Universidad Carlos III de Madrid
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AUTOMATA THEORY AND FORMAL LANGUAGES

UNIT 7: TURING MACHINE

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OUTLINE

- Definition of Turing Machine
- Variations of Turing Machines
- Universal Turing Machine
- Additional issues

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OUTLINE

- **Definition of Turing Machine**
- Variations of Turing Machines
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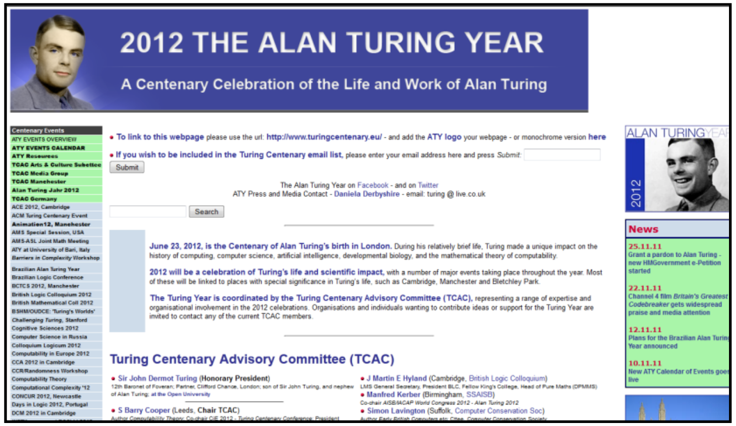
Definition of Turing Machine

Alan Turing

http://www.alanturing.net

- 23 June 1912 - 7 June 1954
- Contributions:
  - Mathematics,
  - Cryptanalysis,
  - Logic,
  - …
  - Artificial Intelligence.



http://www.mathcomp.leeds.ac.uk/turing2012/

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Alan Turing

- http://www.alanturing.net
- http://en.wikipedia.org/wiki/Alan_Turing
- Bibliography:
  - "On Computable Numbers, with an Application to the Entscheidungsproblem" 1936
  - Turing, A.M. Computing machinery and intelligence. Mind, 59, 433-460. 1950
    - "I propose to consider the question, "Can machines think?"
    - http://en.wikipedia.org/wiki/Computing_machinery_and_intelligence
    - http://blog.santafe.edu/wp-content/uploads/2009/05/turing1950.pdf
- Charles Petzold. The Annotated Turing: A Guided Tour Through Alan Turing's Historic Paper on Computability and the Turing Machine. Wiley. 2008. www.theannotatedturing.com

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Can machines do everything?

- **We have studied:**
  - Simple languages.
  - Application of simple languages to solve restricted problems:
    - Analysis.
    - Pattern recognition.
    - Syntax analysis.
- **In this unit, we want to answer:**
  - Which languages can be defined by means of any computational device?
  - Which problems can be solved/computed?

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Can machines do everything?

- Which is the solution?
  - He says that she always say the truth.
  - She says that he always lies (he never says the truth).
- Can a computer answer to any possible question in a dialog system?
- Is a grammar ambiguous?
- Is there a solution for $X^N+Y^N=Z^N$, with N>2?

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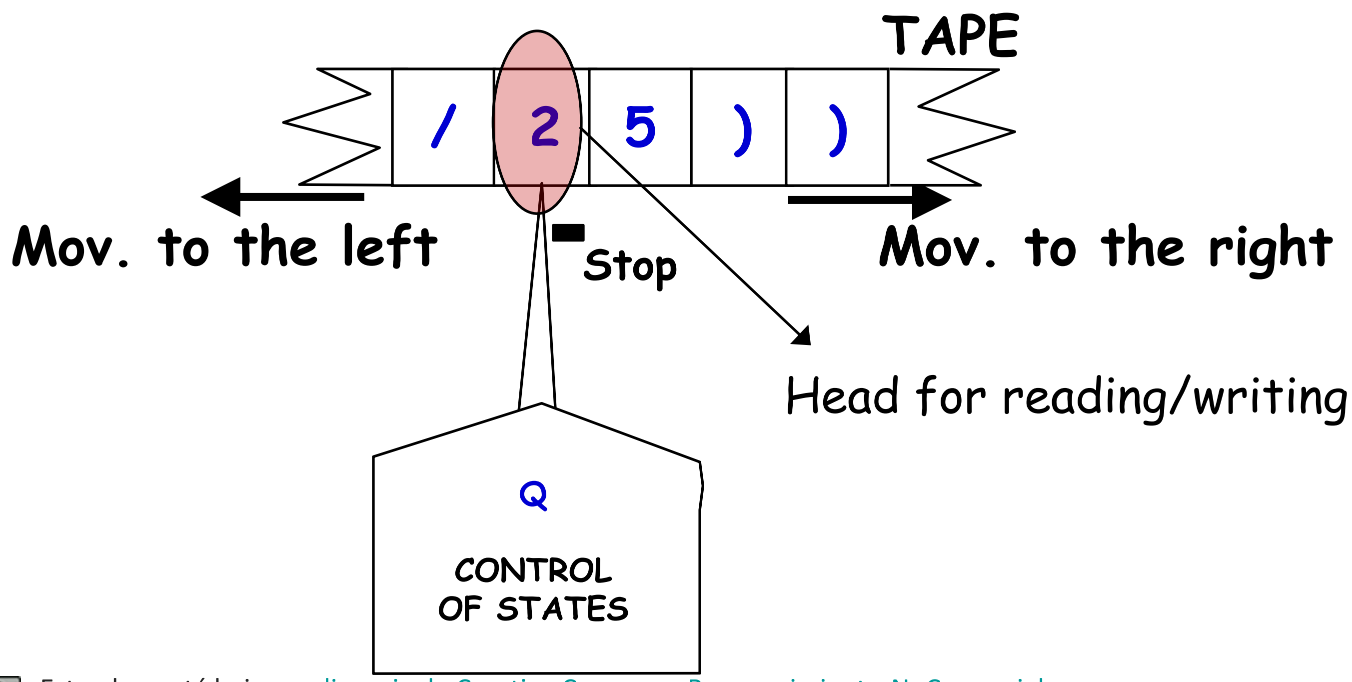
What is a Turing Machine?

- Mechanical device:
  - Infinite tape divided into cells with a head for reading/writing.
  - This head can be moved from to left or right or stay in the same cell.



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Turing Machine: Operation

Operations that a TM carries out:

- Being in a state *p* and reading a symbol in the cell on which the R/W head is, it carries out three actions:
  - Transits to a new state.
  - Writes a new symbol in the tape, in the same cell where the current symbol has been read. This symbol replaces the previously read (unless it is the same).
  - Moves the R/W head to the left, to the right or stops in the same position.

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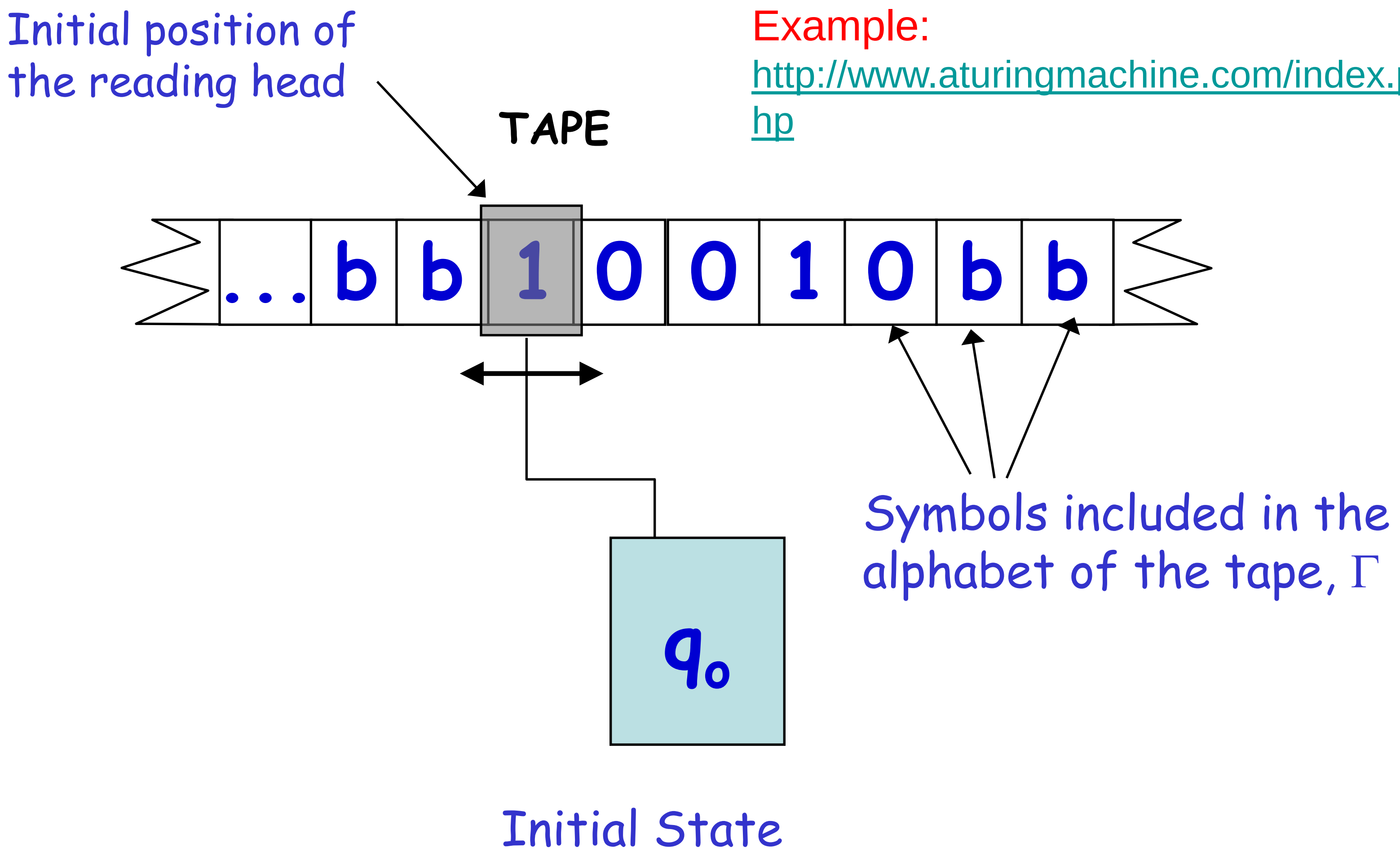
Turing Machine: Initial Situation

Example: http://www.aturingmachine.com/index.php



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Turing Machine: Operation

Characteristics of the Tape:

- Infinite tape.
- It can contain a character in each cell.
- It can be read.
- It can be written.
- Initially it is considered with infinite blank symbols to the right and left of the word.
- It can be moved to the left or right (a cell each time) or not move.

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Turing Machine: Operation

- There are many variants of Turing Machines…
- … but they all are equivalent.
- The tape is one-dimensional and **infinite** by both sides.
- Initially:
  - The tape contains the word, and the rest of elements of the tape (left and right of the word) are the blank symbol (b or □).
  - At the beginning, the R/W head is located on the left-most element of the word.

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Turing Machine: Formal Definition

- Septuple: **(Σ, Γ, b, Q, qo, f, F),** where:
  - **Γ**: alphabet of symbols in the tape
  - **Σ ⊂ Γ**: alphabet of input symbols
  - **b ∈ Γ, b ∉ Σ** : is the blank symbol (the only symbol allowed to be in the tape infinitely at any step during the computation). It indicates empty cell (□).
  - **Q**: set of states (finite).
  - **q_0 ∈ Q**: initial state.
  - **F ⊂ Q**: set of final states.
  - **f**: transition function

Q x Γ → Q x Γ x {L,R,S}

L or -: left
R or +: right
S or =: stay

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Turing Machine: Transition Function

f: Transition function, table with double input

$$Q \times \Gamma \rightarrow Q \times \Gamma \times \{L,R,S\}$$

L: mov. to the left
R: mov. to the right
S: stop

↓Q / Γ→	Symbol	Symbol
Input	State, symbol, movement	…
Input	State, symbol, movement	
,,,	…	

Empty cells in the table:

- Transitions that are NOT possible → The machine stops.

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Turing Machine: Example

$\mathcal{M}$ = (∑={0,1}, Γ ={0,1,□}, □, Q = {q0, q1, qF}, q0, F={qF}, f)

f	0	1	□
-> q0 q1 * qF	(q0, 0, +) (q1, 0, +)	(q1, 1, +) (q0, 1, +)	(qF, 0, =) (qF, 1, =)

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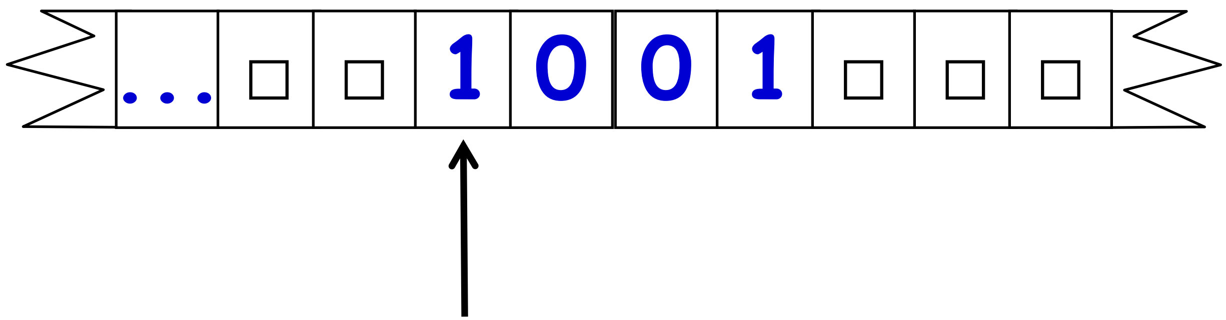
Variations of Turing Machines

Turing Machine: Example

f	0	1	□
-> q0 q1 * qF	(q0, 0, +) (q1, 0, +)	(q1, 1, +) (q0, 1, +)	(qF, 0, =) (qF, 1, =)



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Turing Machine: Example

f	0	1	□
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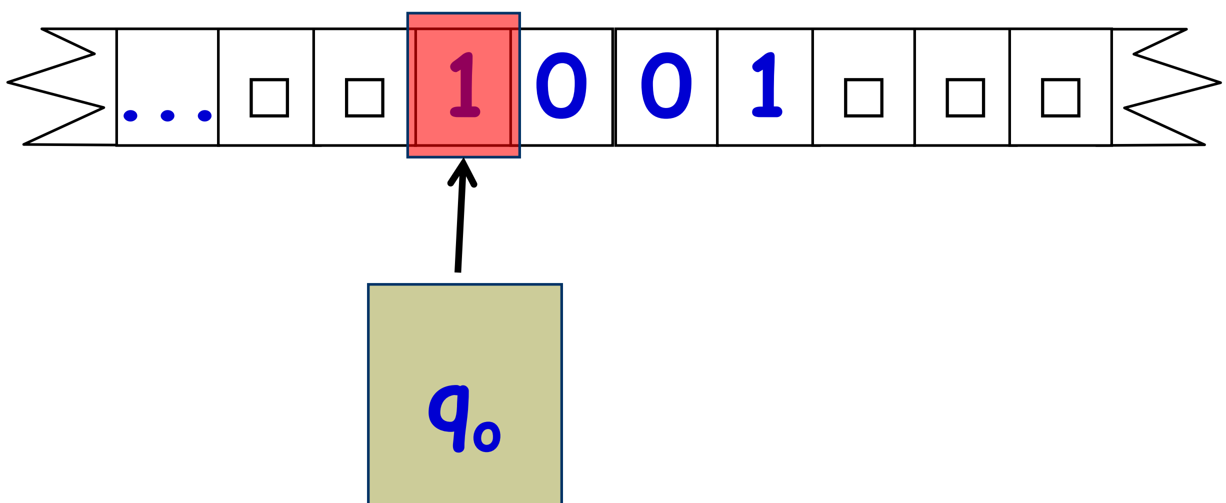

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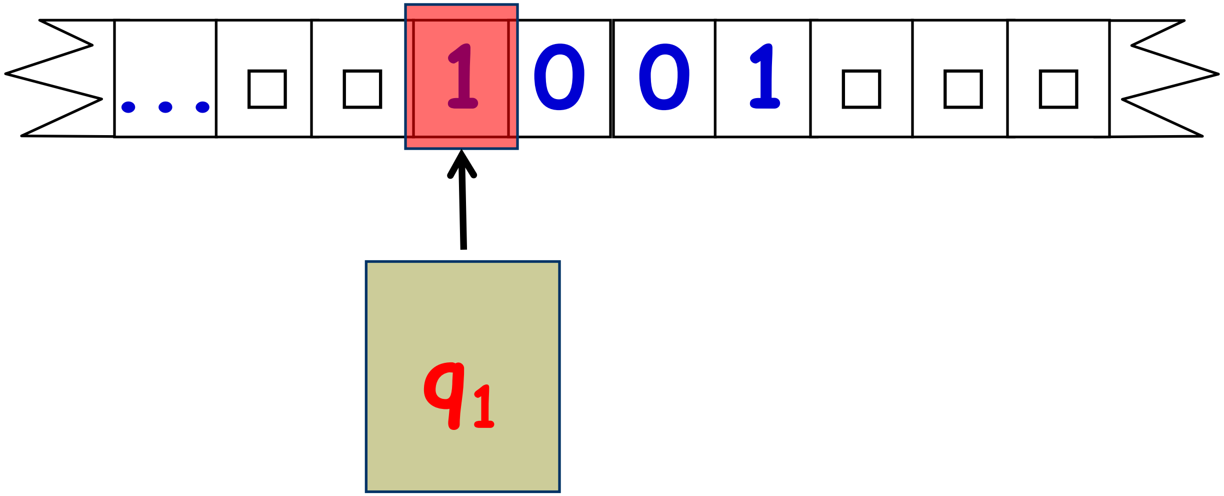

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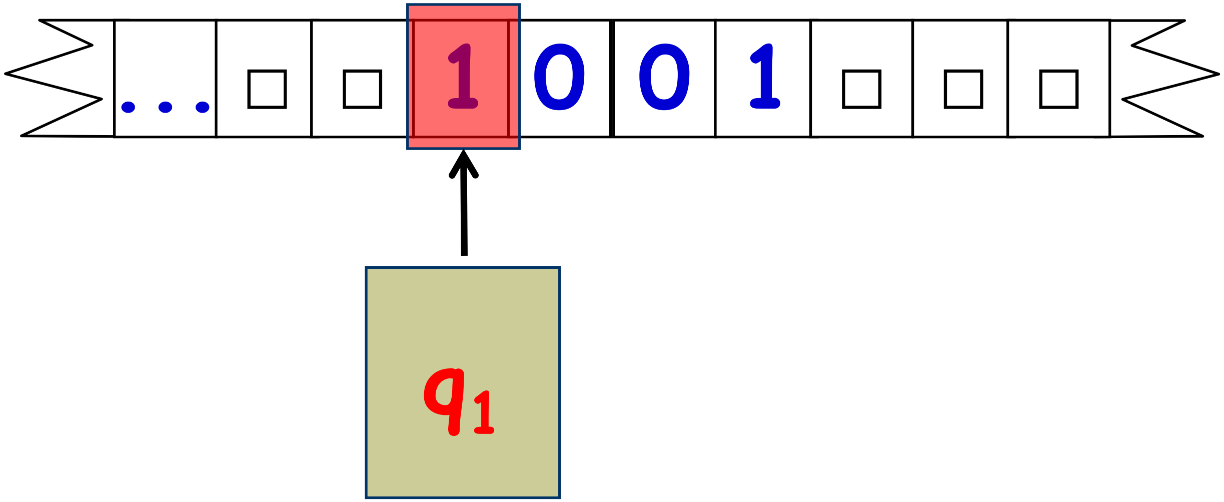

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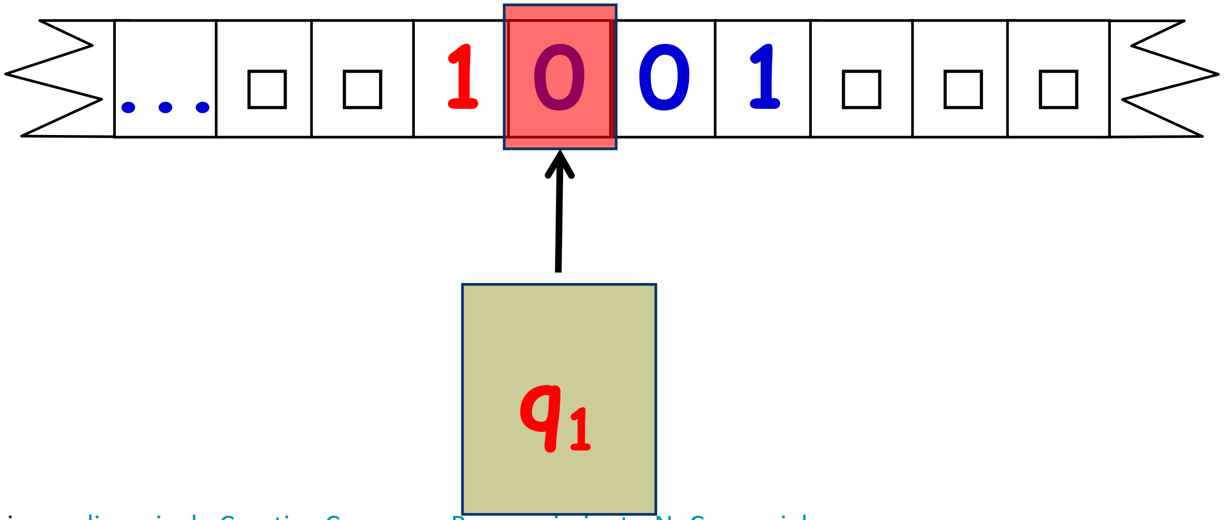

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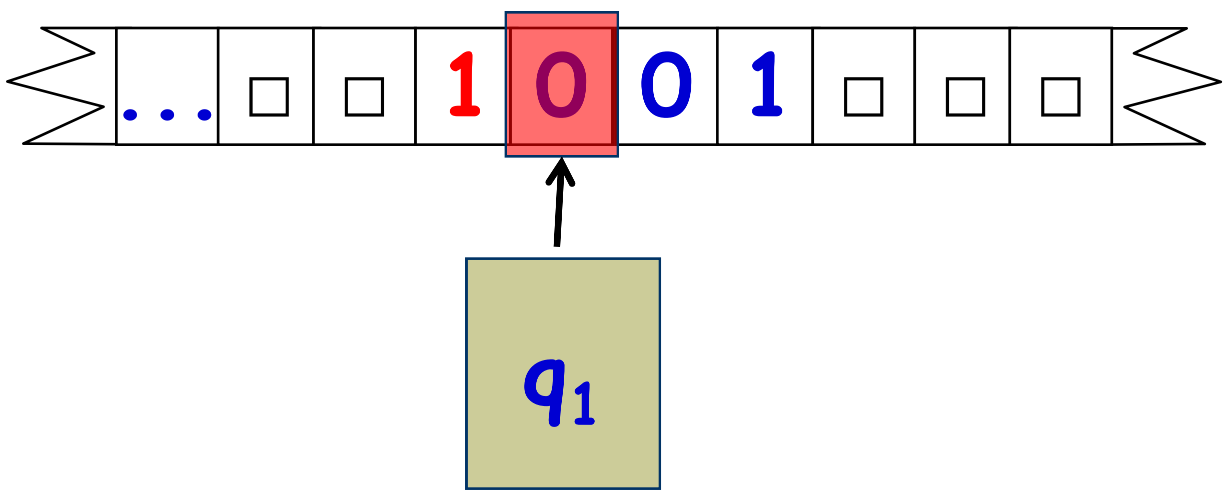

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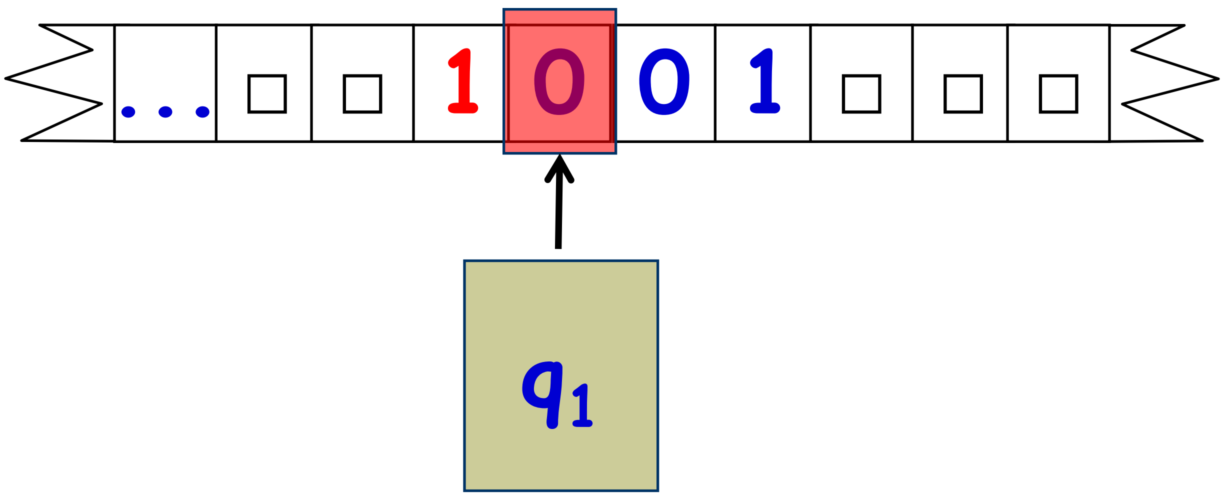

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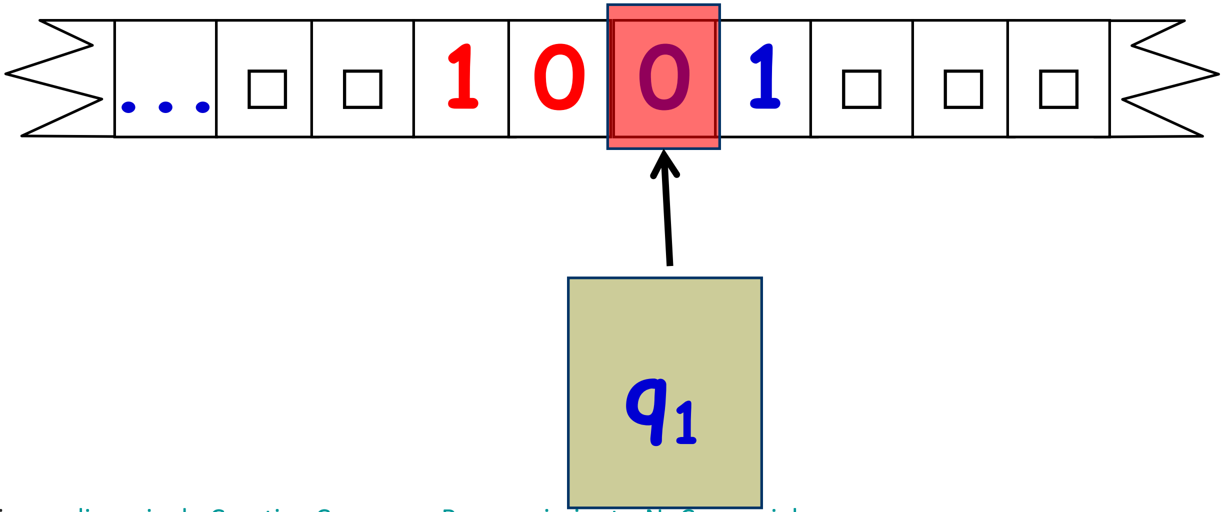

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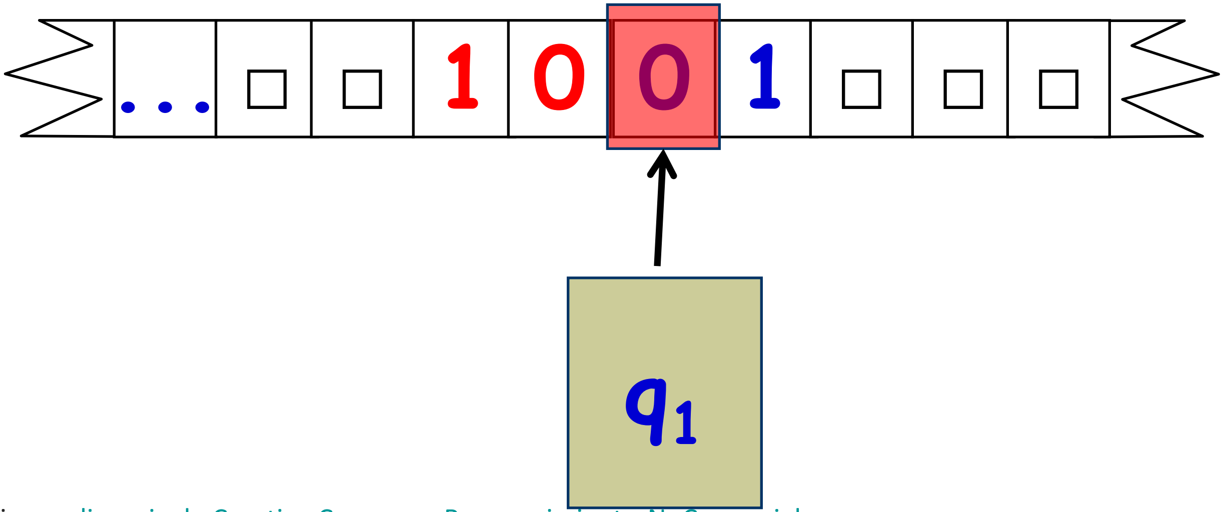

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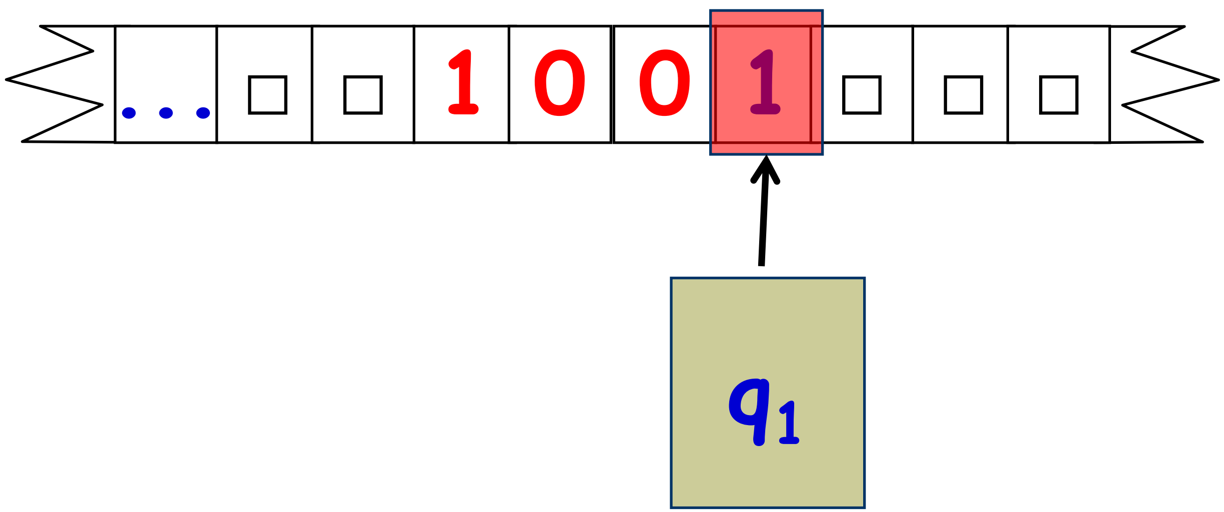

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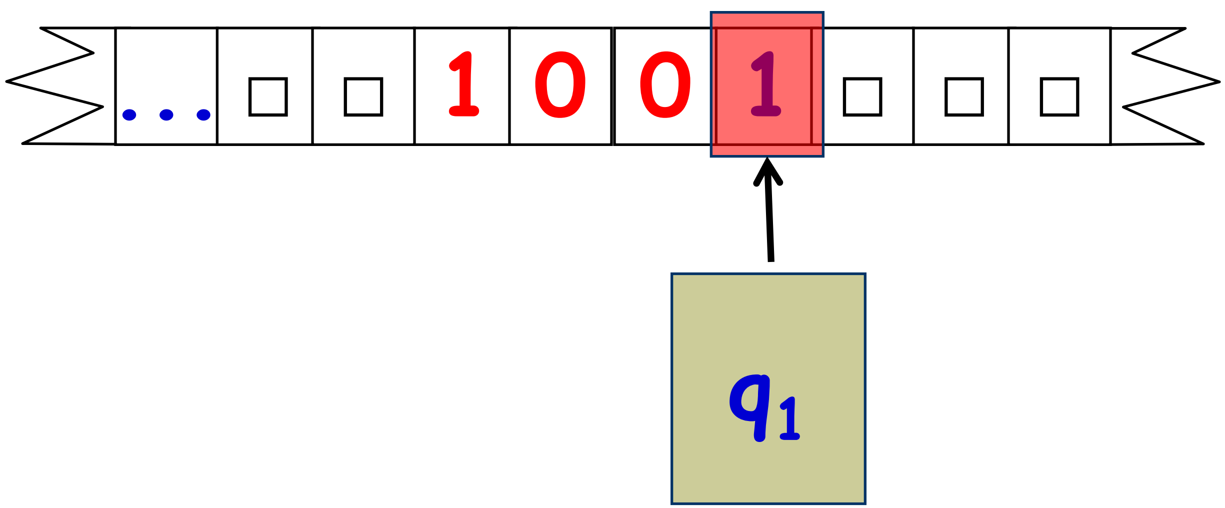

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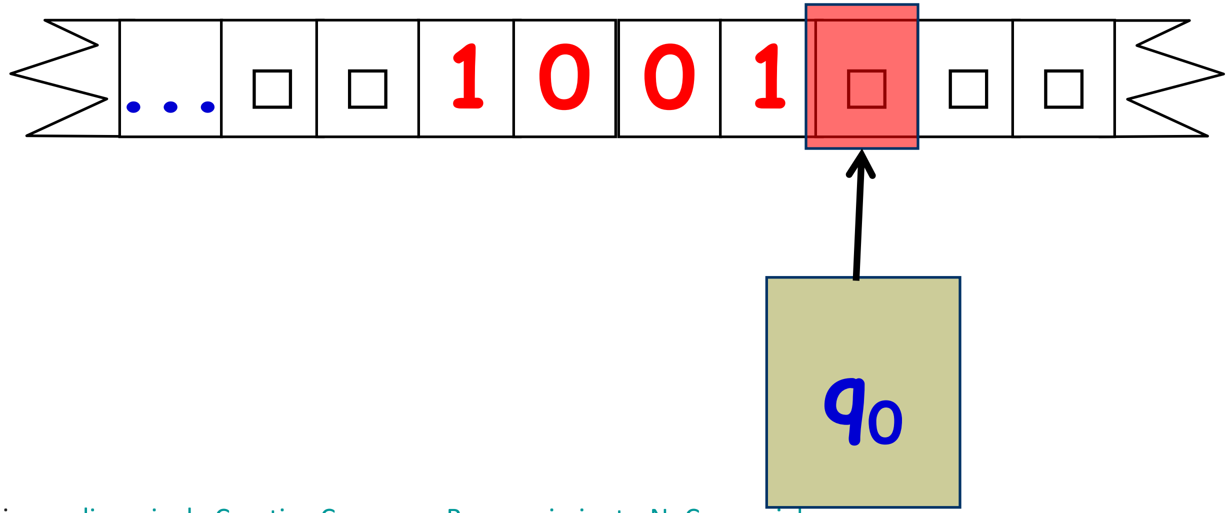

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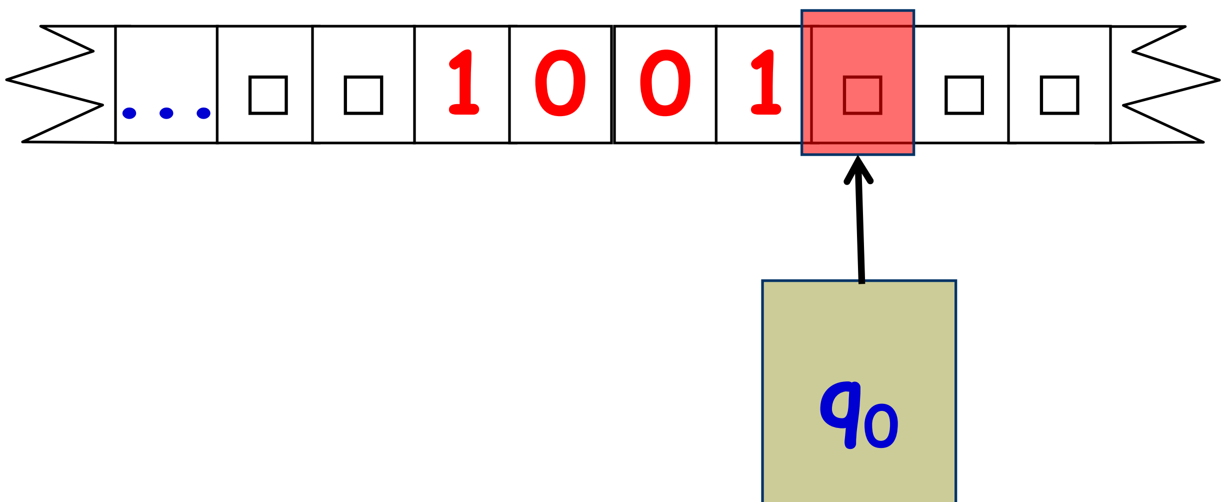

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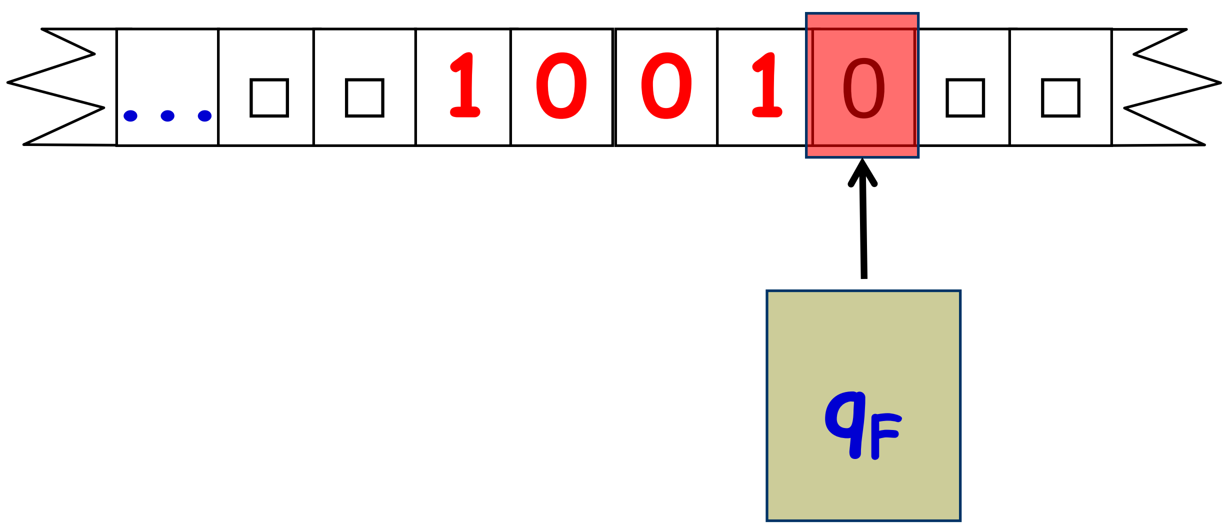

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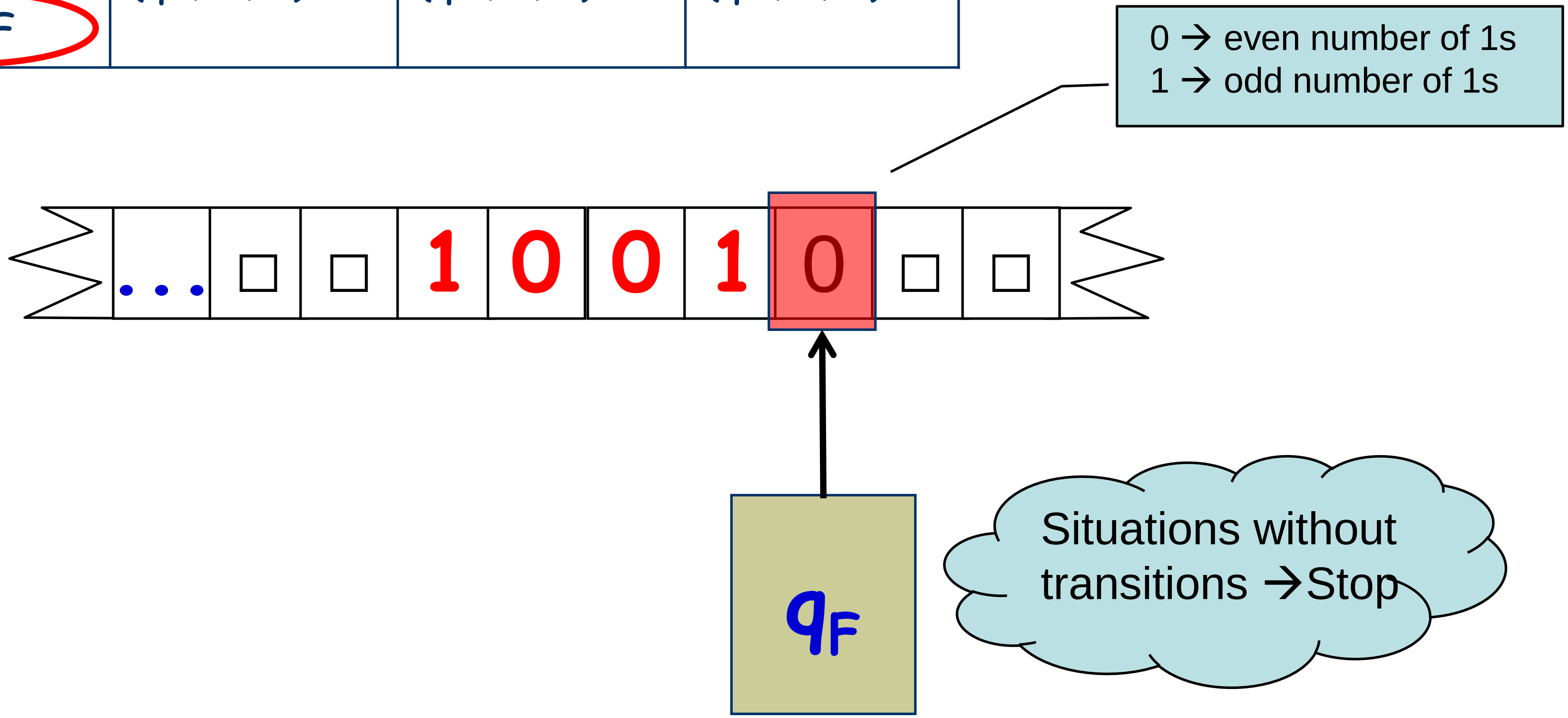

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Turing Machine: Graph Representation

- The transition function can be described using also a diagram with states, i.e. a graph in which:
  - Nodes represent states.
  - Arches represent transitions between states.
  - Each arch is labelled including the requisites and effects of each transition (initial symbol, symbol that is rewritten, and direction to move the input header).

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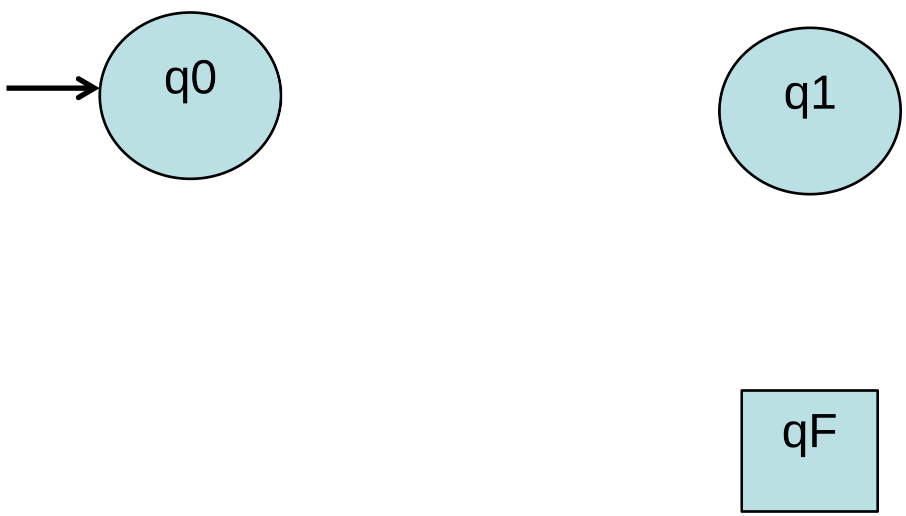

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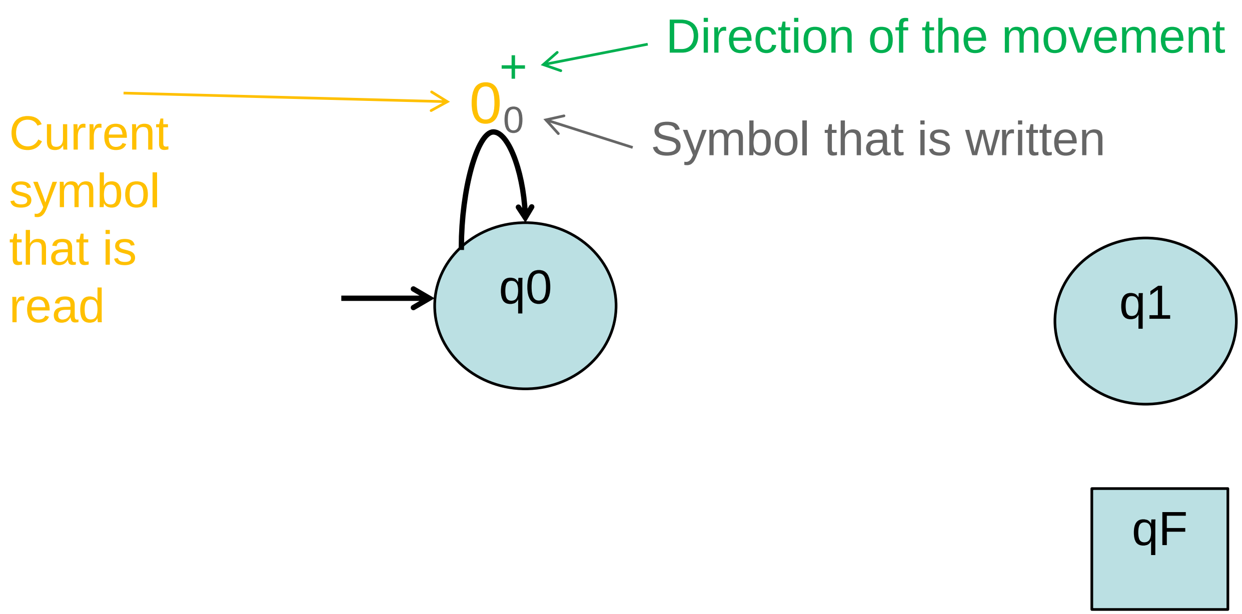

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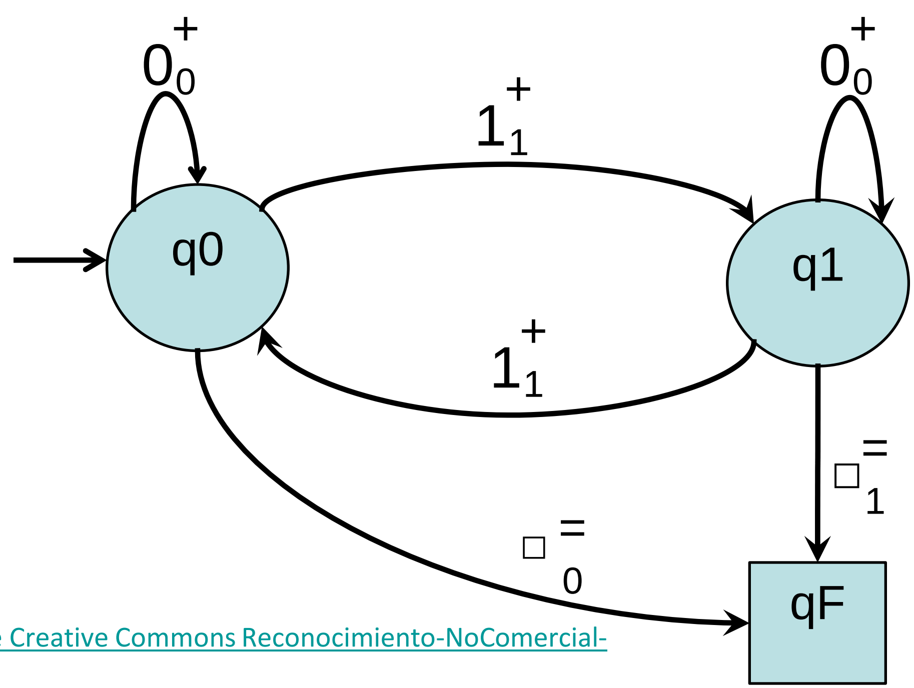

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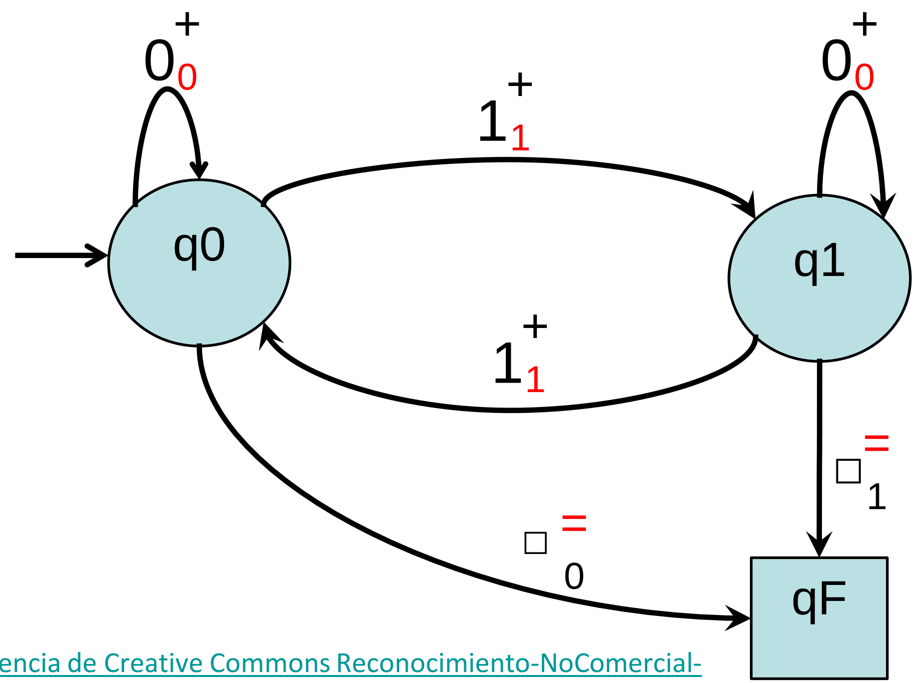

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Turing Machine: Graph Representation

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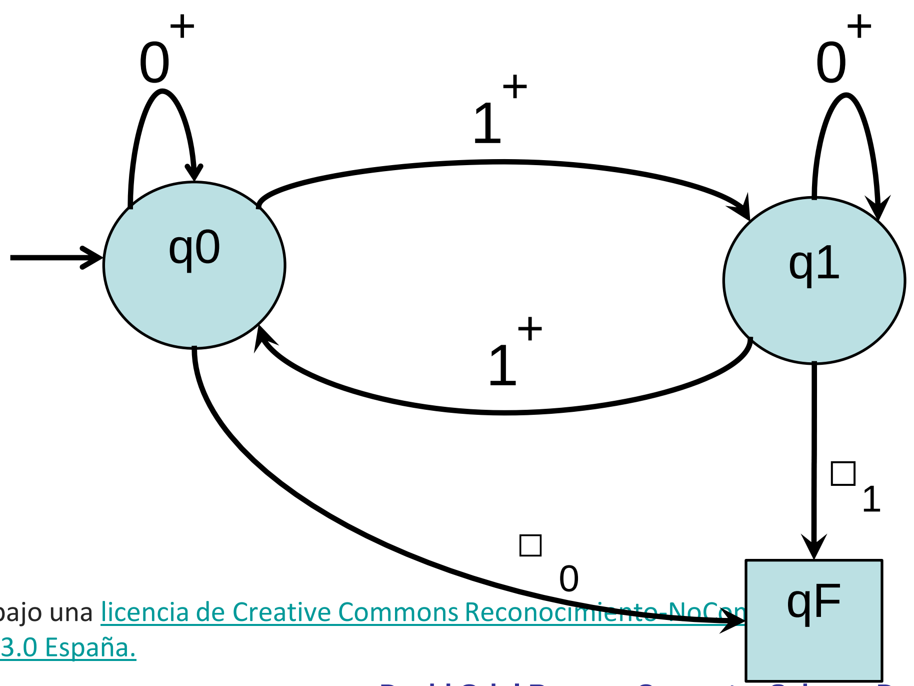

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Turing Machine and Languages

- Turing Machine as TRANSDUCER:
  - It modifies the content of the tape,
  - Examples: TM that replaces digits by zeros.

    TM that appends a parity bit to the input.
- Turing Machine as RECOGNIZER:
  - TM that recognizes a language.
  - TM that accepts a language.

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Turing Machine and Languages

- Turing Machine as TRANSDUCER:
  - **Objective: transform the input (→ Provide the result of an operation).**
    - It verifies:
  - If the input is well-formed, it must finish in a final state.
  - If the input is NOT well-formed, it must finish in a nonfinal state (shows an error in the input word).

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Turing Machine and Languages

- Turing Machine as RECOGNIZER
  - **Objective: Decide if the input string is valid or not, following a specific criterion.**
- Two main concepts: RECOGNIZE, ACCEPT
  - A TM **RECOGNIZES** a language L, if for any input in the tape, w, it stops in a final state iff $w \in L$.
  - A TM **ACCEPTS** a language L if, when analyzing a word w, it stops in a final state iff $w \in L$.
    - If the word does not belong to the language, the TM does not need to stop.

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OUTLINE

- Definition of Turing Machine
- **Variations of Turing Machines**
- Universal Turing Machine
- Additional issues

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Variations of Turing Machines

- We have defined a generic Turing Machine.

- The definition of TM admits many variations, but having the same computation capacity, i.e. **all the variations are equivalent.**

- Two Turing Machines, TM_1 y TM_2 are equivalent **if both carry out the same action for all their inputs**.

  - What does equivalent mean for a Turing Machine?

    ✓ TM **as transducers:** for each possible input, at the beginning of the process, **at the end of this the contents of the tape must be the same.**

    ✓ TM **as recognizers**: both TM **accepts the same words.**

    ✓ If for some input *w*, one TM does not stop, the second one will not stop for such input *w*.

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Variations of Turing Machines

- Using the generic TM it is possible to impose restrictions, without they suppose limitations in the computation capacity.

- These restrictions can be imposed on:

  - **The alphabet of the tape: binary TM.** Γ={0,1}. (~~Not Σ = {0,1} y Γ = {0,1, b}).~~

  - **The structure of the tape: Limited TM.**

    - E.g.: infinite tape only by the right (limited by the left using the input word).

  - **Movements (to write, move and change the state)**

    - E.g.: not to allow that the head remains quiet; not to allow that it writes and changes simultaneously of state; etc.

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Turing Machine with Binary Alphabet

Theorem:

Given a generic TM , there is an equivalent TM with binary alphabet in the tape, Γ = {0,1}

Turing Machine with Binary Alphabet

$M \rightarrow M_{(2}$

IMPORTANT: it is Γ = {0,1} and Σ ⊆ Γ , ~~not Σ = {0,1} and Γ = {0,1, b}~~

Different descriptions in the bibliography

(According to section 2.2.3, Alfonseca 2007)

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Turing Submachines (Subroutines)

- Same concept that functions, methods, procedures (subprograms).
- A TM can, during its execution, invoke to another one.

- **DEFINITION:**
    - A submachine of Turing is a TM that can receive arguments (i.e. symbols) to carry out a specific task specify, and can be invoked with another TM.

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Turing Submachines (Subroutines)

- When a TM M_1 invokes another TM M_2 with an argument σ, the parameter in the definition of the submachine is replaced by the symbol by means it has been invoked: $M_2(\sigma)$.
  - $M_2(\sigma)$ is executed:
    - Using the same tape that M1.
    - From the initial state of M2.
    - With the R/W head of M2 on the same position where it was in M1.

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Turing Submachines (Subroutines)

- To use Turing Submachines does not mean that the computability capacity (calculation) of TM is increased.

- Example:

  - Design a TM (using submachines) that recognizes the words of the language L={$a^n b^n$, $n \geq 0$}

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Turing Submachines (Subroutines)

Example: L={$a^n b^n$, n ≥ 0}

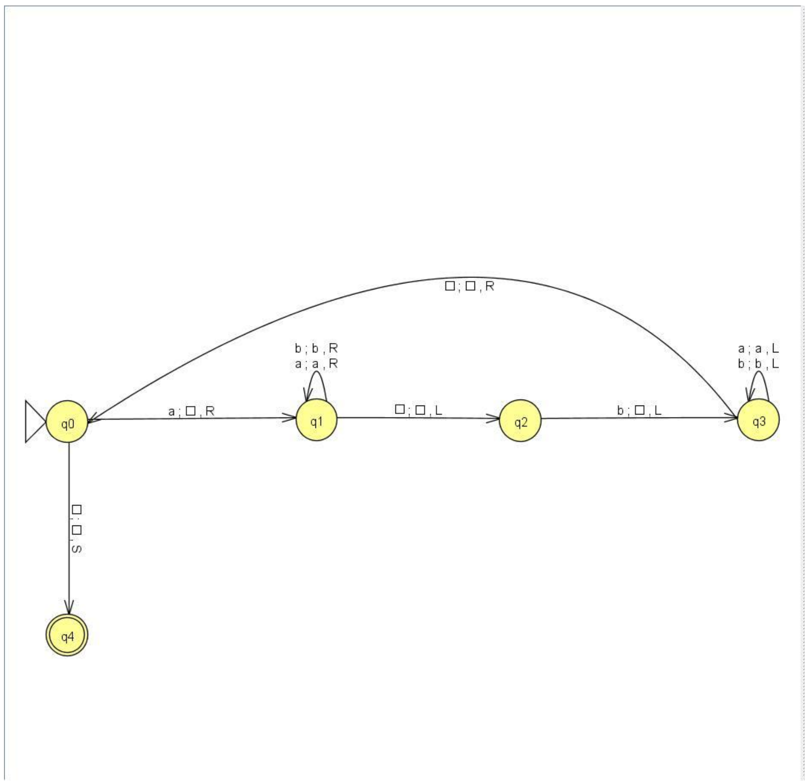

Table Text Size

Input	Output	Result
ab		Accept
ba		Reject
aabb		Accept
aab		Reject
abb		Reject
aaaabbbb		Accept

Load Inputs | Run Inputs | Clear | Enter Lambda | View Trace

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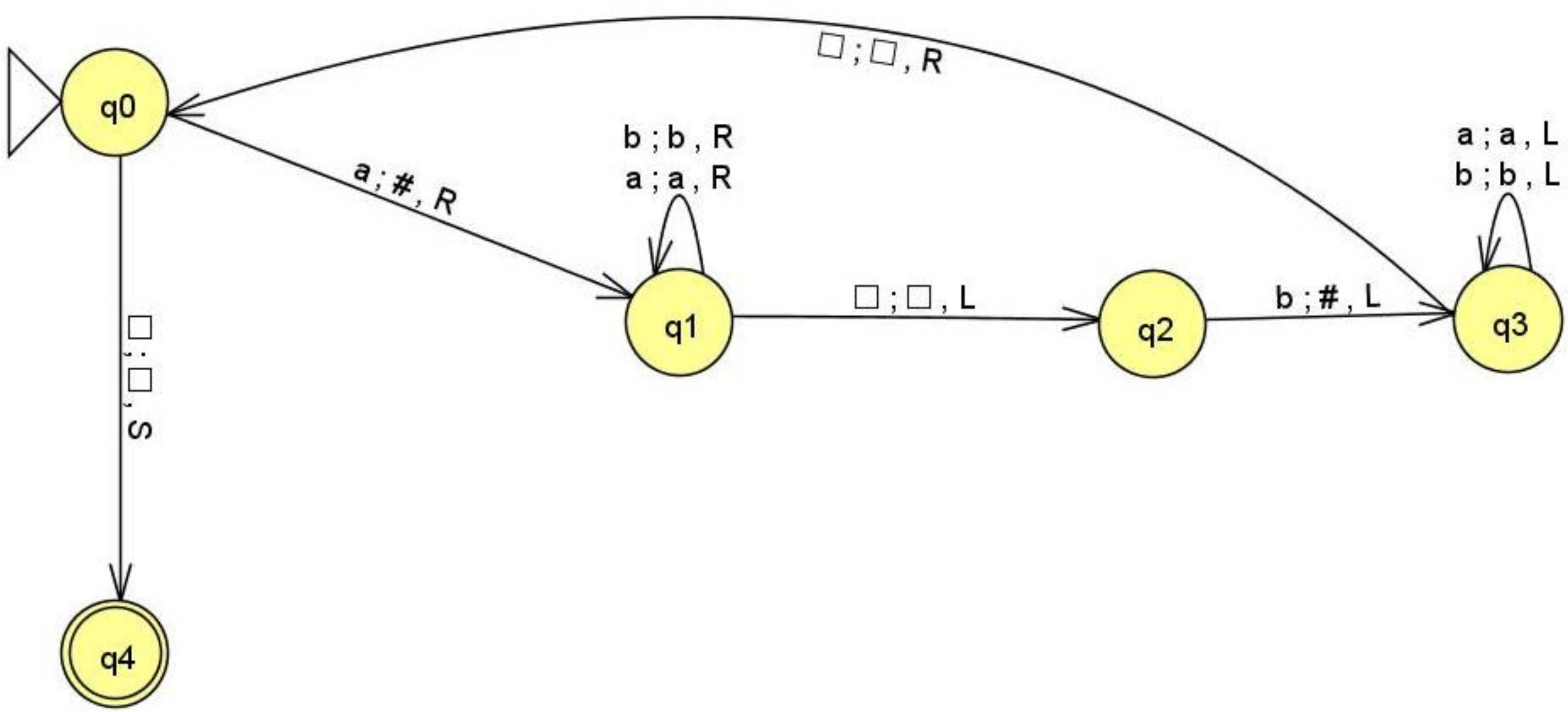
Turing Submachines (Subroutines)

Example: L={$a^n b^n$, n ≥ 0}



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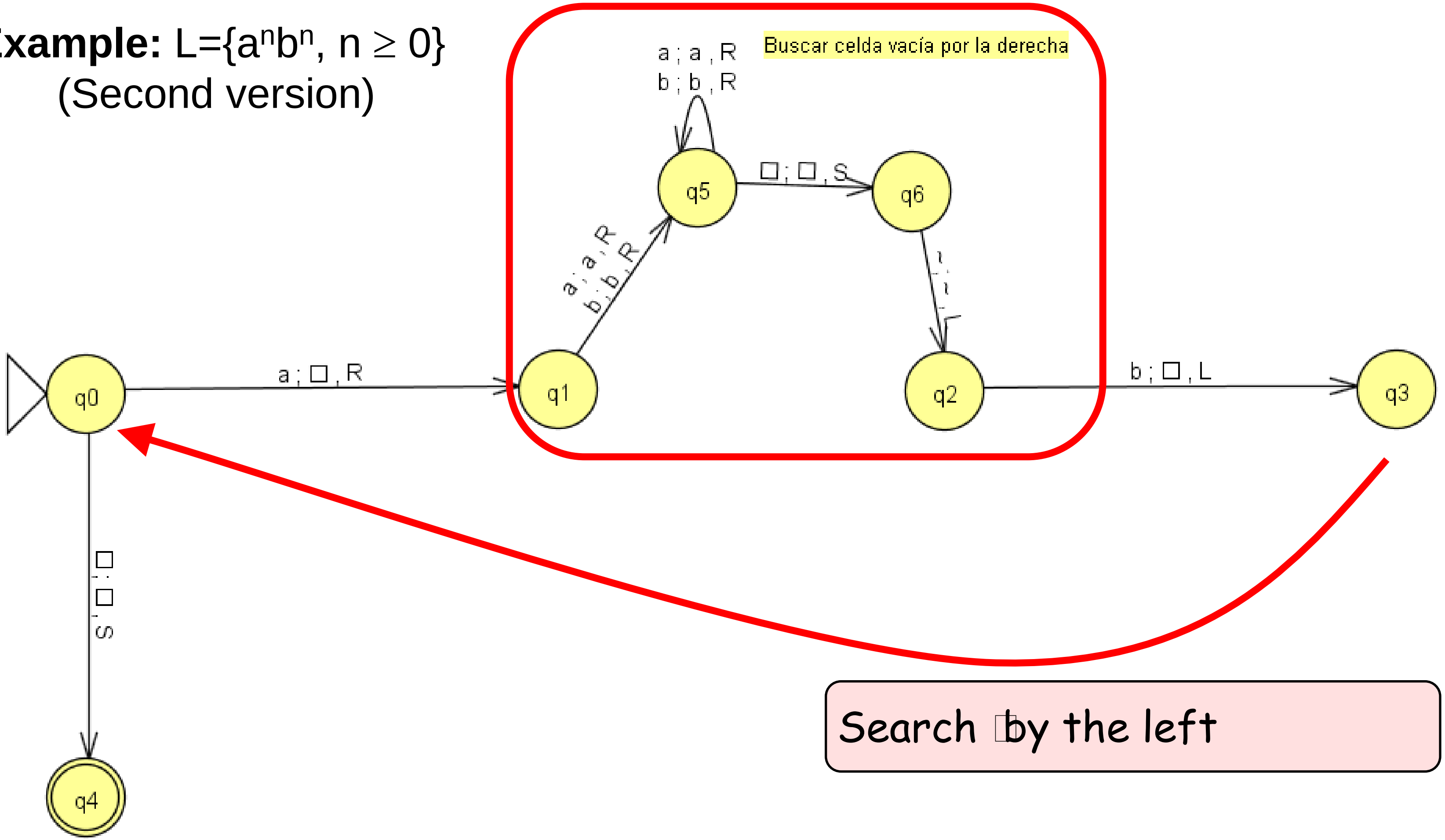
Turing Submachines (Subroutines)

Example: L={$a^n b^n$, n ≥ 0}
(Second version)



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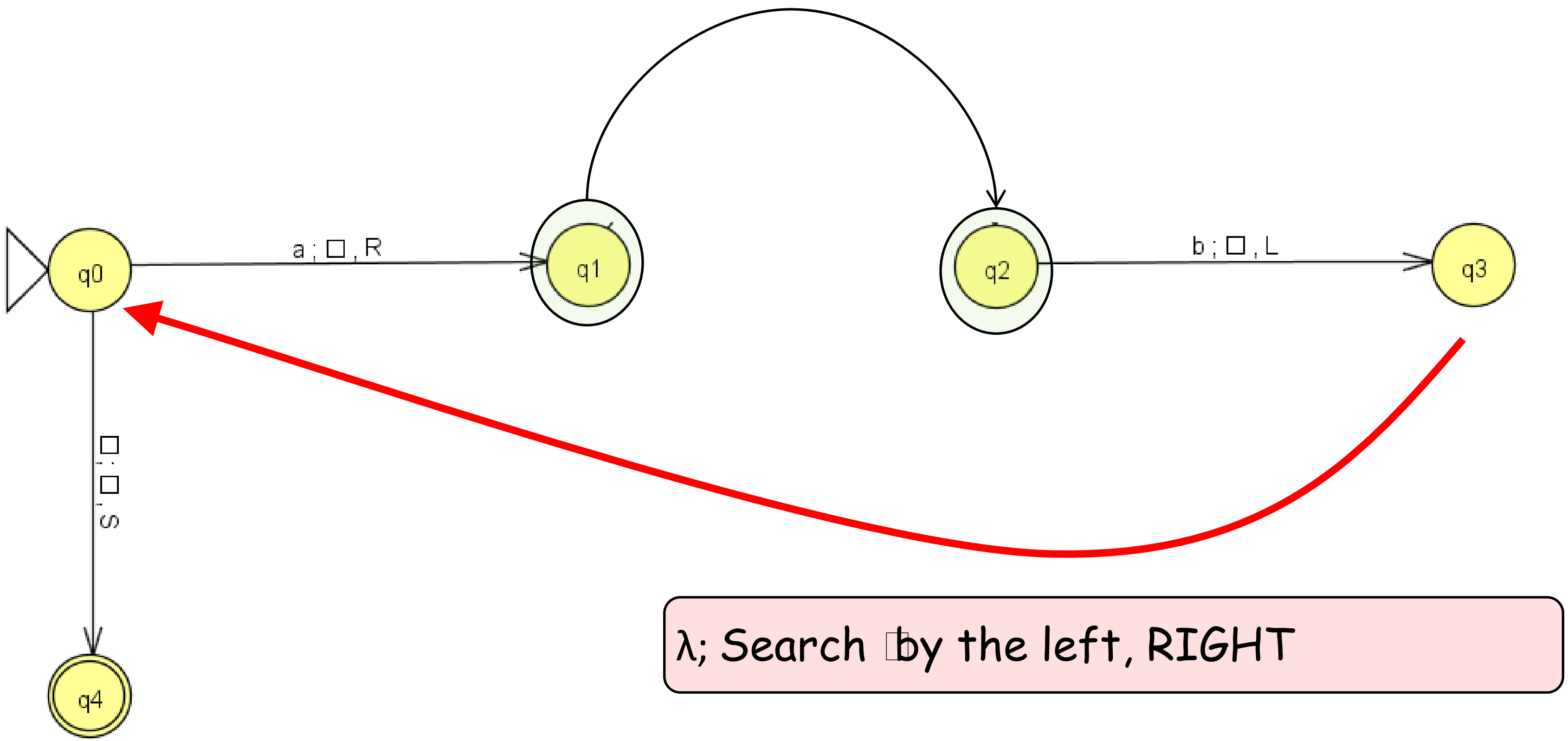
Turing Submachines (Subroutines)

Example: L={$a^n b^n$, n ≥ 0}
(using submachines)

λ; Search □ by the right, LEFT



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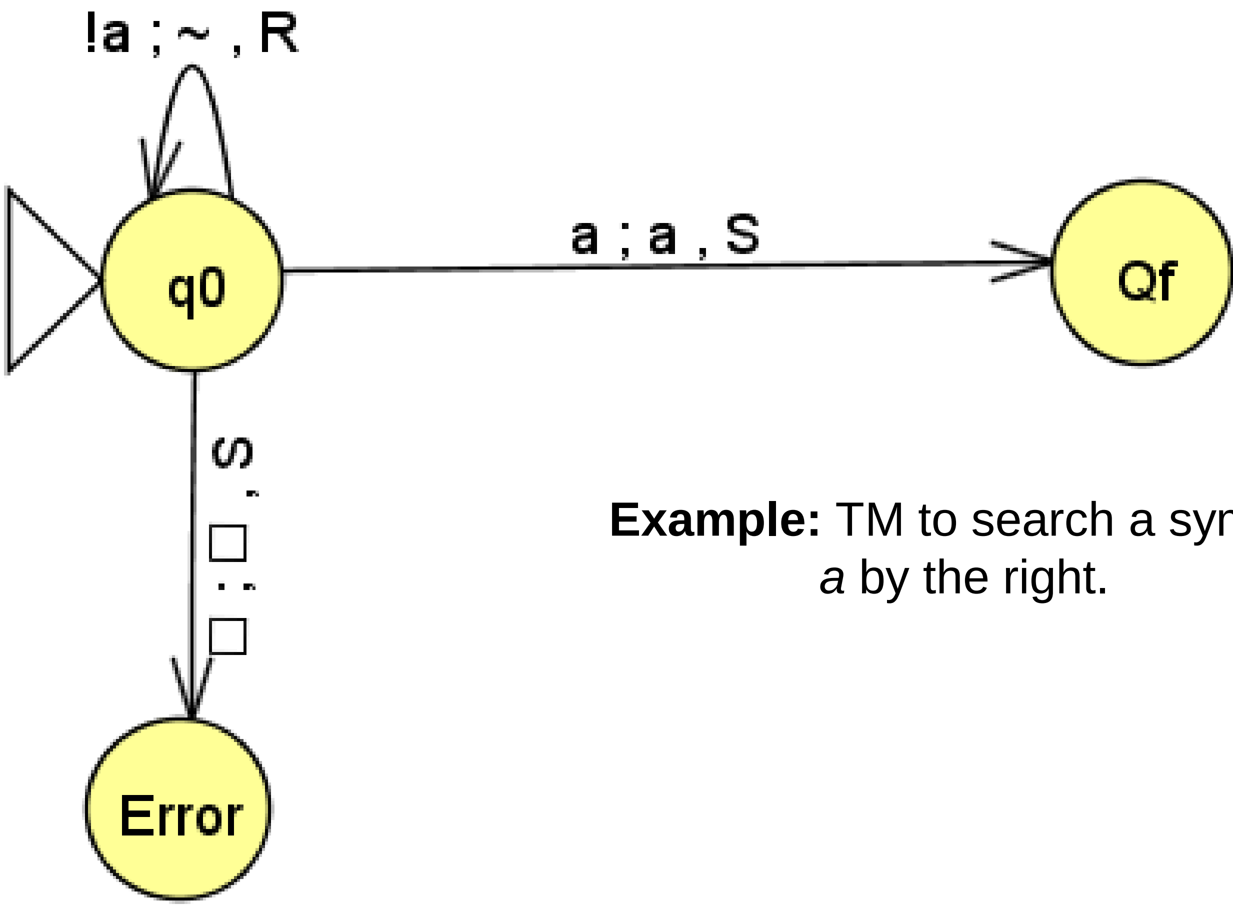
Variations of Turing Machines

Turing Submachines (Subroutines)



Example: TM to search a symbol *a* by the right.

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OUTLINE

- Definition of Turing Machine
- Variations of Turing Machines
- **Universal Turing Machine**
- Additional issues

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Universal Turing Machine

- It is possible to define a TM that **simulates the execution of EVERY** TURING MACHINE.

This machine is called

UNIVERSAL TURING MACHINE (U)

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Universal Turing Machine

- **Universal Turing machine: U**
  - Input:
    - Description of the TM.
    - Input string (word): w.
  - What does U(TM, w) simulate?
    - It simulates the operation of TM, transition by transition.
  - If TM accepts w, then U stops in a final state for that word.
  - If TM does not accept w, U does not stop or it stops in a non-final state for this word.

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Universal Turing Machine

- **Universal Turing Machine: U**
  - It simulates a TM.
  - What does it happen if TM never stops?

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Universal Turing Machine: Undecidability

- HALTING PROBLEM
  - Remember: “*The output of the machine—i.e., the solution to a mathematical query—can be read from the system once the TM has stopped.”*
  - However, in the case of Gödel’s undecidable propositions, the machine would never stop, and this became known as the “halting problem.”
    - It is not possible to decide if, given an input word w, the machine will stop or will be always running.
    - There is not a TM that answers this question.

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OUTLINE

- Definition of Turing Machine
- Variations of Turing Machines
- Universal Turing Machine
- **Additional issues**

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Design issues

- The solution of the problem is the transition table, but this is not enough to complete an exercise.
- It is essential to think and describe the algorithm before to be implemented, as well as the behavior of each one of the states.
- It is precise to evaluate the machine with a significant set of inputs. There are maybe “difficult” cases that have to be considered.
- Many TM operates on input tapes with a specific configuration, that normally we do not verify.

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Design issues

- Any solution is not valid, you must think the algorithm very well and verify that it works for every case.
- If TM must operate as if it had “memory”, additional states can be incorporated (in more complicated machines, the input data can be written in specific positions of the tape).
- If a TM must remember positions within the tape, they usually use additional markers.
- If the task can be divided in several sequential subtasks (or subprogram), then do it.

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