Finite Automata

Part One

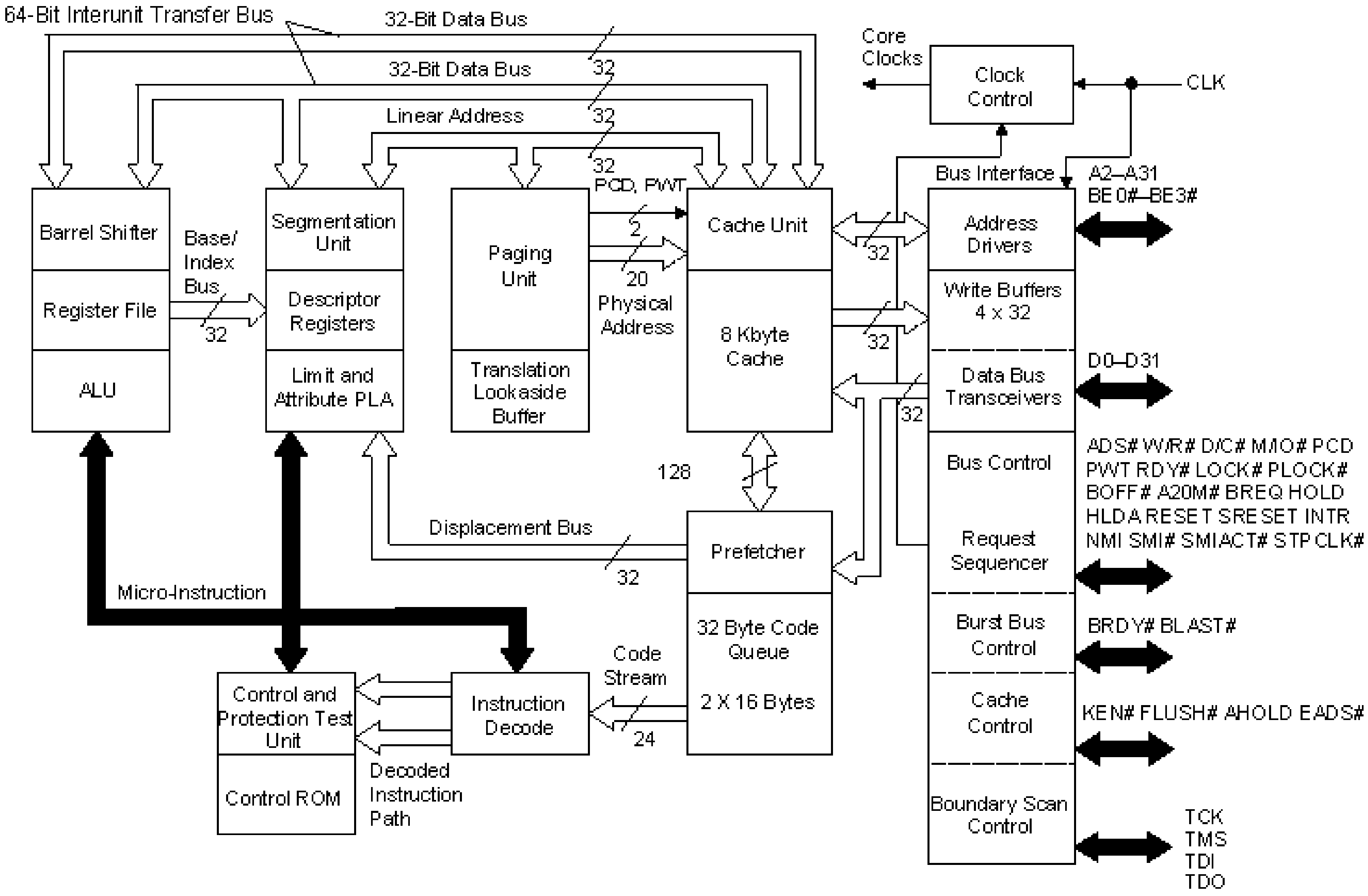
Computability Theory

What problems can we solve with a computer?

What problems can we solve with a computer?

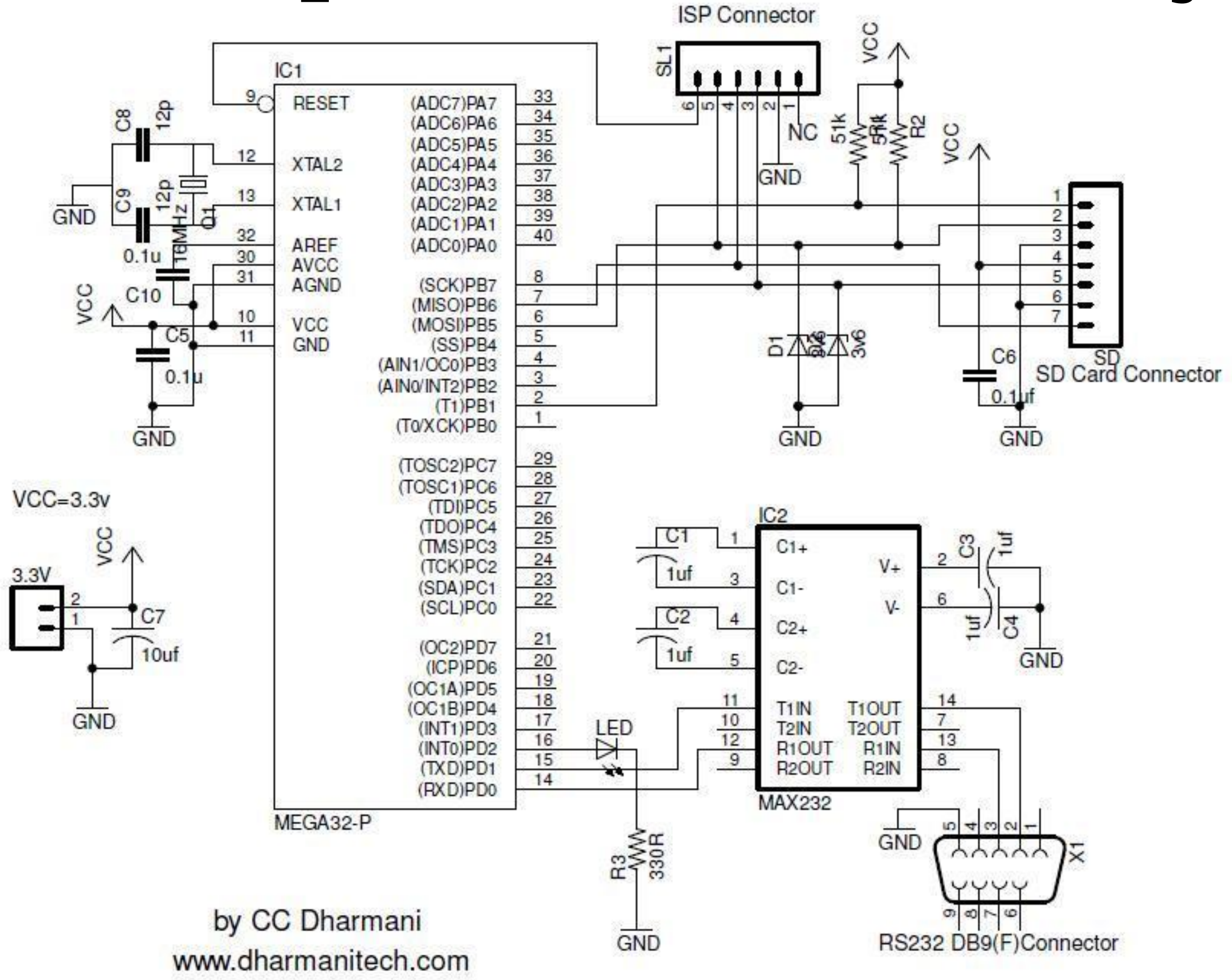
What kind of computer?

Computers are Messy



http://www.intel.com/design/intarch/prodbref/272713.htm

Computers are Messy



by CC Dharmani
www.dharmanitech.com

microSD/SD Card interface with ATmega32 Ver_2.3

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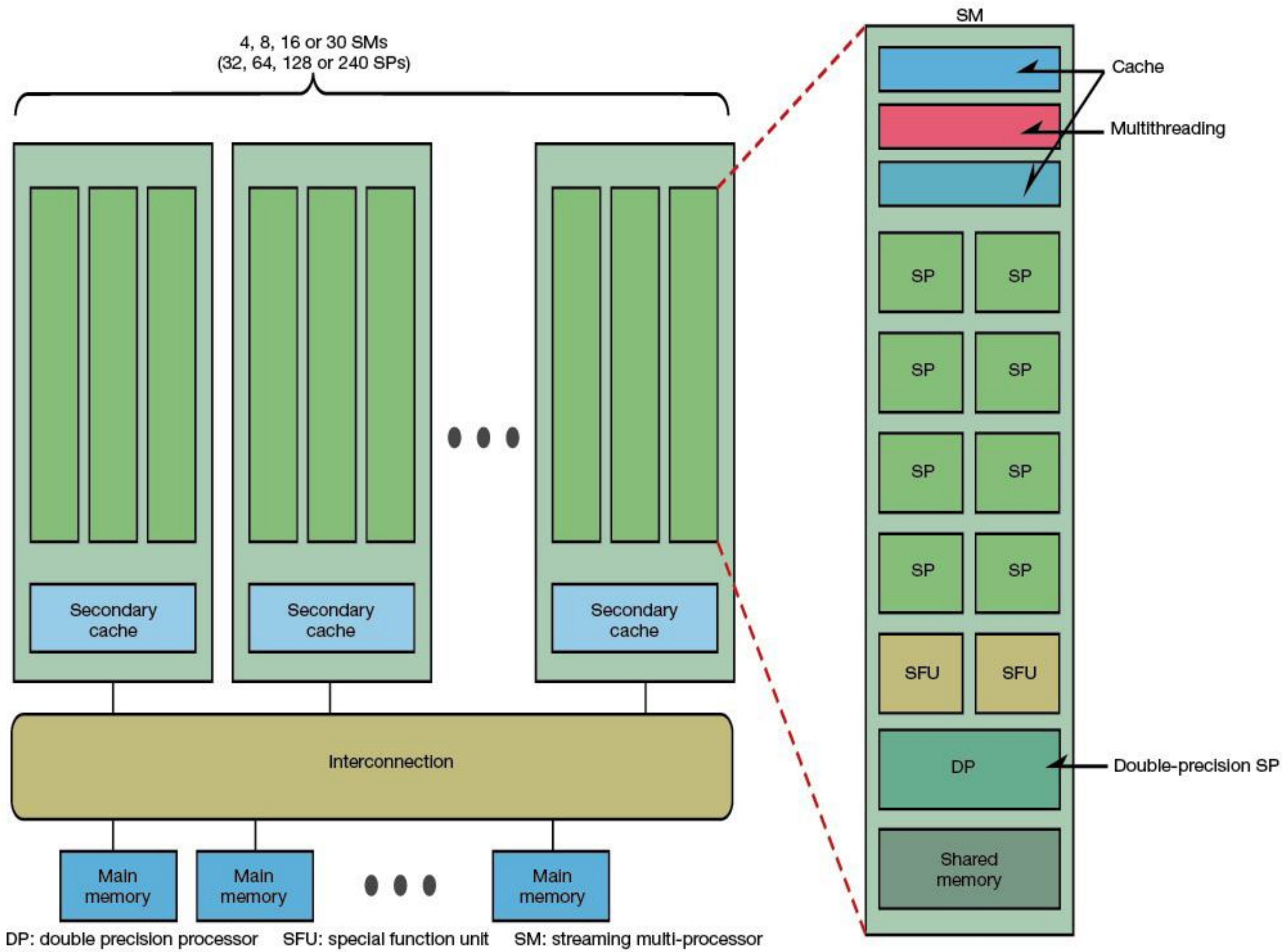

DP: double precision processor SFU: special function unit SM: streaming multi-processor
SP: streaming processor

Fig 2 Covering Everything from PCs to Supercomputers NVIDIA's CUDA architecture boasts high scalability. The quantity of processor units (SM) can be varied as needed to flexibly provide performance from PC to supercomputer levels. Tesla 10, with 240 SPs, also has double-precision operation units (SM) added.

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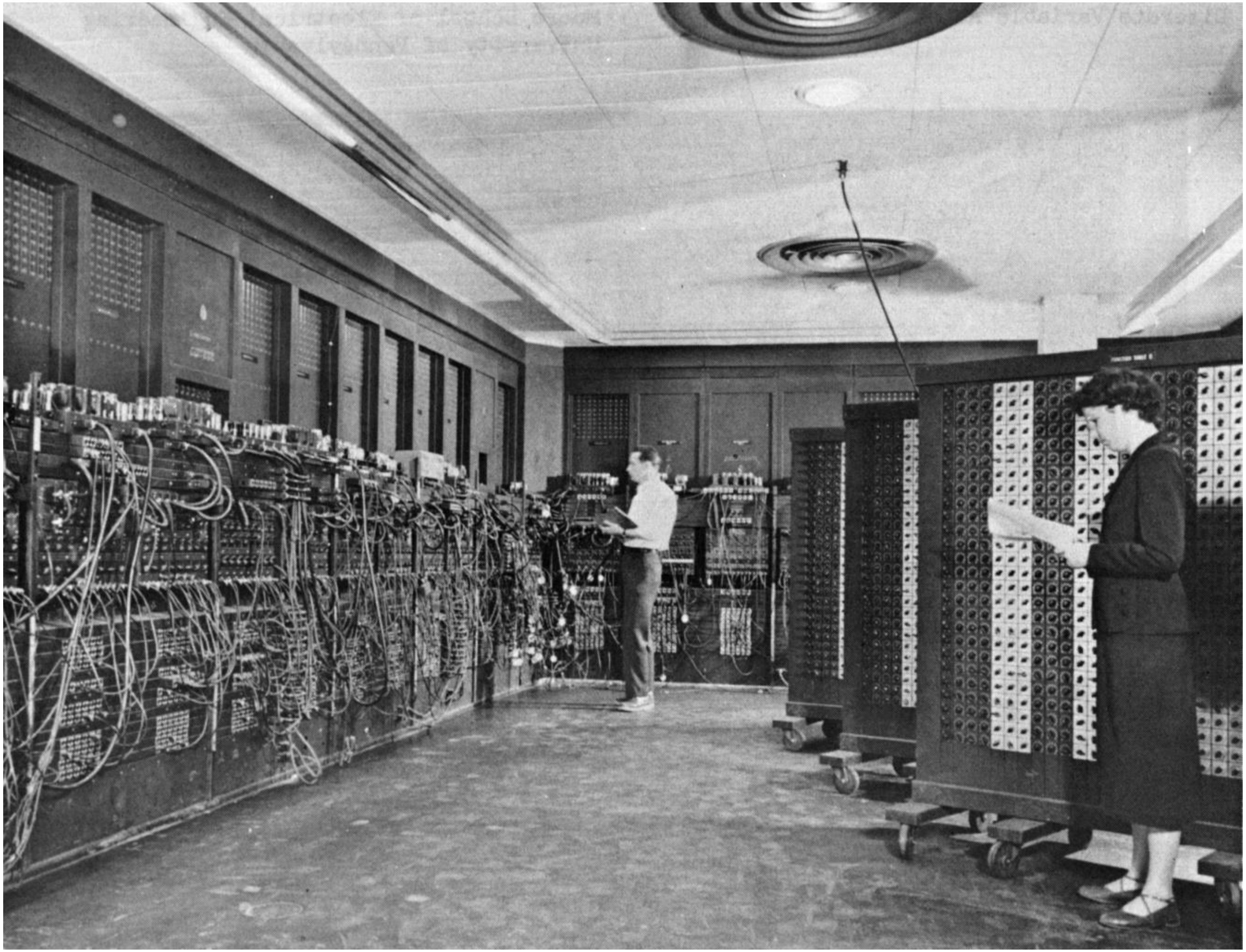
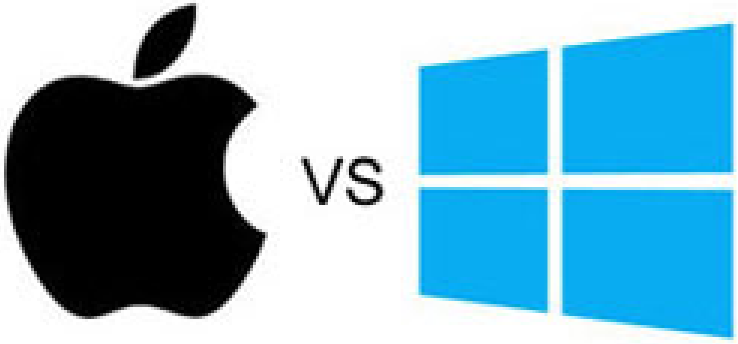


http://en.wikipedia.org/wiki/File:Eniac.jpg

Computers are Messy

That messiness makes it hard to *rigorously* say what we *intuitively* know to be true: that, on some fundamental level, different brands of computers or programming languages are more or less equivalent in what they are capable of doing.

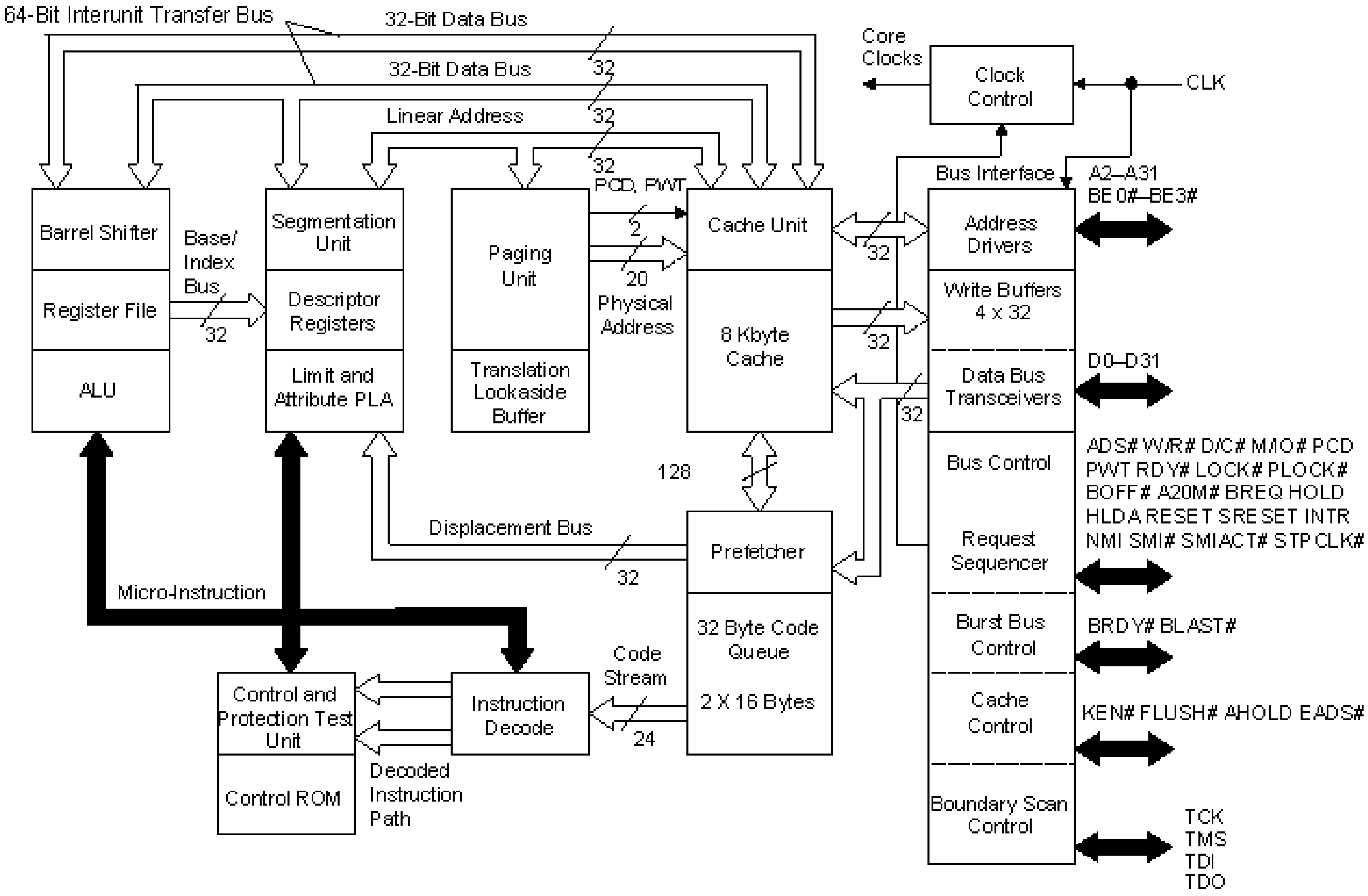


C vs C++
vs Java
vs Python

We need a simpler way of
discussing computing machines.

An ***automaton*** (plural: ***automata***) is a mathematical model of a computing device.

Computers are Messy



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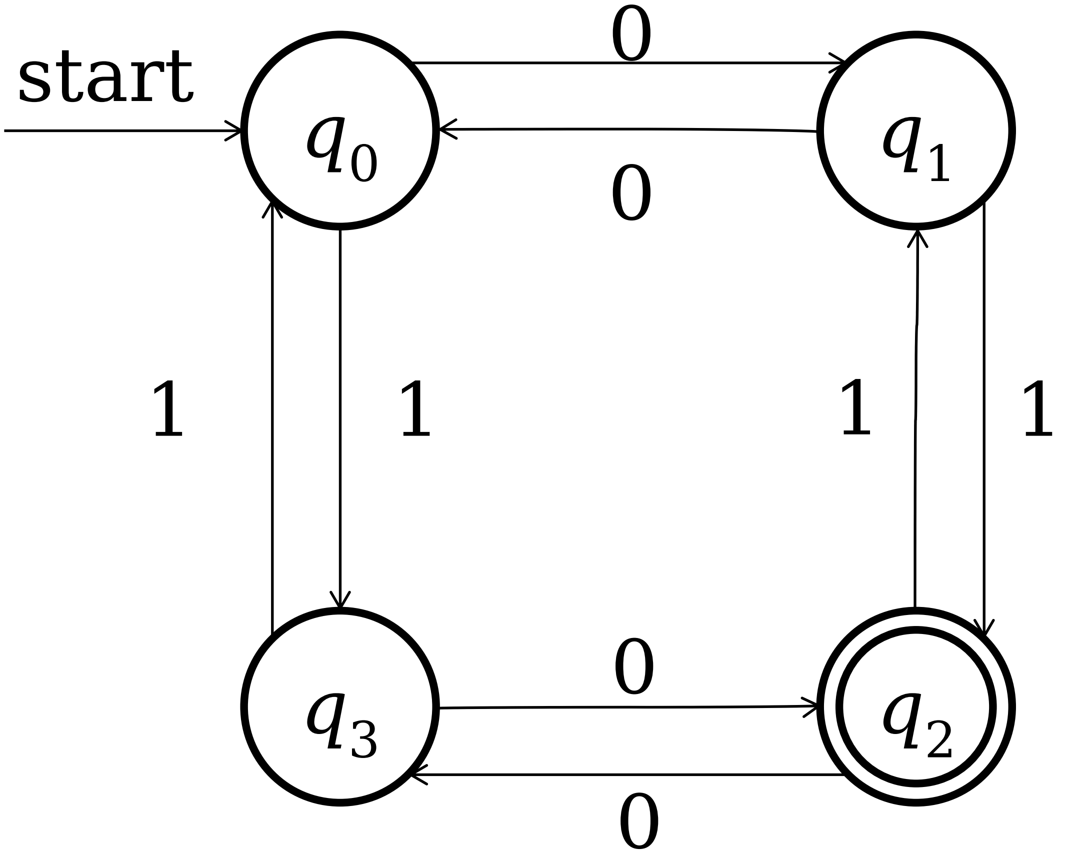
Automata are Clean



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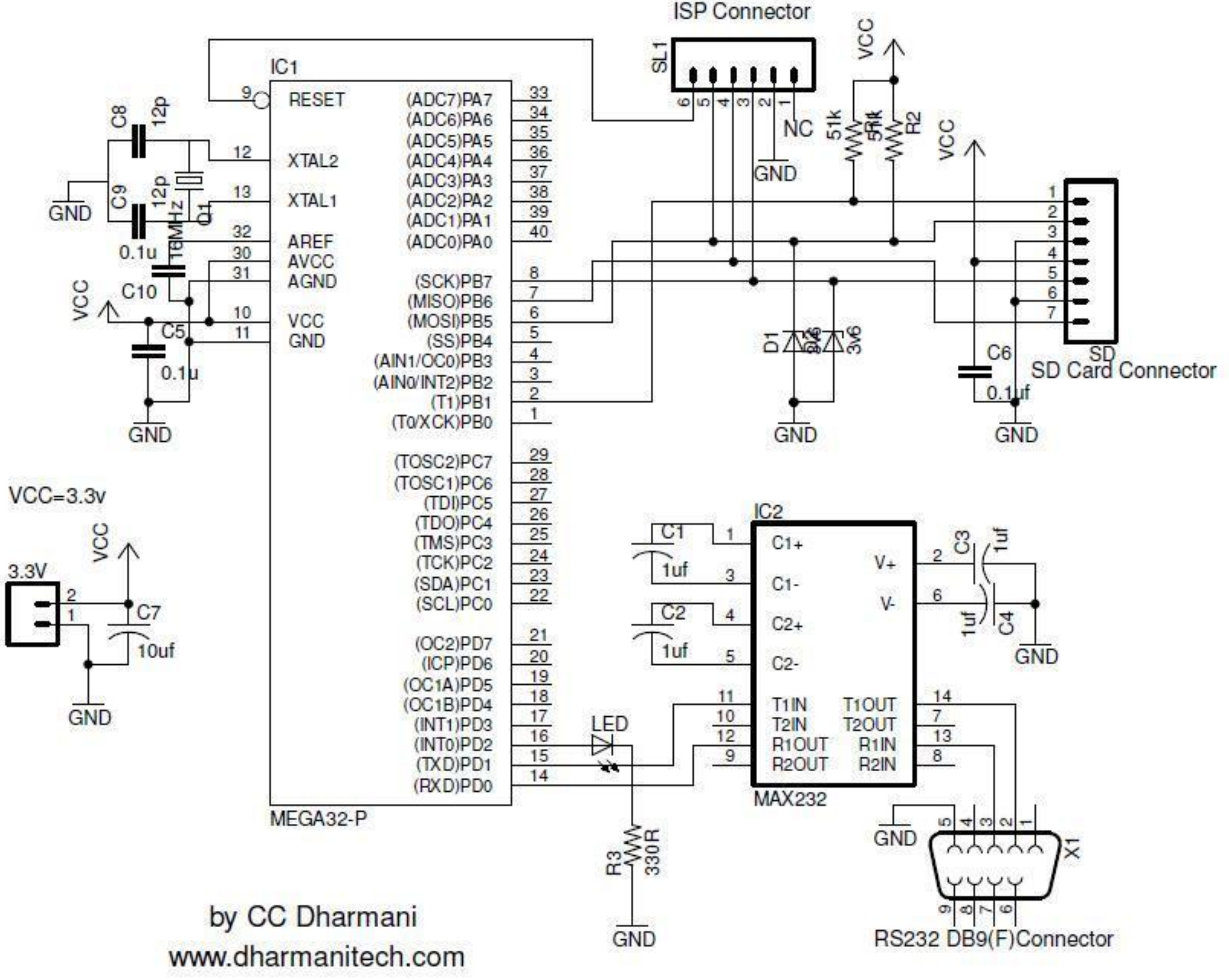

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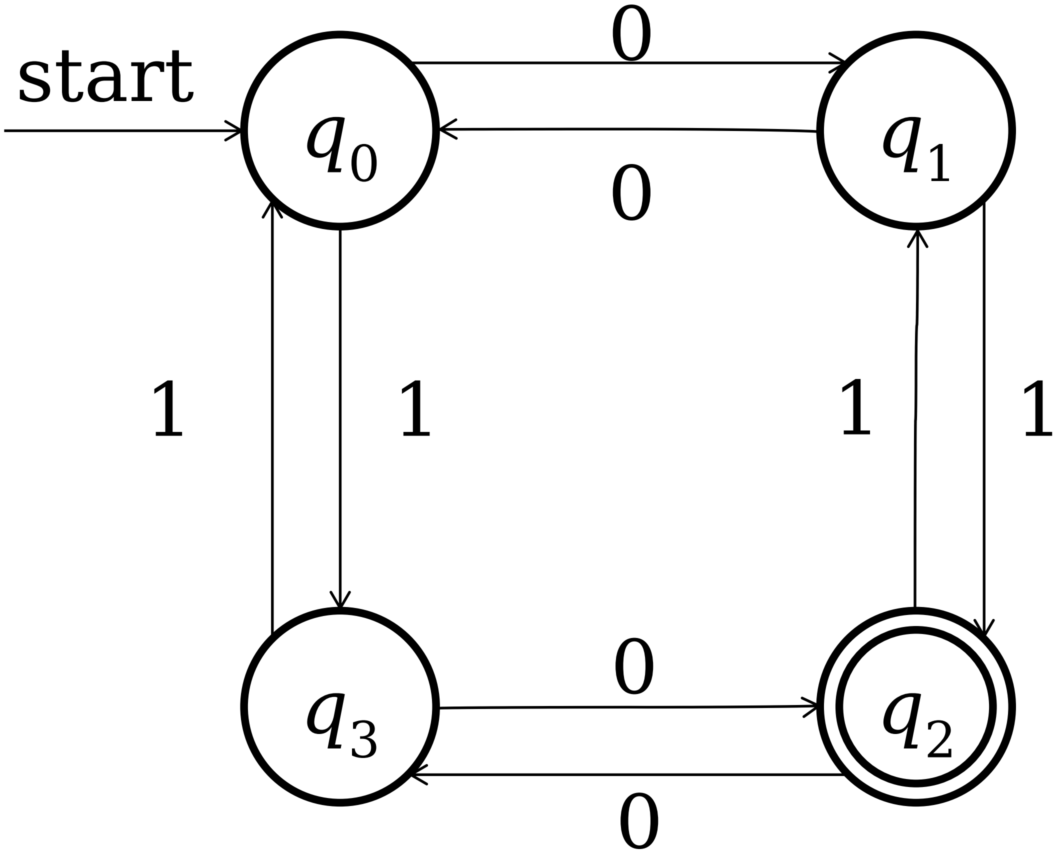

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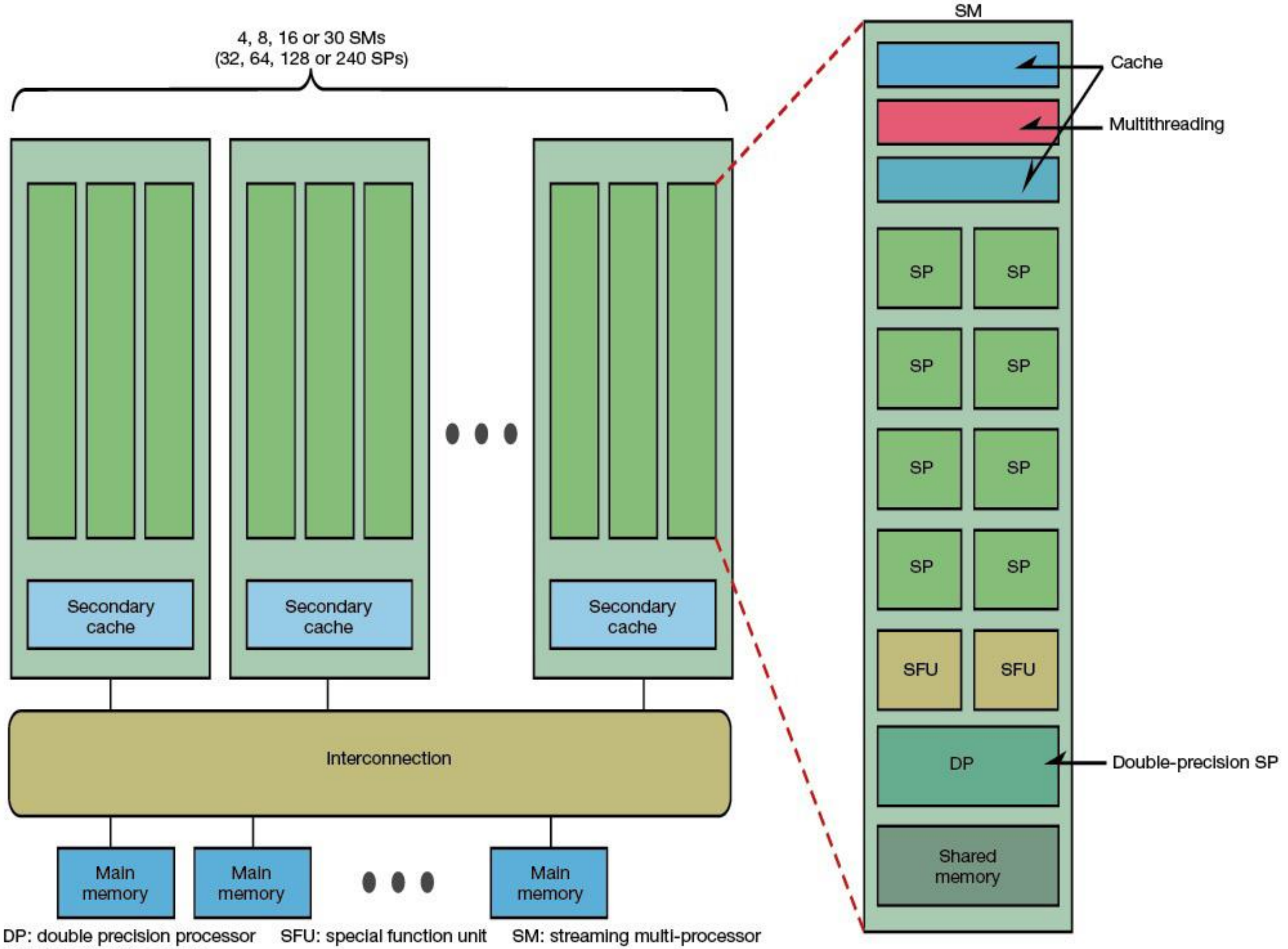

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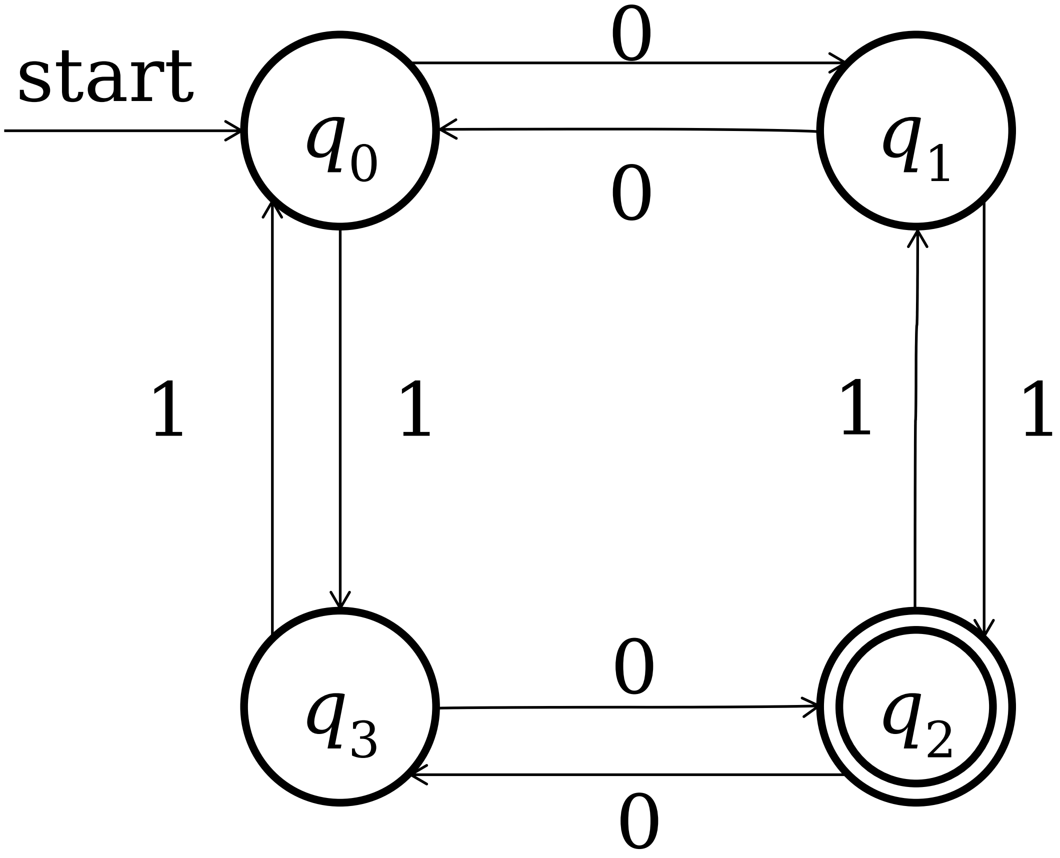

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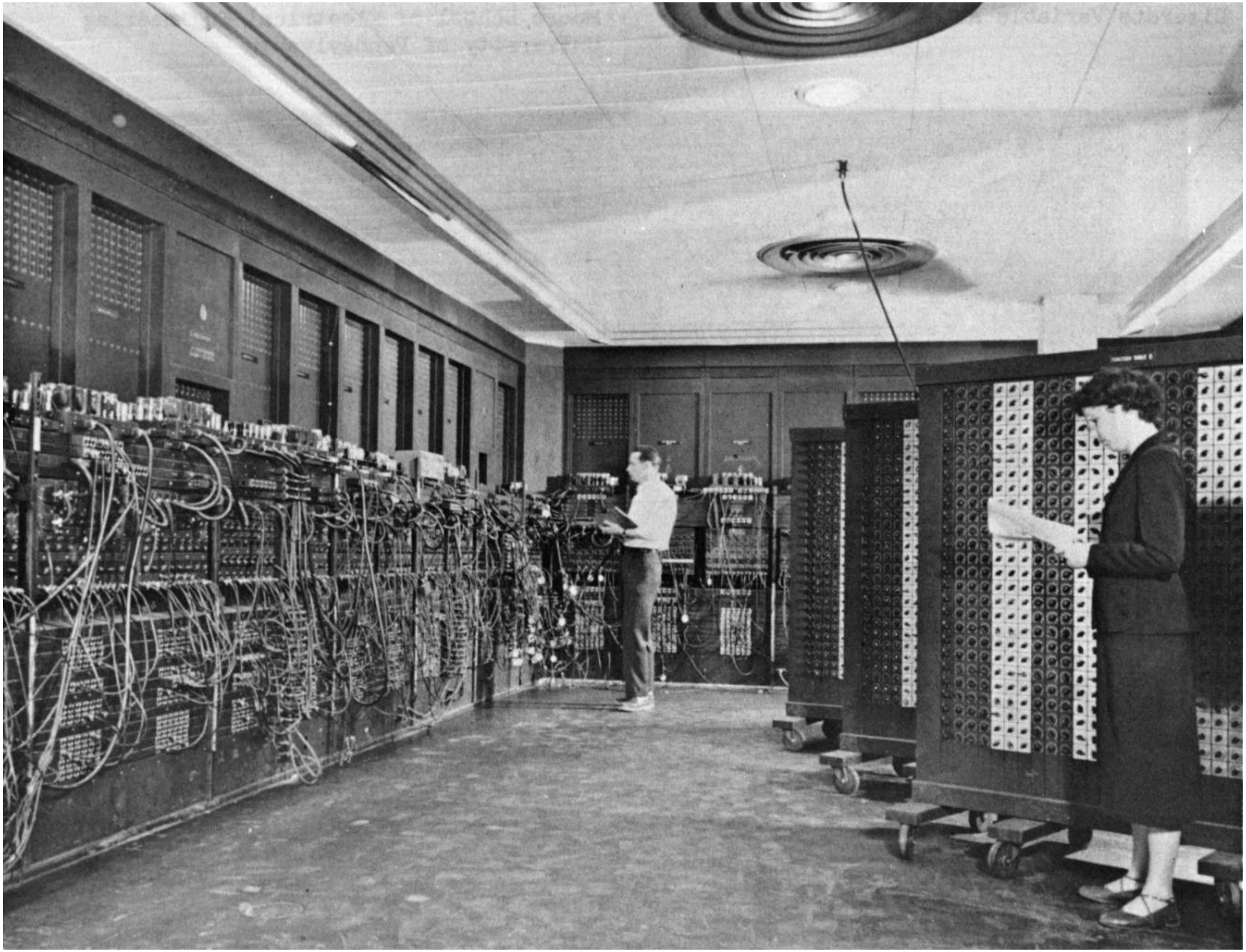

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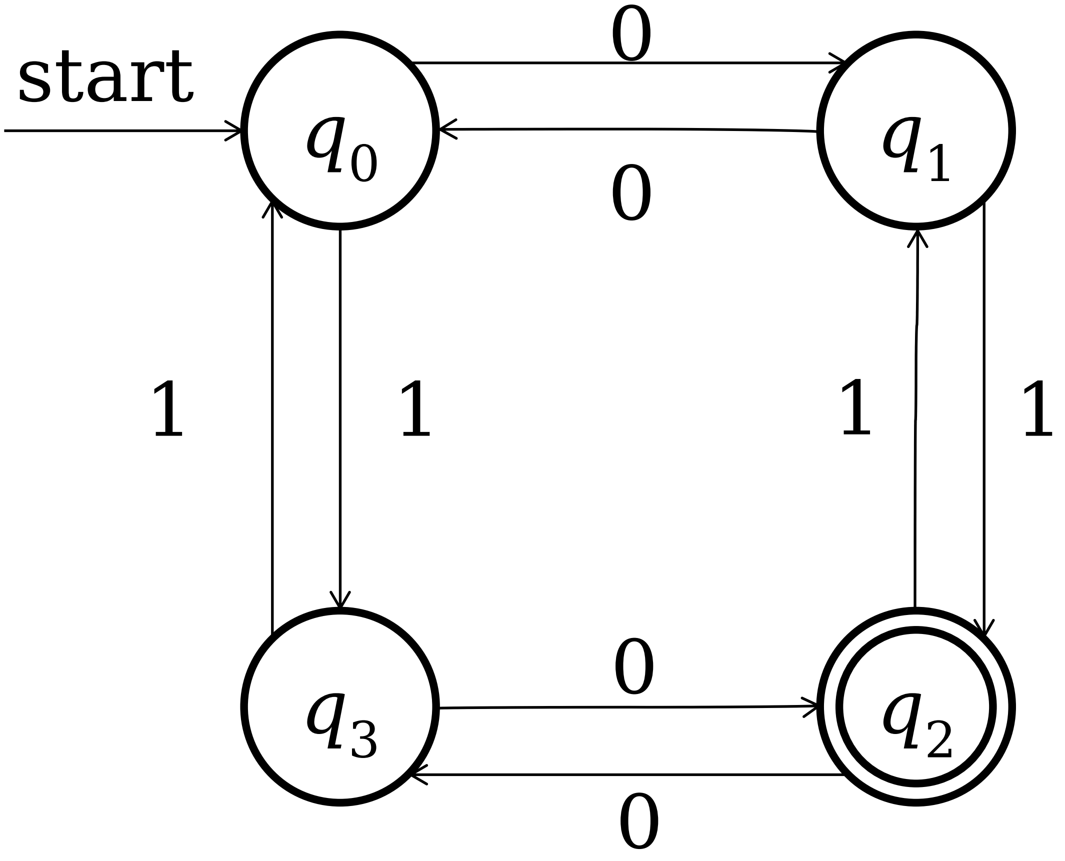


Why Build Models?

Mathematical simplicity.

- It is significantly easier to manipulate our abstract models of computers than it is to manipulate actual computers.

Intellectual robustness.

- If we pick our models correctly, we can make broad, sweeping claims about huge classes of real computers by arguing that they're just special cases of our more general models.

Why Build Models?

The models of computation we will explore in this class correspond to different conceptions of what a computer could do.

Finite automata (this week) are an abstraction of computers with finite resource constraints.

Provide upper bounds for the computing machines that we can actually build.

Turing machines (later) are an abstraction of computers with unbounded resources.

Provide upper bounds for what we could ever hope to accomplish.

What problems can we solve with a computer?

What problems can we solve with a computer?

What is a “problem?”

Problems with Problems

Before we can talk about what problems we can solve, we need a formal definition of a “problem.”

We want a definition that

- corresponds to the problems we want to solve,
- captures a large class of problems, and
- is mathematically simple to reason about.

No one definition has all three properties.

Formal Language Theory

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: Let Σ = {**a**, **b**}. Here are some 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 $L \subseteq \Sigma^*$.

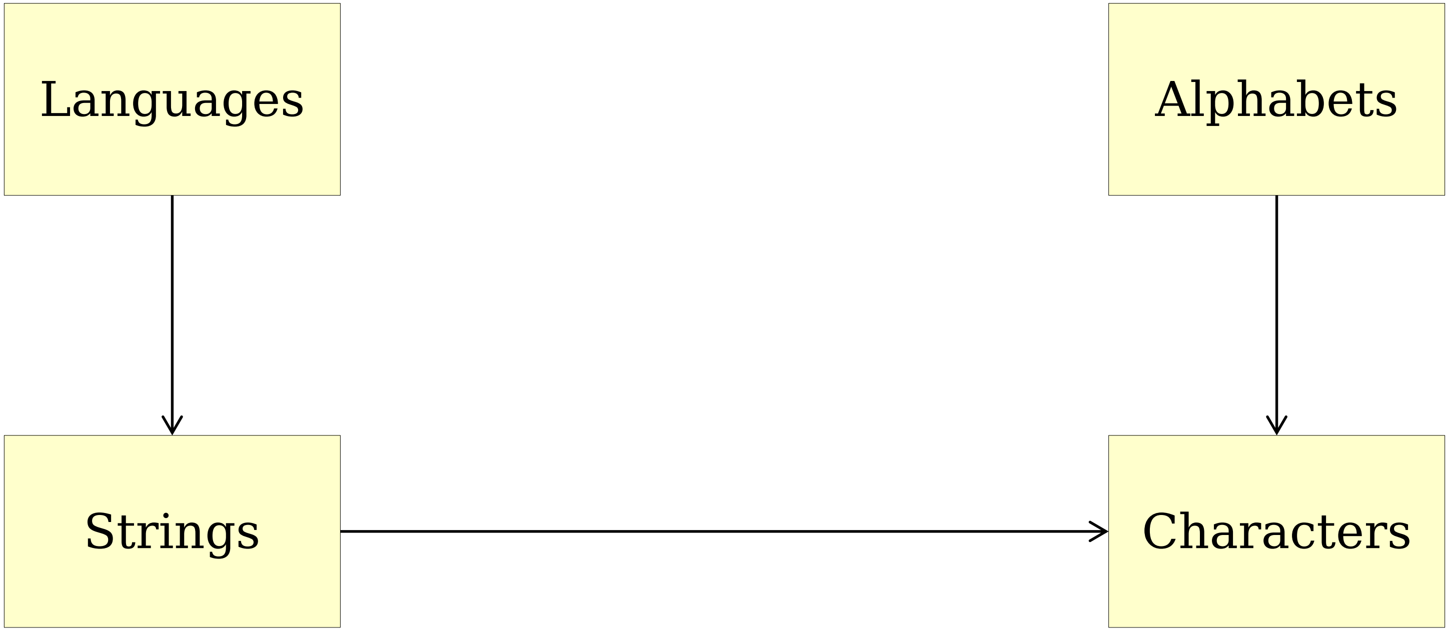
The Cast of Characters

Languages are sets of strings.

Strings are finite sequences of characters.

Characters are individual symbols.

Alphabets are sets of characters.



Strings and Problems

Given a string *w*, determine whether *w* ∈ *S*.

Suppose that L is the language

$$L = \{ \text{"}a\text{"}, \text{"}b\text{"}, \text{"}c\text{"}, \ldots, \text{"}z\text{"} \}$$

This is modeling the problem:

Given a string *w*, determine whether
***w* is a single lower-case English letter.**

Strings and Problems

Given a string *w*, determine whether *w* ∈ *S*.

Suppose that L is the language

$$L = \{ \ p \mid p \text{ is a legal C++ program } \}$$

This is modeling the problem:

Given a string *w*, determine whether *w* is a legal C++ program.

The Model

Fundamental Question: For what languages L can you design an automaton that takes as input a string, then determines whether the string is in L?

The answer depends on the choice of L, the choice of automaton, and the definition of "determines."

In answering this question, we'll go through a whirlwind tour of models of computation and see how this seemingly abstract question has very real and powerful consequences.

To Summarize

An ***automaton*** is an idealized mathematical computing machine.

A ***language*** is a set of strings, a ***string*** is a (finite) sequence of characters, and a ***character*** is an element of an ***alphabet***.

Goal: Figure out in which cases we can build automata for particular languages.

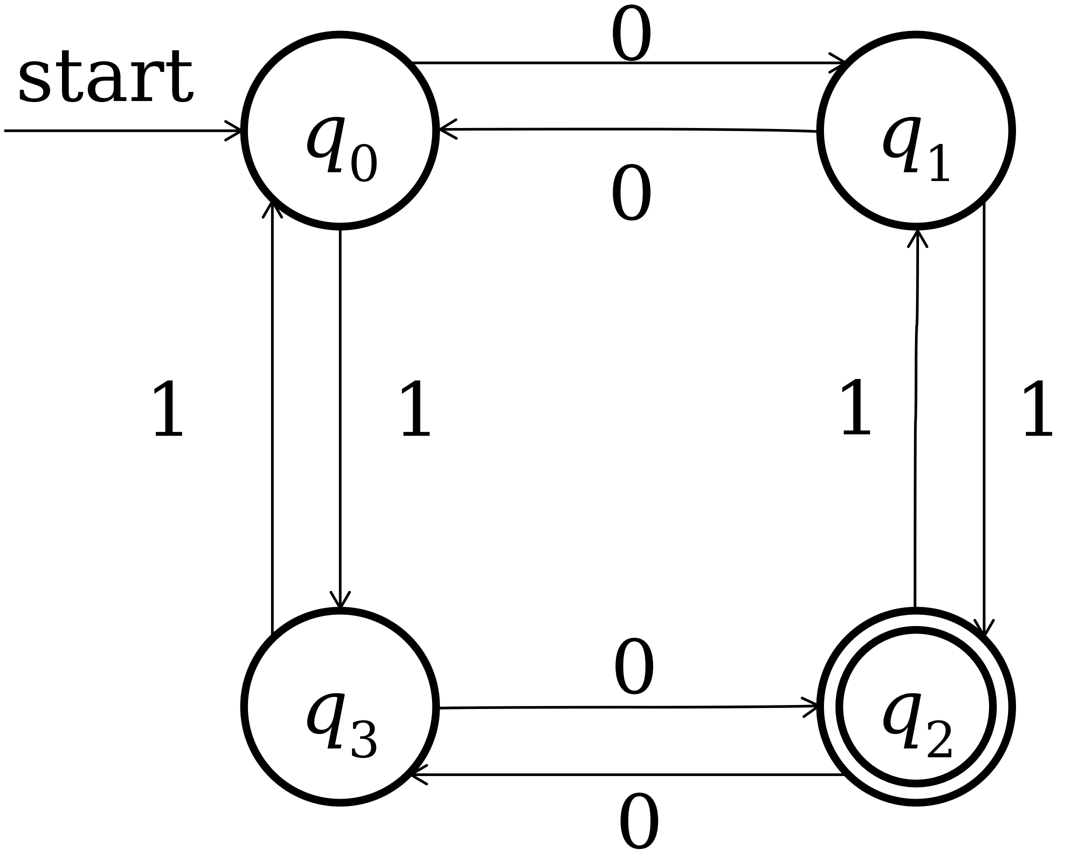
What problems can we solve with a computer?

Finite Automata

A ***finite automaton*** is a simple type of mathematical machine for determining whether a string is contained within some language.

Each finite automaton consists of a set of ***states*** connected by ***transitions***.

A Simple Finite Automaton



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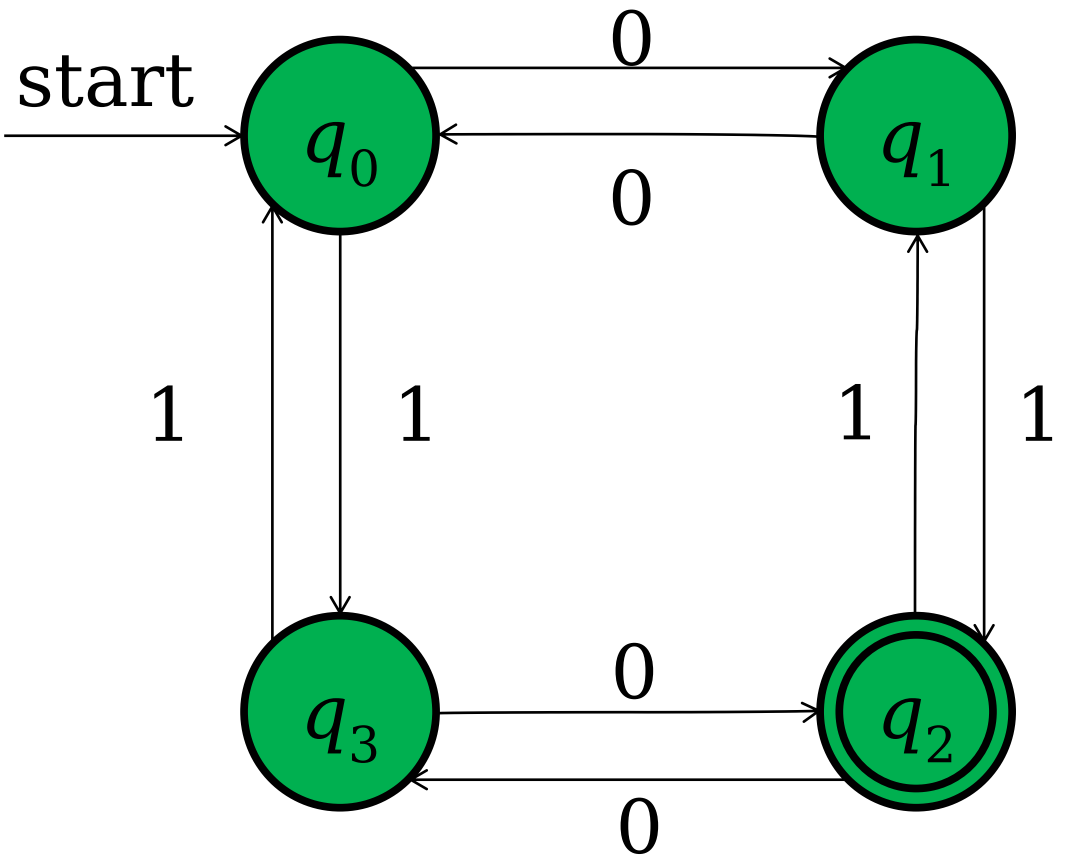
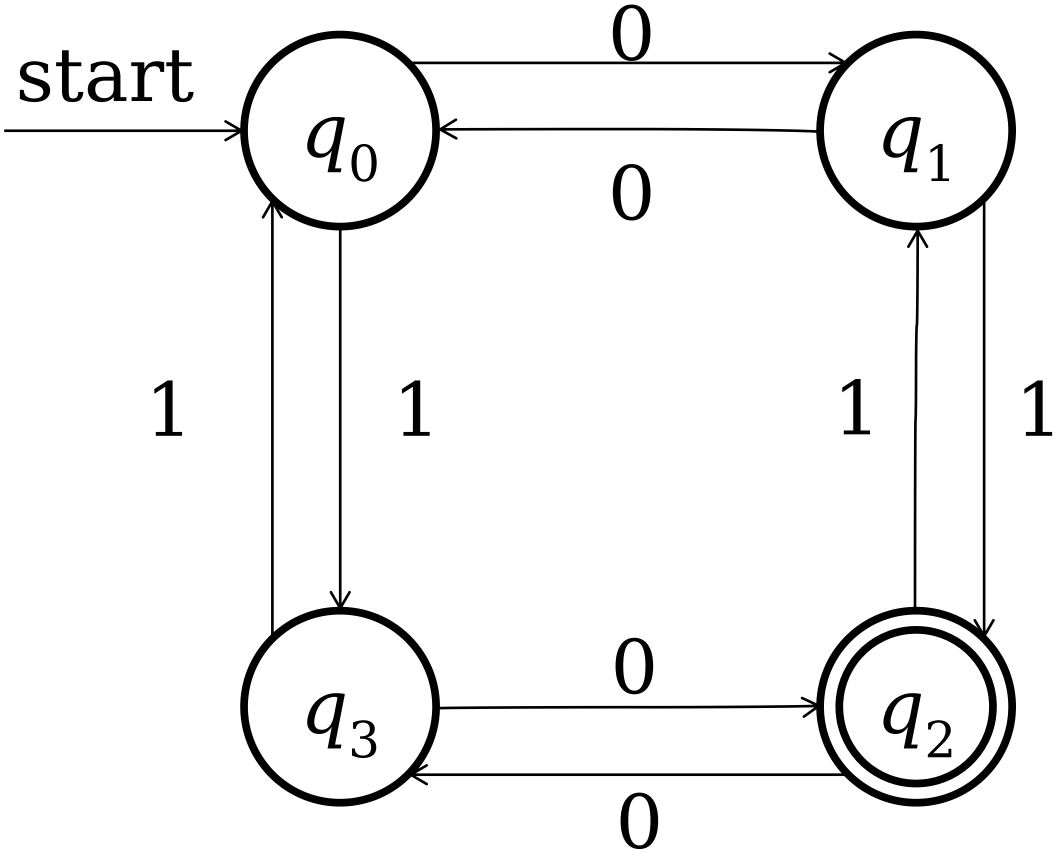


Each circle represents a **state** of the automaton.

A Simple Finite Automaton



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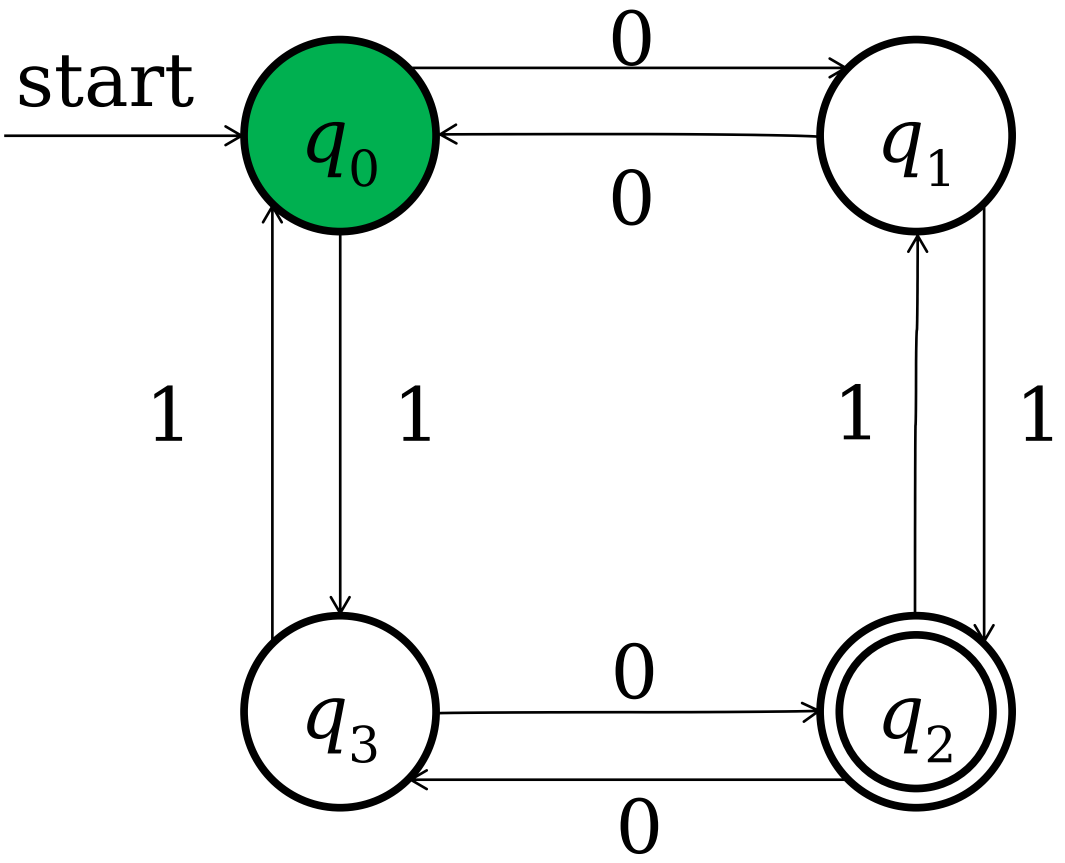
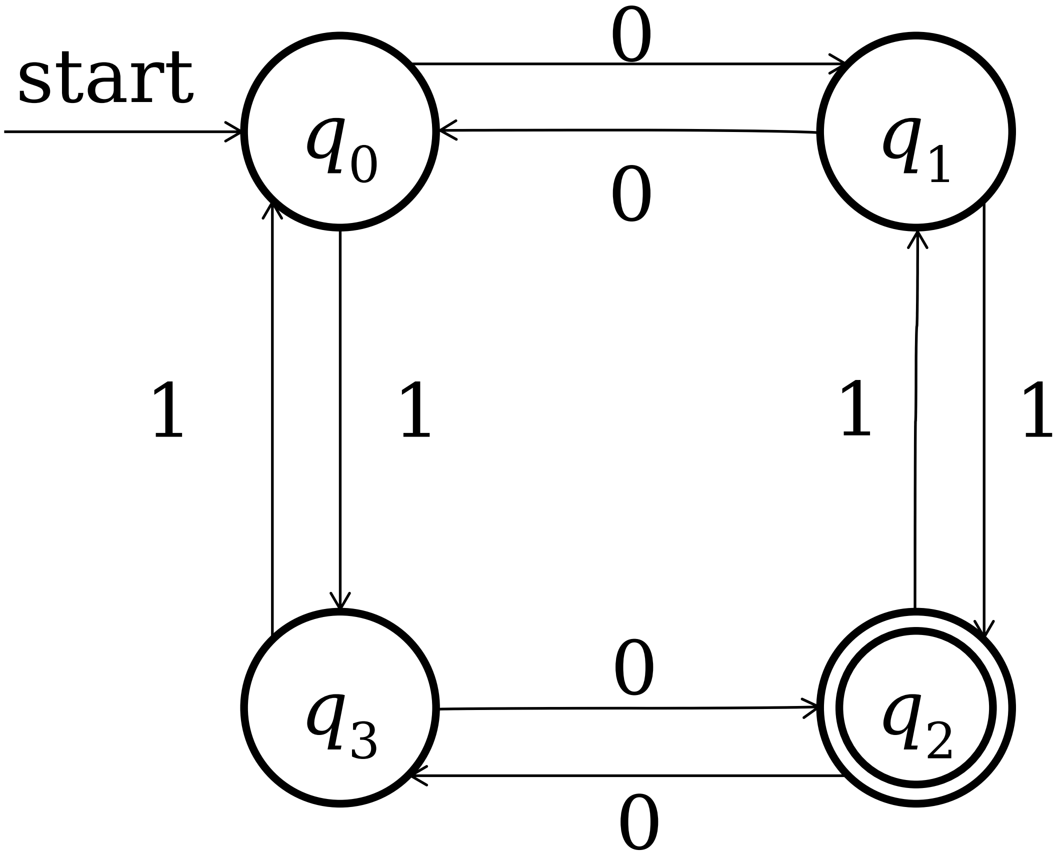


One special state is designated as the **start state**.

A Simple Finite Automaton



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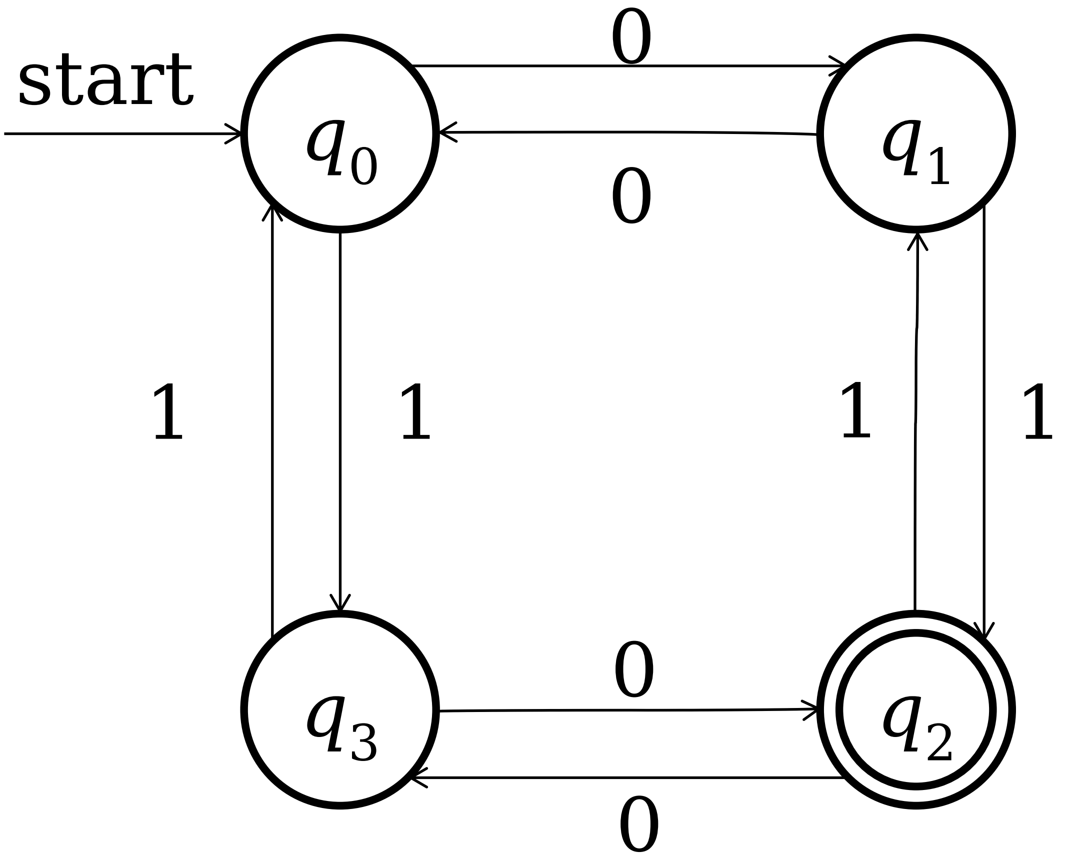

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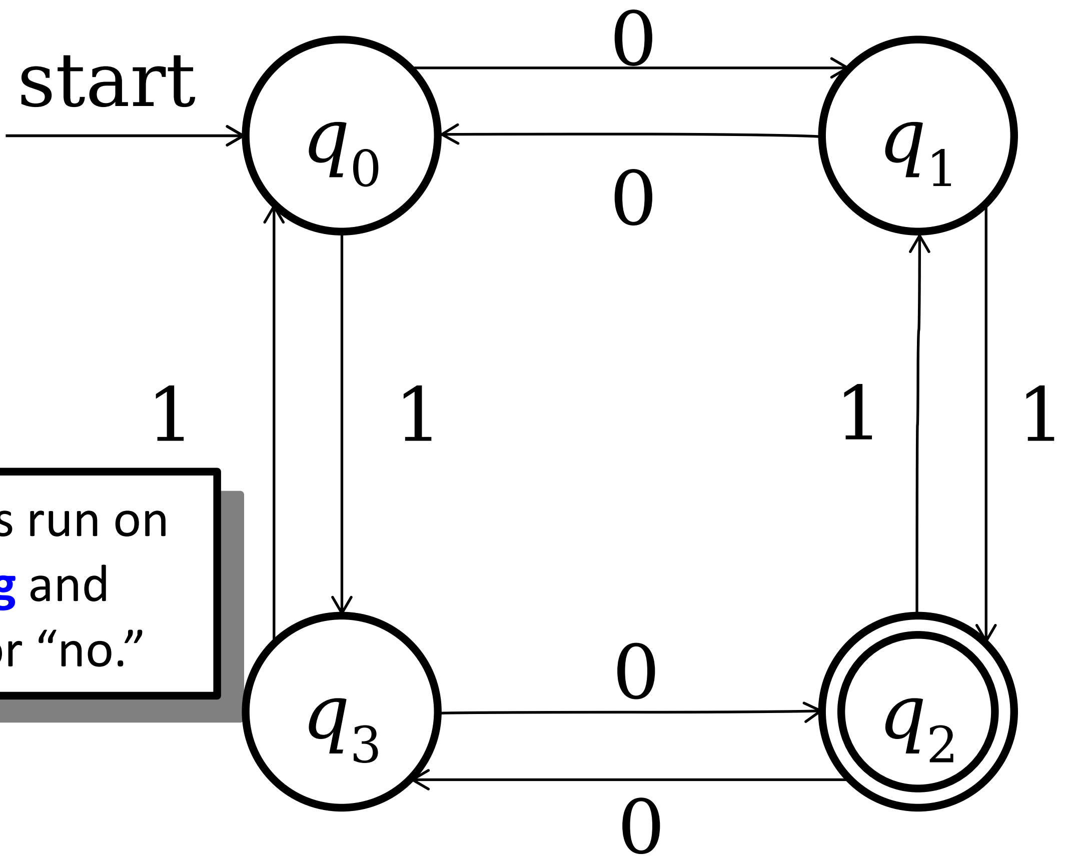
A Simple Finite Automaton



The automaton is run on an **input string** and answers “yes” or “no.”

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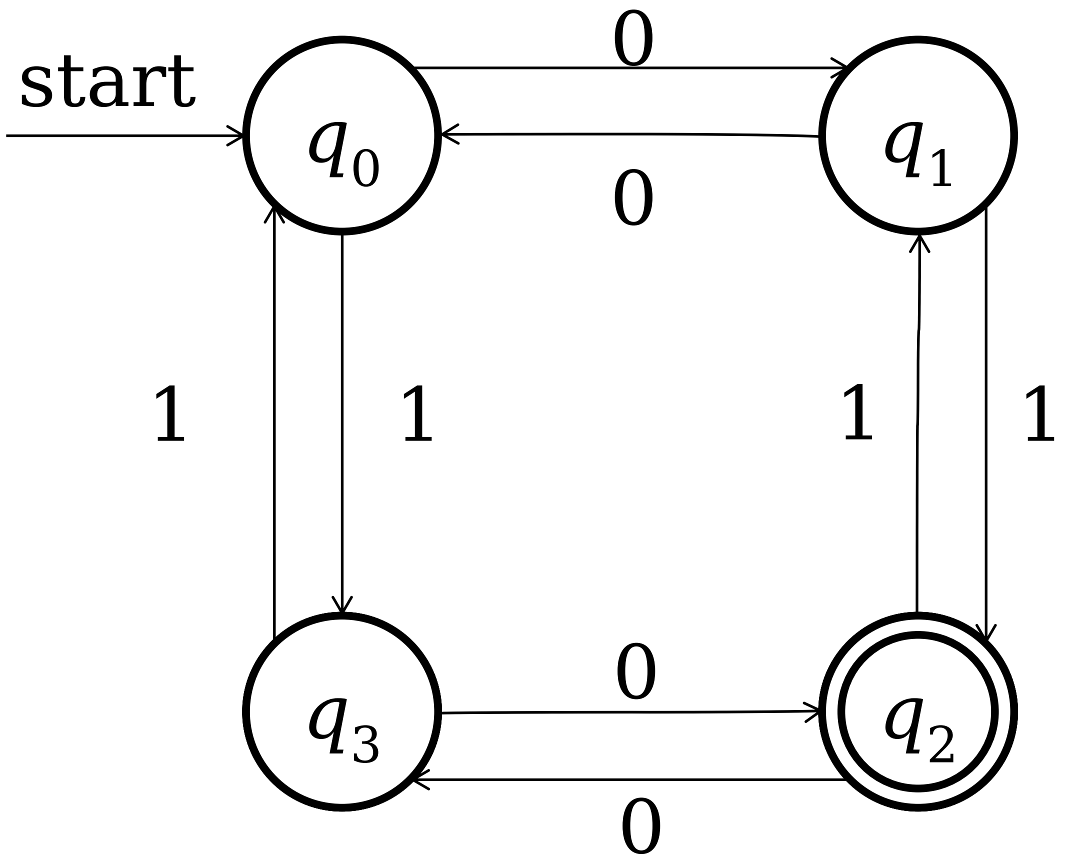
A Simple Finite Automaton



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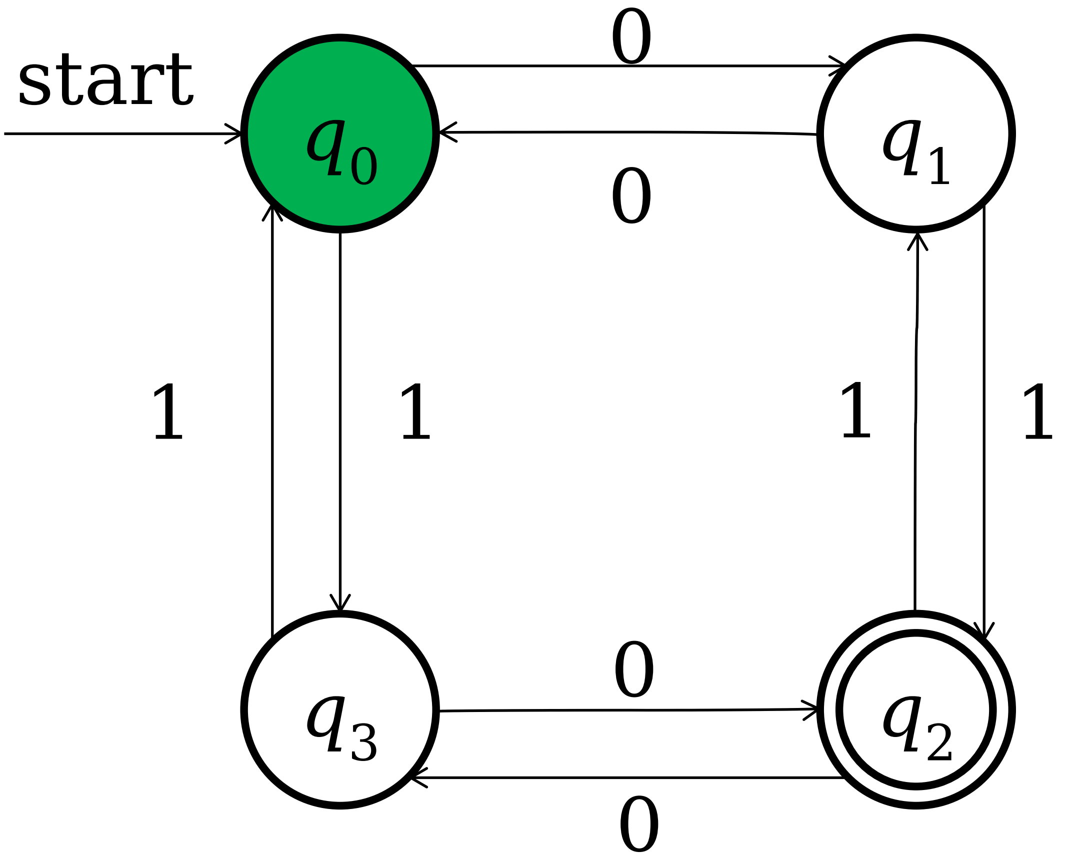

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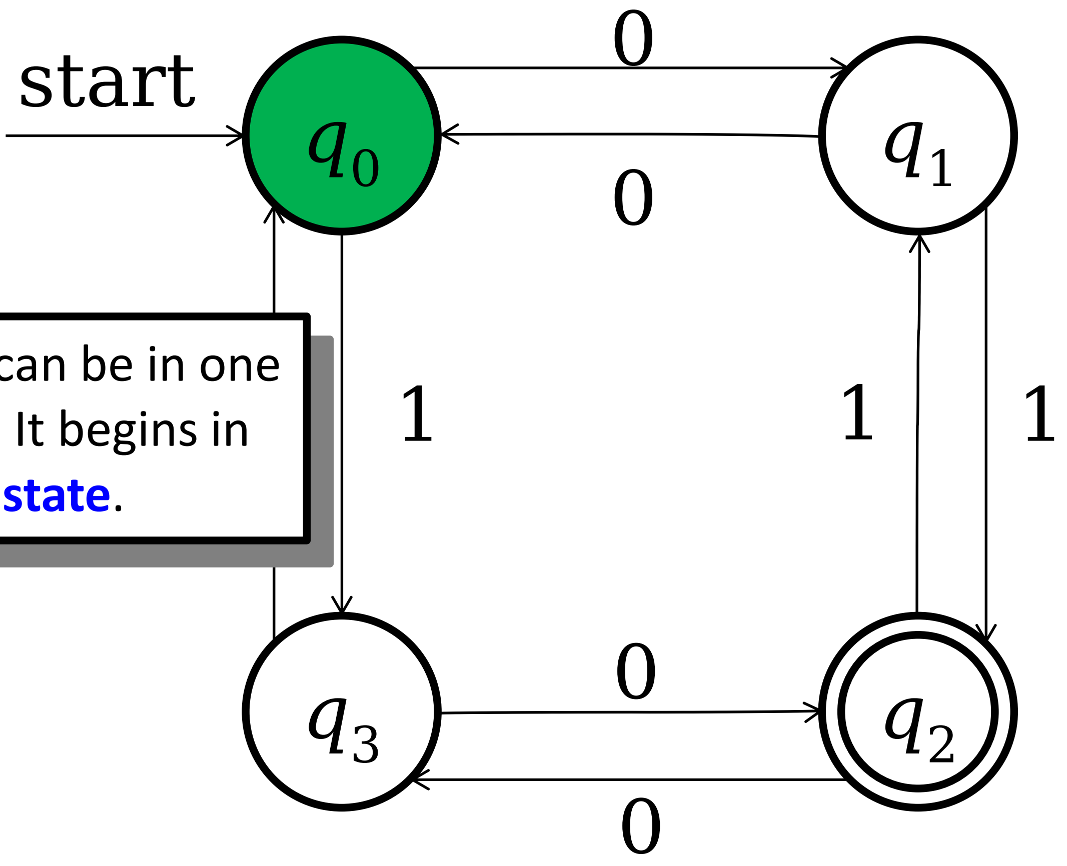

The automaton can be in one state at a time. It begins in the **start state**.

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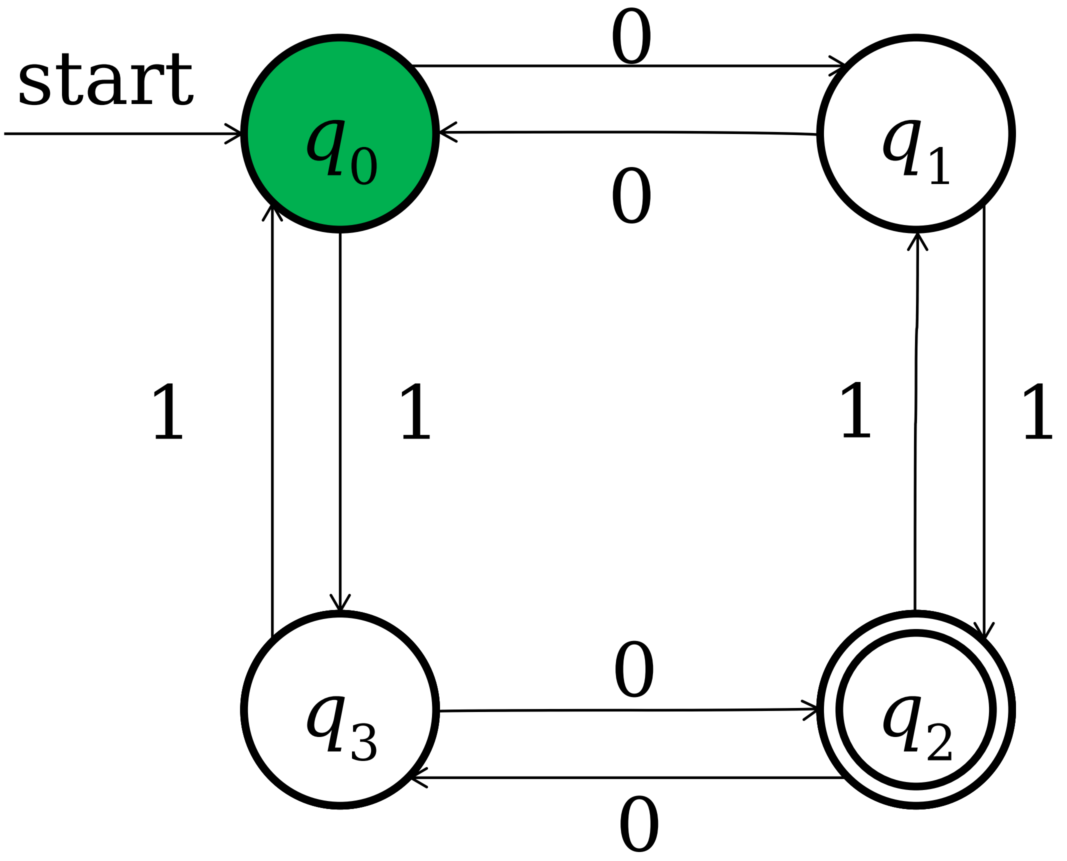
A Simple Finite Automaton



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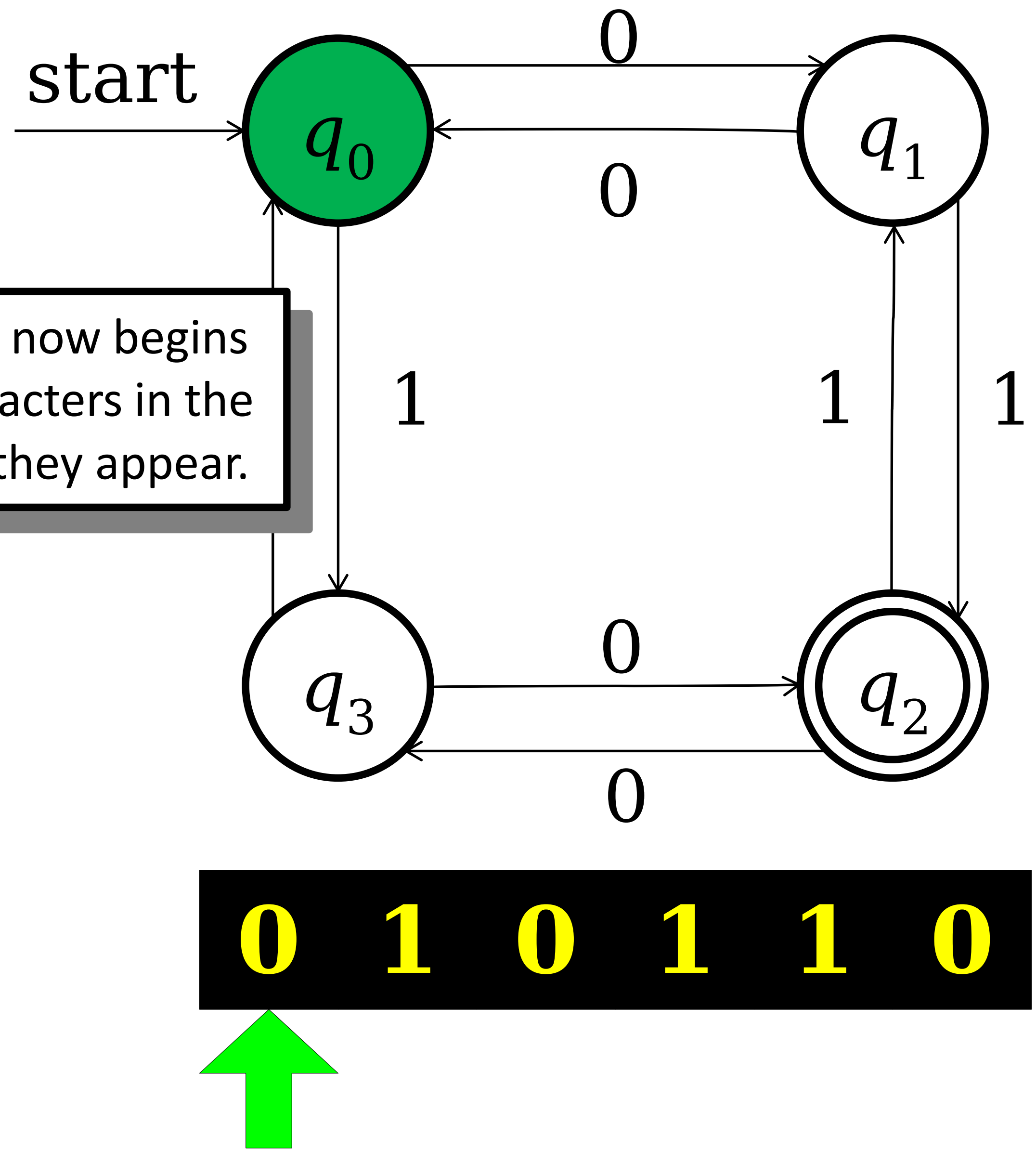

The automaton now begins processing characters in the order in which they appear.

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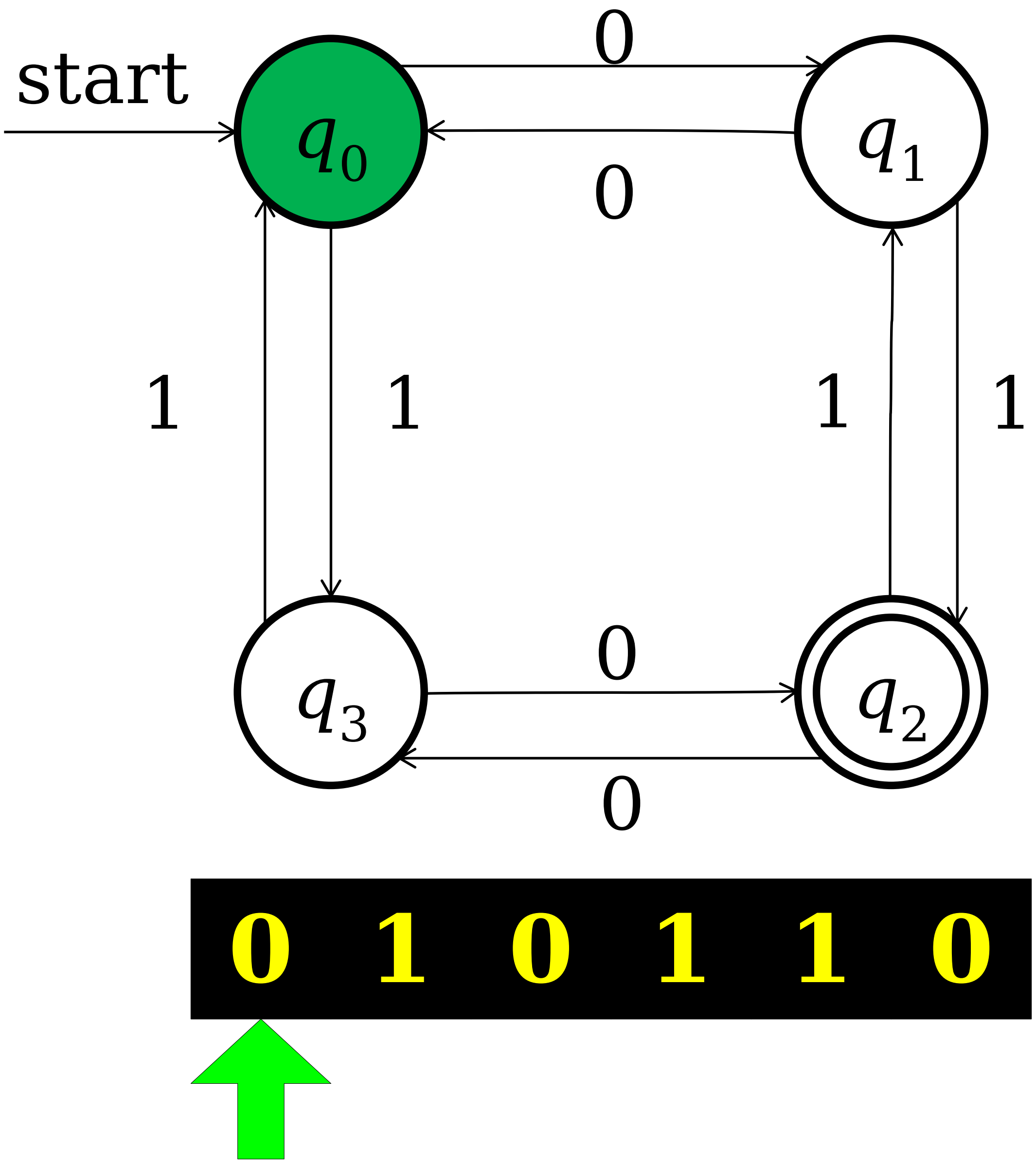

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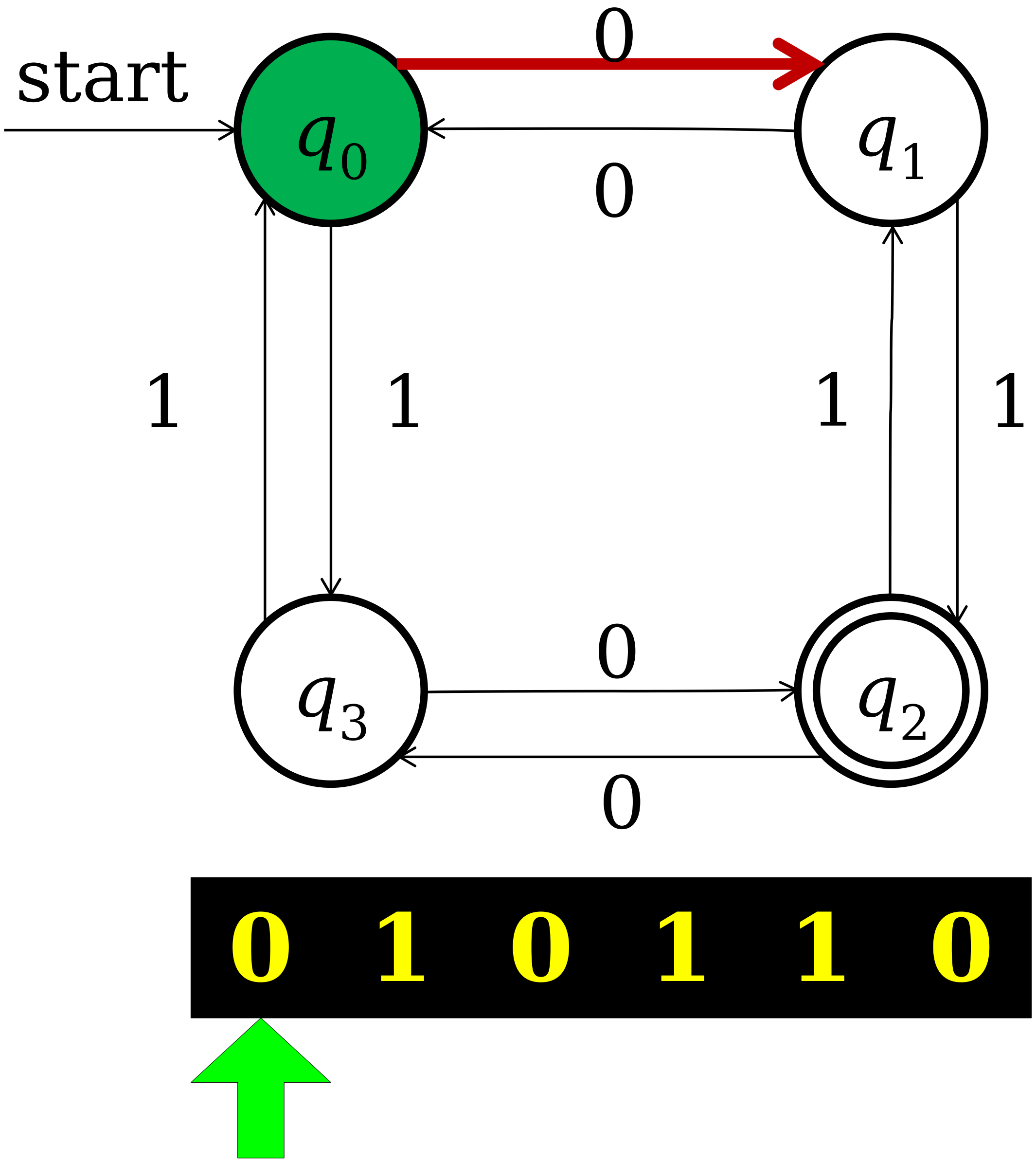

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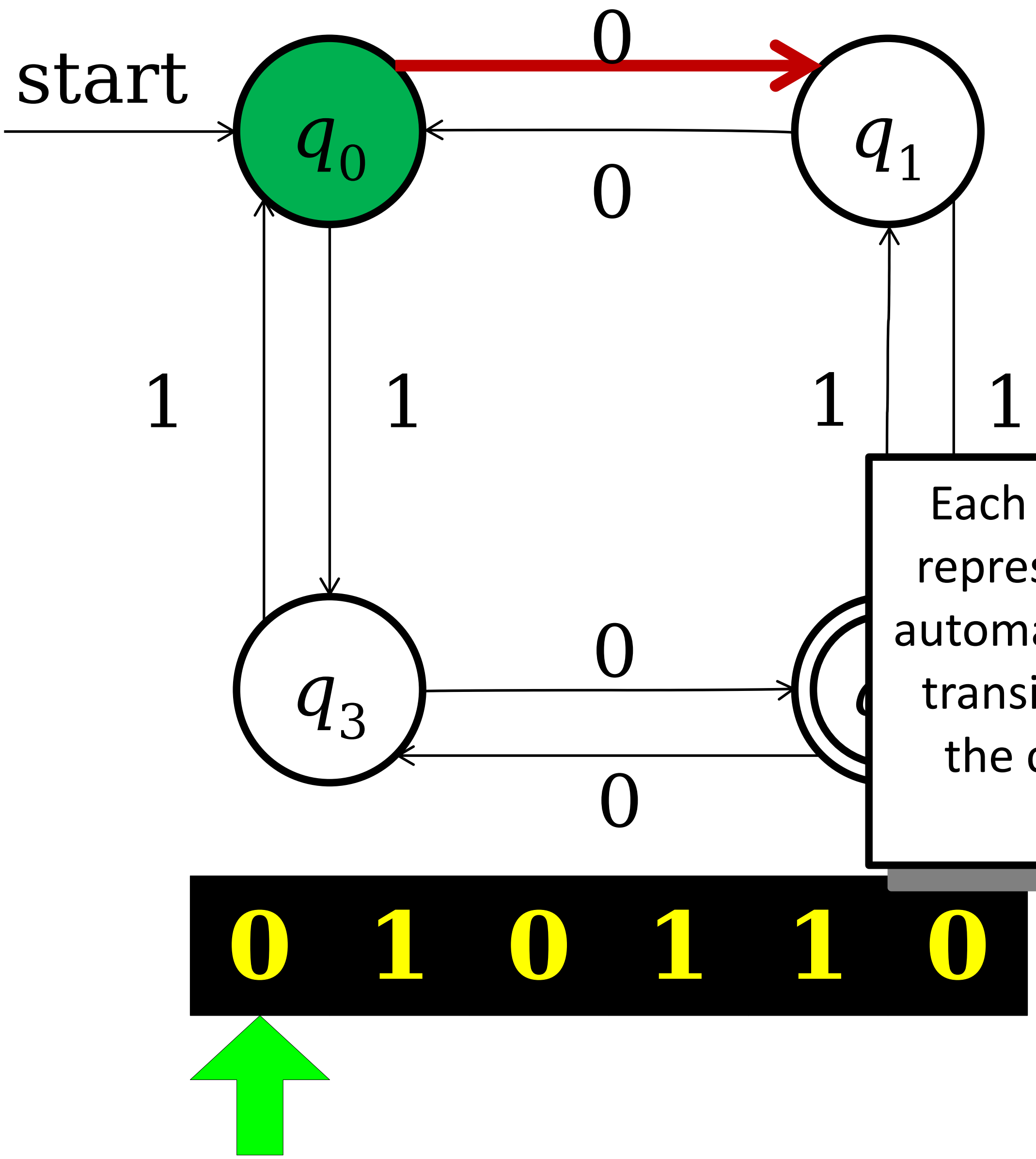

Each arrow in this diagram represents a **transition**. The automaton always follows the transition corresponding to the current symbol being read.

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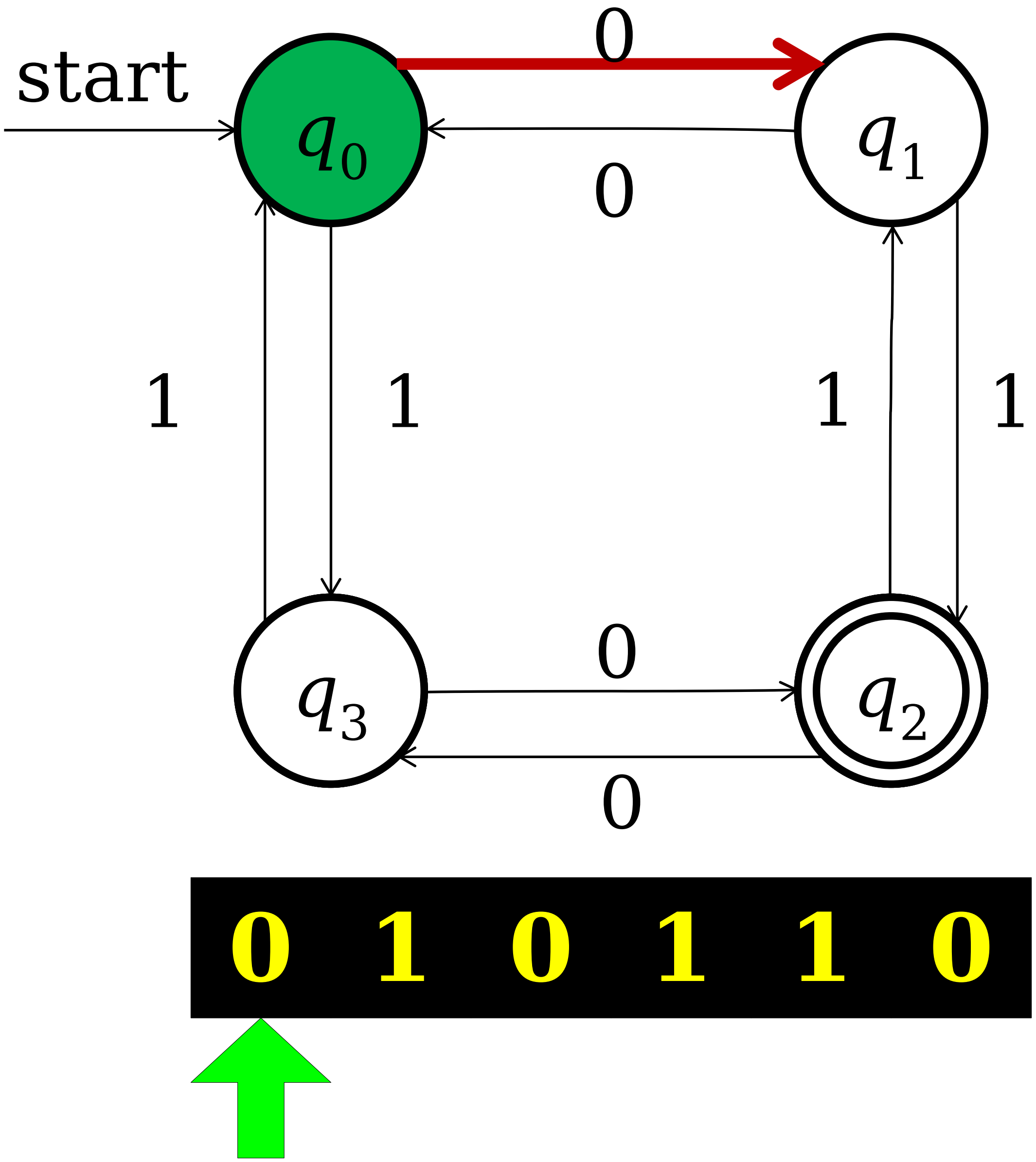

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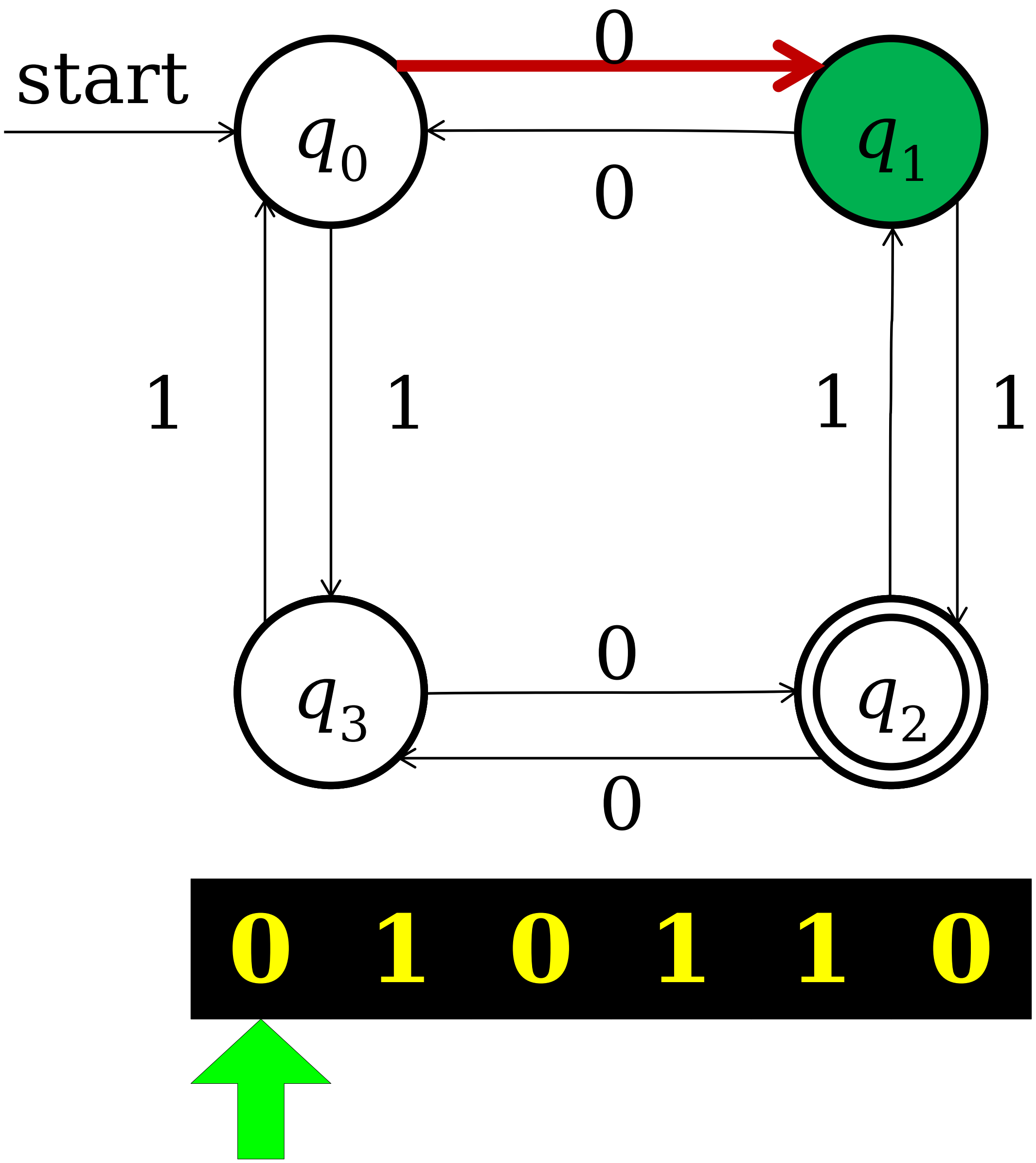

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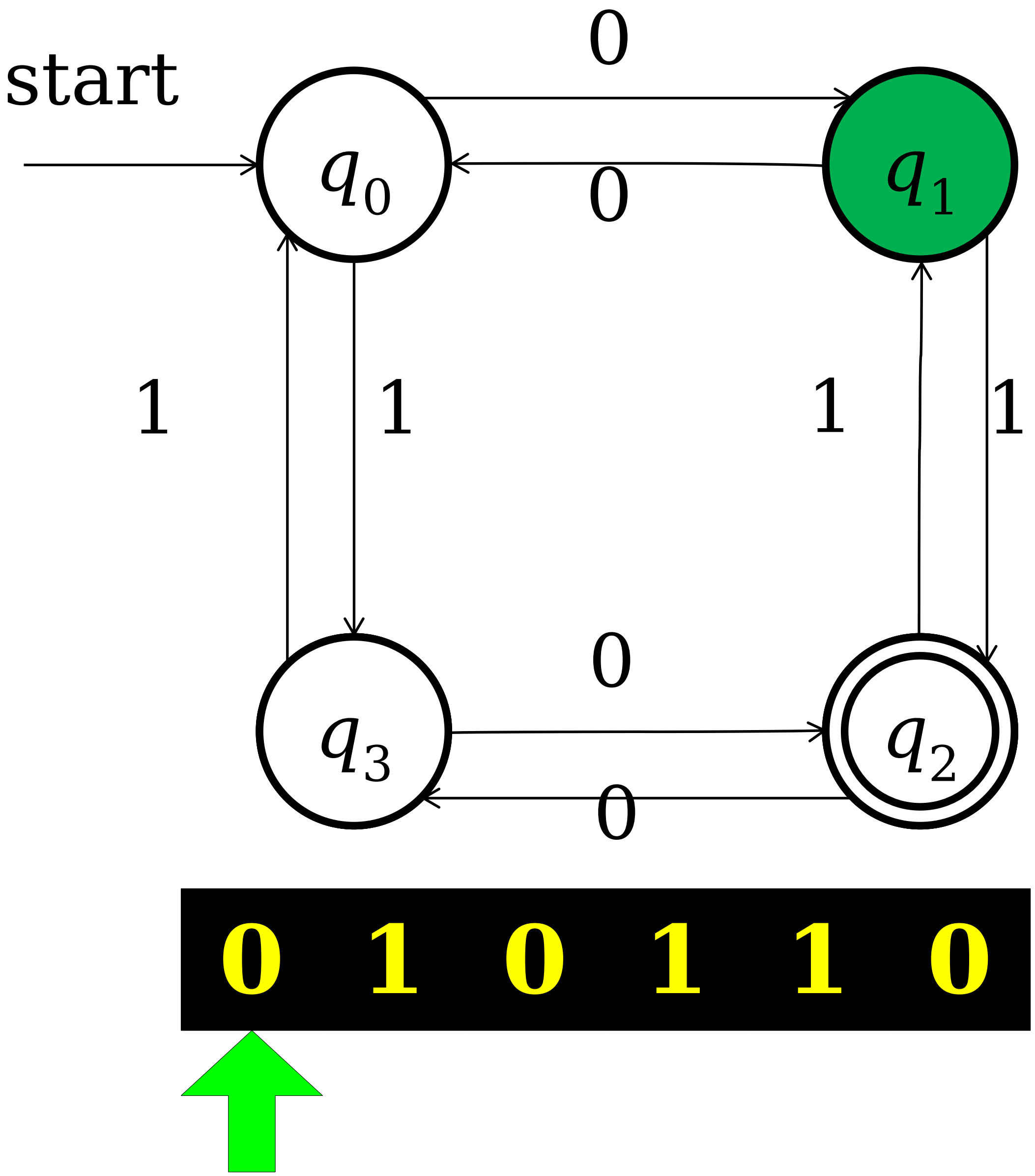

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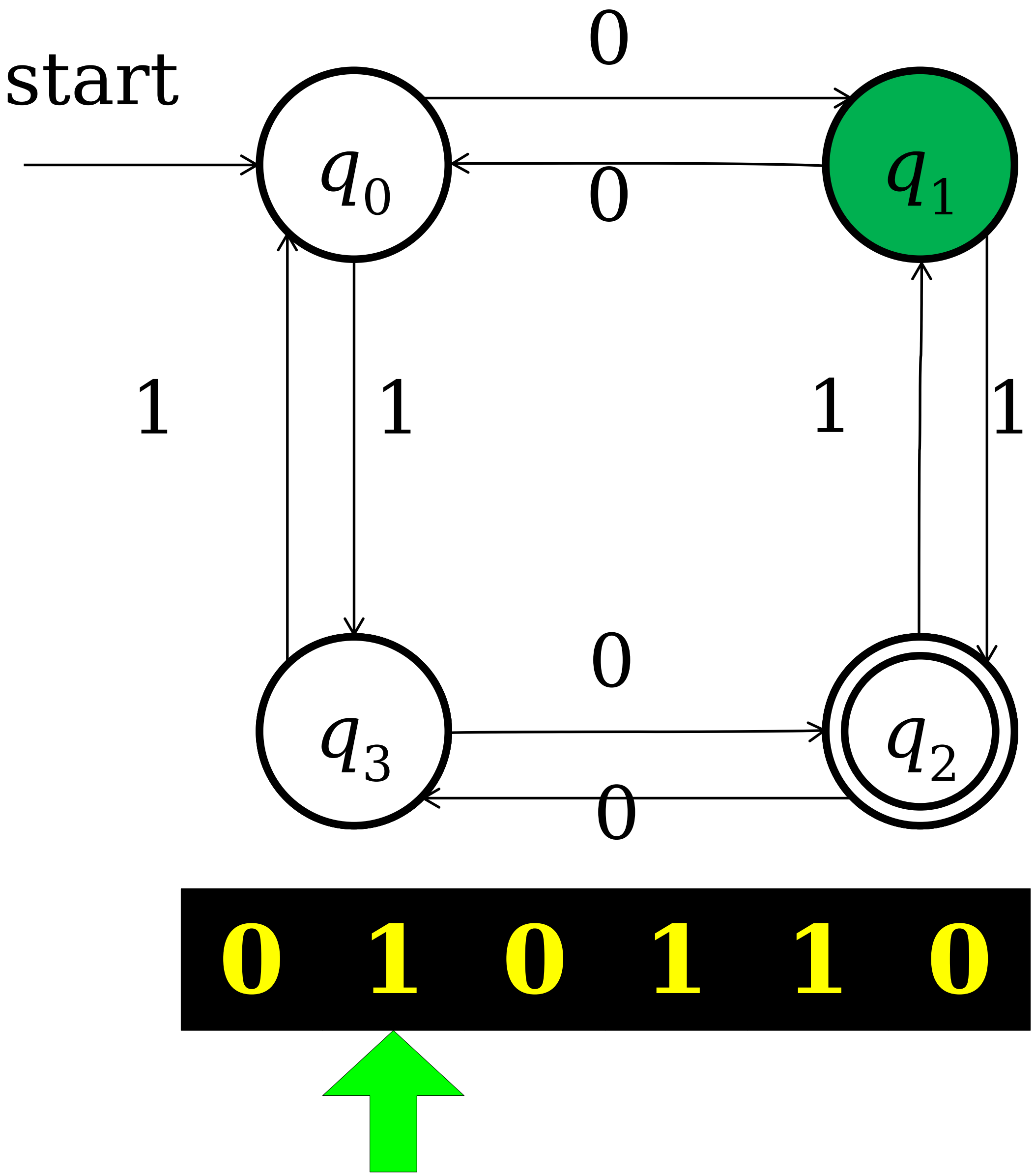

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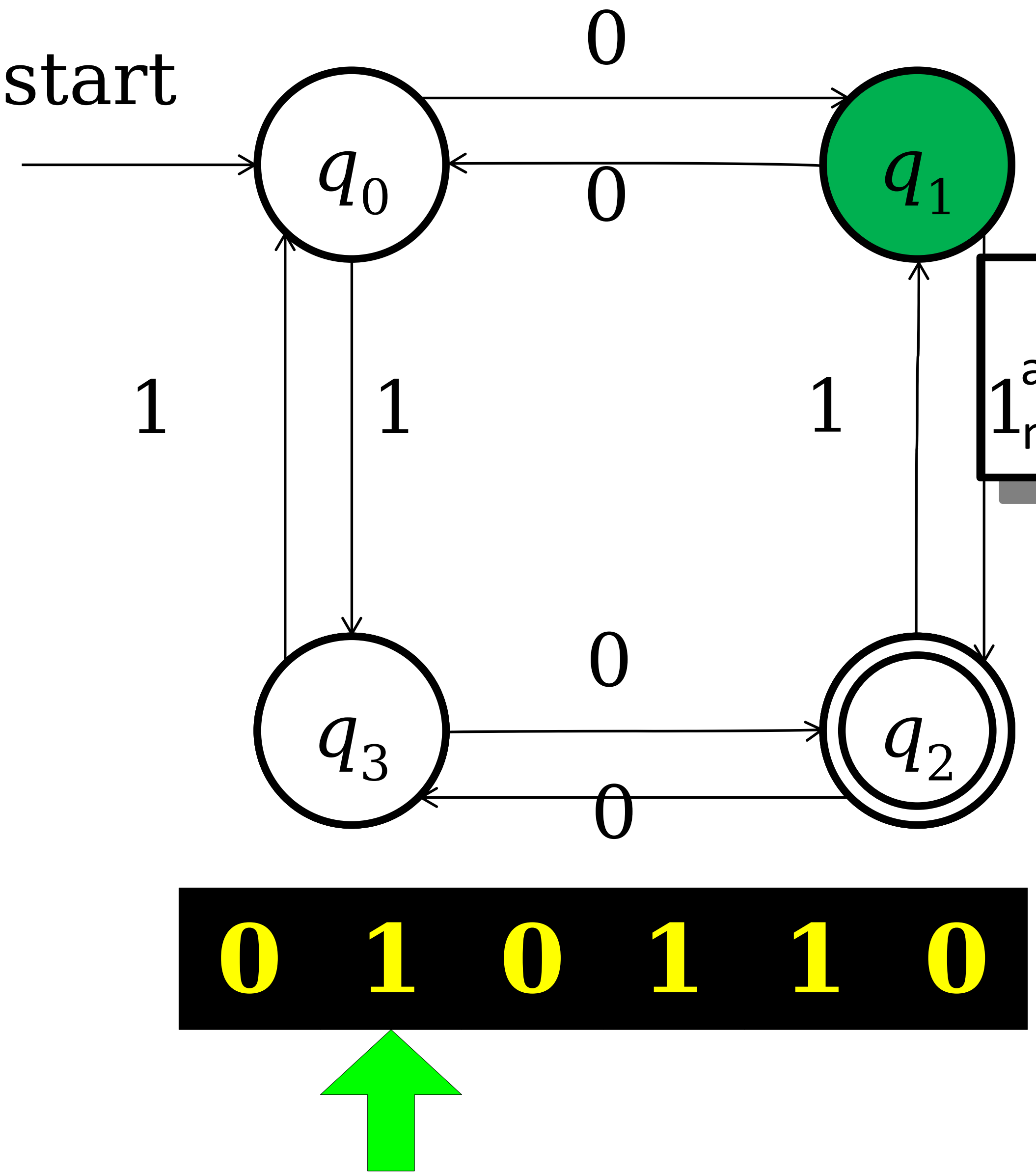

After transitioning, the automaton considers the next symbol in the input.

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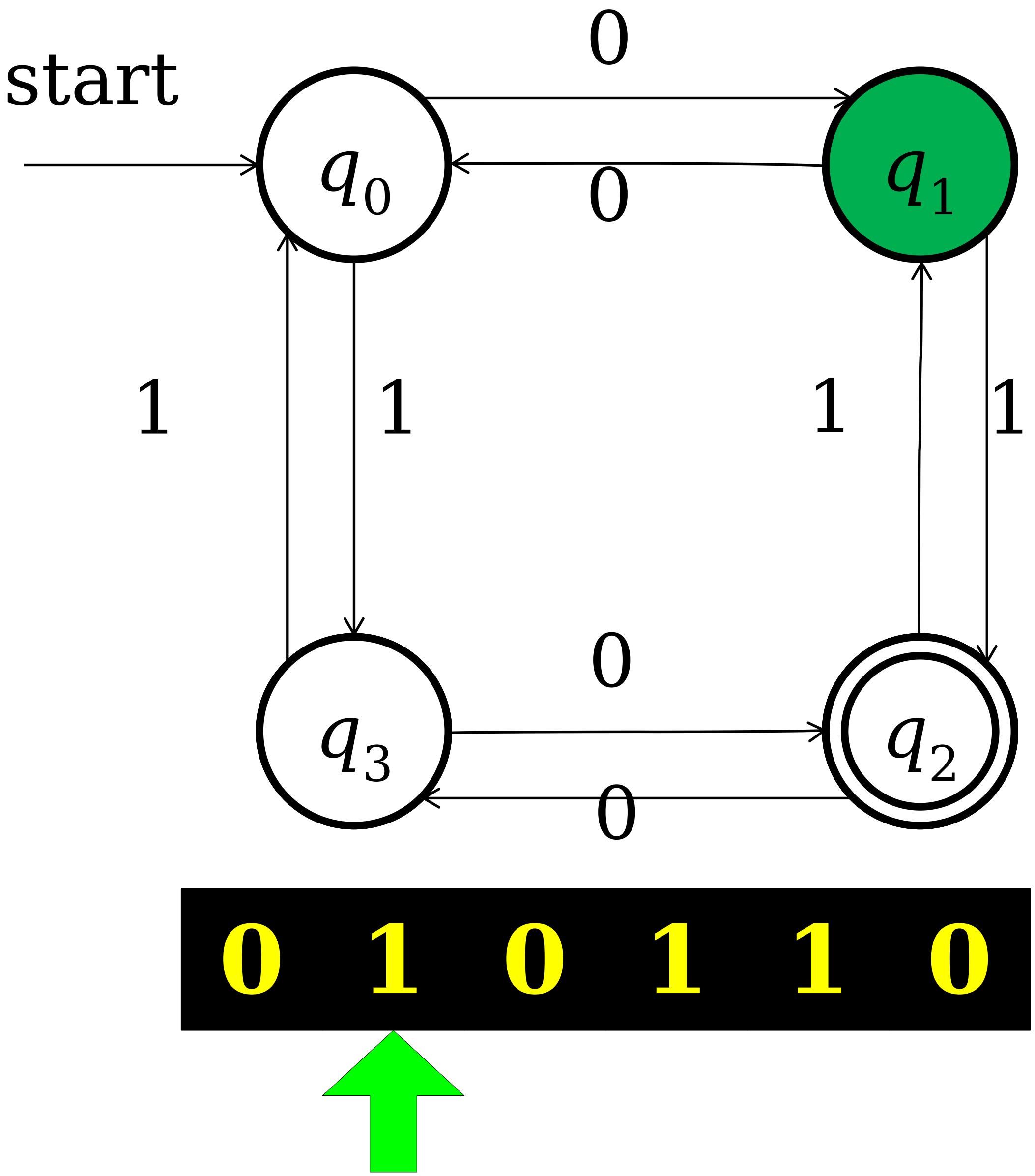

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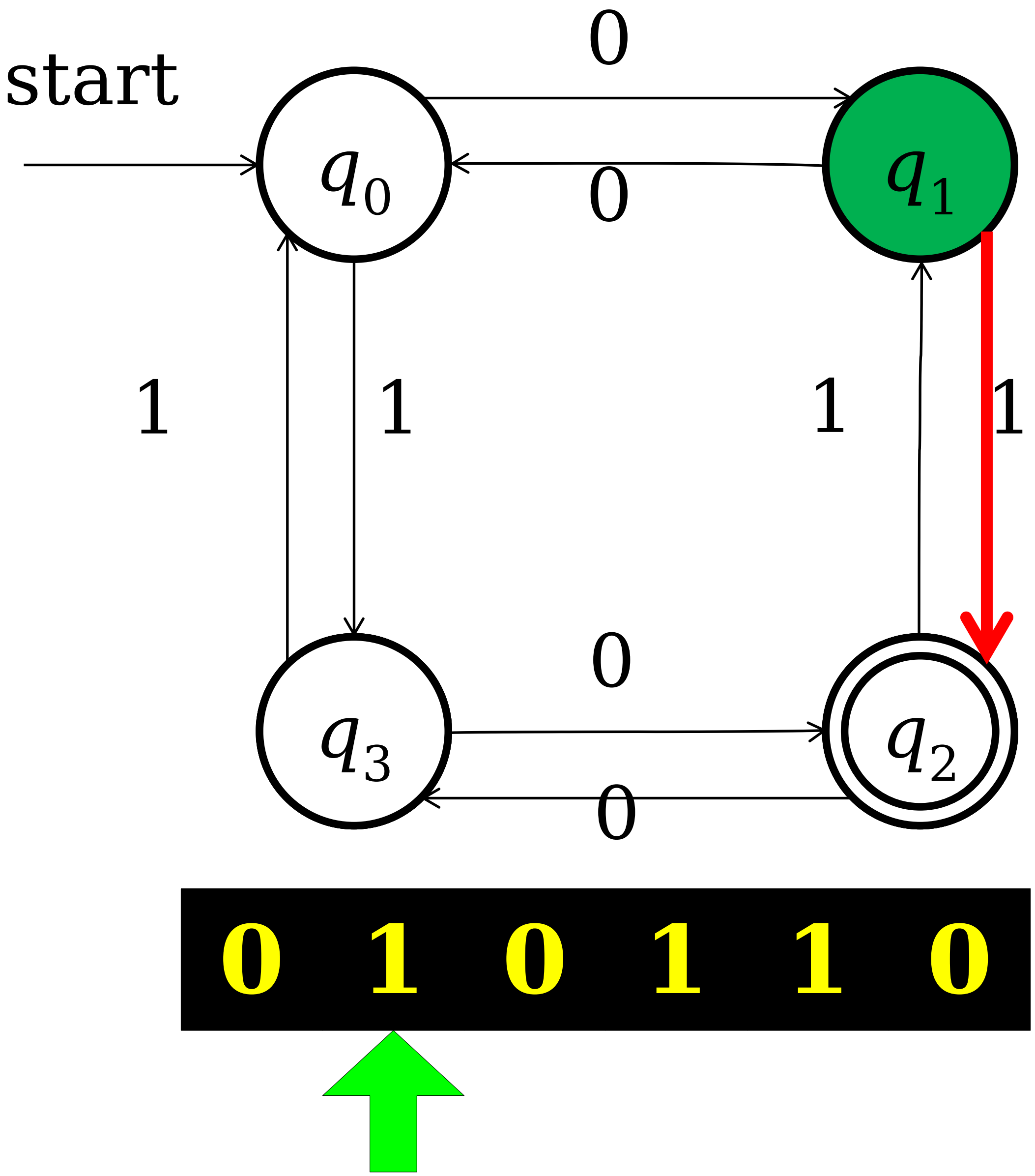

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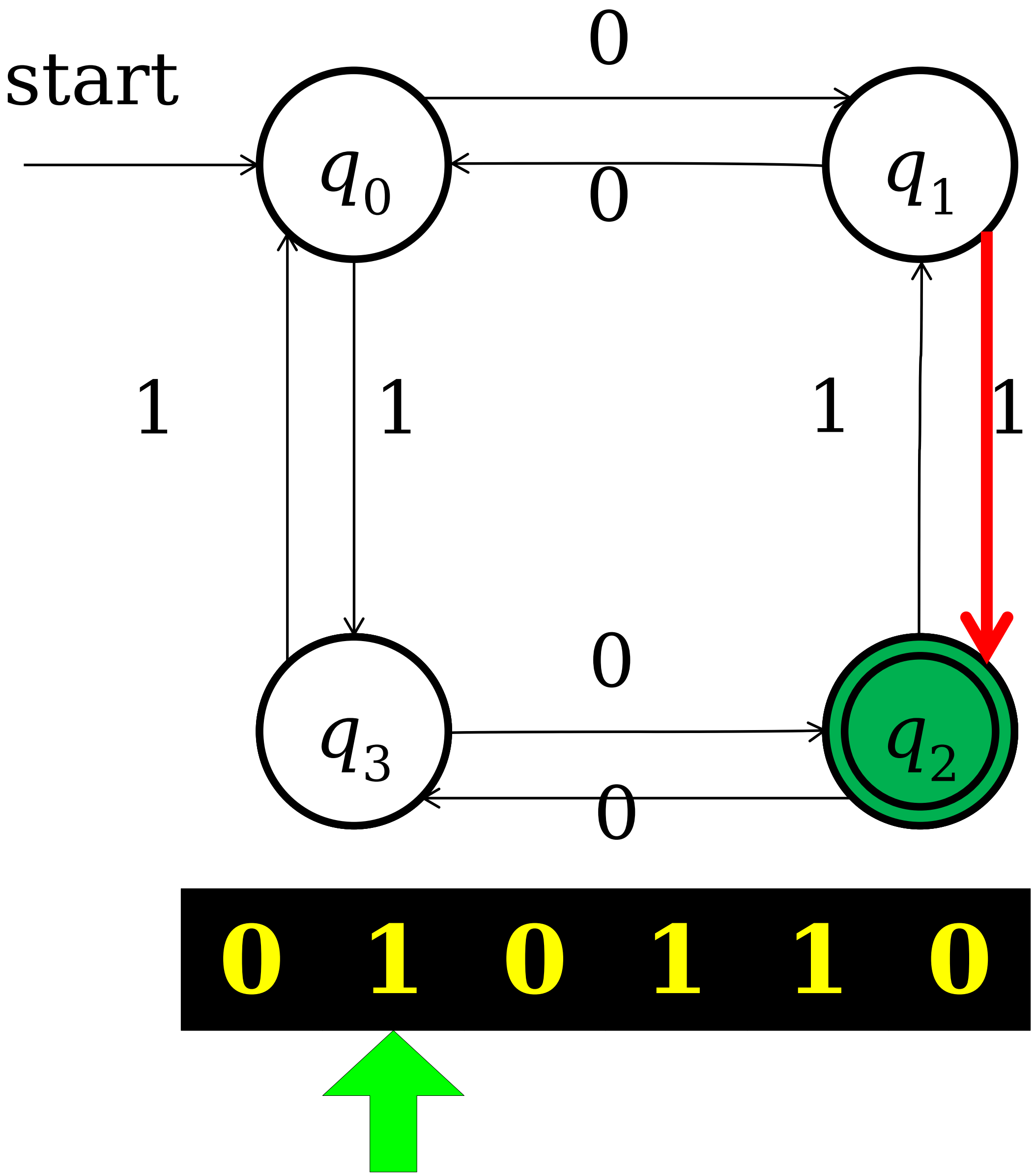

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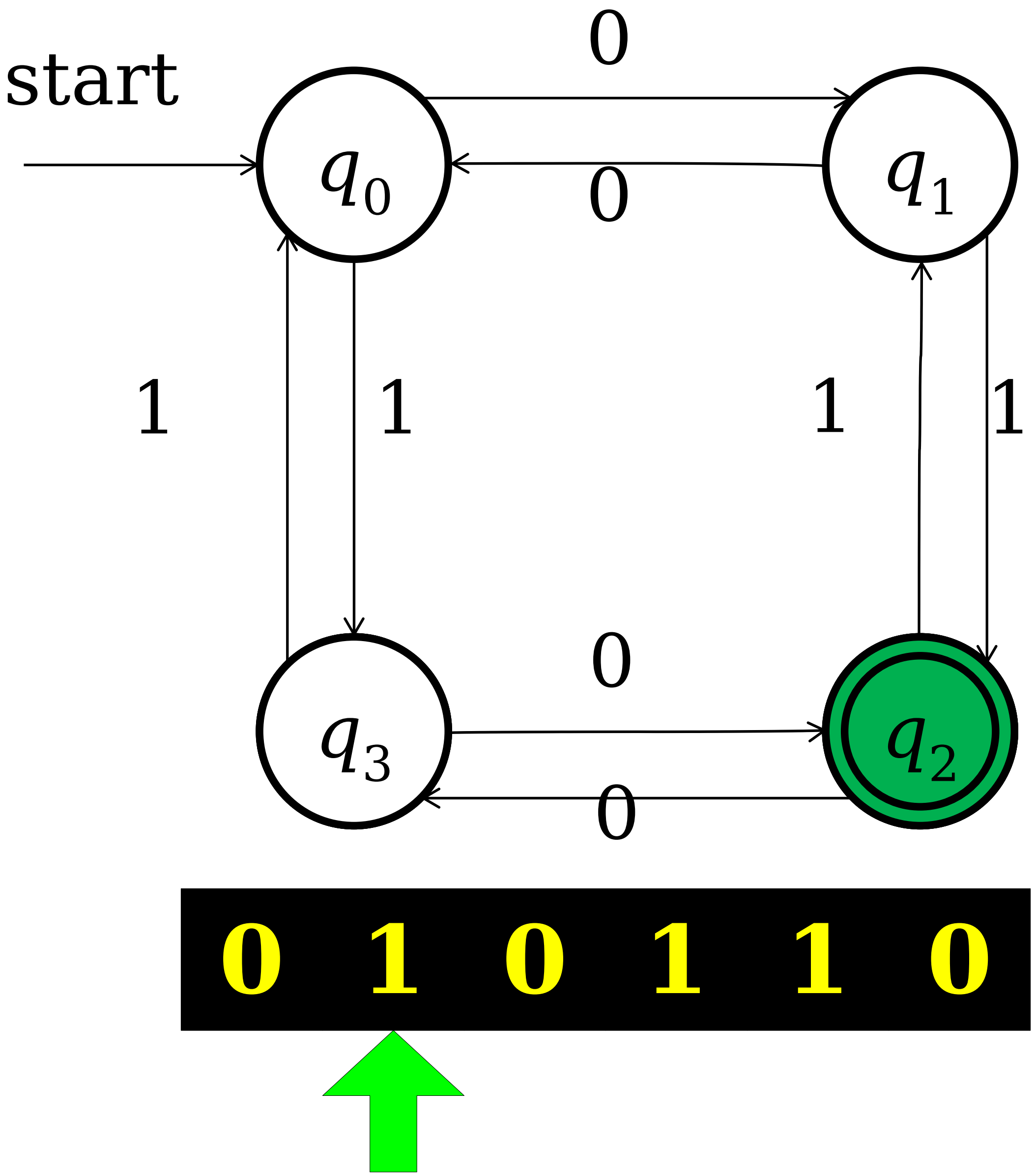

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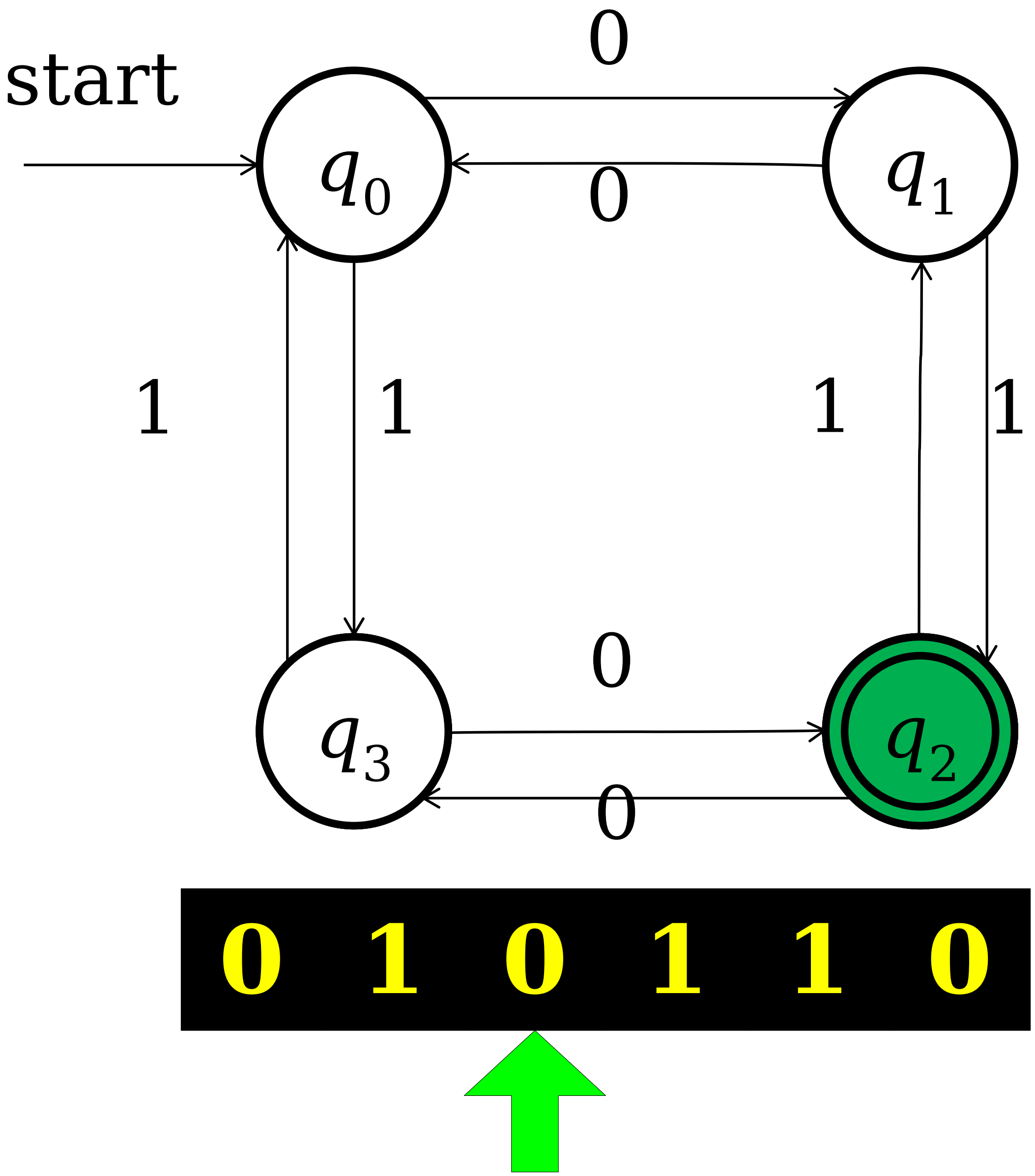

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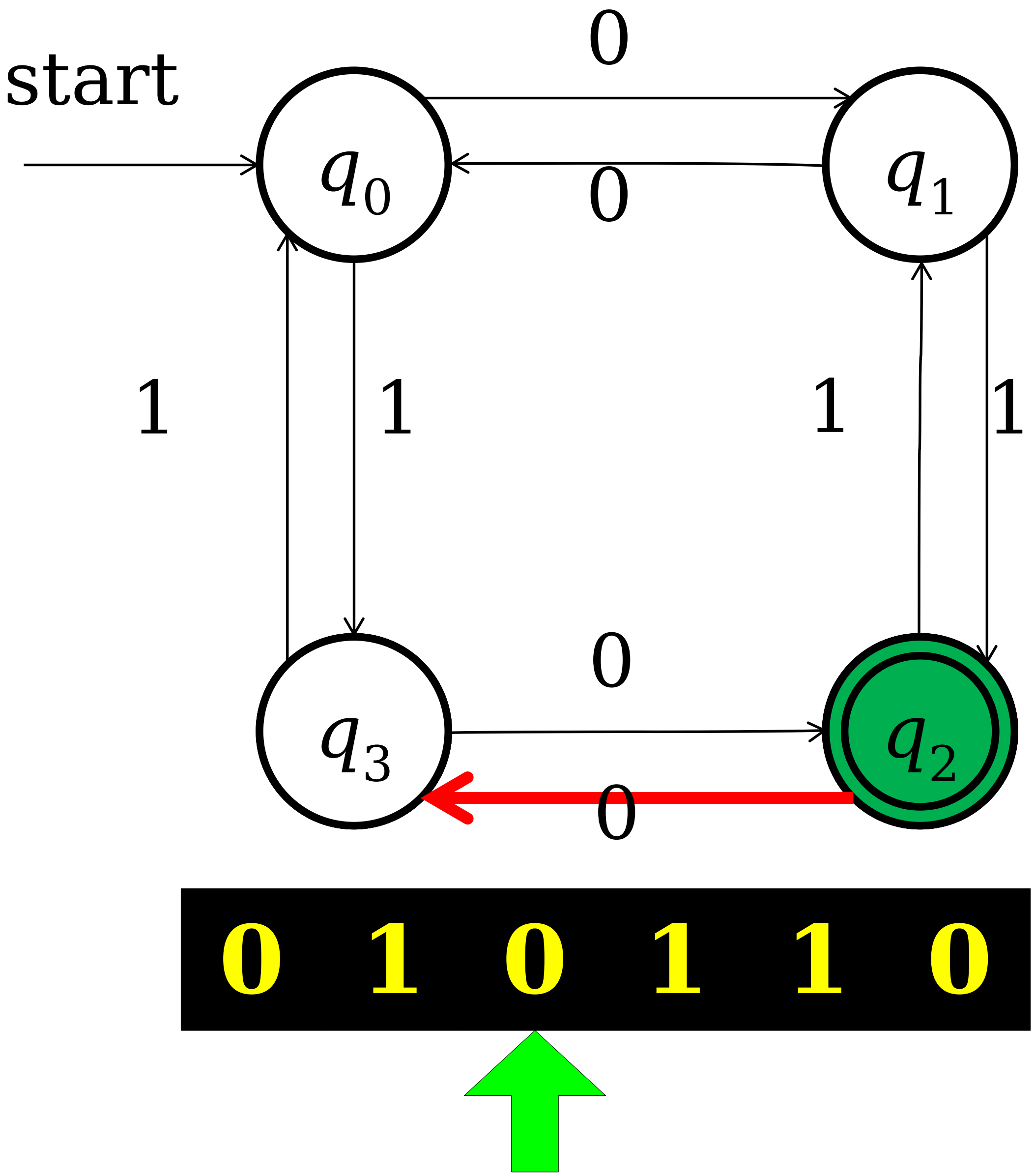

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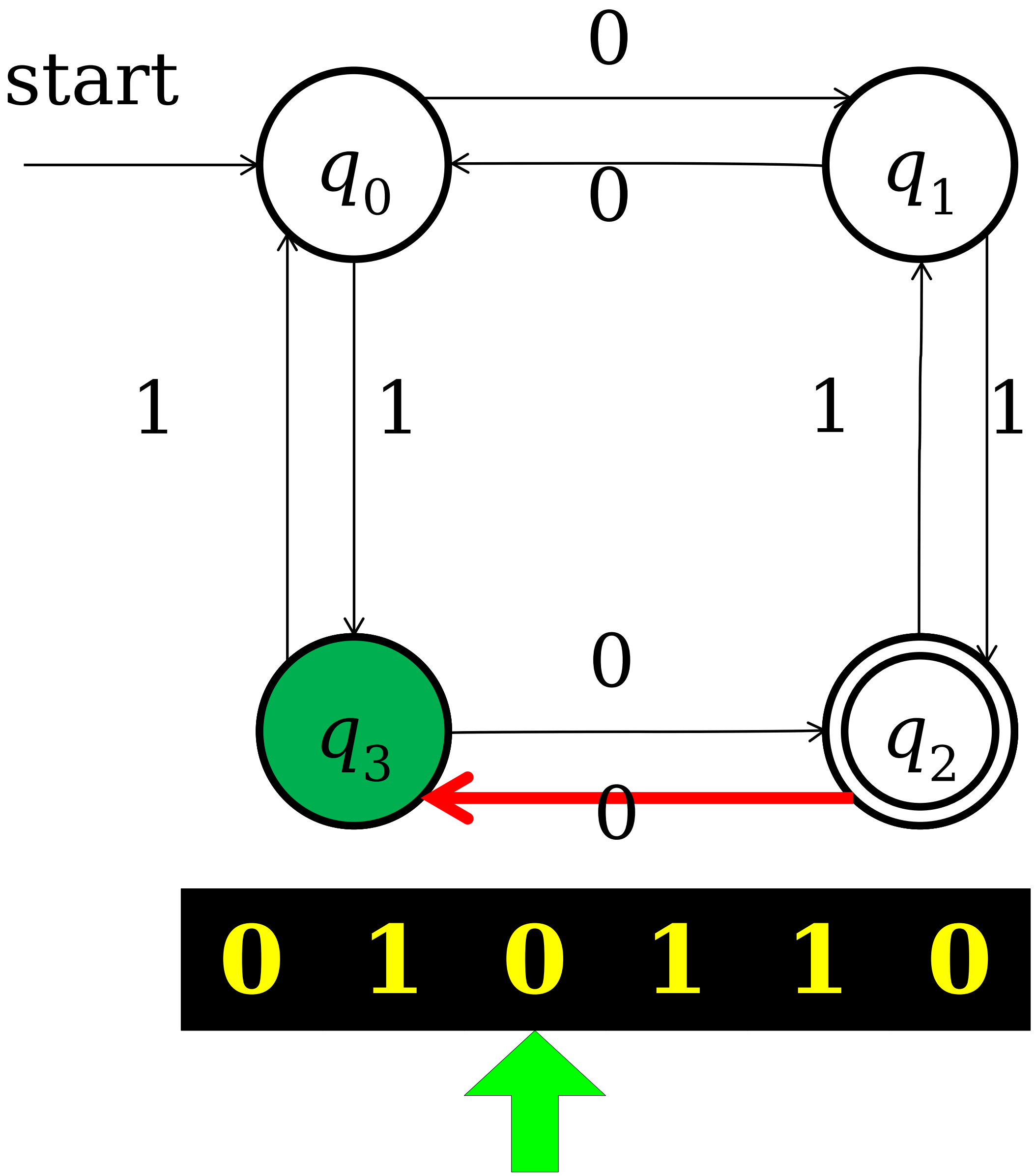

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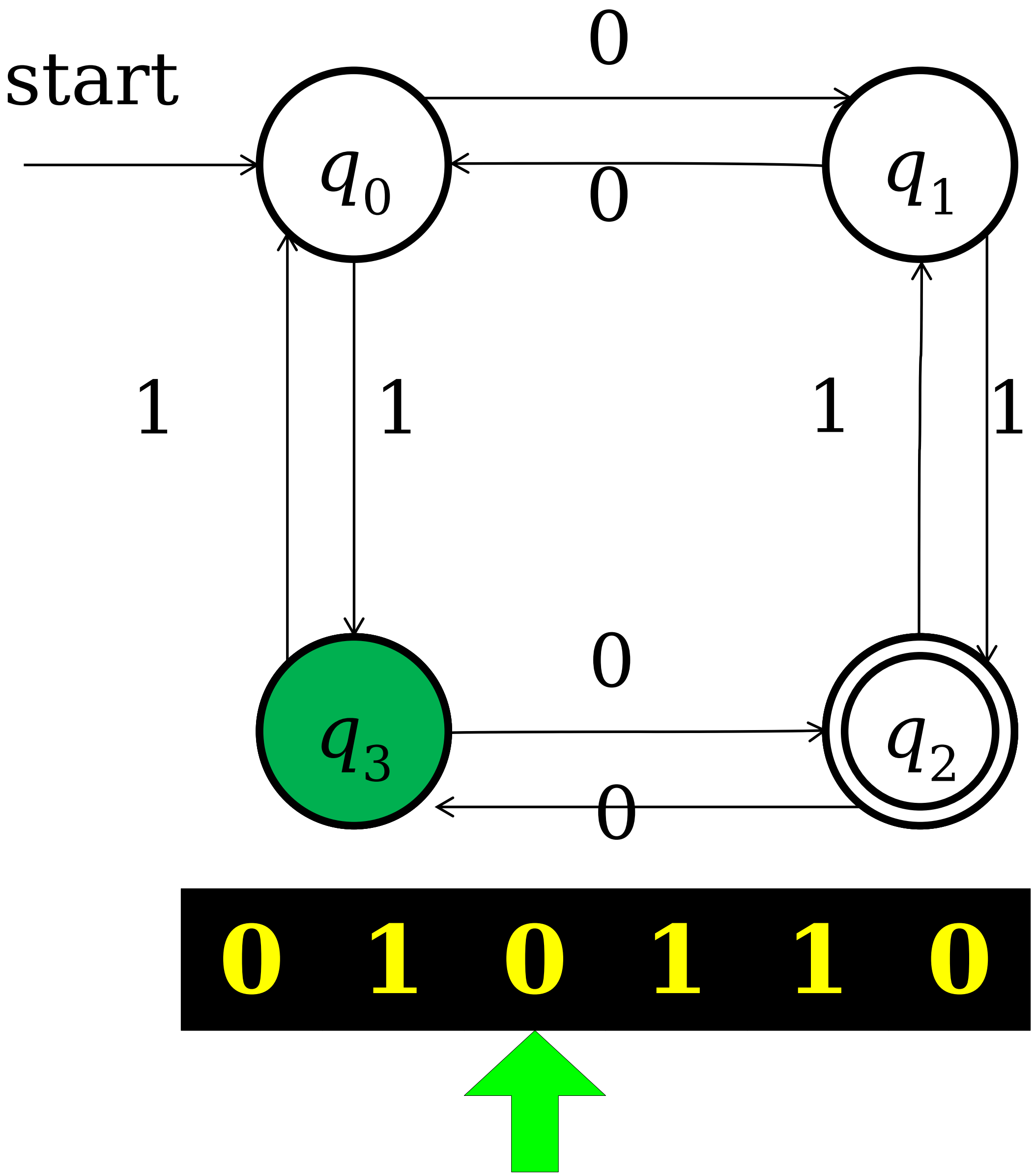

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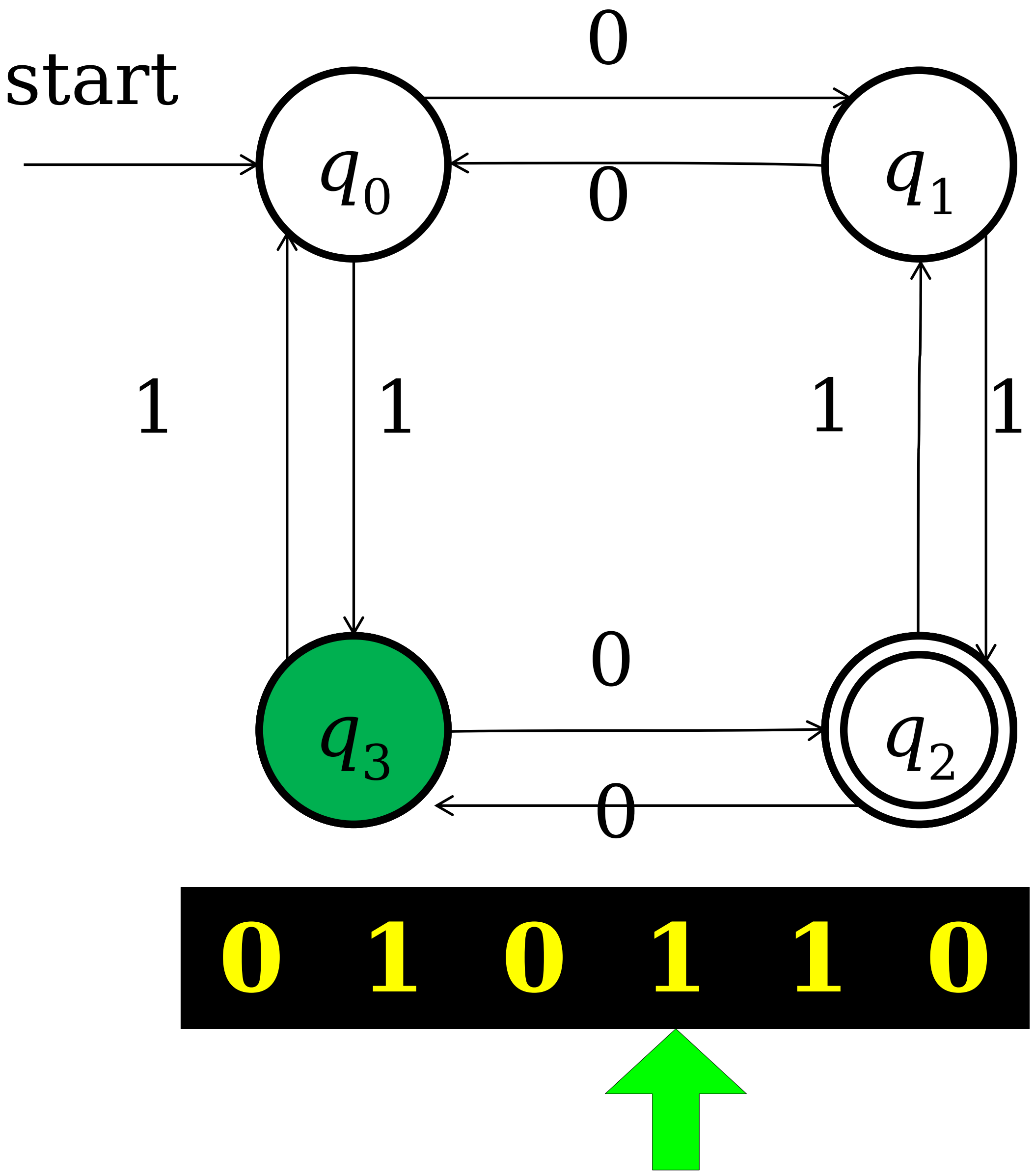

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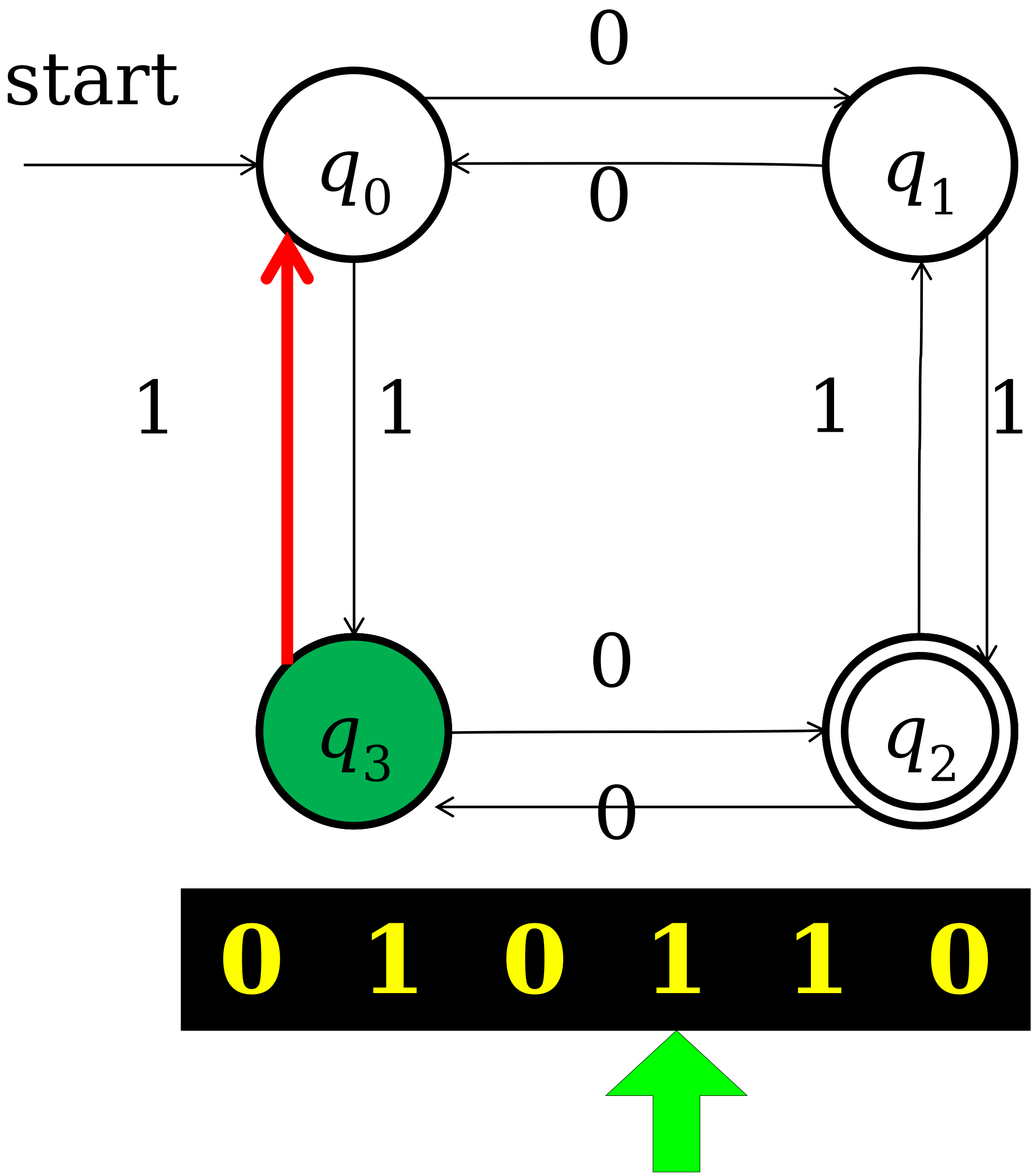

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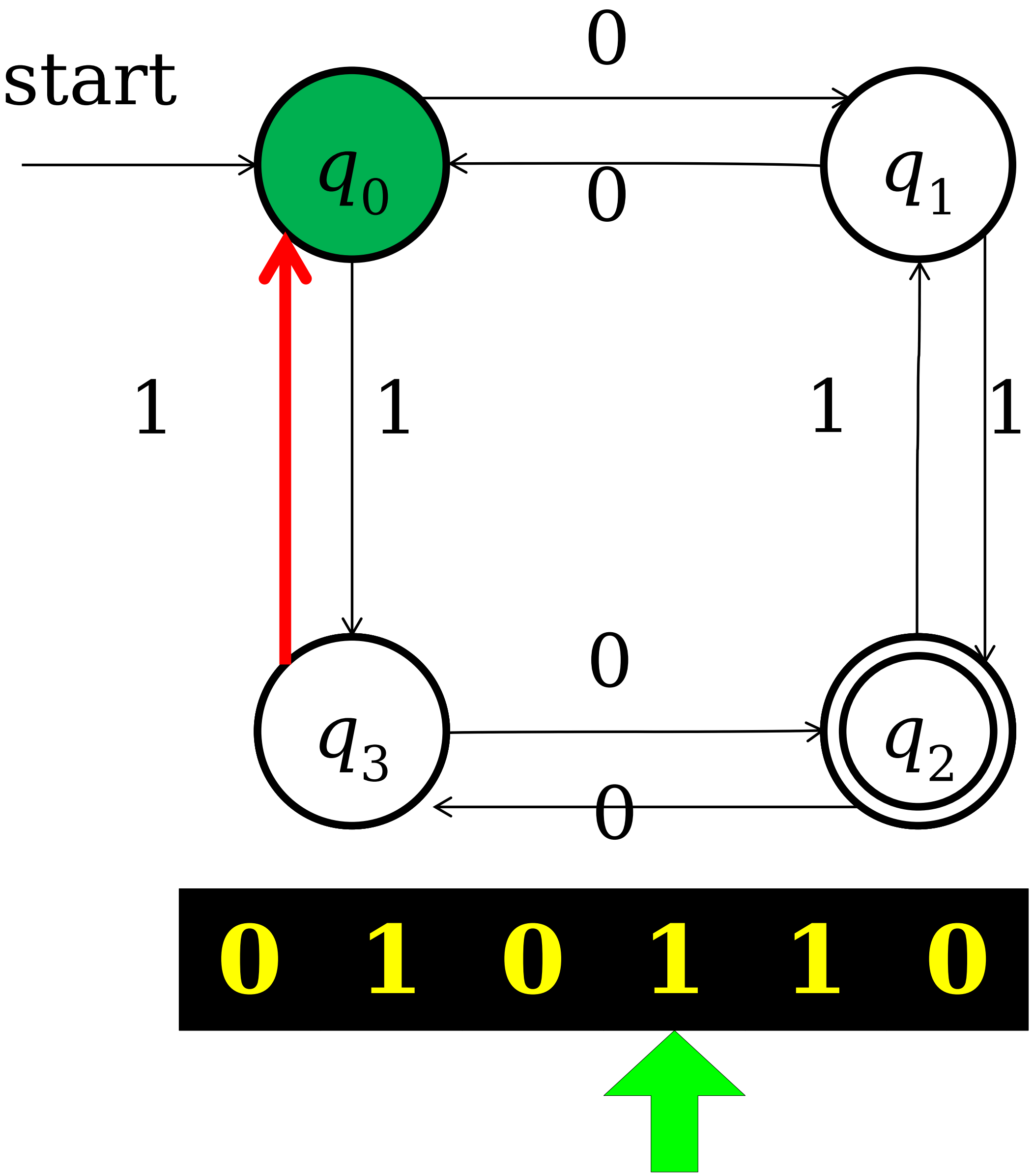

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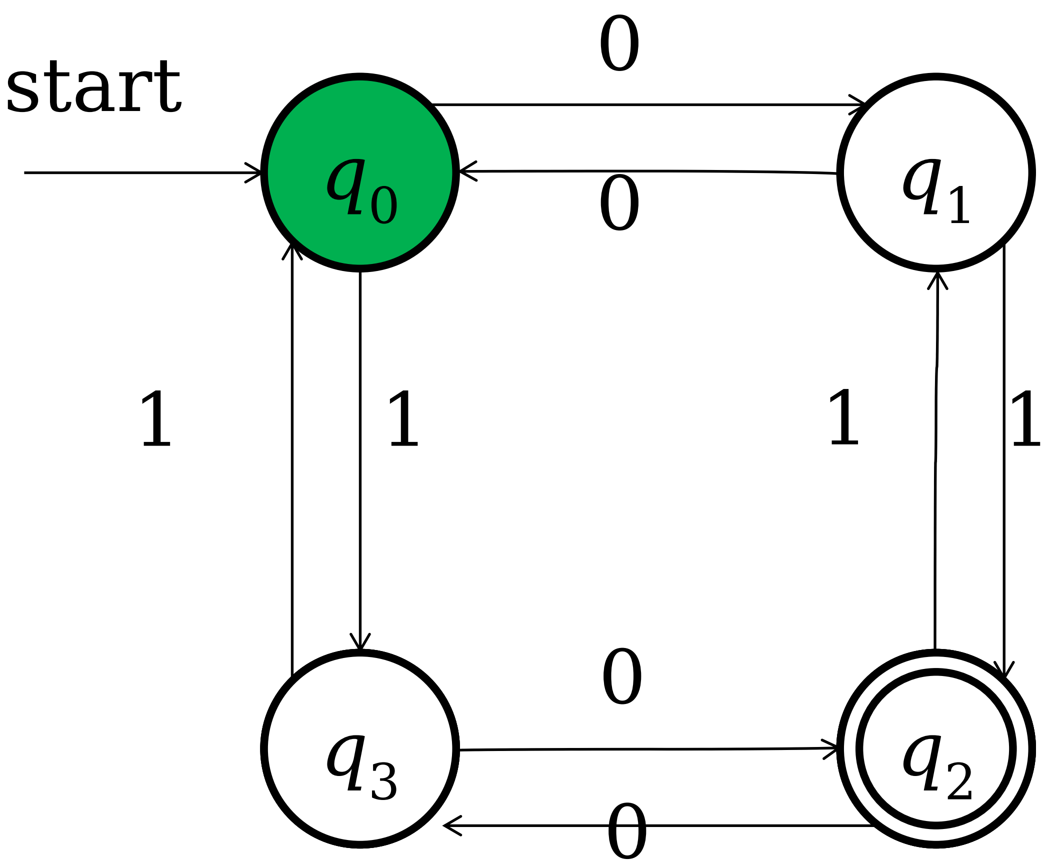

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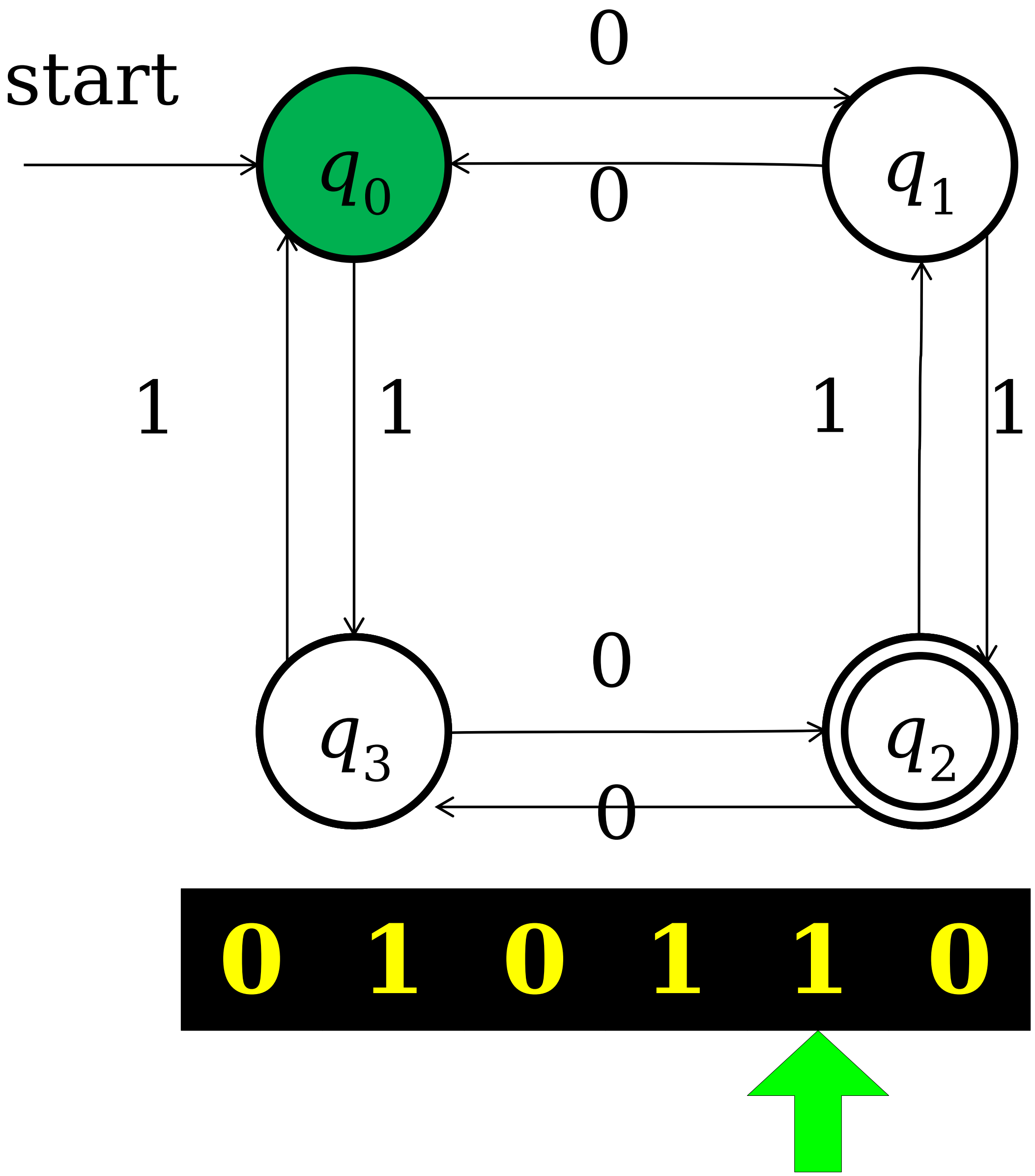

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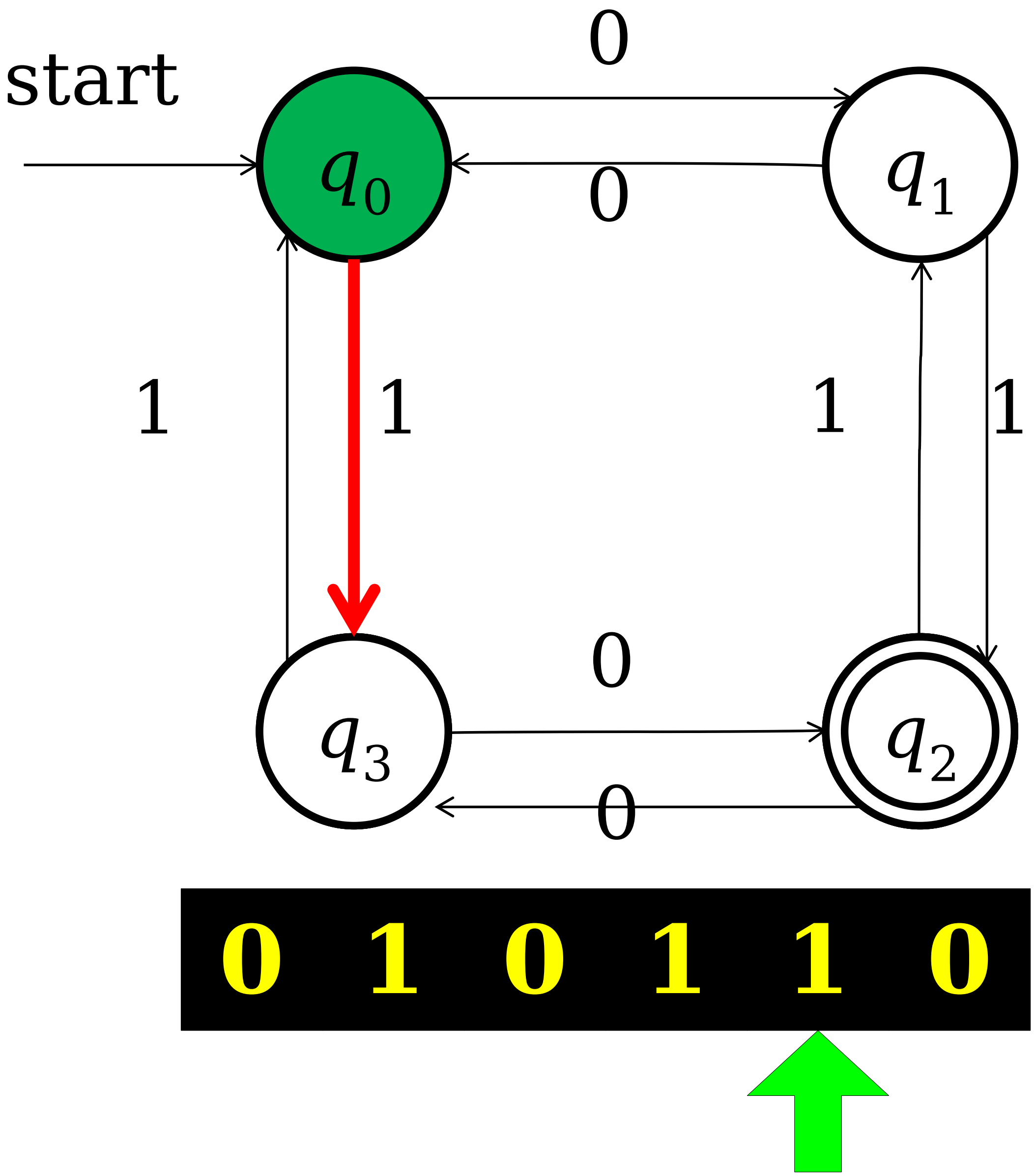

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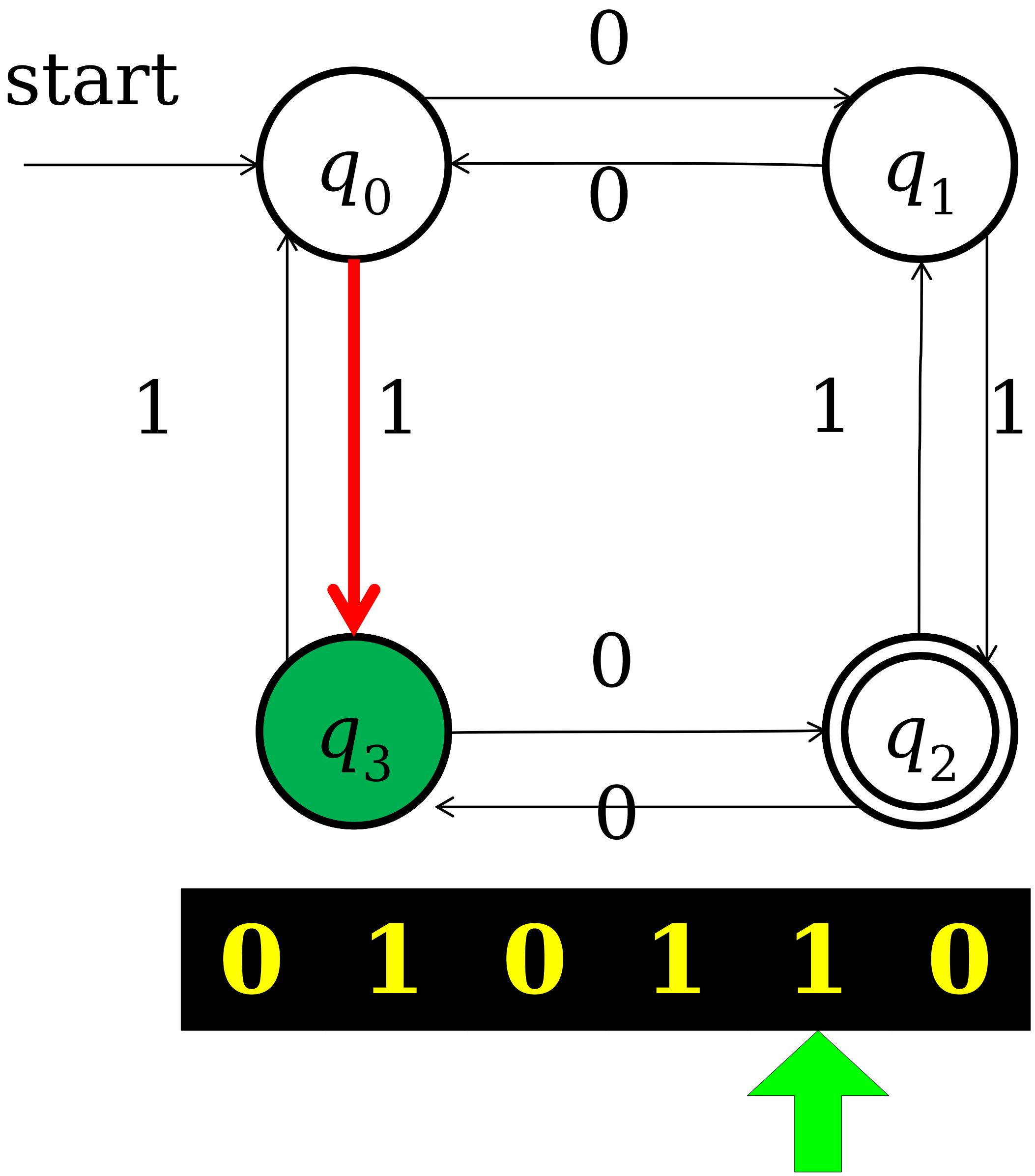

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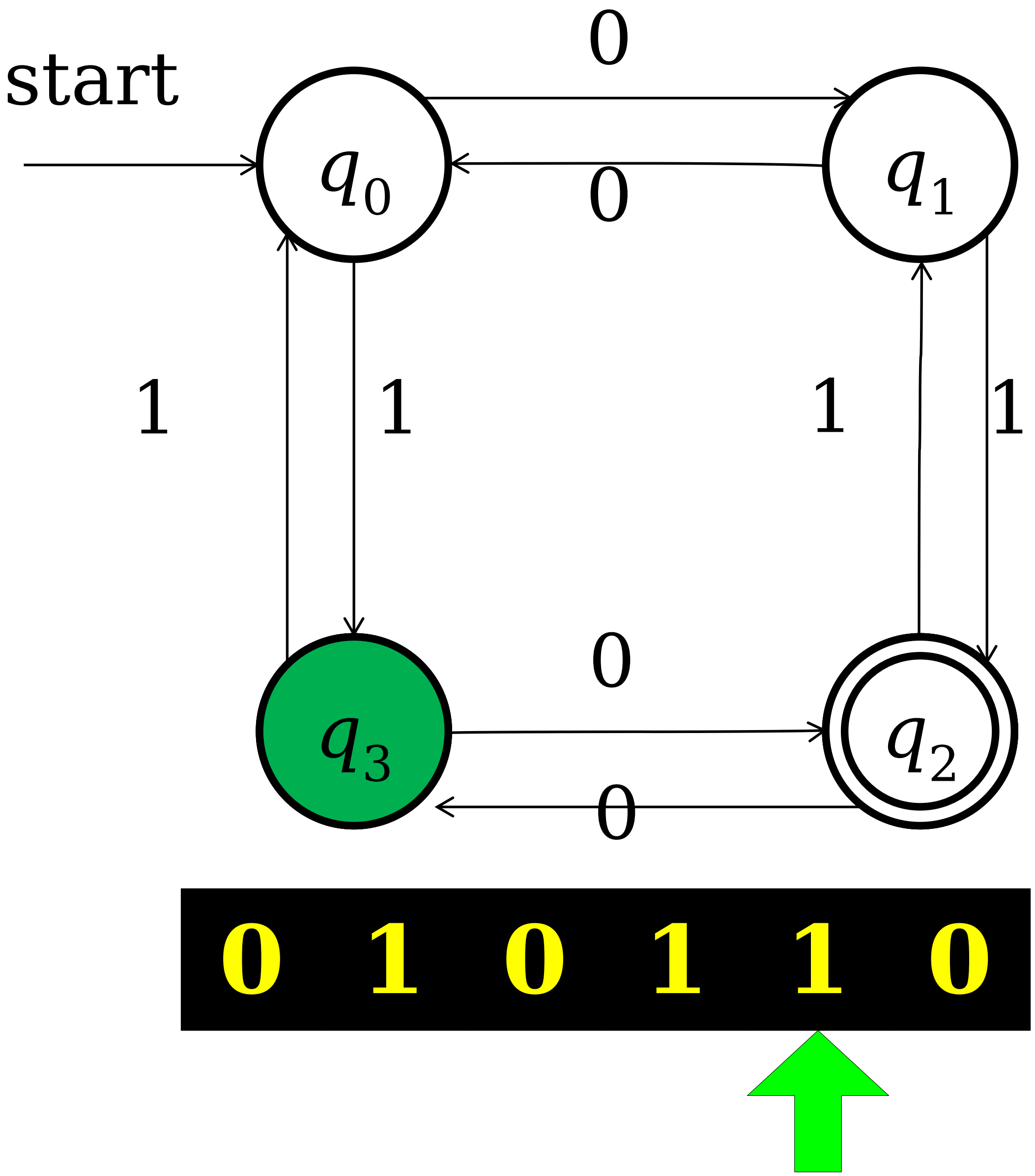

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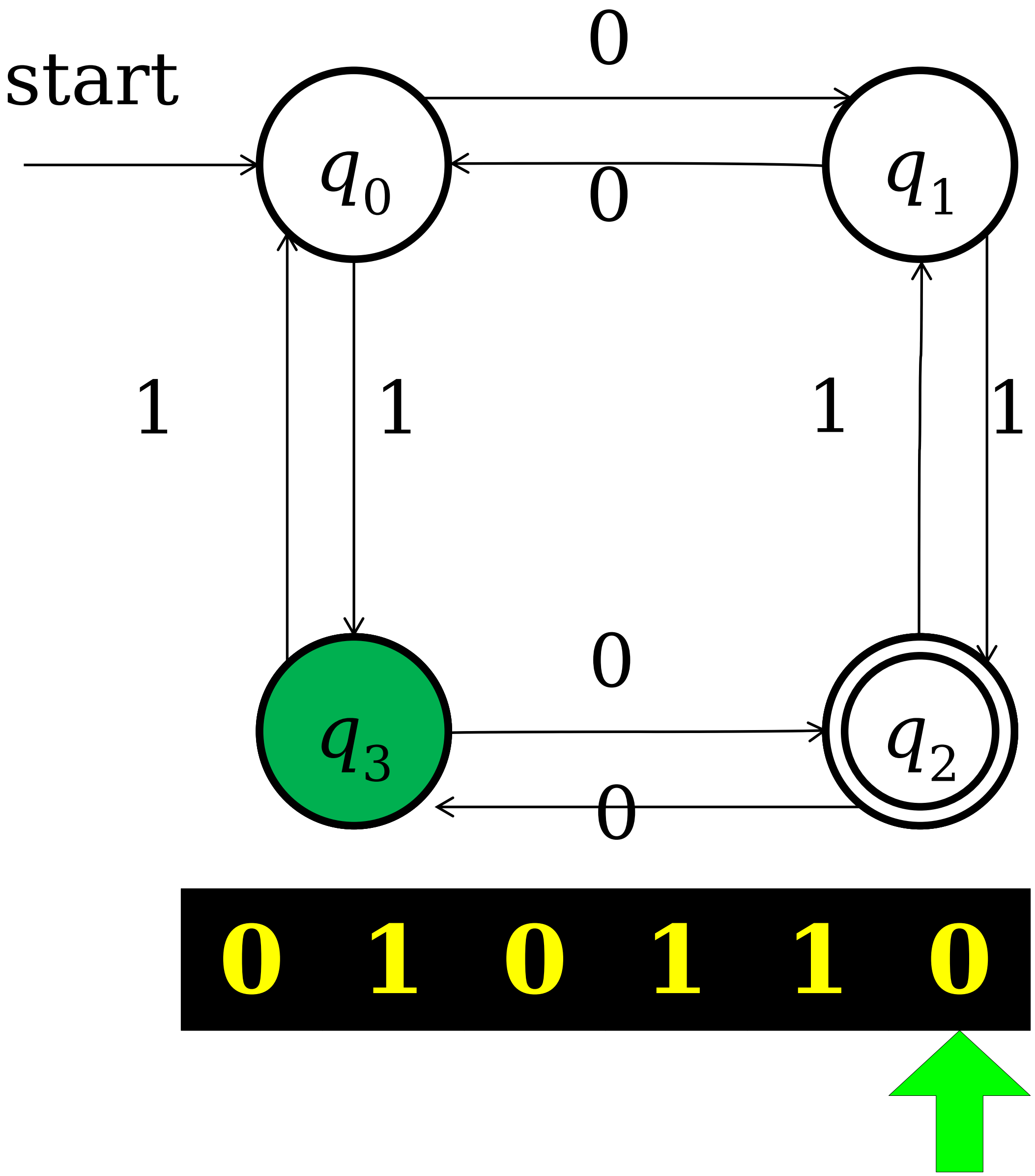

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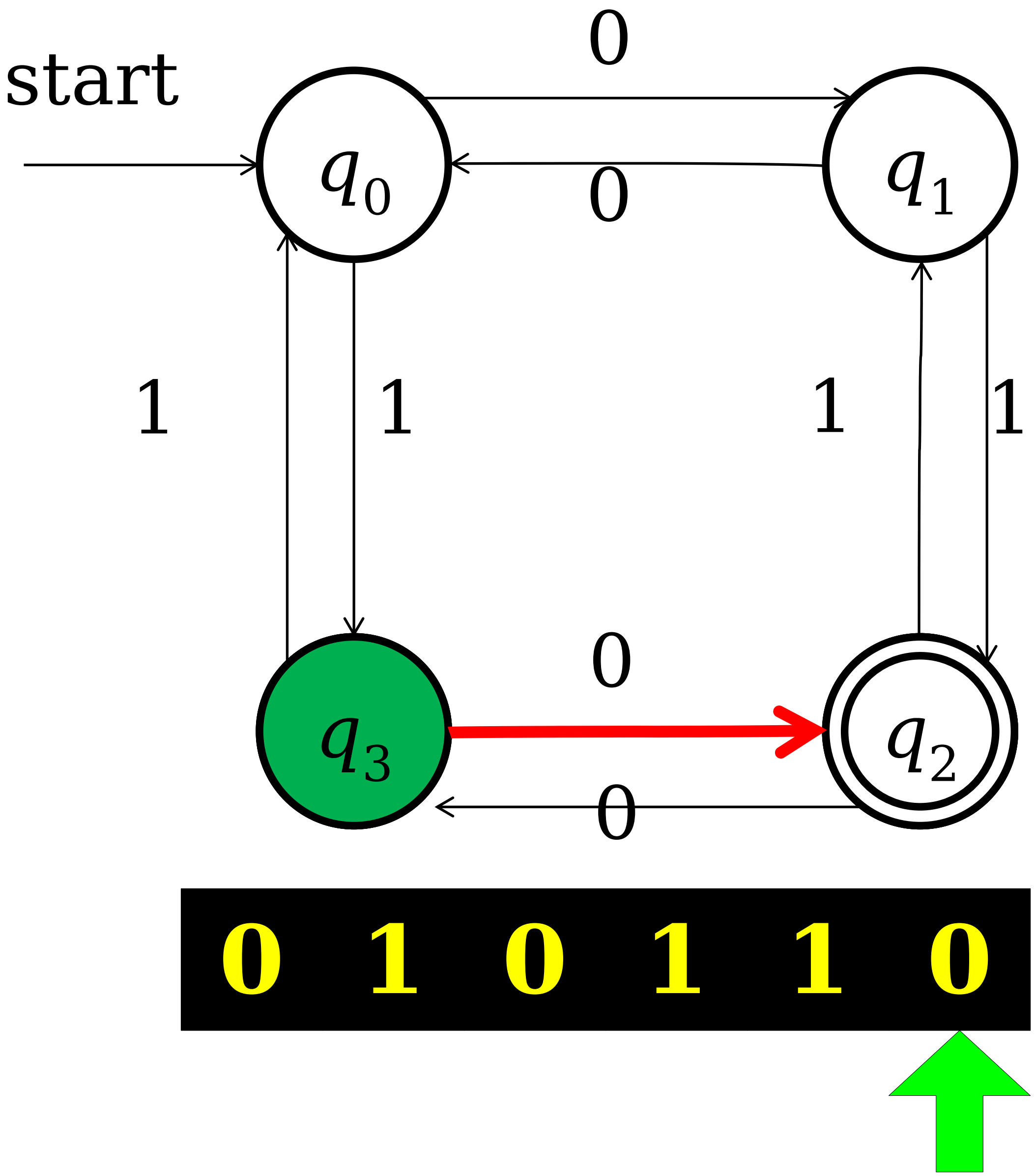

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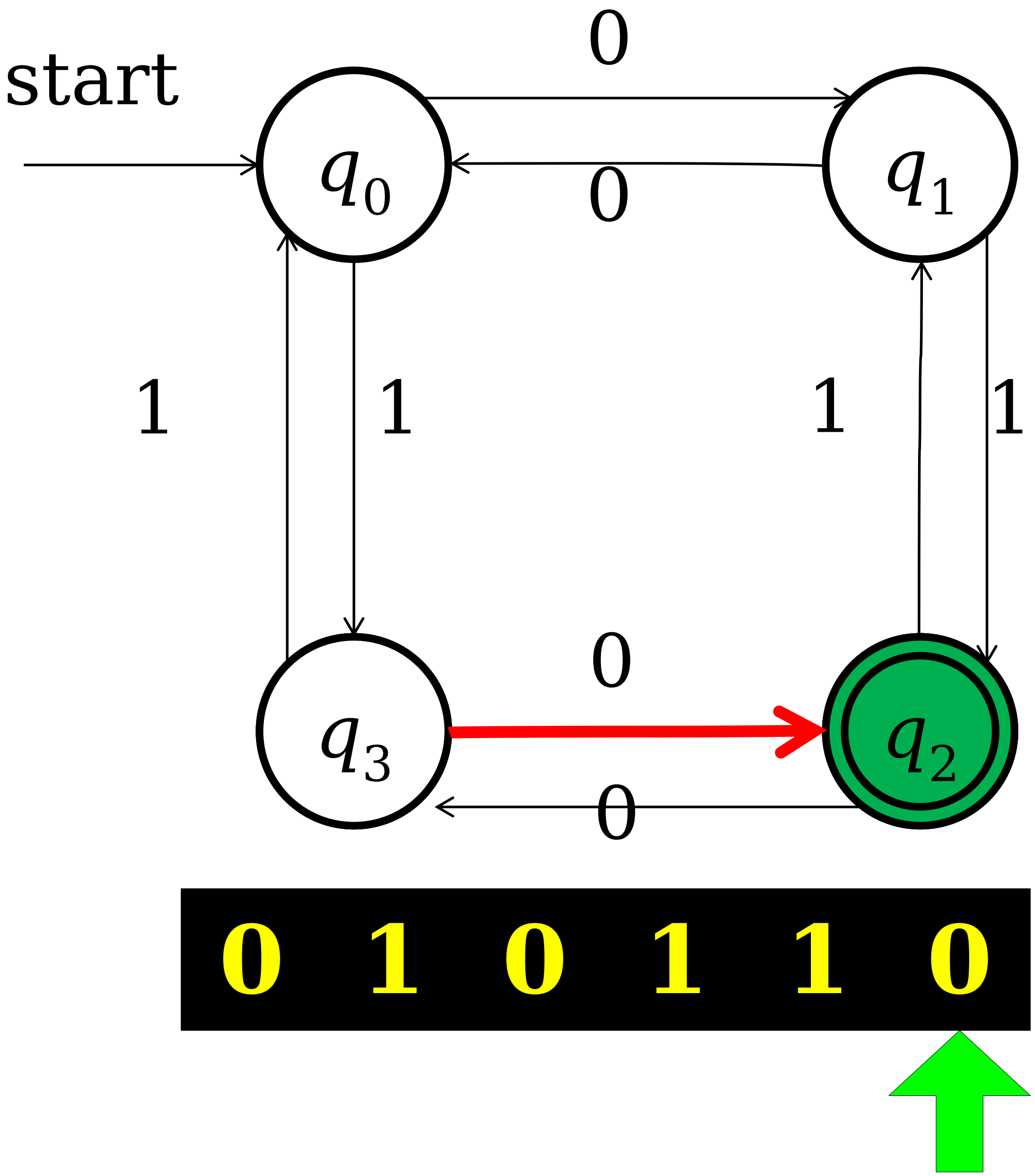

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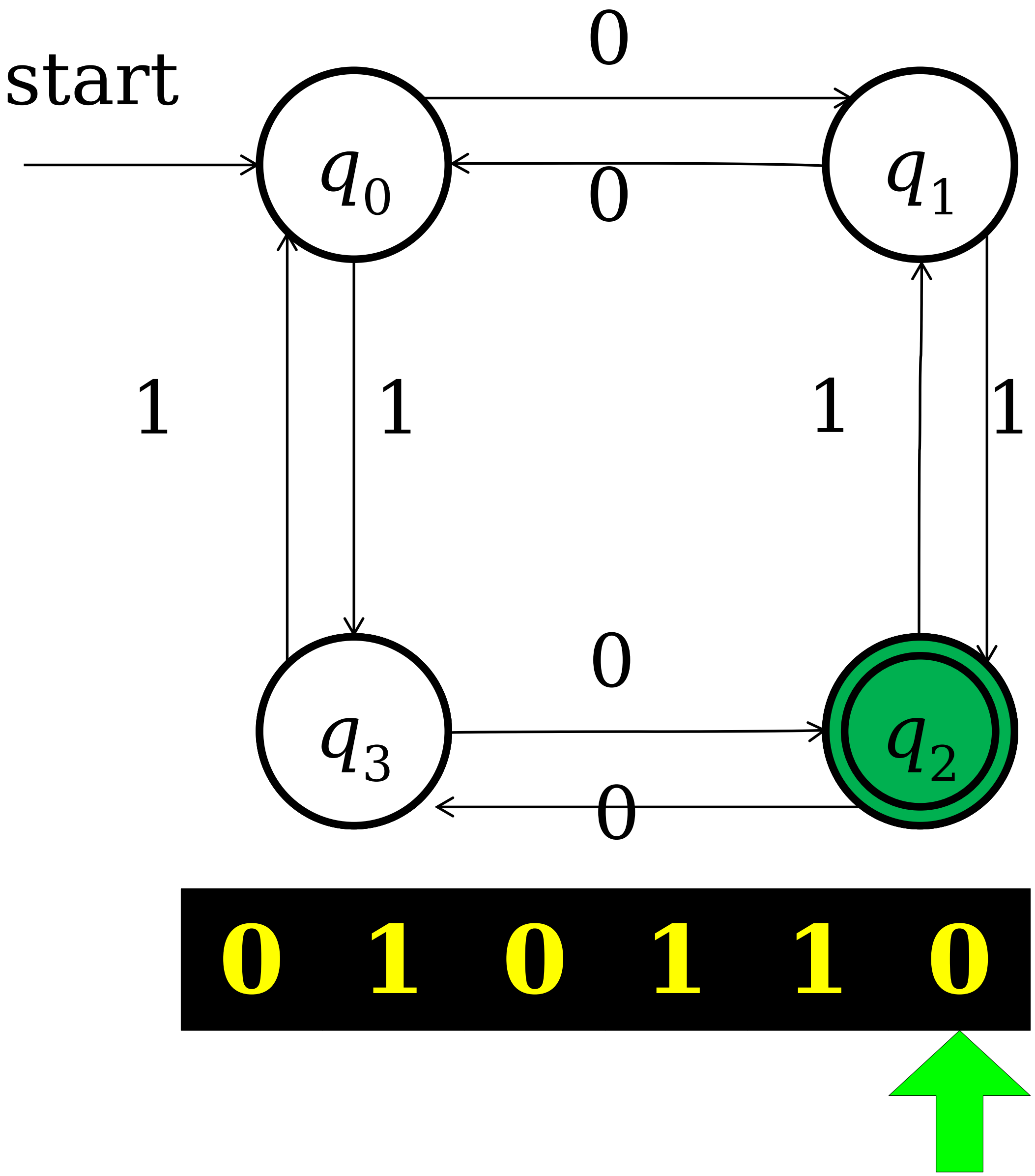

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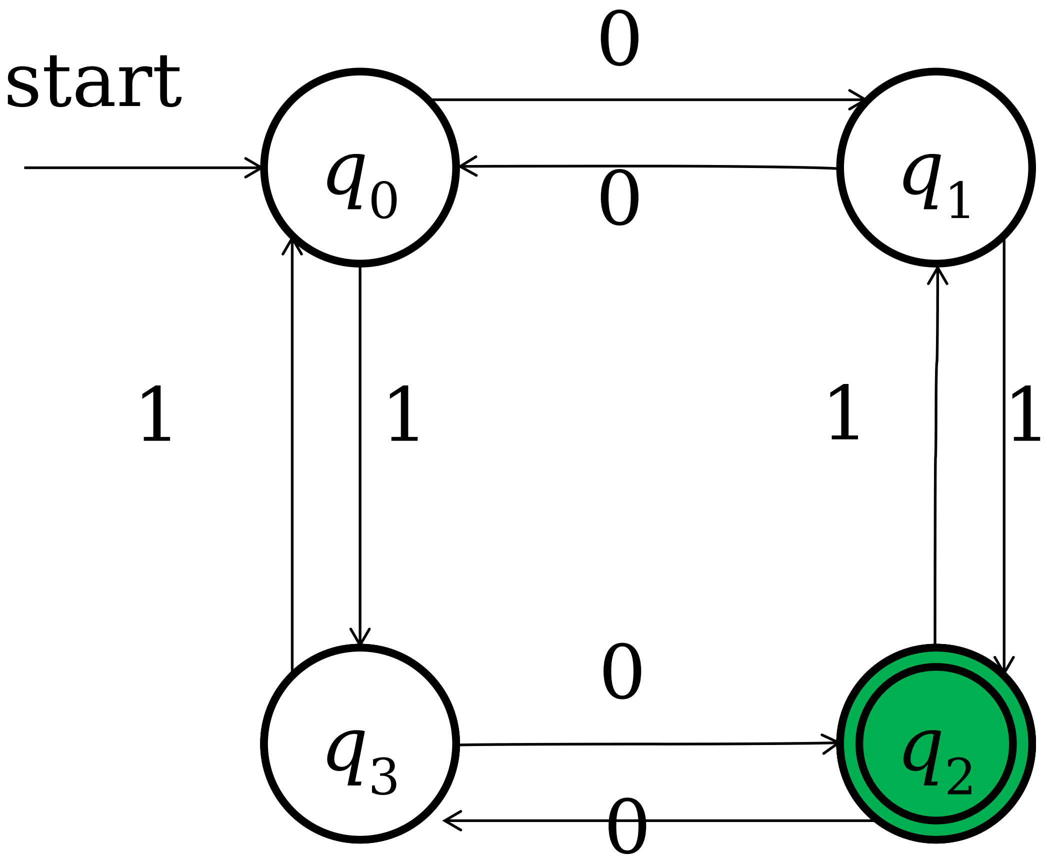

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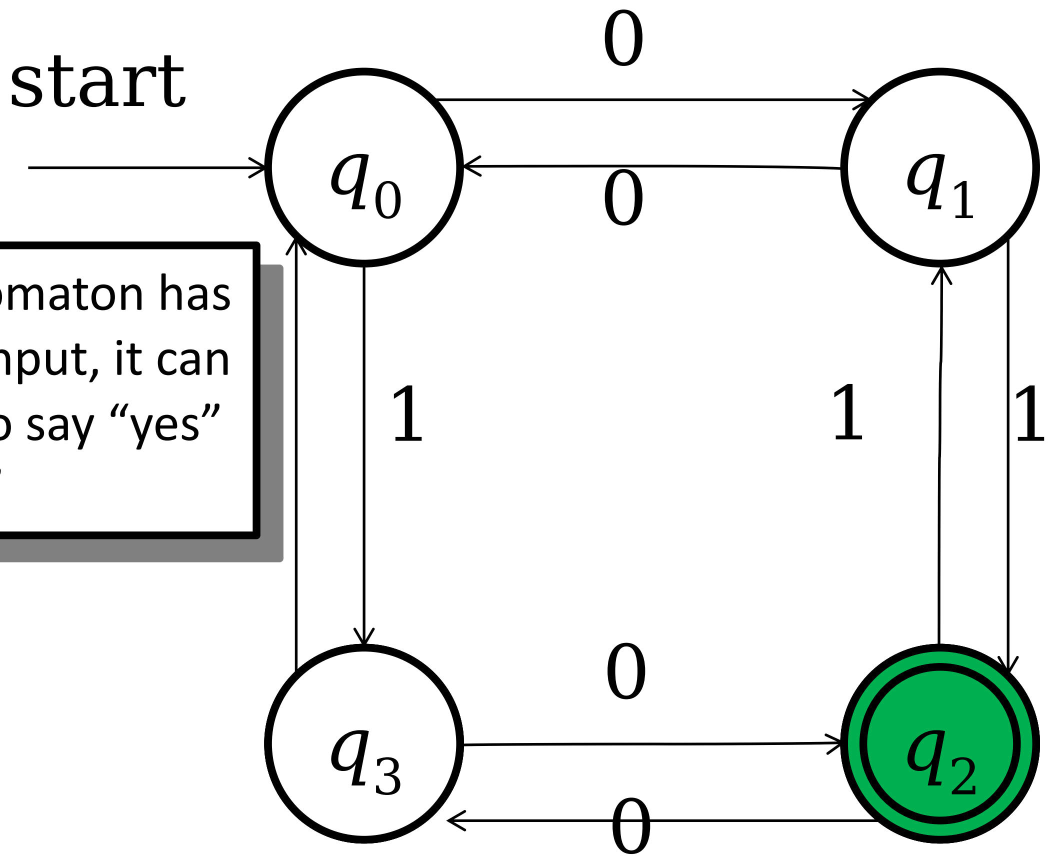
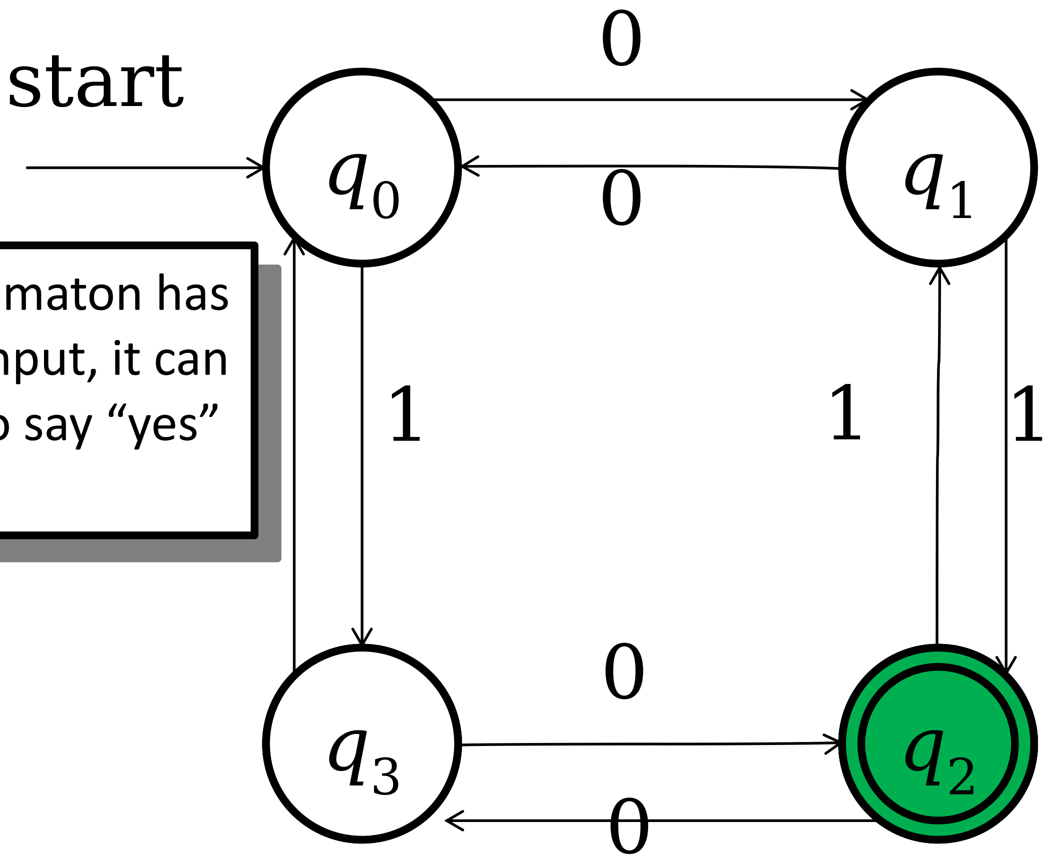


Now that the automaton has looked at all this input, it can decide whether to say "yes" or "no."

0 1 0 1 1 0

A Simple Finite Automaton



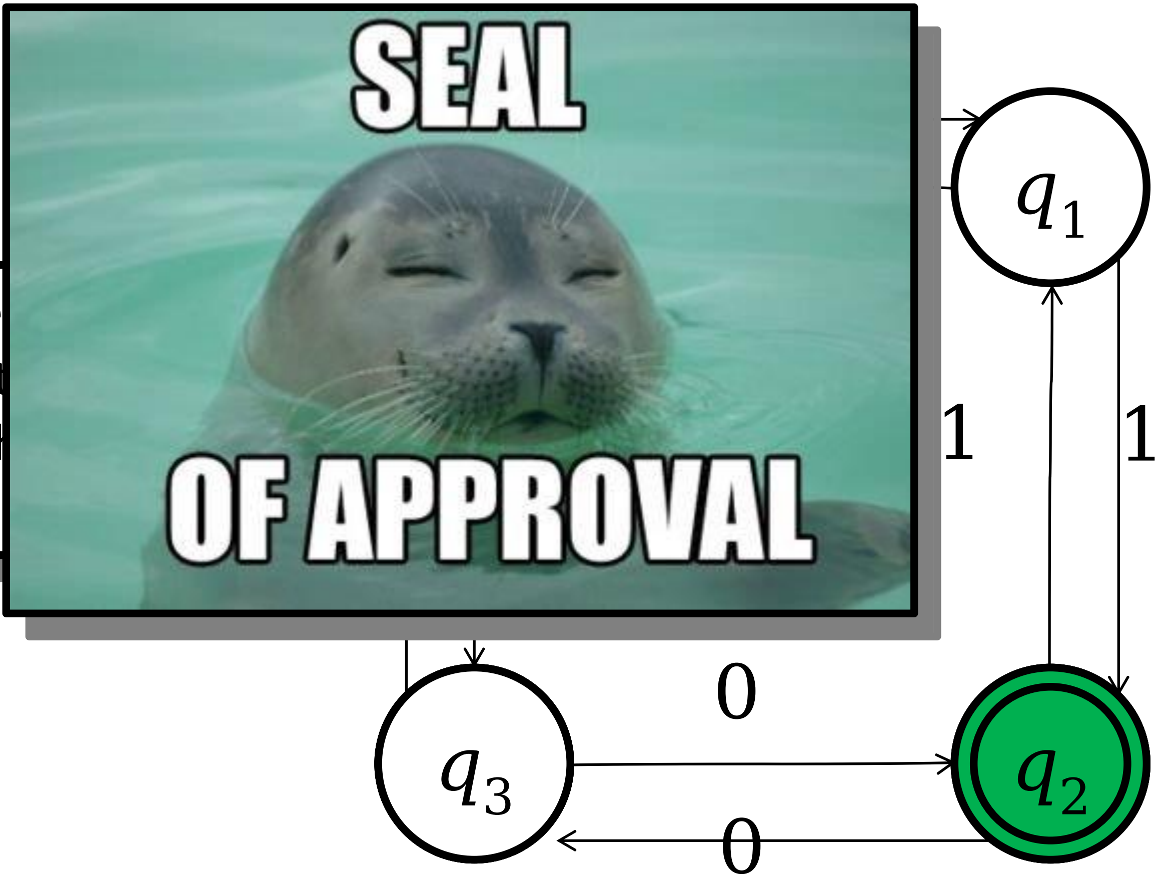
Now that the automaton has looked at all this input, it can decide whether to say “yes” or “no.”

The double circle indicates that this state is an **accepting state**, so the automaton outputs “yes.”

0 1 0 1 1 0

A Simple Finite Automaton

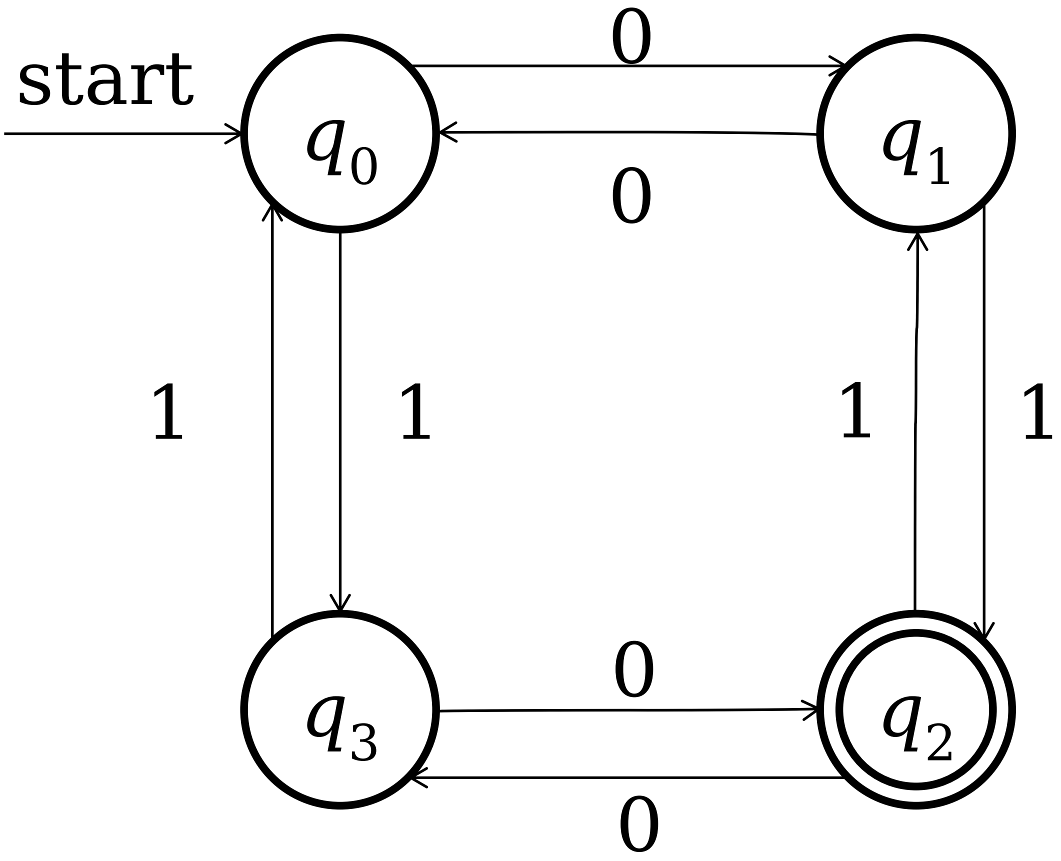
Now that the
looked at all t
decide wheth
or



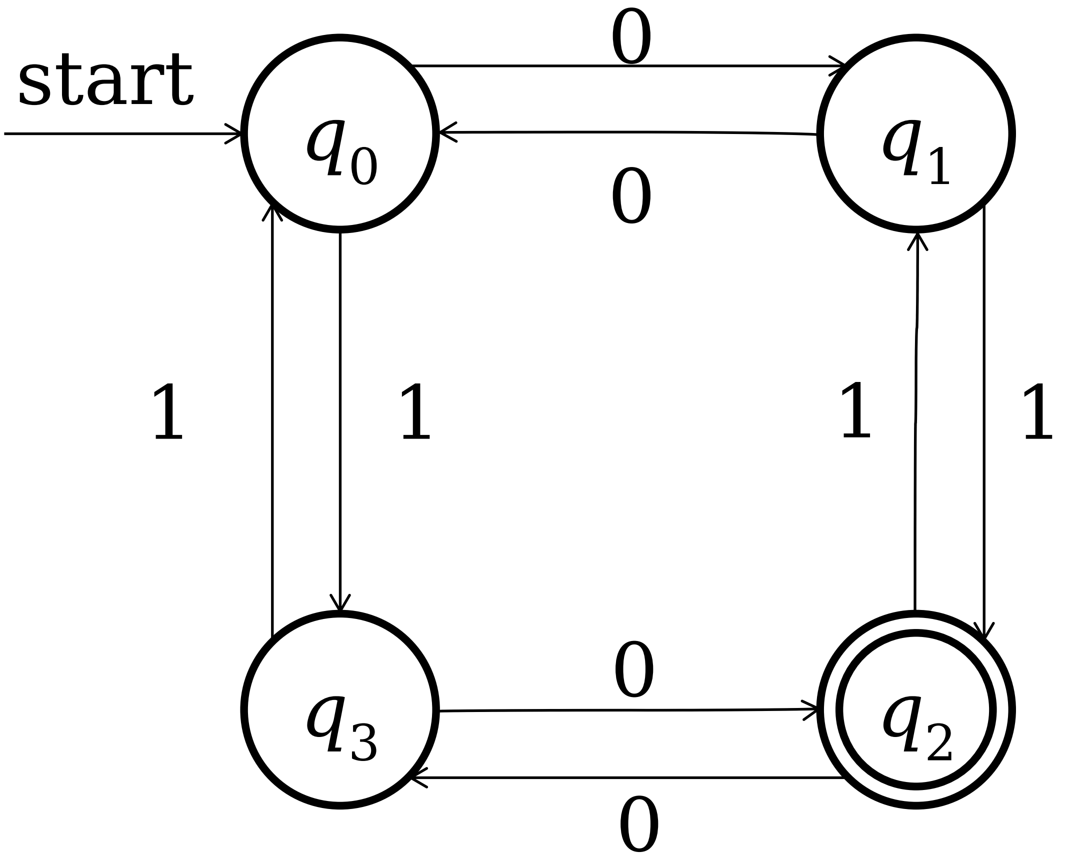
The double circle indicates that this state is an **accepting state**, so the automaton outputs "yes."

0 1 0 1 1 0

A Simple Finite Automaton

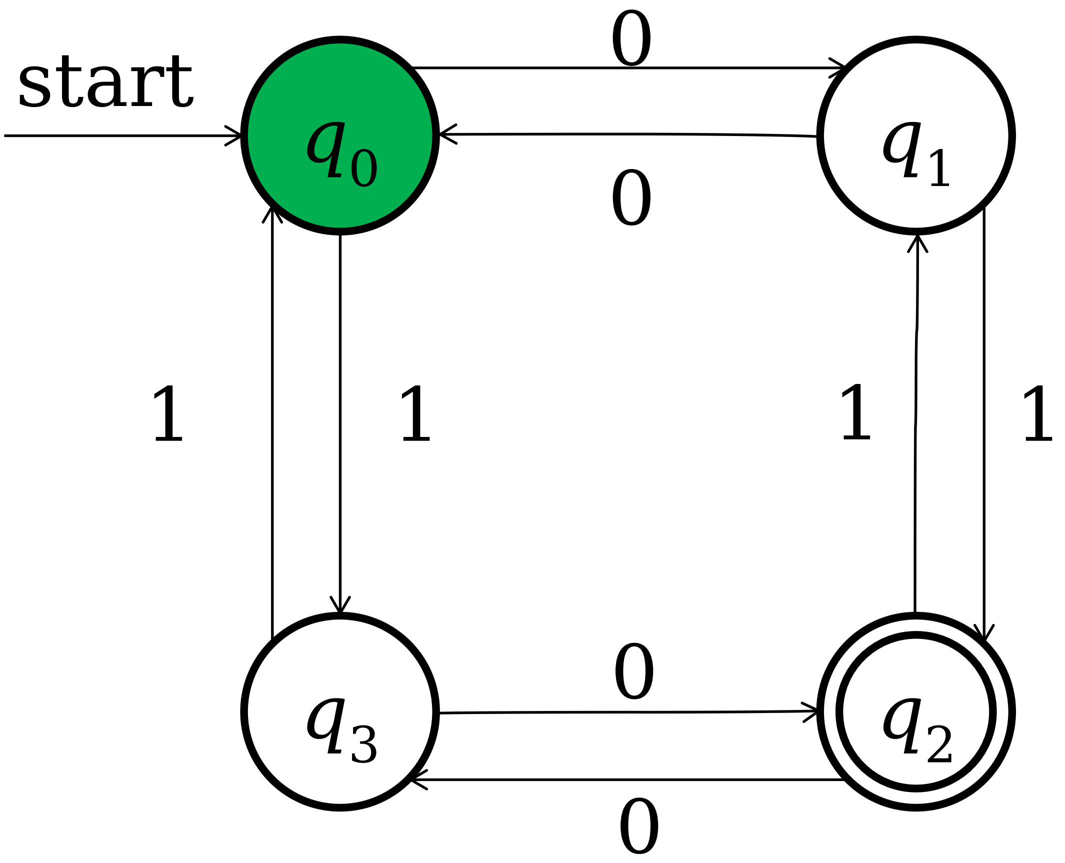


A Simple Finite Automaton



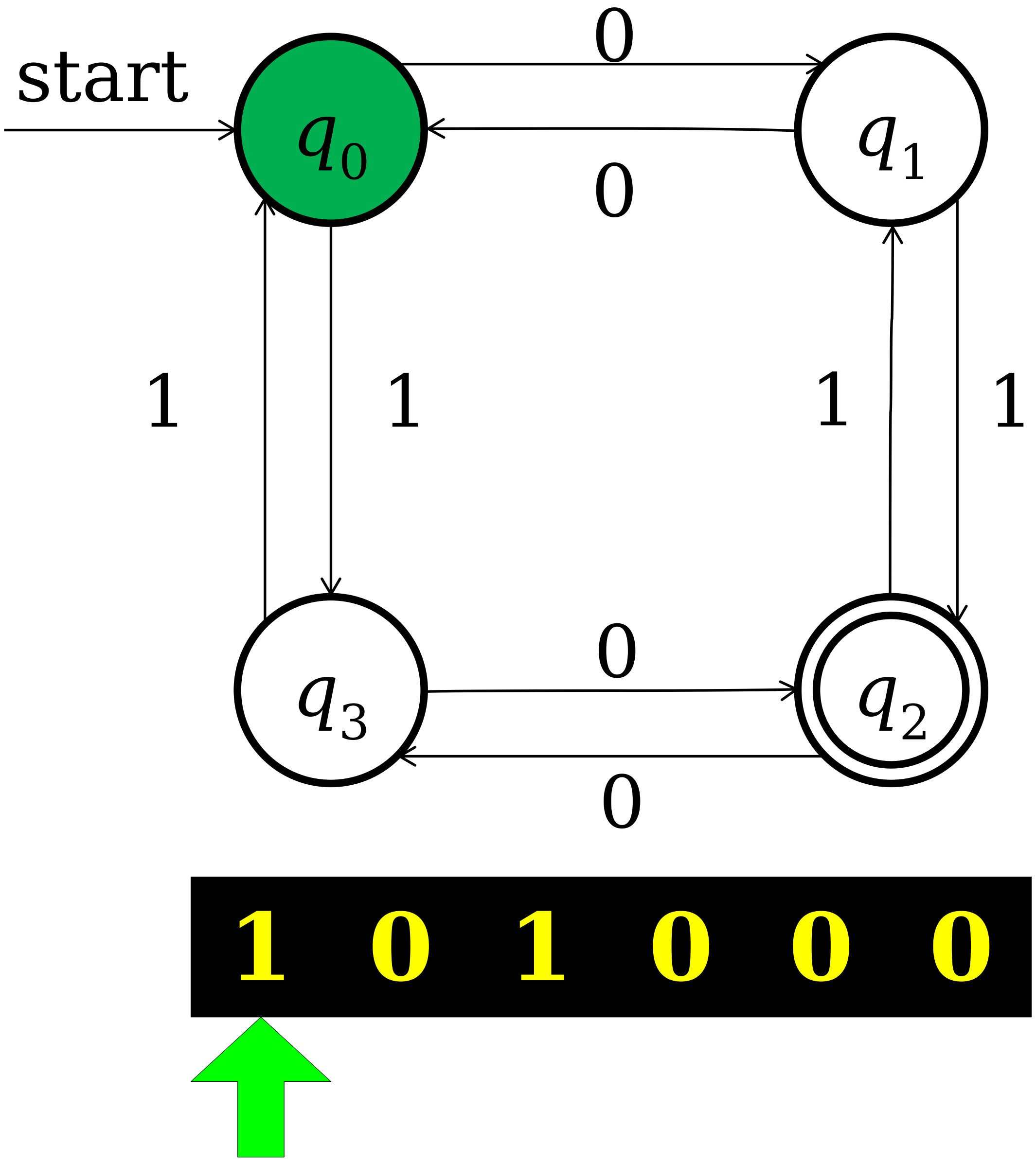
1 0 1 0 0 0

A Simple Finite Automaton

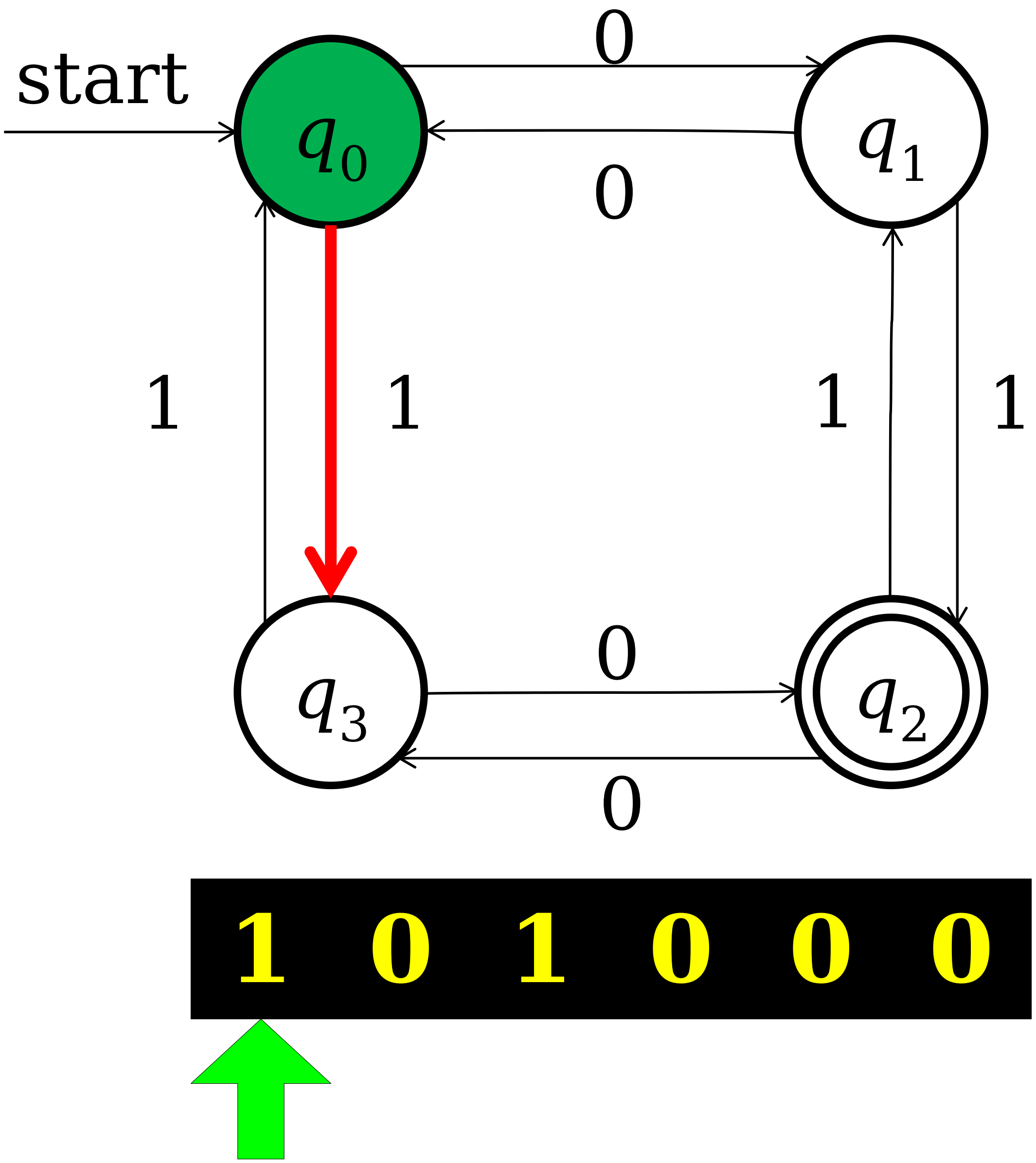


1 0 1 0 0 0

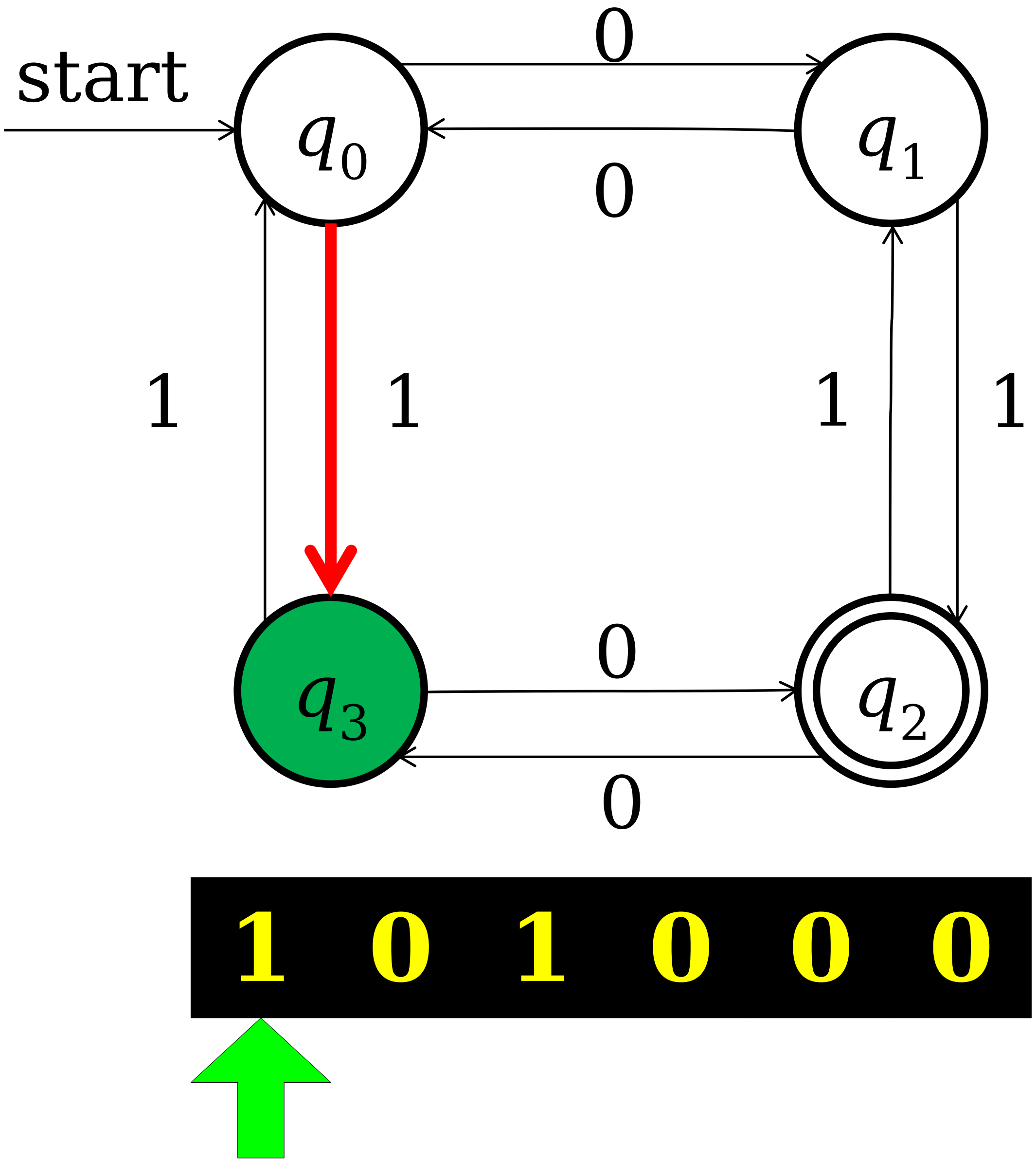
A Simple Finite Automaton



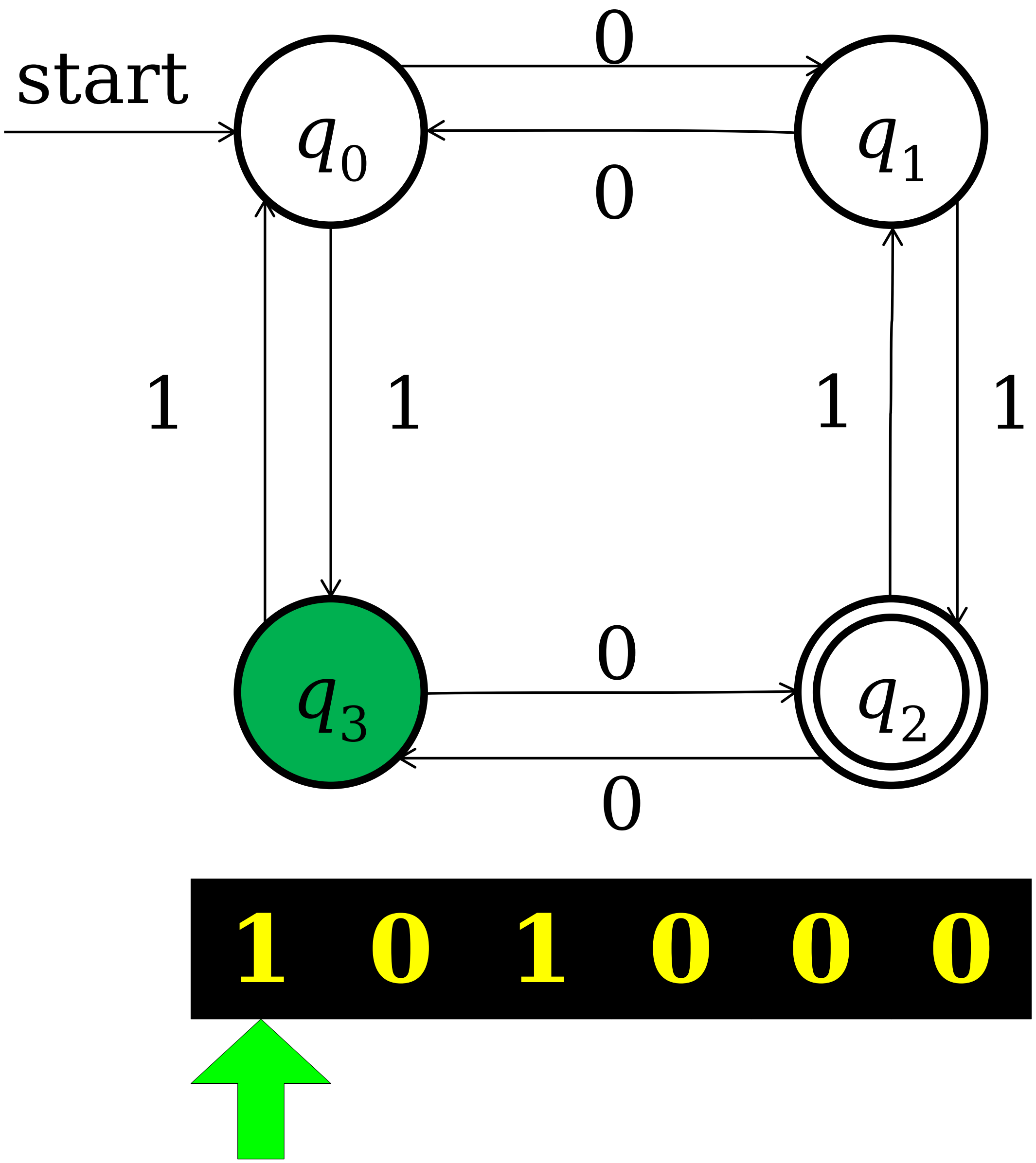
A Simple Finite Automaton



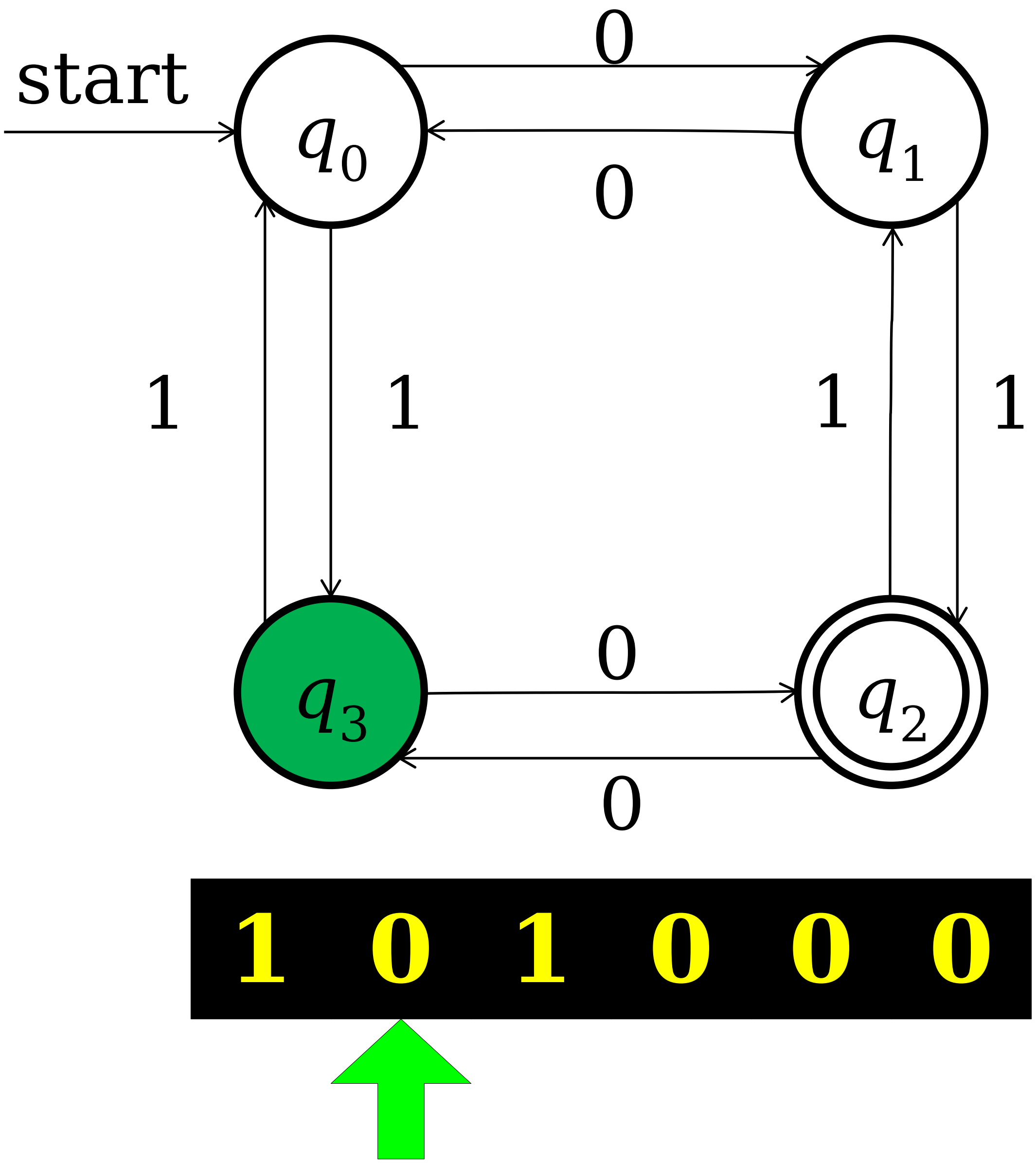
A Simple Finite Automaton



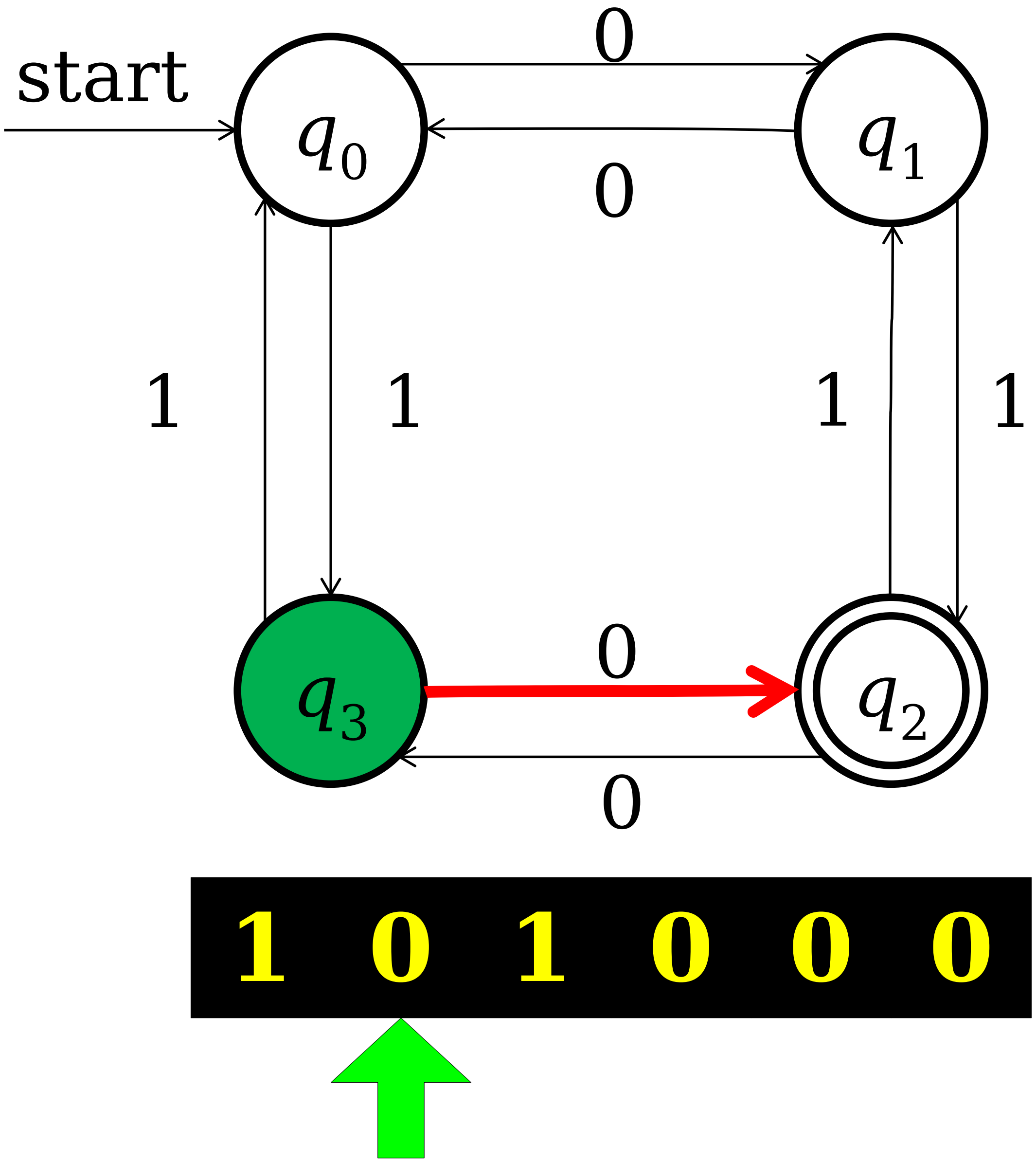
A Simple Finite Automaton



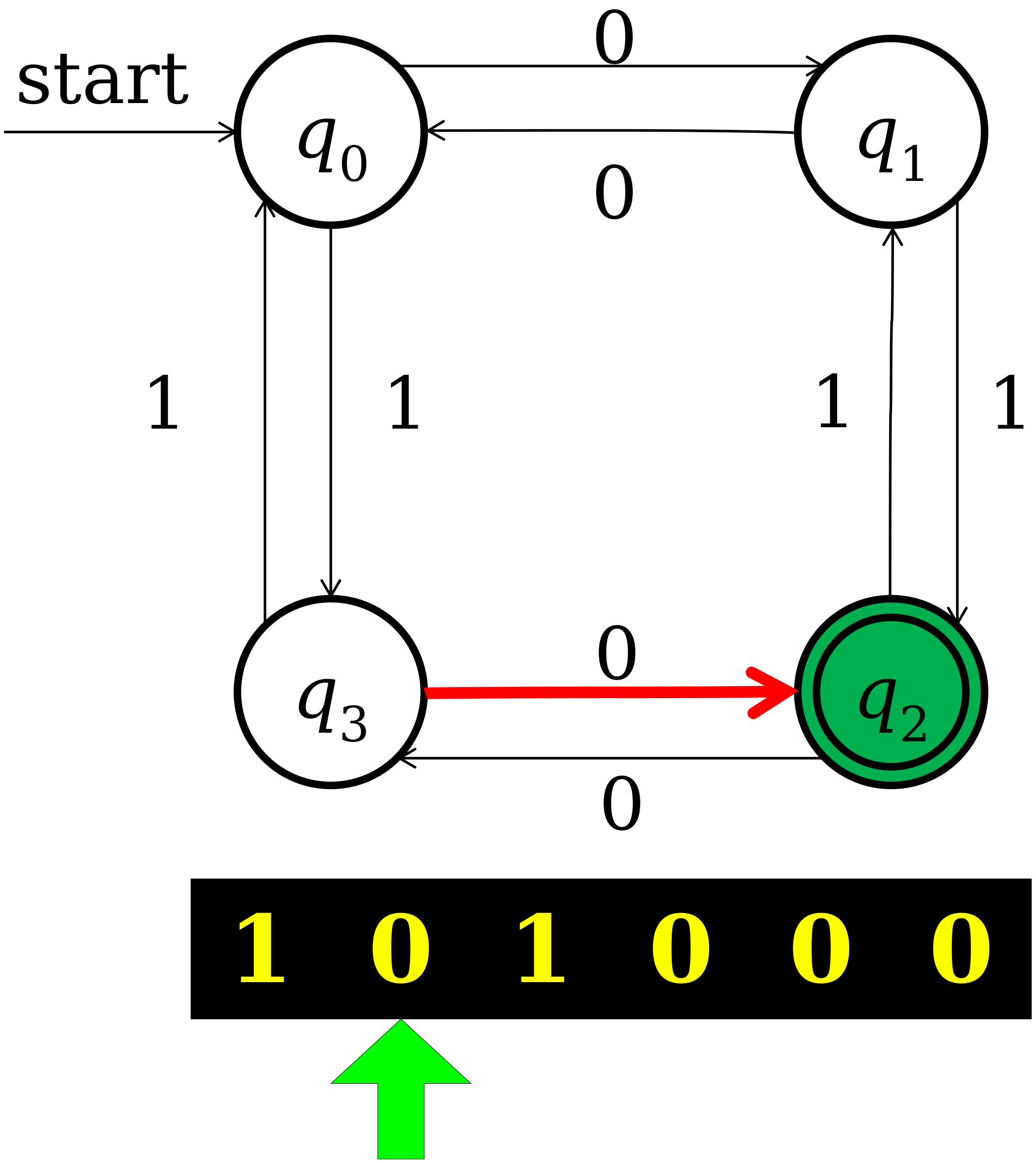
A Simple Finite Automaton



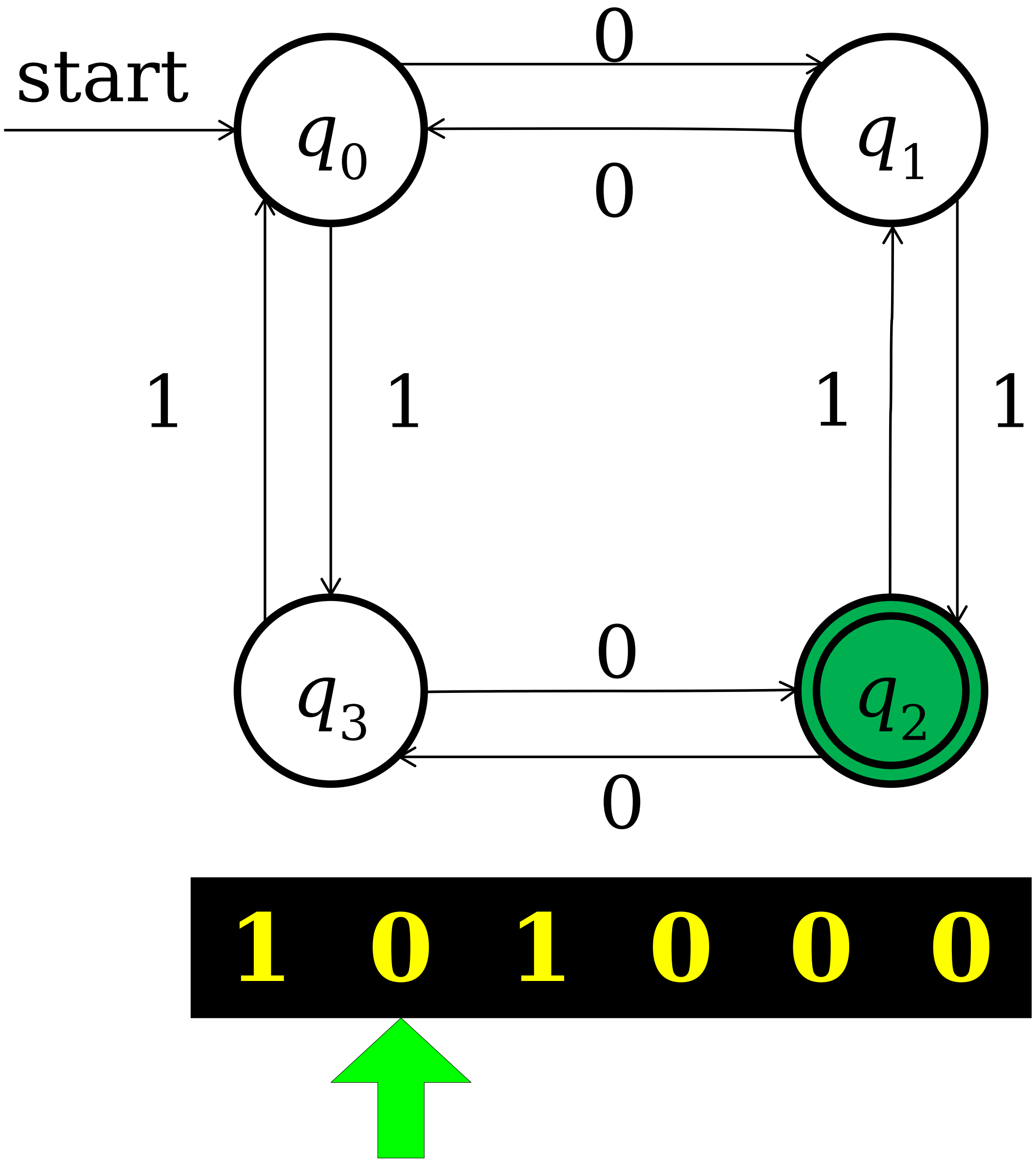
A Simple Finite Automaton



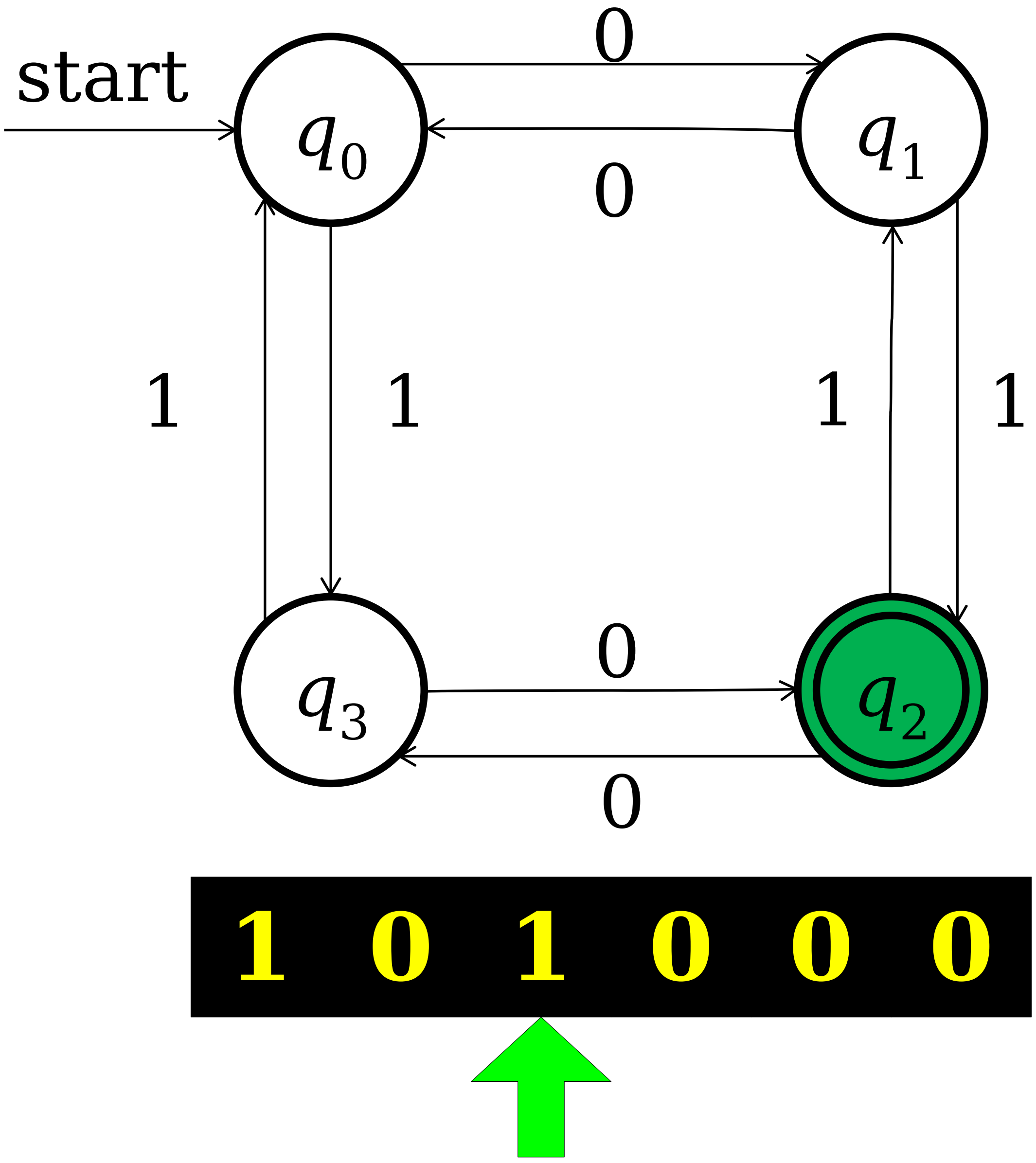
A Simple Finite Automaton



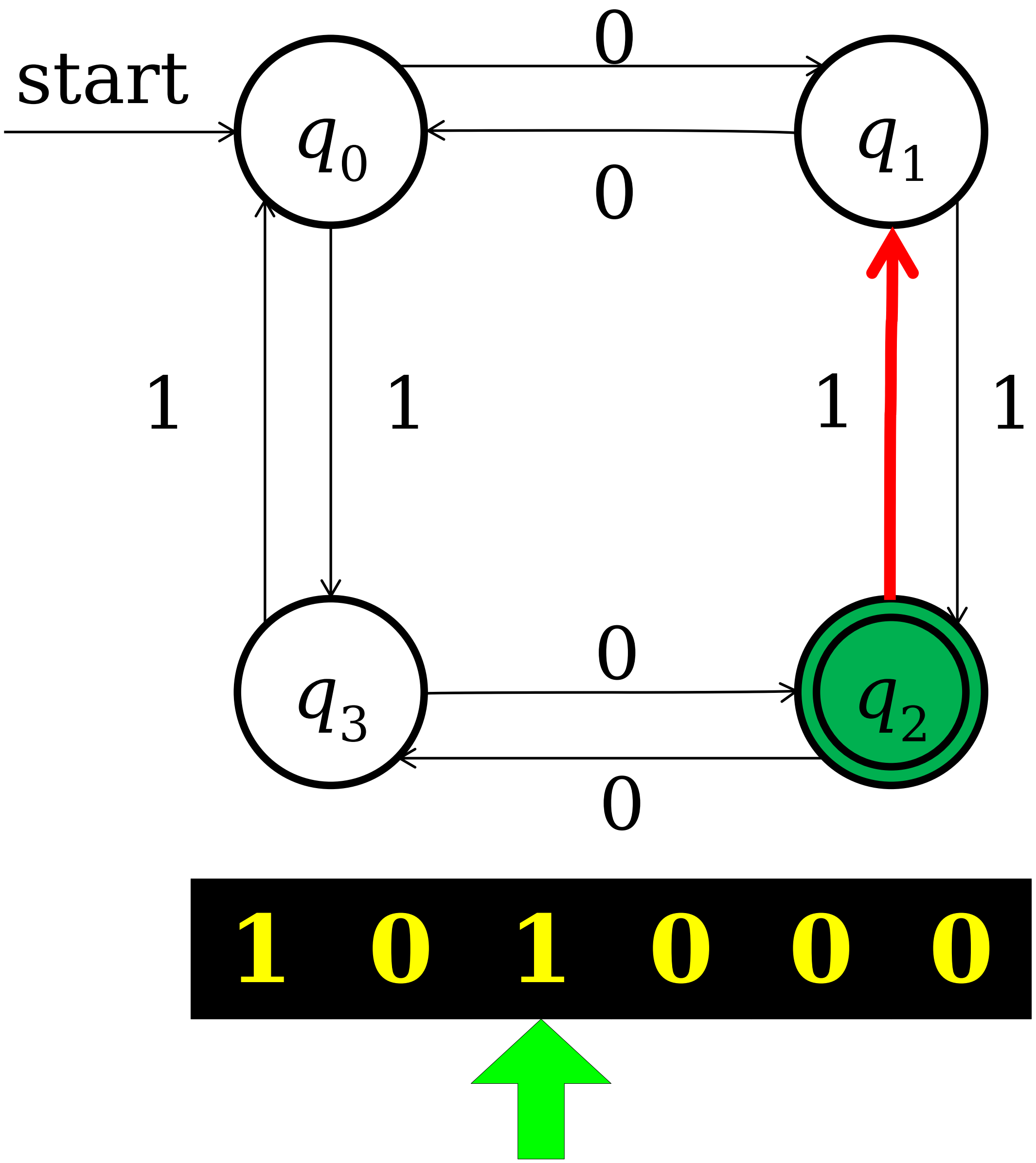
A Simple Finite Automaton



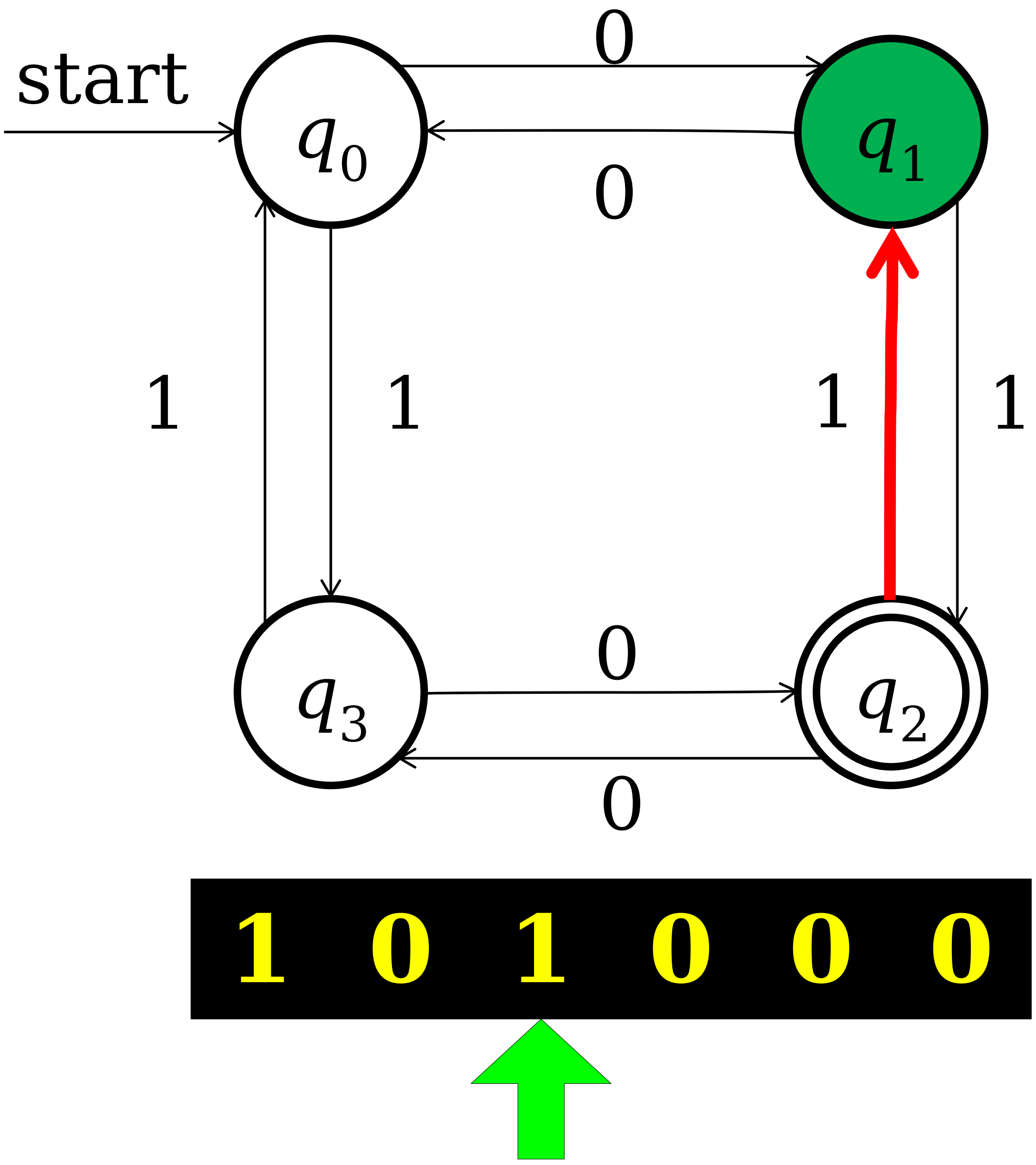
A Simple Finite Automaton



A Simple Finite Automaton

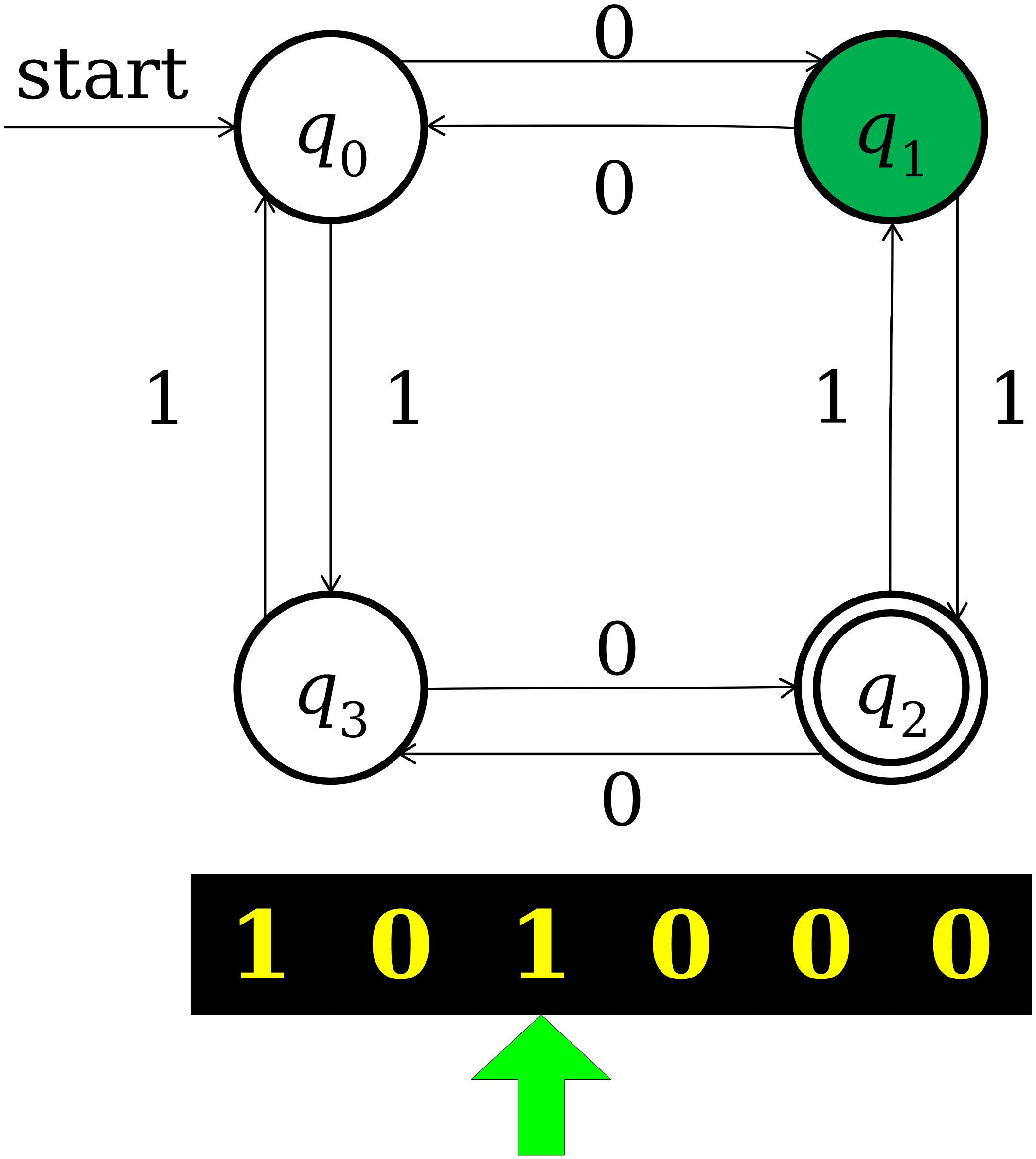


A Simple Finite Automaton

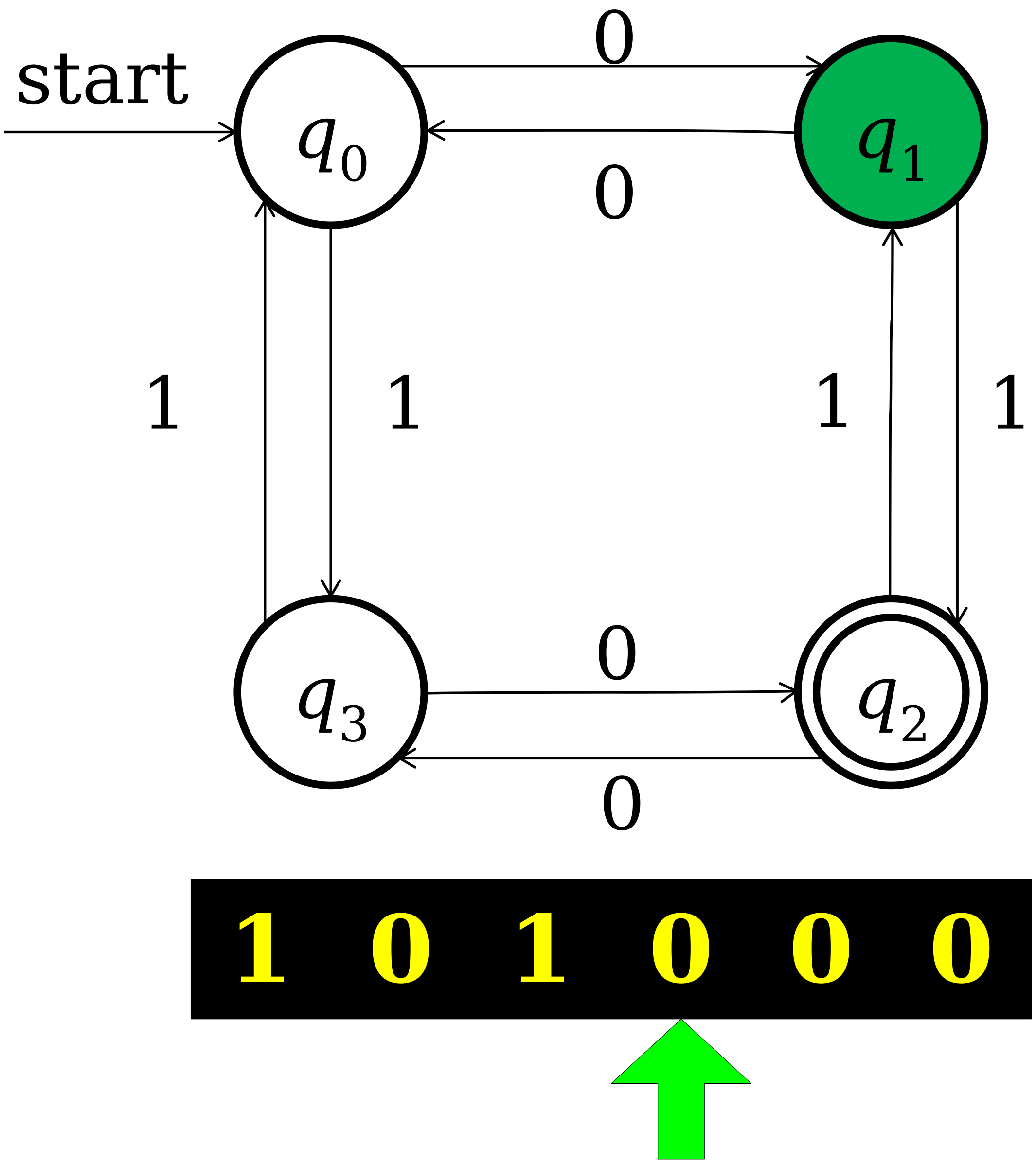


1 0 1 0 0 0

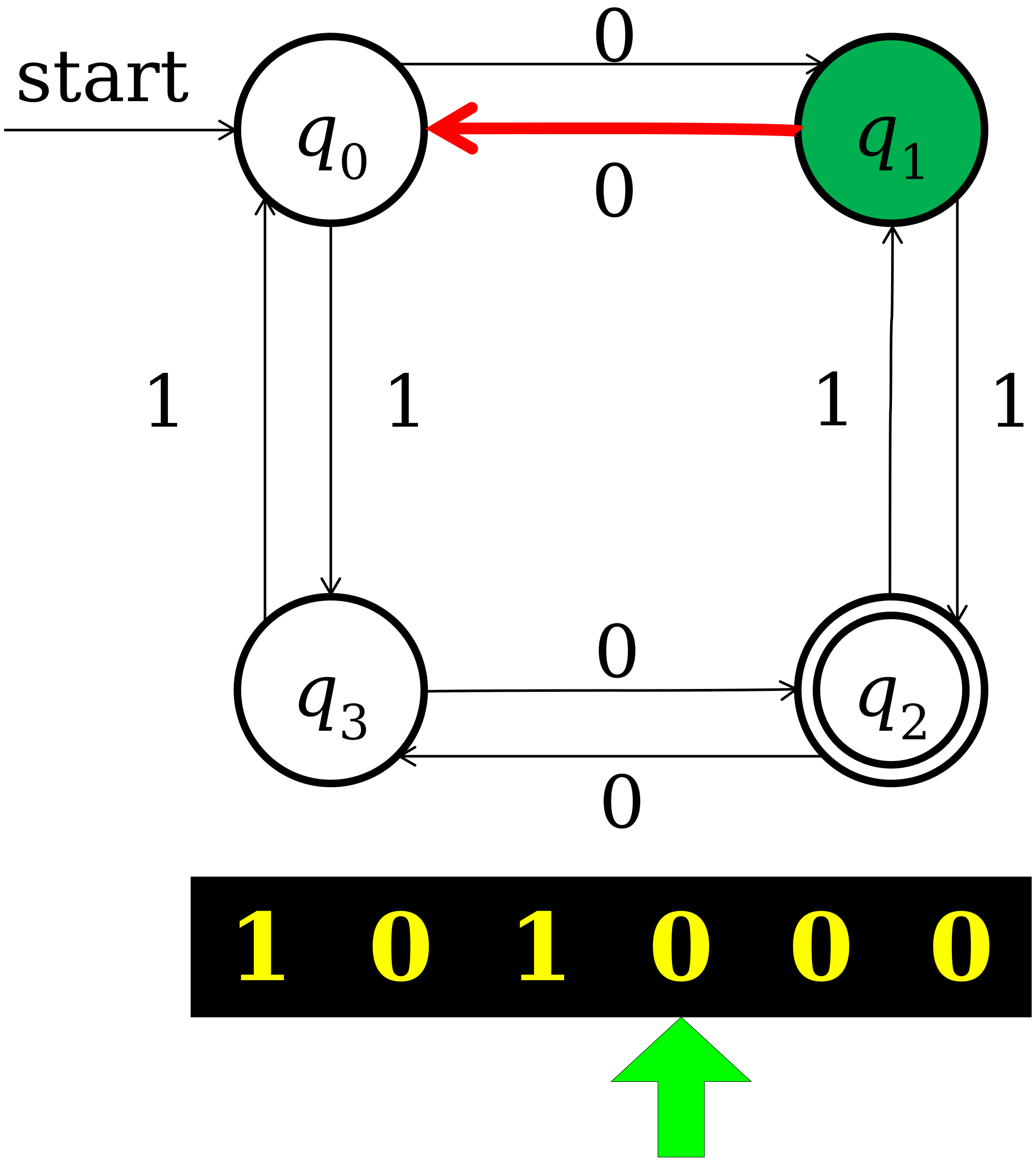
A Simple Finite Automaton



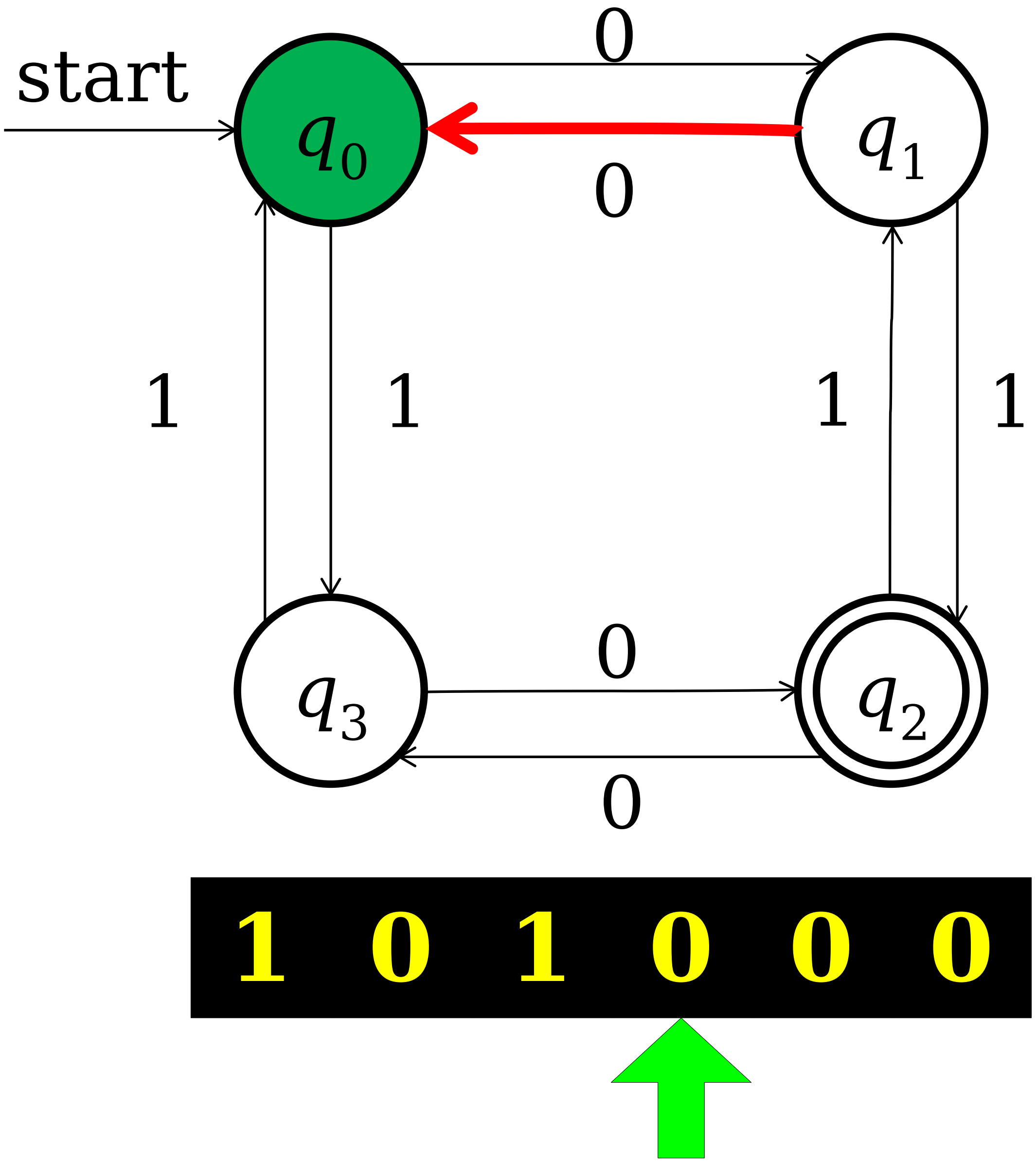
A Simple Finite Automaton



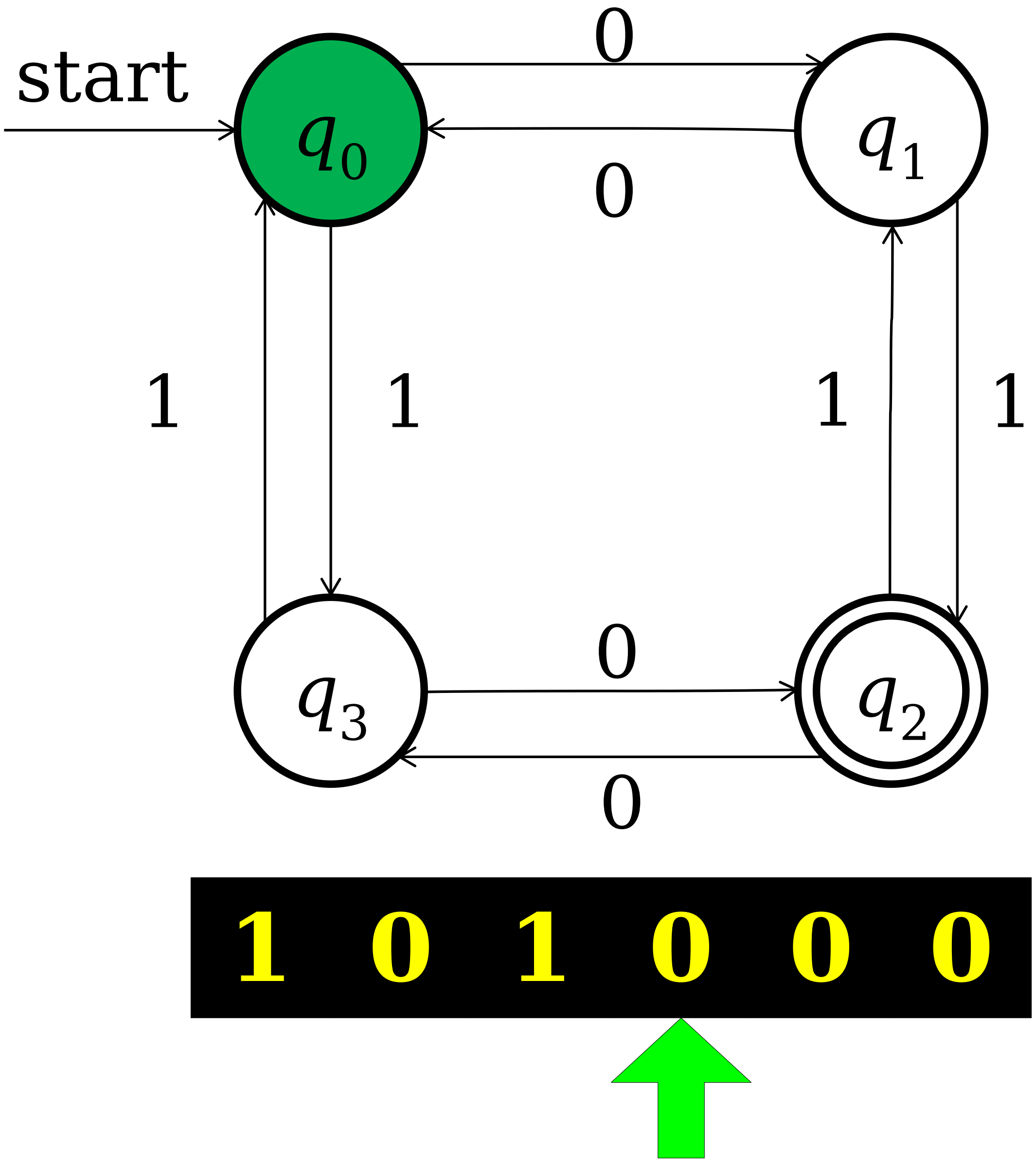
A Simple Finite Automaton



A Simple Finite Automaton

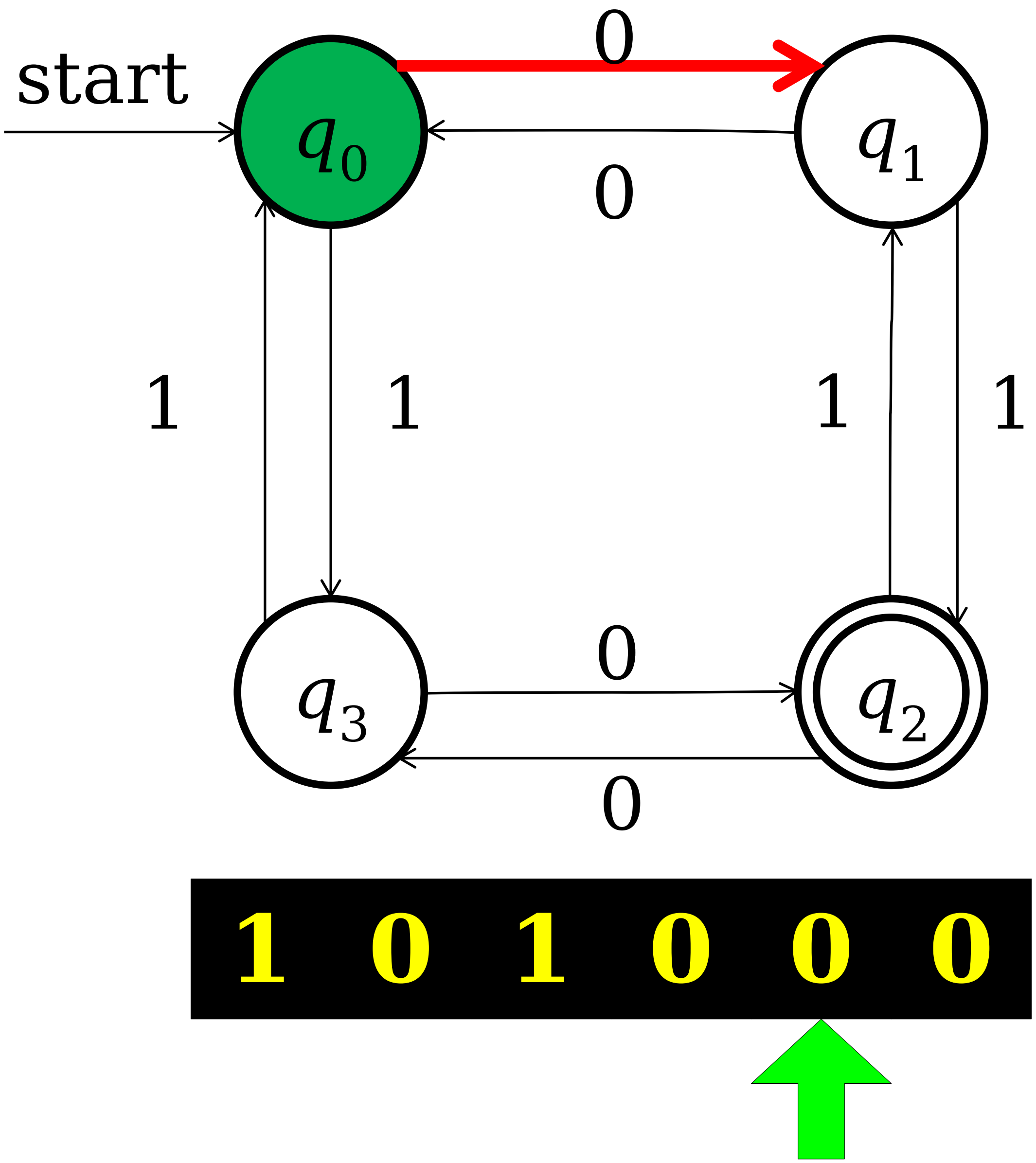


A Simple Finite Automaton



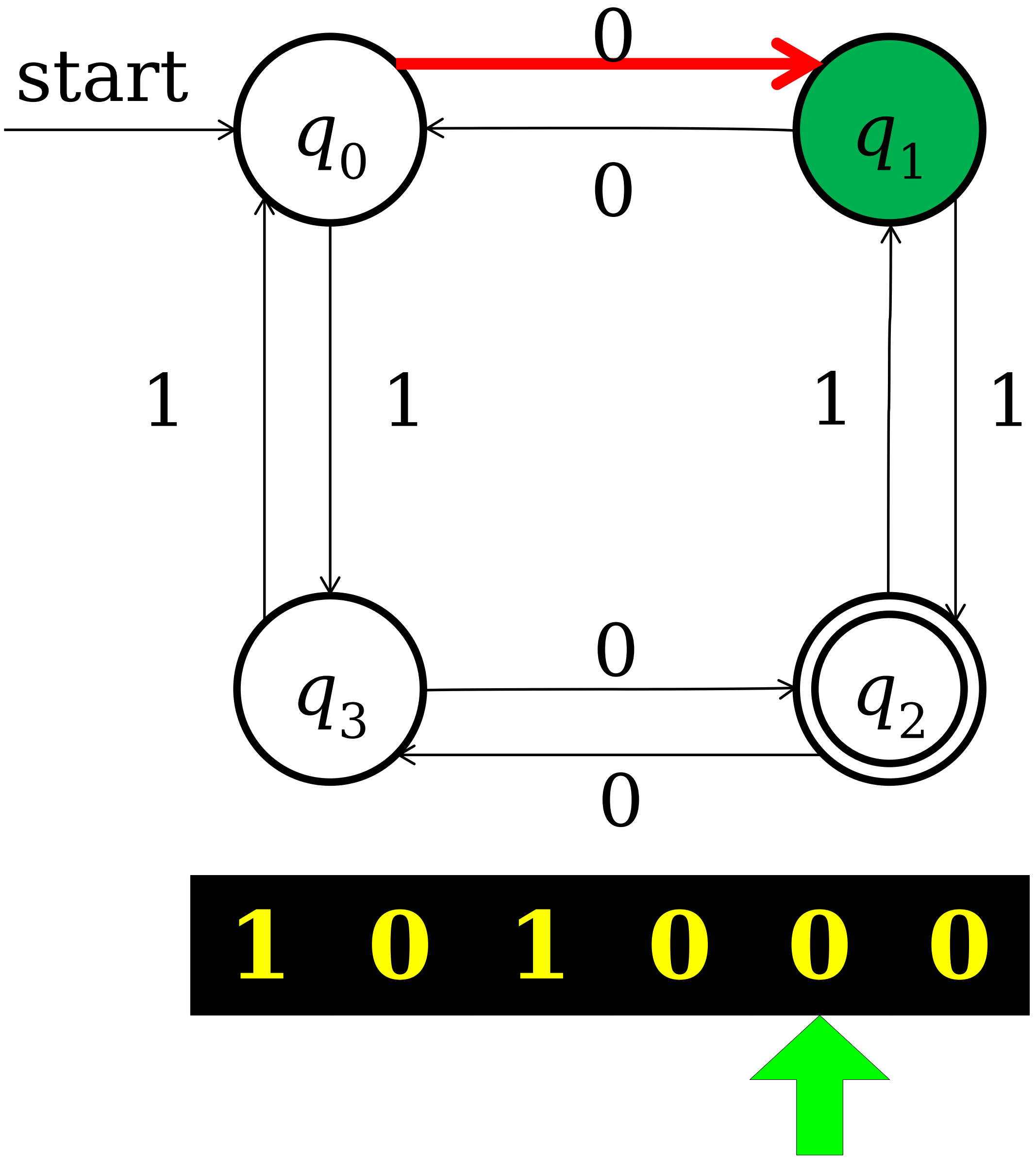
1 0 1 0 0 0

A Simple Finite Automaton

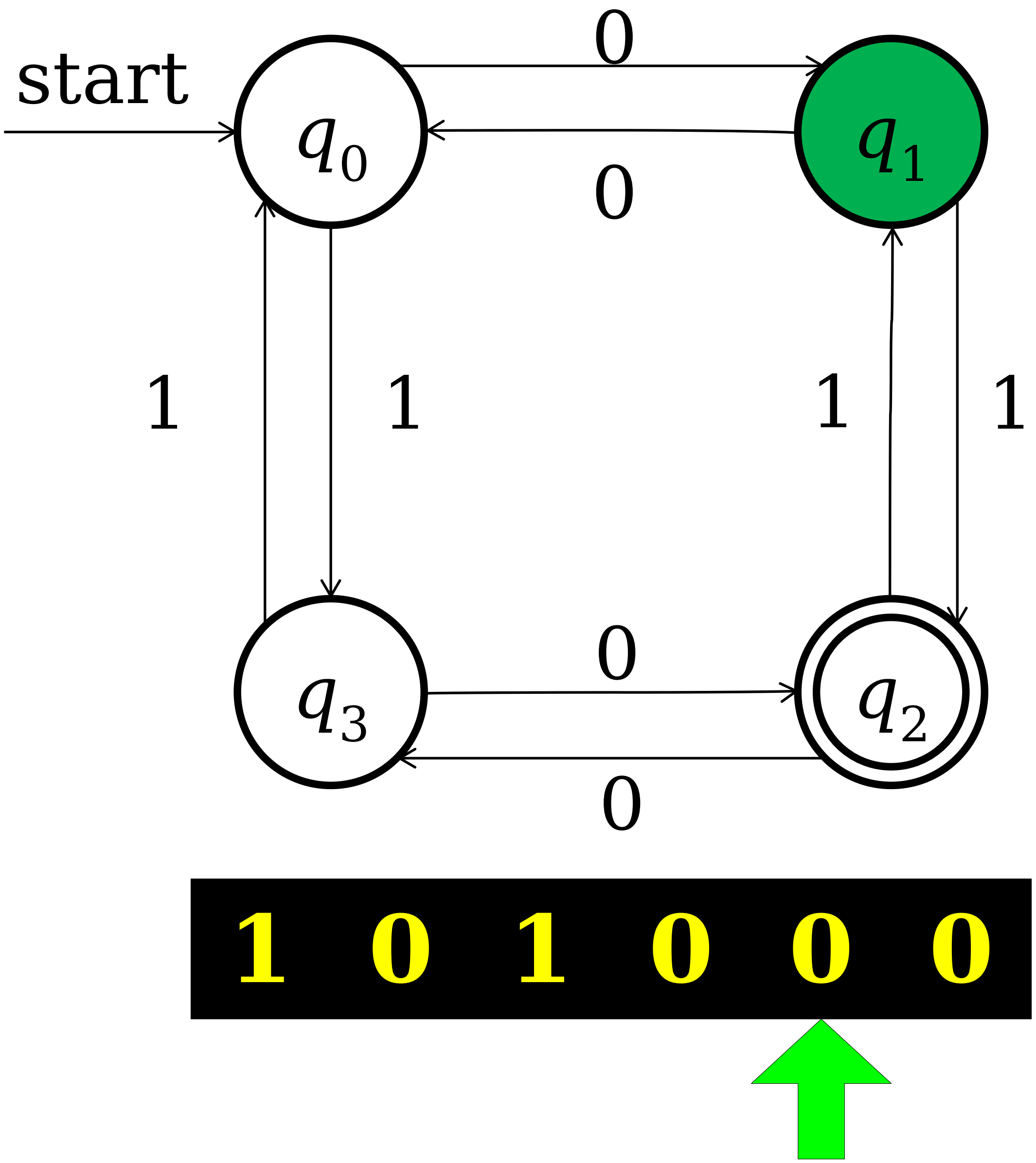


1 0 1 0 0 0

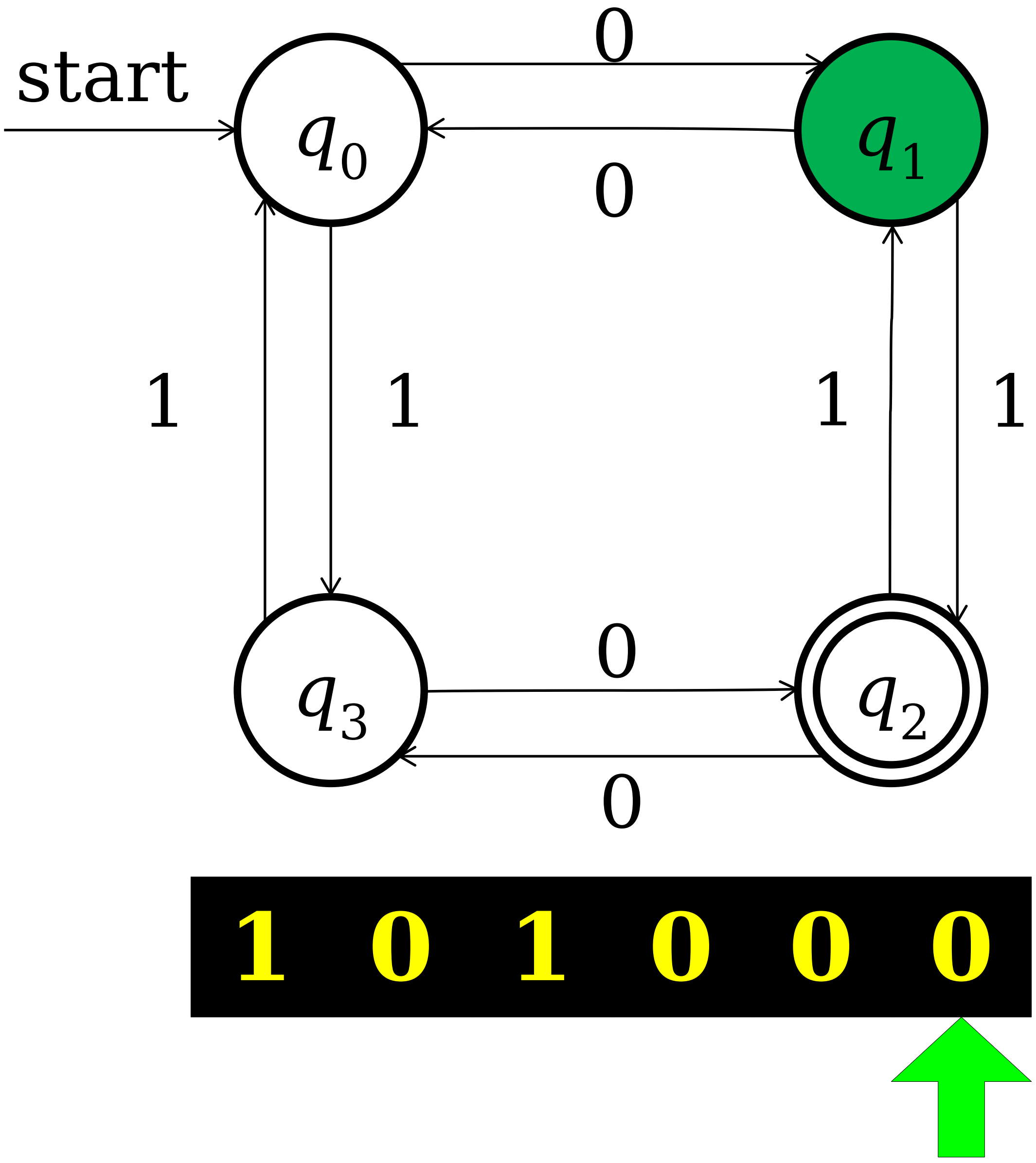
A Simple Finite Automaton



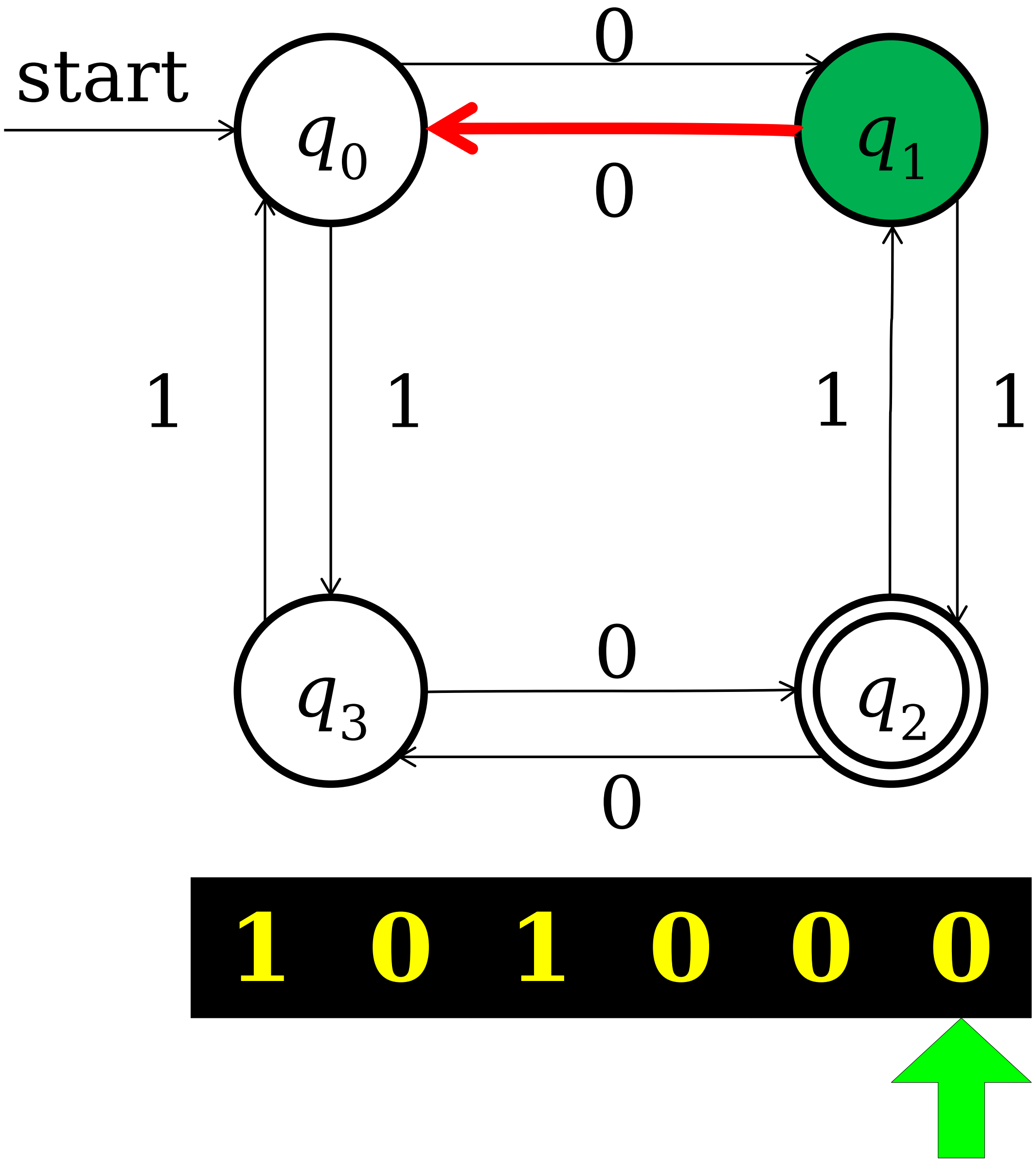
A Simple Finite Automaton



A Simple Finite Automaton

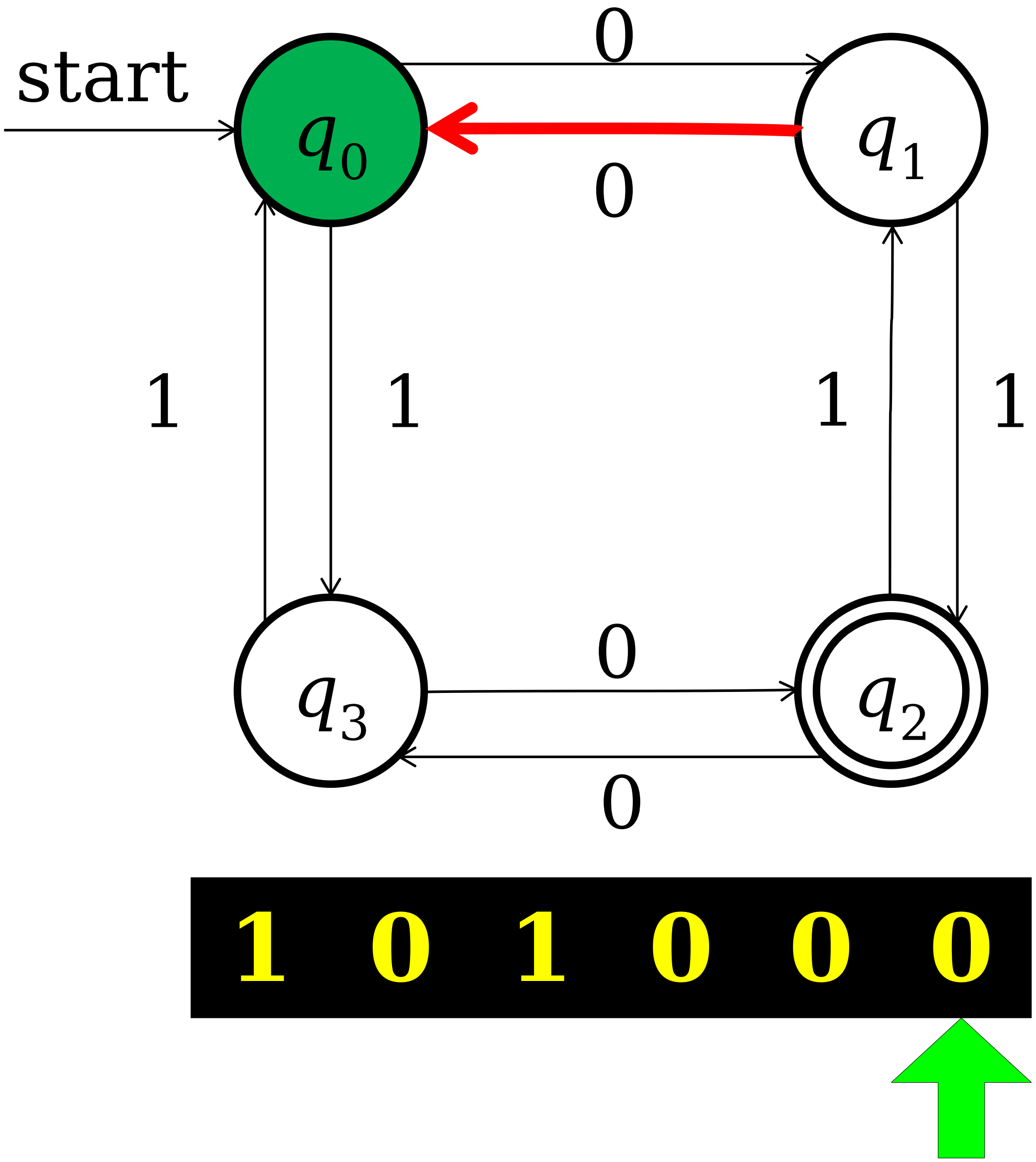


A Simple Finite Automaton

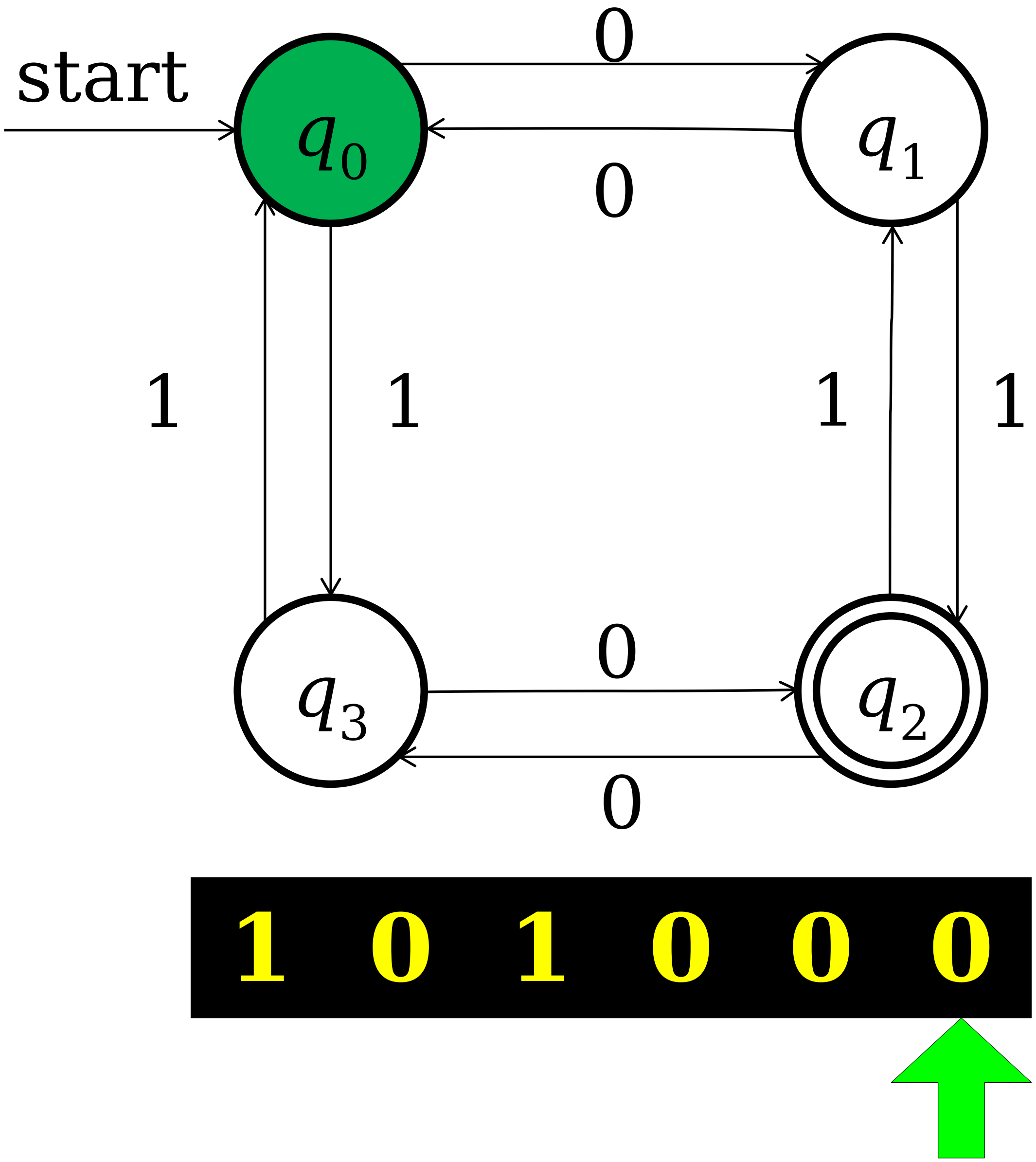


1 0 1 0 0 0

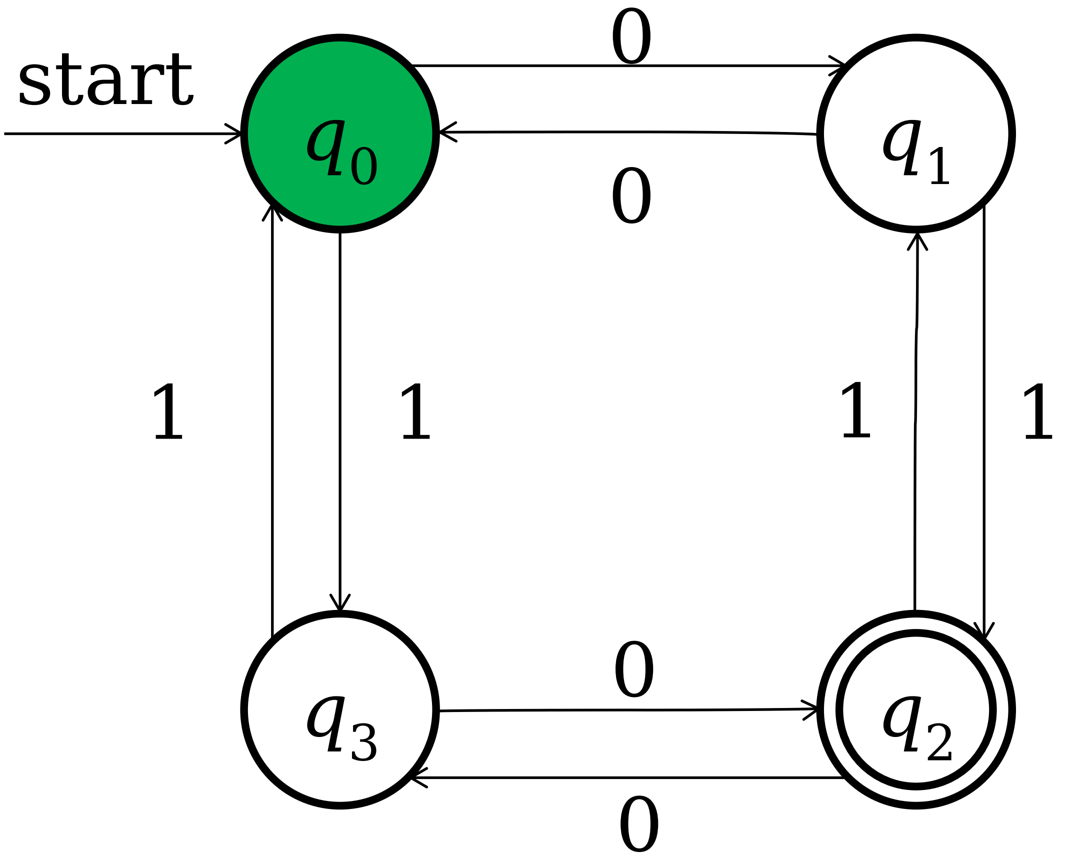
A Simple Finite Automaton



A Simple Finite Automaton

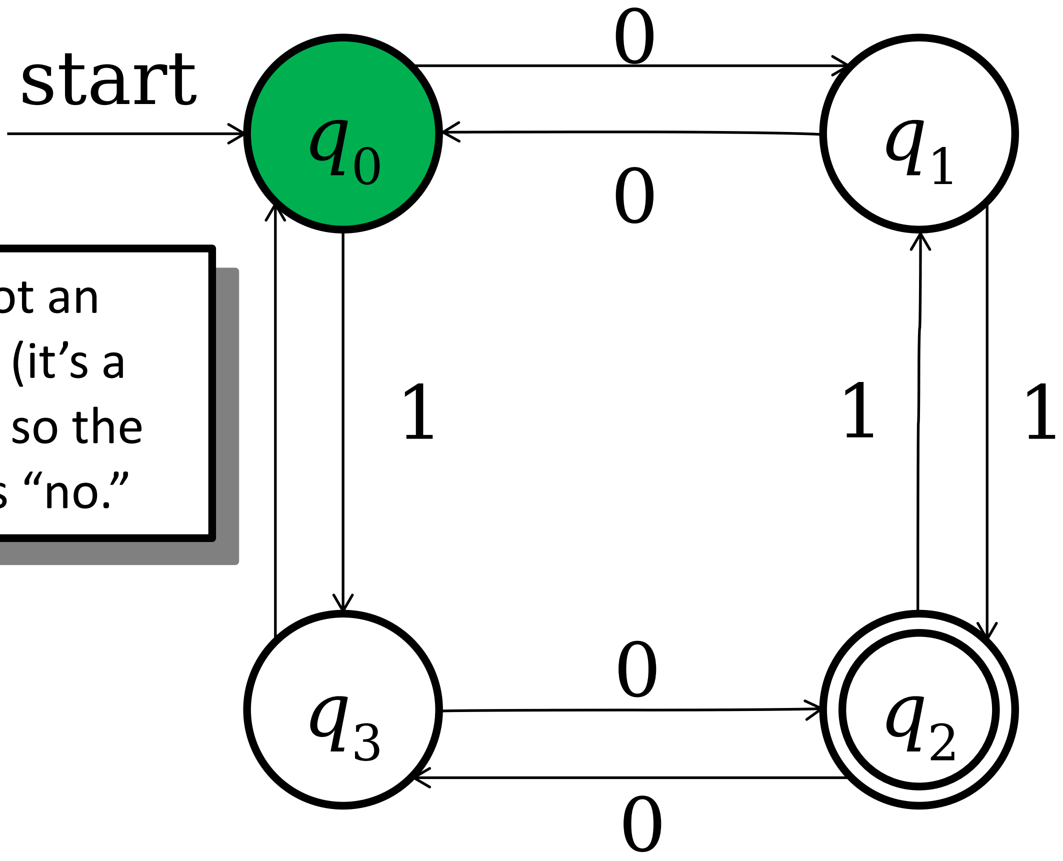


A Simple Finite Automaton



1 0 1 0 0 0

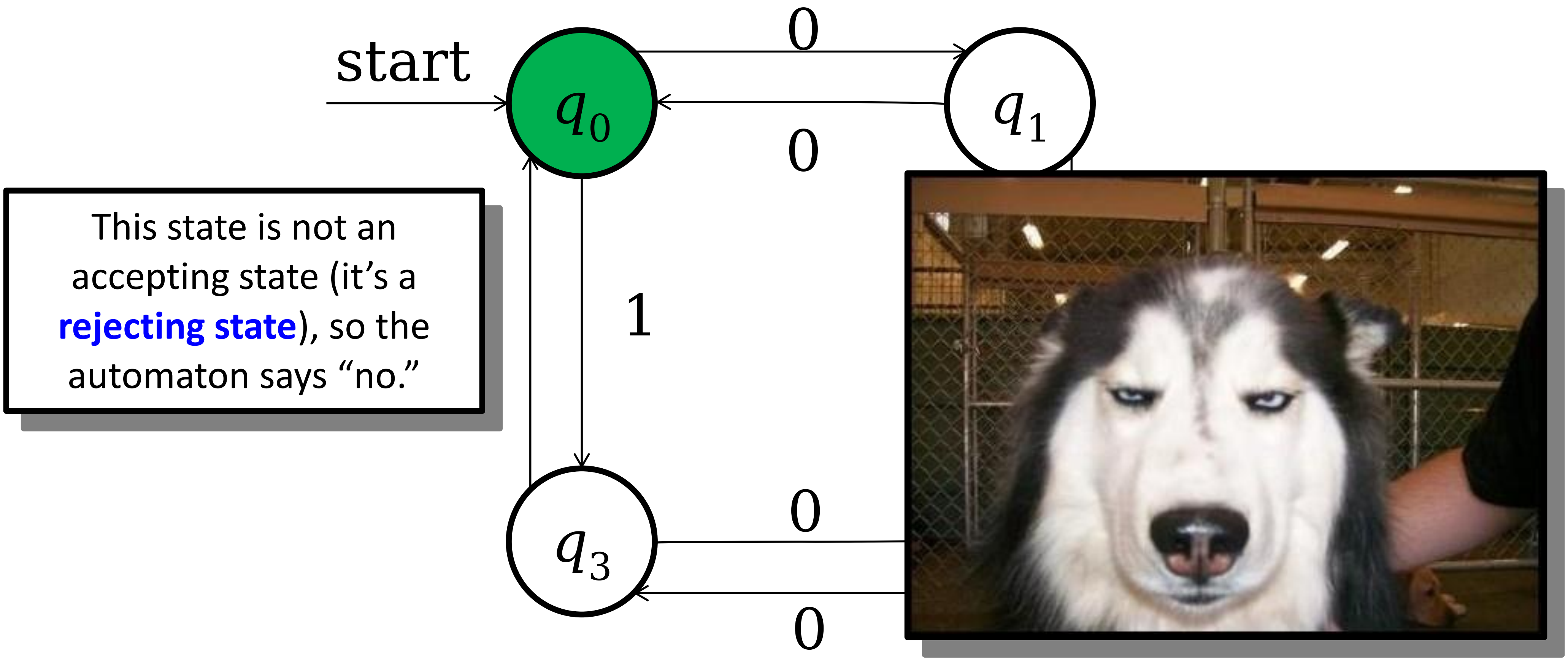
A Simple Finite Automaton



This state is not an accepting state (it's a **rejecting state**), so the automaton says "no."

1 0 1 0 0 0

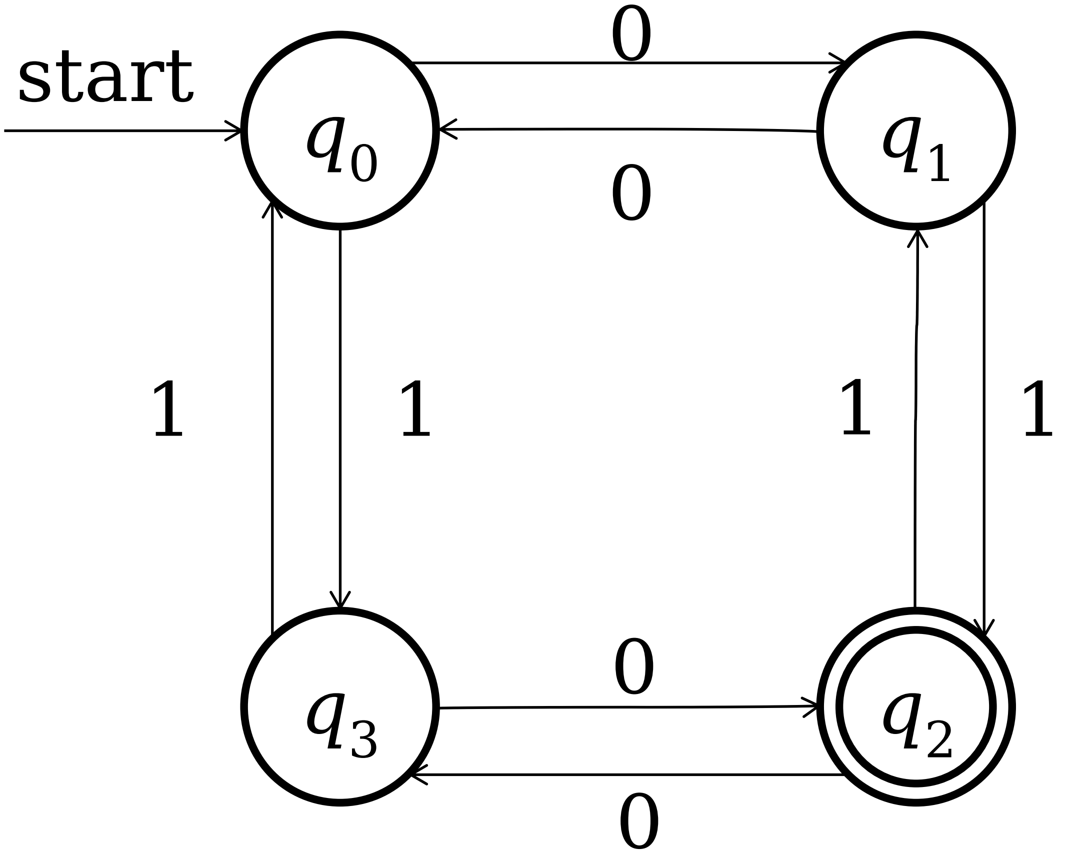
A Simple Finite Automaton



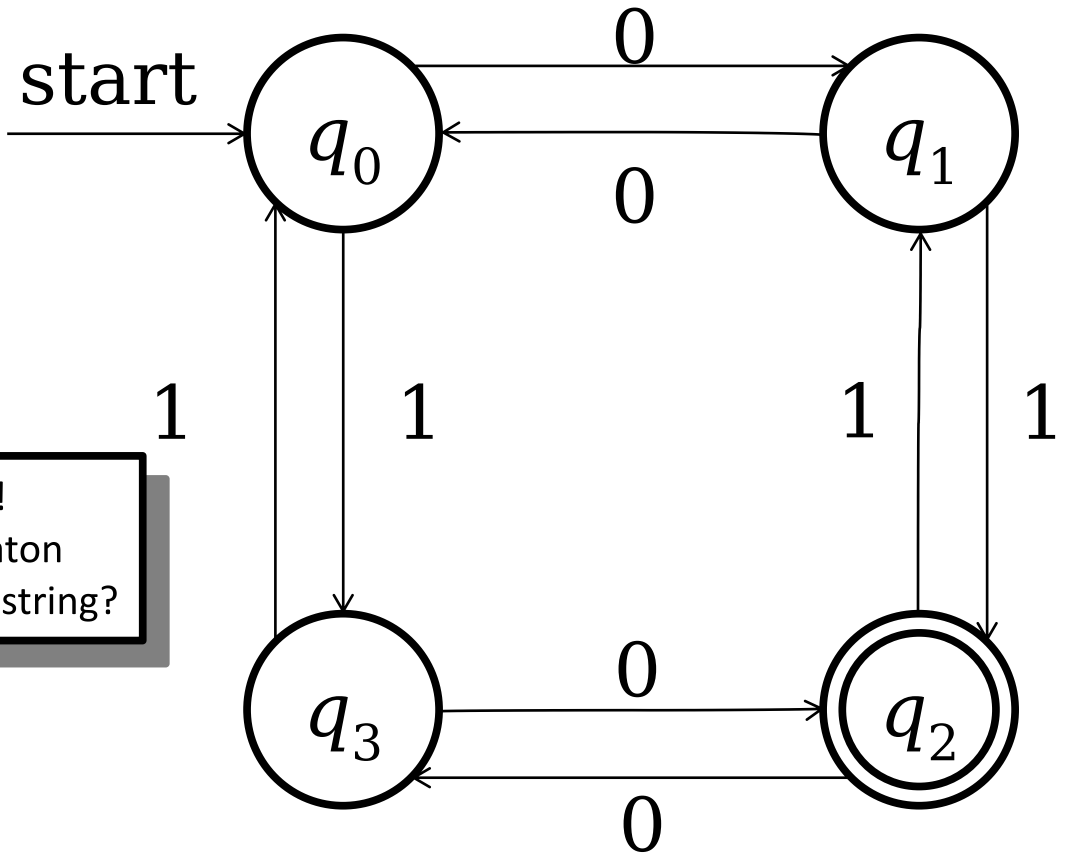
This state is not an accepting state (it's a **rejecting state**), so the automaton says "no."

1 0 1 0 0 0

A Simple Finite Automaton



A Simple Finite Automaton



Try it yourself!
Does this automaton
accept or ***reject*** this string?

1 1 0 1 1 1 0 0

The Story So Far

A ***finite automaton*** is a collection of ***states*** joined by ***transitions***.

Some state is designated as the ***start state***.

Some number of states are designated as ***accepting states***.

The automaton processes a string by beginning in the start state and following the indicated transitions.

If the automaton ends in an accepting state, it ***accepts*** the input.

Otherwise, the automaton ***rejects*** the input.

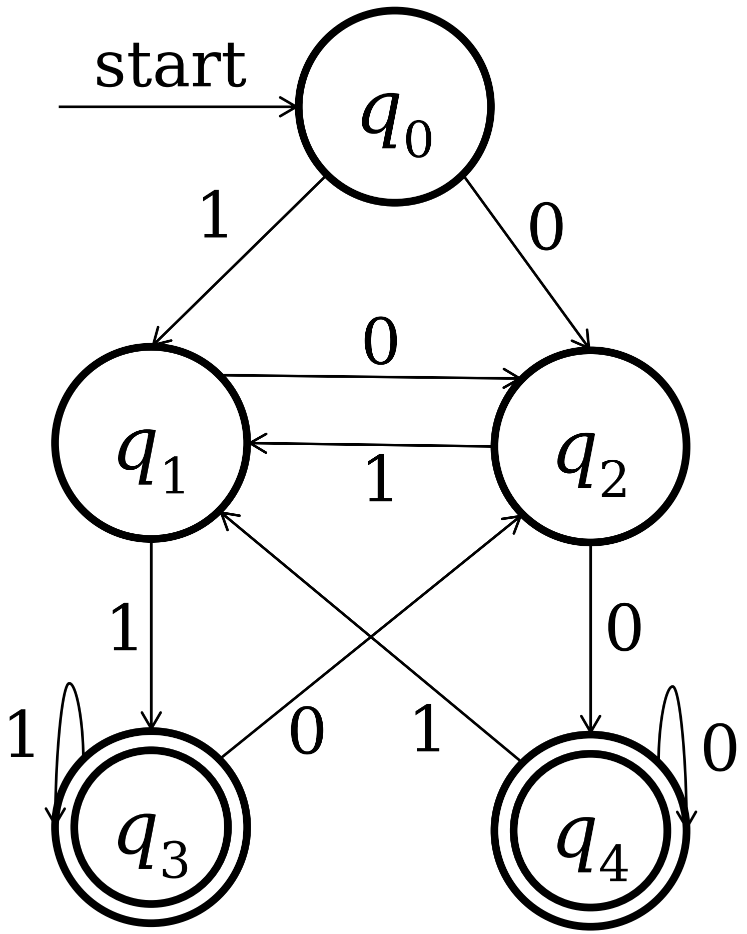
Time-Out For Announcements!

Midterm

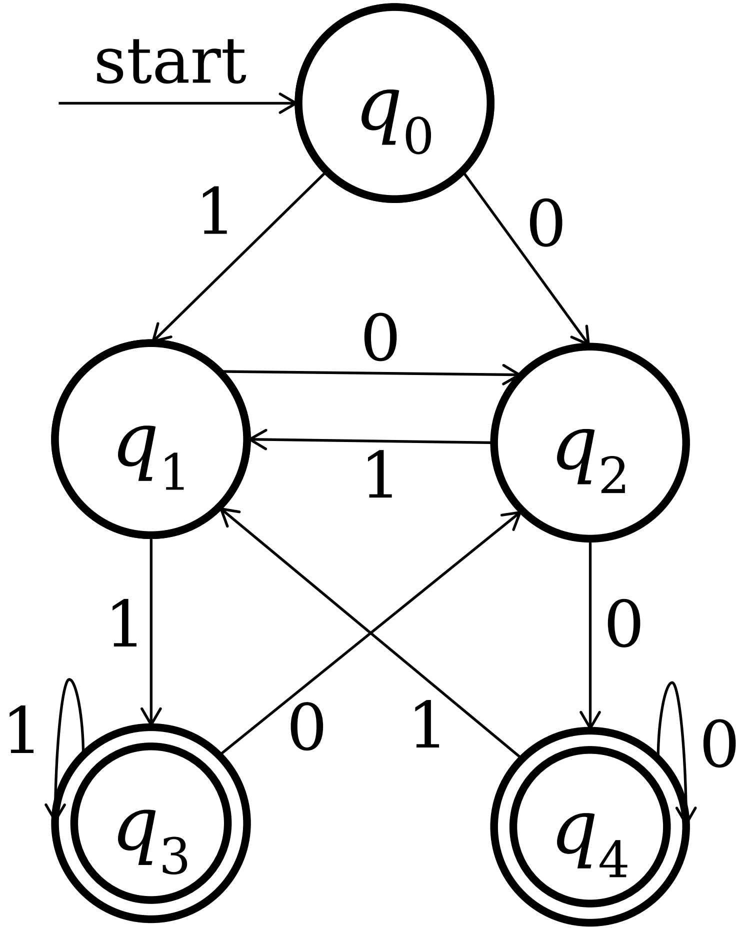
- The midterm will become available at 9:30 AM PDT tomorrow (Thursday). All the details you need to know are on a pinned Campuswire post.
- There are no office hours tomorrow. They’ve all been moved to not happen during the midterm.
- You’ve got this!

Back to CS103!

Just Passing Through

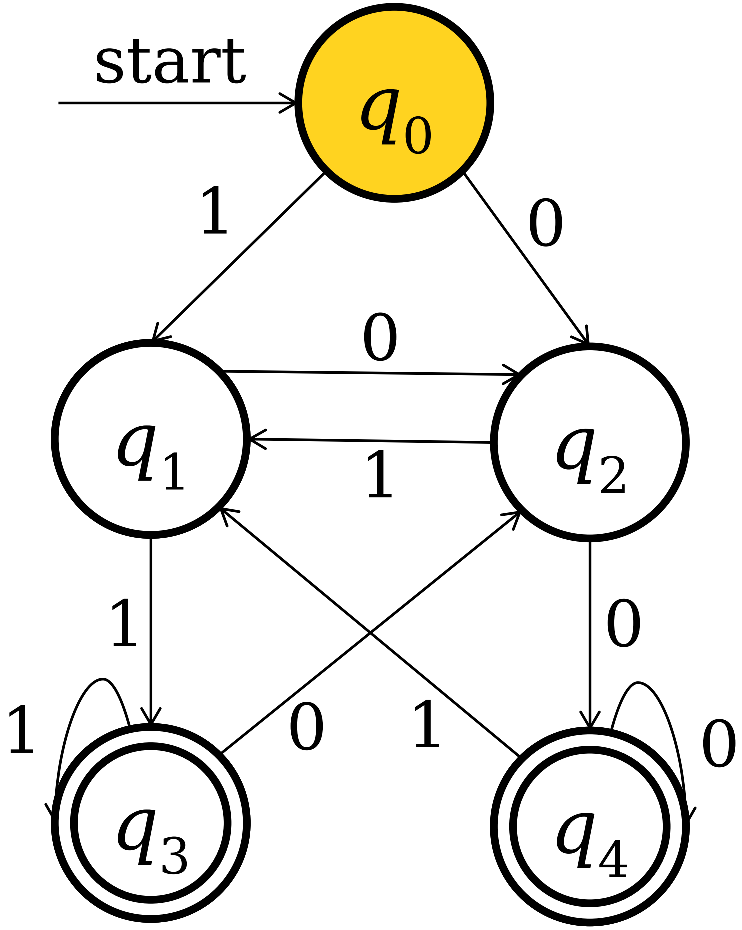


Just Passing Through



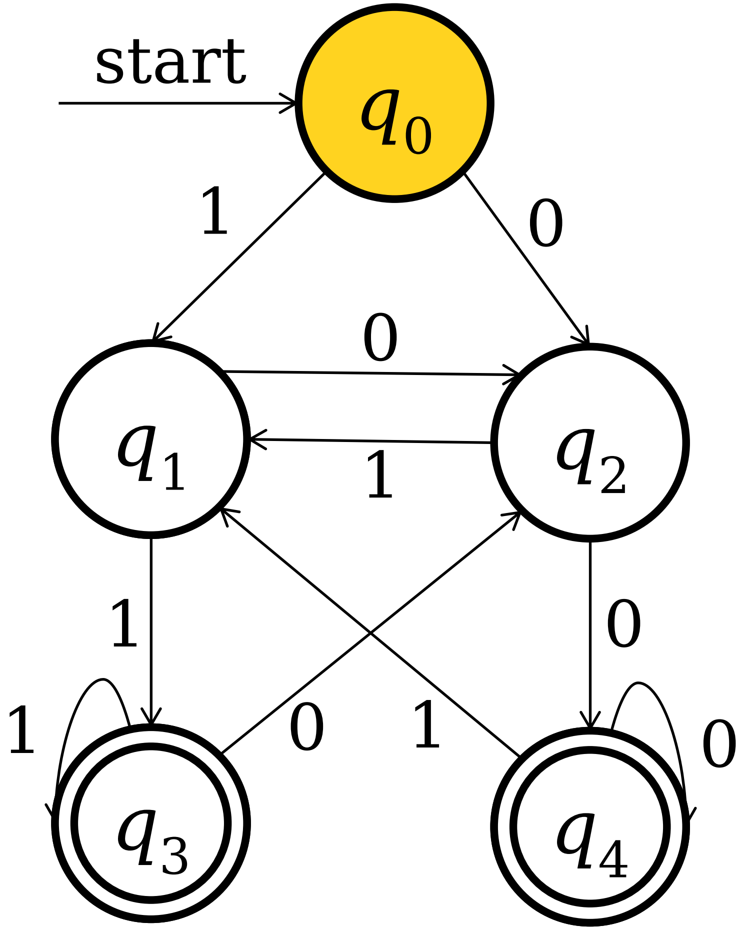
1 1 0 1

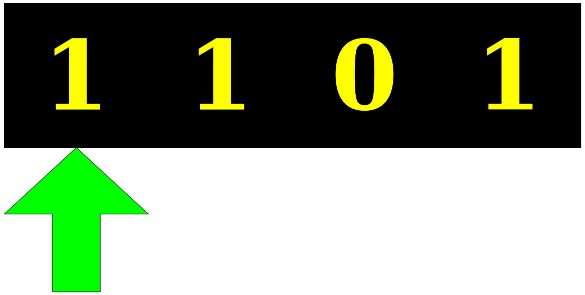
Just Passing Through



1 1 0 1

Just Passing Through





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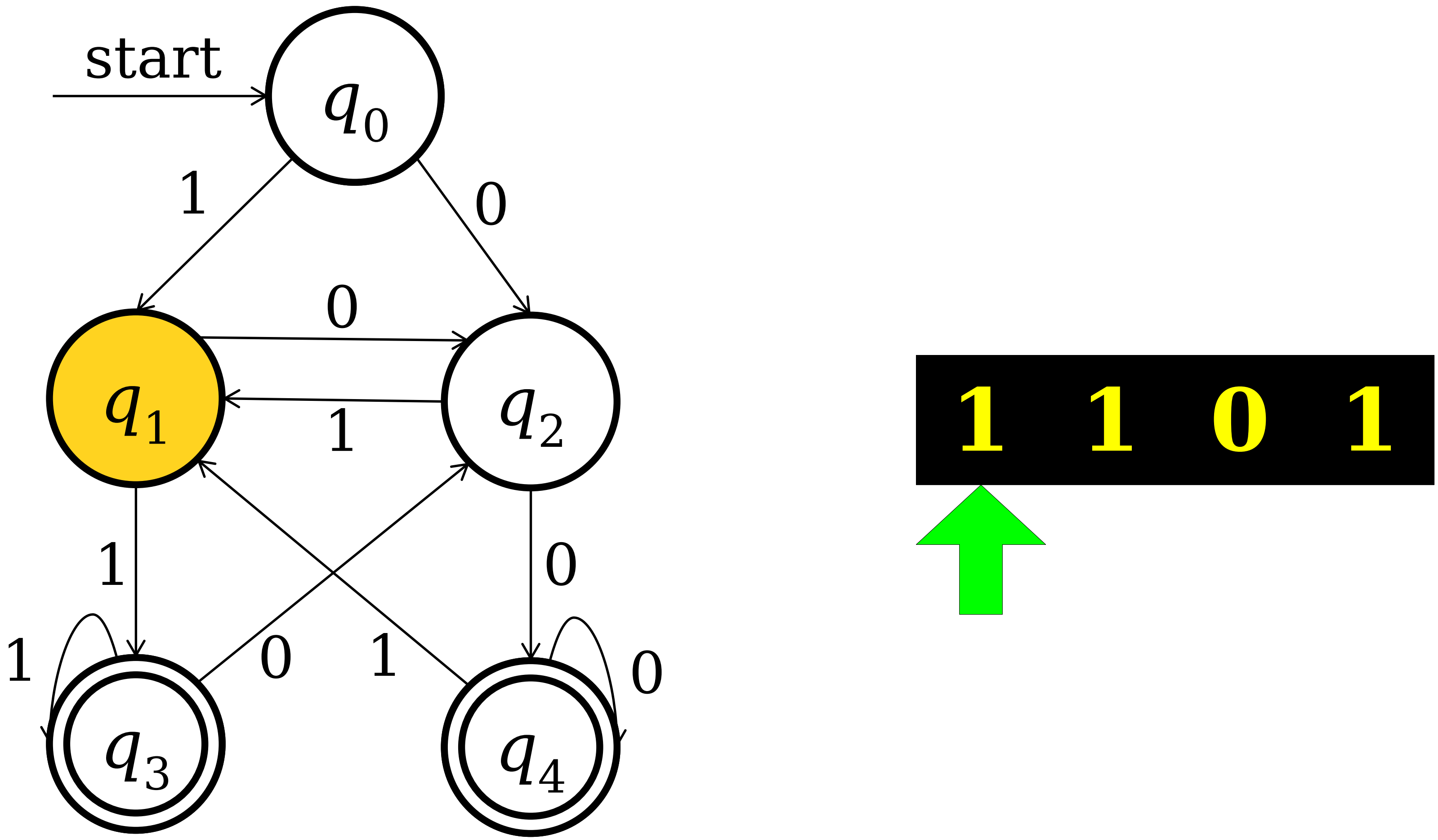

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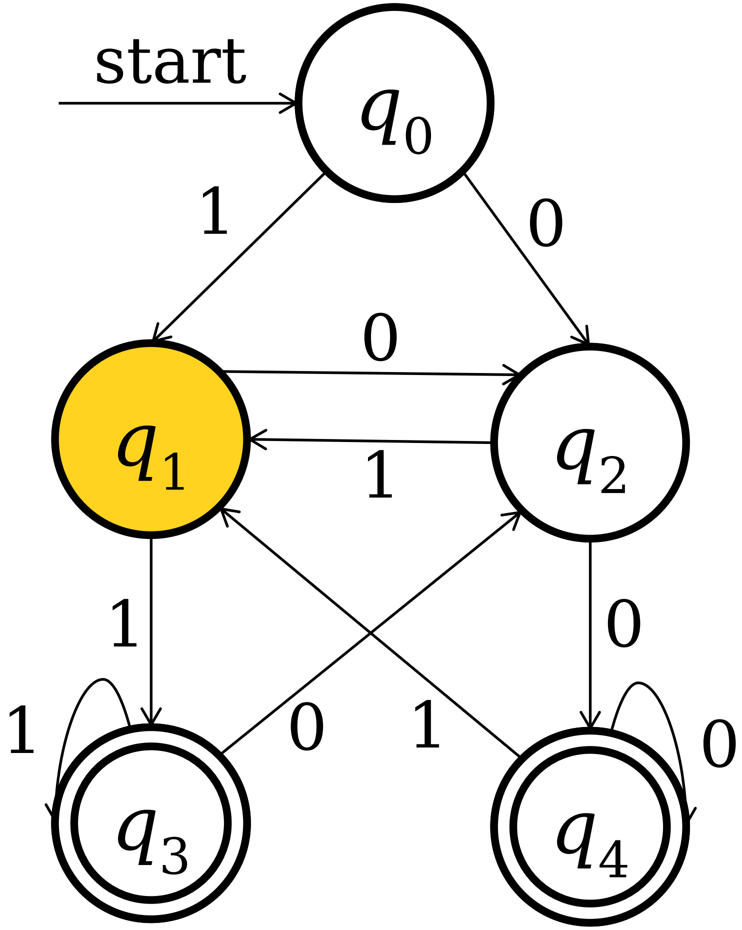

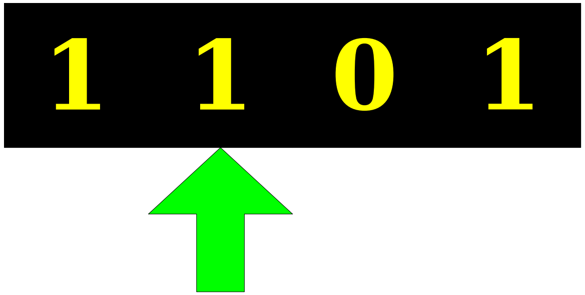

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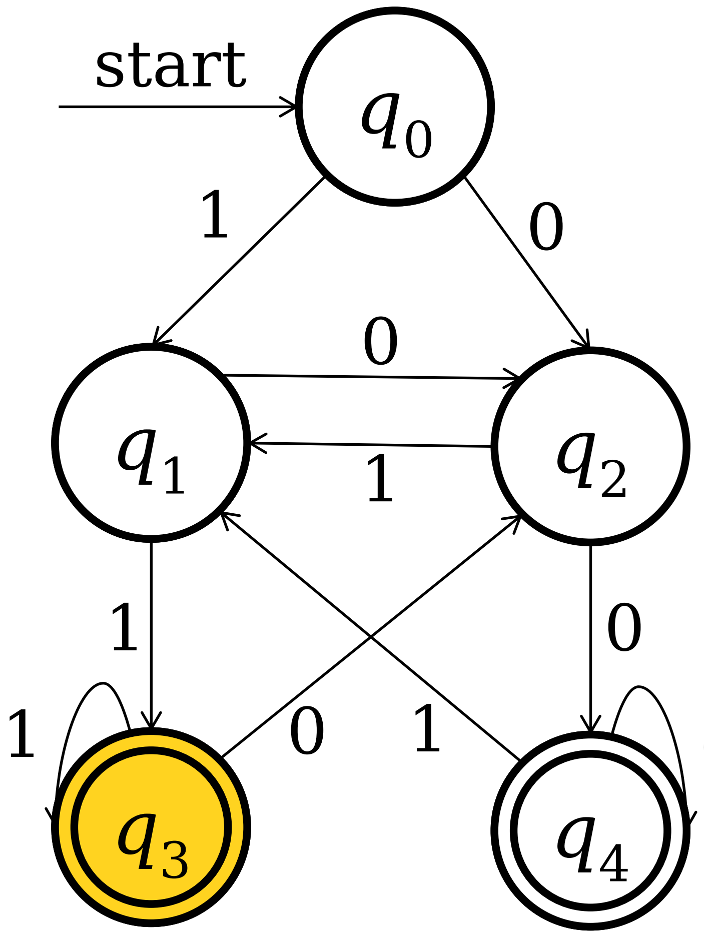

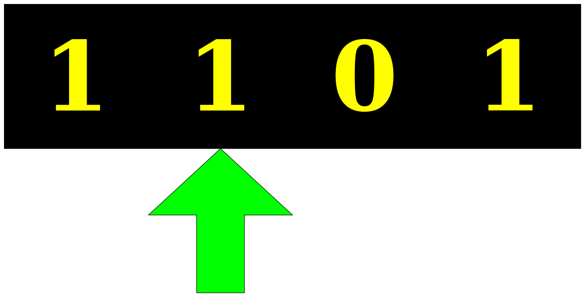

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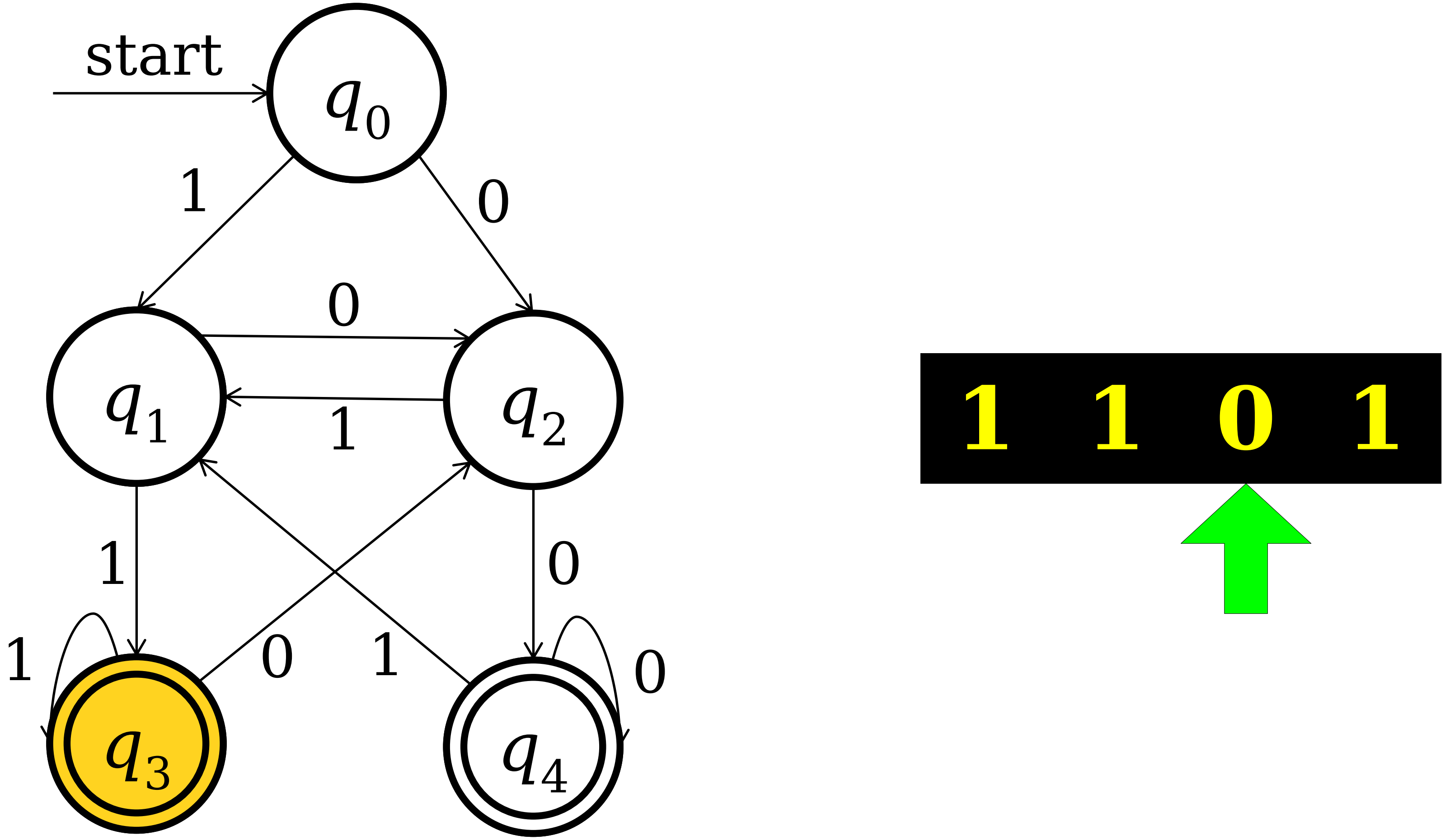

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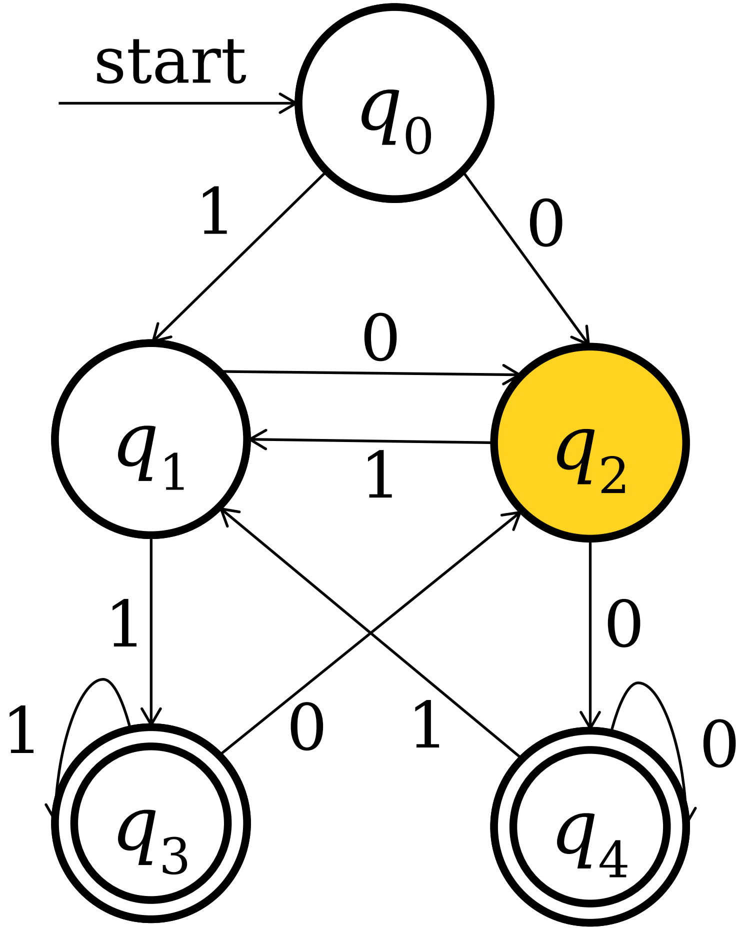

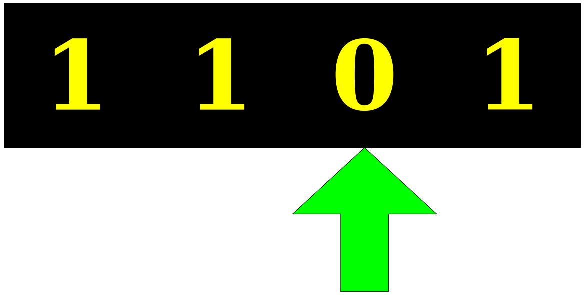

1 1 0 1

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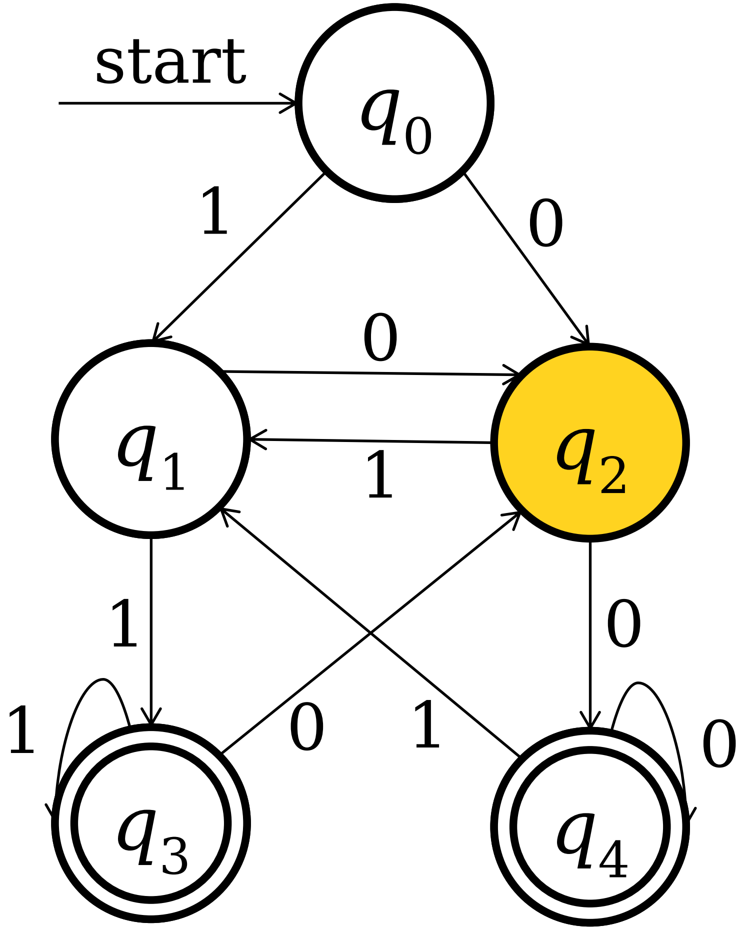
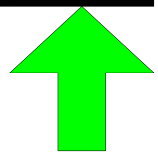


1 1 0 1



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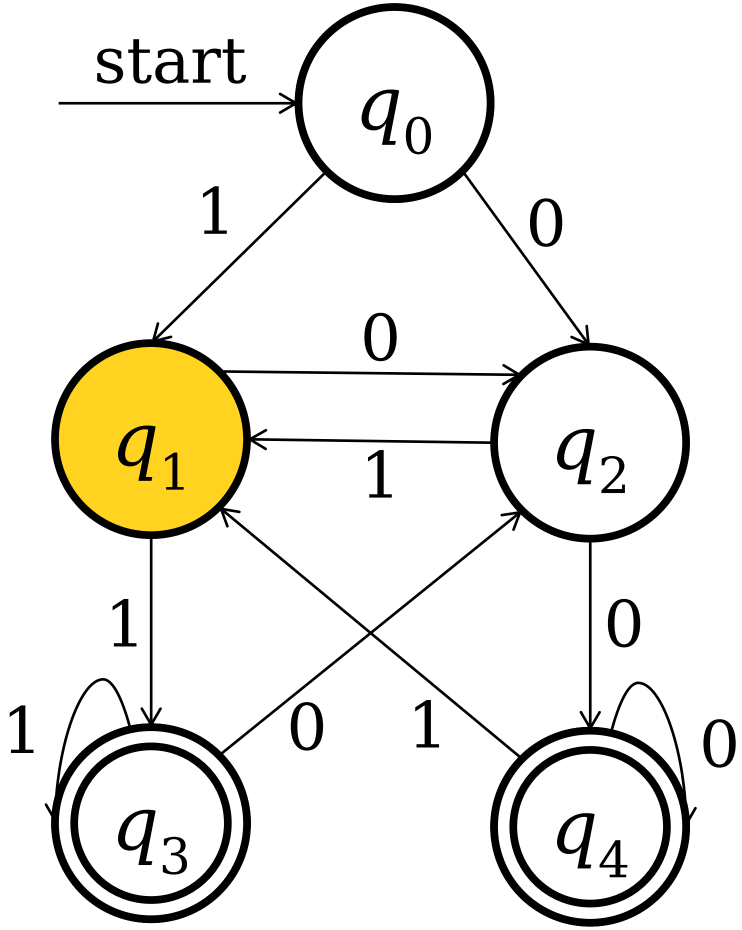

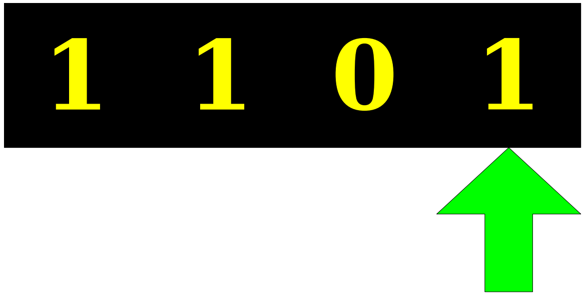

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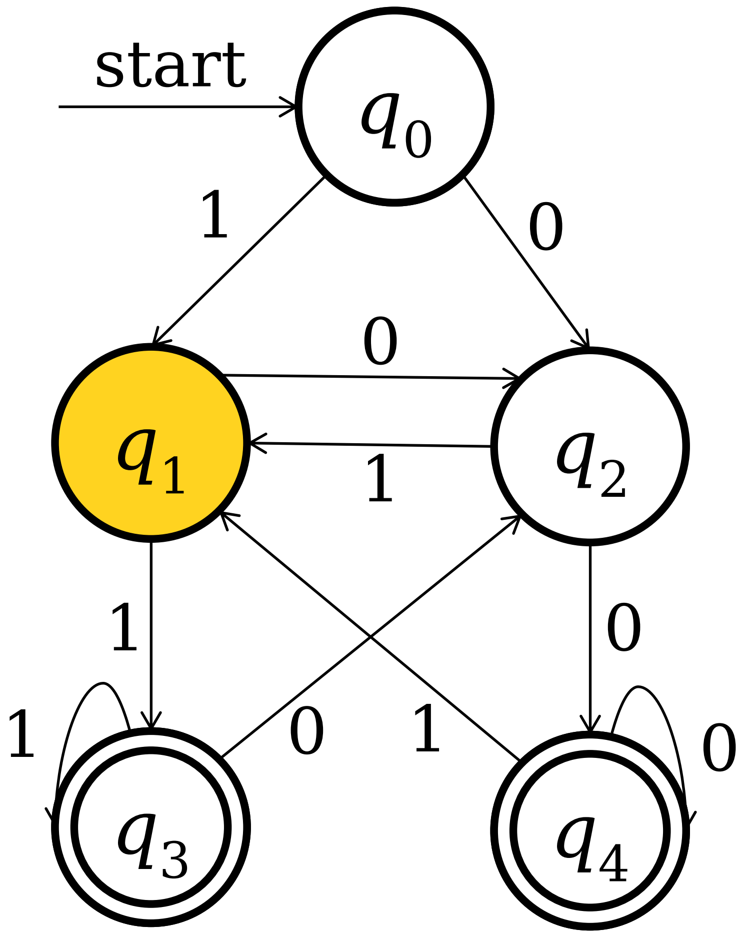

1 1 0 1

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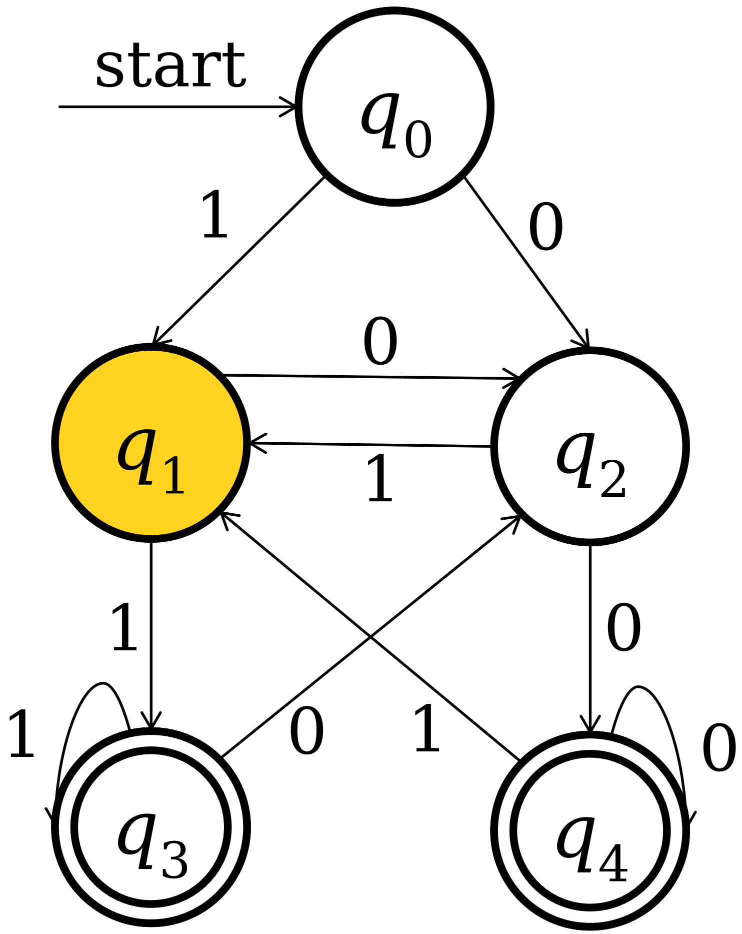

1 1 0 1

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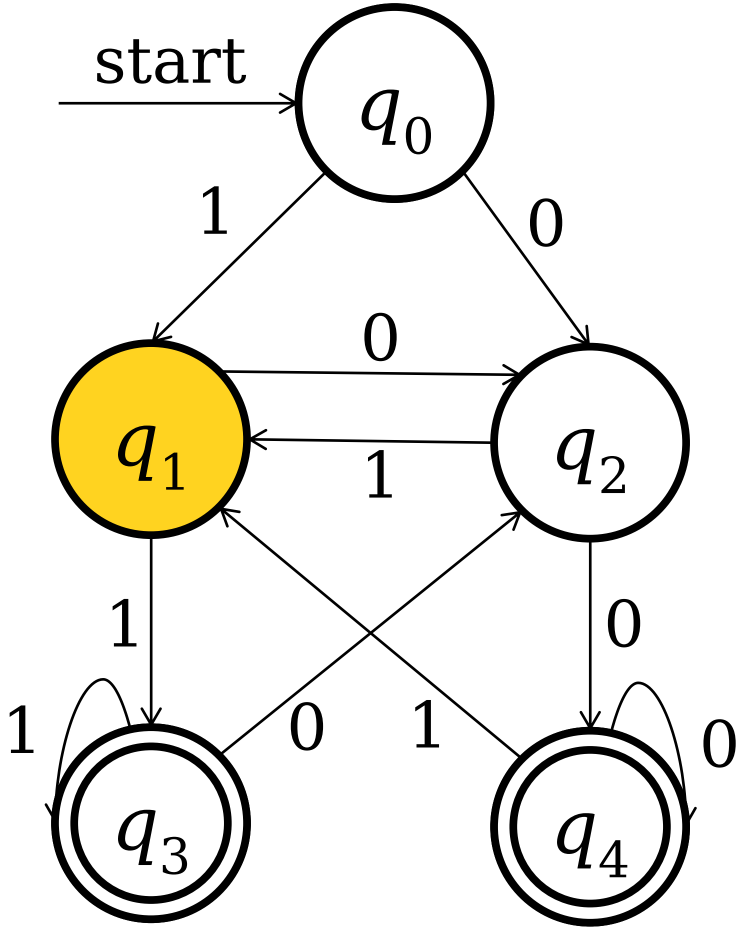
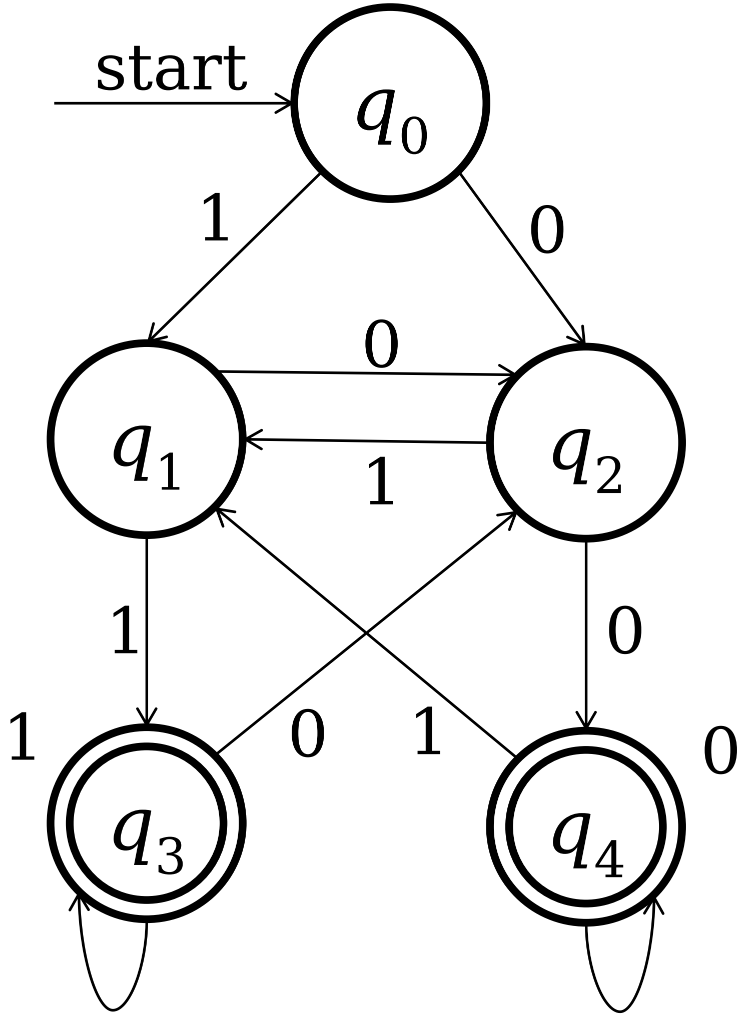


1 1 0 1

A finite automaton does ***not*** accept as soon as it enters an accepting state.

A finite automaton accepts if it ***ends*** in an accepting state.

What Does This Accept?



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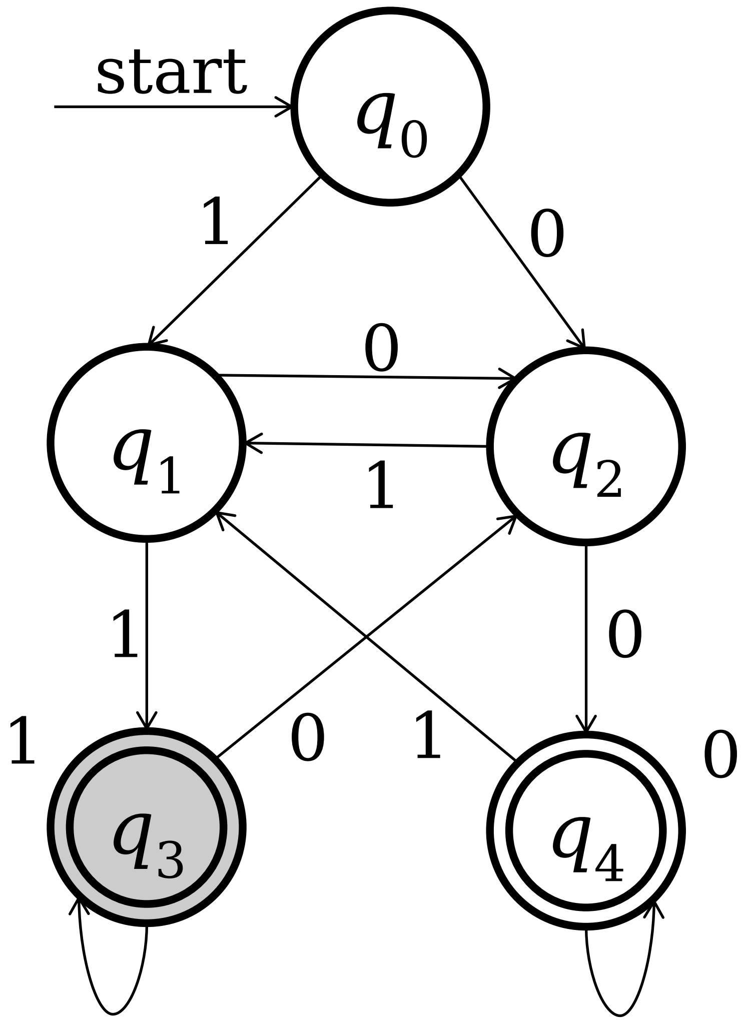

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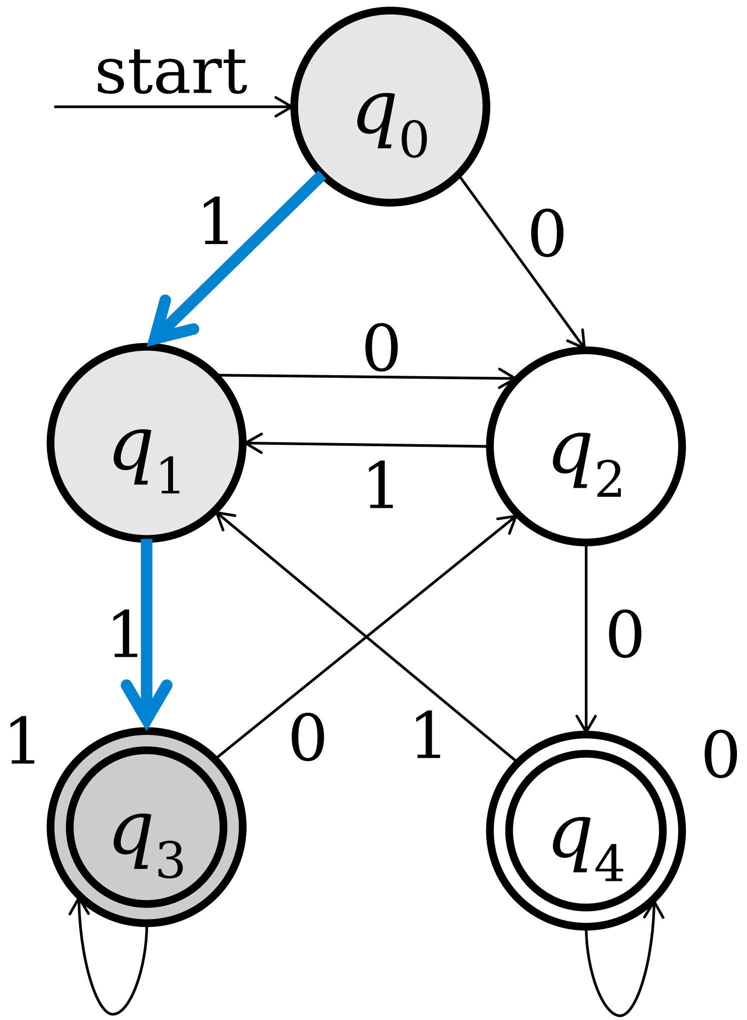

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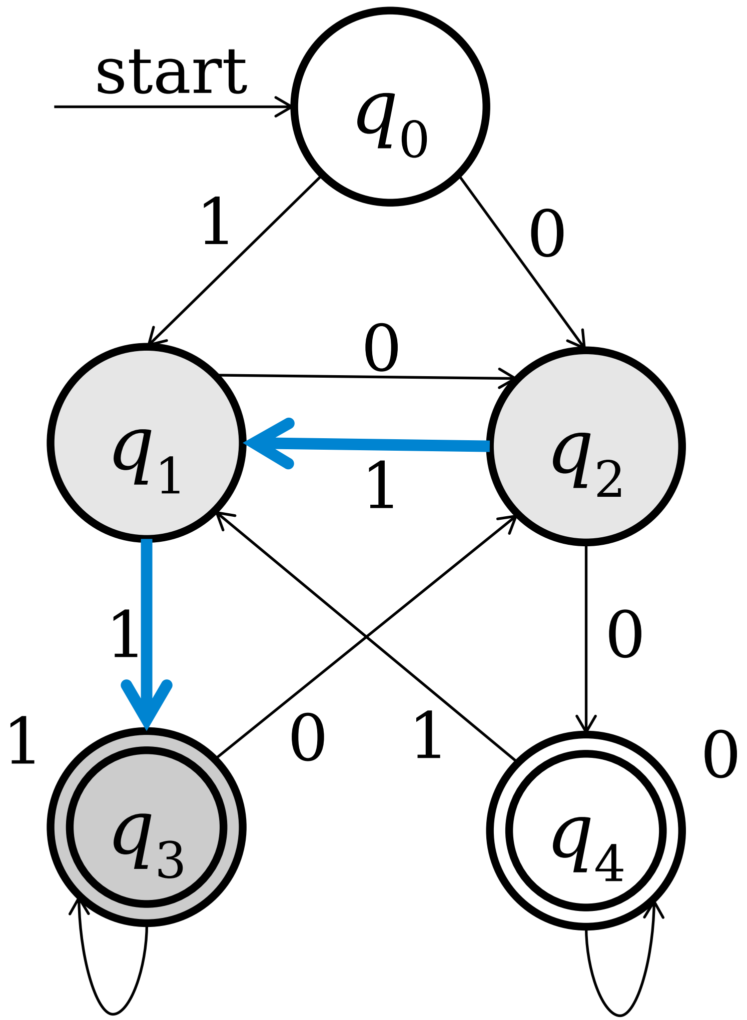

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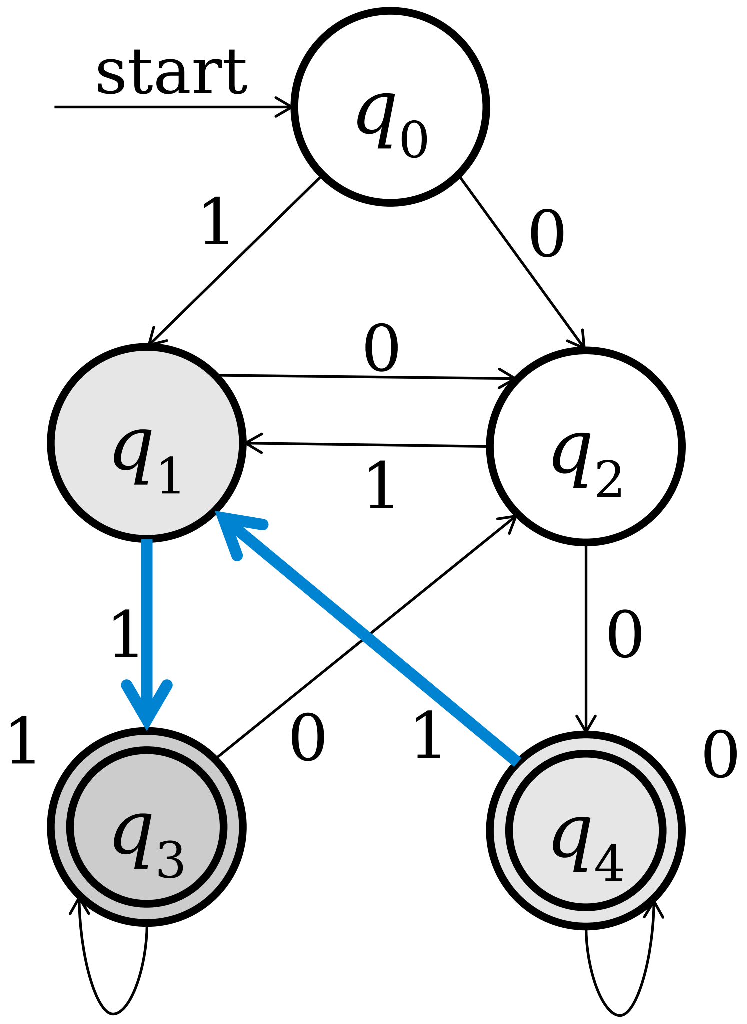

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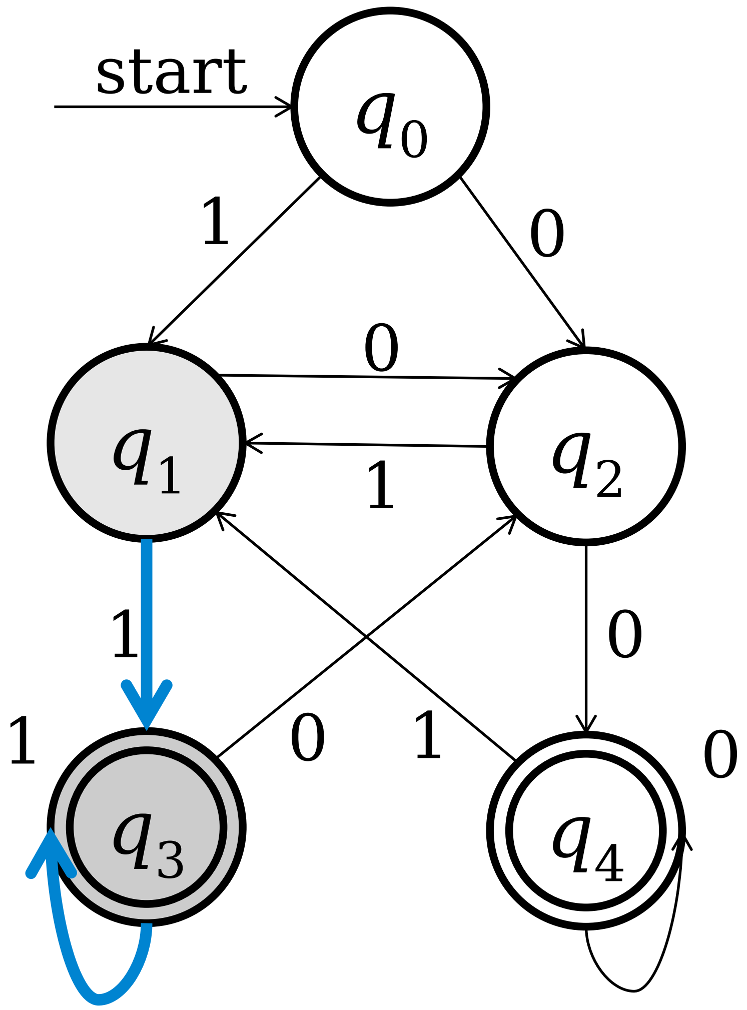

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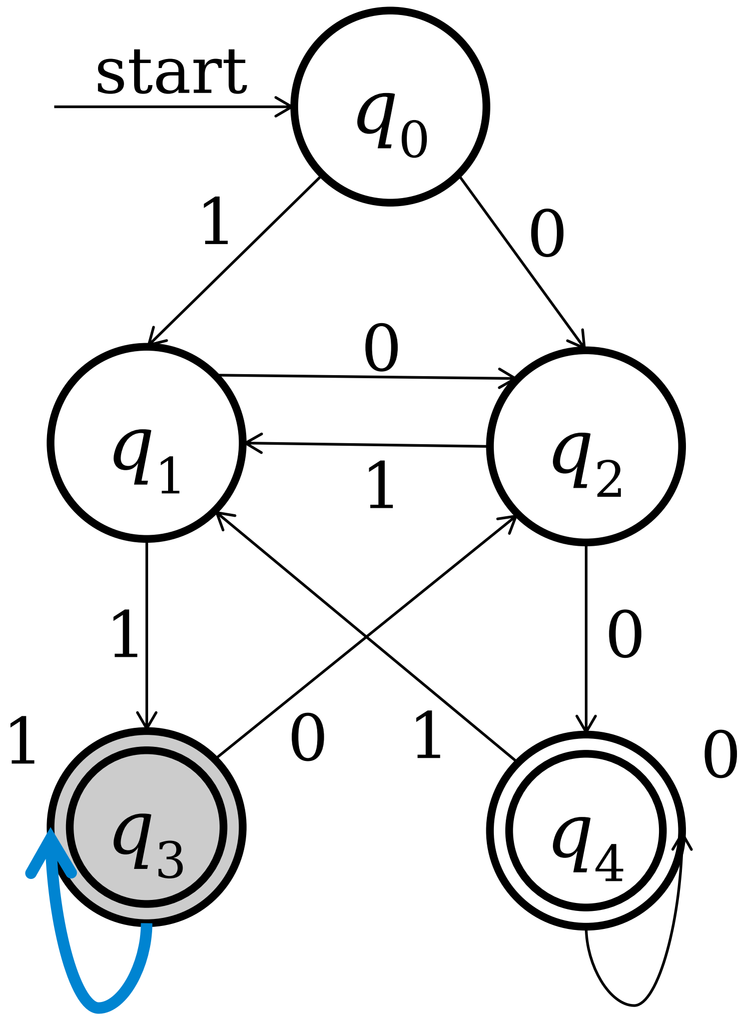

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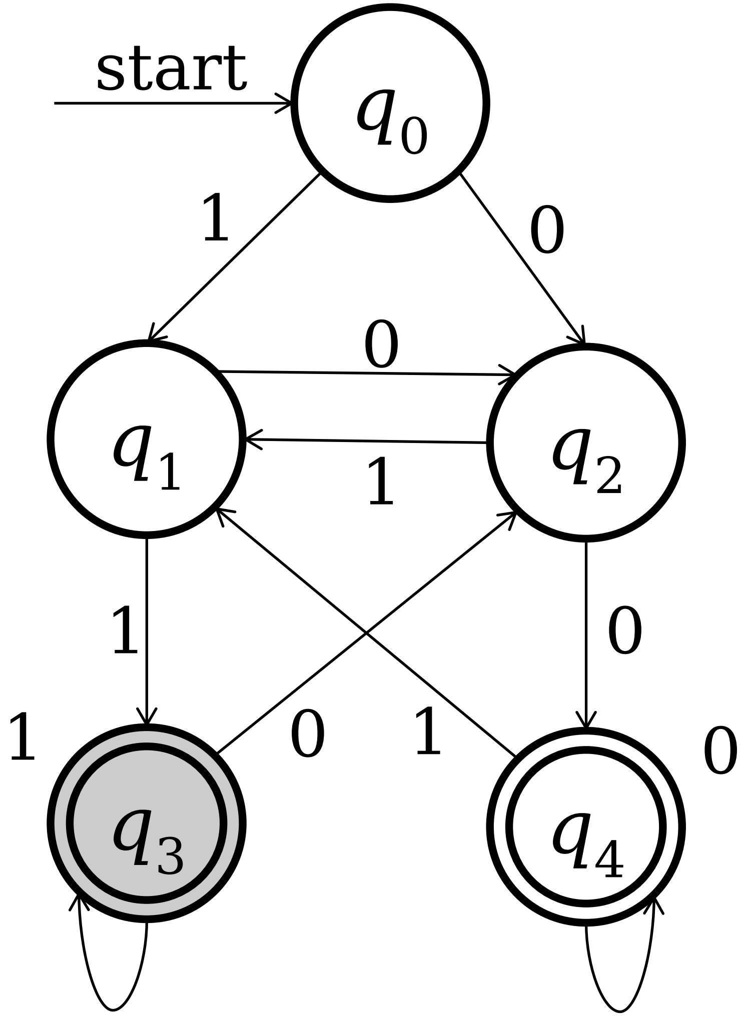
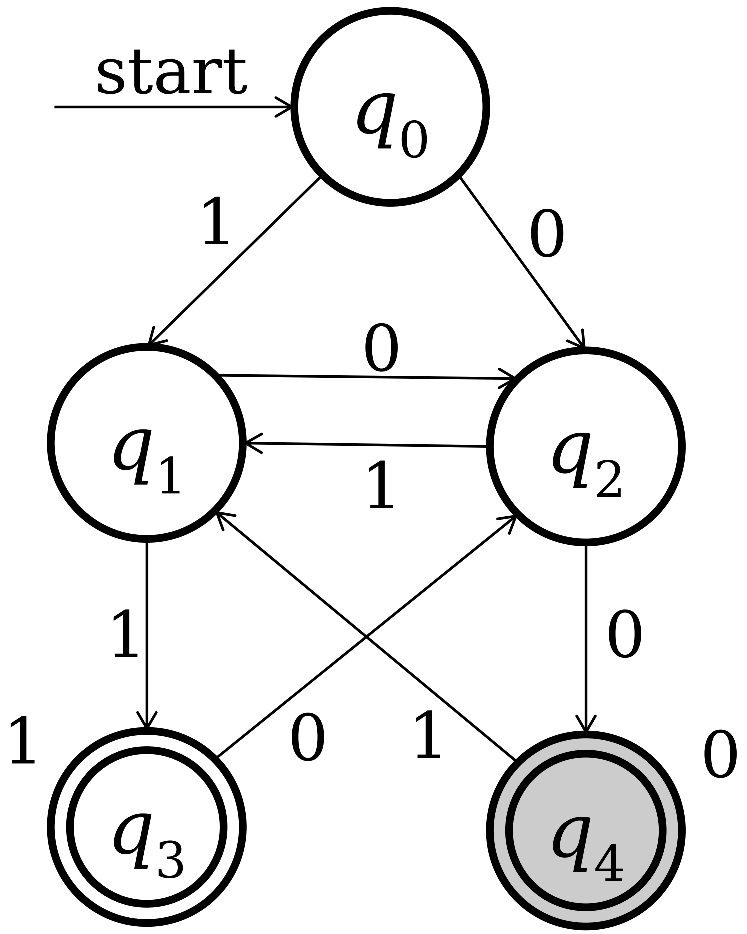


No matter where we start in the automaton, after seeing two 1's, we end up in accepting state q_3.

What Does This Accept?



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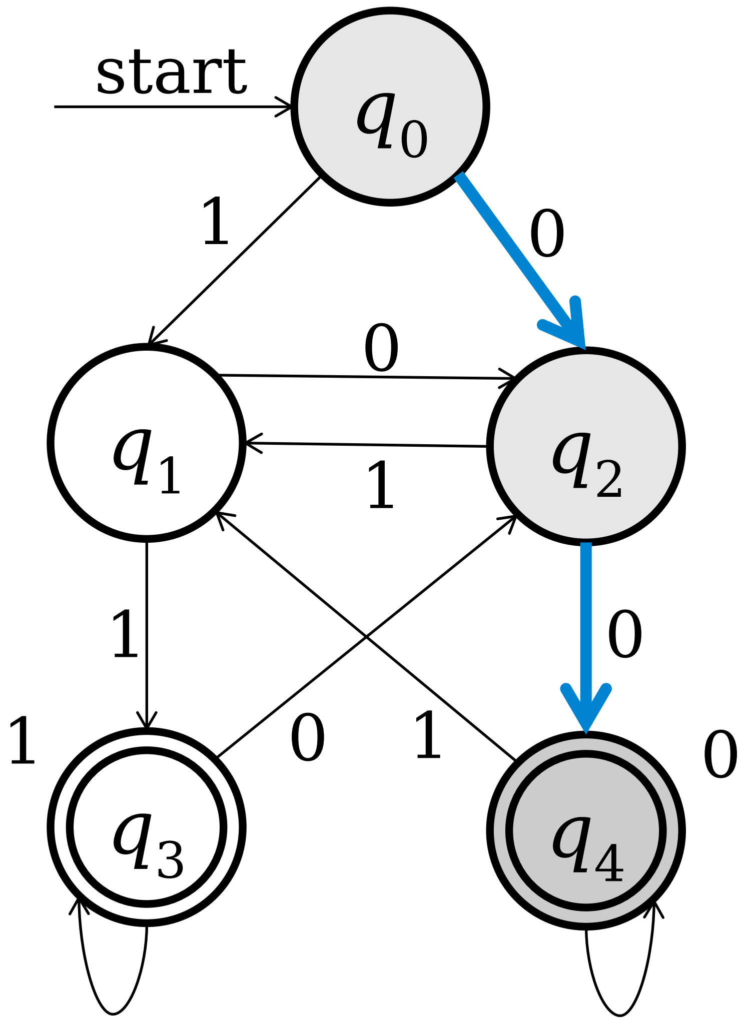

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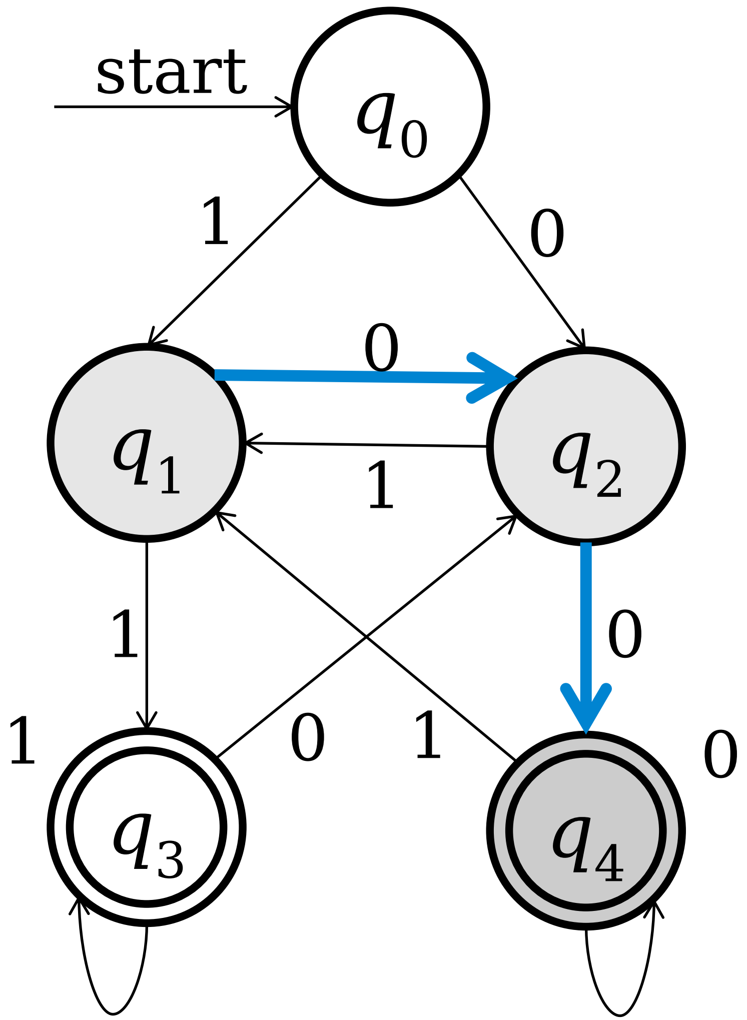

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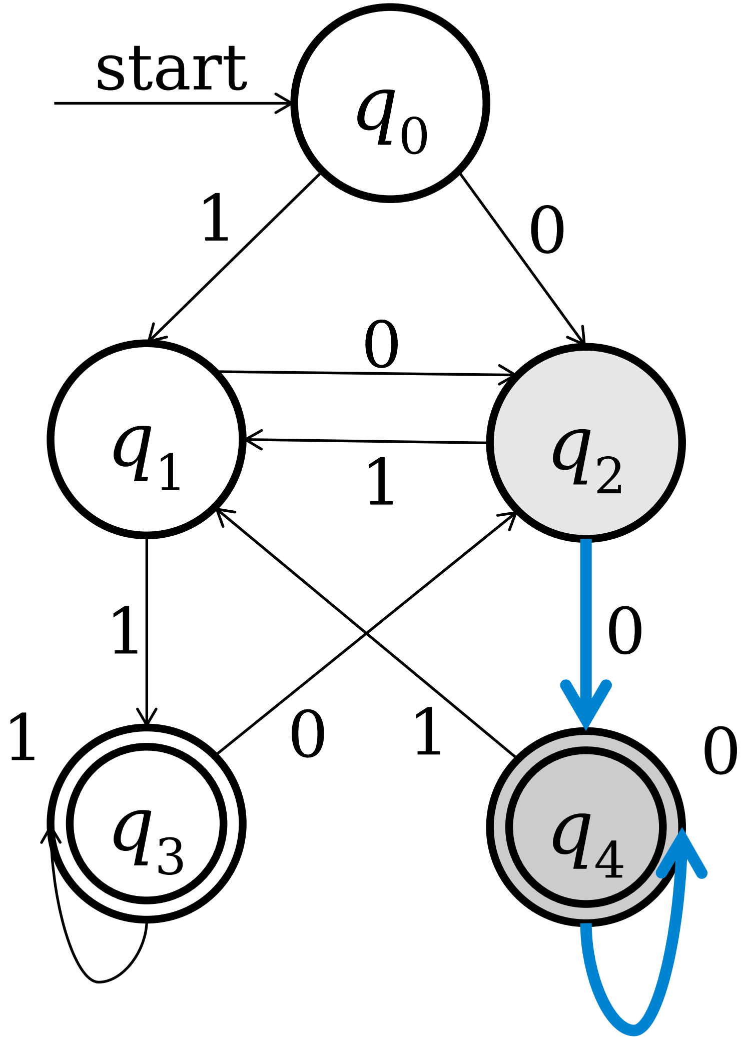

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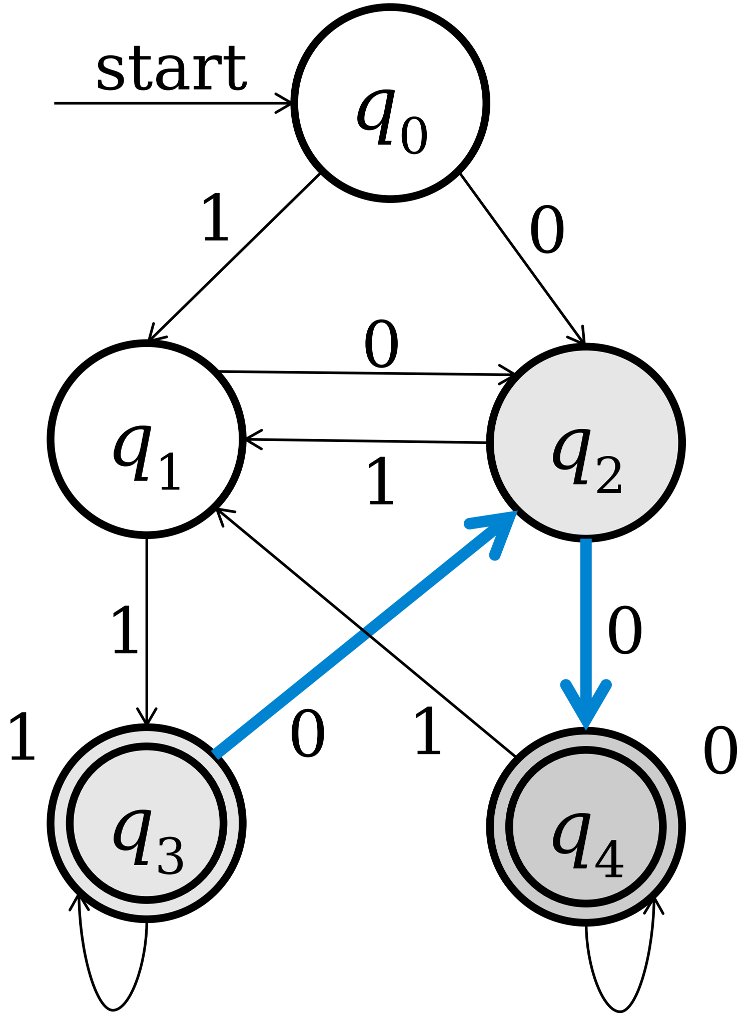

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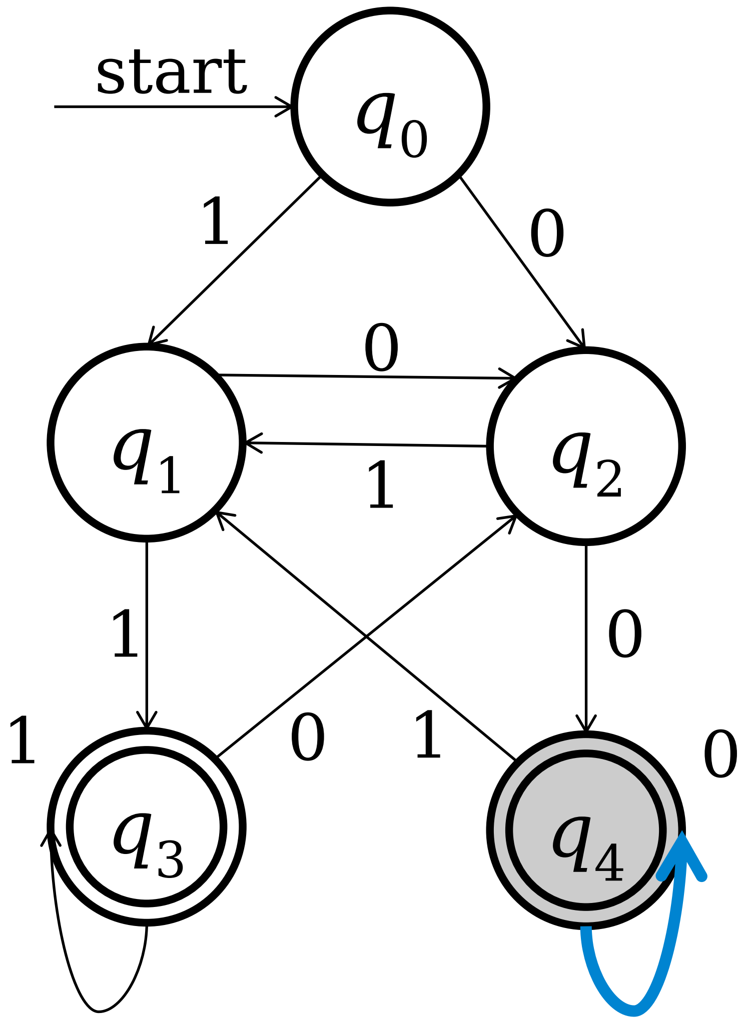
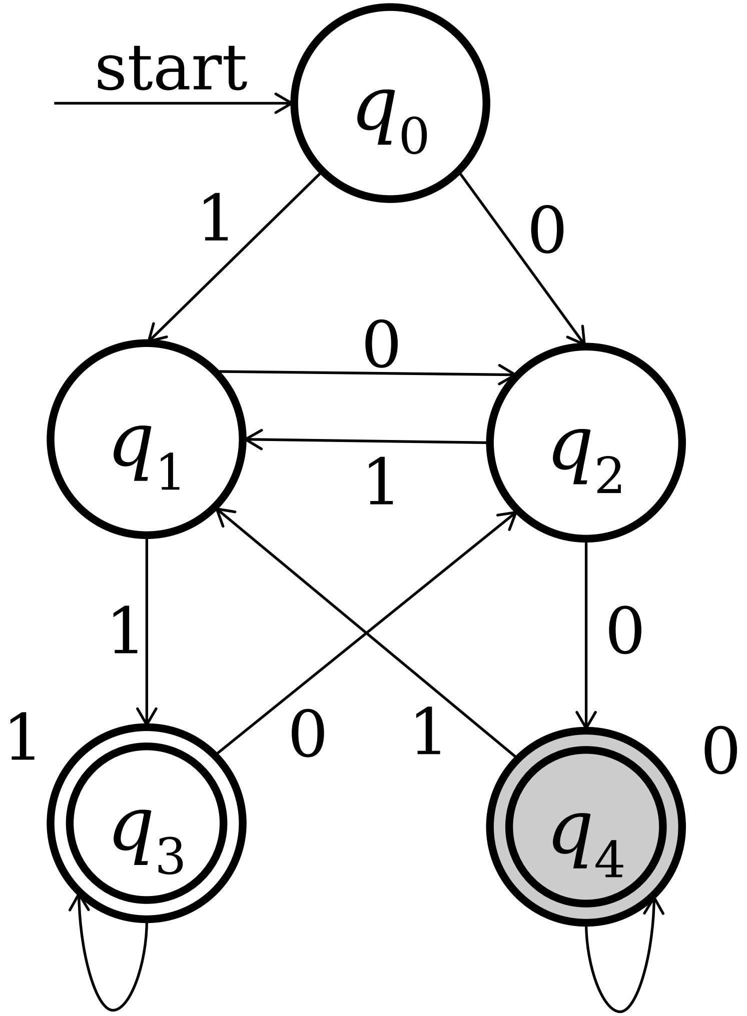
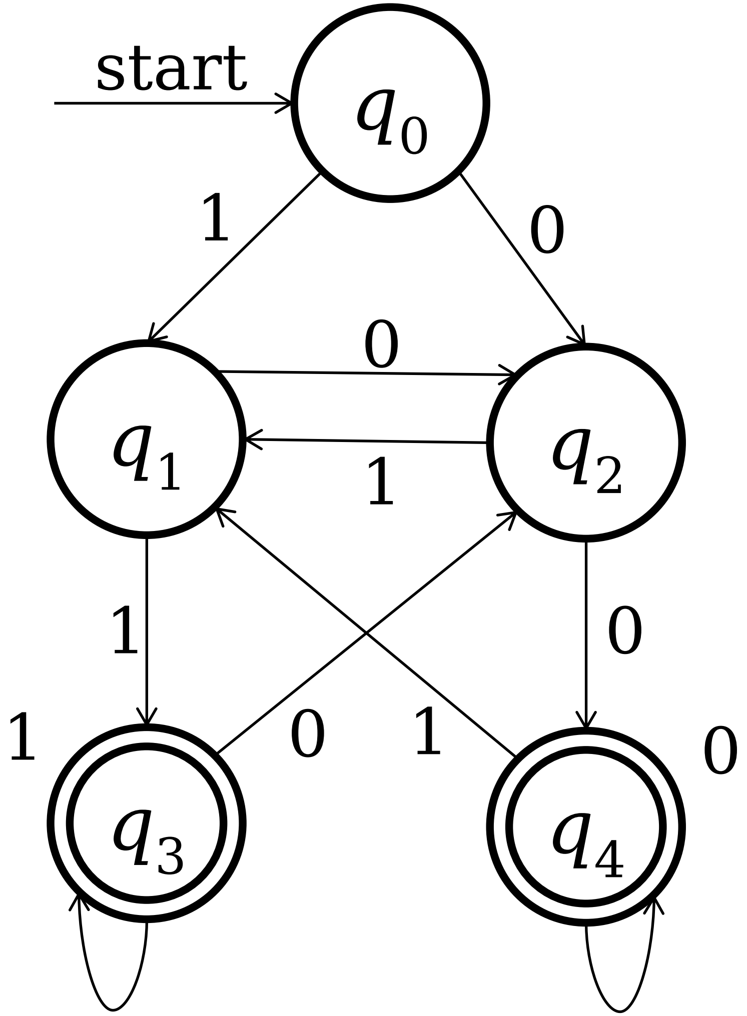


What Does This Accept?



No matter where we start in the automaton, after seeing two 0's, we end up in accepting state q_4.

What Does This Accept?



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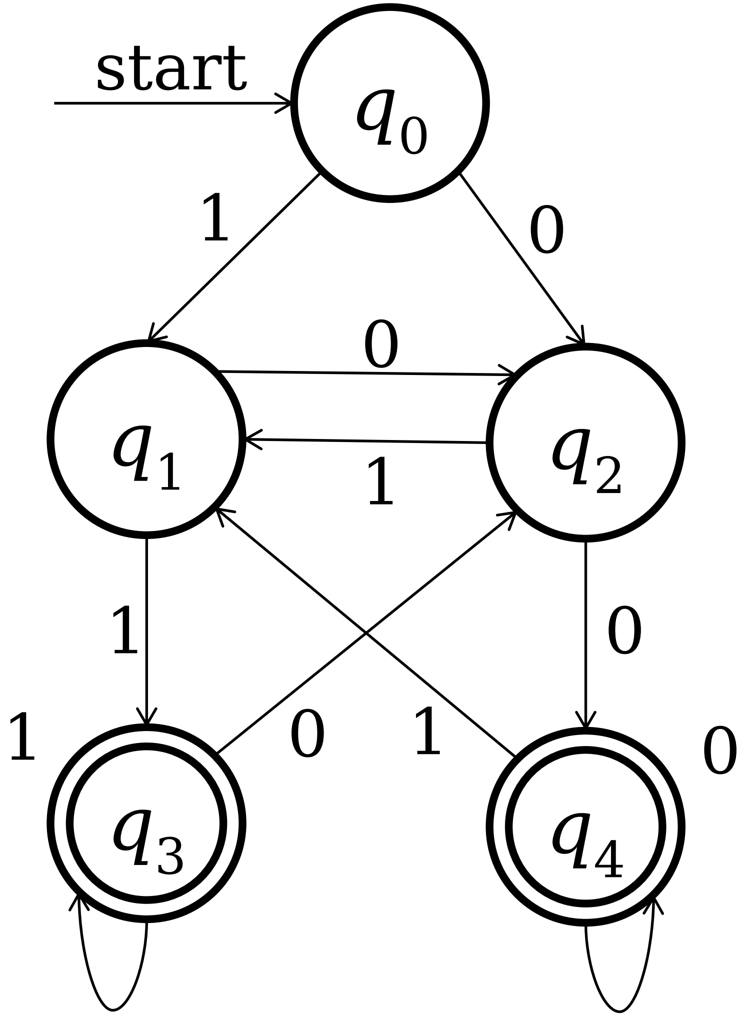


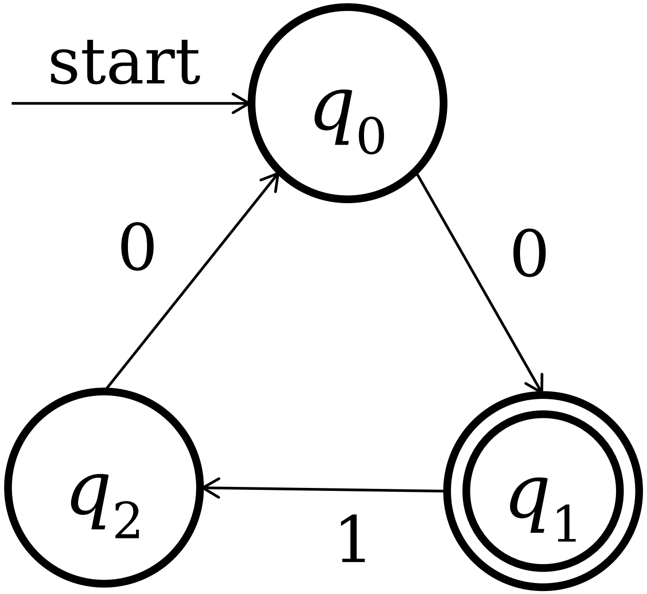
This automaton accepts a string in {**0**, **1**}* iff the string ends in **00** or **11**.

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

If D is an automaton that processes characters from the alphabet Σ, then $\mathscr{L}(\boldsymbol{D})$ is formally defined as

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

A Small Problem



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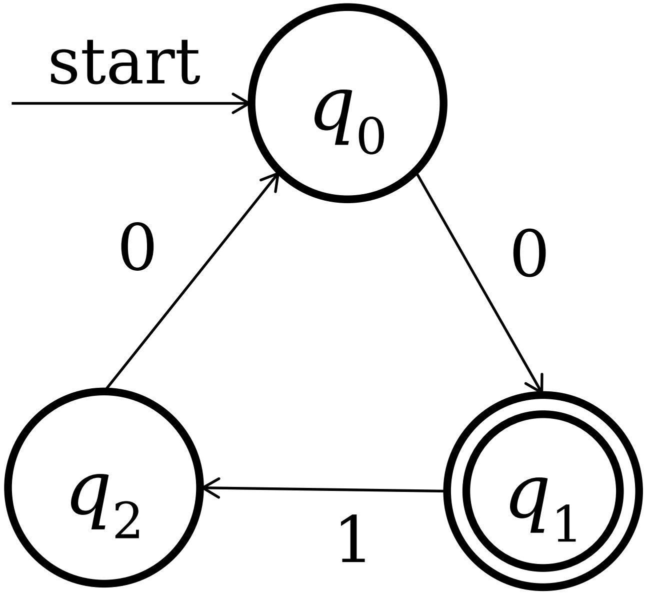

0 1 1 0

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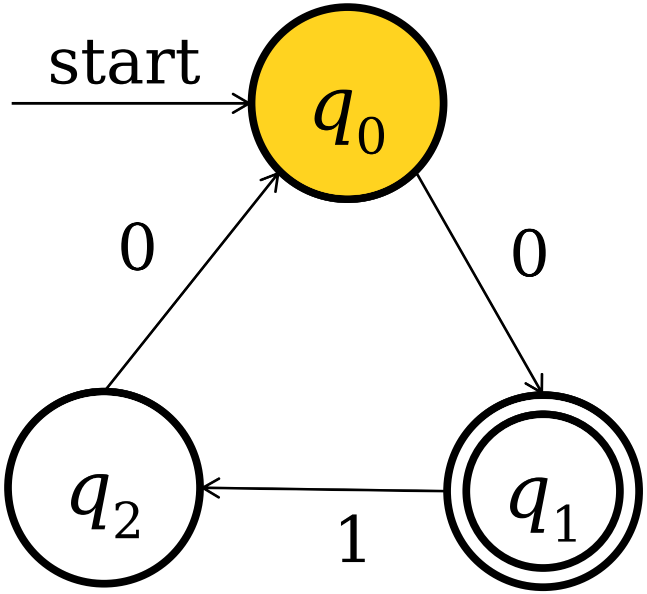

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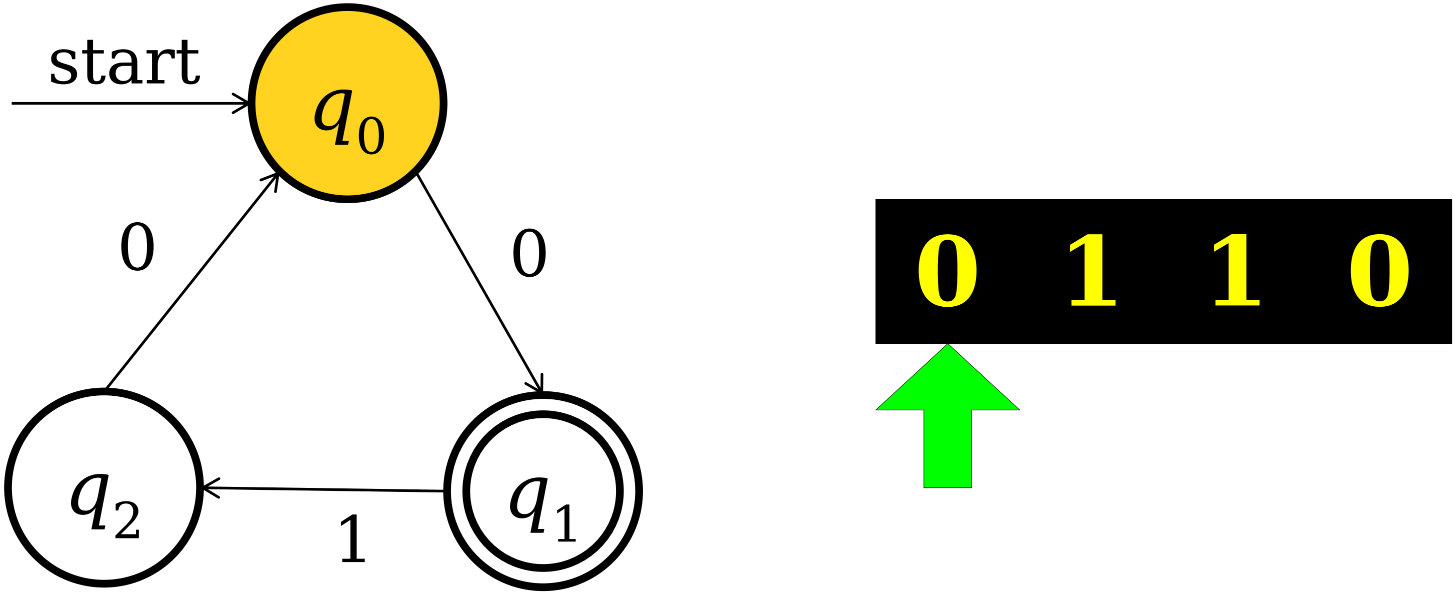

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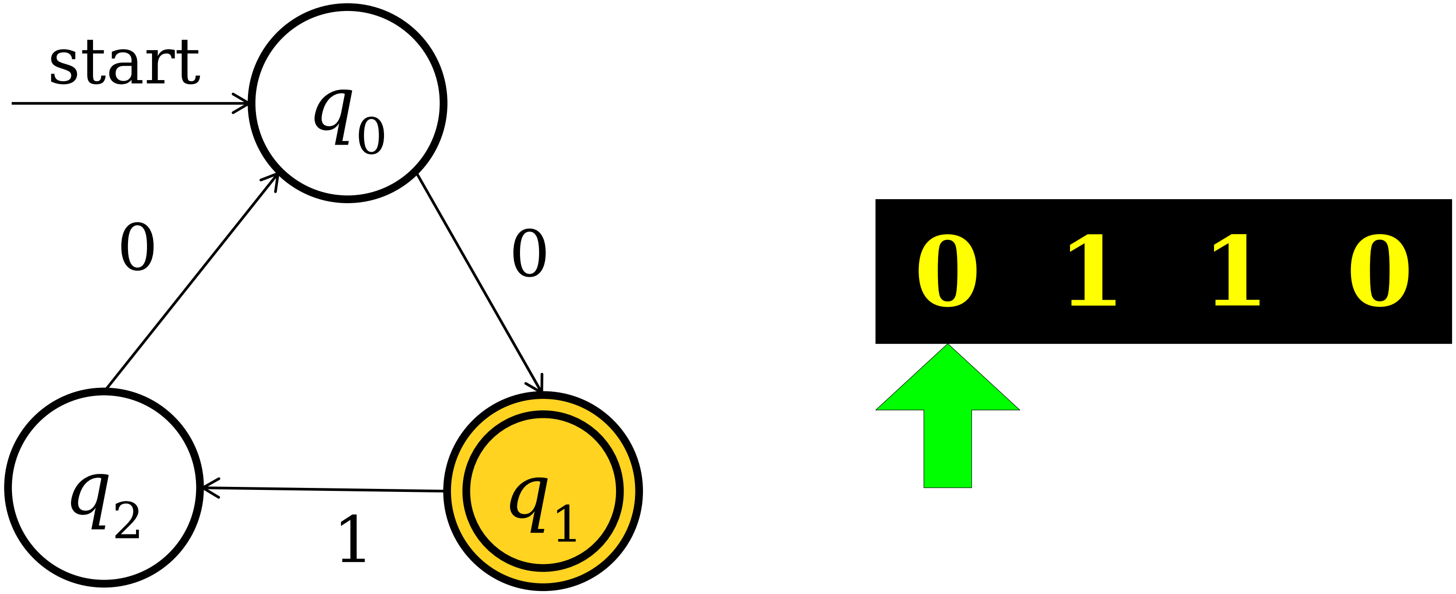

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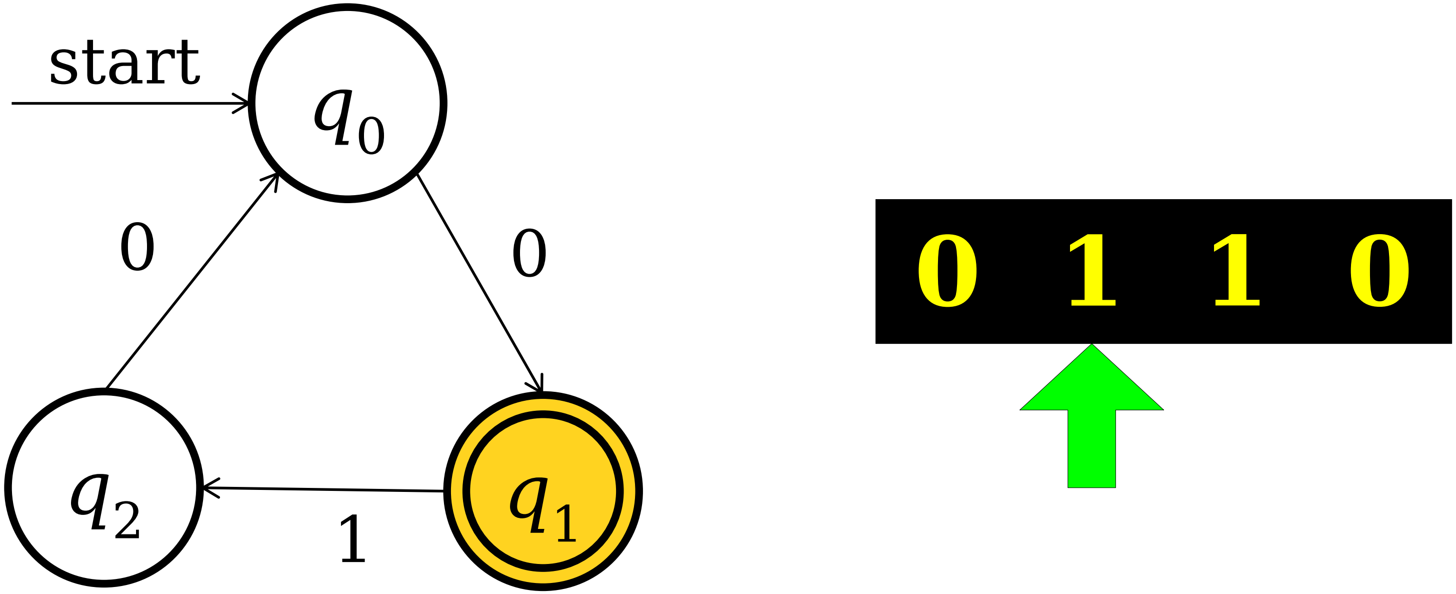

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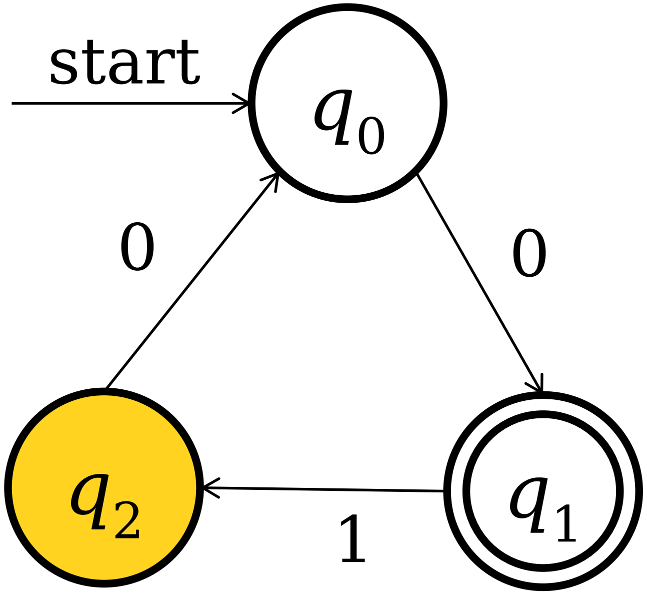

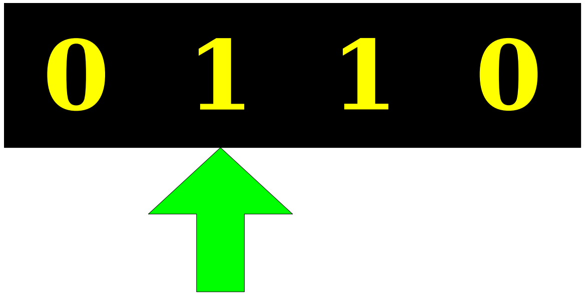

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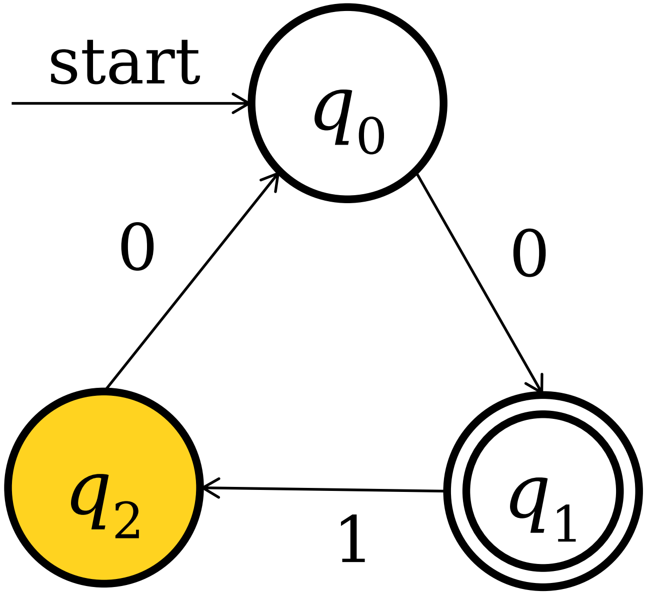

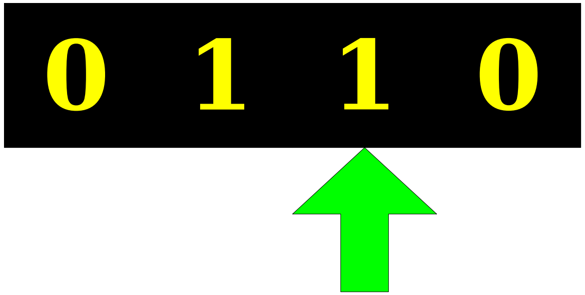

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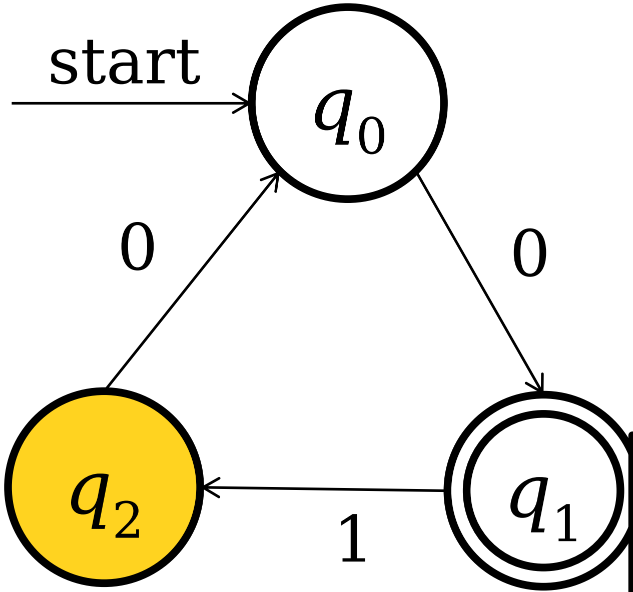
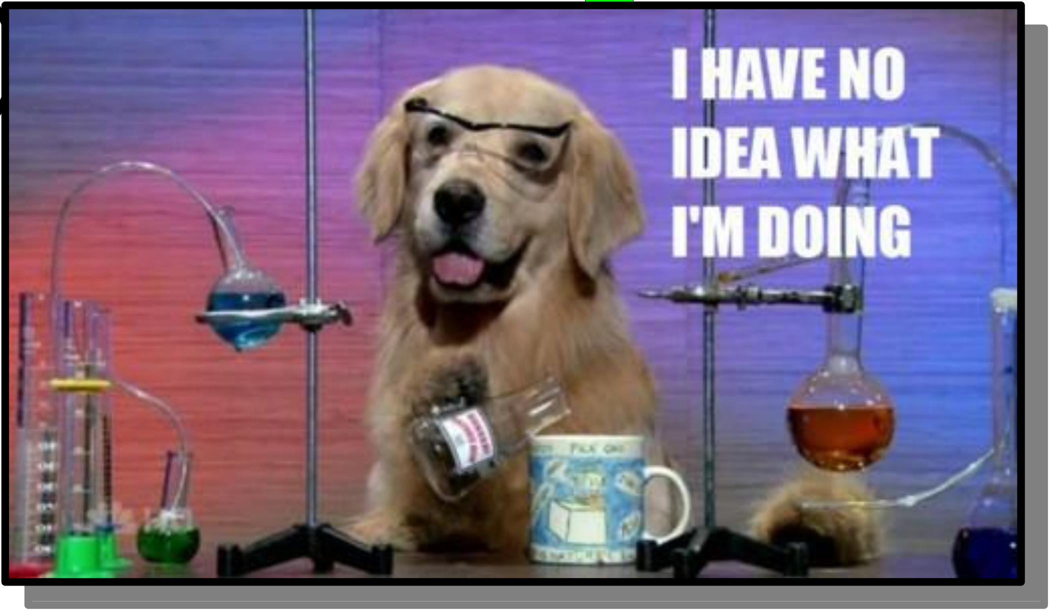


0 1 1 0



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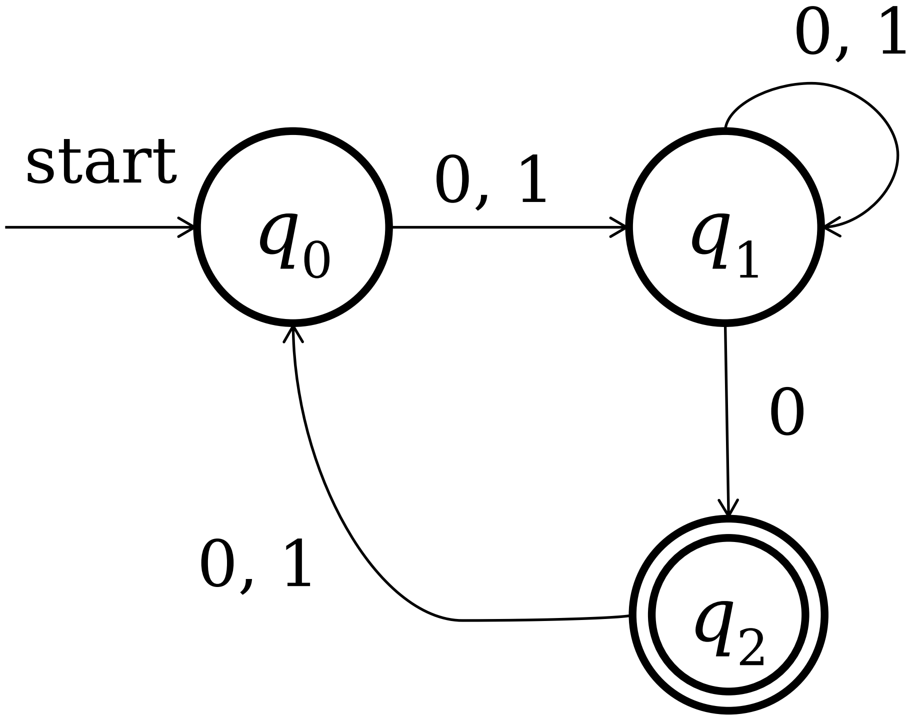

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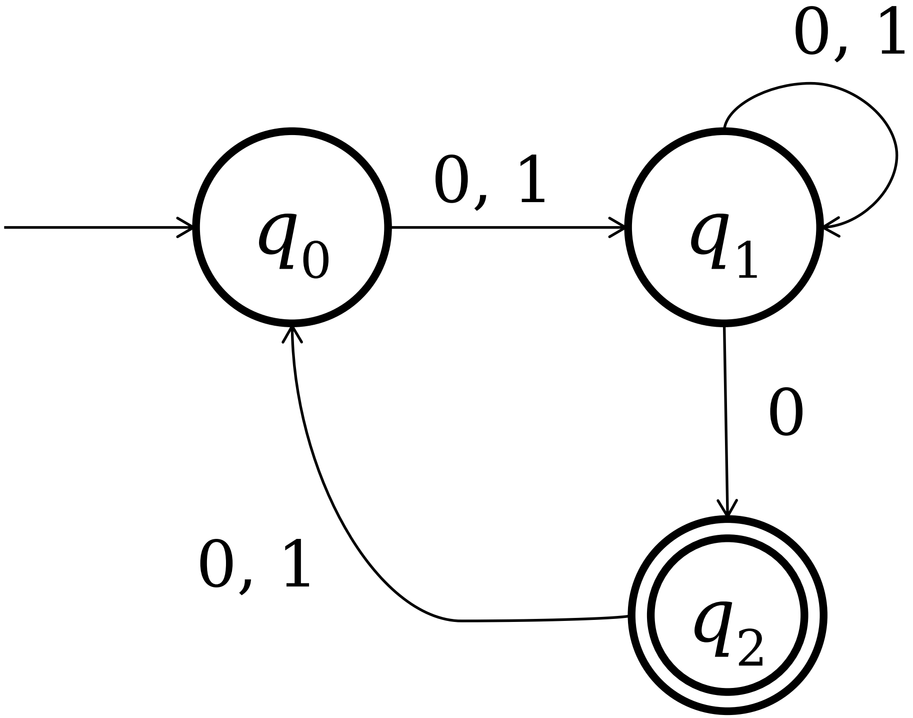

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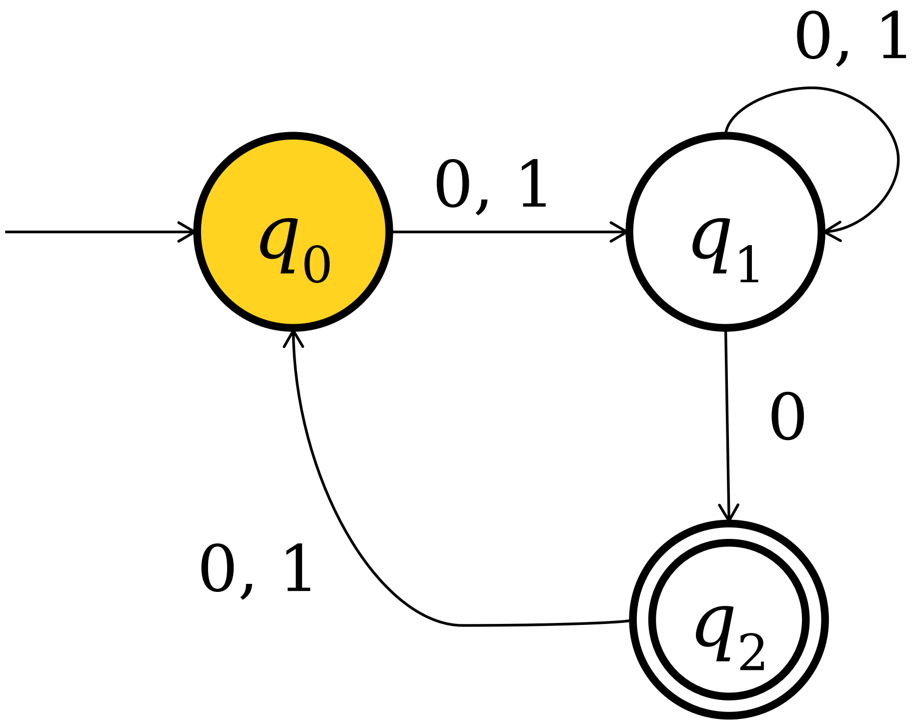

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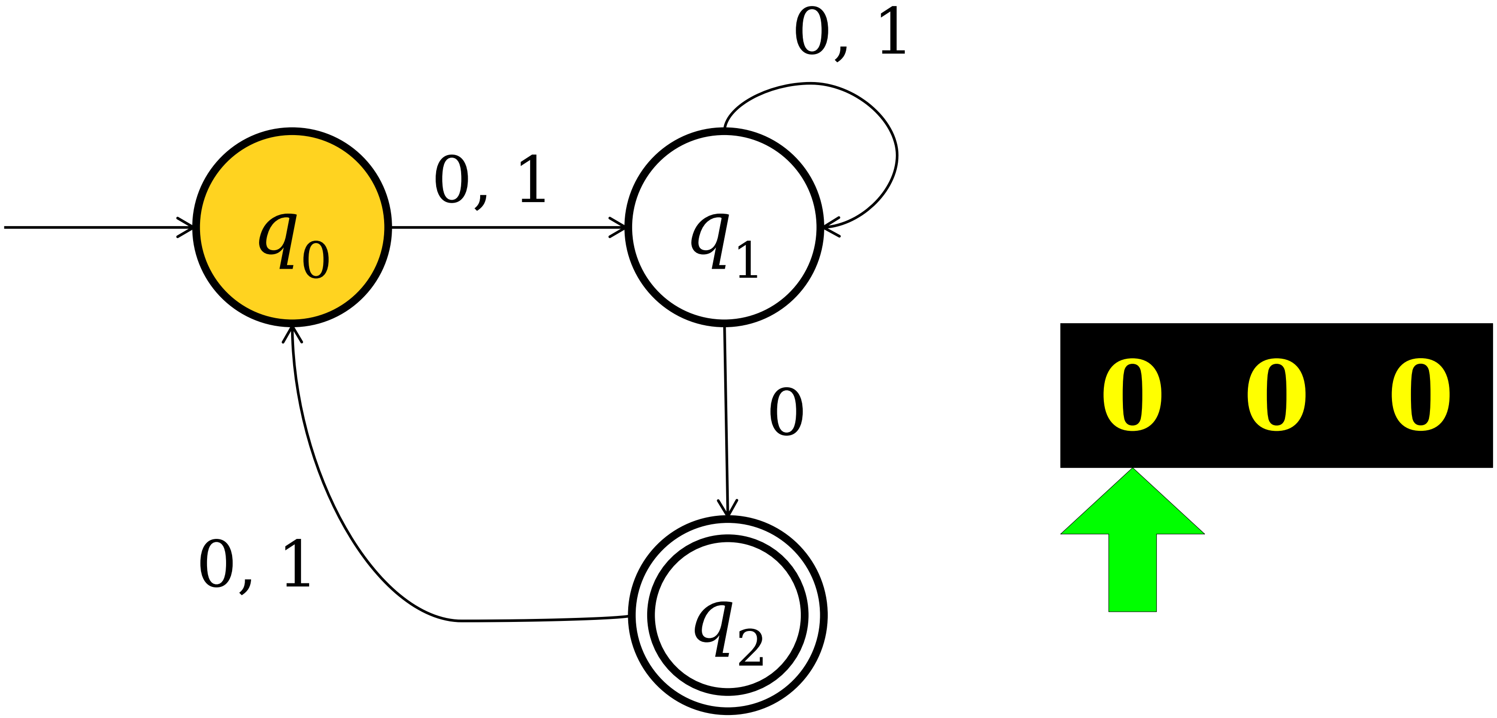

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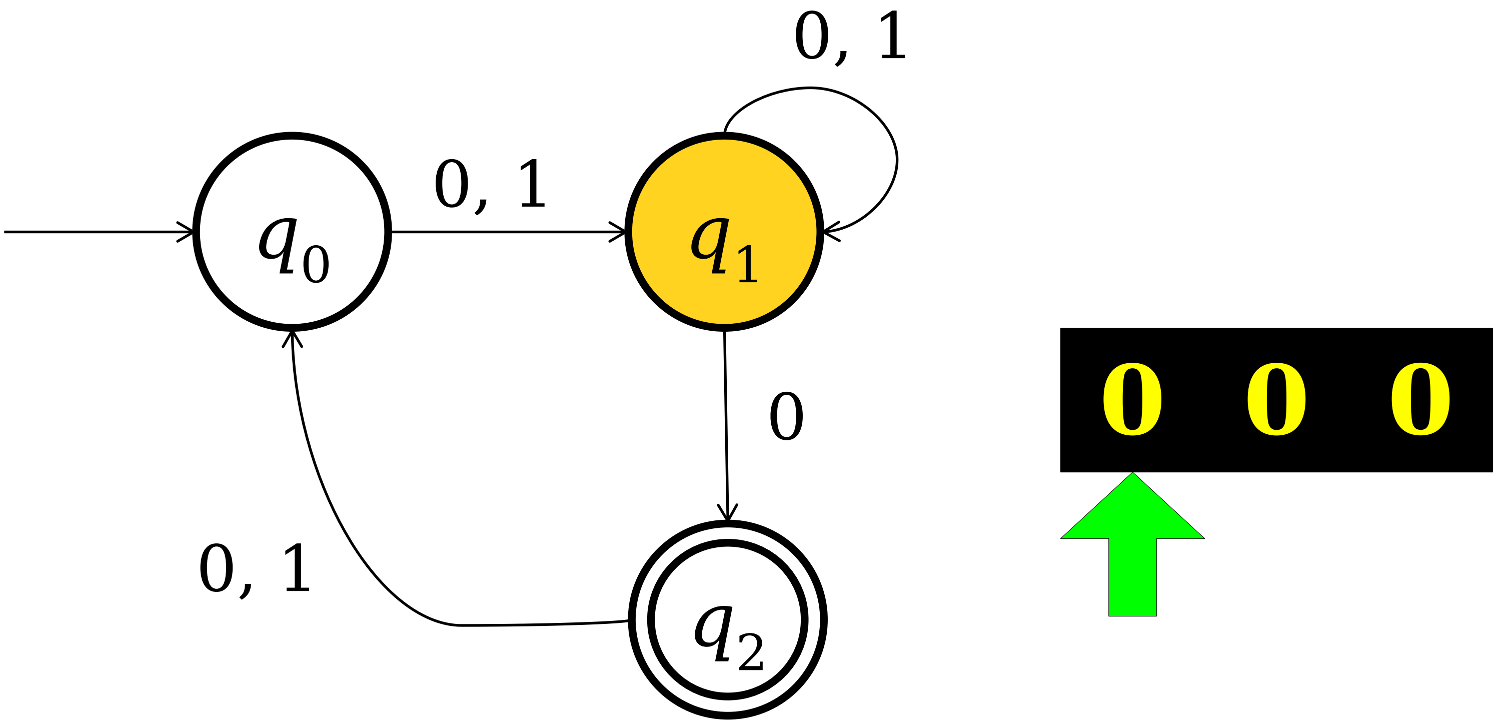

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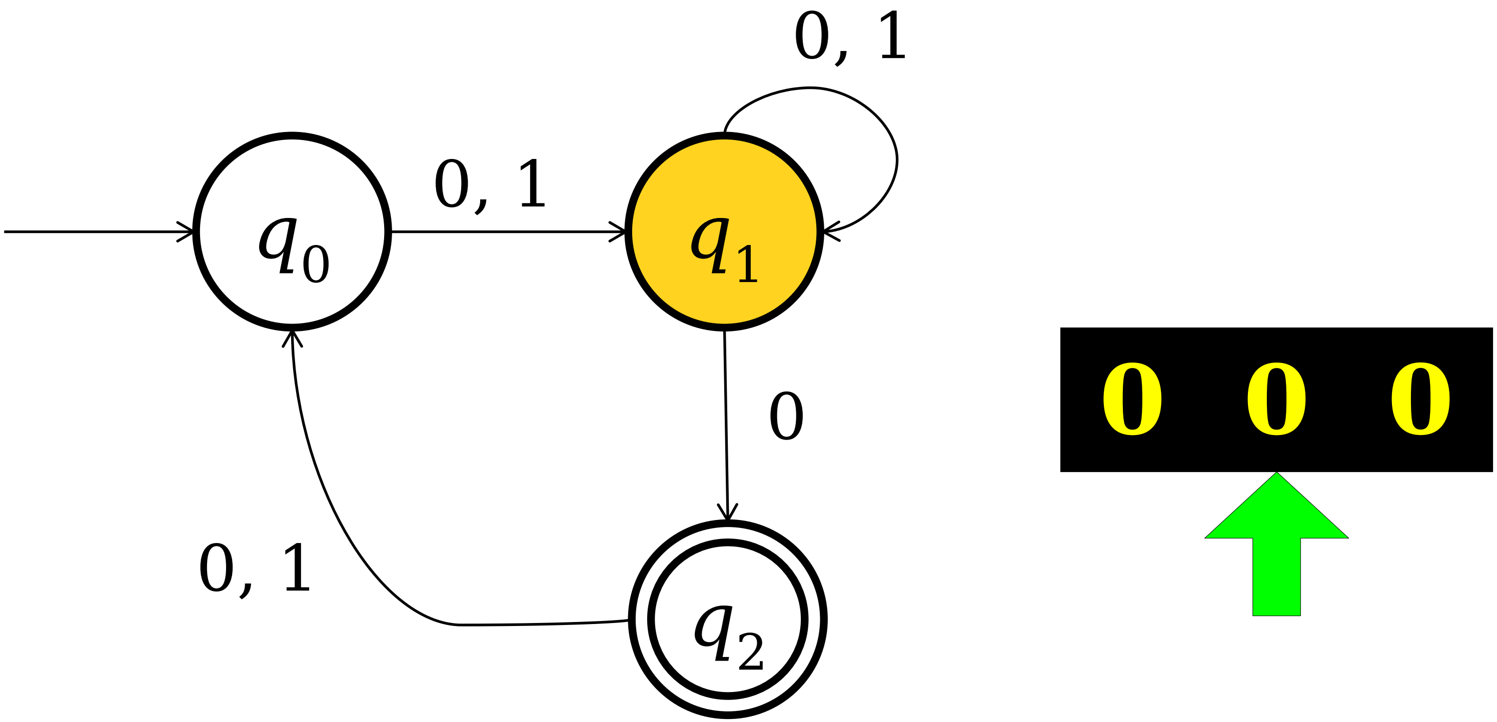

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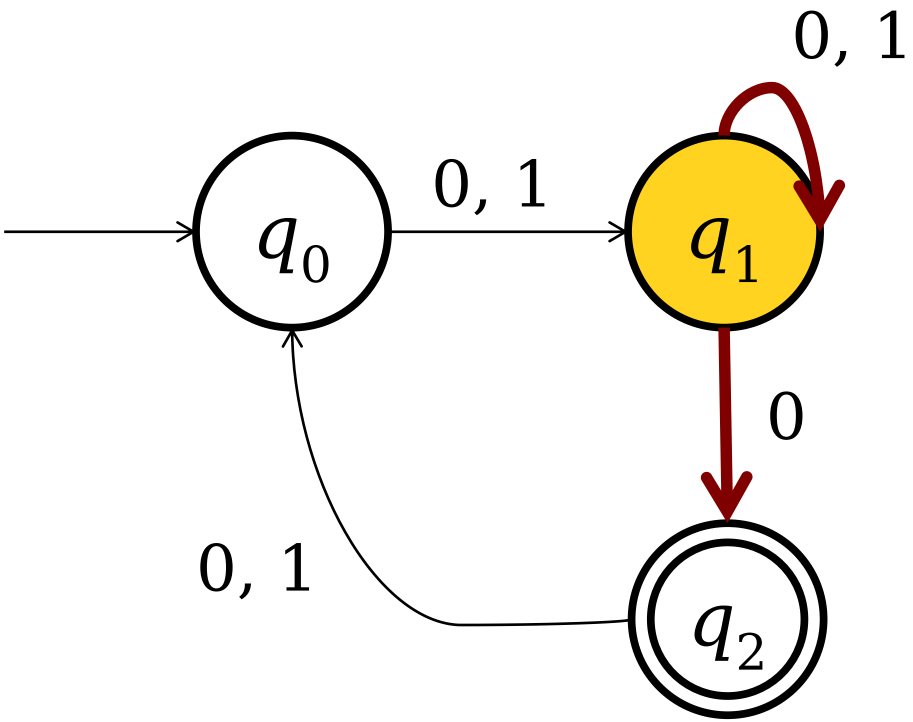

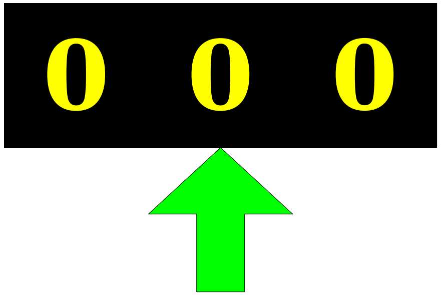
0 0 0

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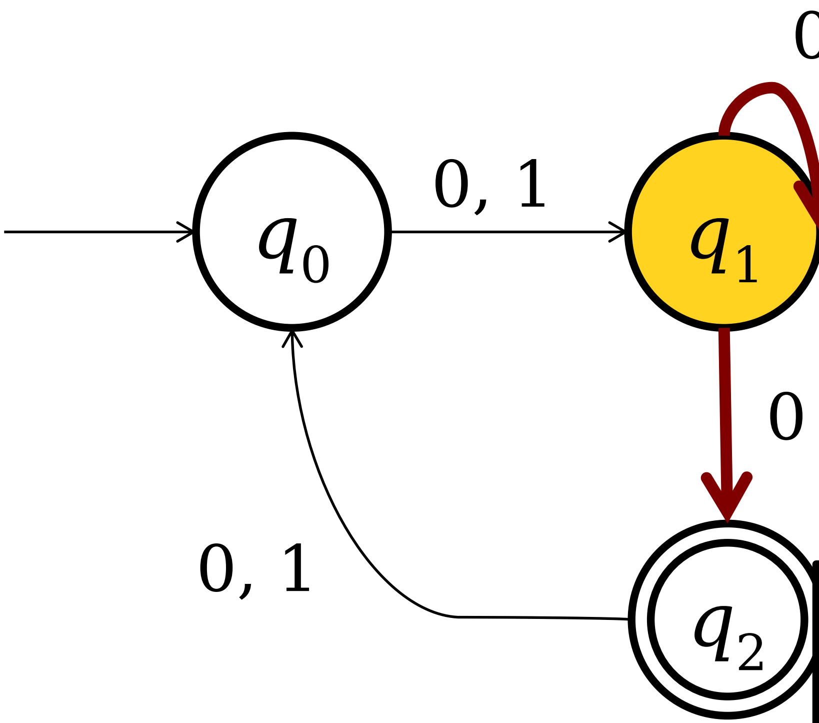
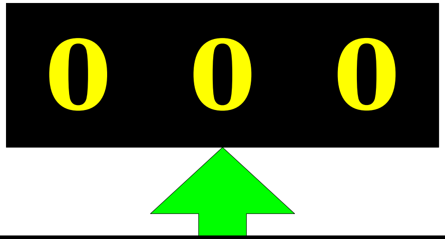
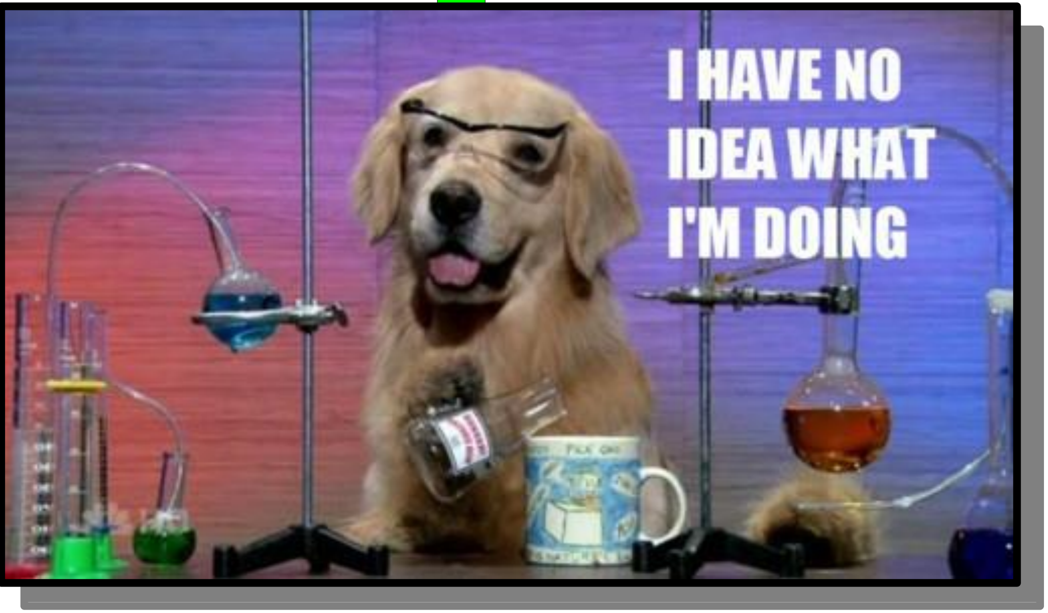






The Need for Formalism

In order to reason about the limits of what finite automata can and cannot do, we need to formally specify their behavior in *all* cases.

All of the following need to be defined or disallowed:

What happens if there is no transition out of a state on some input?

What happens if there are *multiple* transitions out of a state on some input?

DFAs

A ***DFA*** is a

- ***D***eterministic
- ***F***inite
- ***A***utomaton

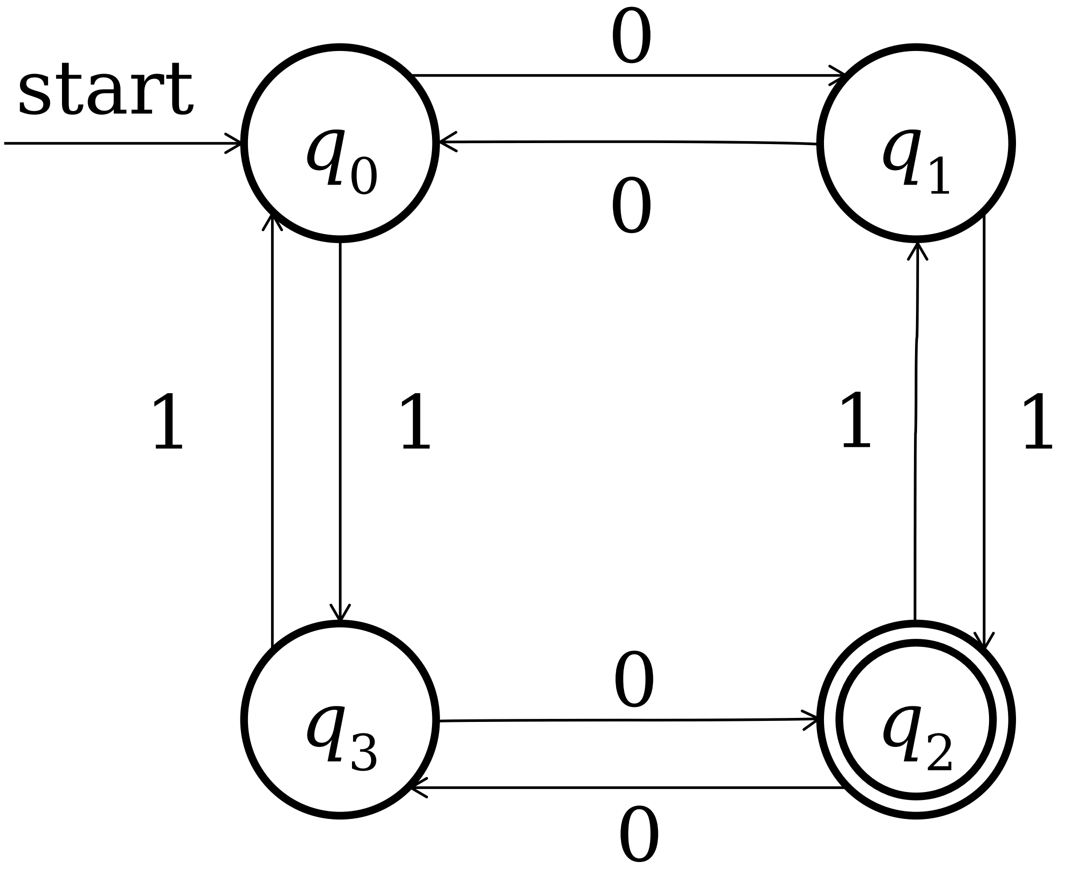
DFAs are the simplest type of automaton that we will see in this course.

DFAs

- 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.

Is this a DFA over $\{0, 1\}$?

Is this a DFA over {0, 1}?



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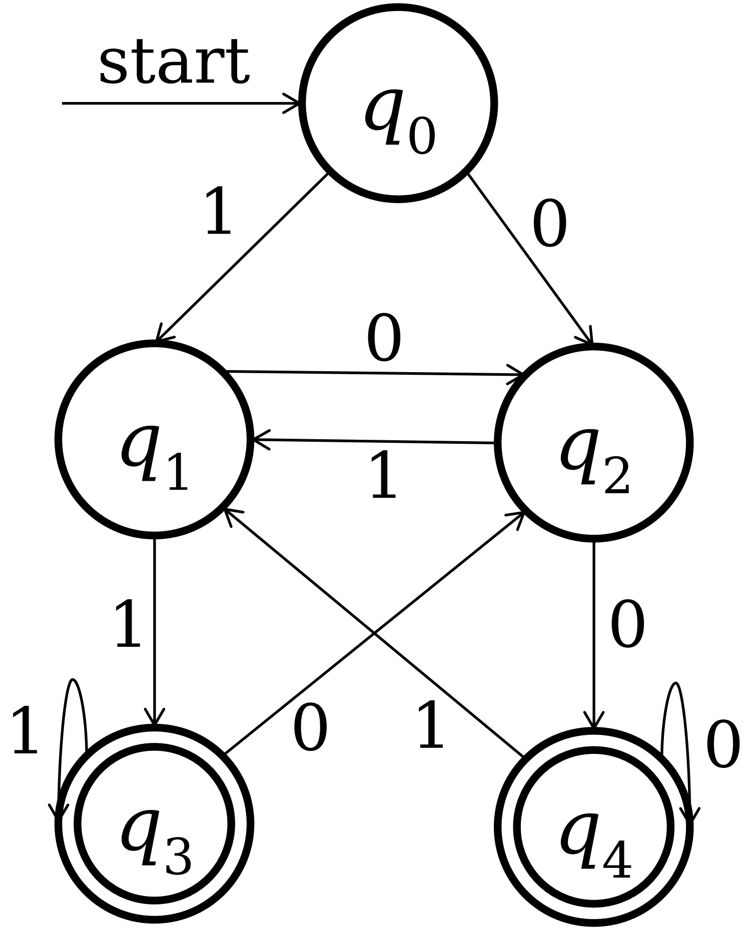

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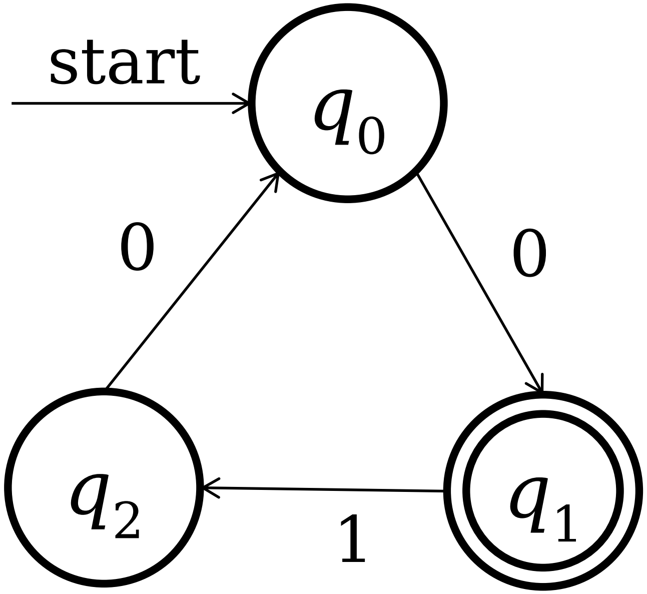

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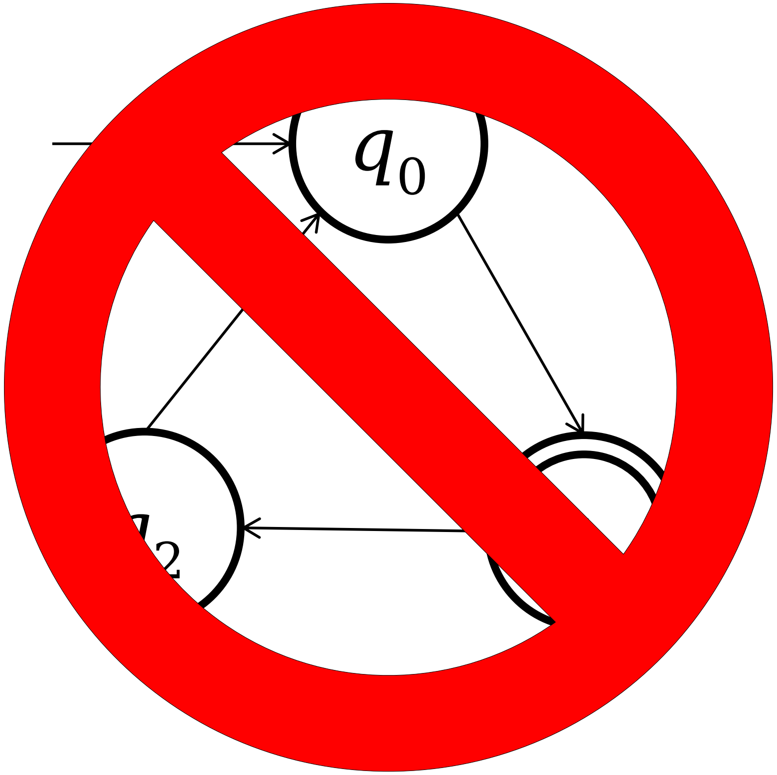

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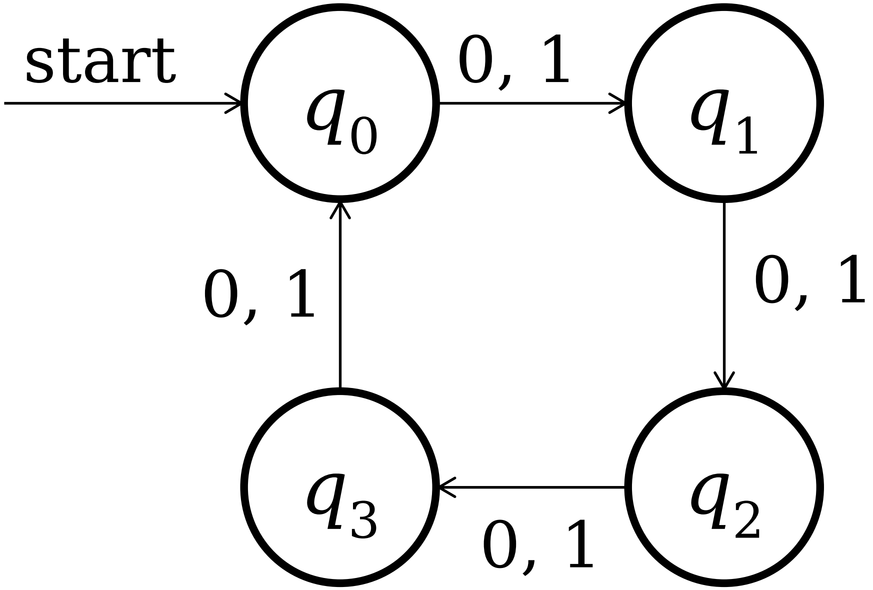

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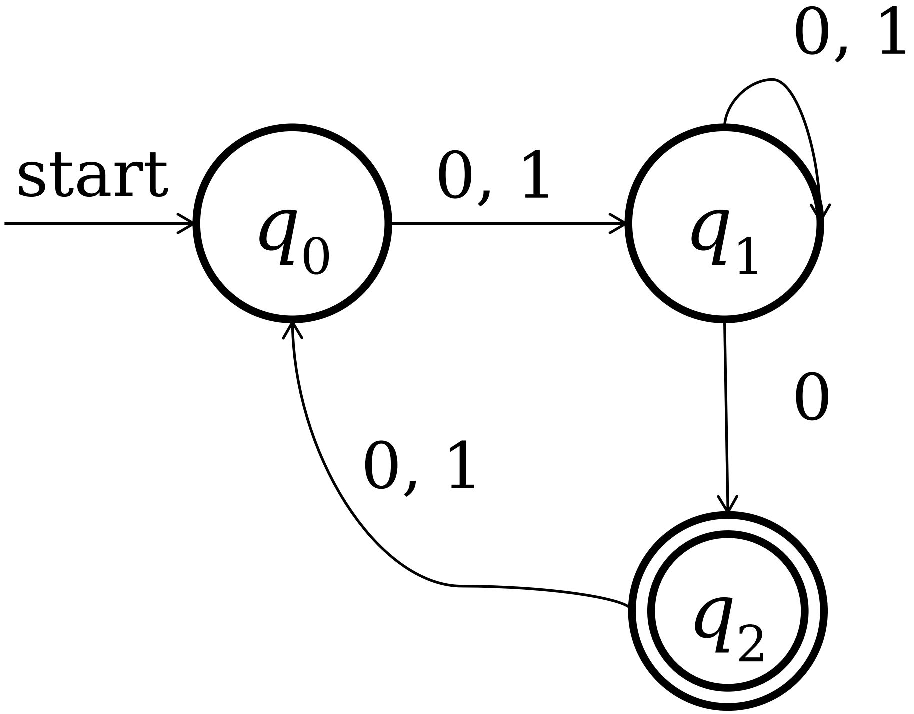

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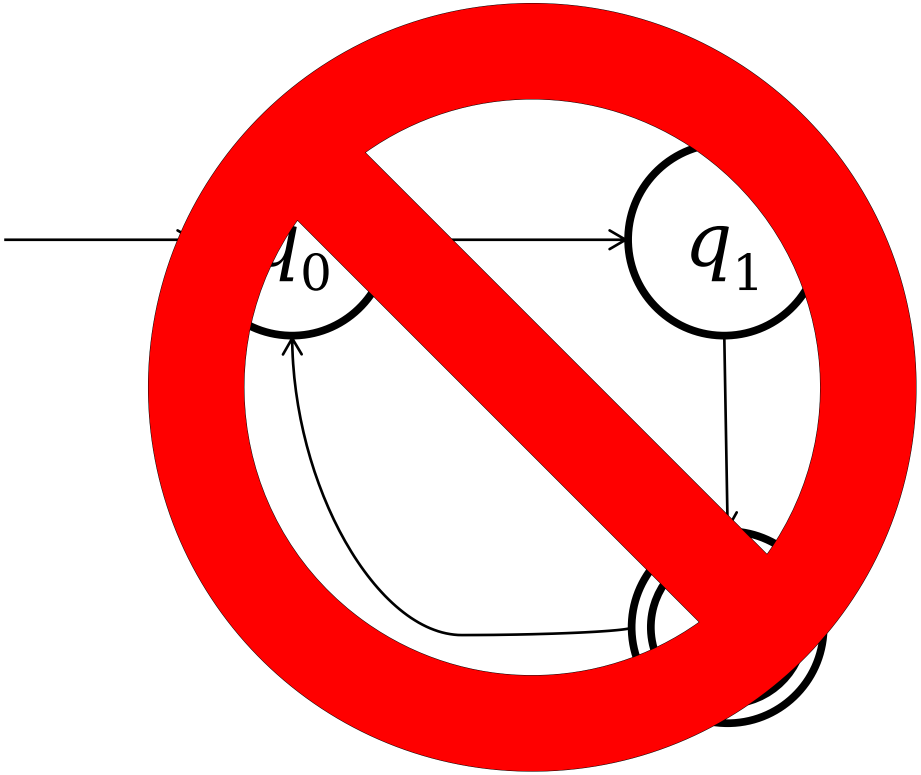

Is this a DFA?

Is this a DFA?

Is this a DFA?

Drinking **F**amily of **A**ardvarks

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 means only finitely many different things the machine can remember.

Recognizing Languages with DFAs

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

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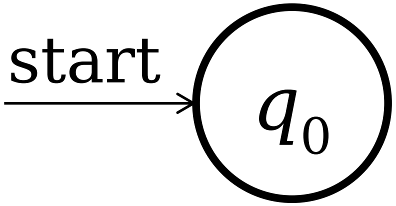

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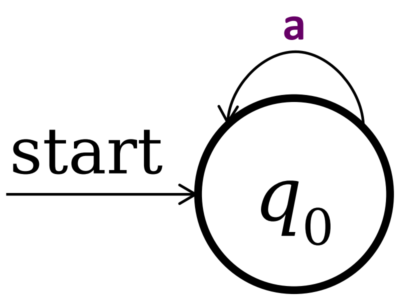

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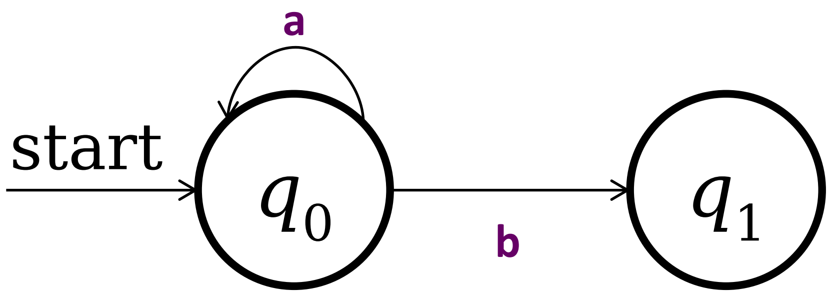

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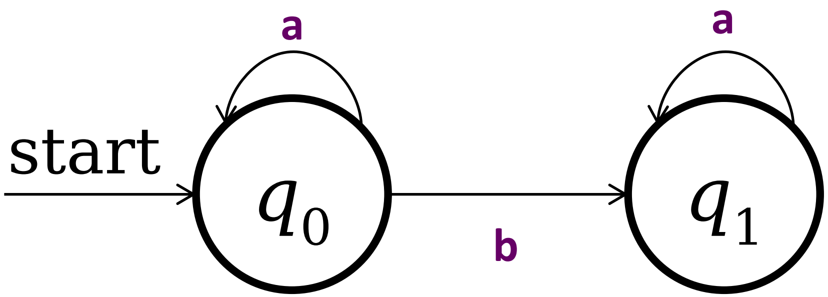

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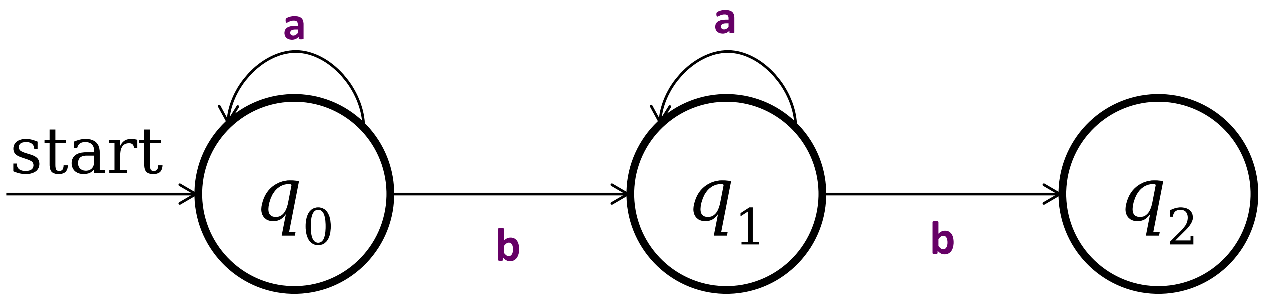

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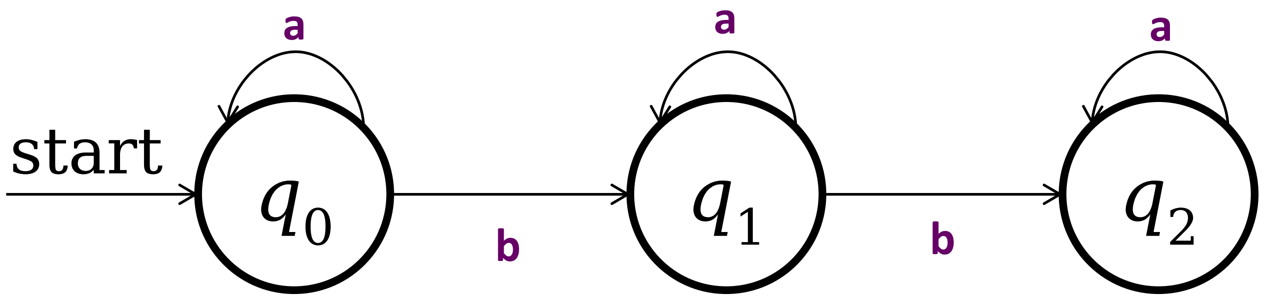

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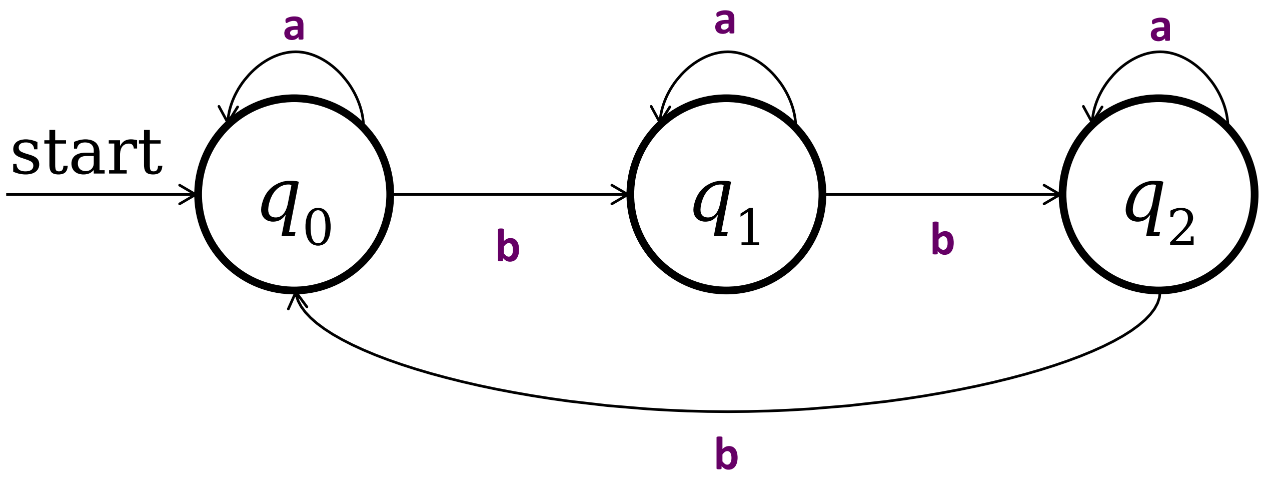

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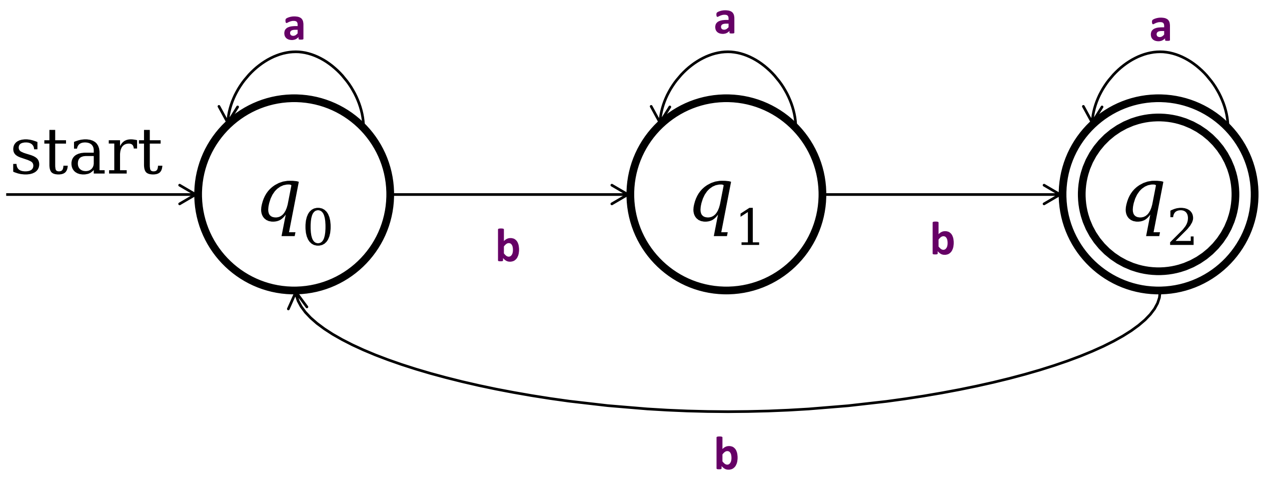

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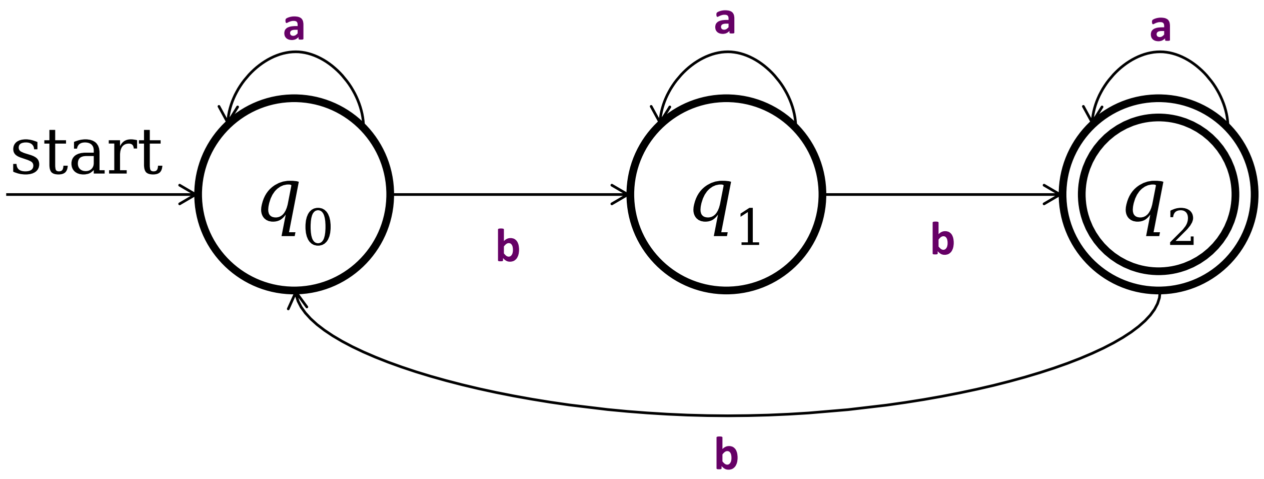

Each state remembers the remainder of the number of **b**s seen so far modulo three.

Recognizing Languages with DFAs

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

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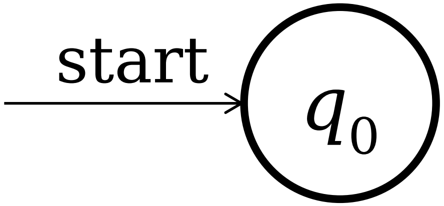

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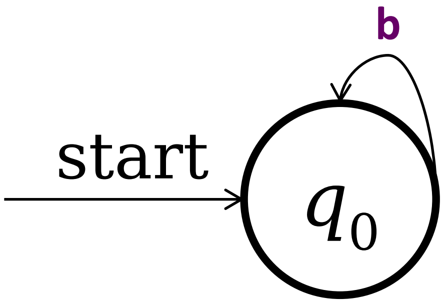

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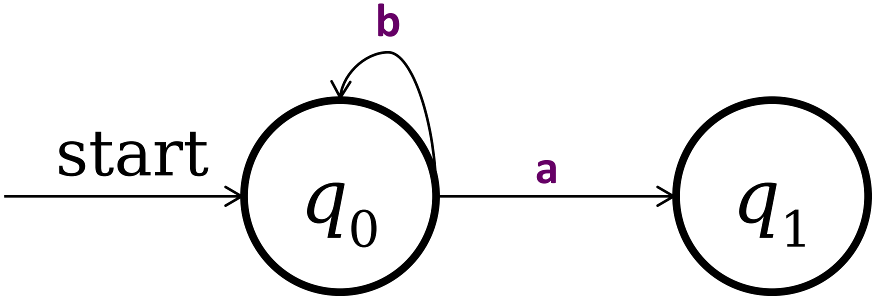

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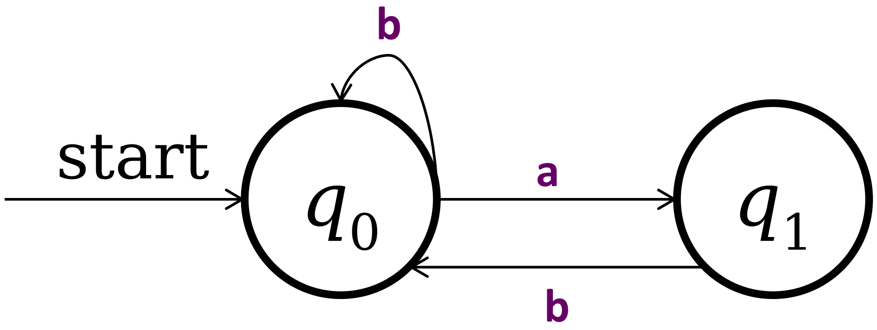

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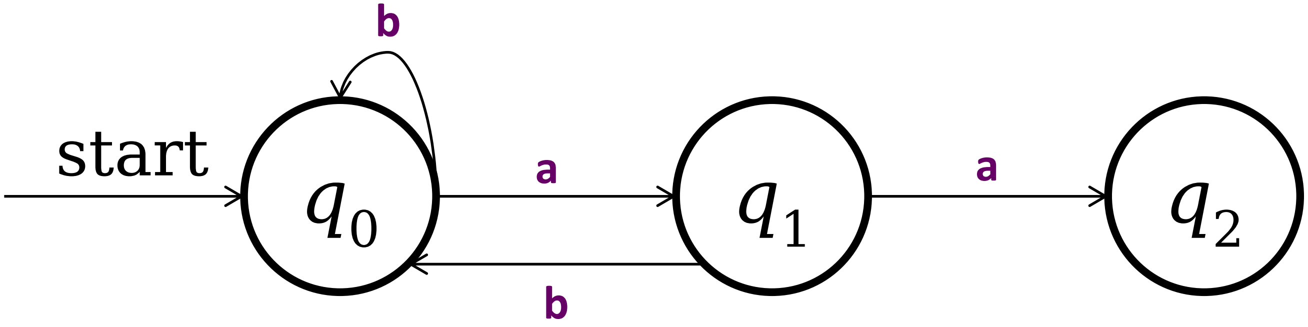

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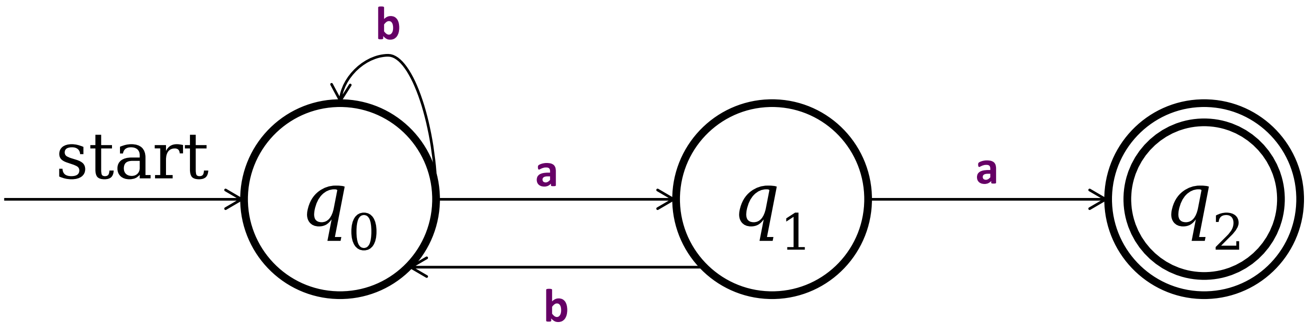

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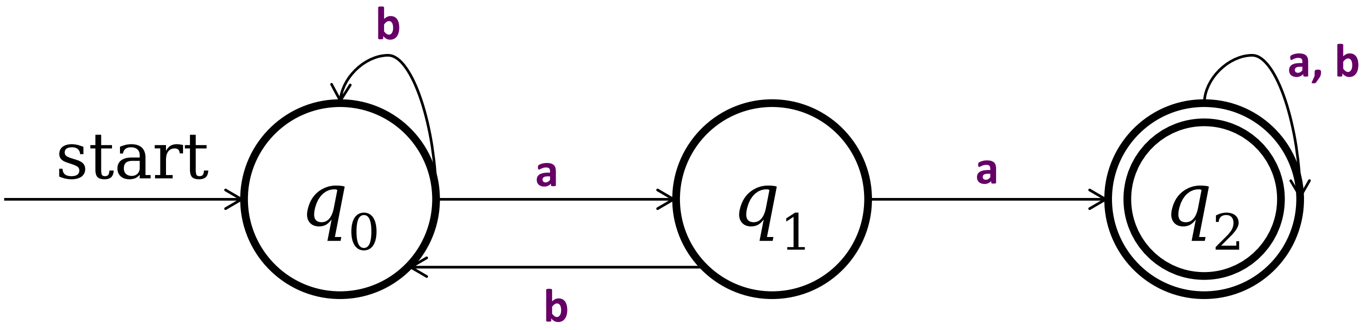

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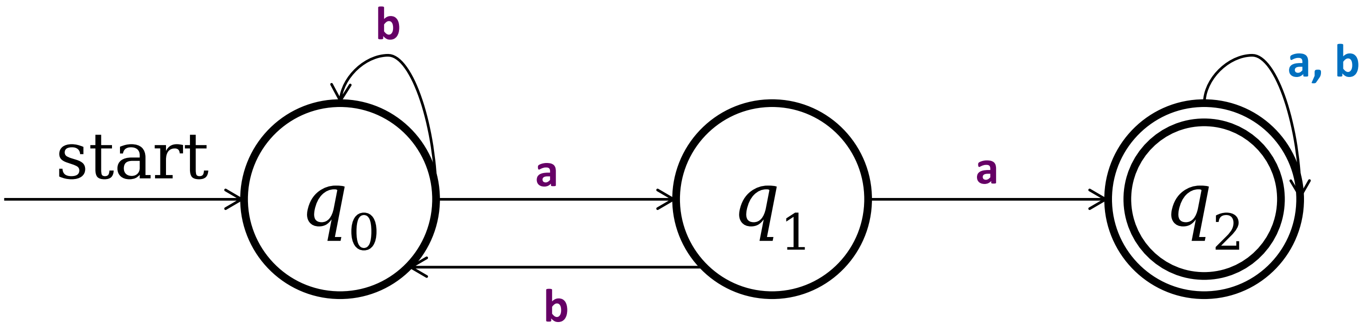

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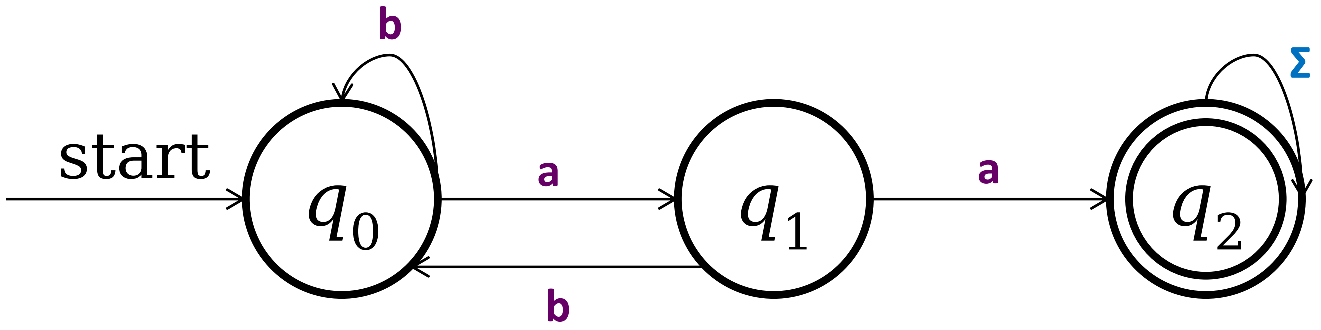

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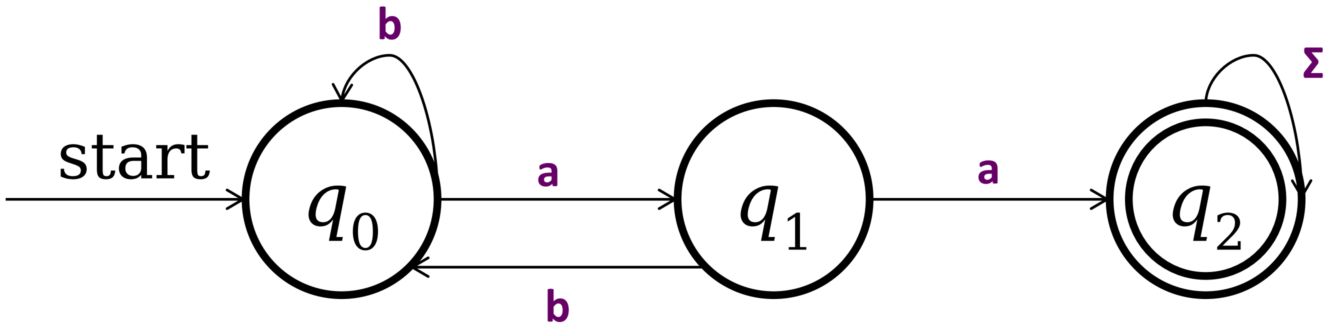


More Elaborate DFAs

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

Let’s have the **a** symbol be a placeholder for “some character that isn’t a star or slash.”

Try designing a DFA for comments! Here’s some test cases to help you check your work:

Accepted:

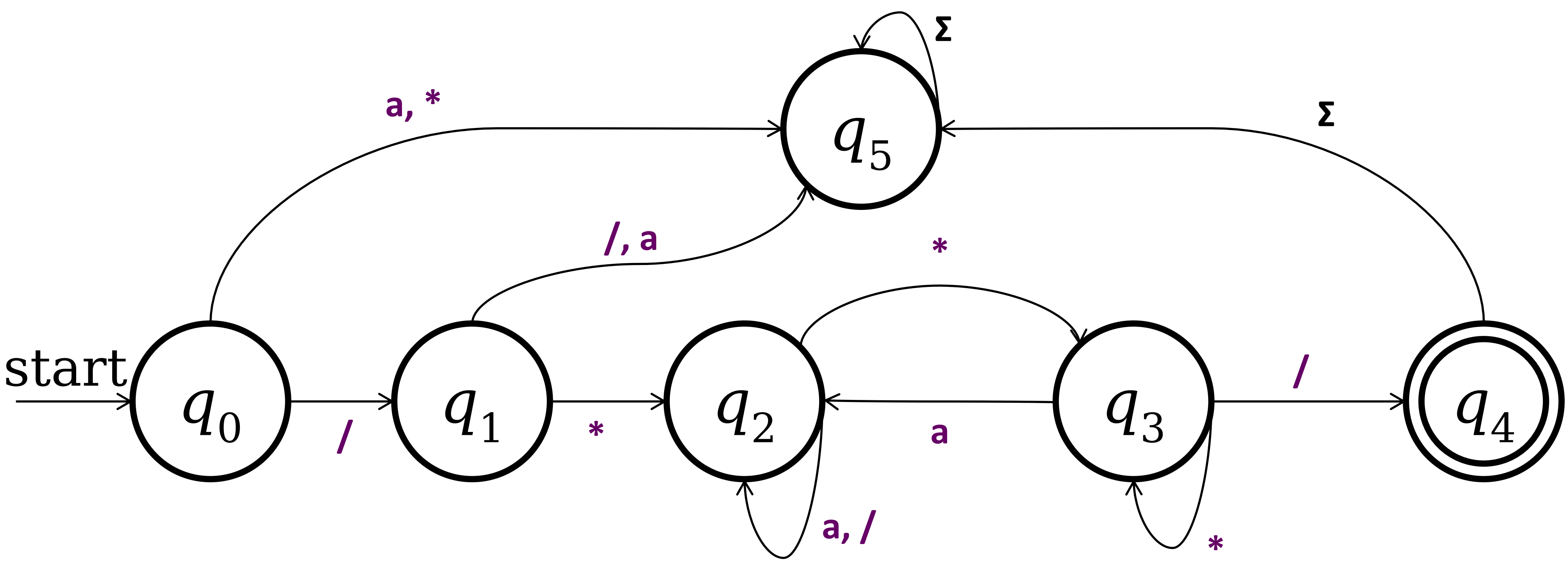
/*a*/
//**
/*/**
/*aaa*aaa*/
/*a/a*/

Rejected:

/**
//a/*aa*/**
aaa//aa**
/*/
/a/**
//aaaa

More Elaborate DFAs

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

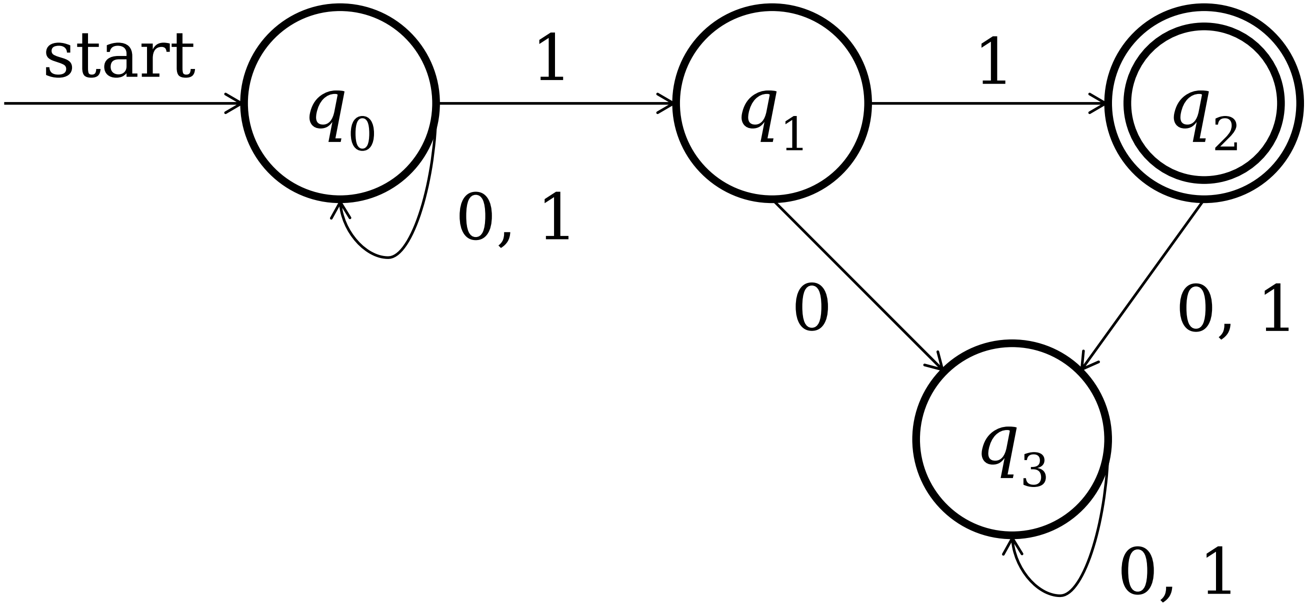


The Regular Languages

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

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

Revisiting a Problem



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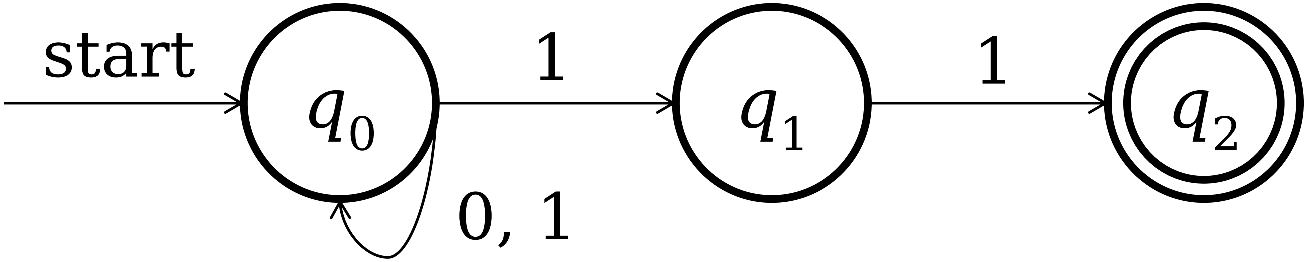


NFAs

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.

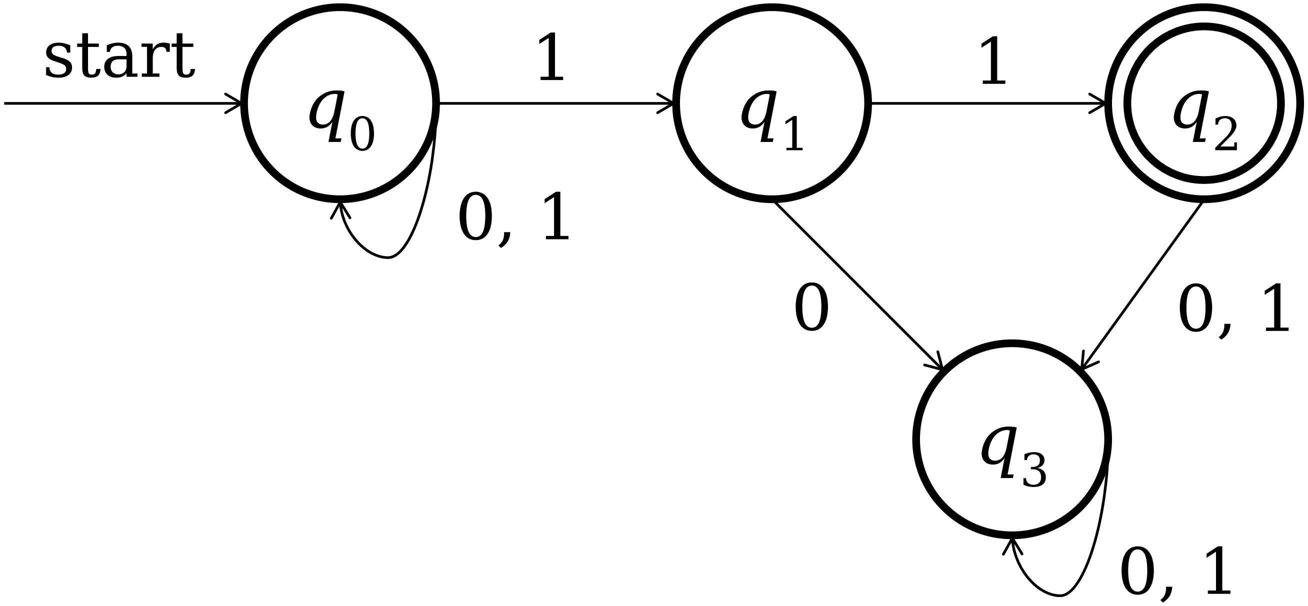
The machine accepts if that series of choices leads to an accepting state.

A model of computation is ***nondeterministic*** if the computing machine may have multiple decisions that it can make at one point.

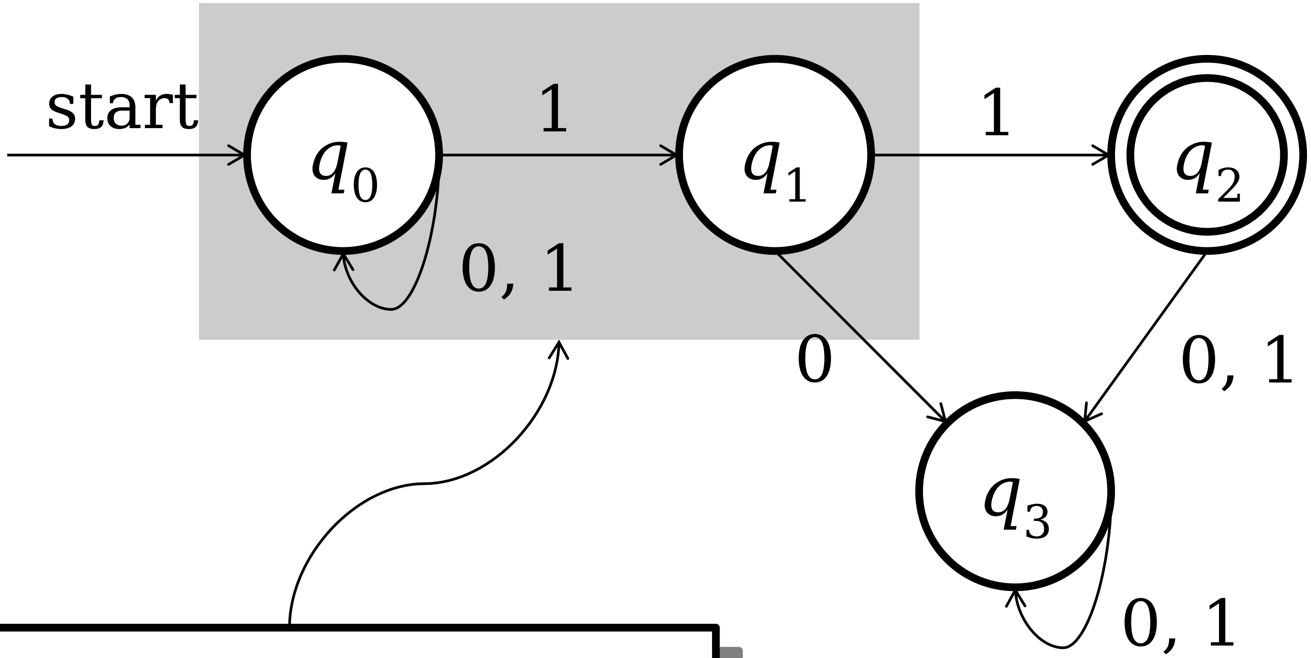
The machine accepts if ***any*** series of choices leads to an accepting state.

(This sort of nondeterminism is technically called ***existential nondeterminism***, the most philosophical-sounding term we'll introduce all quarter.)

A Simple NFA

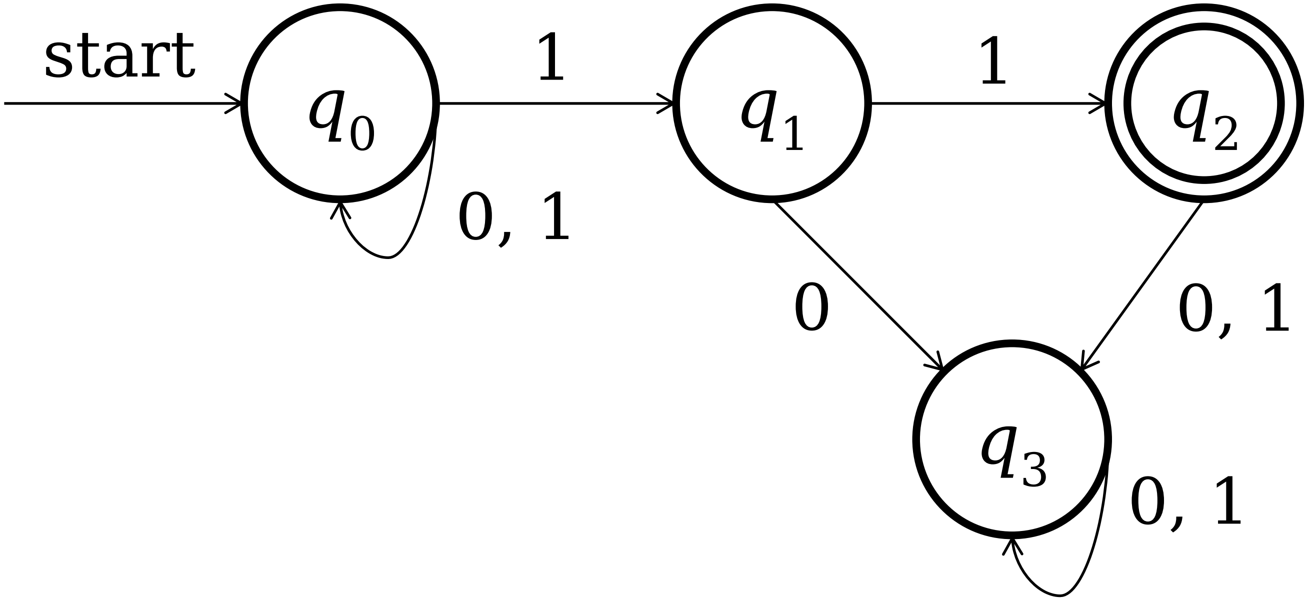


A Simple NFA



q_0 has two transitions defined on 1!

A Simple NFA



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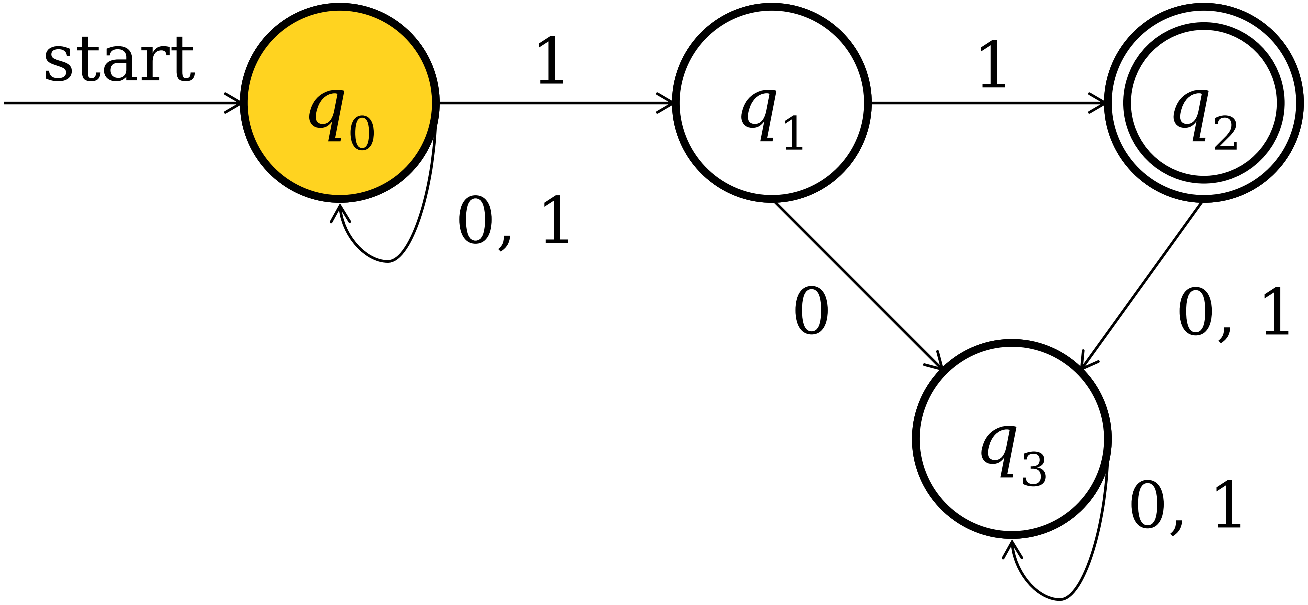
A Simple NFA



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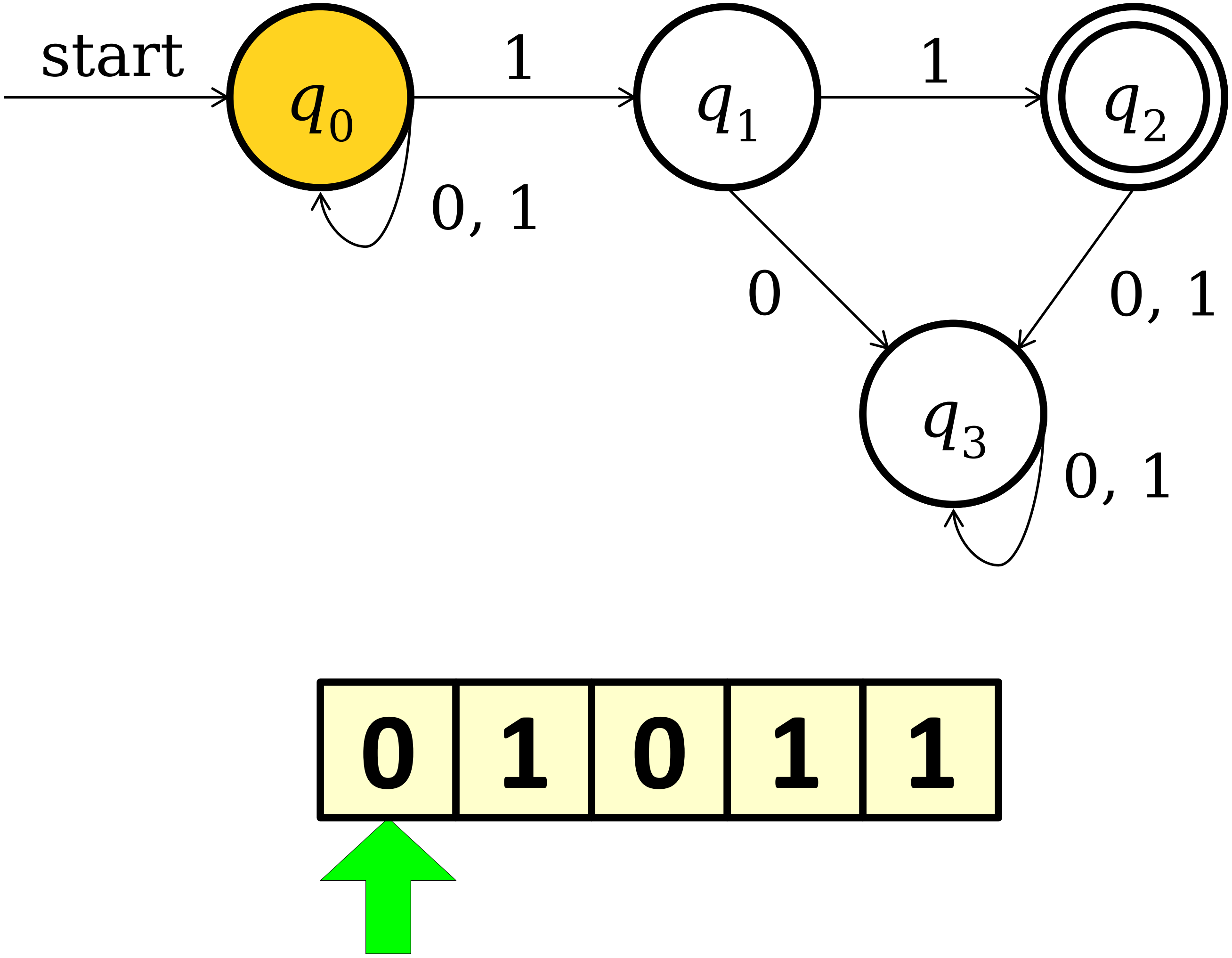
A Simple NFA



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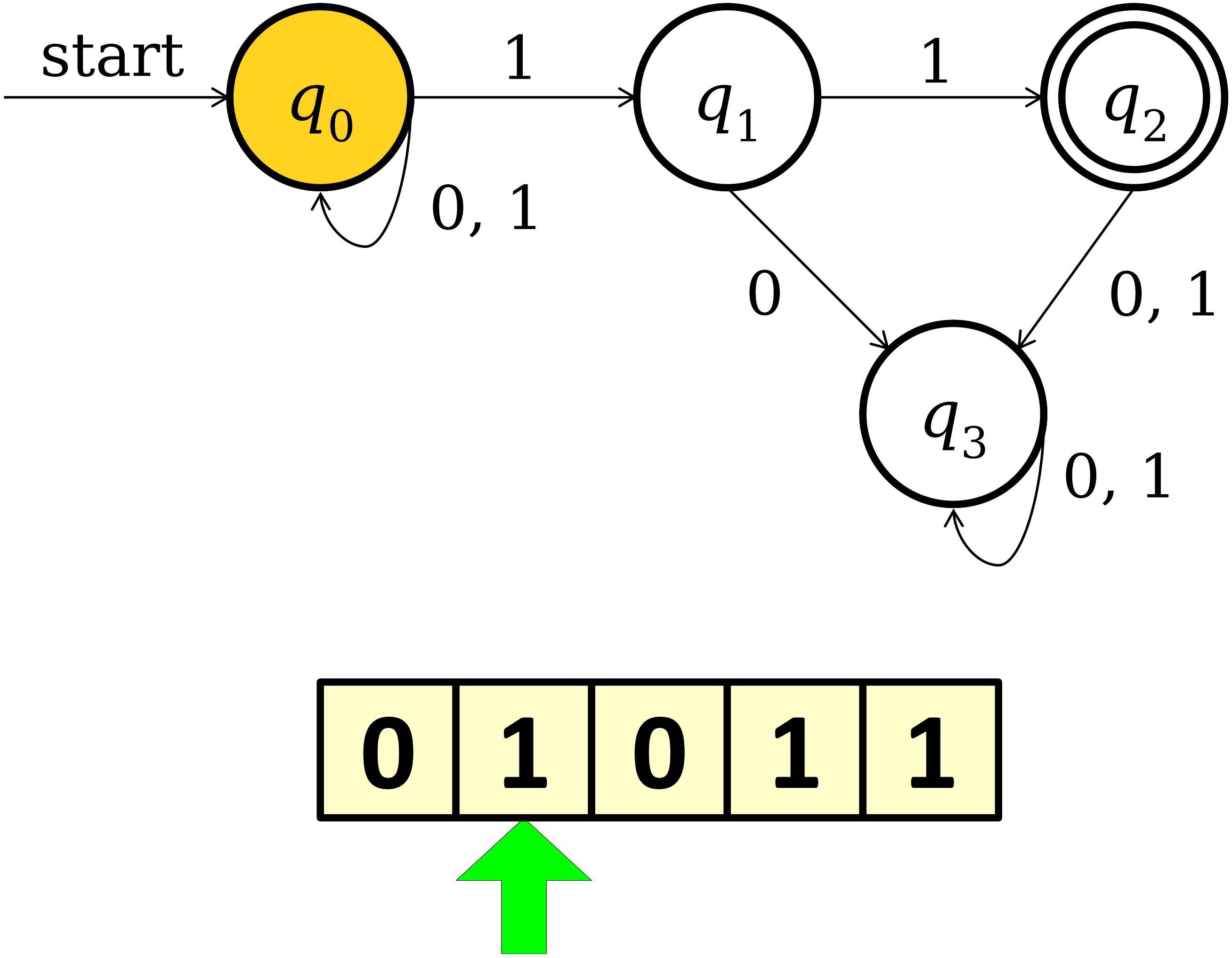

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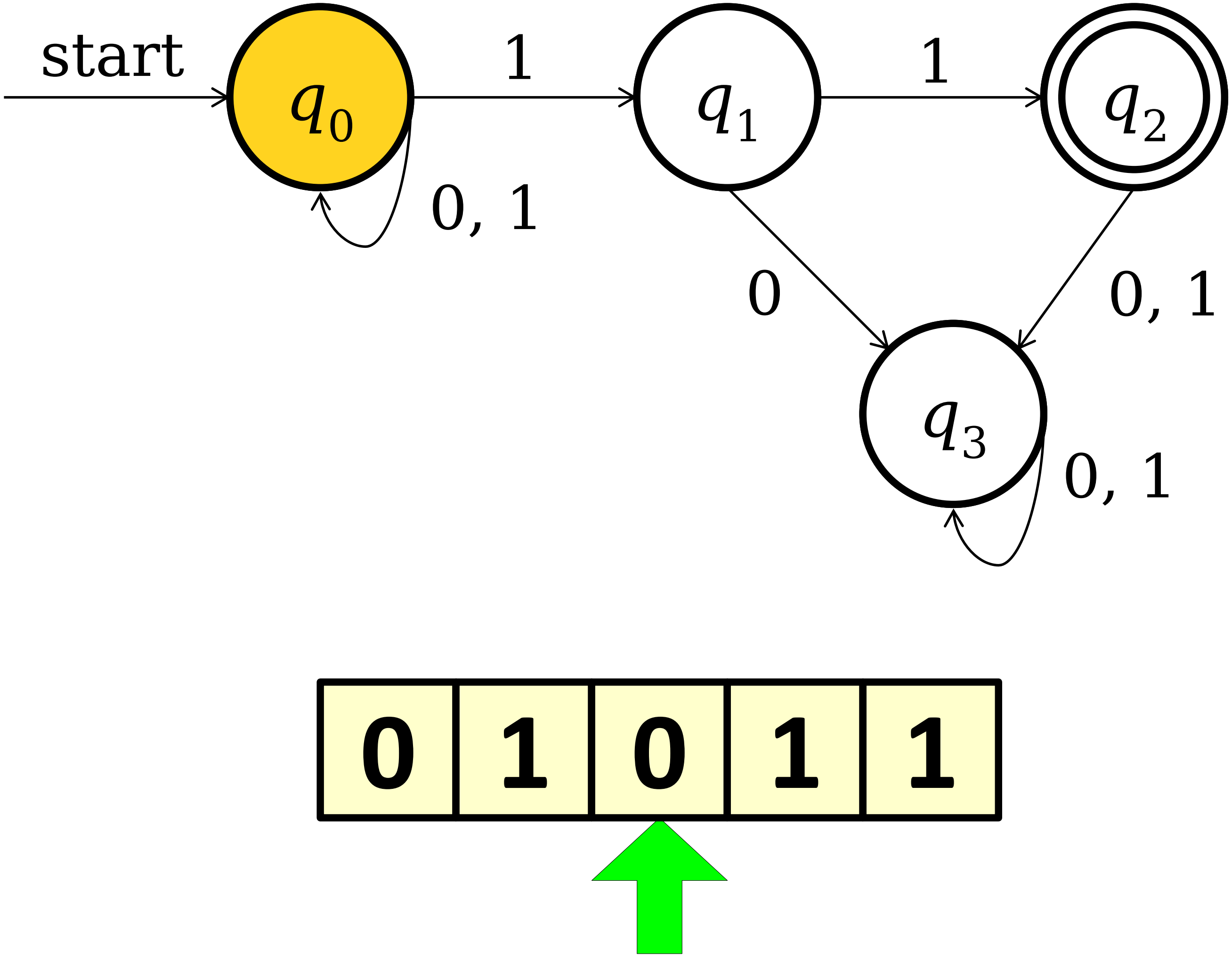

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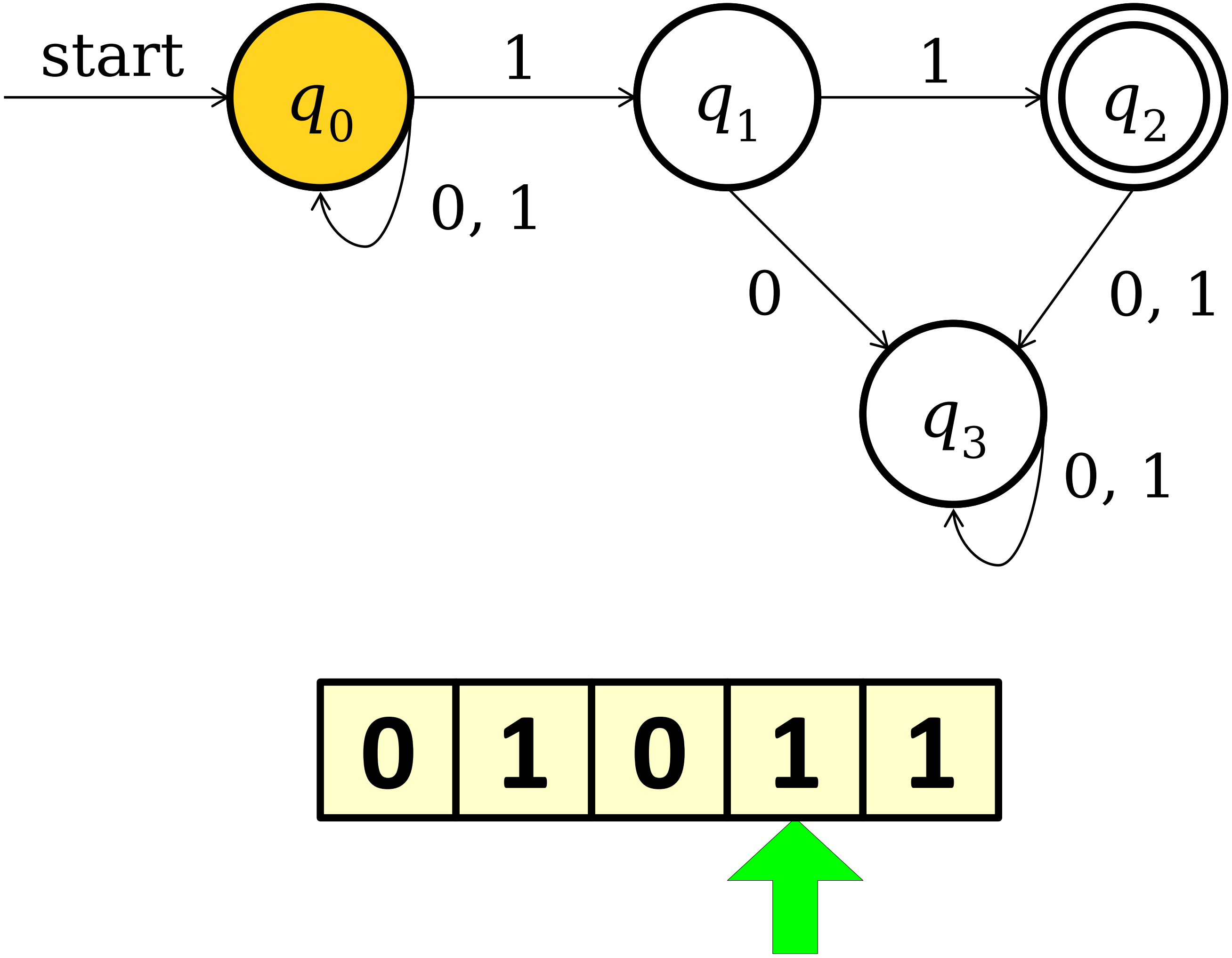

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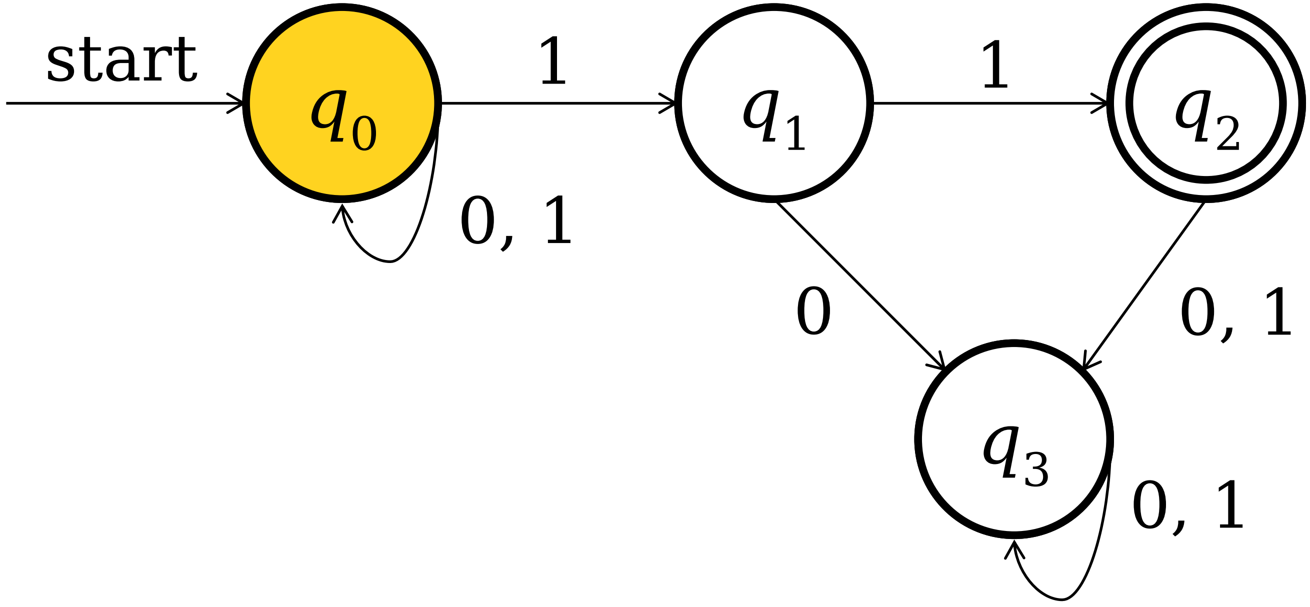

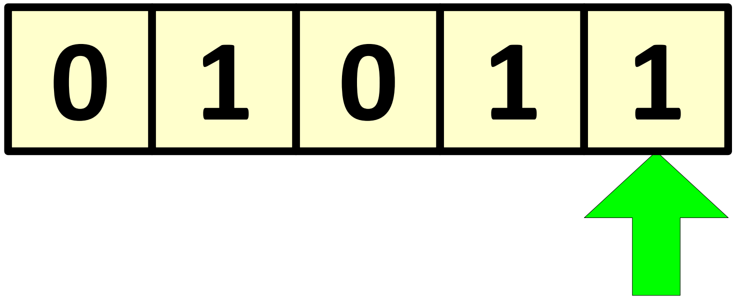

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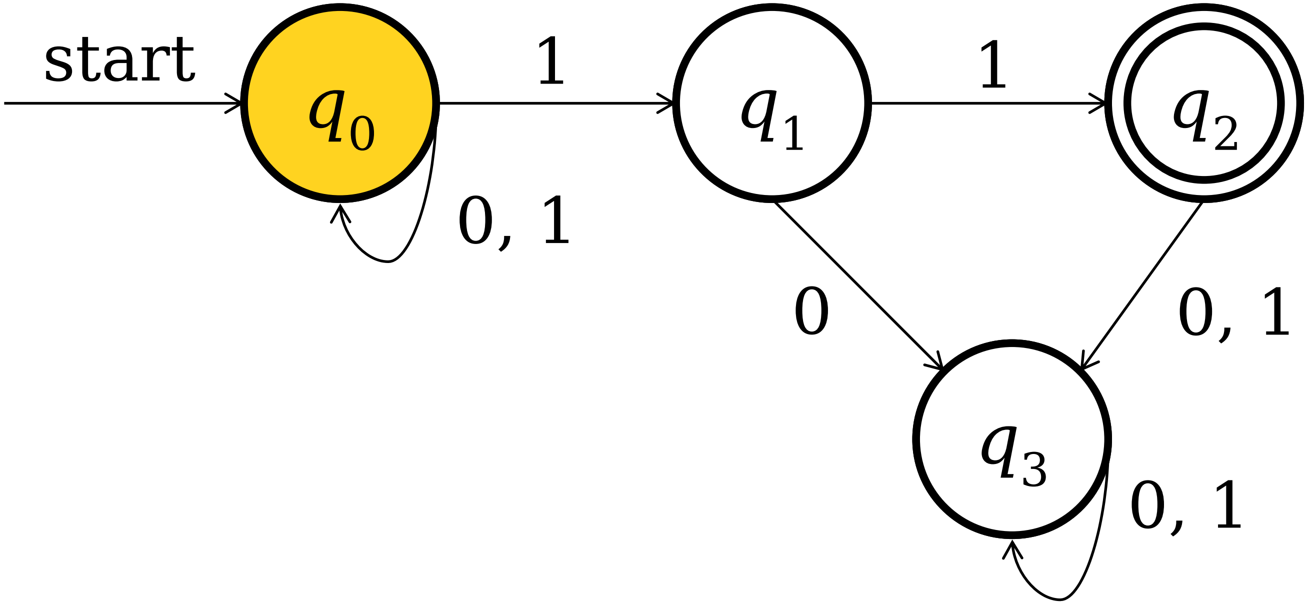

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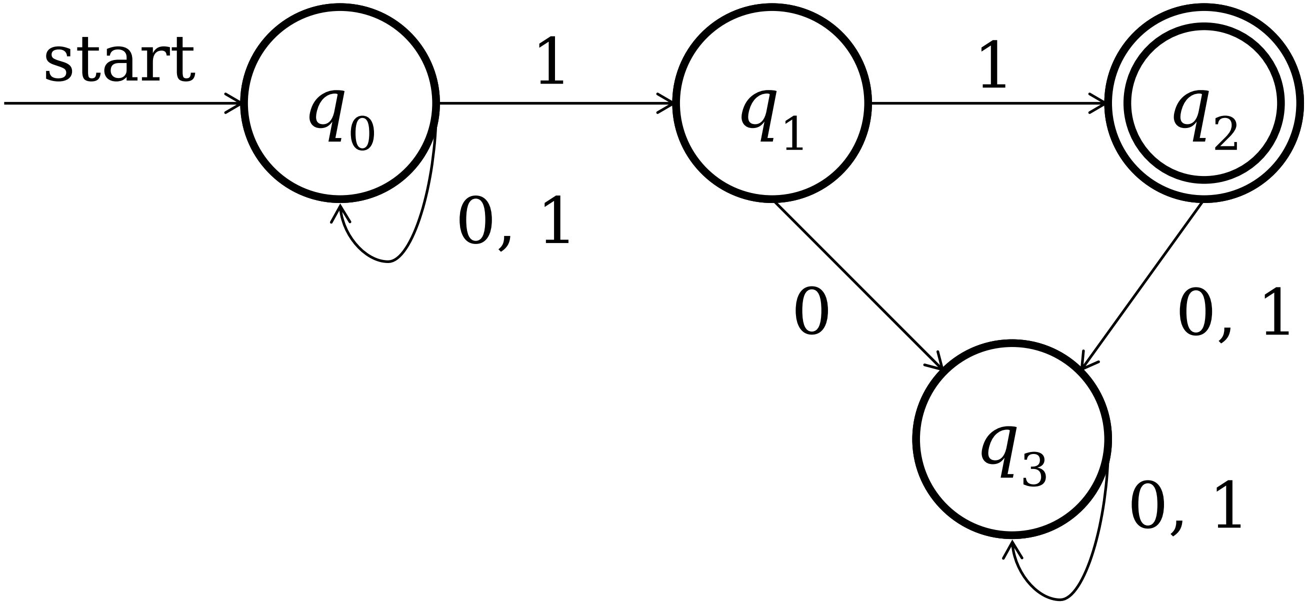
A Simple NFA



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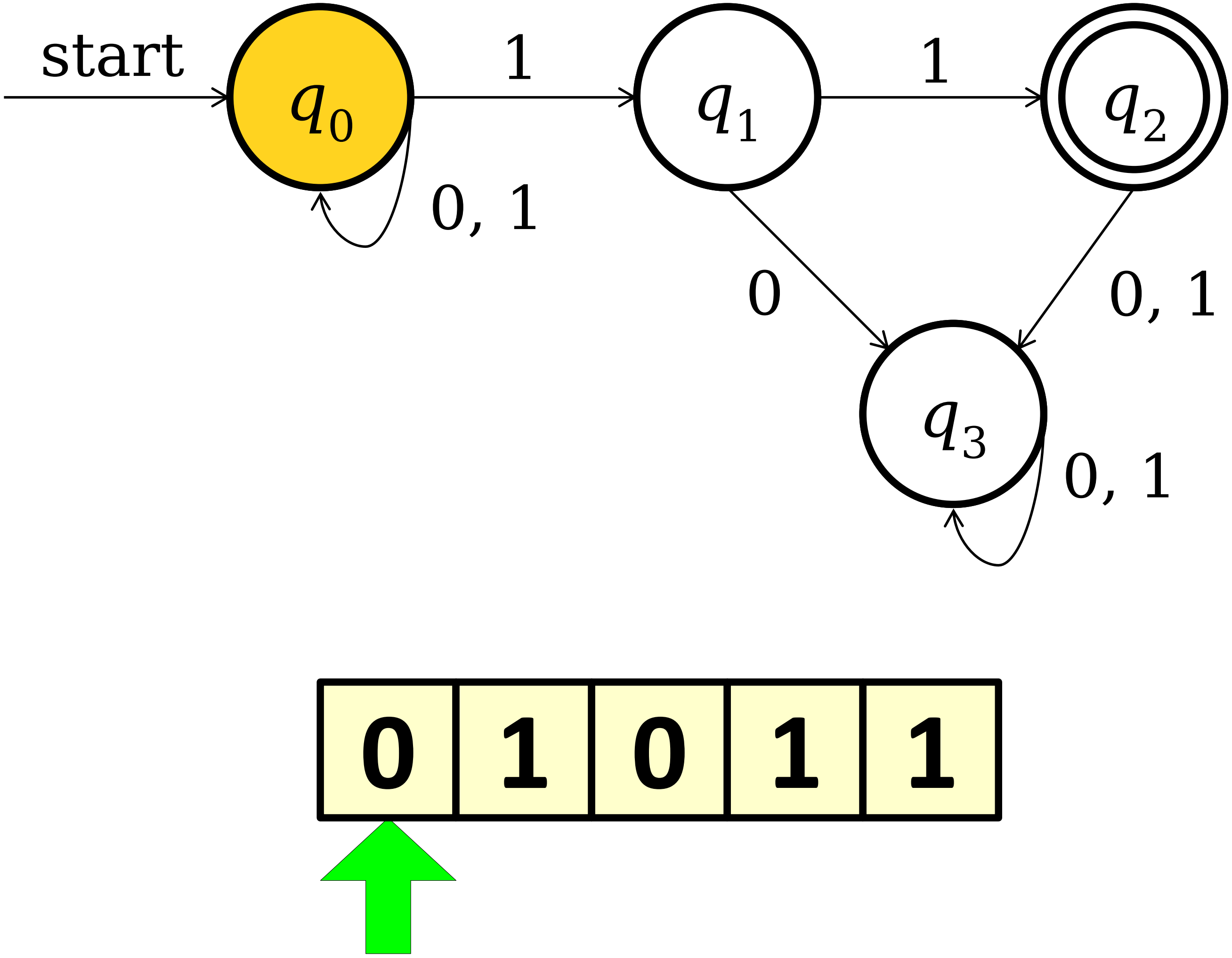

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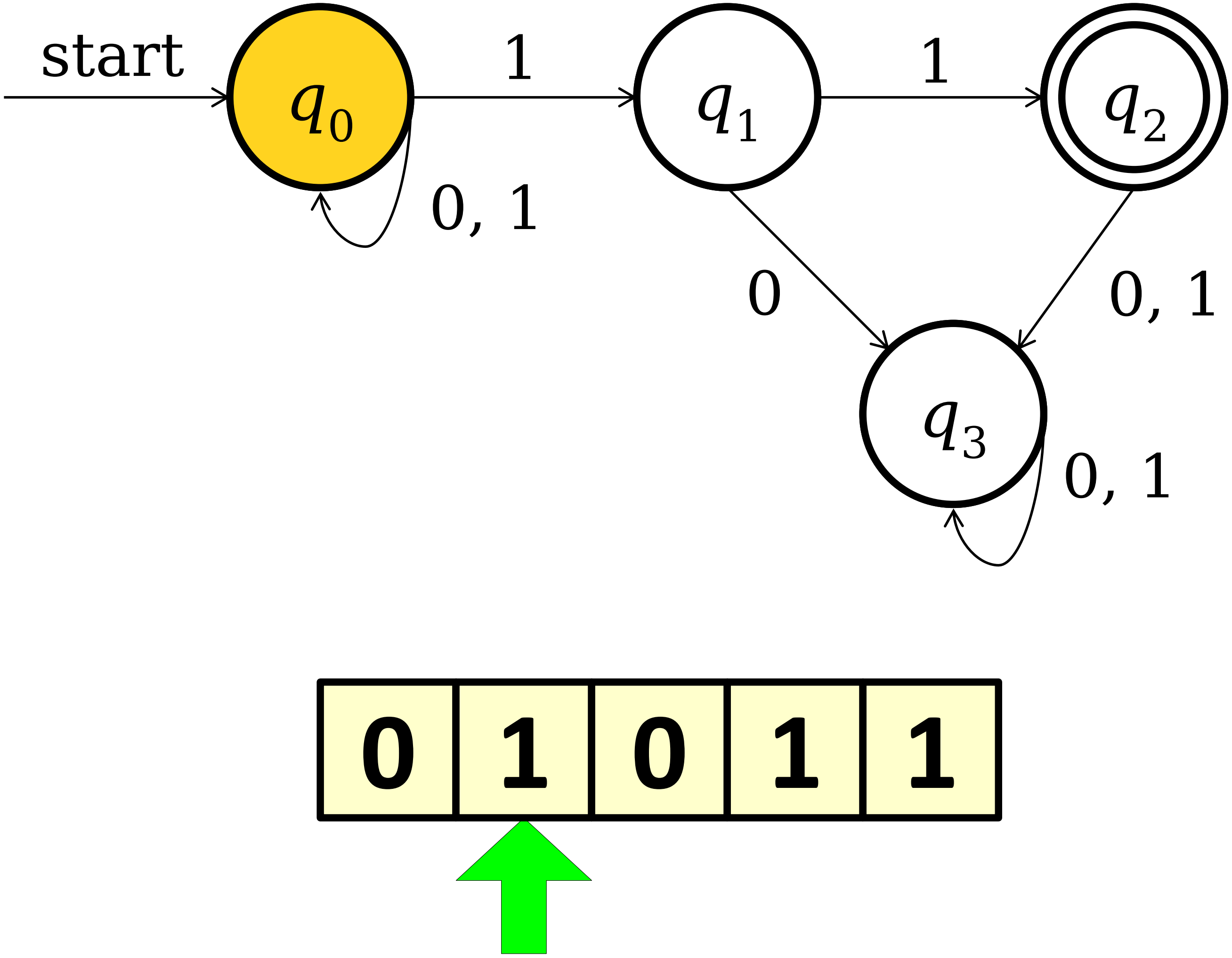

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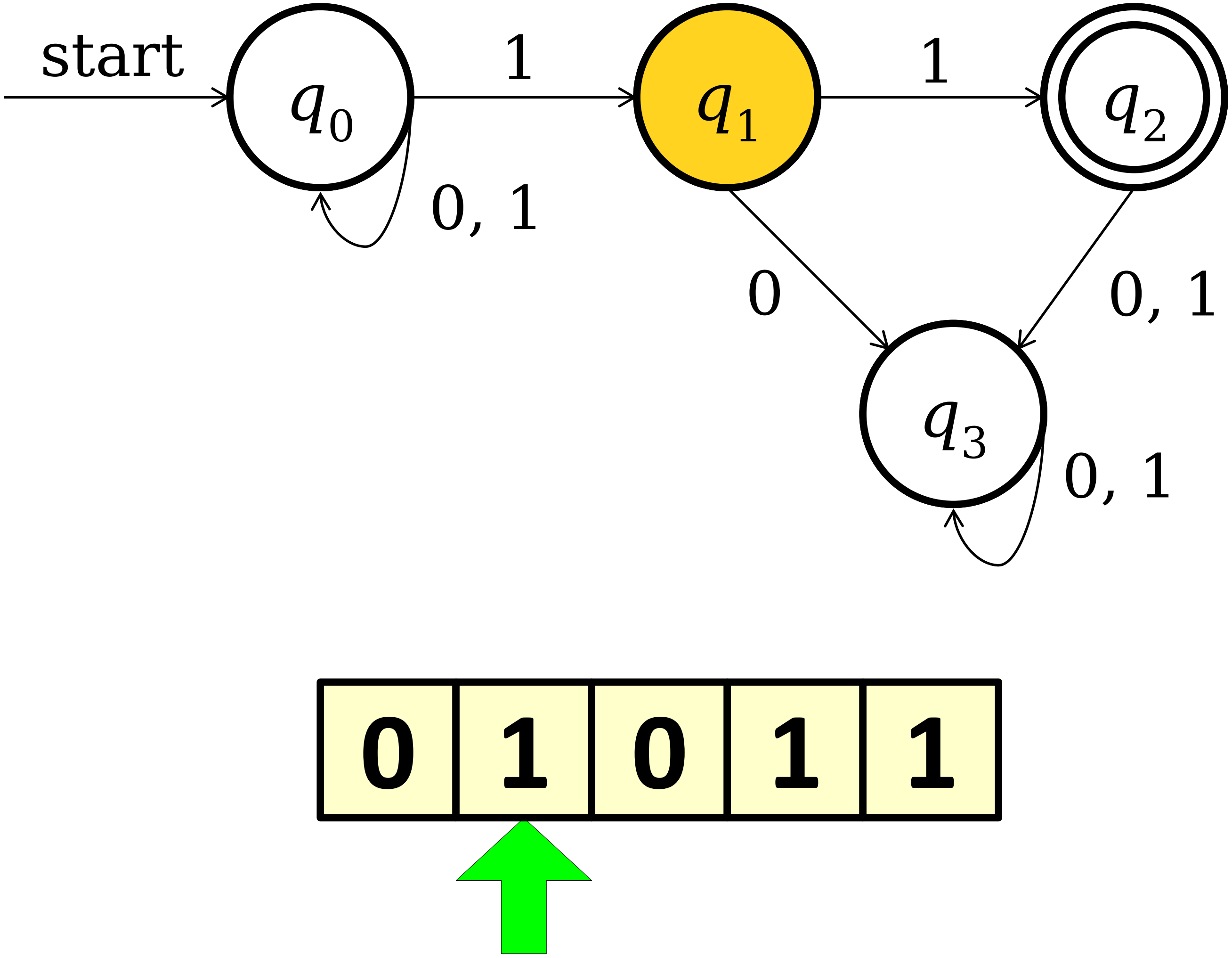

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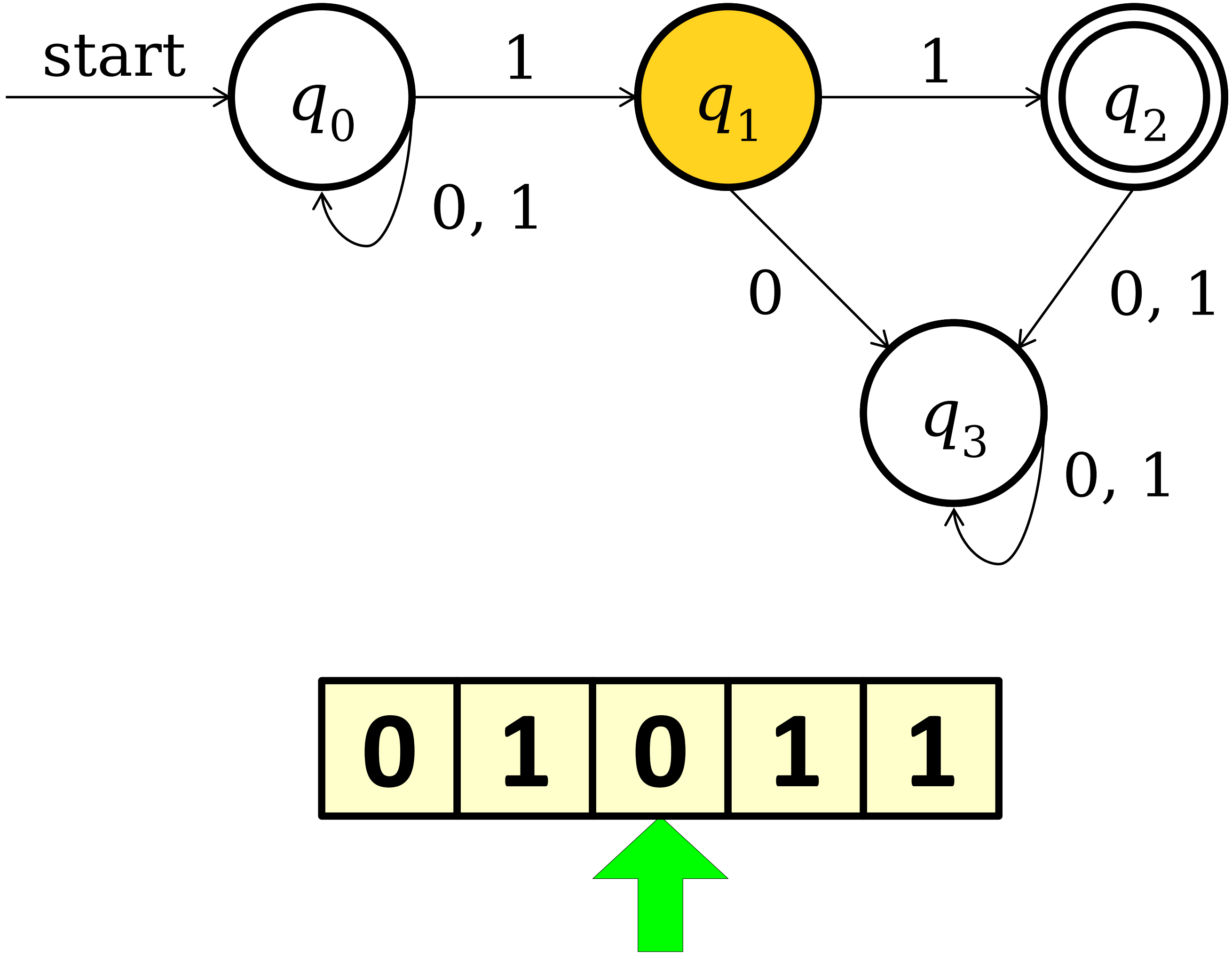

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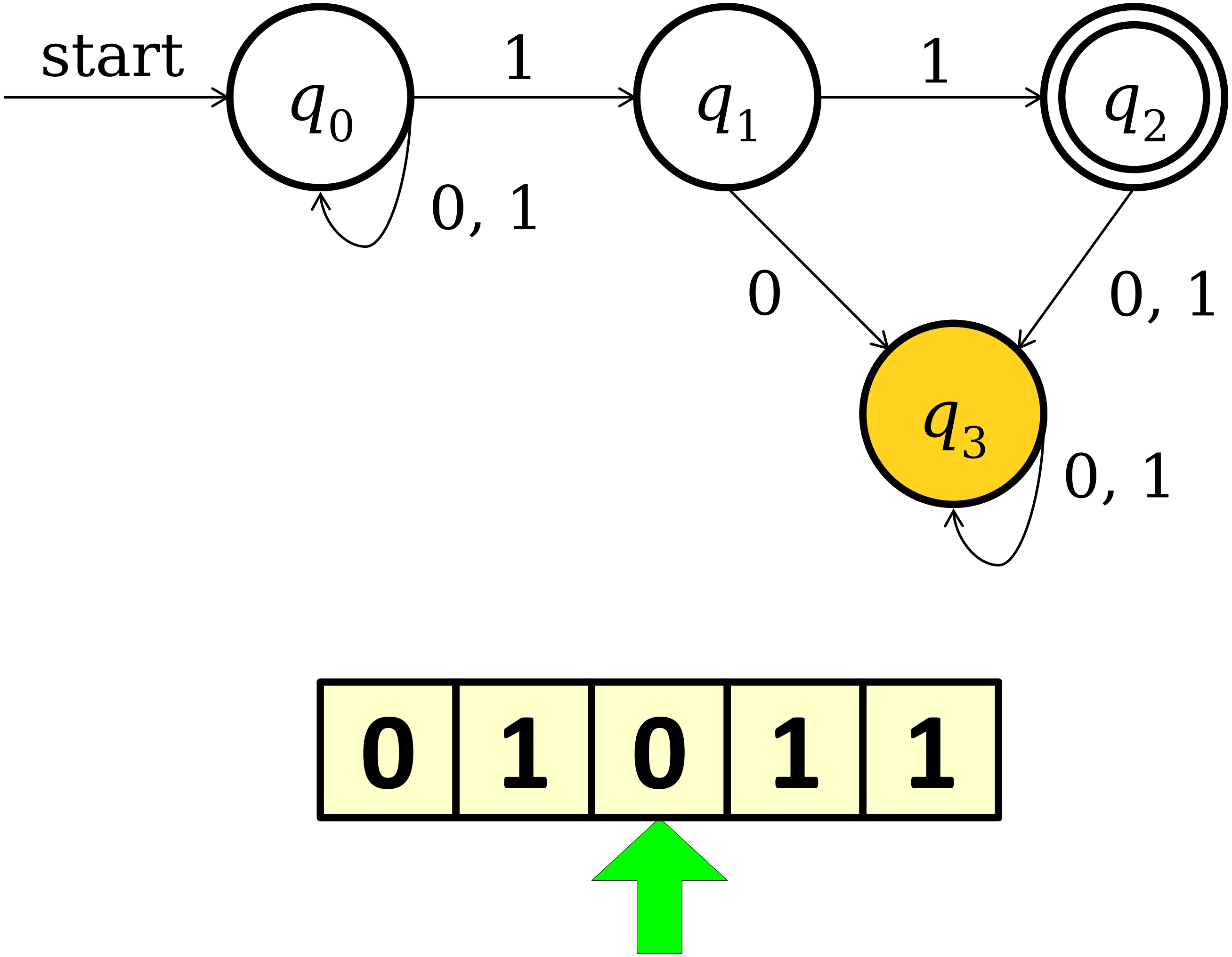

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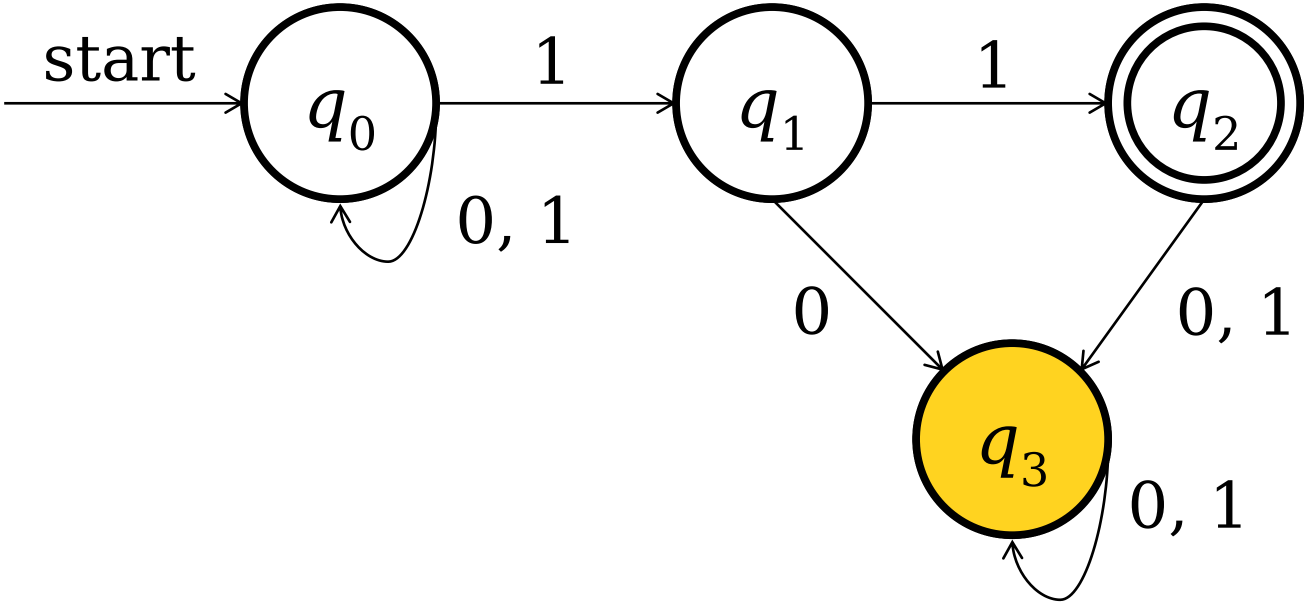

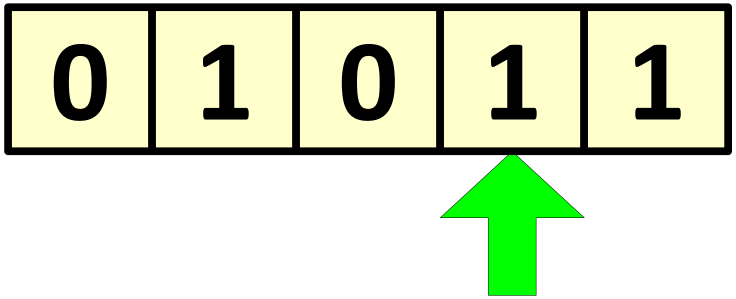

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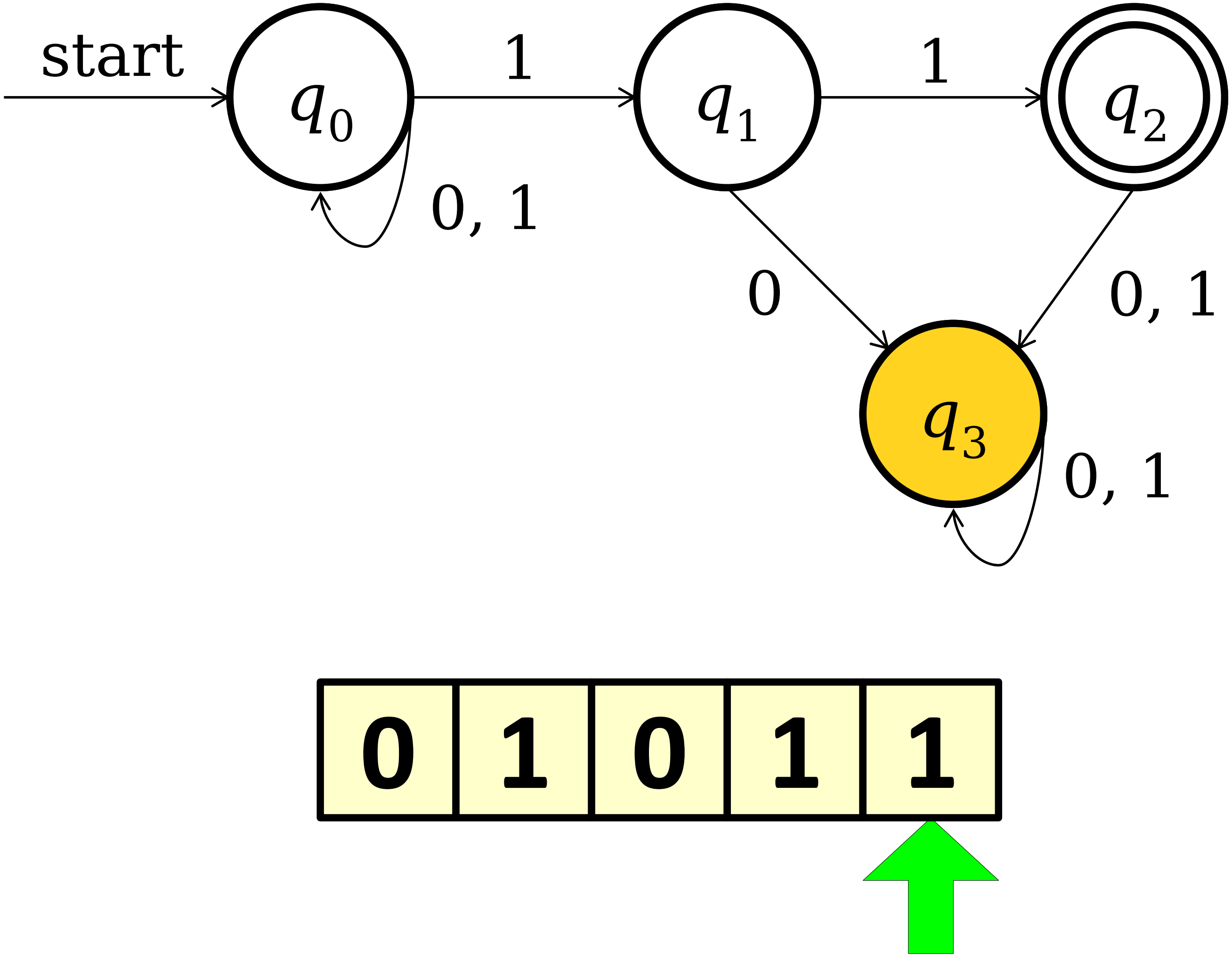
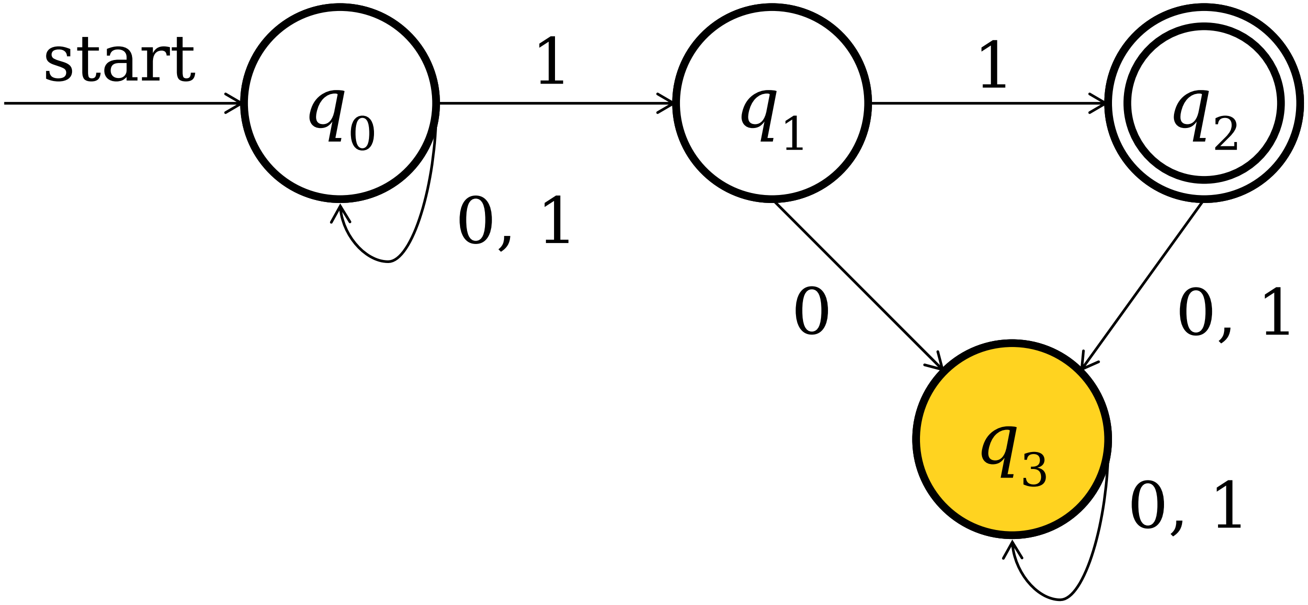
A Simple NFA



A Simple NFA



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

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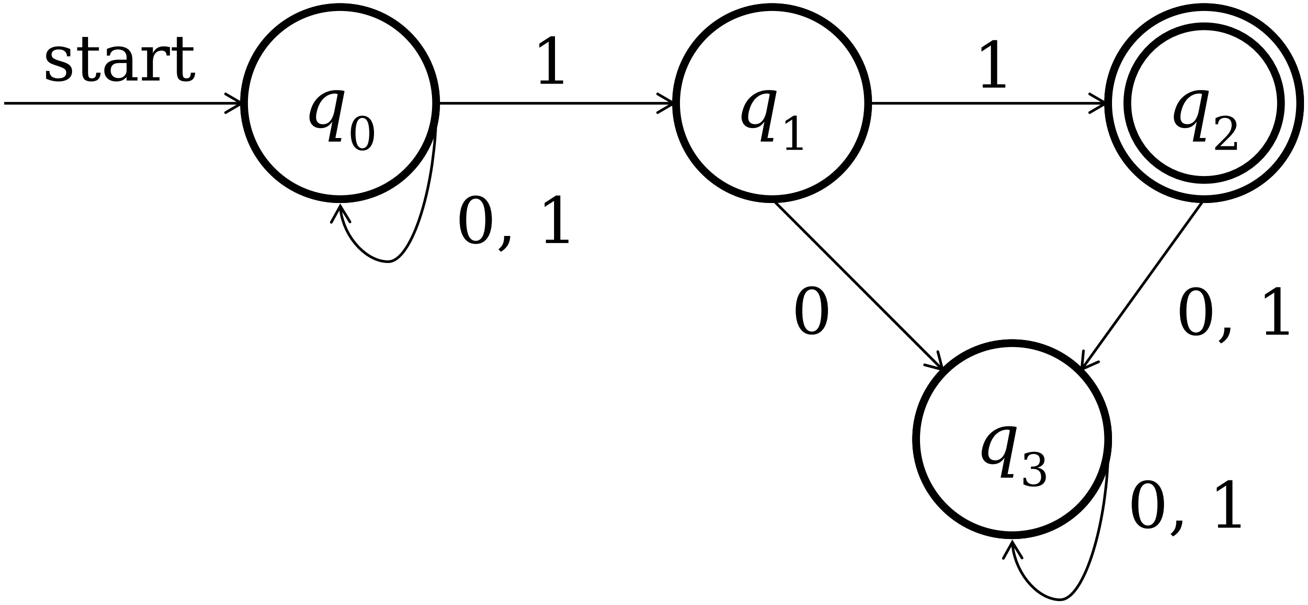

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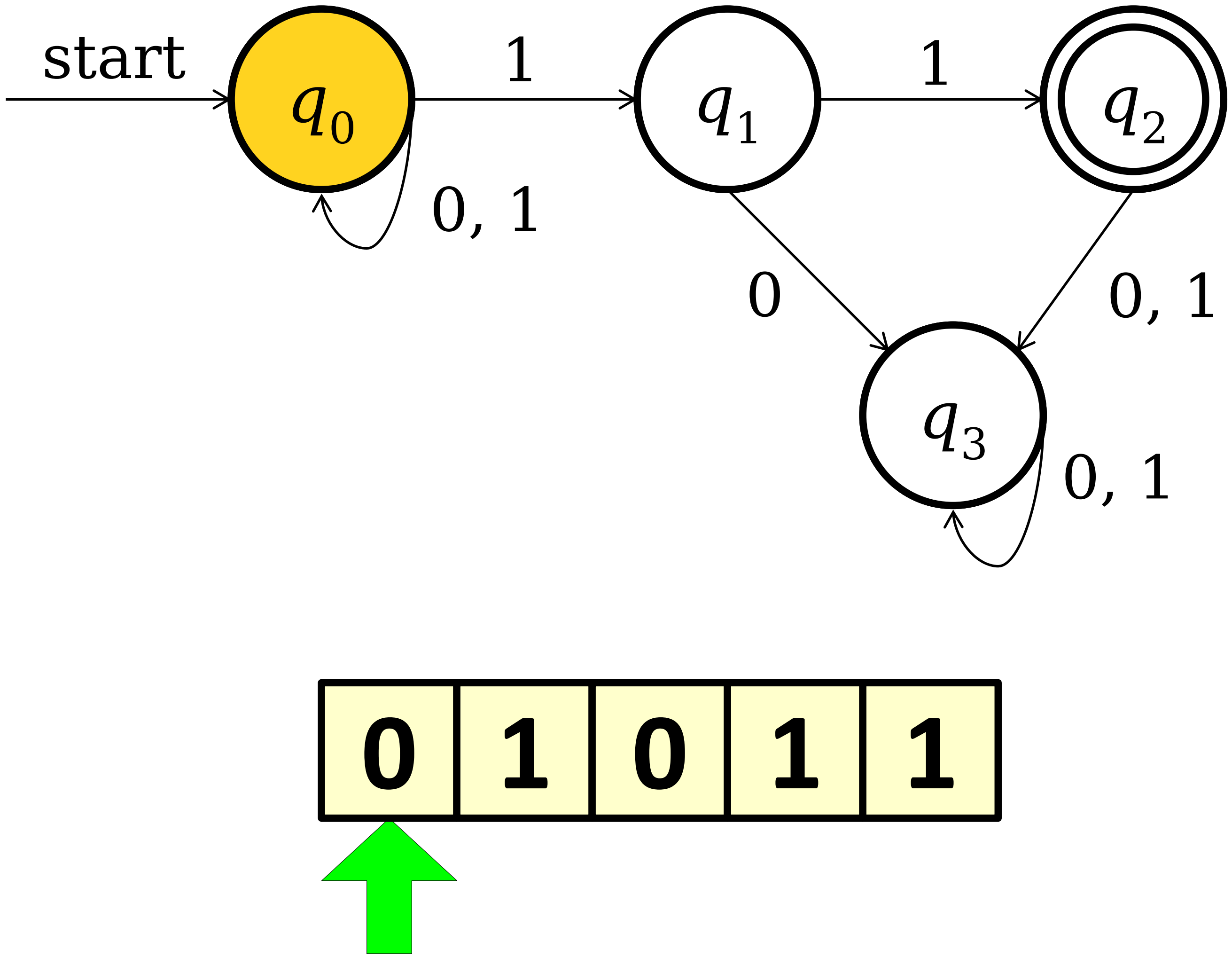

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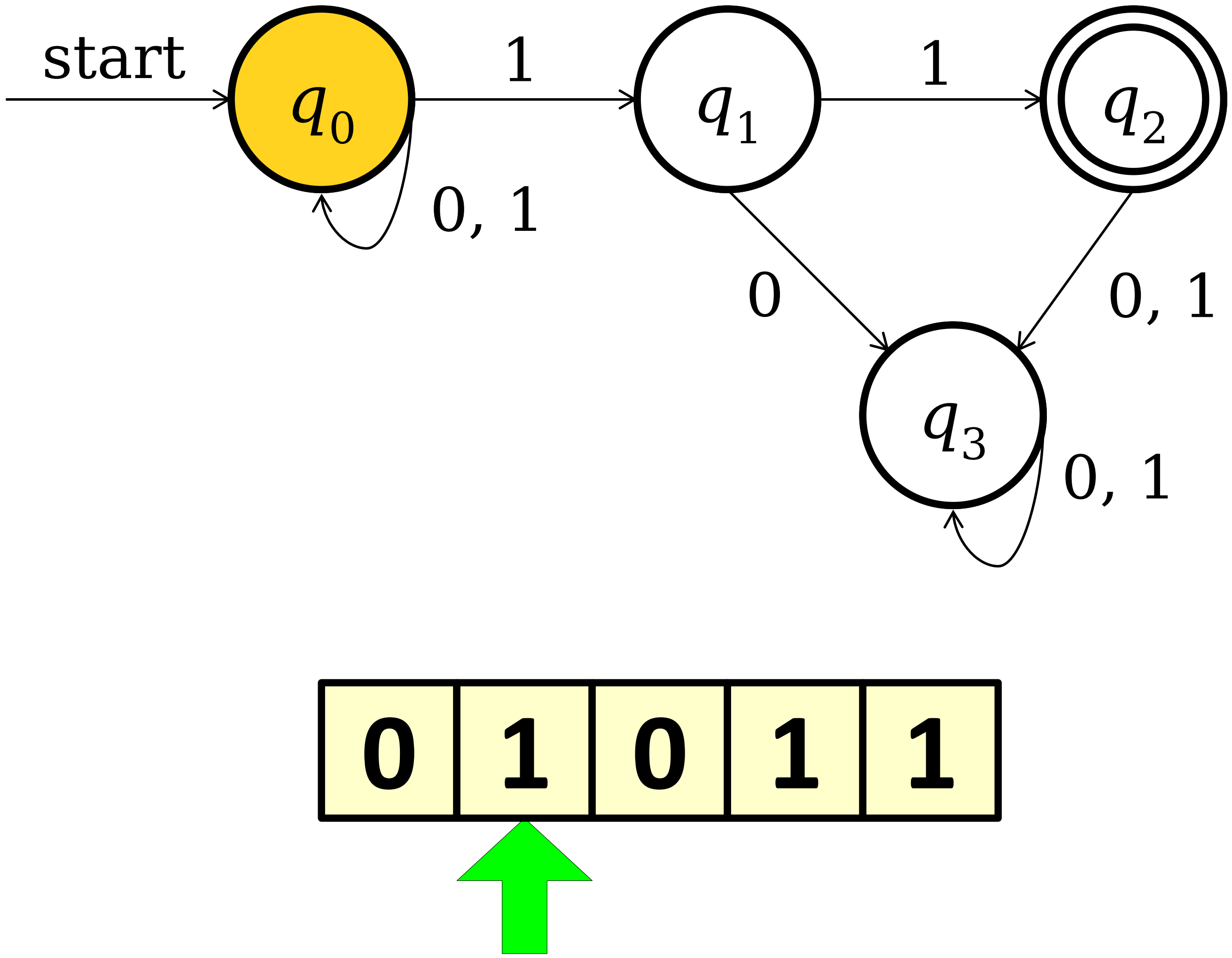

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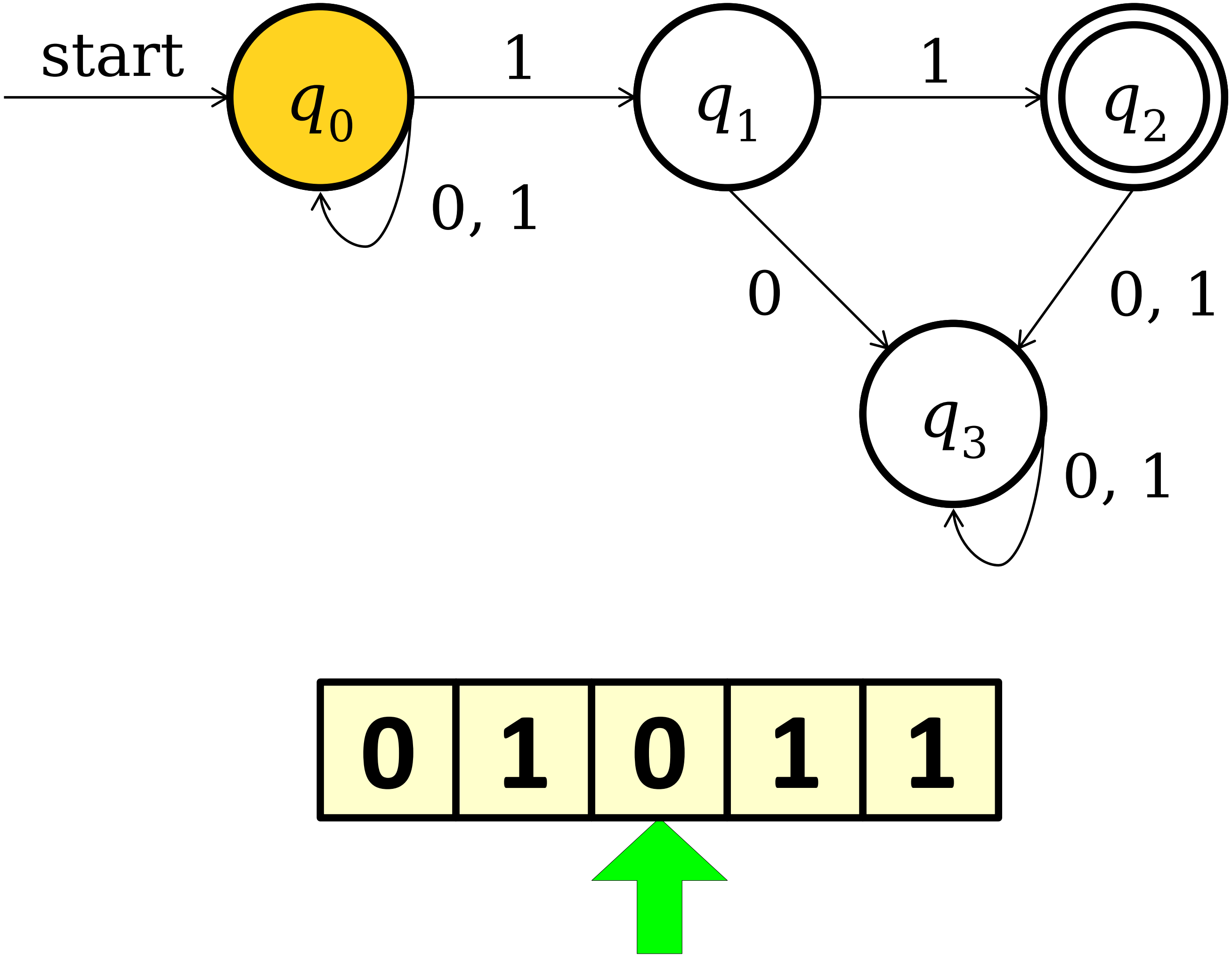

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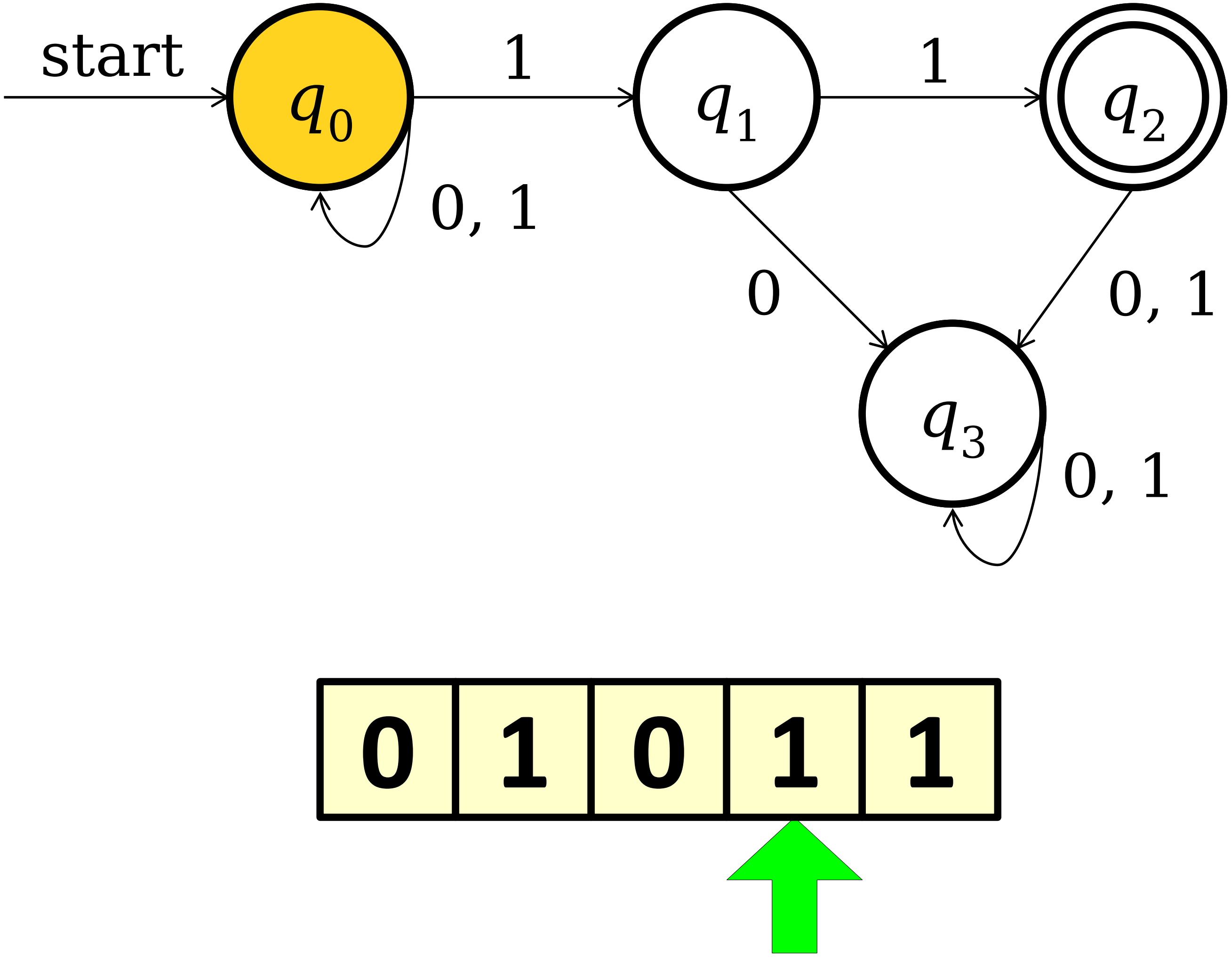

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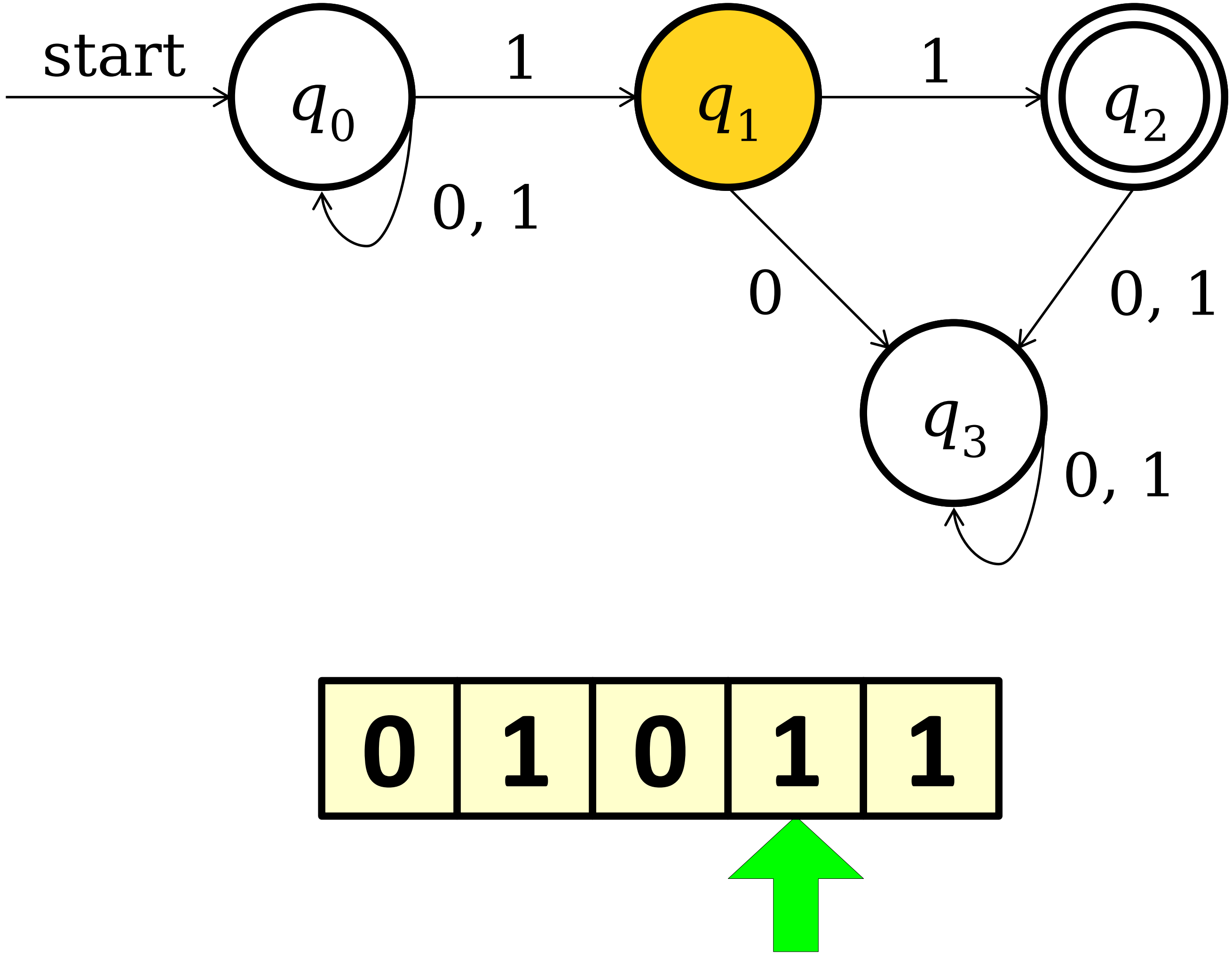

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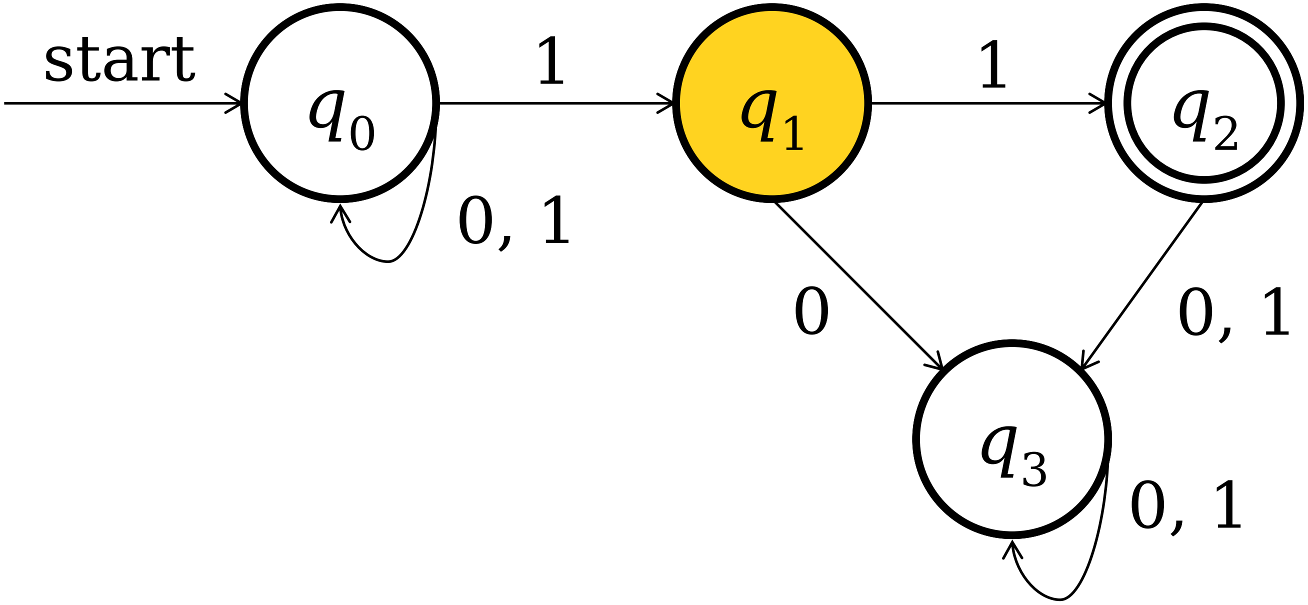

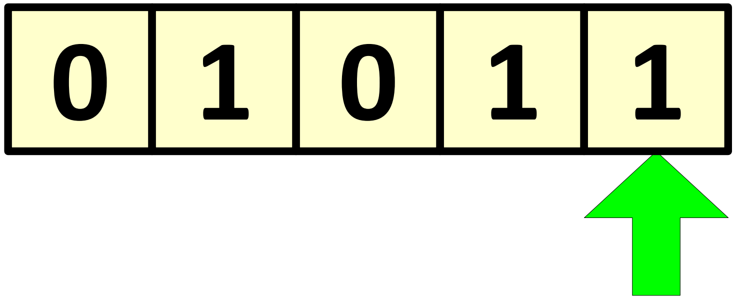

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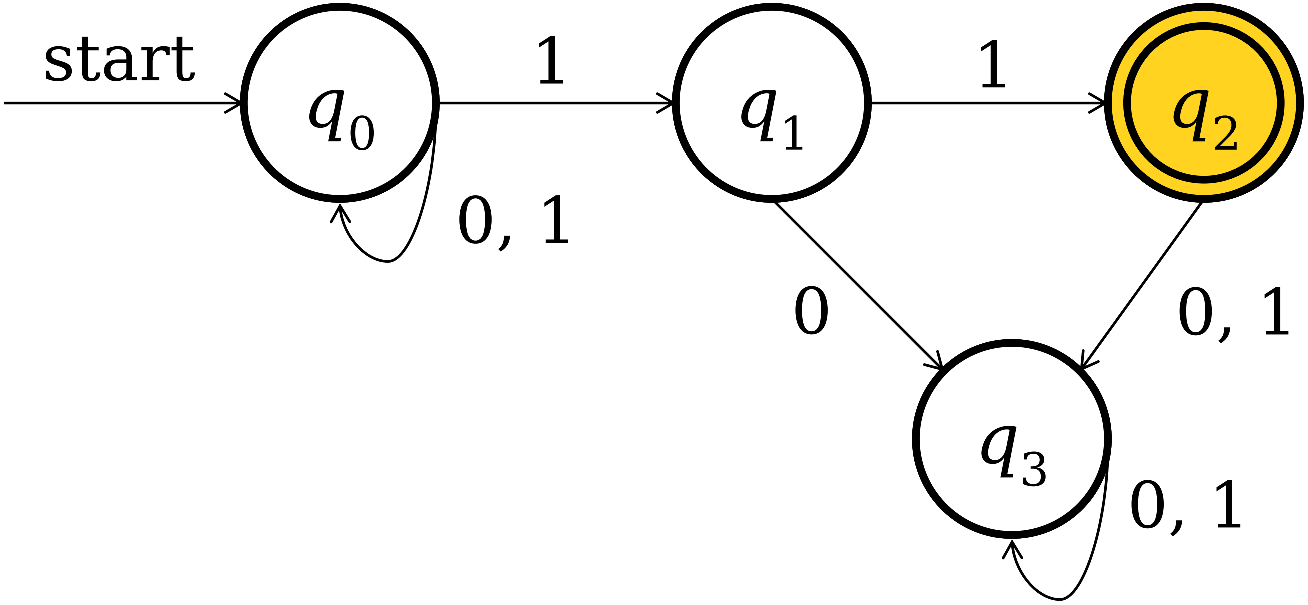
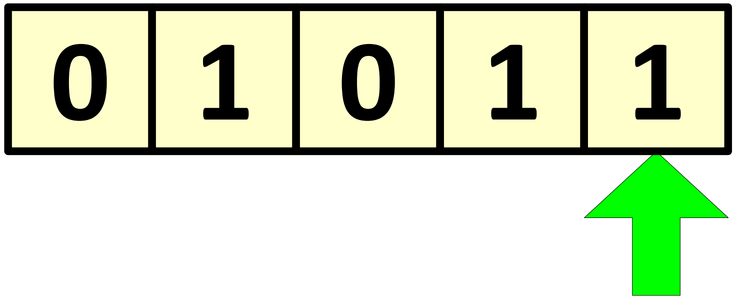
A Simple NFA





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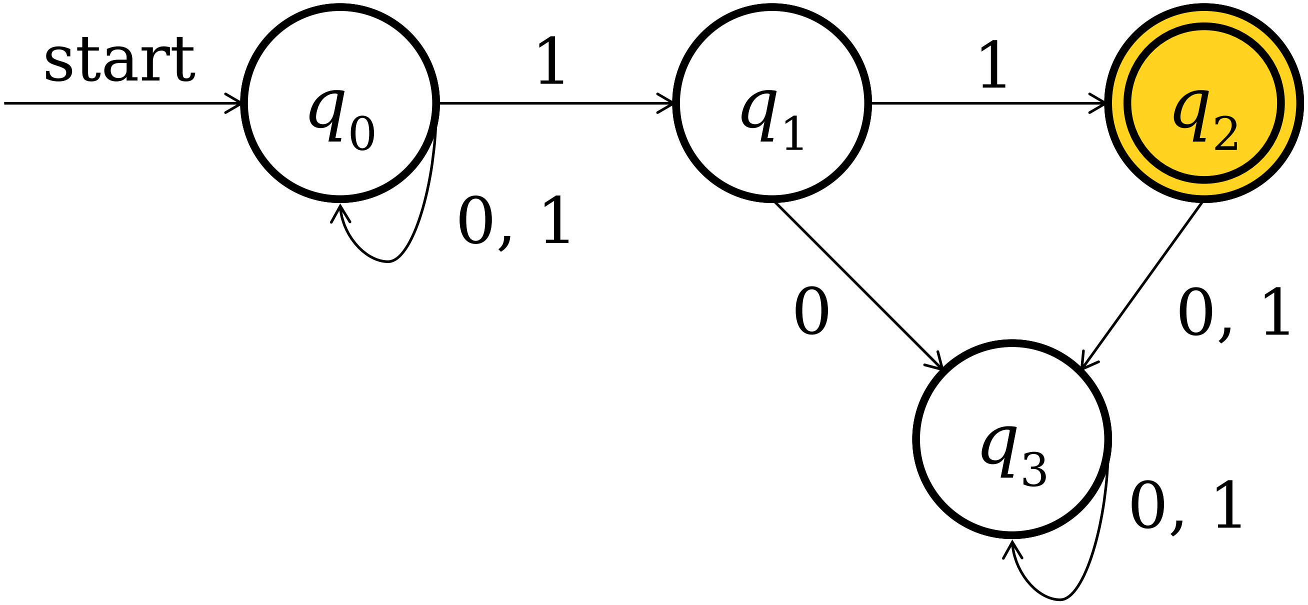

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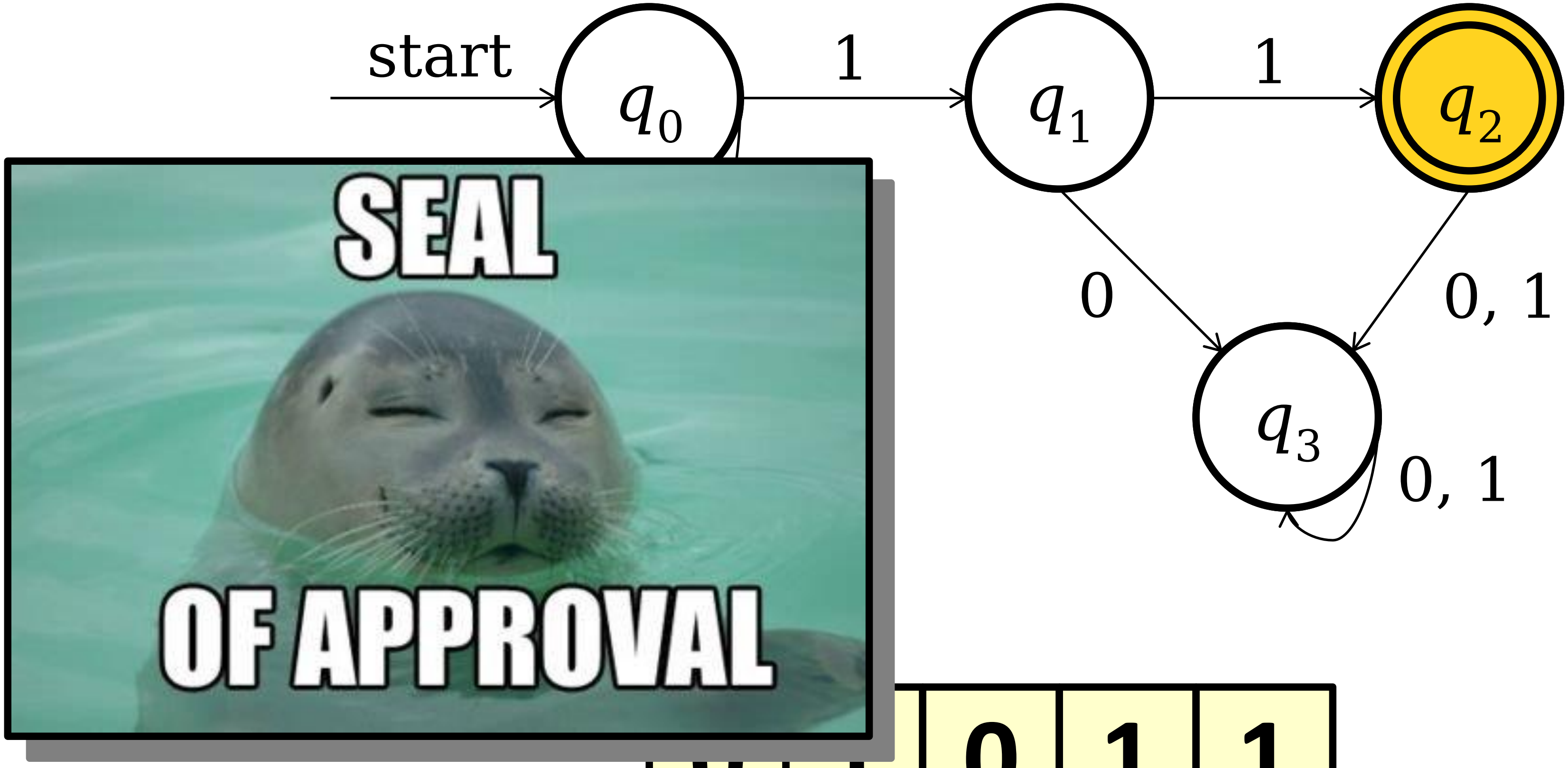

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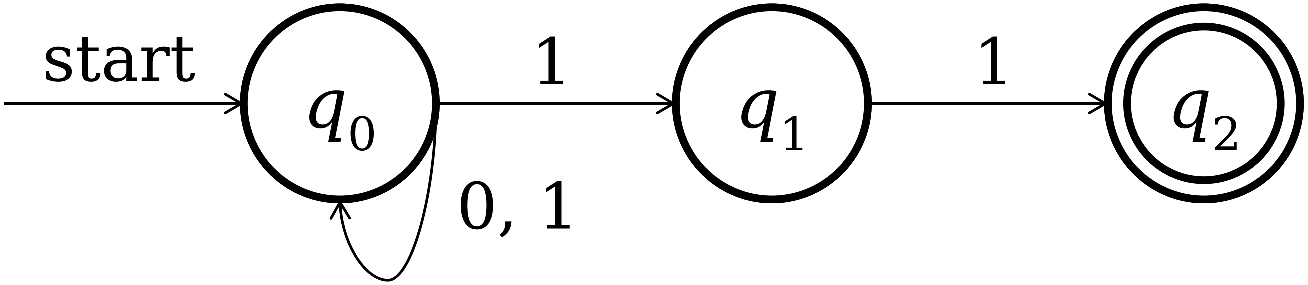
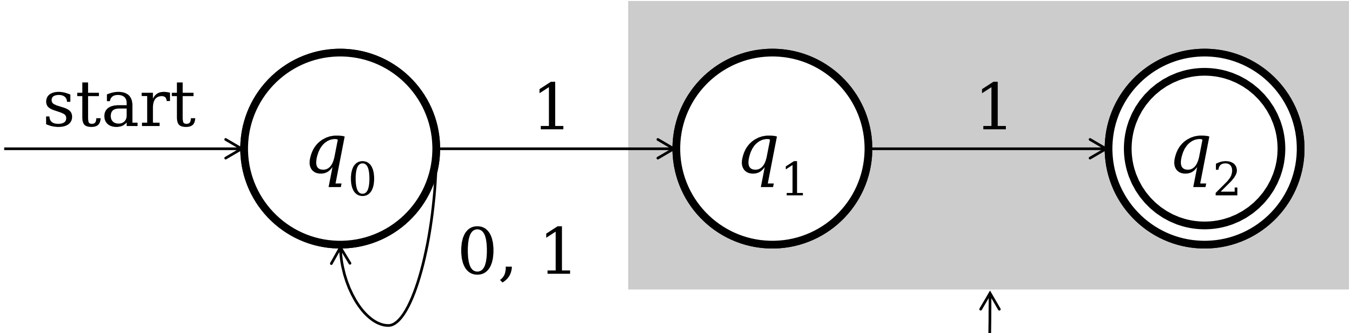
A More Complex NFA

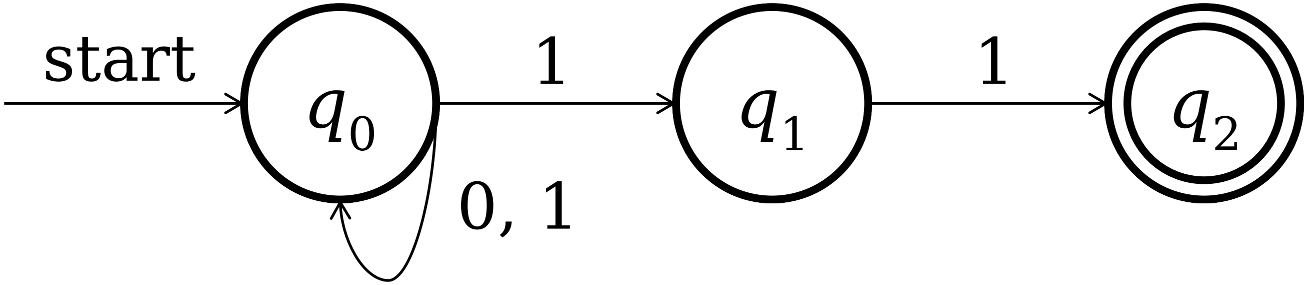


A More Complex NFA



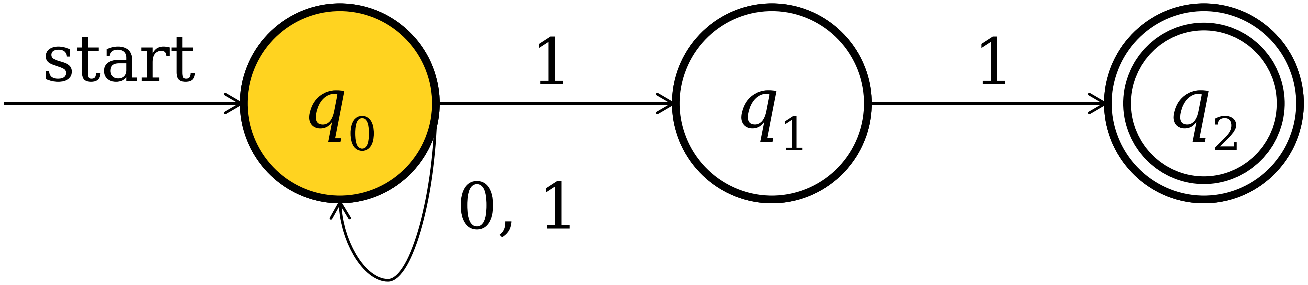
If a NFA needs to make a transition when no transition exists, the automaton **dies** and that particular path does not accept.

A More Complex NFA



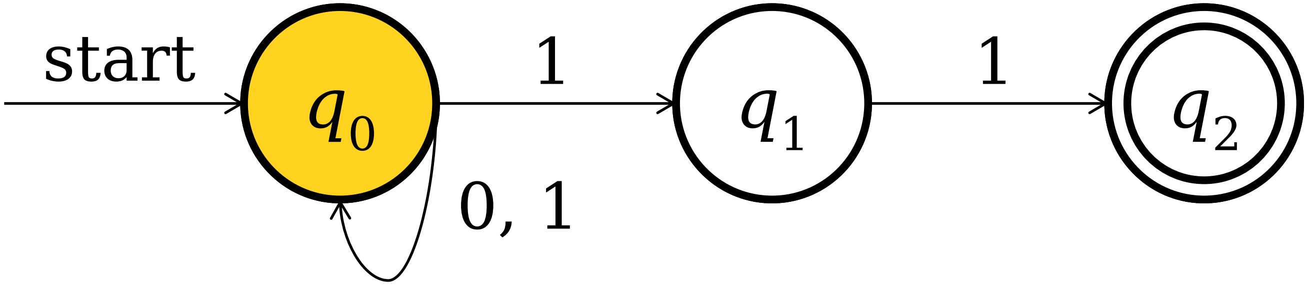
0	**1**	**0**	**1**	**1**

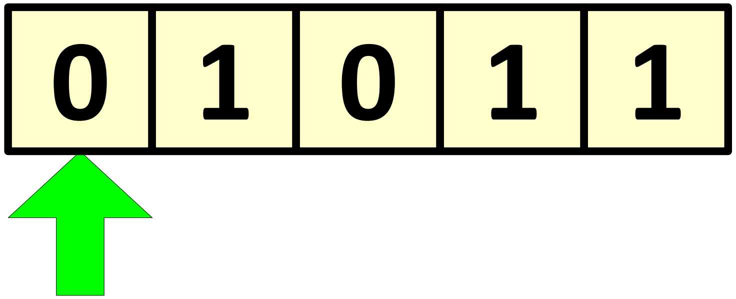
A More Complex NFA



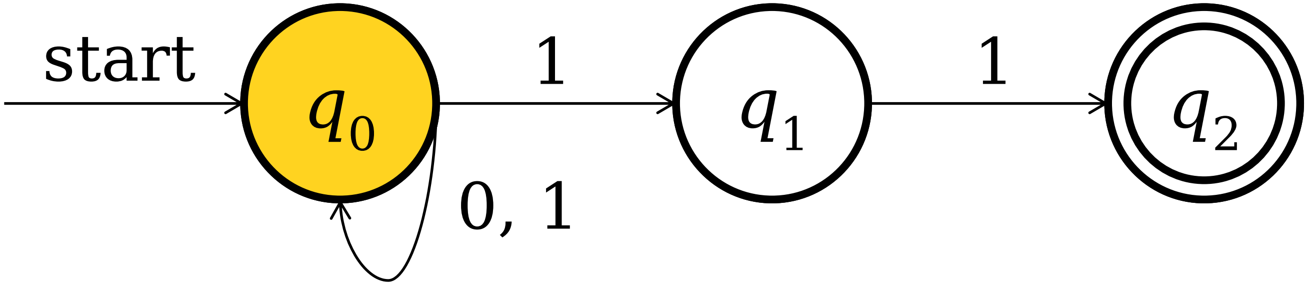
0	**1**	**0**	**1**	**1**

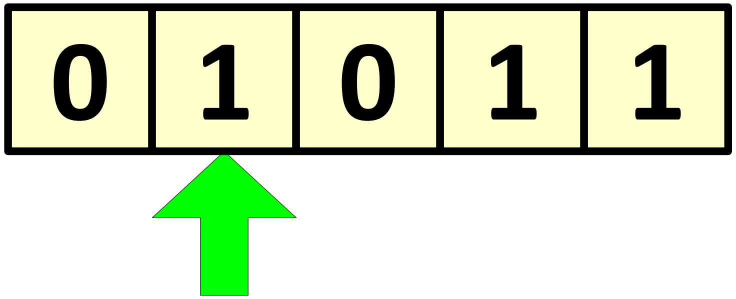
A More Complex NFA





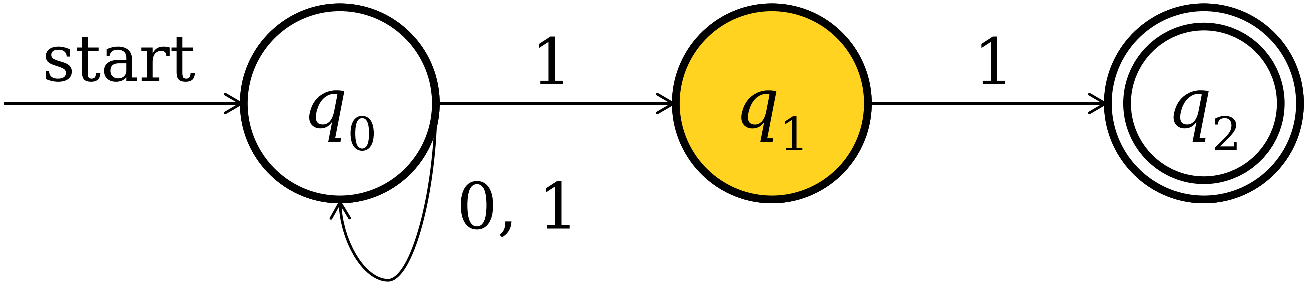
A More Complex NFA

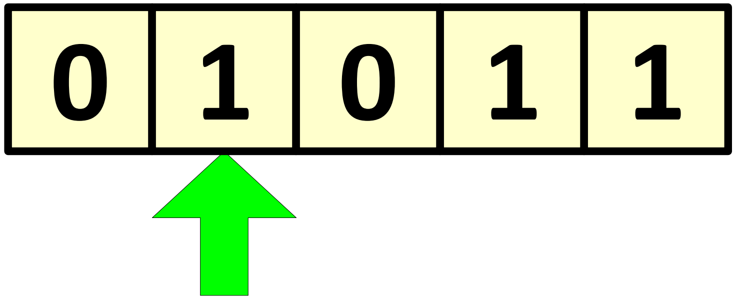




0	1	0	1	1

A More Complex NFA





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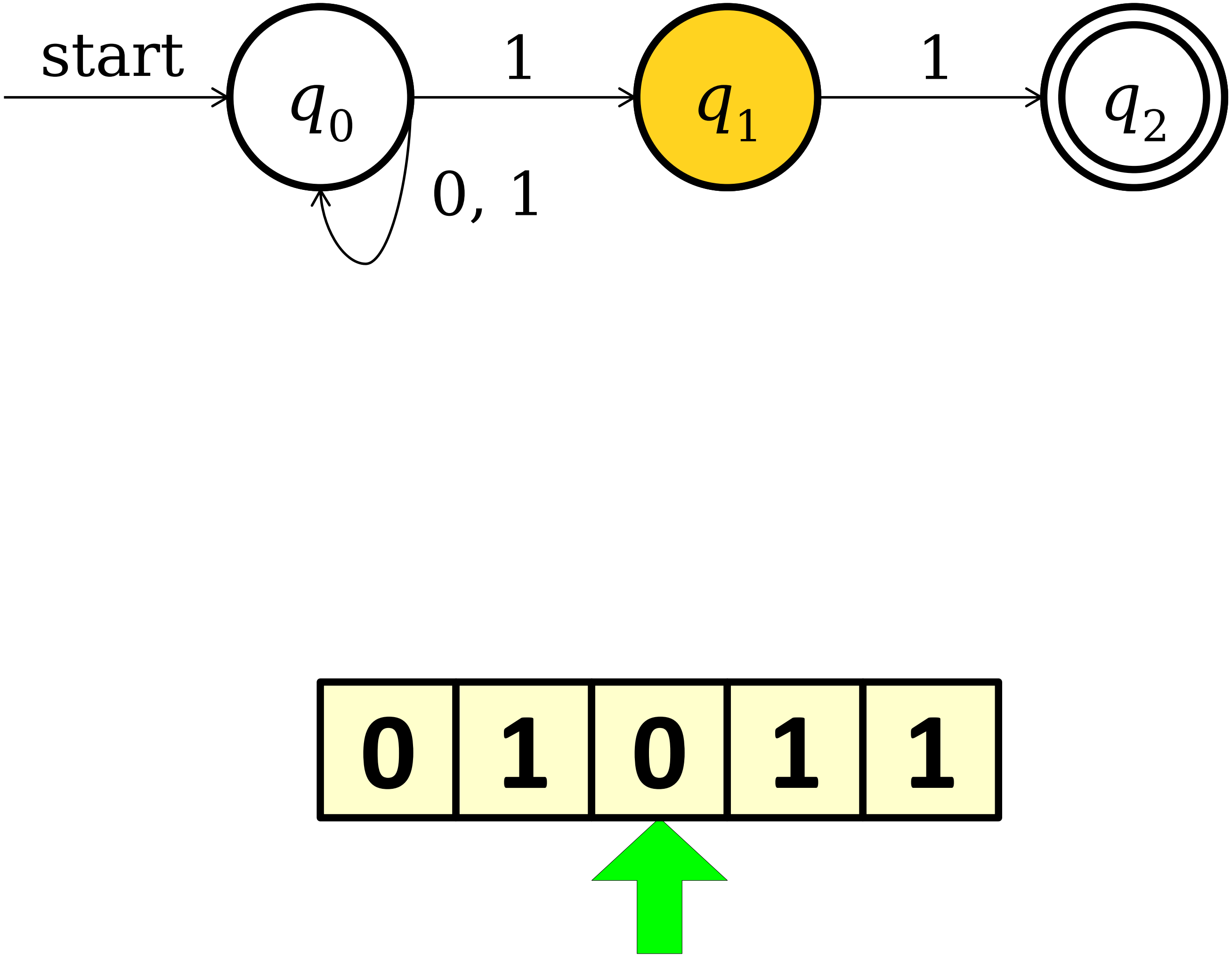
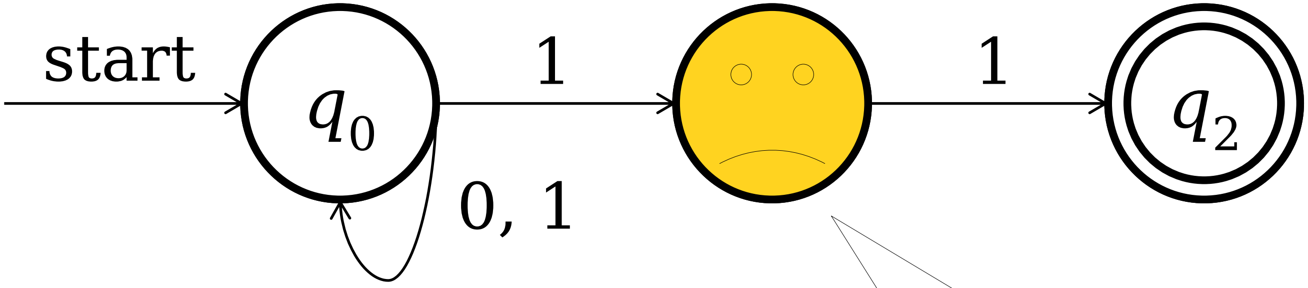
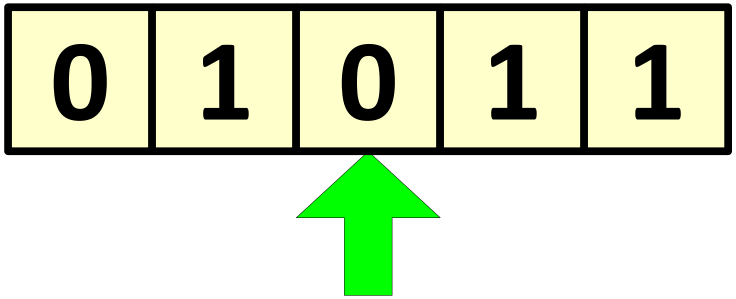
A More Complex NFA



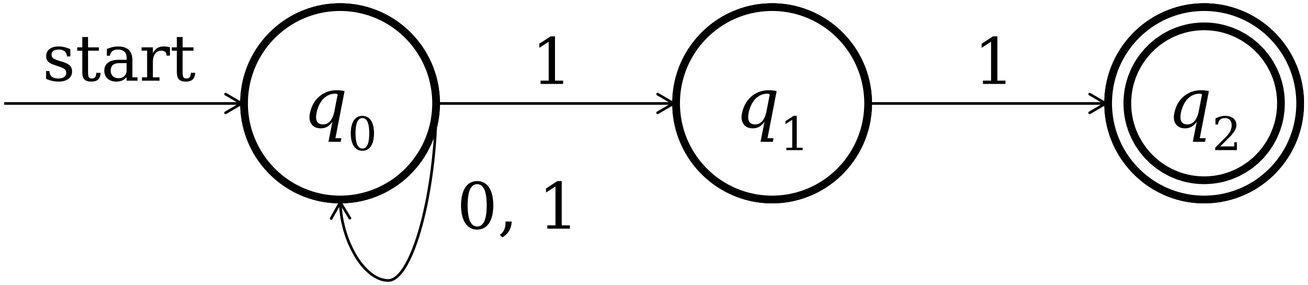
A More Complex NFA

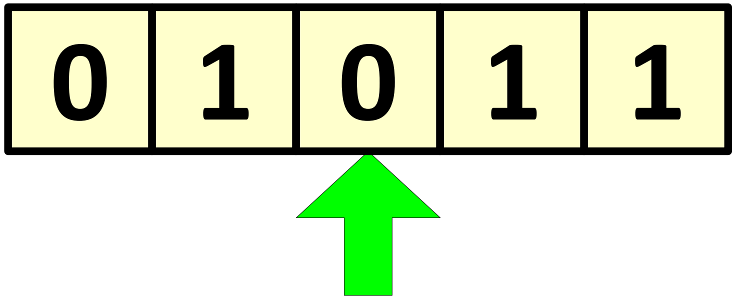


Oh no! There's no transition defined!



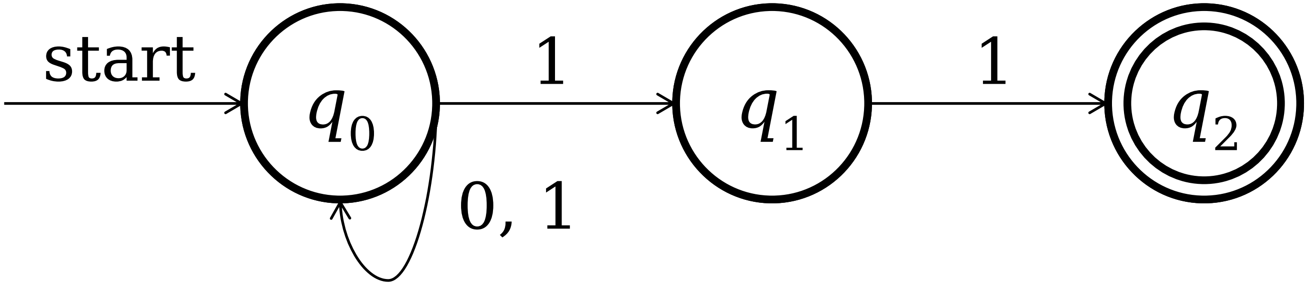
A More Complex NFA





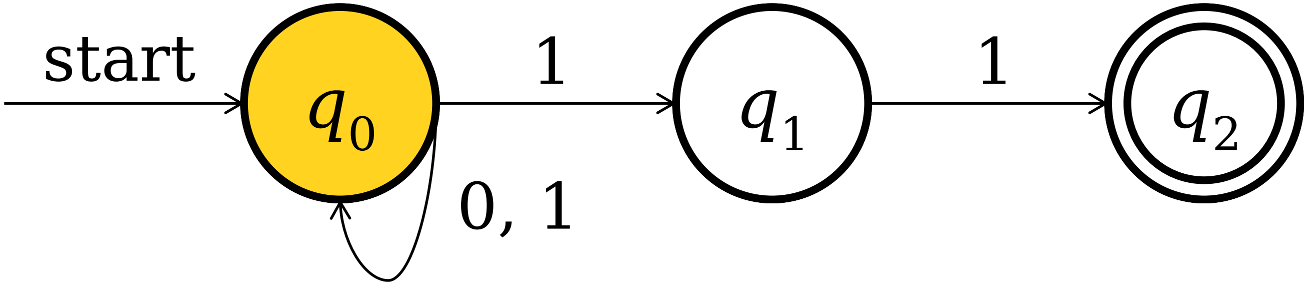
0	**1**	**0**	**1**	**1**

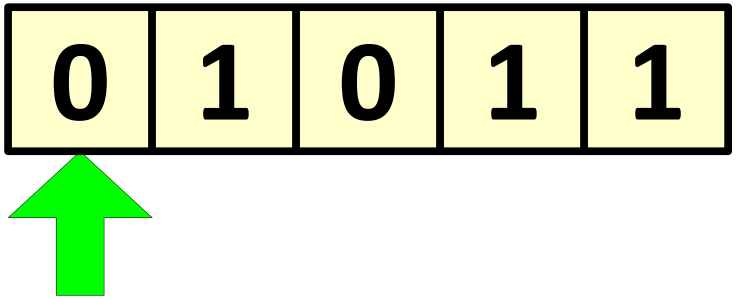
A More Complex NFA



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

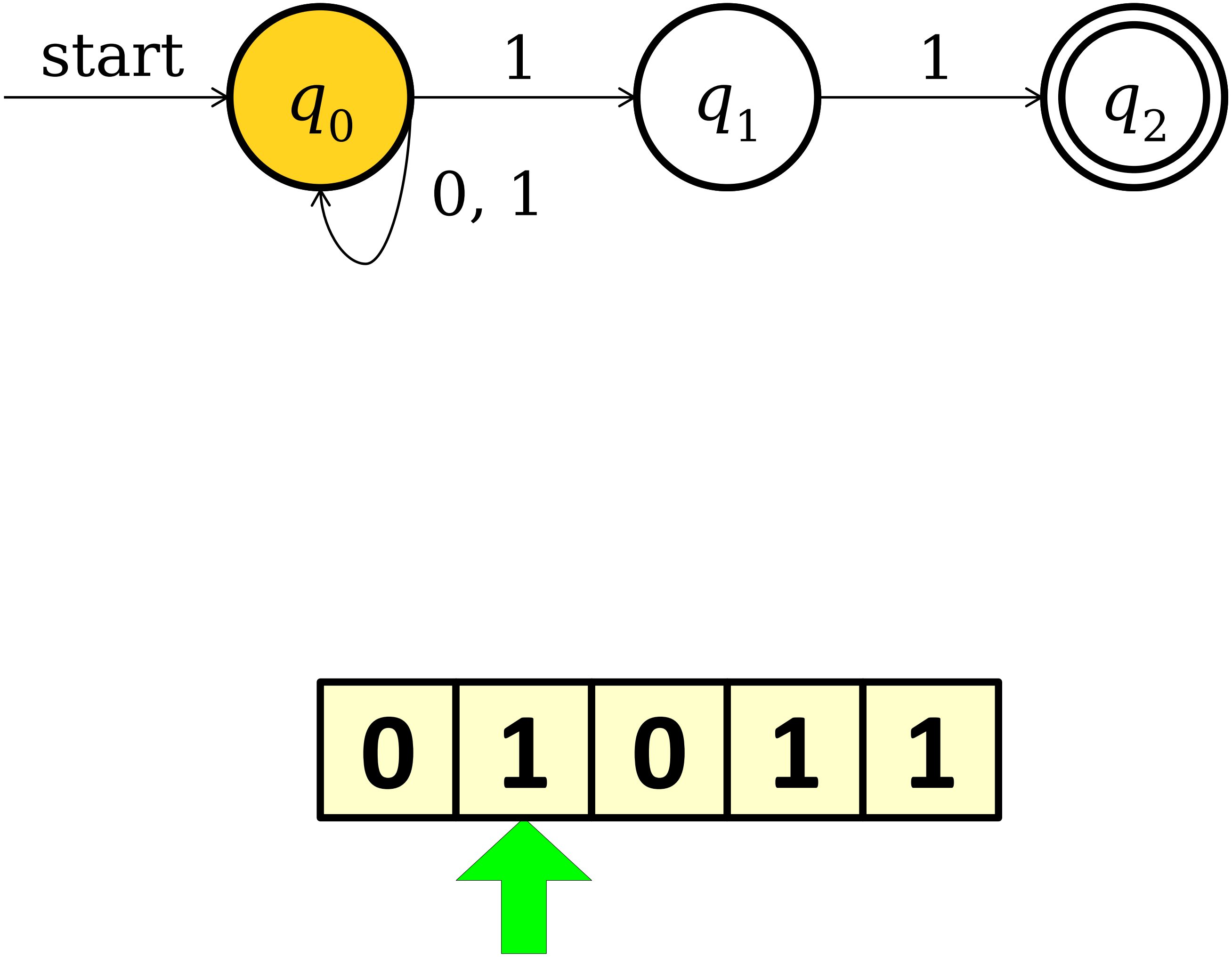
A More Complex NFA





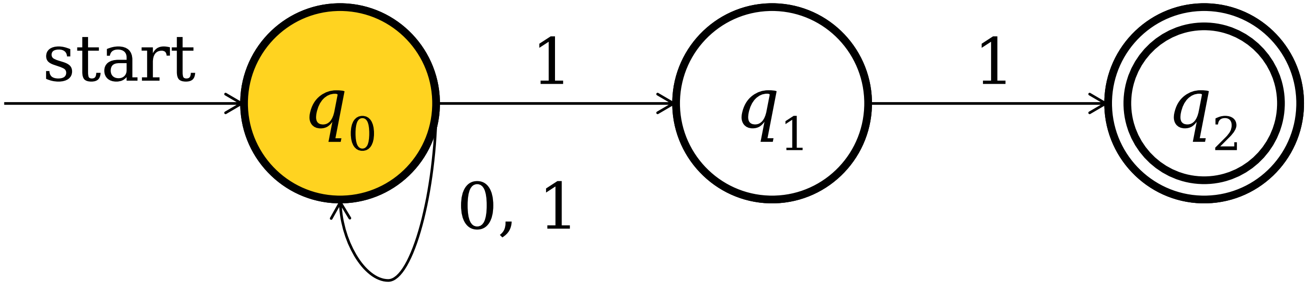
0	**1**	**0**	**1**	**1**

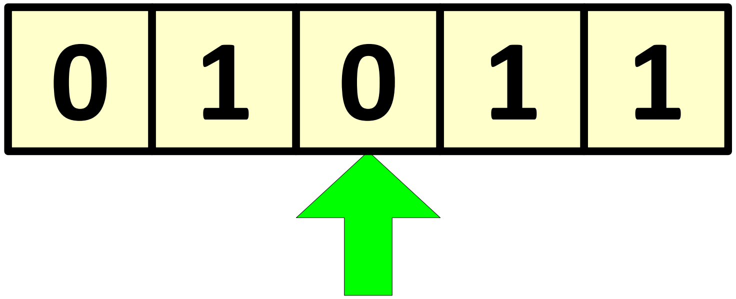
A More Complex NFA



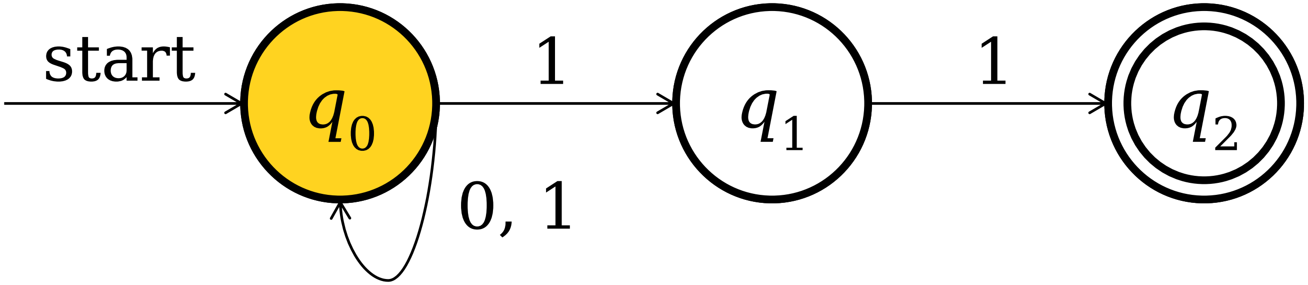
0	**1**	**0**	**1**	**1**

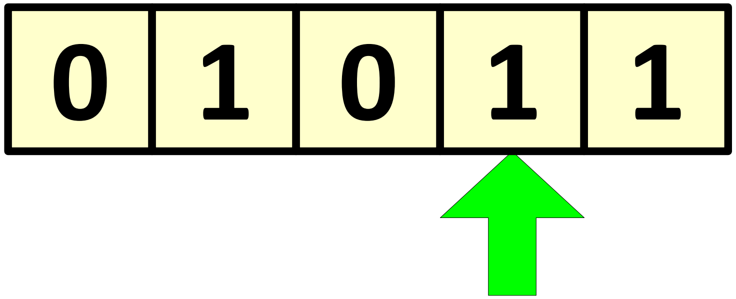
A More Complex NFA



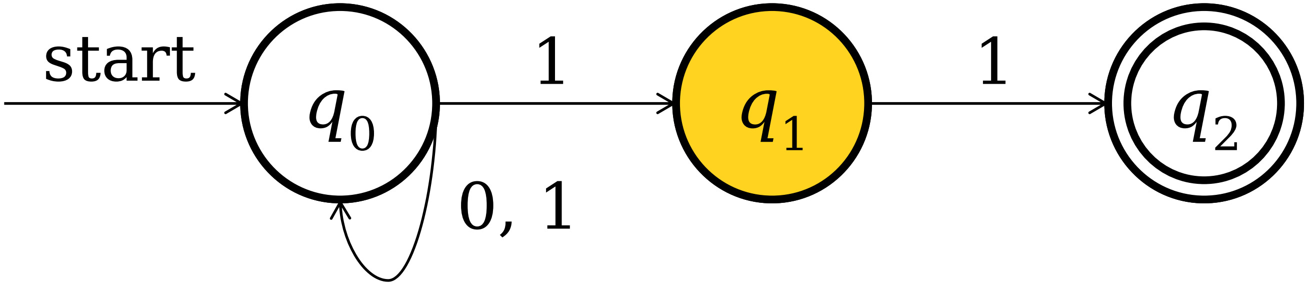


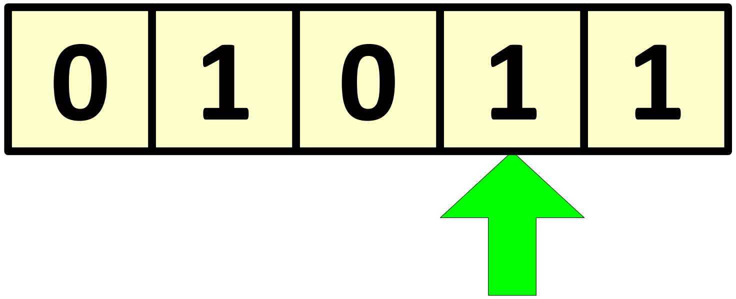
A More Complex NFA





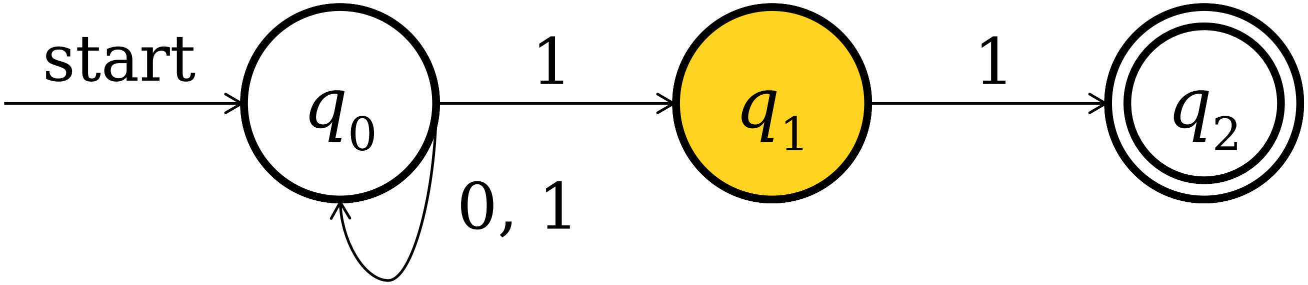
A More Complex NFA

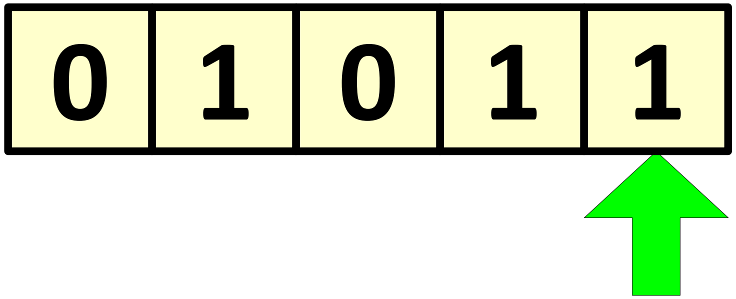




0	**1**	**0**	**1**	**1**

A More Complex NFA





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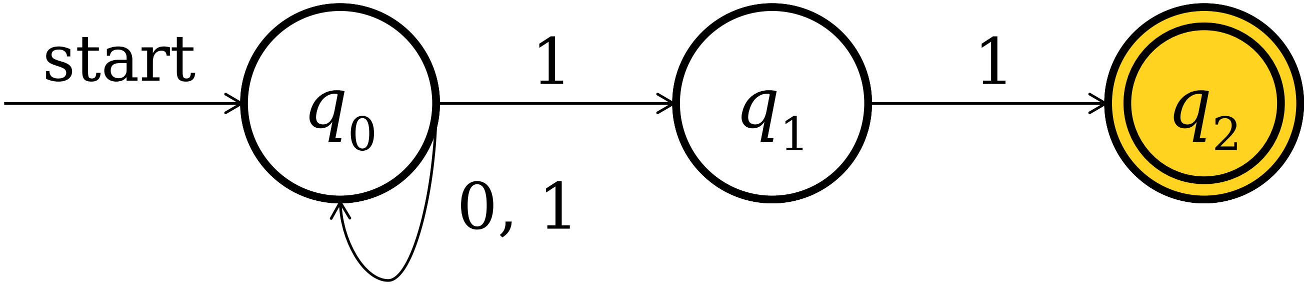
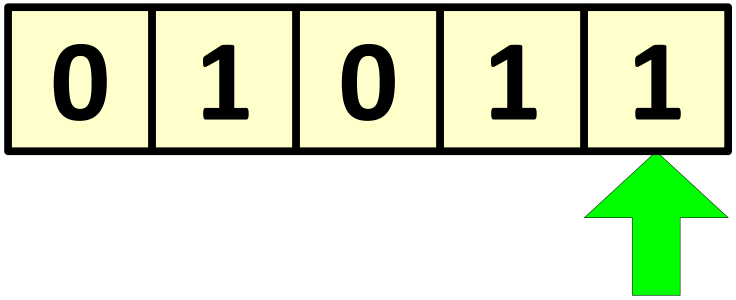
A More Complex NFA





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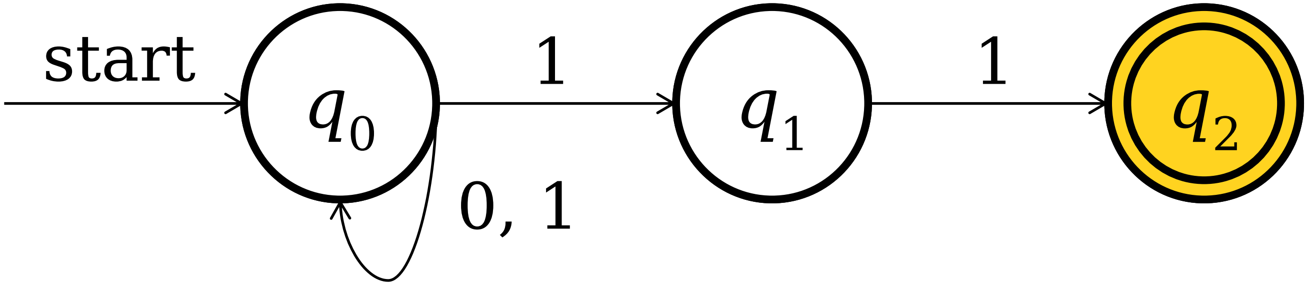
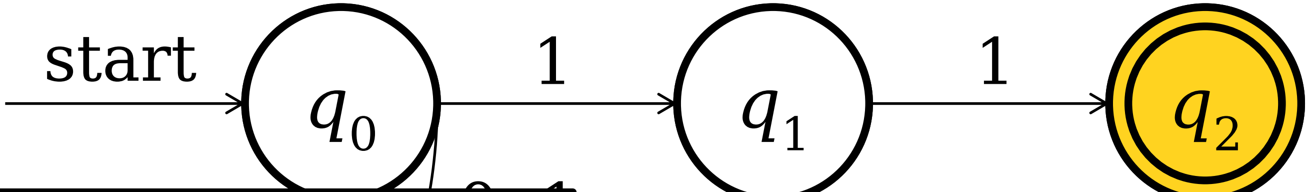


0	**1**	**0**	**1**	**1**

A More Complex NFA



0	1	0	1	1

Next Time

DFAs vs NFAs

How do these two models of computation relate?

Regular Languages

A first classification of “problems”.