Finite Automata

Part Two

Recap from Last Time

Strings

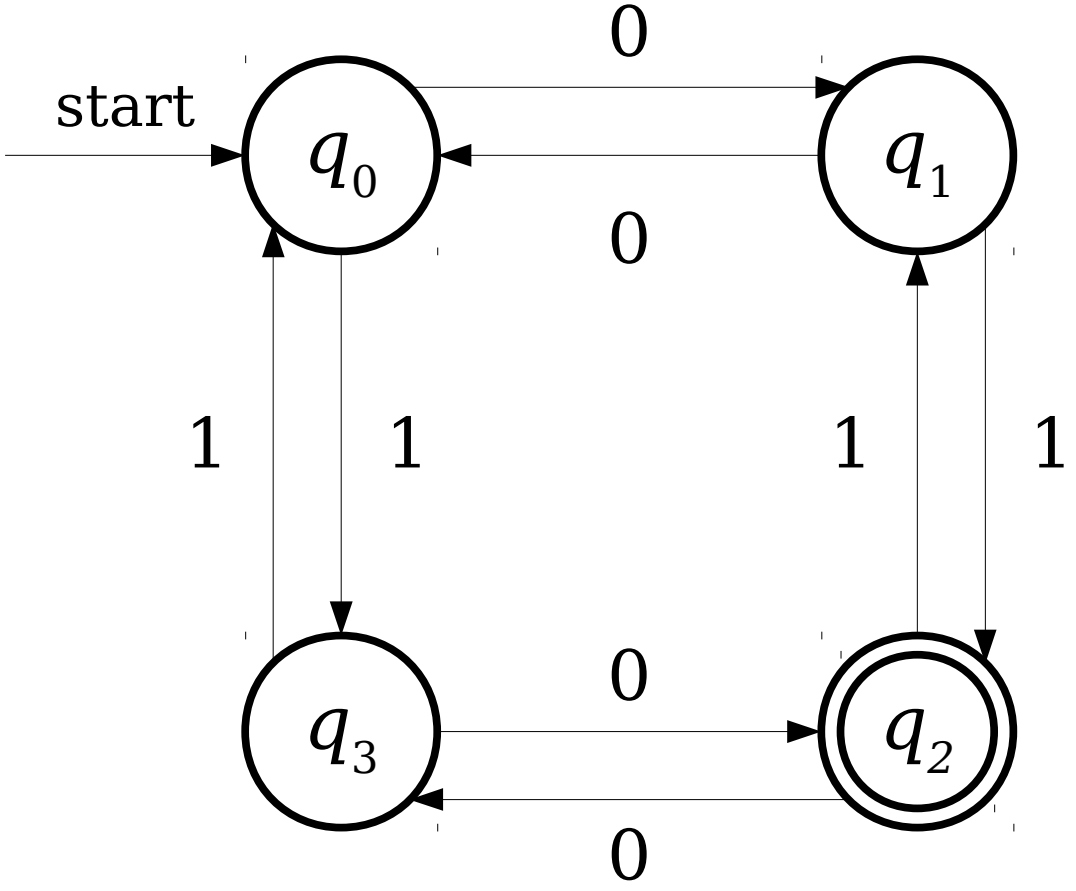
- An ***alphabet*** is a finite, nonempty set of symbols called ***characters***.
  - Typically, we use the symbol **Σ** to refer to an alphabet.
- A ***string over an alphabet Σ*** is a finite sequence of characters drawn from Σ.
- Example: If Σ = {**a**, **b**}, here are some valid strings over Σ:

  a **aabaaabbabaaabaaaabbb** **abbababba**
- The ***empty string*** has no characters and is denoted **ε**.
- Calling attention to an earlier point: since all strings are finite sequences of characters from Σ, you cannot have a string of infinite length.

Languages

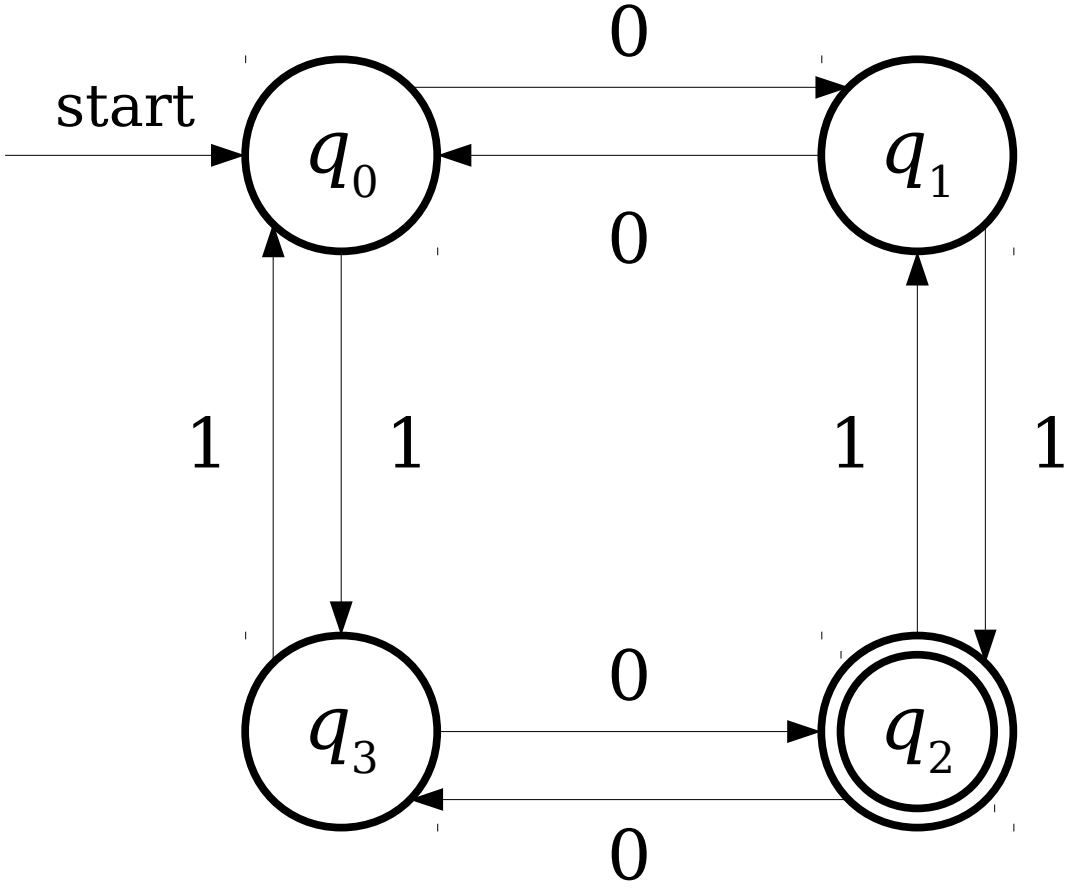
- A ***formal language*** is a set of strings.
- We say that L is a ***language over Σ*** if it is a set of strings over Σ.
- Example: The language of palindromes over Σ = {**a**, **b**, **c**} is the set
  - {ε, **a**, **b**, **c**, **aa**, **bb**, **cc**, **aaa**, **aba**, **aca**, **bab**, … }
- The set of all strings composed from letters in Σ is denoted **Σ***.
- Formally, we say that L is a language over Σ if $L \subseteq \Sigma^*$.

A Simple Finite Automaton



0 1 0 1 1 0

A Simple Finite Automaton



1 0 1 0 0 0

The ***language of an automaton*** is the set of strings that it accepts.

If D is an automaton, we denote the language of D as $\mathscr{L}(D)$.

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

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.

DFAs, Informally

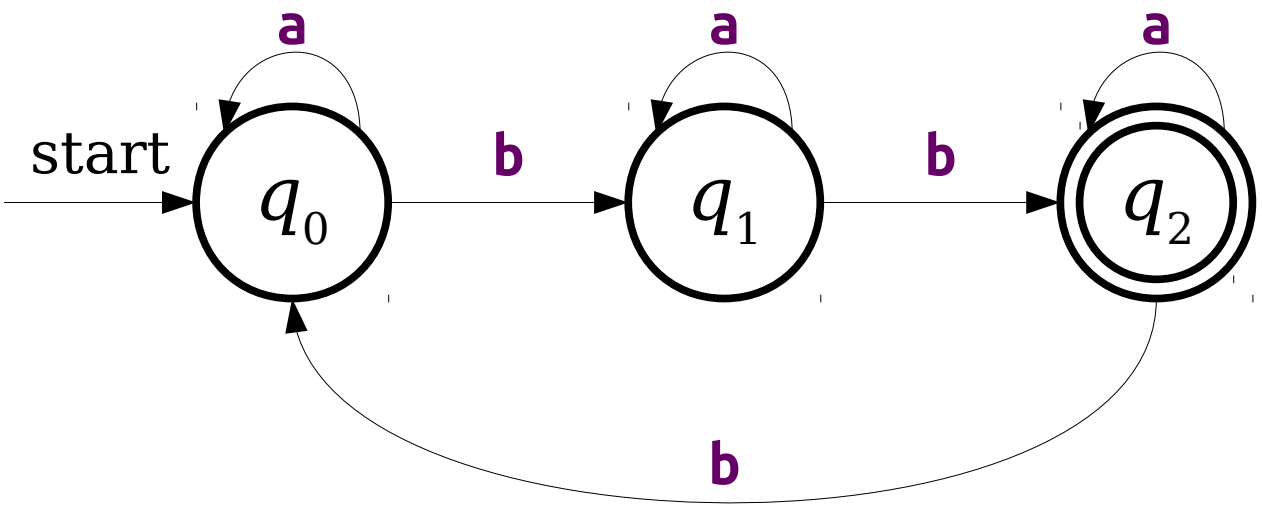
- A DFA is defined relative to some alphabet Σ.
- For each state in the DFA, there must be ***exactly one*** transition defined for each symbol in Σ.
  - This is the “deterministic” part of DFA.
- There is a unique start state.
- There are zero or more accepting states.

Designing DFAs

- At each point in its execution, the DFA can only remember what state it is in.
- ***DFA Design Tip:*** Build each state to correspond to some piece of information you need to remember.
  - Each state acts as a “memento” of what you're supposed to do next.
  - Only finitely many different states ≈ only finitely many different things the machine can remember.

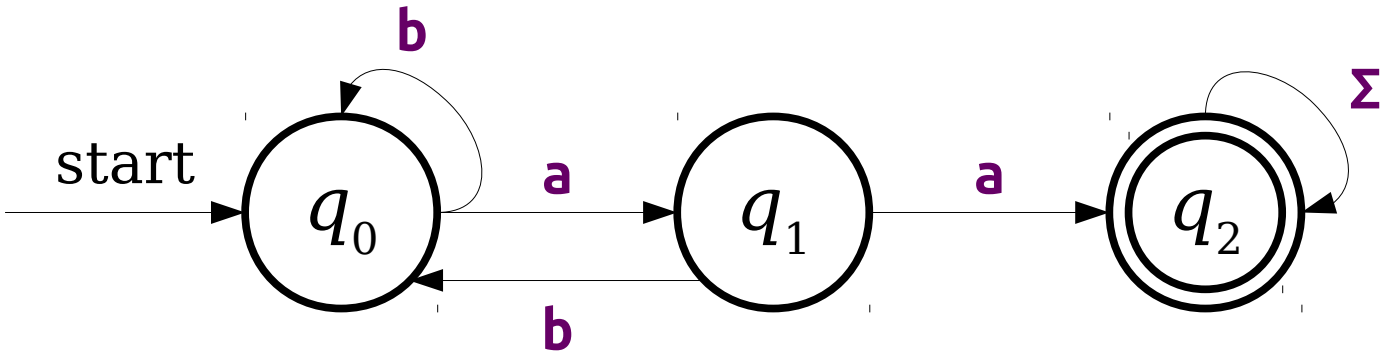
Recognizing Languages with DFAs

$L = \{ w \in \{\mathtt{a}, \mathtt{b}\}^* |$ the number of **b**'s in w is congruent to two modulo three $\}$



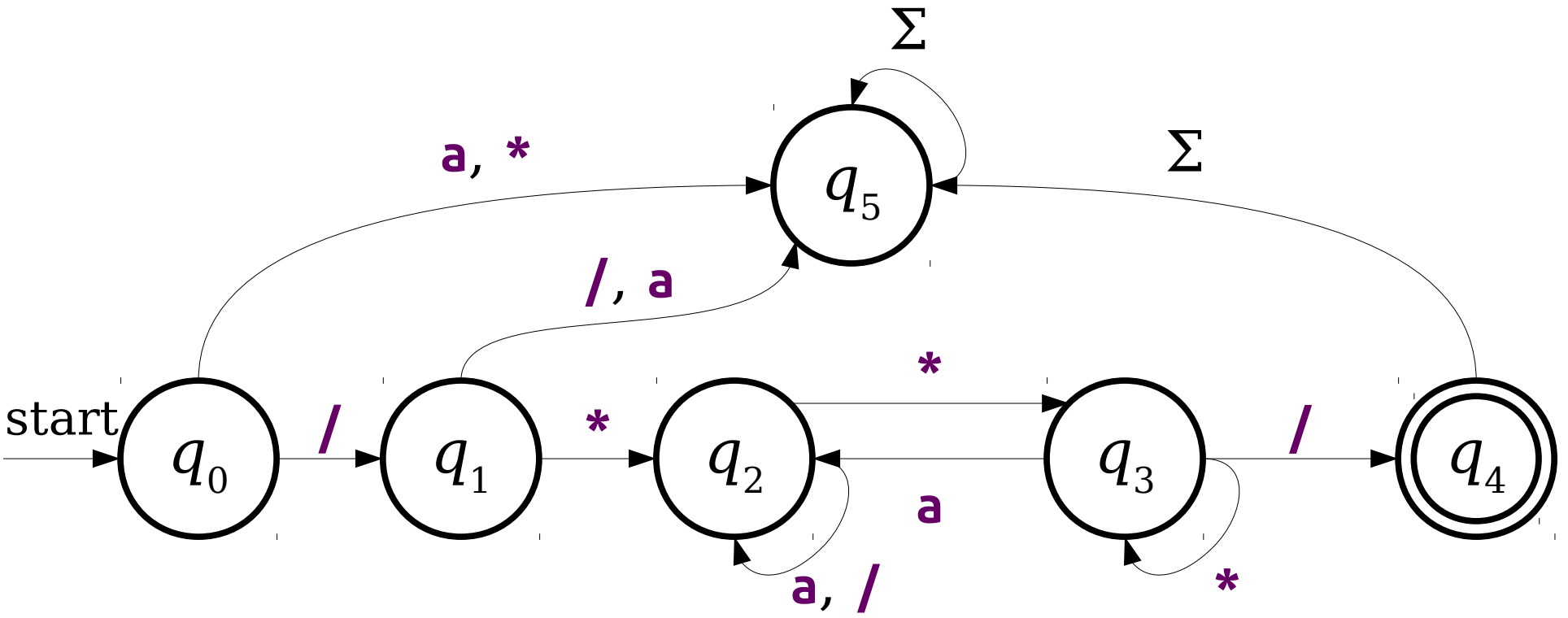
Recognizing Languages with DFAs

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



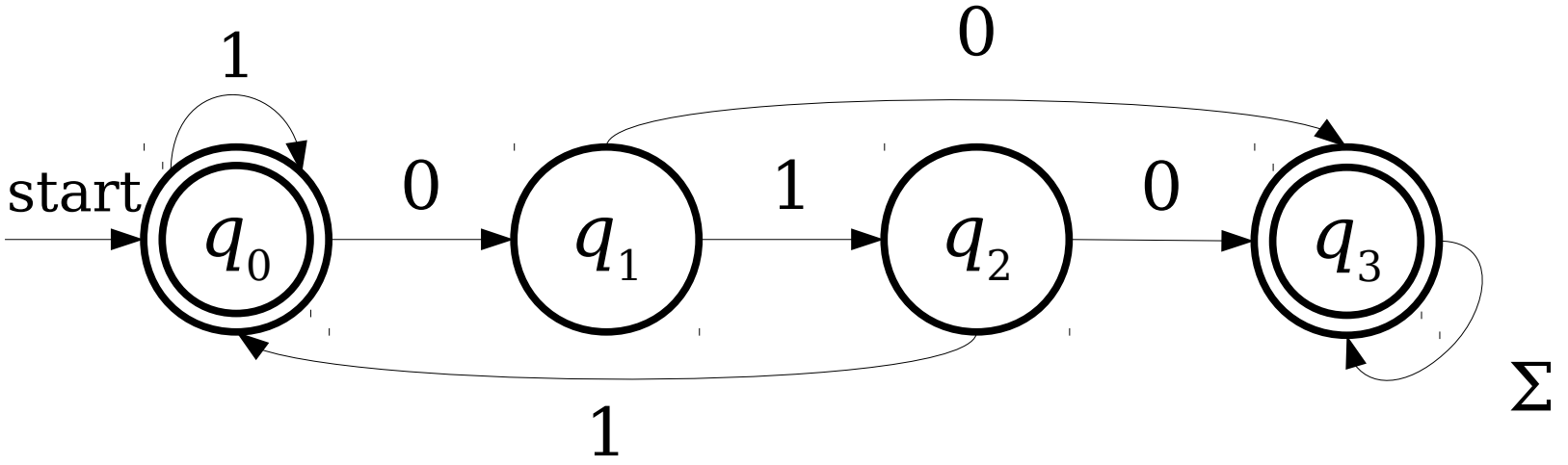
Recognizing Languages with DFAs

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

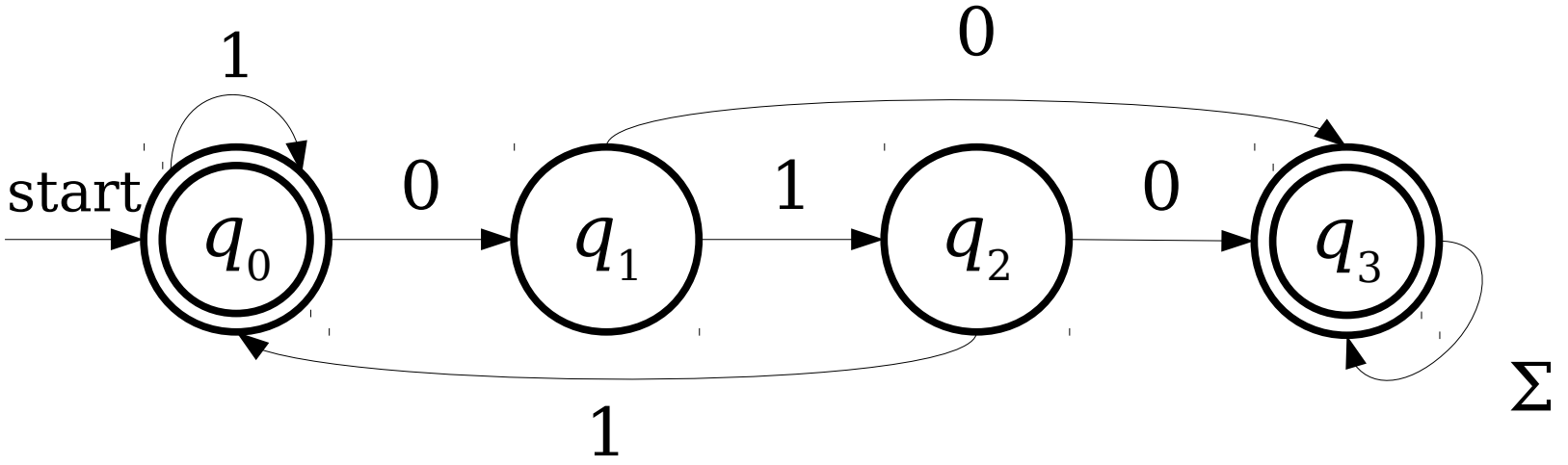


New Stuff!

Tabular DFAs

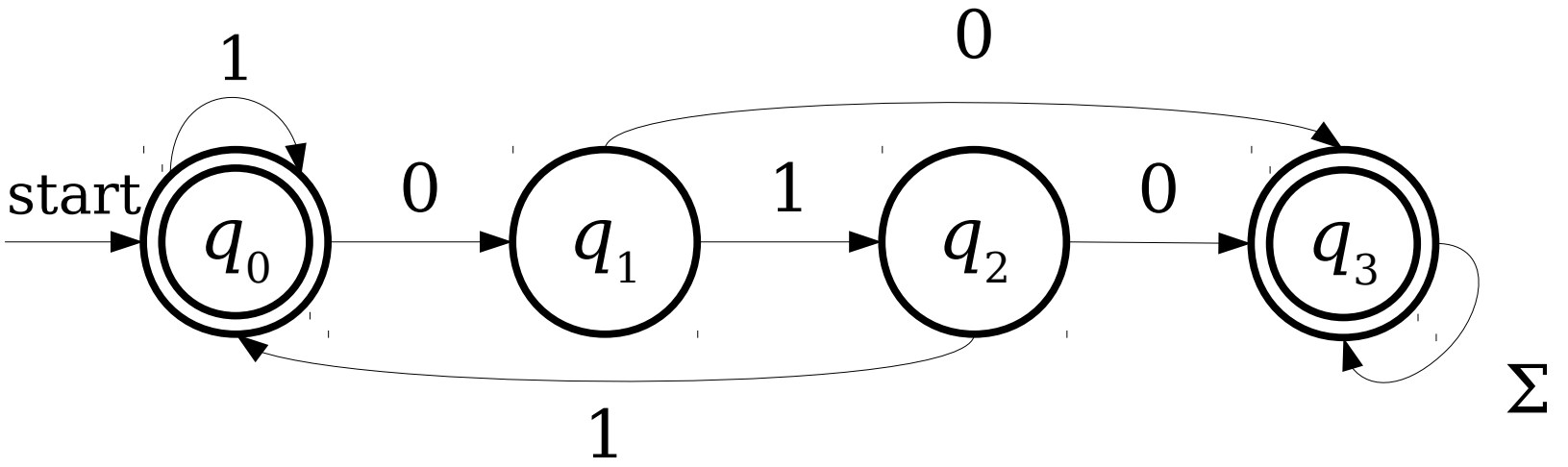


Tabular DFAs



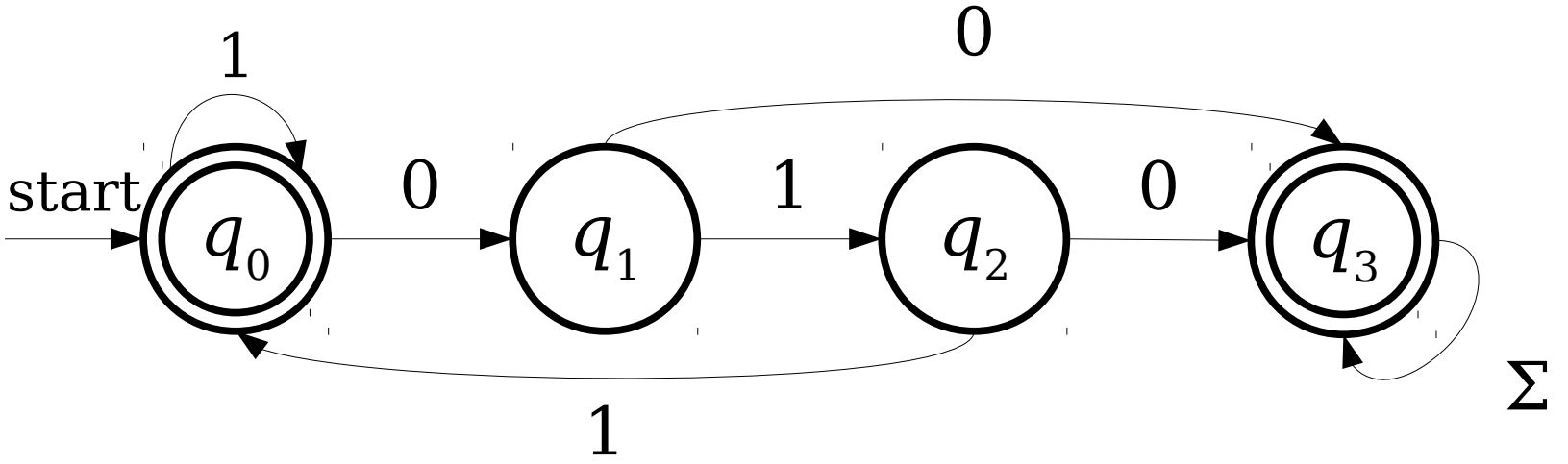
	0	1
q_0		
q_1		
q_2		
q_3		

Tabular DFAs



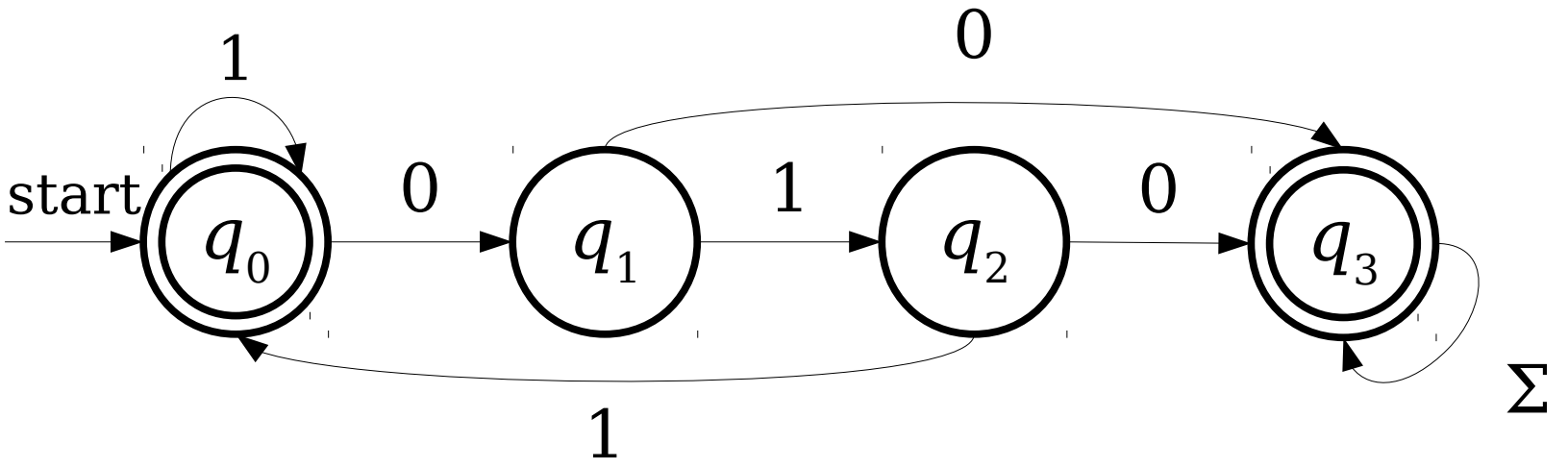
	0	1
q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
q_3	q_3	q_3

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

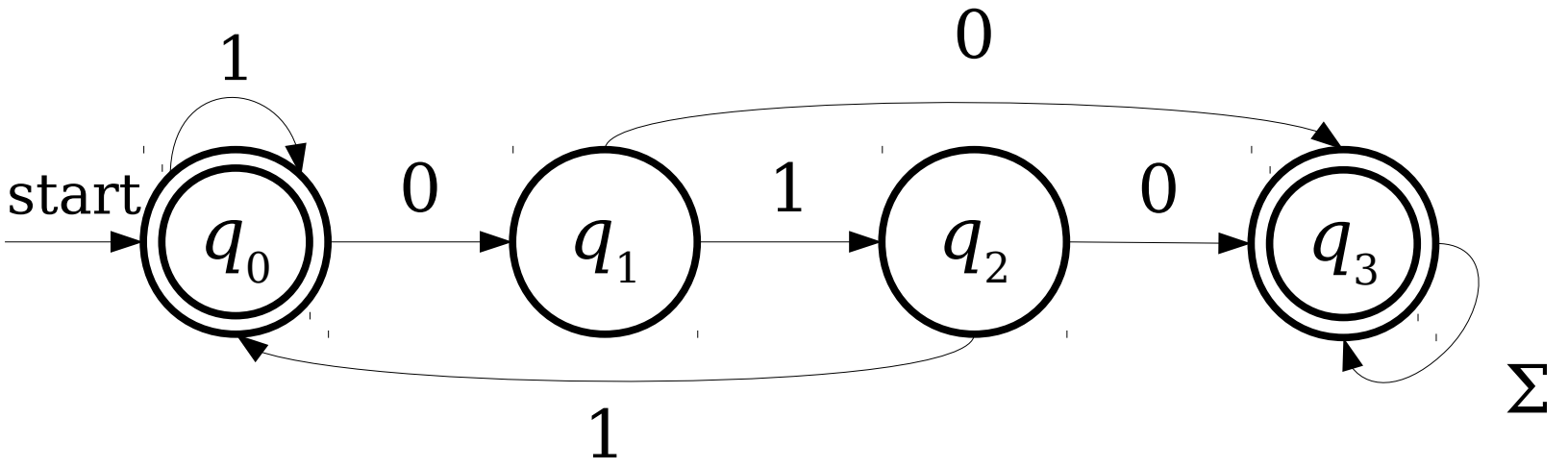
Tabular DFAs



	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.

My Turn to Code Things Up!

```
int kTransitionTable[kNumStates][kNumSymbols] = {
     {0, 0, 1, 3, 7, 1, …},
      …
};
bool kAcceptTable[kNumStates] = {
    false,
    true,
    true,
    …
};
bool SimulateDFA(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 $\mathscr{L}(D) = L$.

The Complement of a Language

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

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

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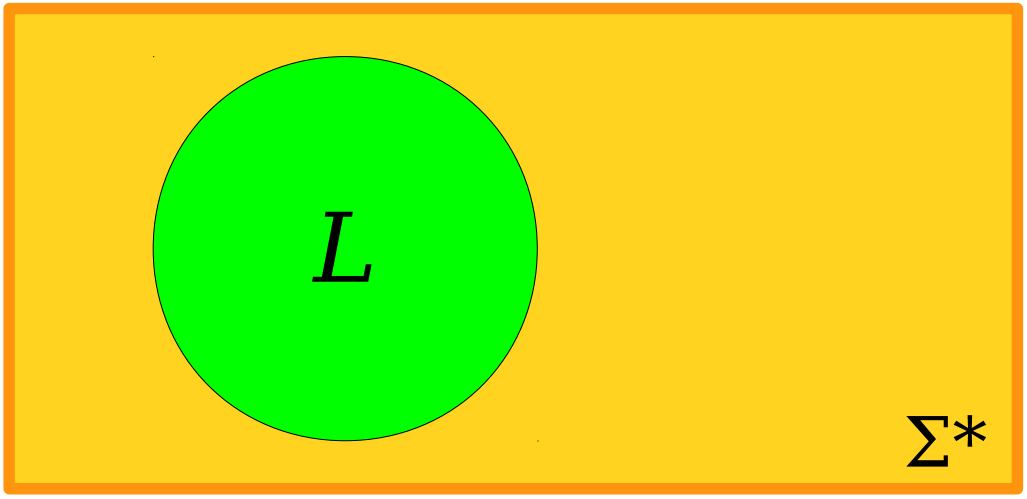

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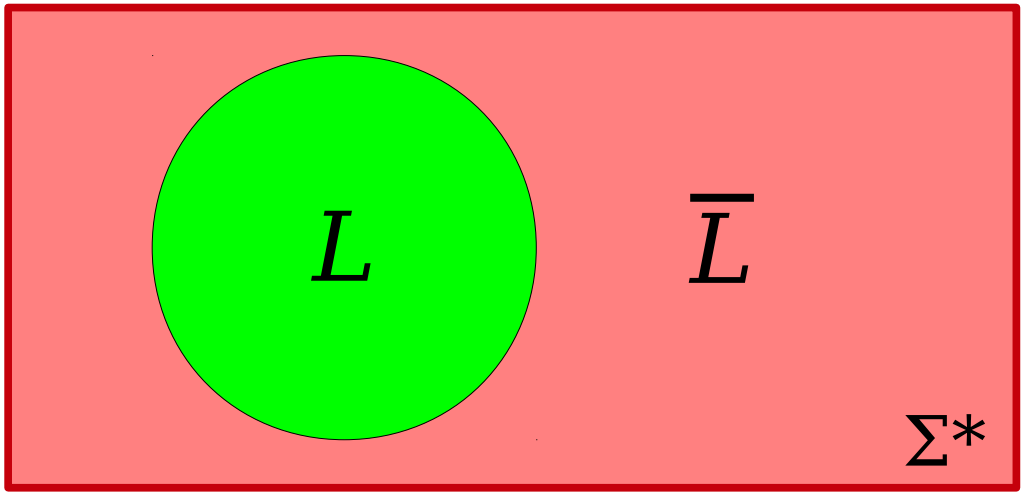
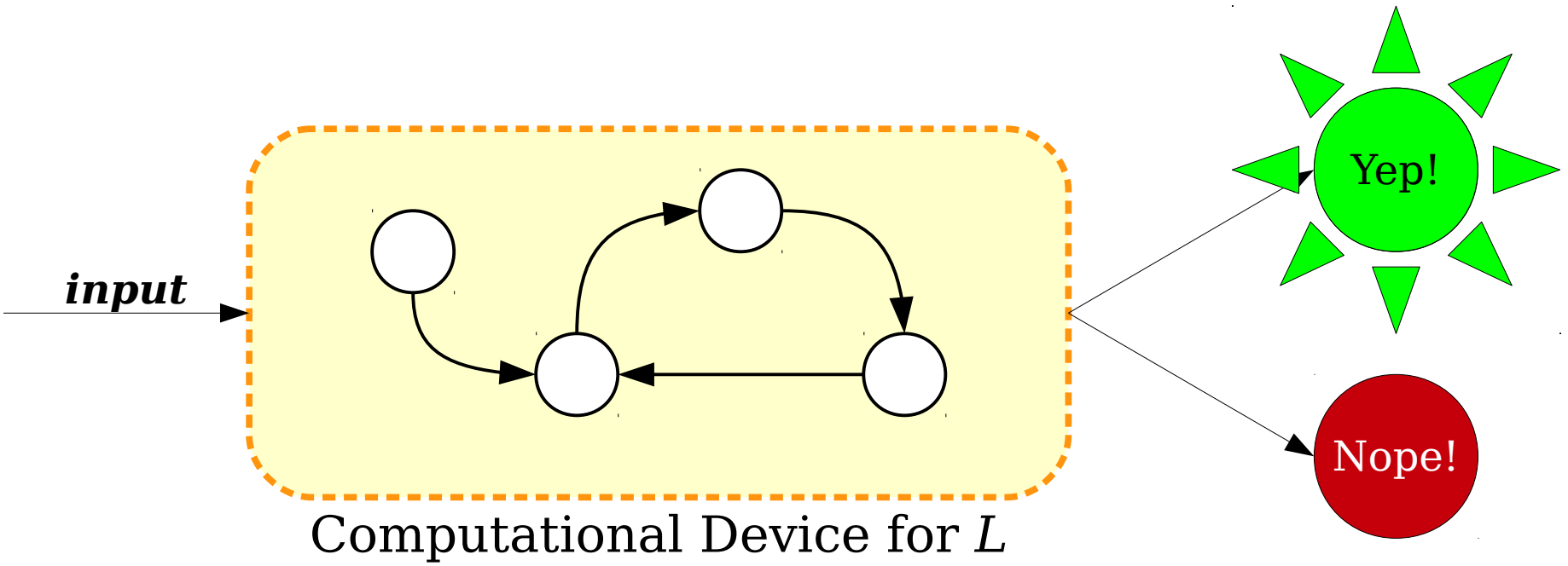
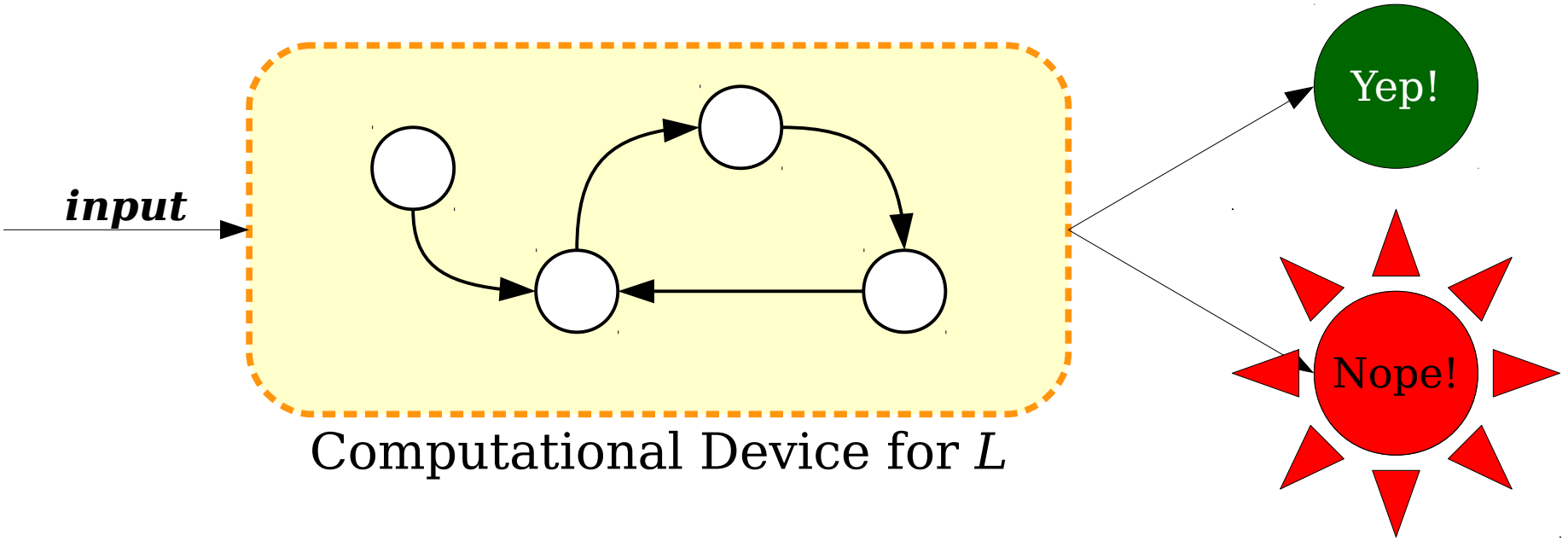


Complements of Regular Languages

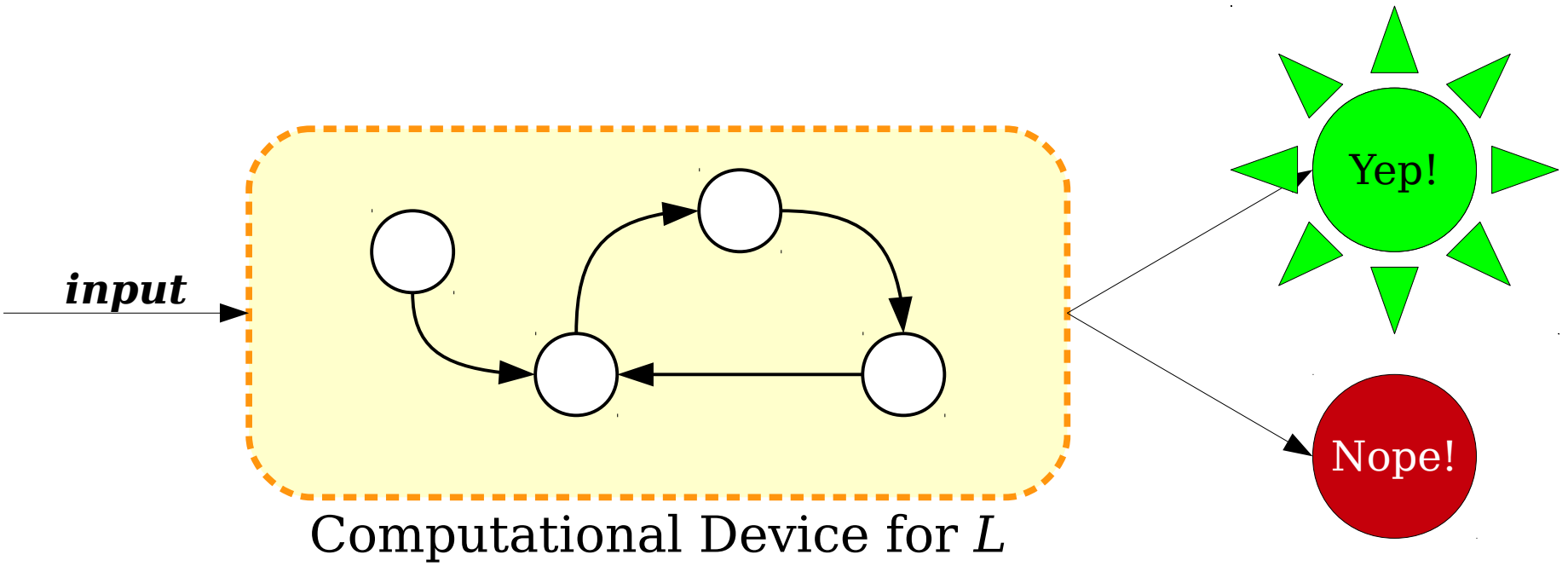
- As we saw a few minutes ago, a ***regular language*** is a language accepted by some DFA.
- ***Question:*** If L is a regular language, is $\overline{L}$ necessarily a regular language?
- If the answer is "yes," then if there is a way to construct a DFA for L, there must be some way to construct a DFA for $\overline{L}$.
- If the answer is "no," then some language L can be accepted by some DFA, but $\overline{L}$ cannot be accepted by any DFA.

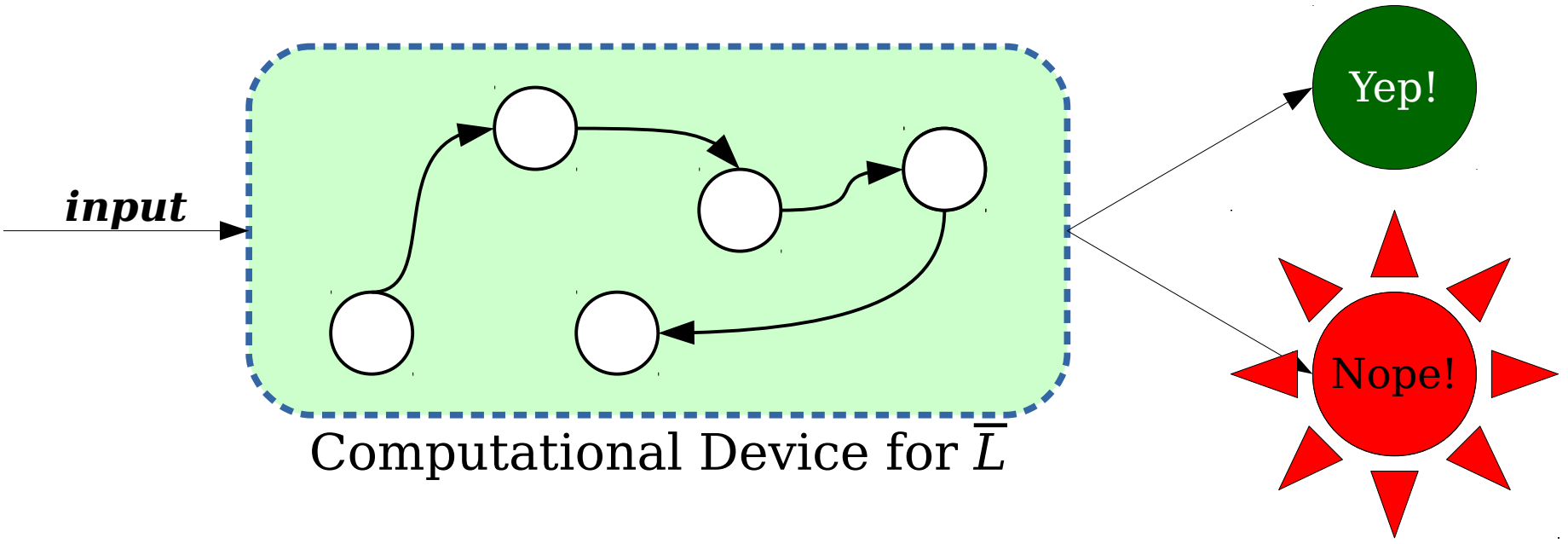


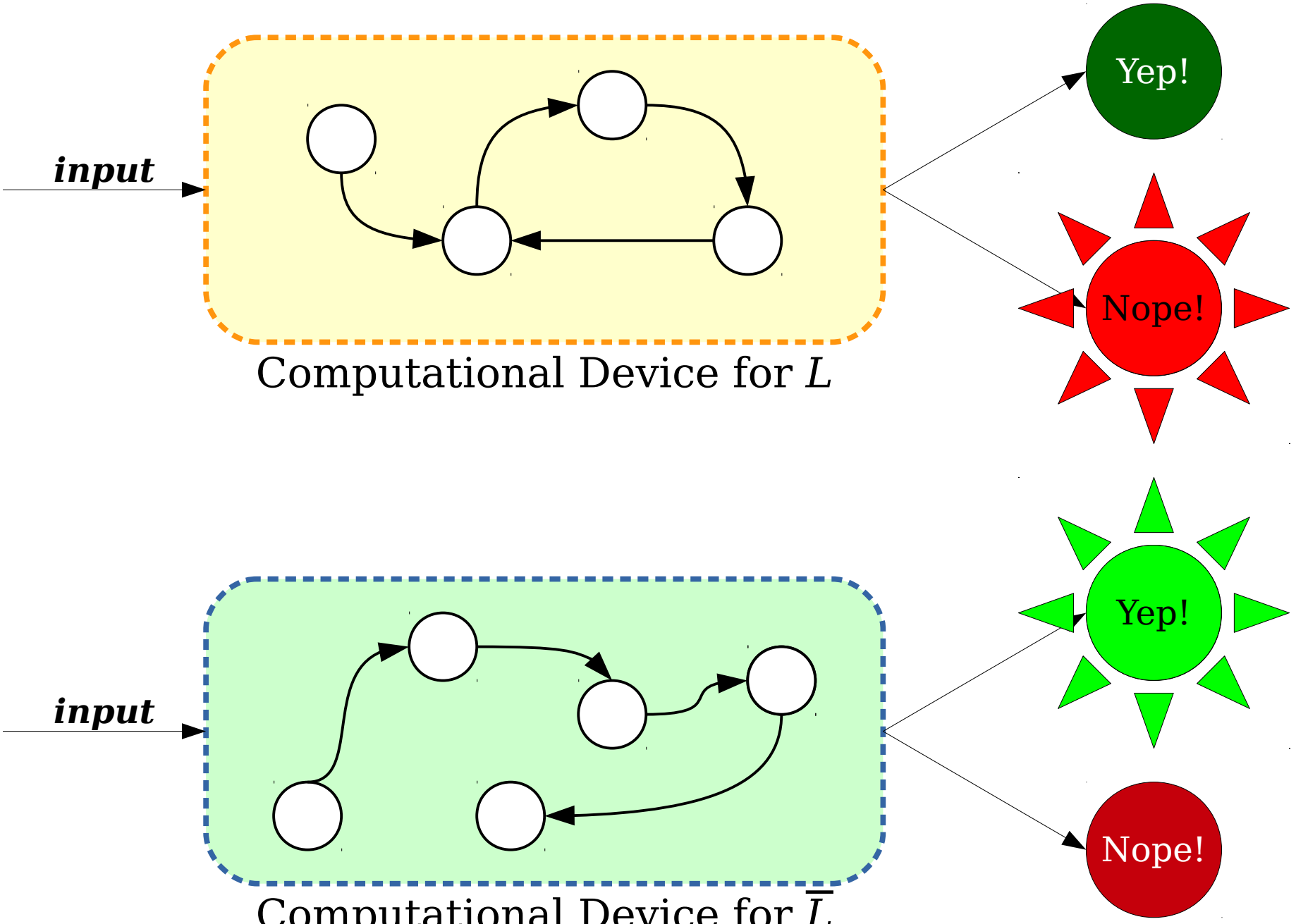
Computational Device for L



Computational Device for L

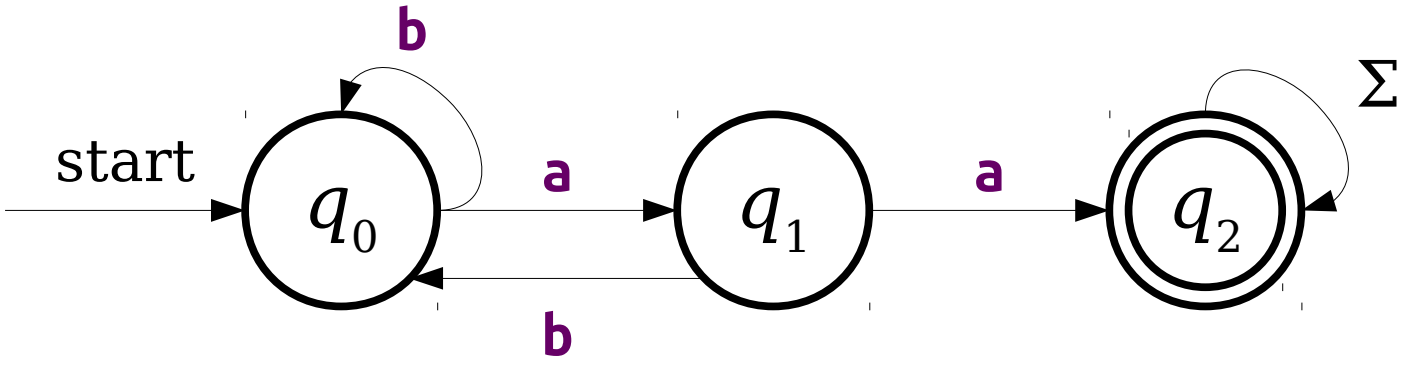

input
Yep!
Nope!
Computational Device for L


input
Yep!
Nope!
Computational Device for $\overline{L}$

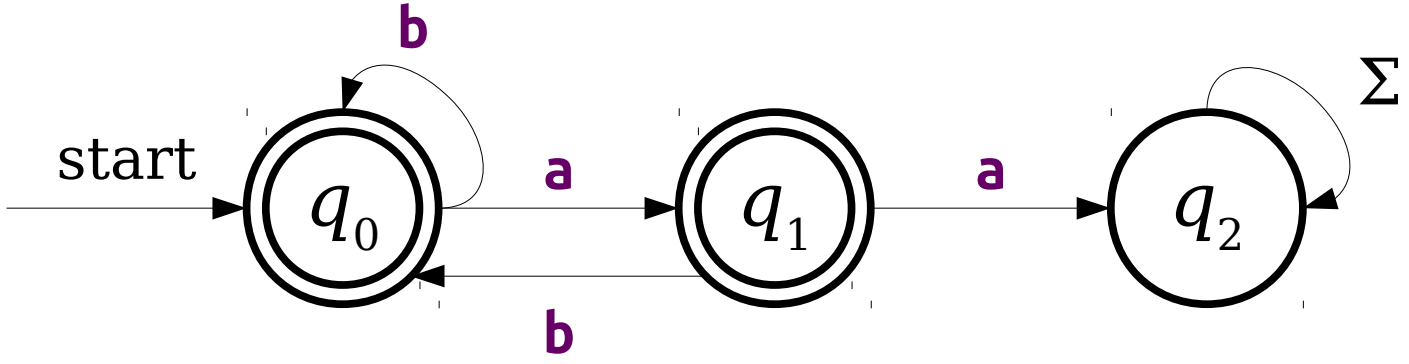

input
Yep!
Nope!
Computational Device for L
input
Yep!
Nope!
Computational Device for $\overline{L}$

Complementing Regular Languages

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

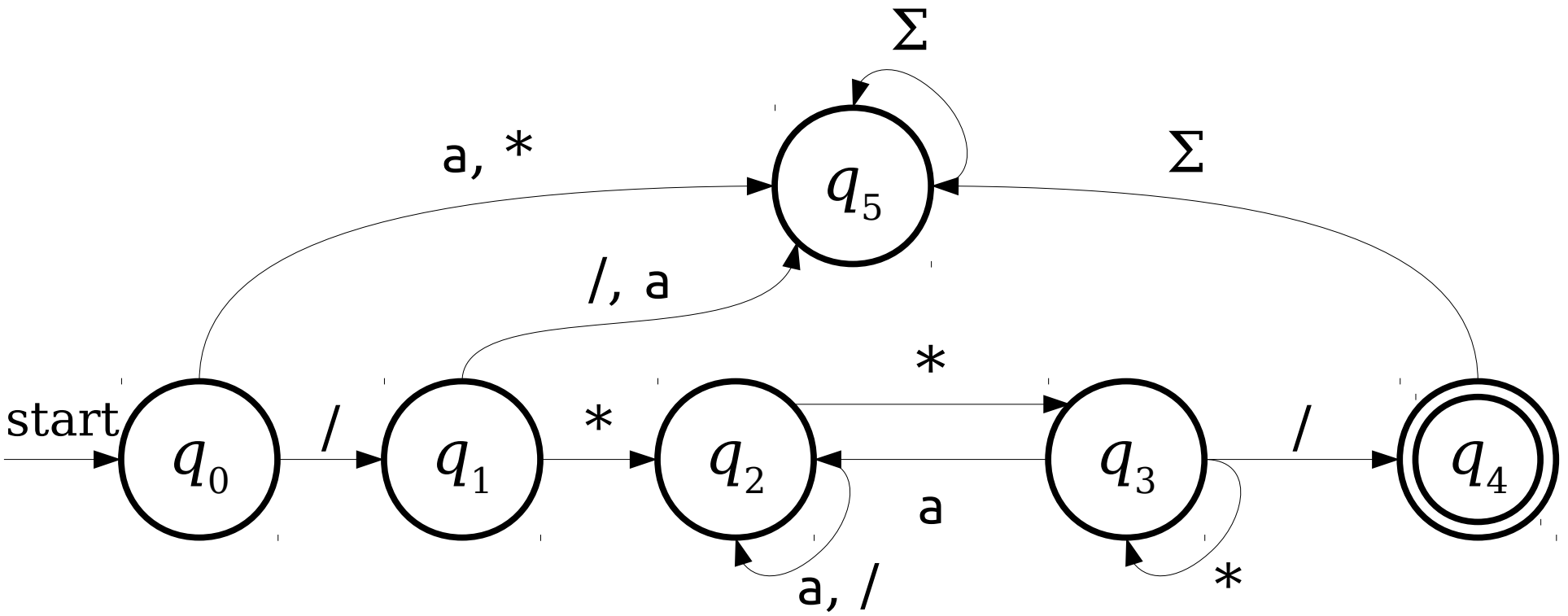


$\overline{L} = \{ w \in \{\texttt{a}, \texttt{b}\}^* \mid w \textbf{\textit{ does not }} \text{contain } \texttt{aa} \text{ as a substring} \}$



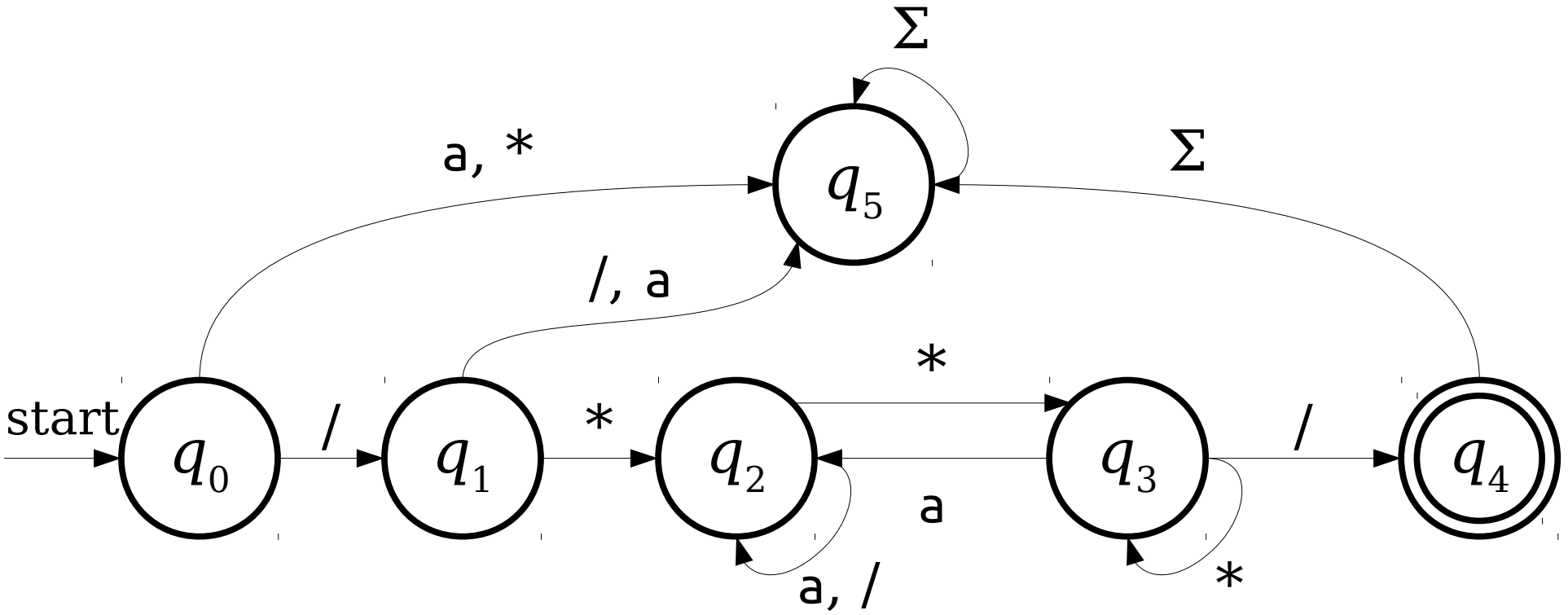
More Elaborate DFAs

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



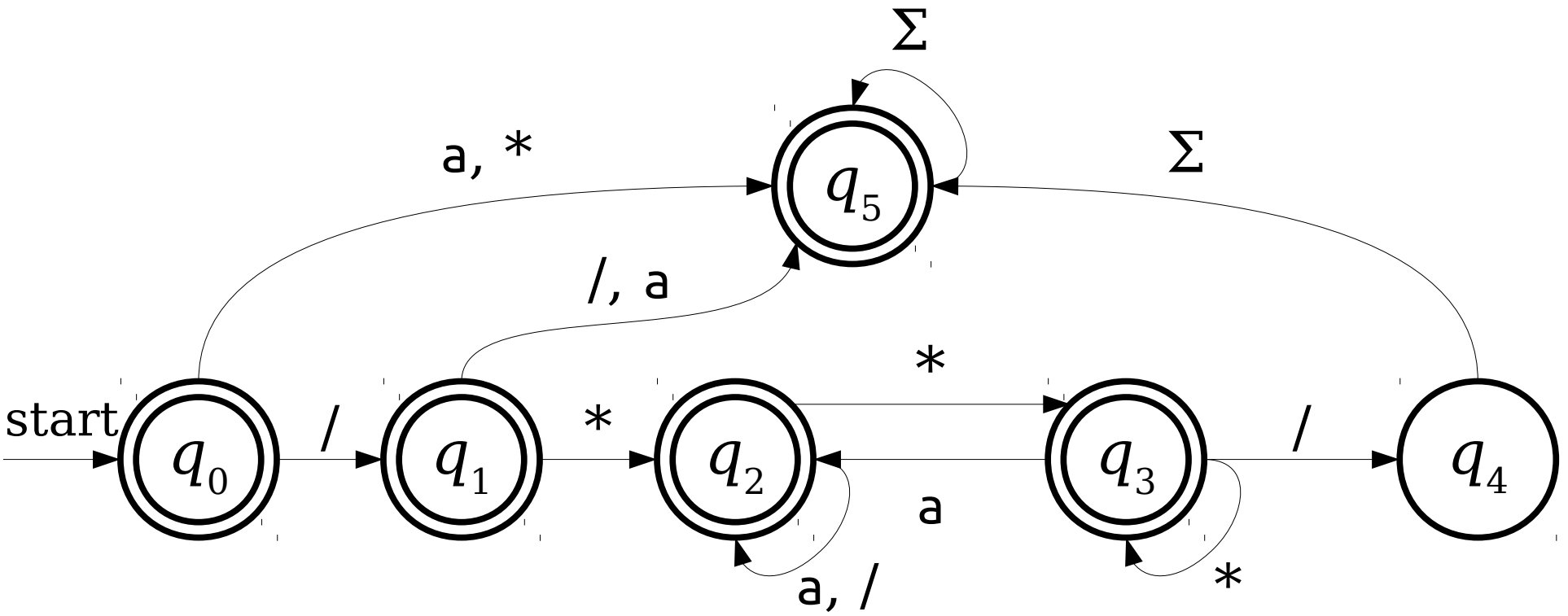
More Elaborate DFAs

$\overline{L}$ = { $w \in$ {a, *, /}* | *w doesn't* represent a C-style comment }



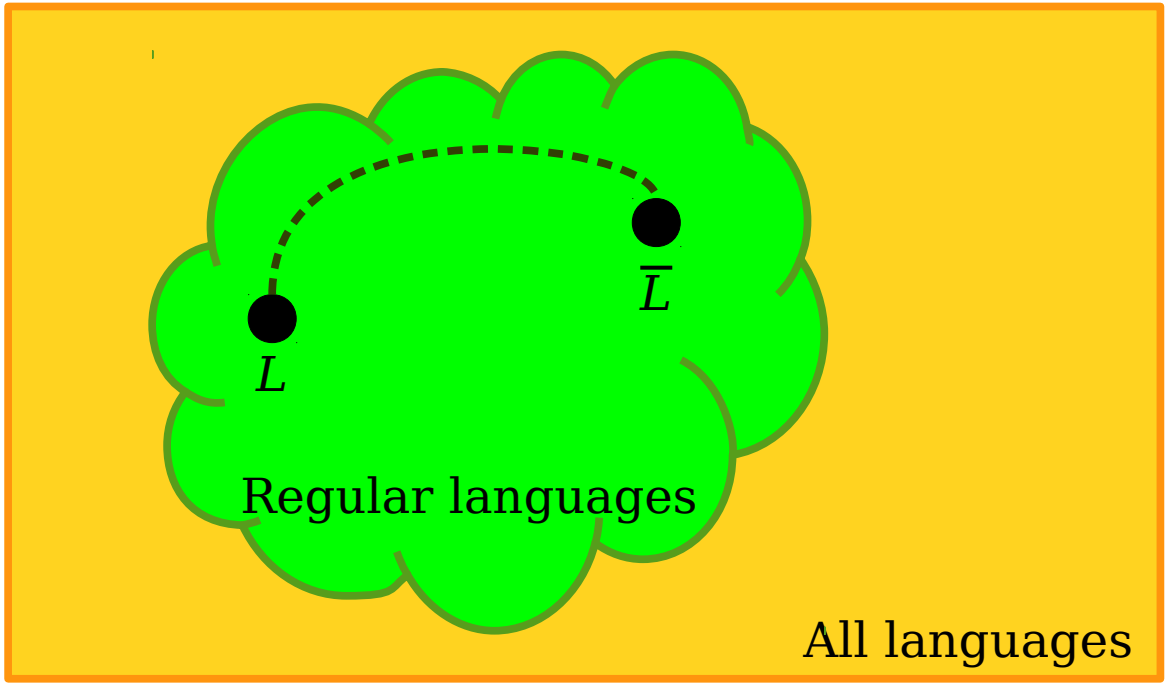
More Elaborate DFAs

$\overline{L}$ = { $w \in$ {**a**, *****, **/**}* | *w doesn't* represent a C-style comment }



Closure Properties

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



Time-Out For Announcements!

CODE2040 INFO SESSION

FRIDAY, NOV 3 | 7PM - 8PM

OLD UNION, ROOM 200

Talk to Your Provost

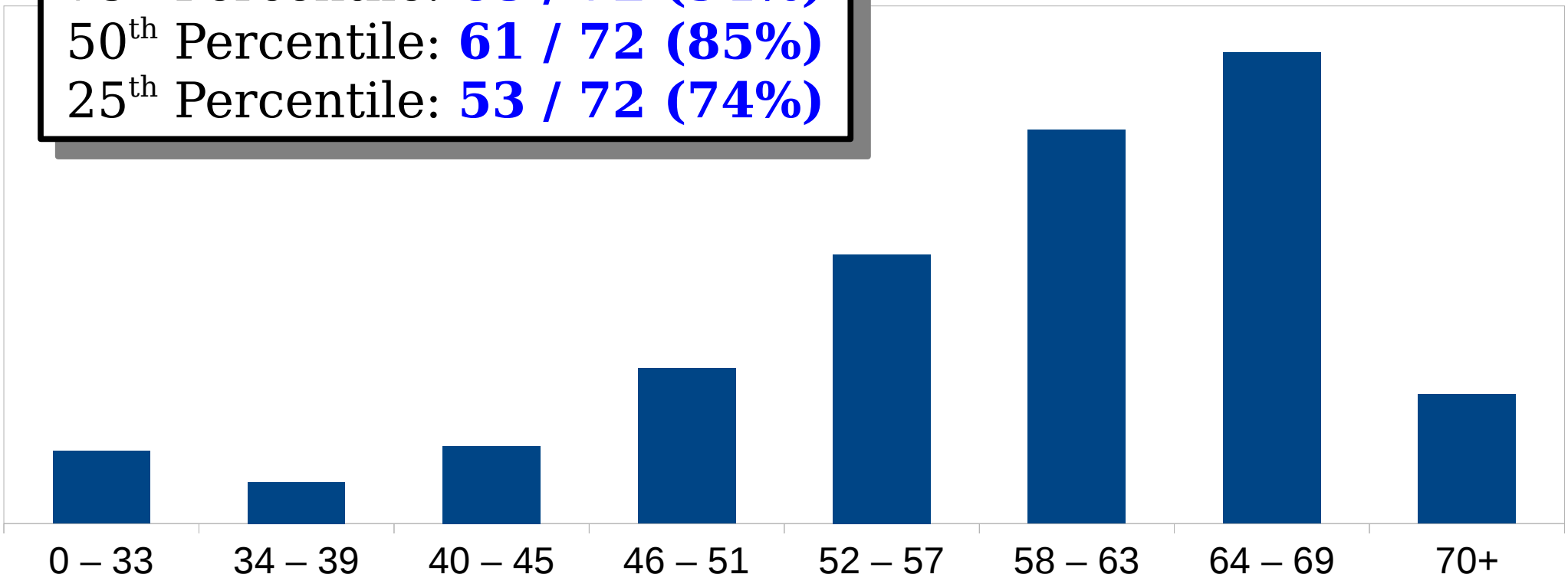
- Provost Persis Drell will be holding office hours in Lathrop 143 next Monday, November 6, from 4PM – 6PM.
- Have any suggestions for the university? Want to change anything? Stop on by to chat!

CS Career Panel

- Greg Ramel, our wonderful CS course advisor, is organizing a CS career panel.
- It's tomorrow (Thursday, November 2nd) in Gates 219 and runs from 5:45PM – 7:00PM.
- Please RSVP using **this link**.
- There's a great mix of panelists. Highly recommended!

Problem Set Four Graded

75th Percentile: **68 / 72 (94%)**
50th Percentile: **61 / 72 (85%)**
25th Percentile: **53 / 72 (74%)**



Extra Practice Problems 2

- We've just released another set of extra practice problems to the course website.
- Need to review some concepts? Want more practice? Try these questions out! There's a ton of variety.
- Solutions will go out on Friday.

Your Questions

“I've struggled as a public speaker for as long as I can remember and watching your lectures, I'm amazed by how good you are. How do you do it?”

When I first started teaching I was so terrified of speaking to crowds that I literally memorized everything I was going to say and rehearsed for like ten hours each time. After I realized that most people are nice and won't eat you if you make a mistake, I started backing down from that and just worked out a general game plan for each lecture. Essentially, I just slowly stepped up the amount of improvisation I had in each lecture until I got the hang of it. Right now there's a balance between making things up as I go and falling back on things I know work well.

“Any movie / TV recommendations?”

My unsorted top movies: “Twelve Angry Men,” “Seven Samurai,” “The Lives of Others,” “Amelie,” “The Babadook,” “Brazil,” and “Lawrence of Arabia.”

Unsorted top TV shows: “The Wire.”

Back to CS103!

NFAs

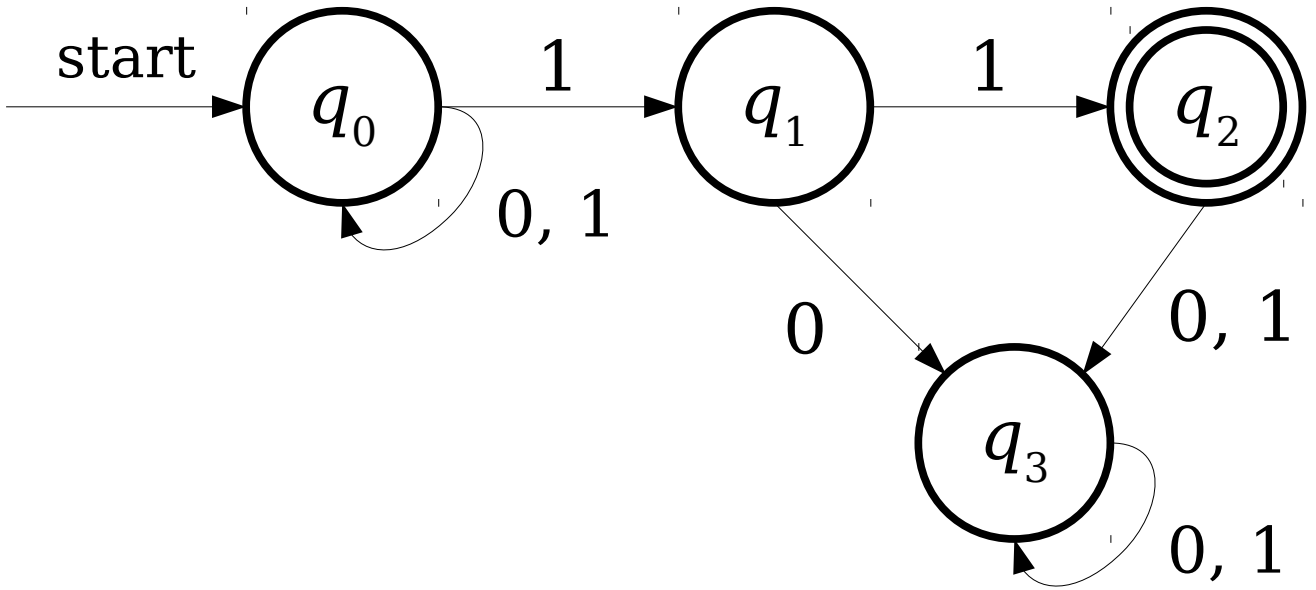
NFAs

- 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.

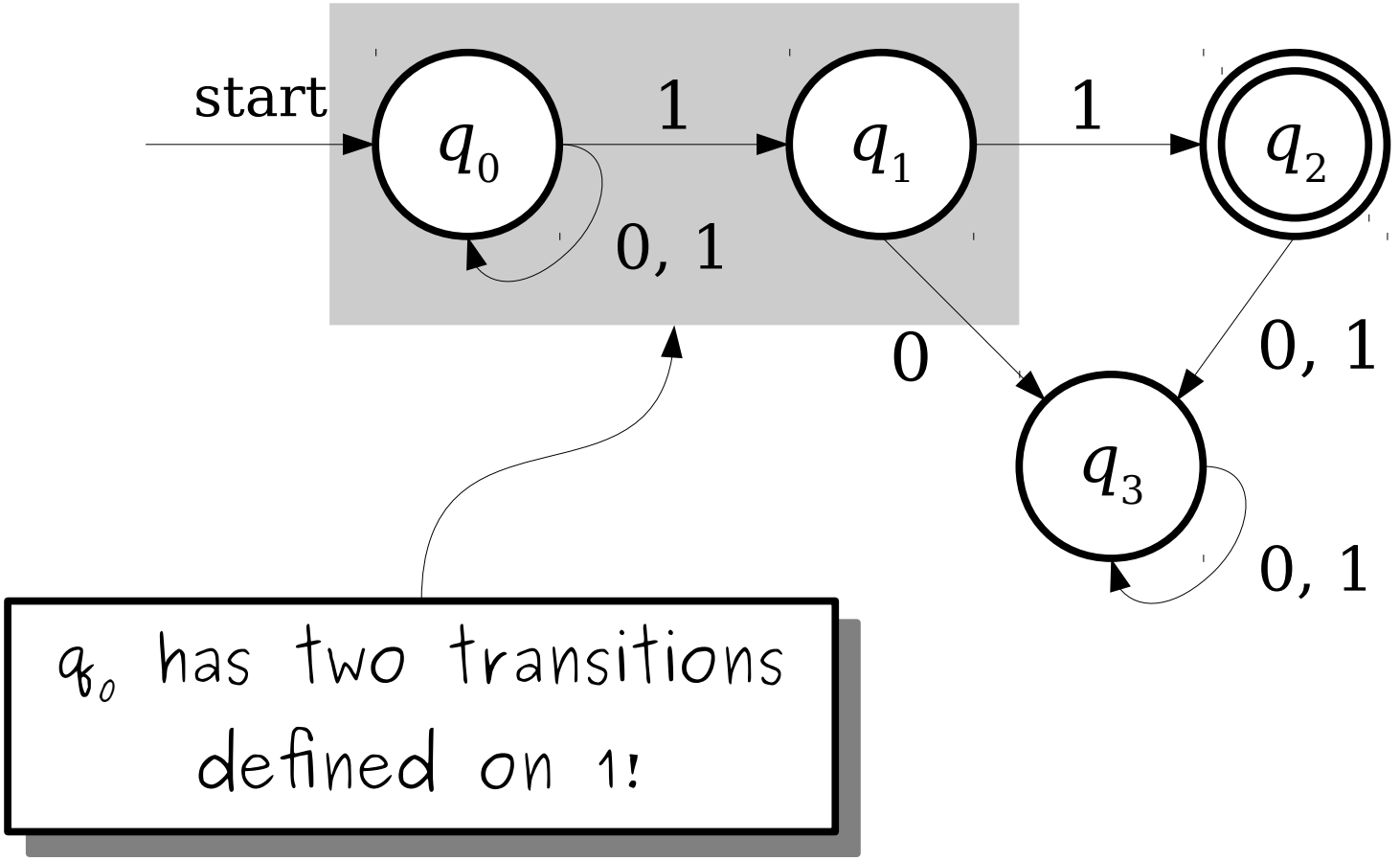
(Non)determinism

- 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 may have multiple decisions that it can make at one point.
- The machine accepts if ***any*** series of choices leads to an accepting state.

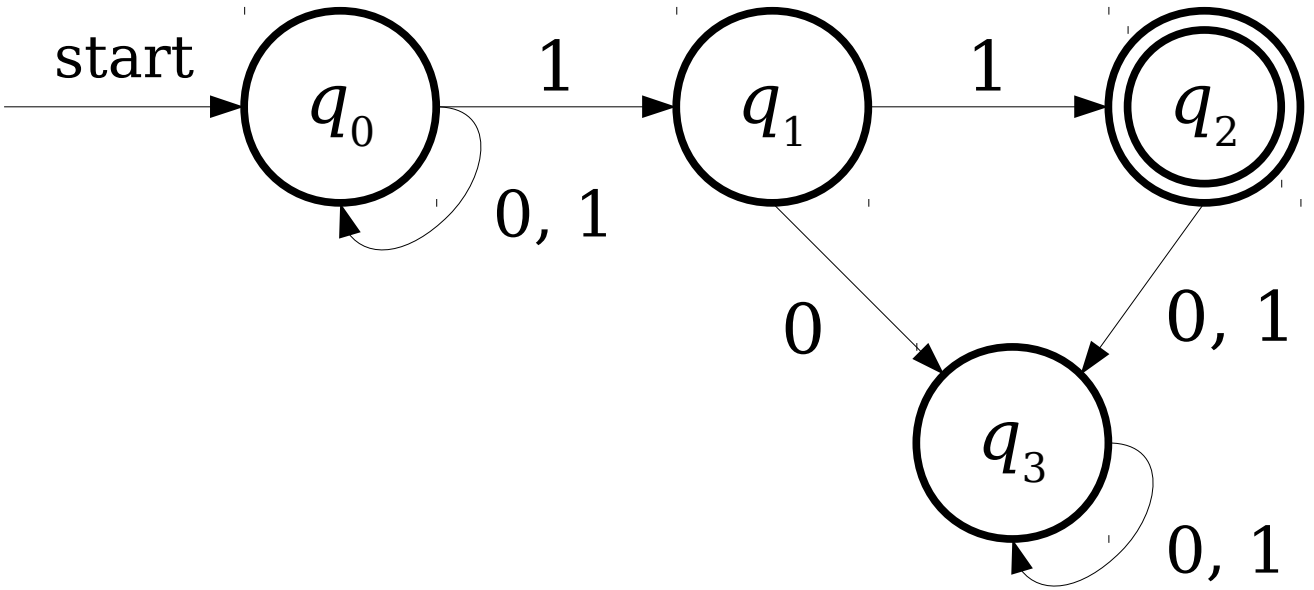
A Simple NFA



A Simple NFA

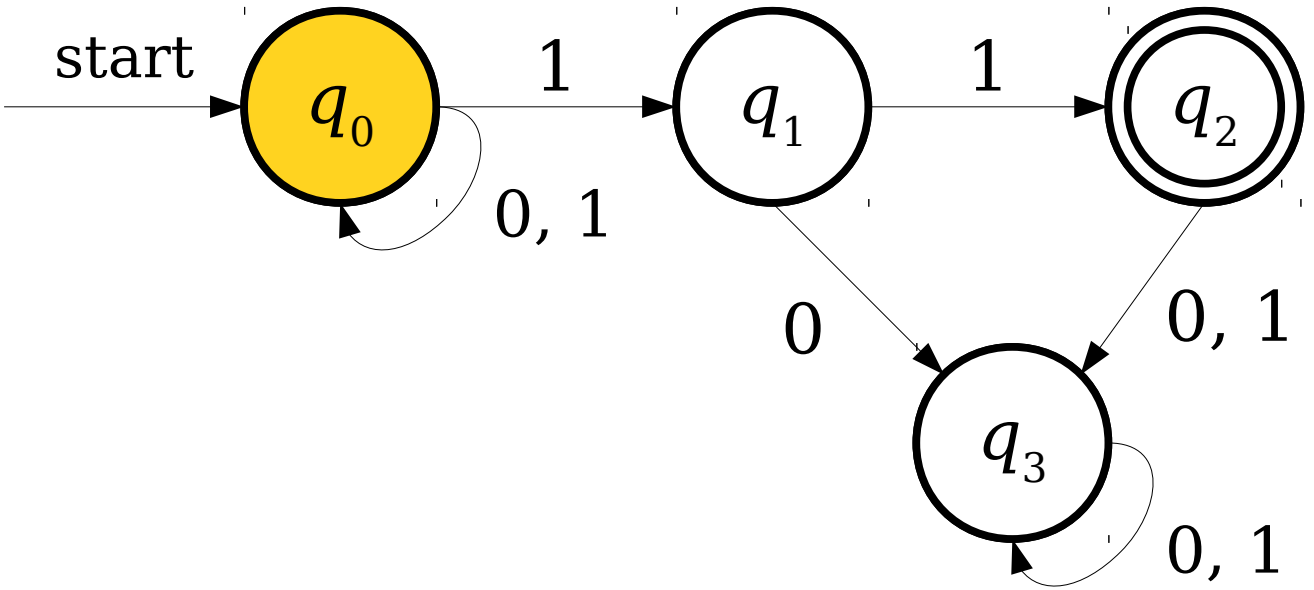

start
q_0
q_1
q_2
q_3
1
1
0, 1
0
0, 1
0, 1
q_0 has two transitions defined on 1!

A Simple NFA



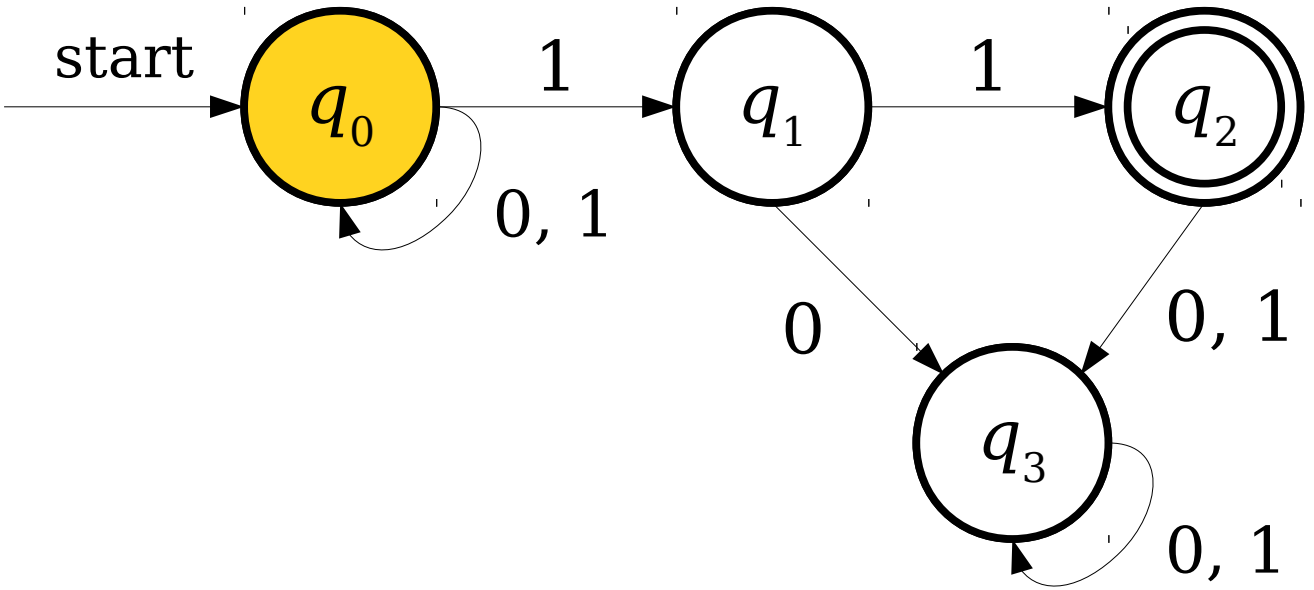
0 1 0 1 1

A Simple NFA



0 1 0 1 1

A Simple NFA



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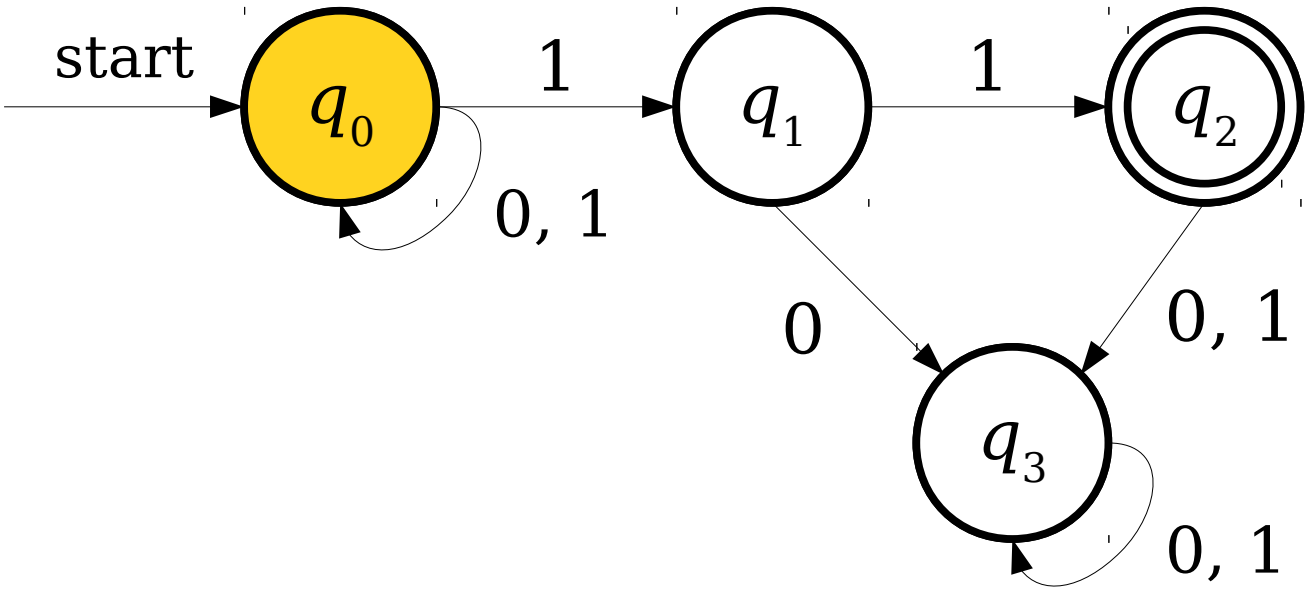

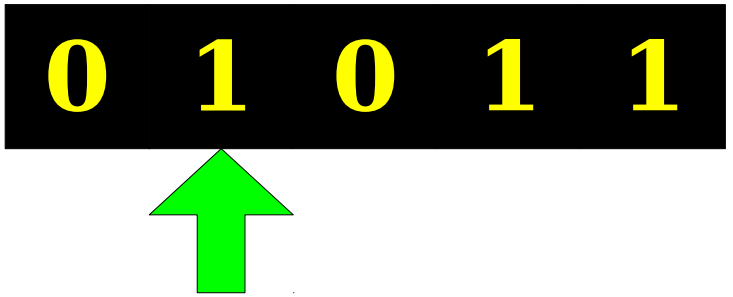

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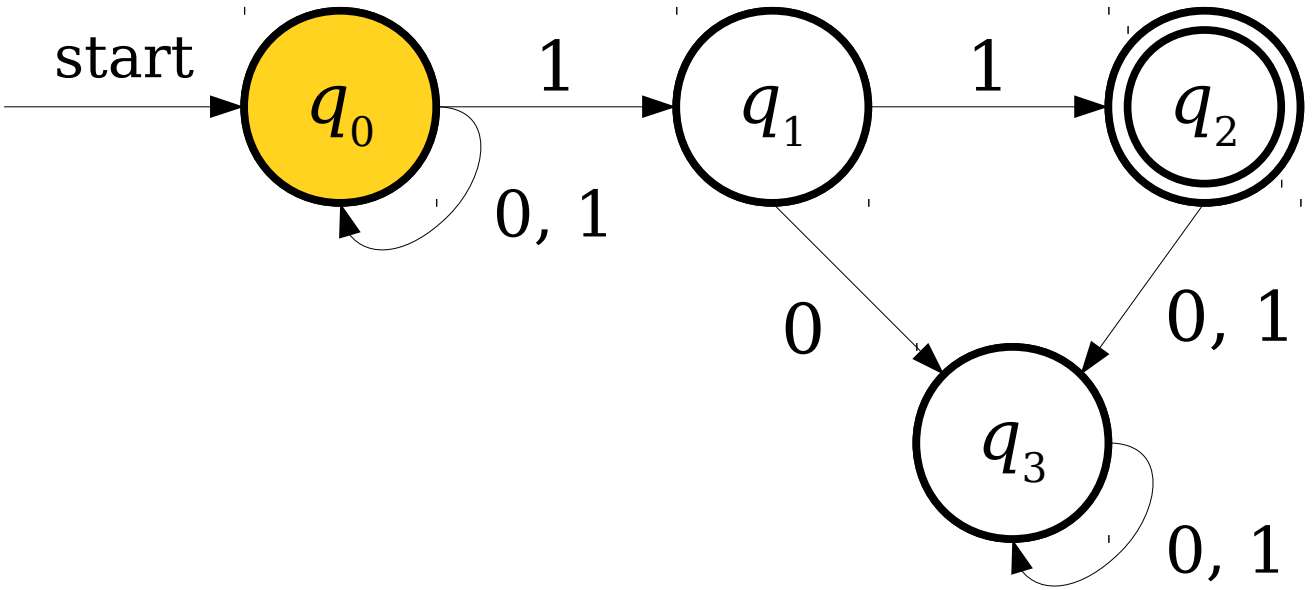
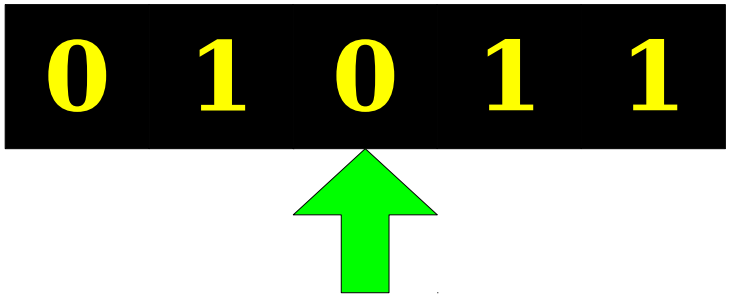
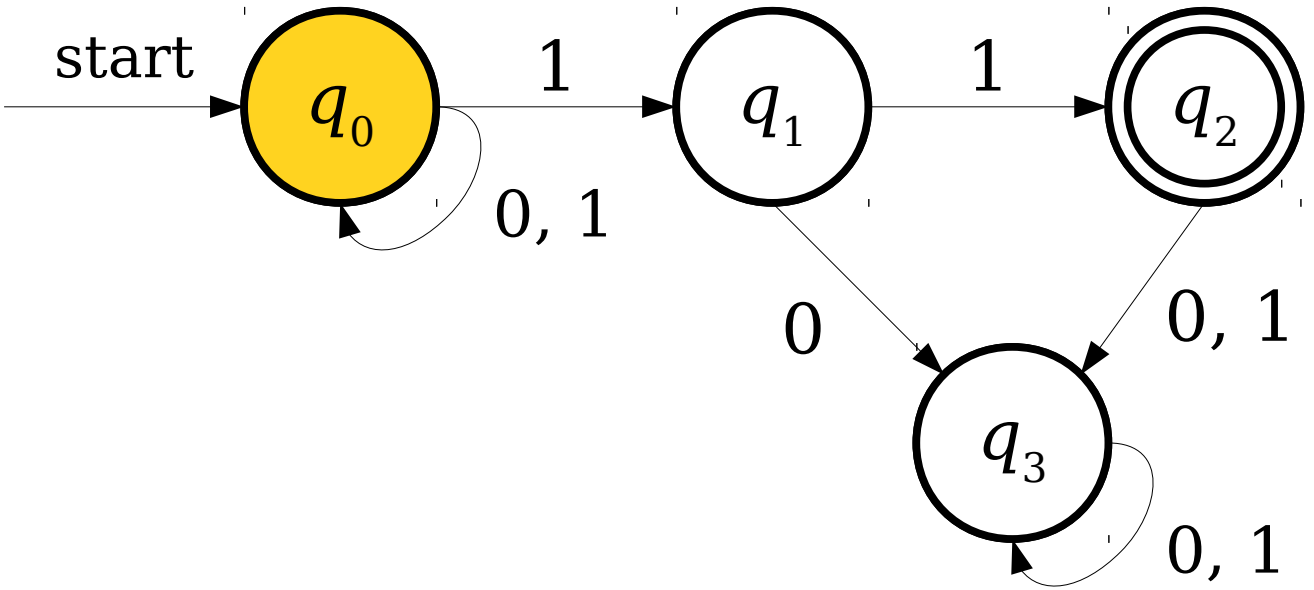
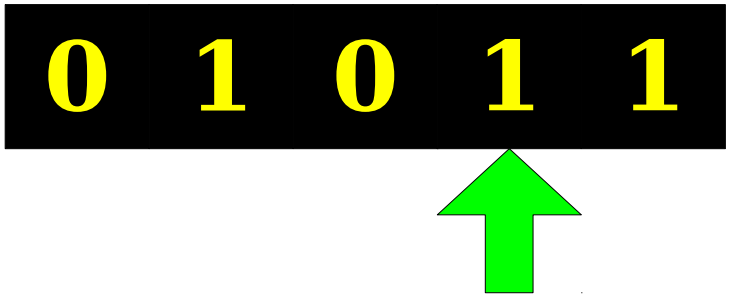




A Simple NFA





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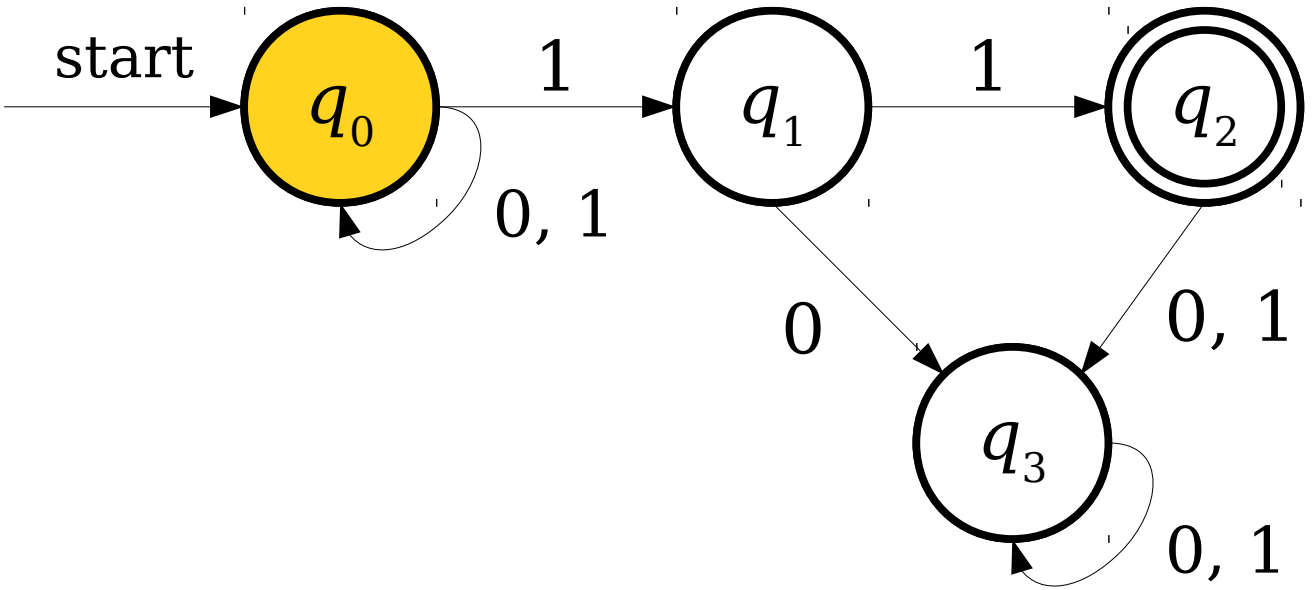

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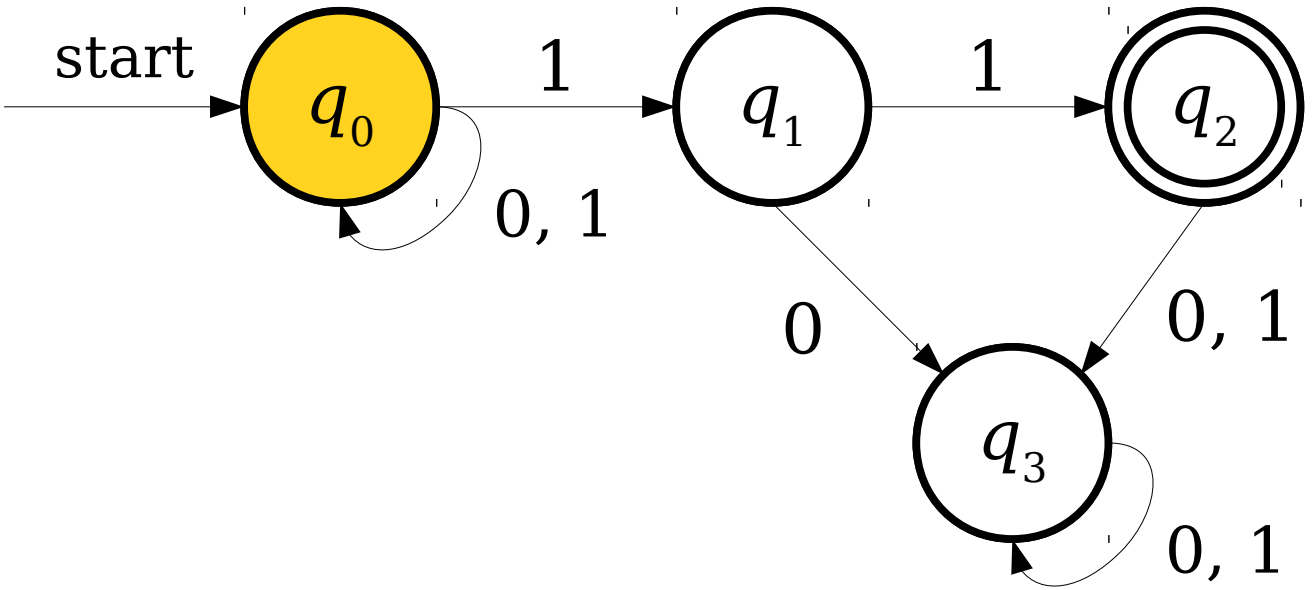
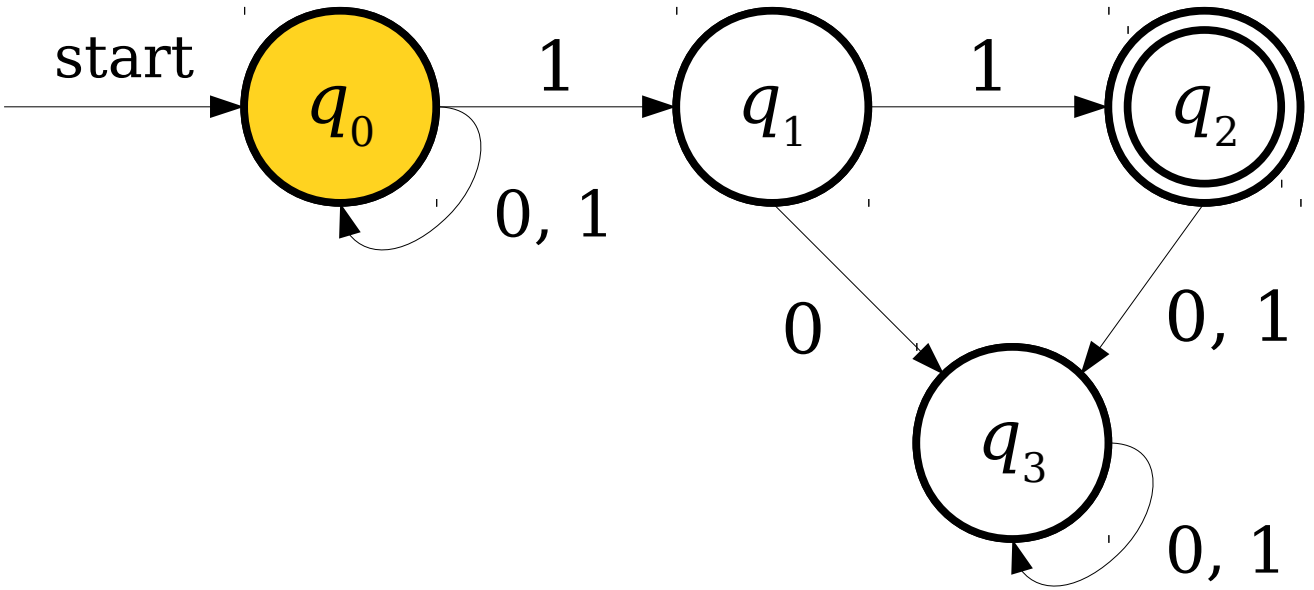
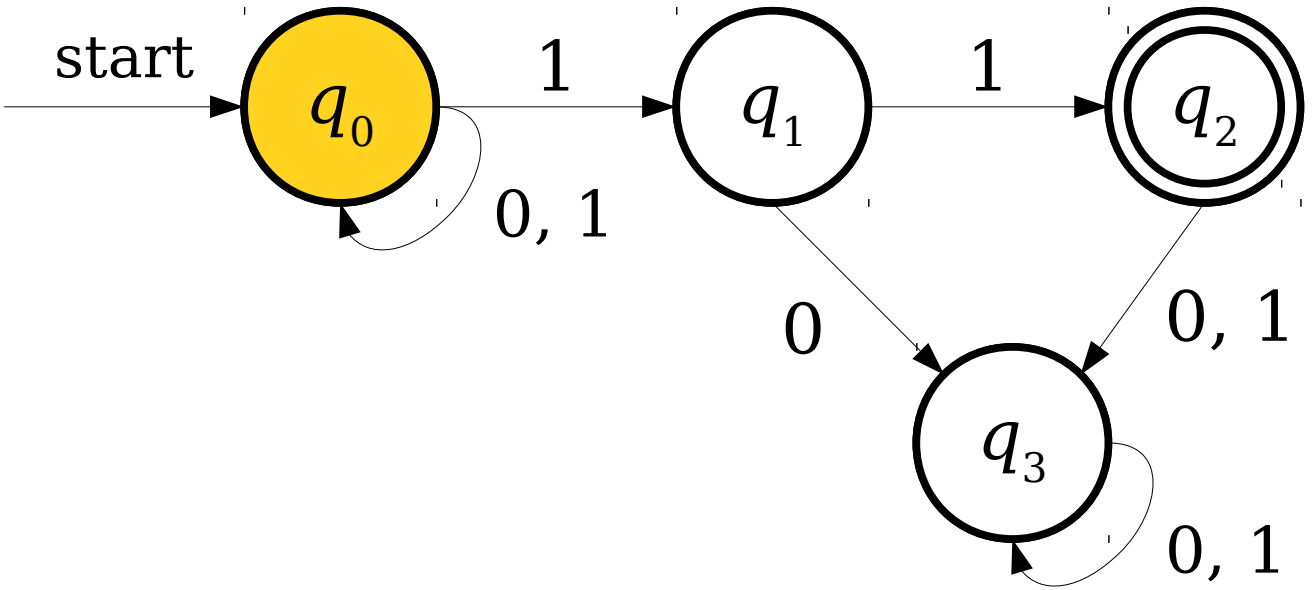


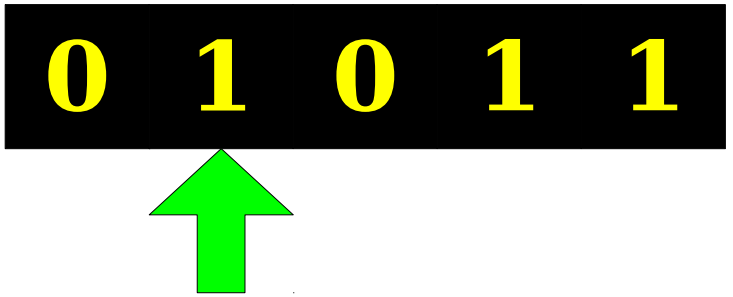
0 1 0 1 1

A Simple NFA



A Simple NFA





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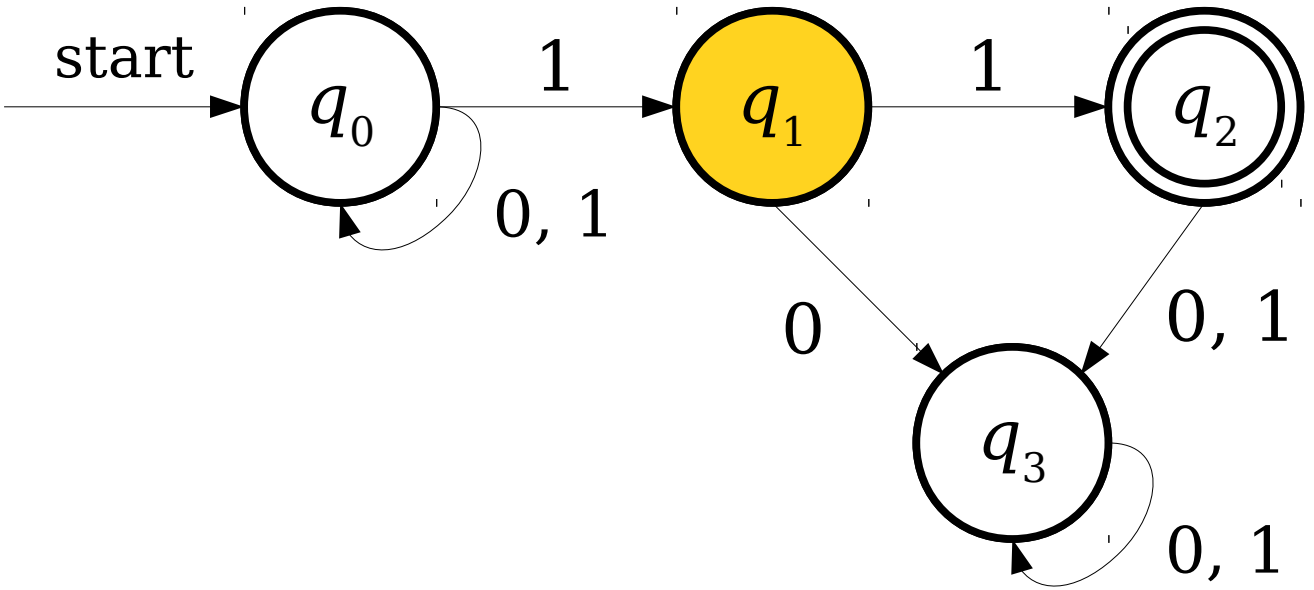

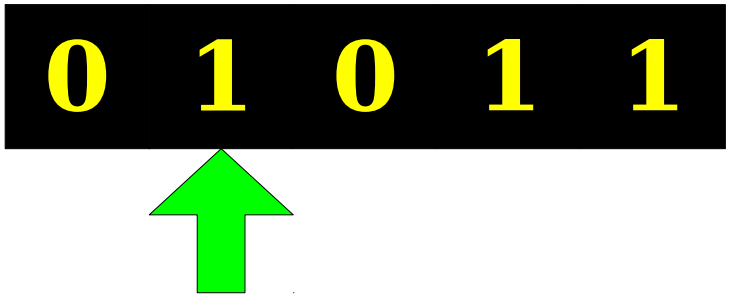

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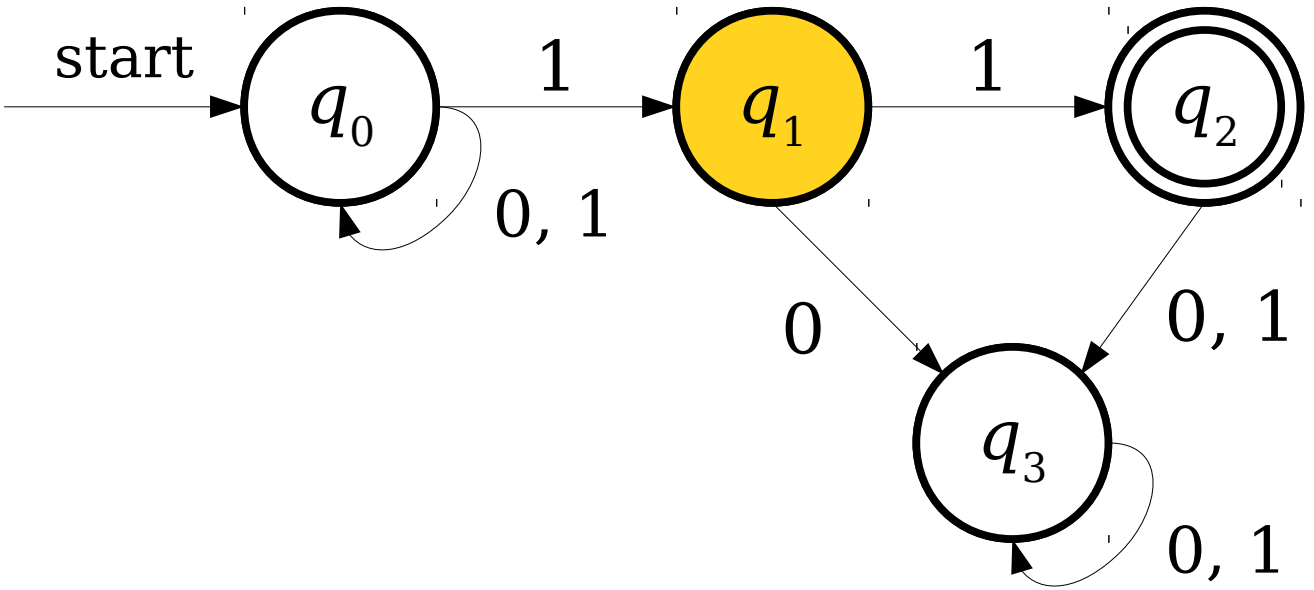

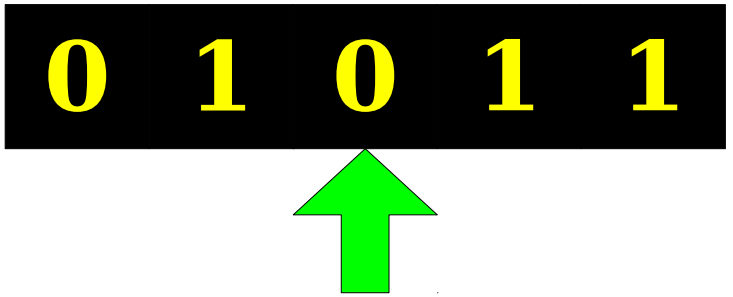

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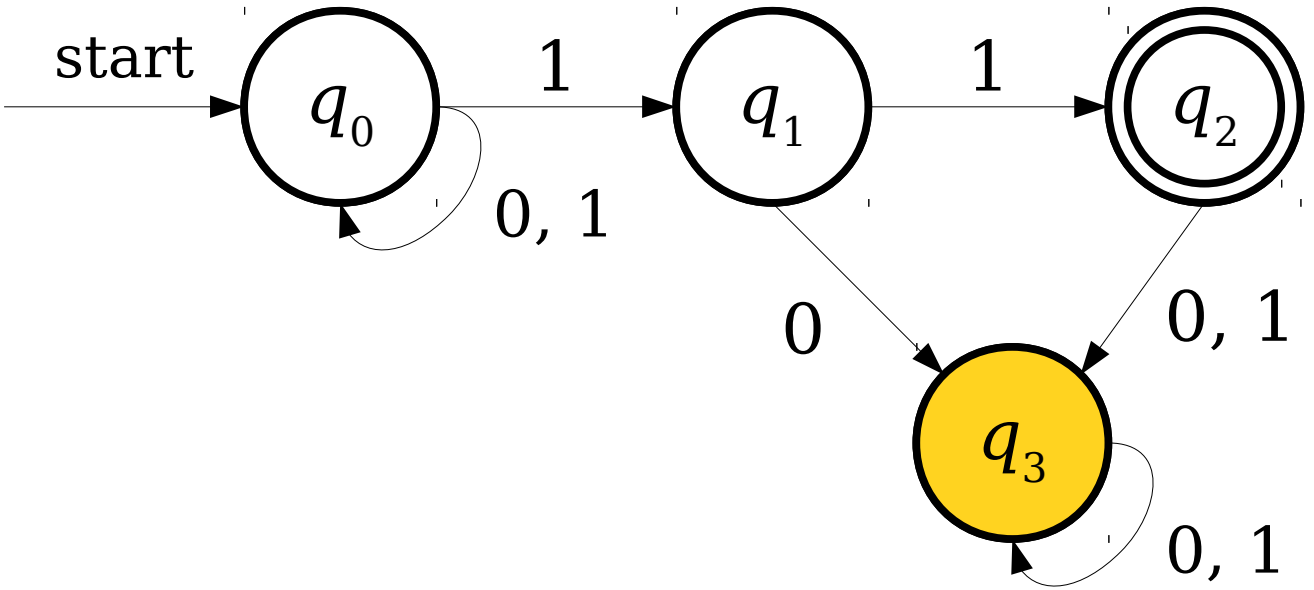

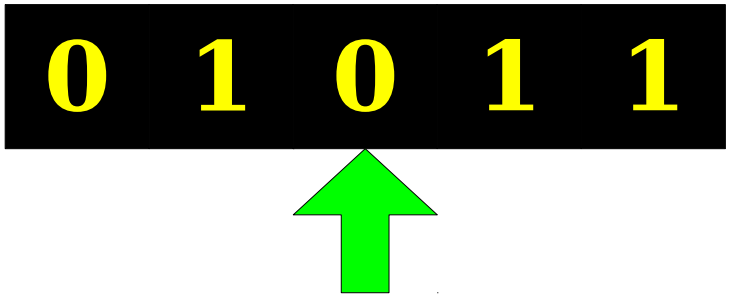

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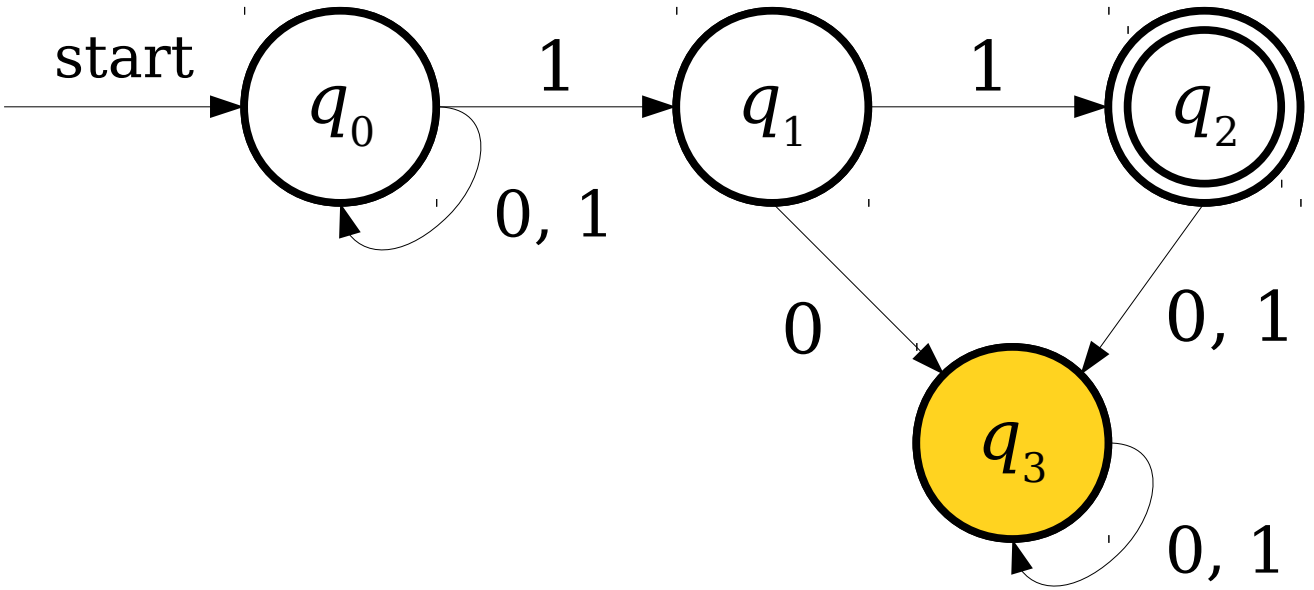

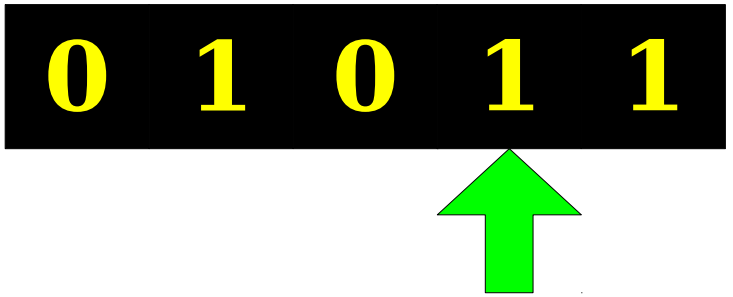

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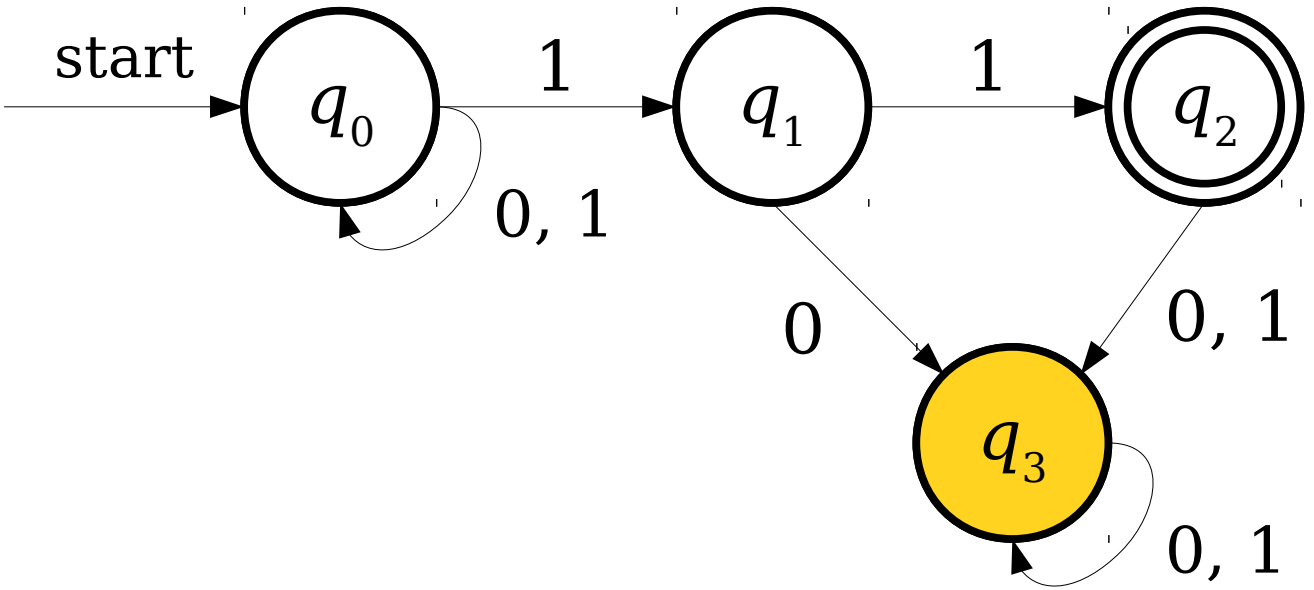

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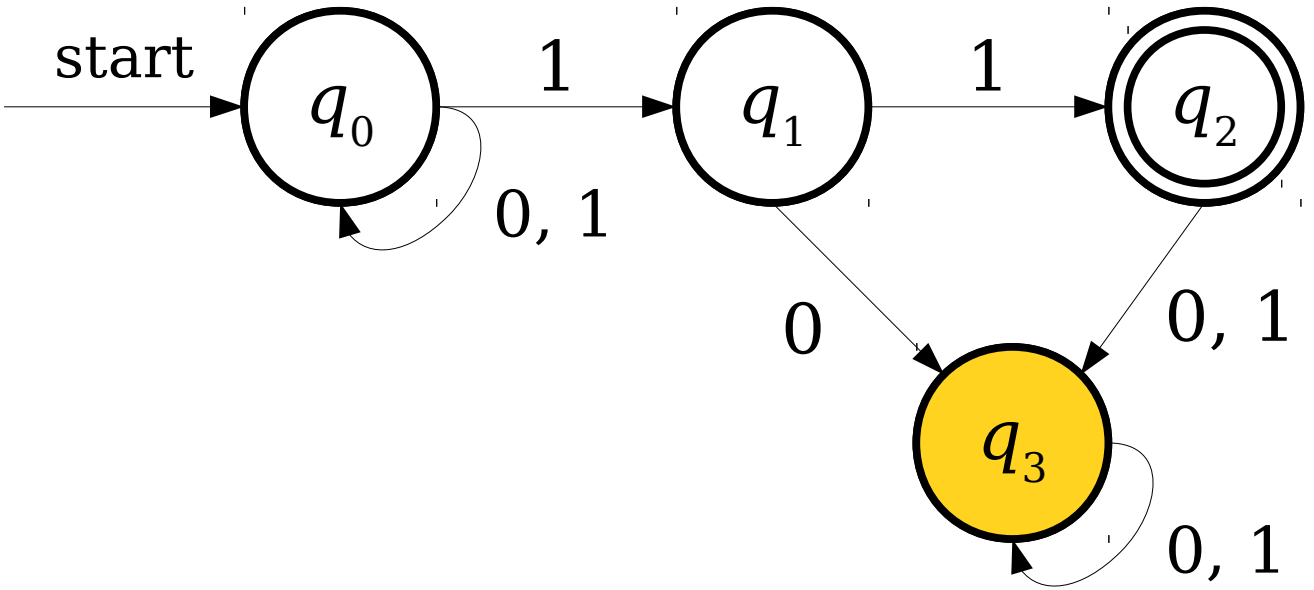

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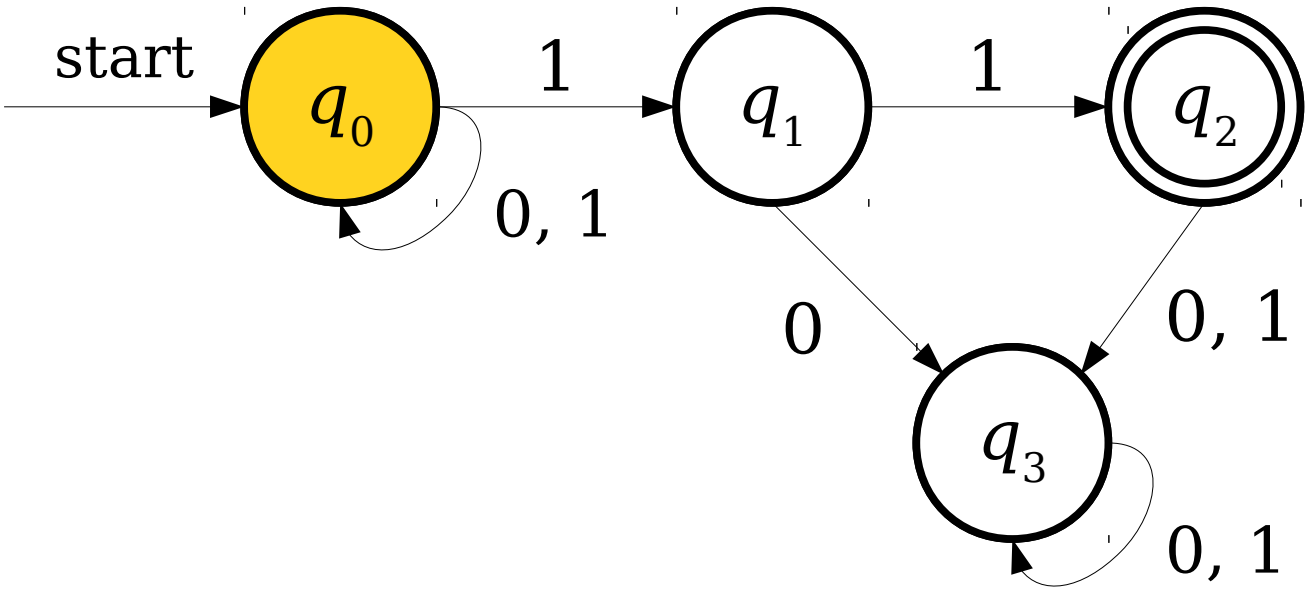

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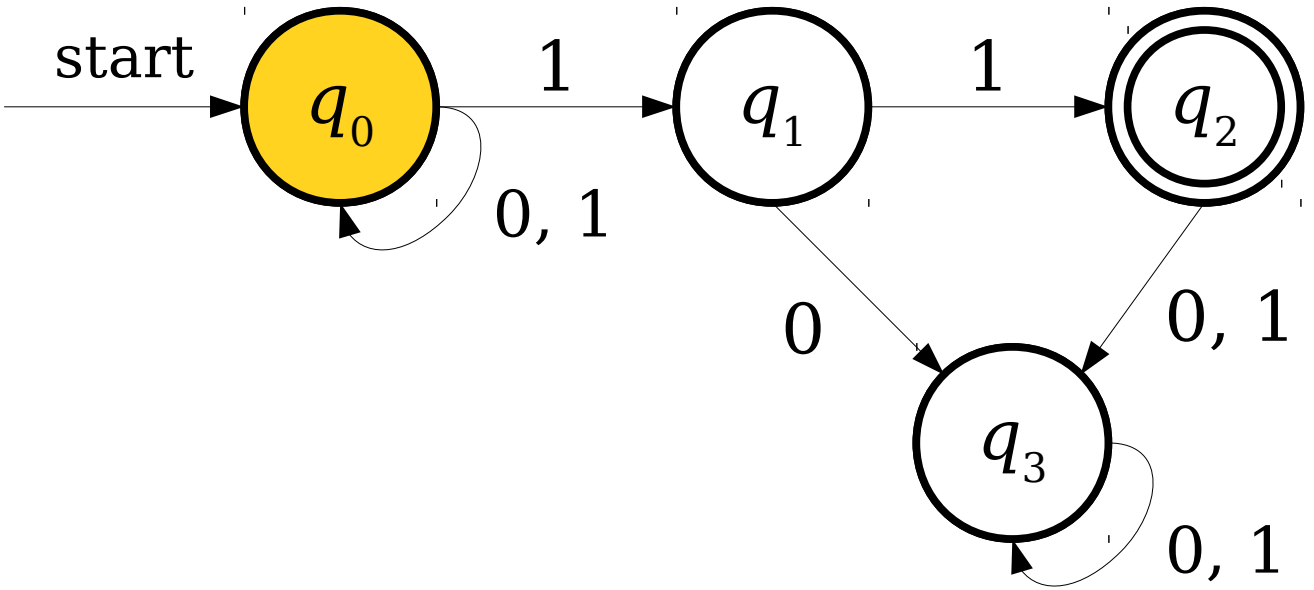

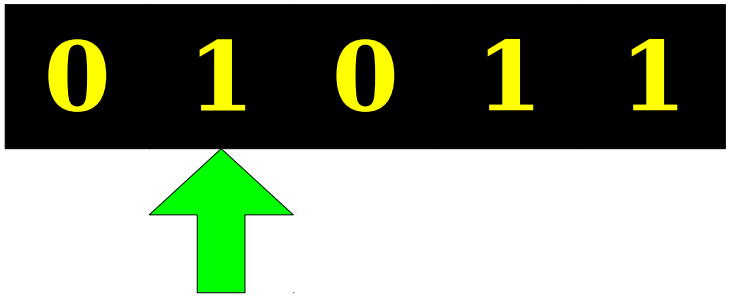

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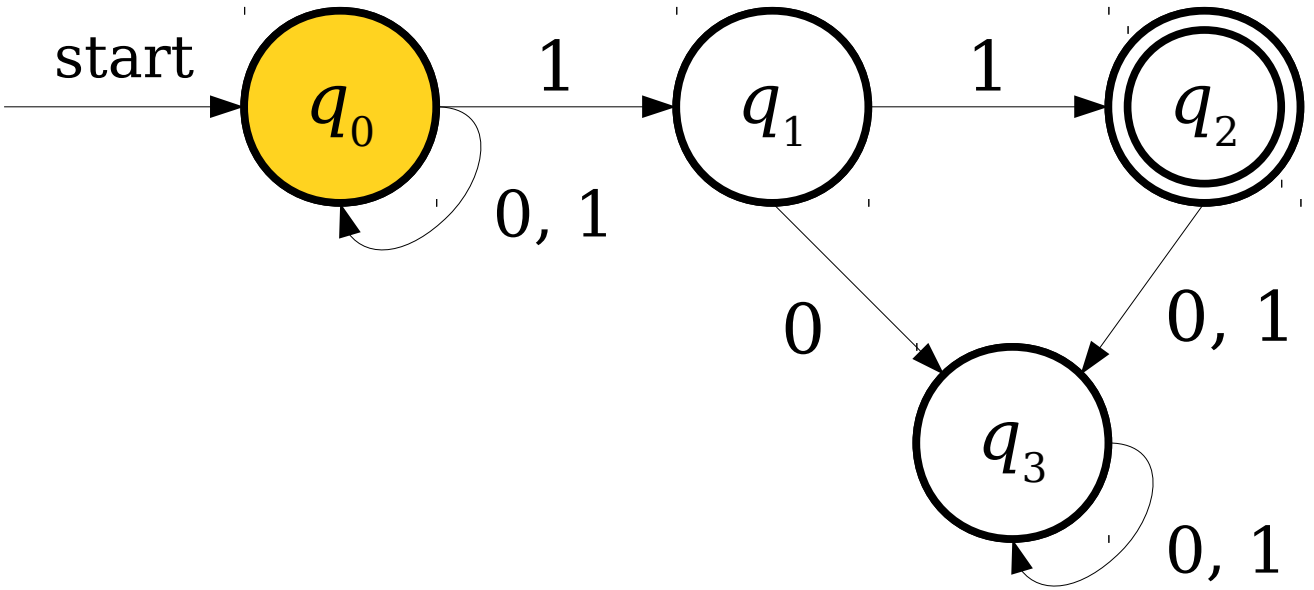

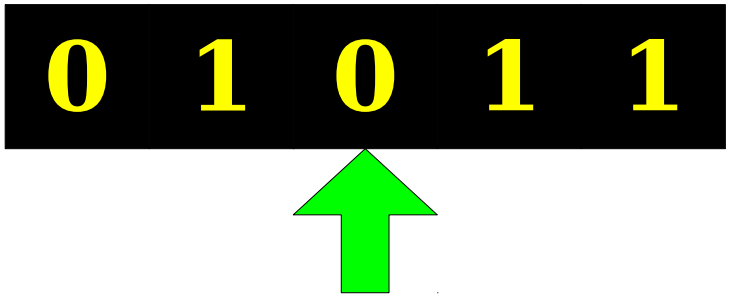

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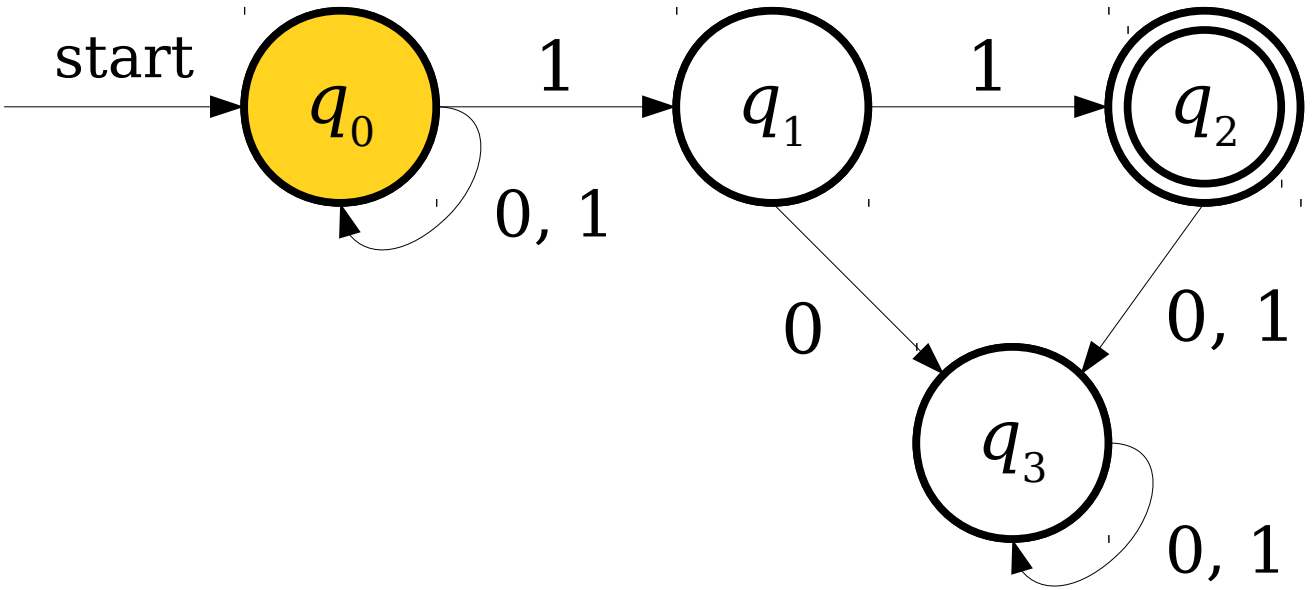

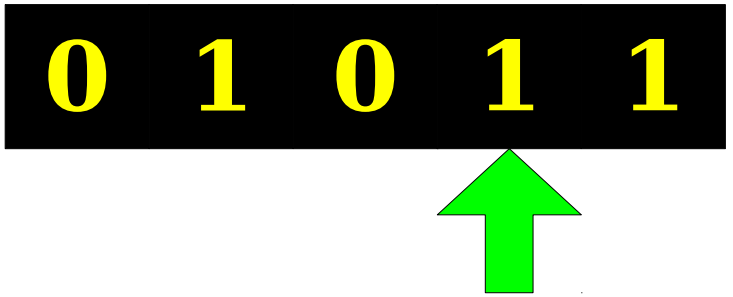

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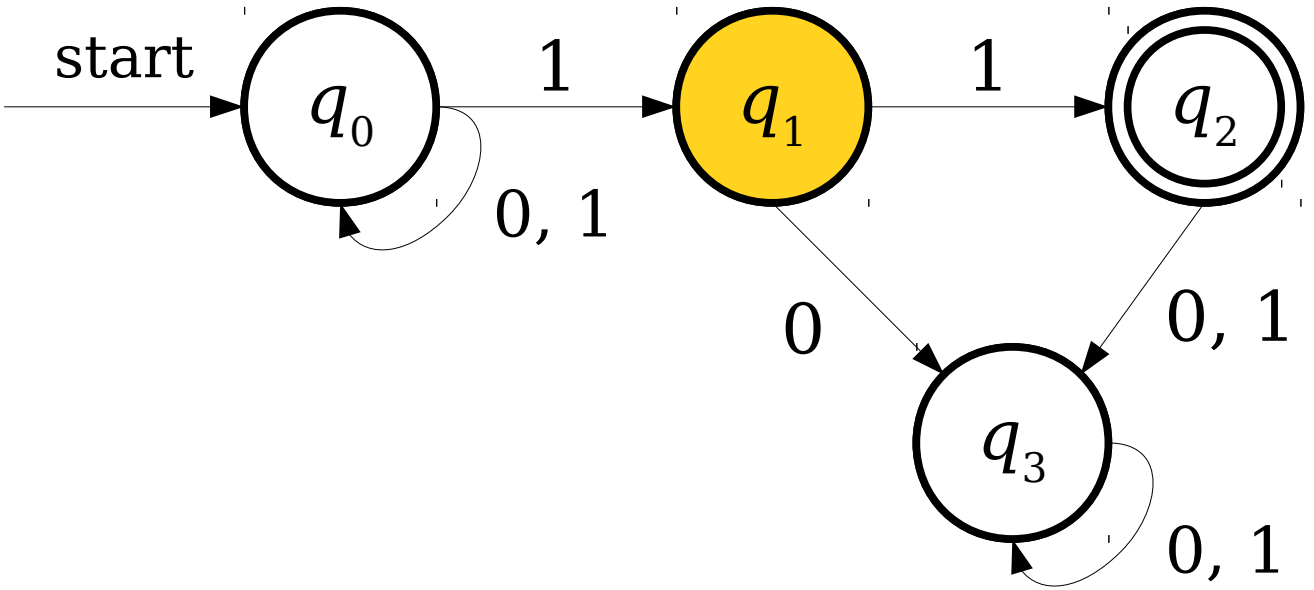

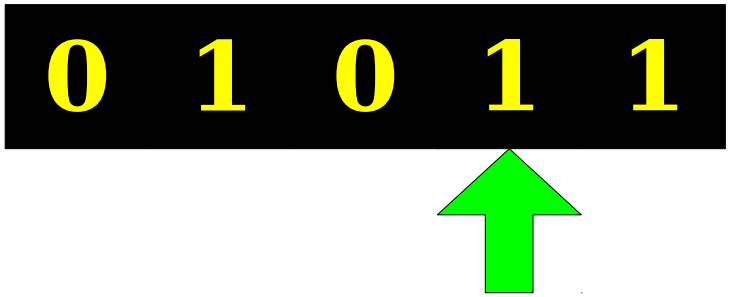

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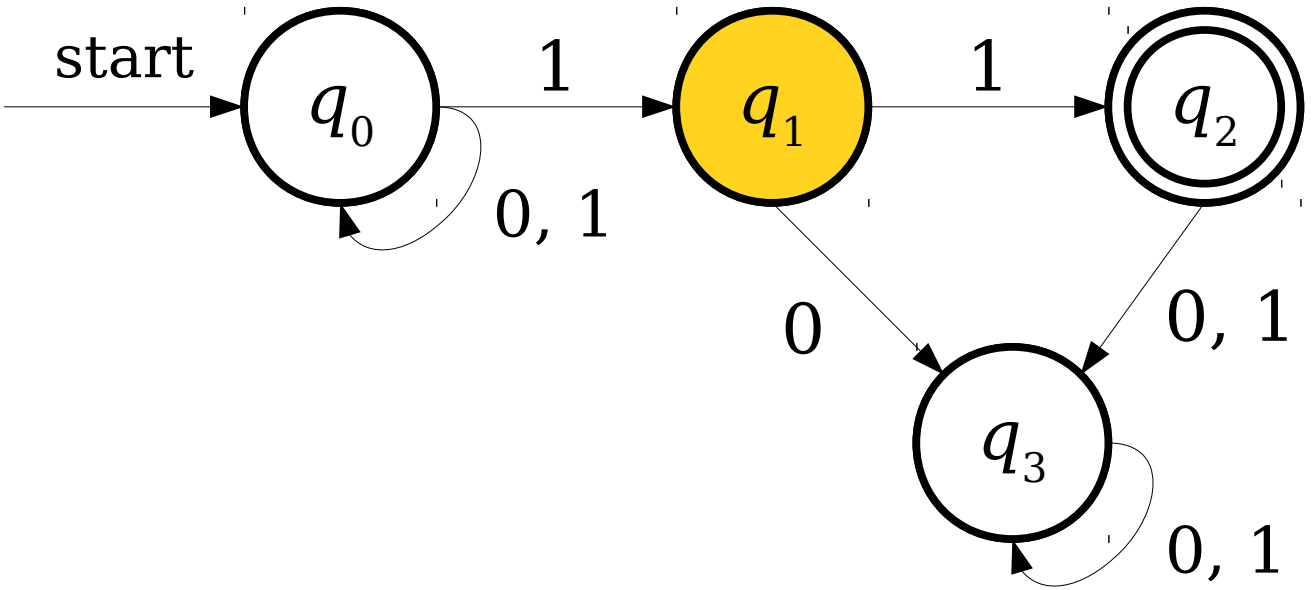

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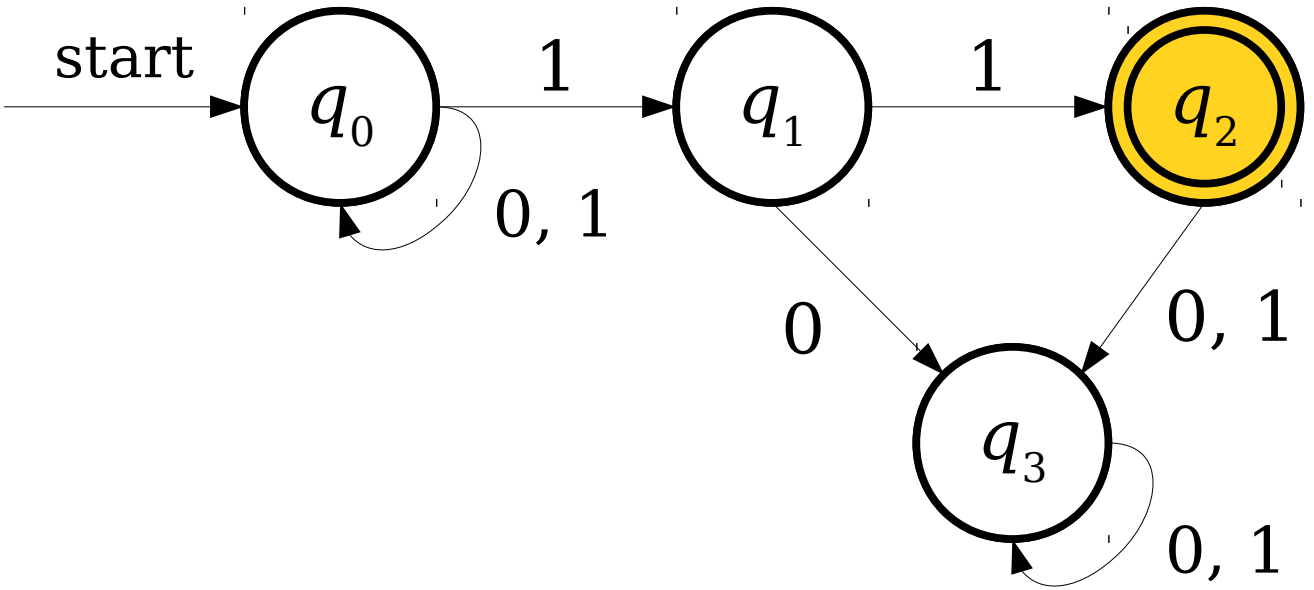

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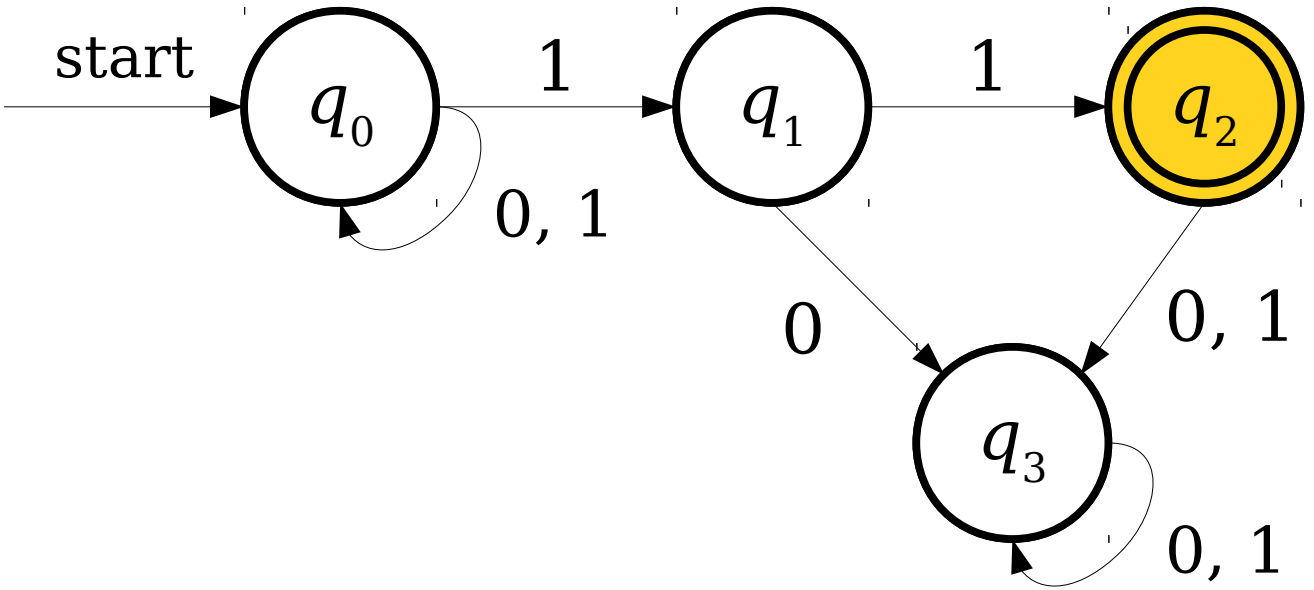

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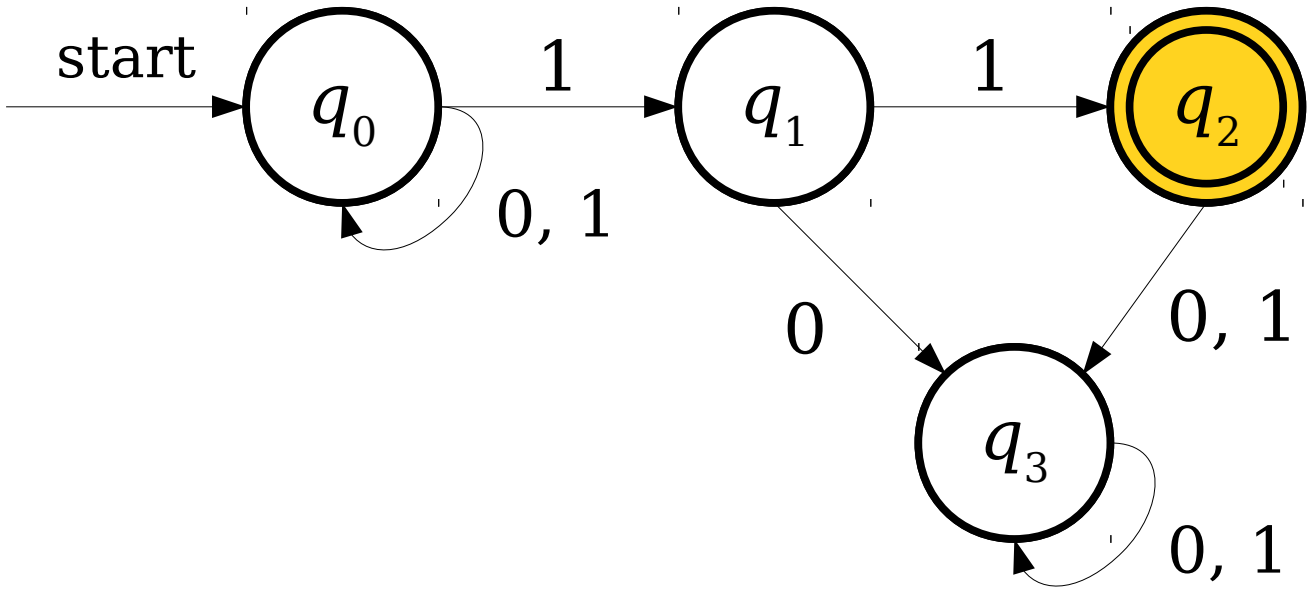

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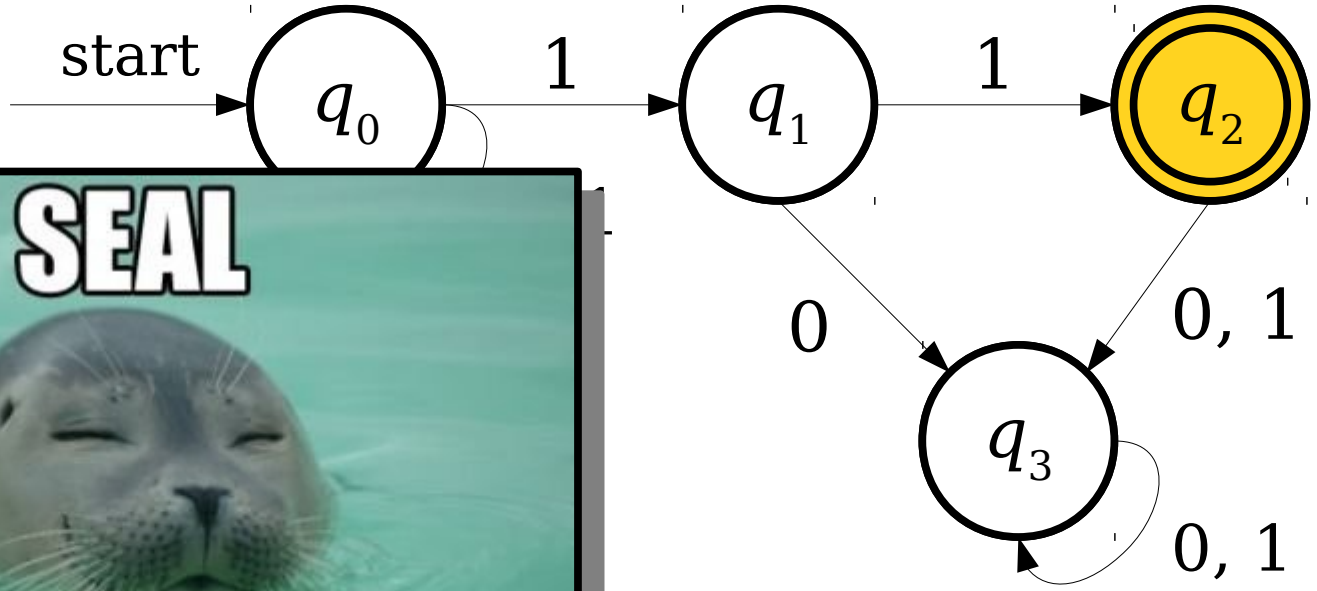

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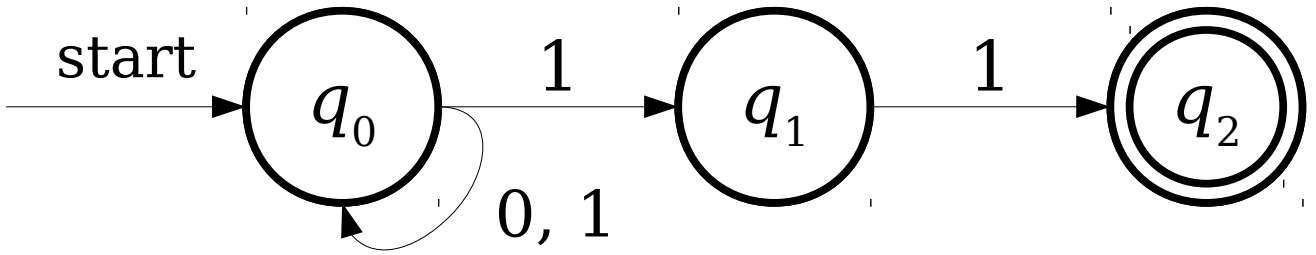

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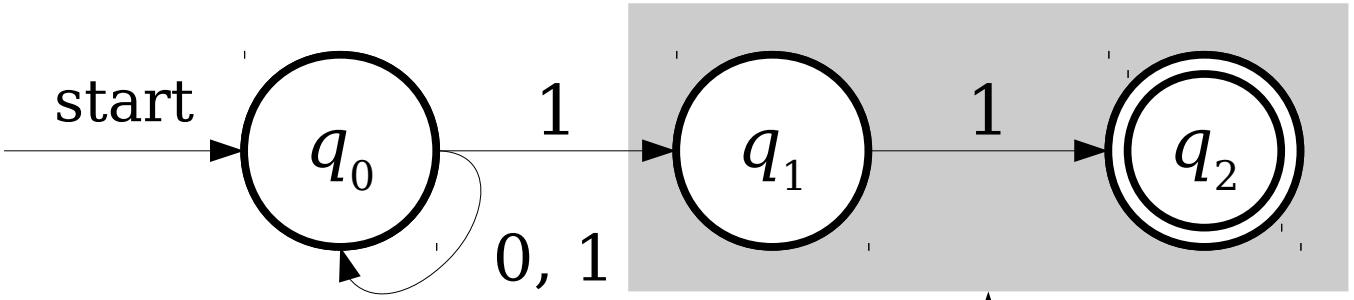
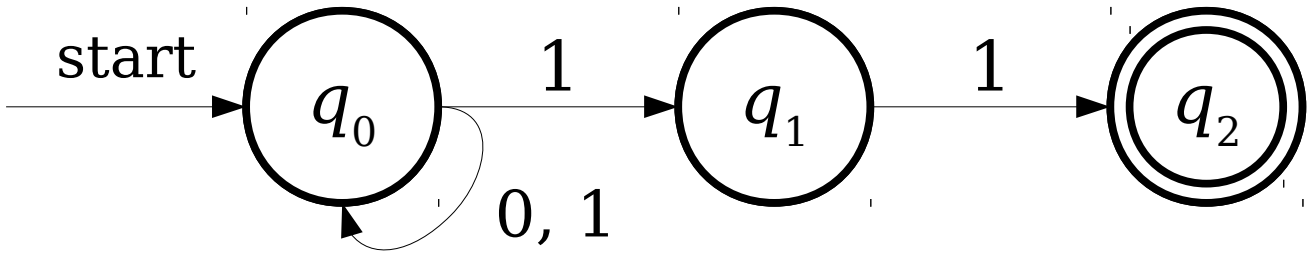


If a NFA needs to make a transition when no transition exists, the automaton dies and that particular path rejects.

A More Complex NFA



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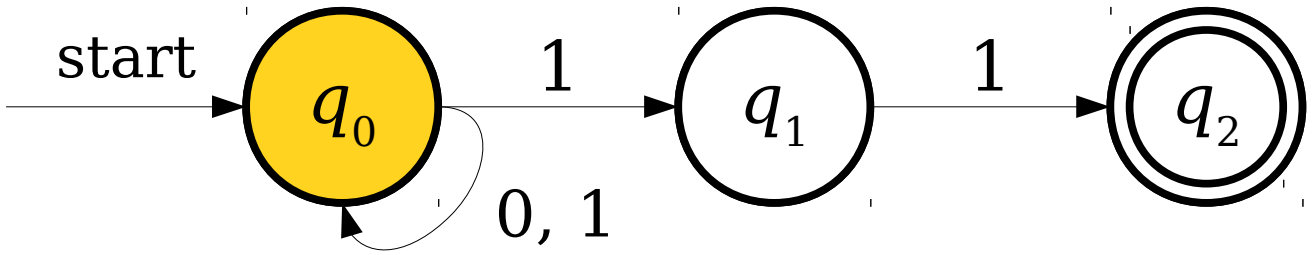

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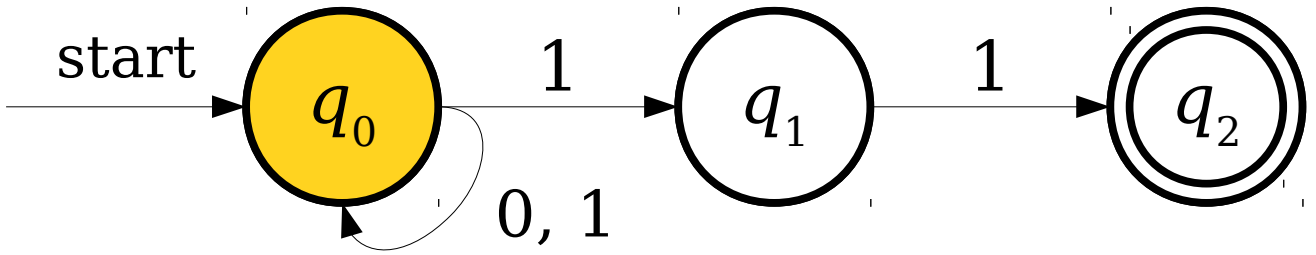

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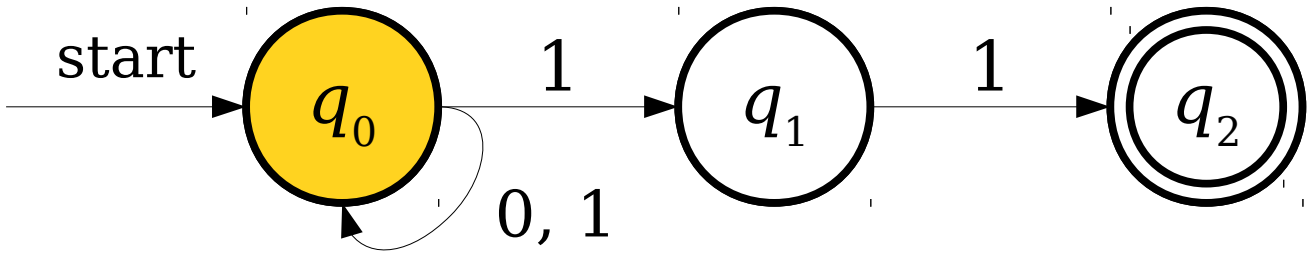

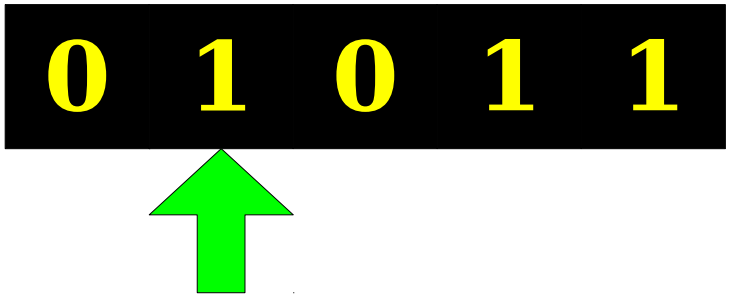

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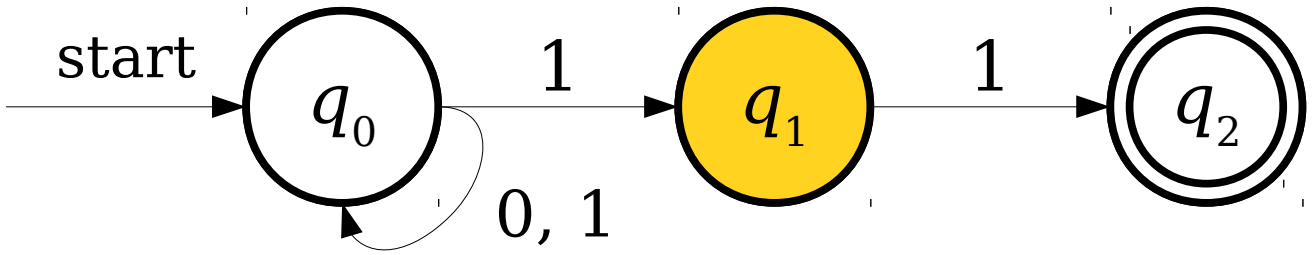

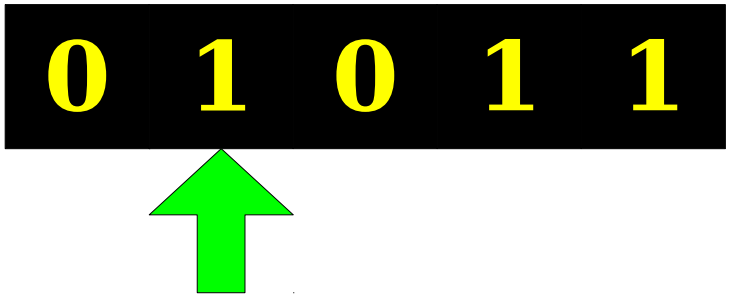

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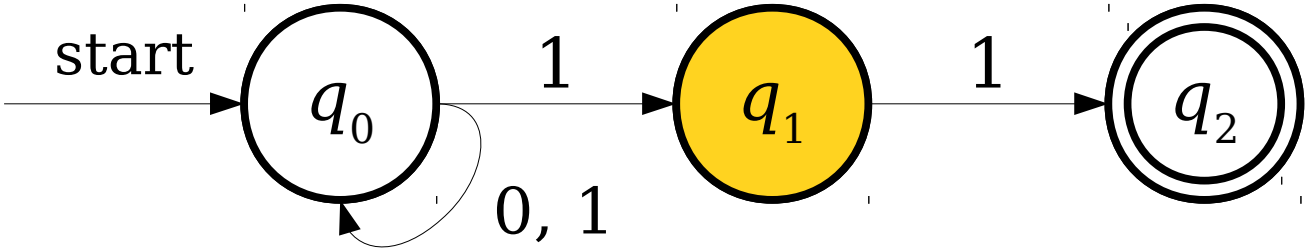

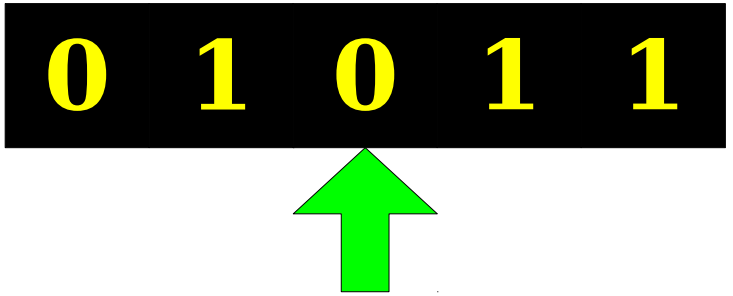

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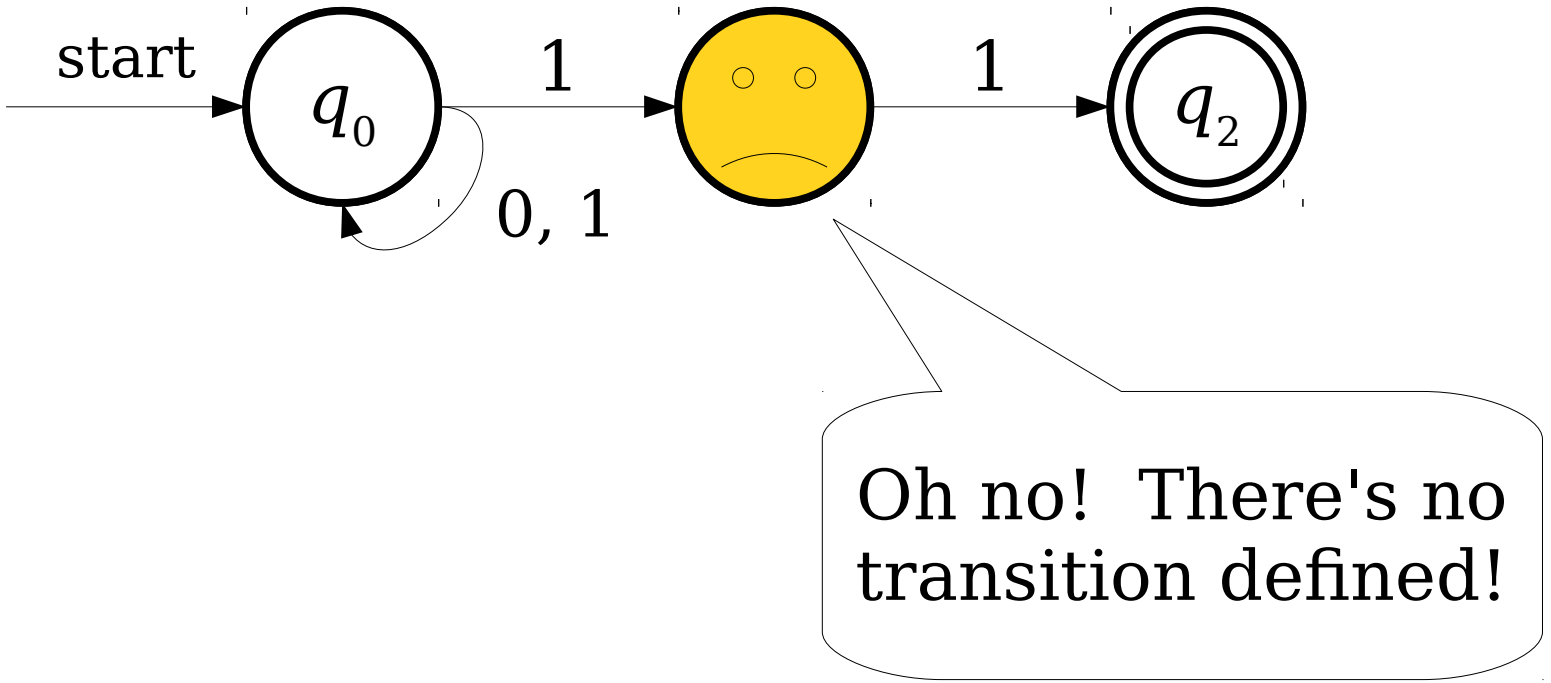

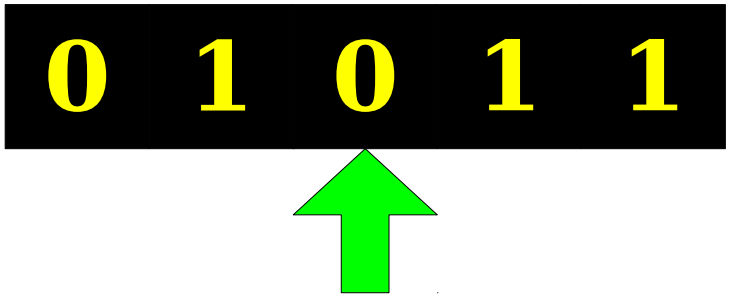

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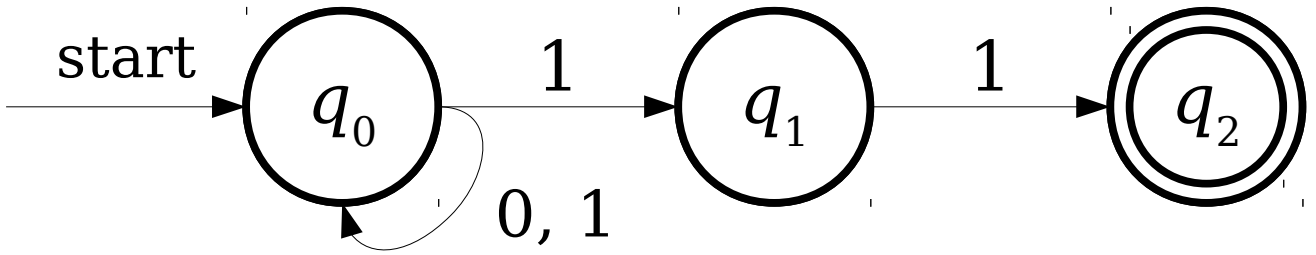

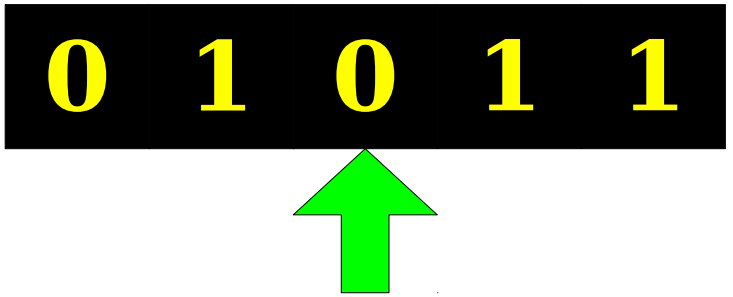

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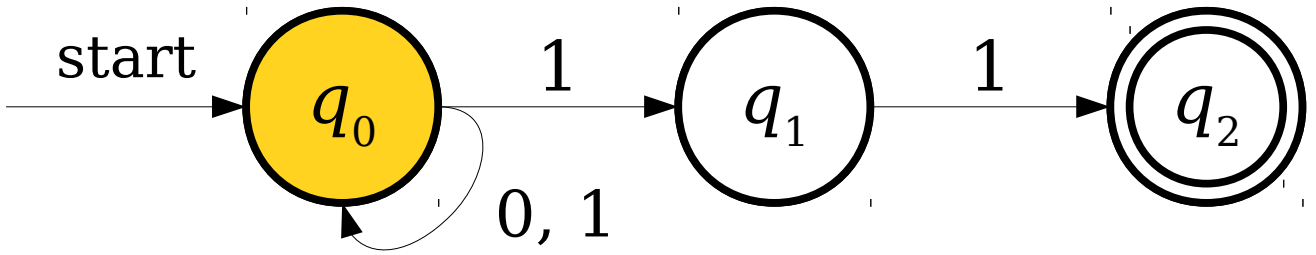

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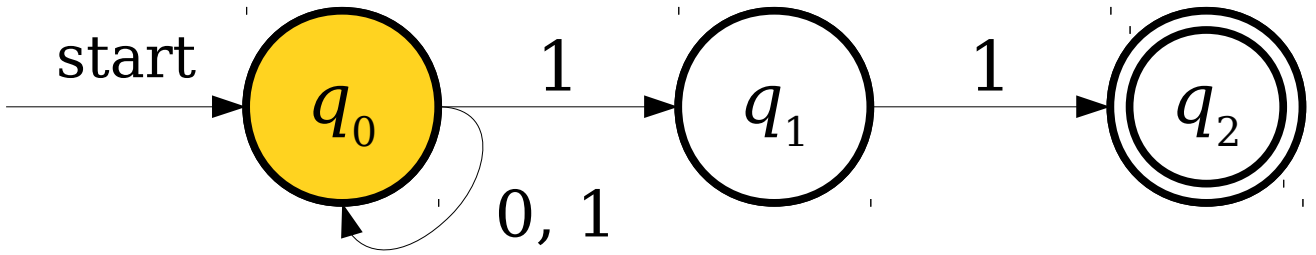

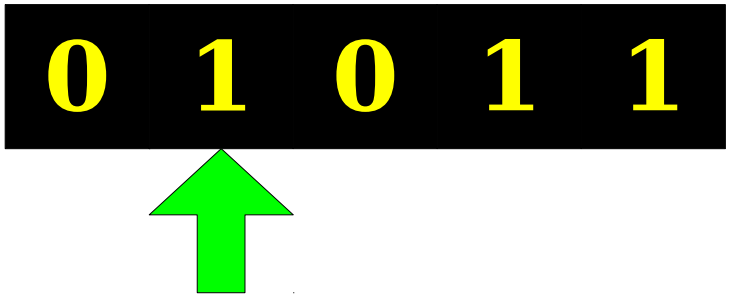

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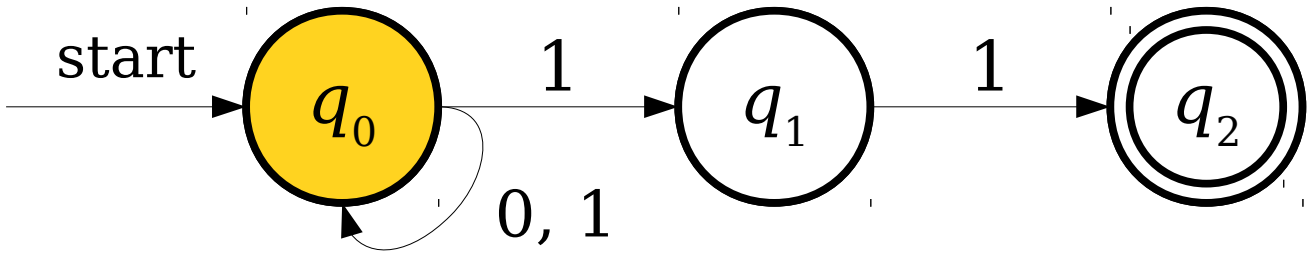

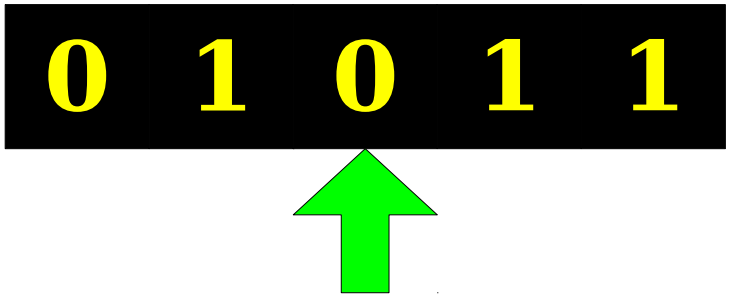

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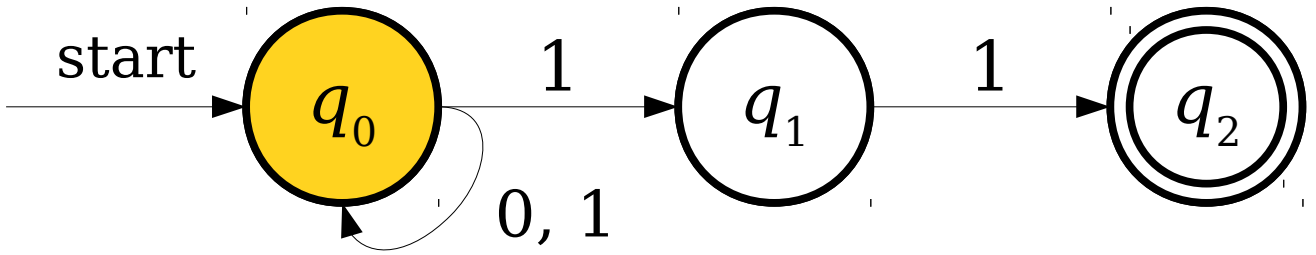

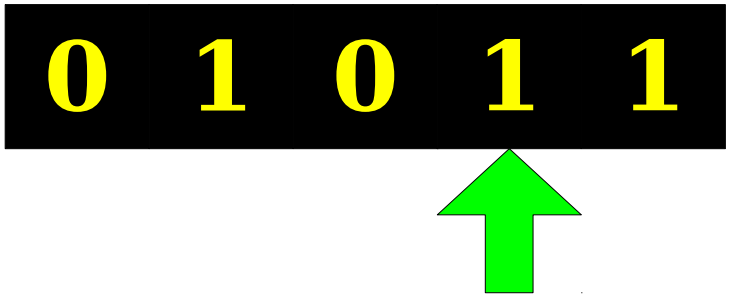

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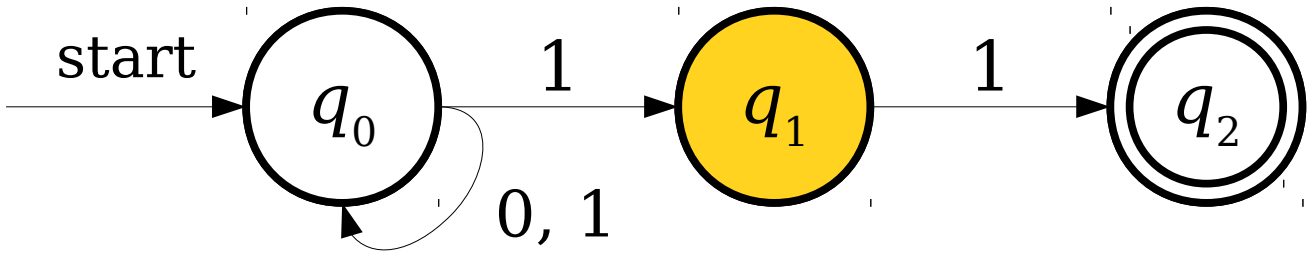

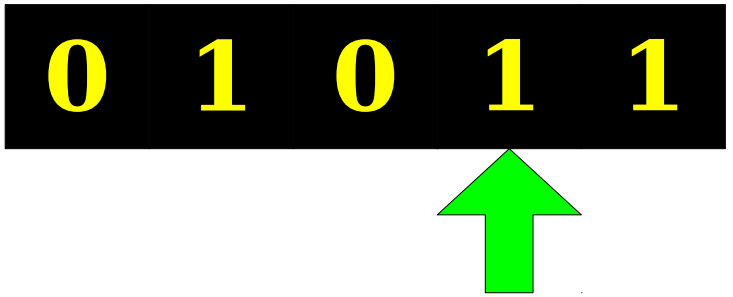

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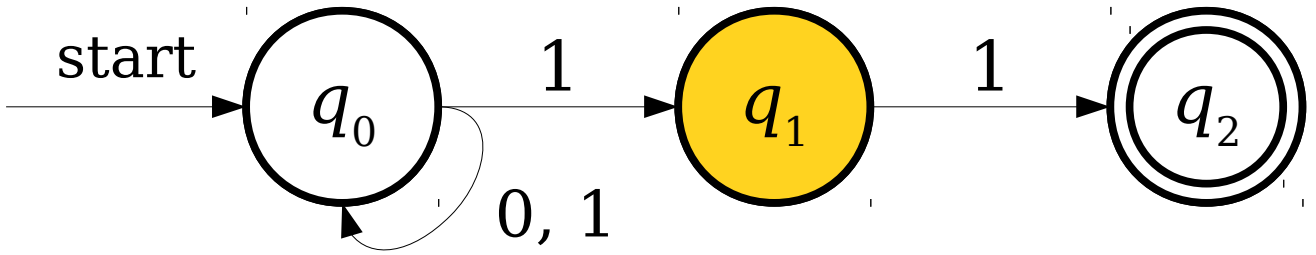

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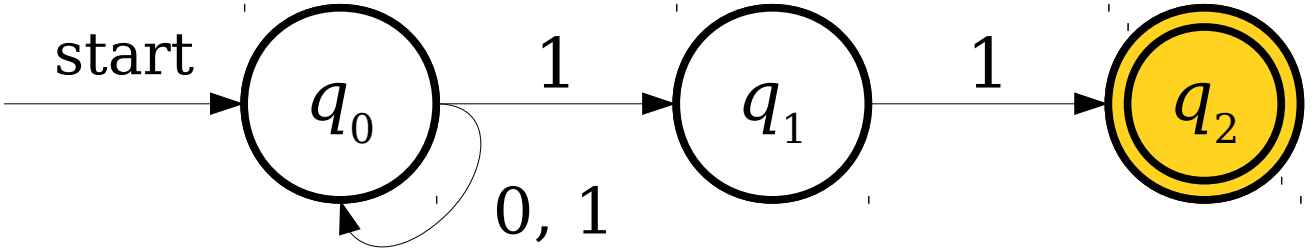

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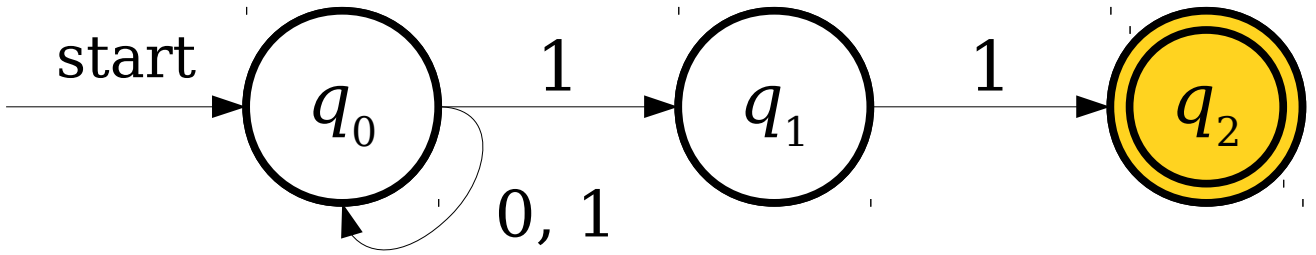

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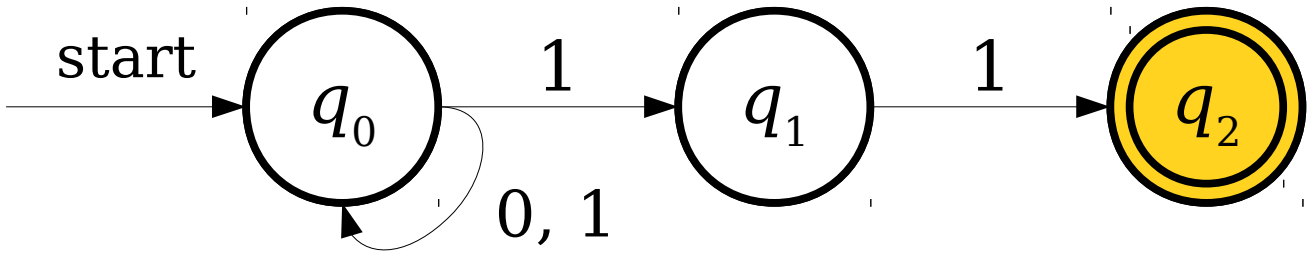

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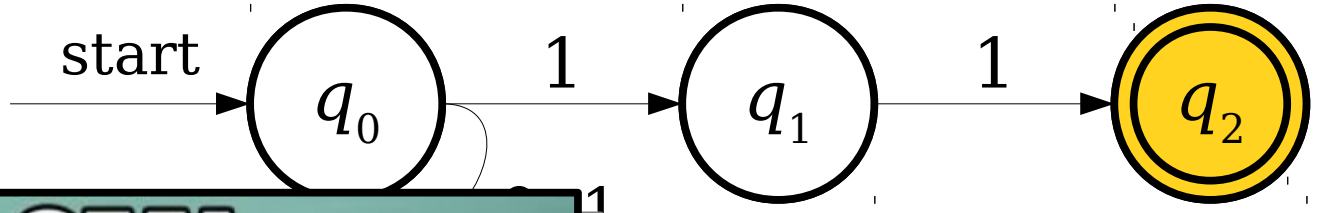

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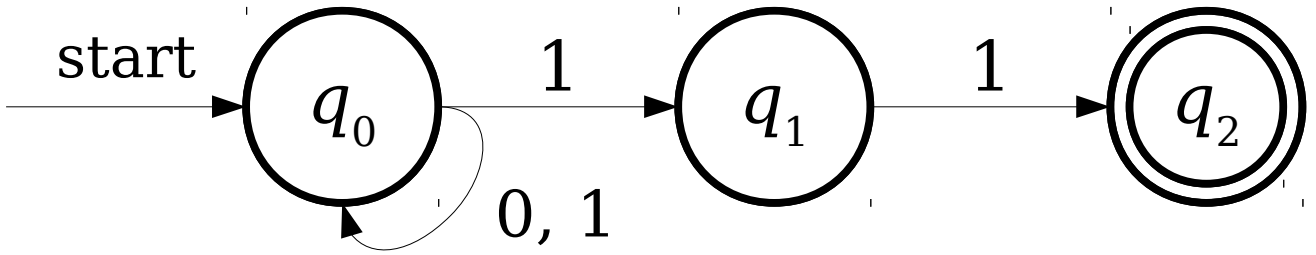

Question to ponder:
What does this NFA accept?

NFA Acceptance

- An NFA *N* accepts a string *w* if there is some series of choices that lead to an accepting state.
- Consequently, an NFA *N* rejects a string *w* if *no possible* series of choices lead it into an accepting state.
- It's easier to show that an NFA does accept something than to show that it doesn't

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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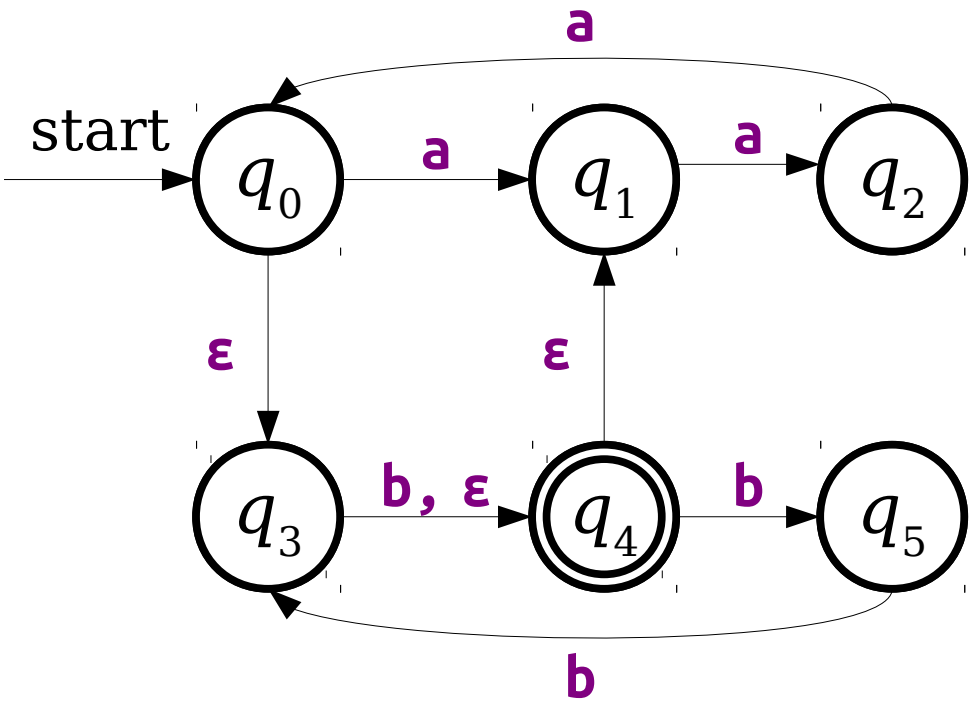

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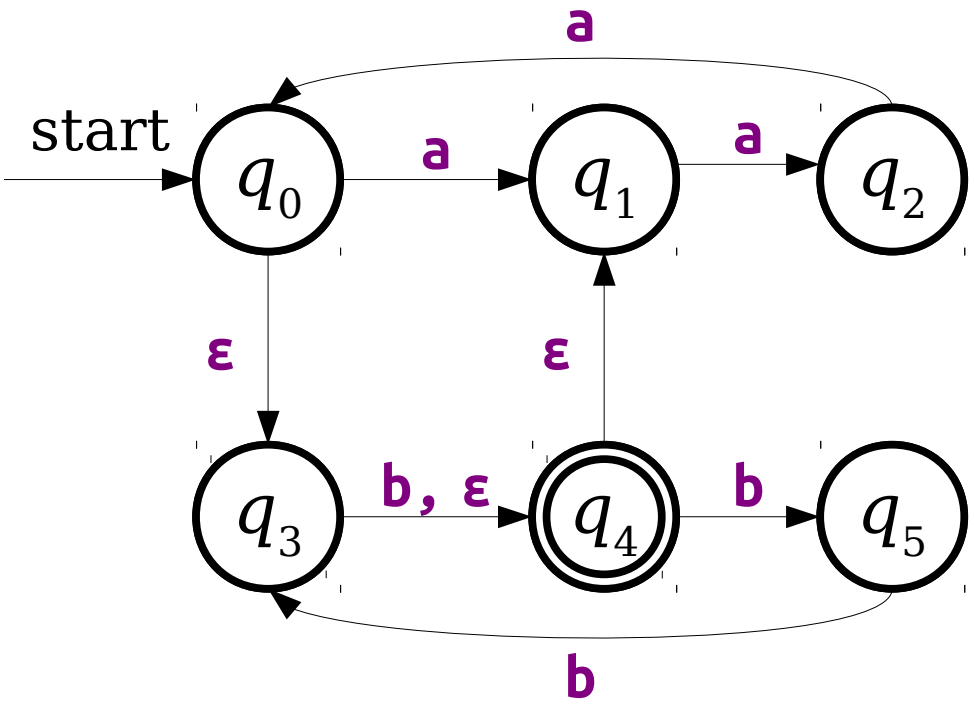

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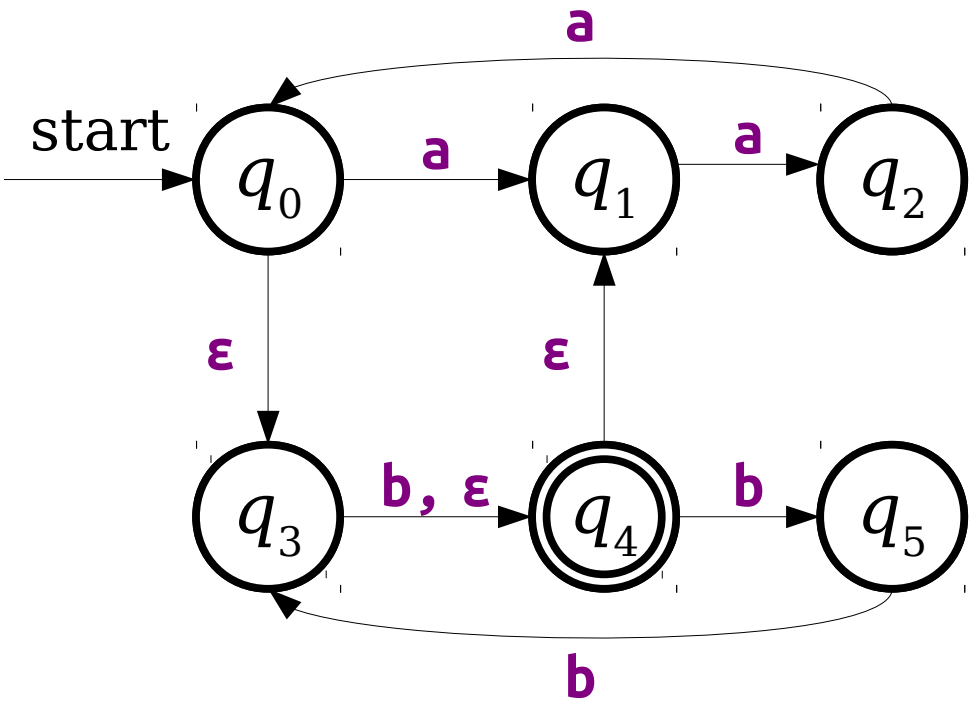

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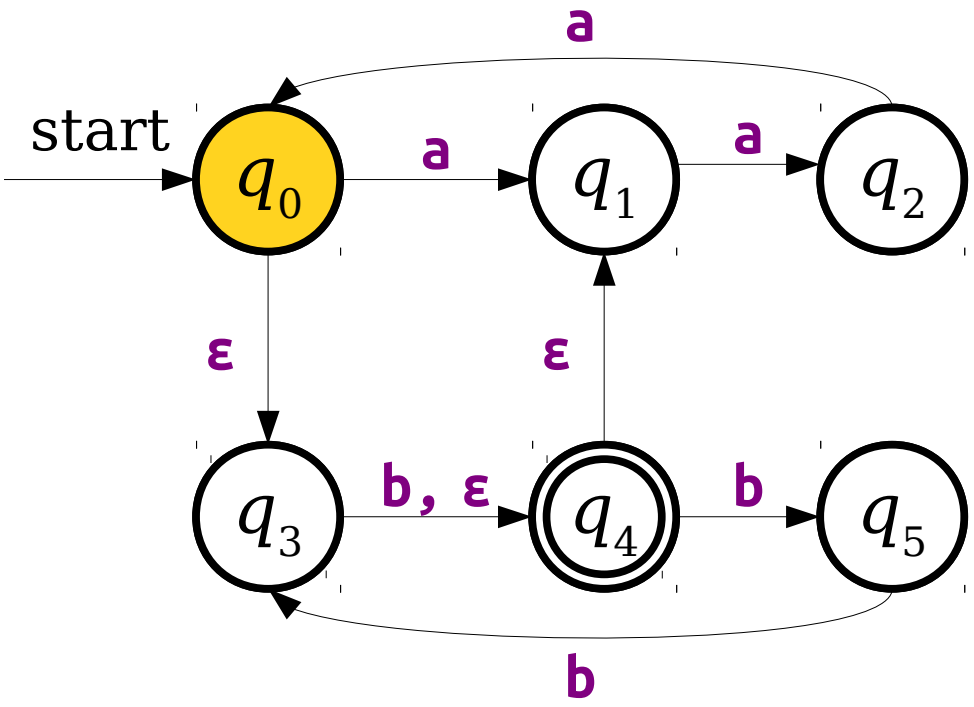

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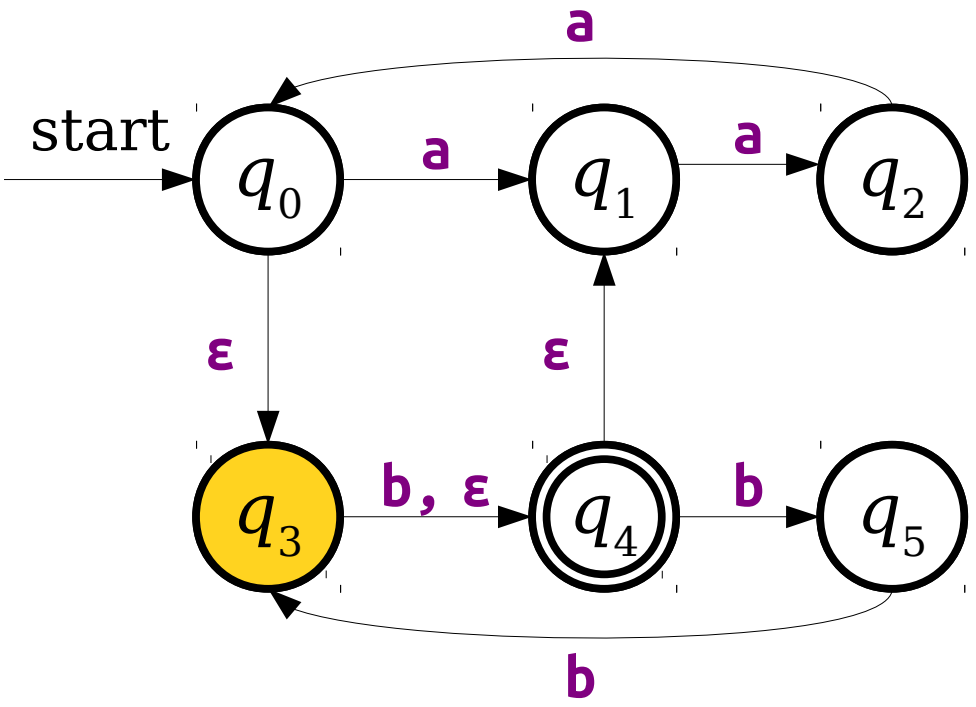

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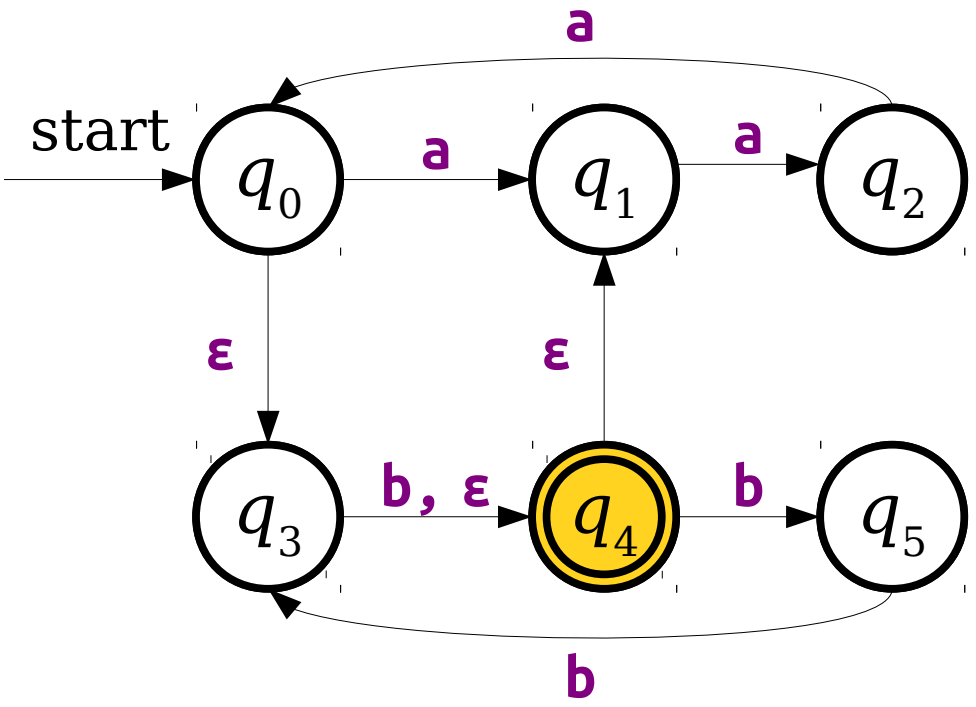

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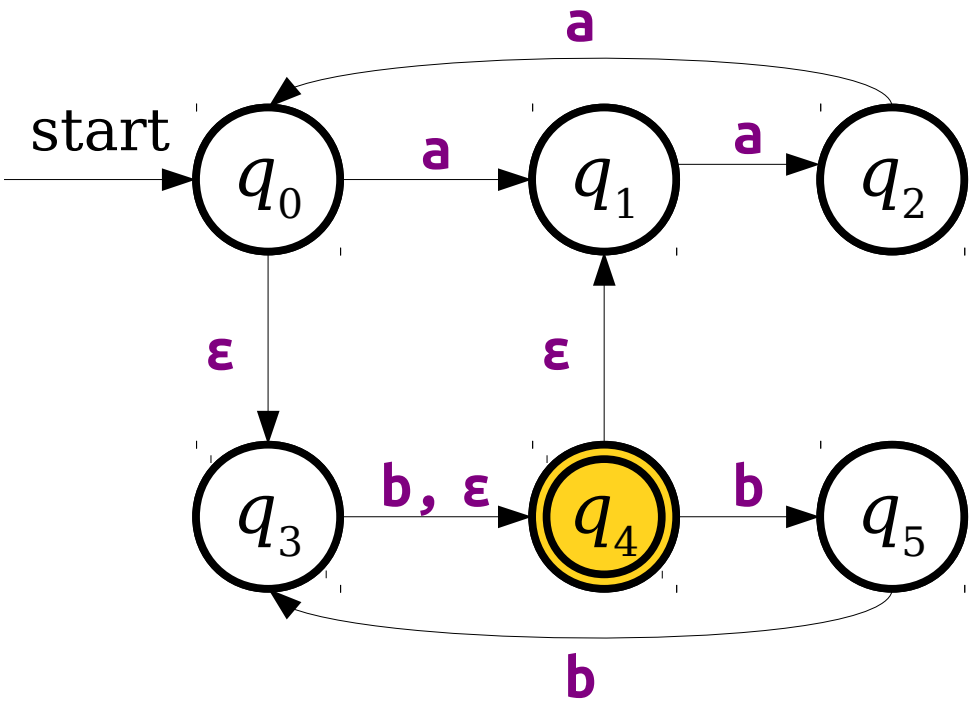

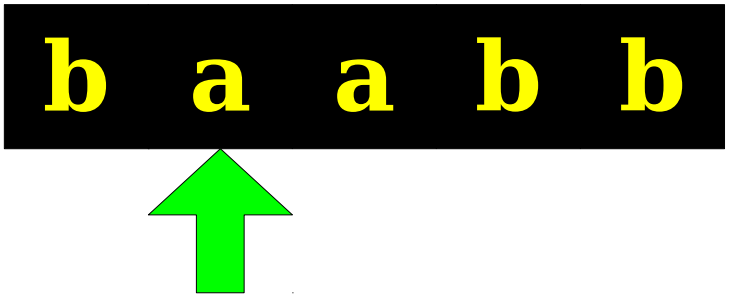

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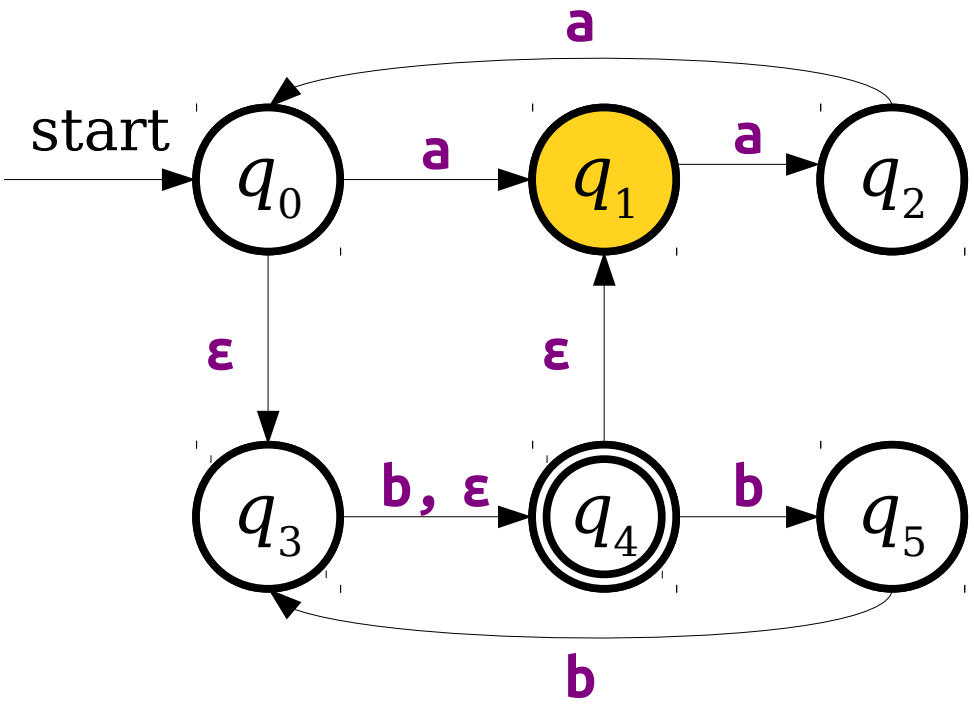

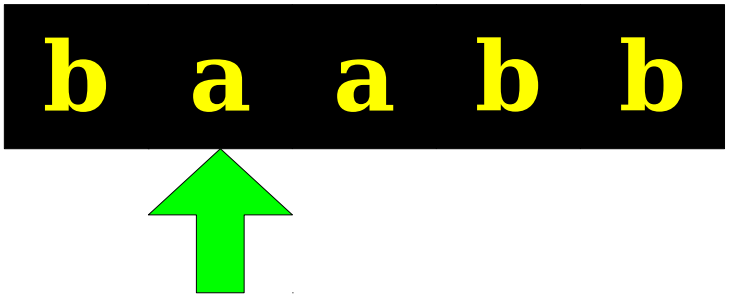

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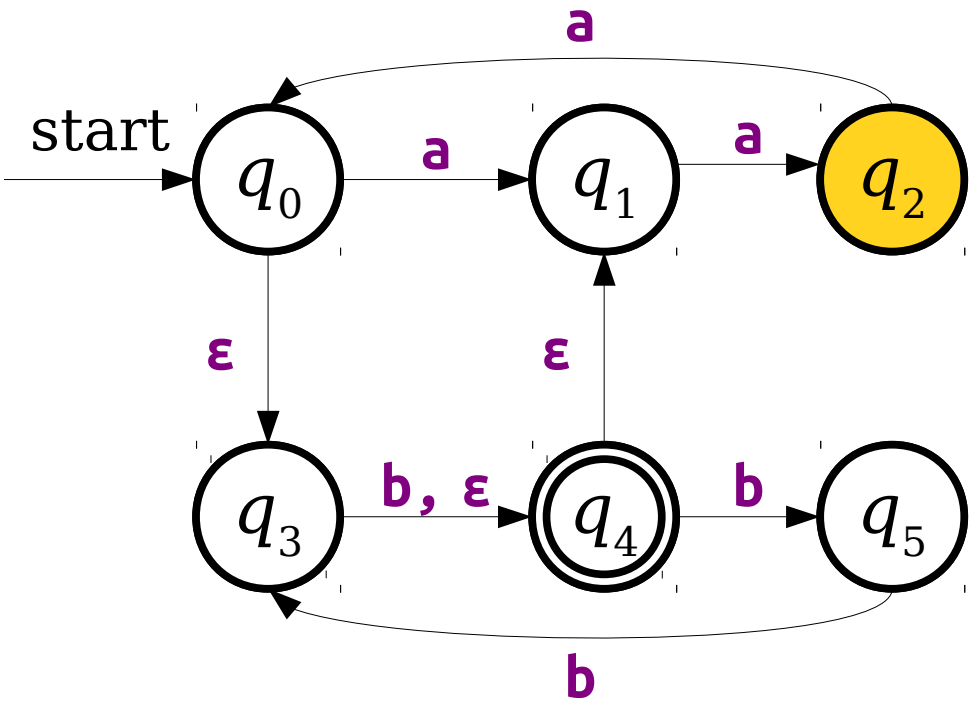

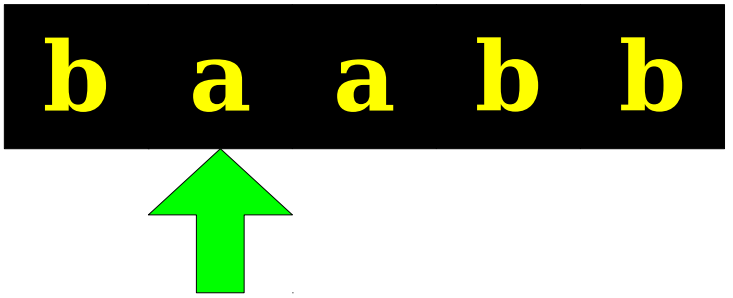

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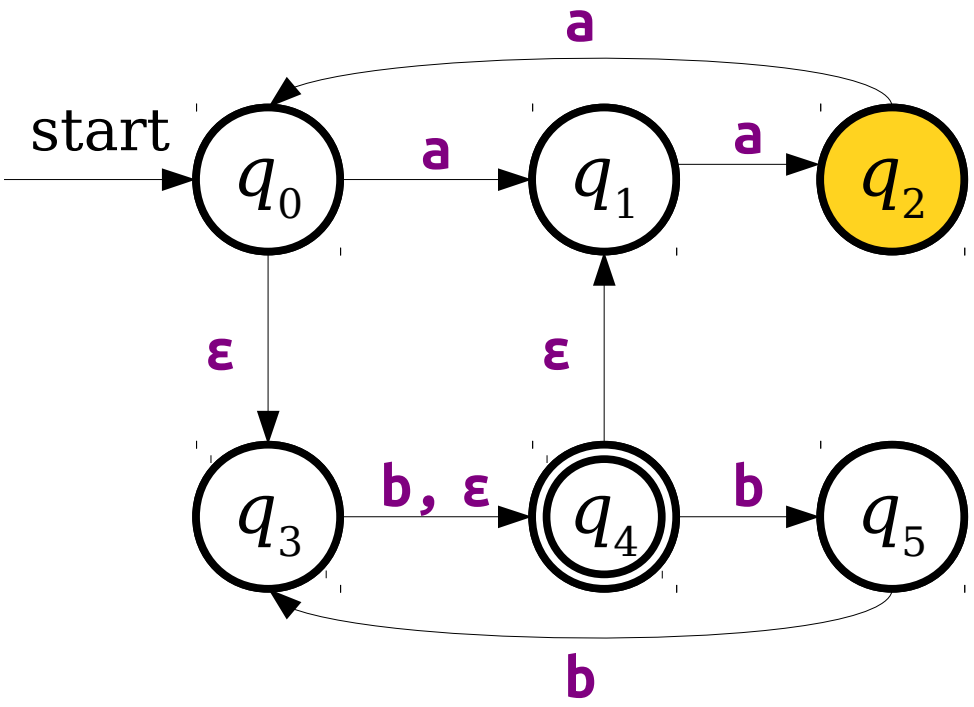

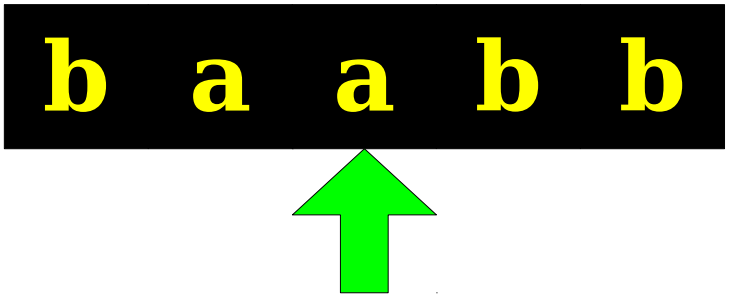

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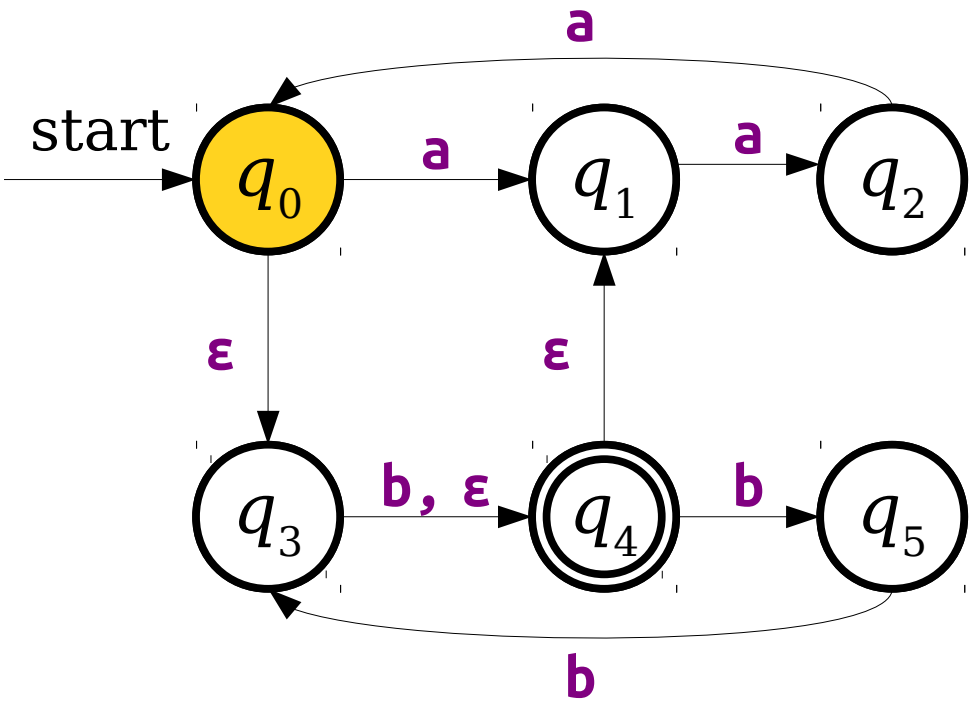

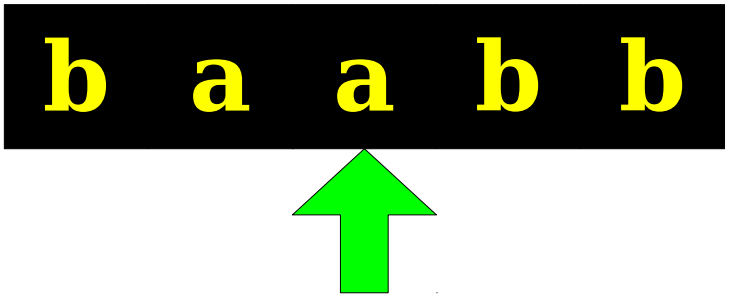

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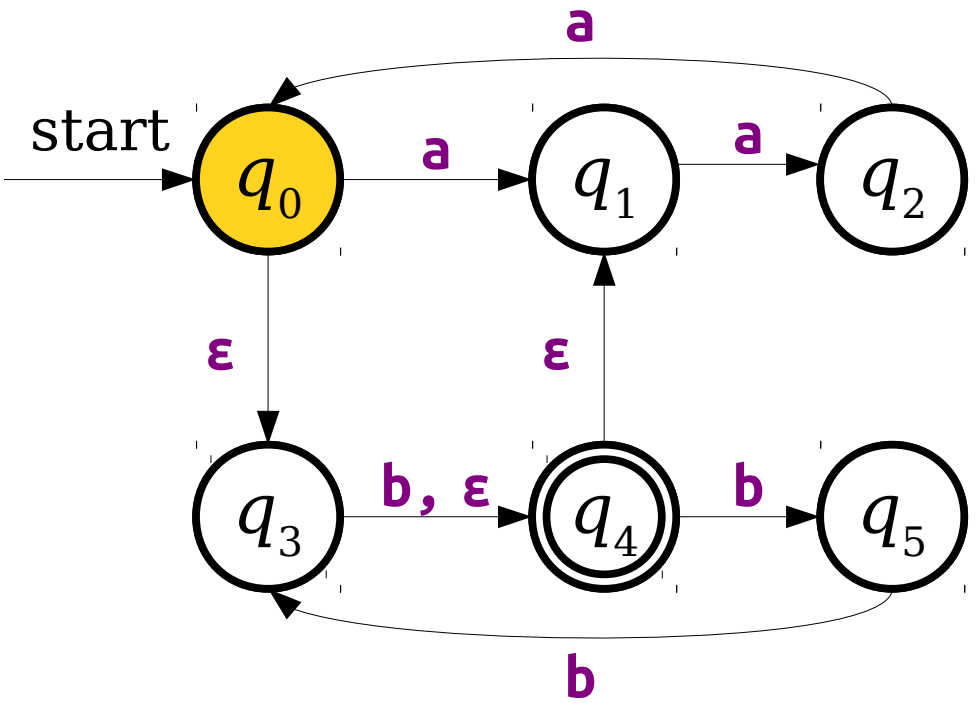

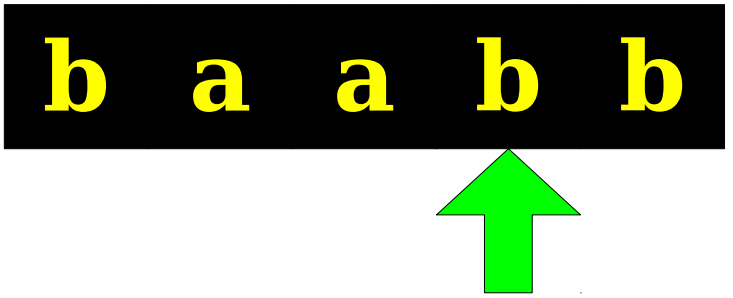

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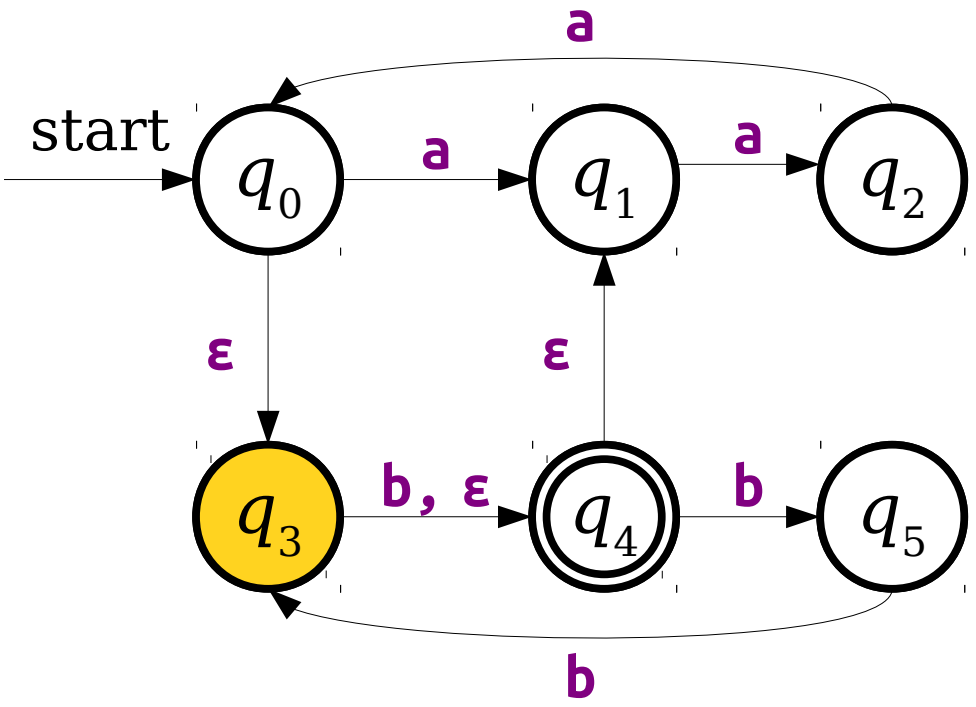

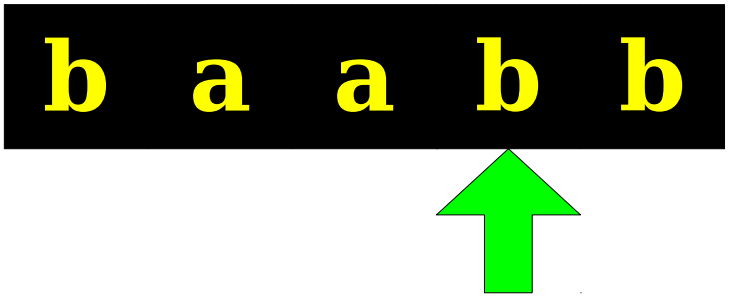

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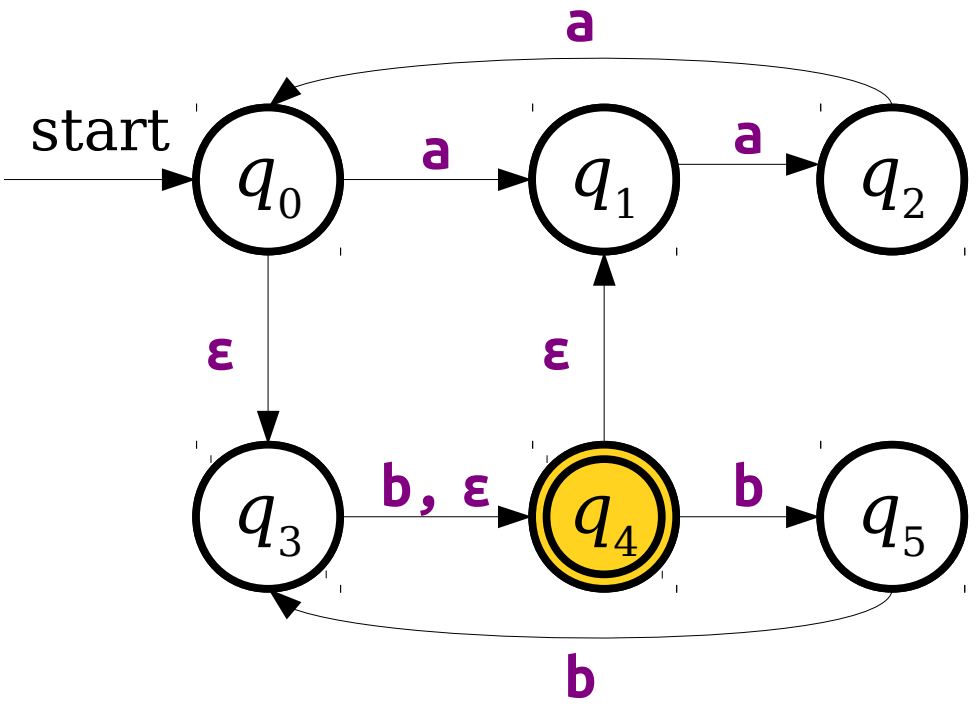

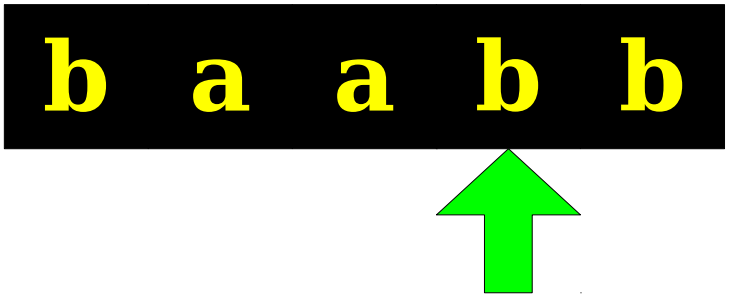

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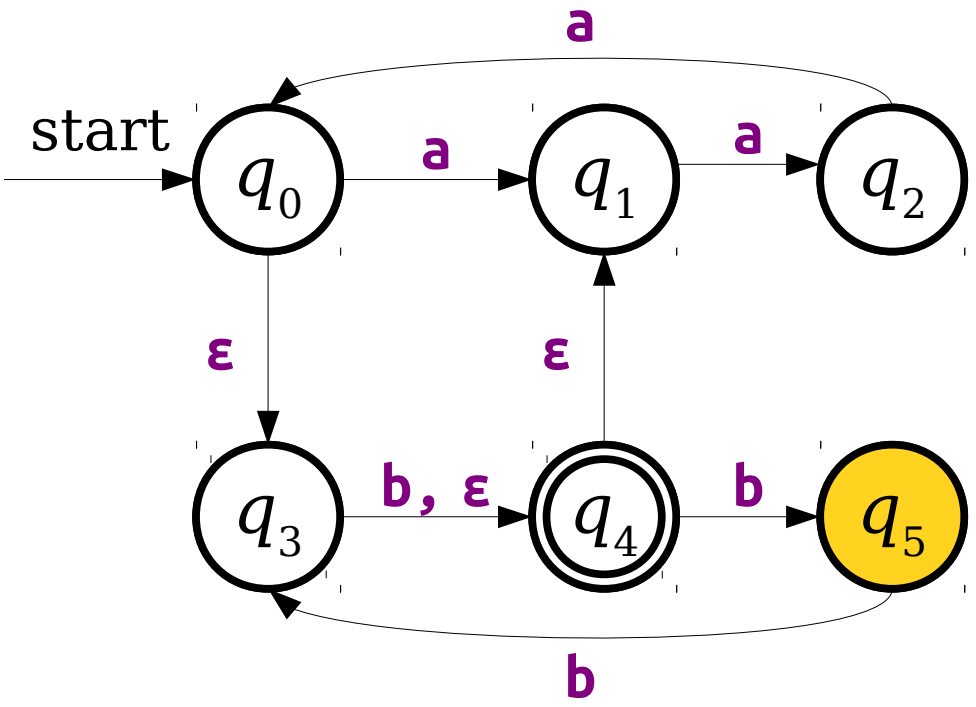

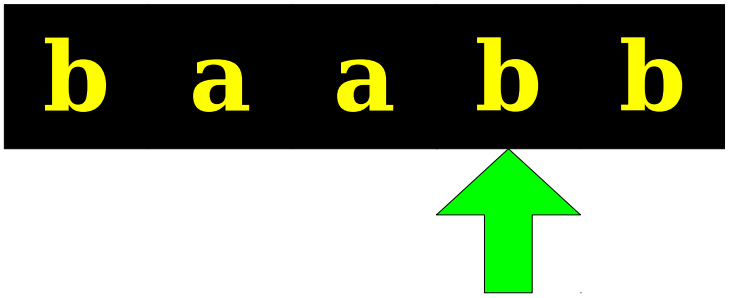

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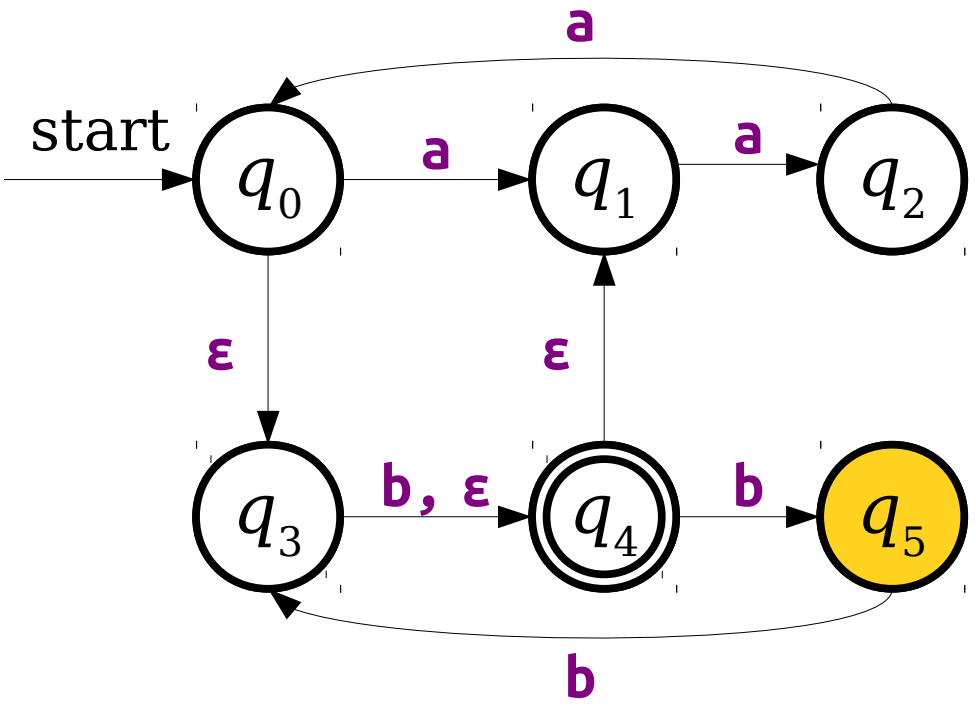

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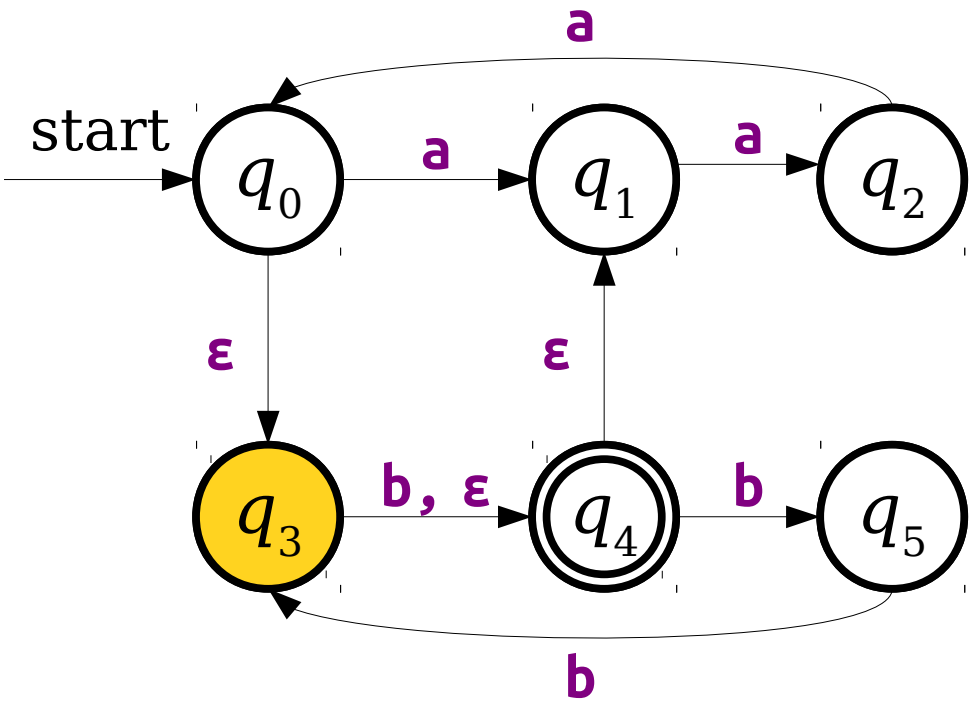

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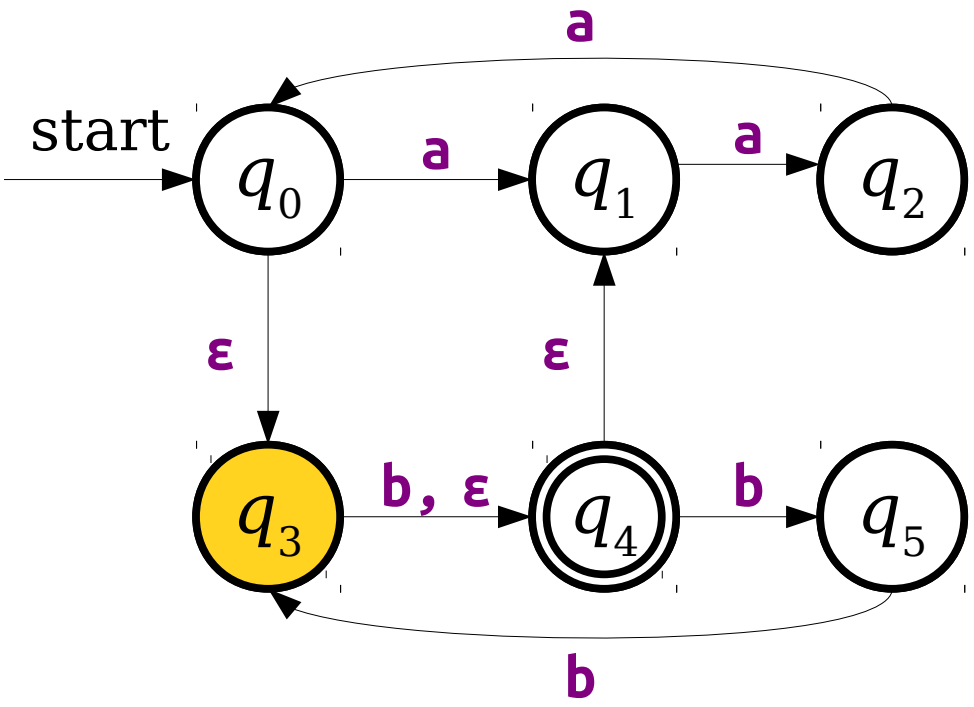

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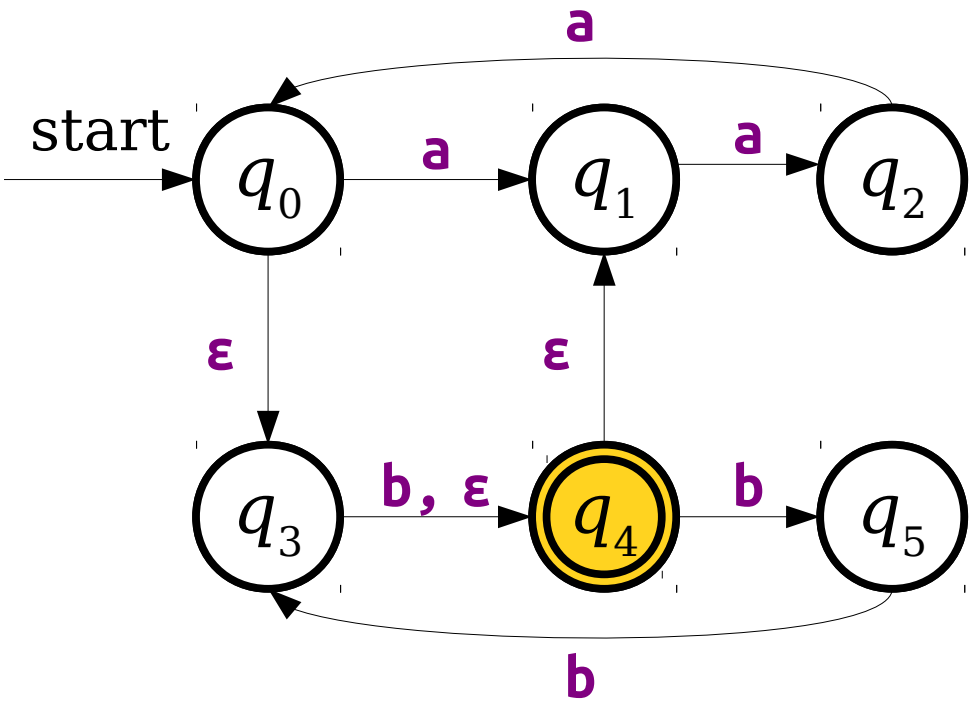

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- NFAs have a special type of transition called the **ε-transition**.
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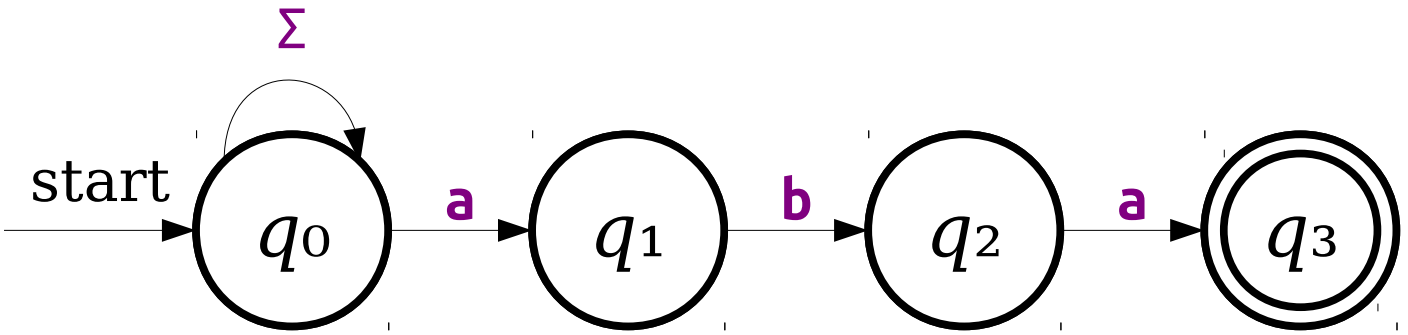
- NFAs are not *required* to follow ε-transitions. It's simply another option at the machine's disposal.

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 guessing***
  - ***Massive parallelism***

Perfect Guessing



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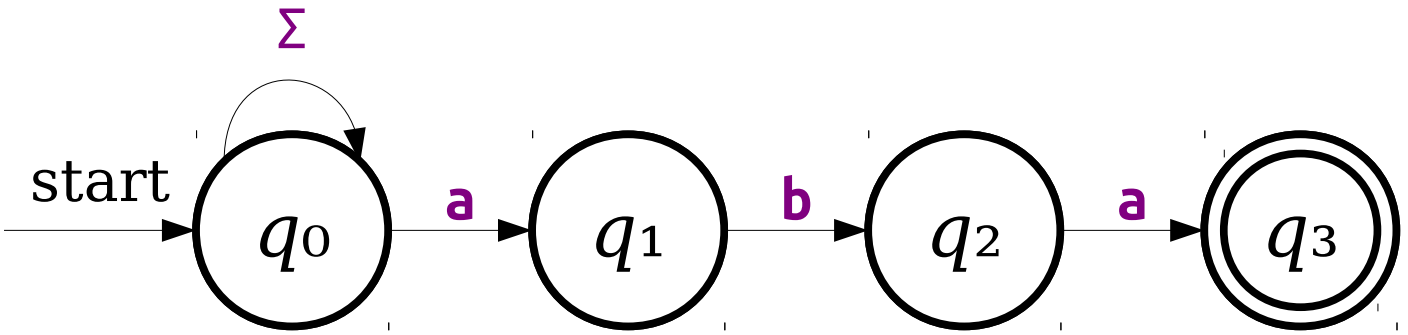

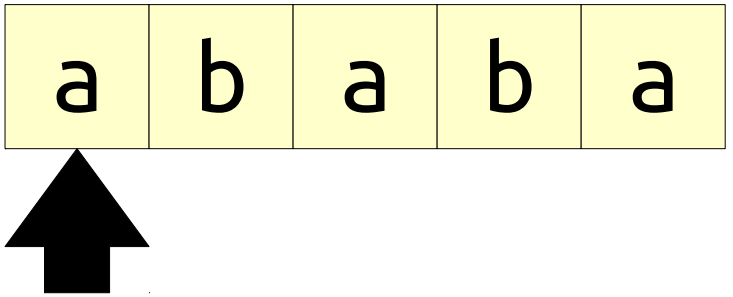

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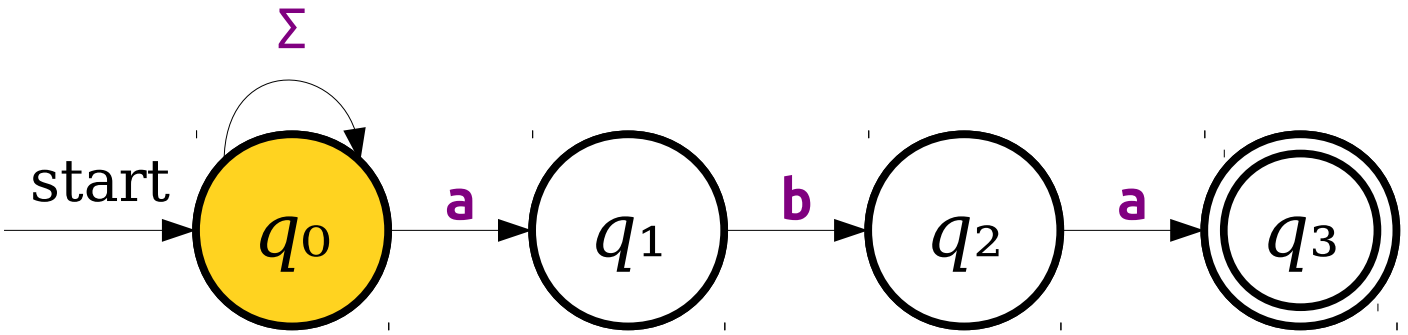

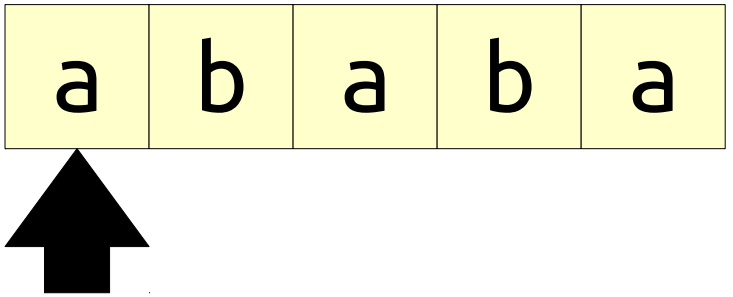

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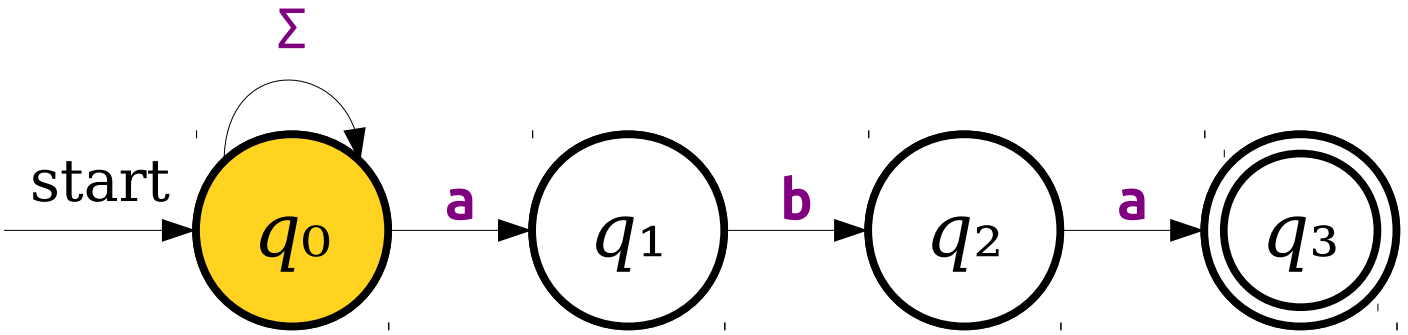

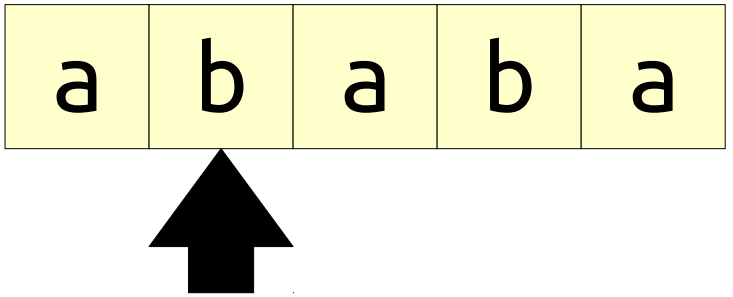

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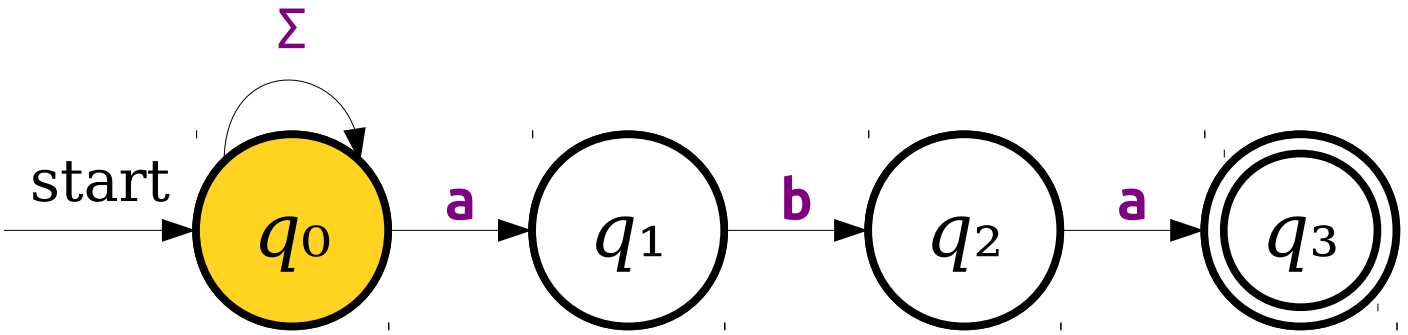

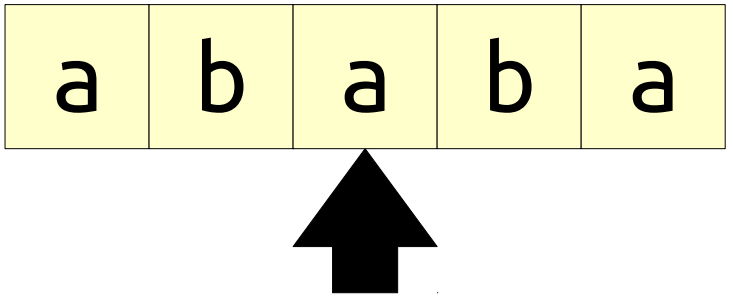

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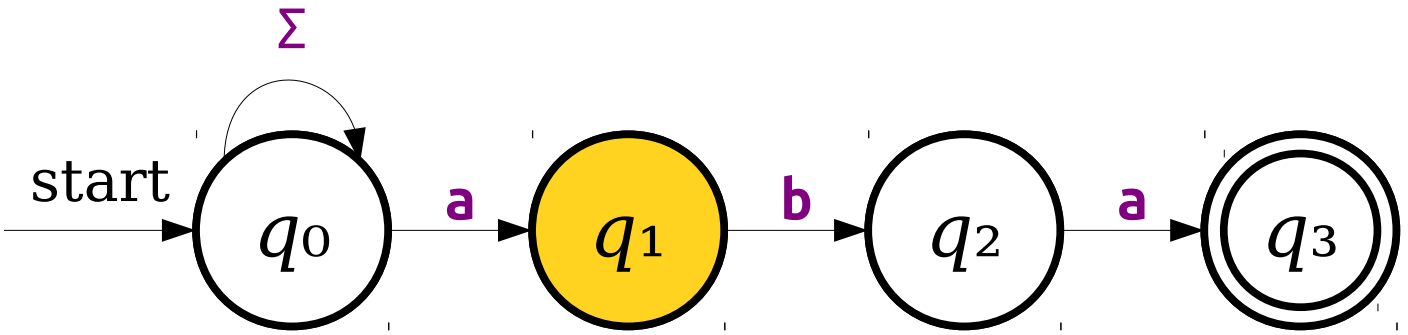

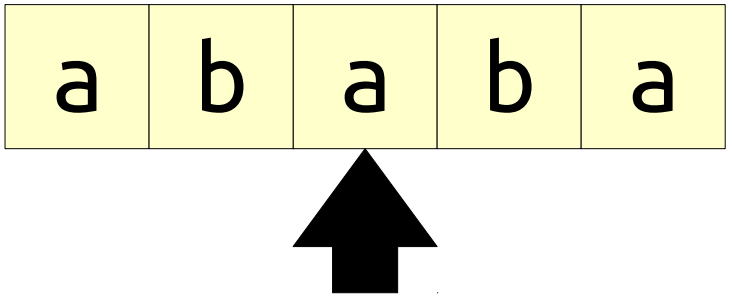

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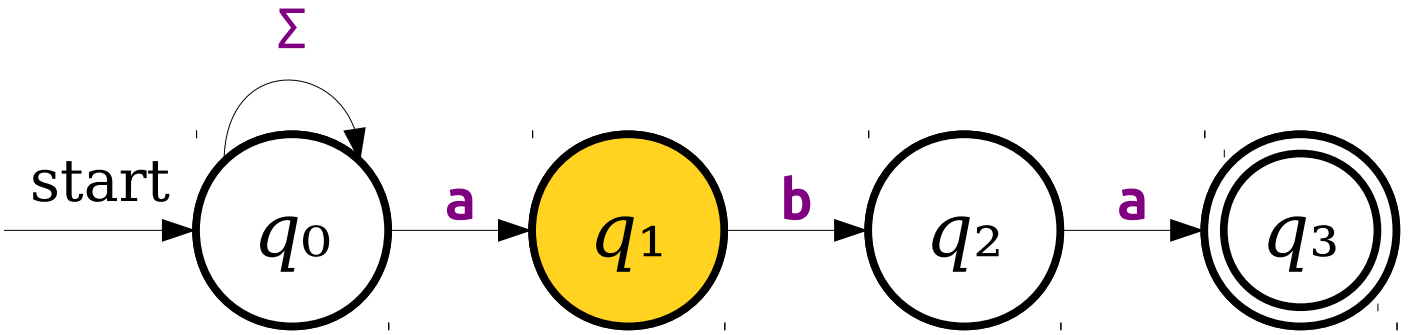

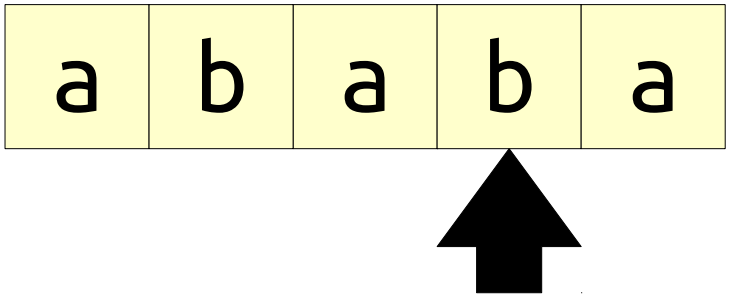

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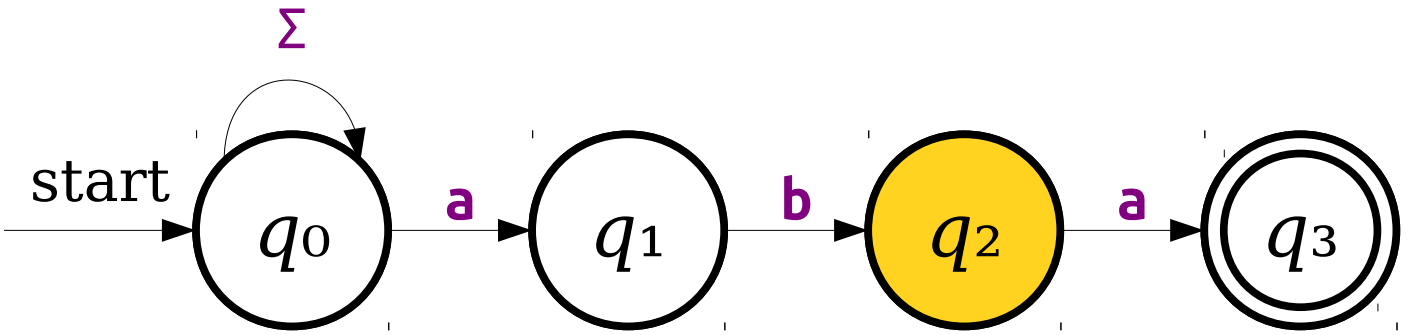

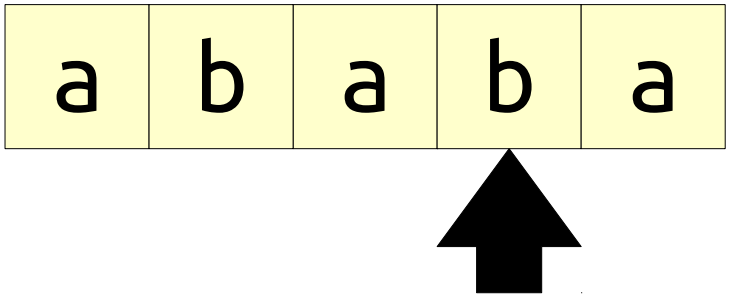

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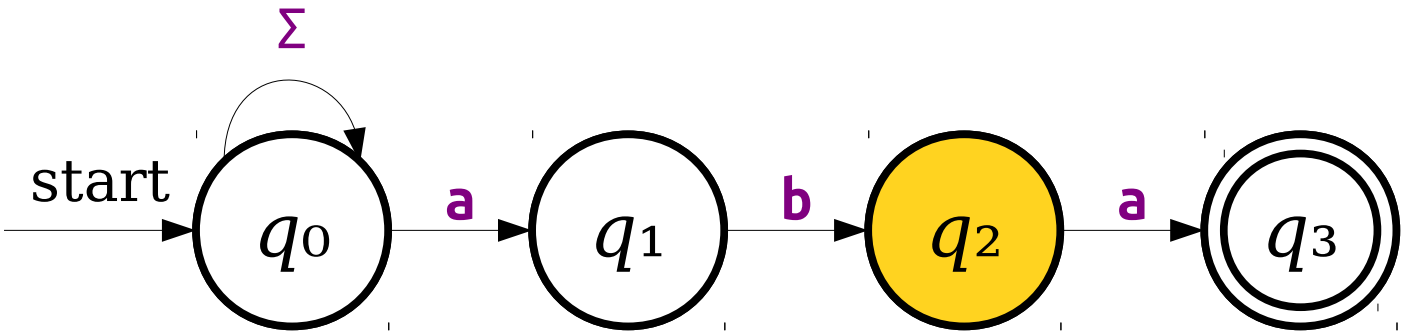

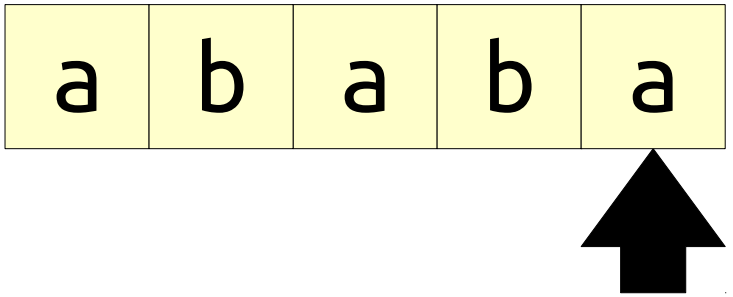

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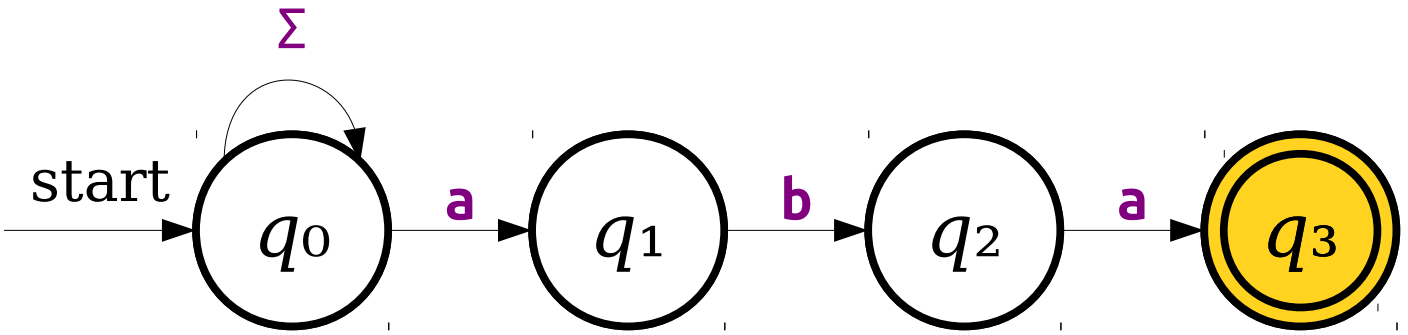

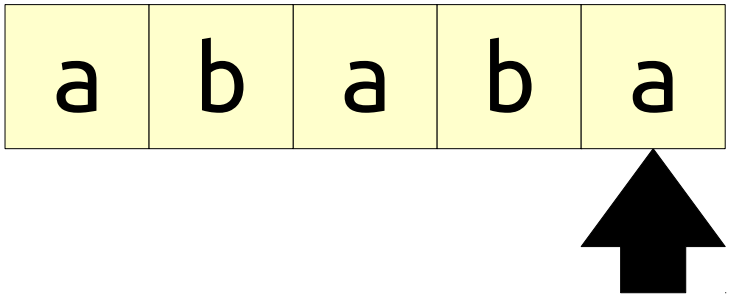

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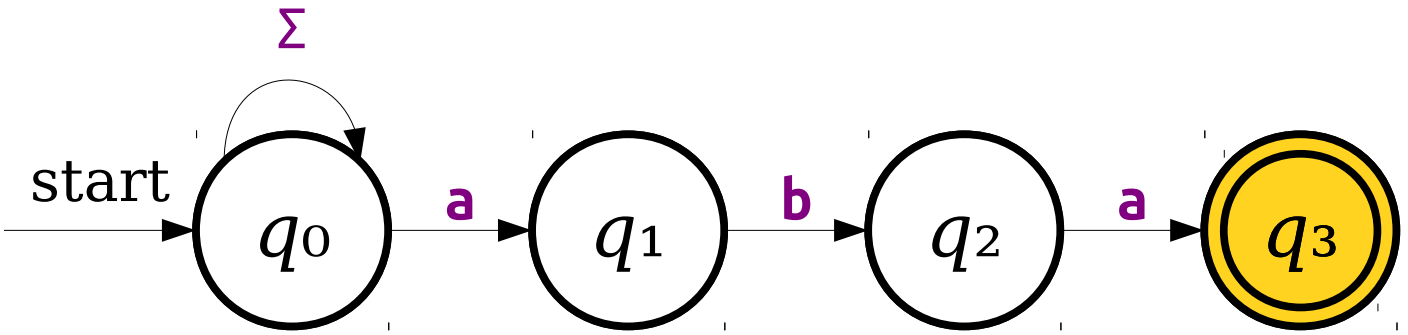
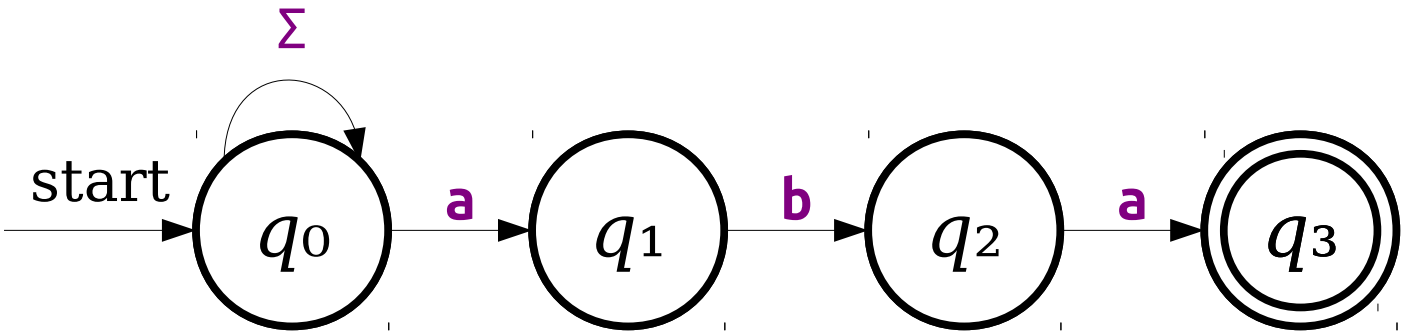


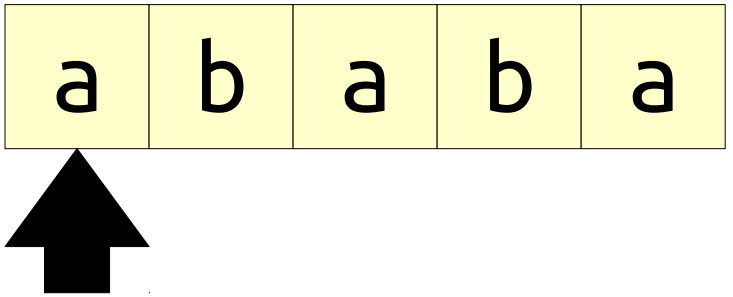
a	b	a	b	a

Perfect 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.
- No known physical analog for this style of computation – this is totally new!

Massive Parallelism





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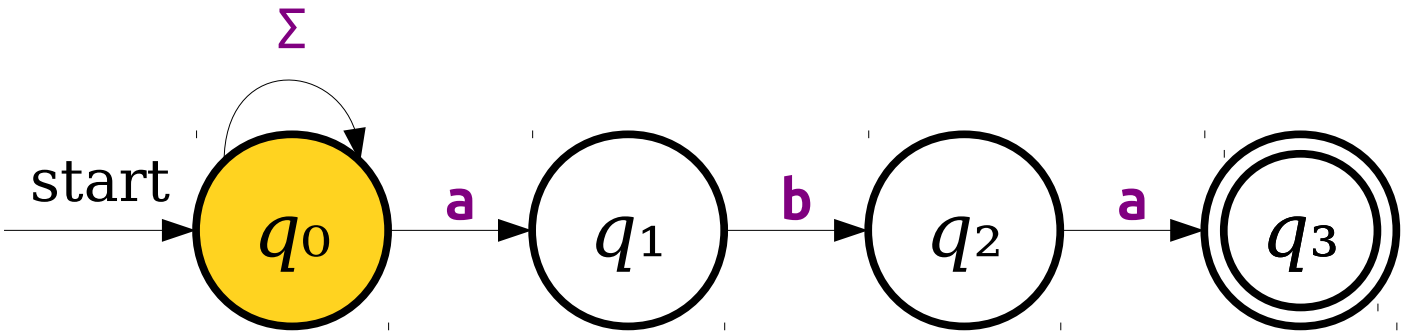

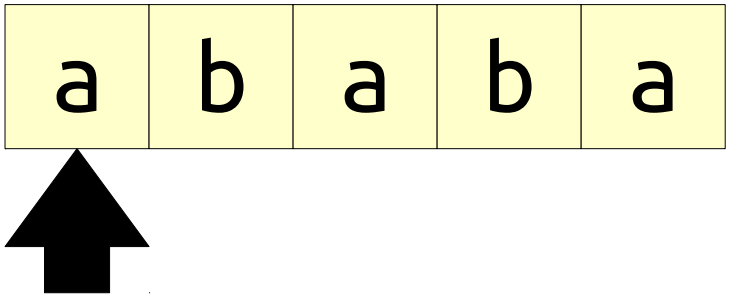

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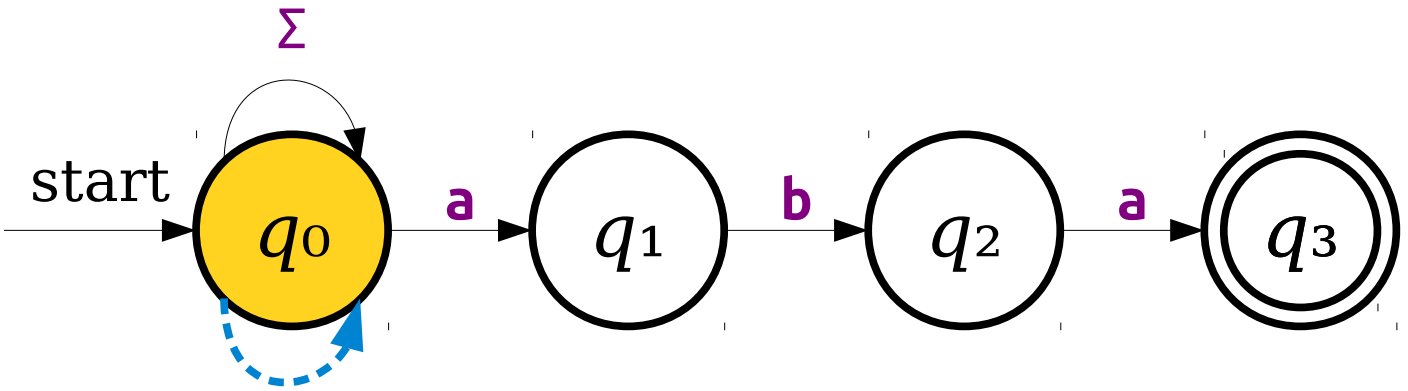
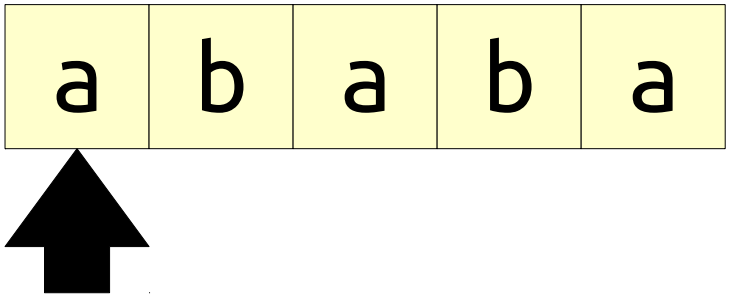
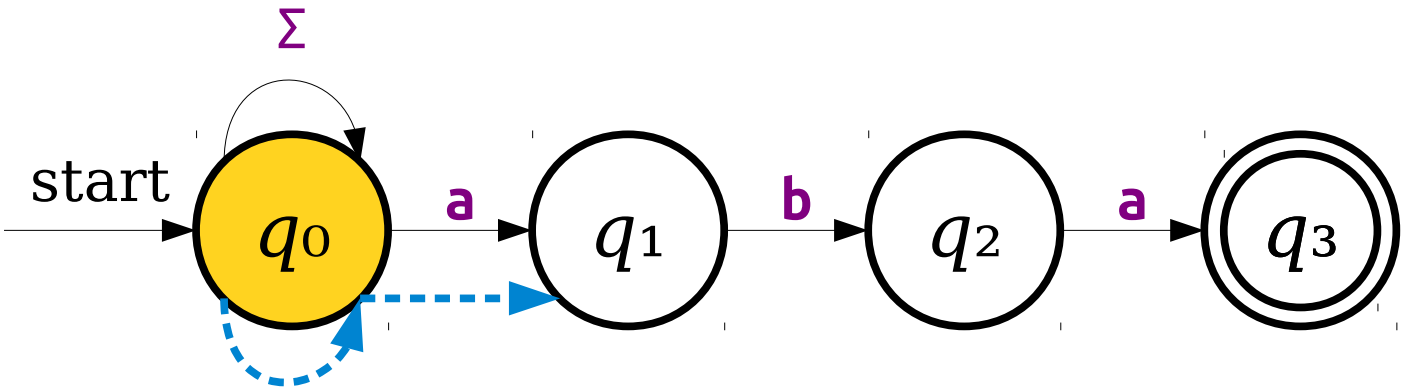
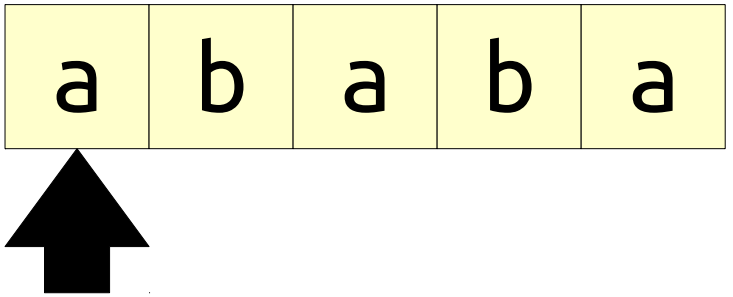




Massive Parallelism





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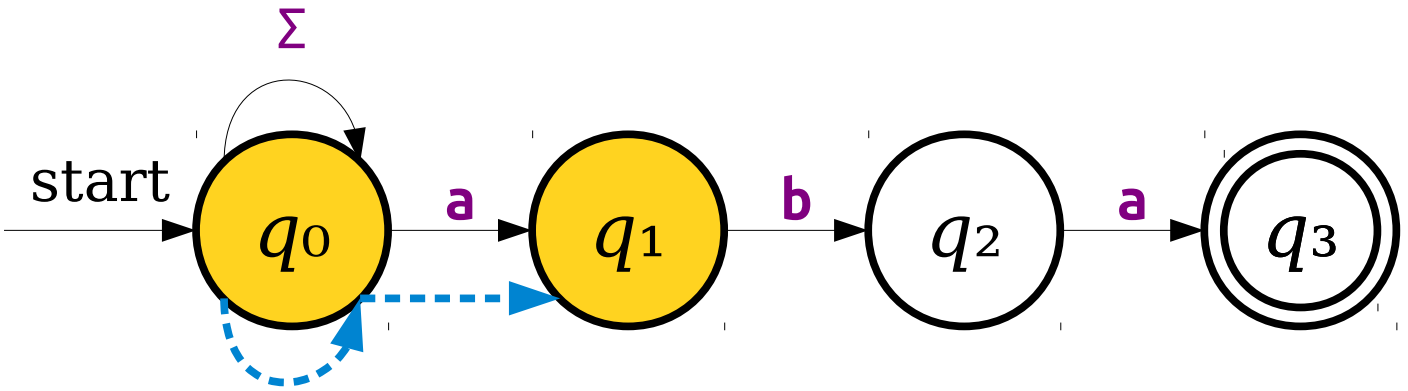

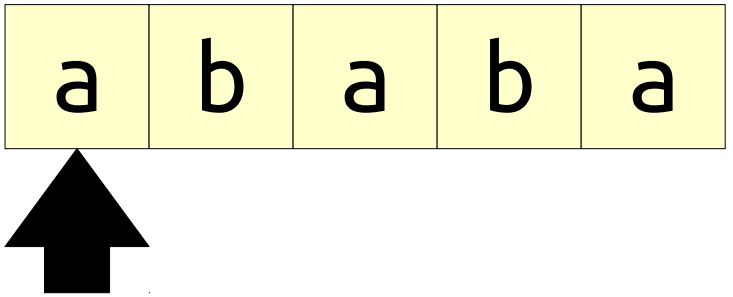

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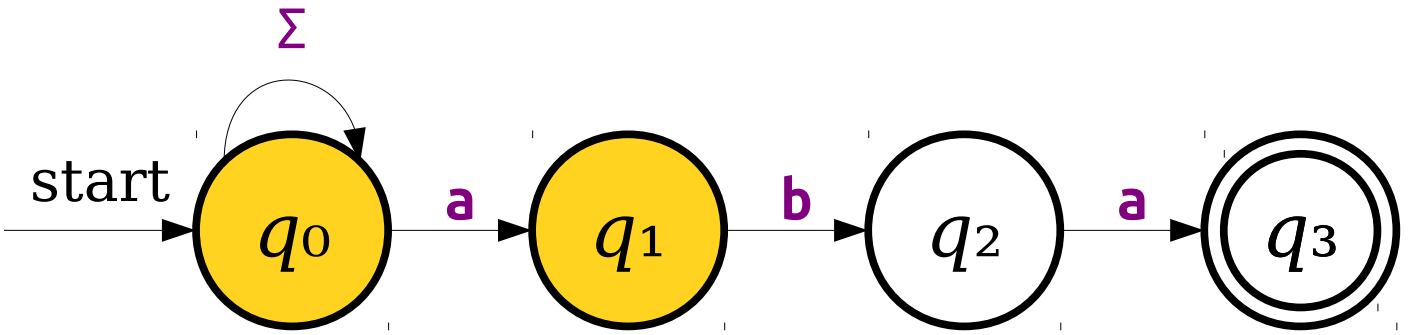

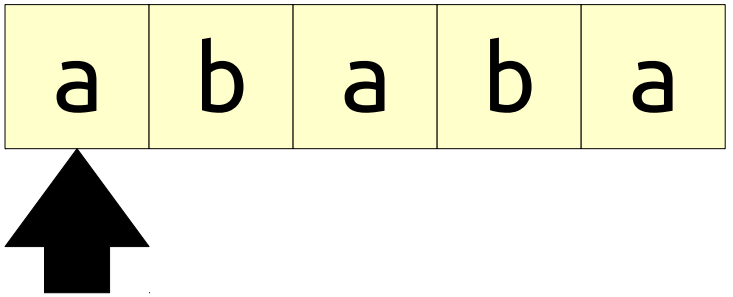

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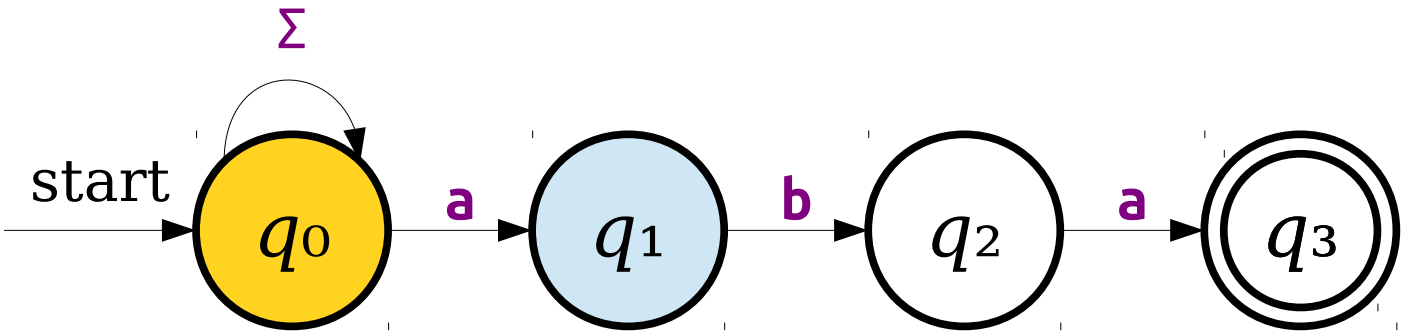

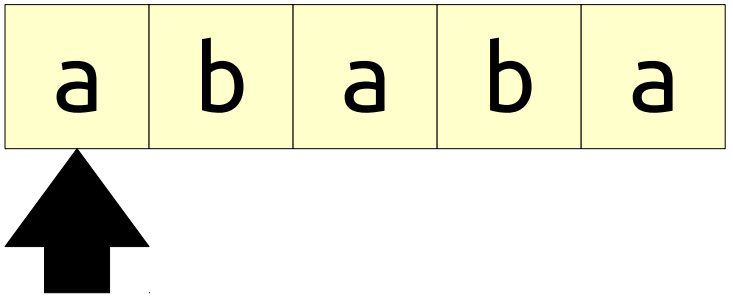

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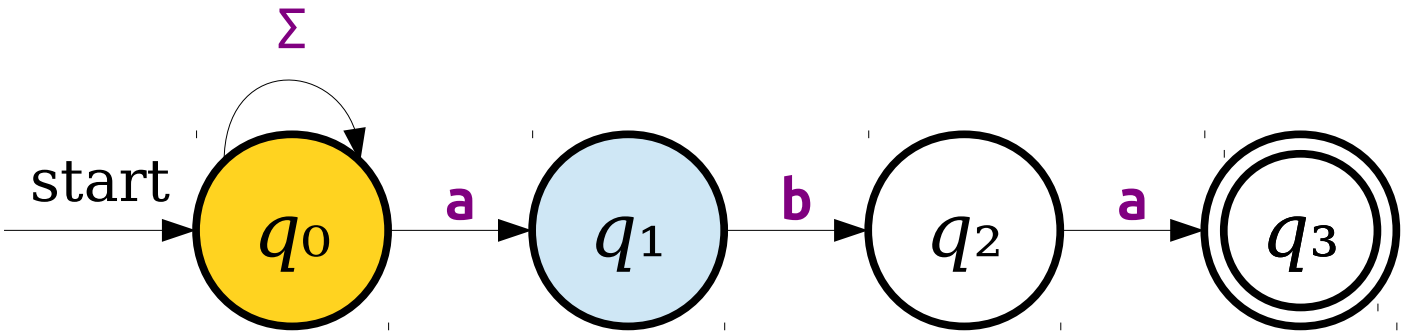

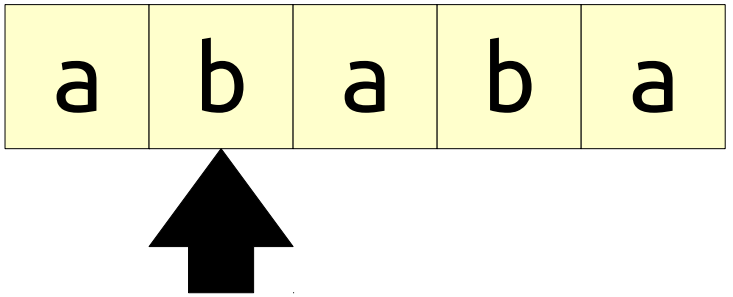

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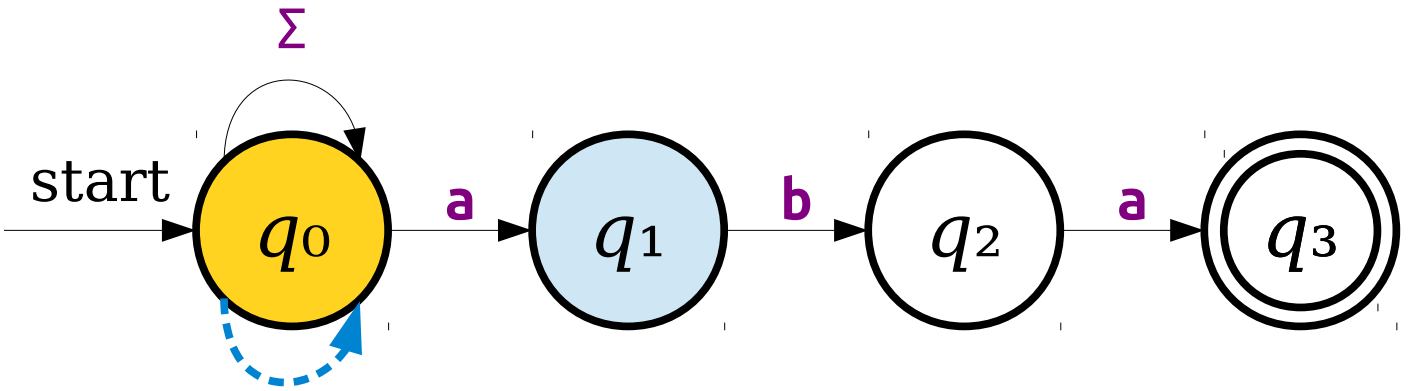

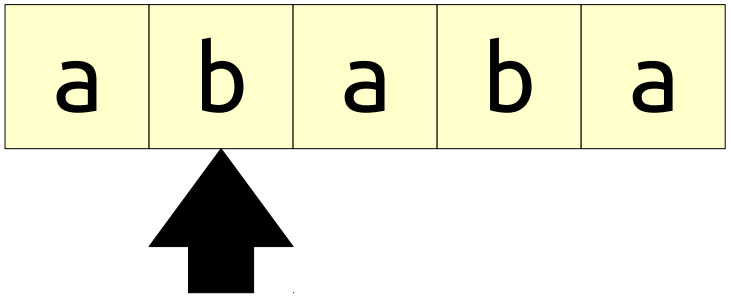

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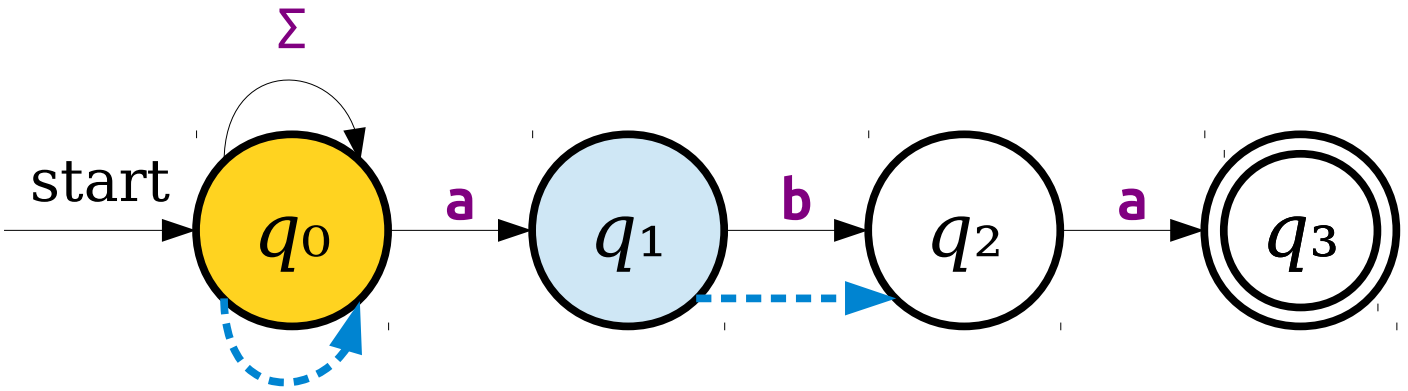

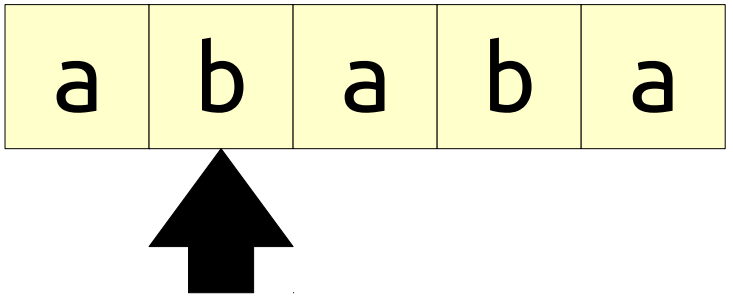

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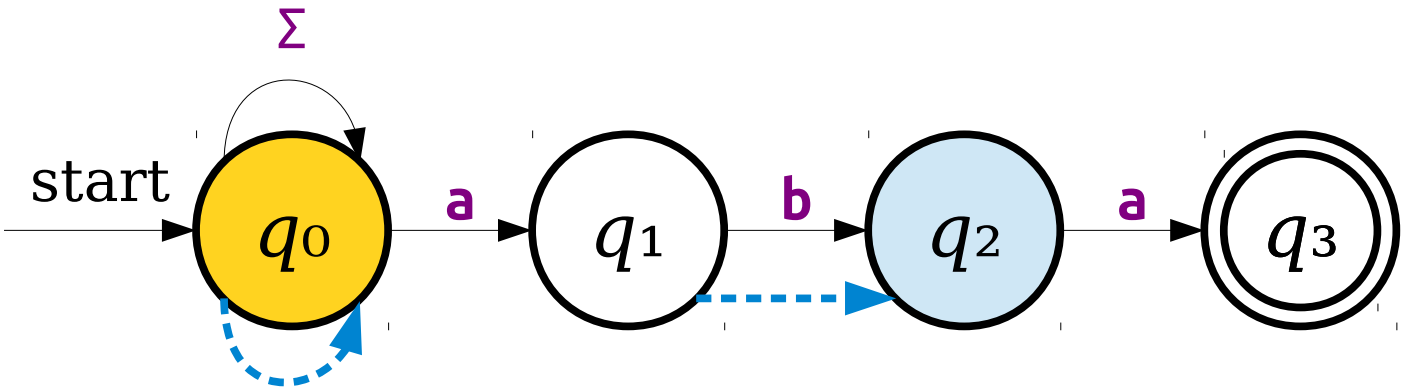

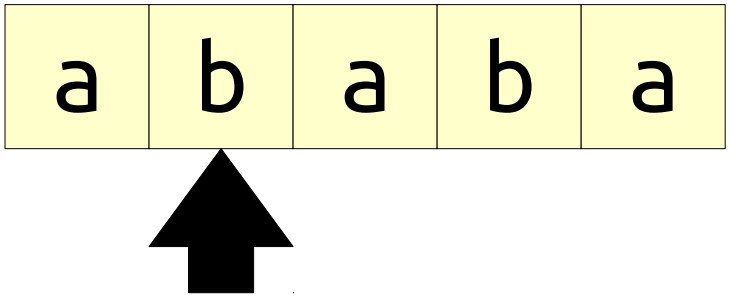

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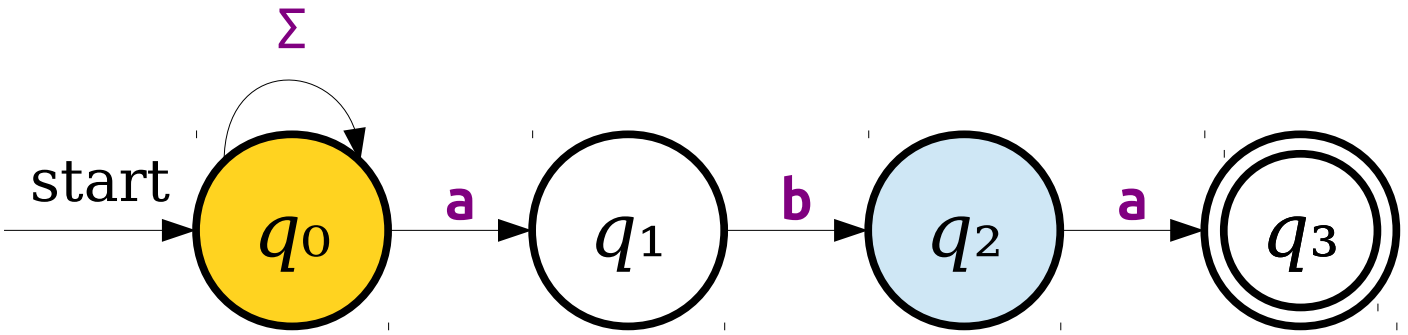

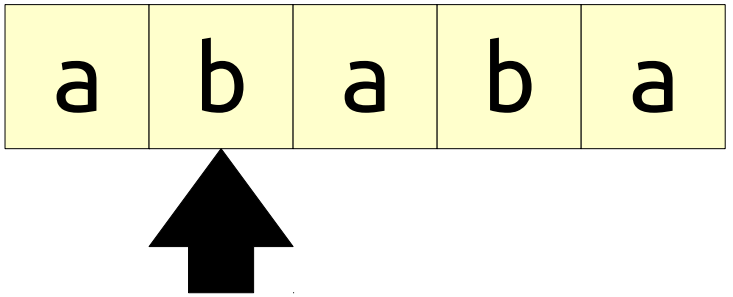

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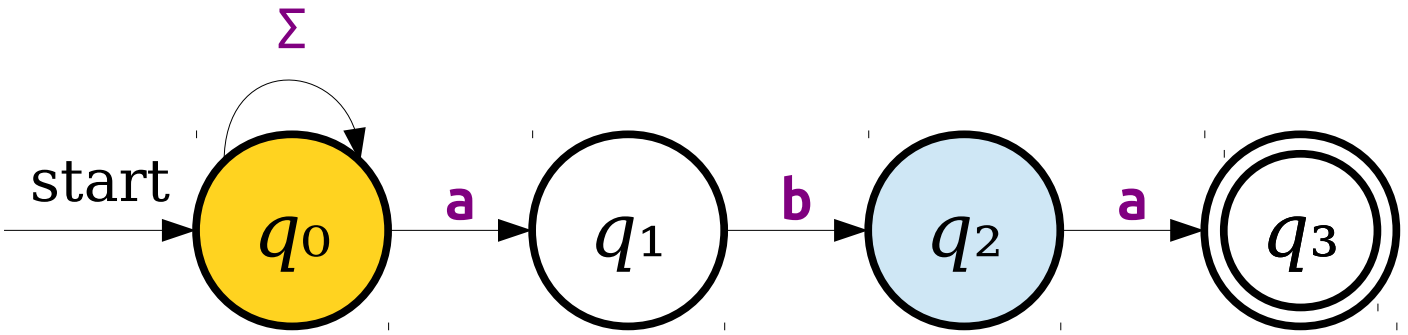

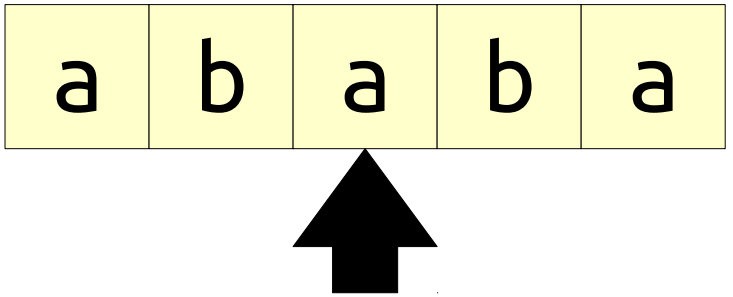

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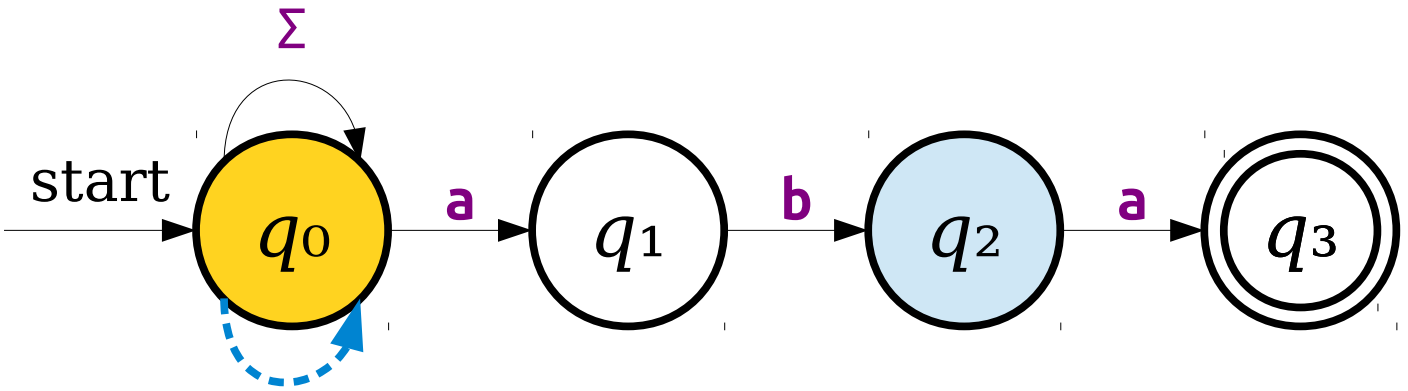

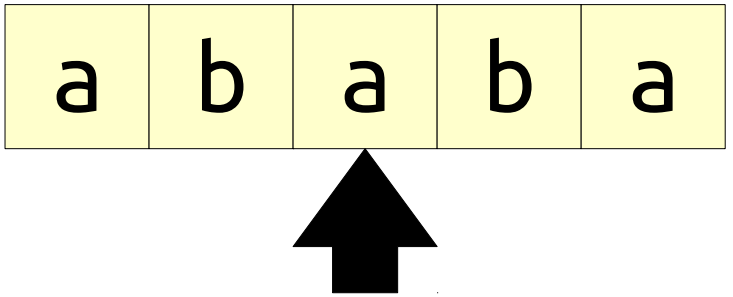

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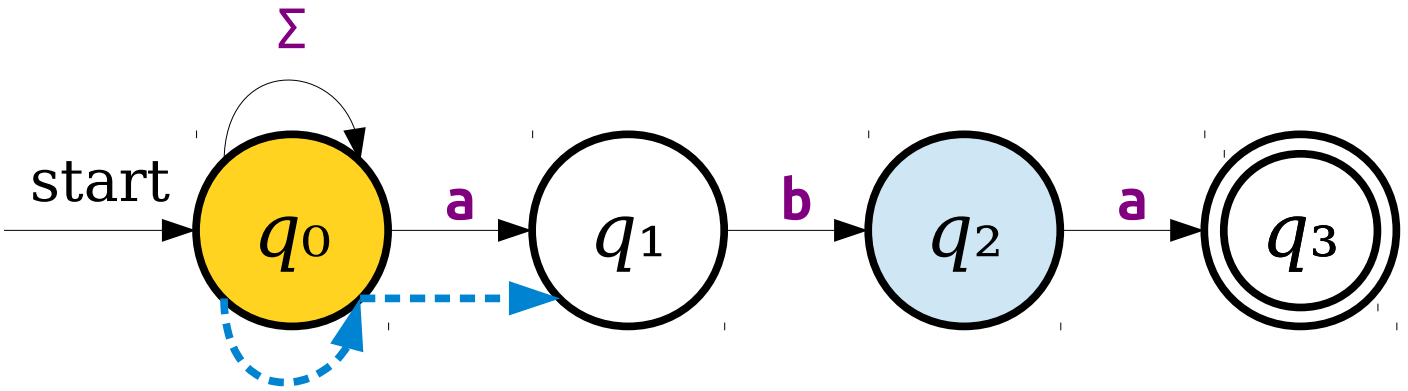

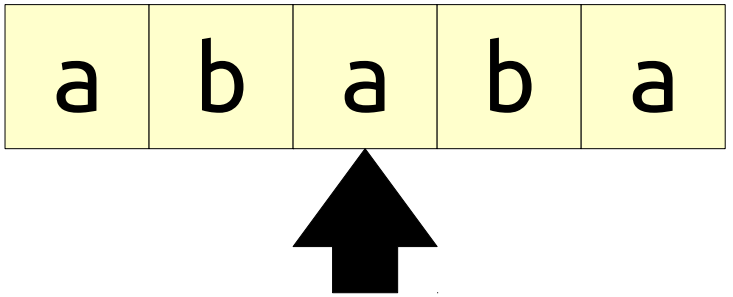

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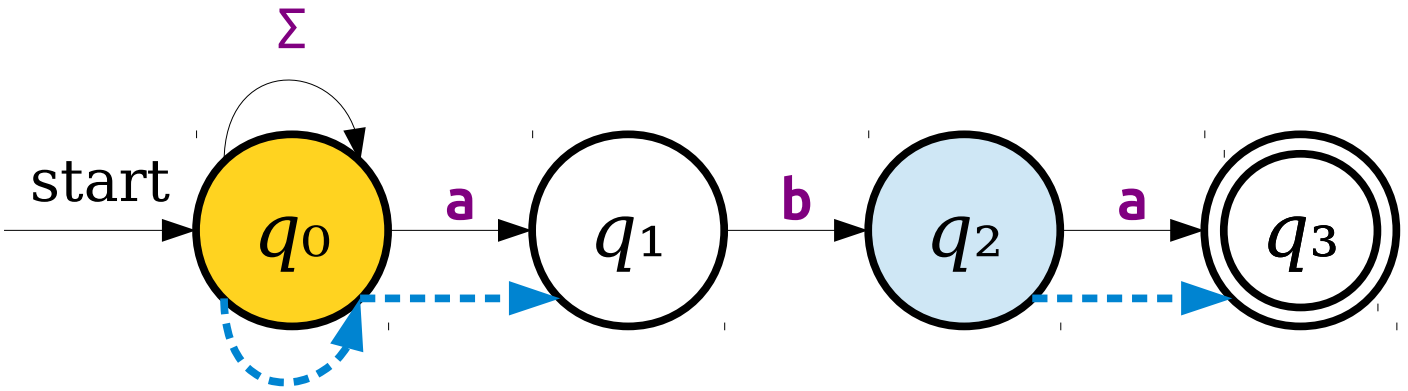

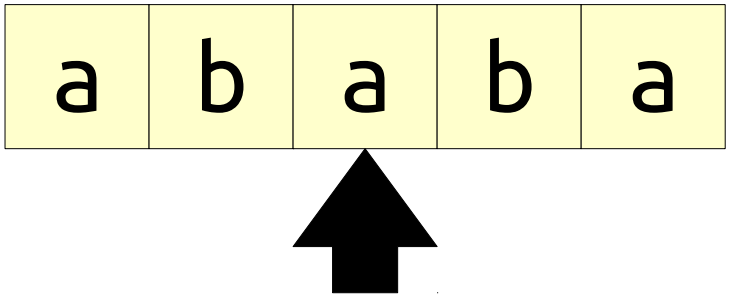

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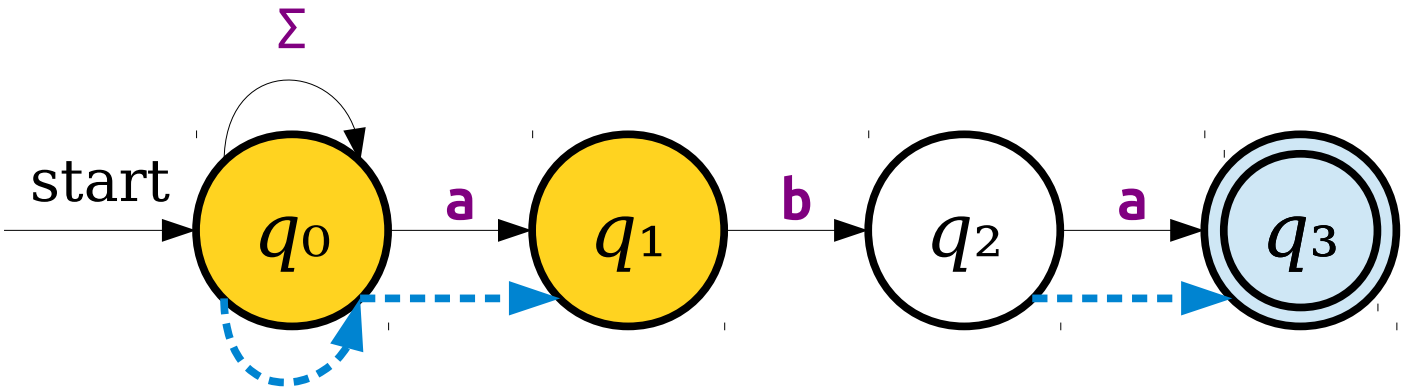

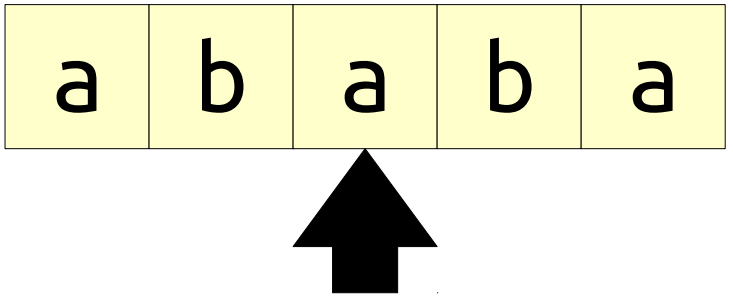

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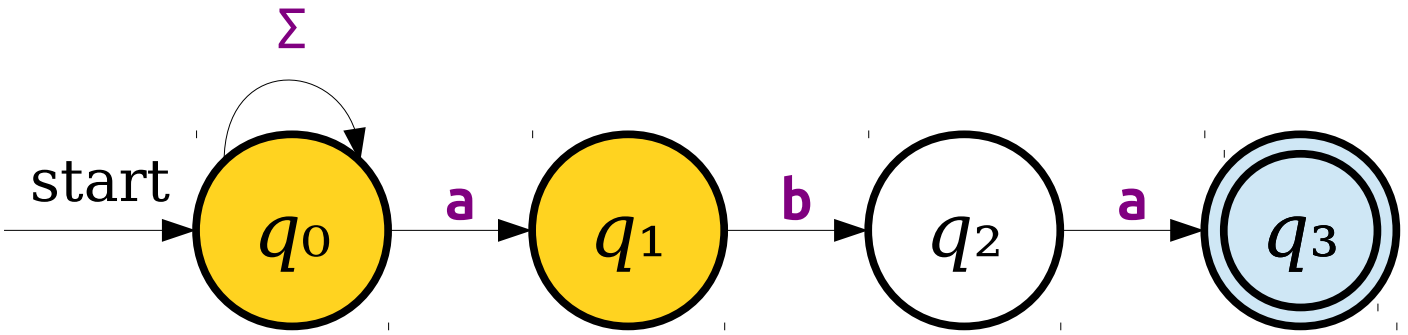

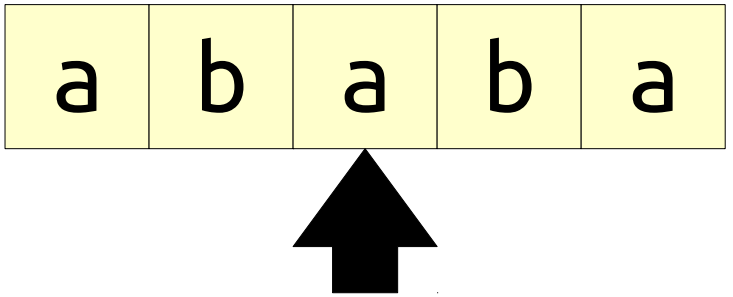

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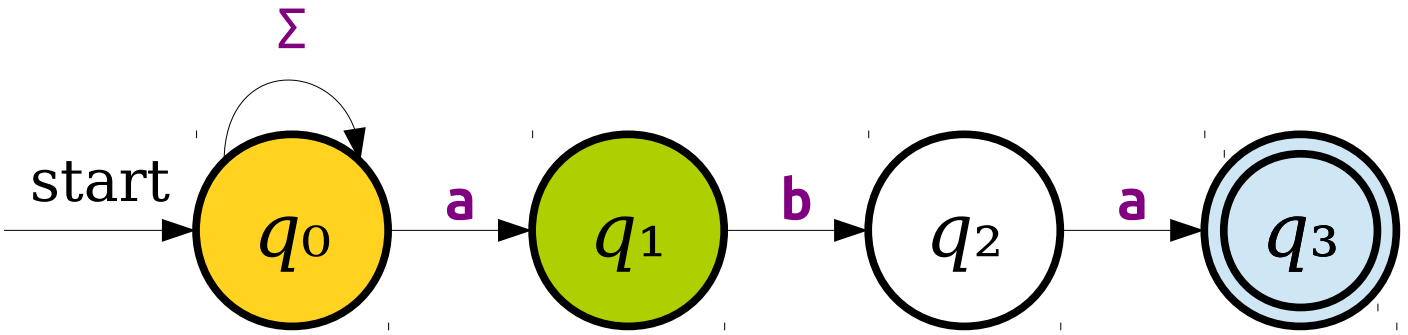

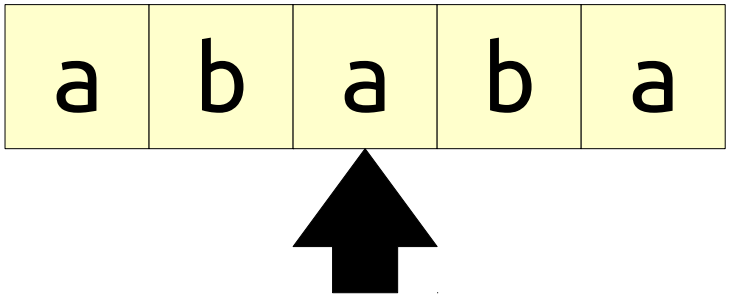

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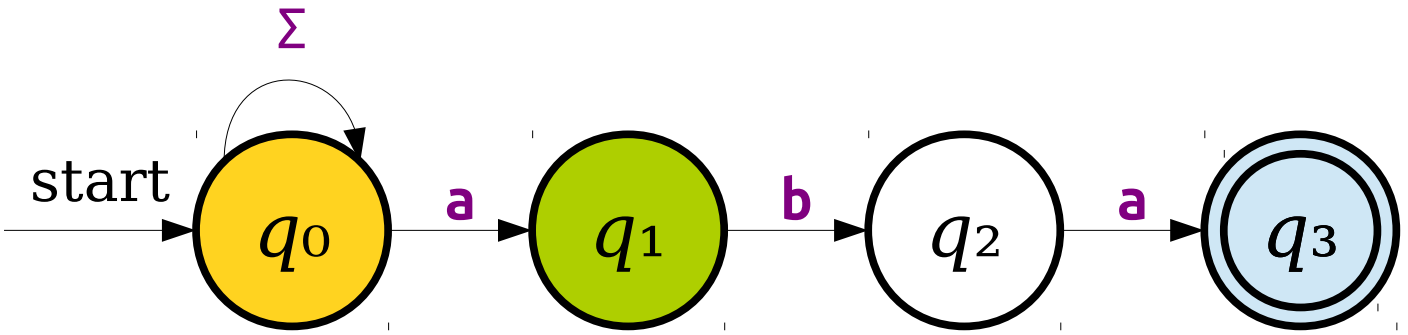

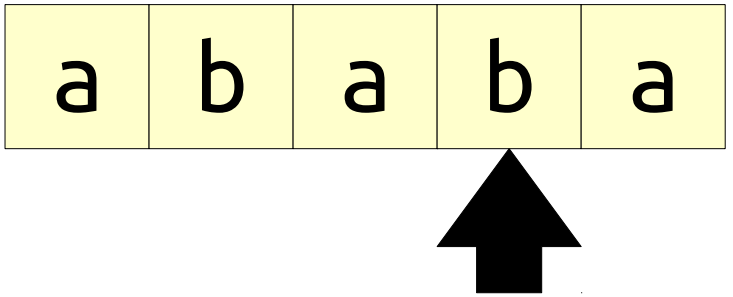

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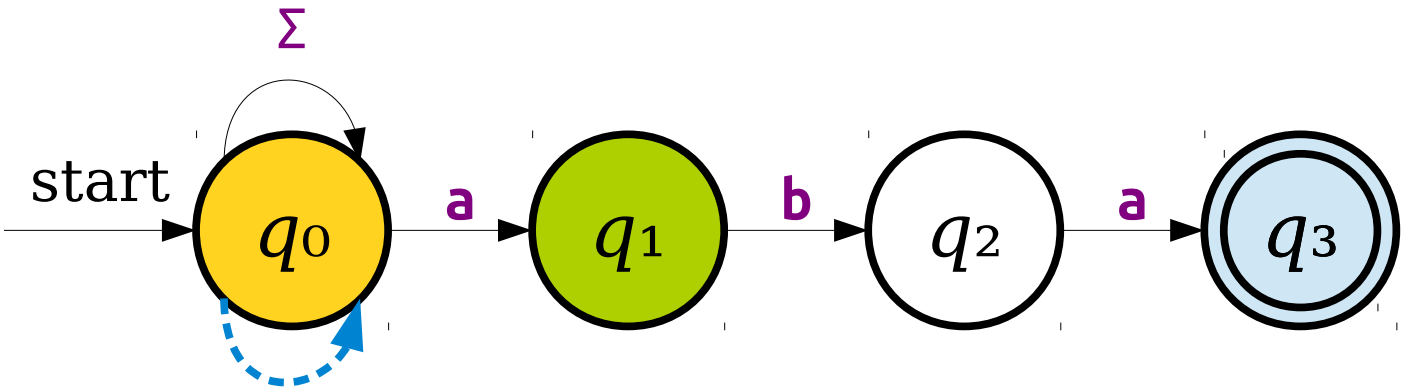

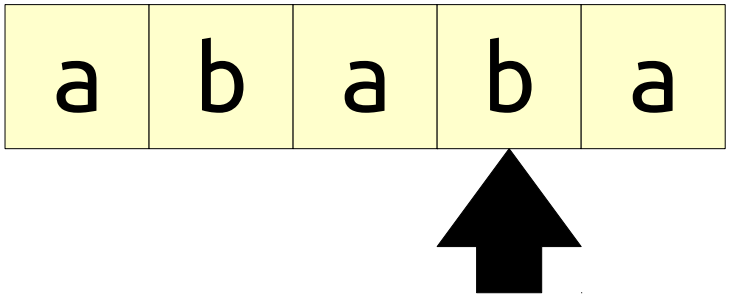

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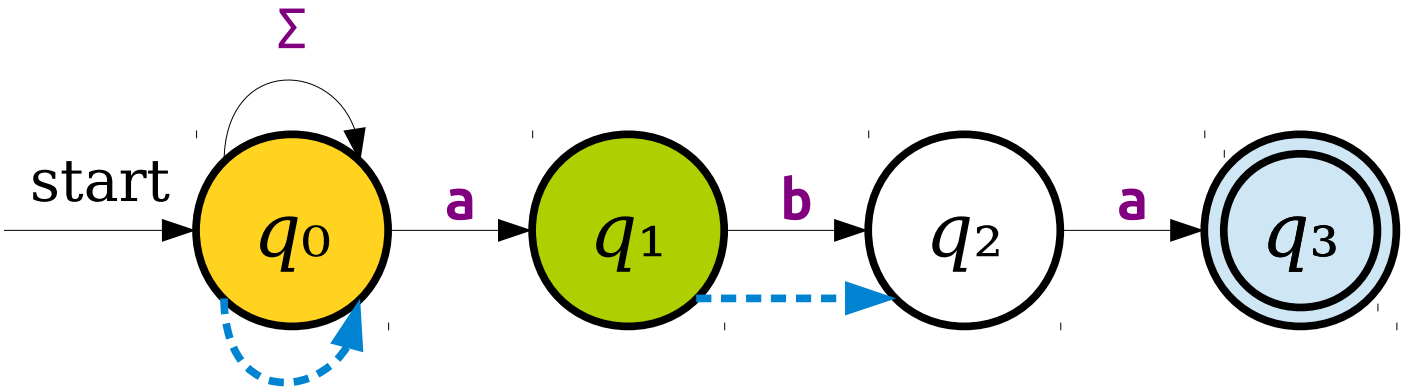

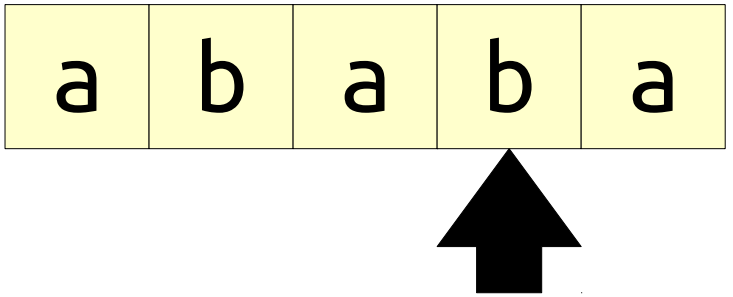

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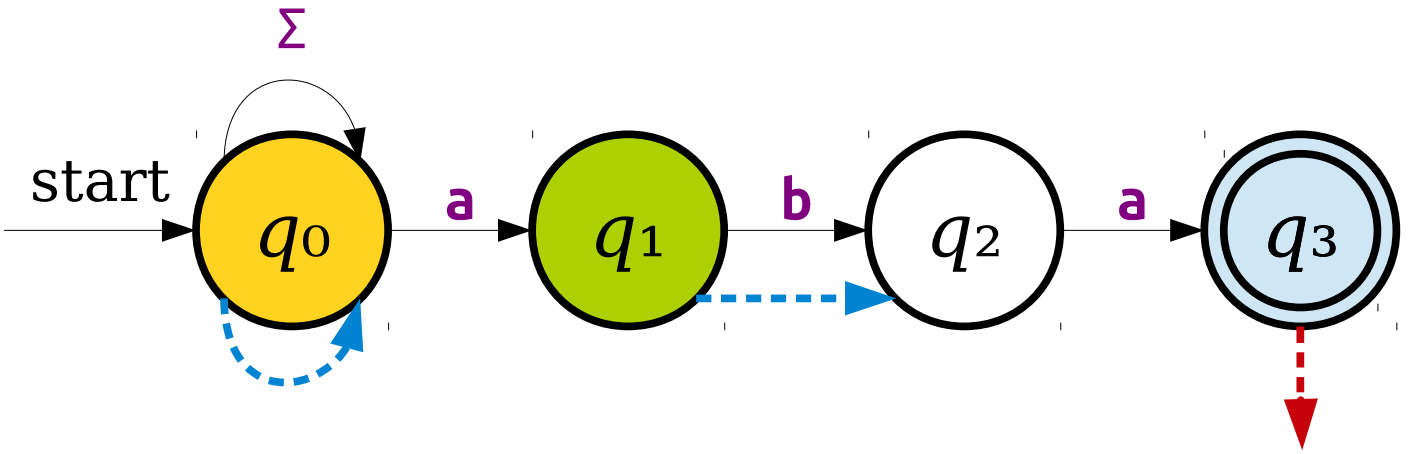

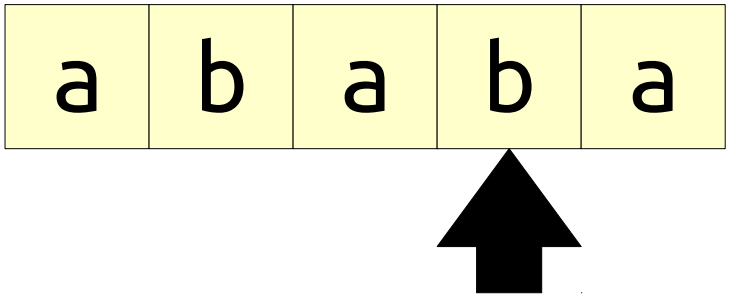

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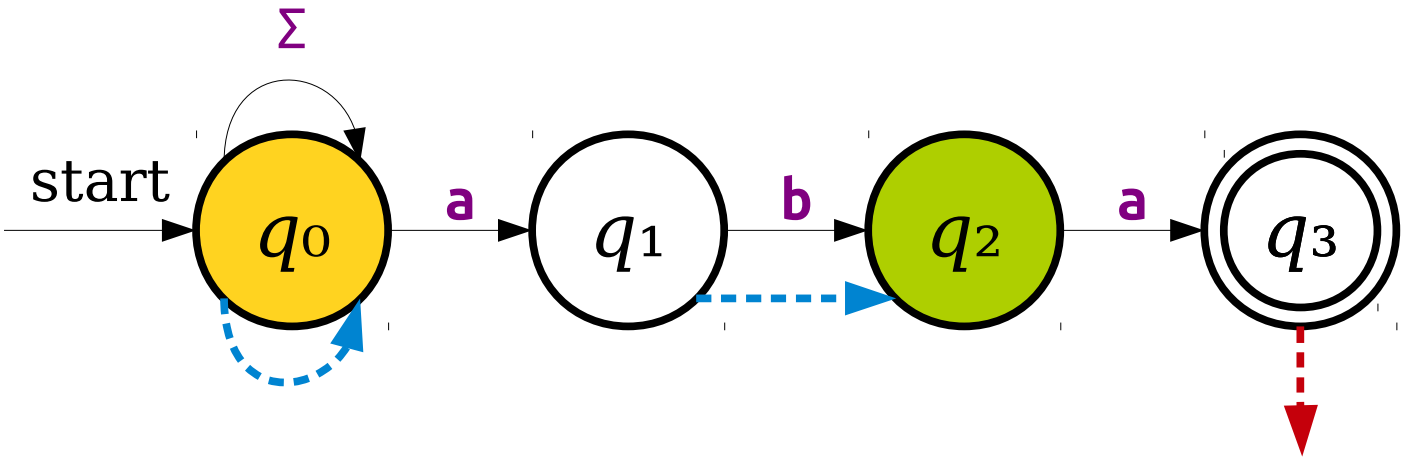

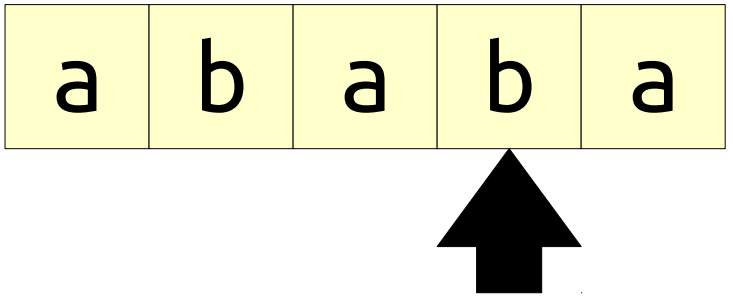

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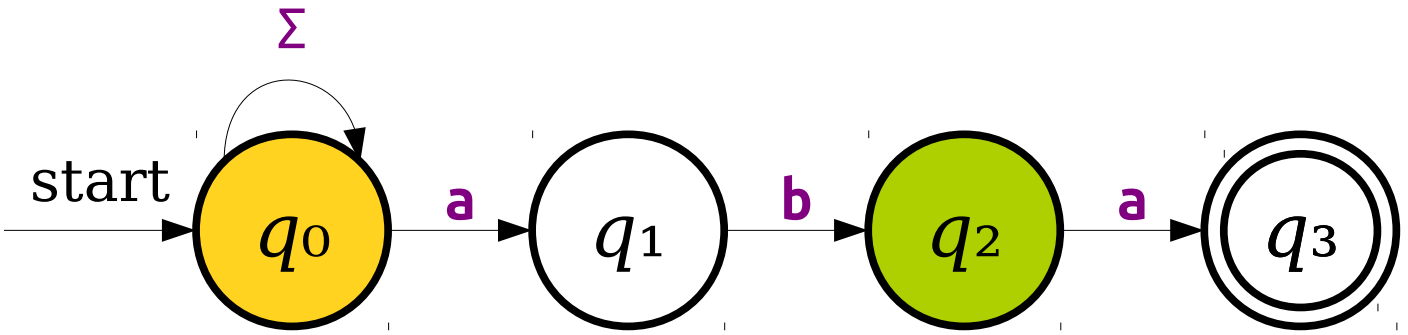

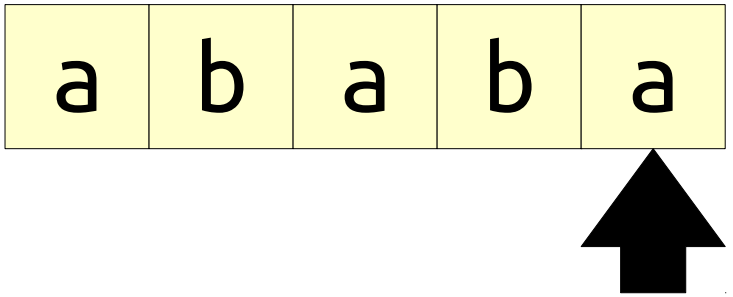

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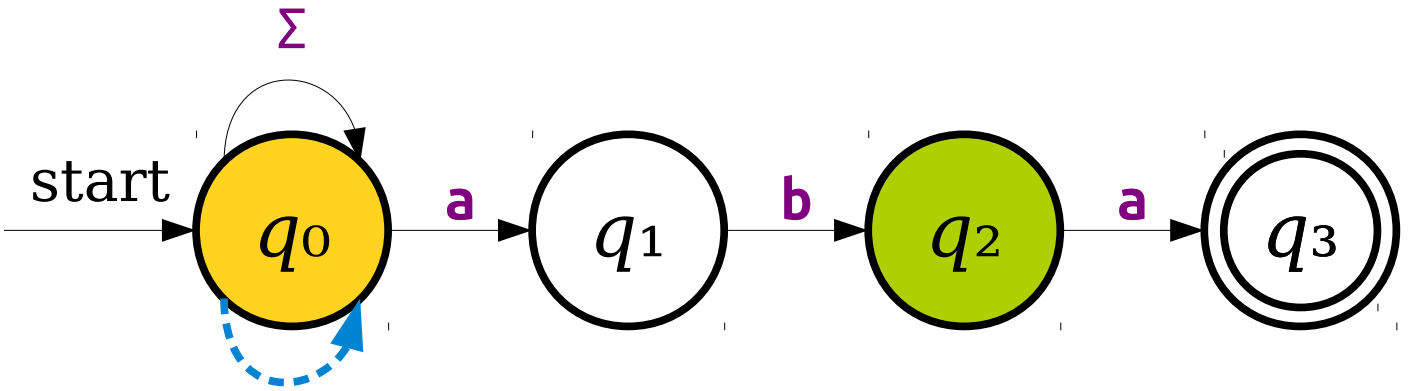

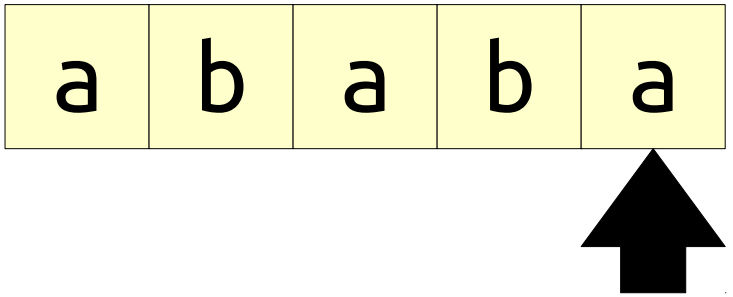

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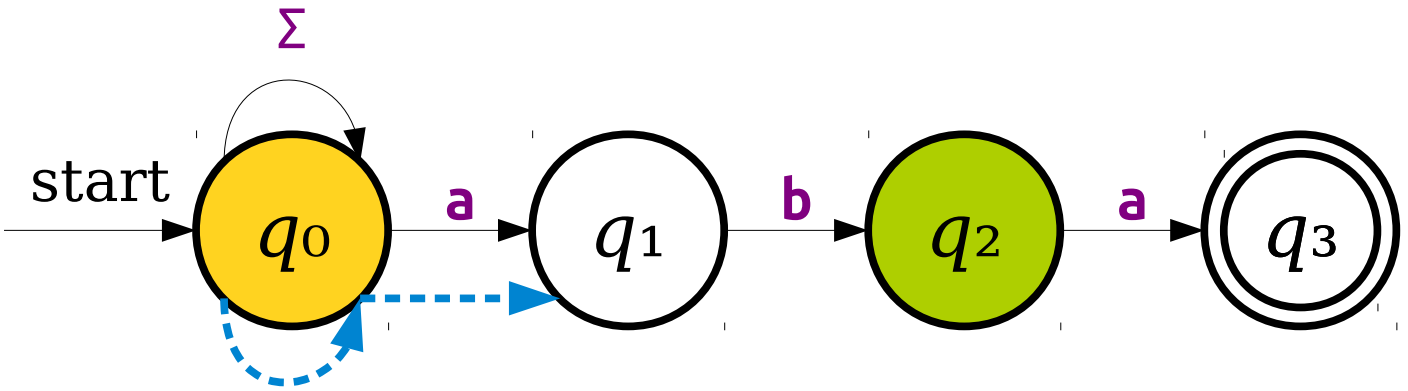

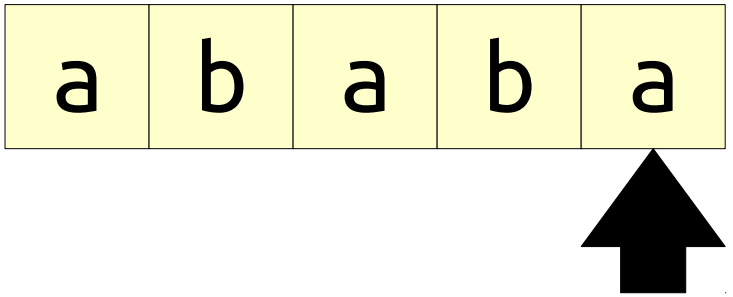

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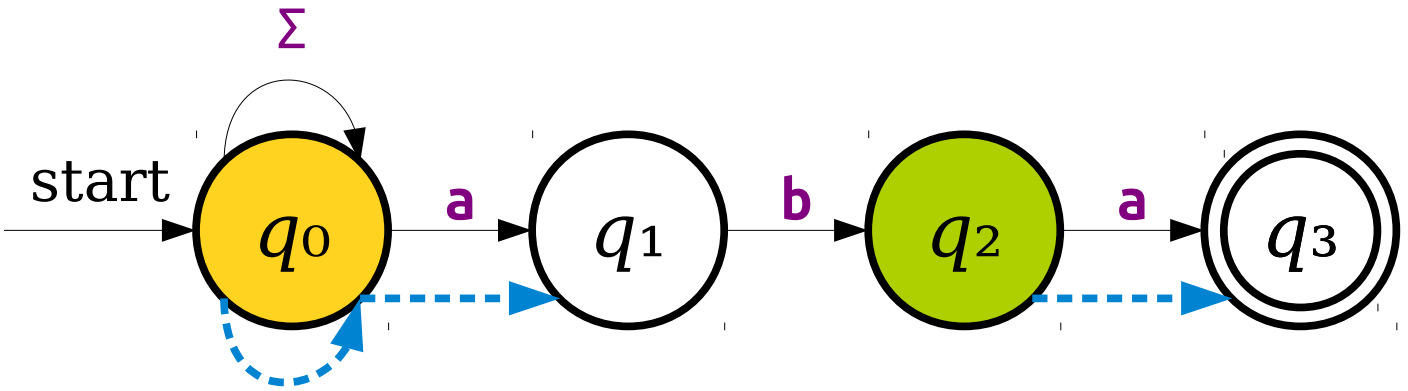

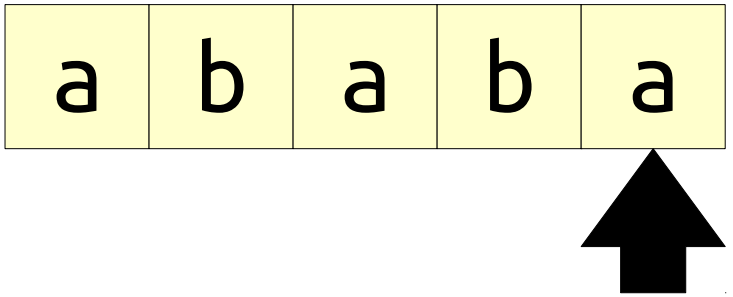

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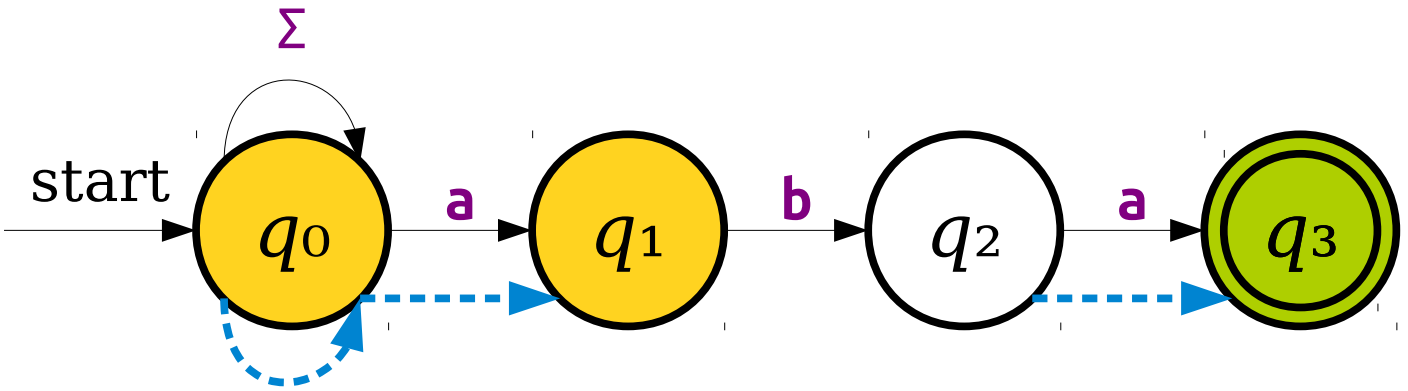

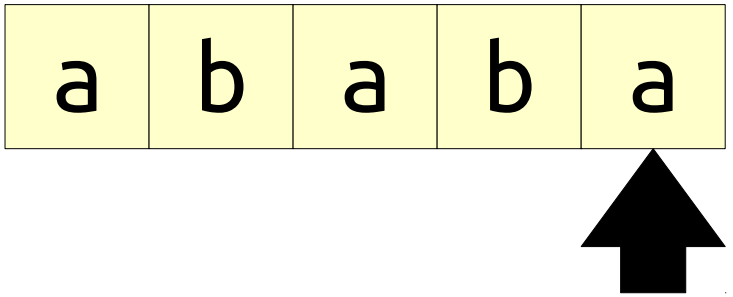

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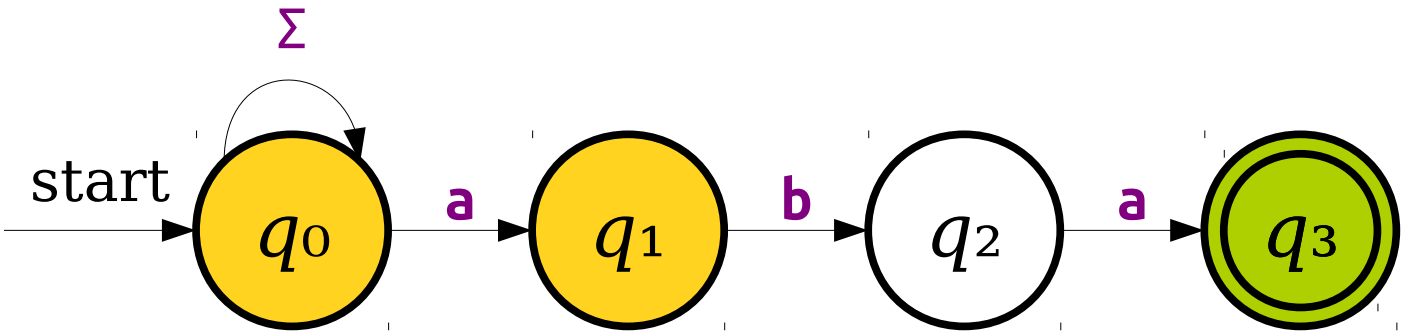
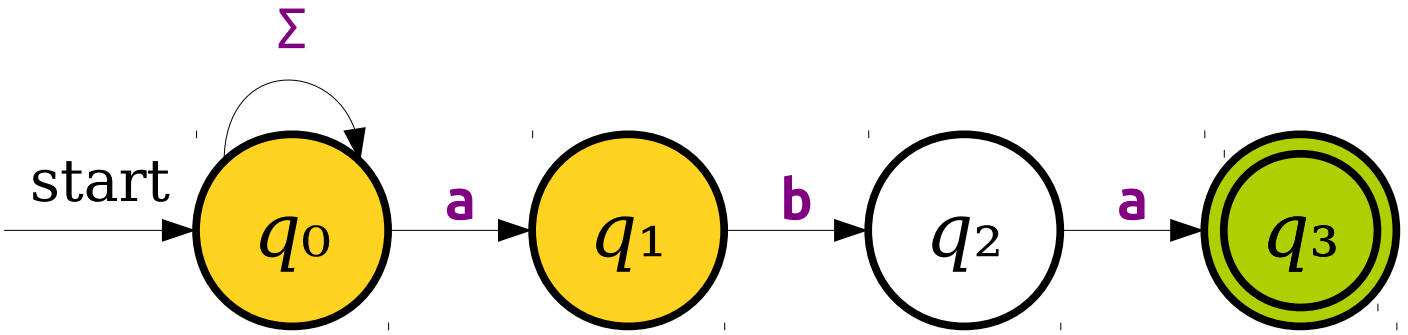


a	b	a	b	a

Massive Parallelism



a	b	a	b	a

We're in at least one accepting state, so there's some path that gets us to an accepting state.

Therefore, we accept!

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.

So What?

- Each intuition of nondeterminism is useful in a different setting:
  - Perfect guessing is a great way to think about how to design a machine.
  - Massive parallelism is a great way to test machines – and has nice theoretical implications.
- Nondeterministic machines may not be feasible, but they give a great basis for interesting questions:
  - Can any problem that can be solved by a nondeterministic machine be solved by a deterministic machine?
  - Can any problem that can be solved by a nondeterministic machine be solved ***efficiently*** by a deterministic machine?
- The answers vary from automaton to automaton.

Designing NFAs

Designing NFAs

- When 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

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

Guess-and-Check

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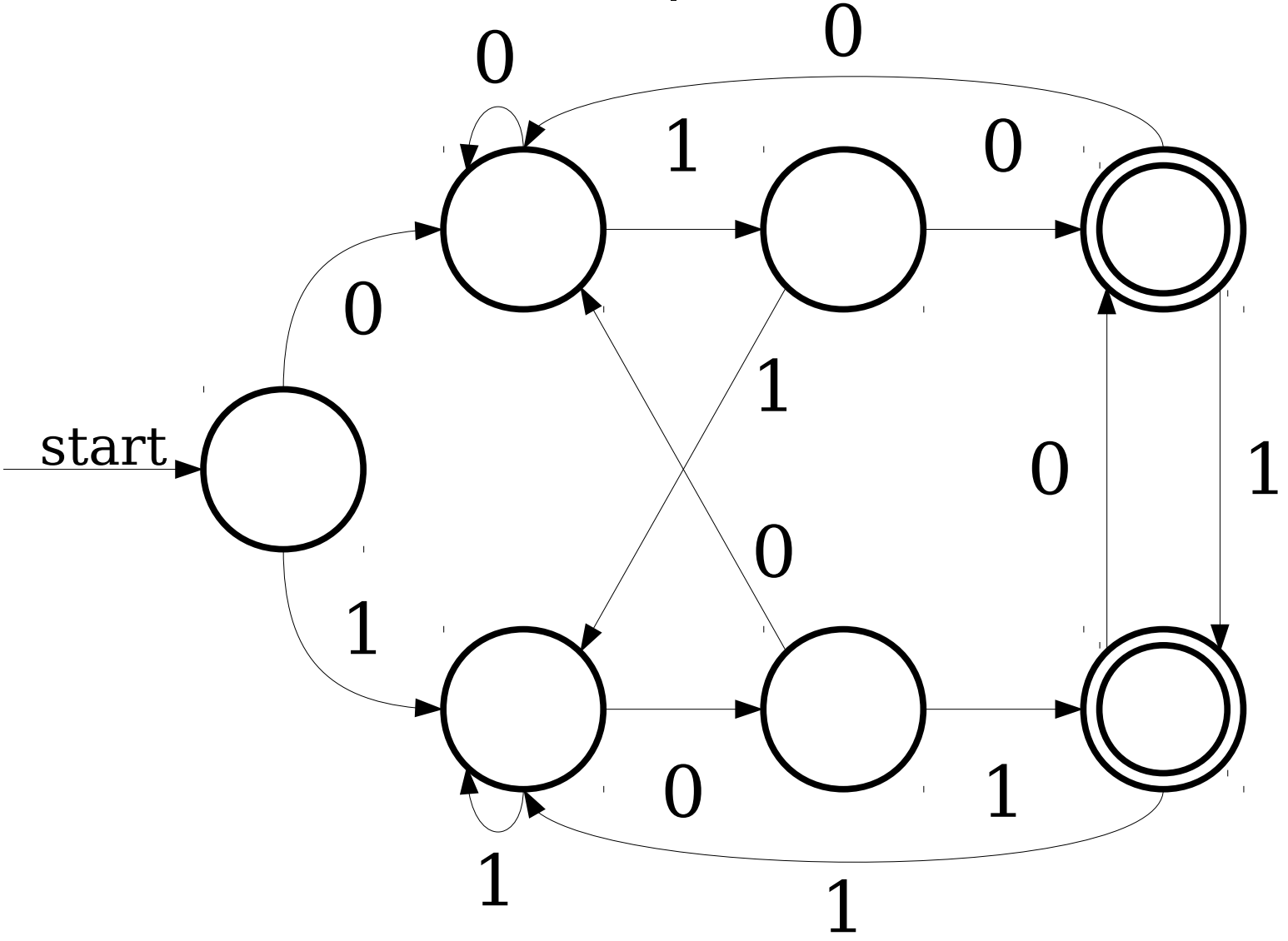
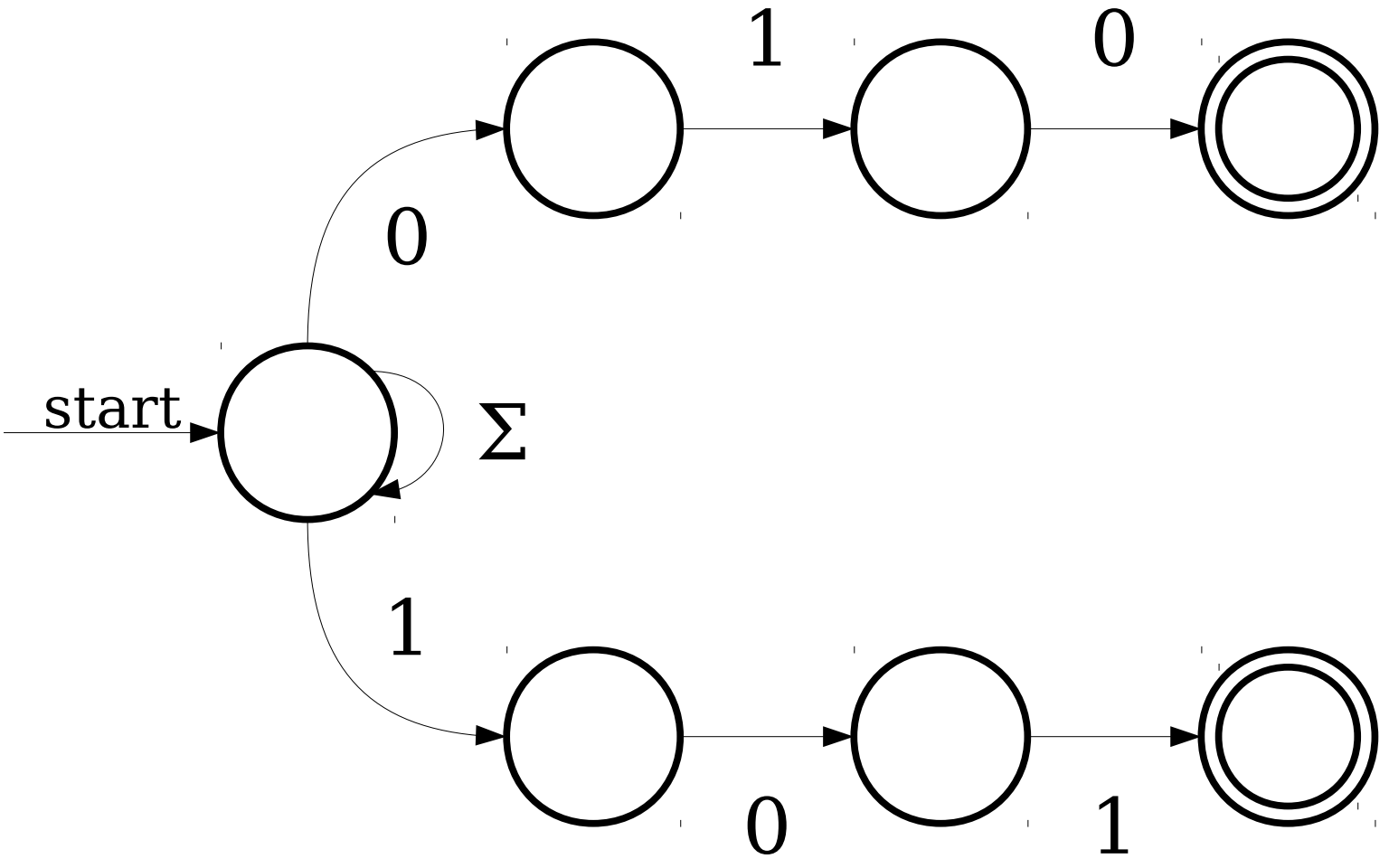


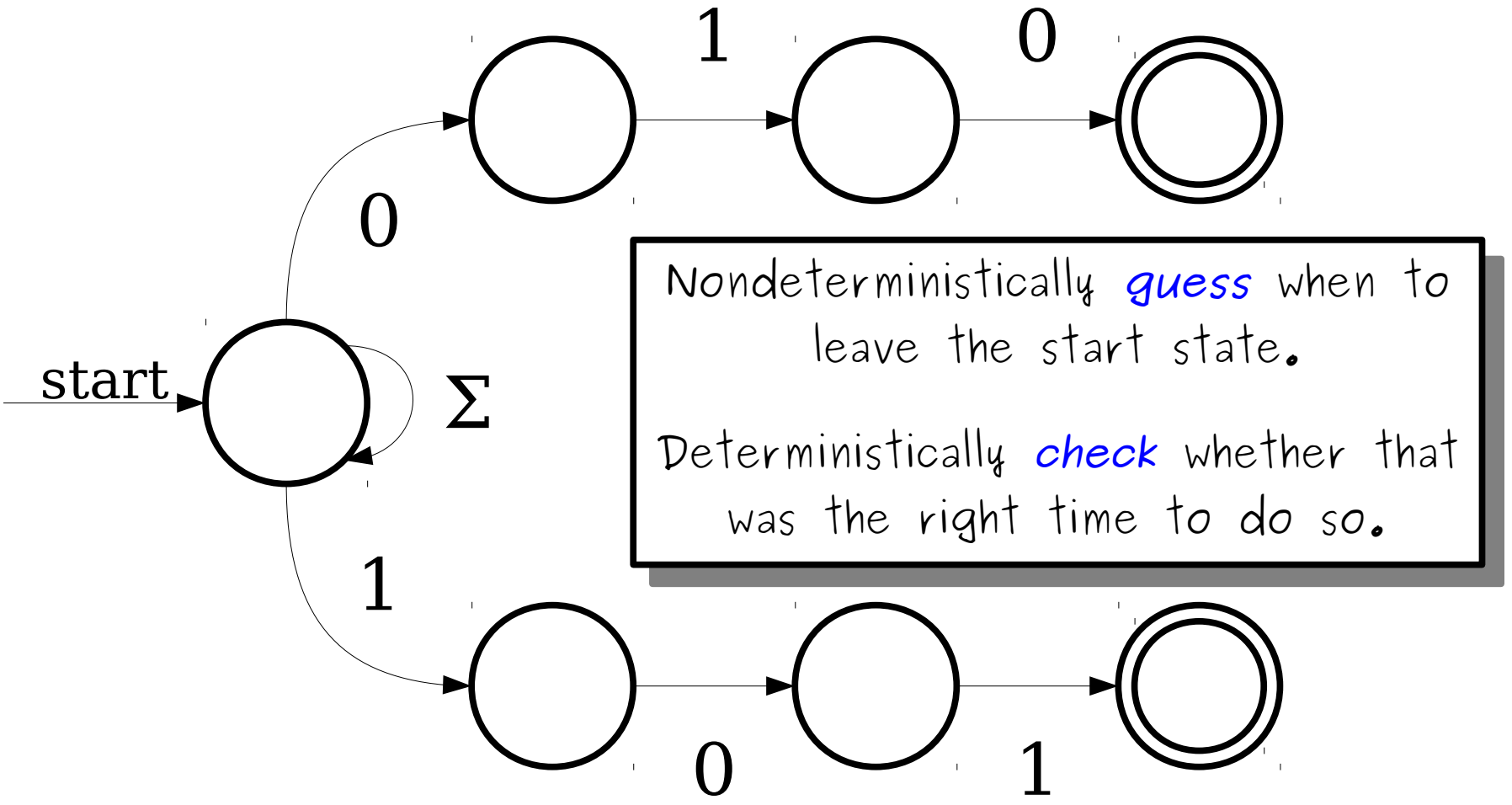
Guess-and-Check

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



Guess-and-Check

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

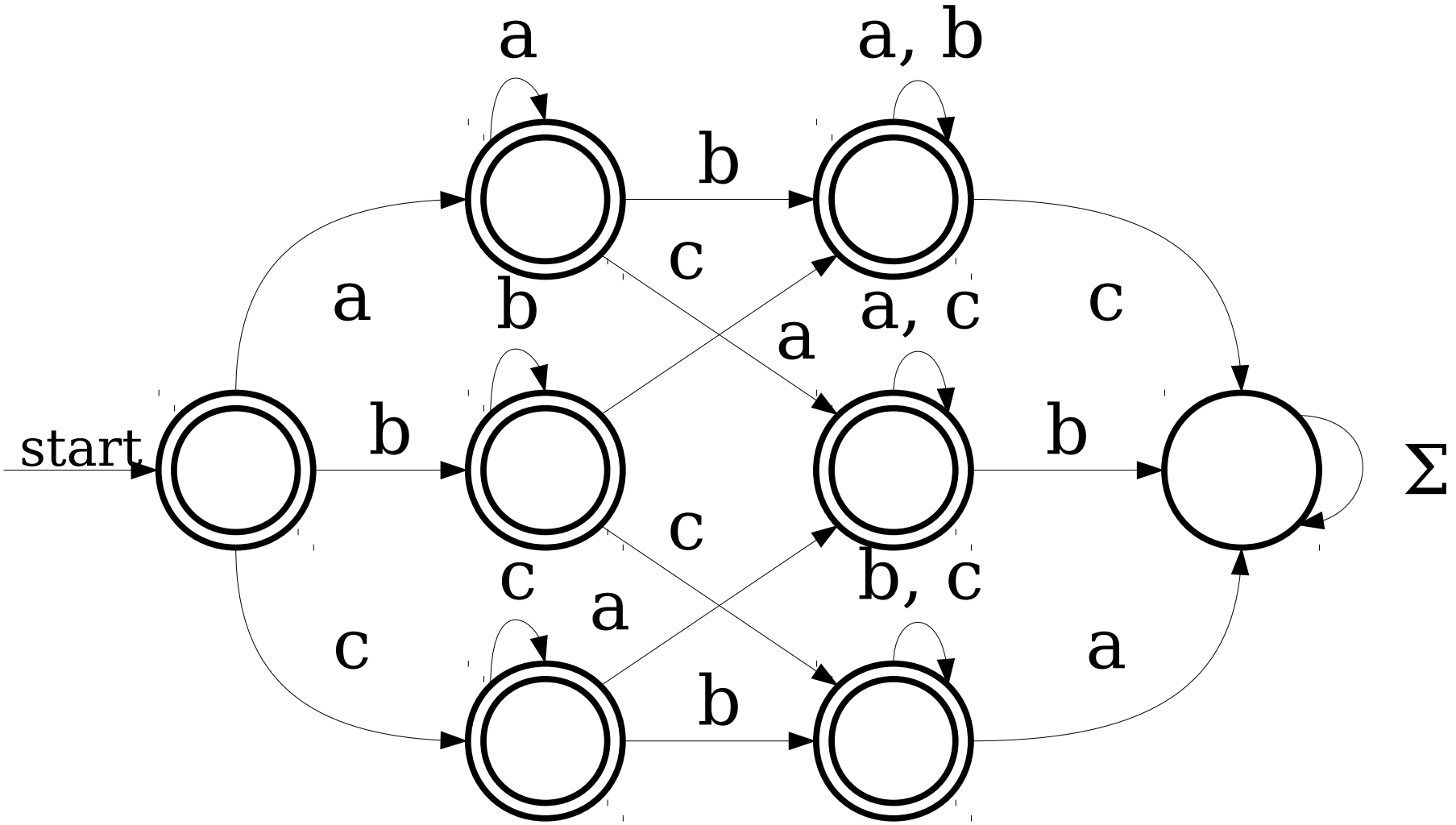


Guess-and-Check

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

Guess-and-Check

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



Guess-and-Check

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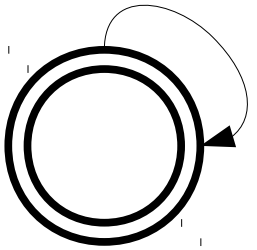
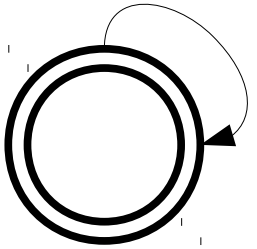
$L = \{ w \in \{\texttt{a}, \texttt{b}, \texttt{c}\}^* \mid$ at least one of **a**, **b**, or **c** is not in $w \}$



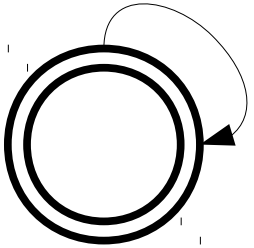
Guess-and-Check

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

a, b



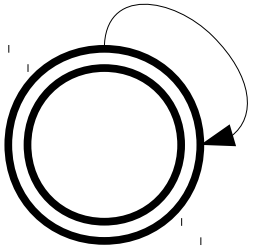
a, c



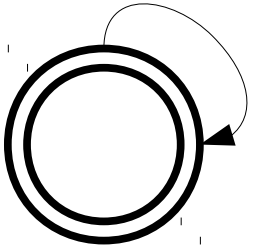
Guess-and-Check

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

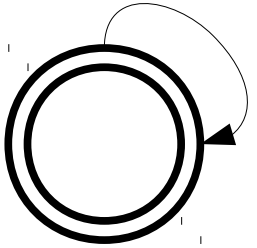
a, b



a, c

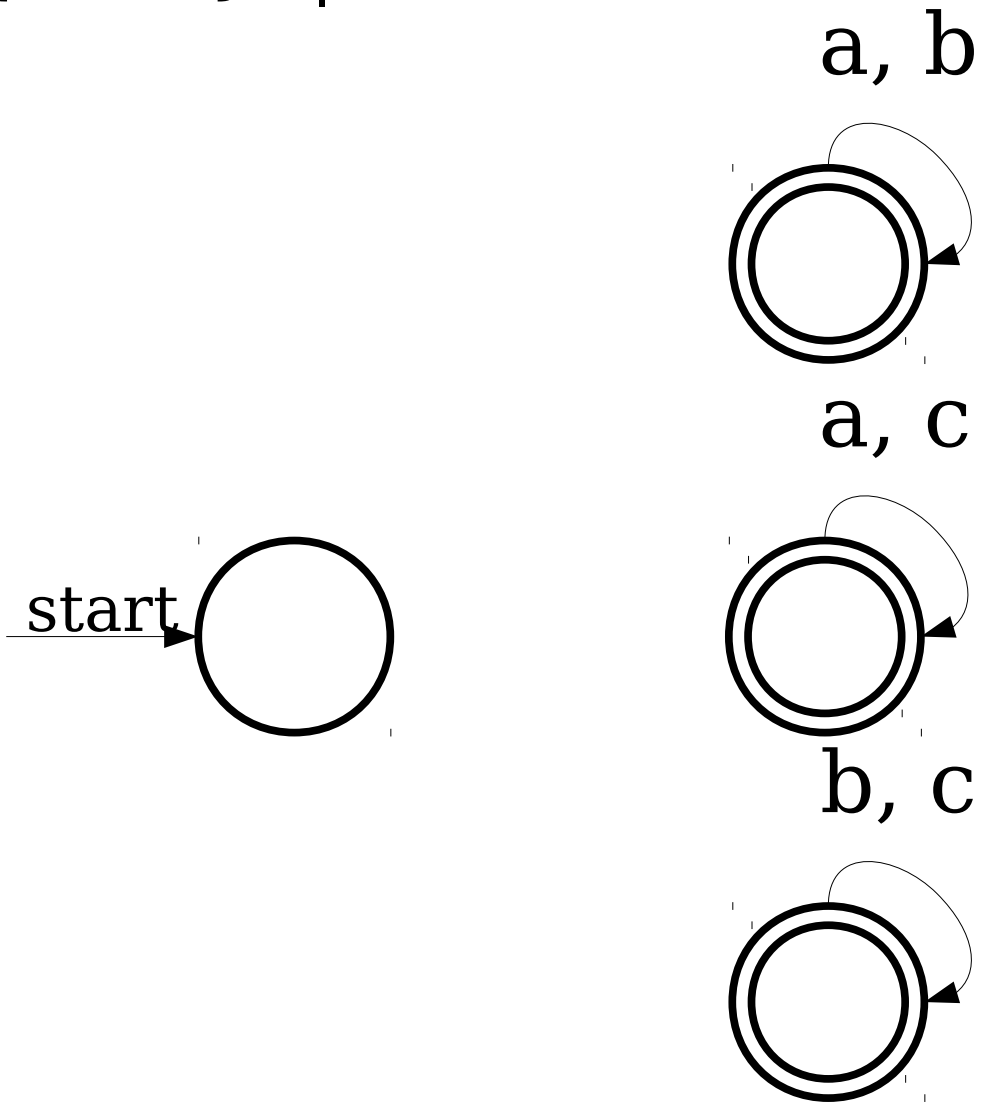


b, c



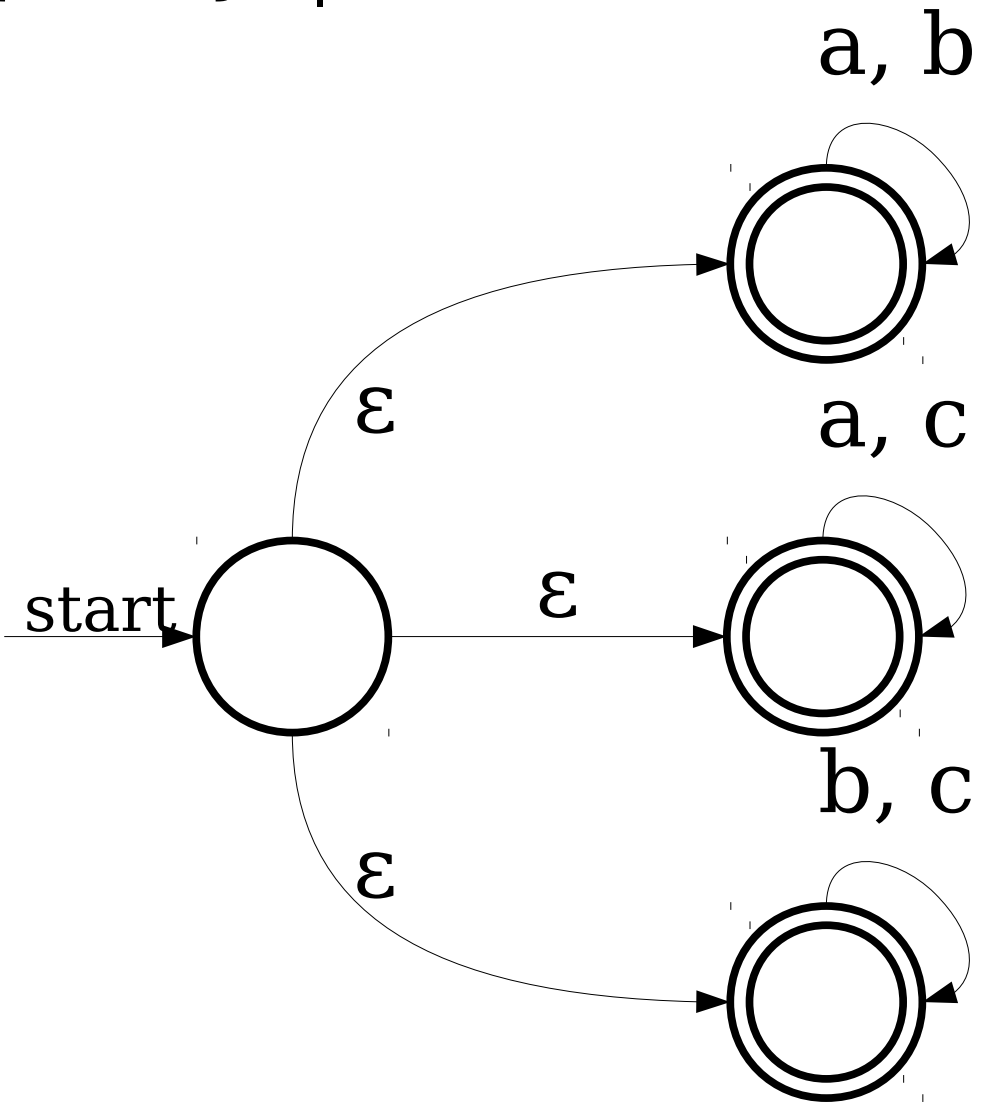
Guess-and-Check

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



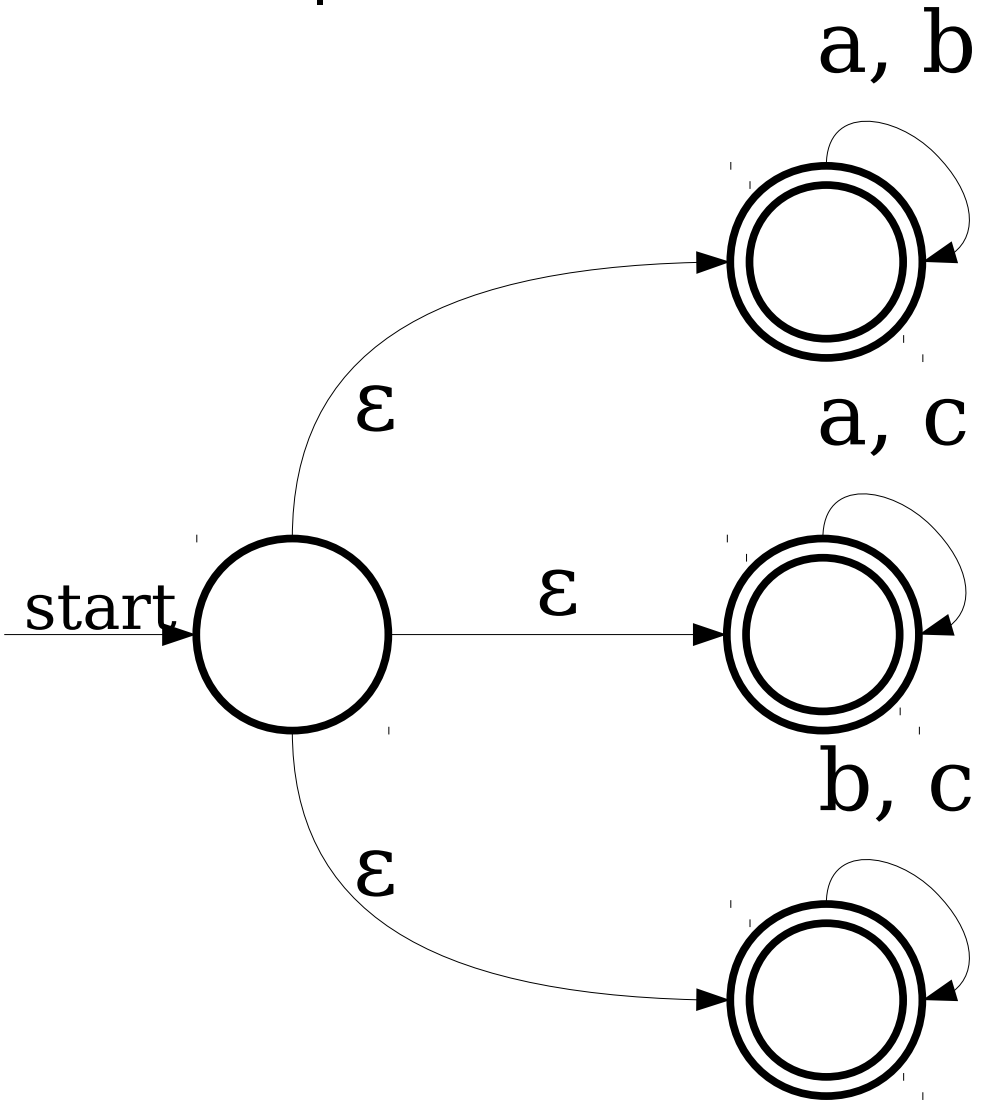
Guess-and-Check

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



Guess-and-Check

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



Nondeterministically *guess* which character is missing.

Deterministically *check* whether that character is indeed missing.

Just how powerful are NFAs?