Finite Automata

Part Two

Announcements

- Practice midterm solutions available.
- Second practice midterm available soon.
- Problem Set 3 and Problem Set 4 Checkpoints graded; will be returned at end of lecture.

A Friendly Reminder

$\forall$ goes with $\rightarrow$

$\exists$ goes with $\wedge$

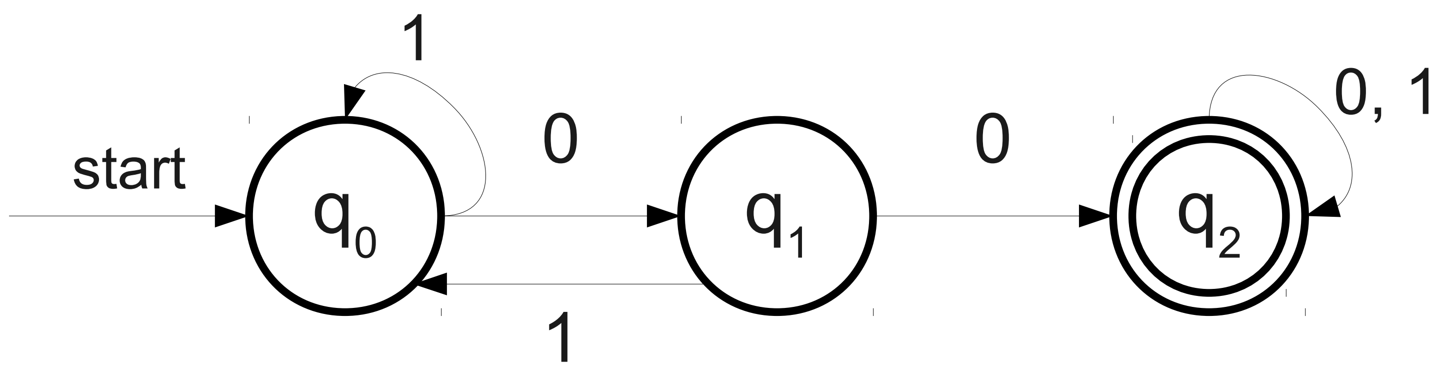
Finite Automata

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 the alphabet.
  - This is the "deterministic" part of DFA.
- There is a **unique** start state.
- There may be multiple accepting states.

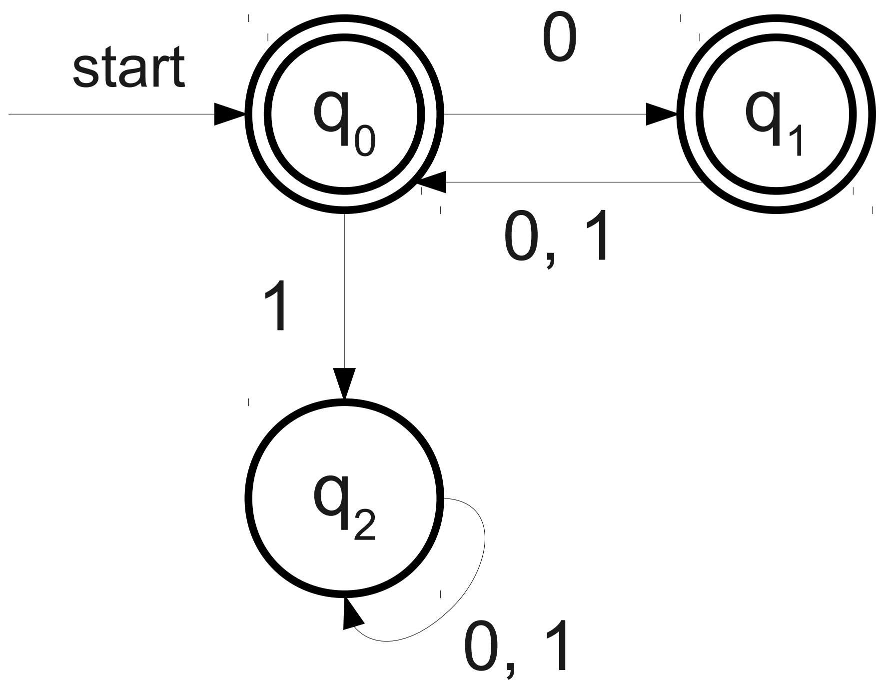
Recognizing Languages with DFAs

$L = \{ w \in \{0, 1\}^* \mid w \text{ contains } 00 \text{ as a substring } \}$



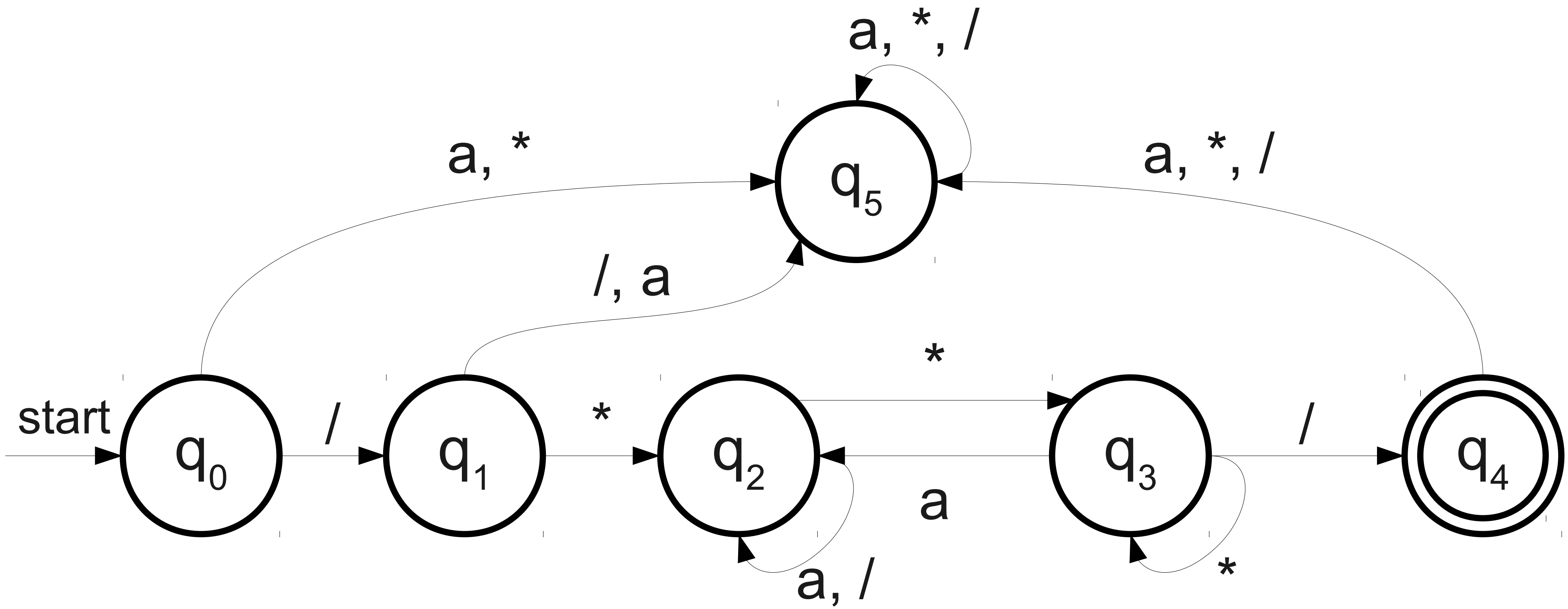
Recognizing Languages with DFAs

$L = \{ w \in \{0, 1\}^* |$ all even-numbered characters of w are 0 $\}$



More Elaborate DFAs

$L = \{ w \mid w \text{ is a C-style comment } \}$



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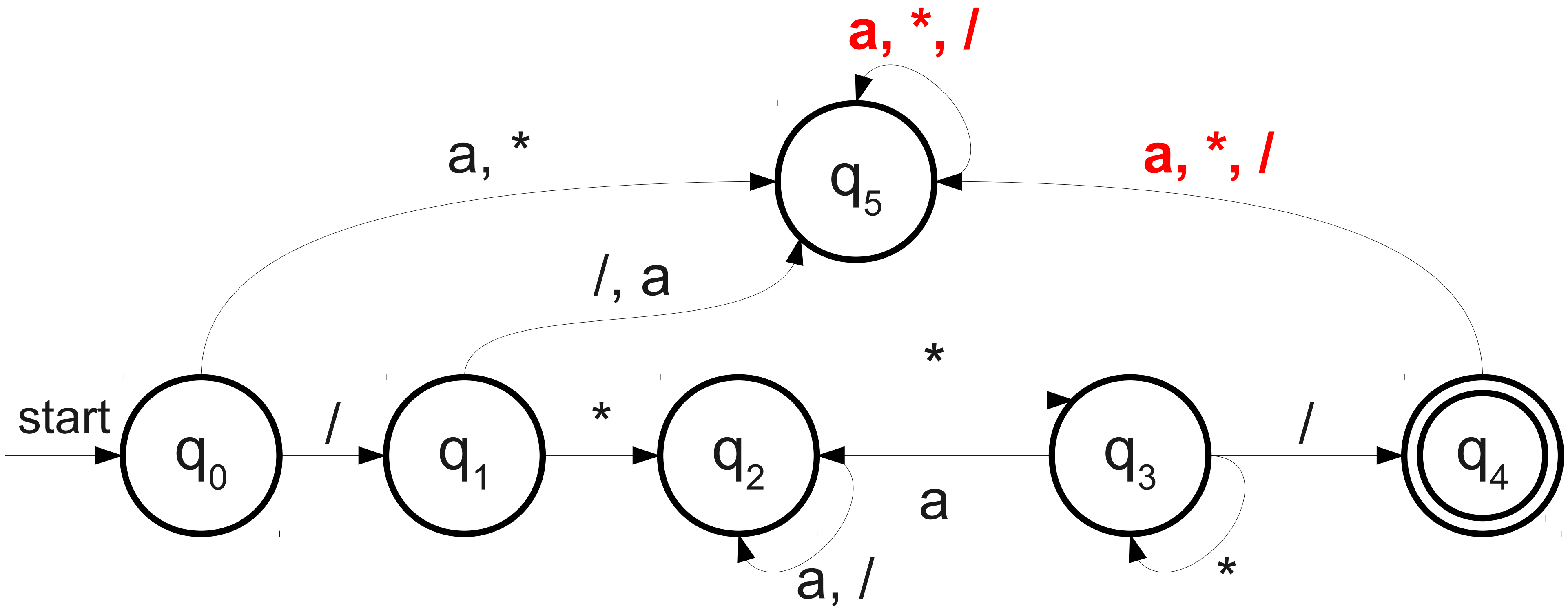

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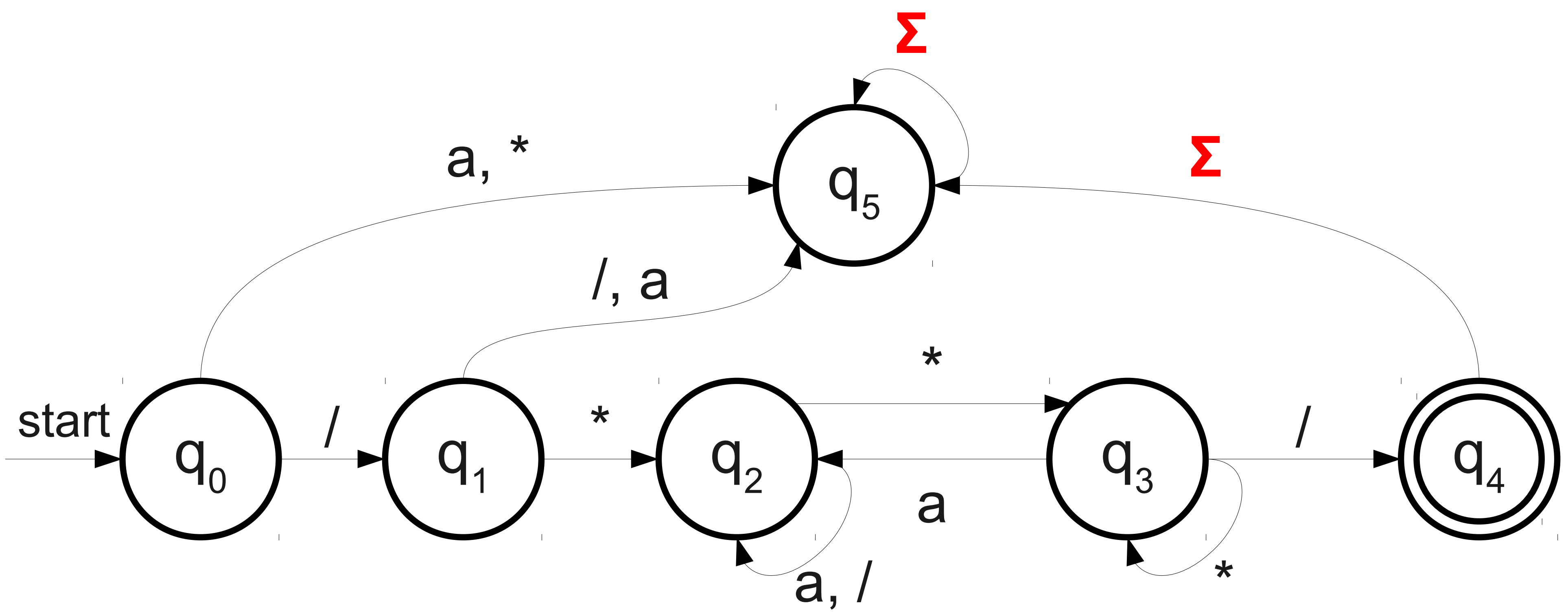

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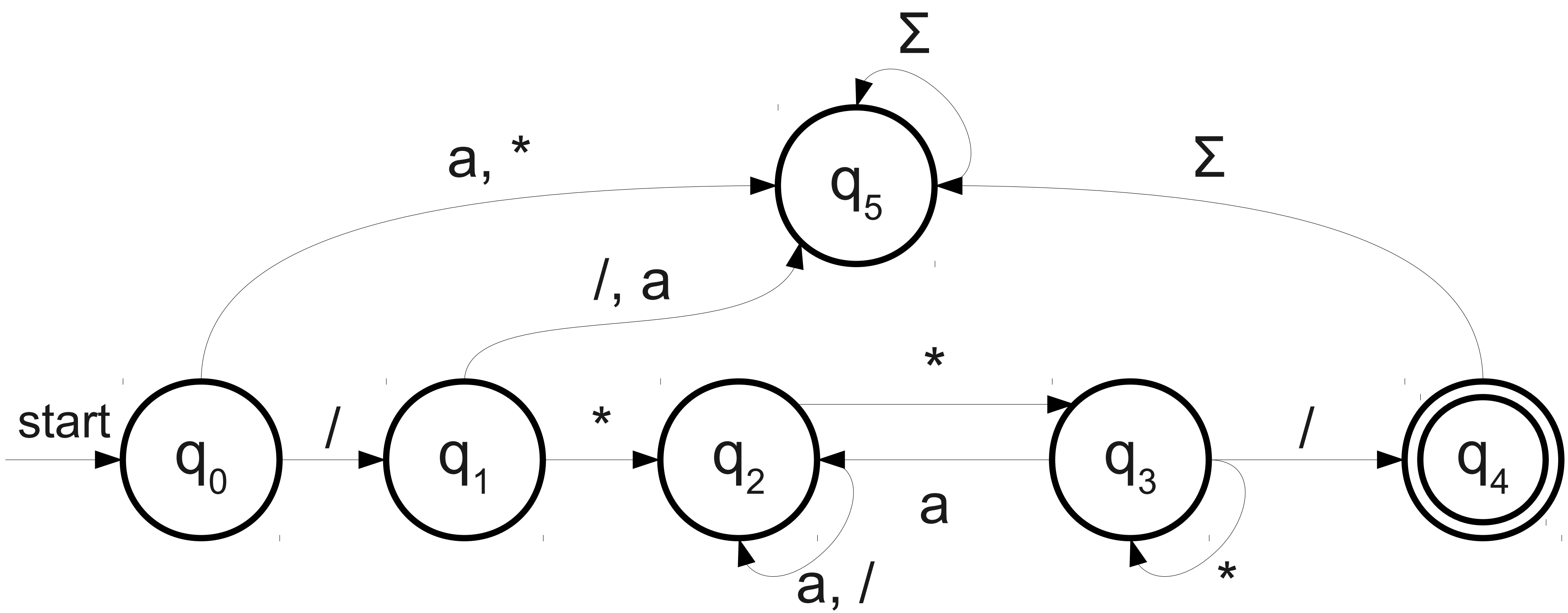

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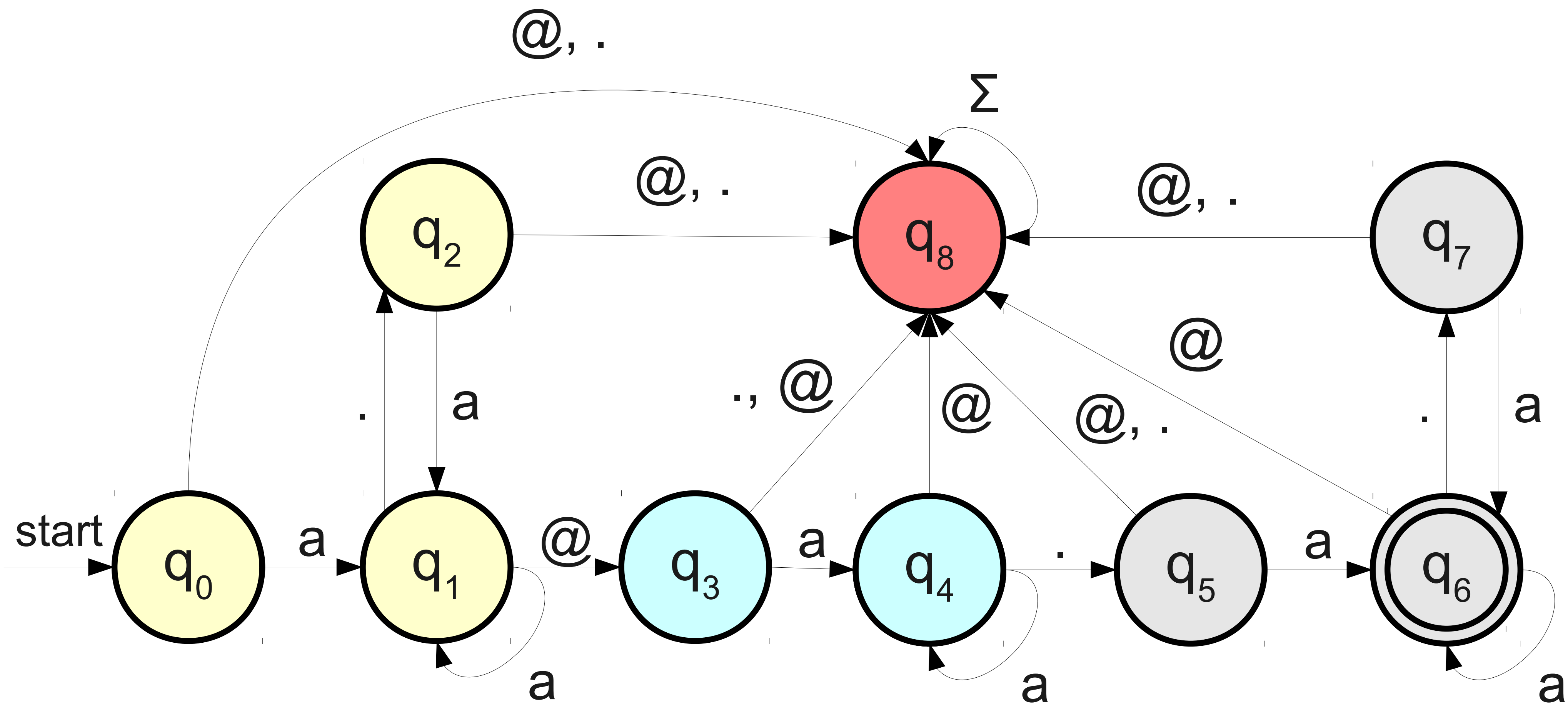
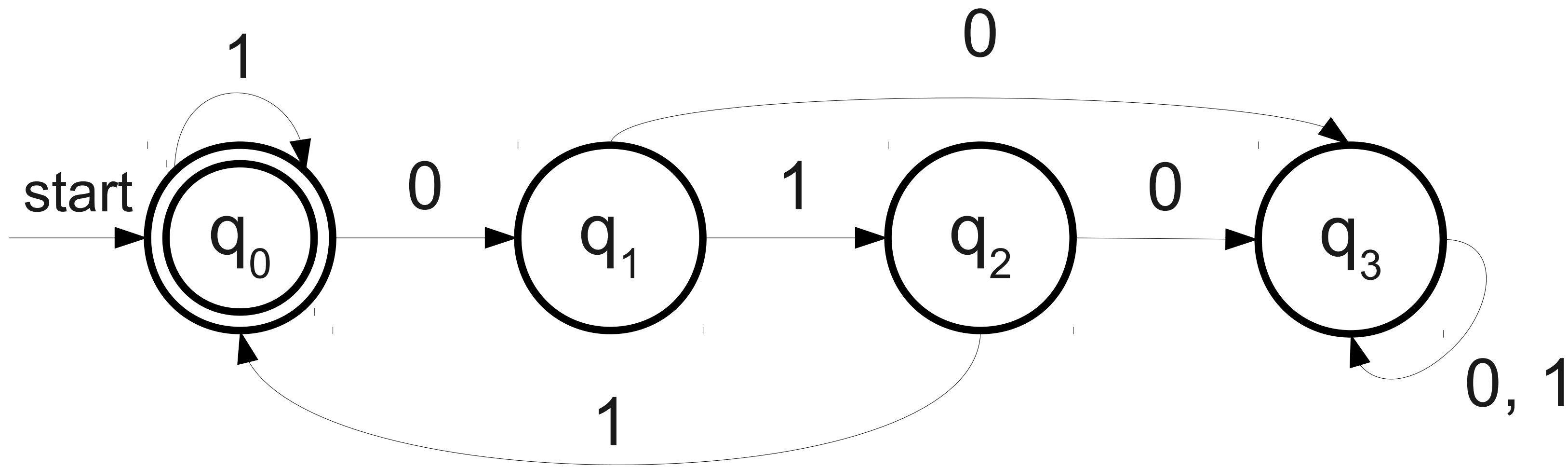


Tabular DFAs



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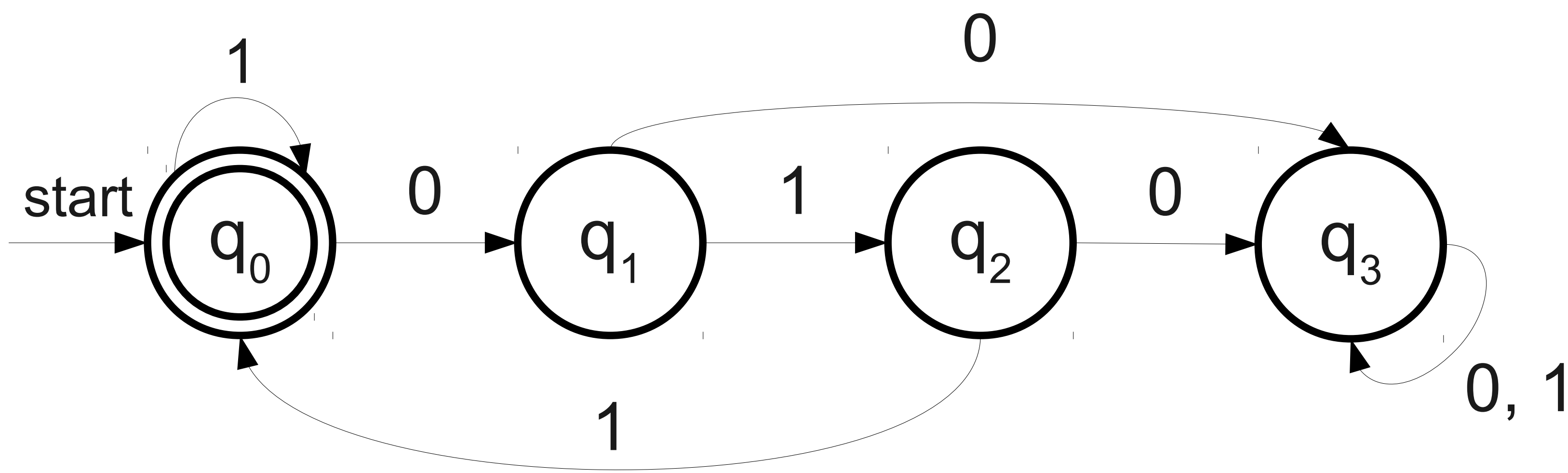

	0	1
q_0		
q_1		
q_2		
q_3		

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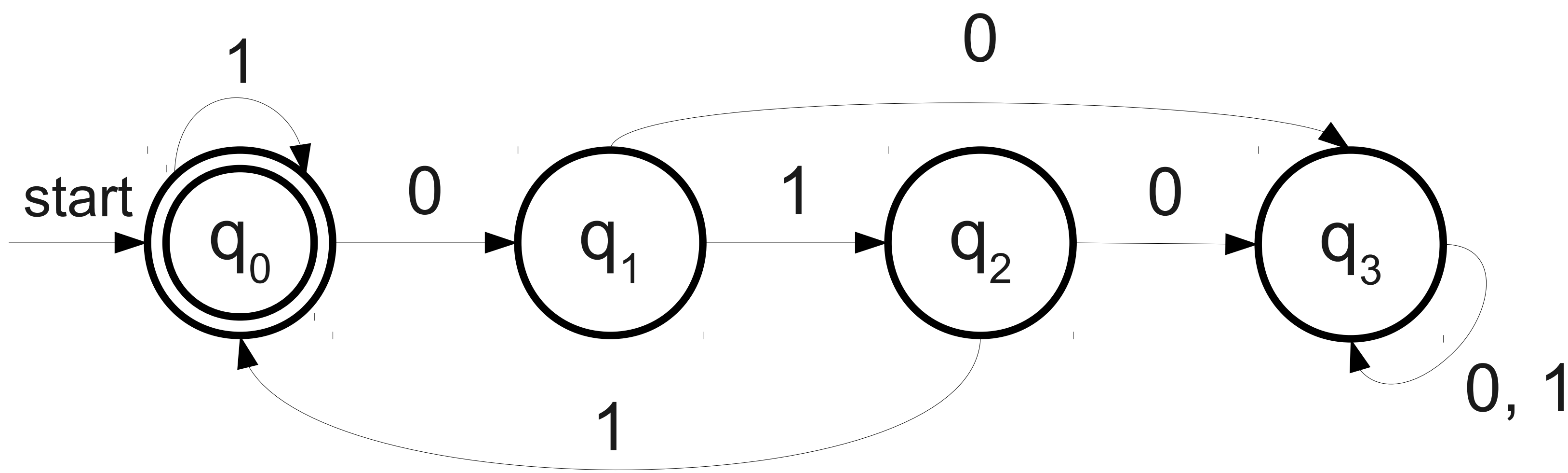

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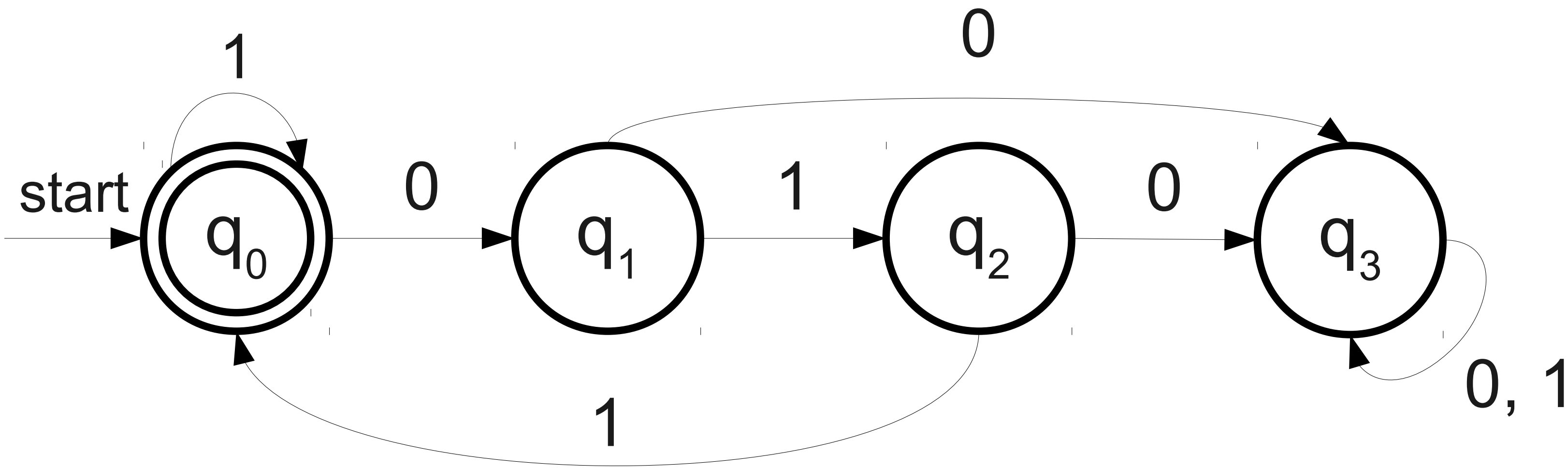

	0	1
q_0	q_1	q_0
q_1		
q_2		
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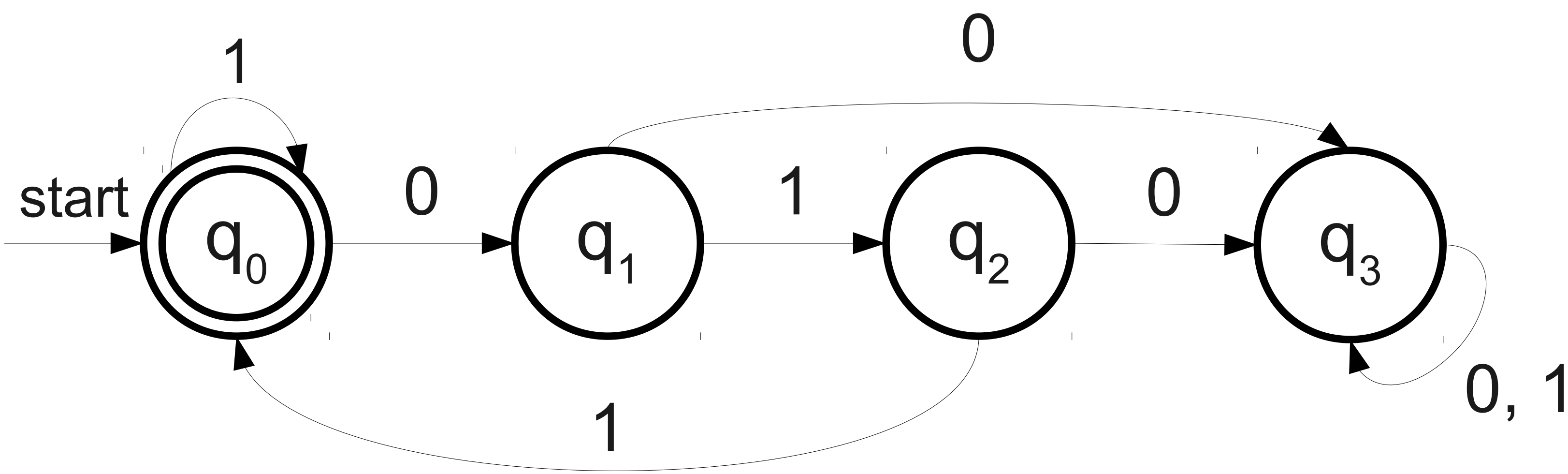

	0	1
q_0	q_1	q_0
q_1	q_3	
q_2		
q_3		

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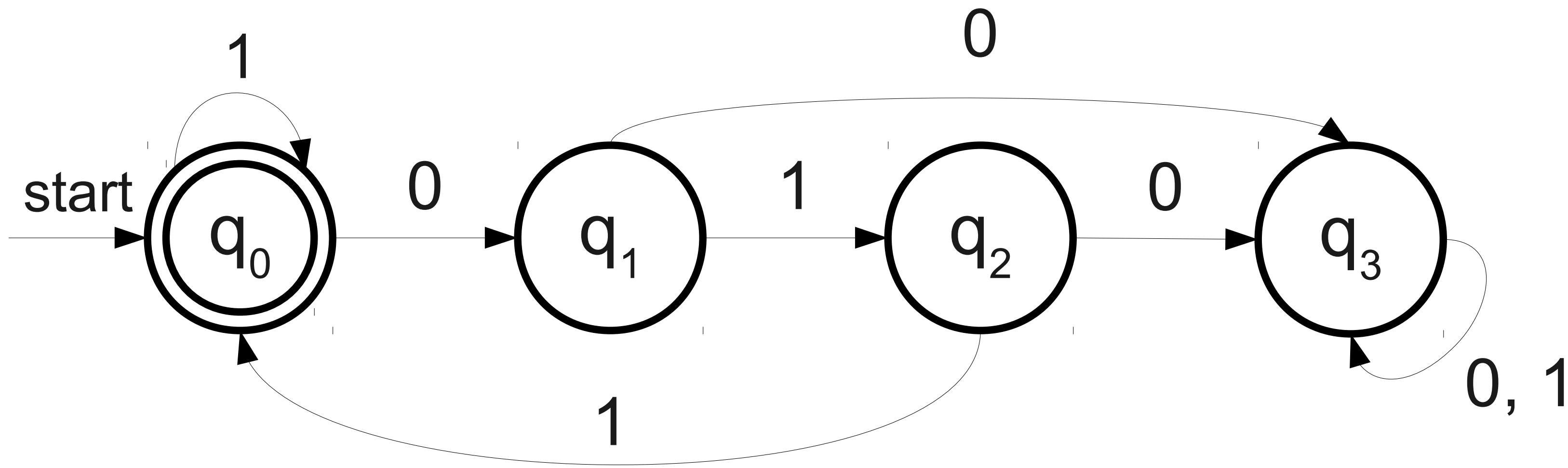

	0	1
q_0	q_1	q_0
q_1	q_3	q_2
q_2		
q_3		

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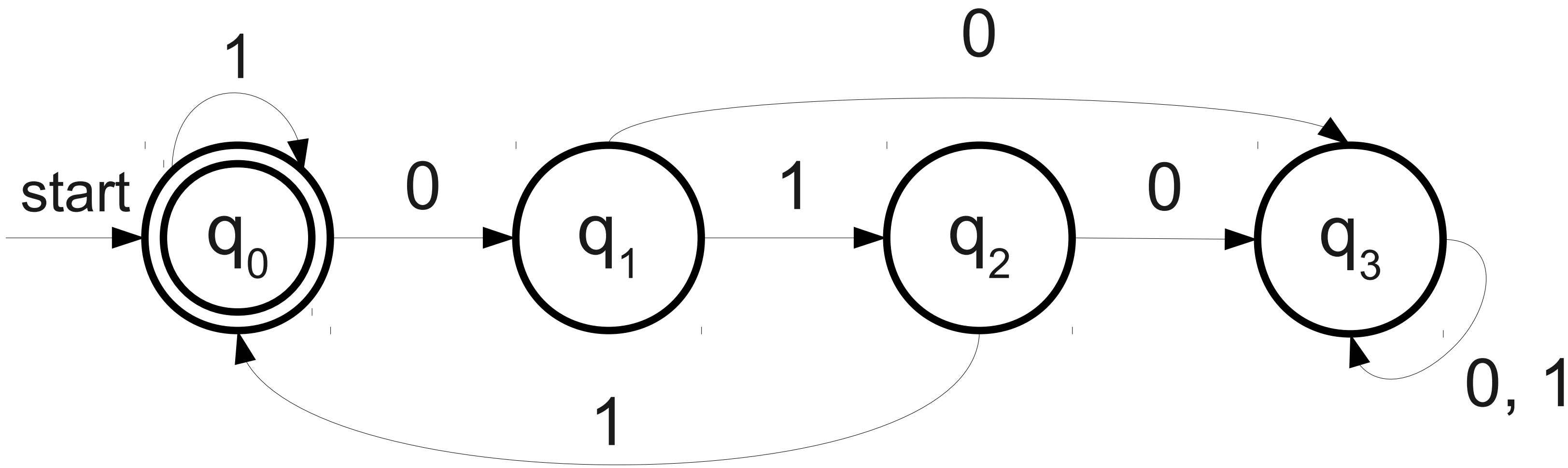

	0	1
q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	
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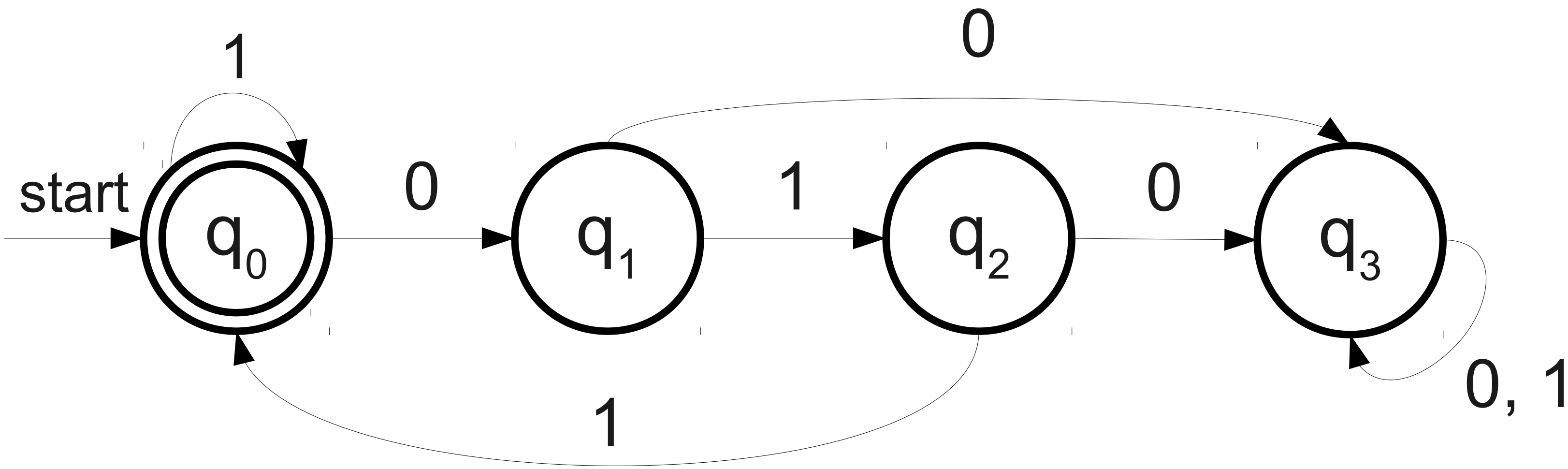

	0	1
q_0	q_1	q_0
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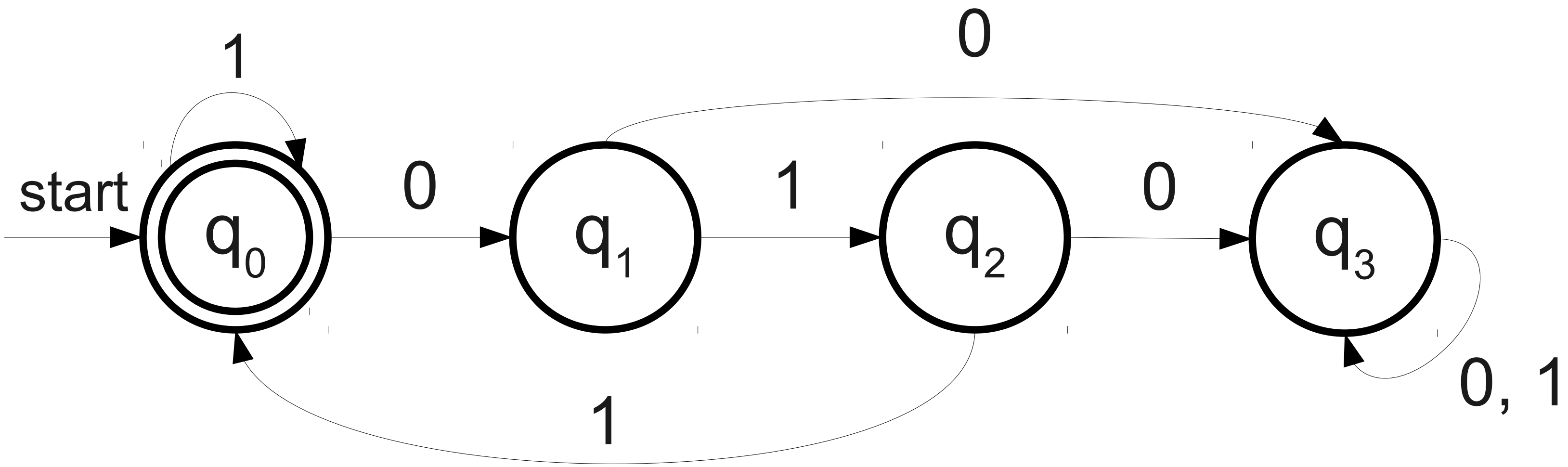

	0	1
q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
q_3	q_3	

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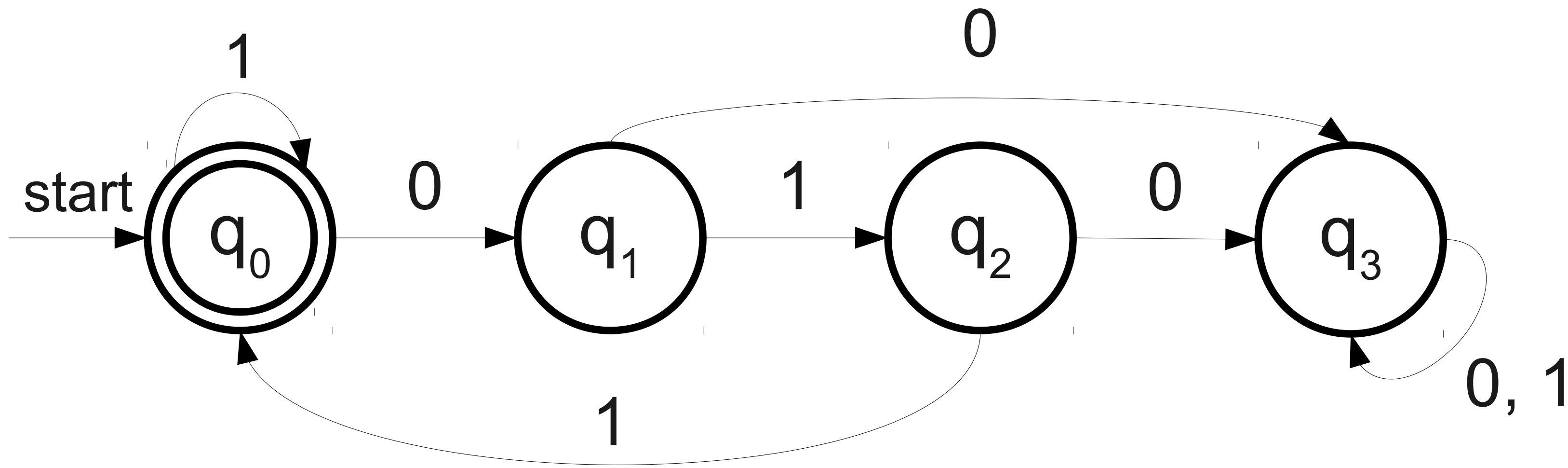

	0	1
q_0	q_1	q_0
q_1	q_3	q_2
q_2	q_3	q_0
q_3	q_3	q_3

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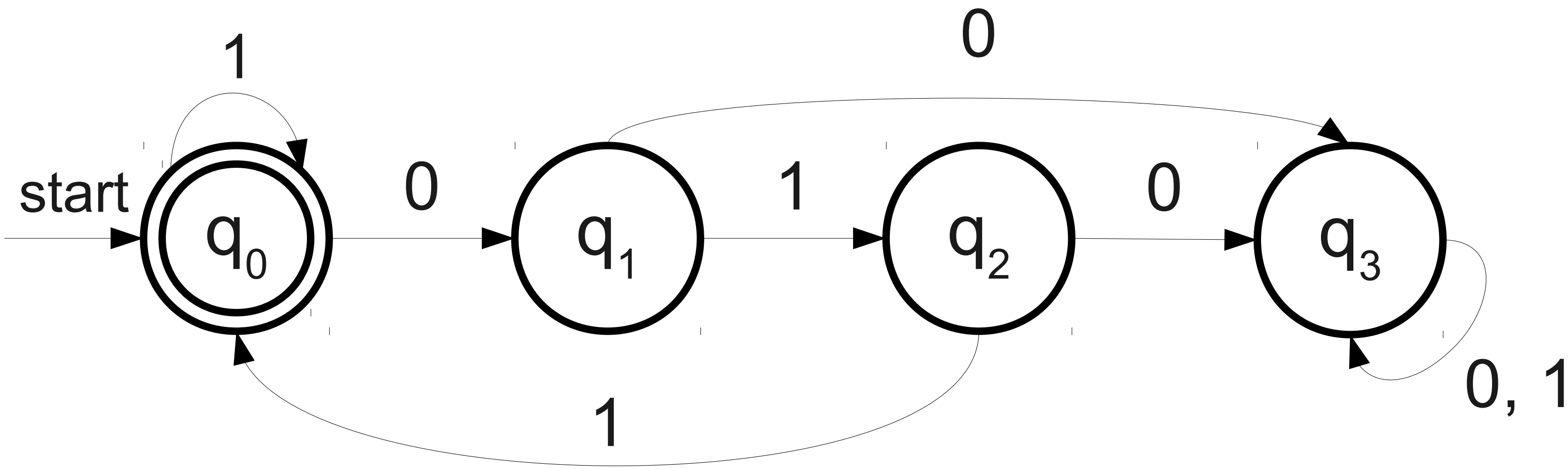

	0	1
*q_0	q_1	q_0
q_1	q_3	q_2
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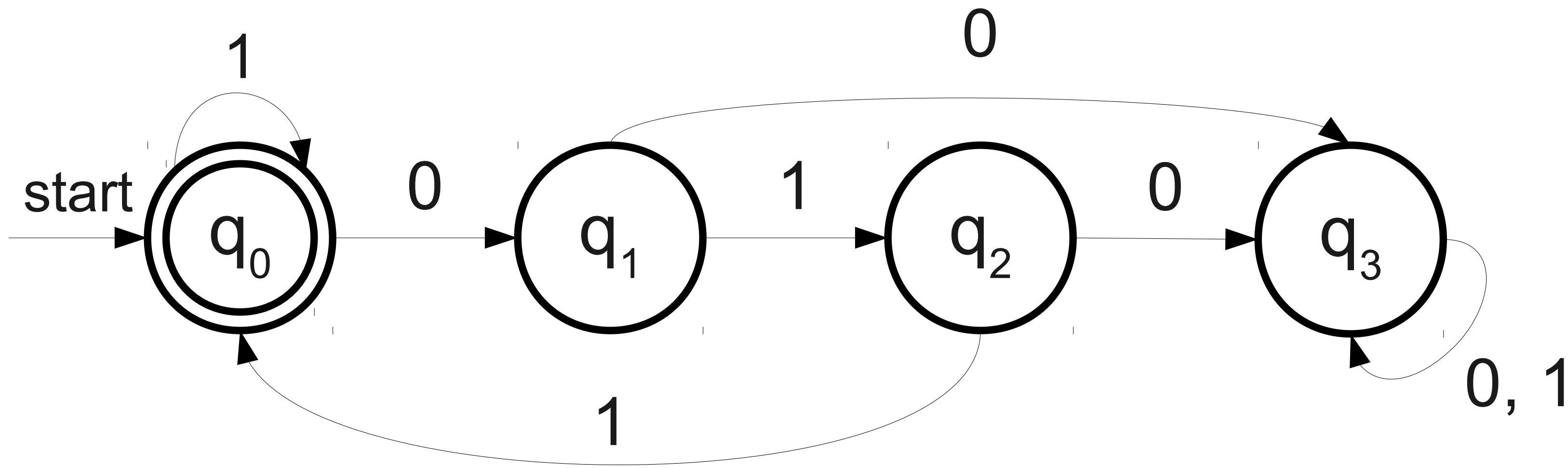
q_3	q_3	q_3

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

The star indicates that this is an accepting state.

Code? In a Theory Course?

```
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];
}
```

A language L is called a **regular language** iff 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^* not in L.
- Formally:

$$\overline{L} = \{ \ w \mid w \in \Sigma^* \land w \notin L \ \}$$

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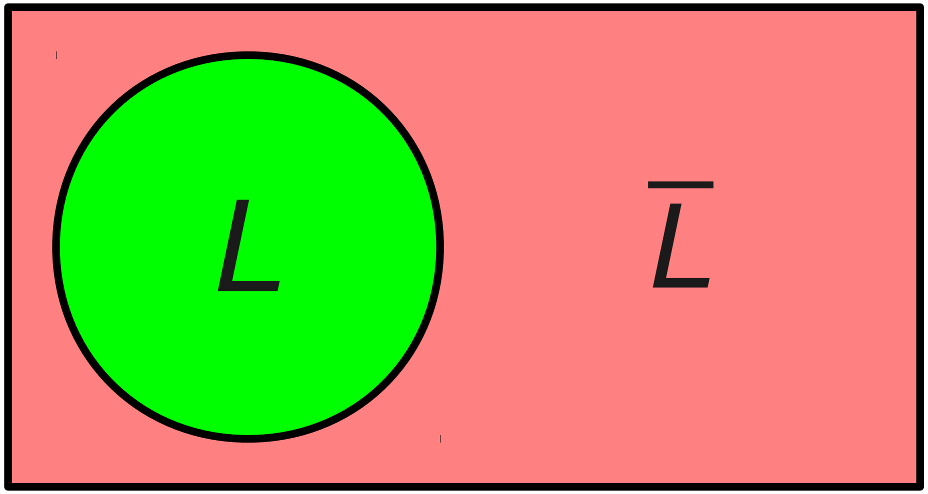

Complementing Regular Languages

- Recall: A **regular language** is a language accepted by some DFA.
- **Question:** If L is a regular language, is $\overline{L}$ a regular language?
- If the answer is "yes," then 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 a DFA, but $\overline{L}$ cannot be accepted by any DFA.

Complementing Regular Languages

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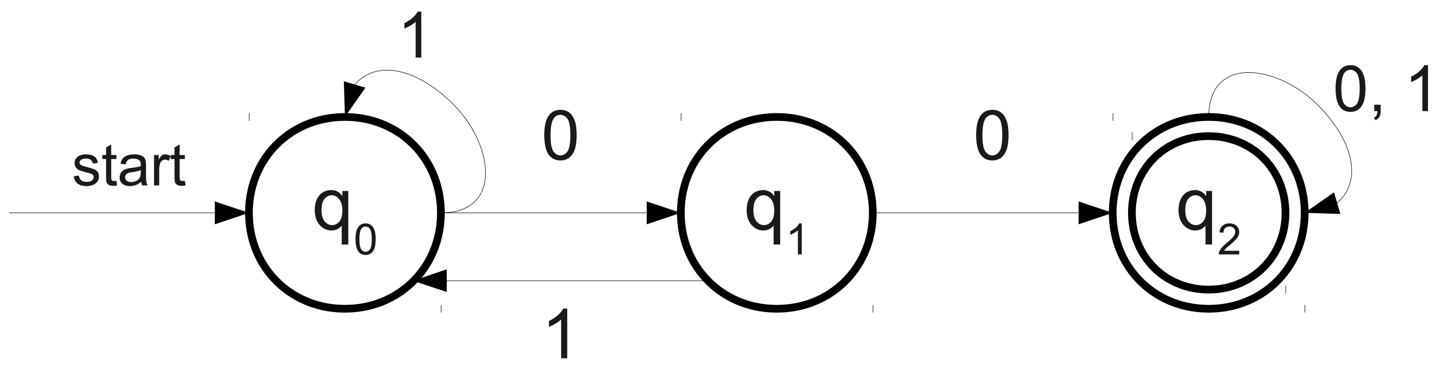

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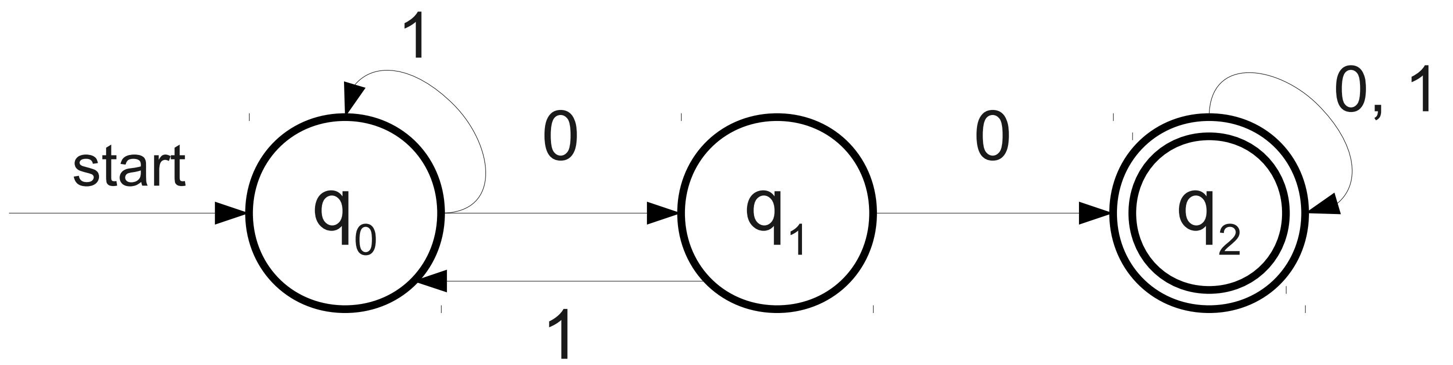

$\overline{L} = \{ \ w \in \{0, 1\}^* \mid w$ **does not contain** 00 as a substring $\}$

Complementing Regular Languages

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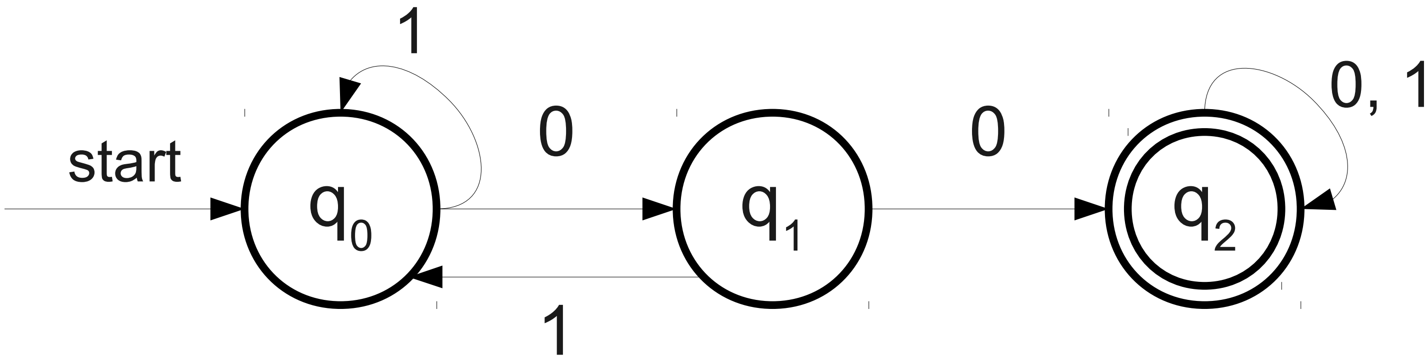

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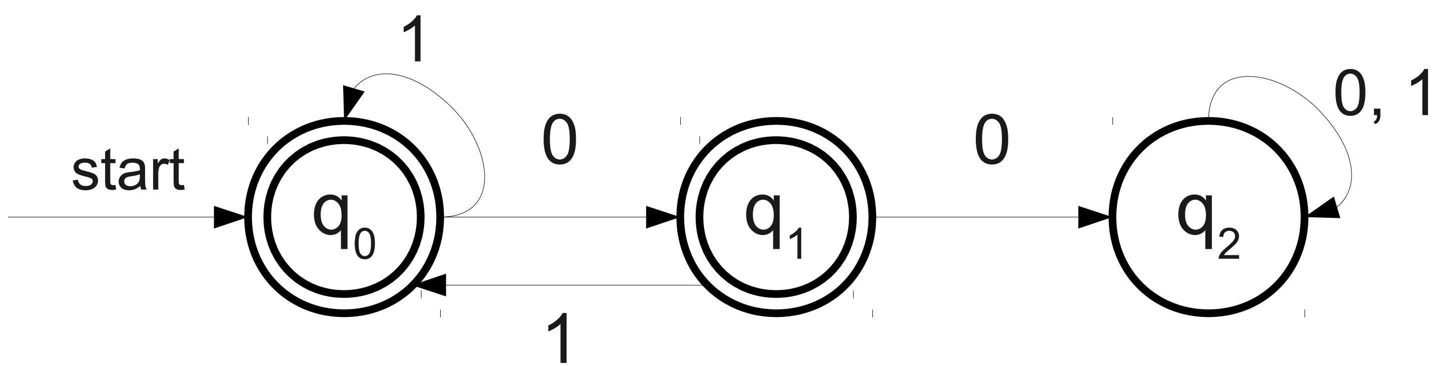

Complementing Regular Languages

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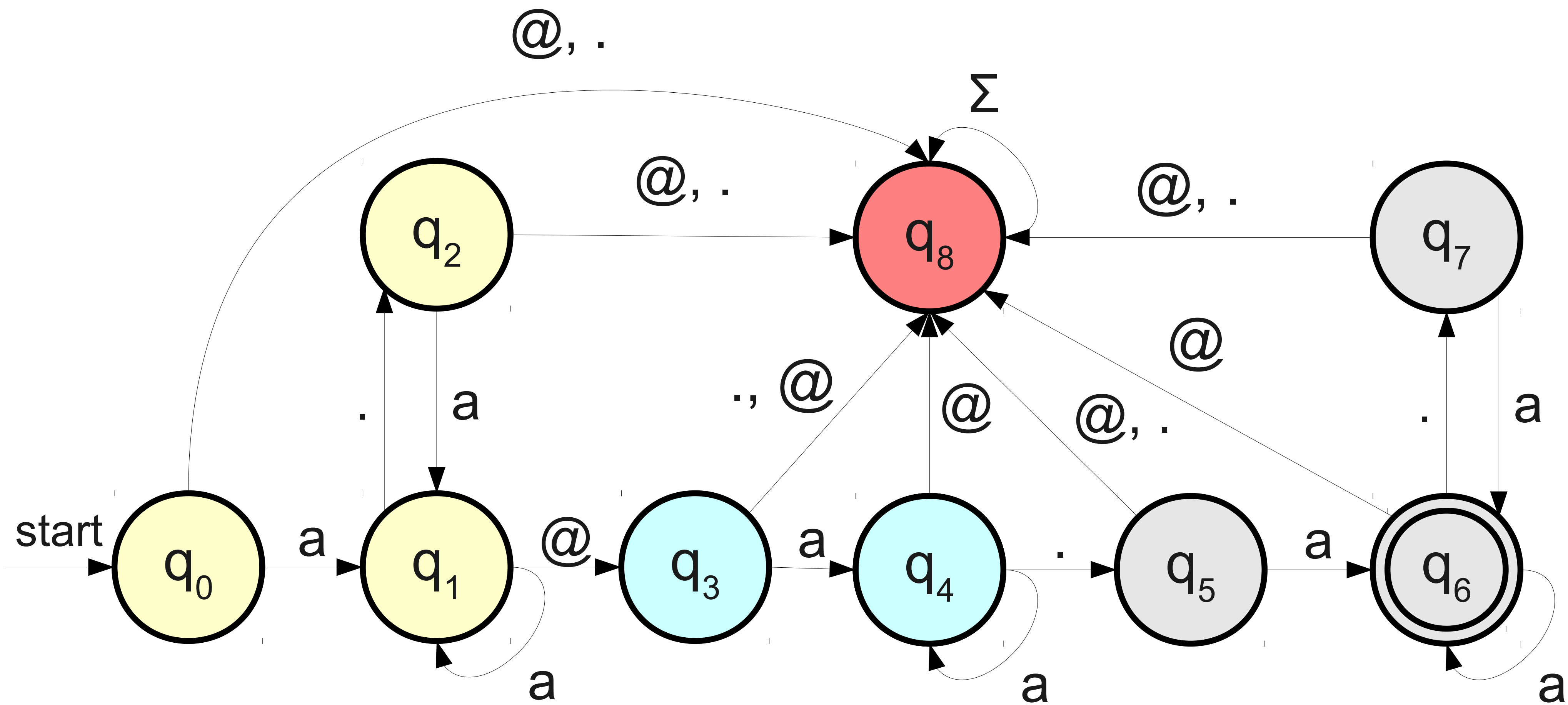

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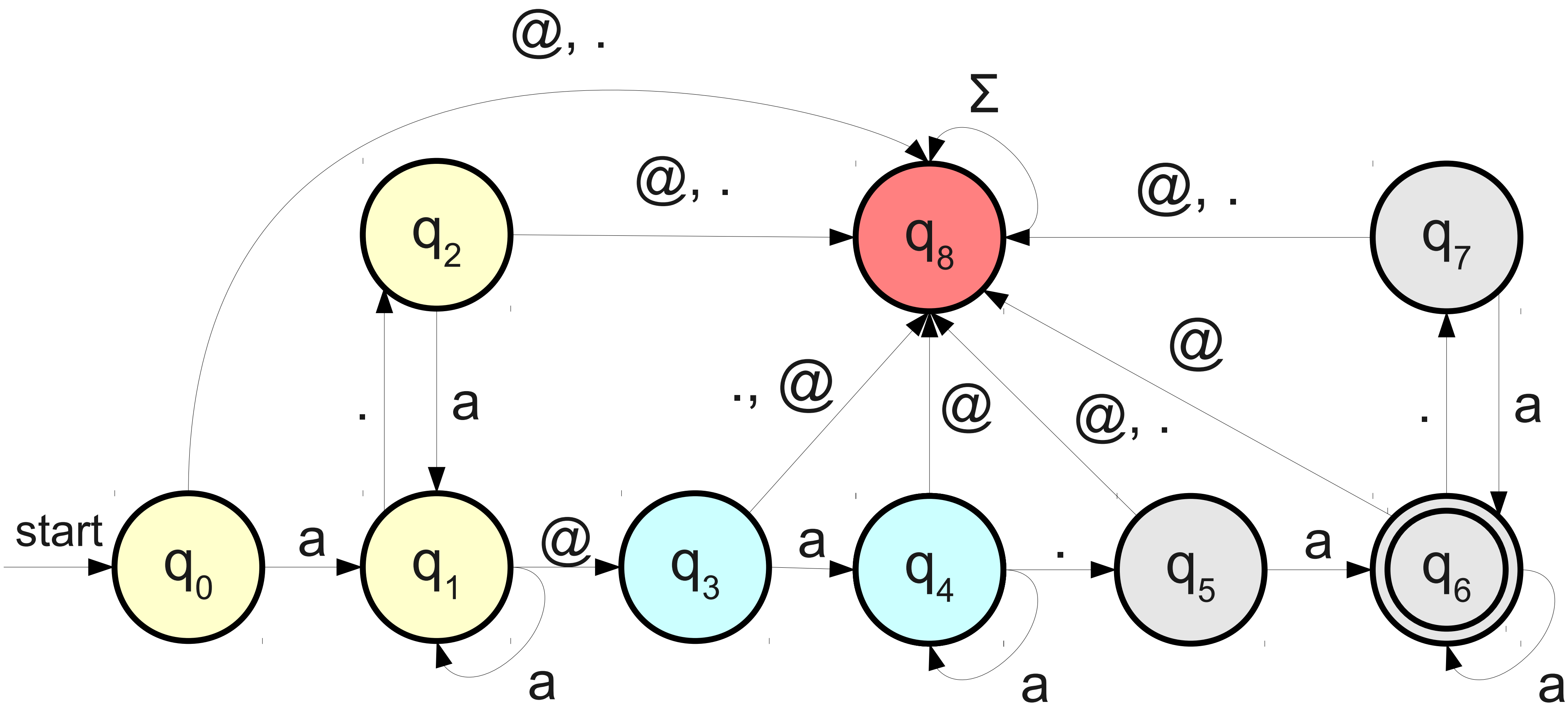

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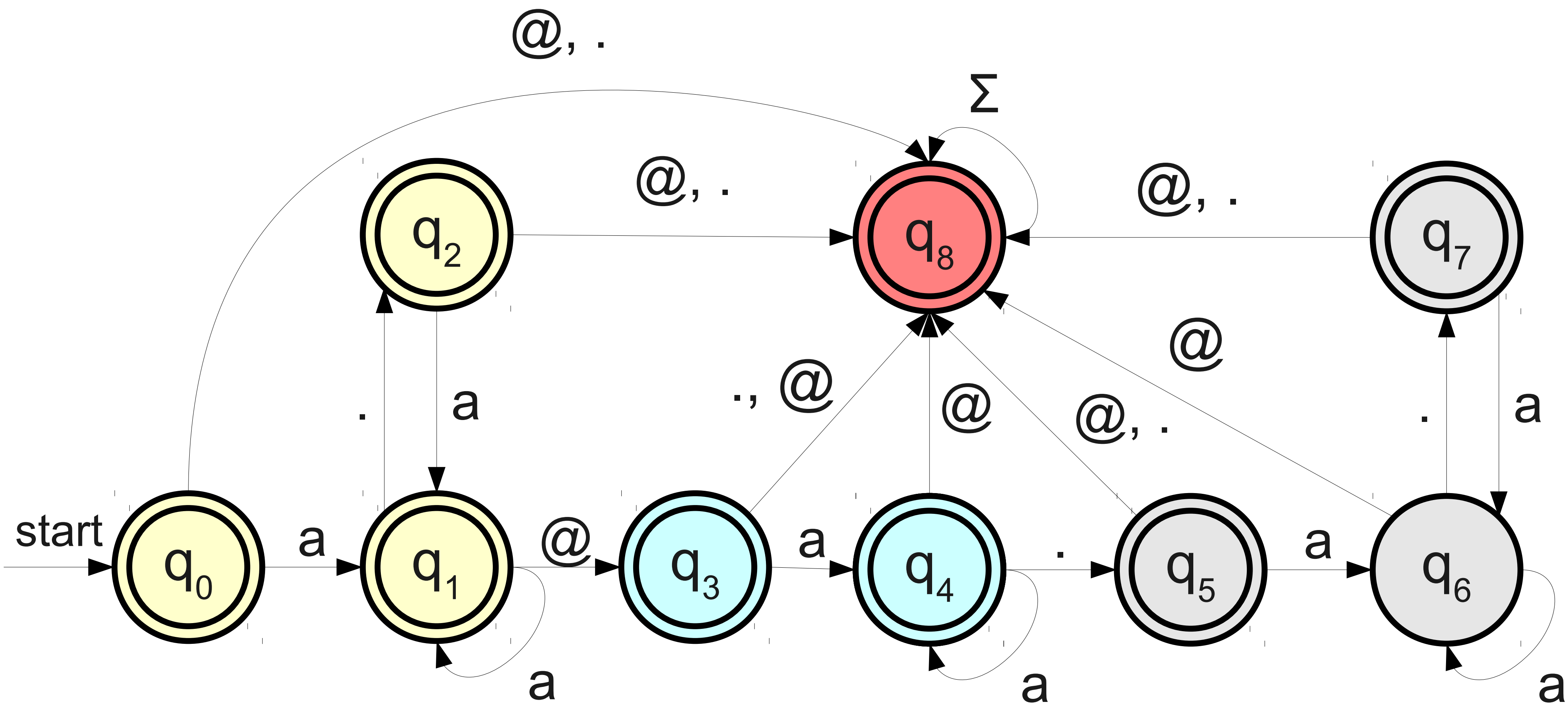


Constructions on Automata

- Much of our discussion of automata will consider constructions that transform one automaton into another.
- Exchanging accepting and rejecting states is a simple construction sometimes called the **complement construction**.

Closure Properties

- If L is a regular language, $\overline{L}$ is a regular language.
- If we begin with a regular language and complement it, we end up with a regular language.
- This is an example of a **closure property of regular languages**.
  - The regular languages are **closed under complementation**.
  - We'll see more such properties later on.

NFAs

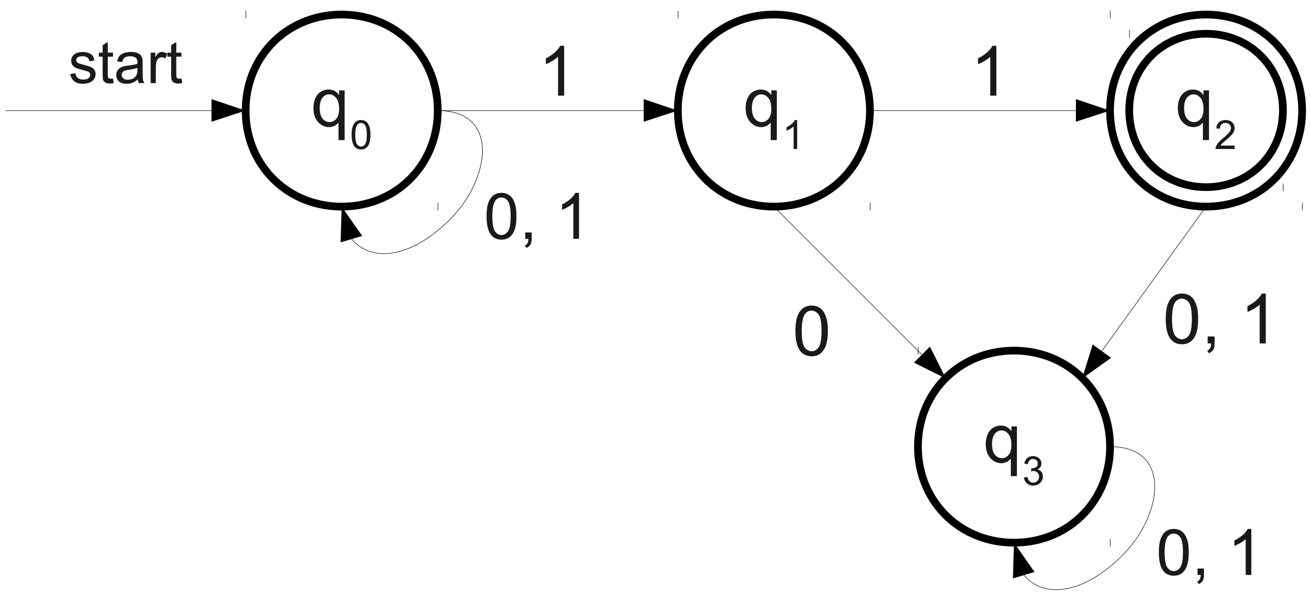
NFAs

- An **NFA** is a
  - **N**ondeterministic
  - **F**inite
  - **A**utomaton
- Conceptually similar to a DFA, but equipped with the vast power of **nondeterminism**.

(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



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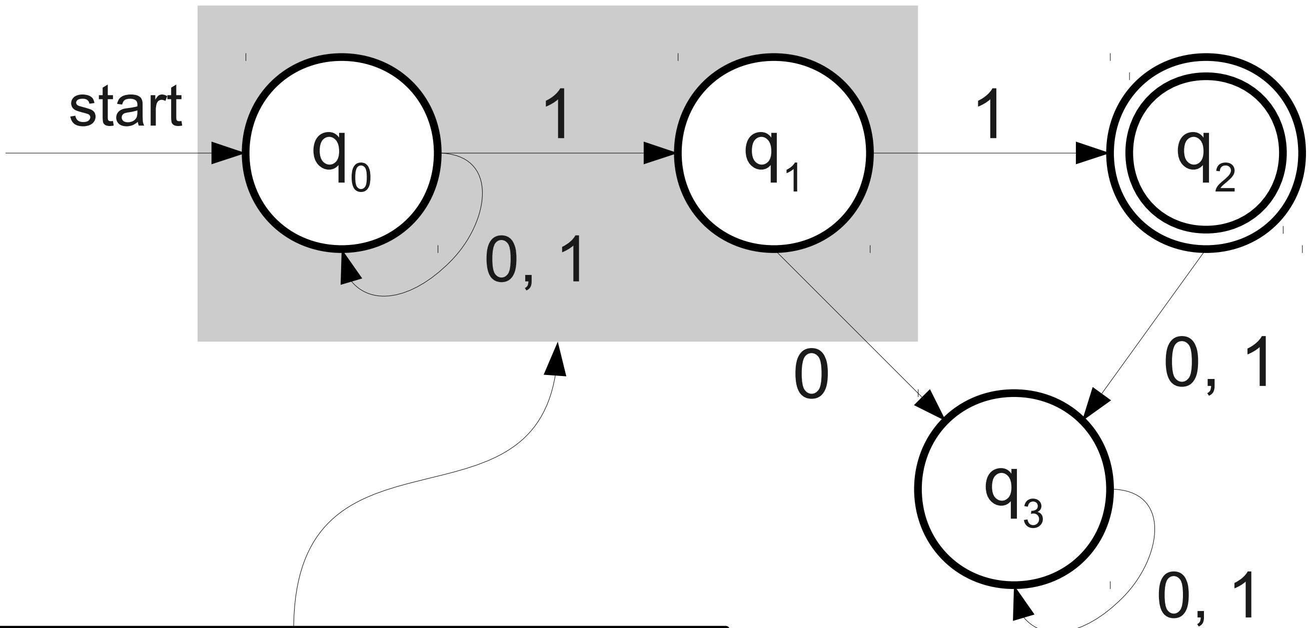
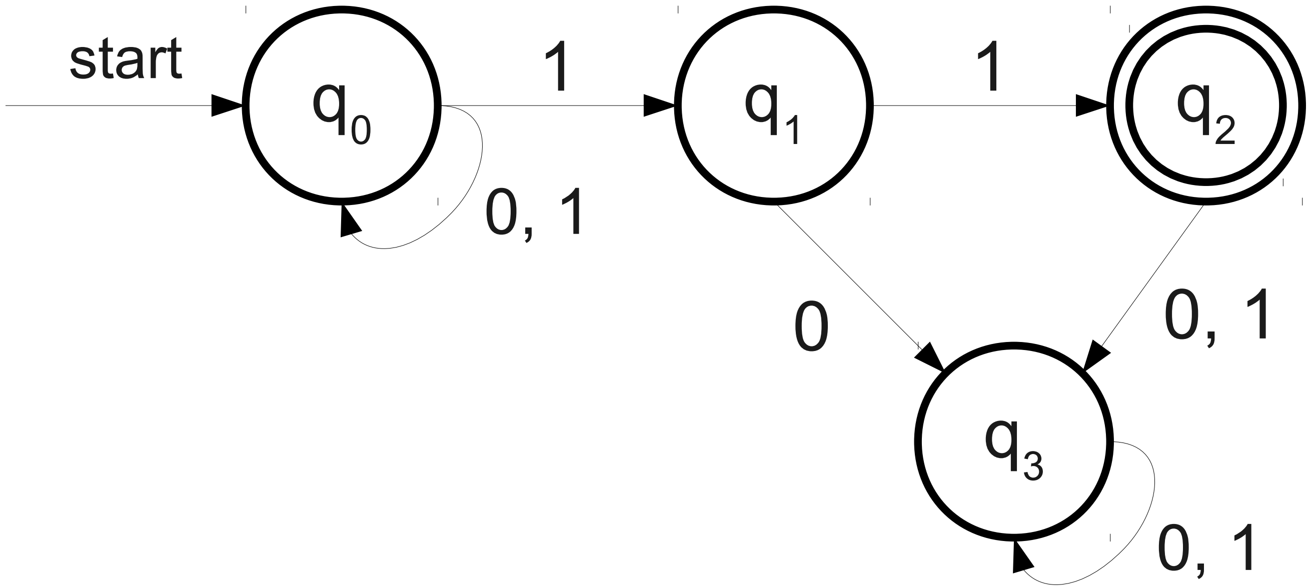
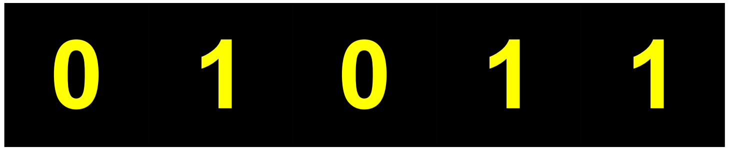


q_0 has two transitions defined on 1!

A Simple NFA





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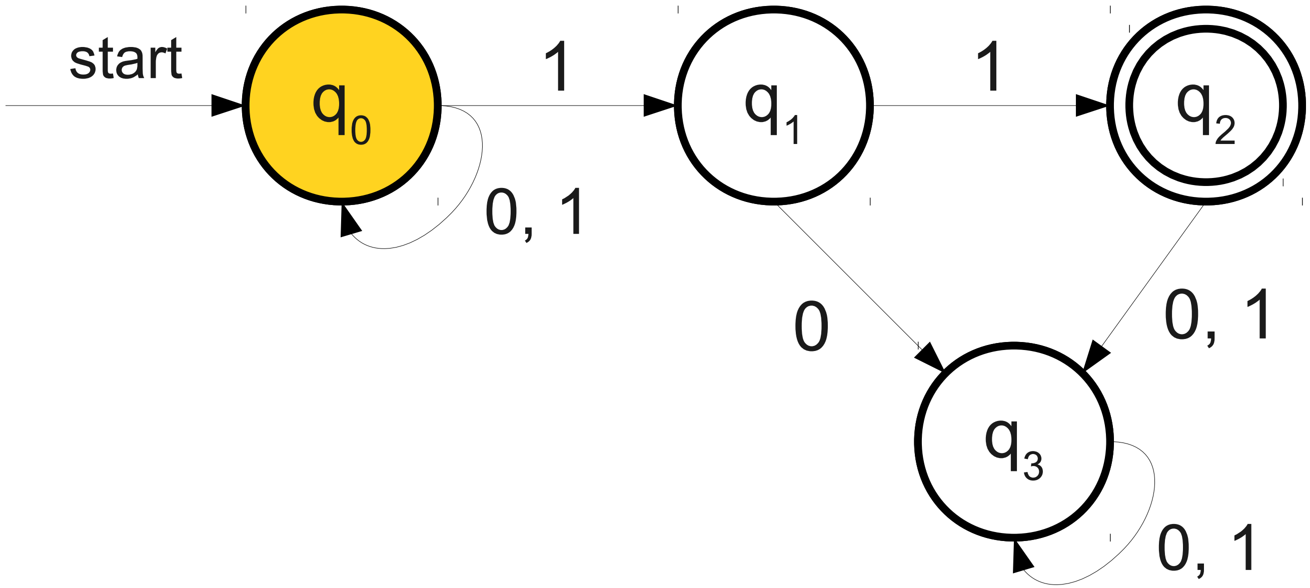
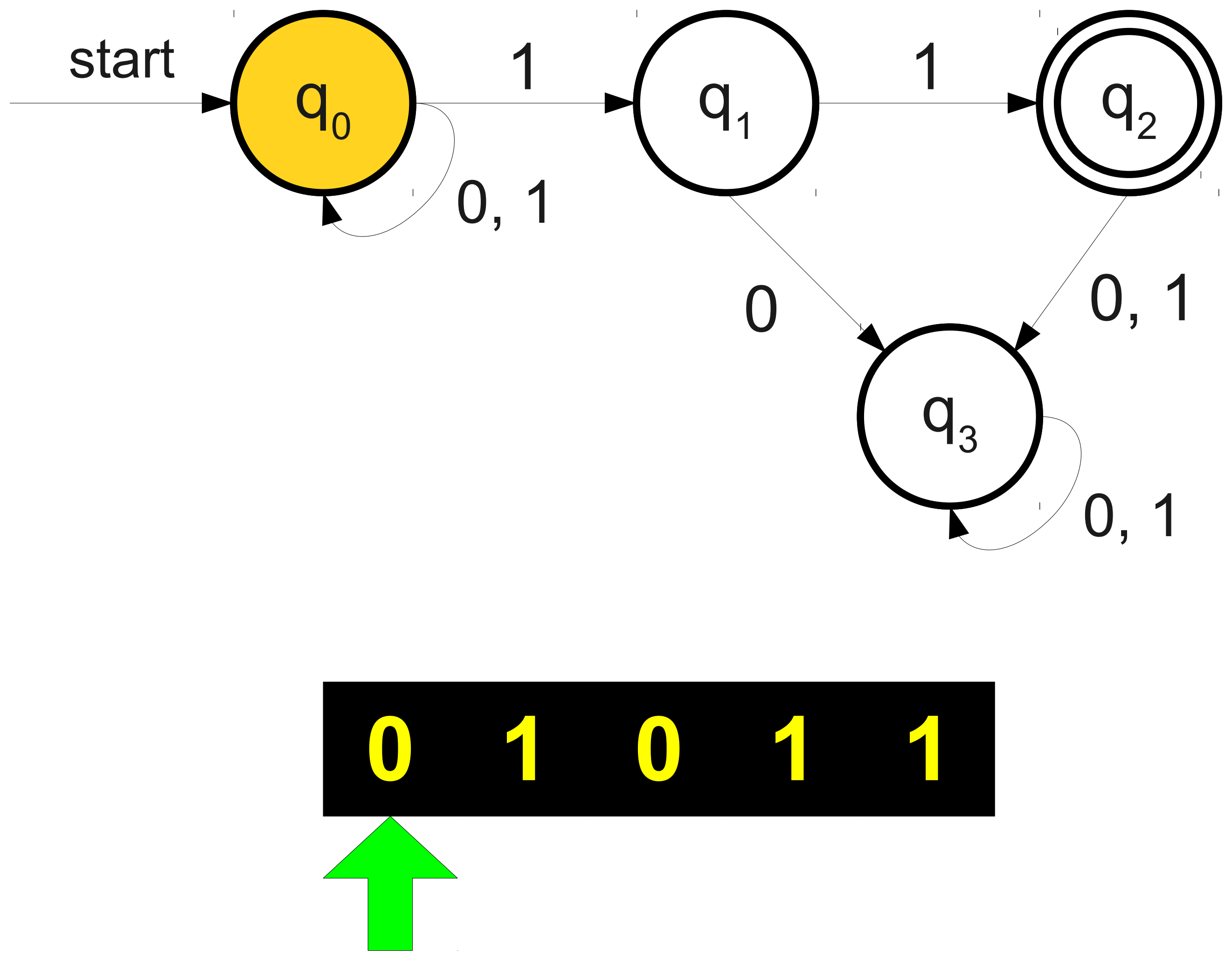


0 1 0 1 1

A Simple NFA



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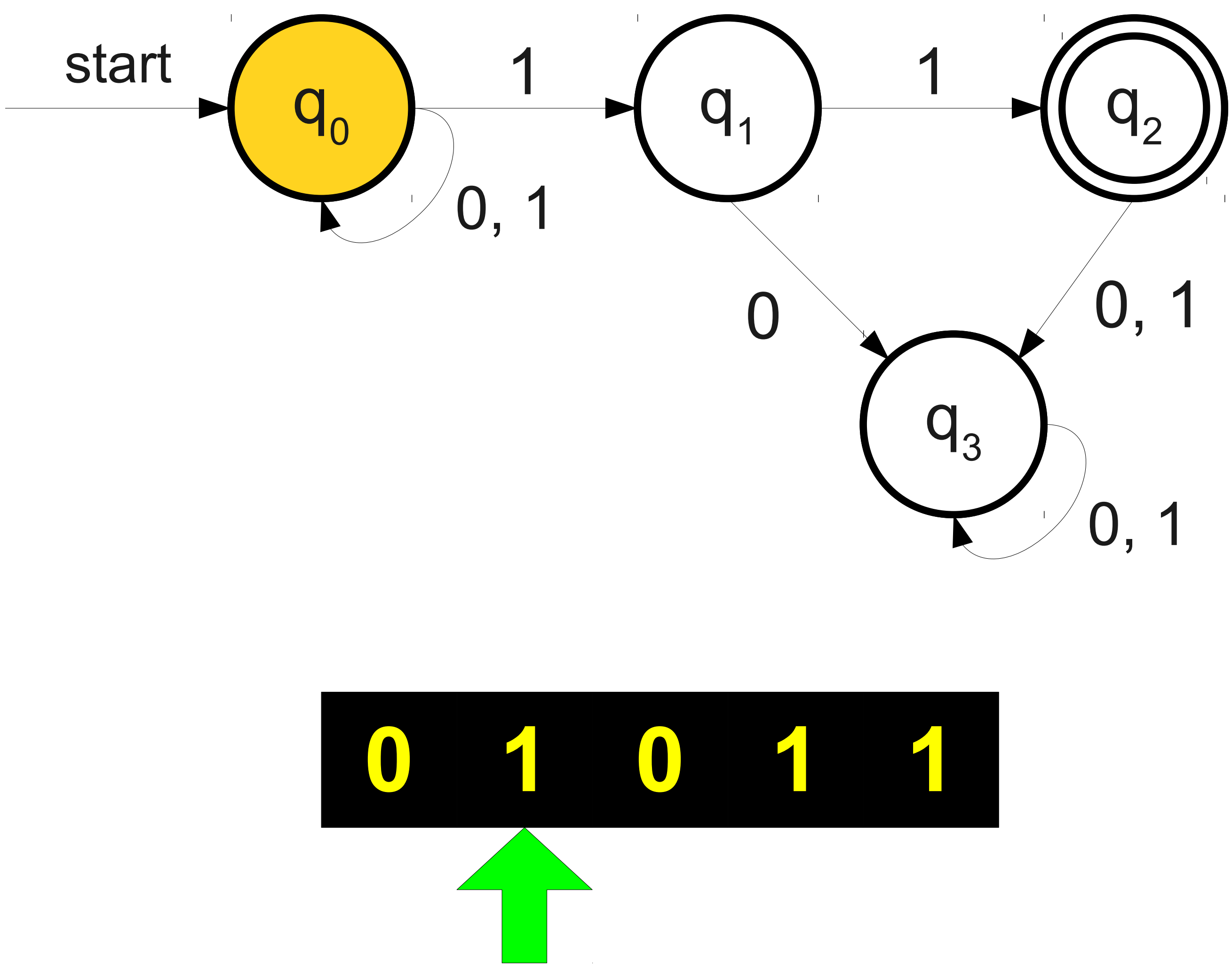

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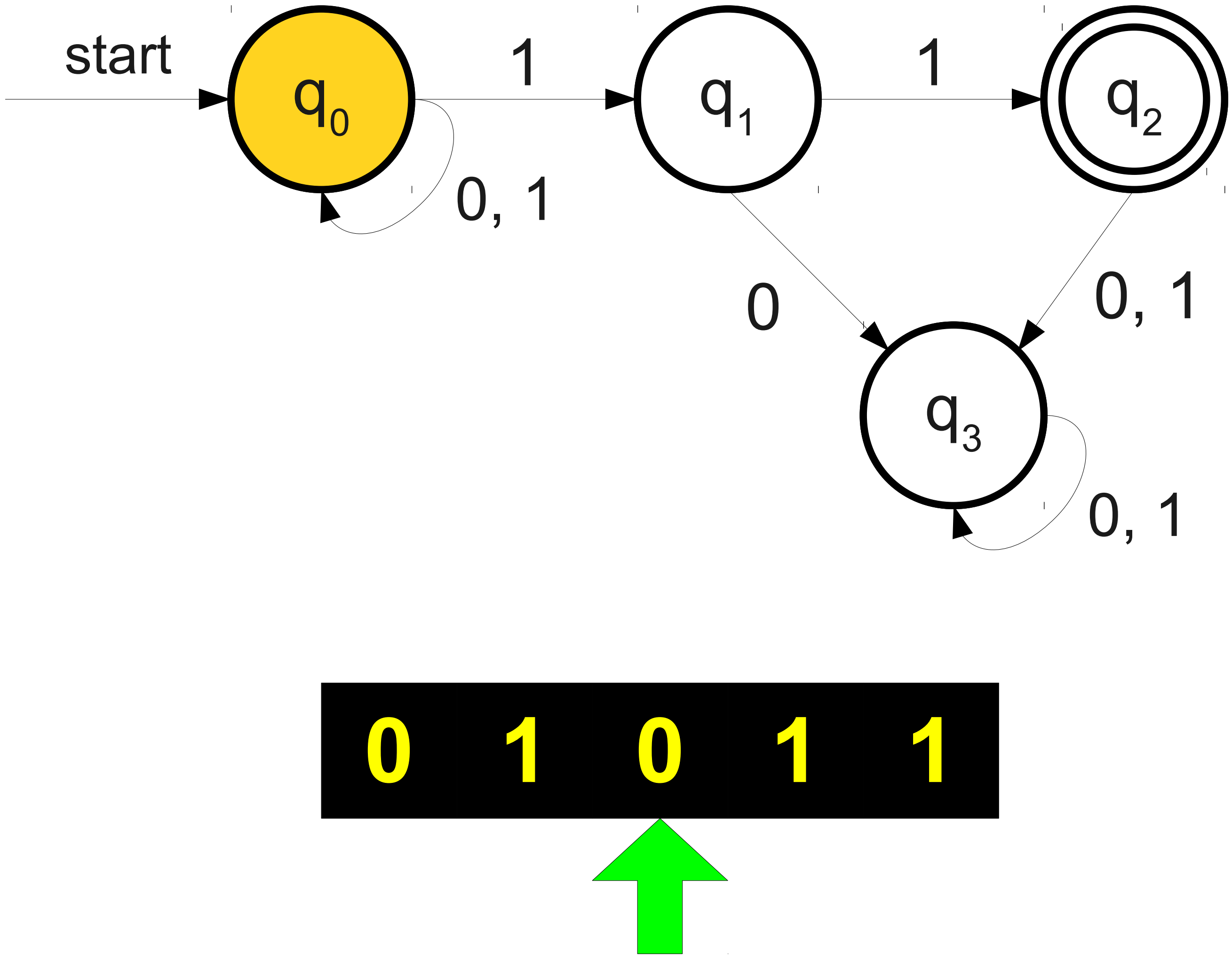

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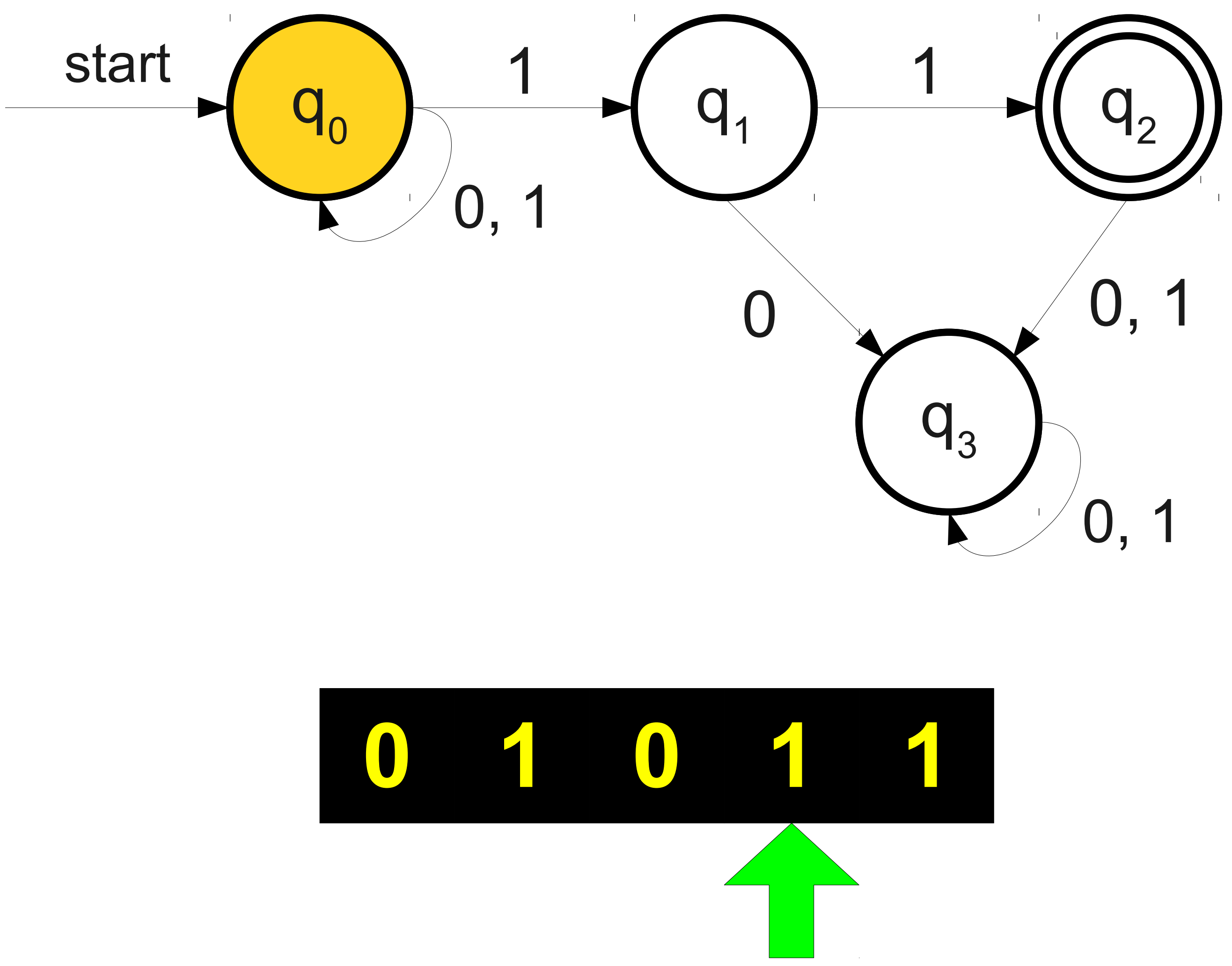

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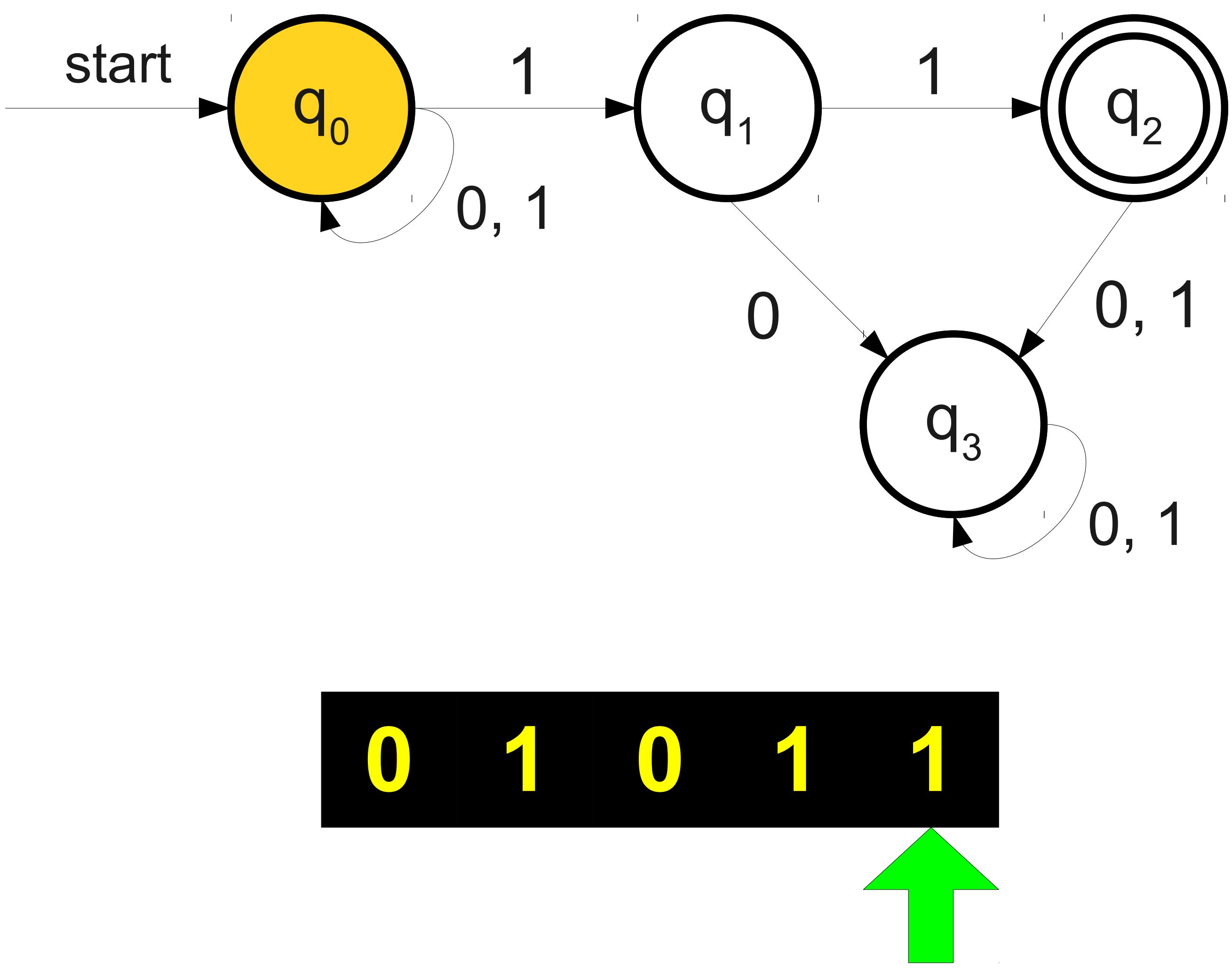

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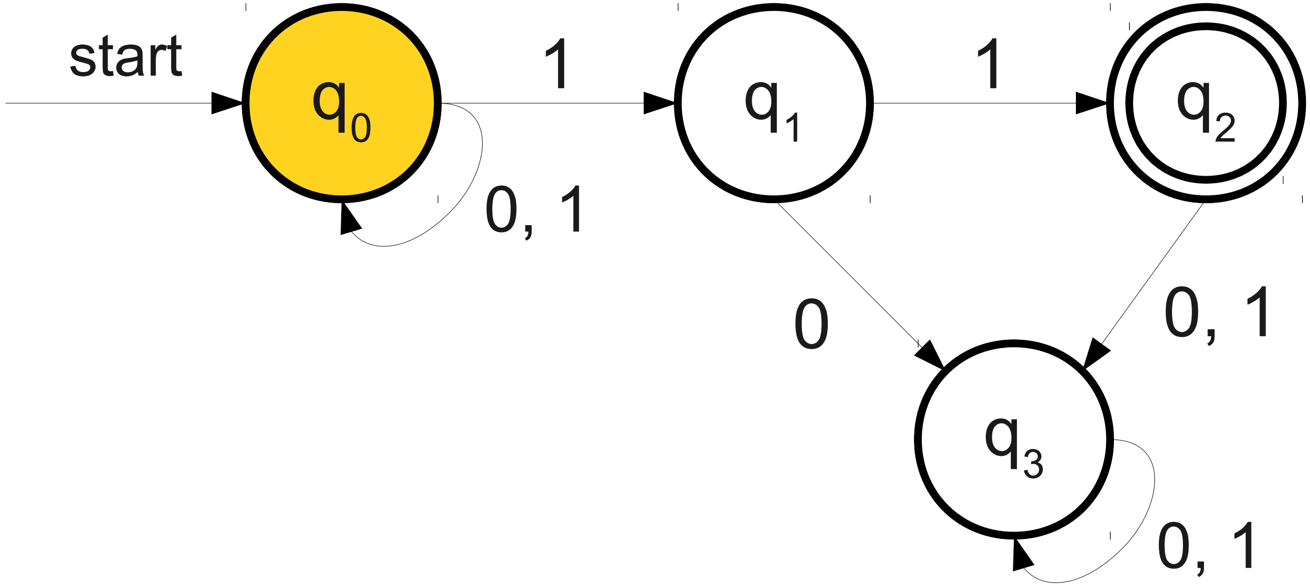

0 1 0 1 1

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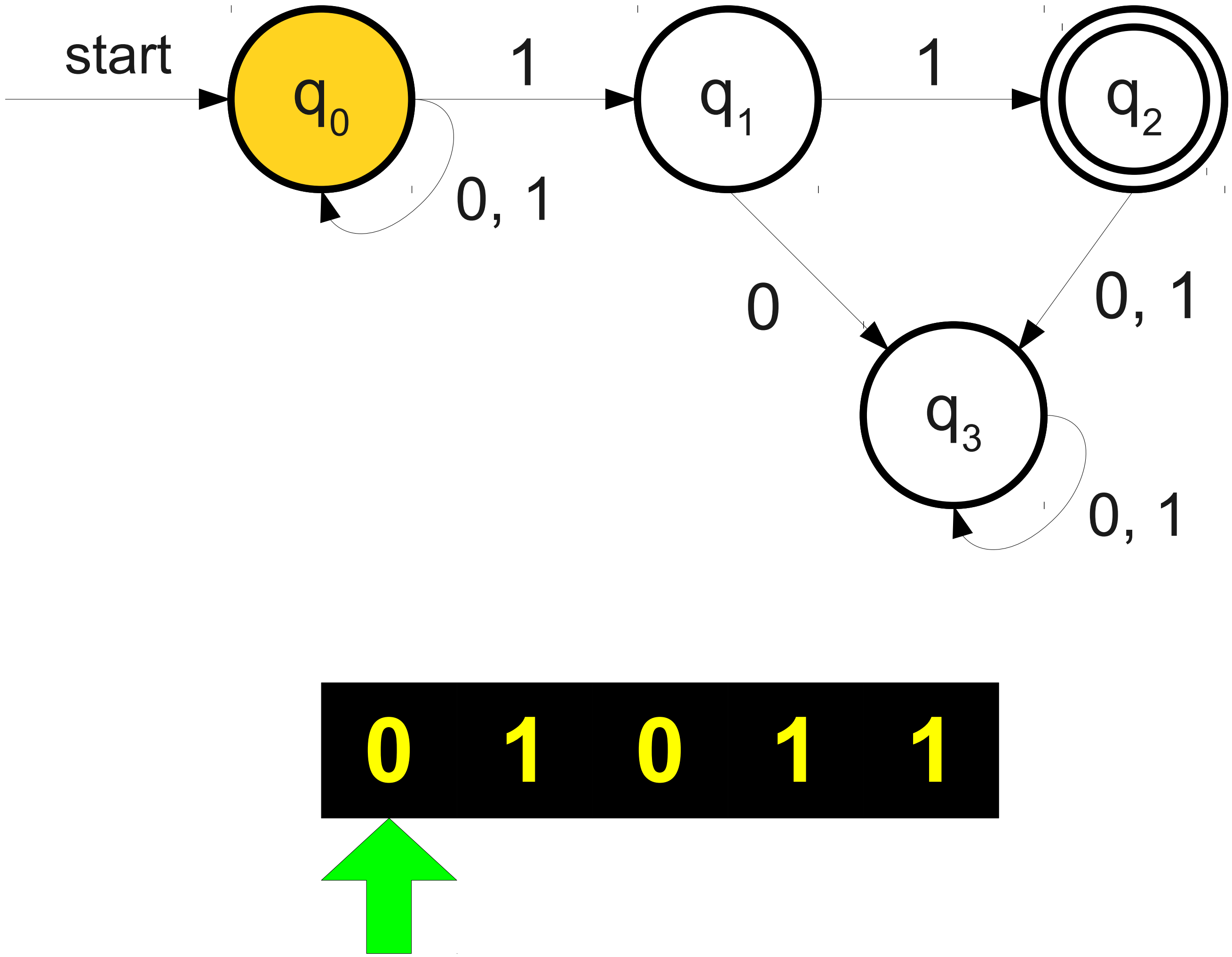

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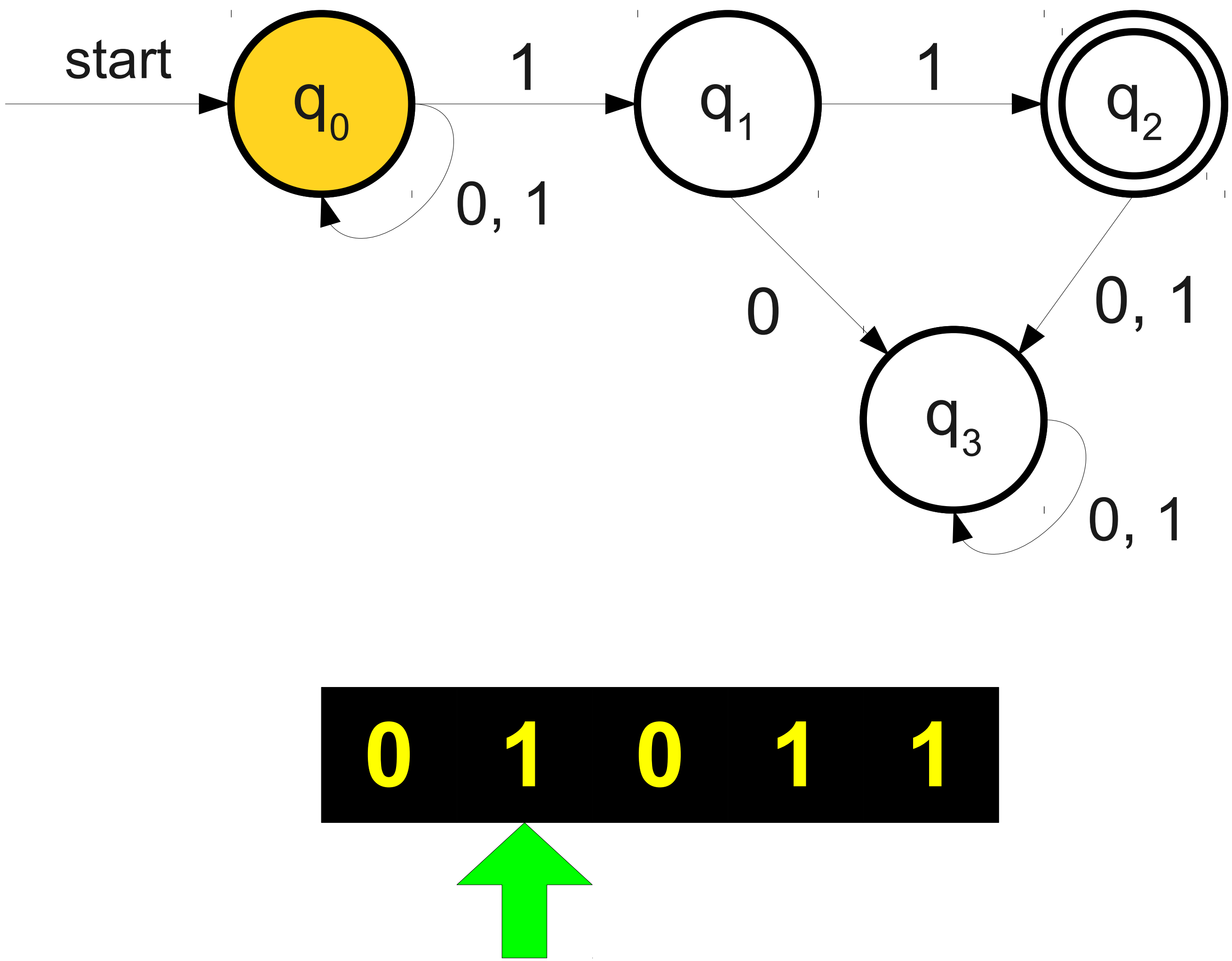

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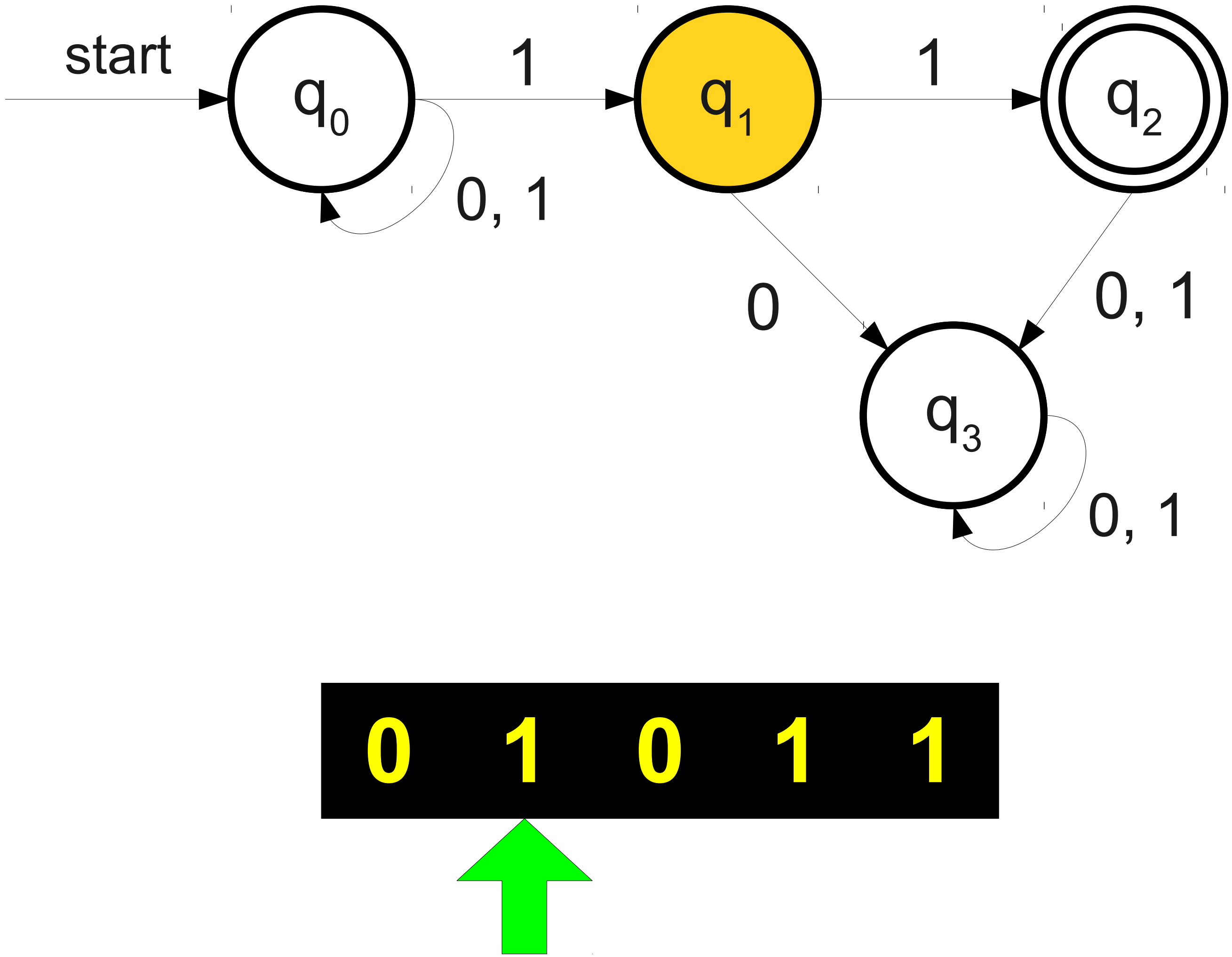

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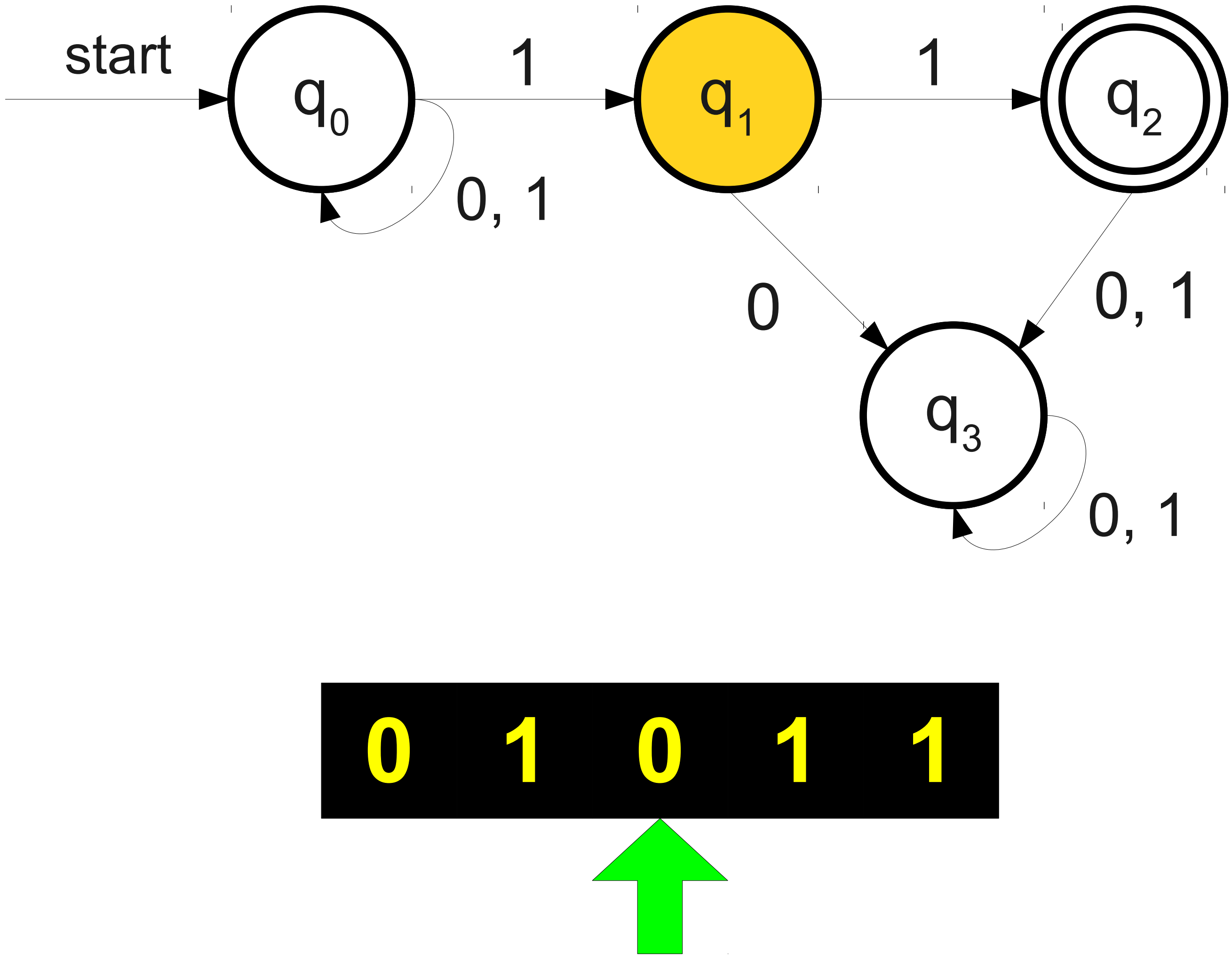

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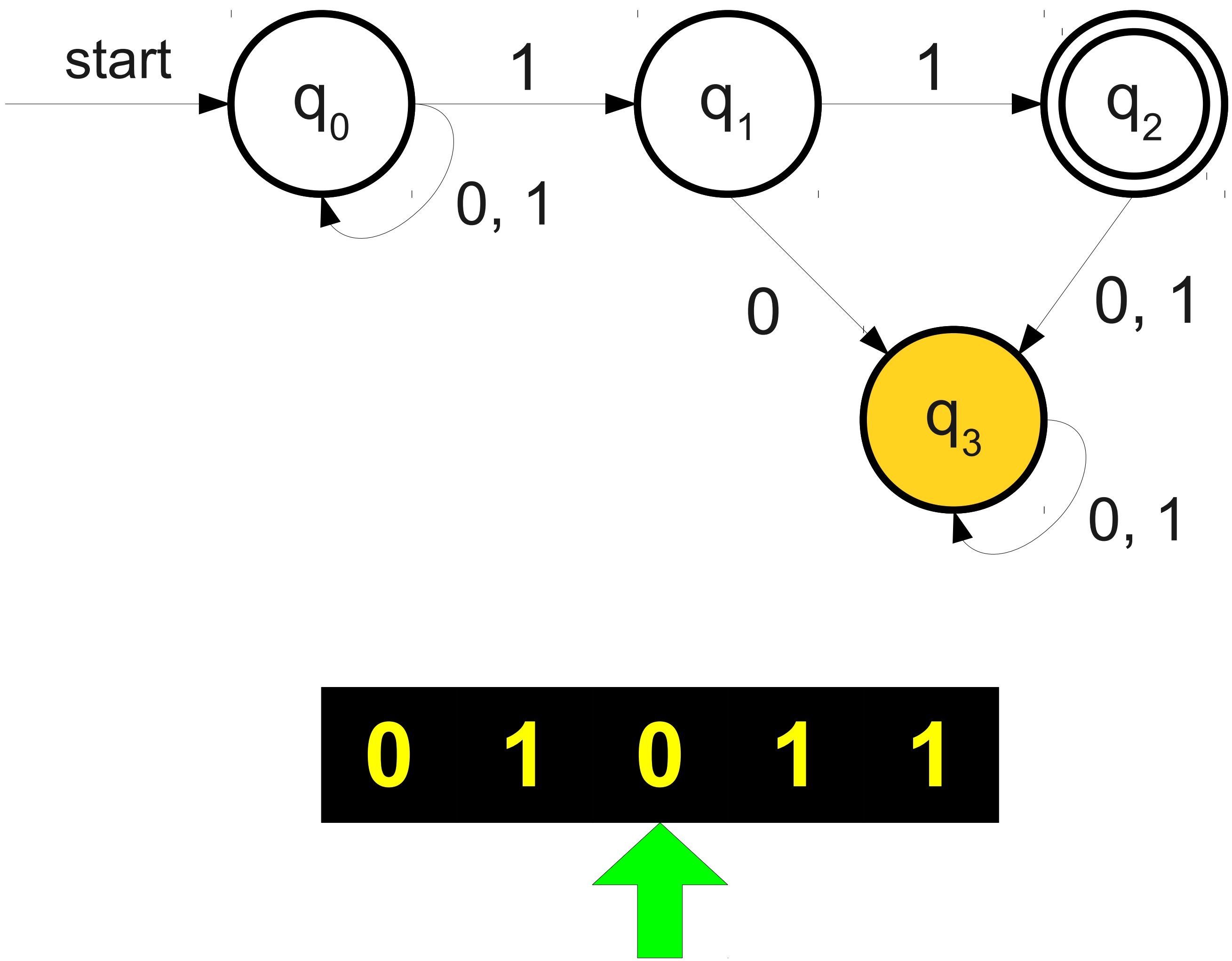

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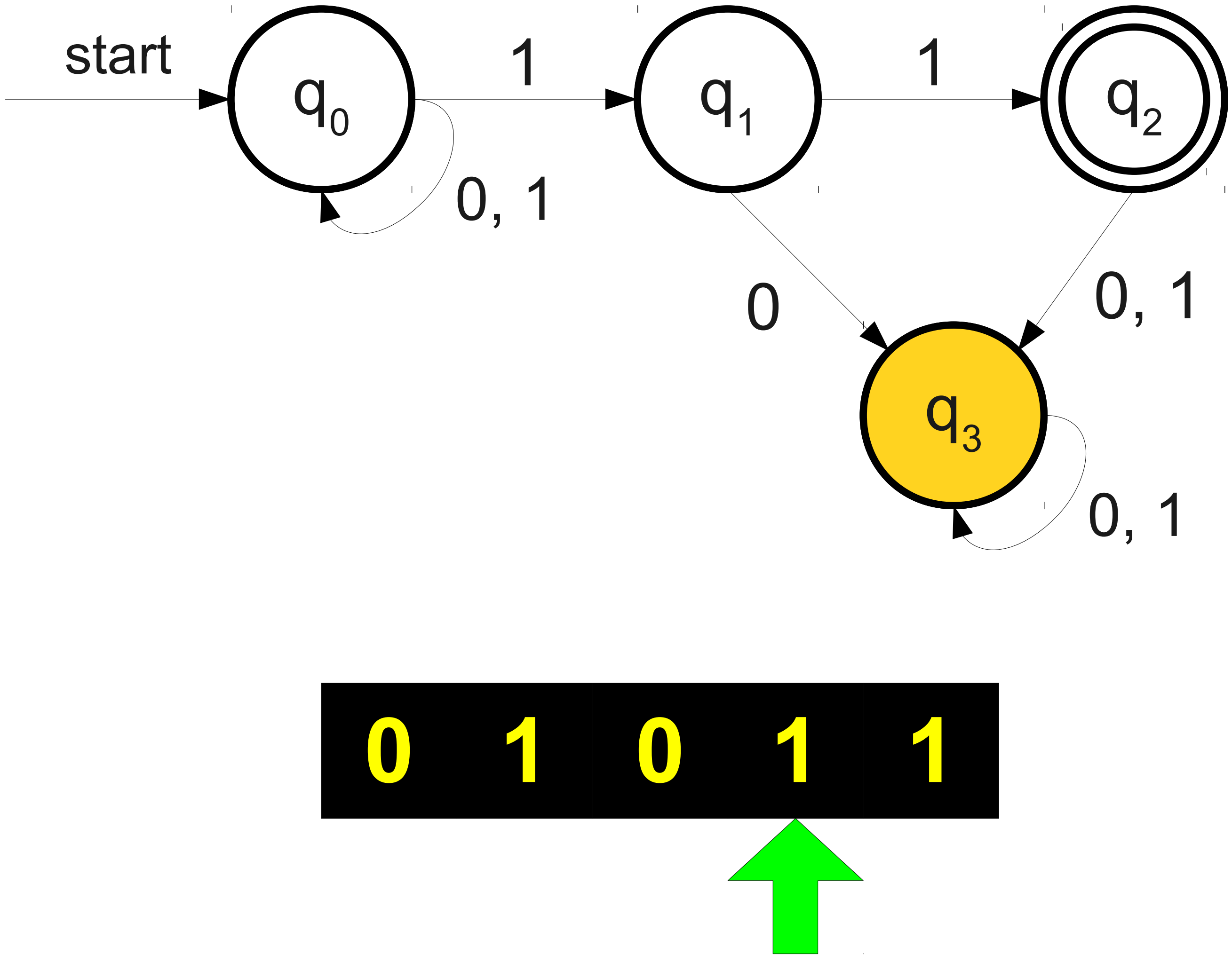

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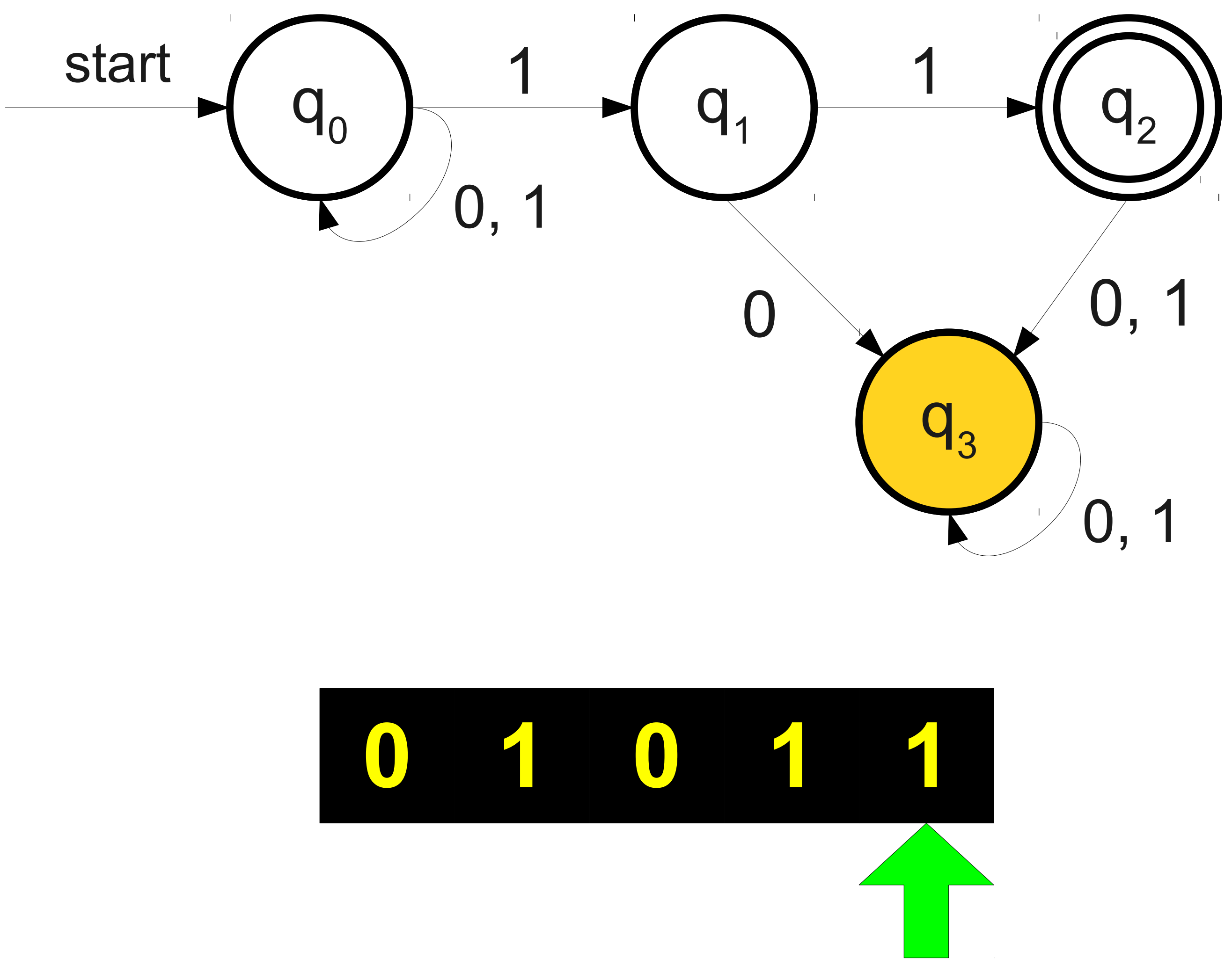

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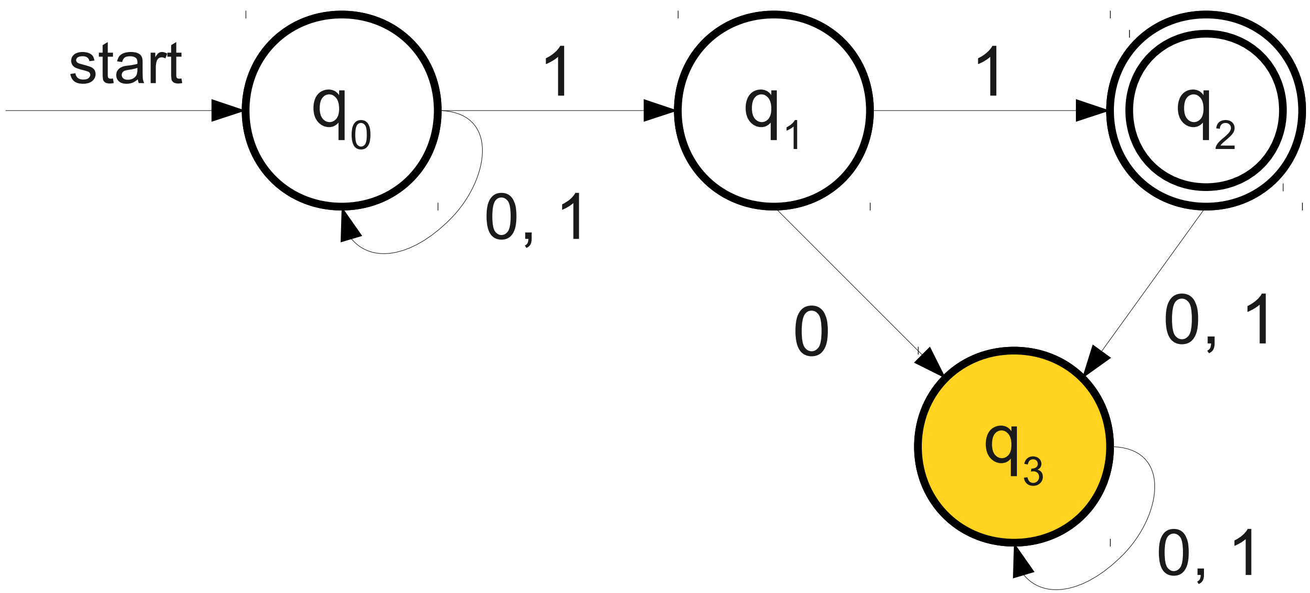

0 1 0 1 1

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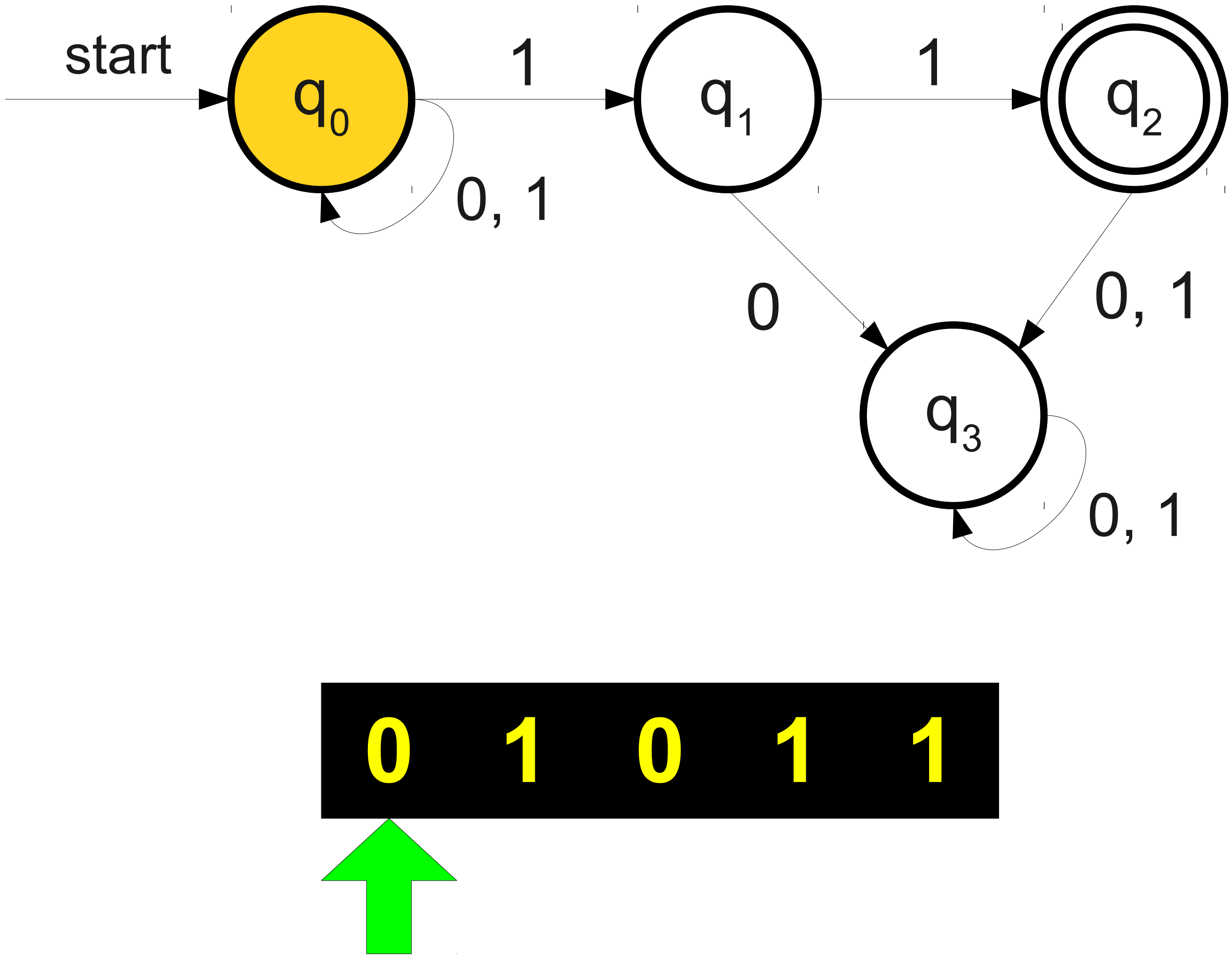

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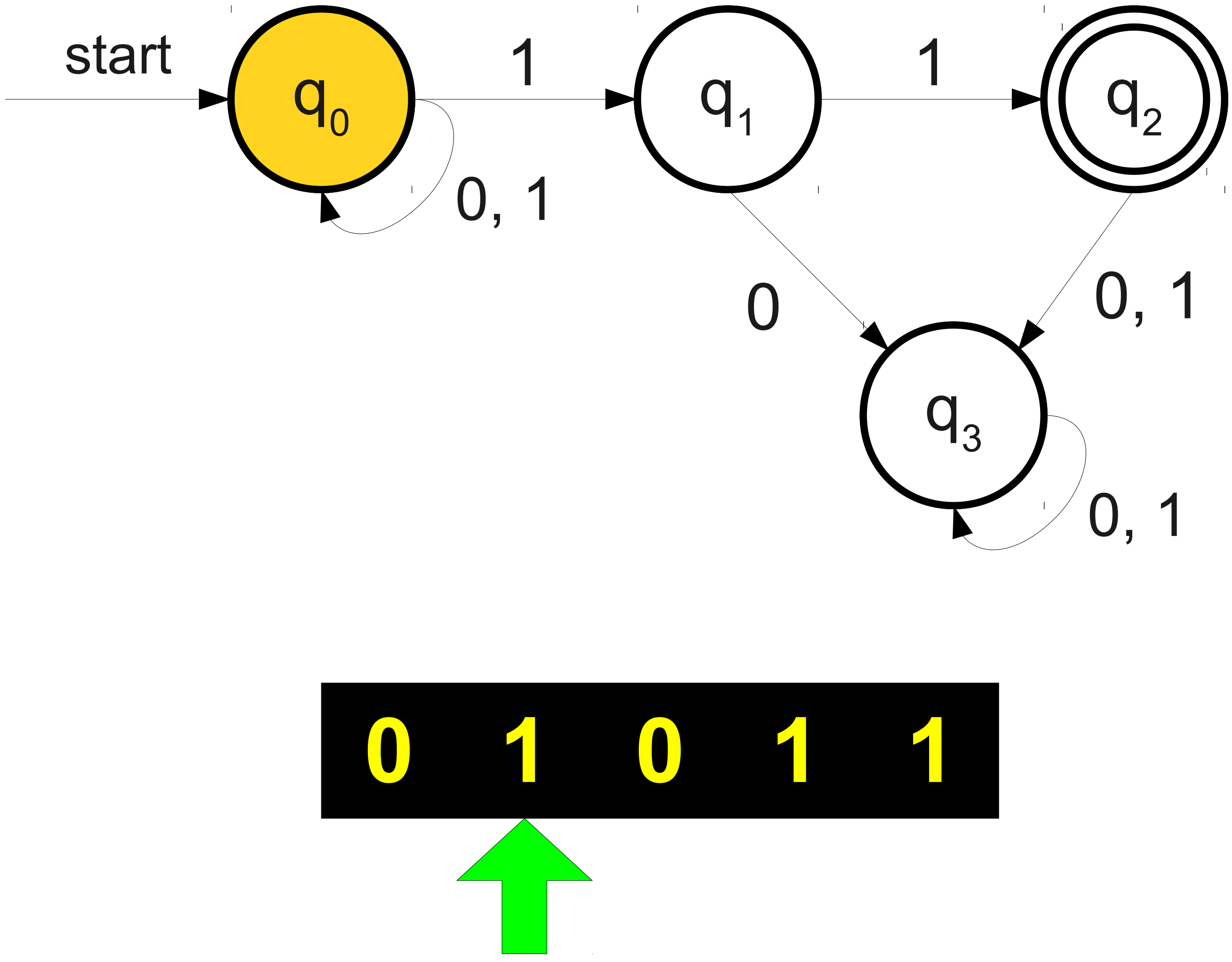

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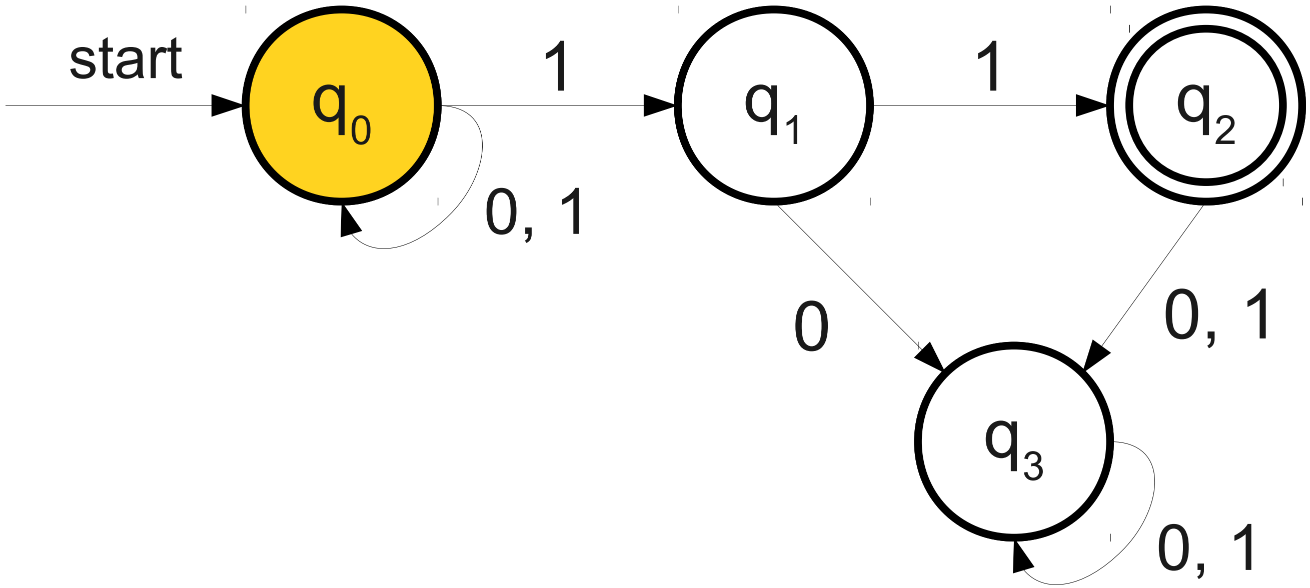

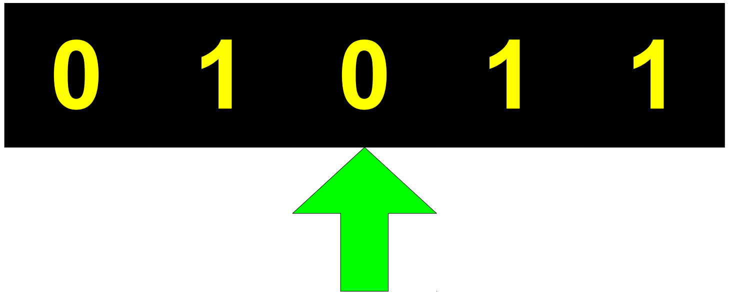

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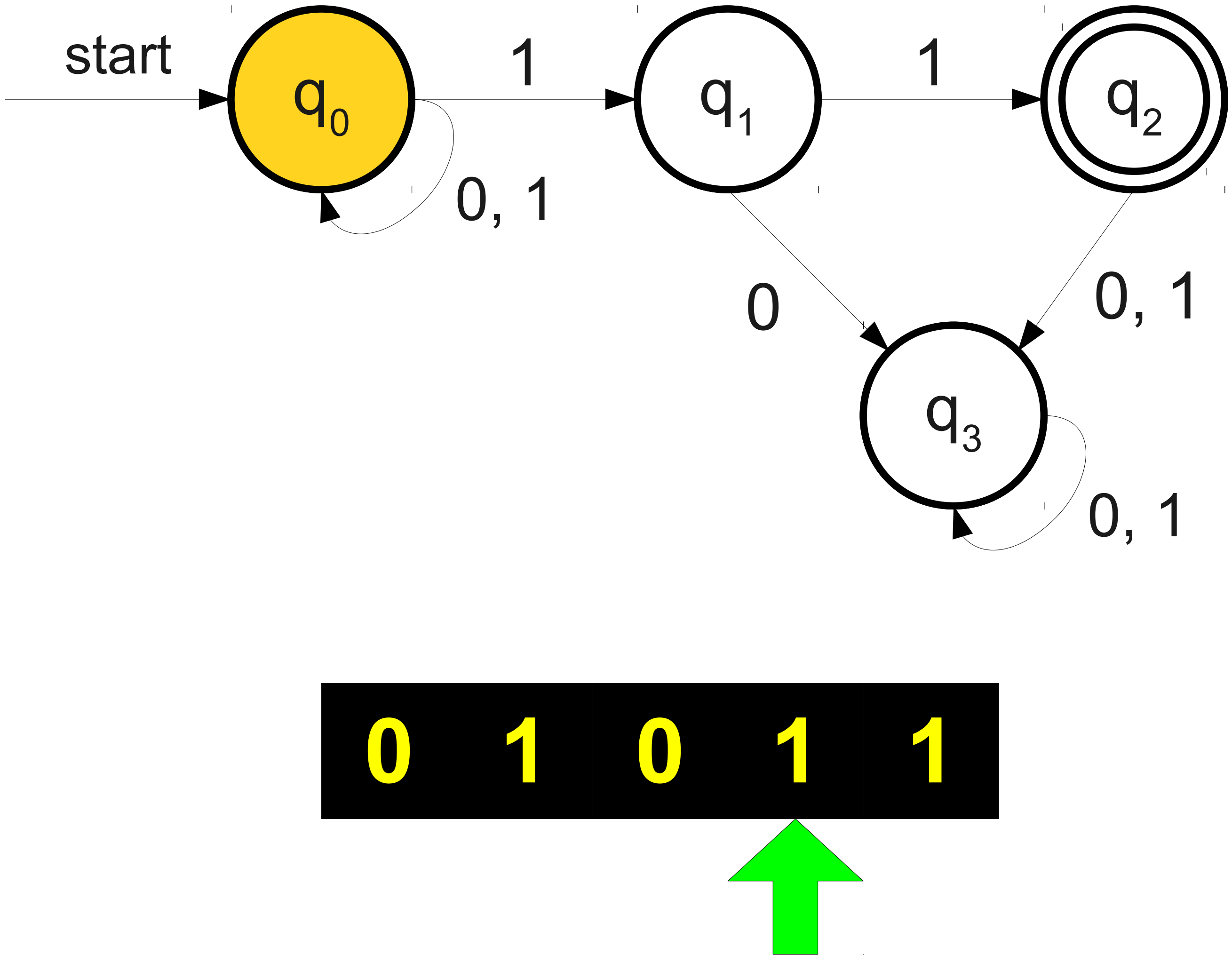

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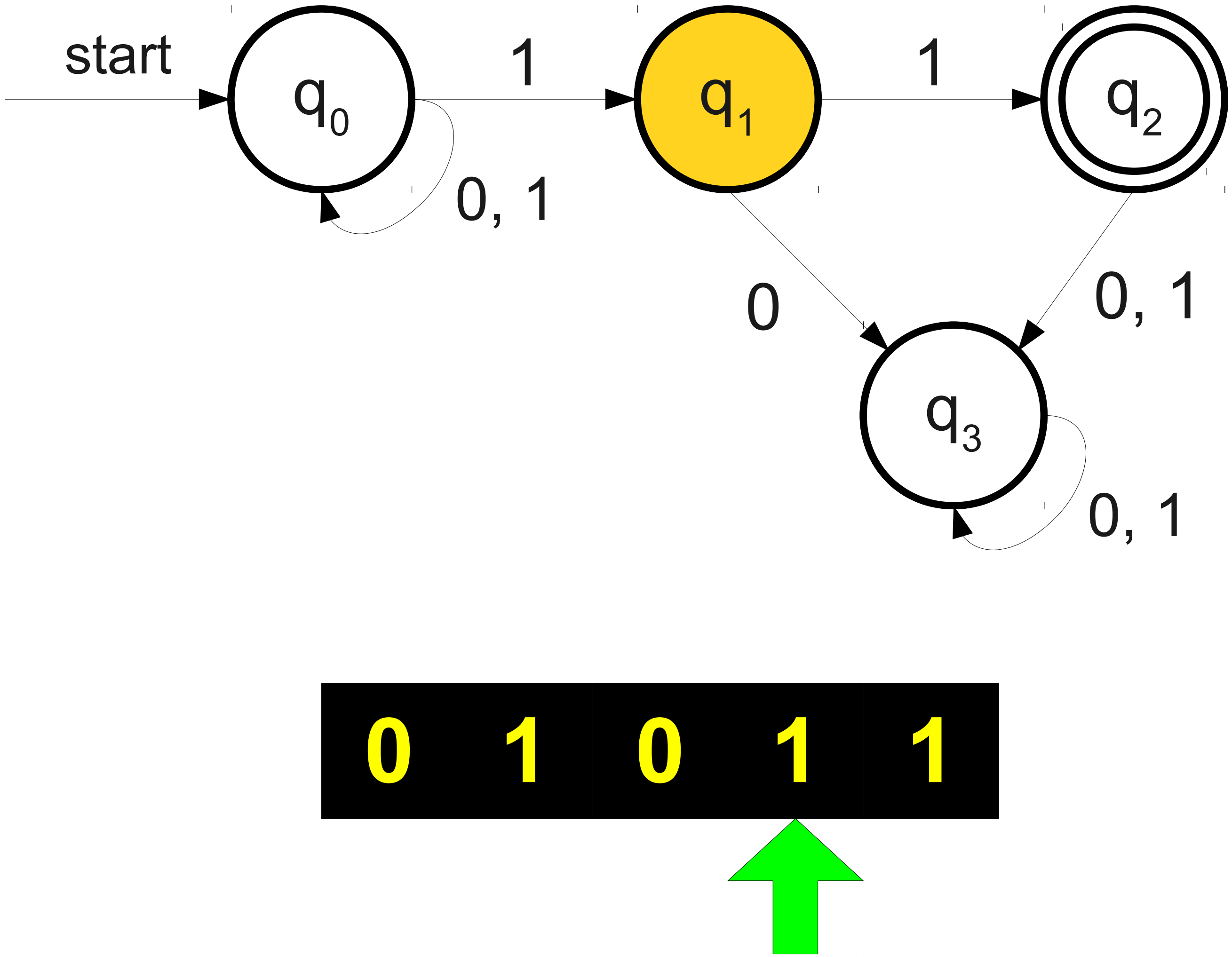

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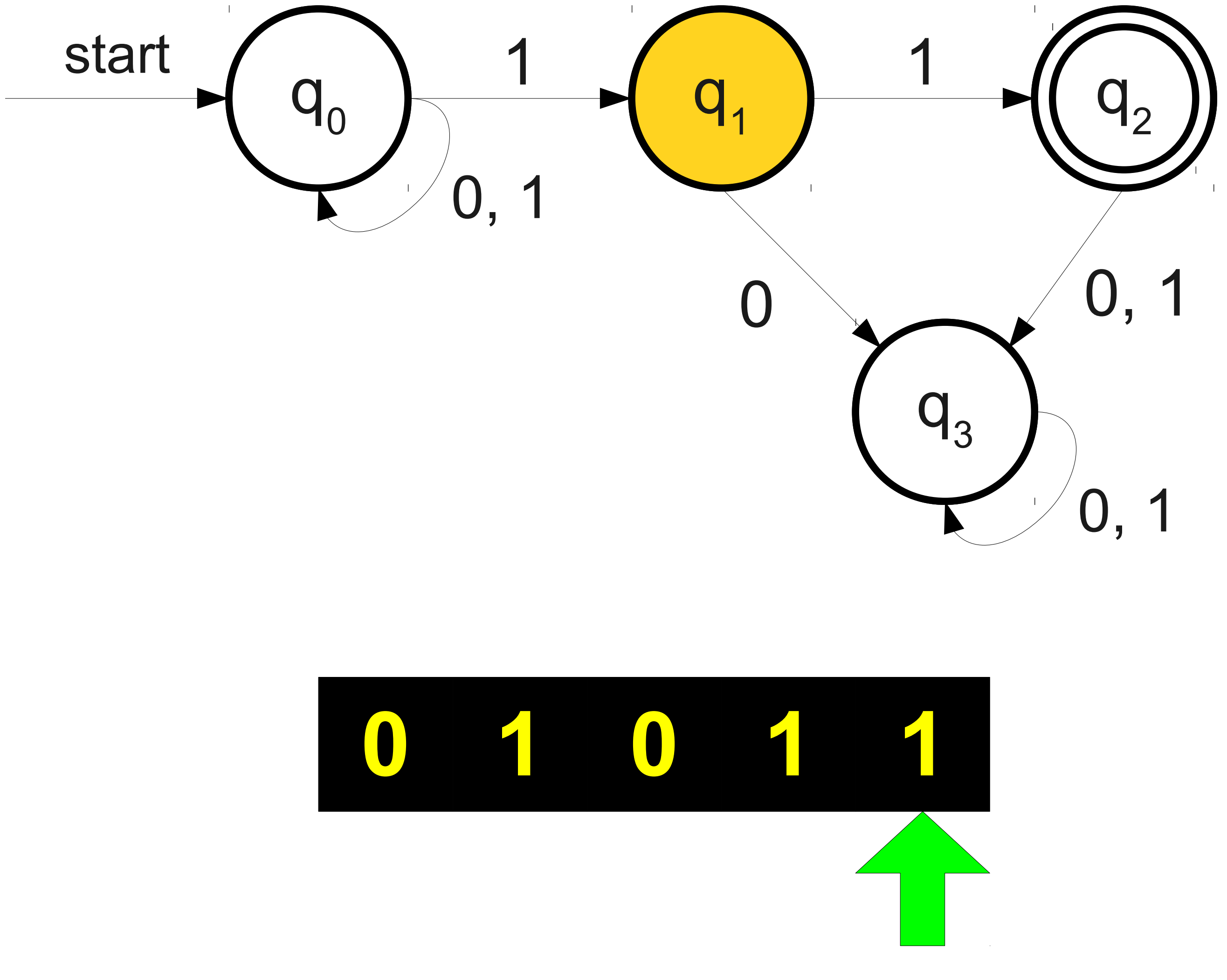

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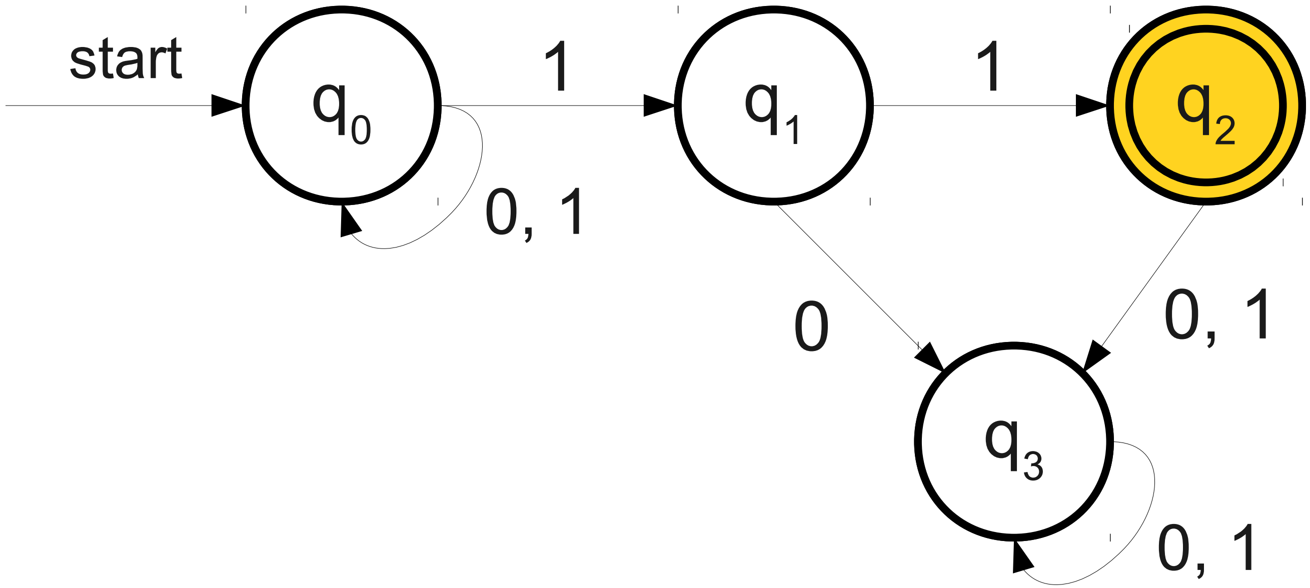
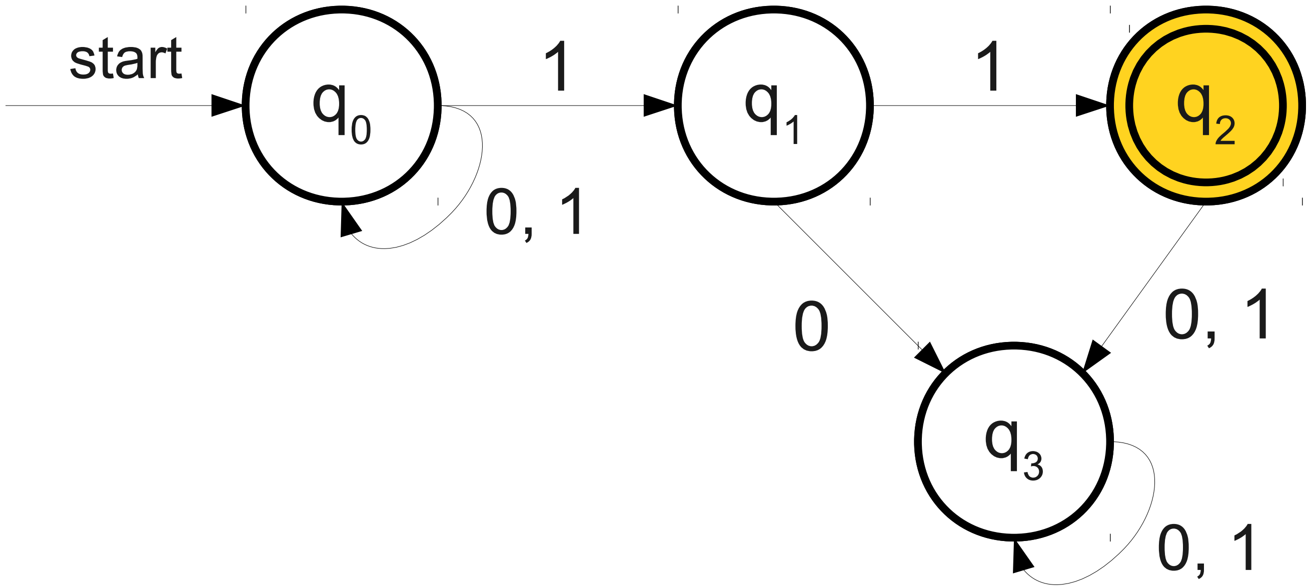


A Simple NFA



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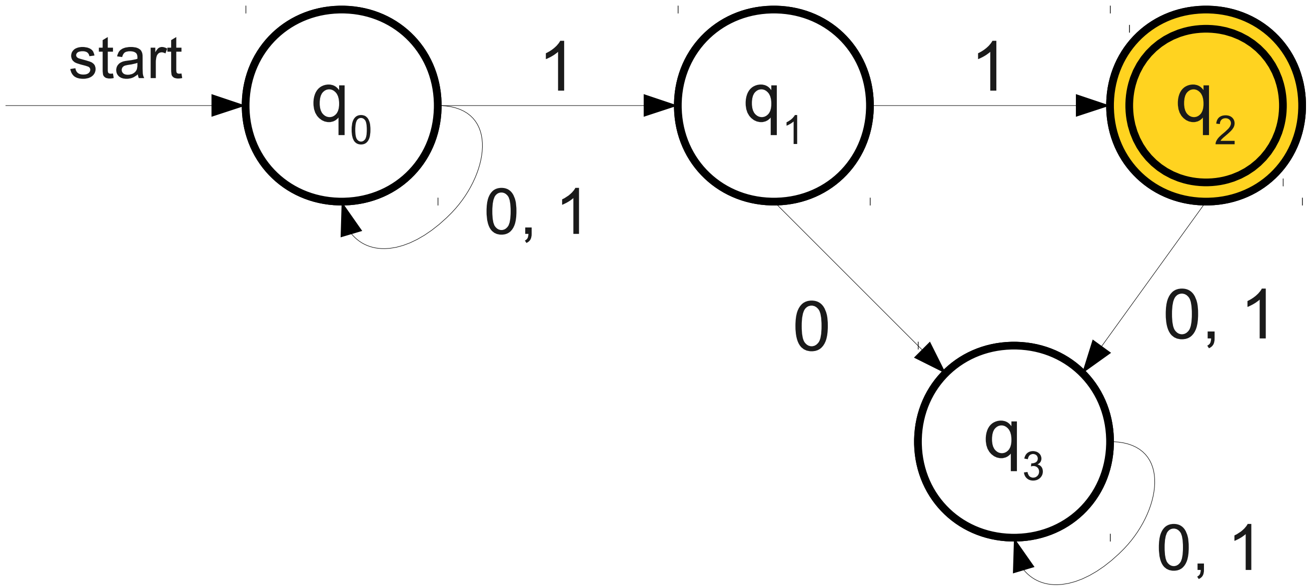
A Simple NFA



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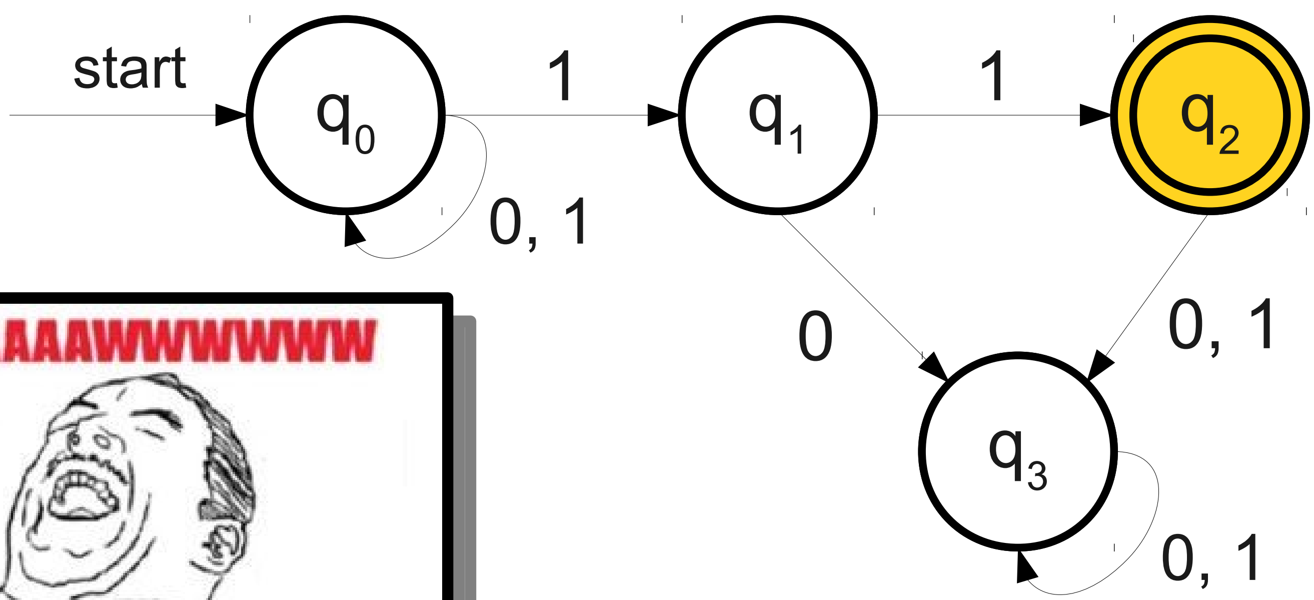

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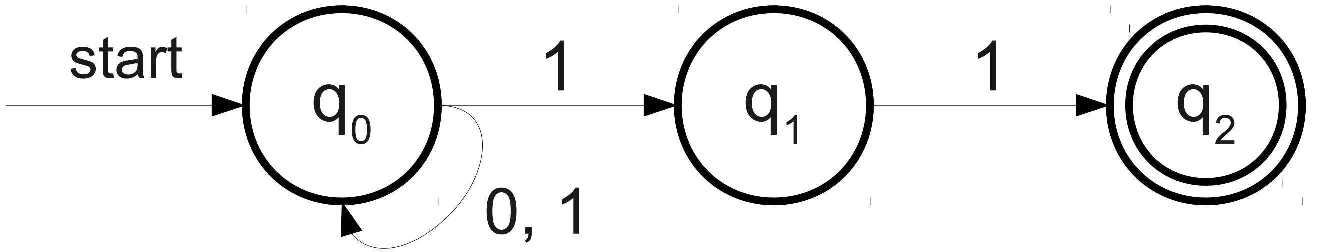

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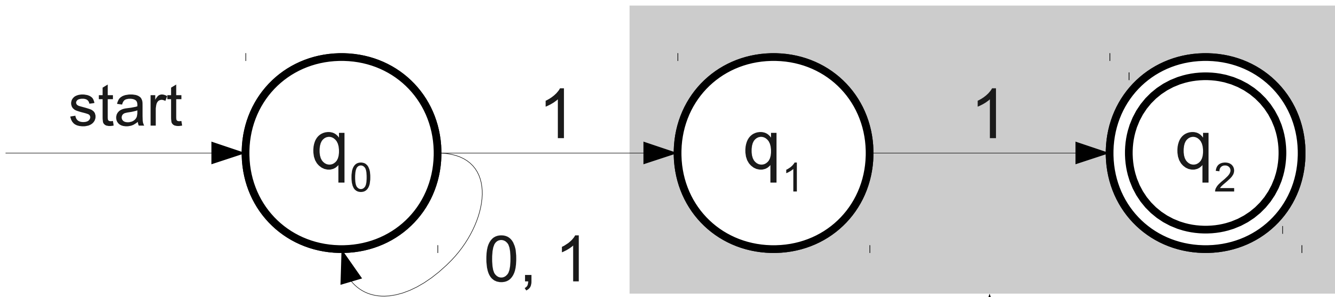
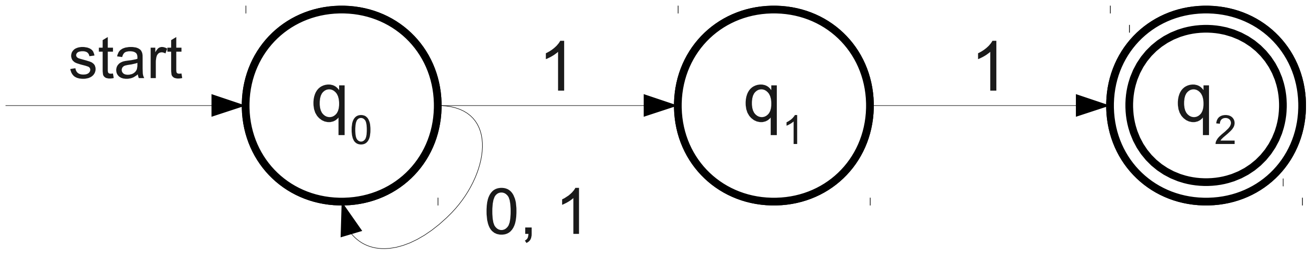


If a NFA needs to make a transition when no transition exists, the automaton dies and that particular path rejects.

A More Complex NFA



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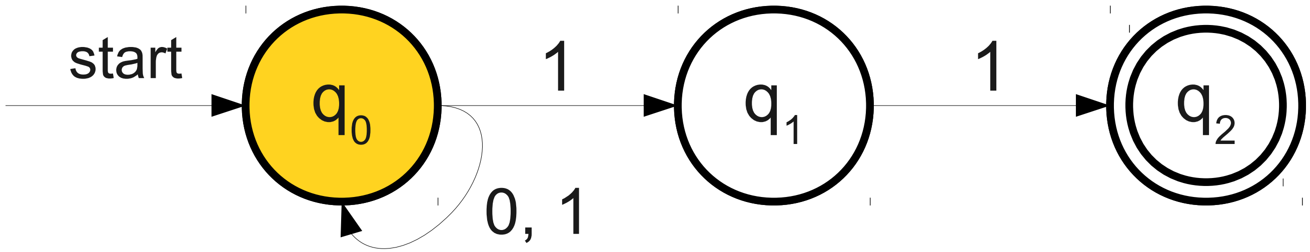
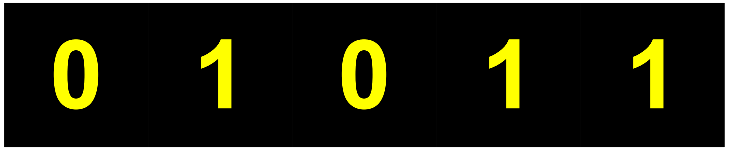
A More Complex NFA





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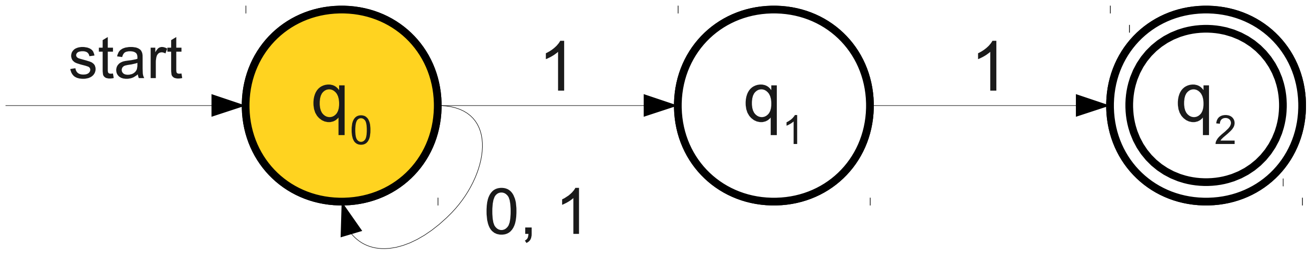

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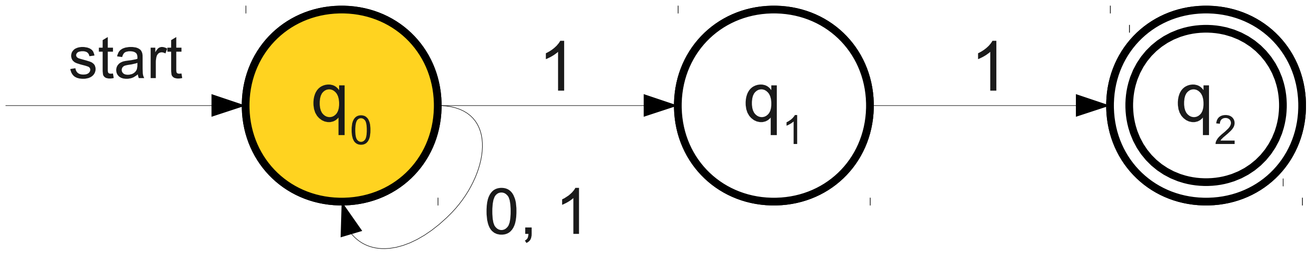

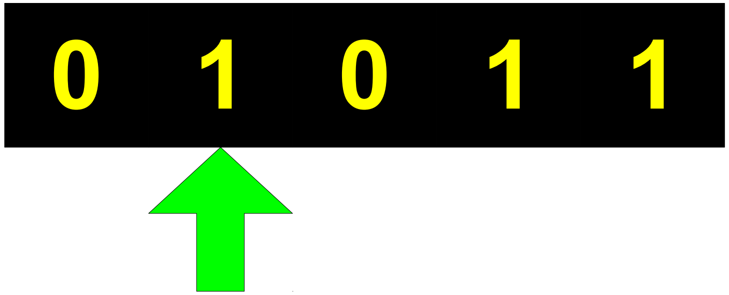

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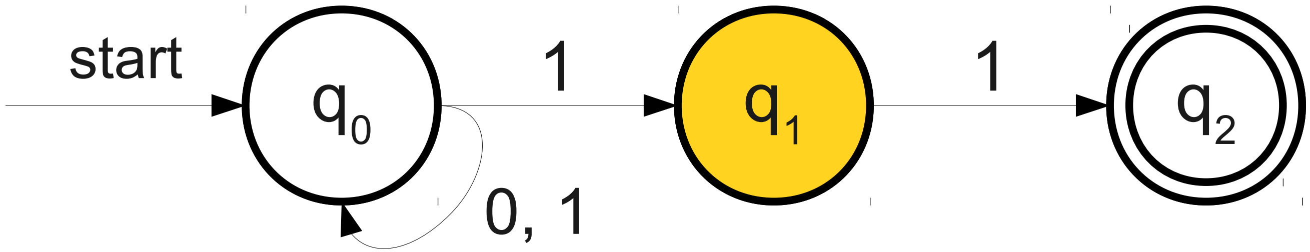

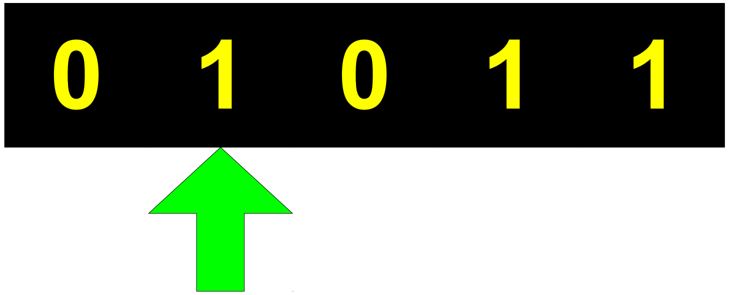

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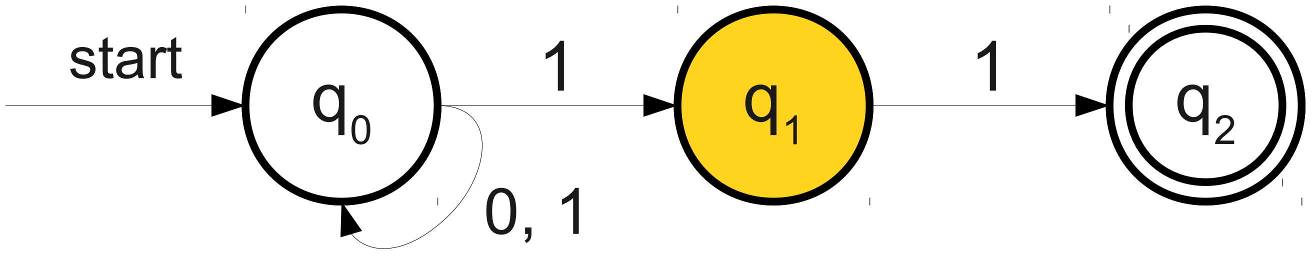

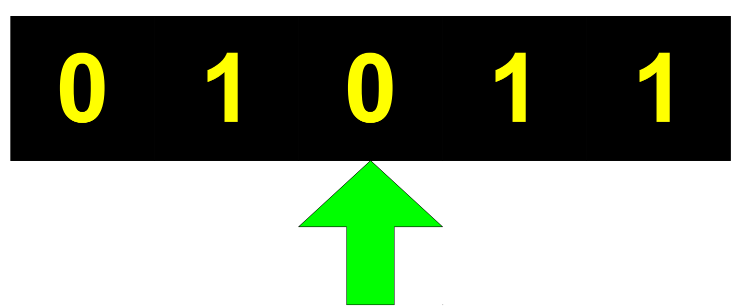

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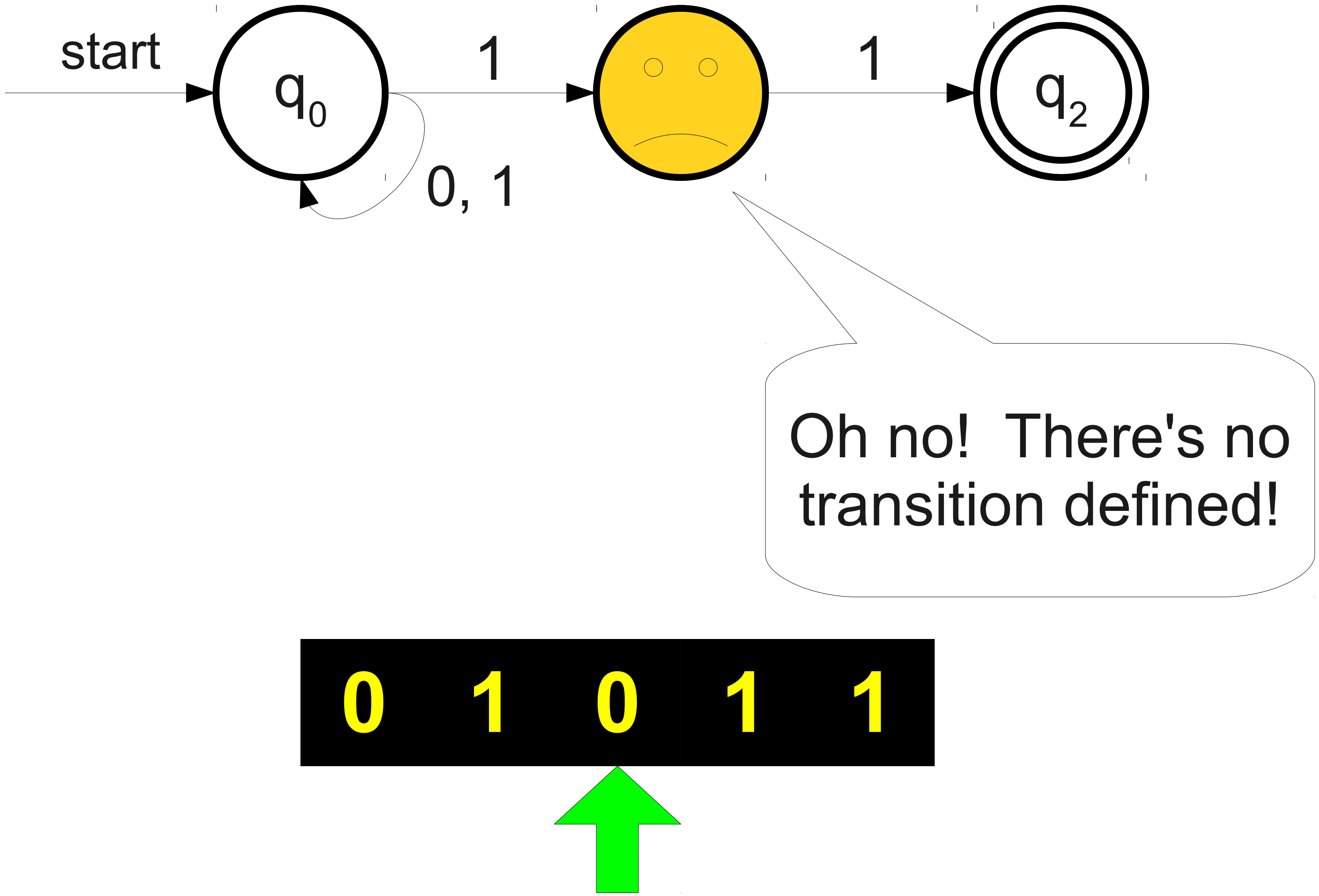

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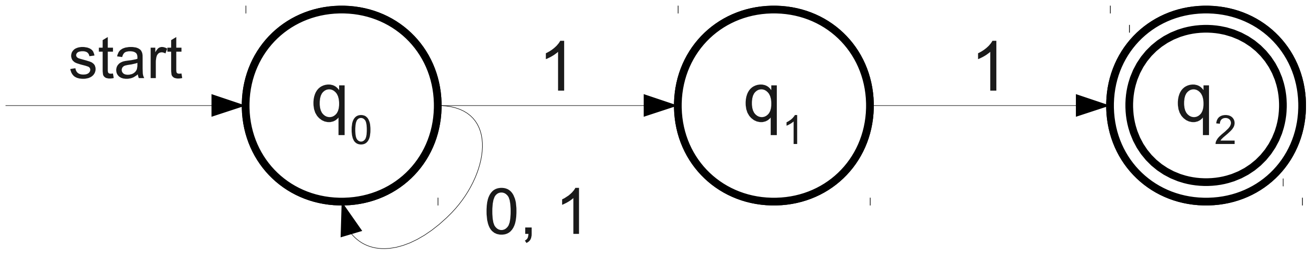

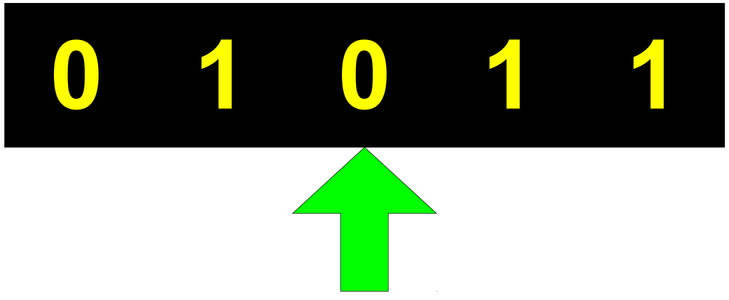

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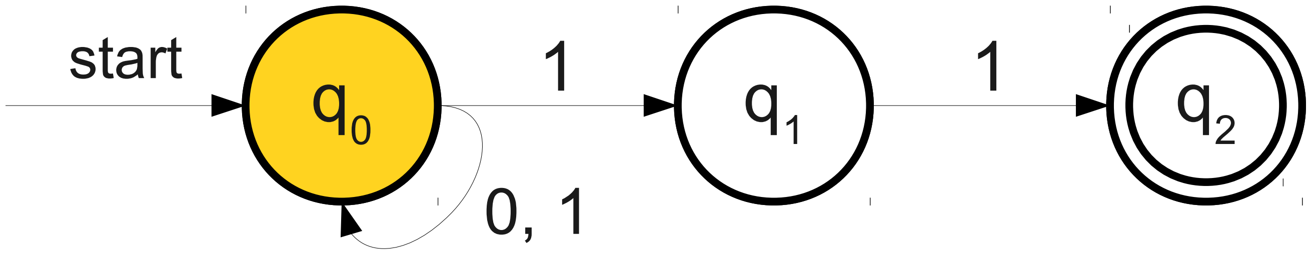

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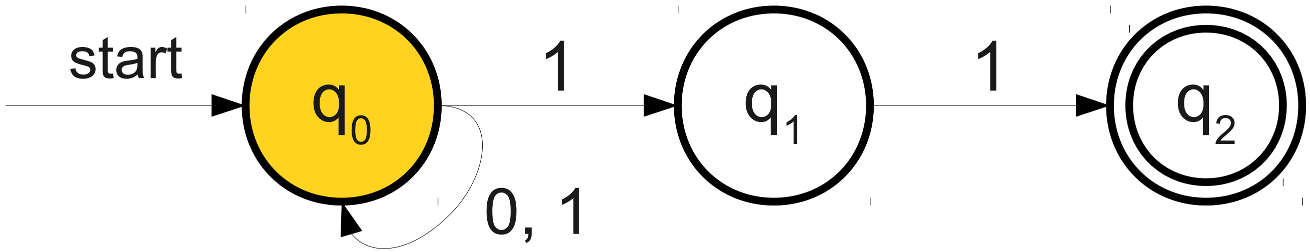

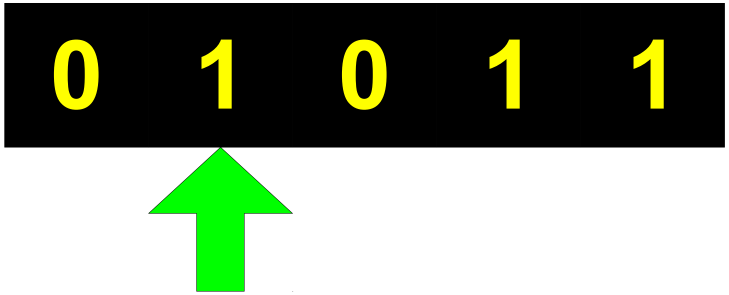

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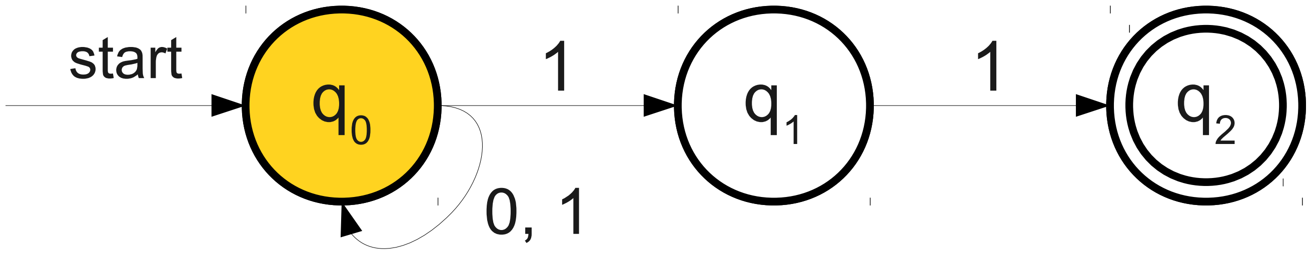

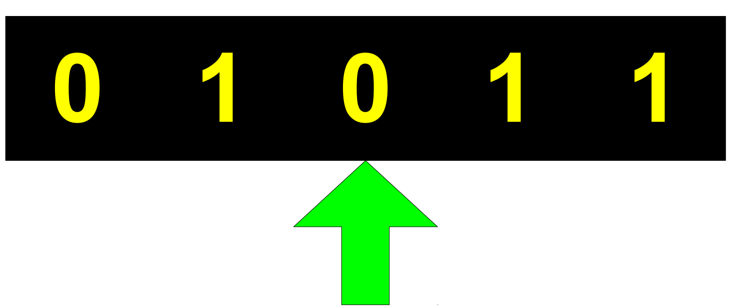

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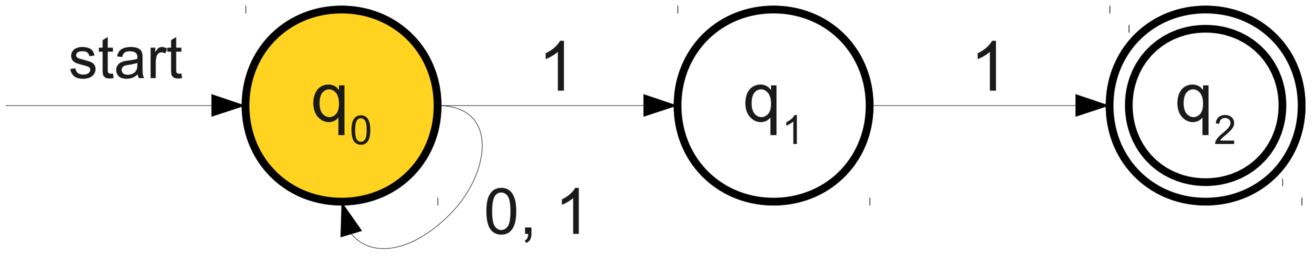

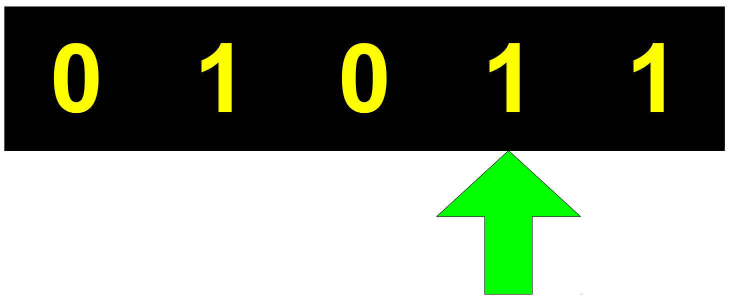

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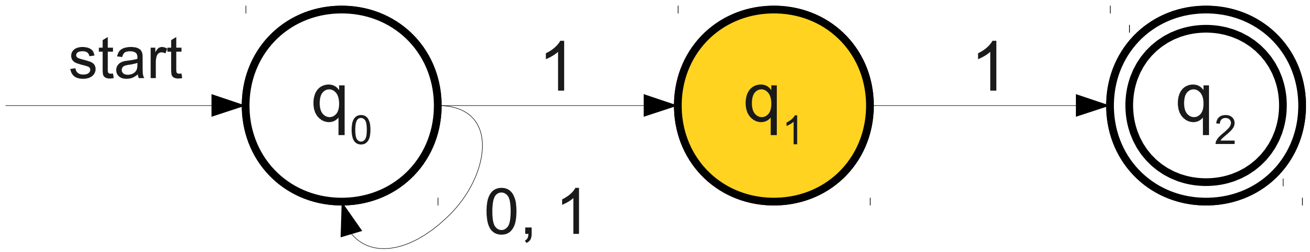

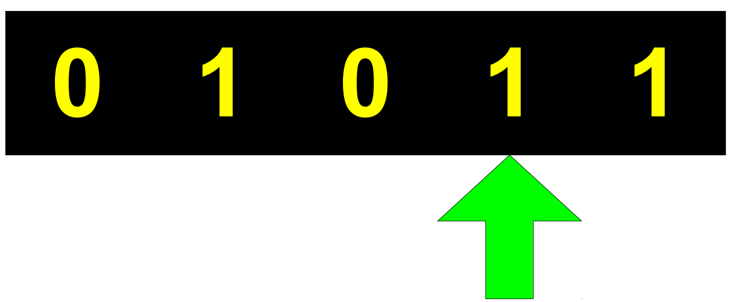

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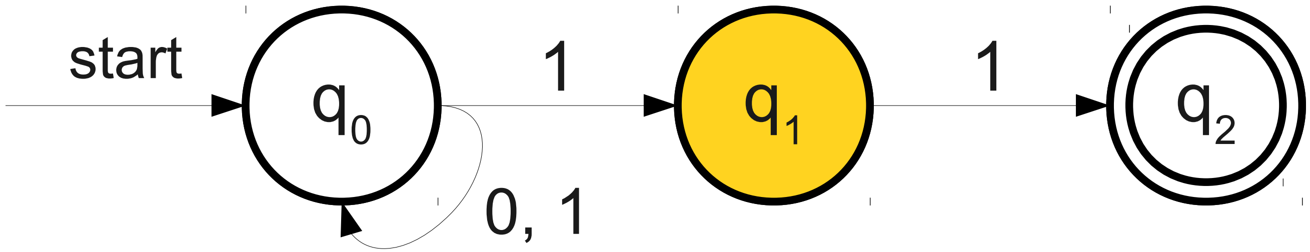

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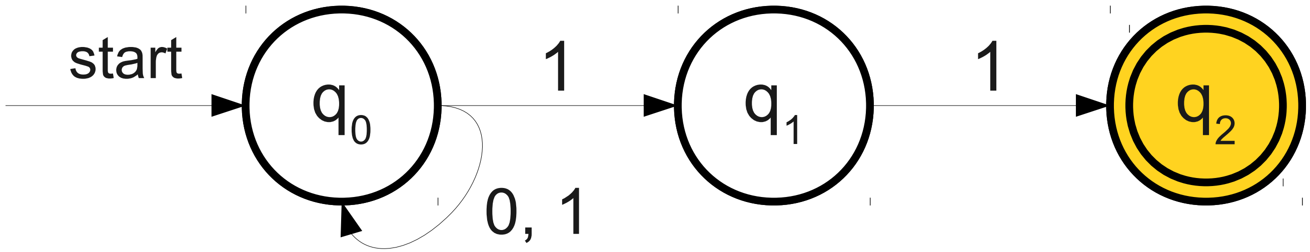

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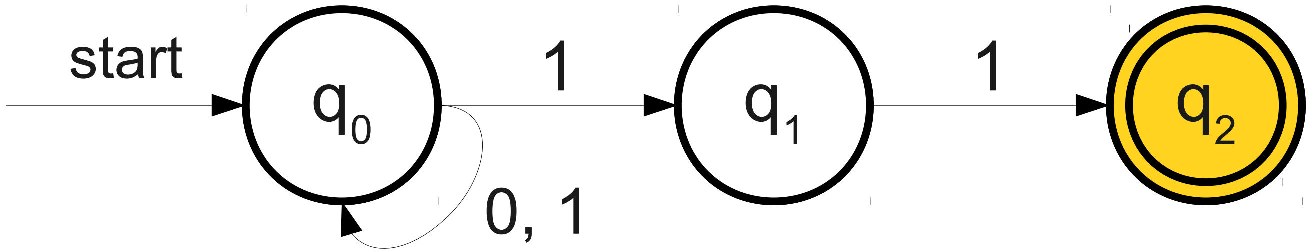

0 1 0 1 1

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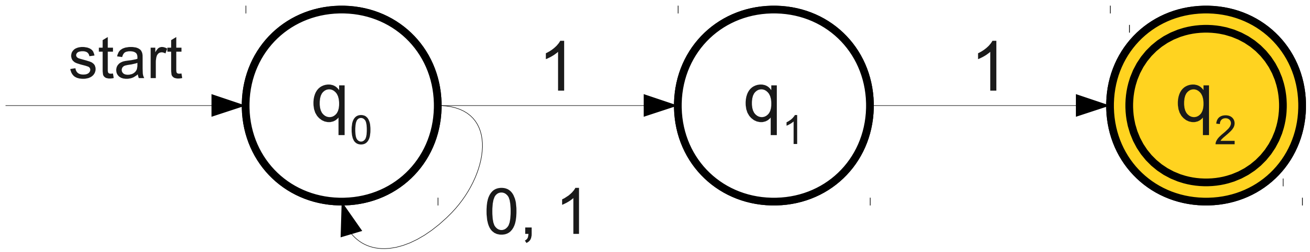

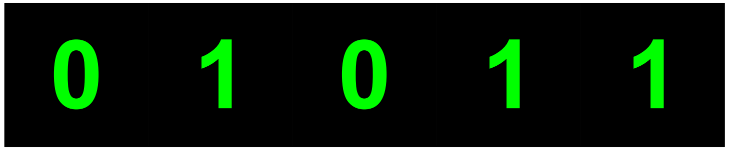

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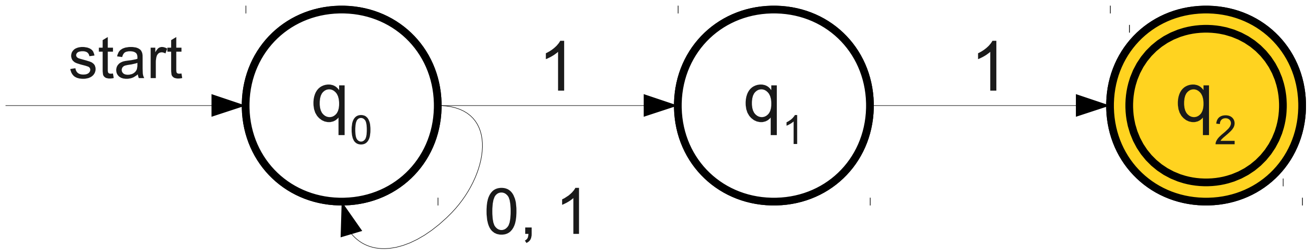
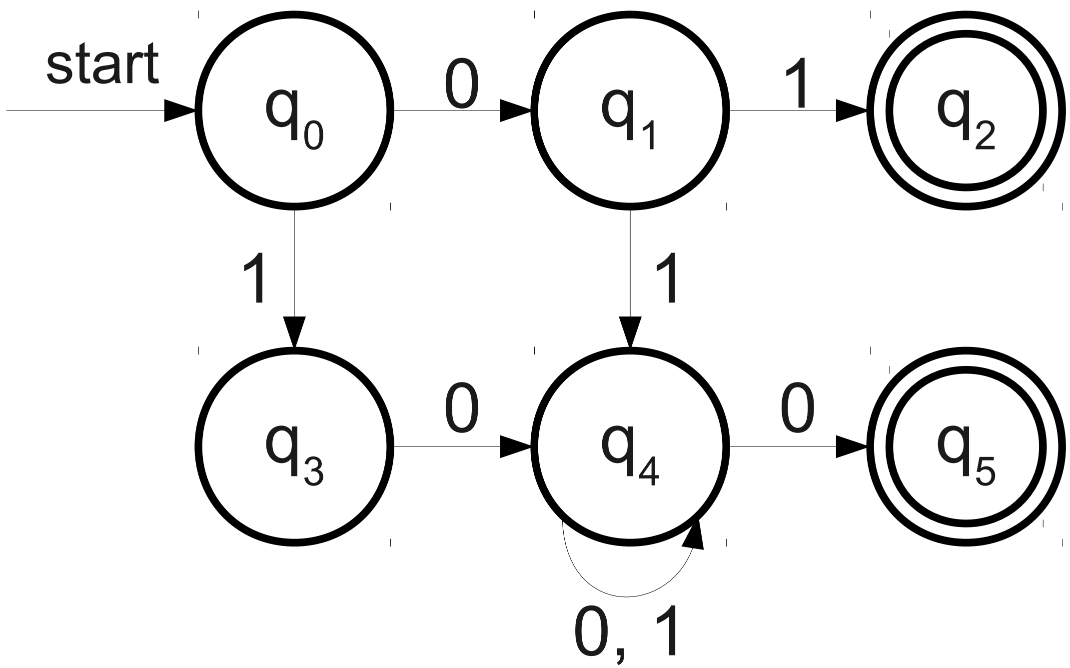


1 0 1 1

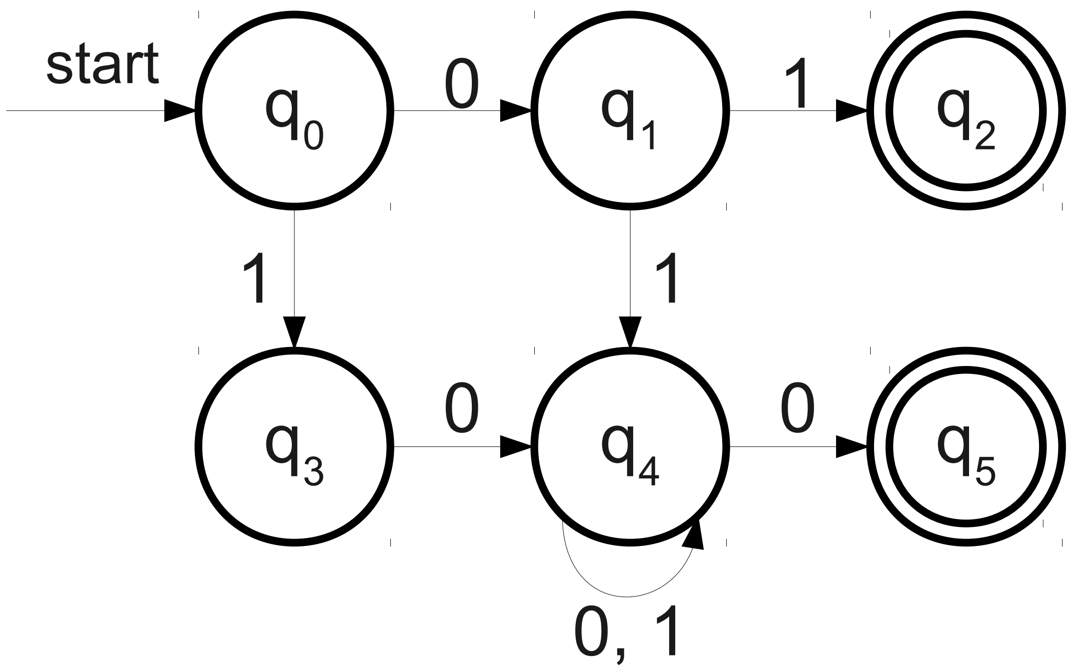
Intuiting Nondeterminism

- Nondeterministic machines are a serious departure from physical computers.
- How can we build up an intuition for them?
- Three approaches:
  - **Tree computation**
  - **Perfect guessing**
  - **Massive parallelism**

Tree Computation

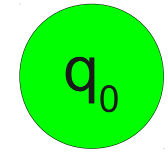


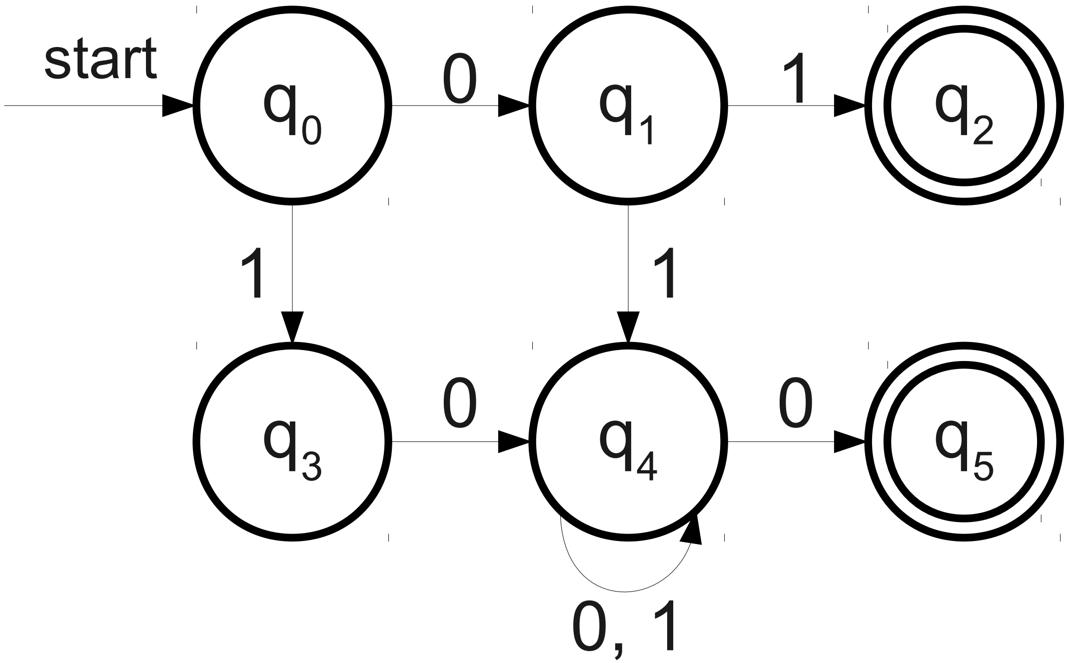
Tree Computation

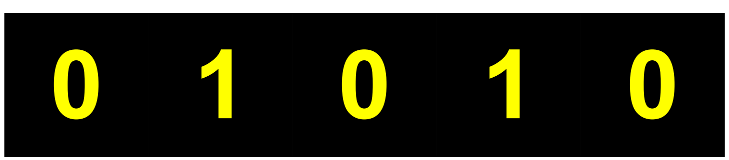


0	**1**	**0**	**1**	**0**

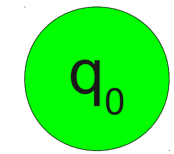
Tree Computation

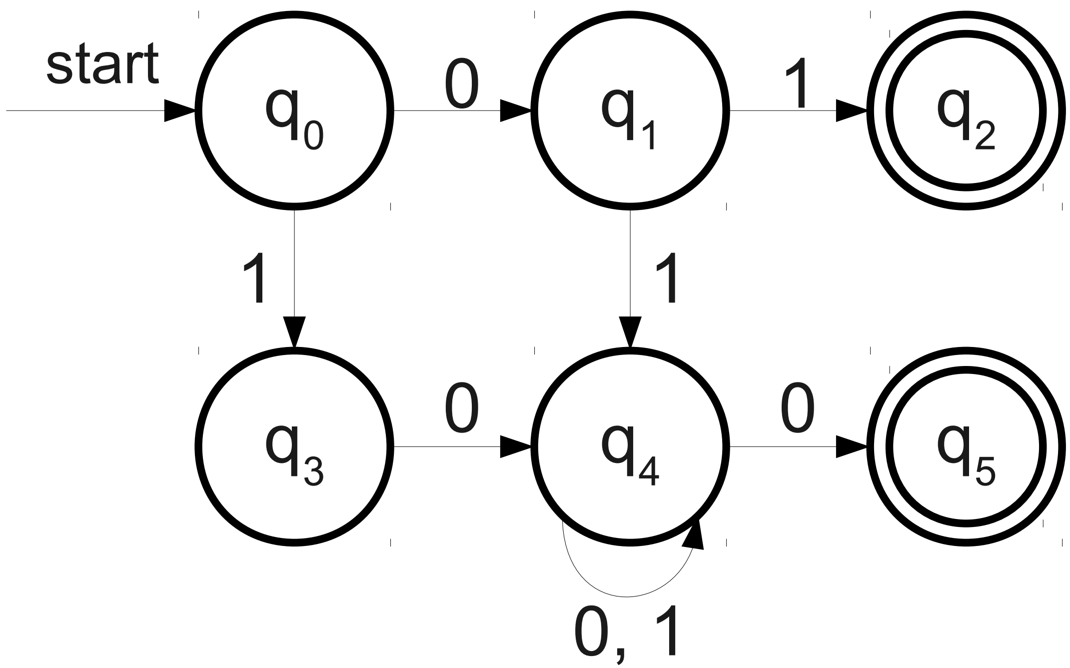






Tree Computation





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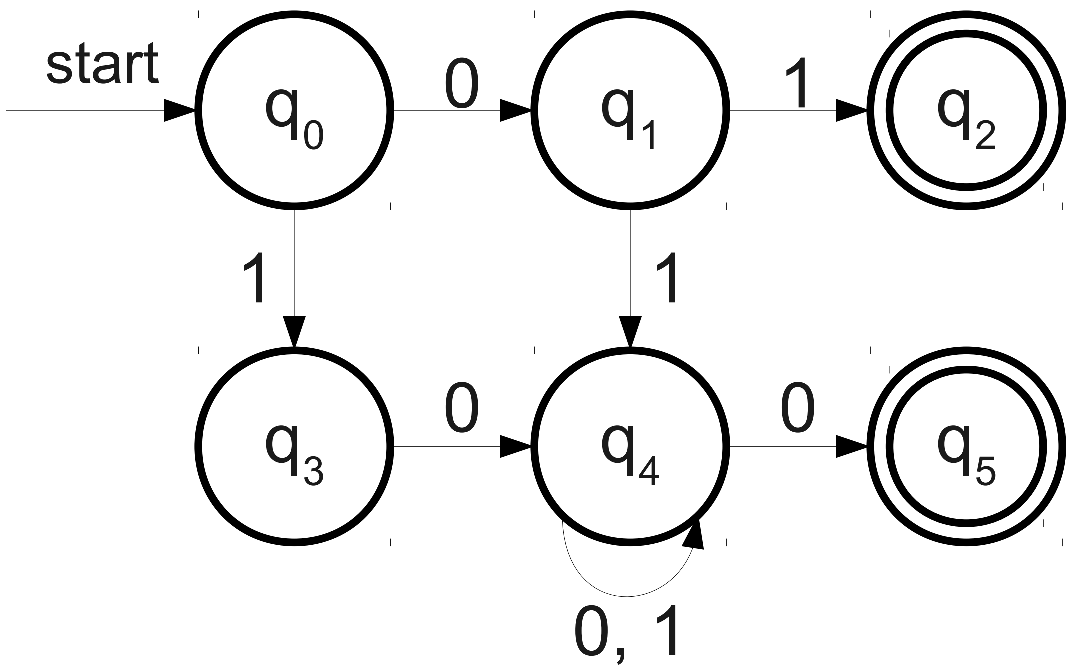

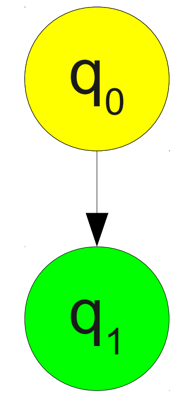

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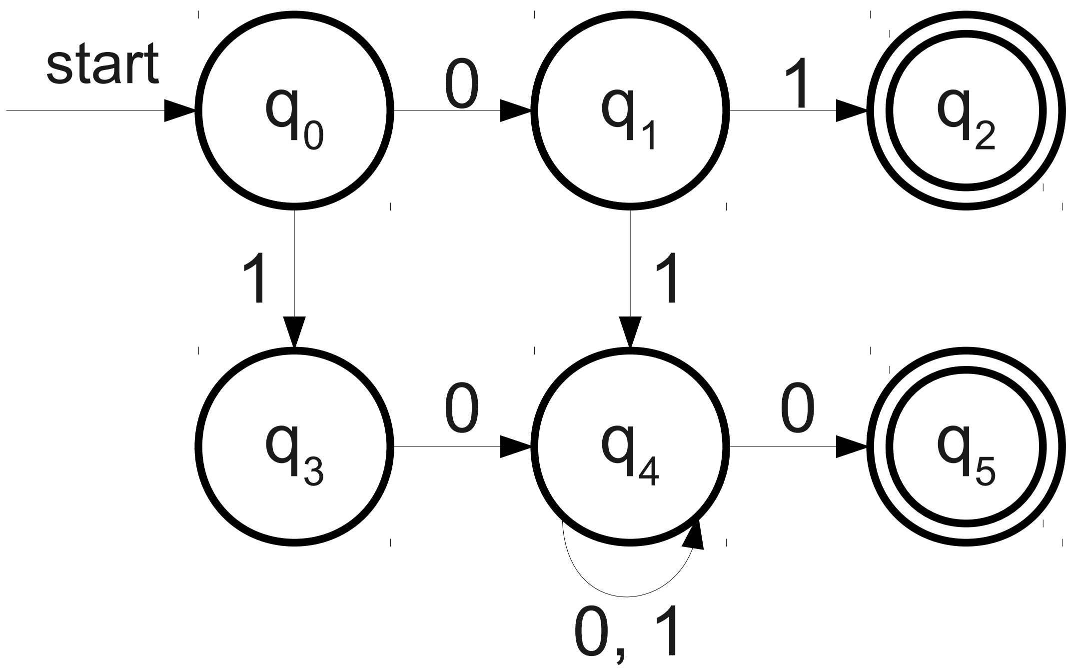

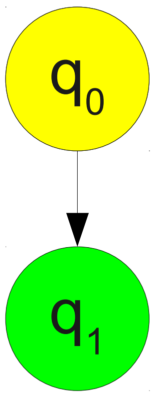

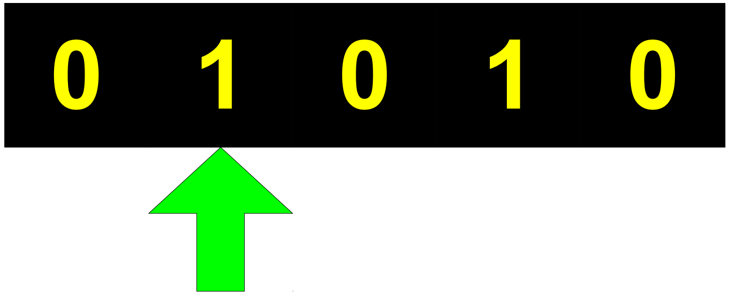

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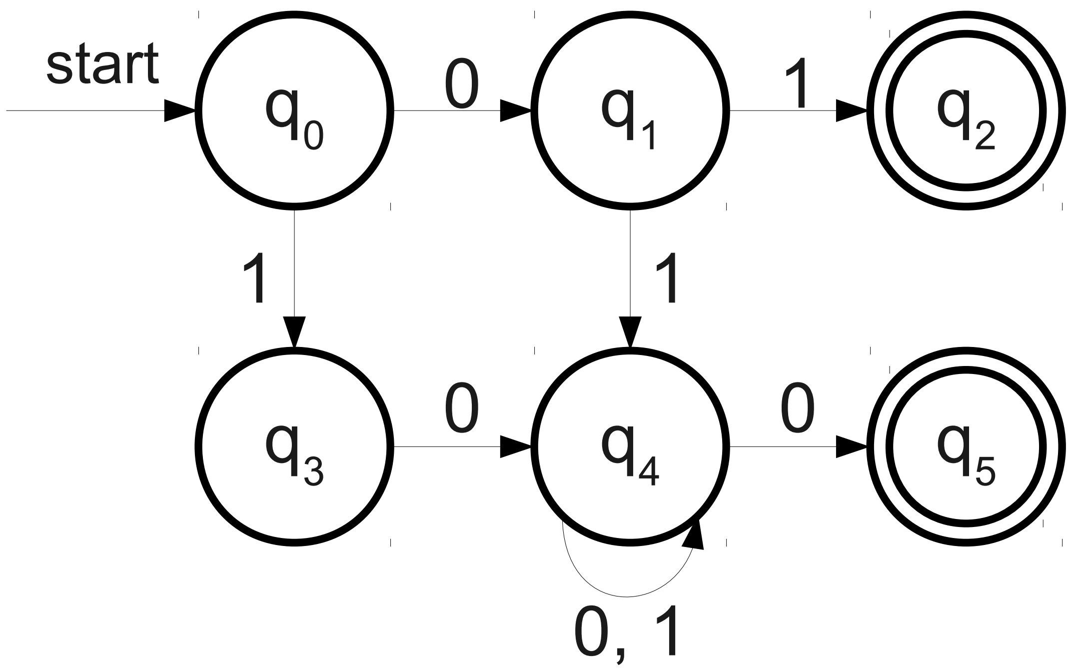

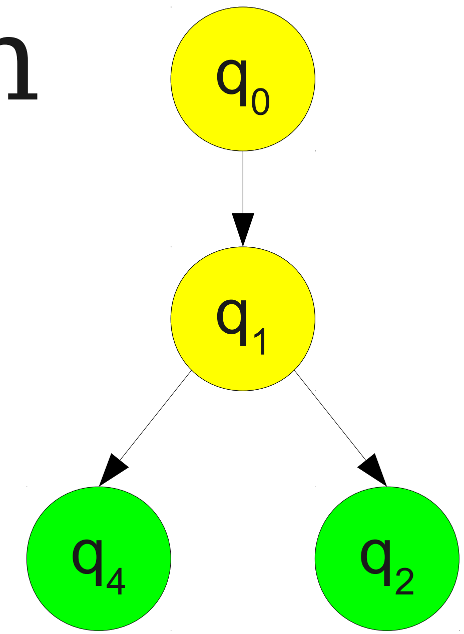

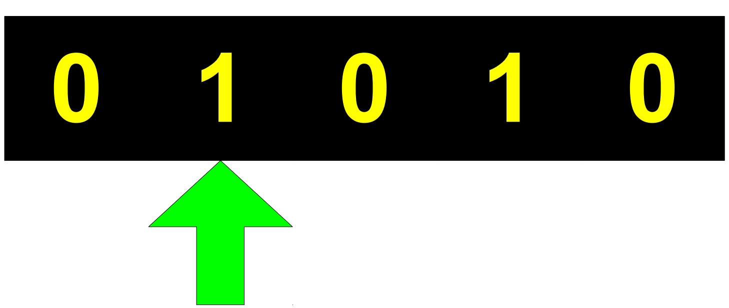

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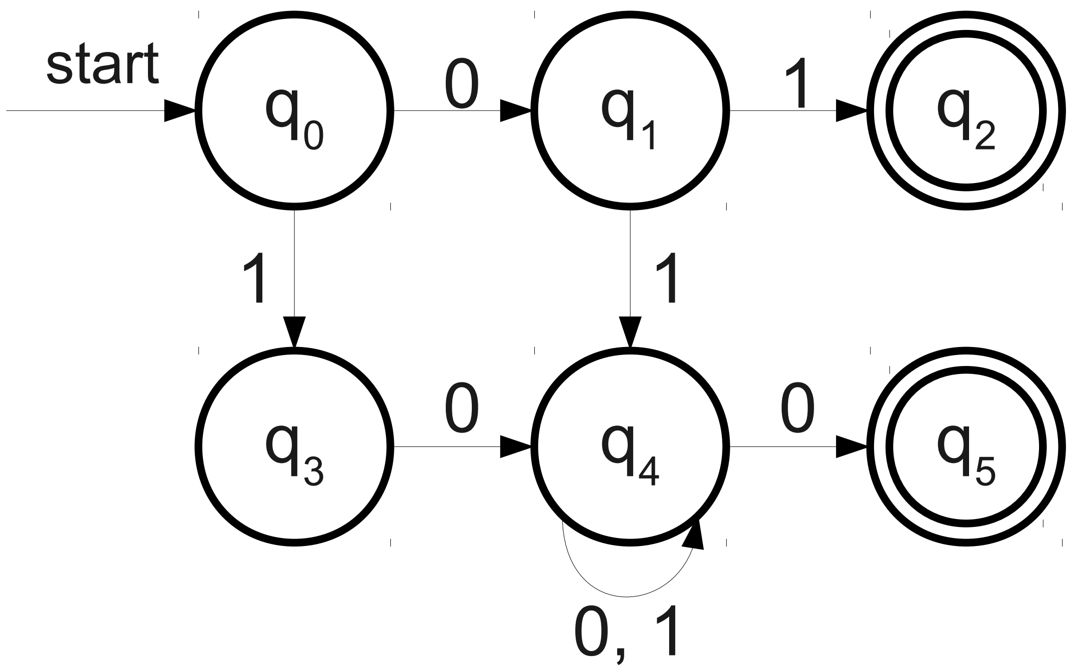
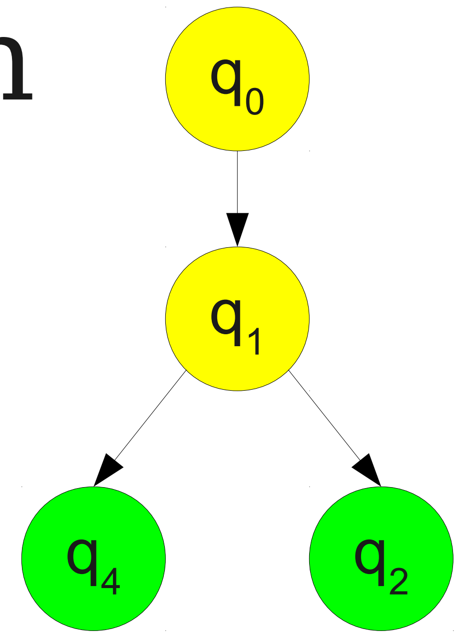
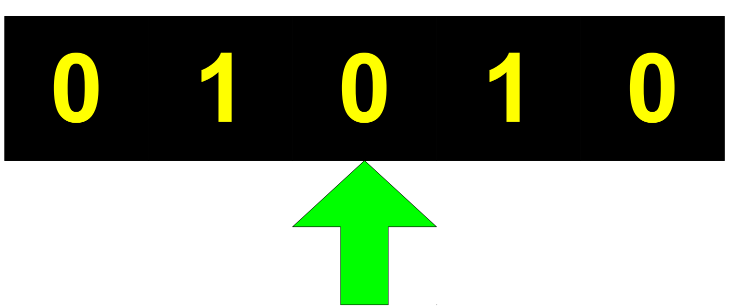
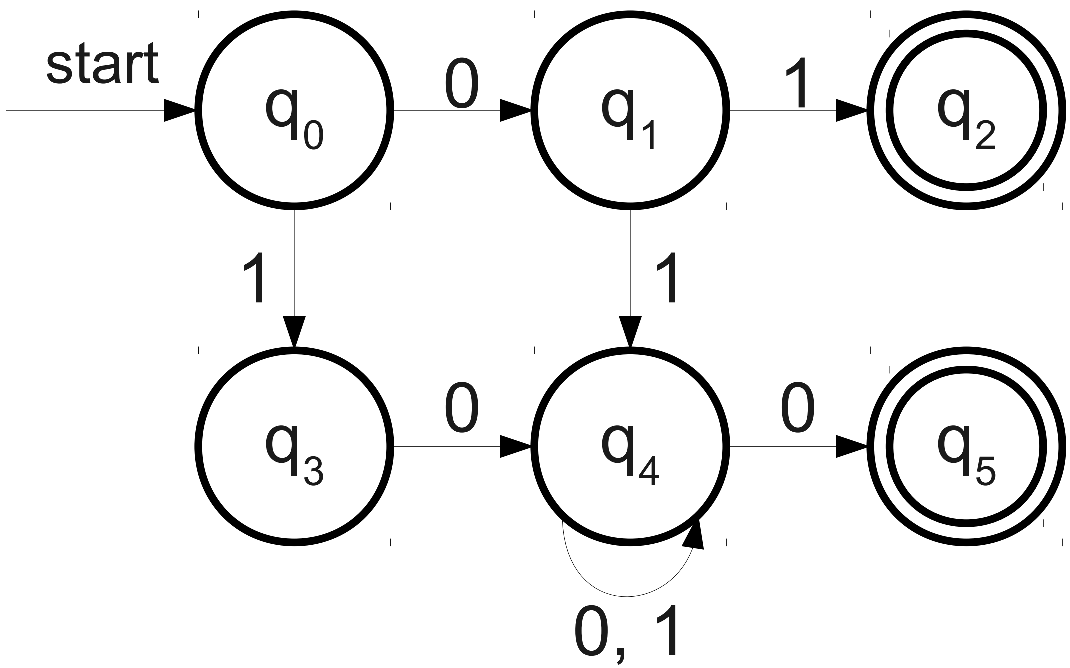
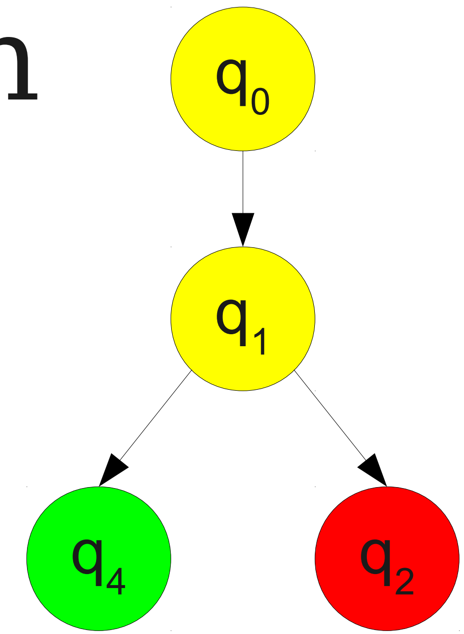


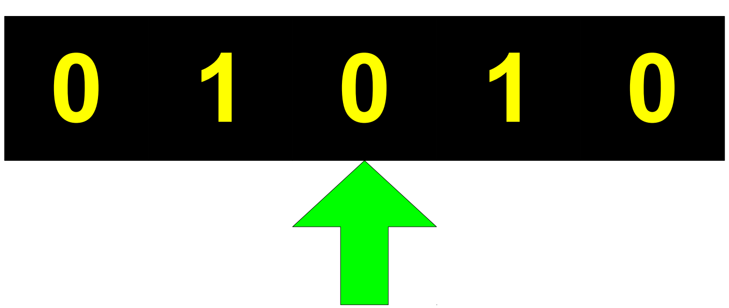




Tree Computation







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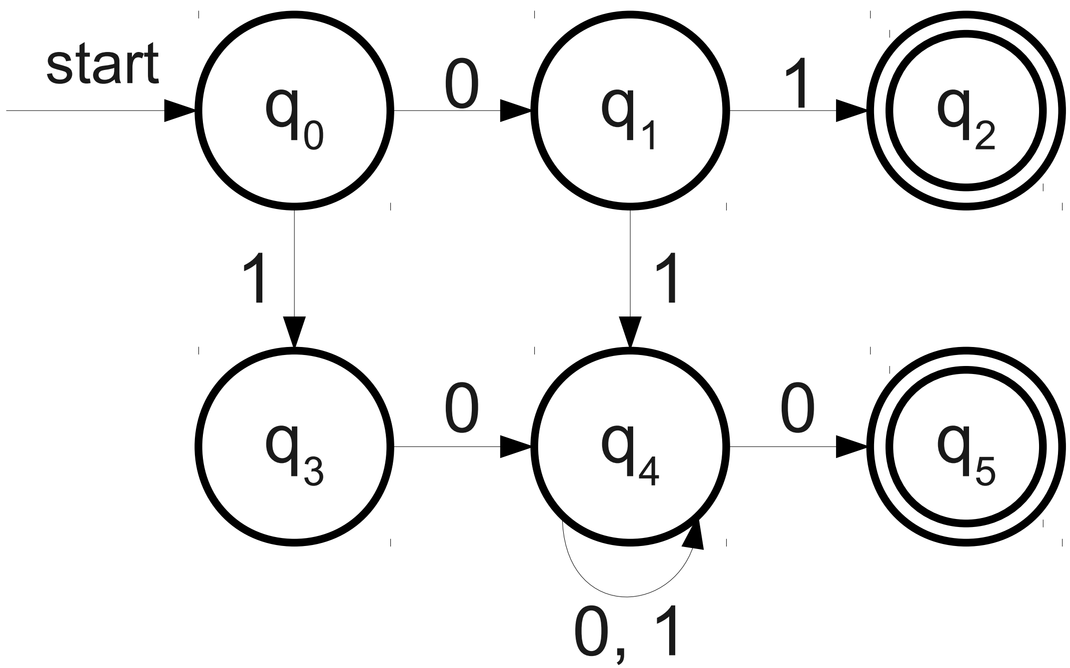

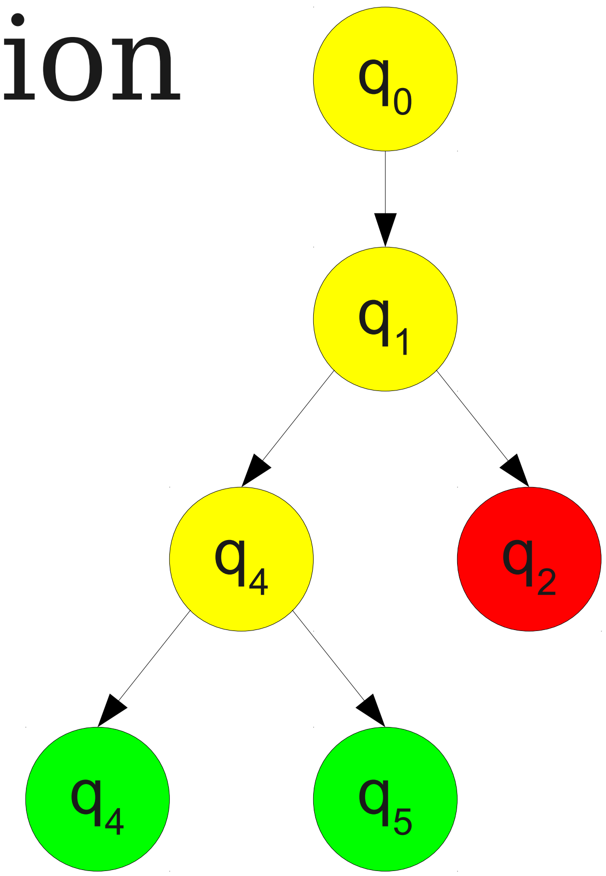

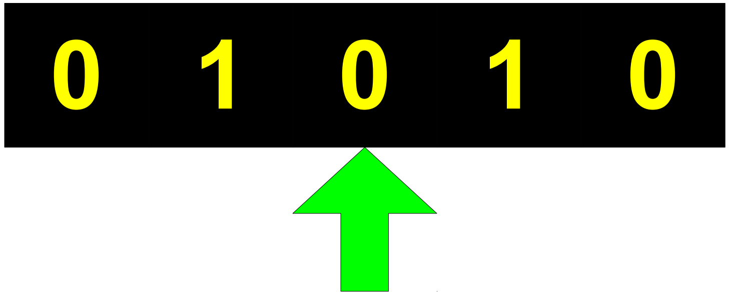

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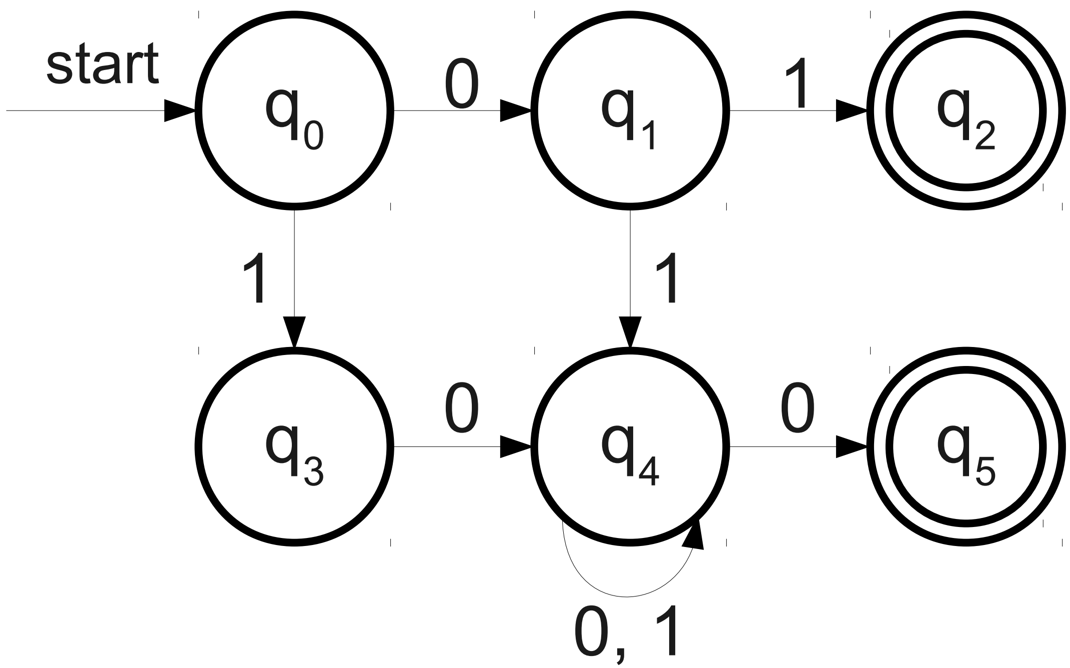

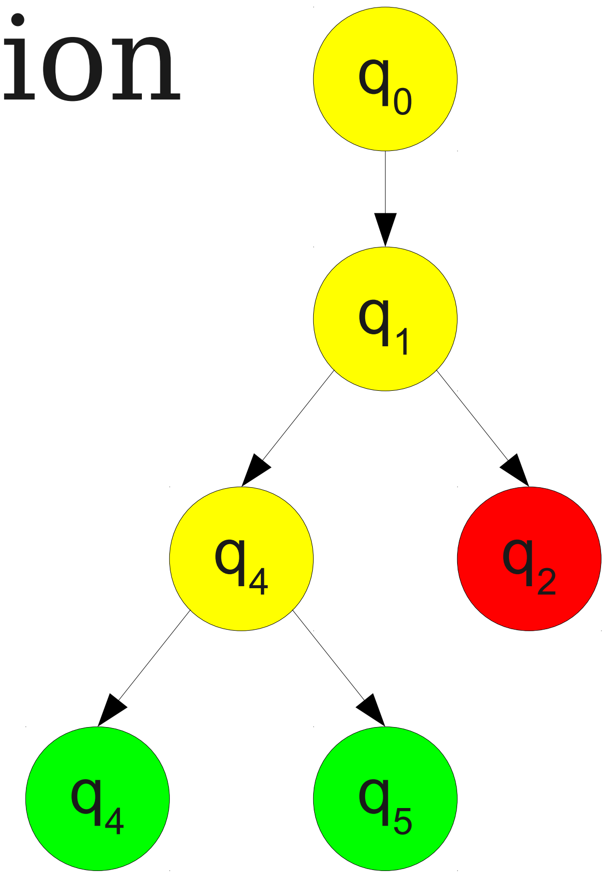

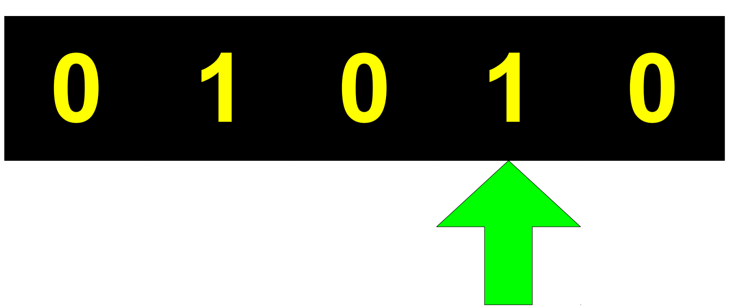

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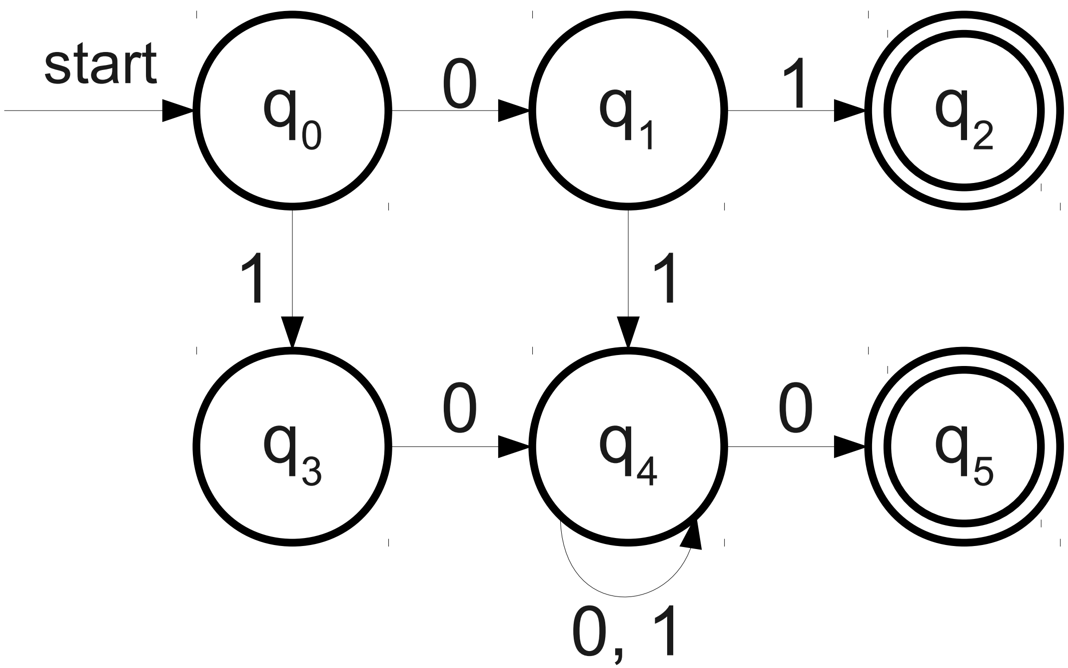

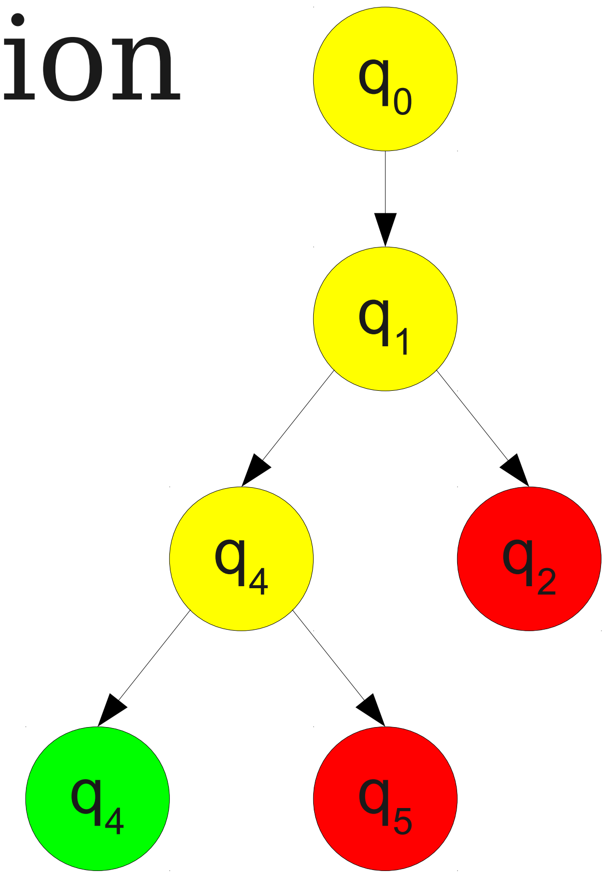

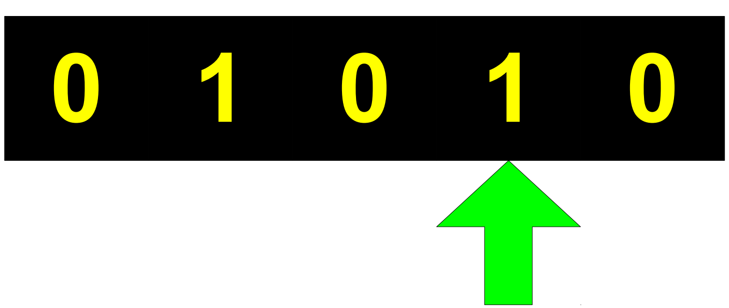

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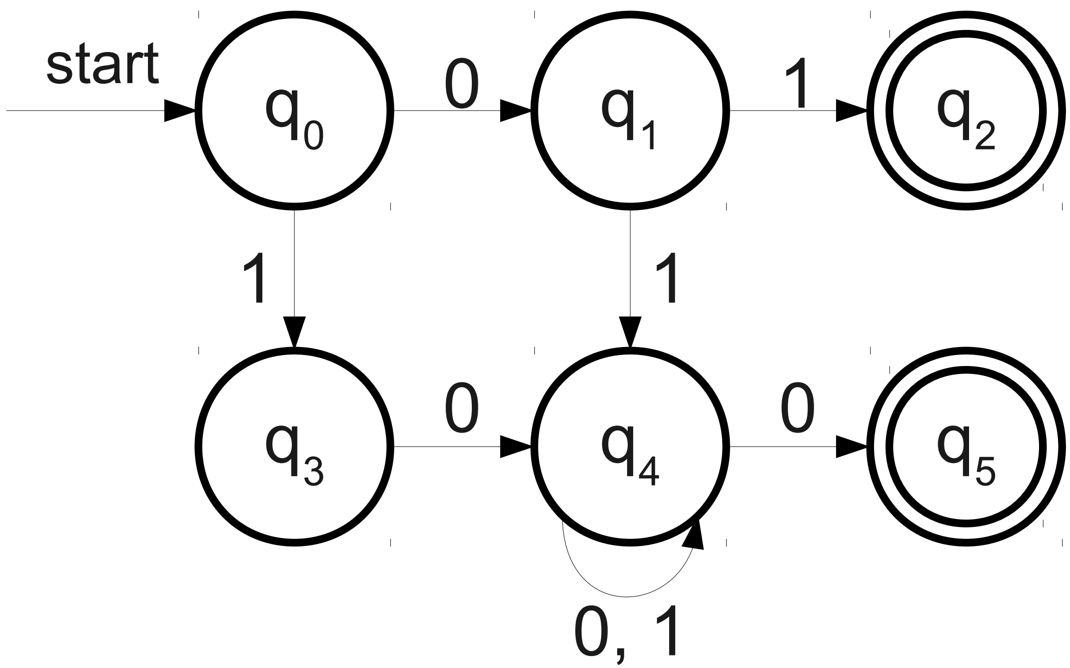

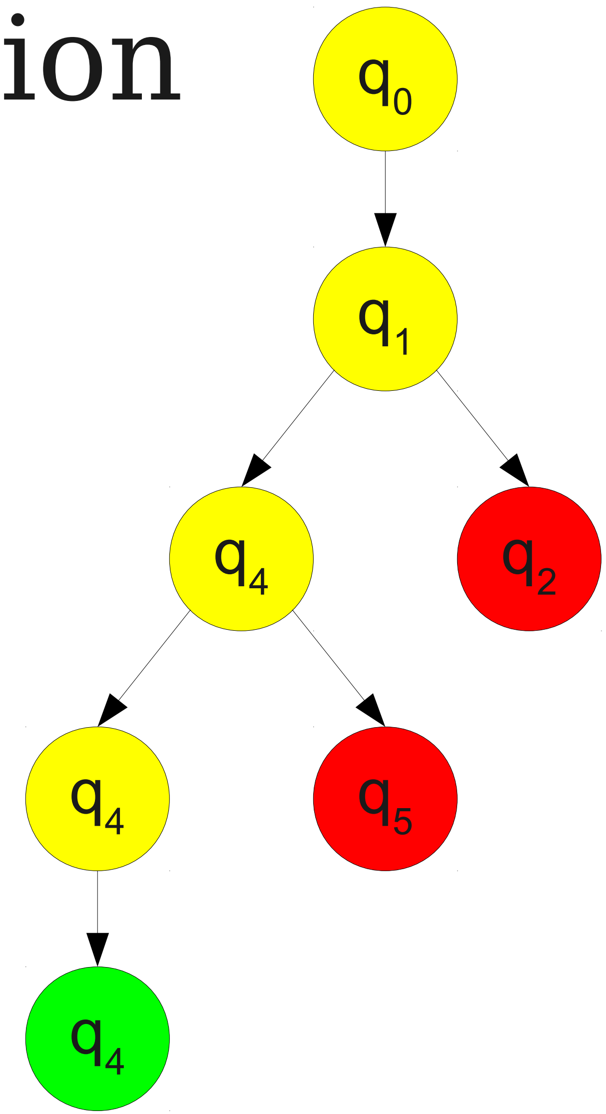

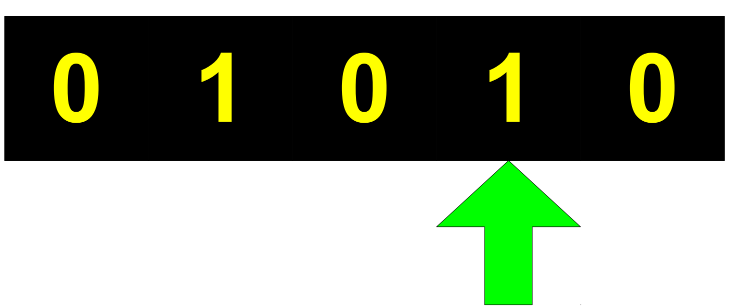

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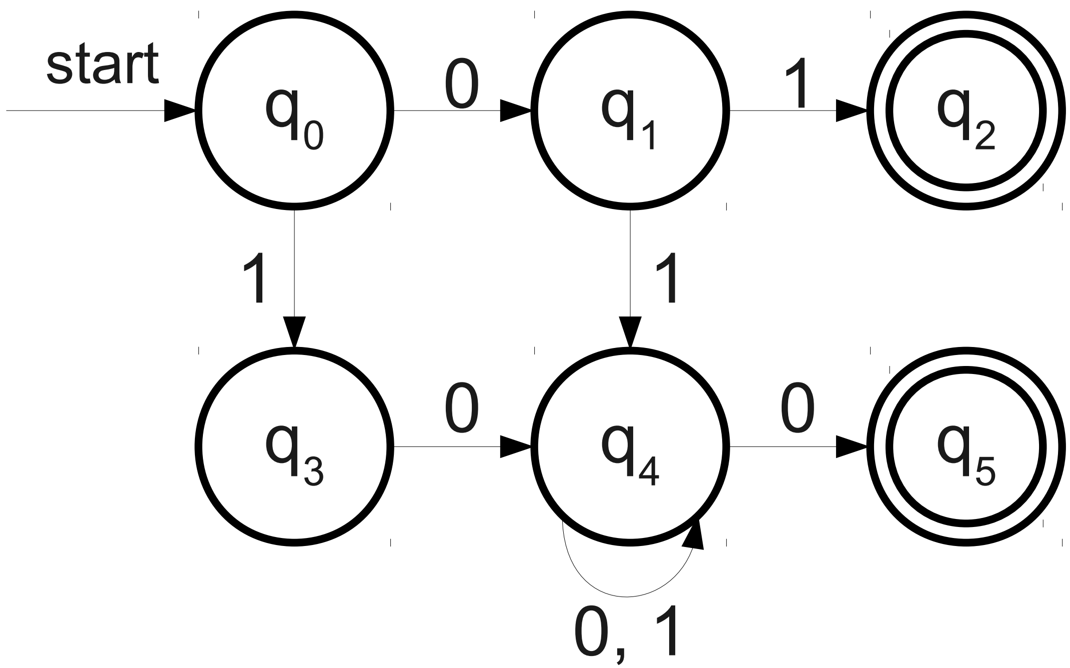

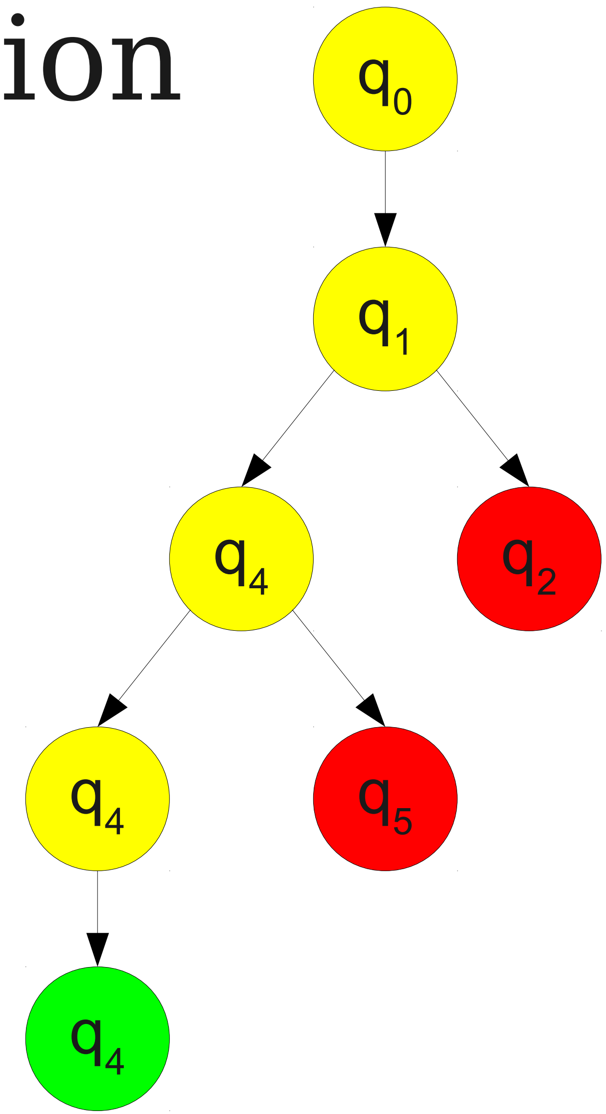

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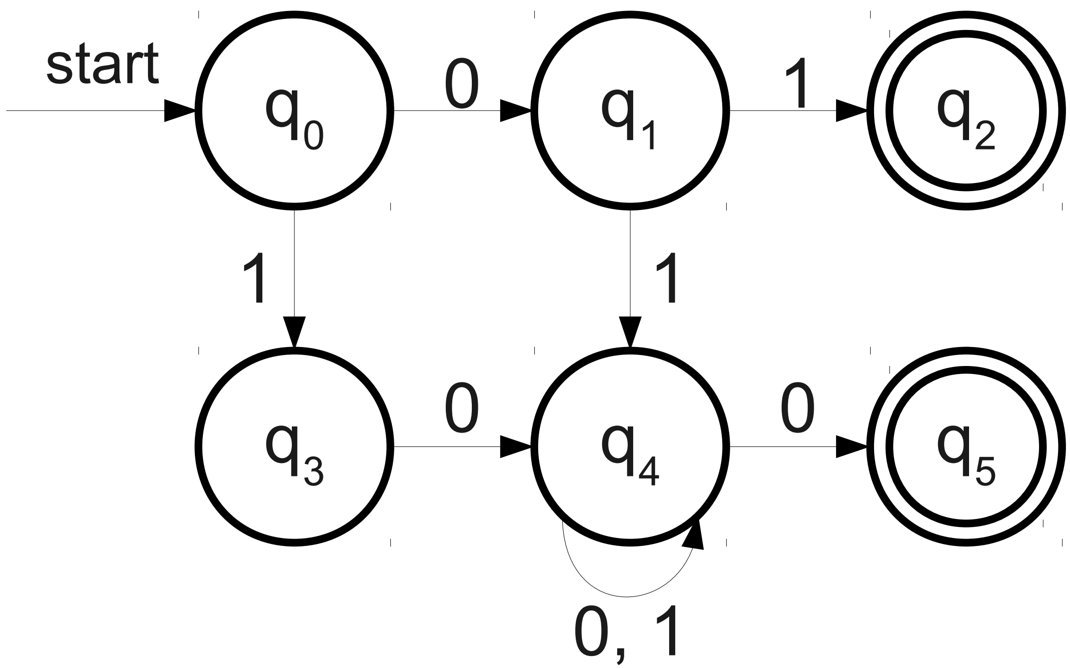

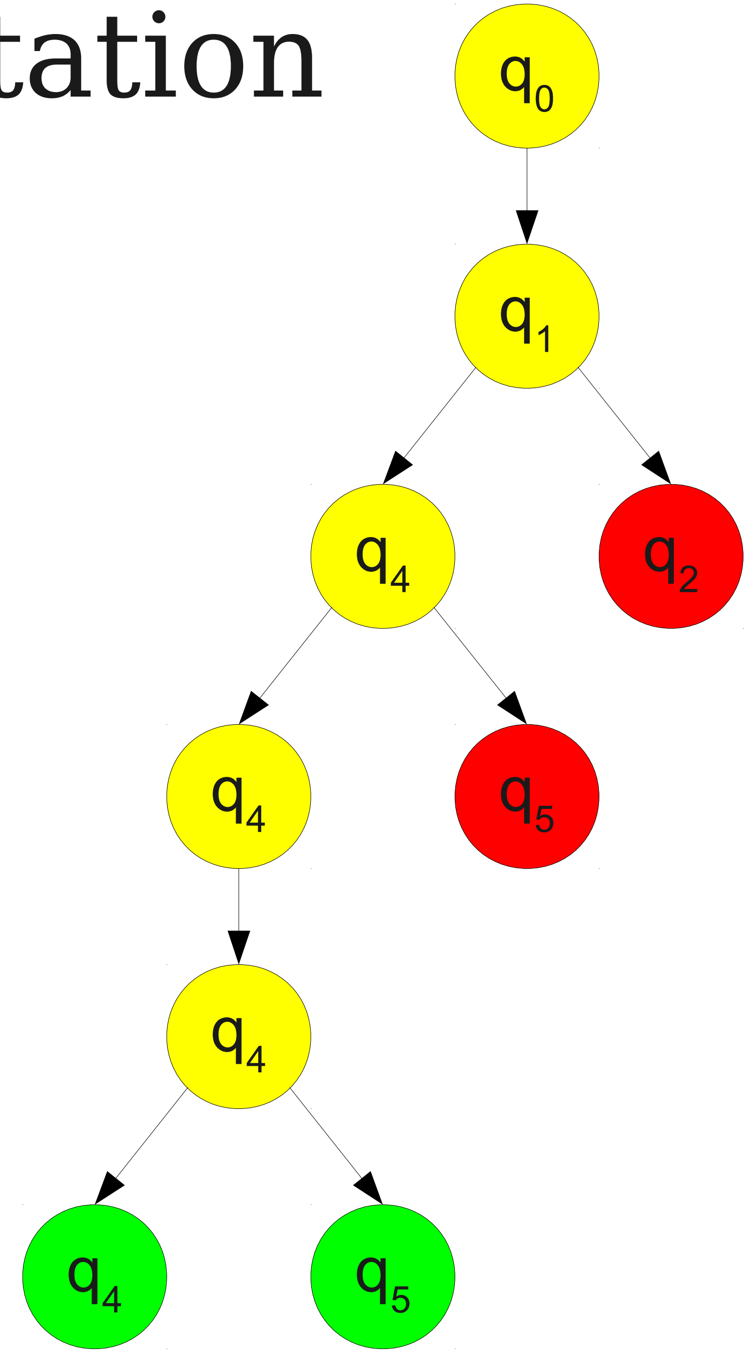

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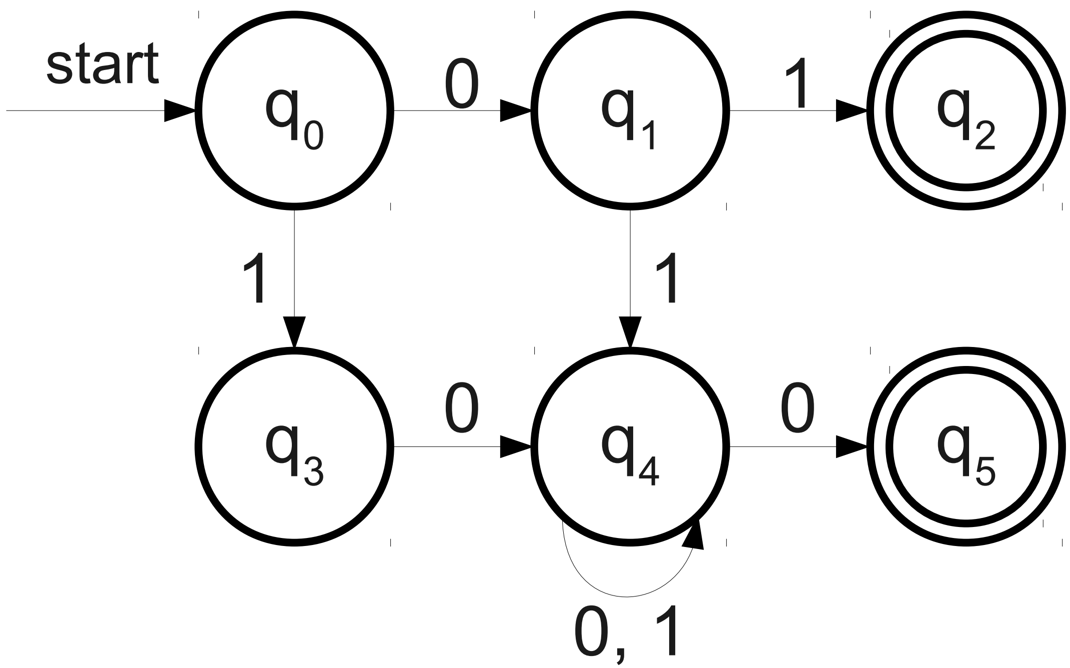

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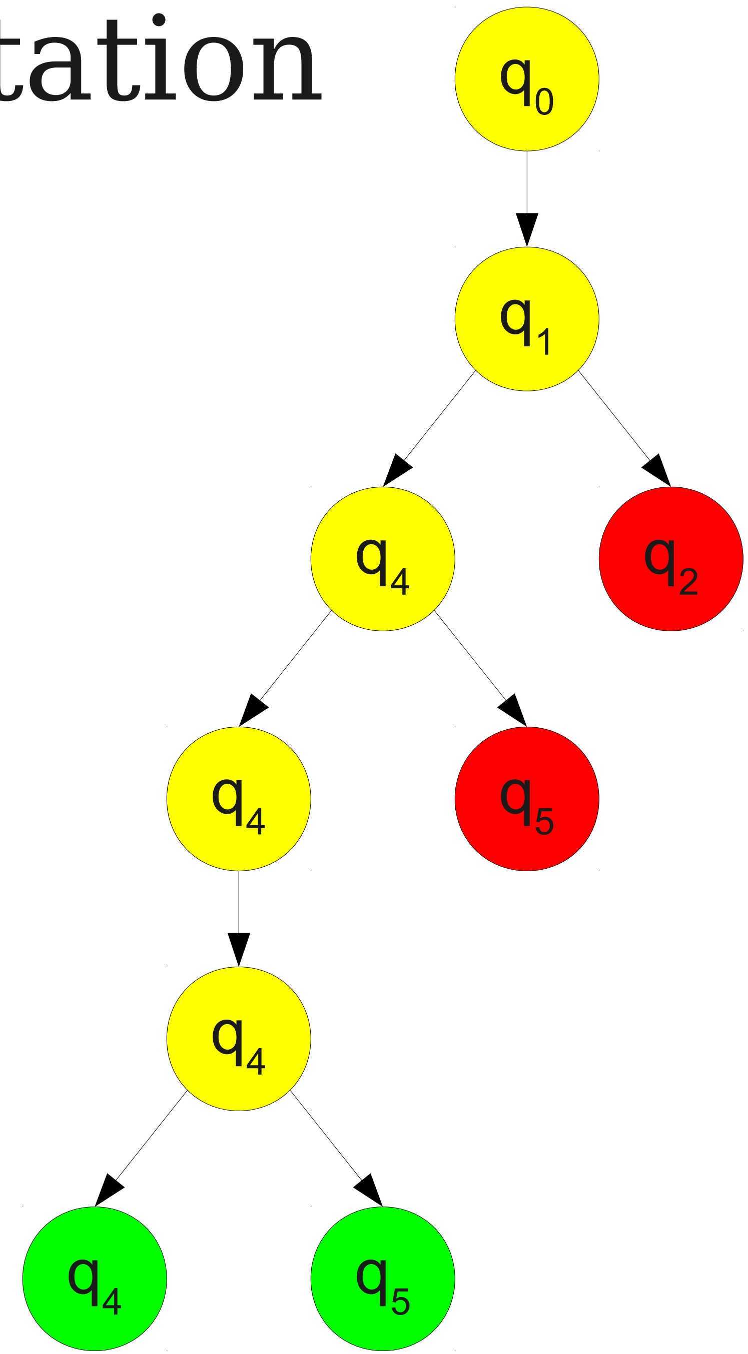

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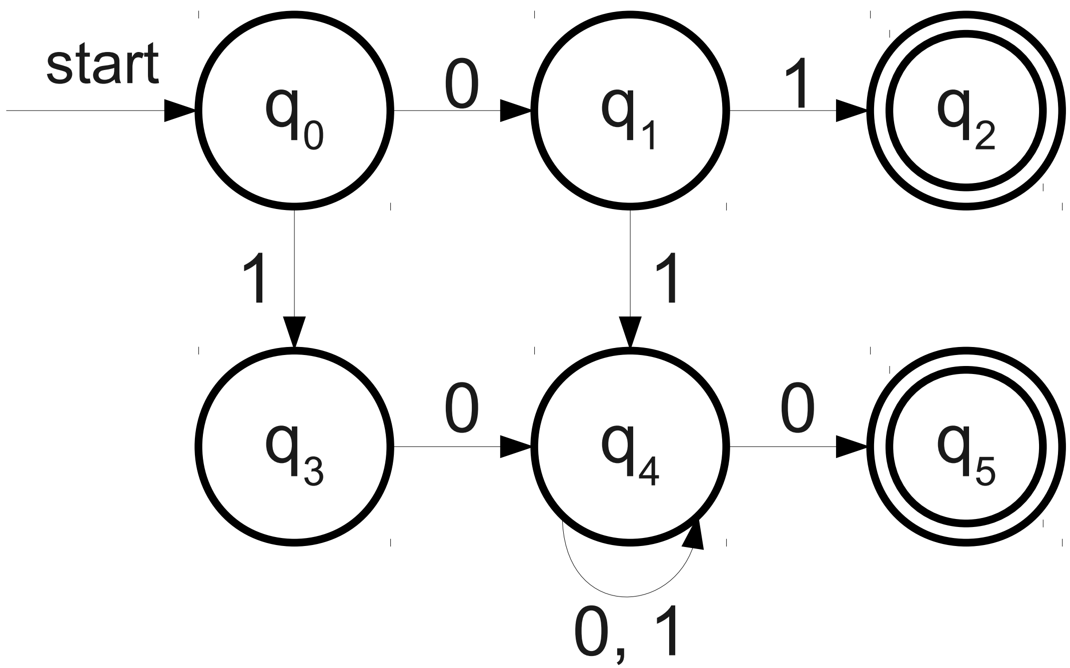

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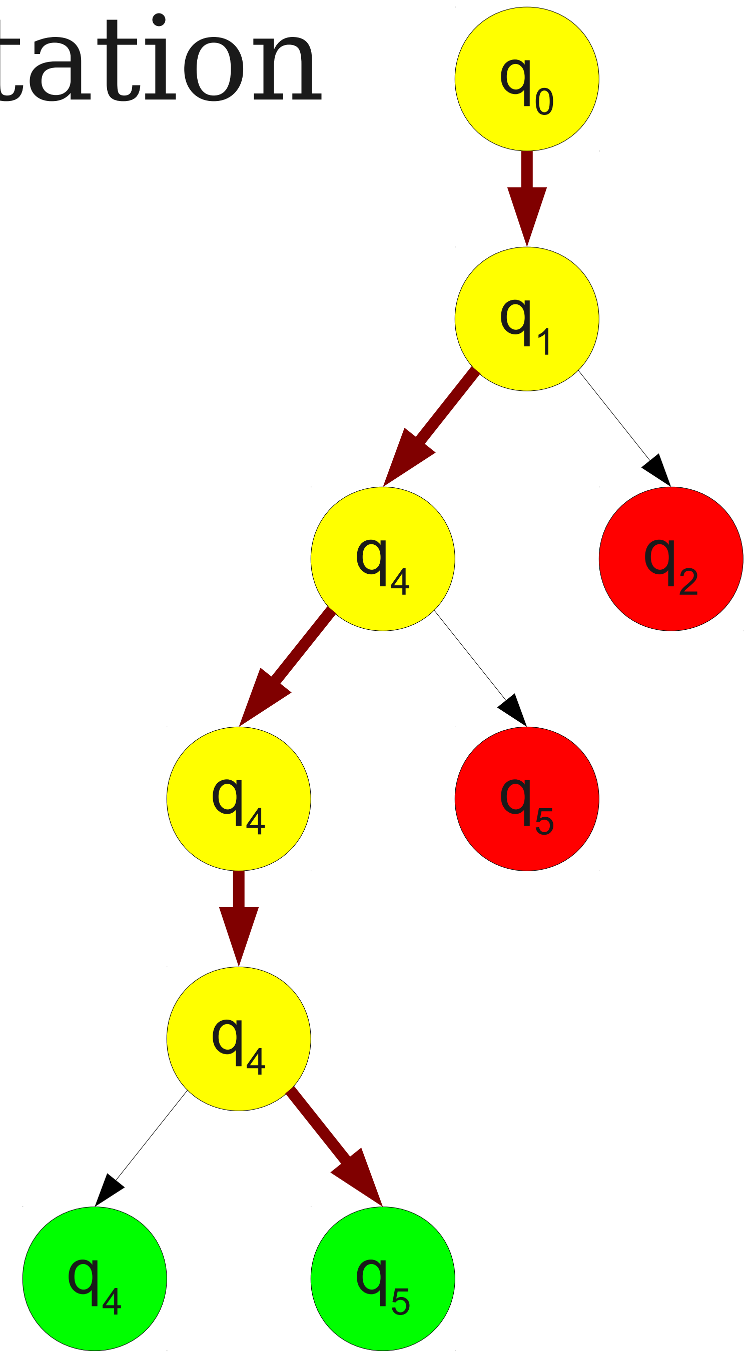
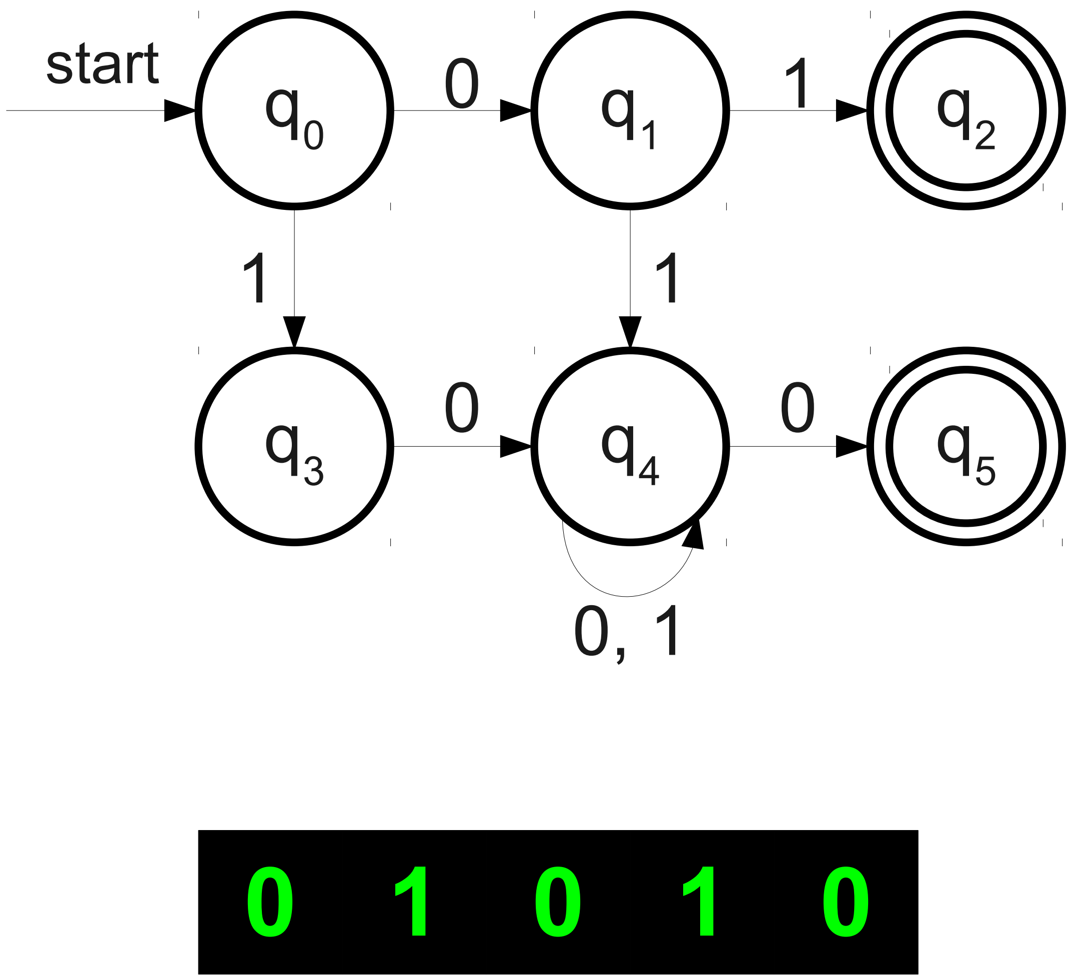
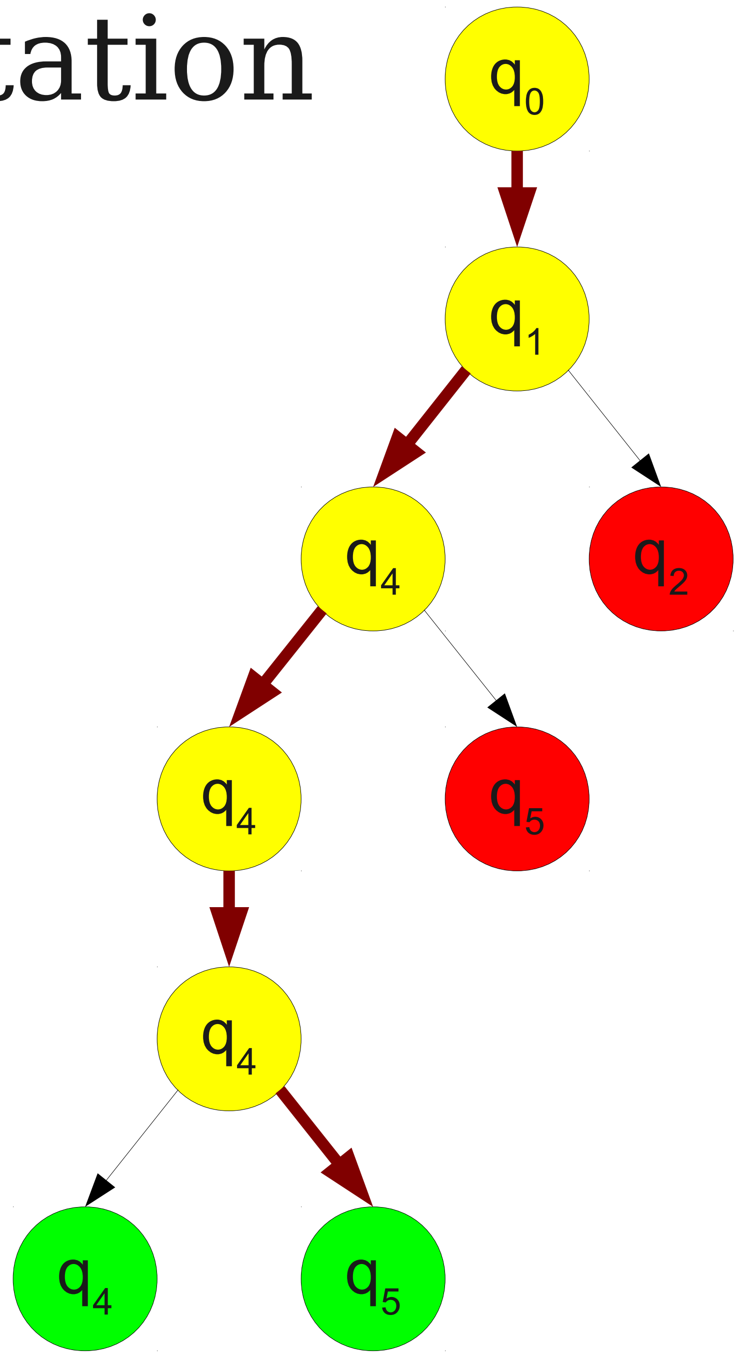


Tree Computation

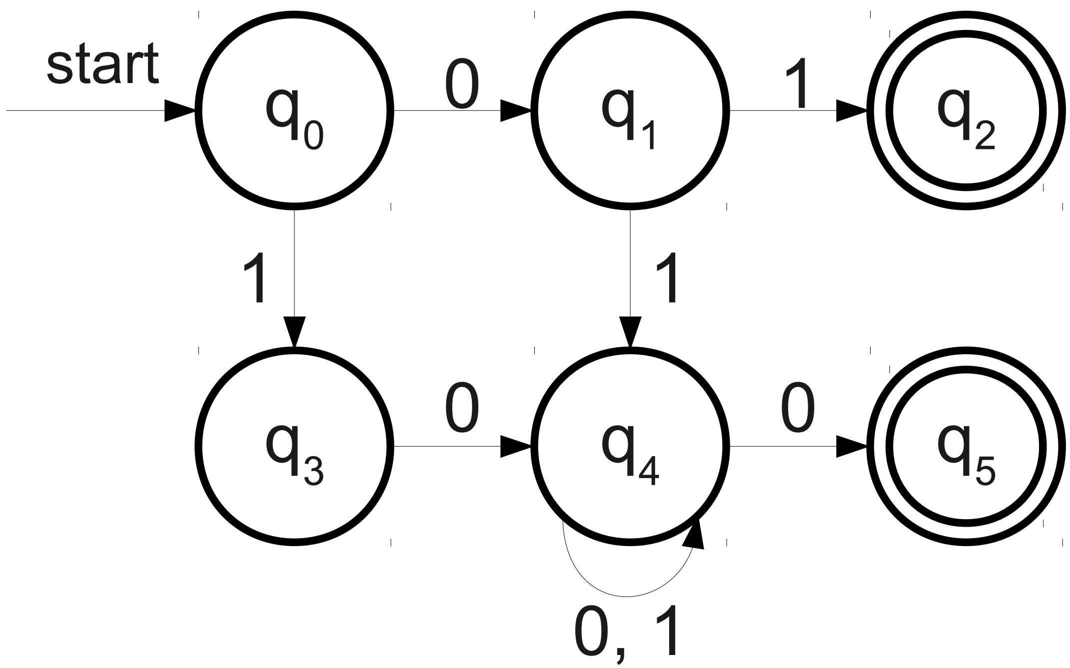




Nondeterminism as a Tree

- At each decision point, the automaton clones itself for each possible decision.
- The series of choices forms a directed, rooted tree.
- At the end, if any active accepting states remain, we accept.

Perfect Guessing



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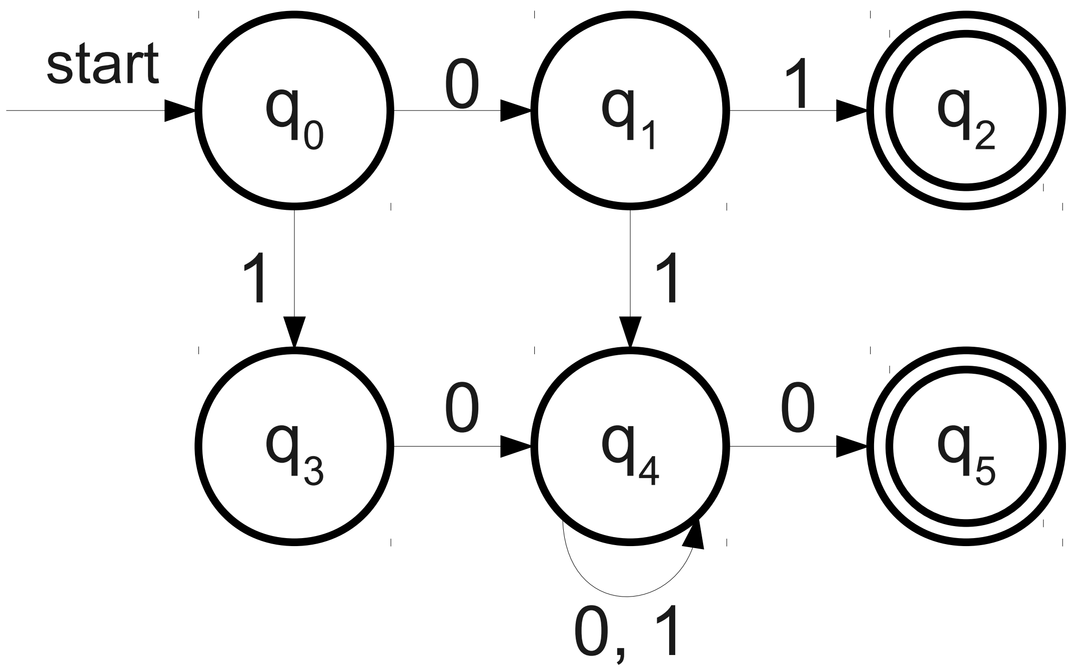

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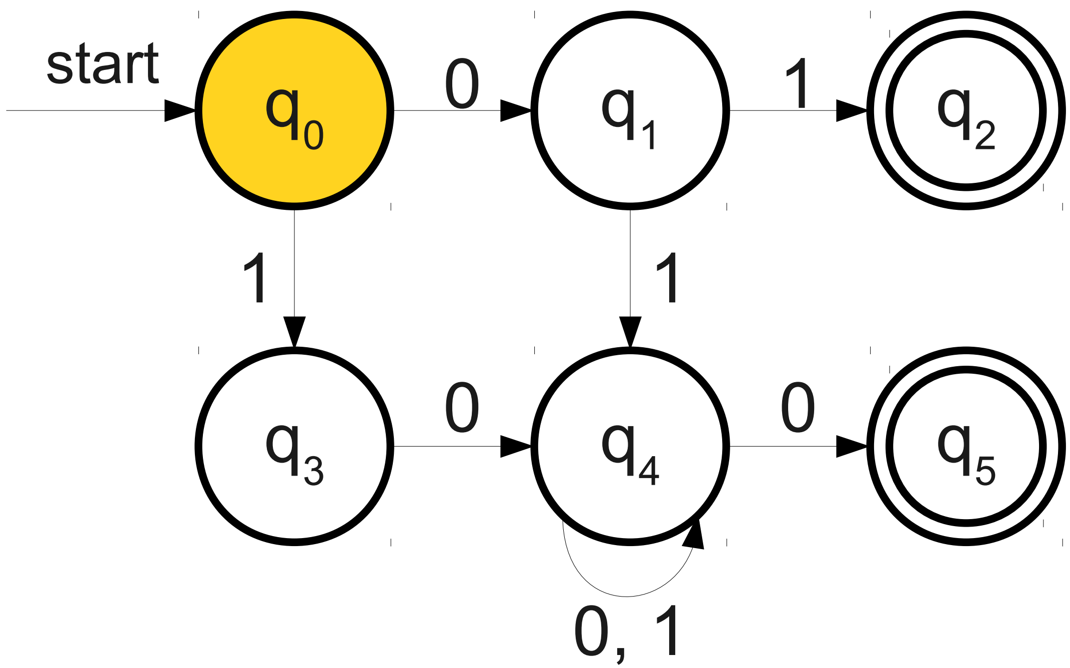

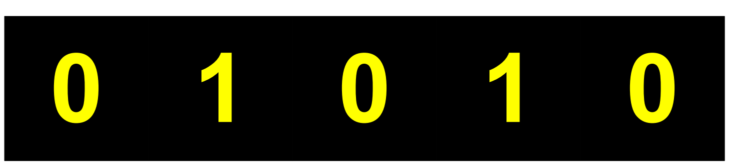

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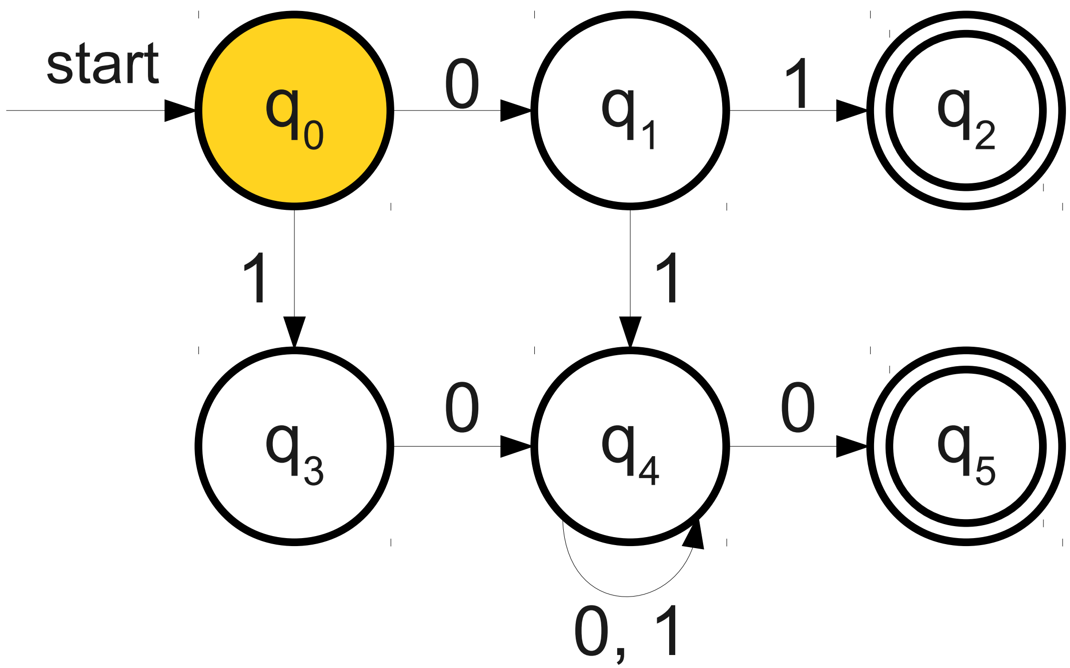

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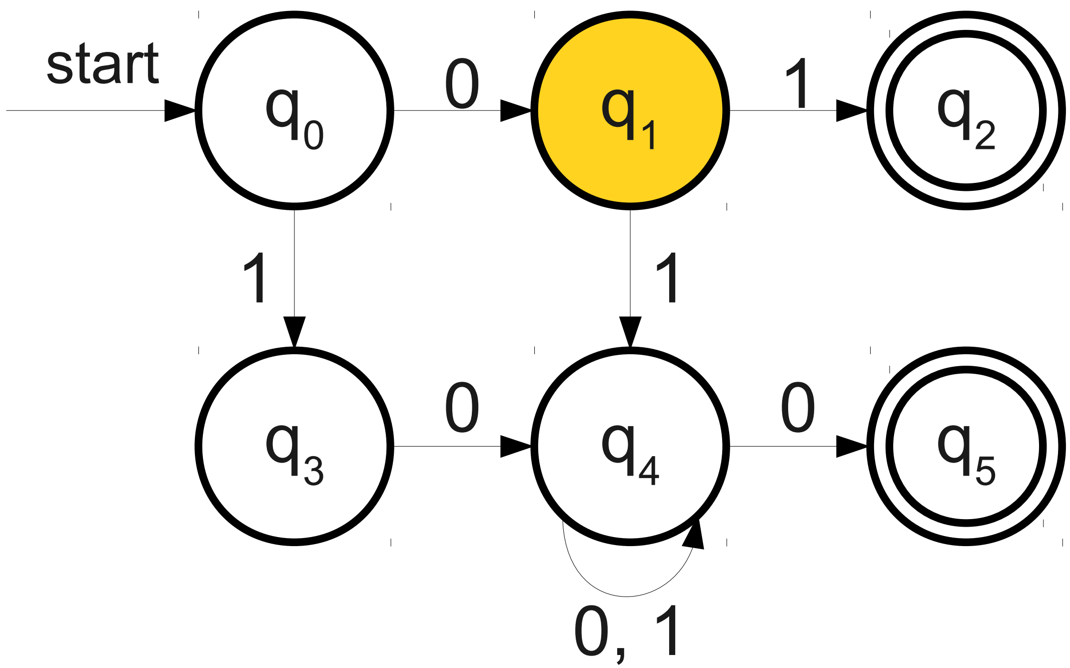

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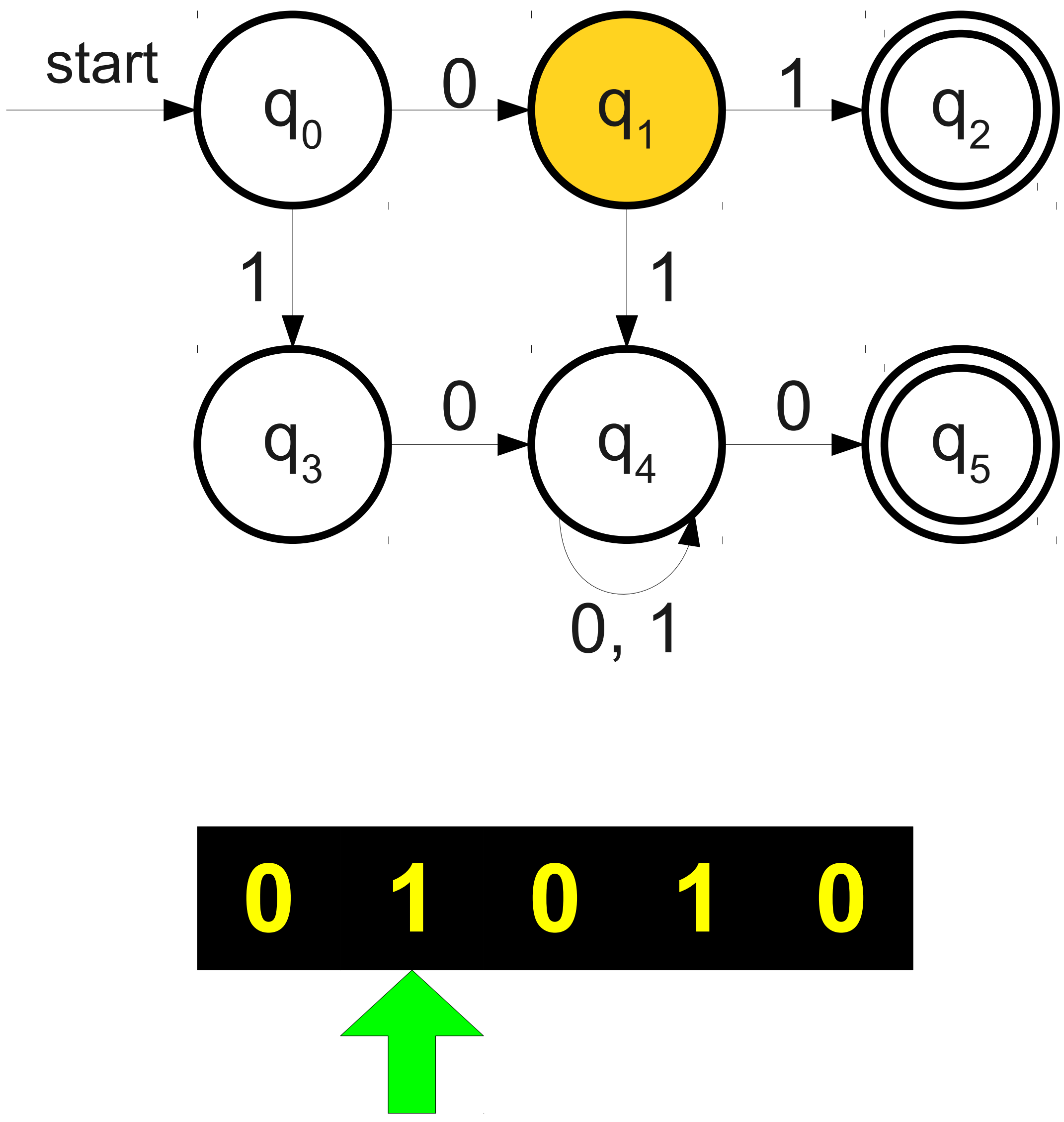

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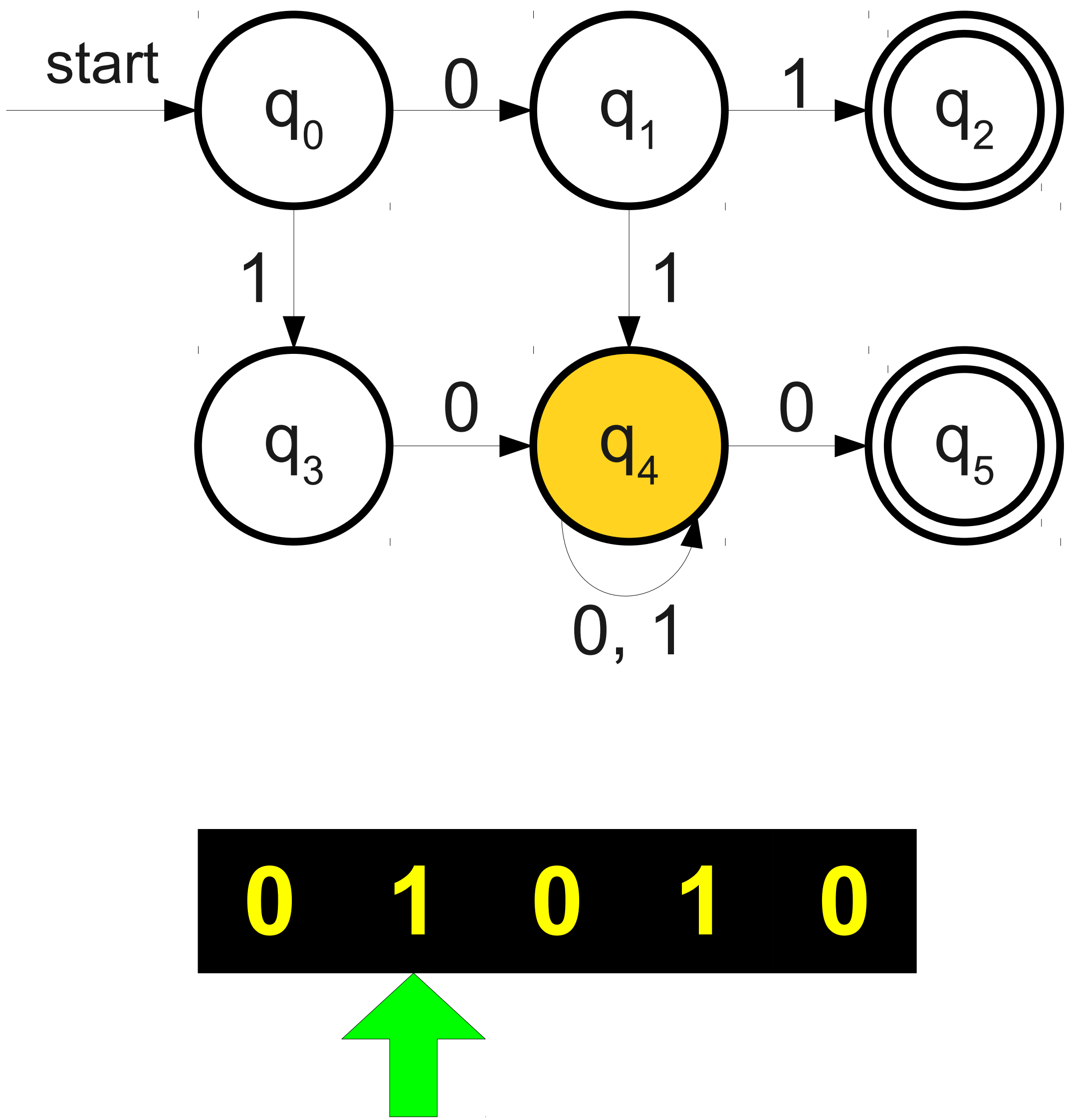

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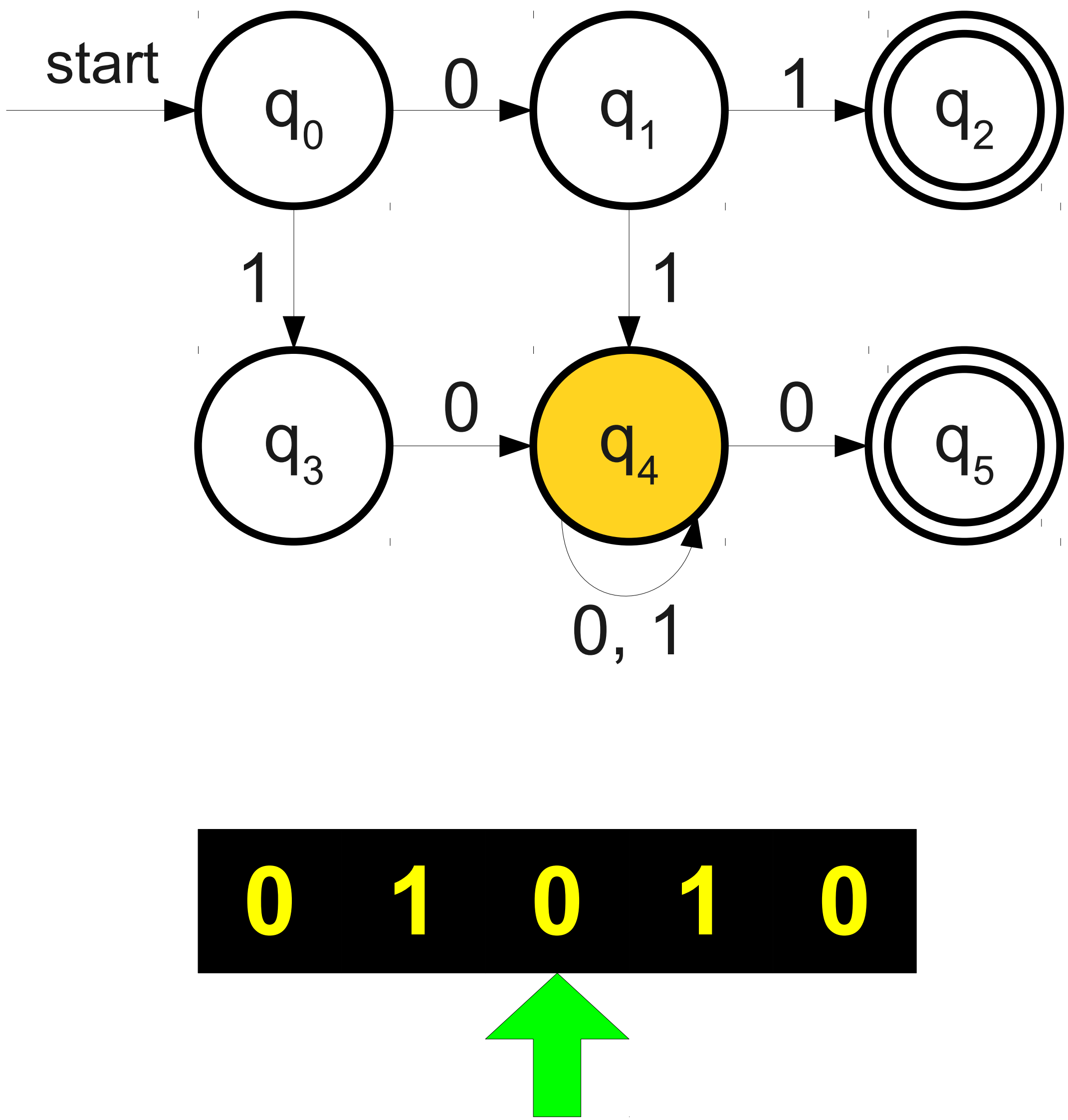

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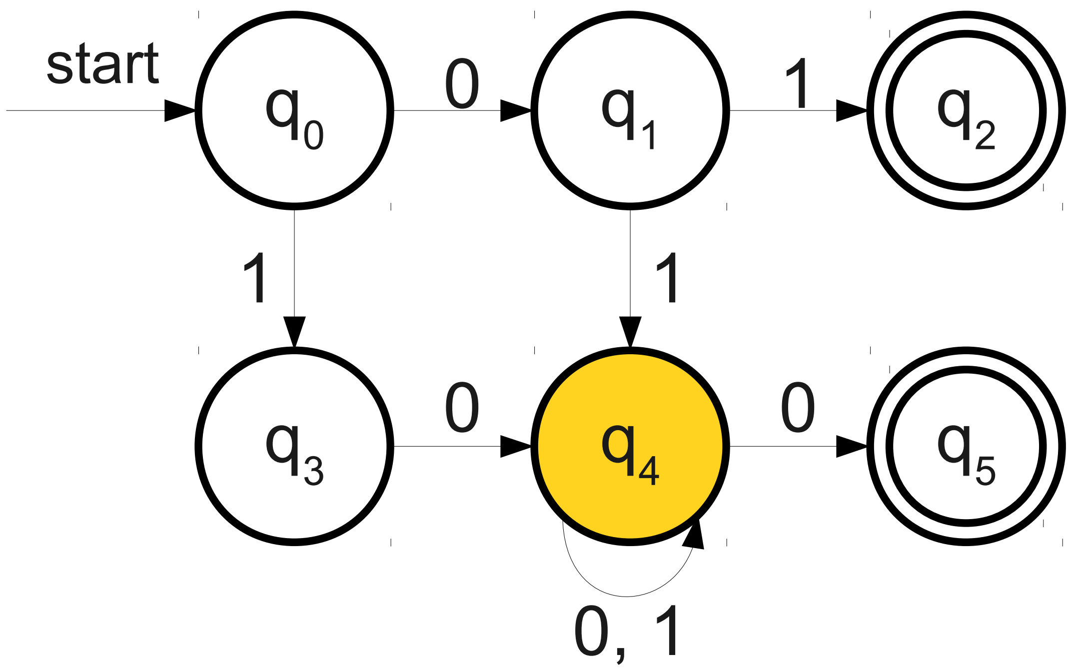

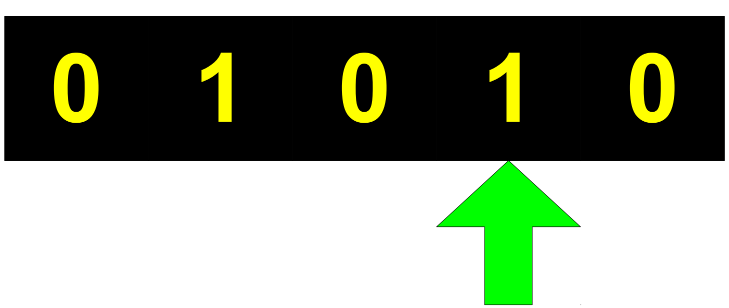

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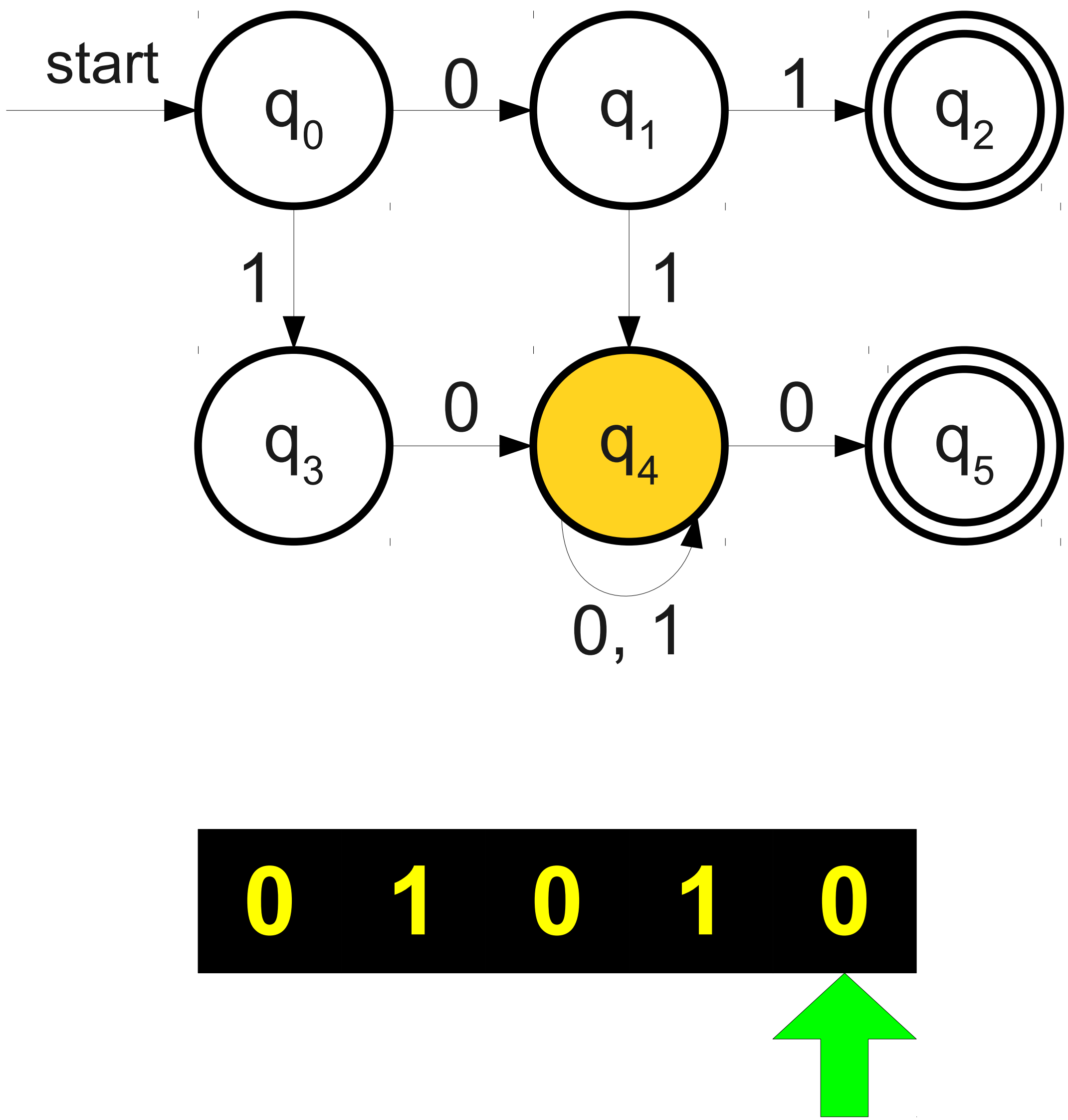

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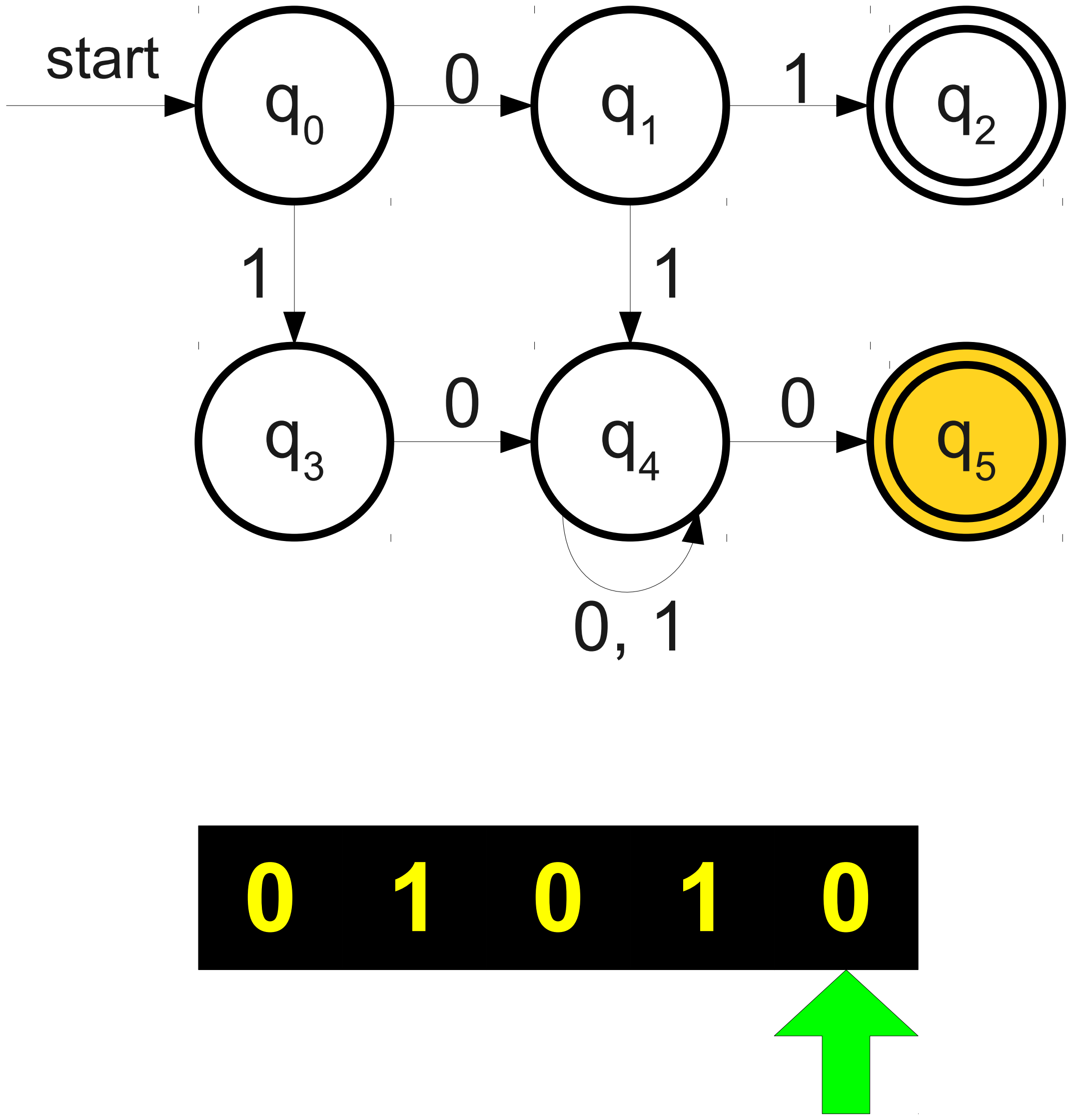

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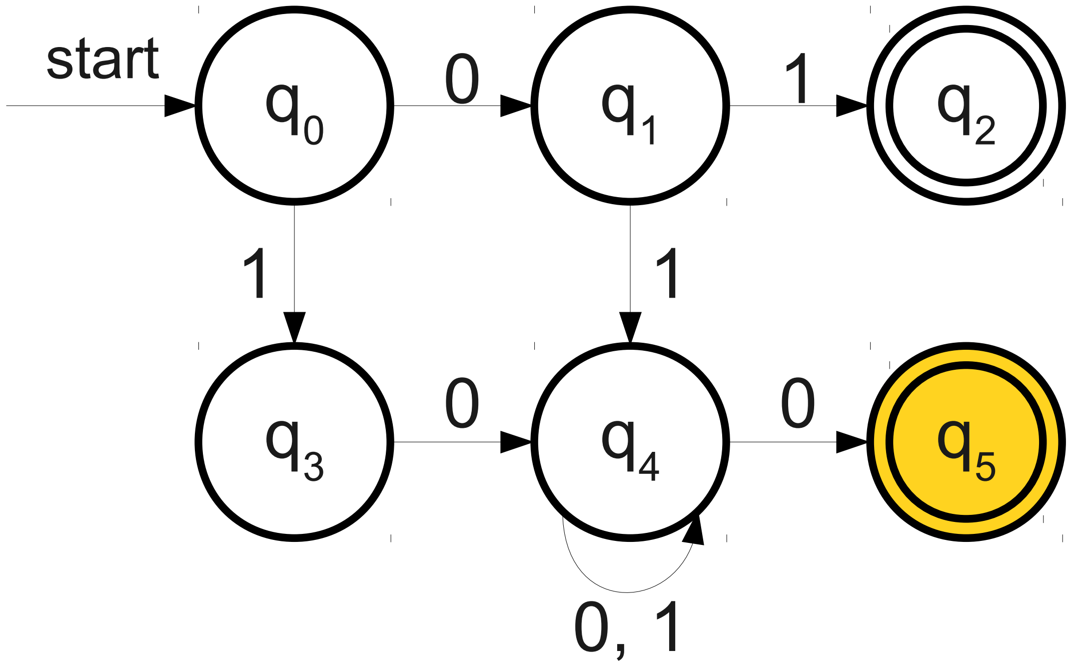

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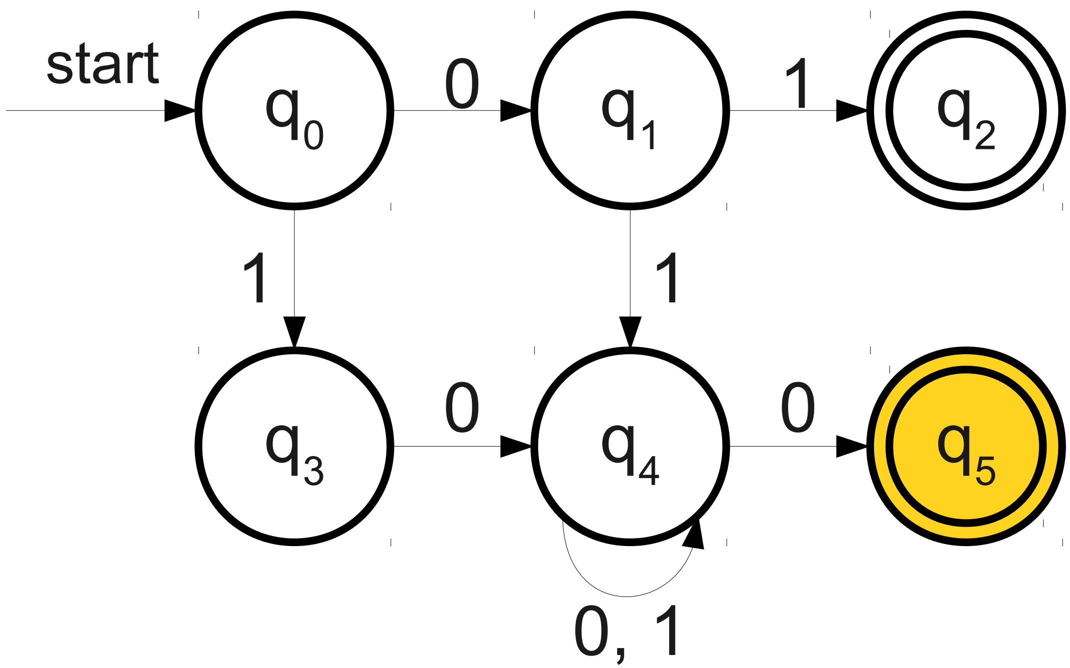
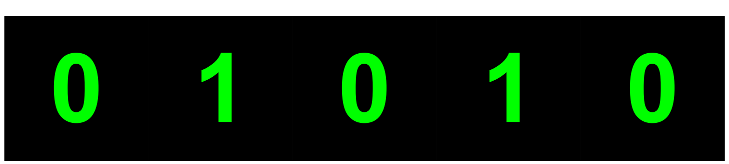
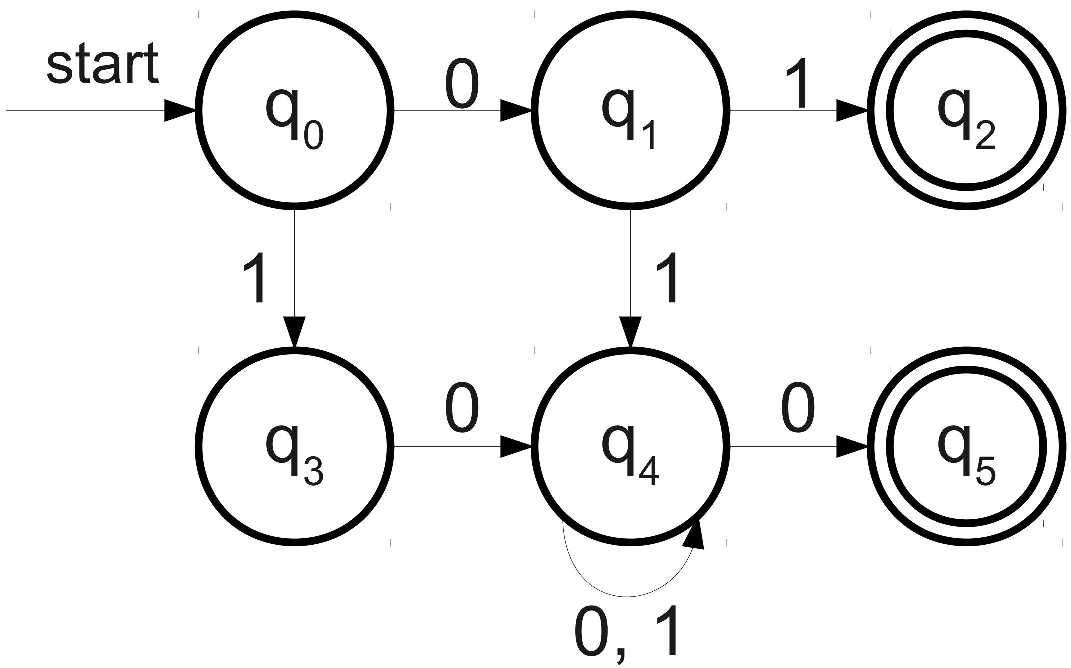


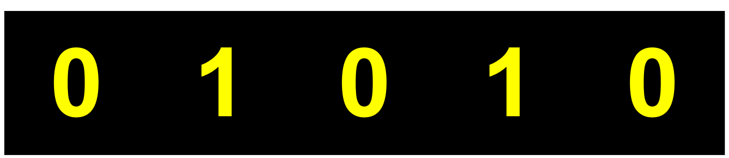


Perfect Guessing

- We can view nondeterministic machines as having **Magic Superpowers** that enable them to guess the correct choice of moves to make.
- Idea: Machine can always guess the right choice if one exists.
- No physical analog for something of this sort.
  - (Those of you thinking quantum computing – this is not the same thing. We actually don't fully know the relation between quantum and nondeterministic computation.)

Massive Parallelism





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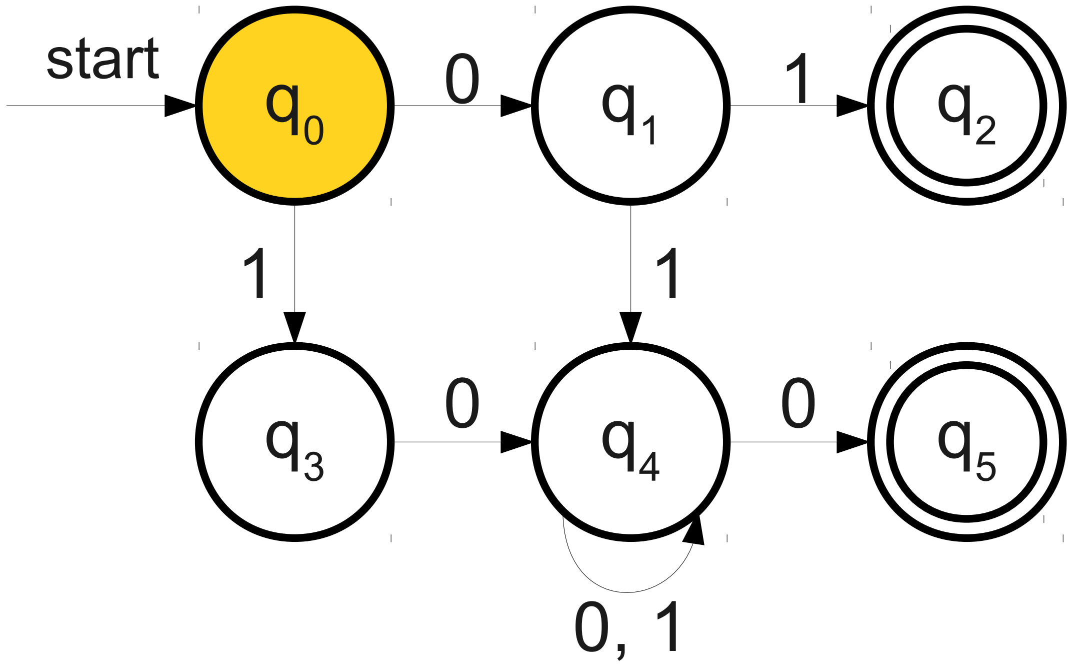

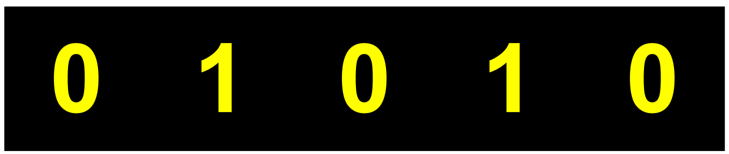

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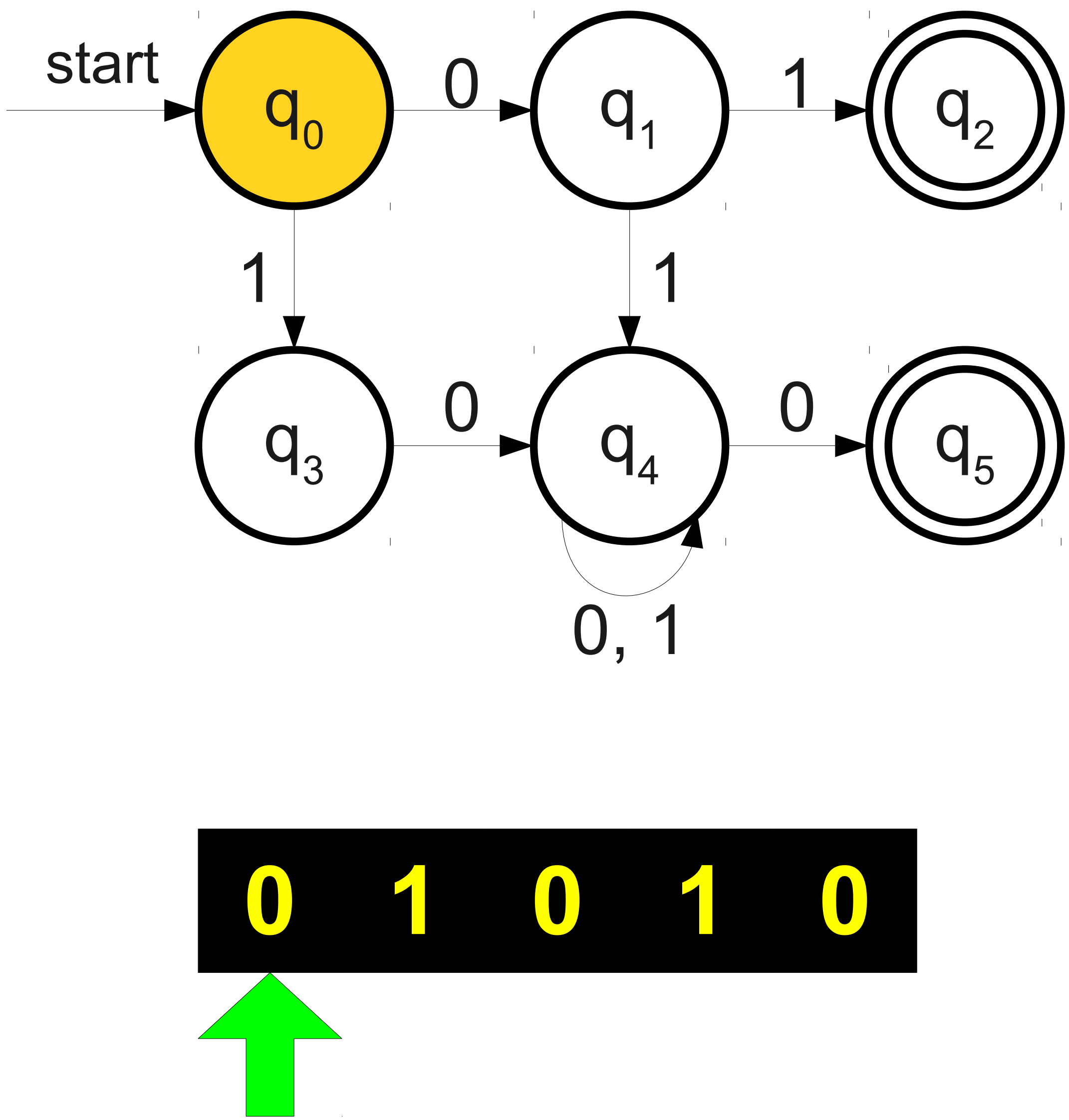

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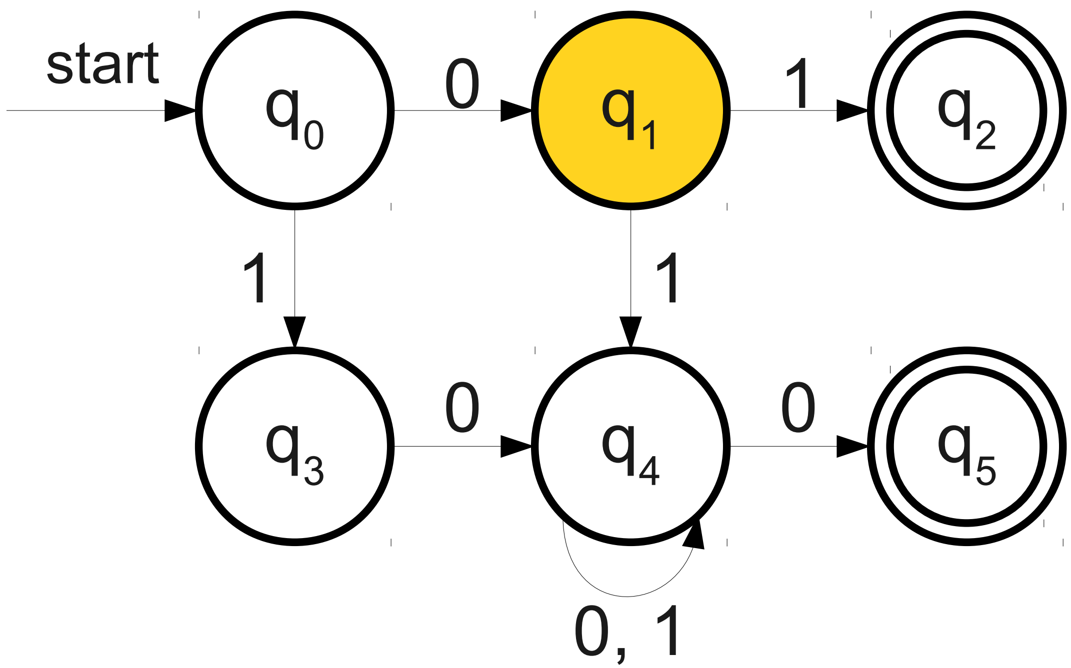

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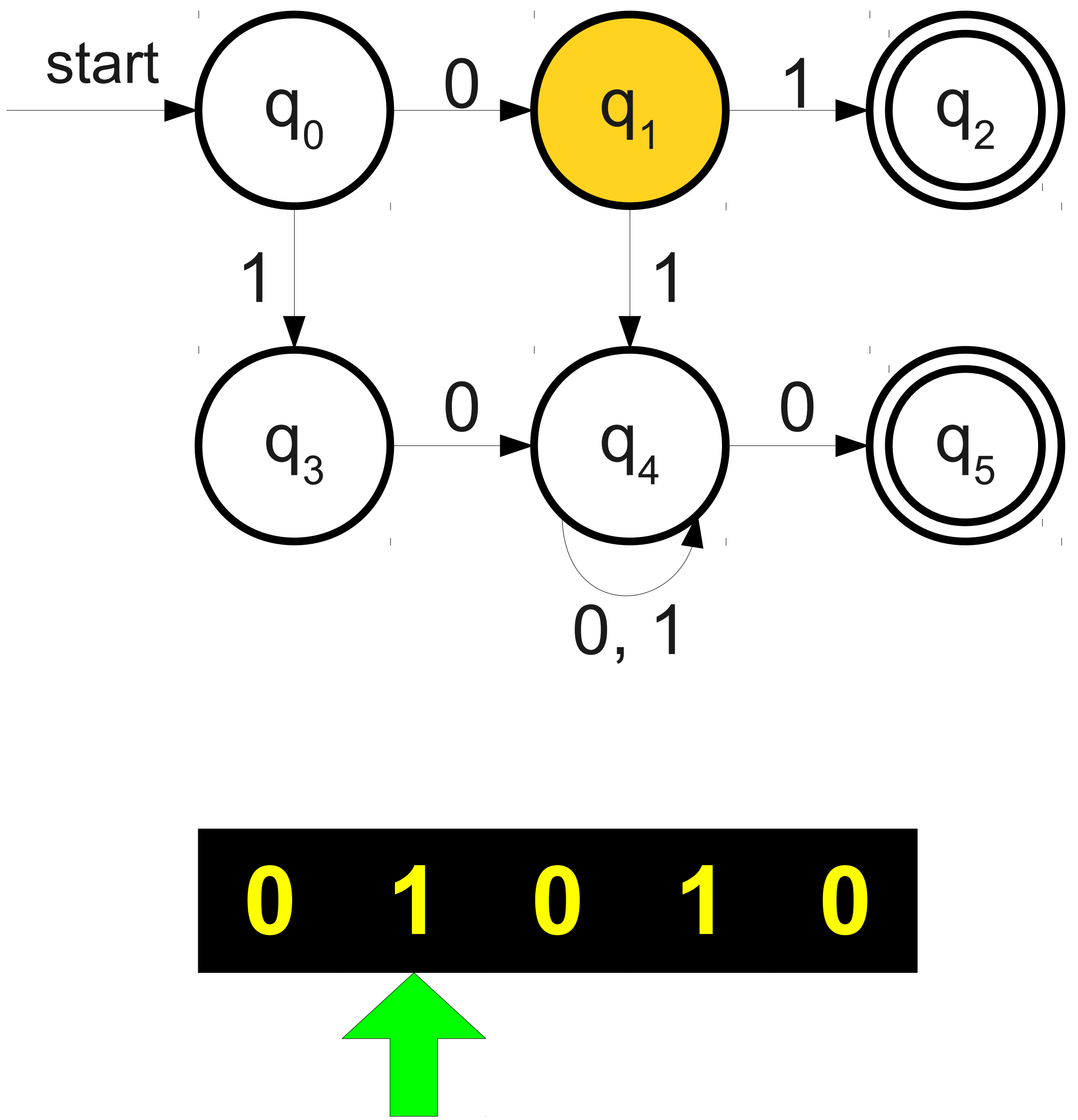

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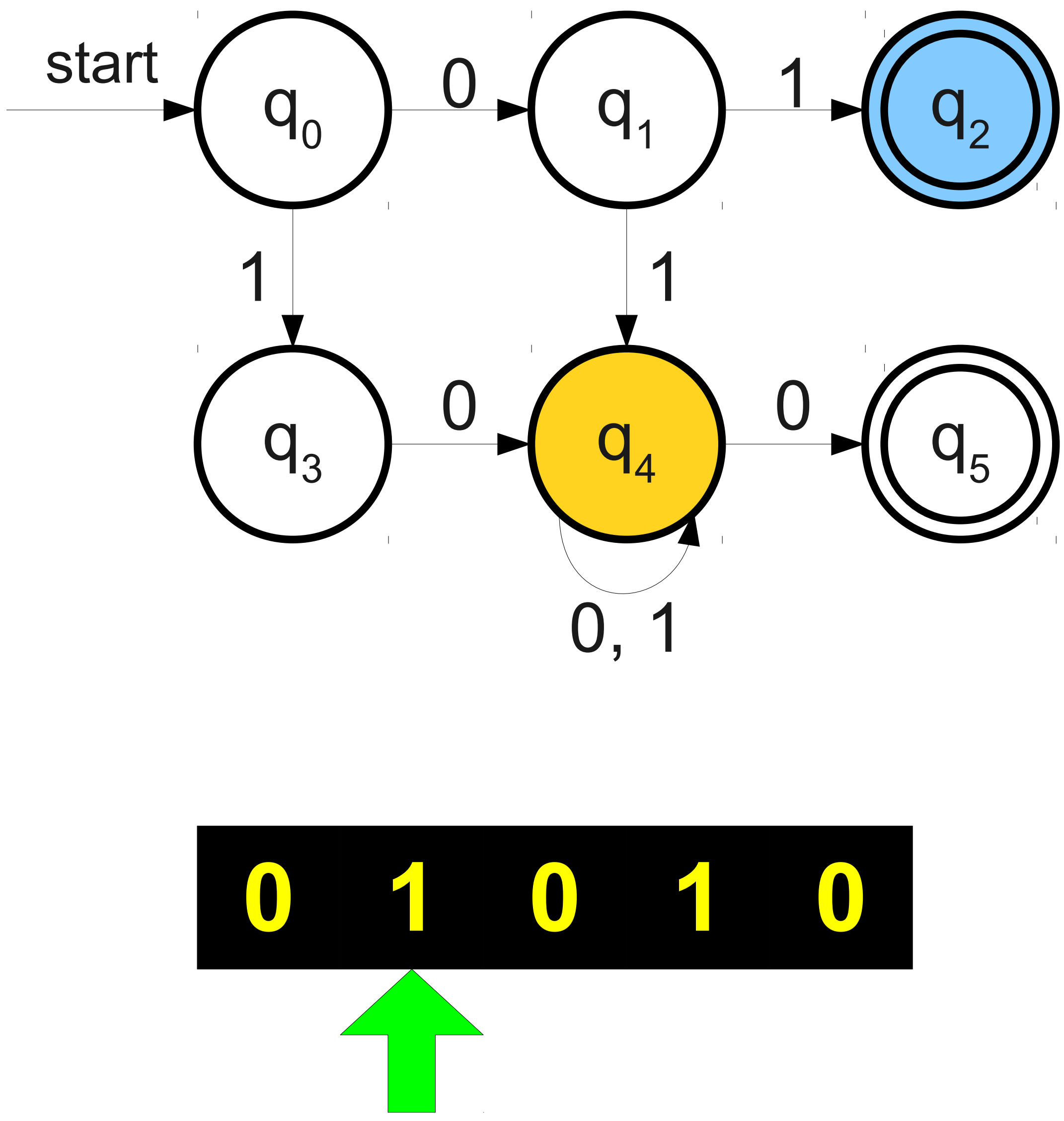

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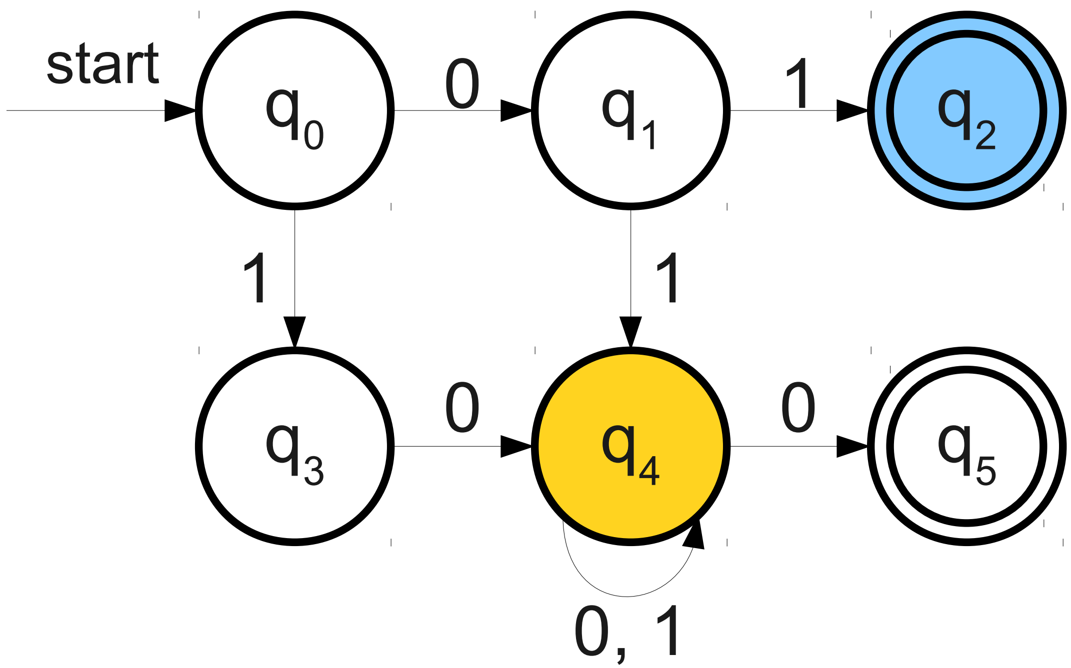

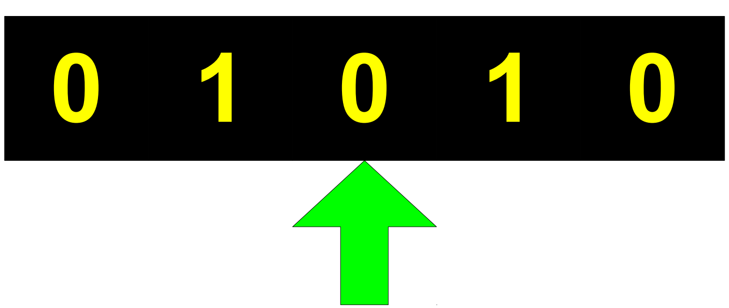

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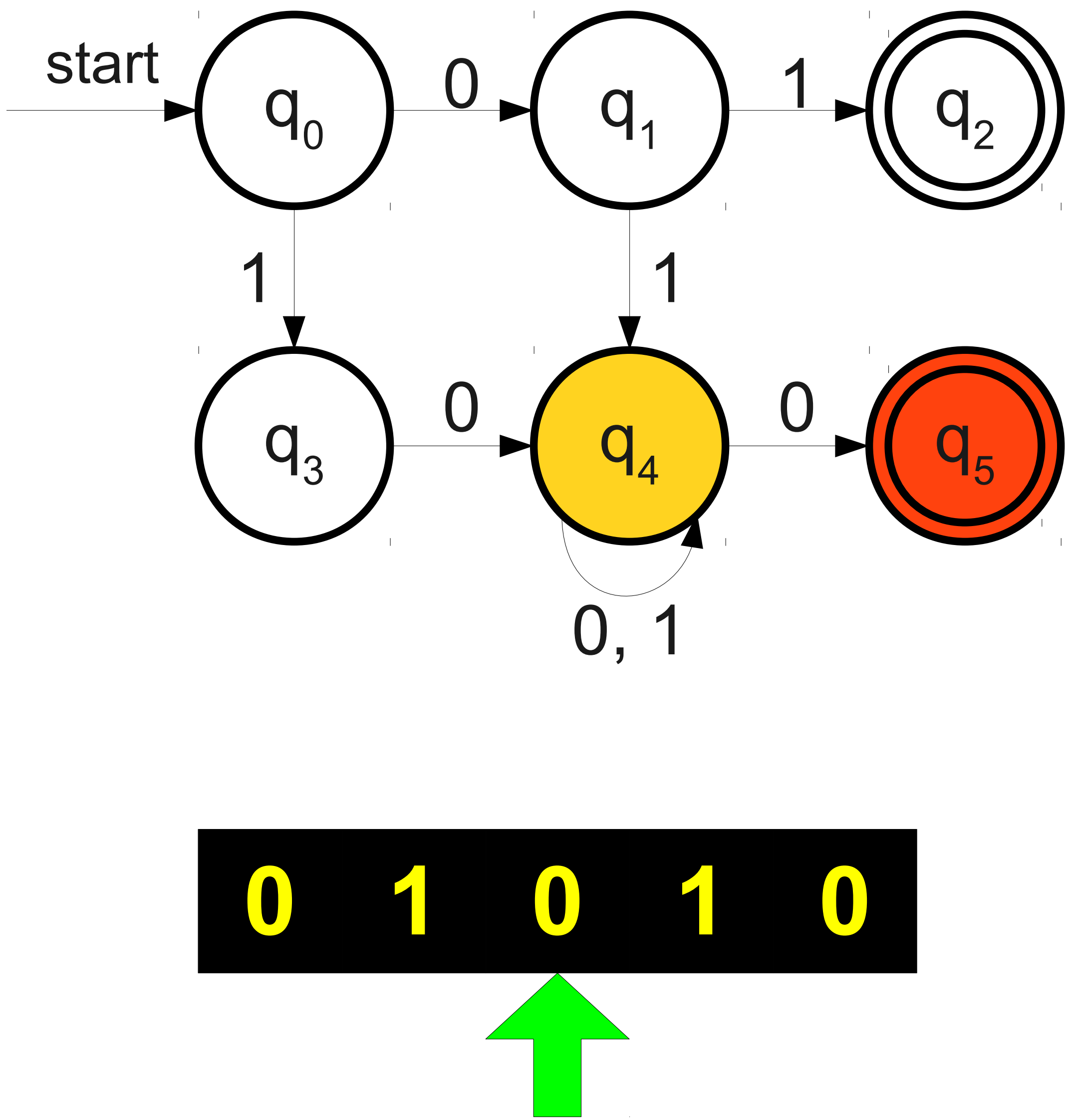

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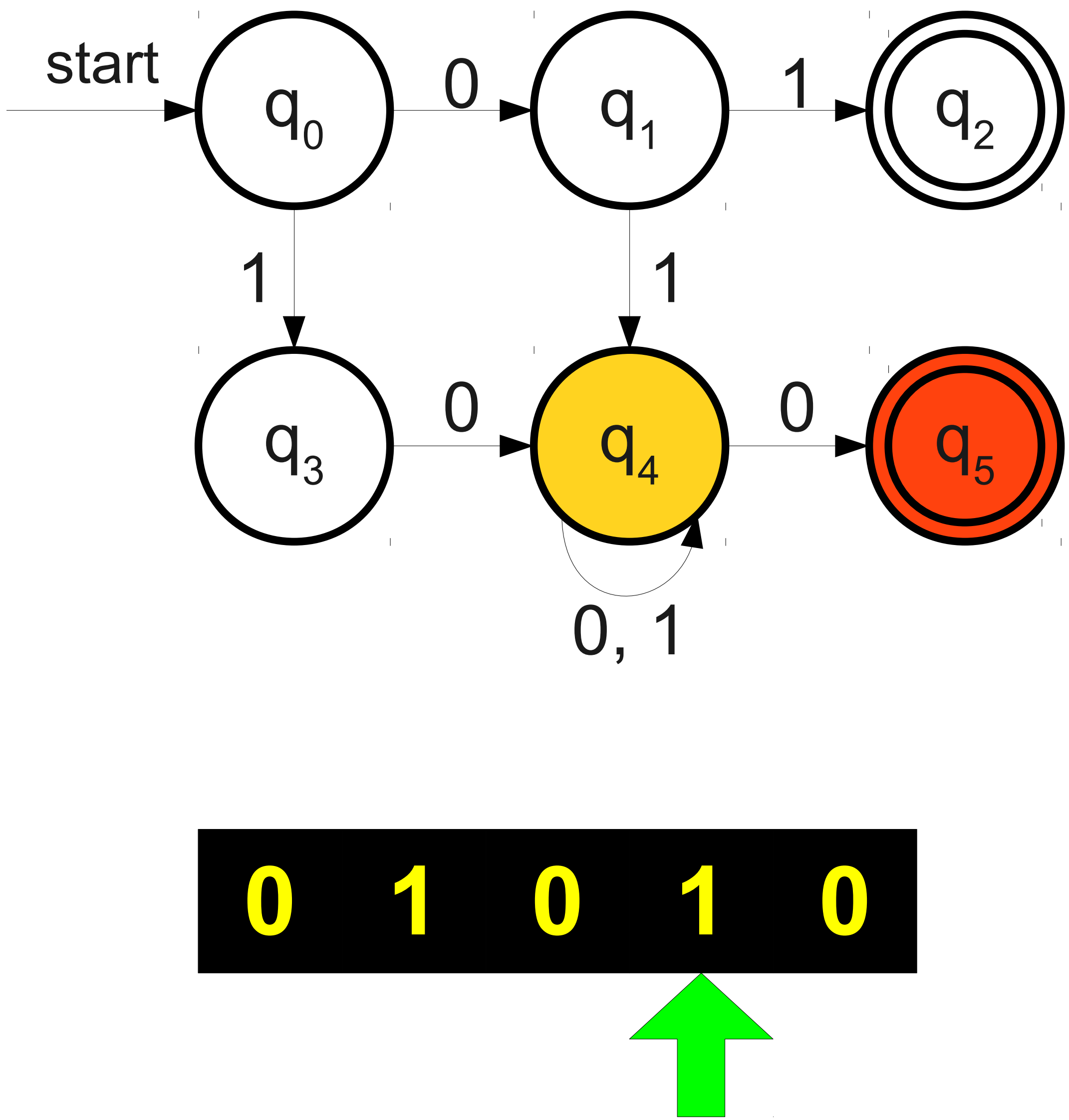

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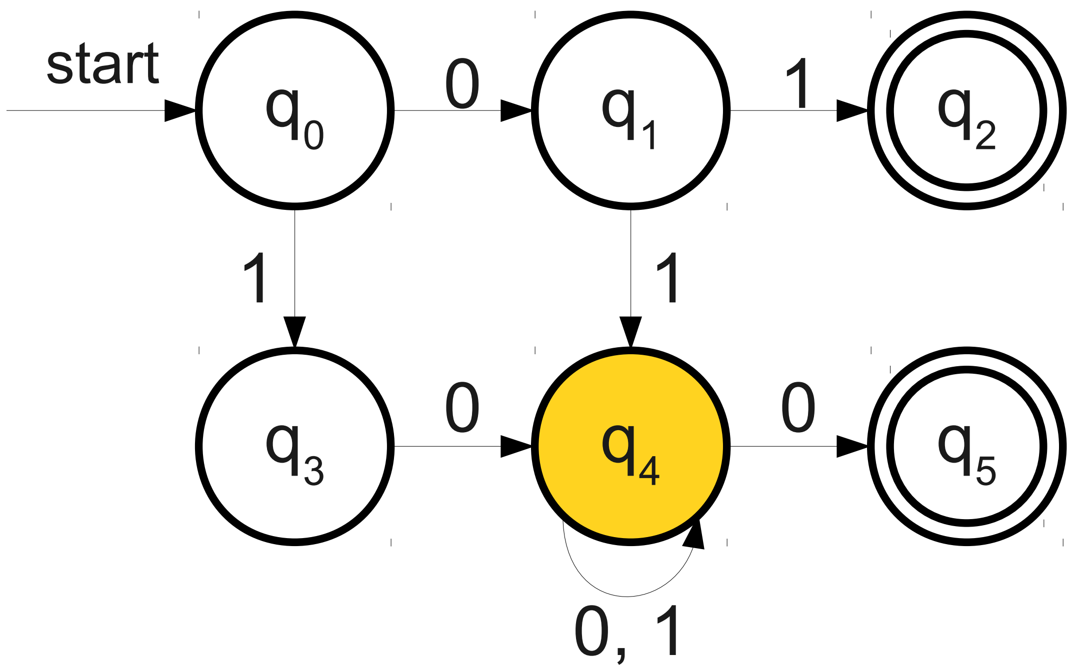

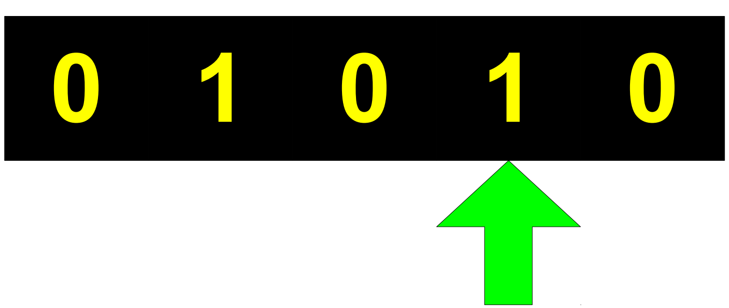

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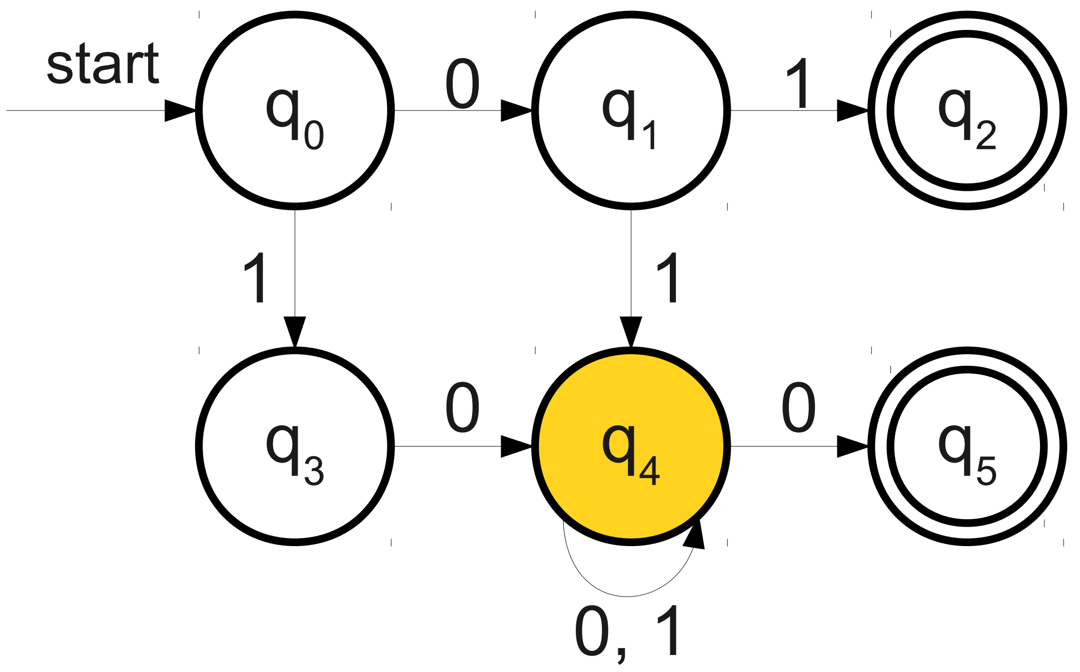

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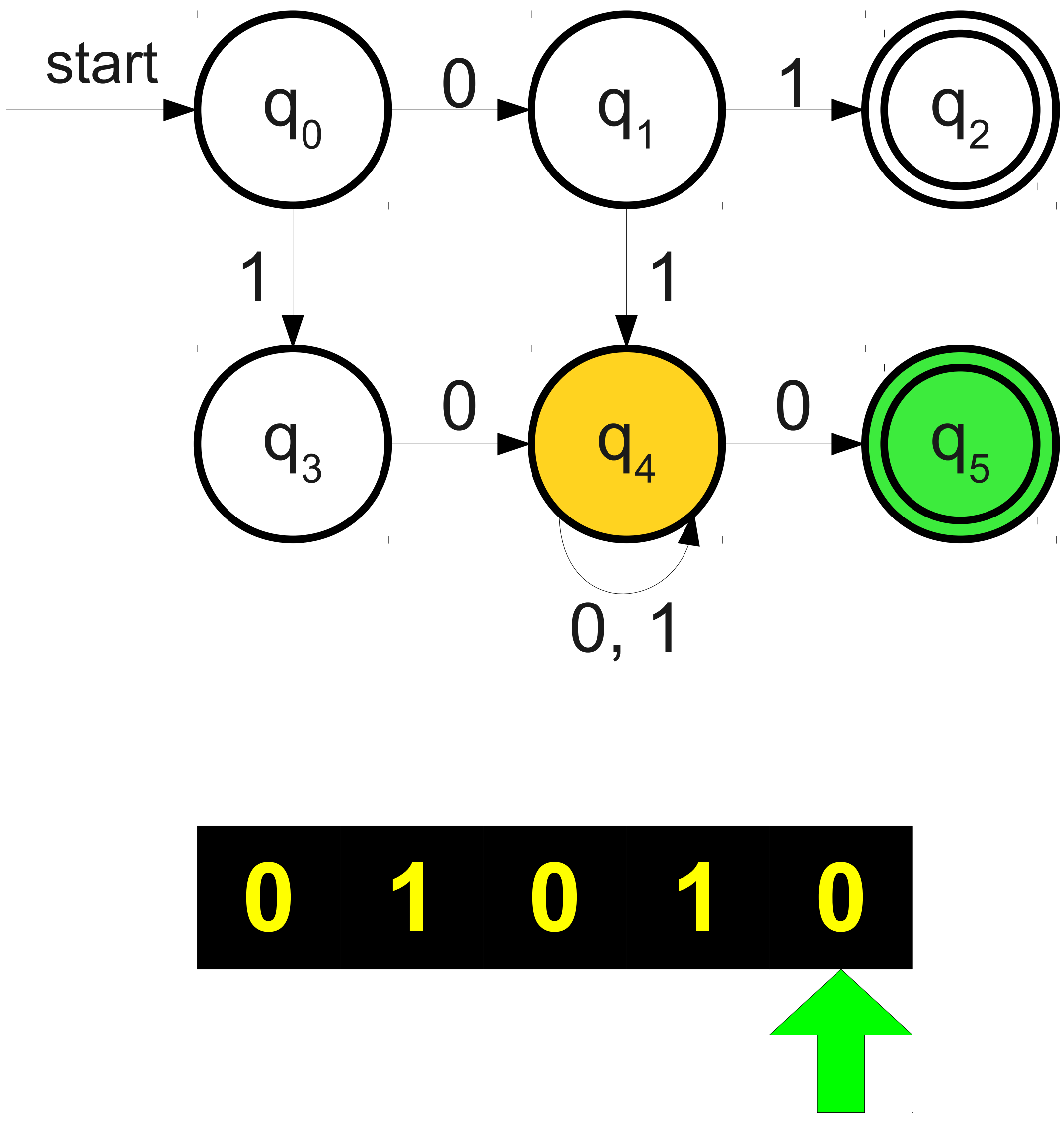

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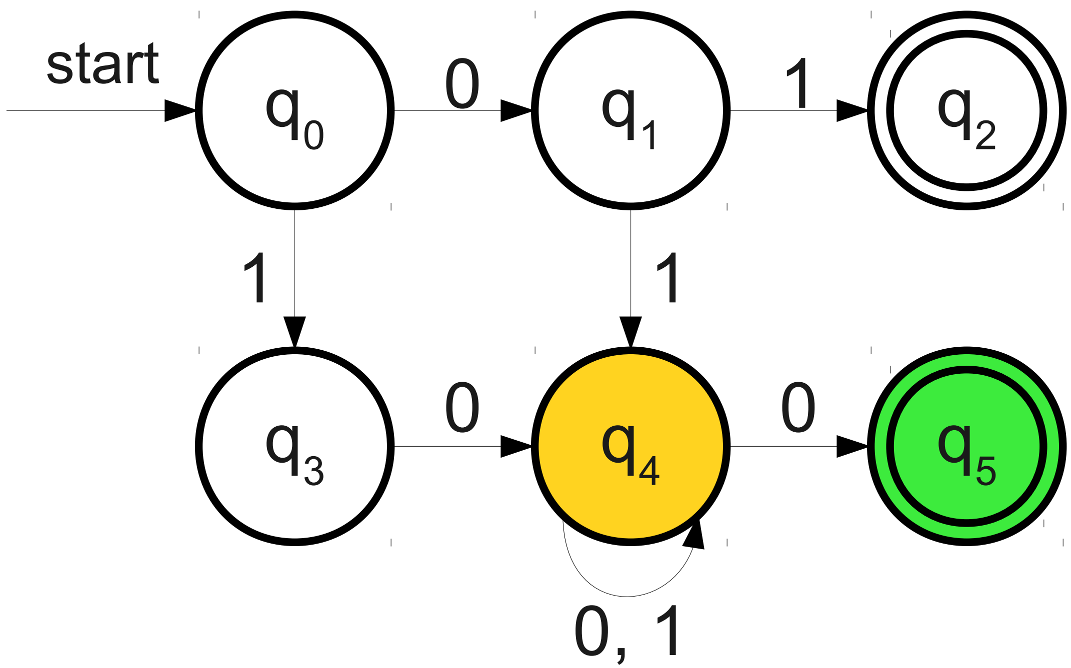

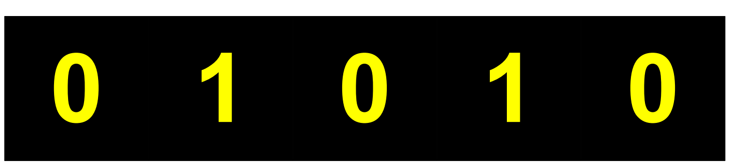

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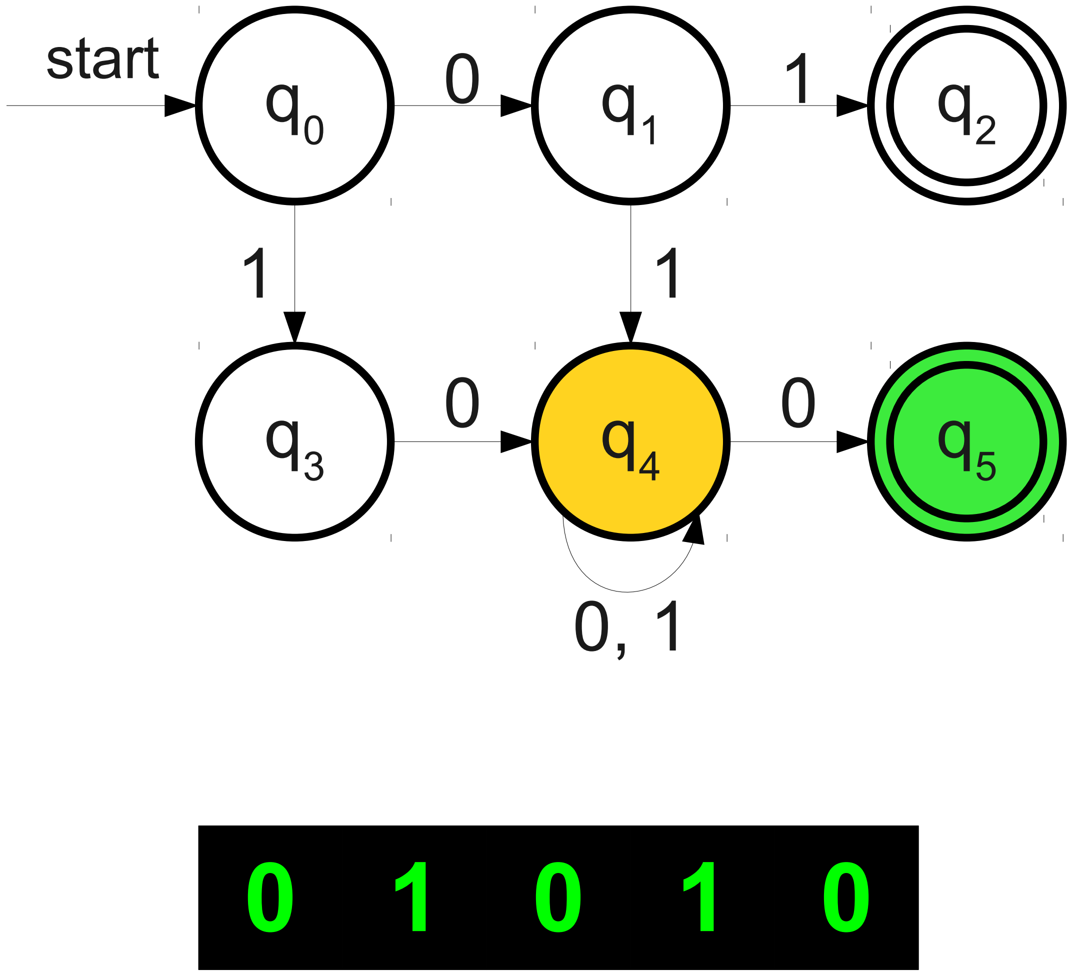


Massive Parallelism

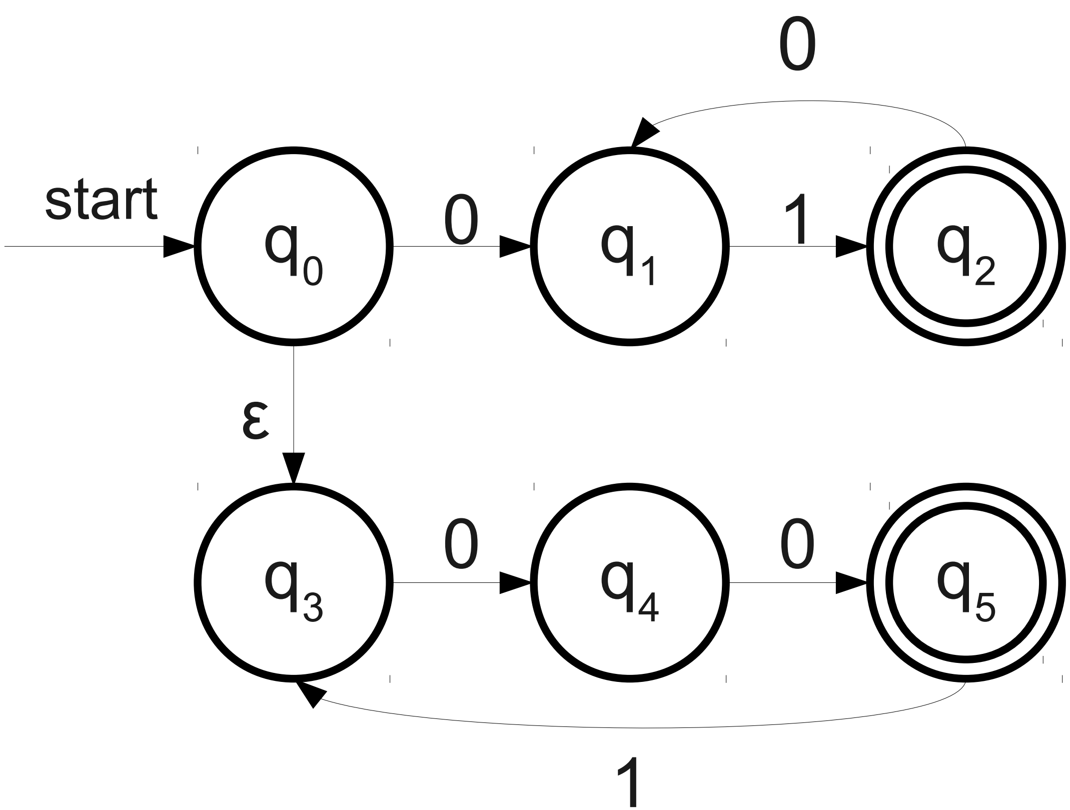
- An NFA can be thought of as a DFA that can be in many states at once.
- Each symbol read causes a transition on every active state into each potential state that could be visited.
- Nondeterministic machines can be thought of as machines that can try any number of options in parallel.
  - No fixed limit on processors; makes multicore machines look downright wimpy!

So What?

- We will turn to these three intuitions for nondeterminism more later in the quarter.
- 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.

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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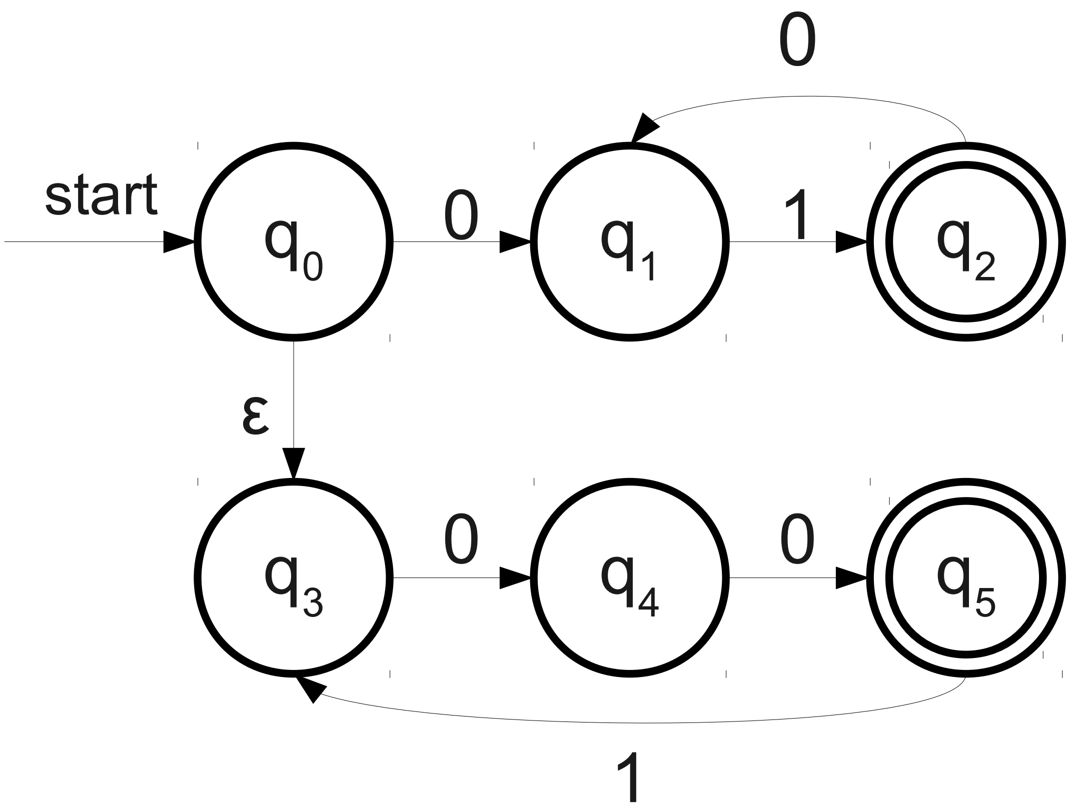

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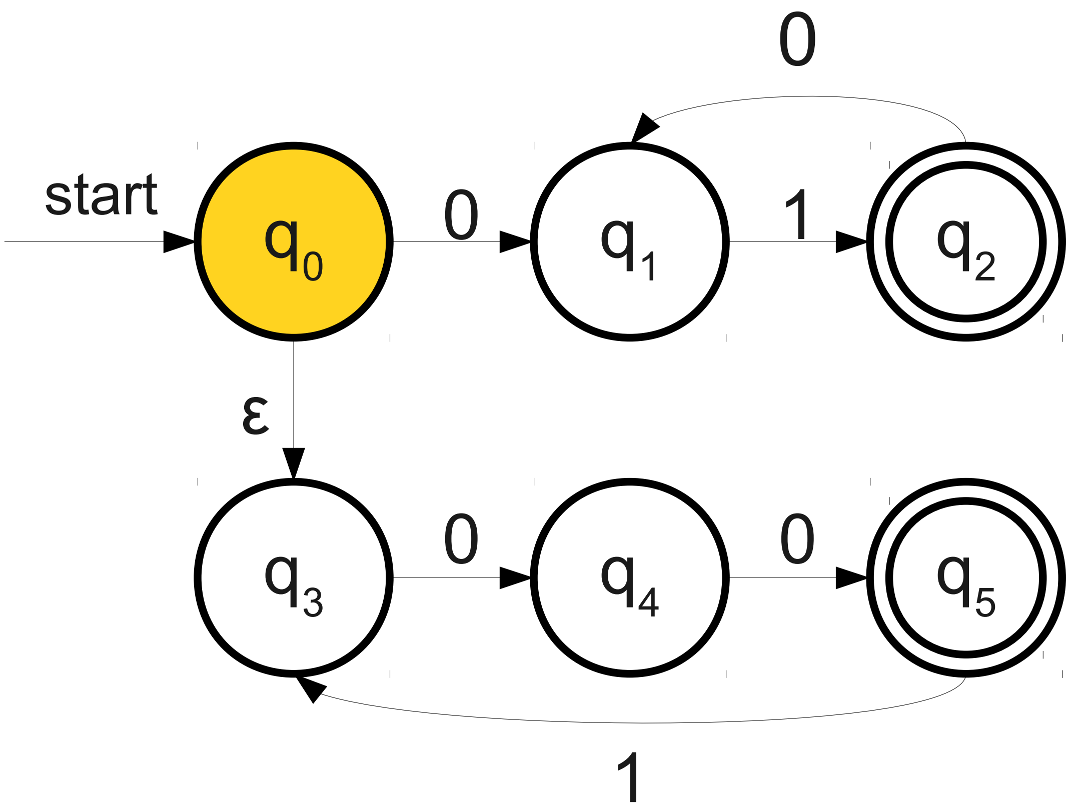

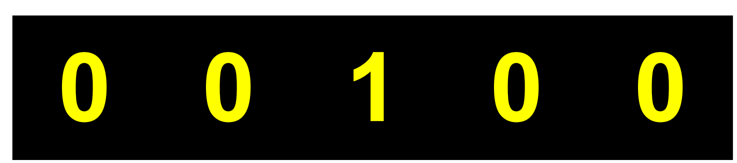

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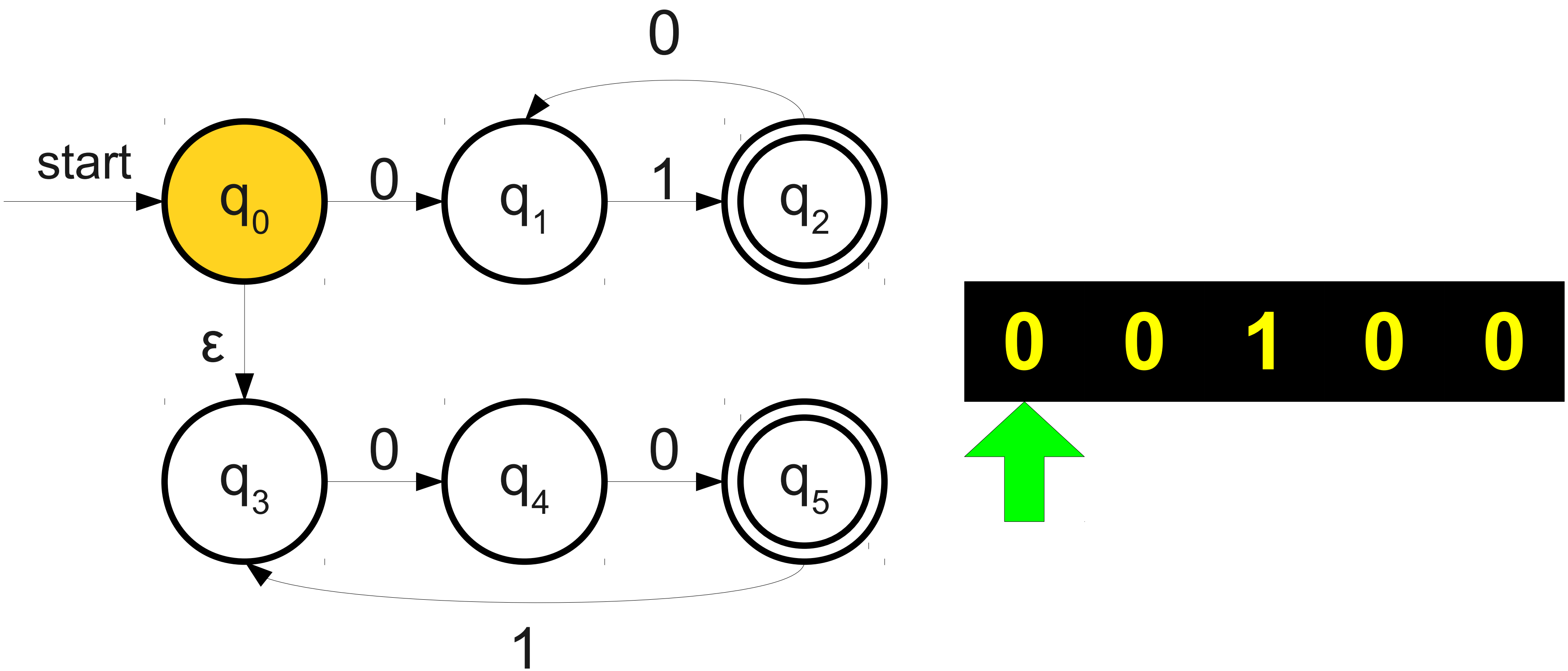

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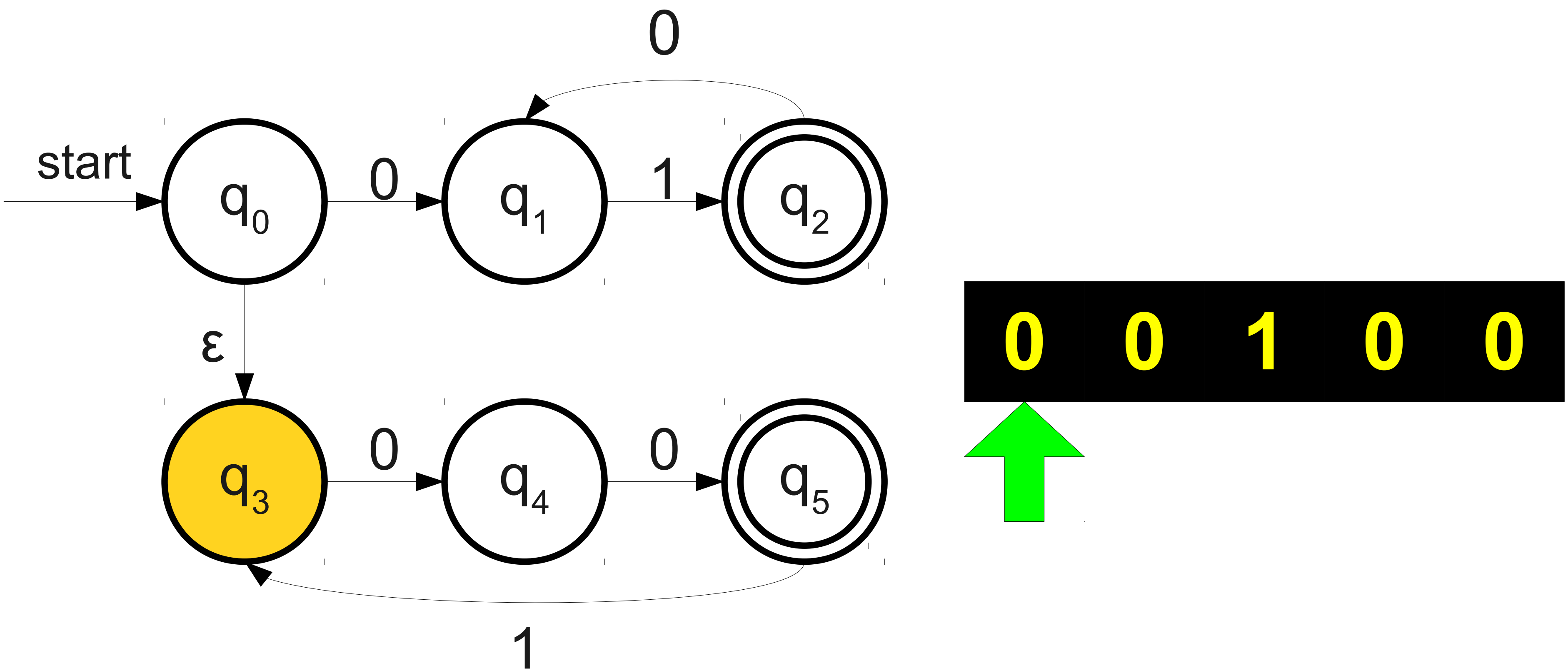

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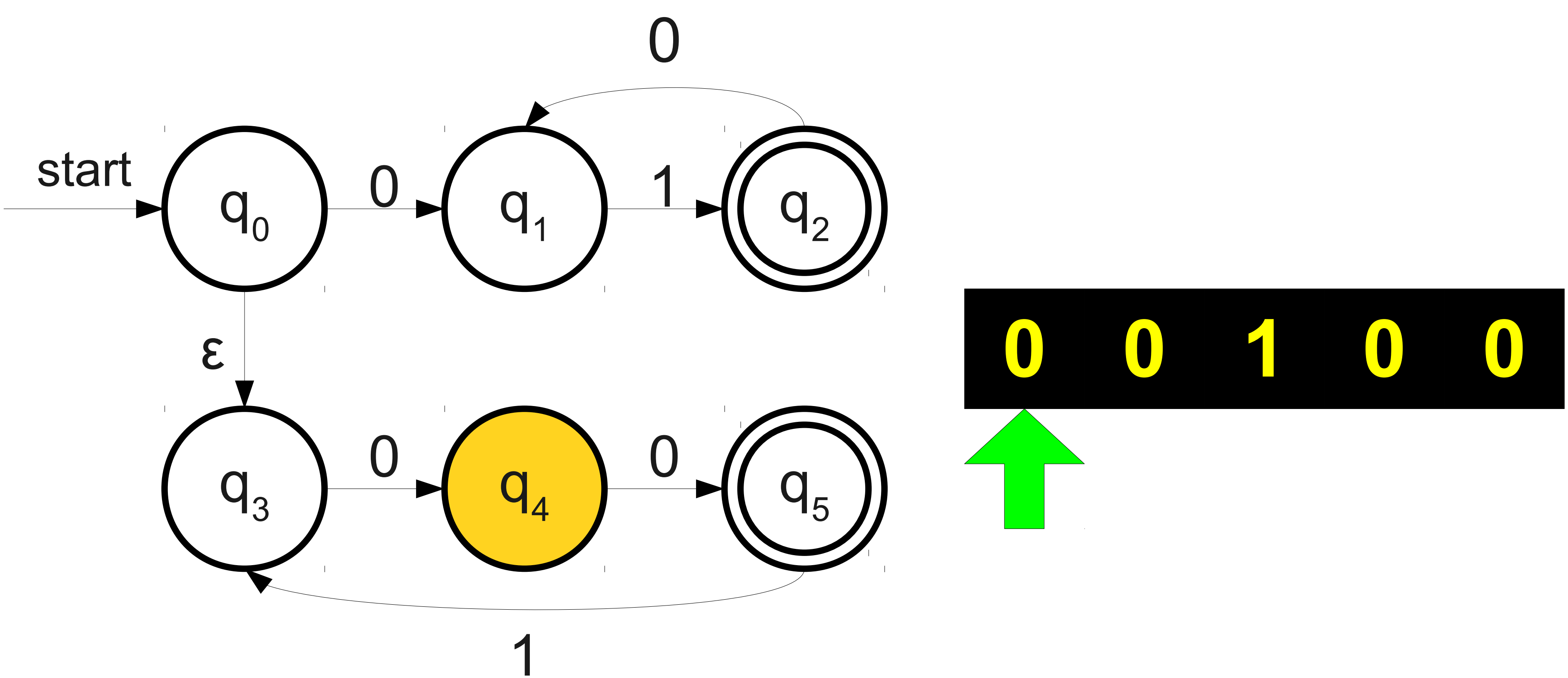

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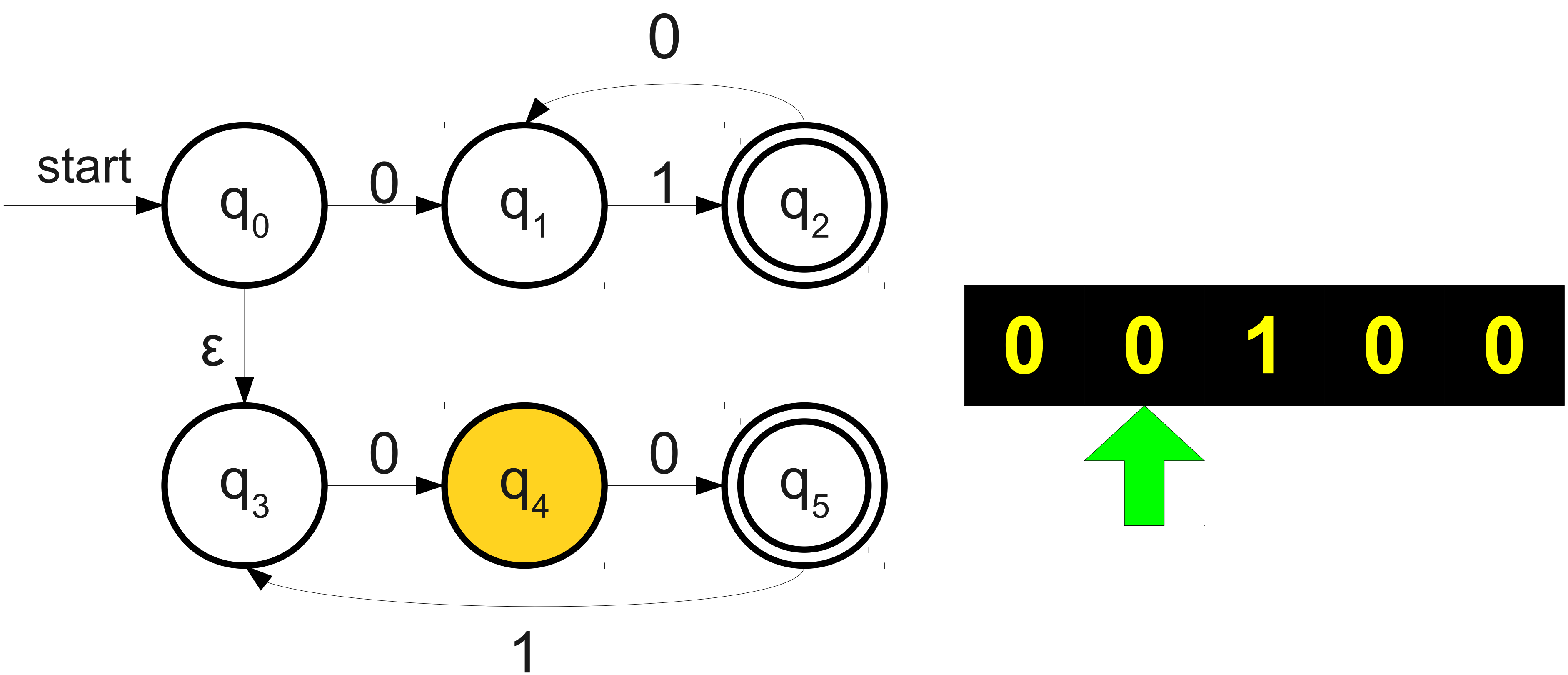

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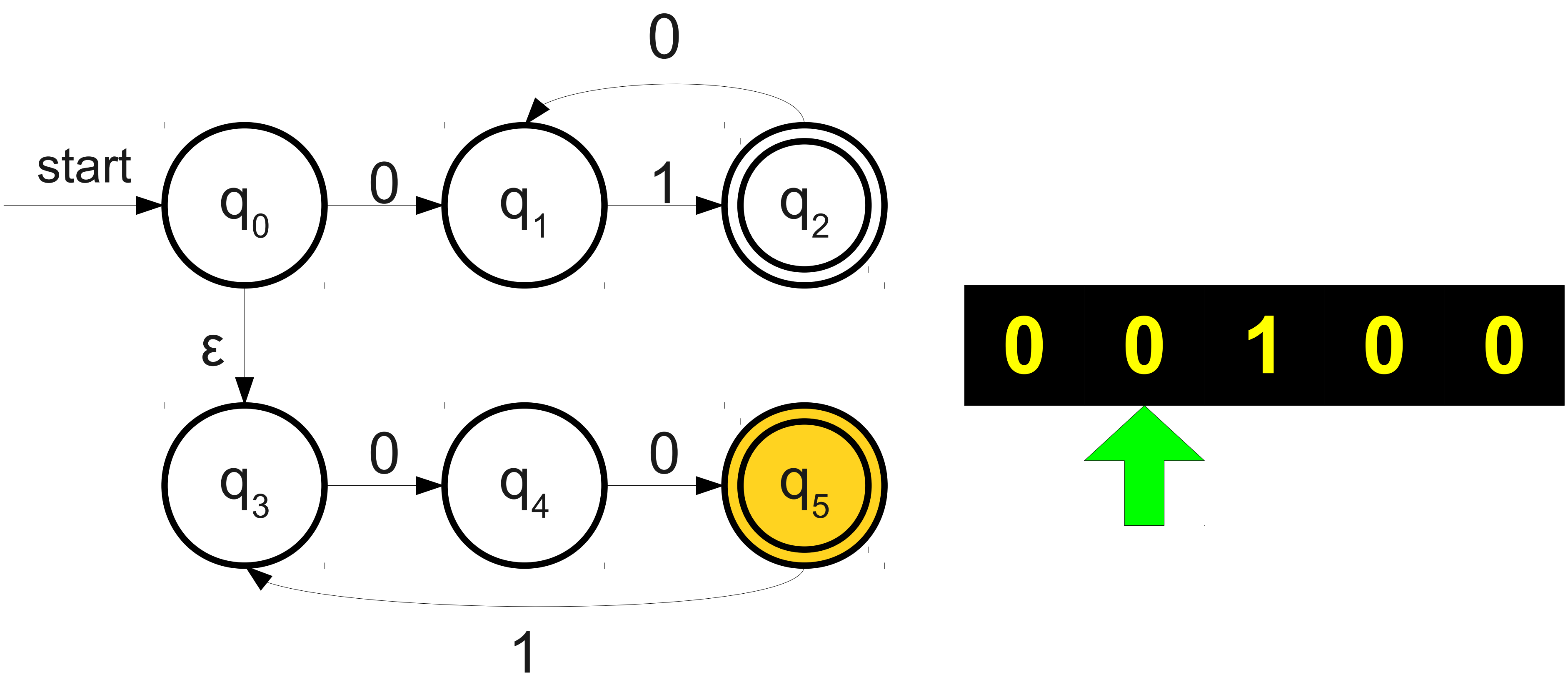

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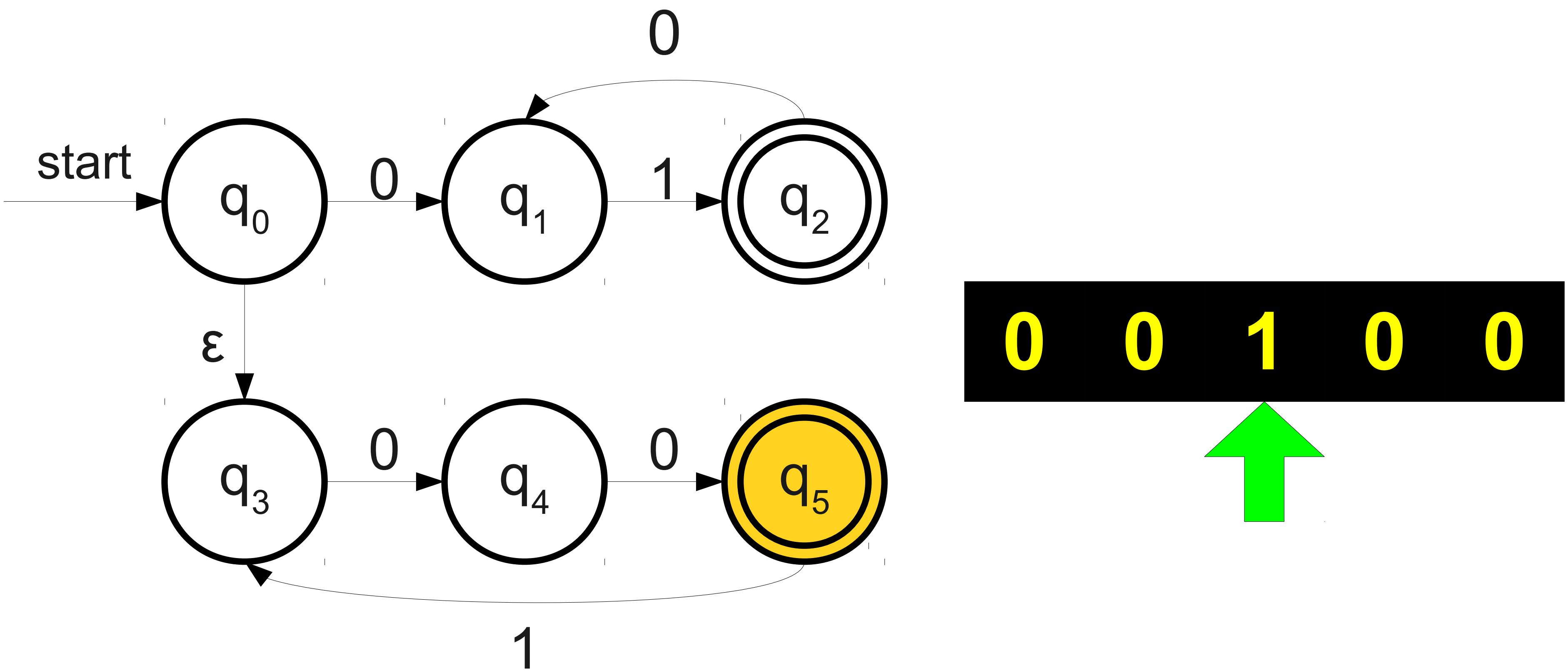

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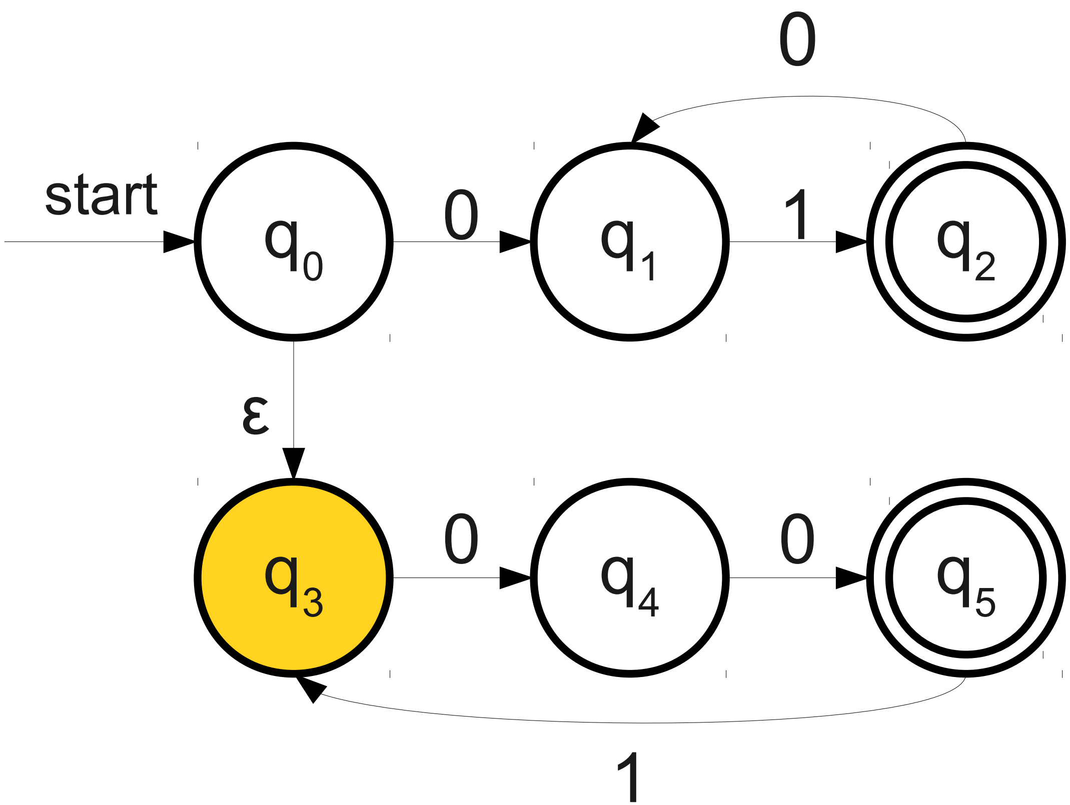

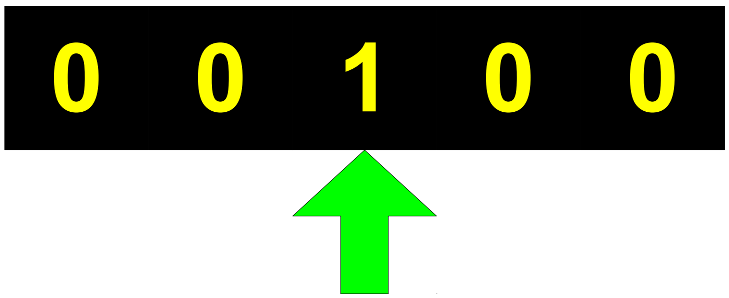

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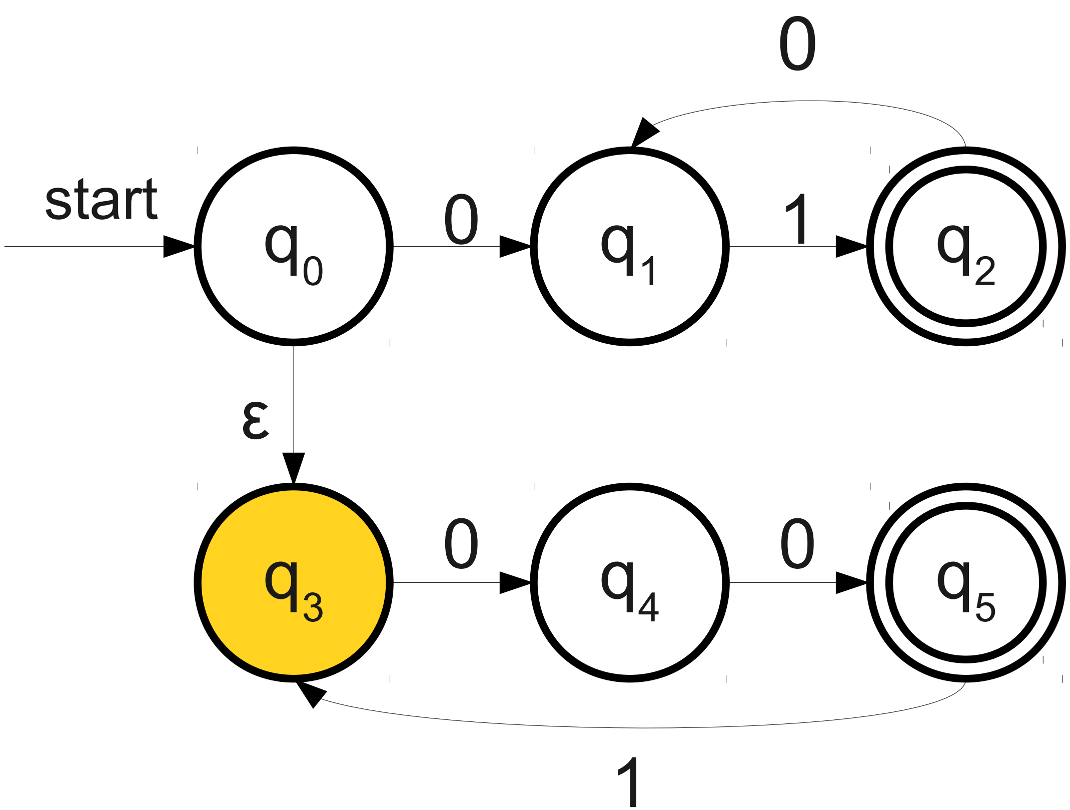

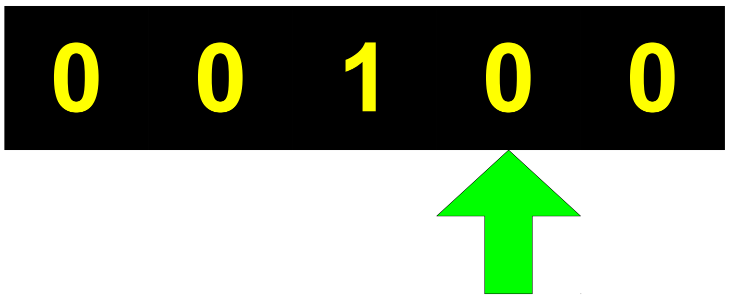

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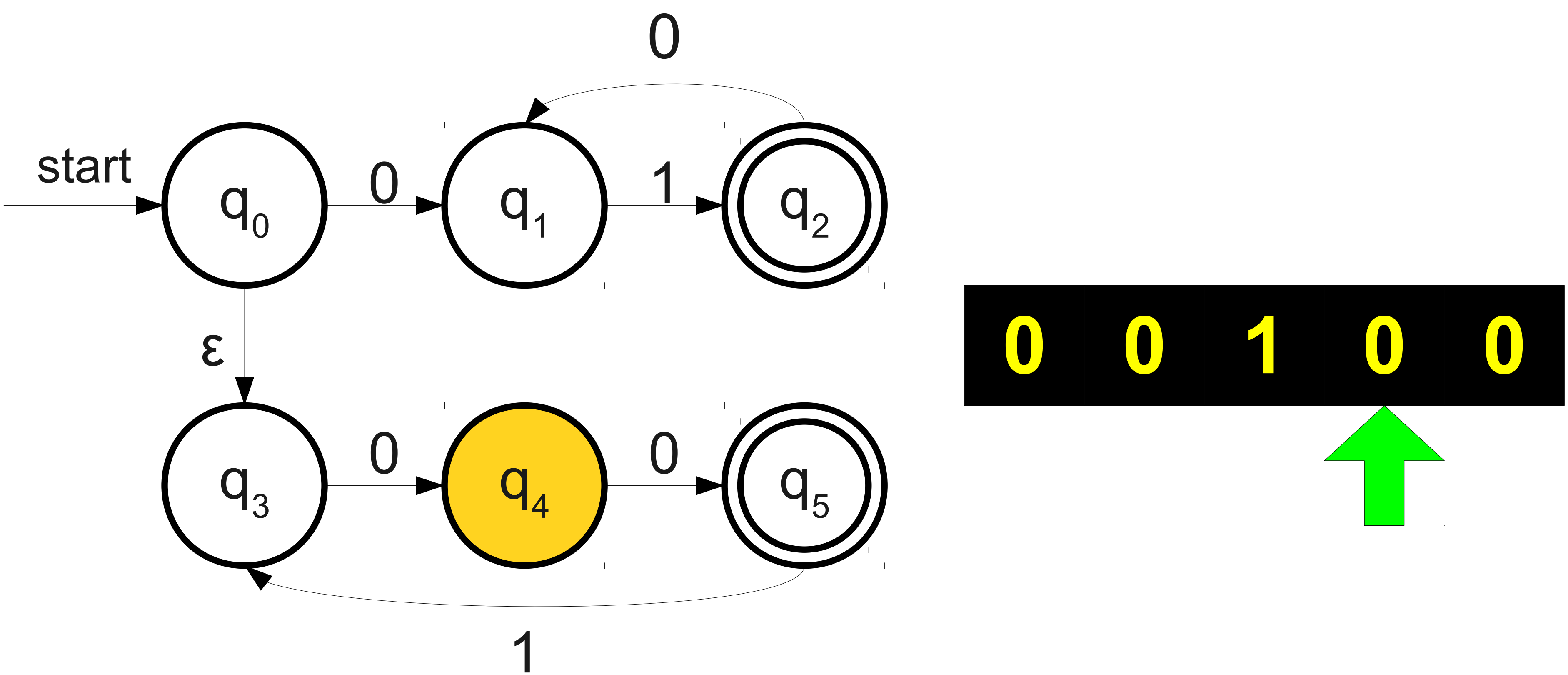

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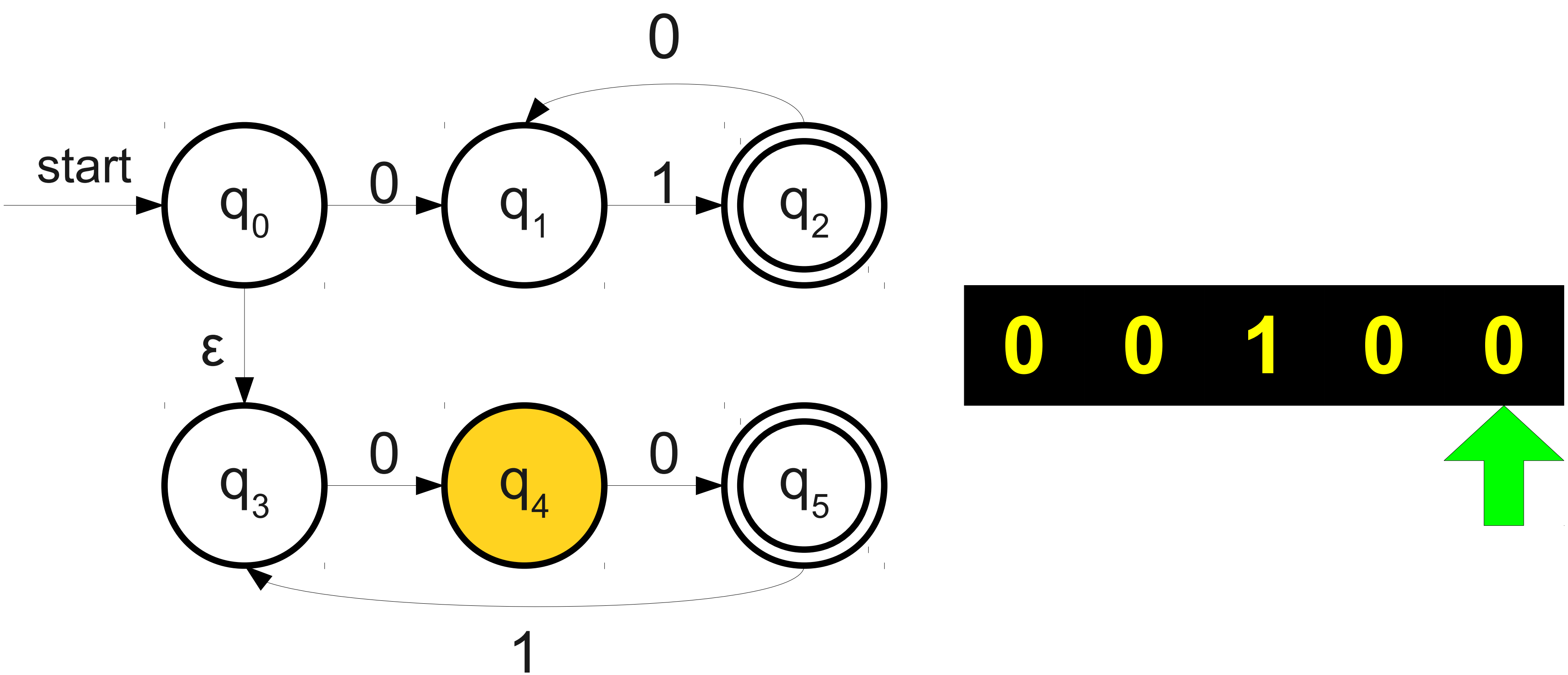

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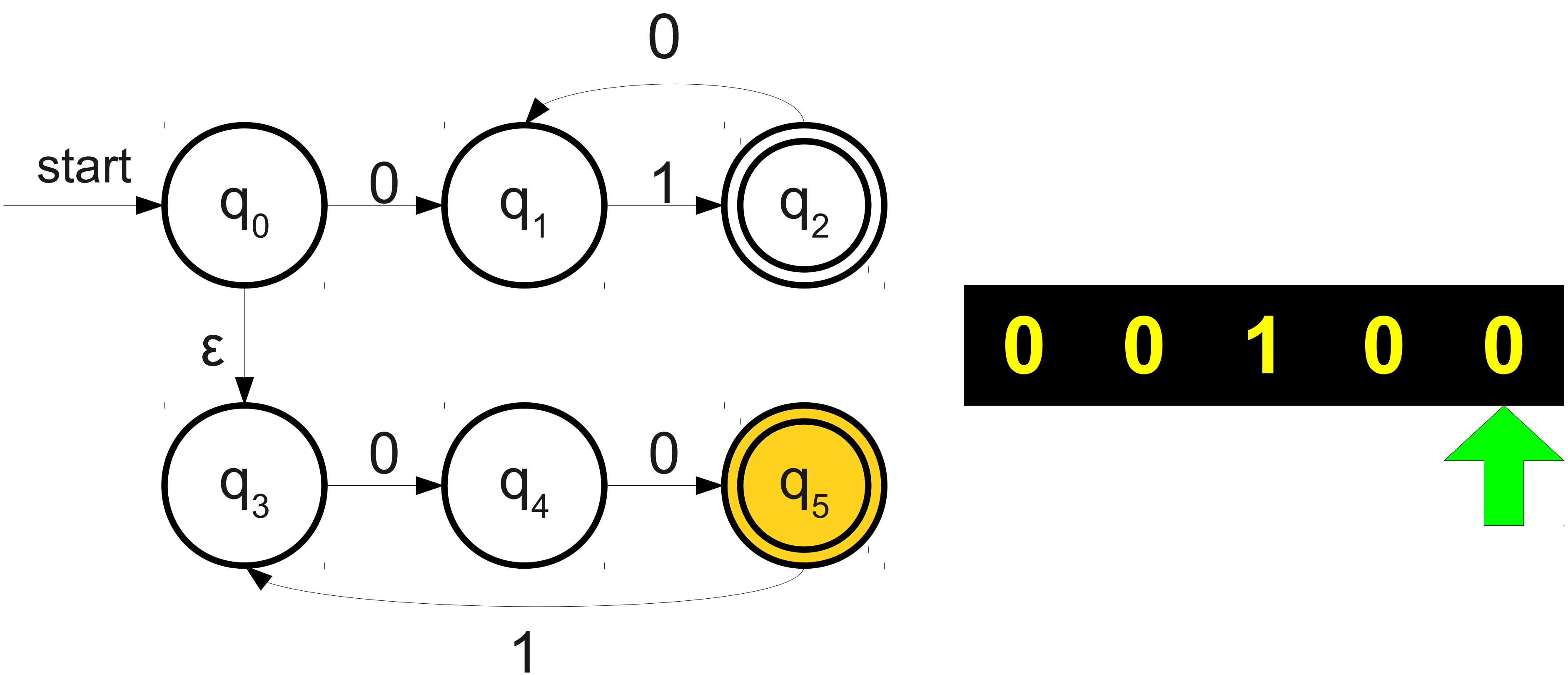

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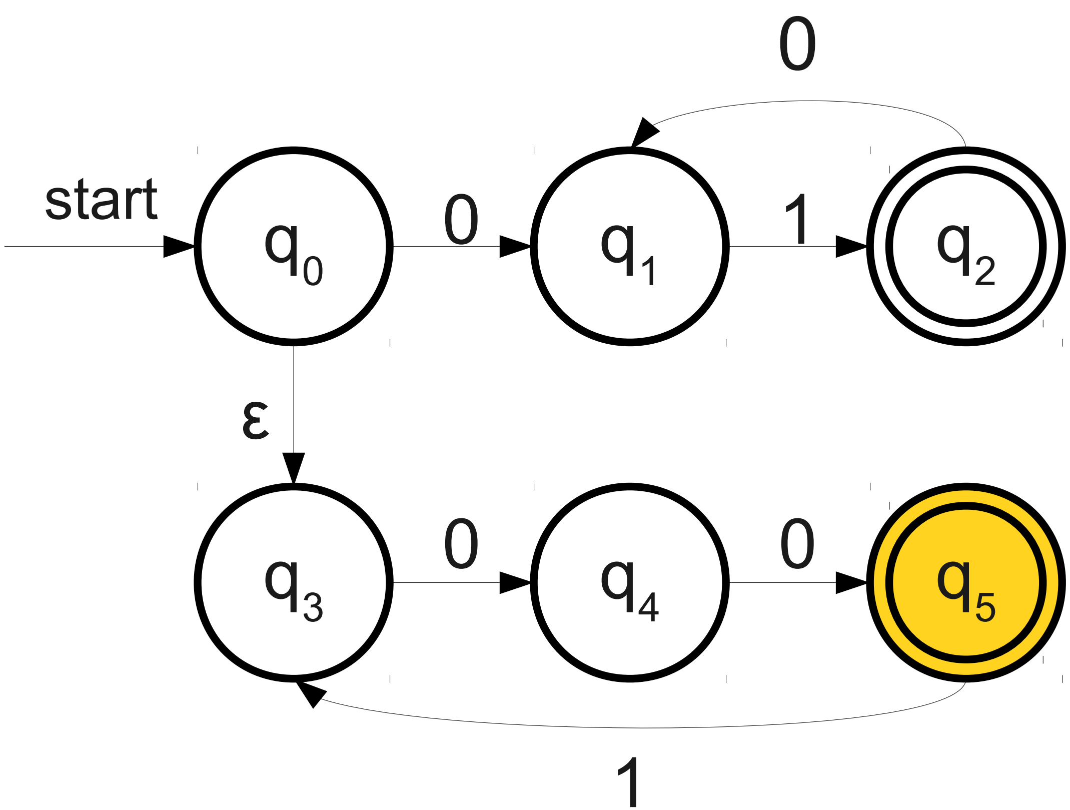

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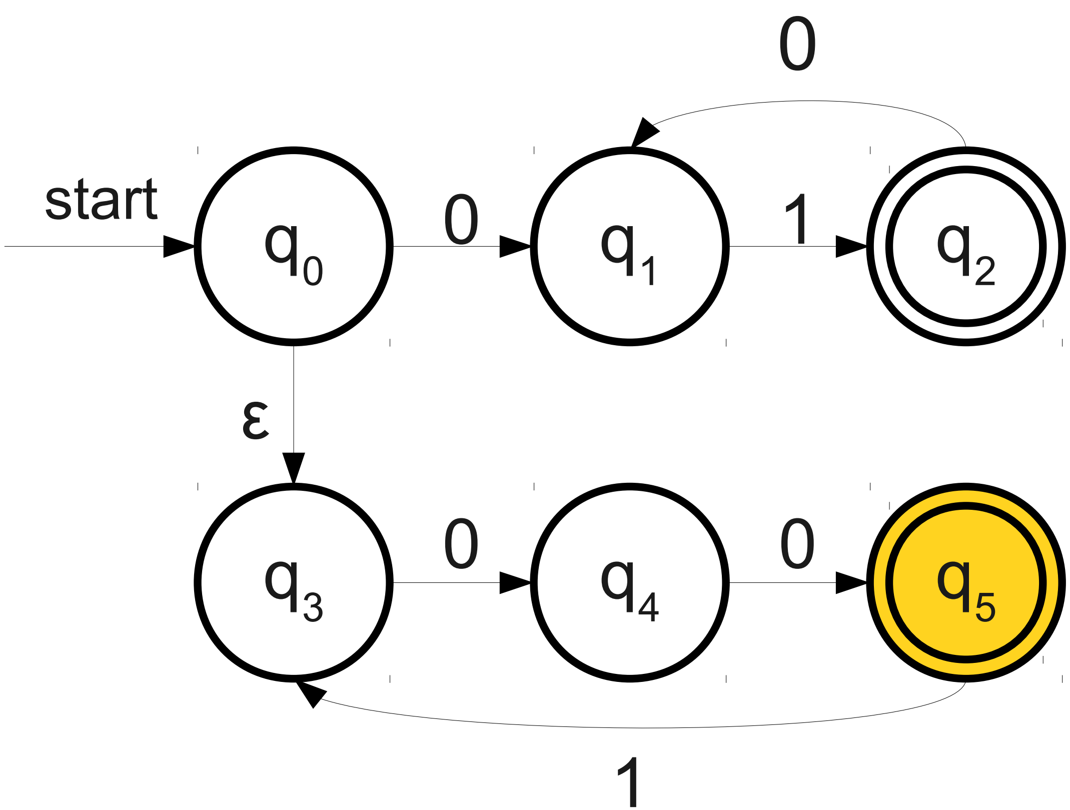

0	0	1	0	0

Designing NFAs

Designing NFAs

- When designing NFAs, *embrace the nondeterminism!*
- Good model: **Guess-and-check**:
  - Have the machine *nondeterministically guess* what the right choice is.
  - Have the machine *deterministically check* that the choice was correct.

Guess-and-Check

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

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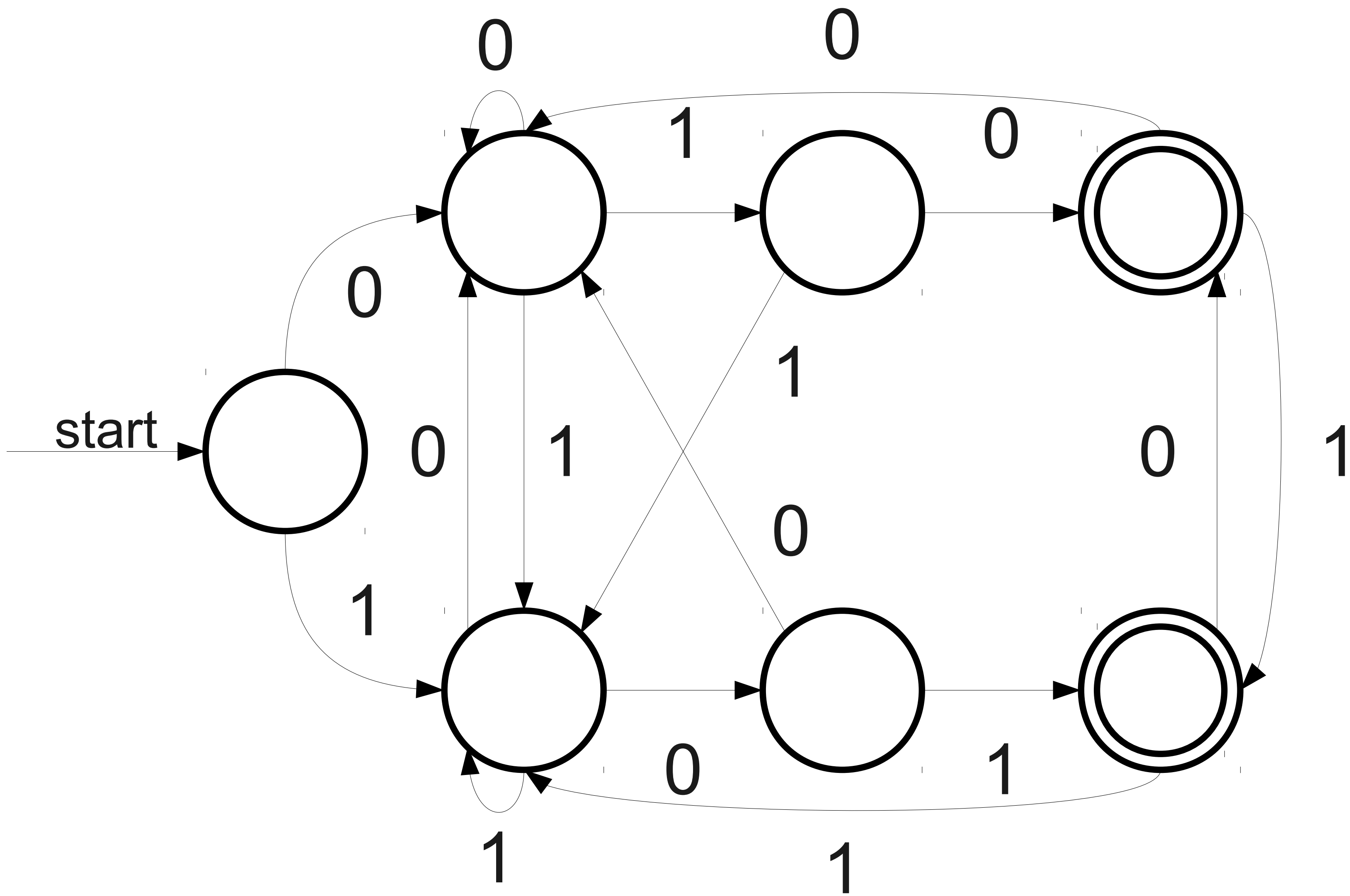

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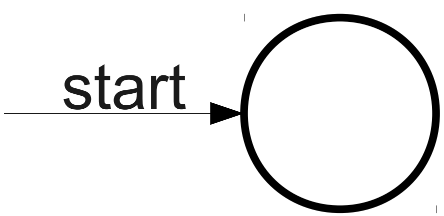

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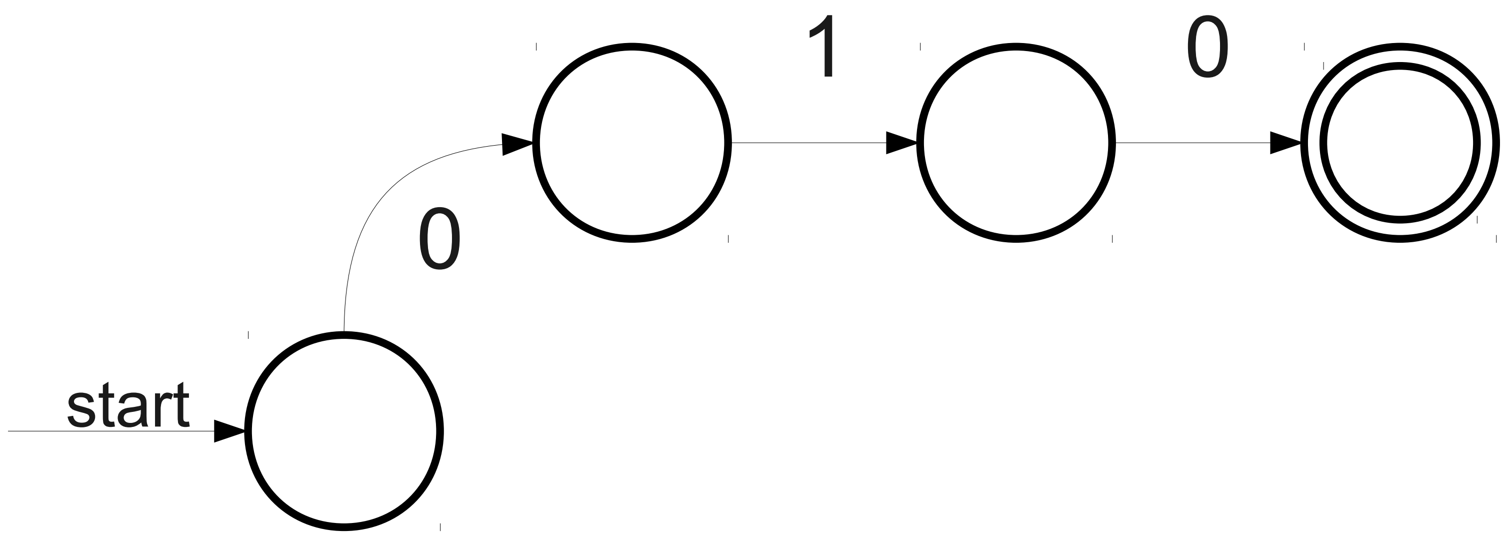

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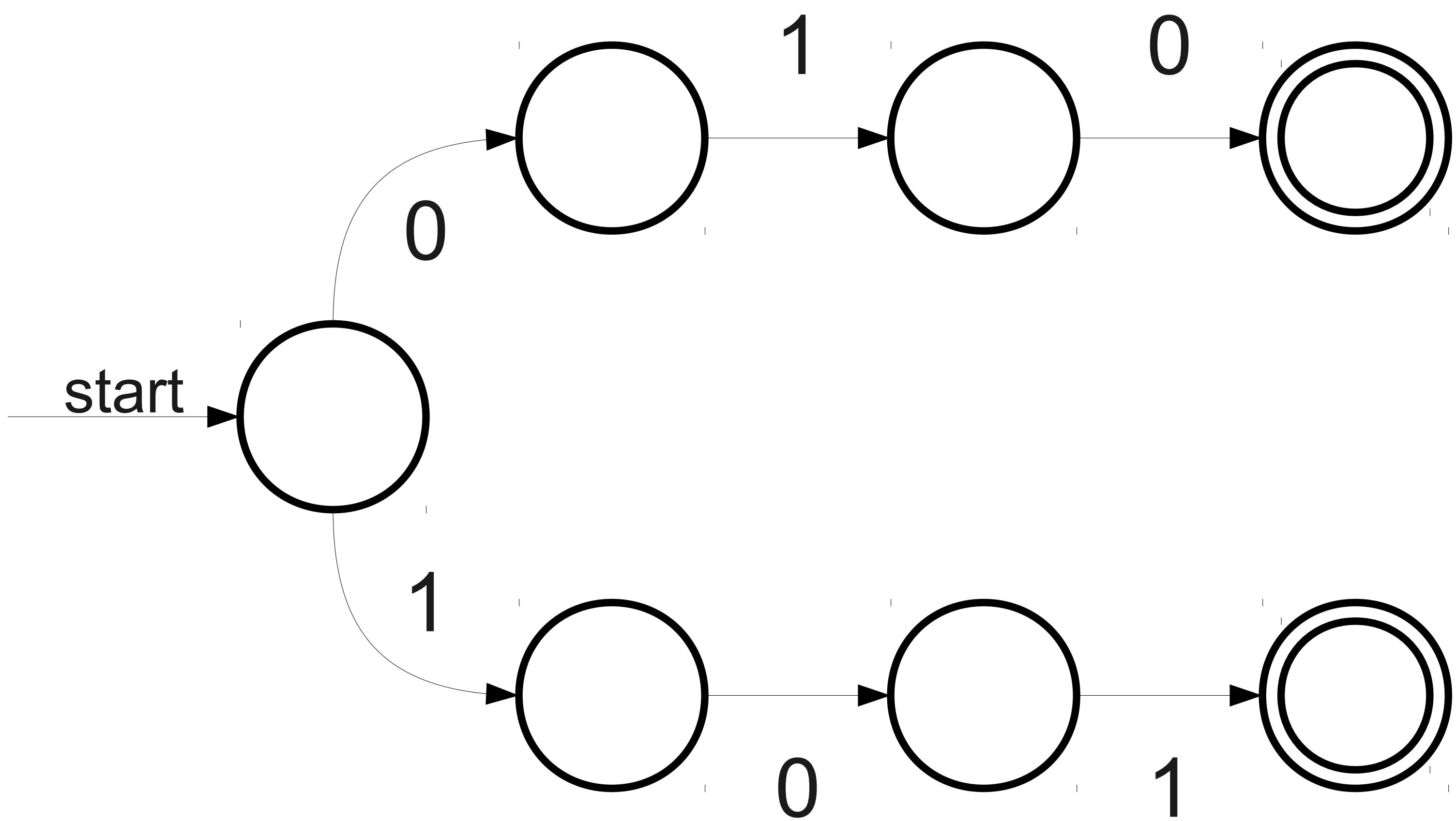
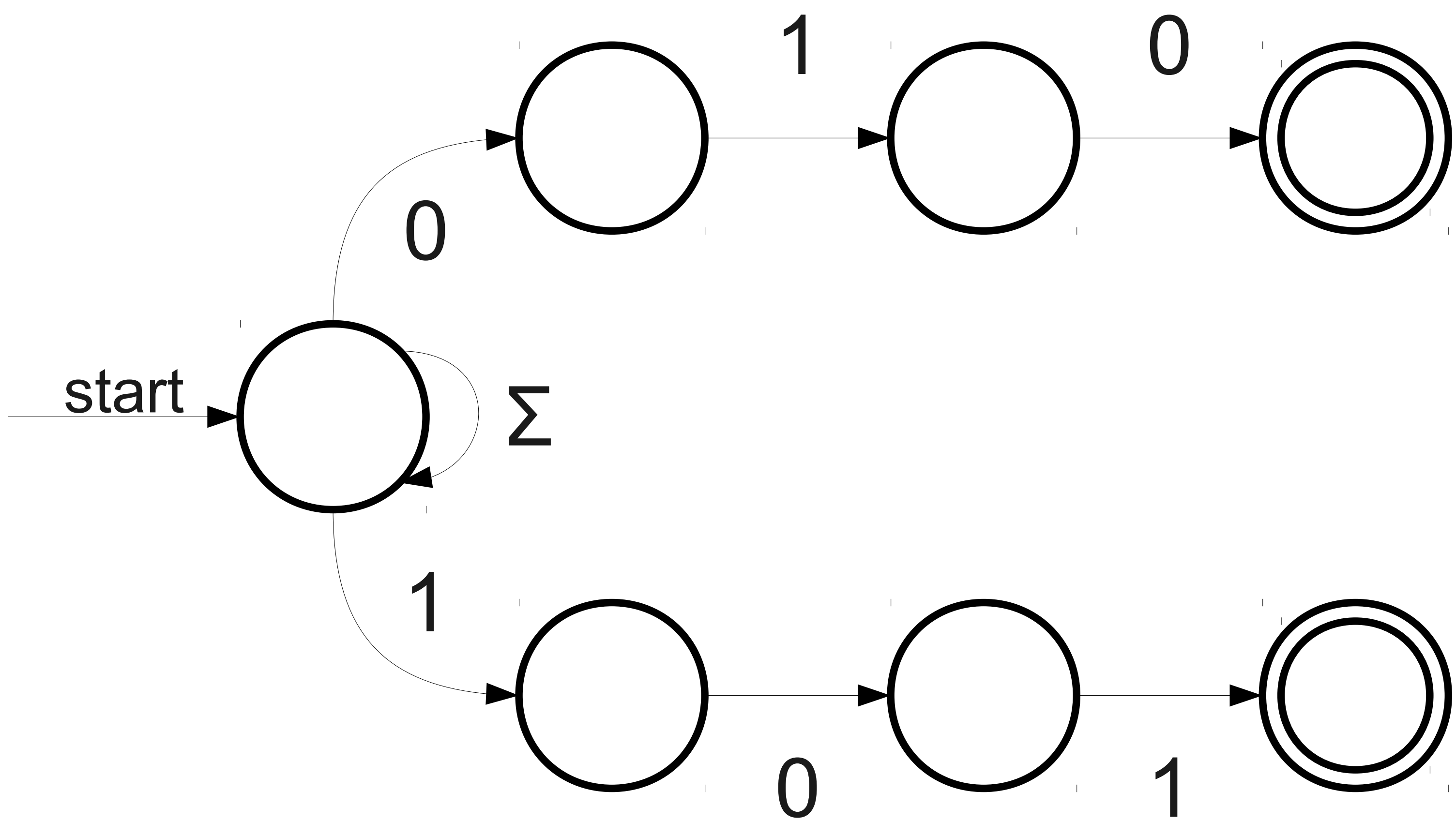


Guess-and-Check

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

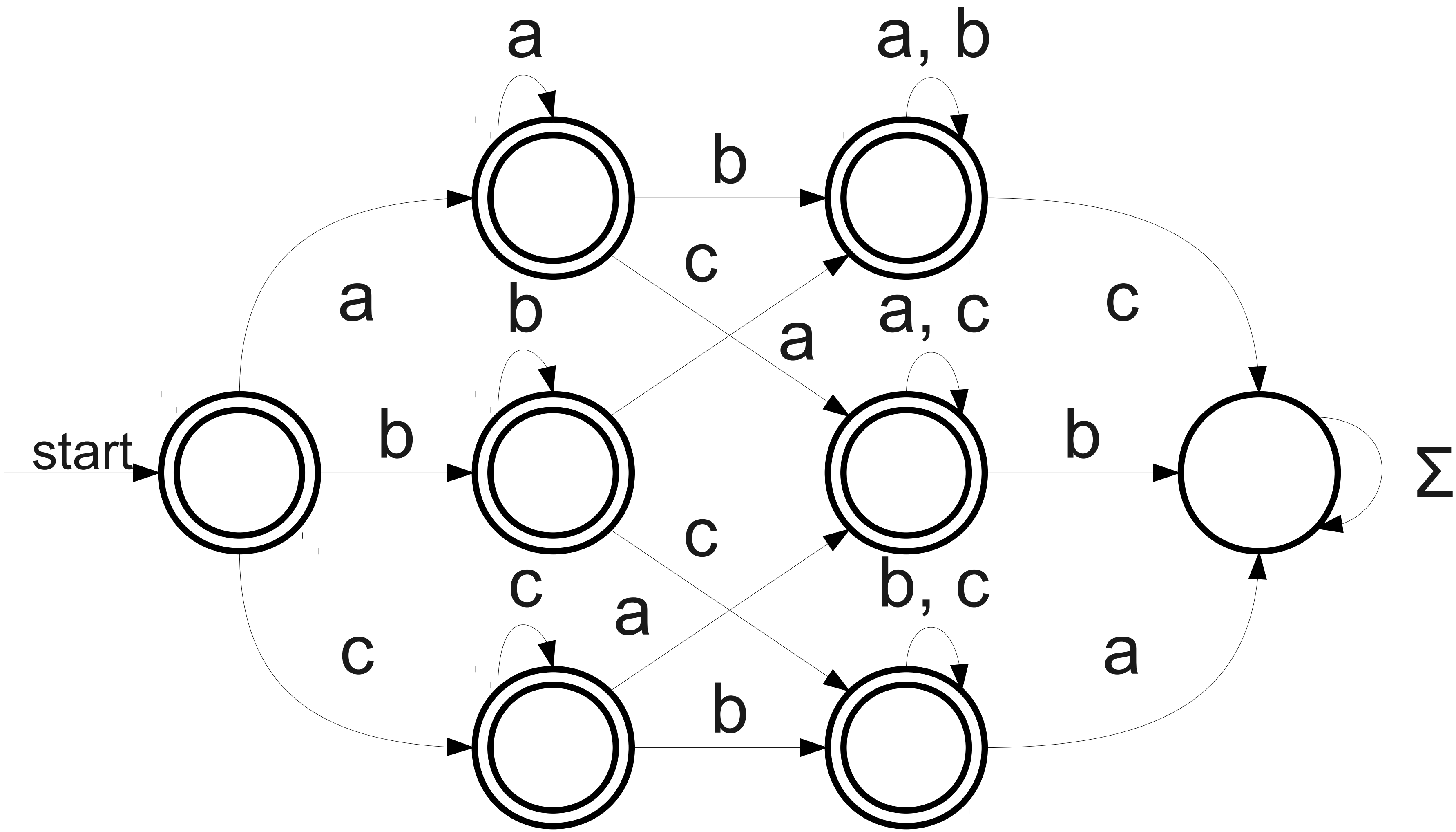


Guess-and-Check

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

Guess-and-Check

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



Guess-and-Check

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

Guess-and-Check

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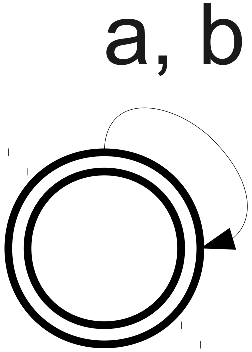
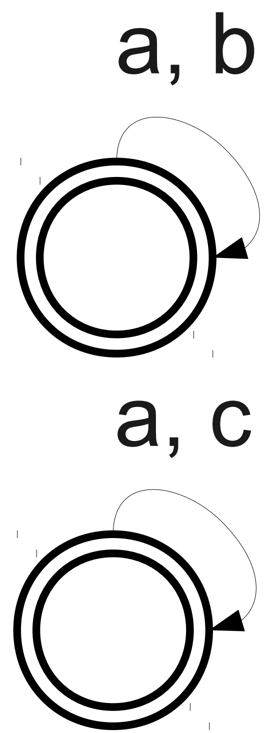


Guess-and-Check

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



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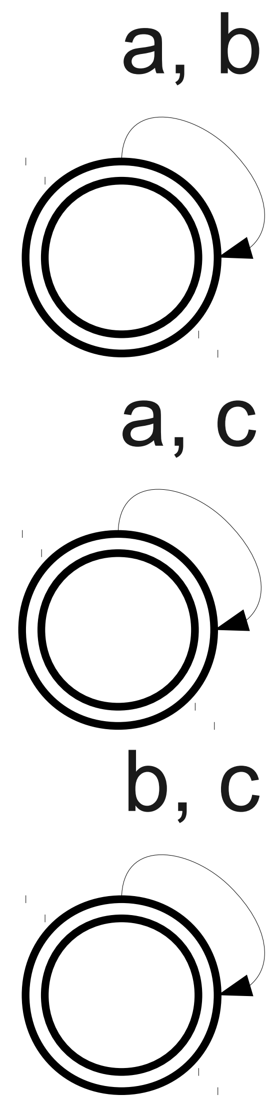

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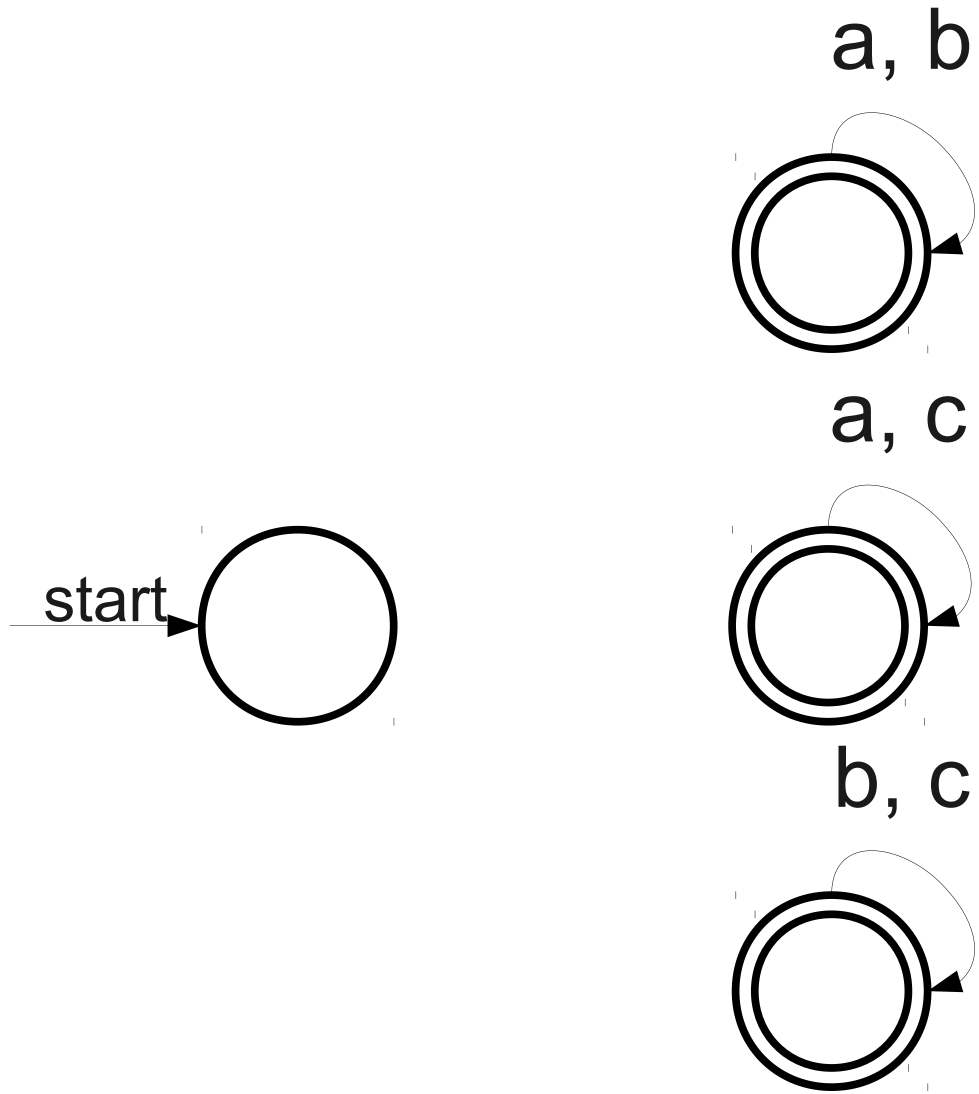

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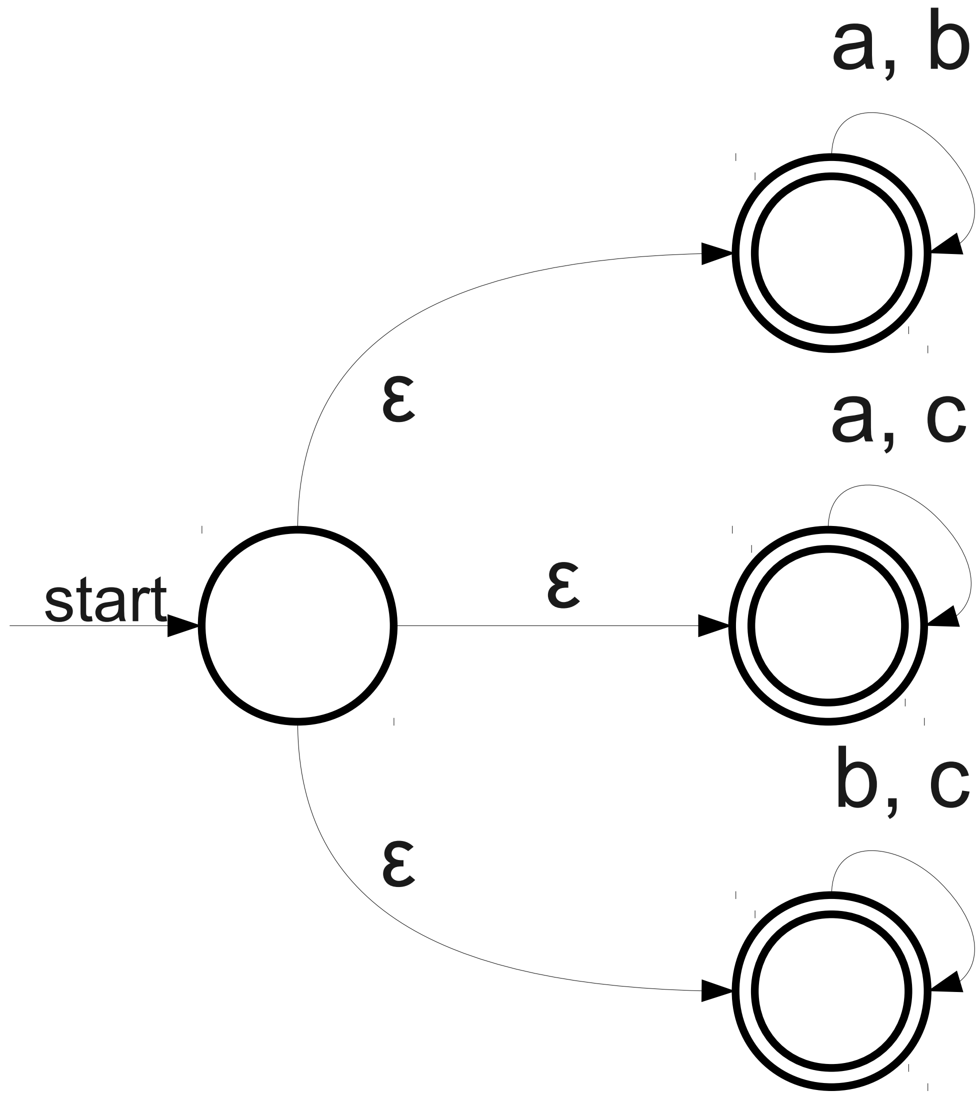


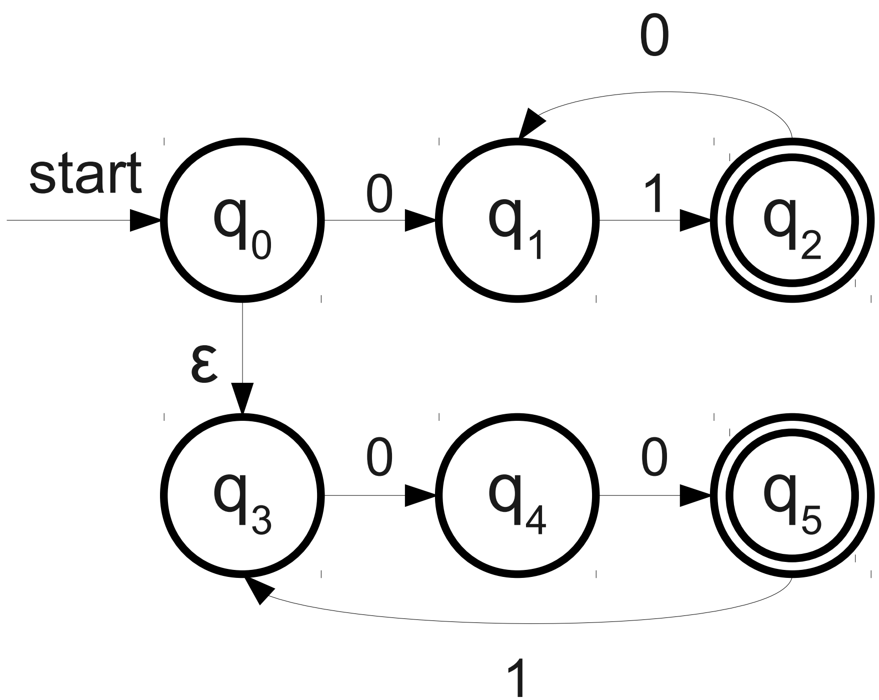
NFAs and DFAs

- Any language that can be accepted by a DFA can be accepted by an NFA.
- Why?
  - Just use the same set of transitions as before.
- **Question**: Can any language accepted by an NFA also be accepted by a DFA?
- Surprisingly, the answer is **yes!**

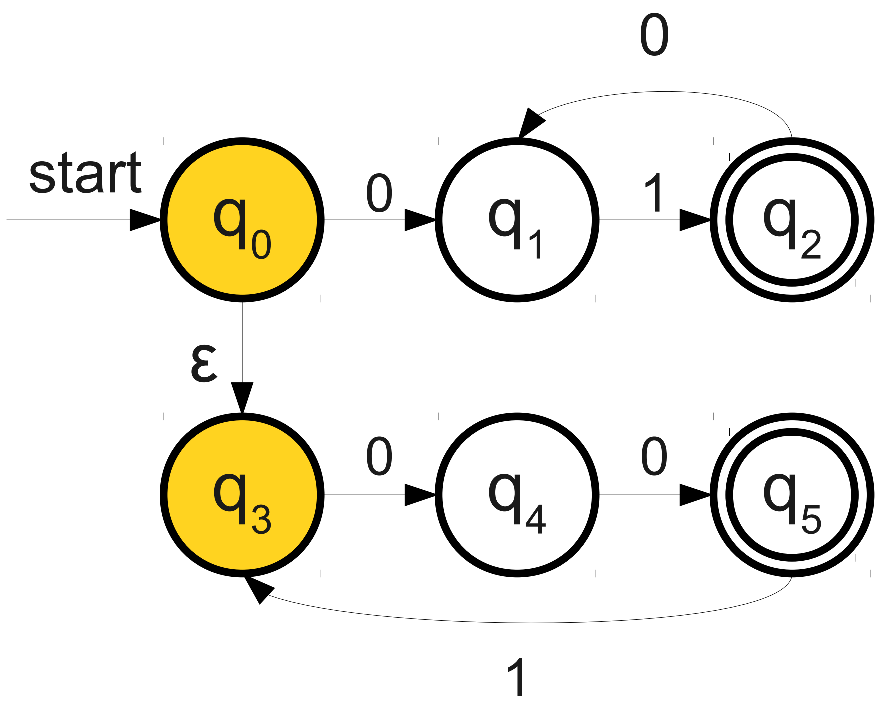
Simulation

- **Simulation** is a key technique in computability theory.
- If we can build an automaton A' whose behavior ***simulates*** that of another automaton A, then we can make a connection between A and A'.
- To show that any language accepted by an NFA can be accepted by a DFA, we will show how to make a DFA that ***simulates*** the execution of an NFA.

Simulating an NFA with a DFA



Simulating an NFA with a DFA



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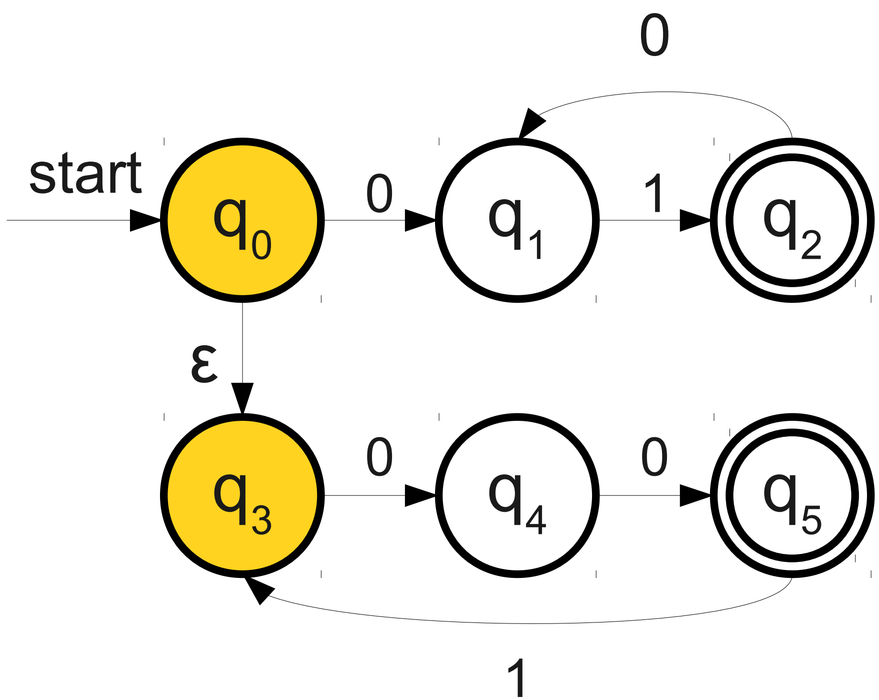

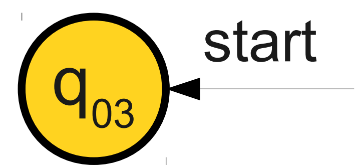

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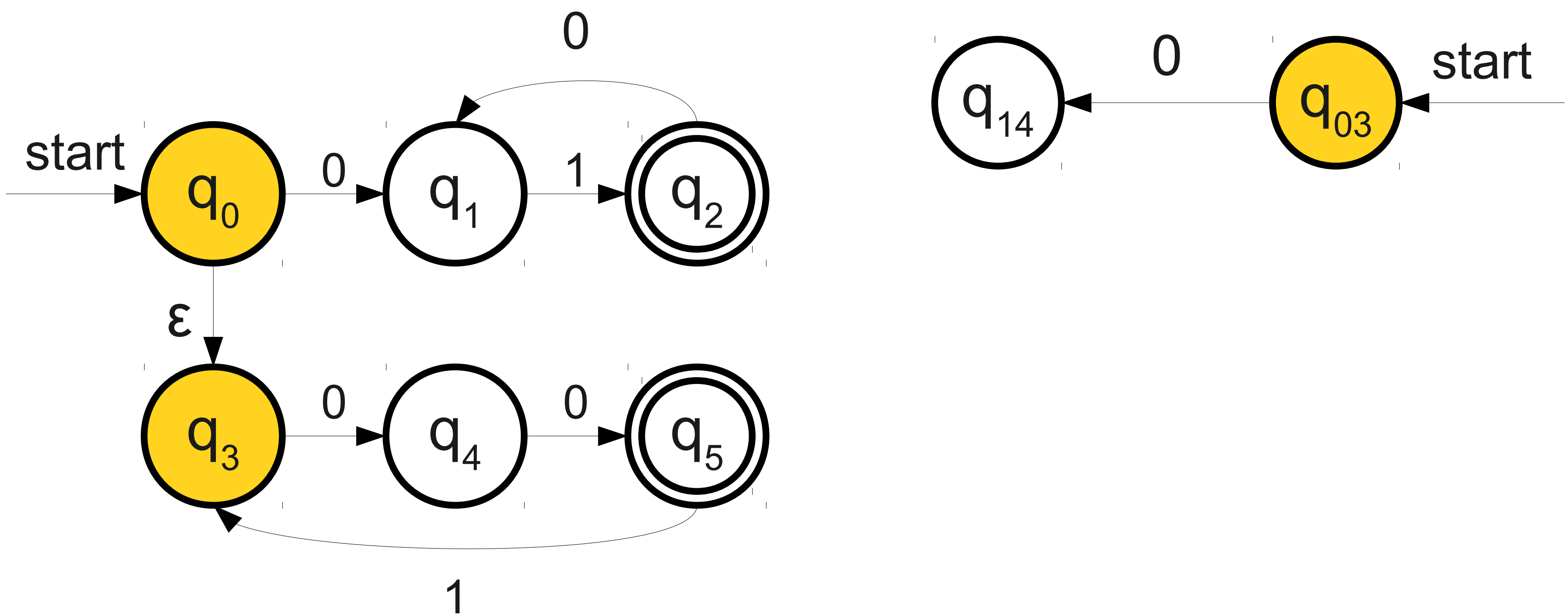

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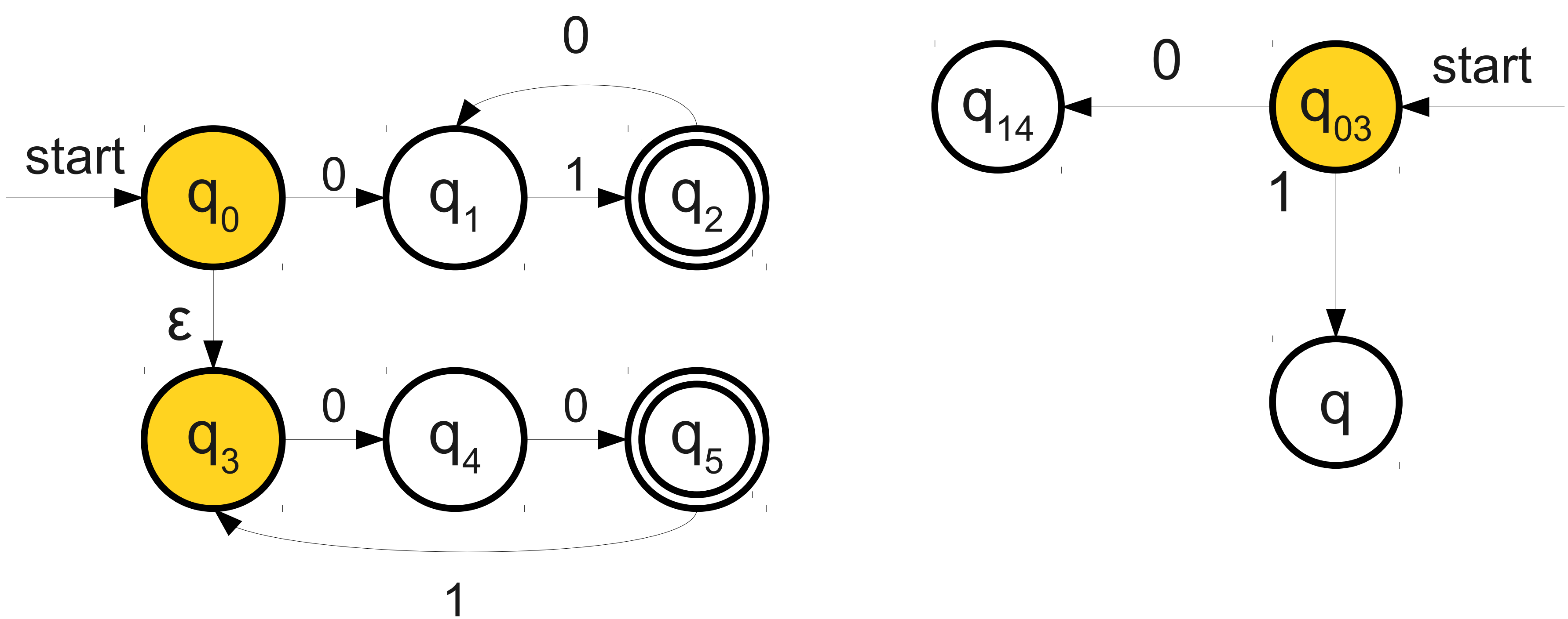

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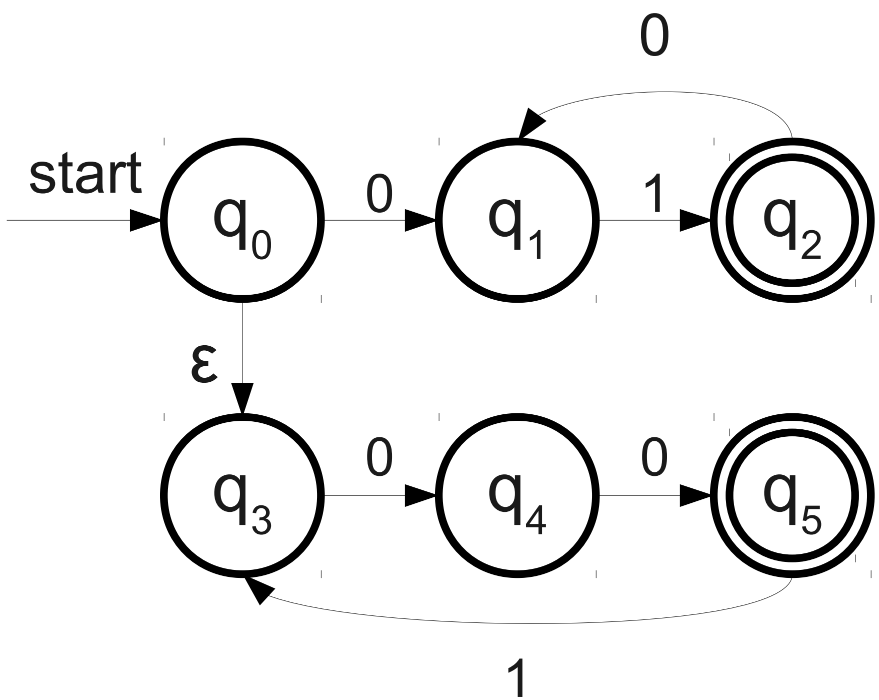

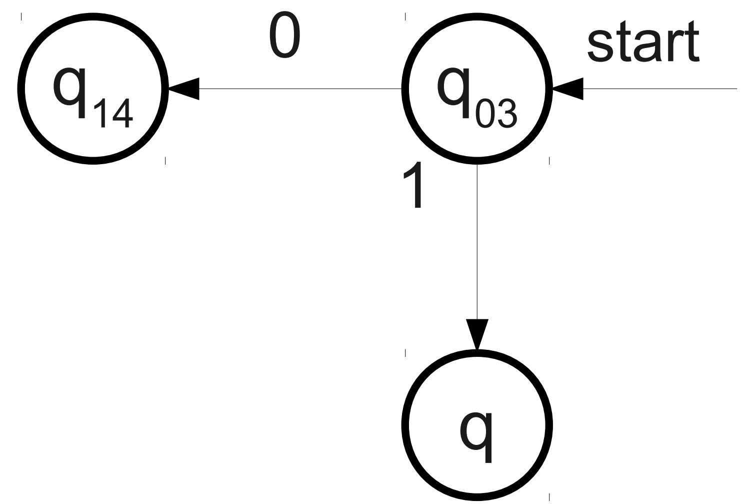

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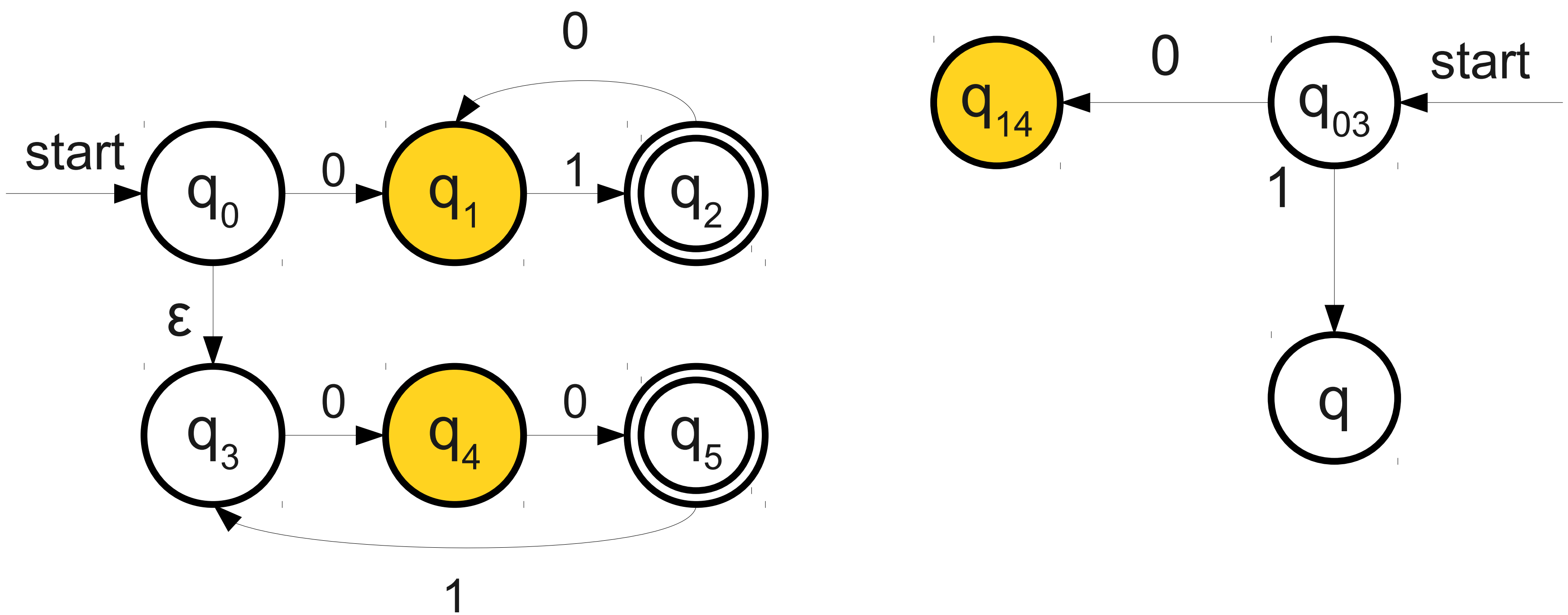

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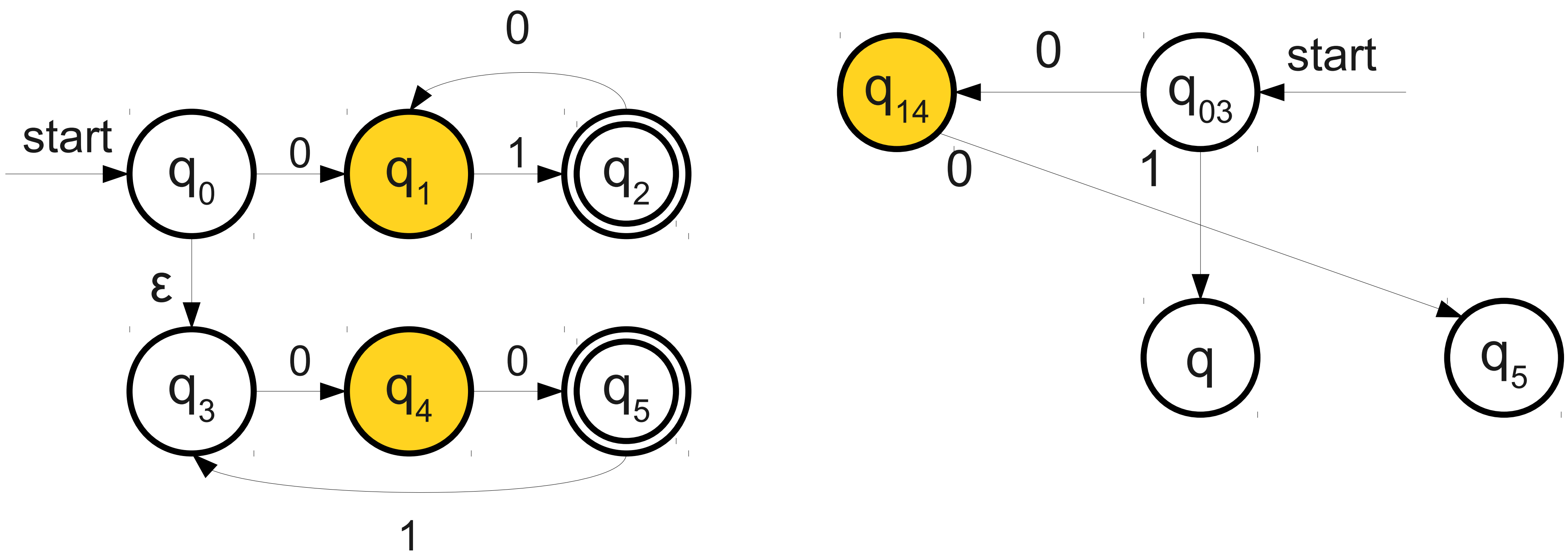

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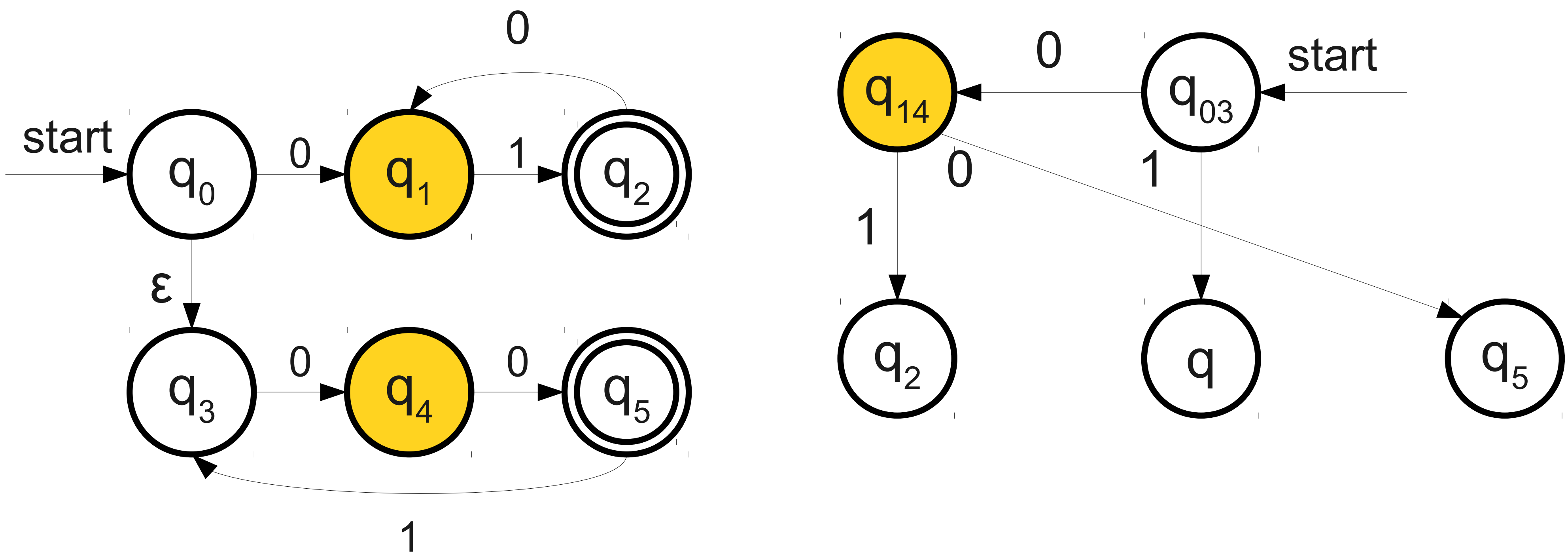

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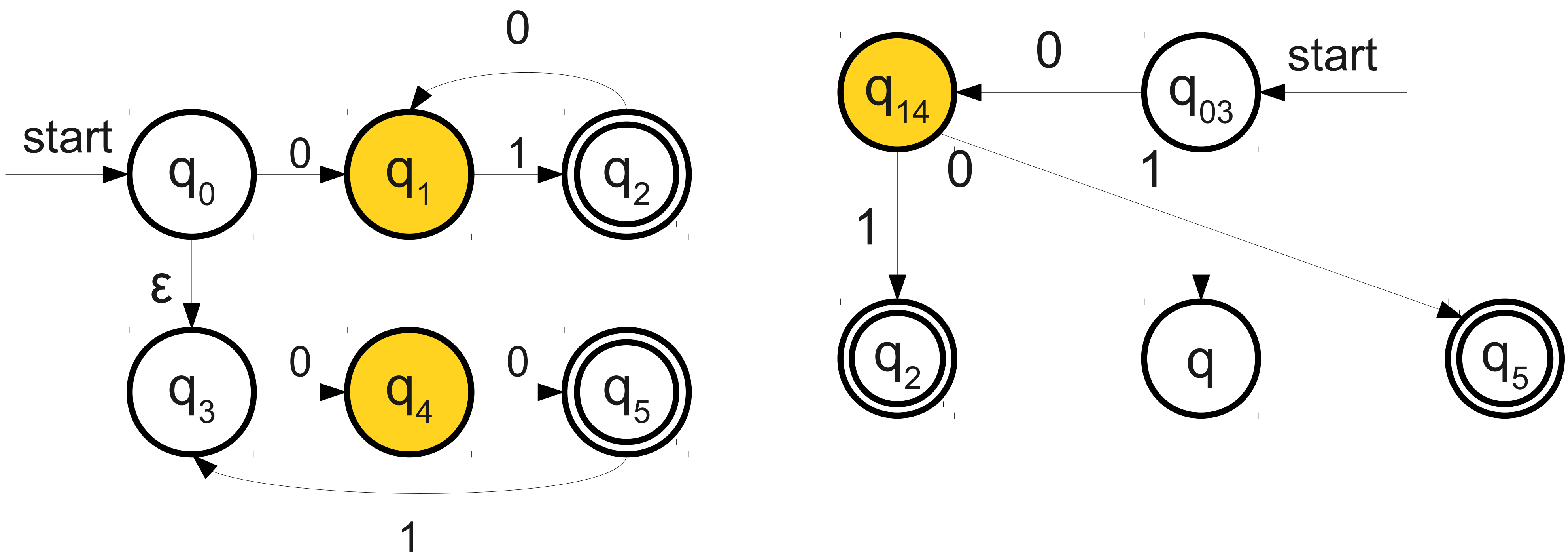

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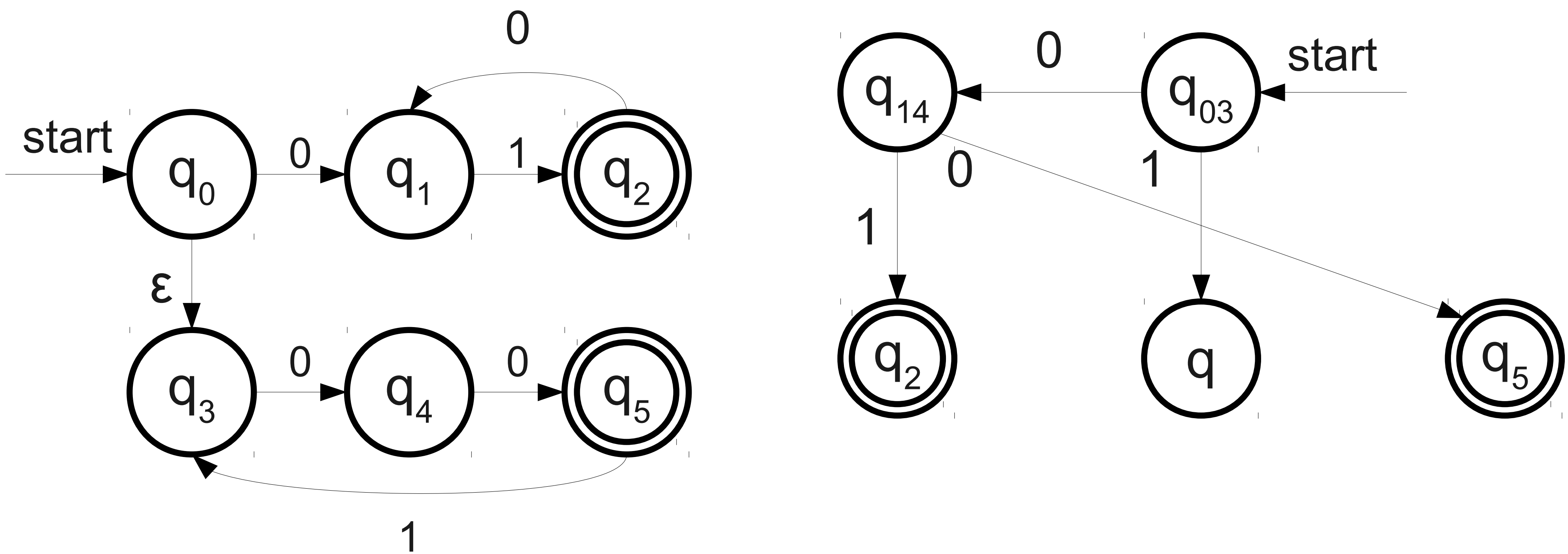

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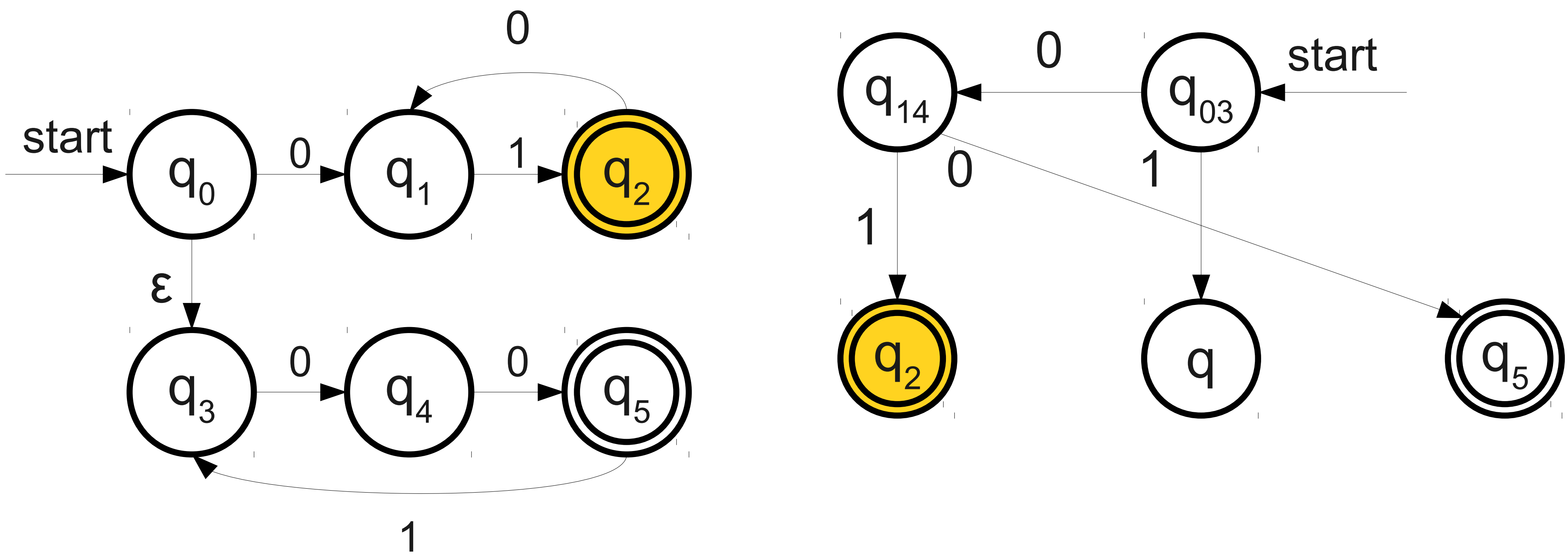

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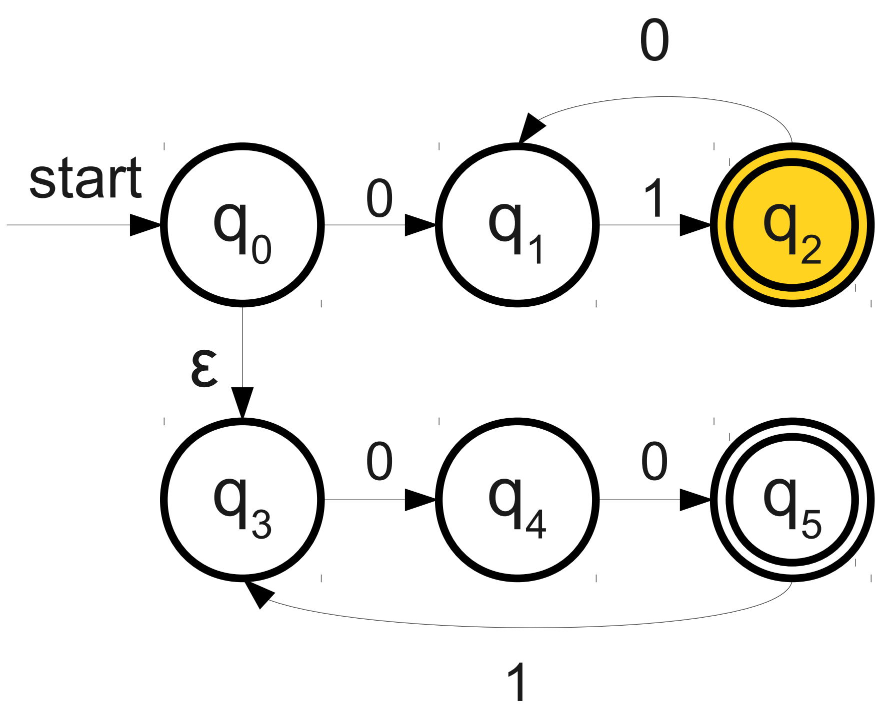

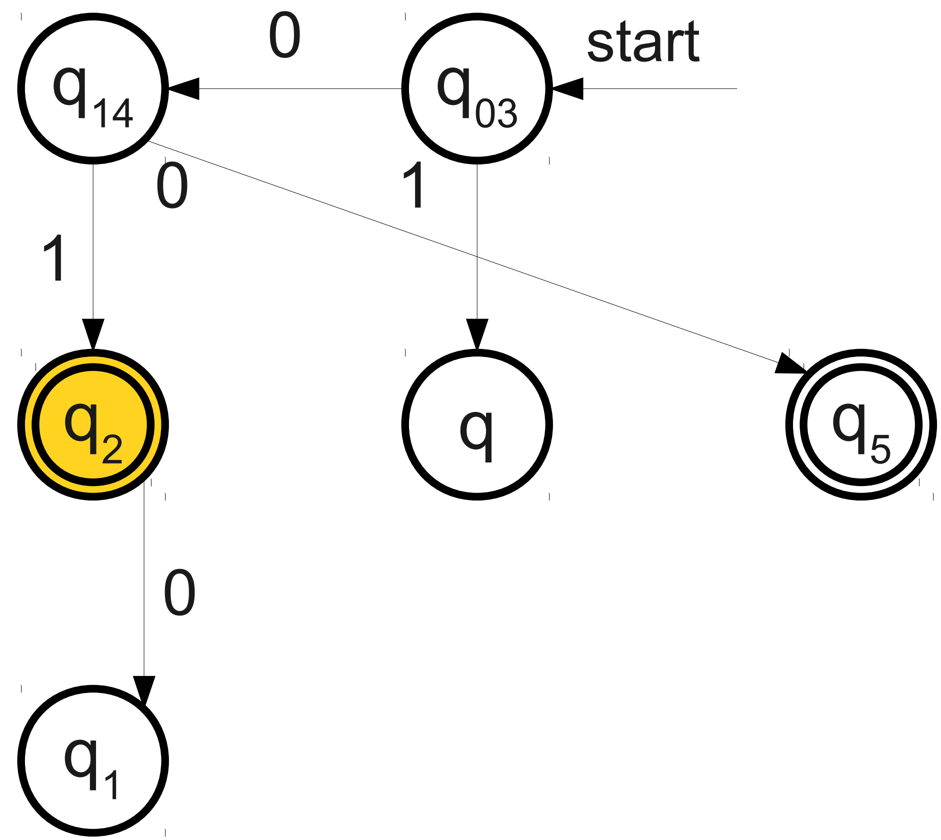

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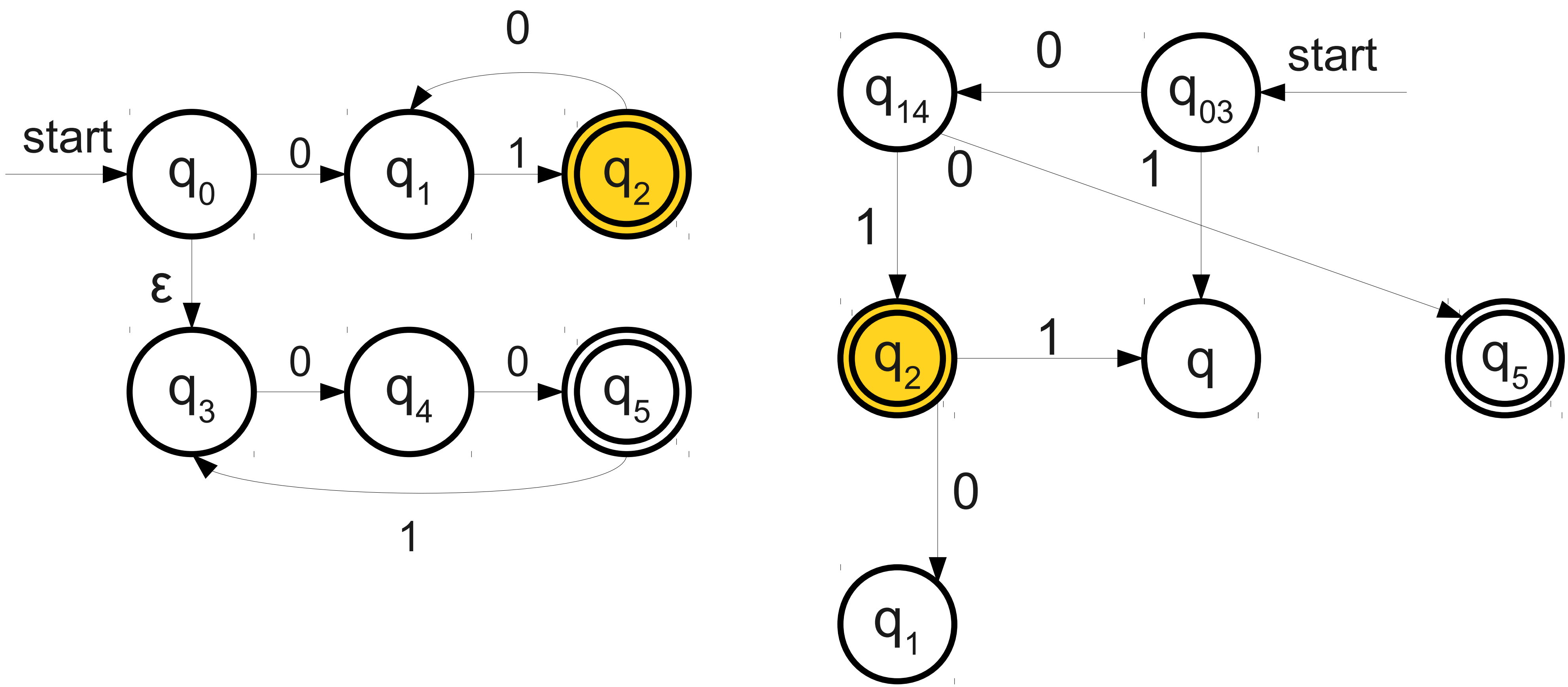

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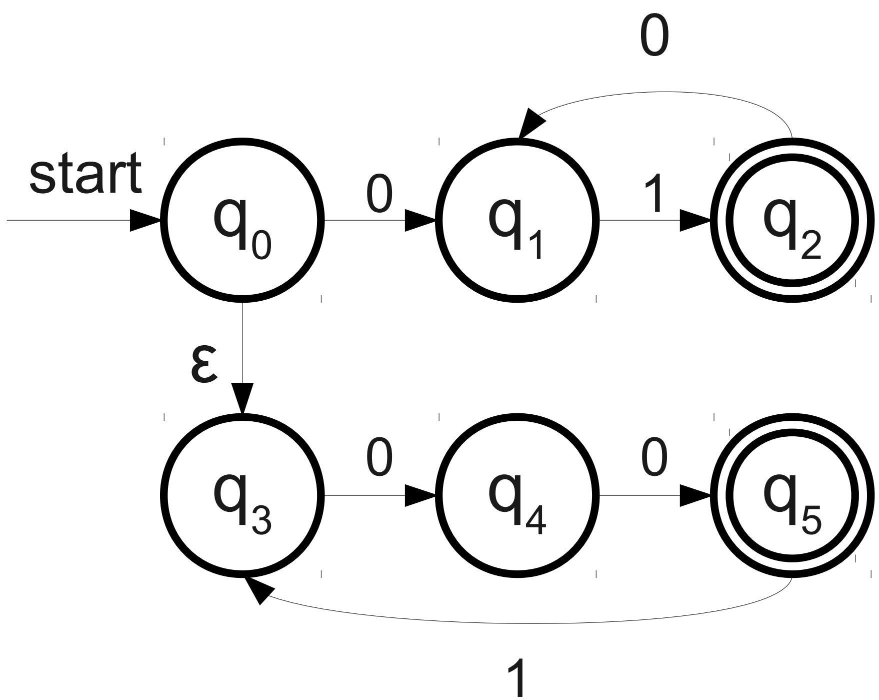

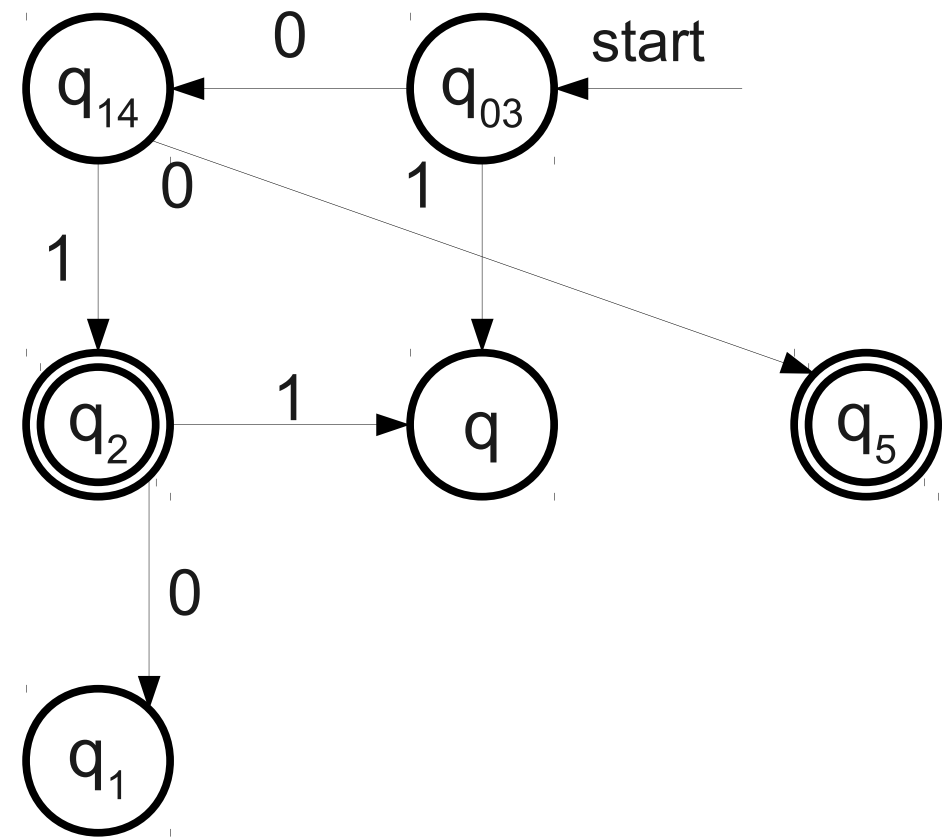

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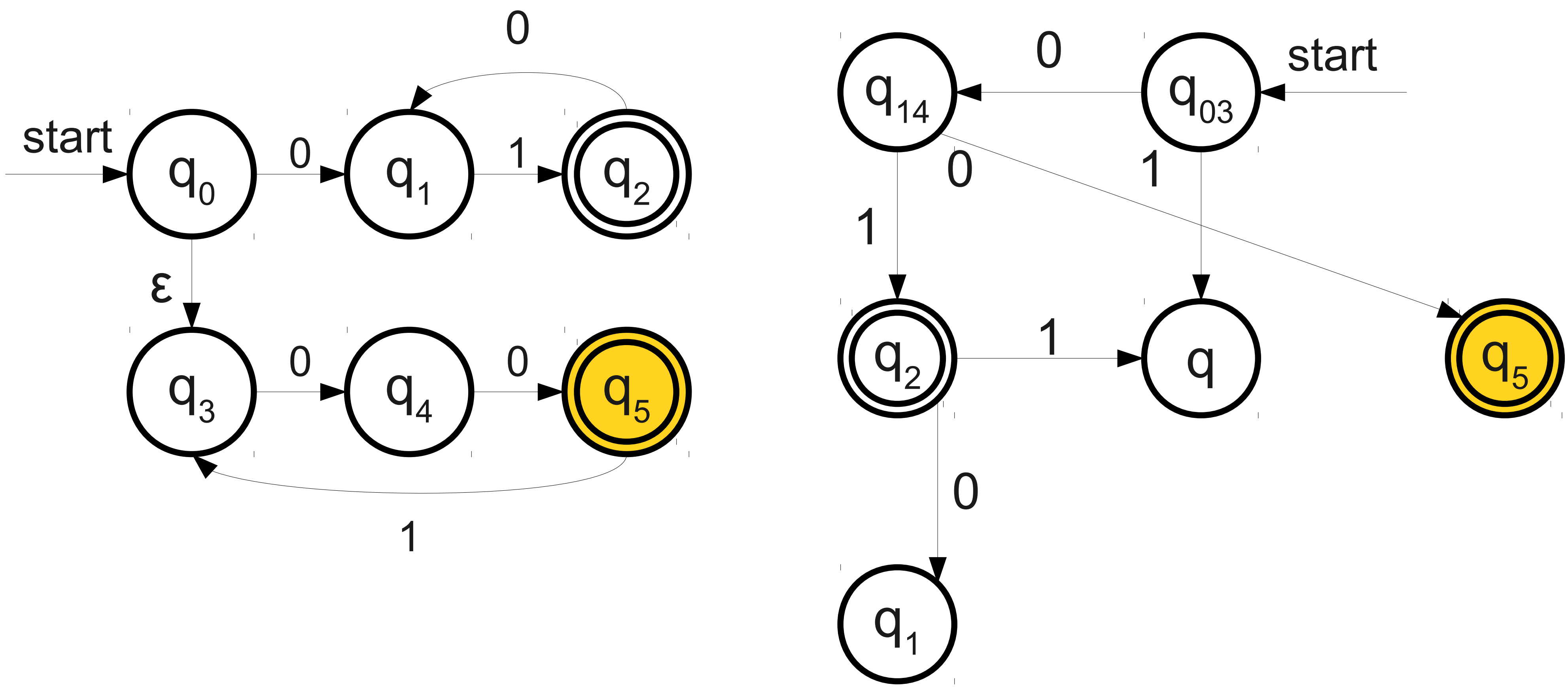

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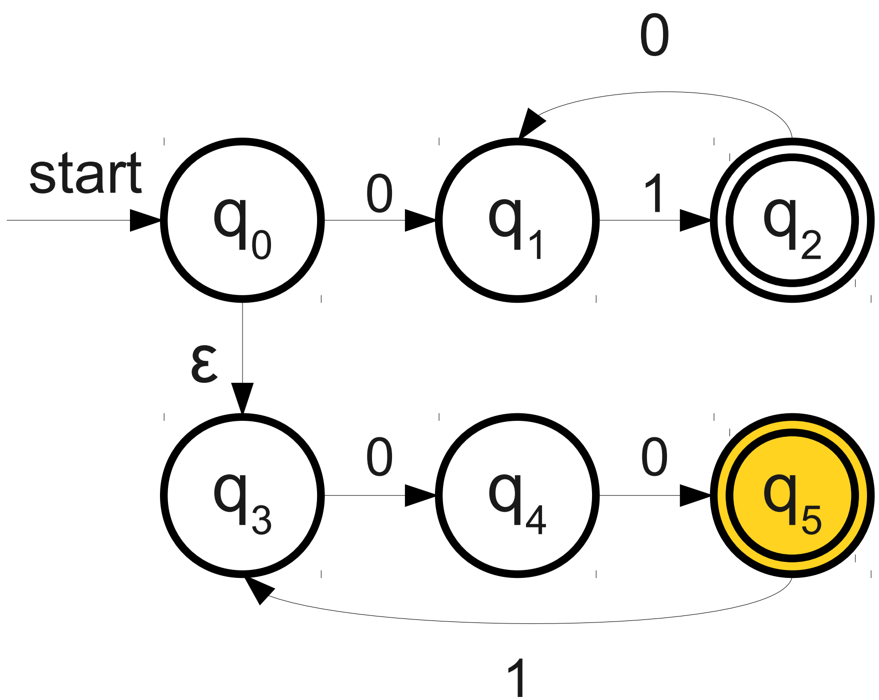

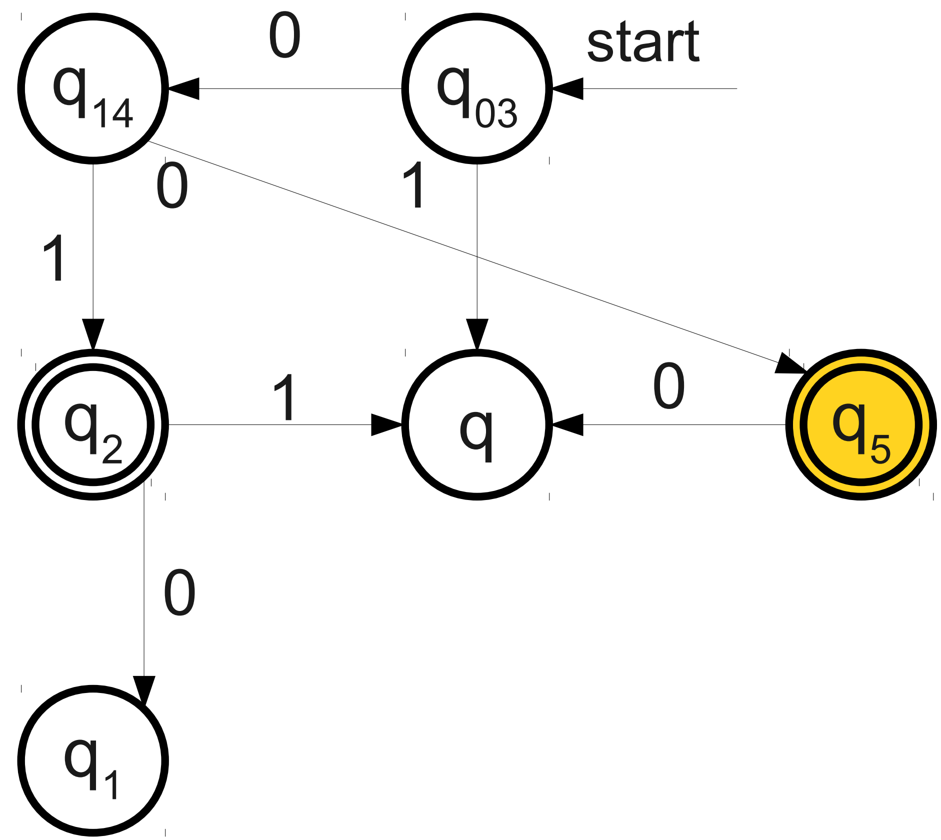

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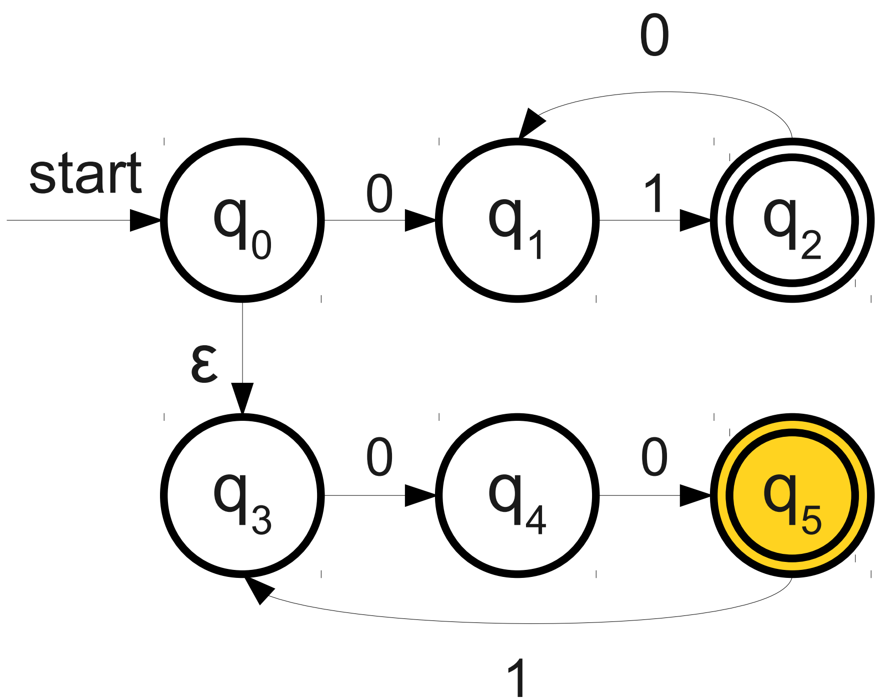

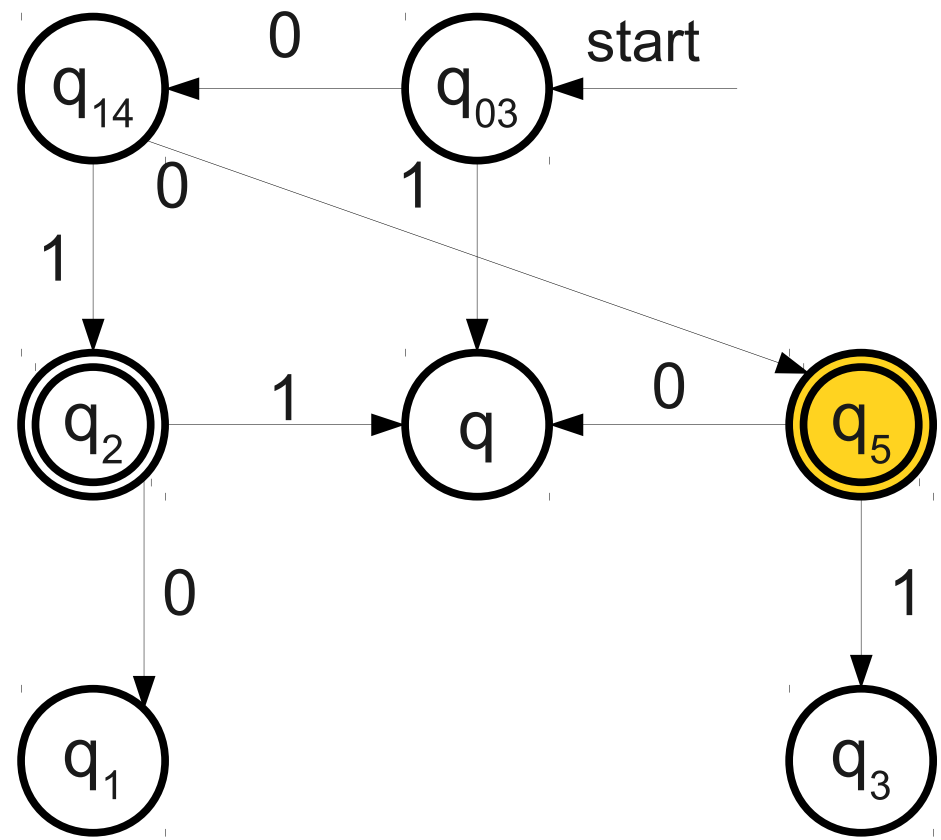

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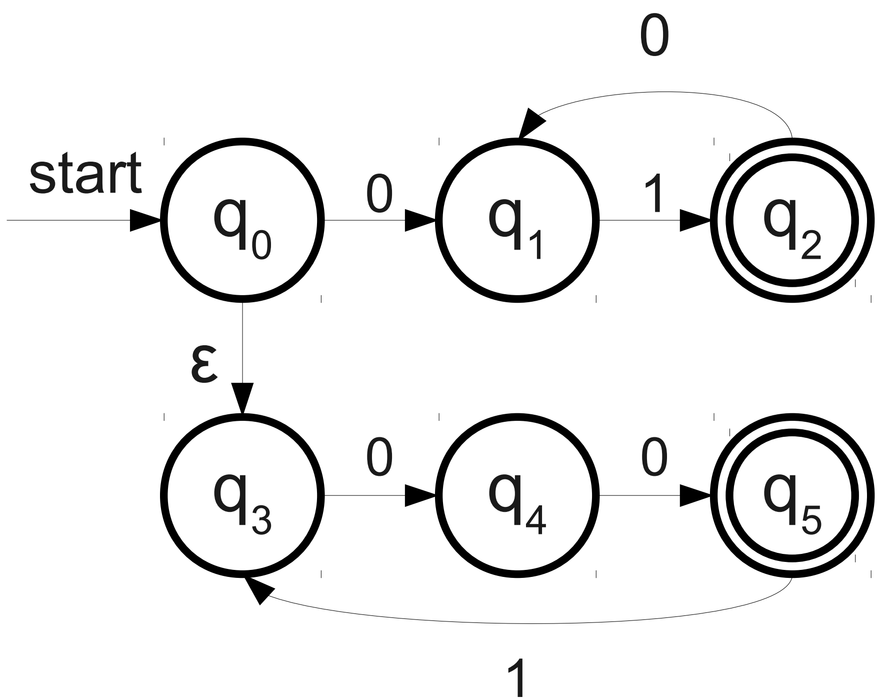

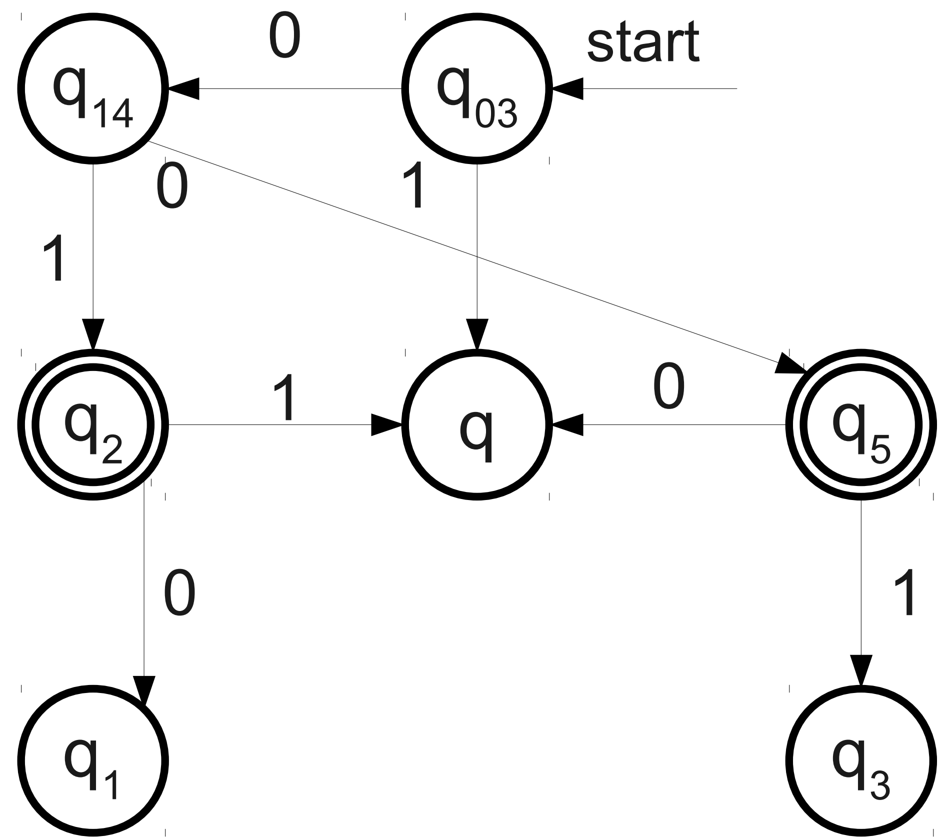

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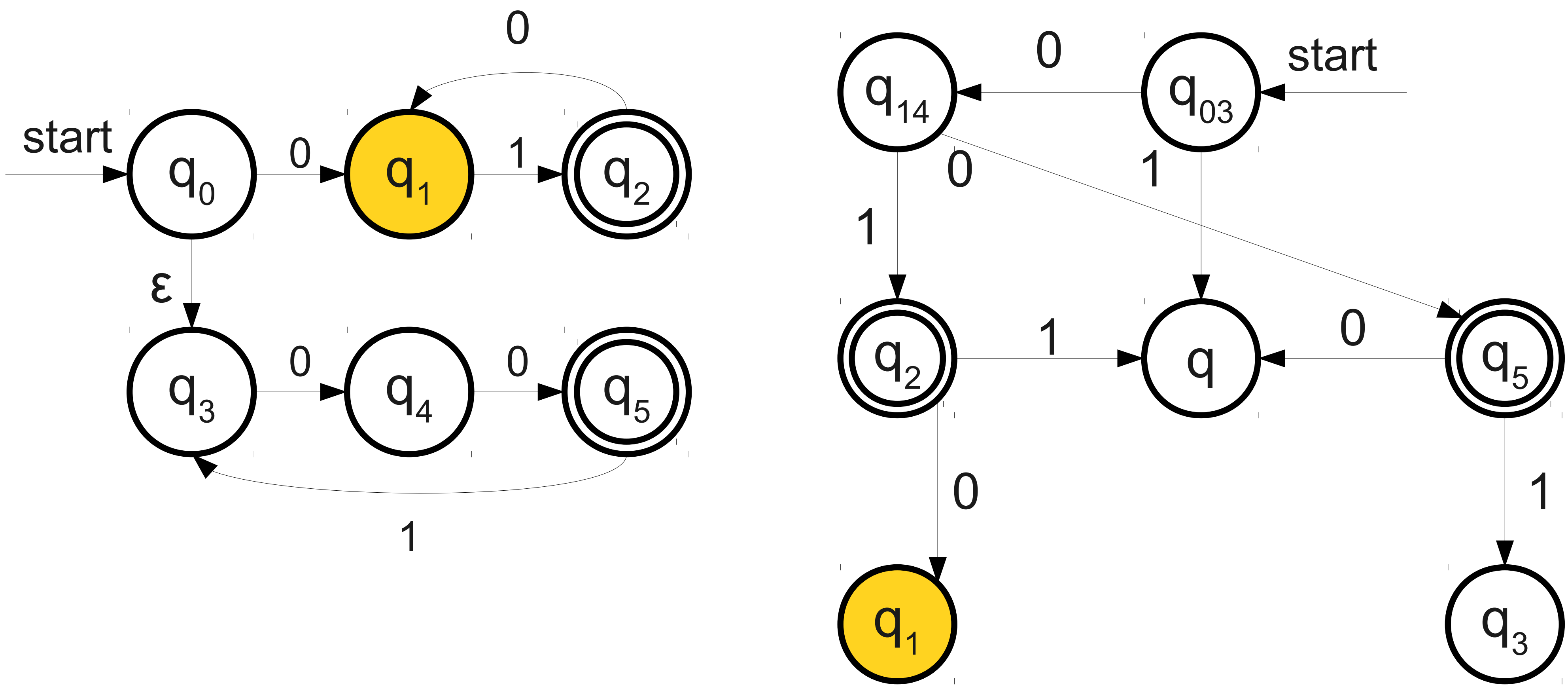

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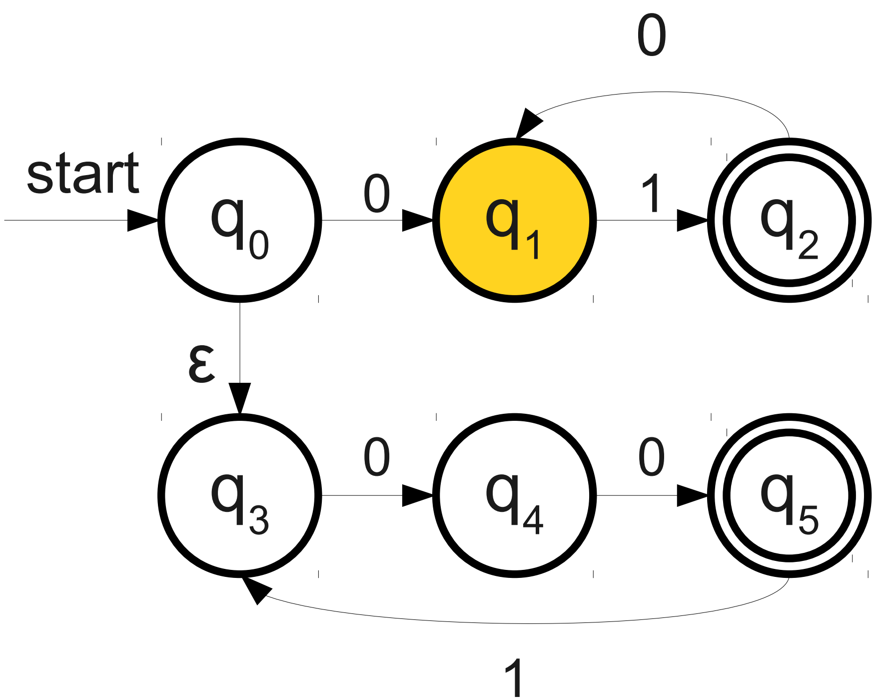

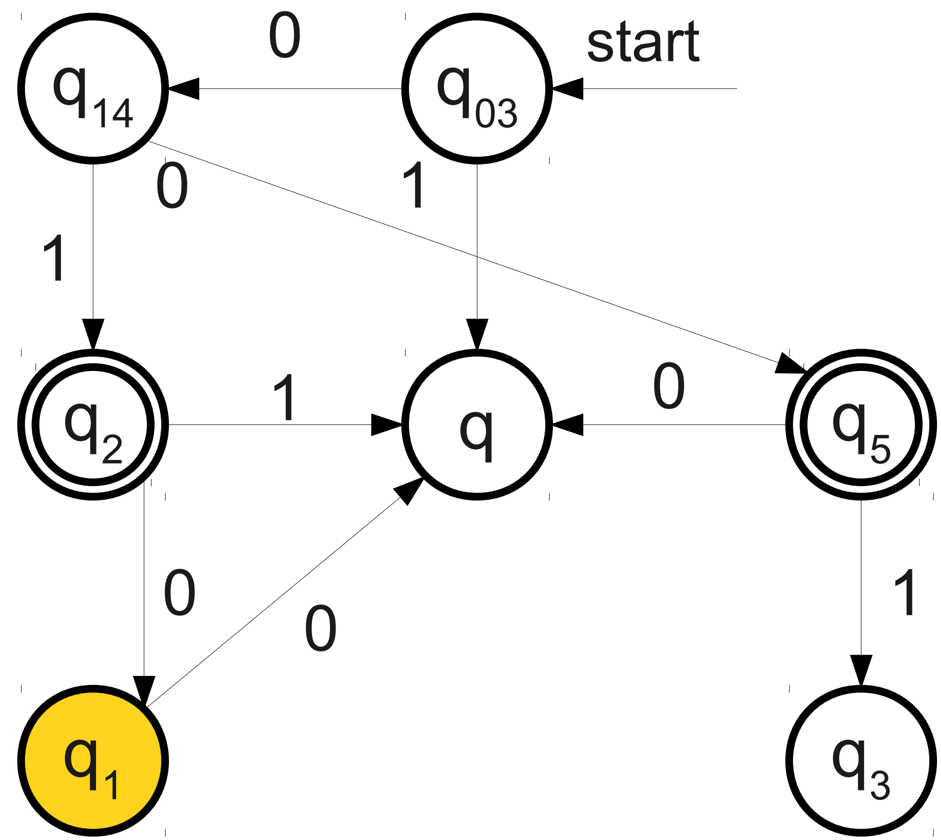

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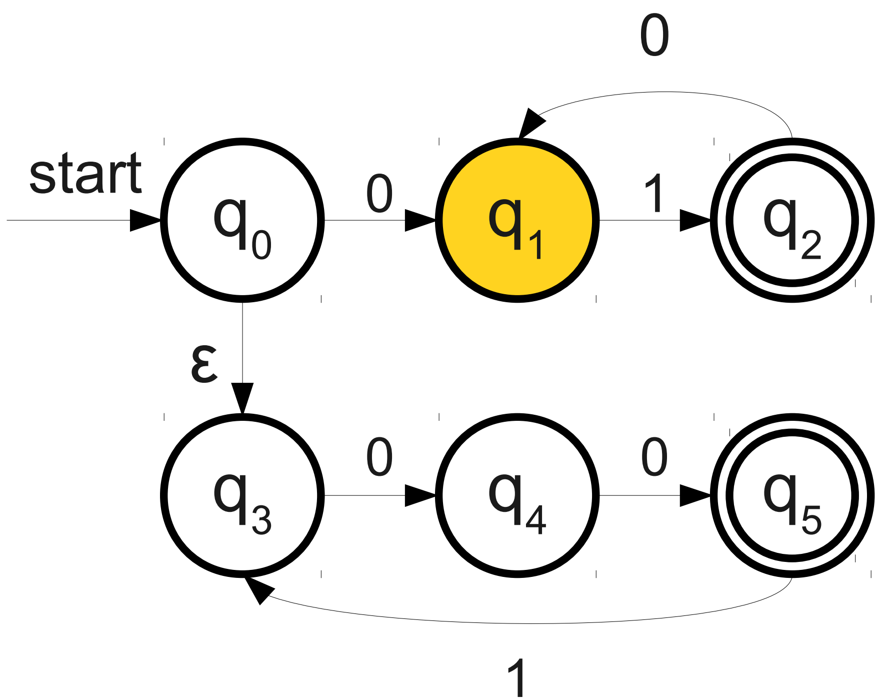

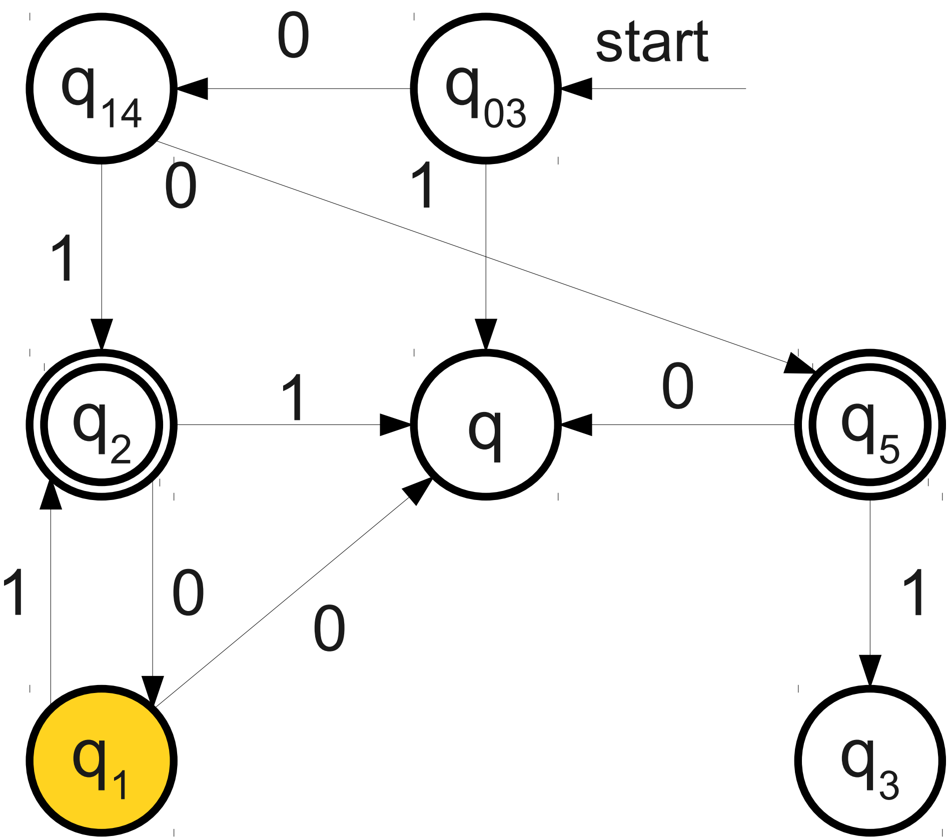

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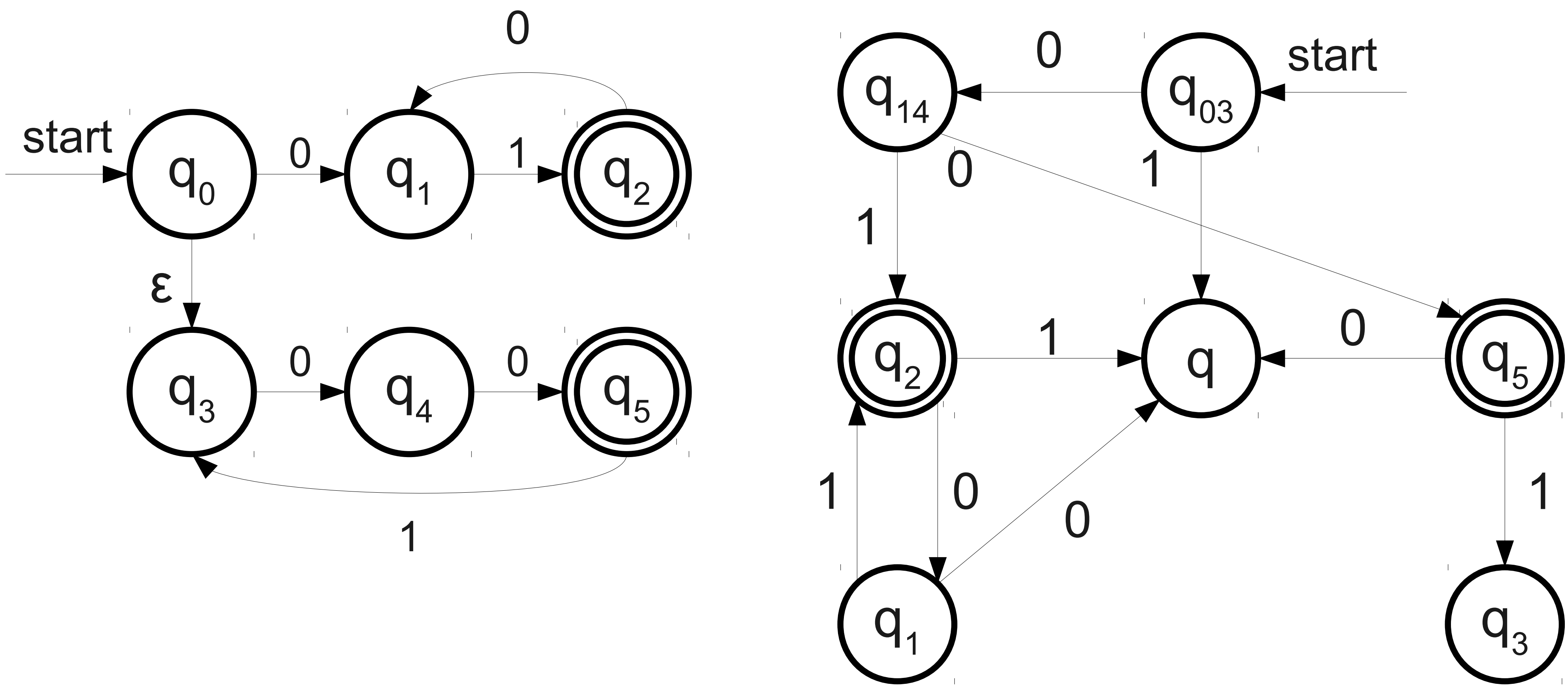

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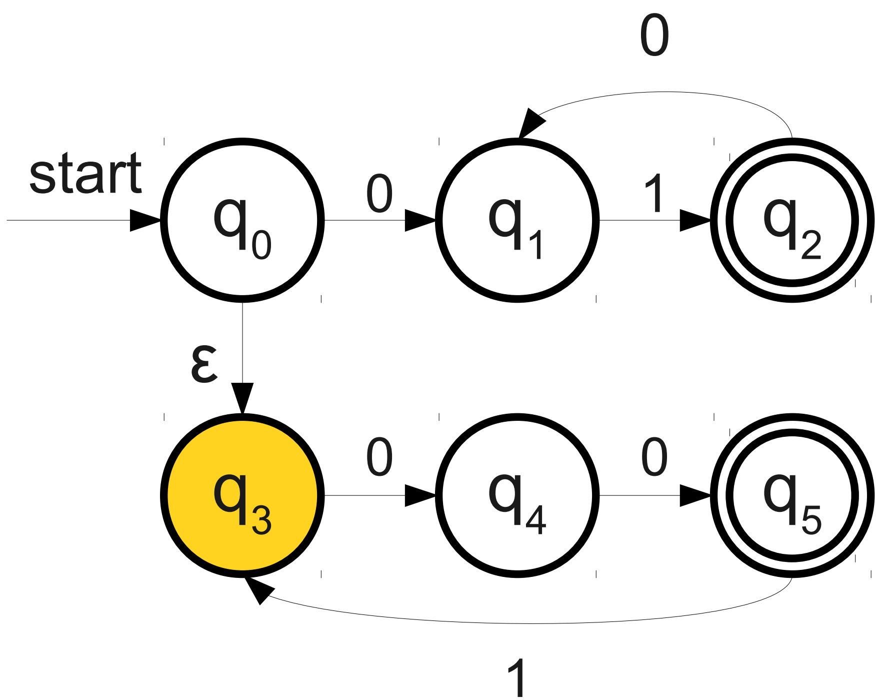

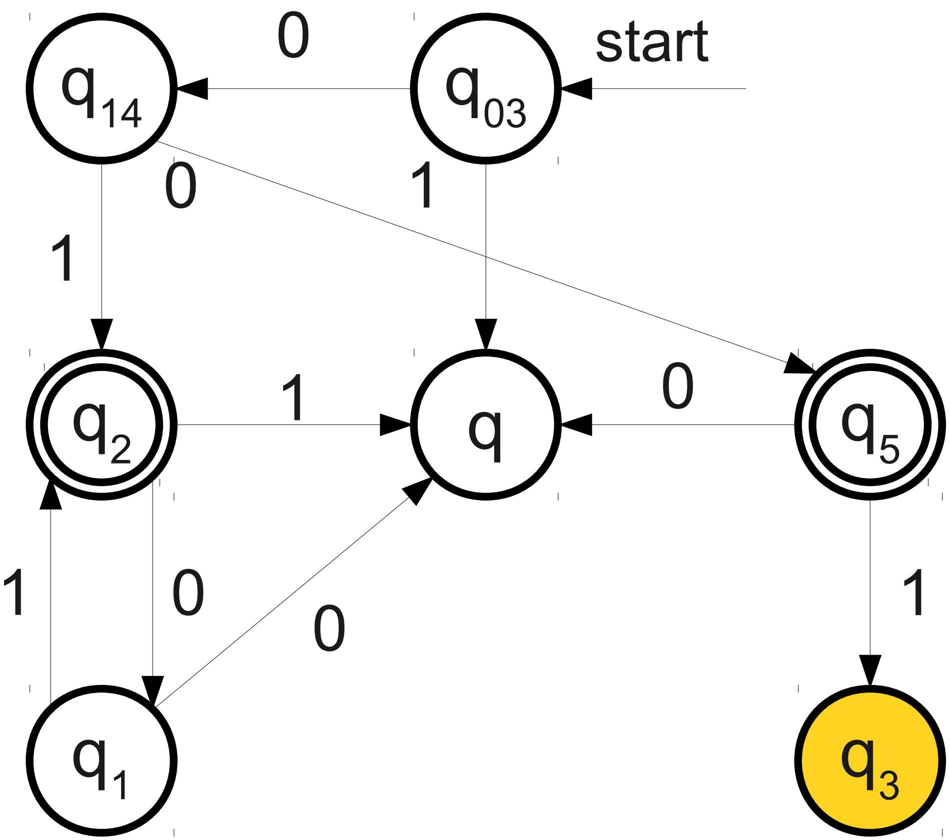

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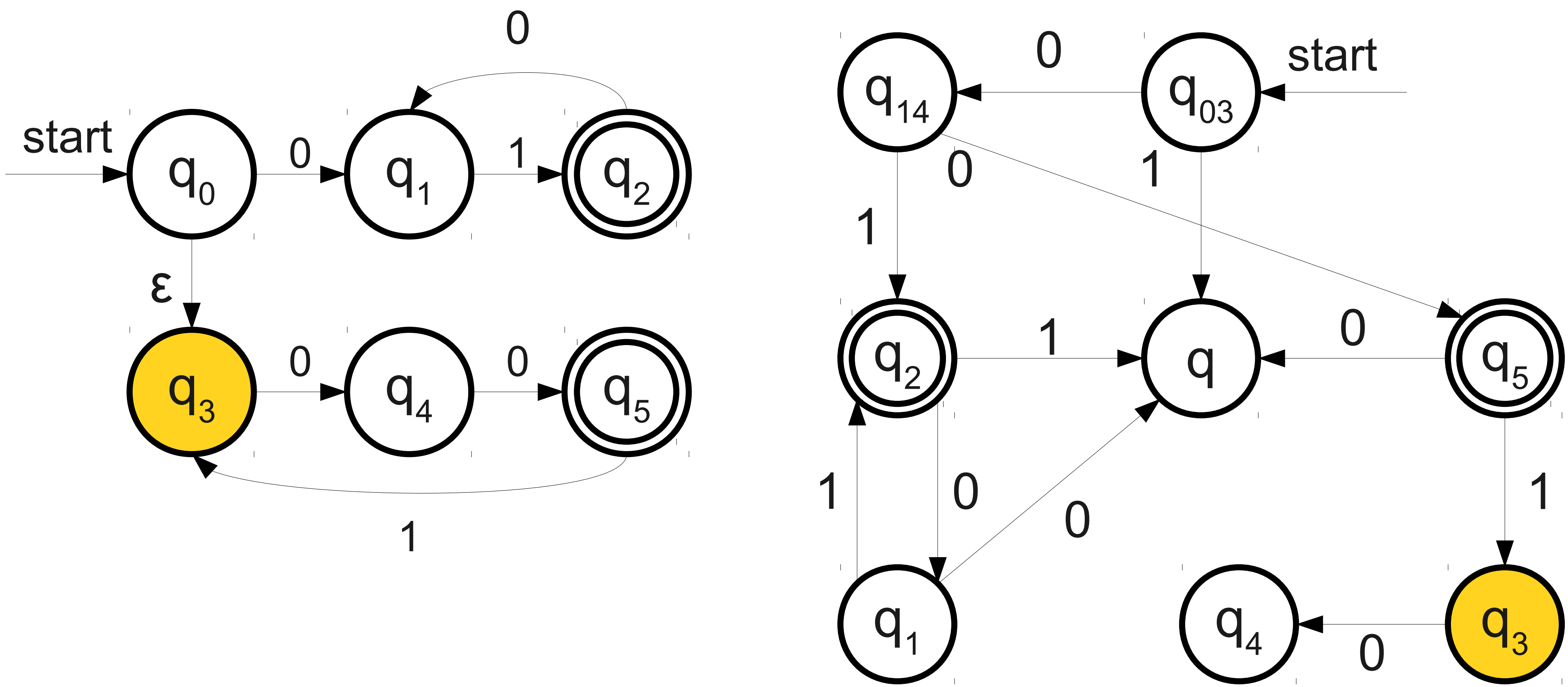

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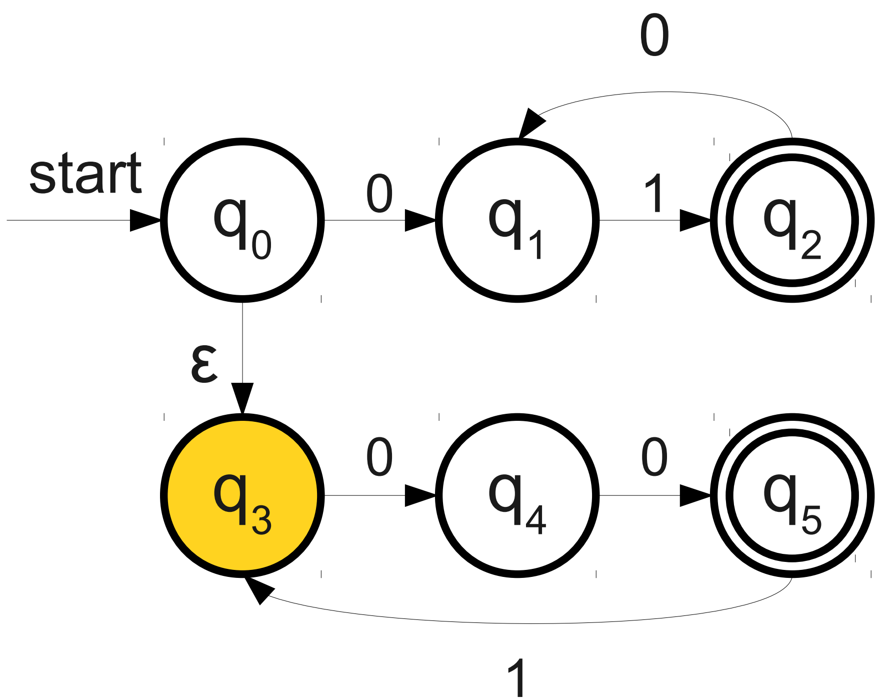

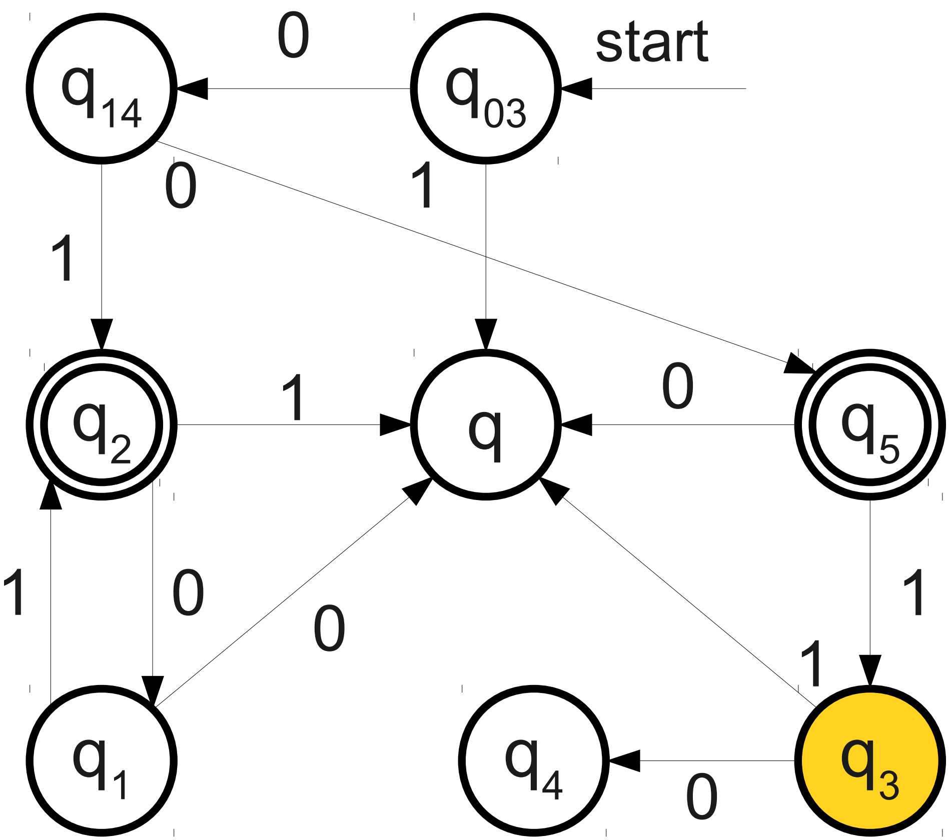

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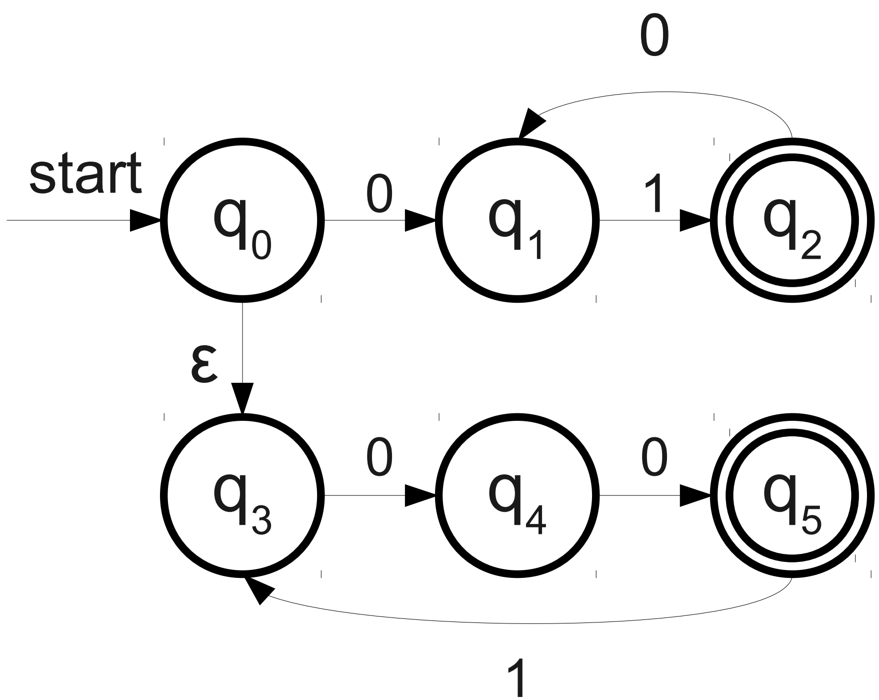

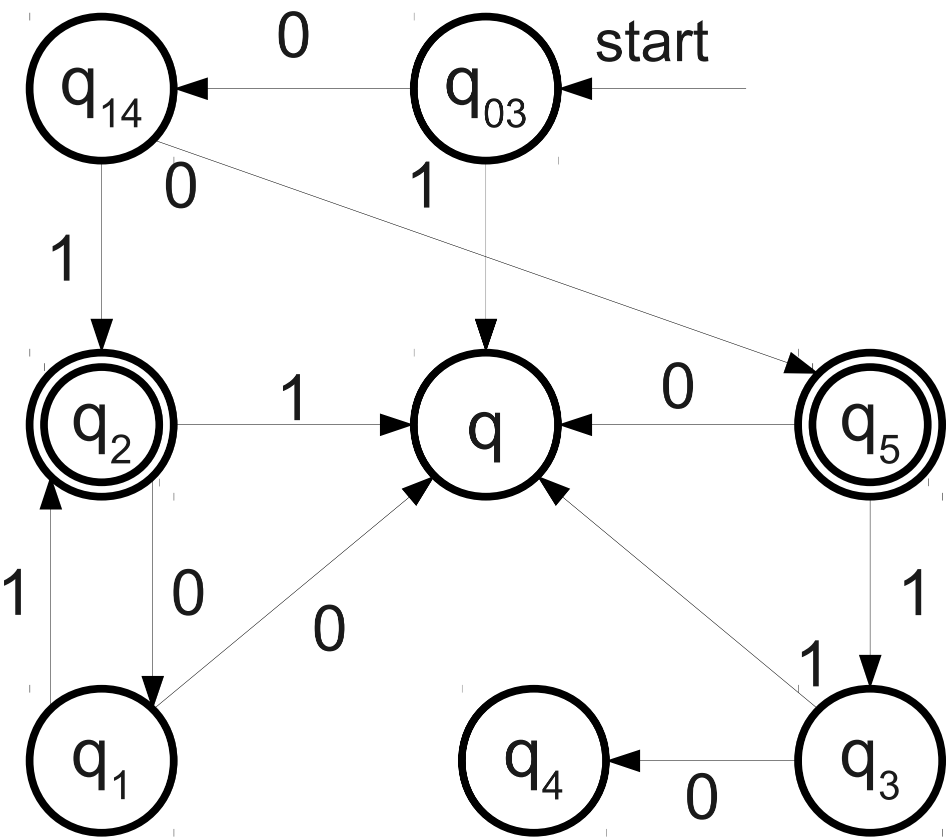

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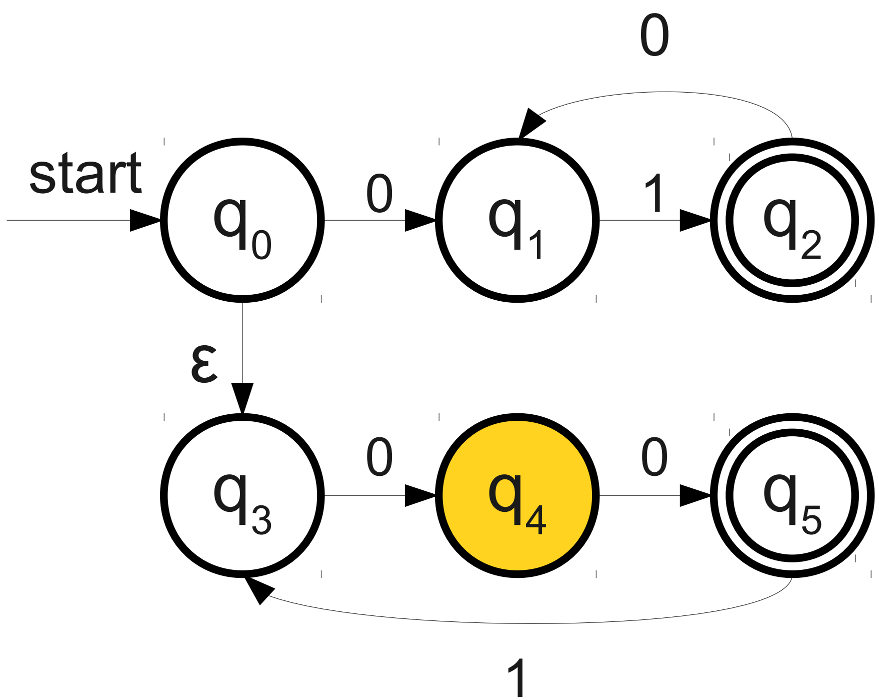

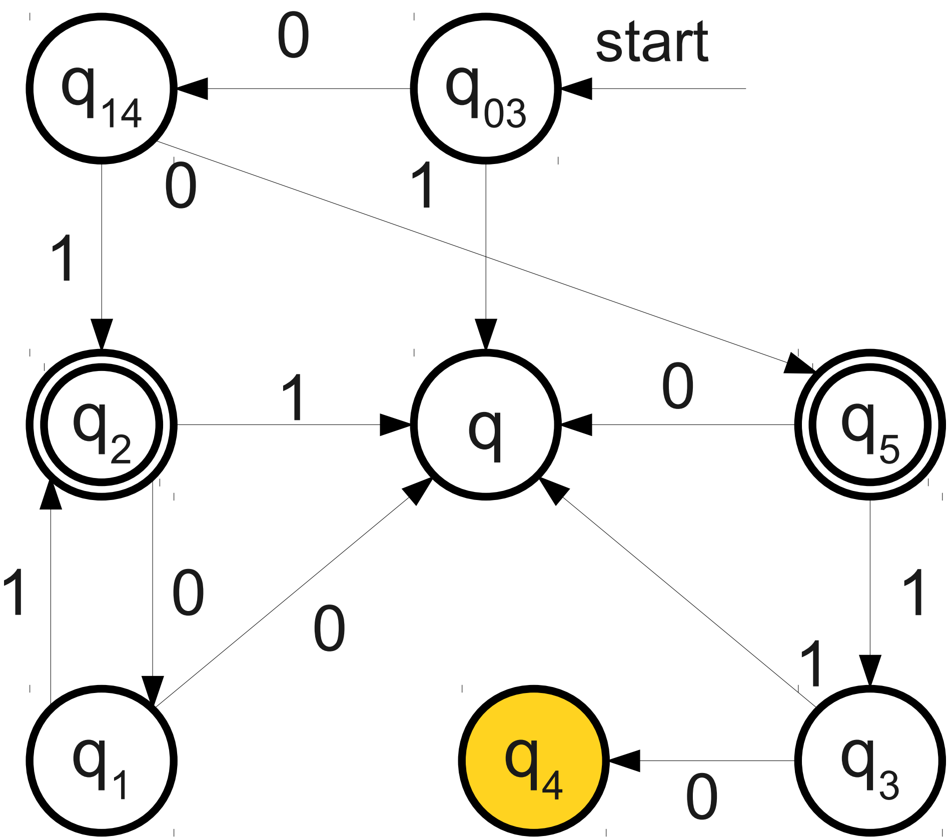

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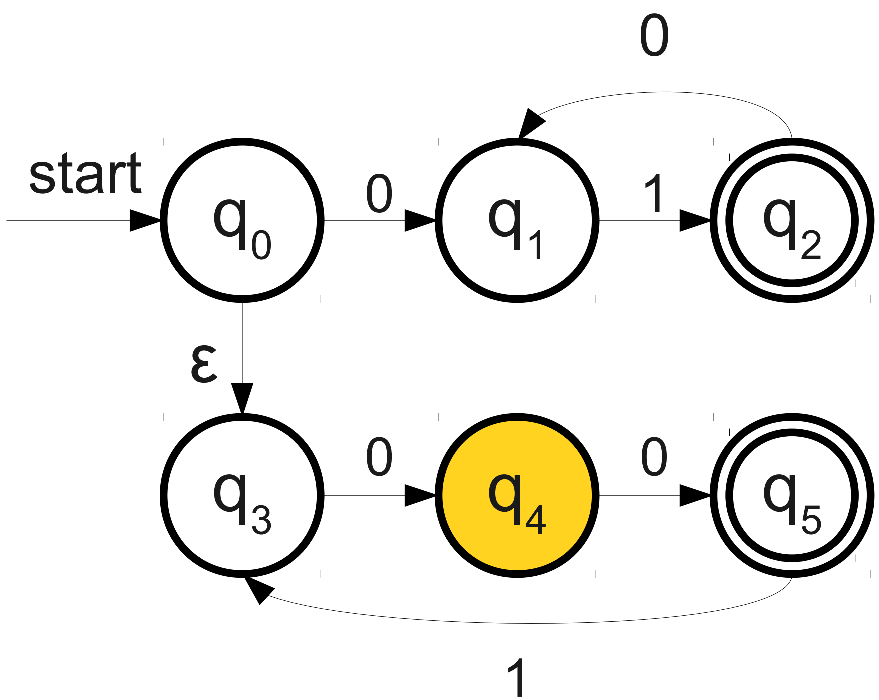

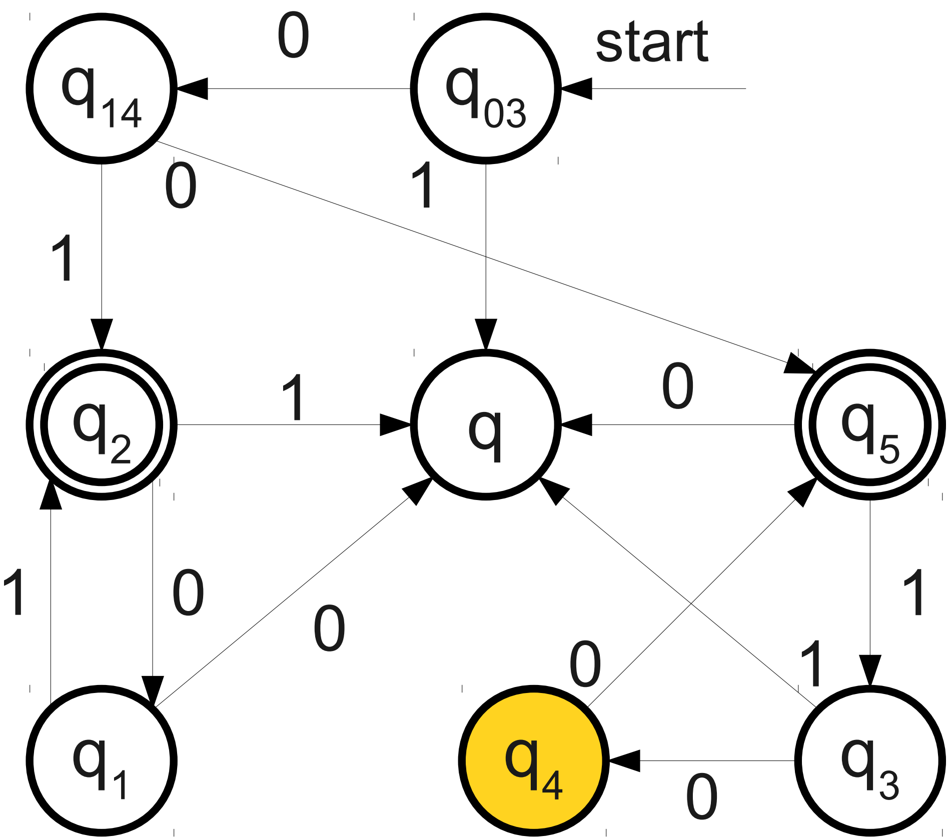

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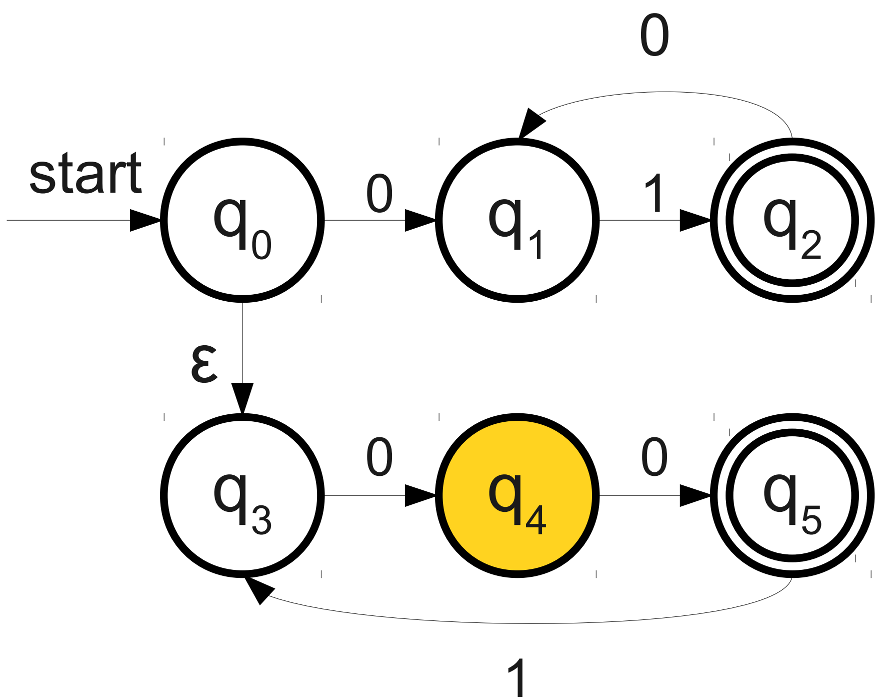

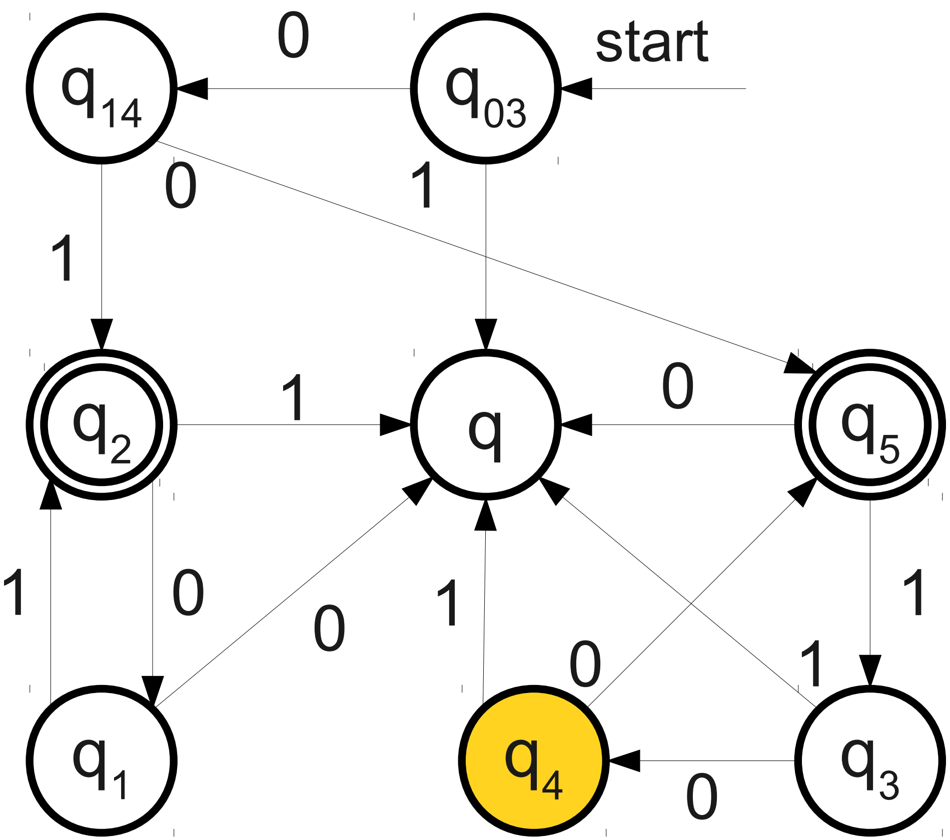

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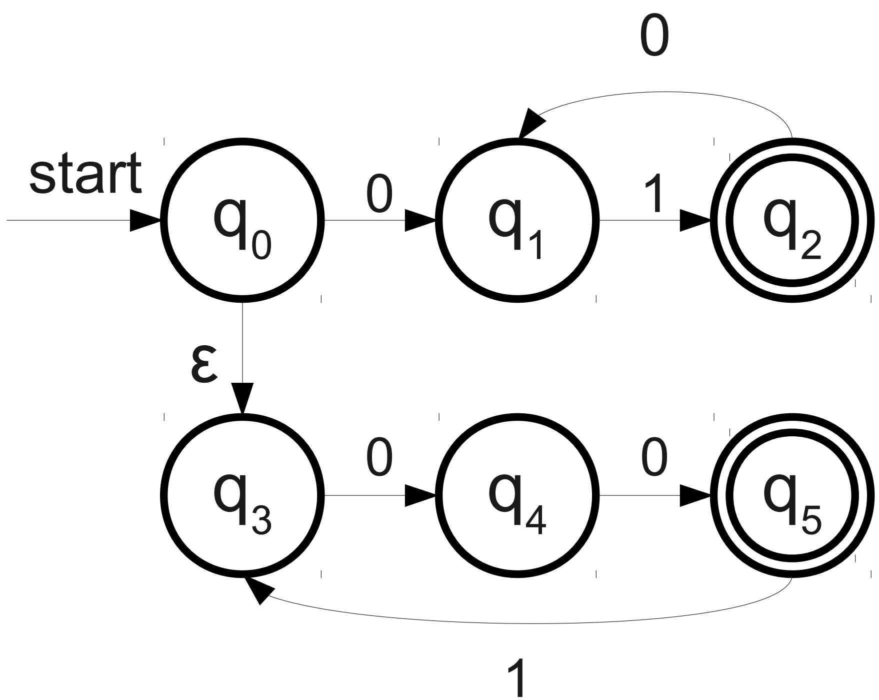

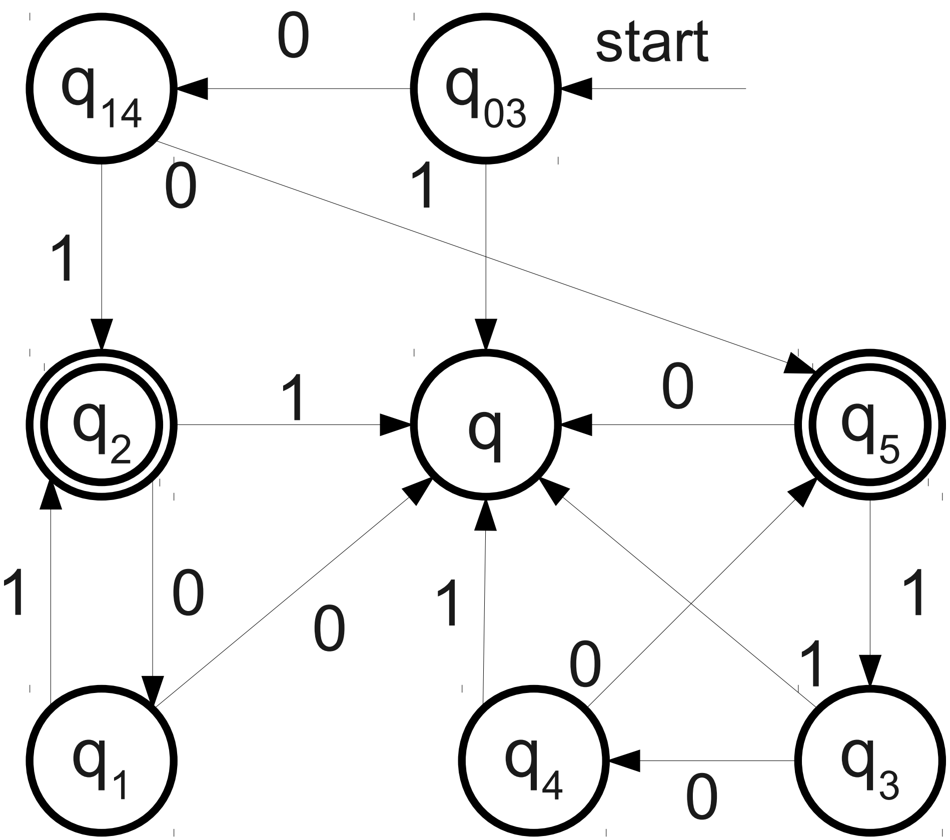

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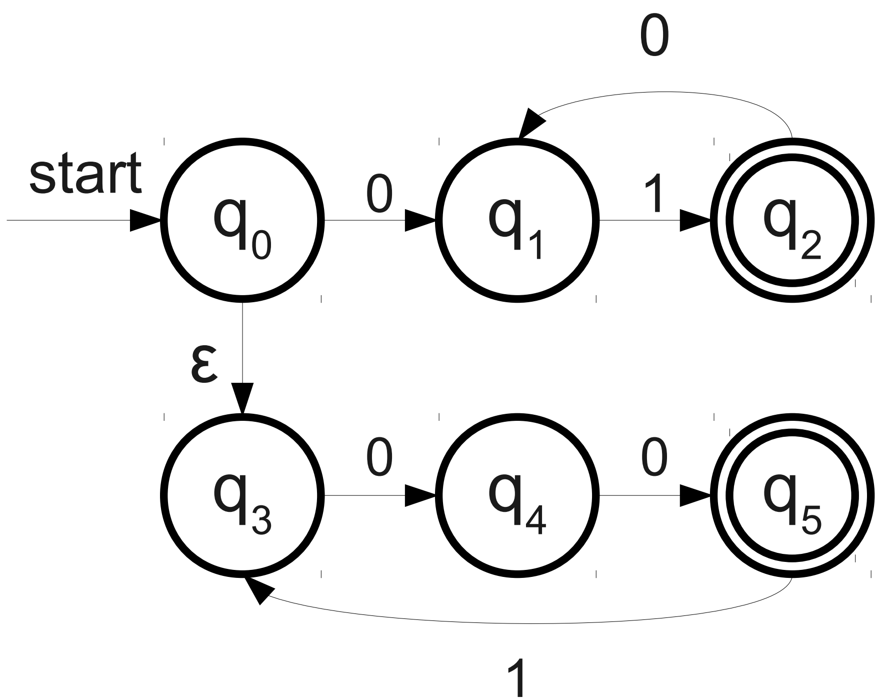

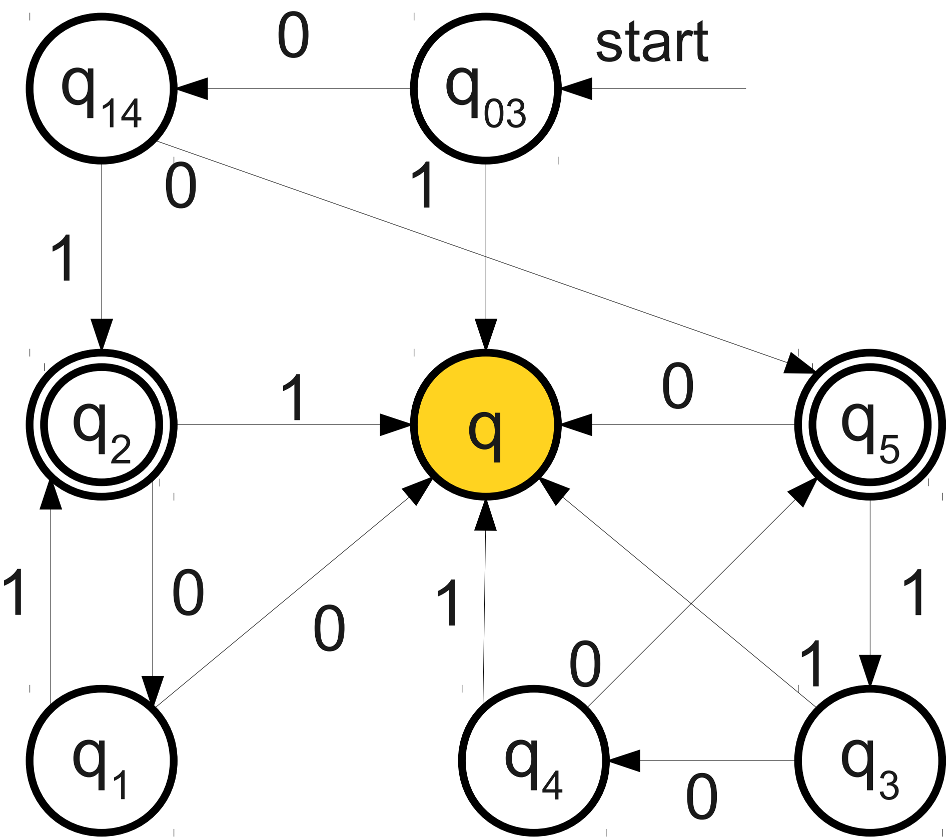

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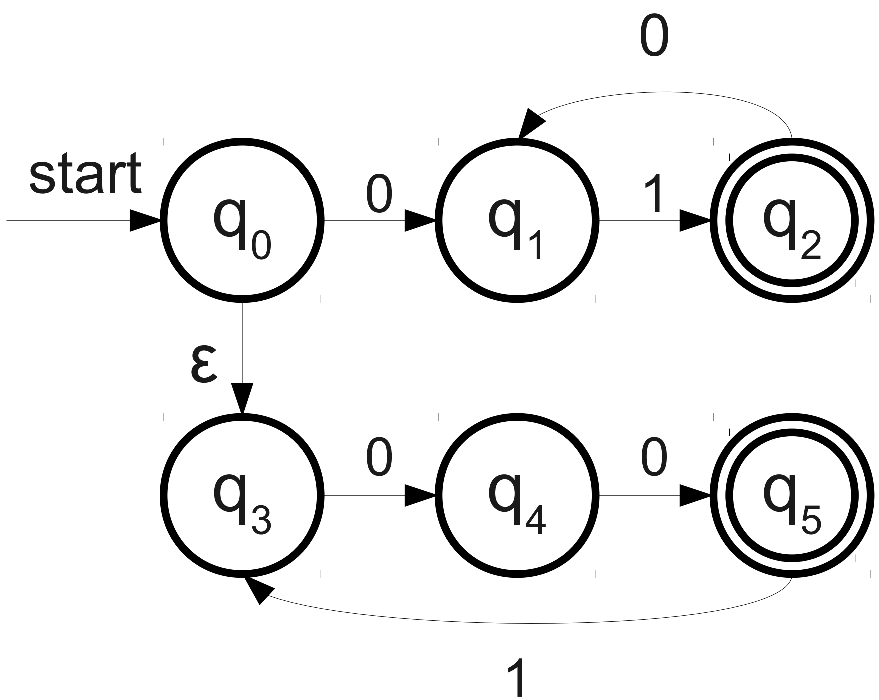

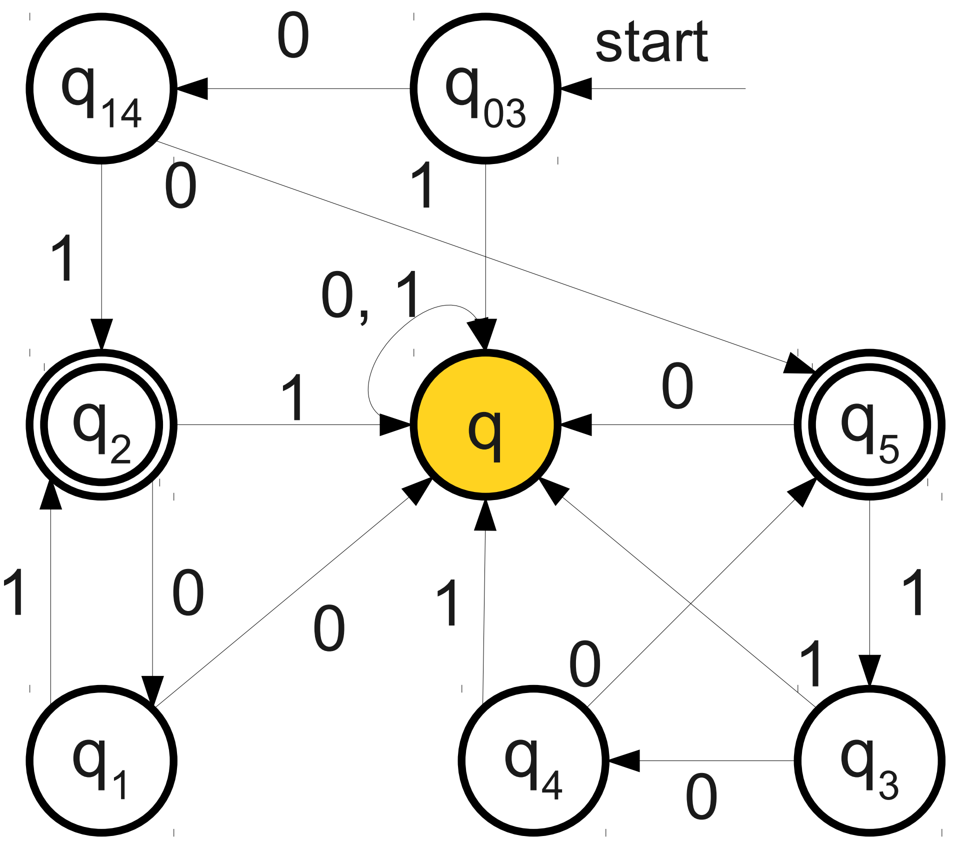

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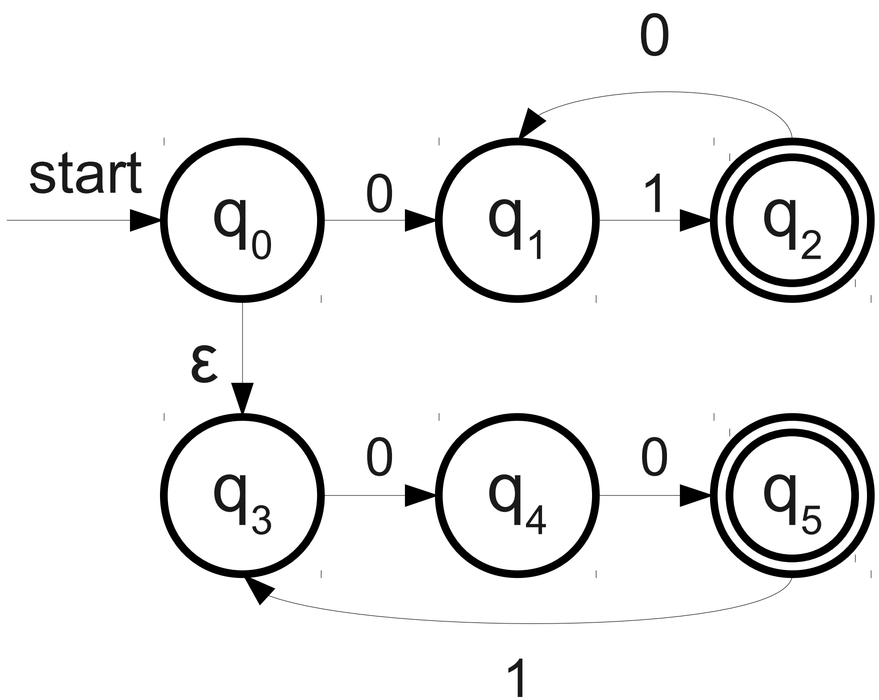

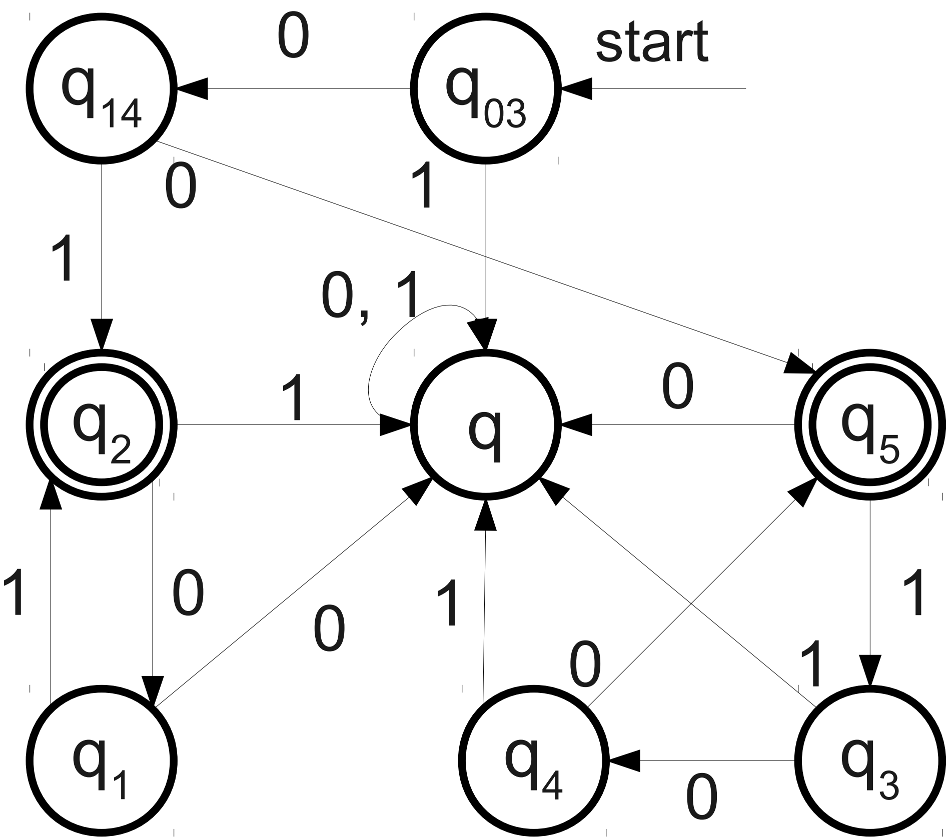

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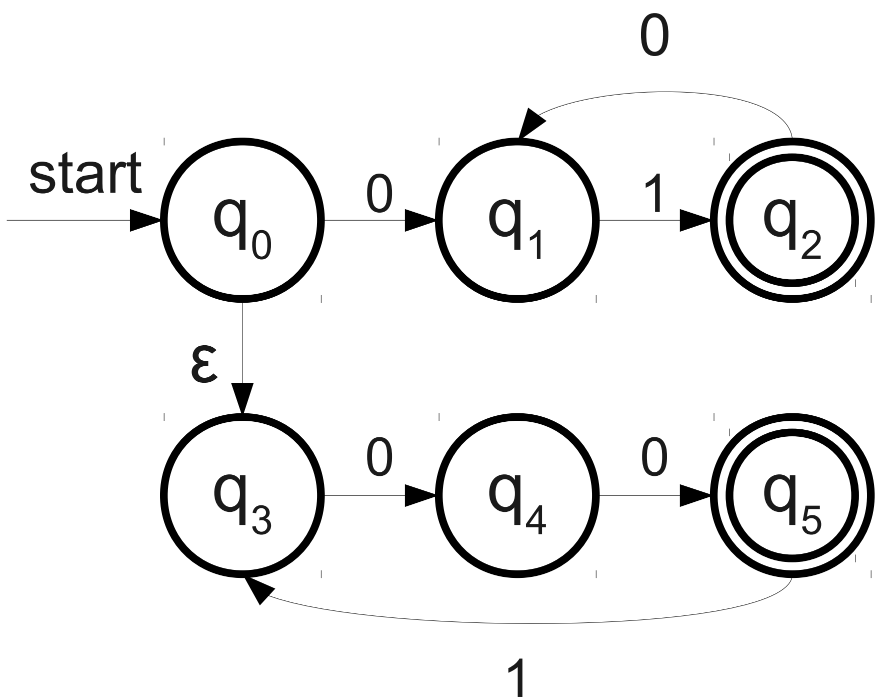

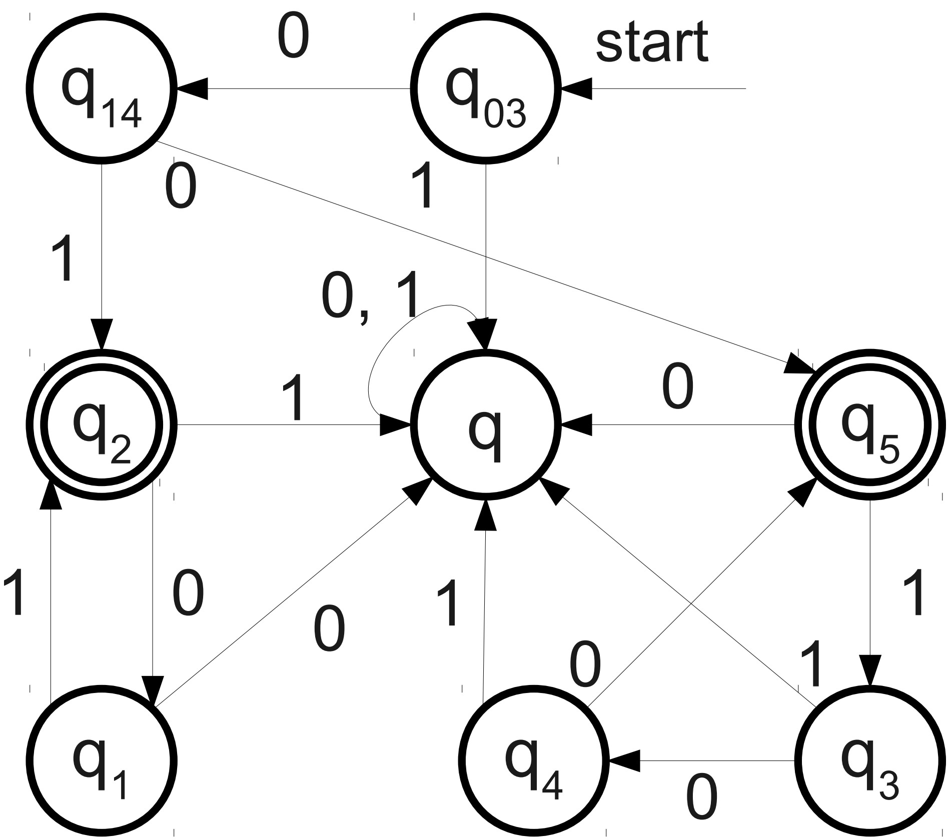

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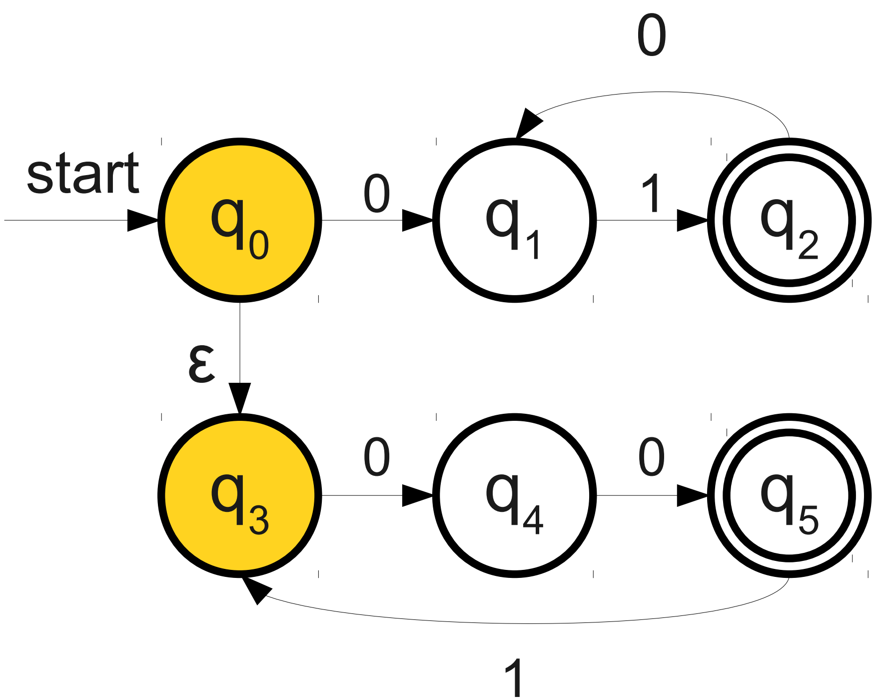

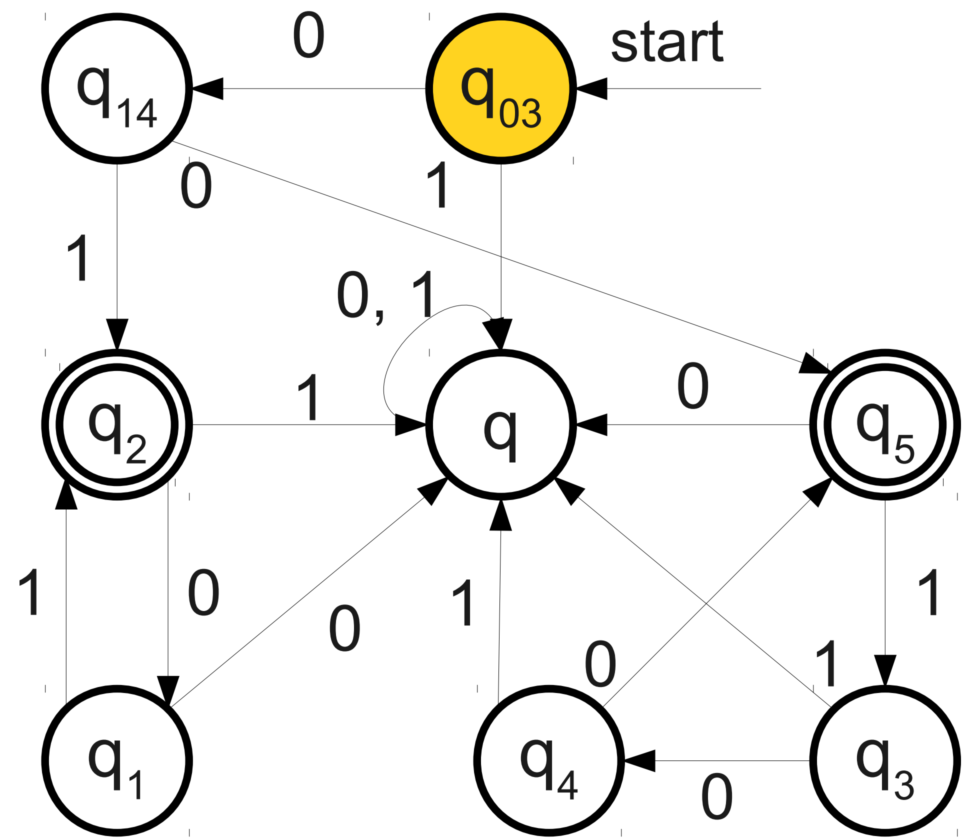

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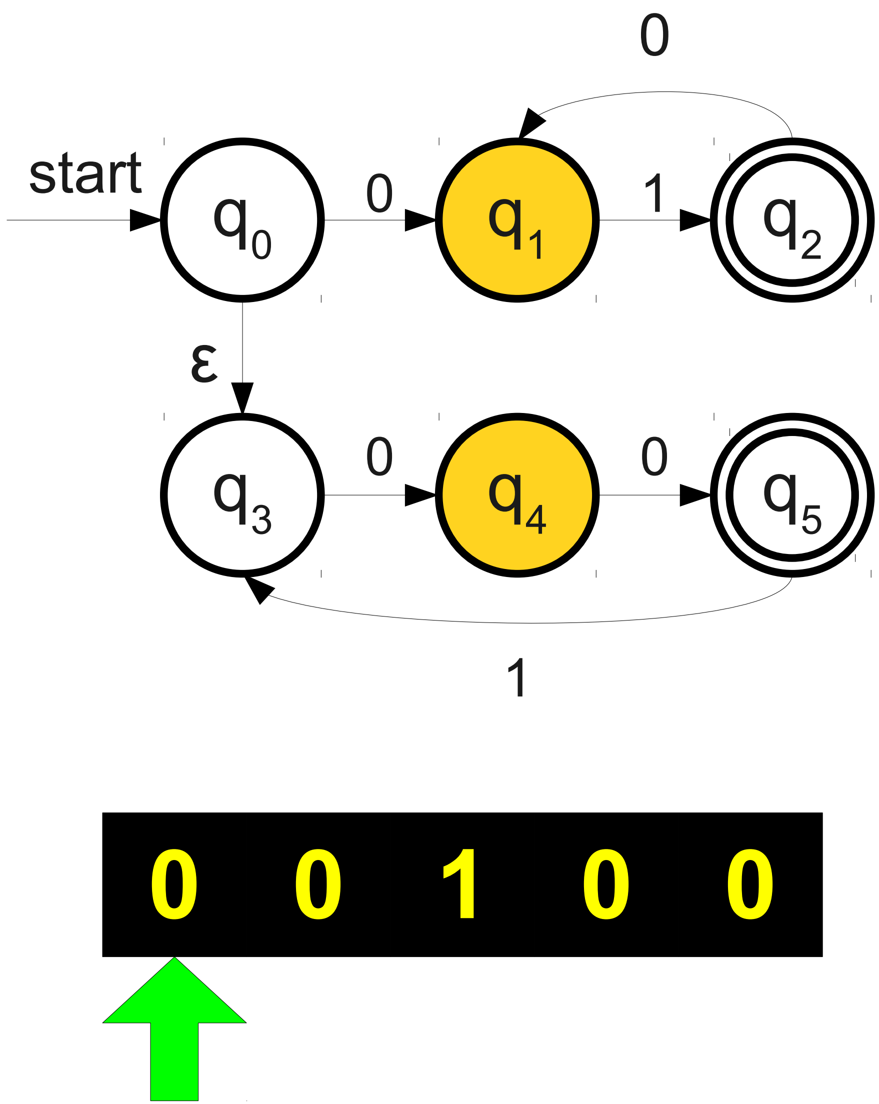

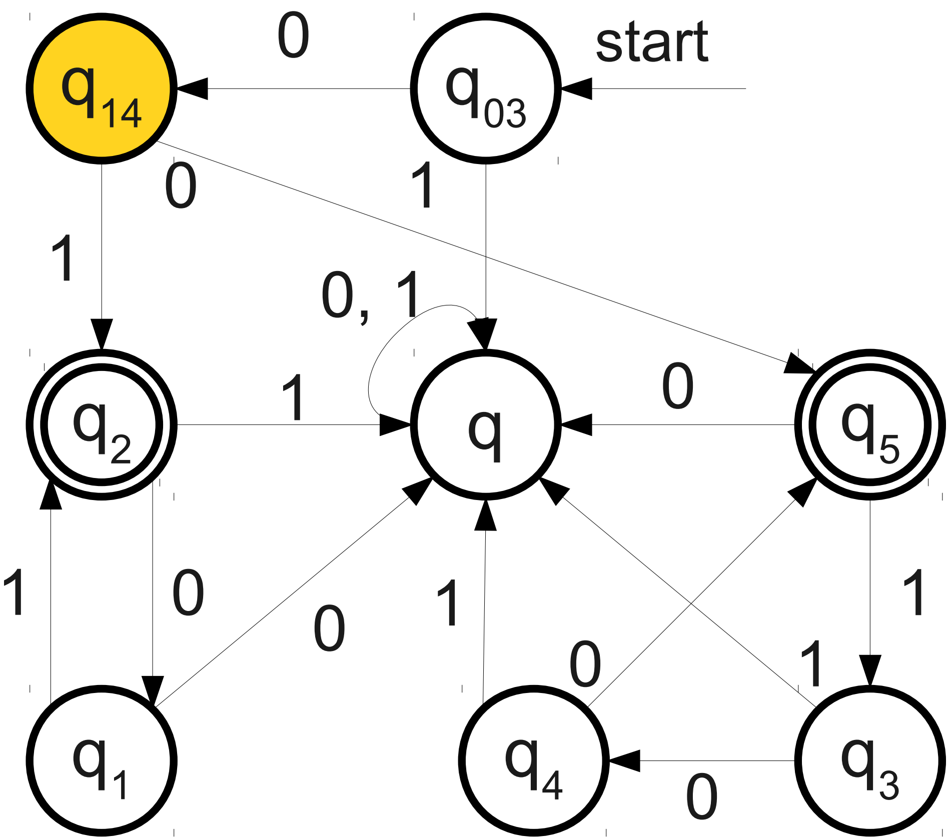

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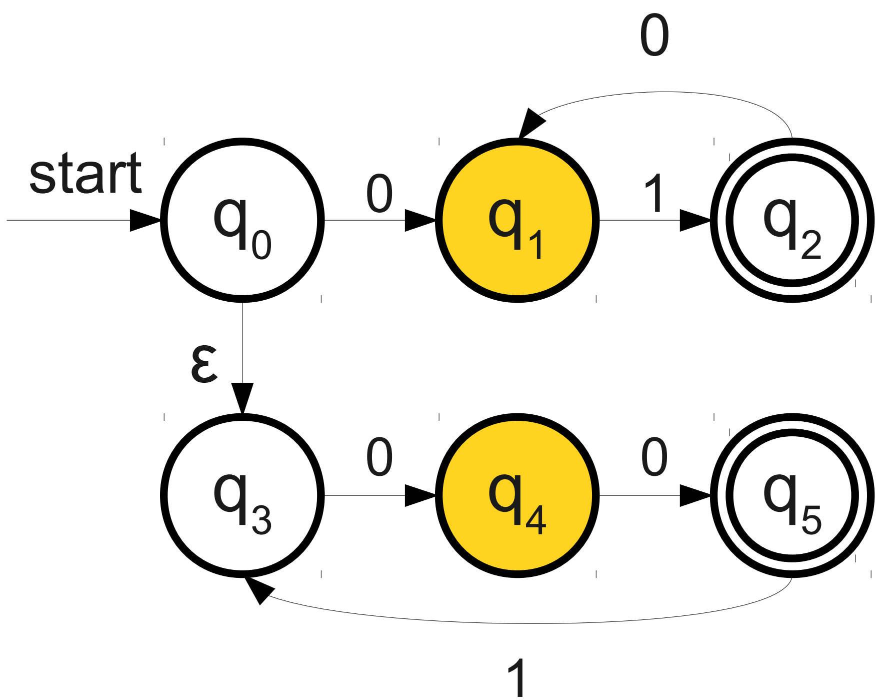

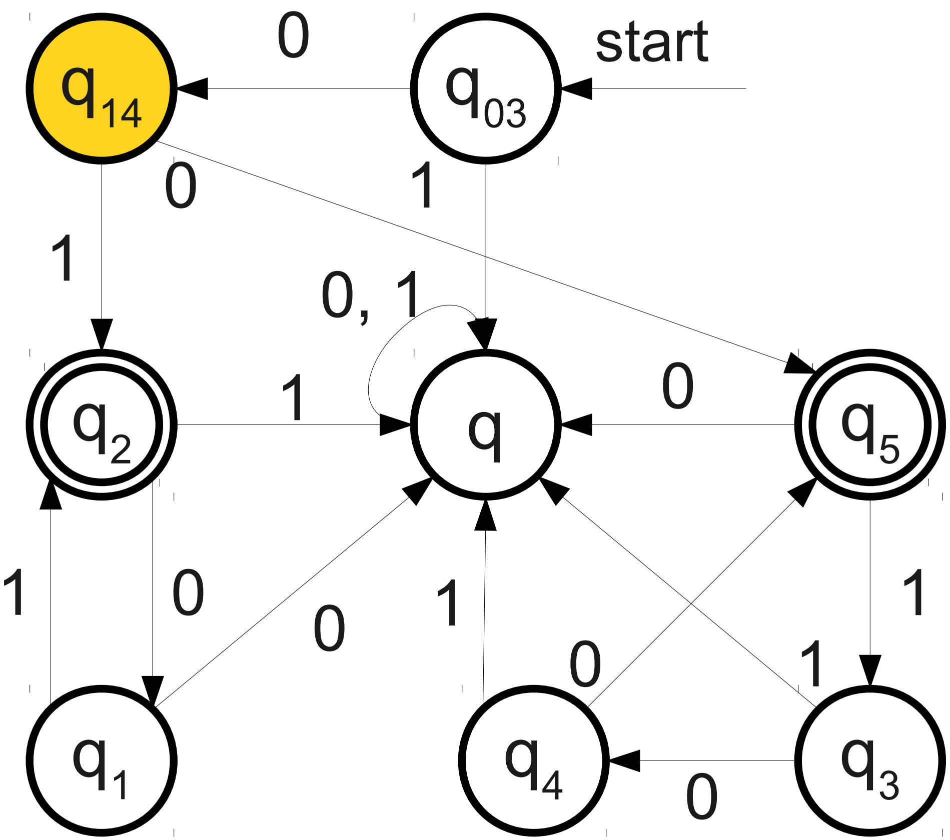

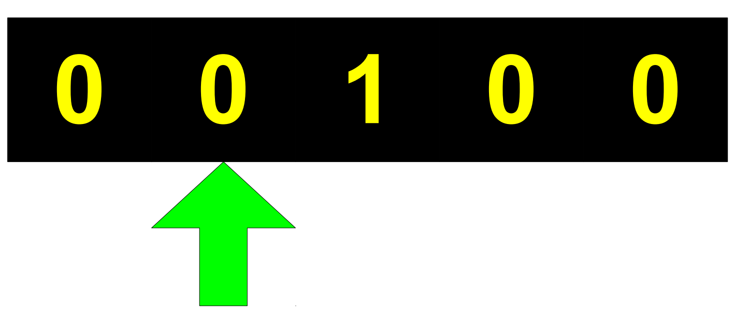

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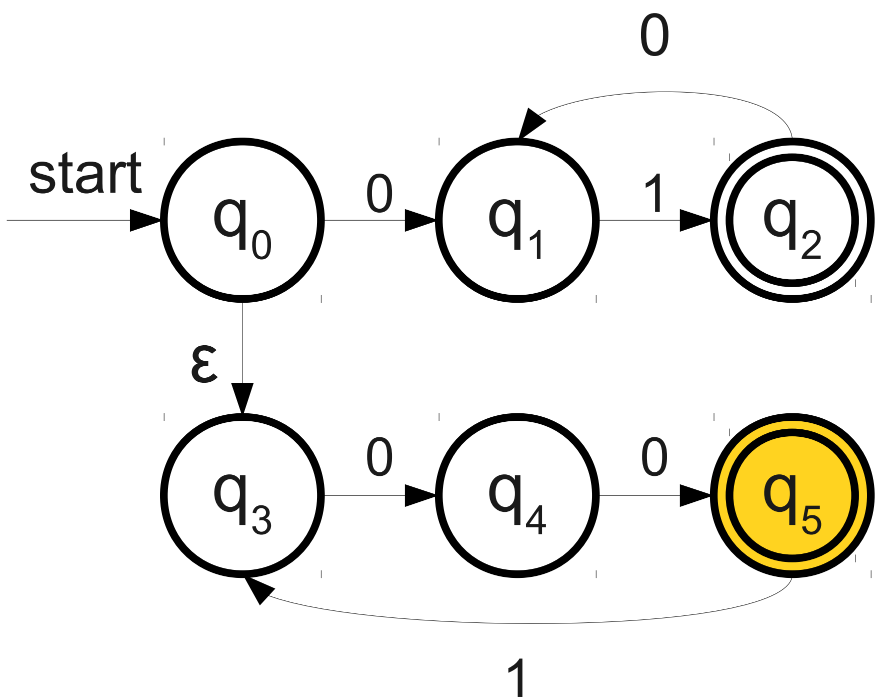

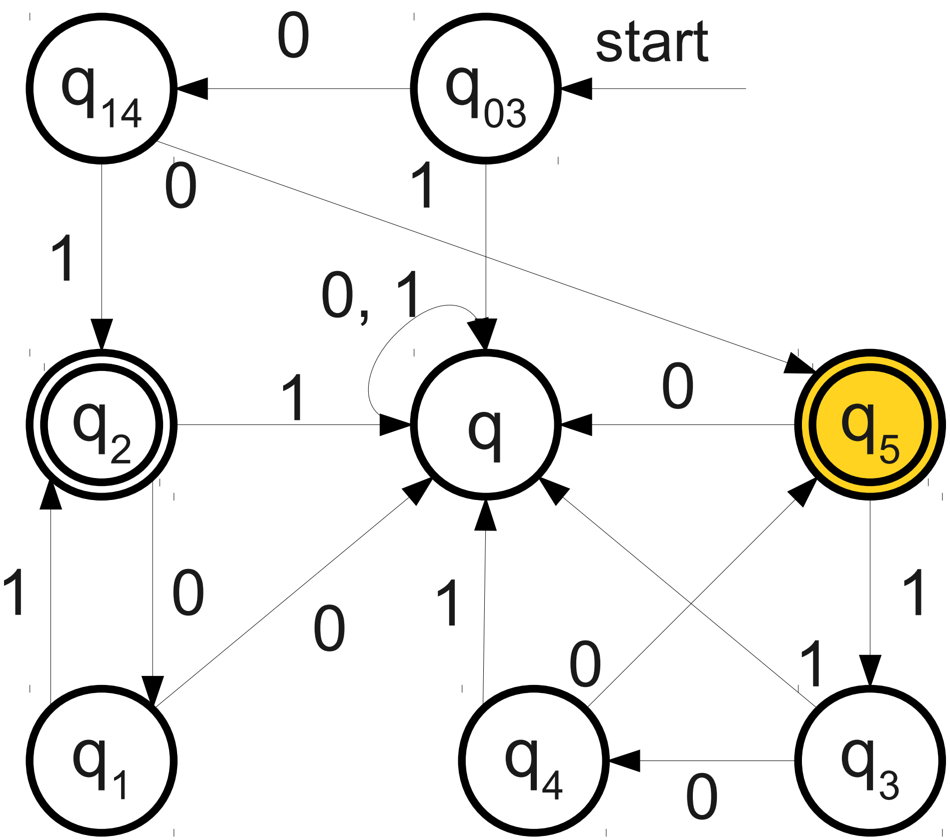

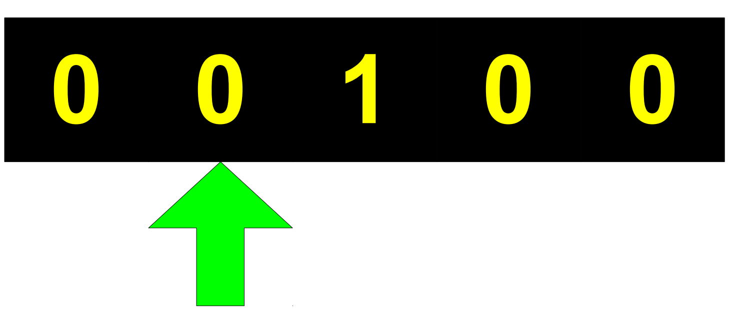

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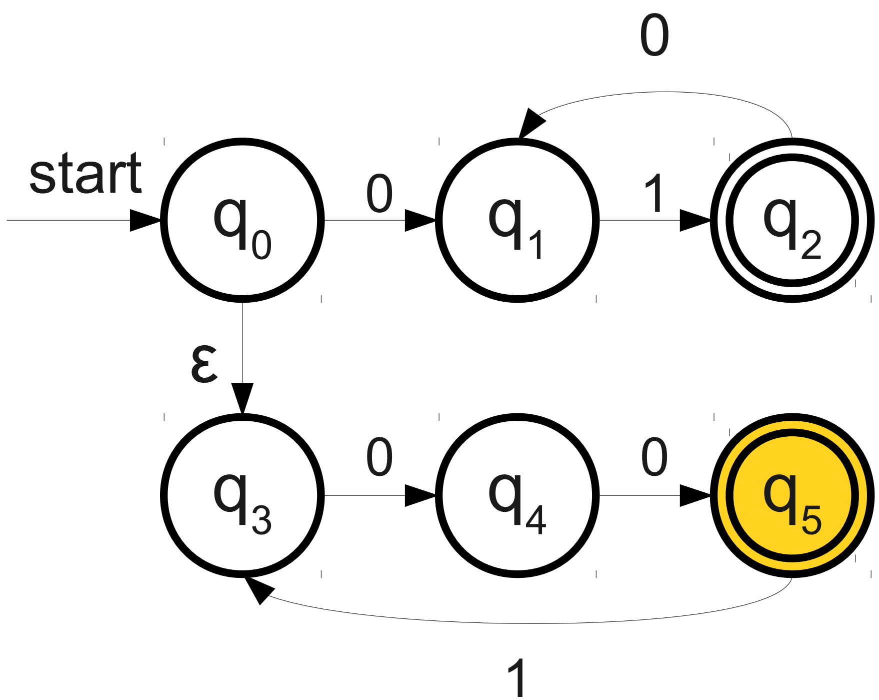

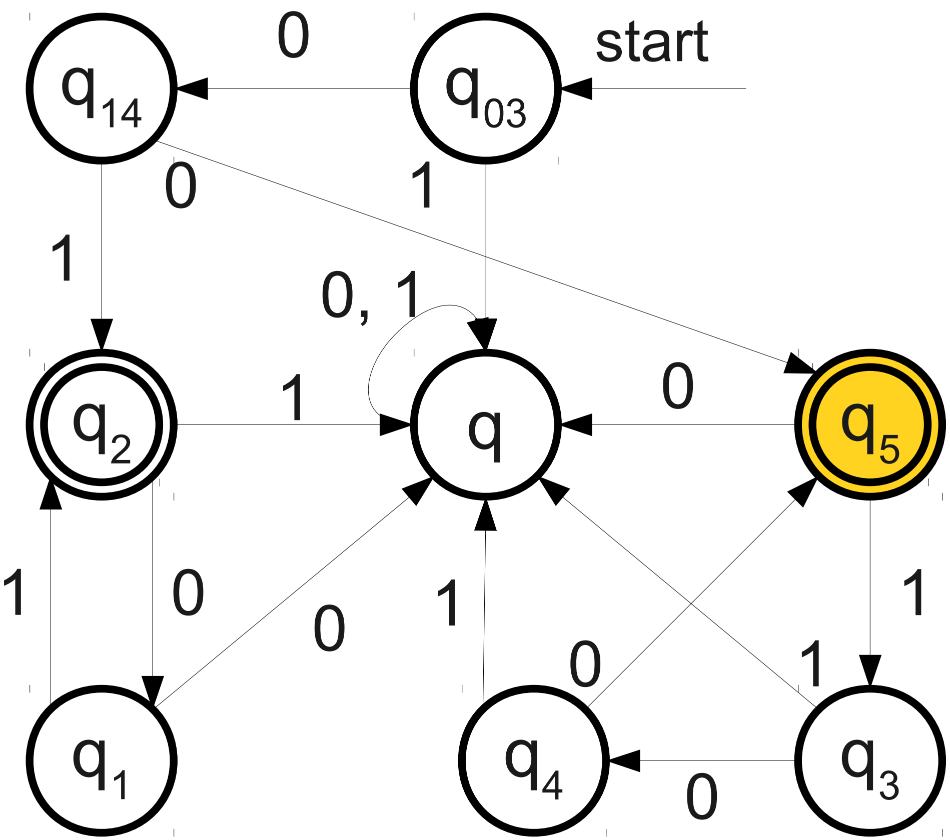

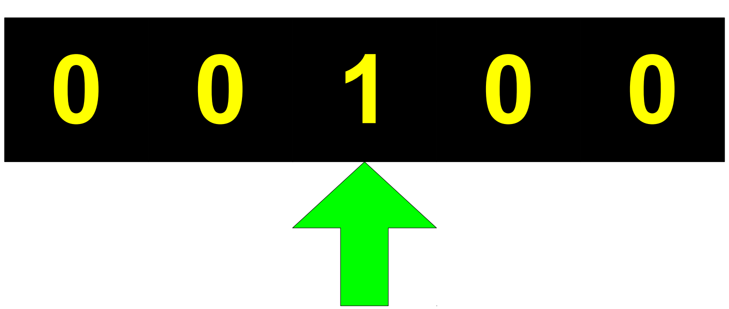

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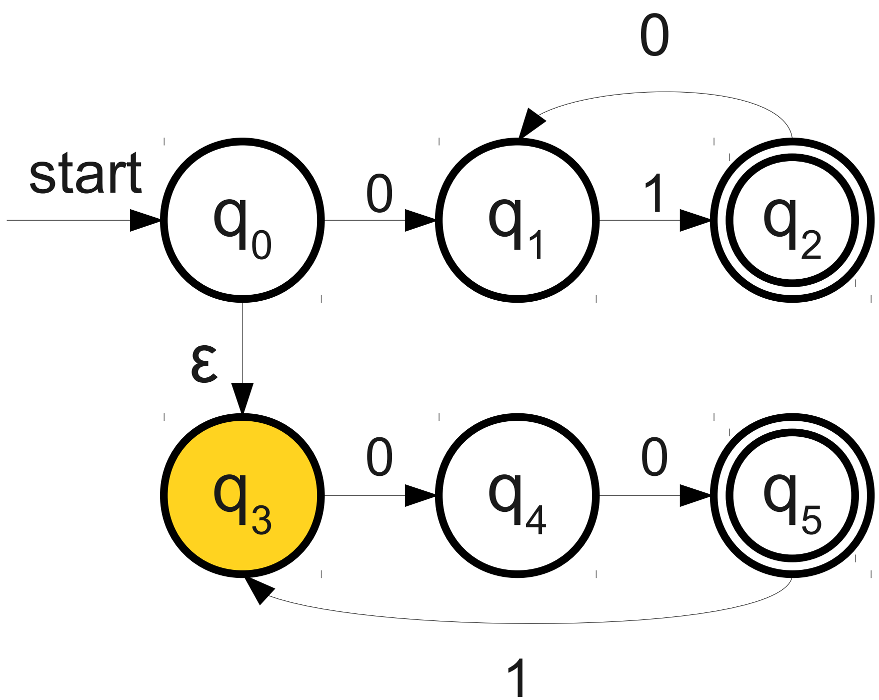

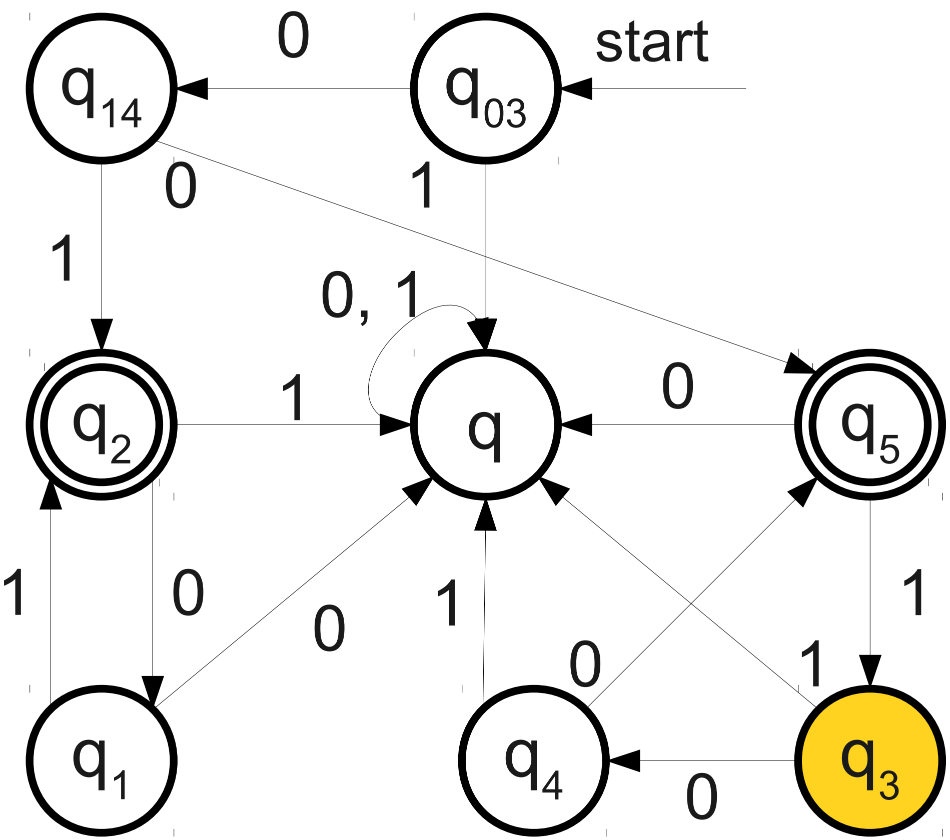

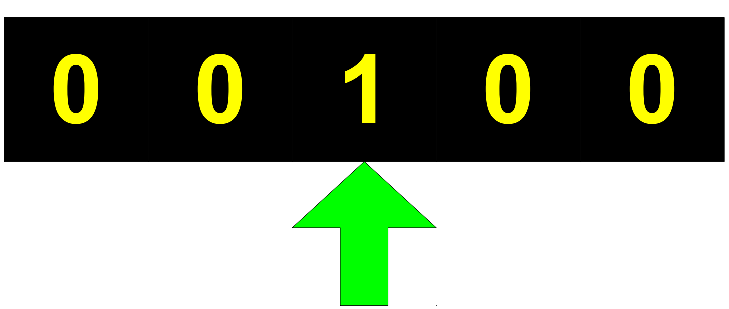

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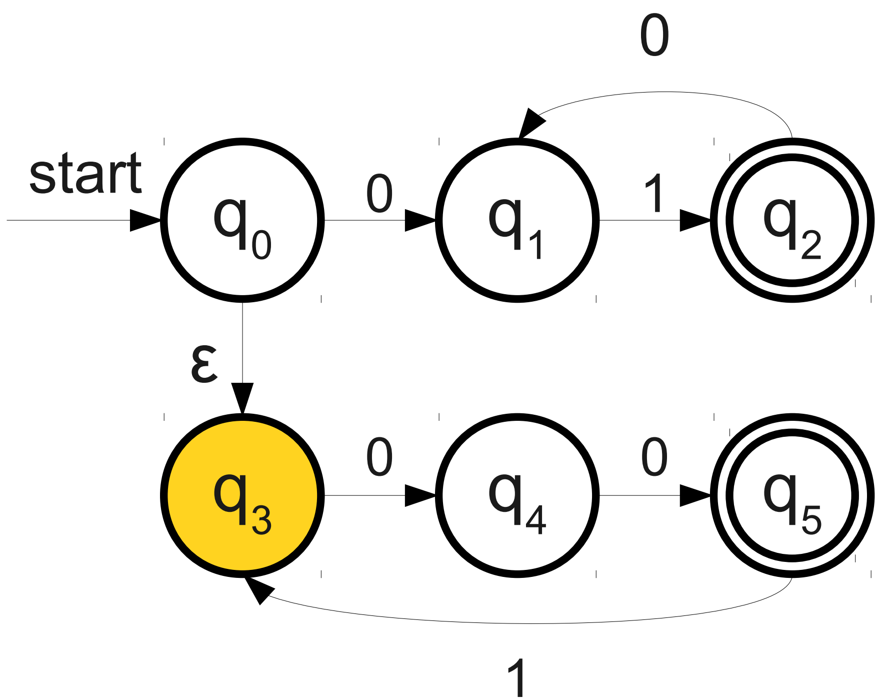

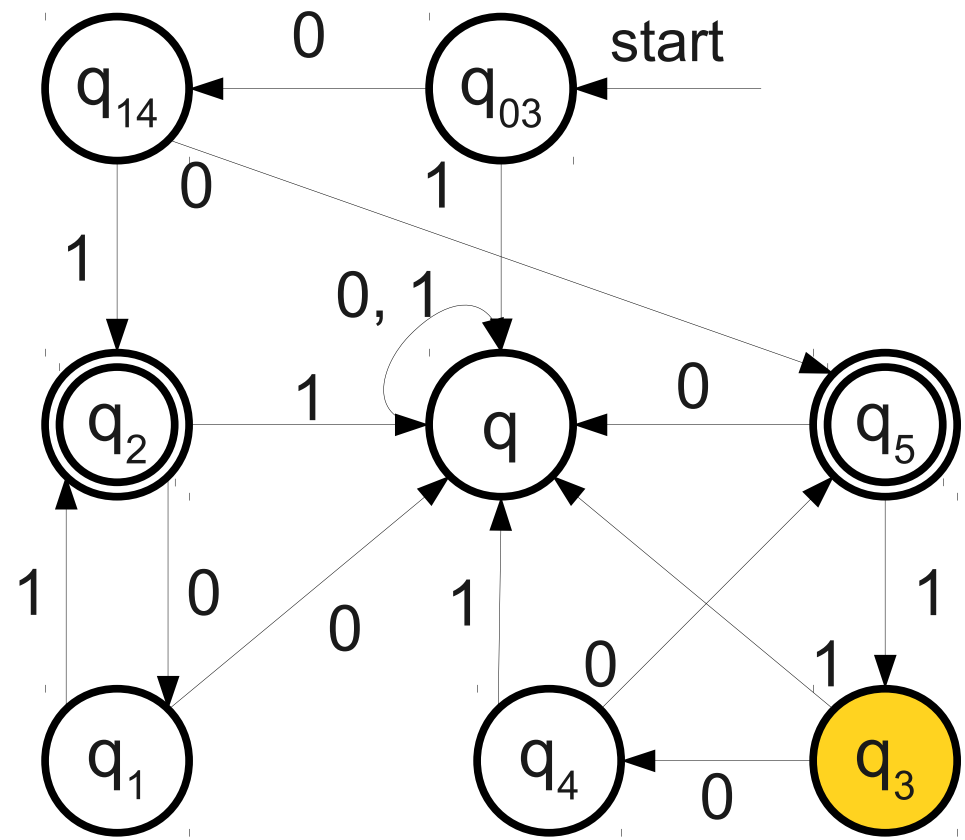

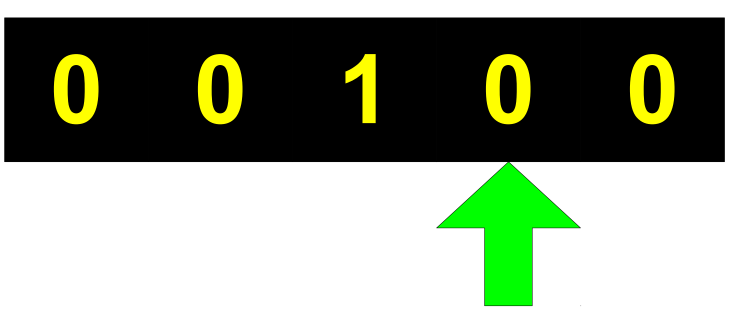

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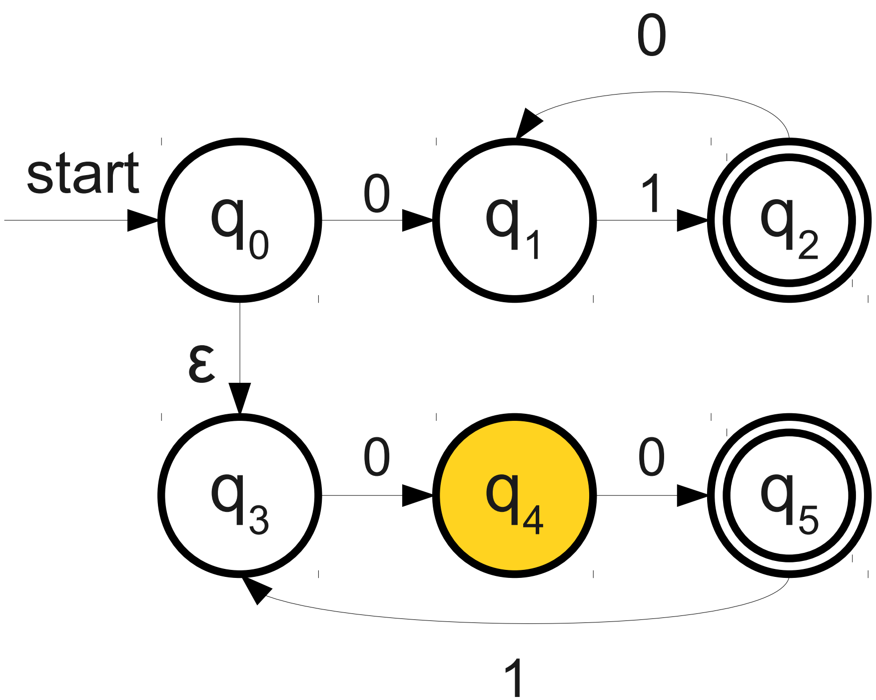

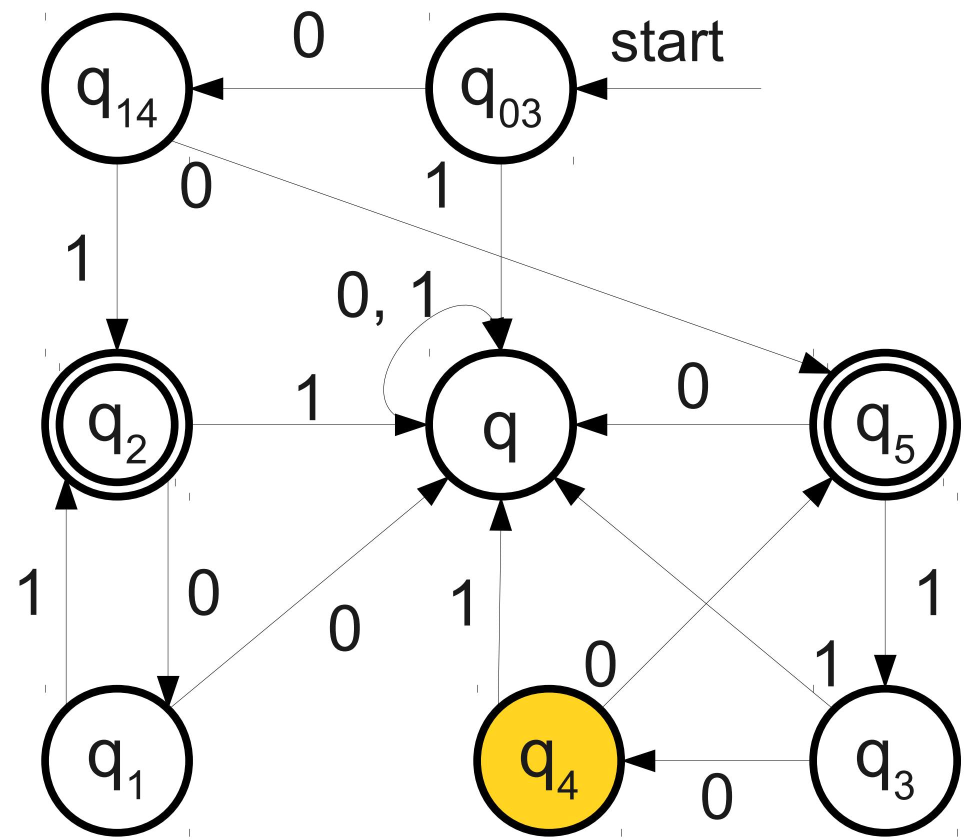

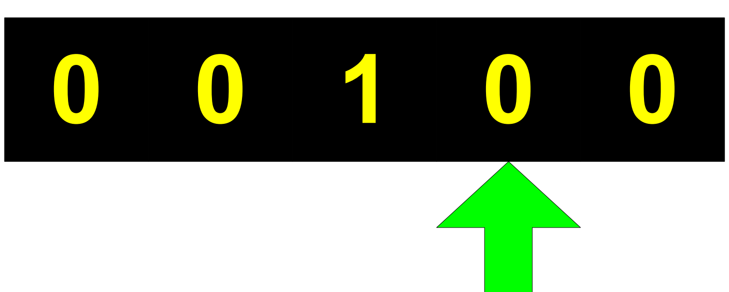

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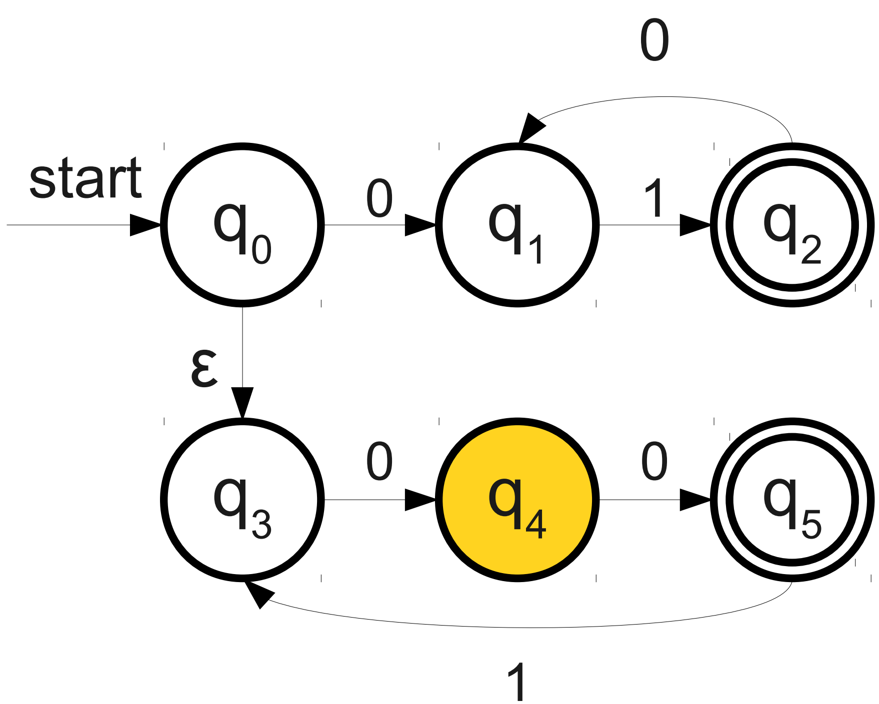

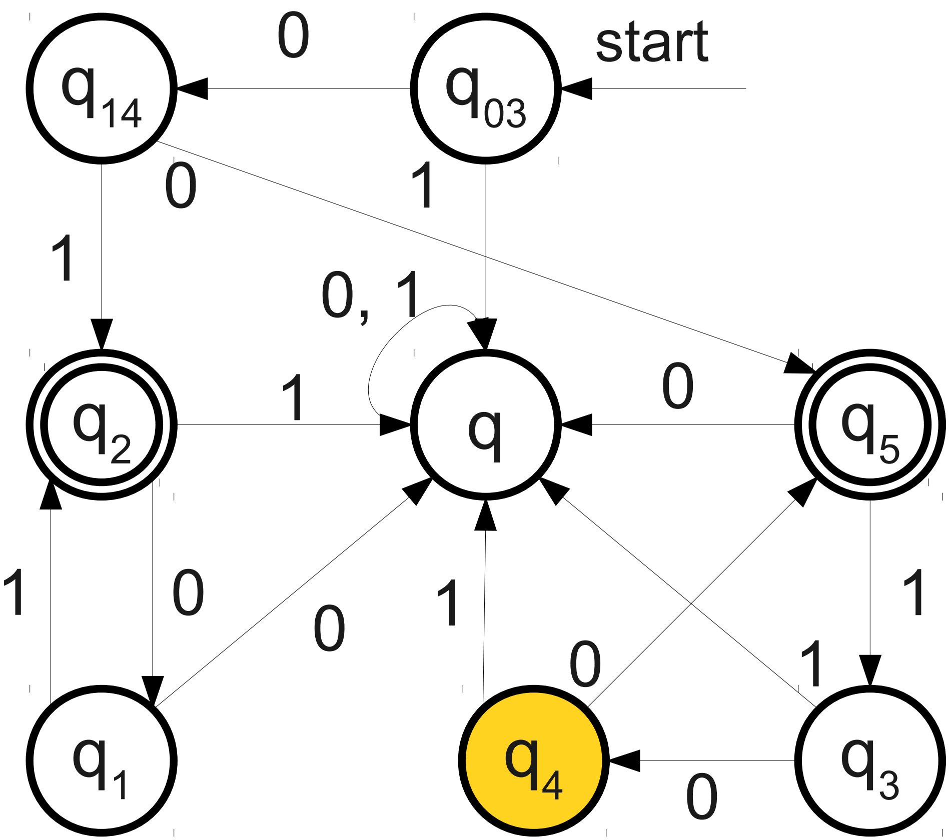

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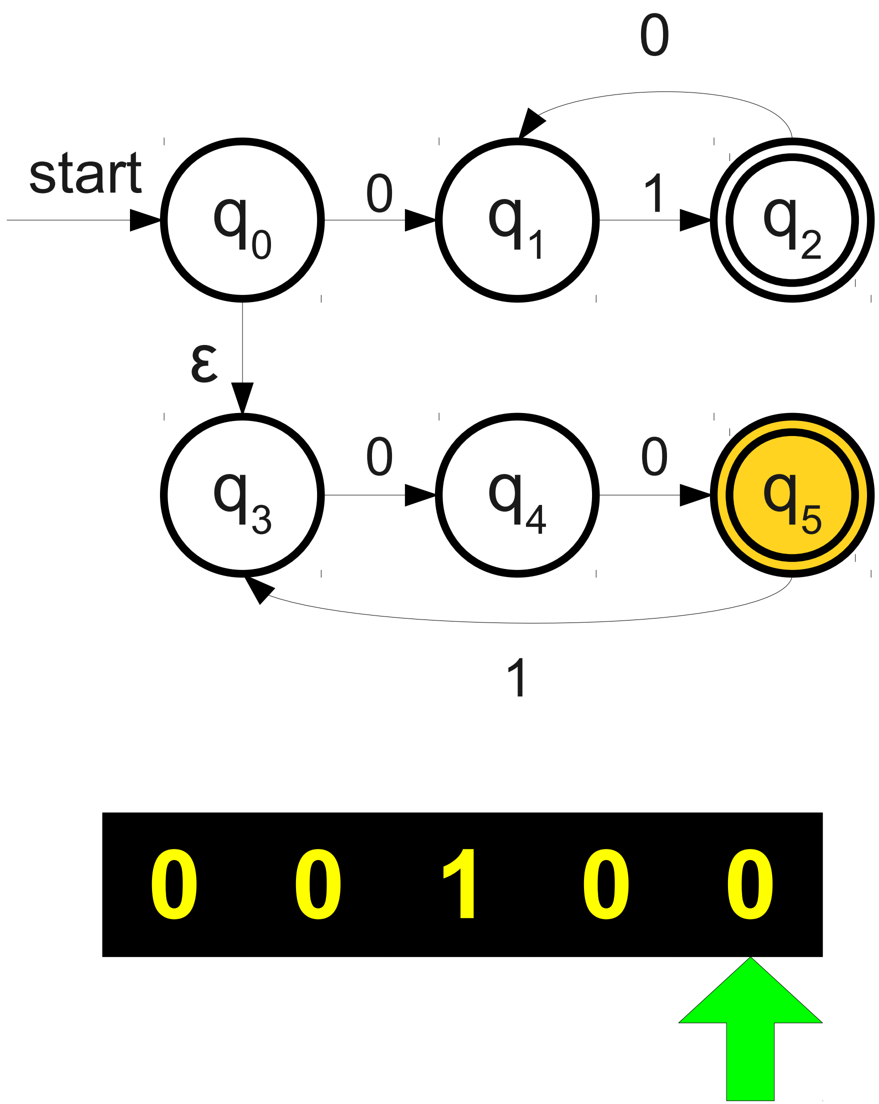

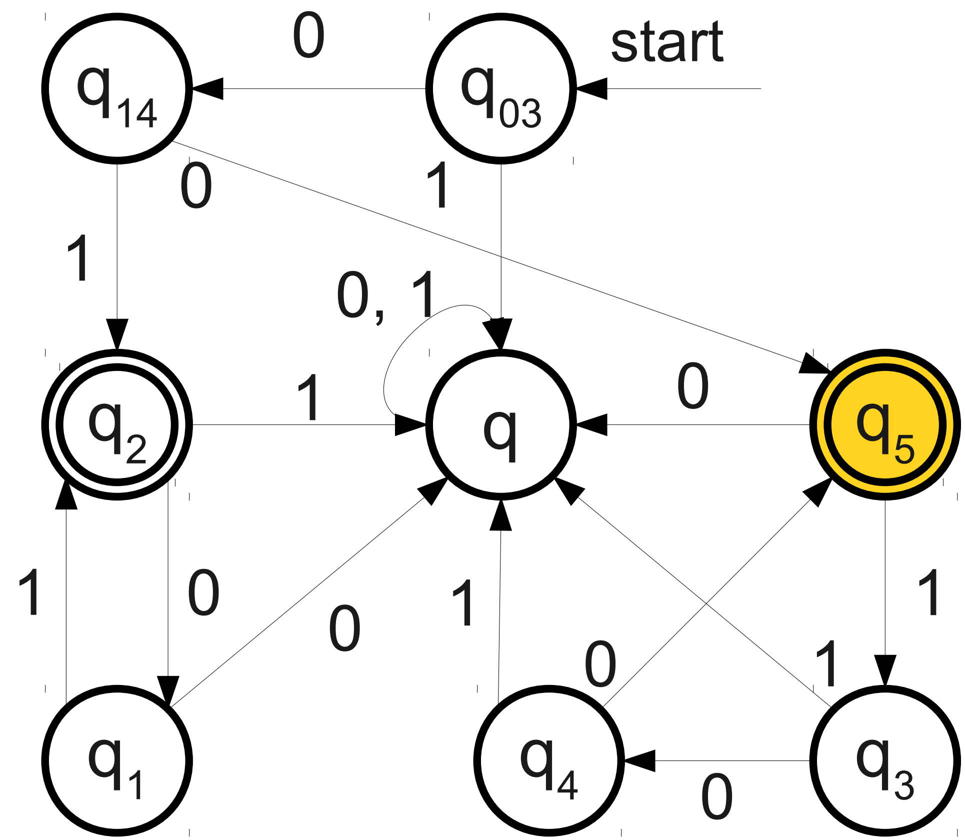

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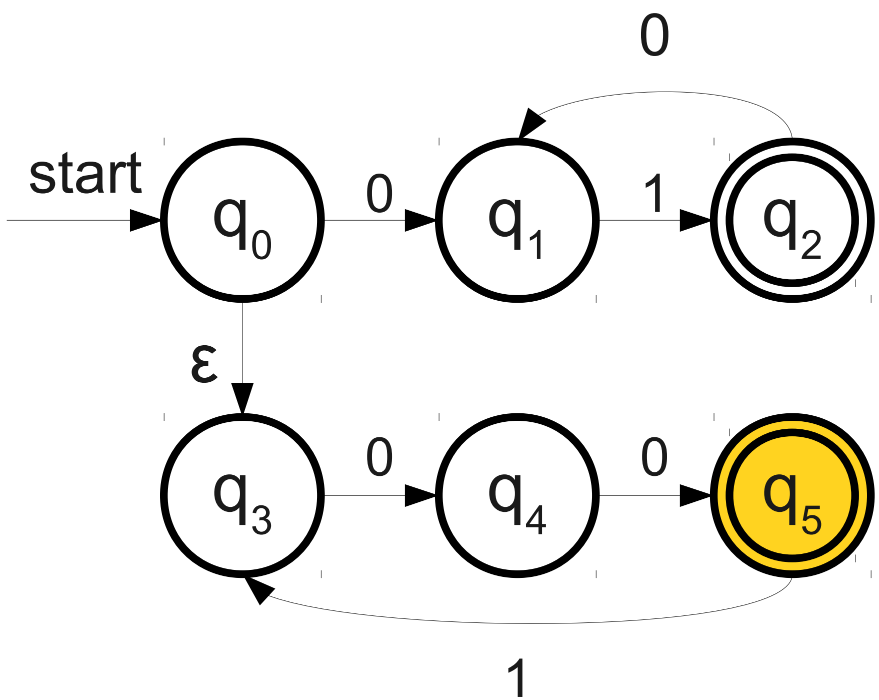

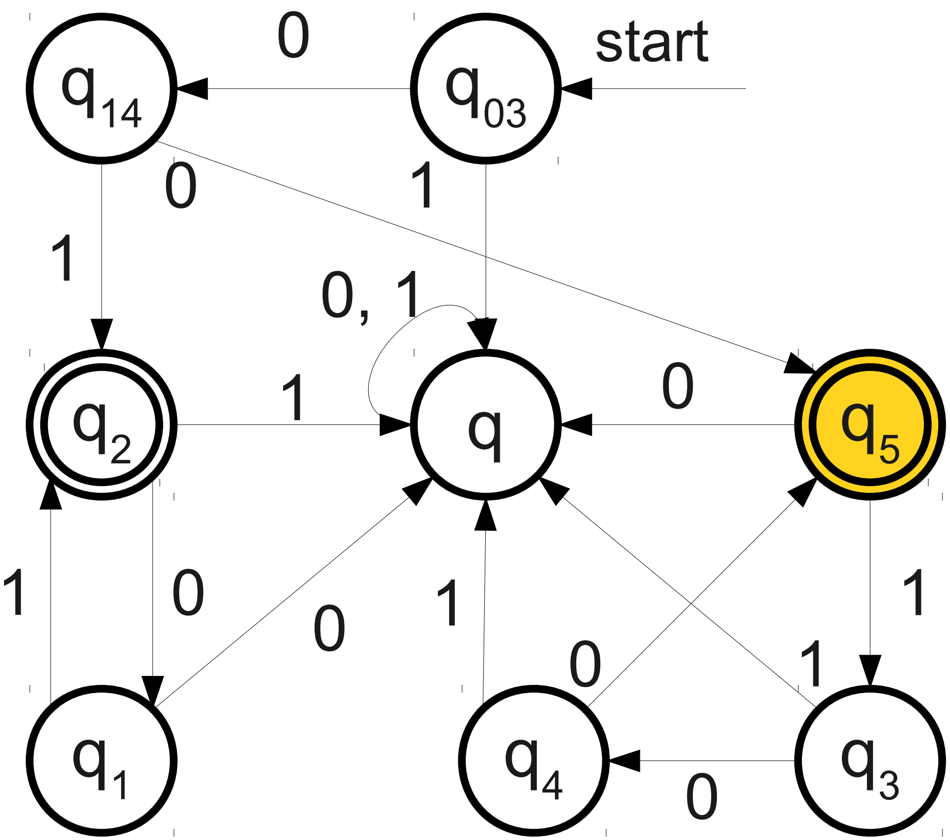

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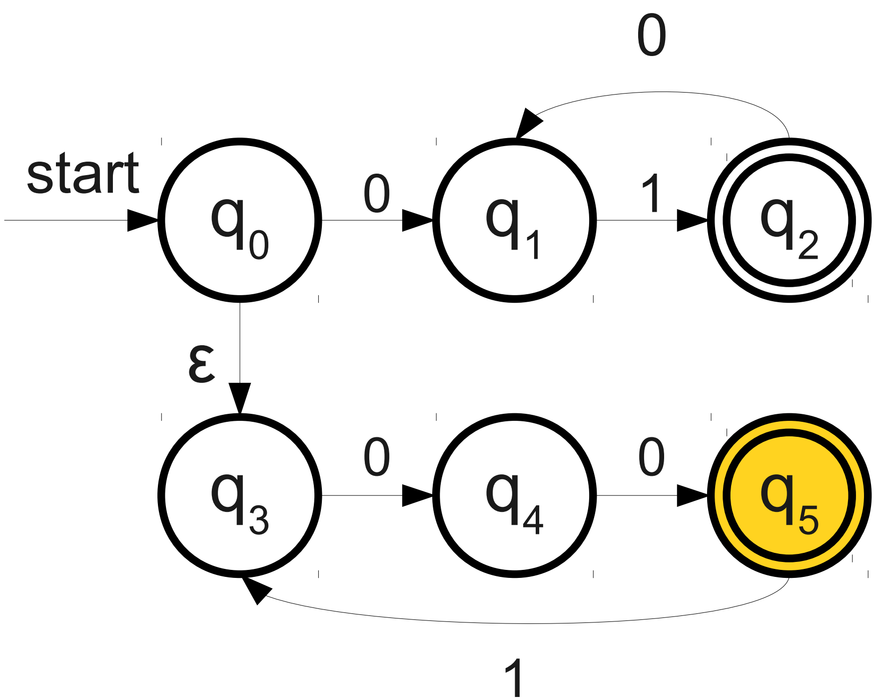

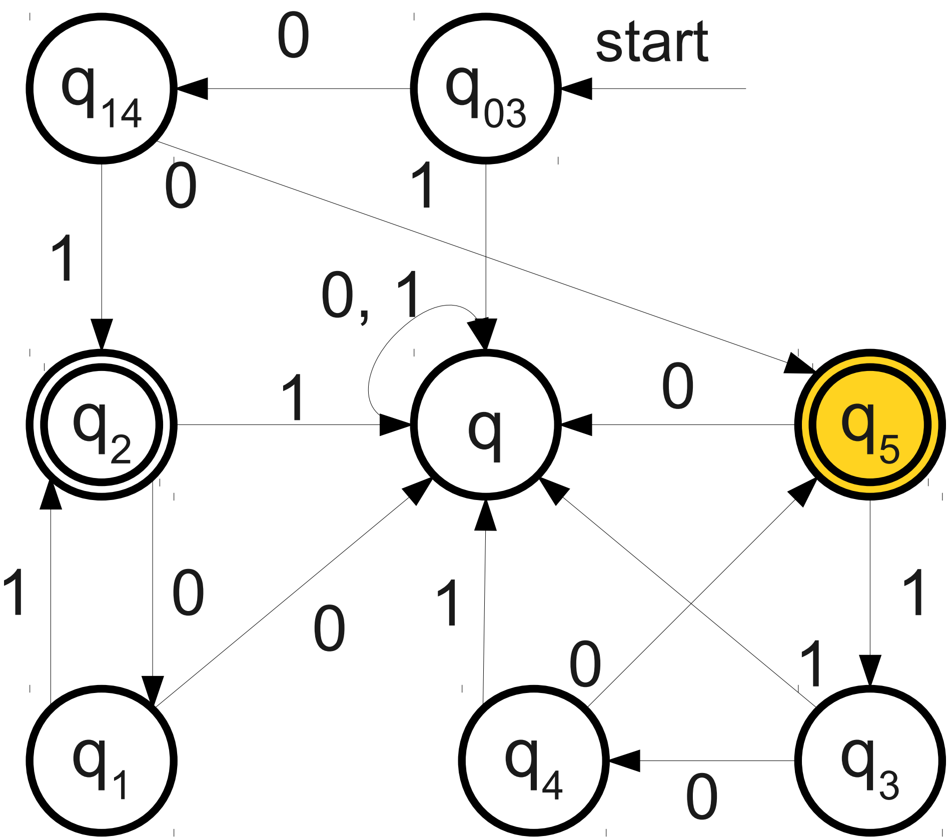

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The Subset Construction

- This construction for transforming an NFA into a DFA is called the **subset construction** (or sometimes the **powerset construction**).
- Intuitively:
  - States of the new DFA correspond to **sets of states** of the NFA.
  - The initial state is the start state, plus all states reachable from the start state via ε-transitions.
  - Transition on state S on character a is found by following all possible transitions on a for each state in S, then taking the set of states reachable from there by ε-transitions.
  - Accepting states are any set of states where *some* state in the set is an accepting state.
- **Read Sipser for a formal account.**