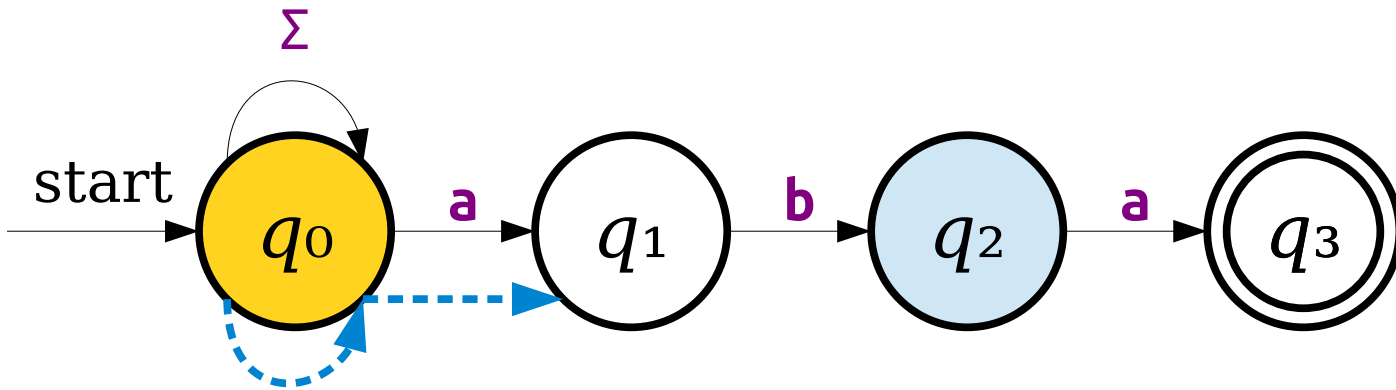
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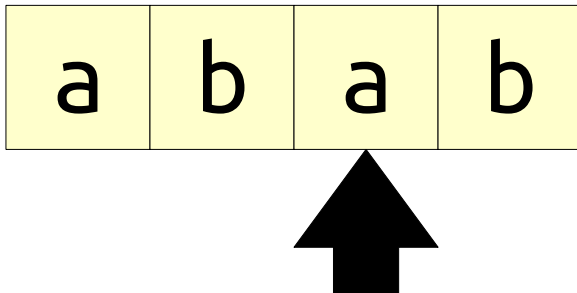
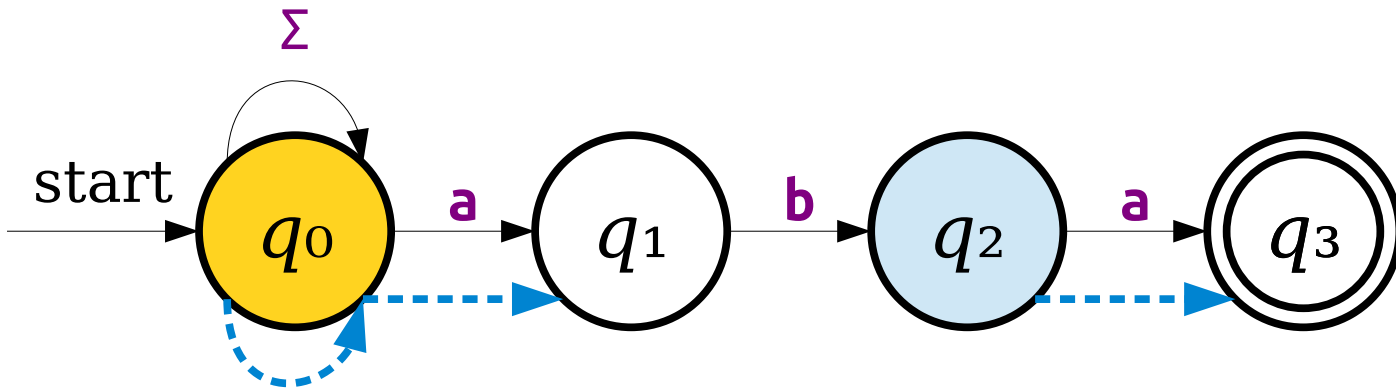
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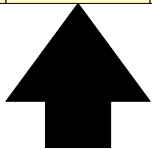
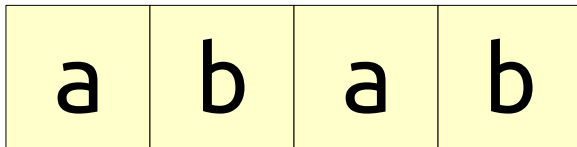
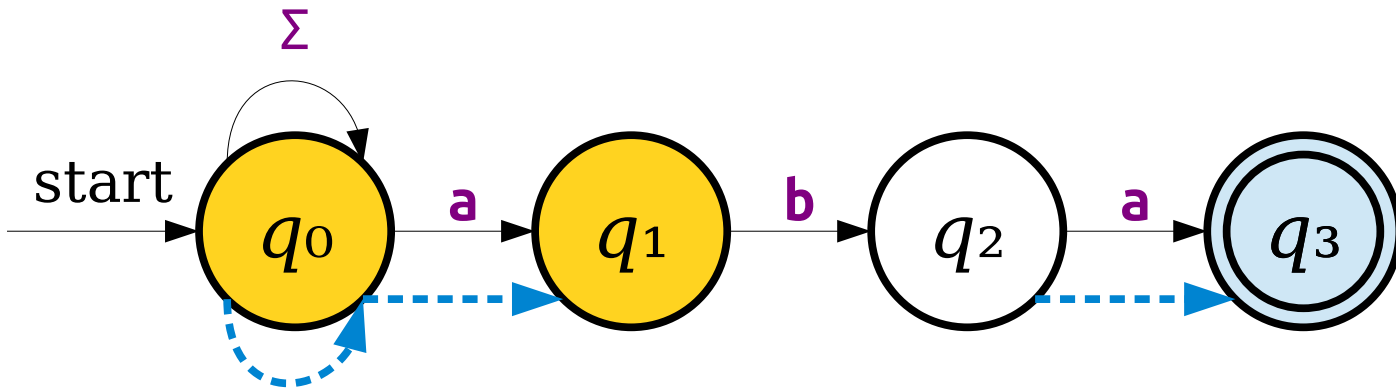
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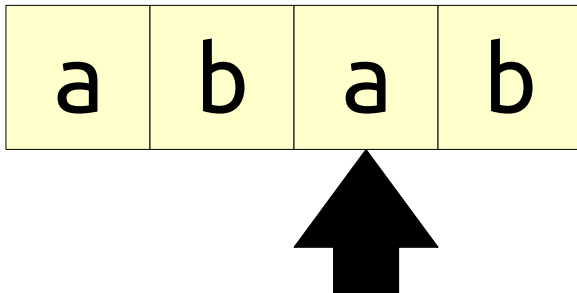
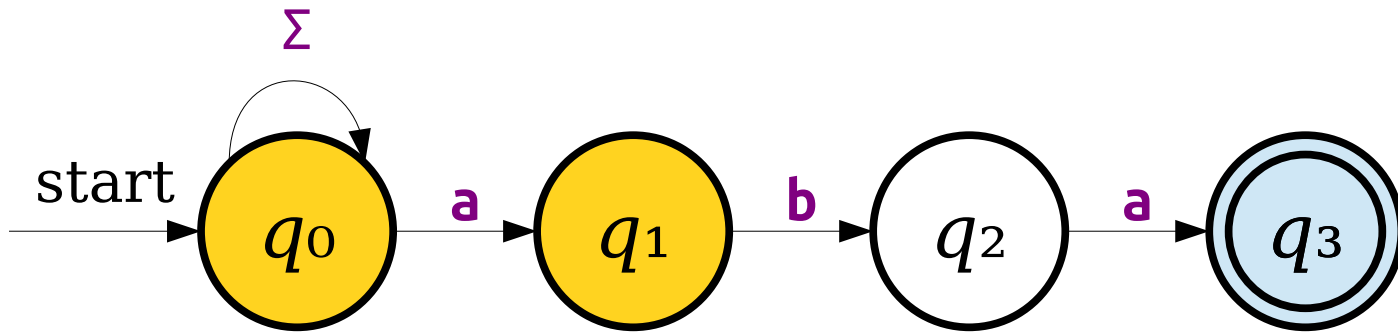
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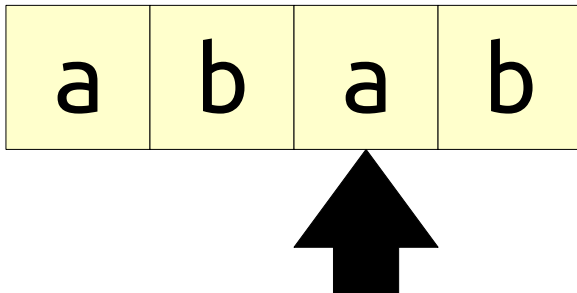
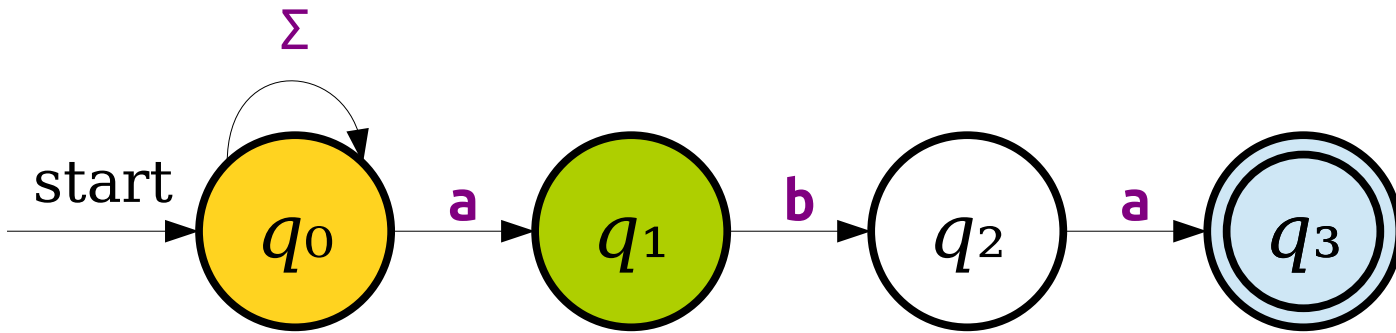
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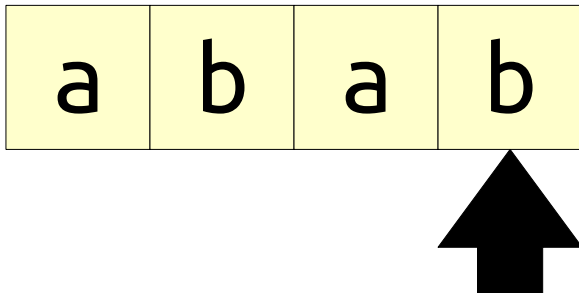
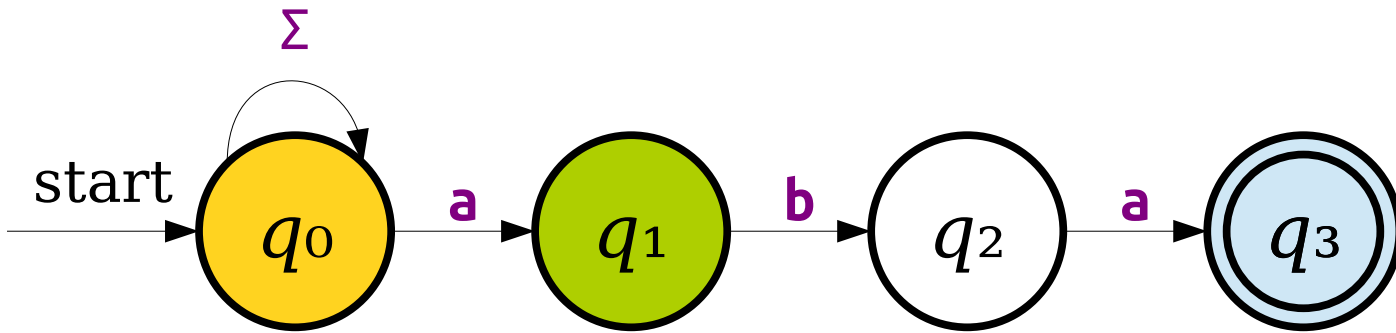
Massive Parallelism



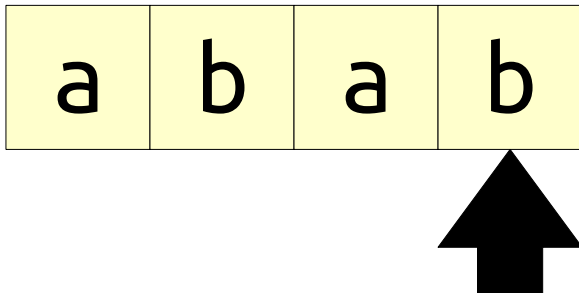
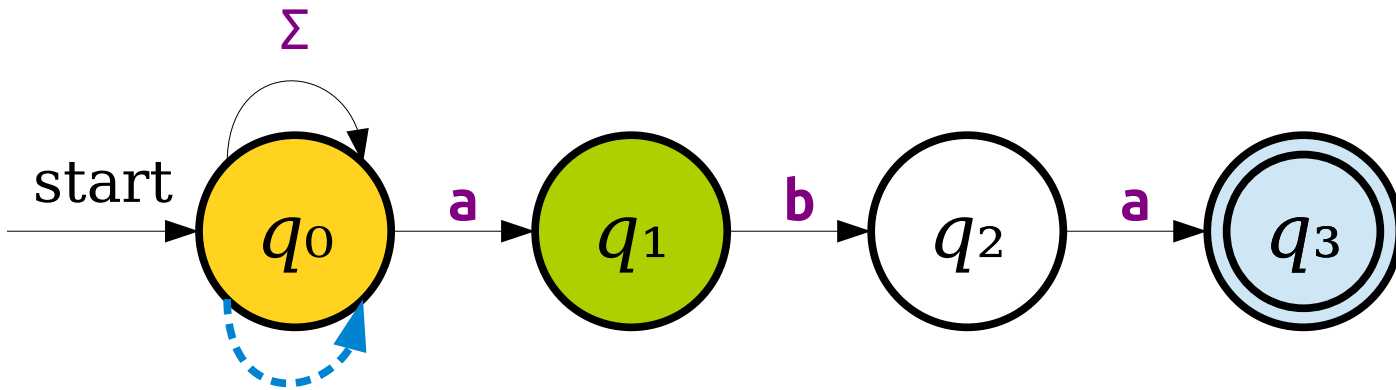
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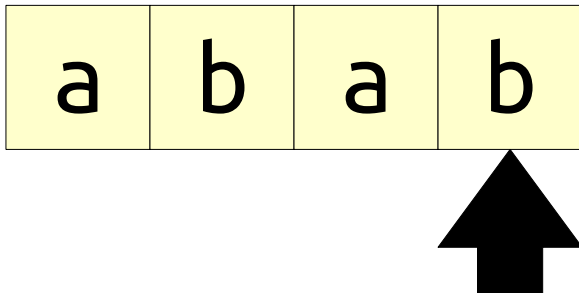
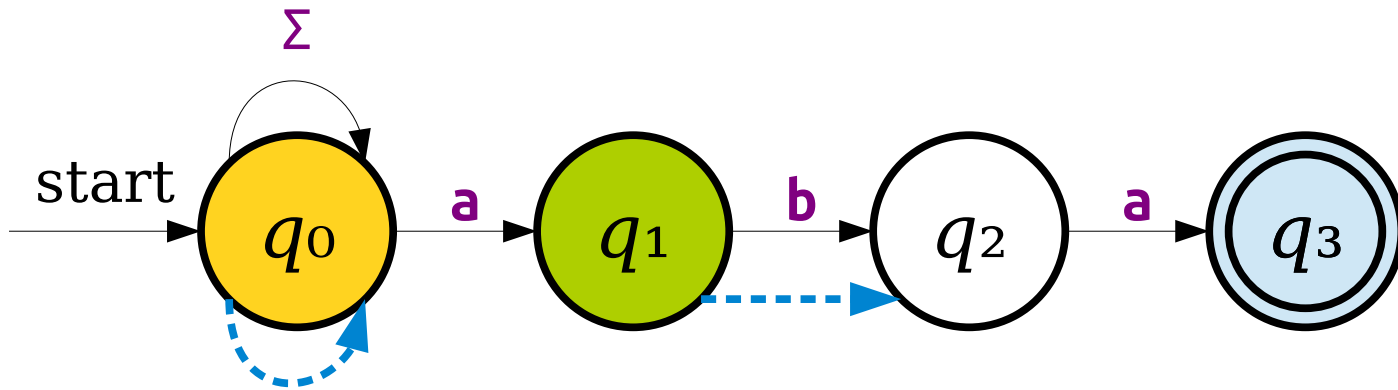
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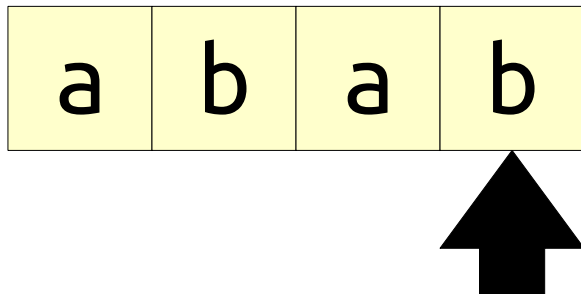
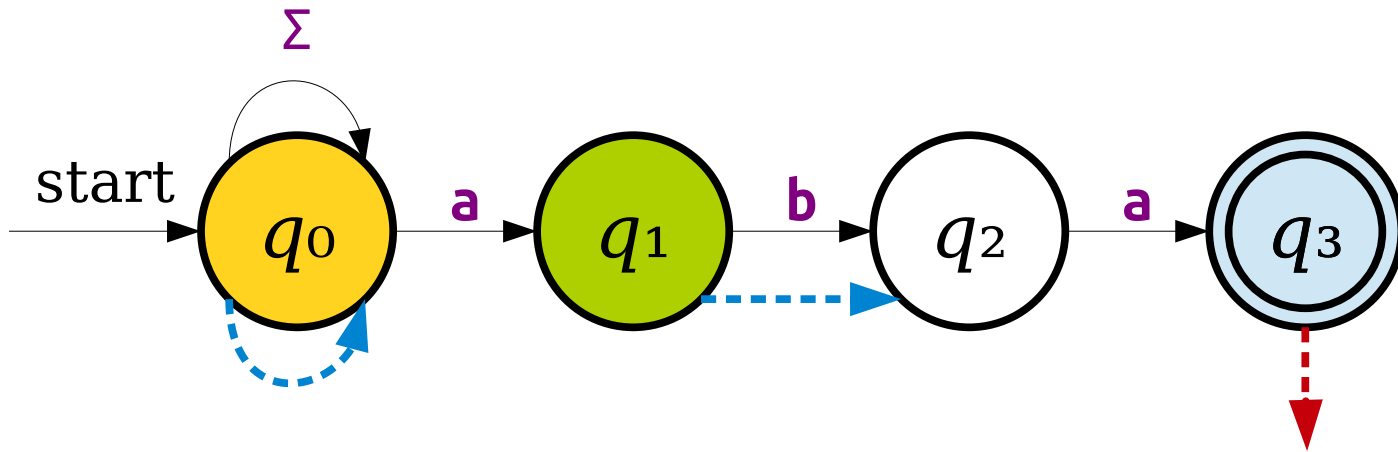
Massive Parallelism



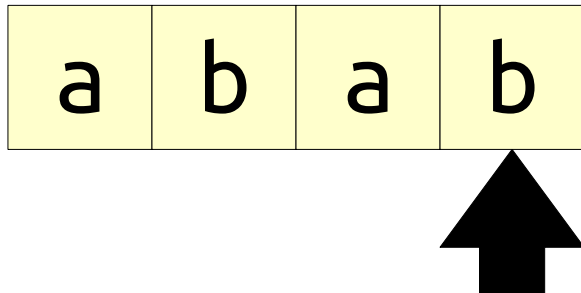
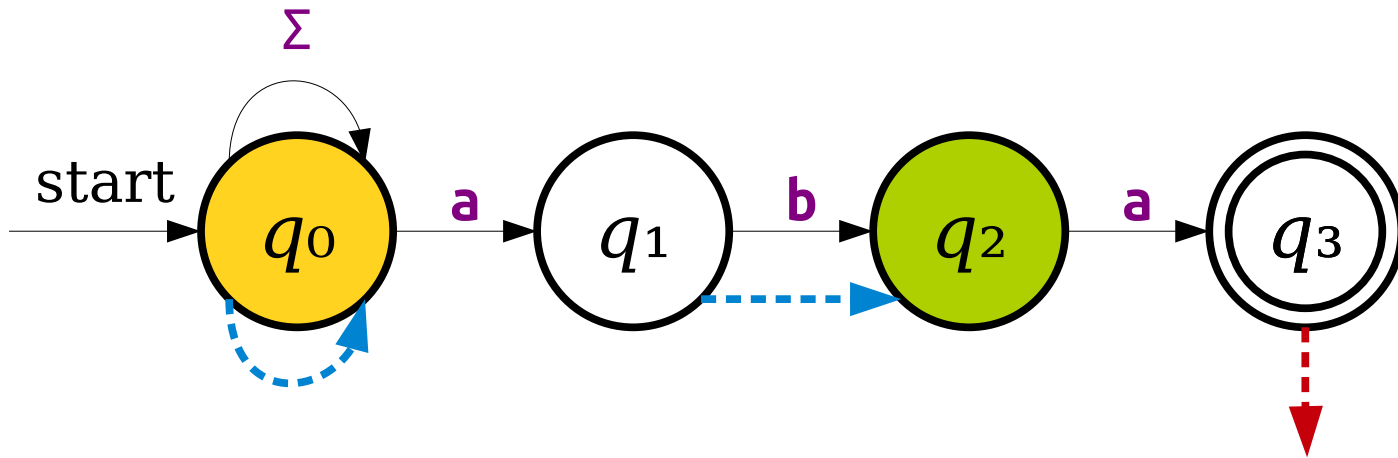
Massive Parallelism



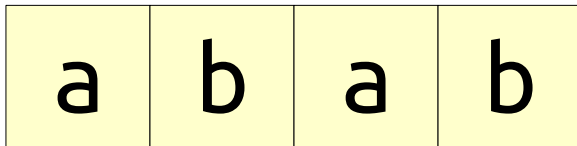
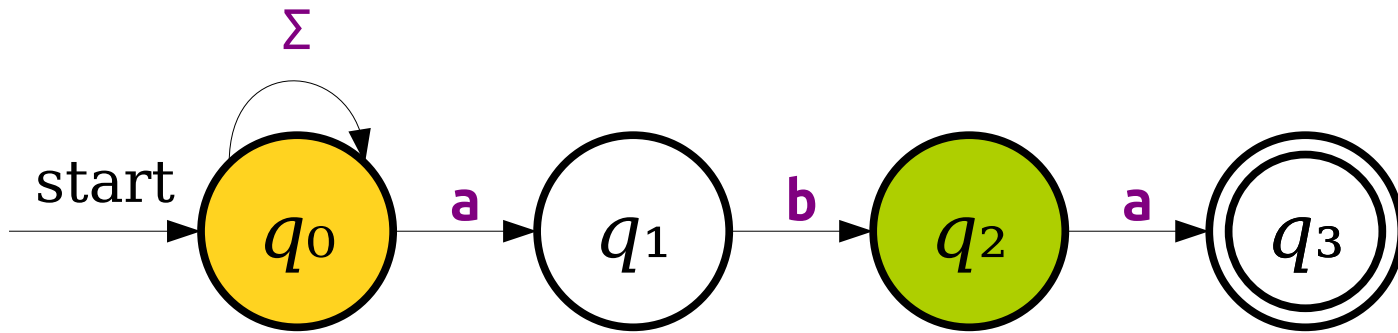
Massive Parallelism



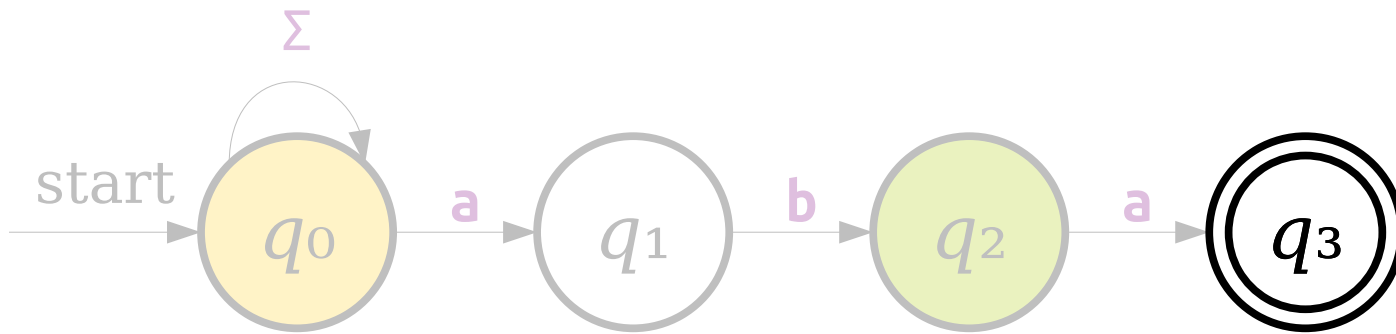
Massive Parallelism



Massive Parallelism



Massive Parallelism



We're not in any accepting state, so no possible path accepts.

a	b	a	b
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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.
- (Here's a rigorous explanation about how this works; read this on your own time).
 - Start off in the set of all states formed by taking the start state and including each state that can be reached by zero or more ϵ -transitions.
 - When you read a symbol **a** in a set of states S :
 - Form the set S' of states that can be reached by following a single **a** transition from some state in S .
 - Your new set of states is the set of states in S' , plus the states reachable from S' by following zero or more ϵ -transitions.

Designing NFAs

Designing NFAs

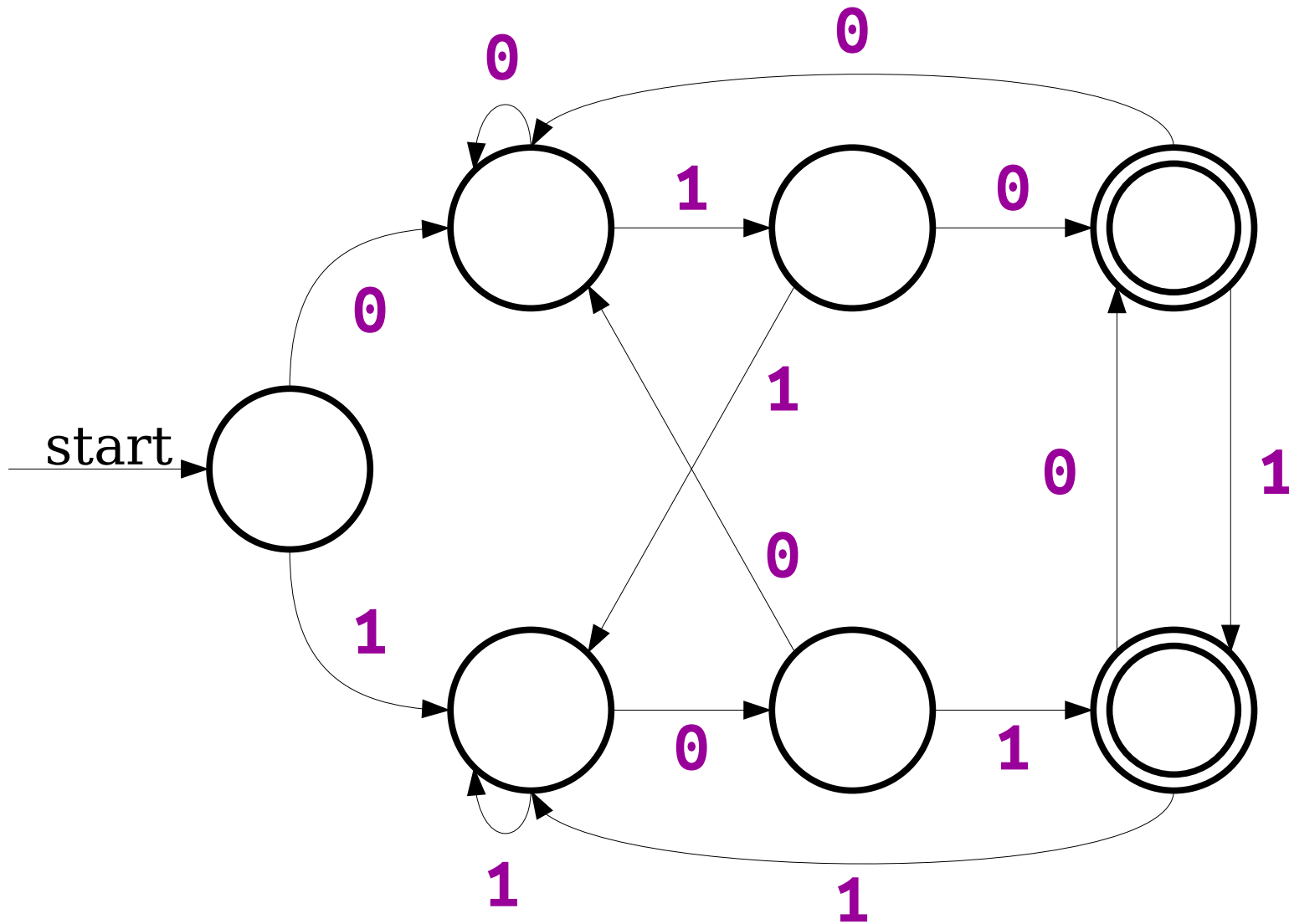
- ***Embrace the nondeterminism!***
- Good model: ***Guess-and-check:***
 - Is there some information that you'd really like to have? Have the machine *nondeterministically guess* that information.
 - Then, have the machine *deterministically check* that the choice was correct.
- The *guess* phase corresponds to trying lots of different options.
- The *check* phase corresponds to filtering out bad guesses or wrong options.

Guess-and-Check

$$L = \{ w \in \{0, 1\}^* \mid w \text{ ends in } 010 \text{ or } 101 \}$$

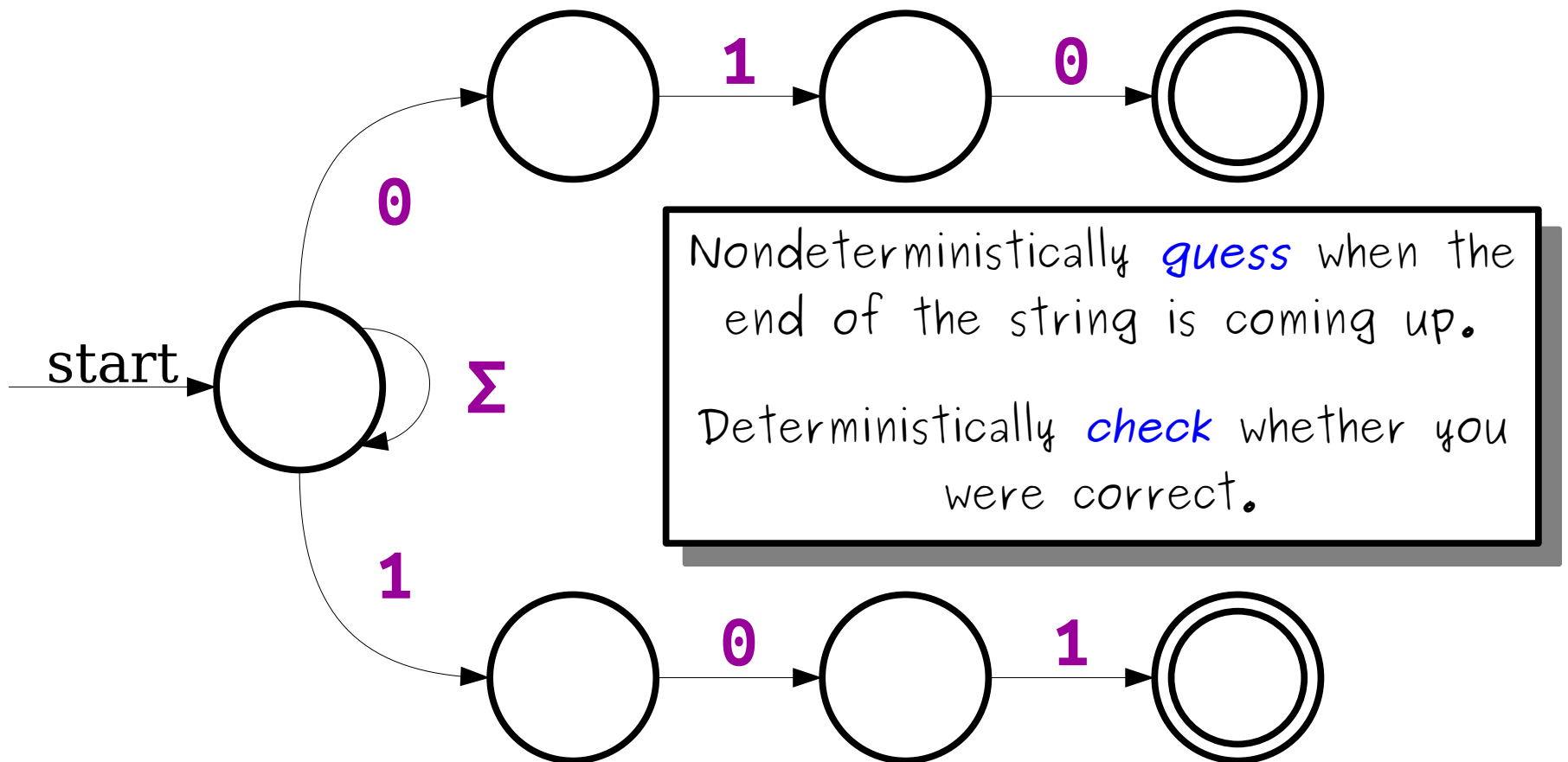
Guess-and-Check

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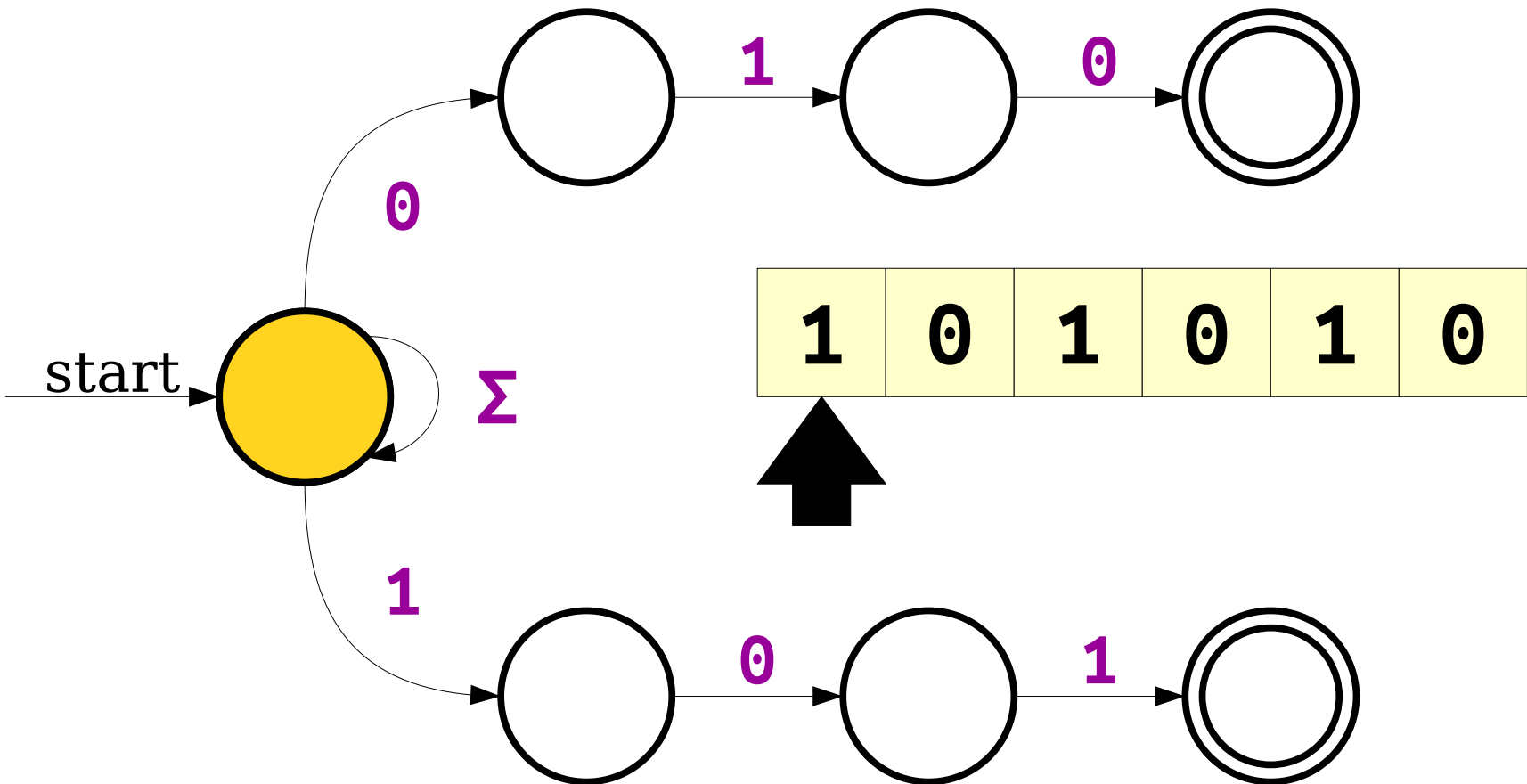
Guess-and-Check

$$L = \{ w \in \{0, 1\}^* \mid w \text{ ends in } 010 \text{ or } 101 \}$$



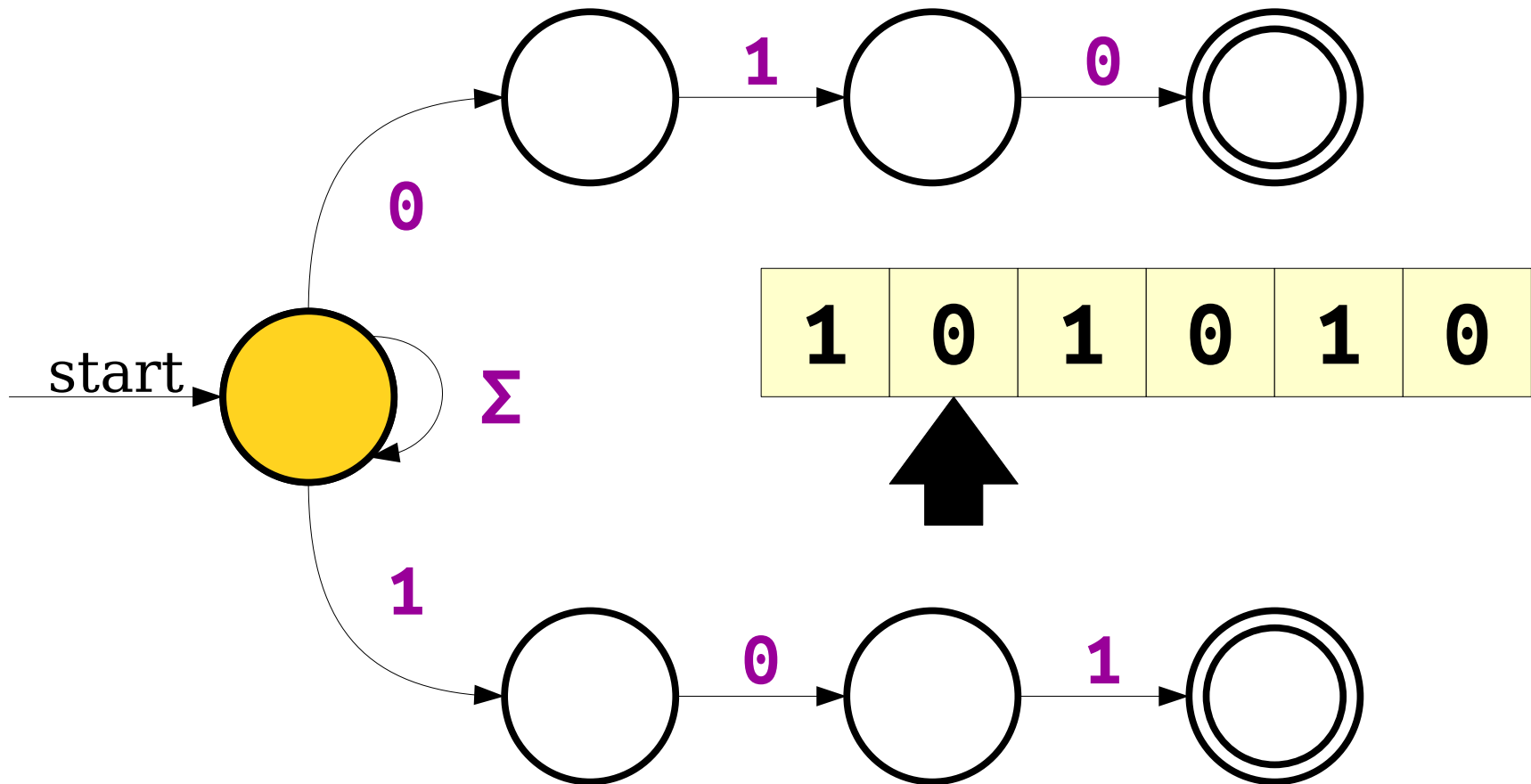
Guess-and-Check

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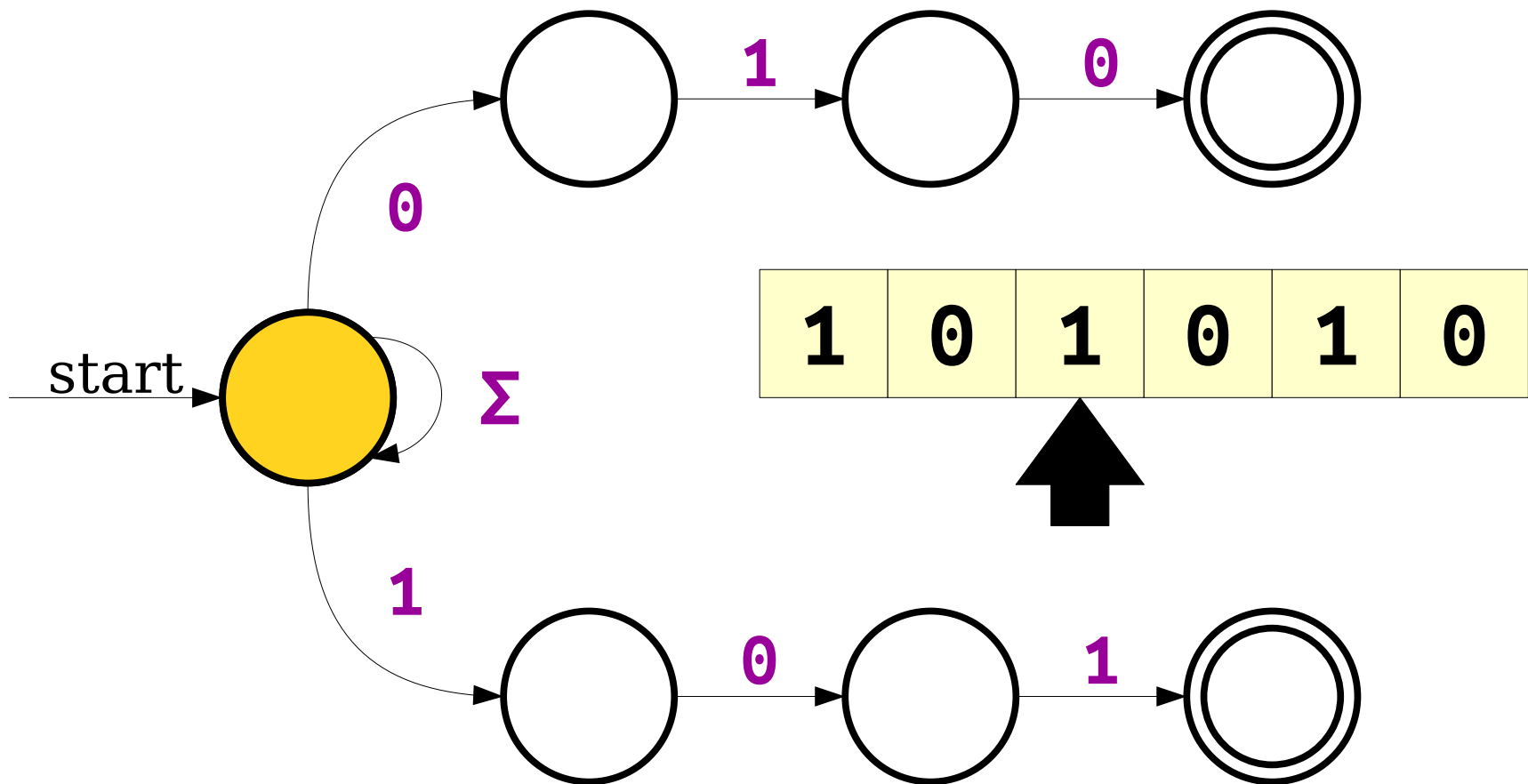
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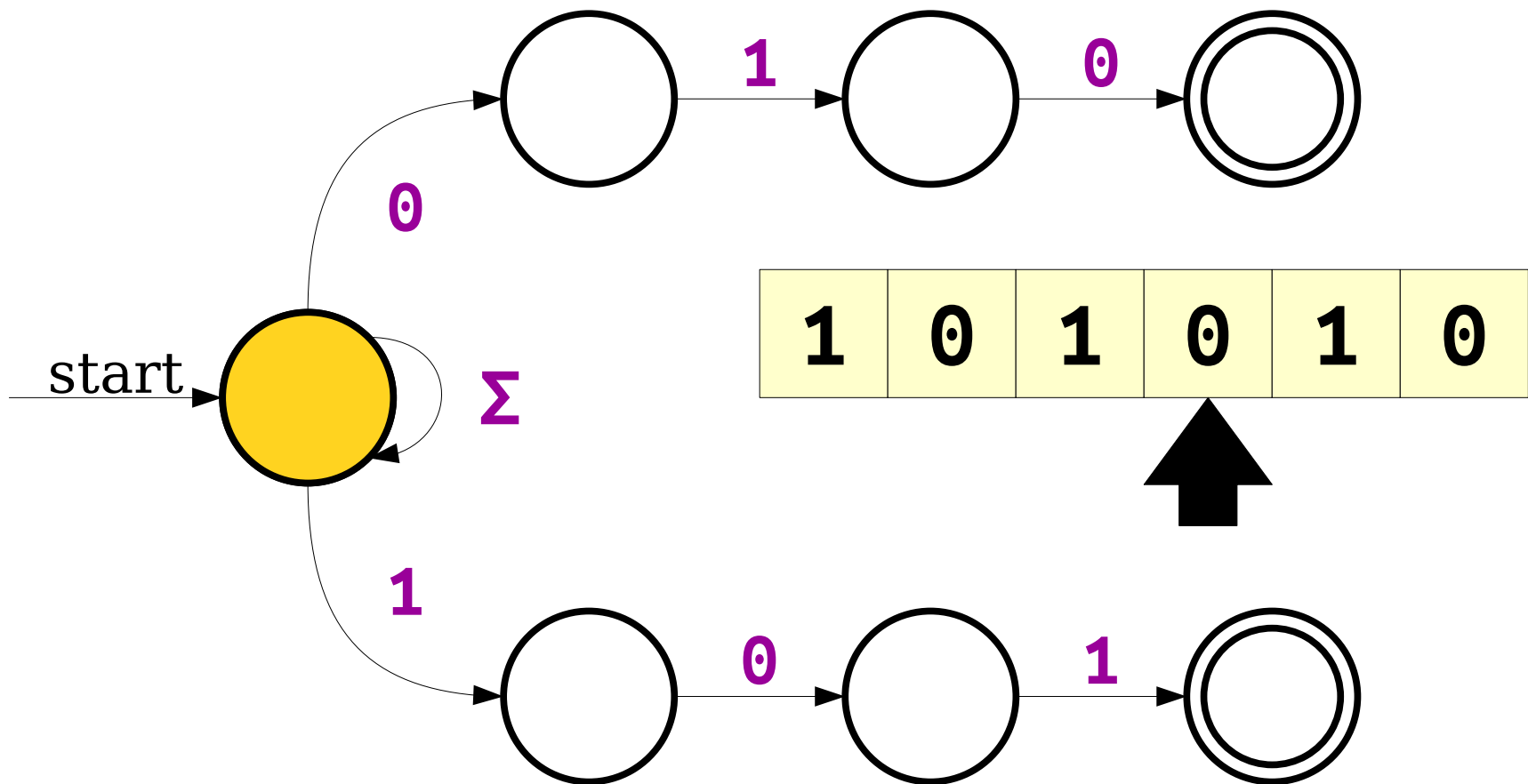
Guess-and-Check

$$L = \{ w \in \{0, 1\}^* \mid w \text{ ends in } 010 \text{ or } 101 \}$$



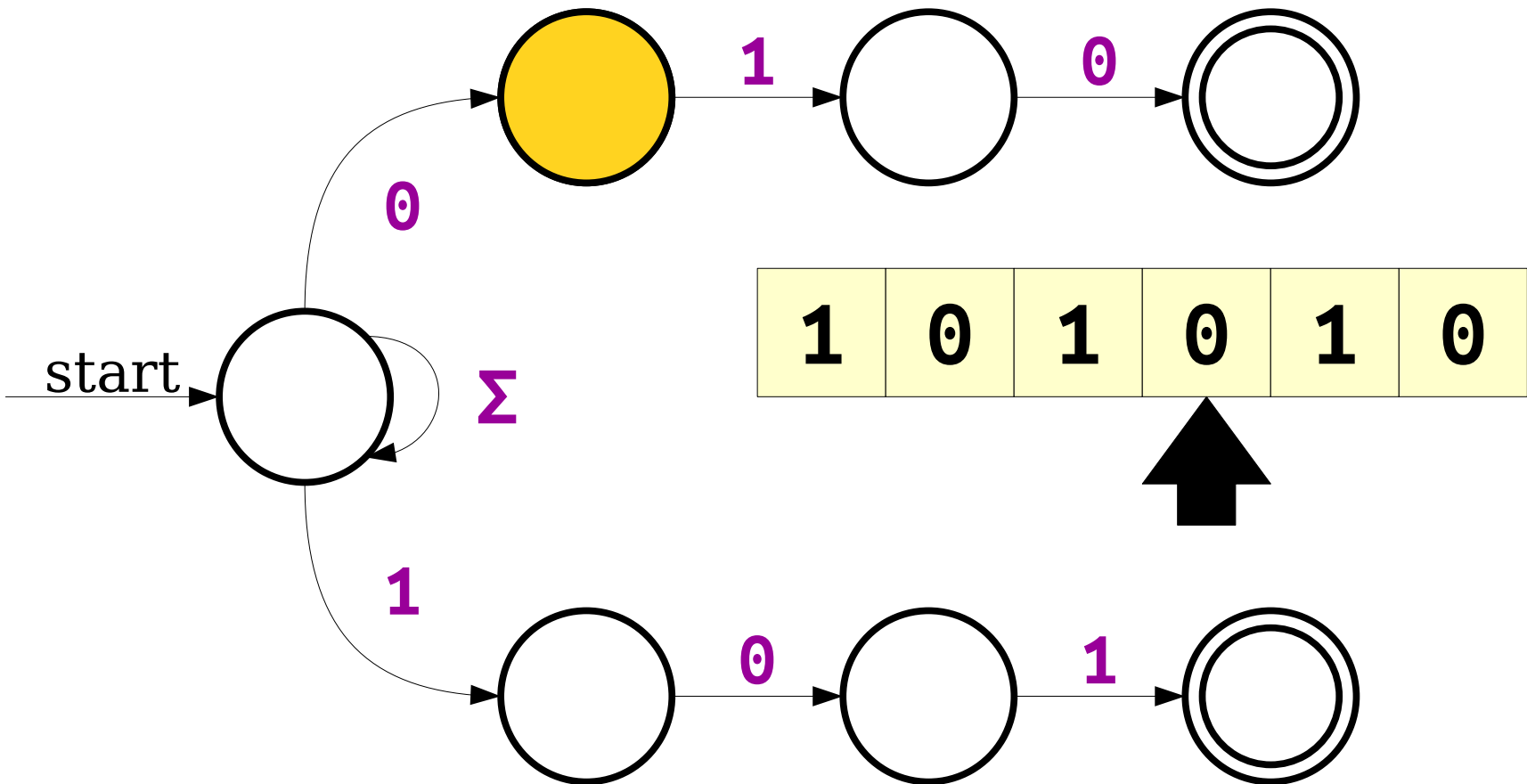
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$$L = \{ w \in \{0, 1\}^* \mid w \text{ ends in } 010 \text{ or } 101 \}$$



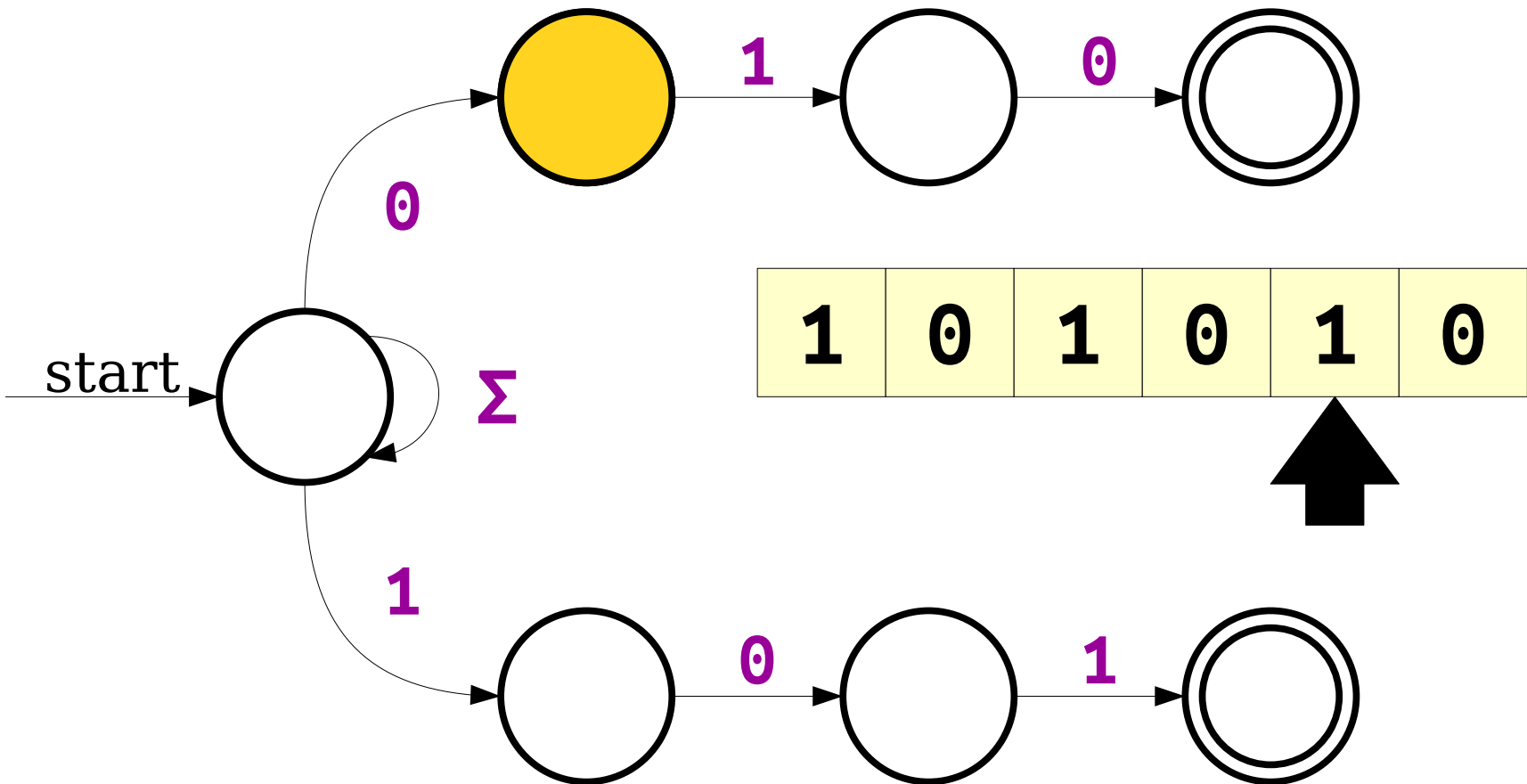
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$$L = \{ w \in \{0, 1\}^* \mid w \text{ ends in } 010 \text{ or } 101 \}$$



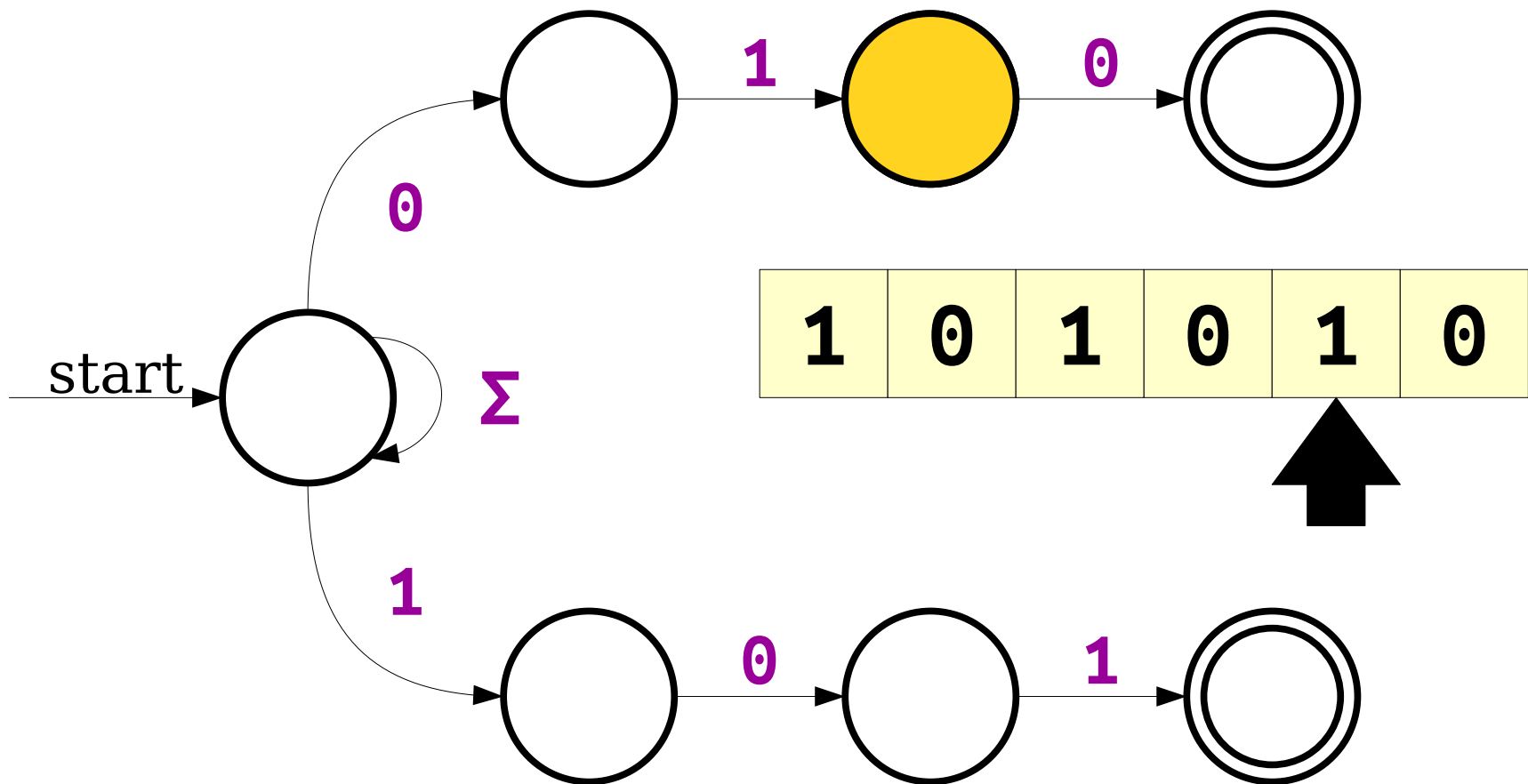
Guess-and-Check

$$L = \{ w \in \{0, 1\}^* \mid w \text{ ends in } 010 \text{ or } 101 \}$$



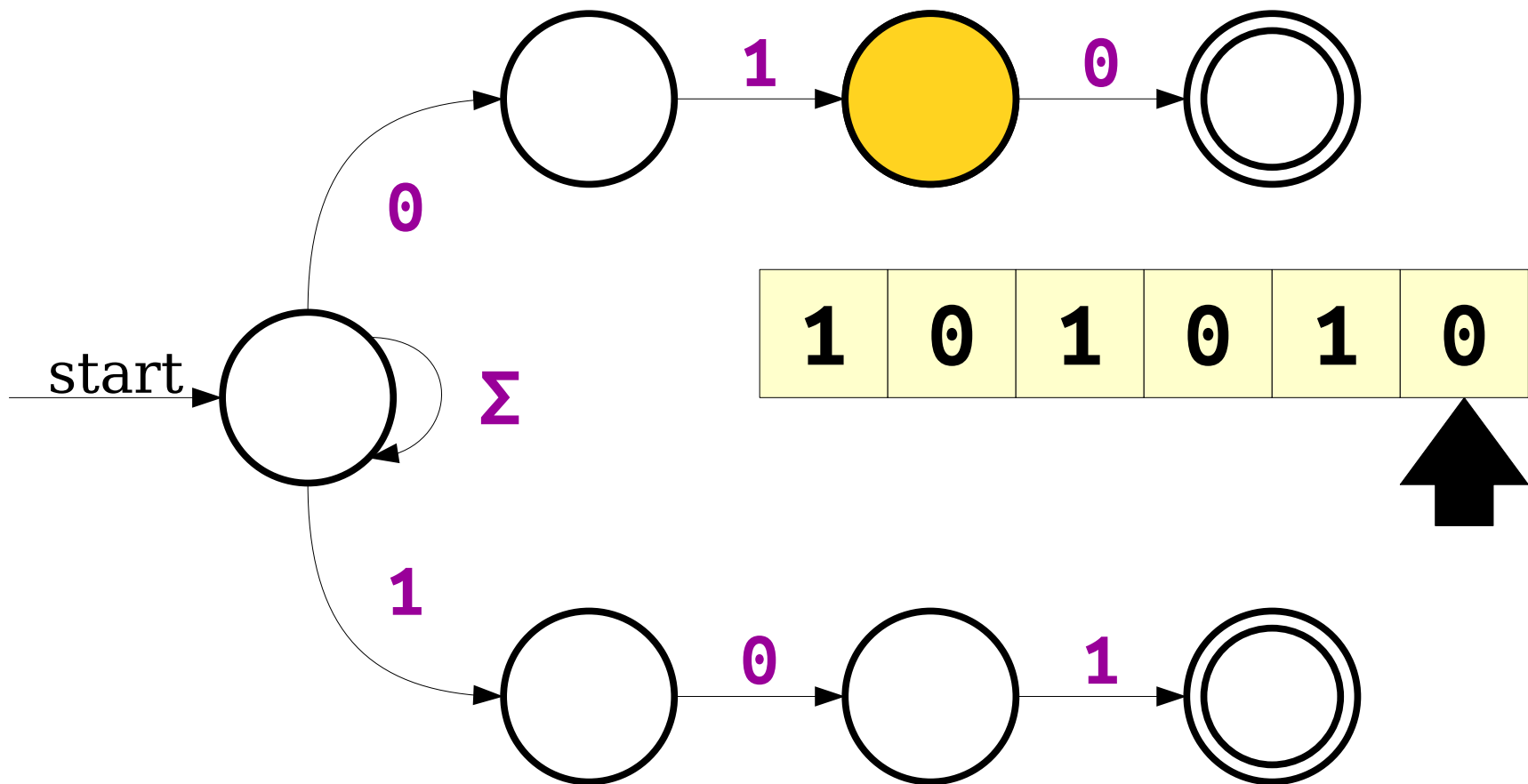
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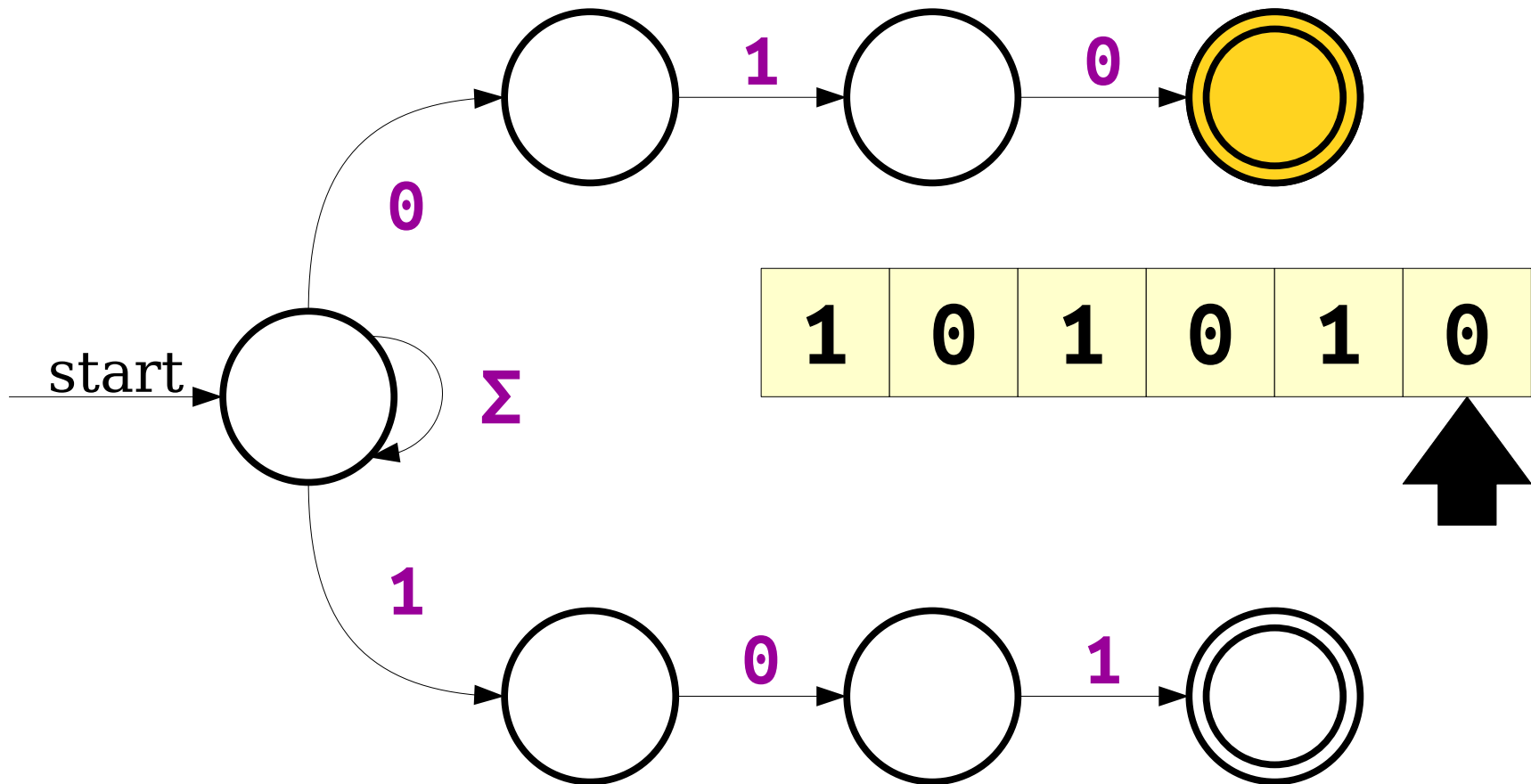
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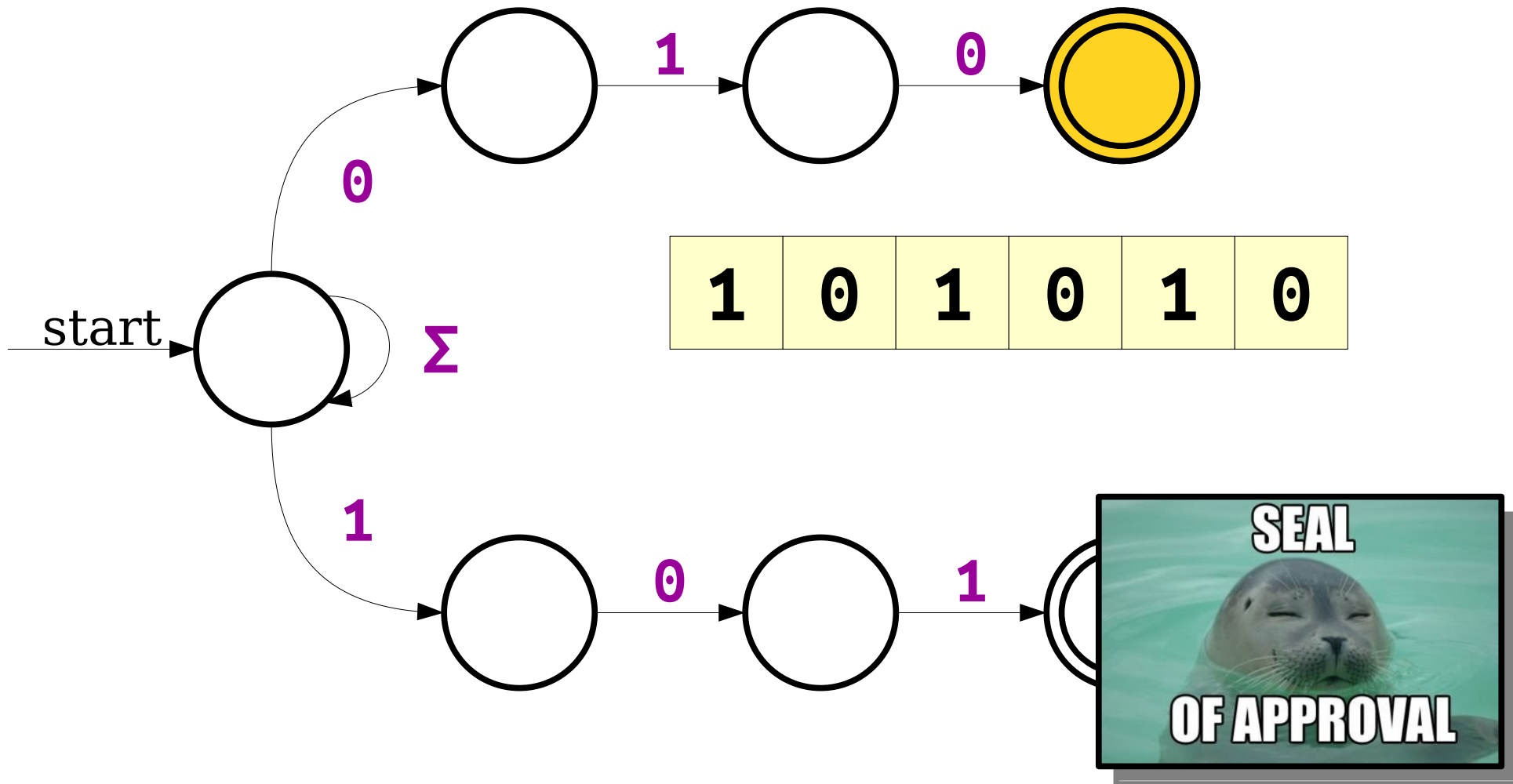
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Guess-and-Check

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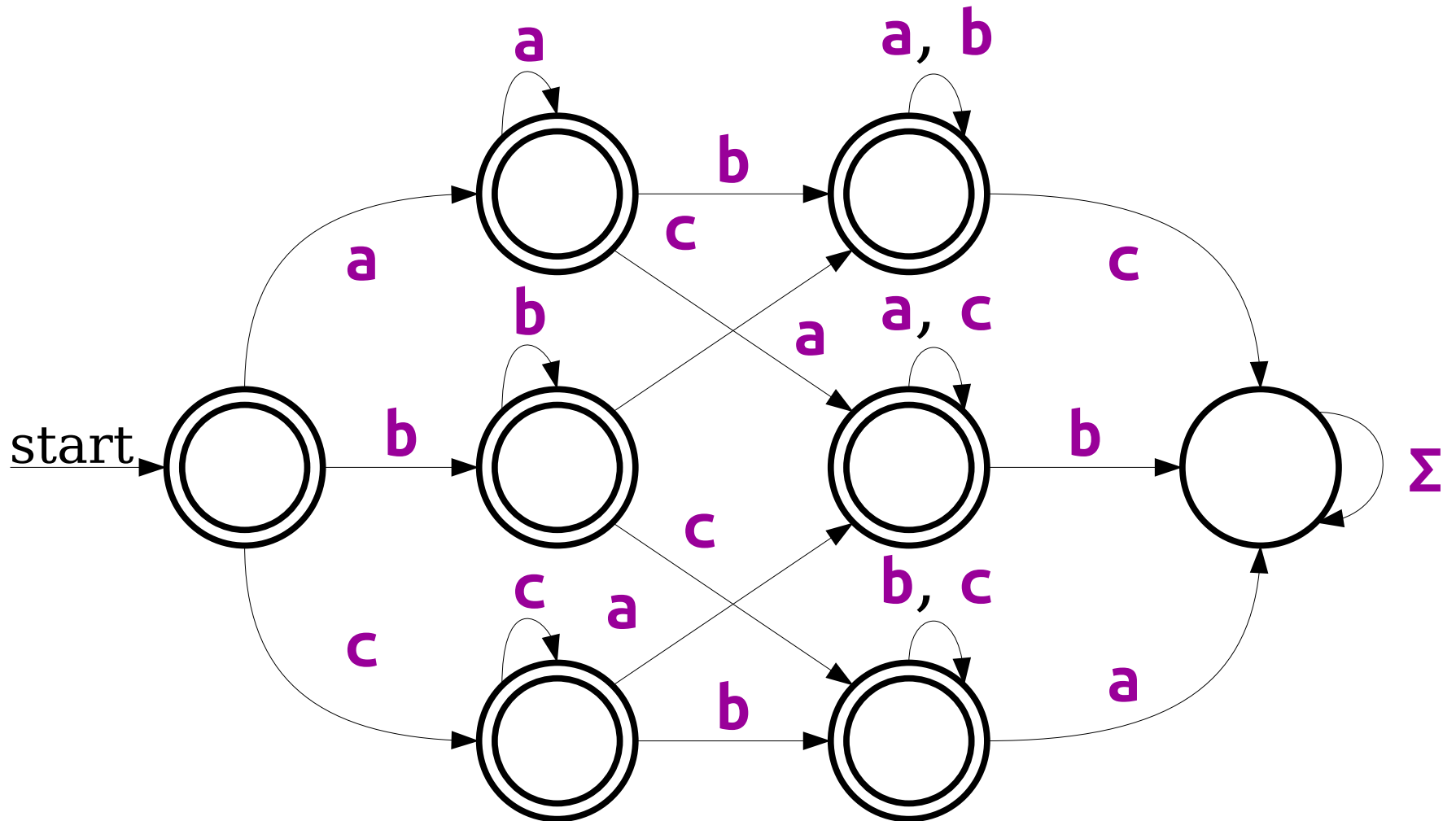


Guess-and-Check

$L = \{ w \in \{a, b, c\}^* \mid \text{at least one of } a, b, \text{ or } c \text{ is not in } w \}$

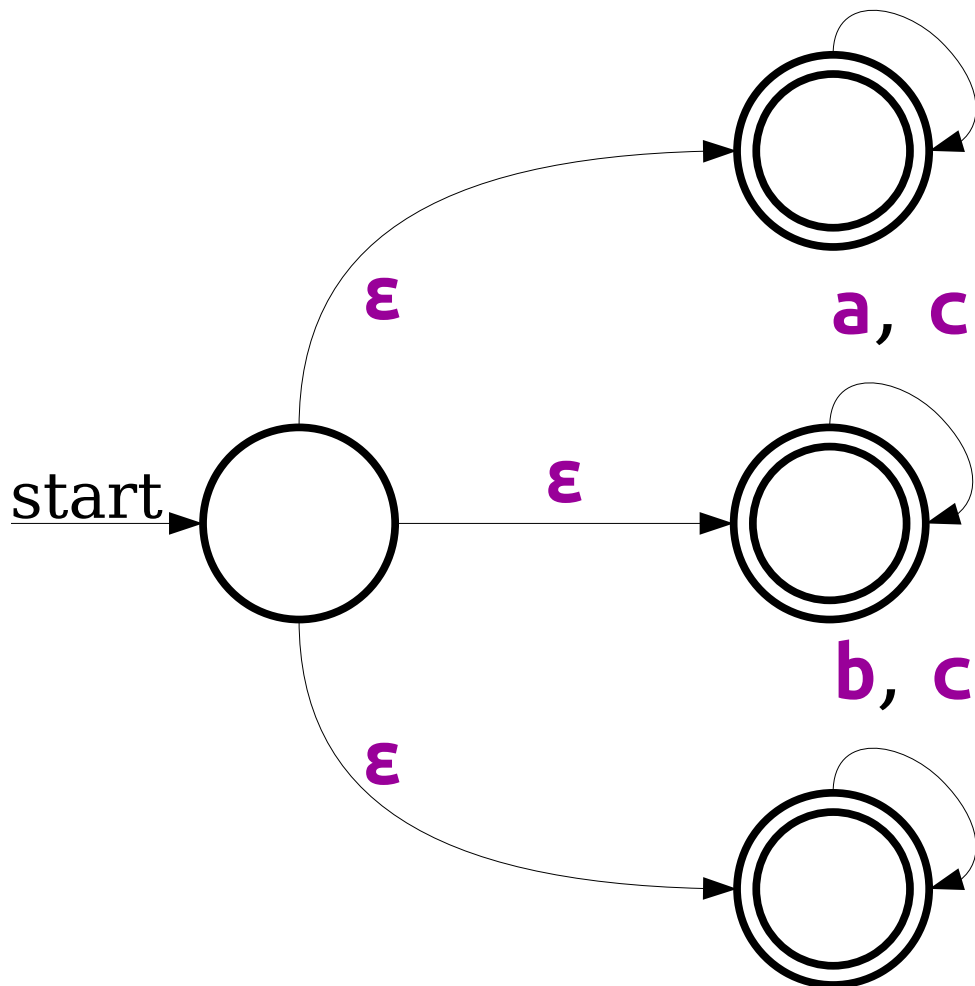
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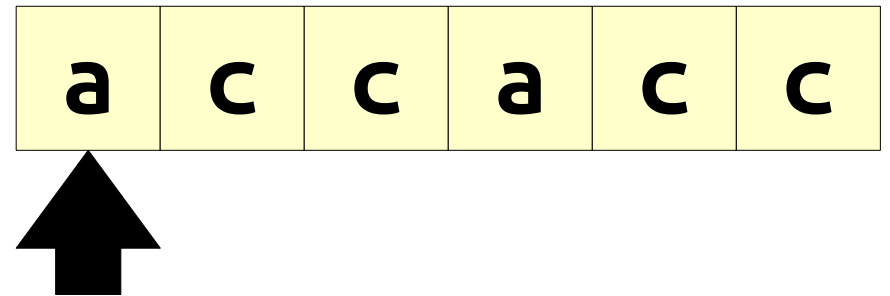
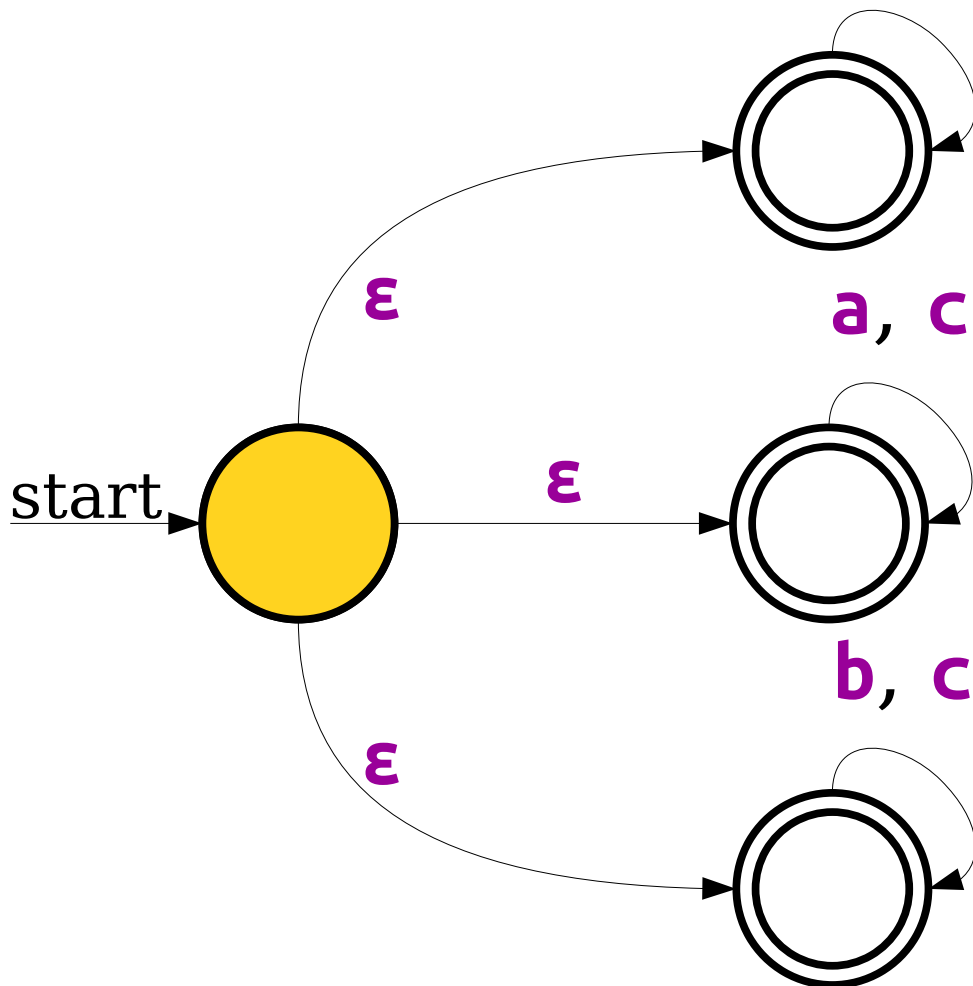


Nondeterministically *guess* which character is missing.

Deterministically *check* whether that character is indeed missing.

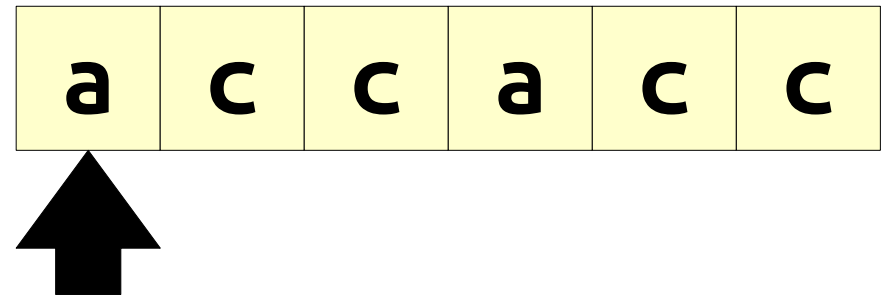
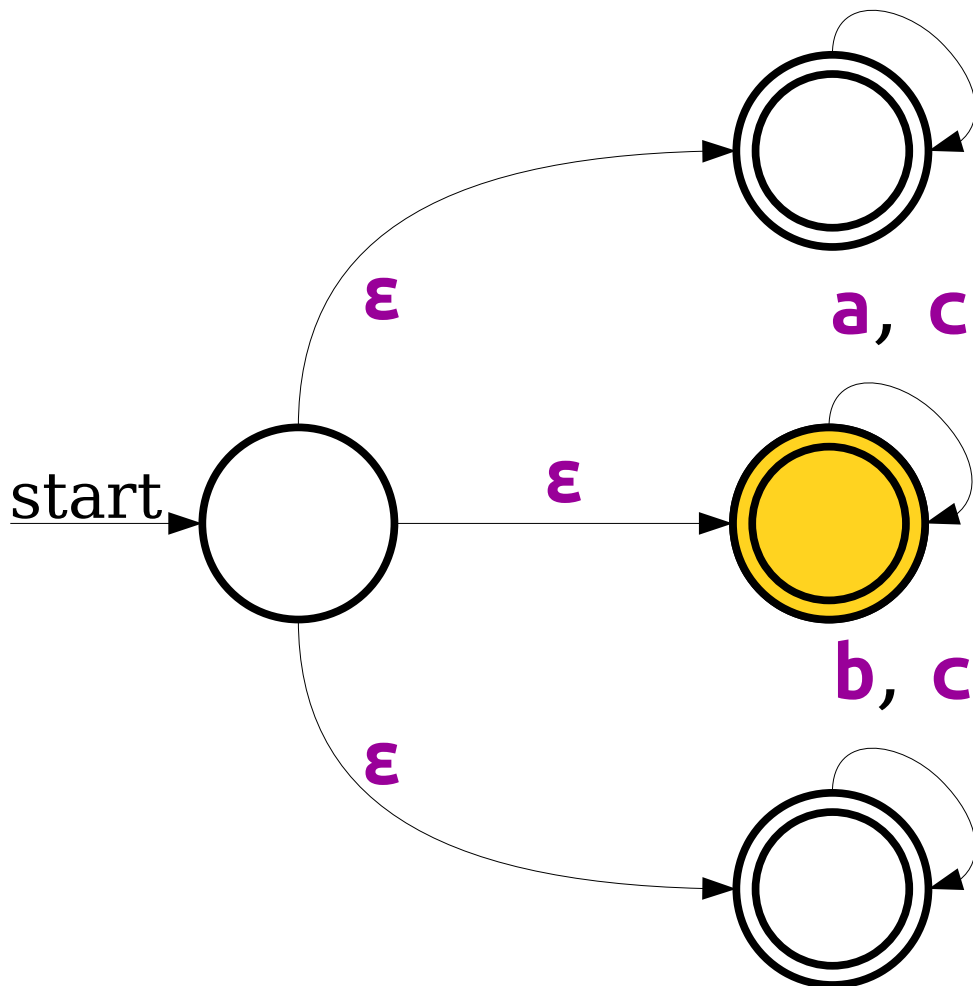
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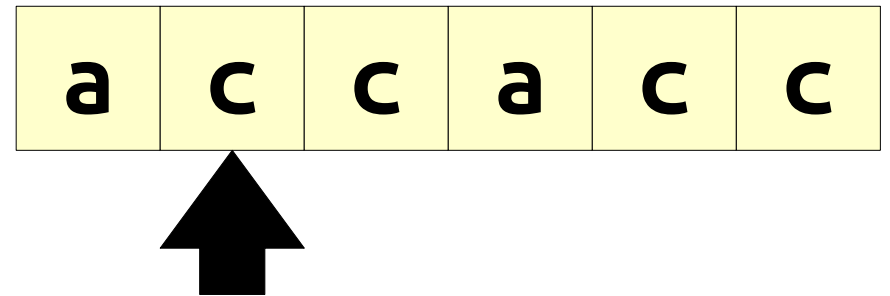
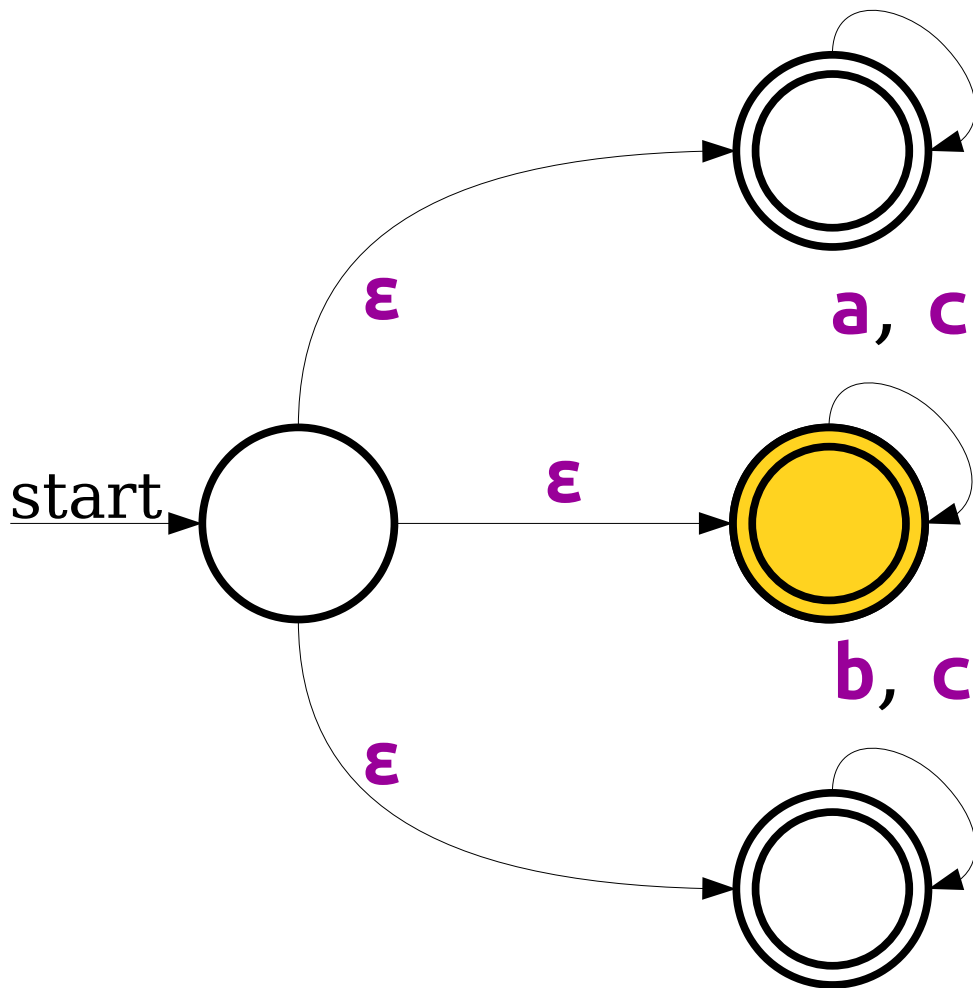
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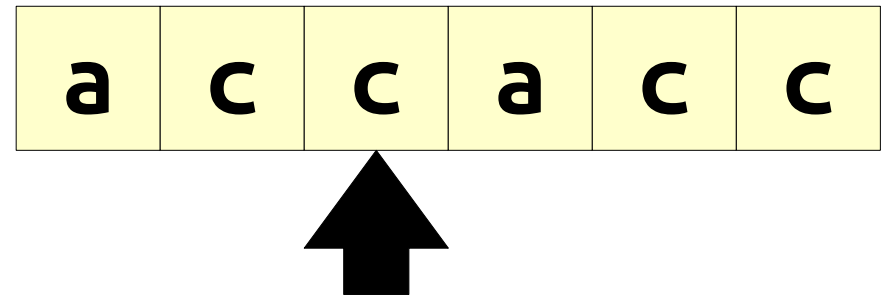
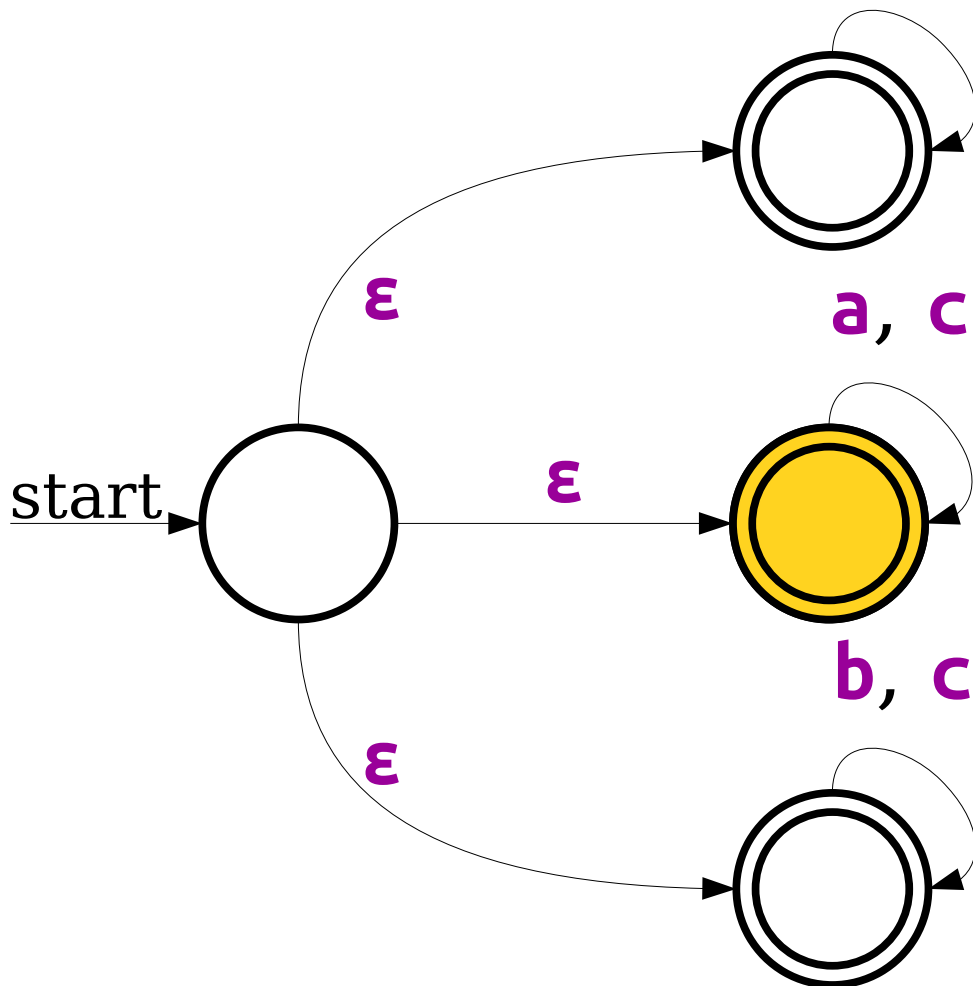
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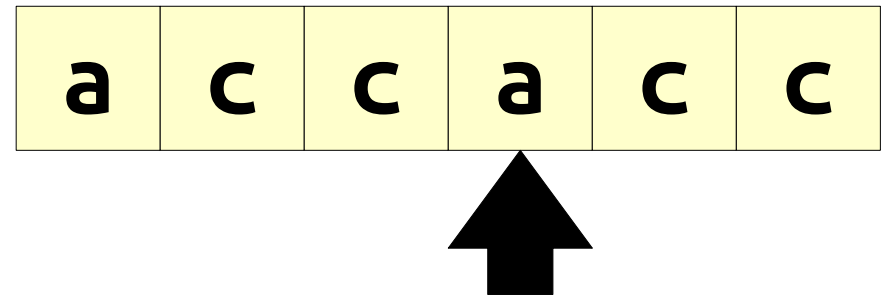
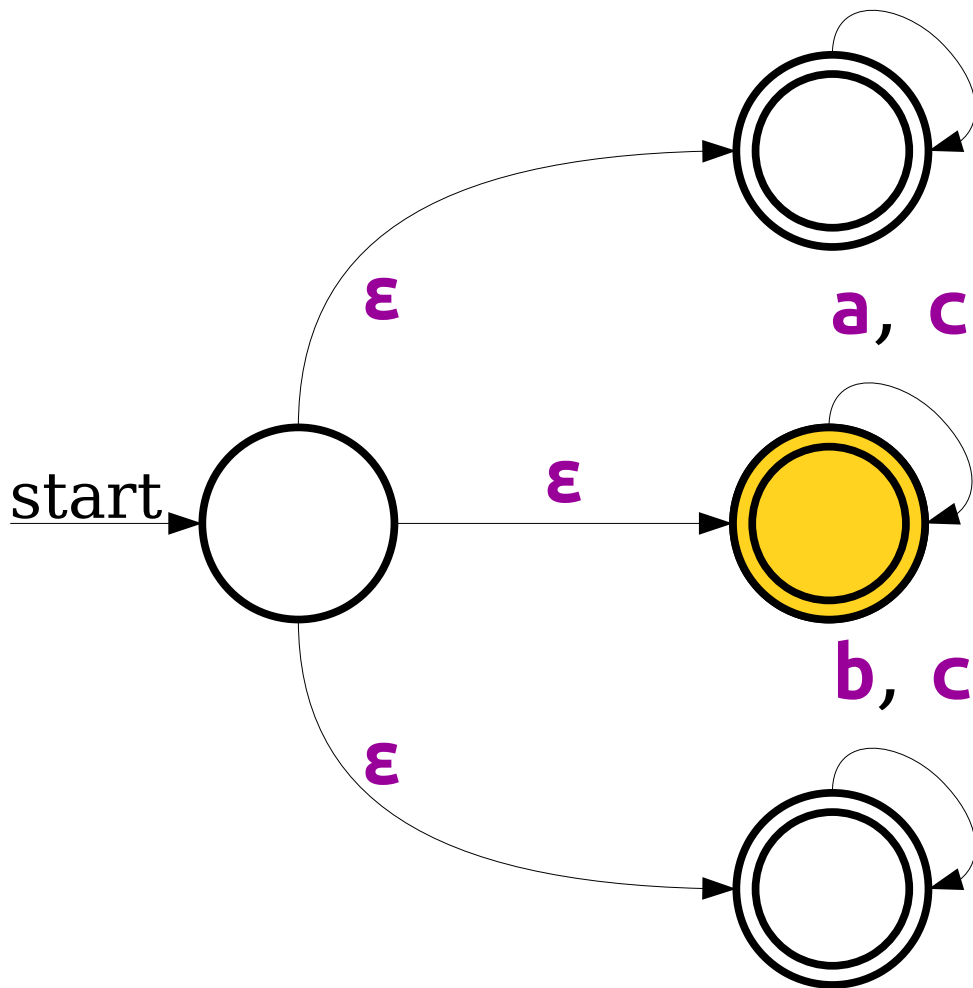
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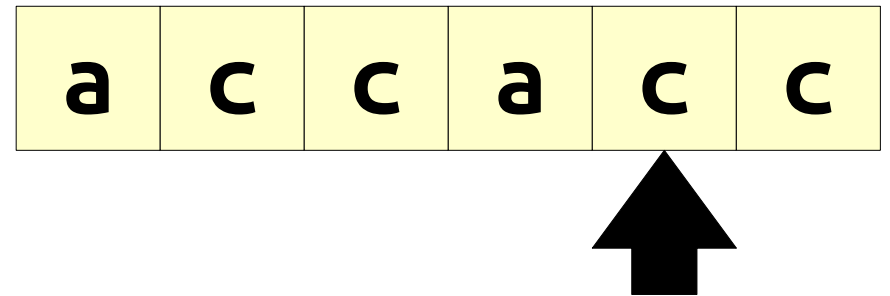
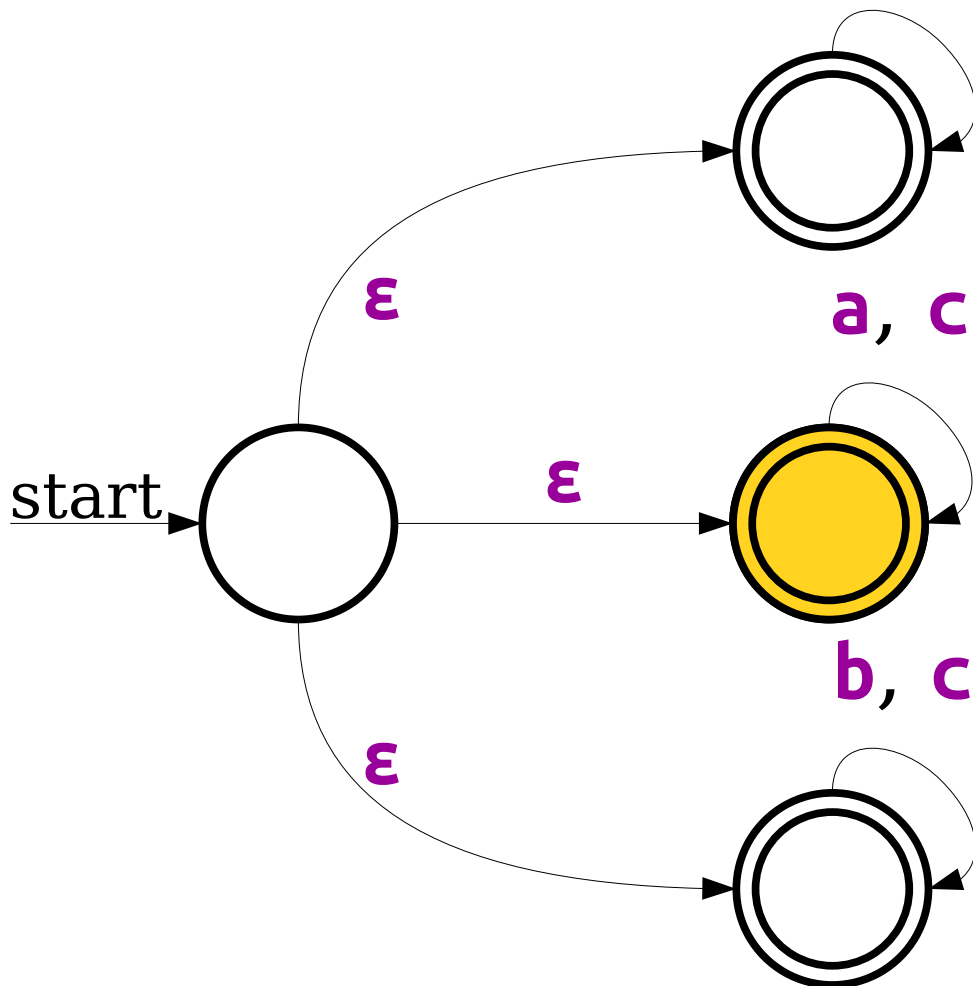
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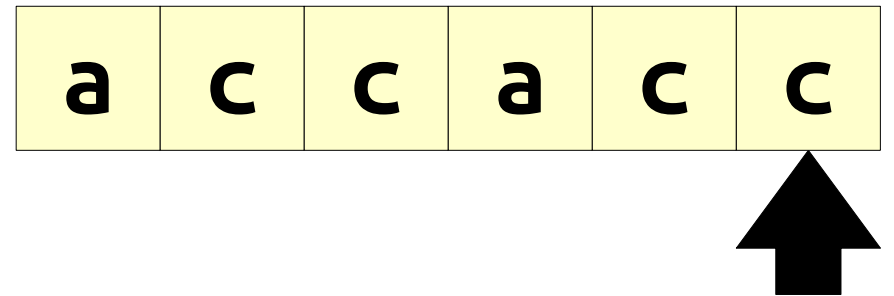
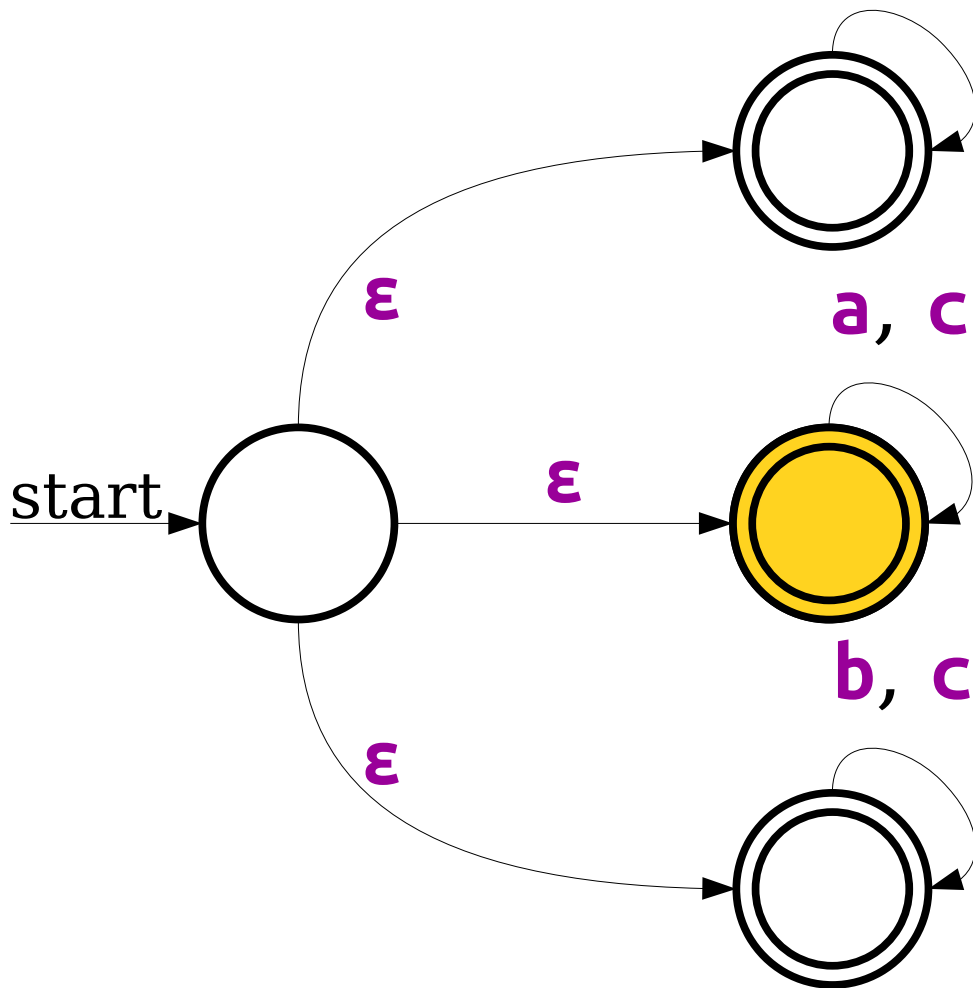
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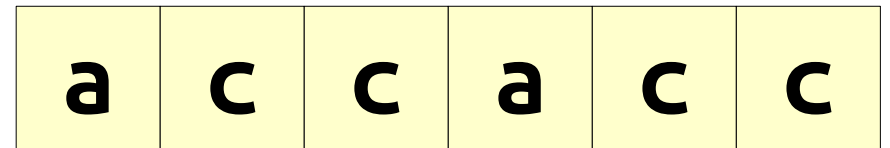
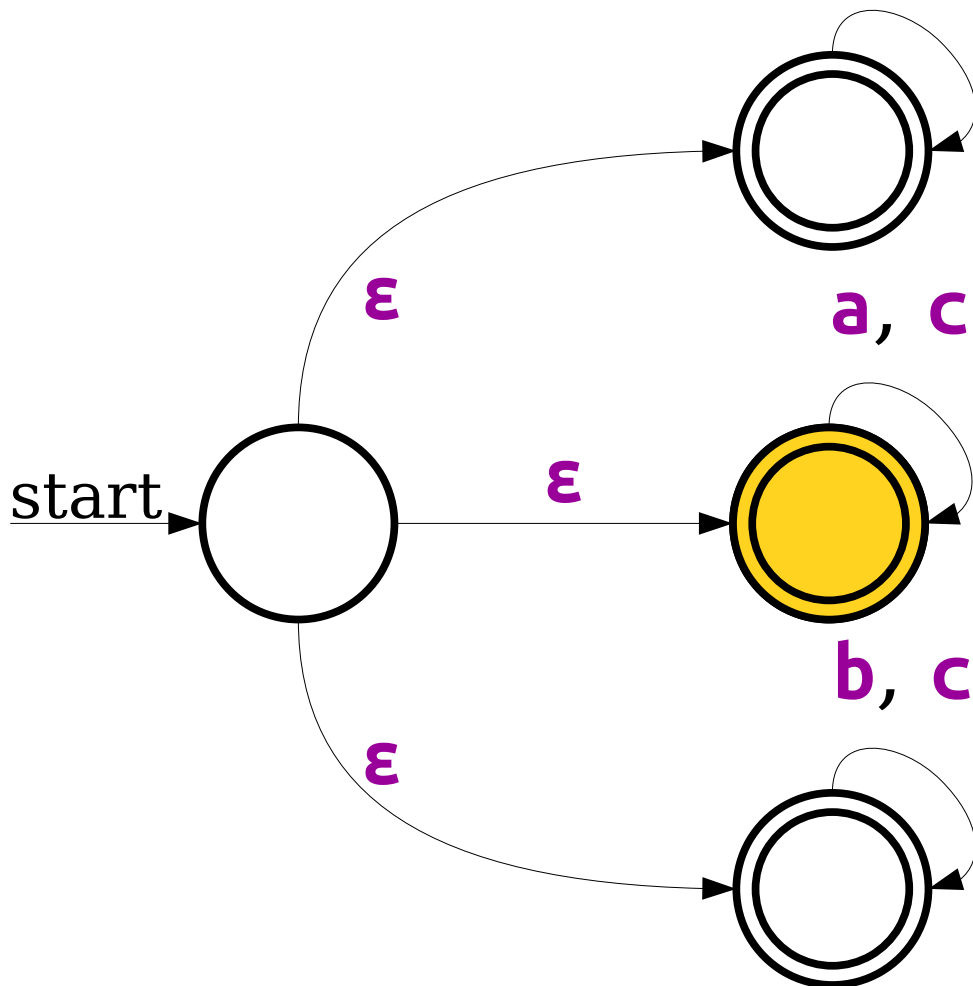
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Just how powerful are NFAs?

Next Time

- ***The Subset Construction***
 - So beautiful. So elegant. So cool!
- ***Closure Properties of Regular Languages***
 - Transforming languages by transforming machines.
- ***The Kleene Closure***
 - What's the deal with the notation Σ^* ?