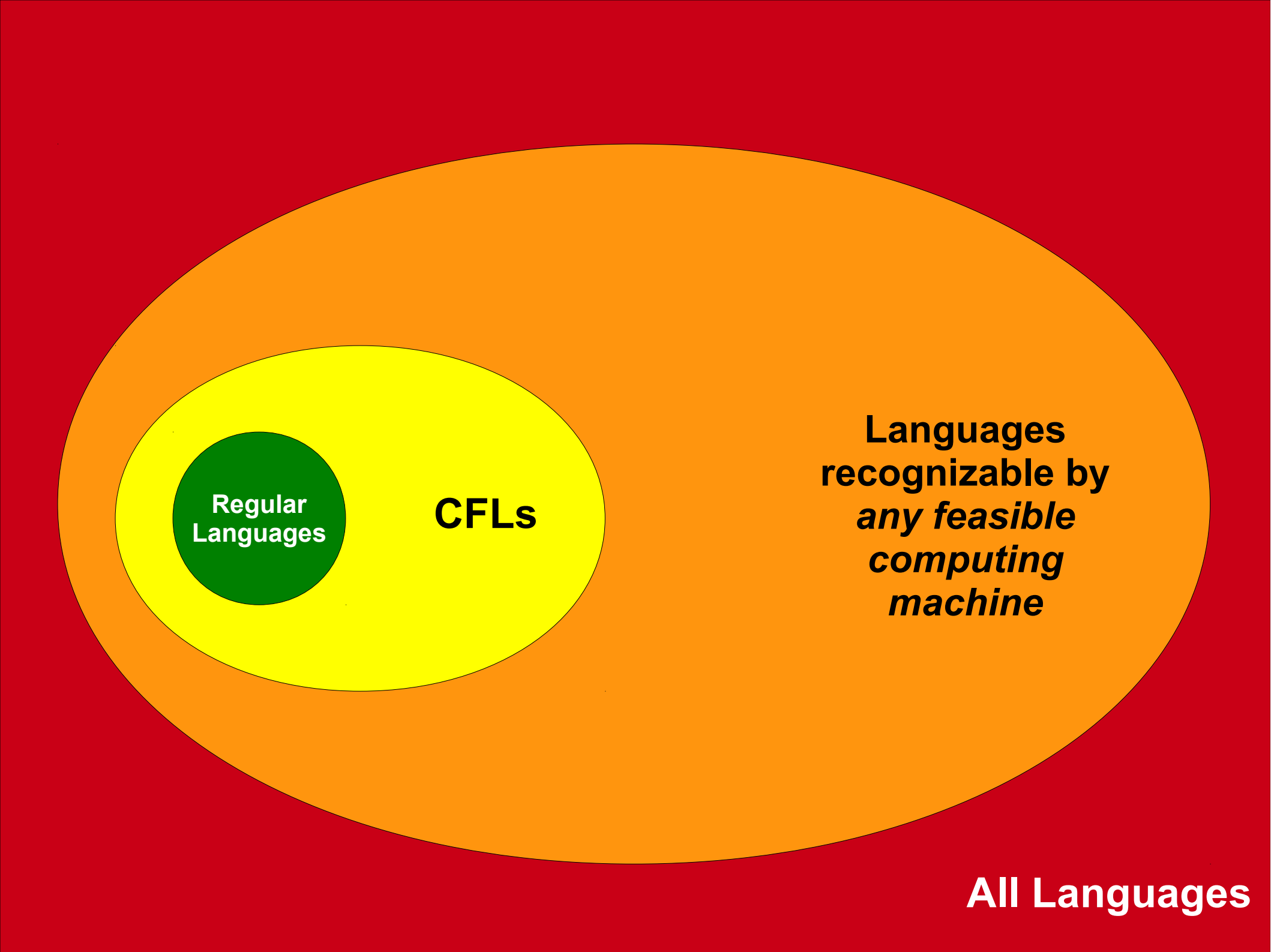
Turing Machines

Part One

Are some problems inherently harder than others?


Regular Languages
CFLs
Languages recognizable by *any feasible computing machine*
All Languages

That same drawing, to scale.

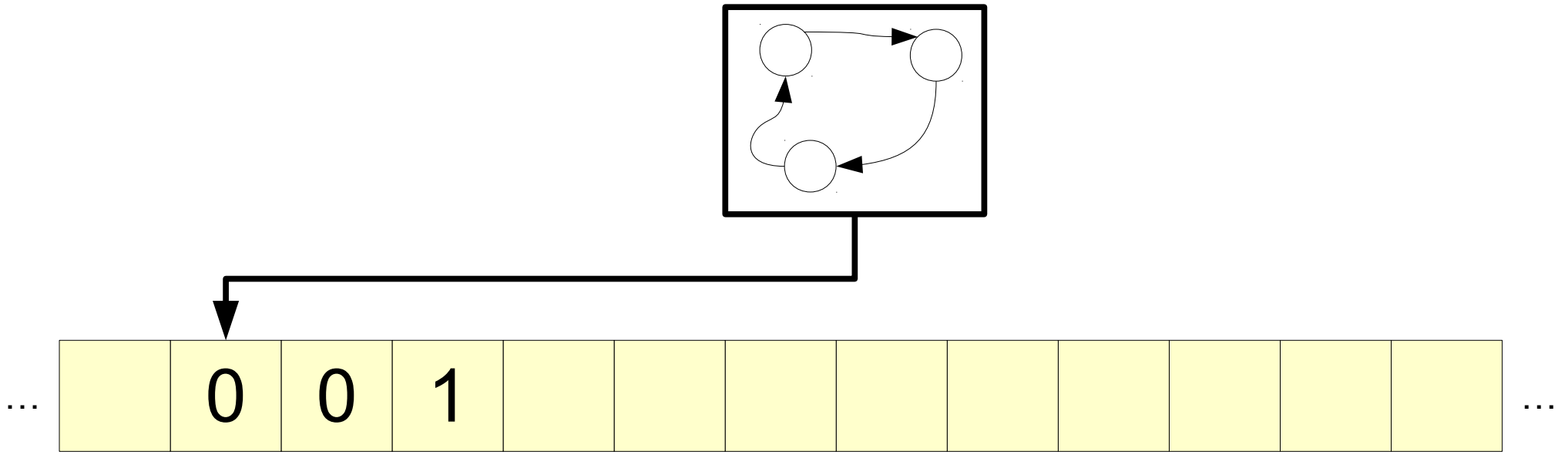
All Languages

The Problem

- Finite automata accept precisely the regular languages.
- We may need unbounded memory to recognize context-free languages.
  - e.g. $\{ \texttt{a}^n\texttt{b}^n \mid n \in \mathbb{N} \}$ requires unbounded counting.
- How do we build an automaton with finitely many states but unbounded memory?

A Better Memory Device

- A **Turing machine** is a finite automaton equipped with an **infinite tape** as its memory.
- The tape begins with the input to the machine written on it, surrounded by infinitely many blank cells.
- The machine has a **tape head** that can read and write a single memory cell at a time.



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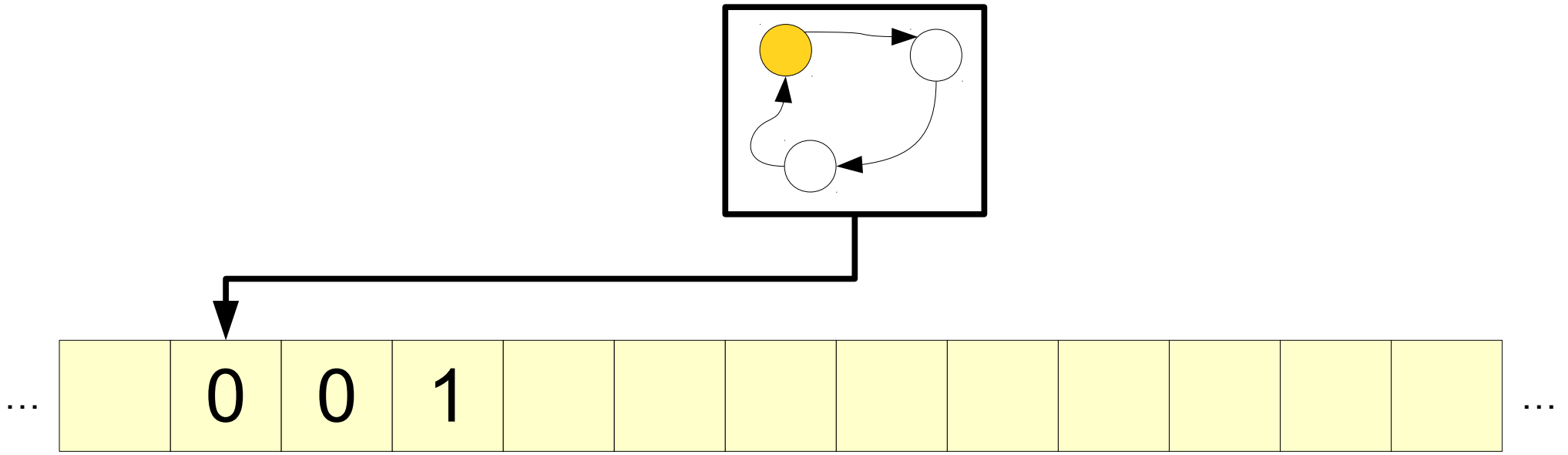

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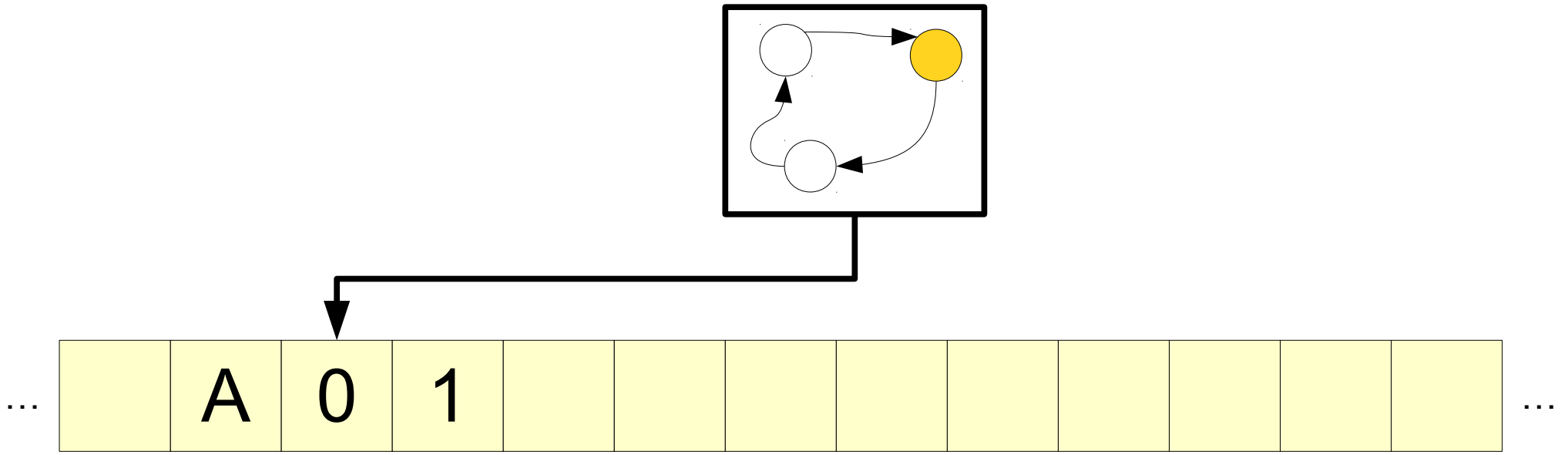

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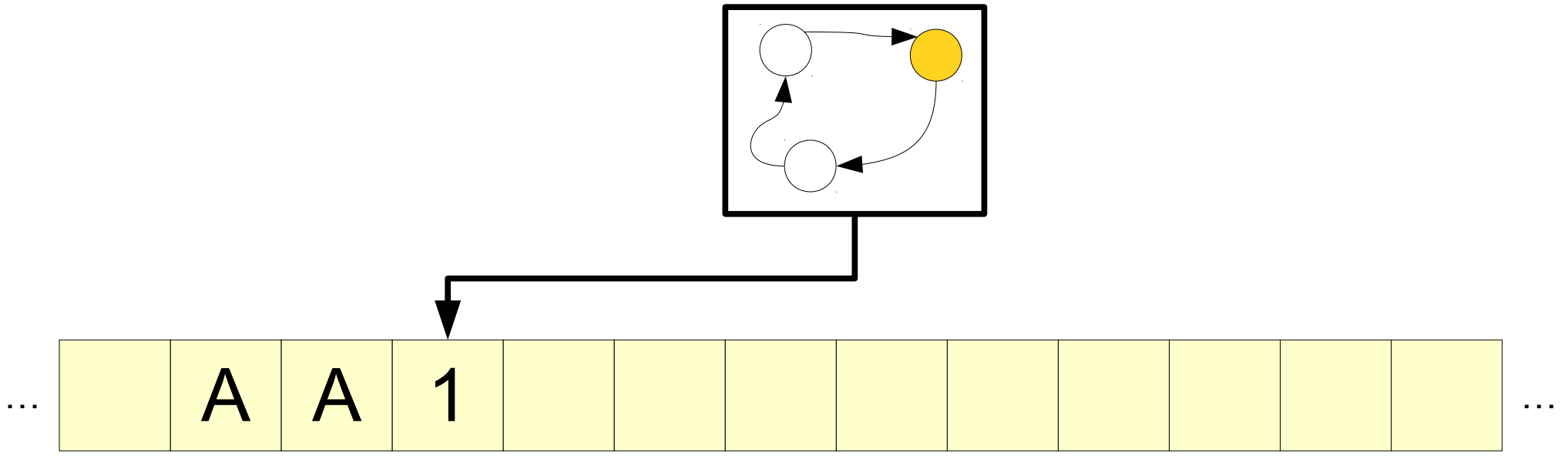

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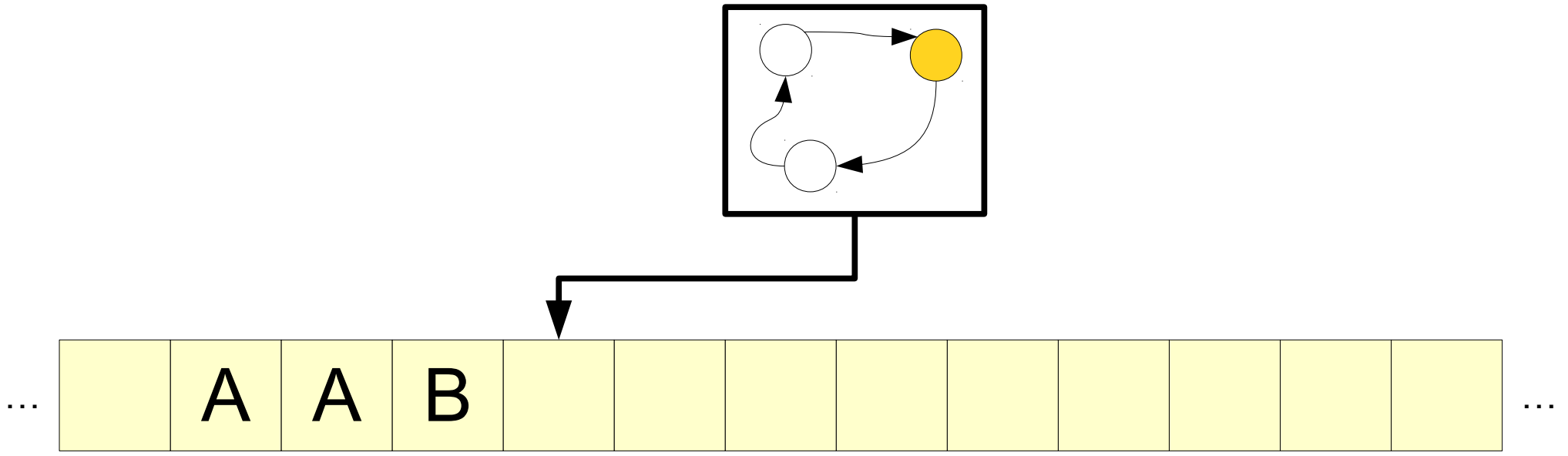

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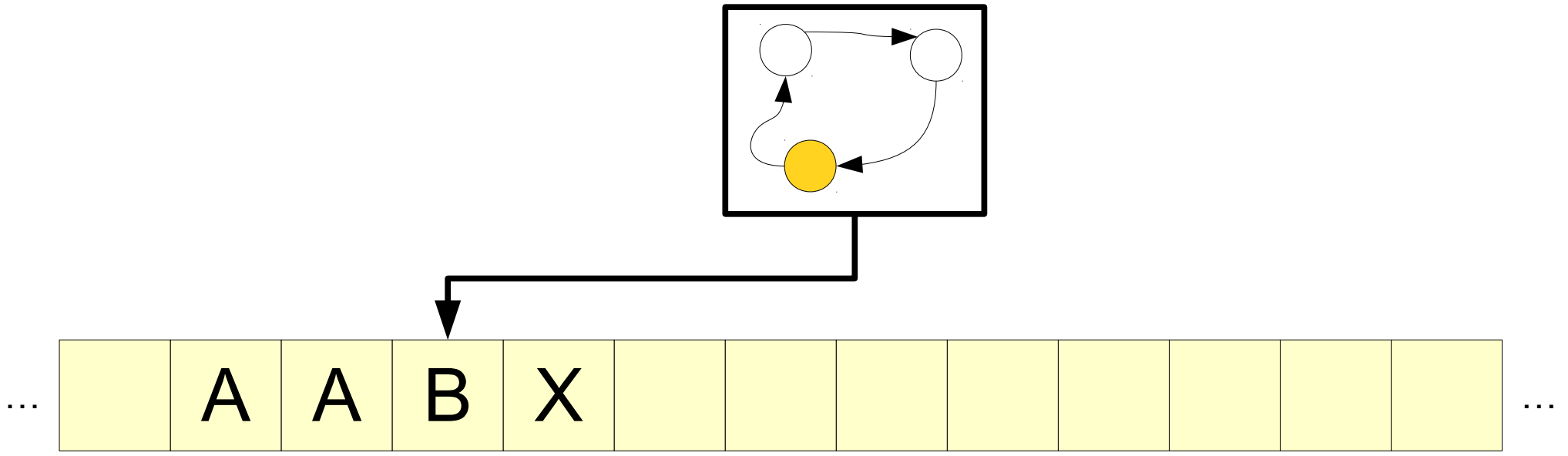

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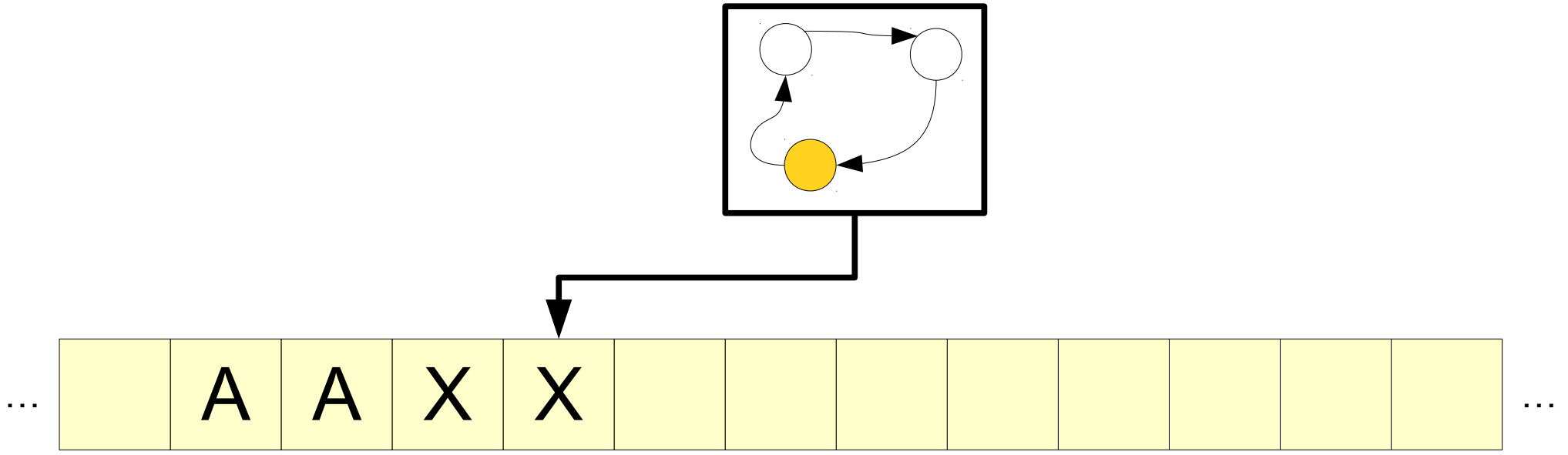

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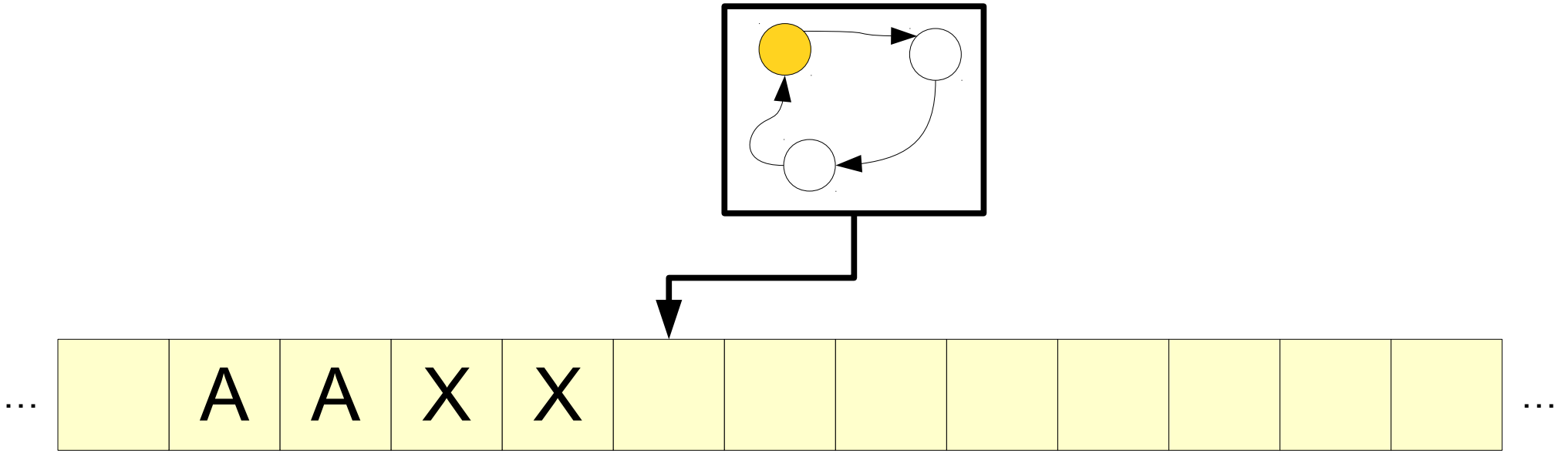

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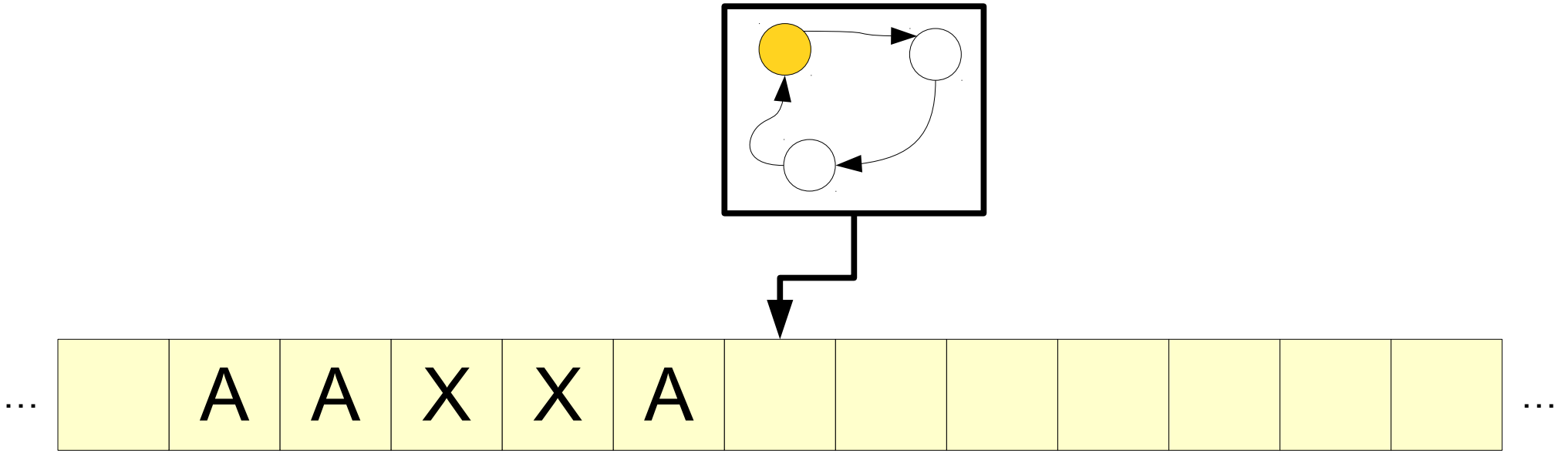

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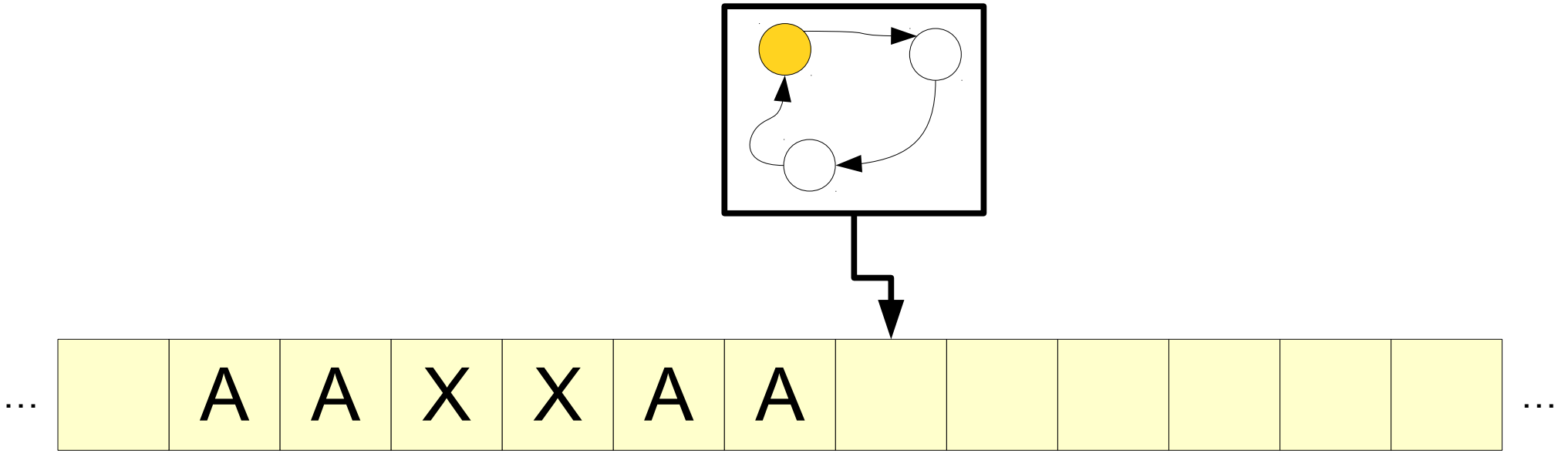

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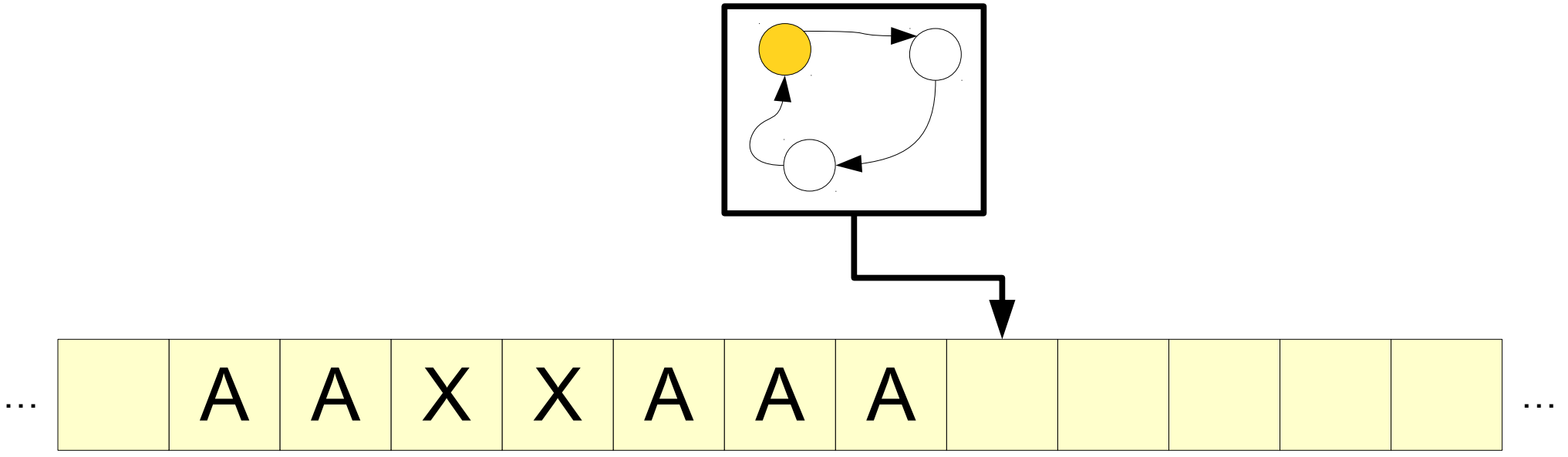


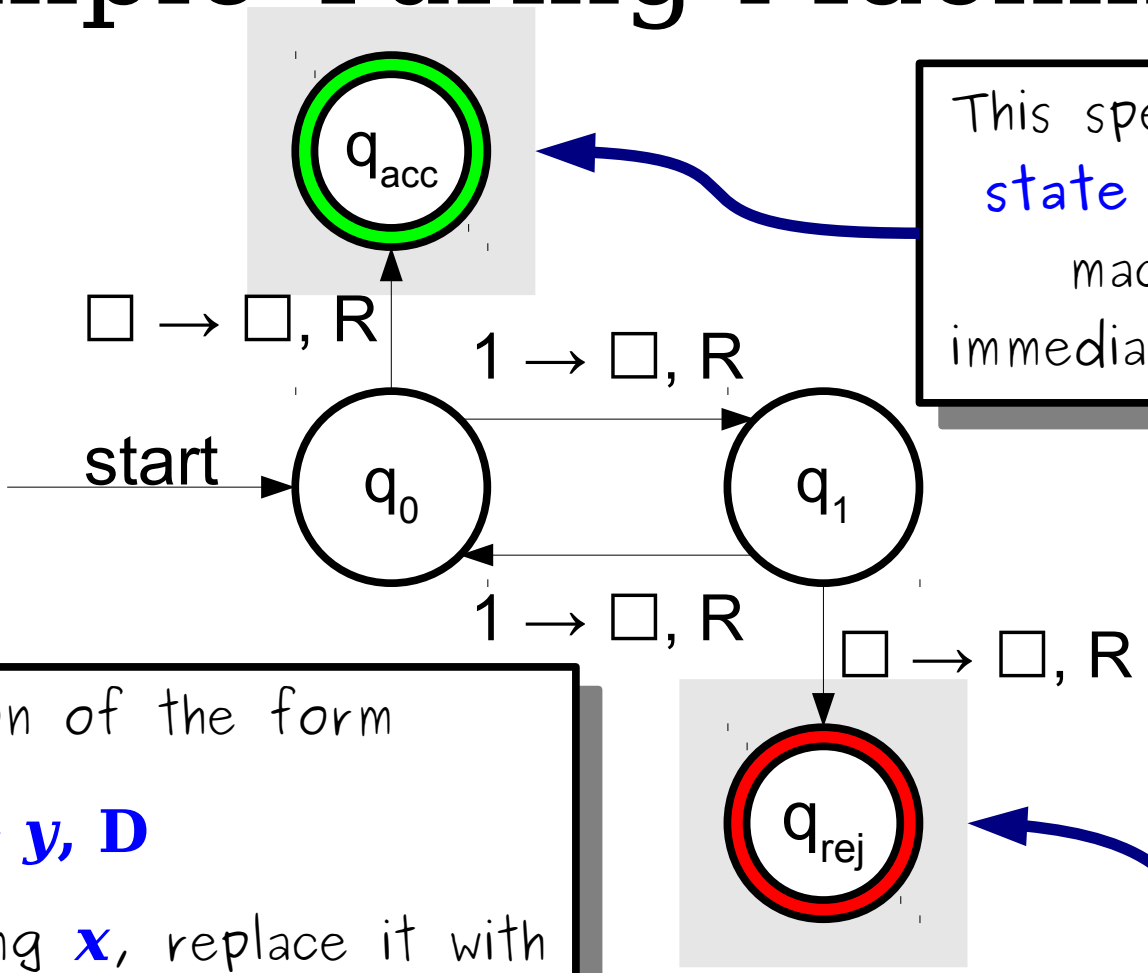
The Turing Machine

- A Turing machine consists of three parts:
  - A **finite-state control** that issues commands,
  - an **infinite tape** for input and scratch space, and
  - a **tape head** that can read and write a single tape cell.
- At each step, the Turing machine
  - writes a symbol to the tape cell under the tape head,
  - changes state, and
  - moves the tape head to the left or to the right.

Input and Tape Alphabets

- A Turing machine has two alphabets:
  - An **input alphabet** Σ. All input strings are written in the input alphabet.
  - A **tape alphabet** Γ, where Σ ⊆ Γ. The tape alphabet contains all symbols that can be written onto the tape.
- The tape alphabet Γ can contain any number of symbols, but always contains at least one **blank symbol**, denoted □. You are guaranteed □ ∉ Σ.
- At startup, the Turing machine begins with an infinite tape of □ symbols with the input written at some location. The tape head is positioned at the start of the input.

A Simple Turing Machine



This special **accept state** causes the machine to immediately accept.

Each transition of the form

$$x \to y, D$$

means "upon reading x, replace it with symbol y and move the tape head in direction D (which is either **L** or **R**). The symbol □ represents the **blank symbol**.

This special **reject state** causes the machine to immediately reject.

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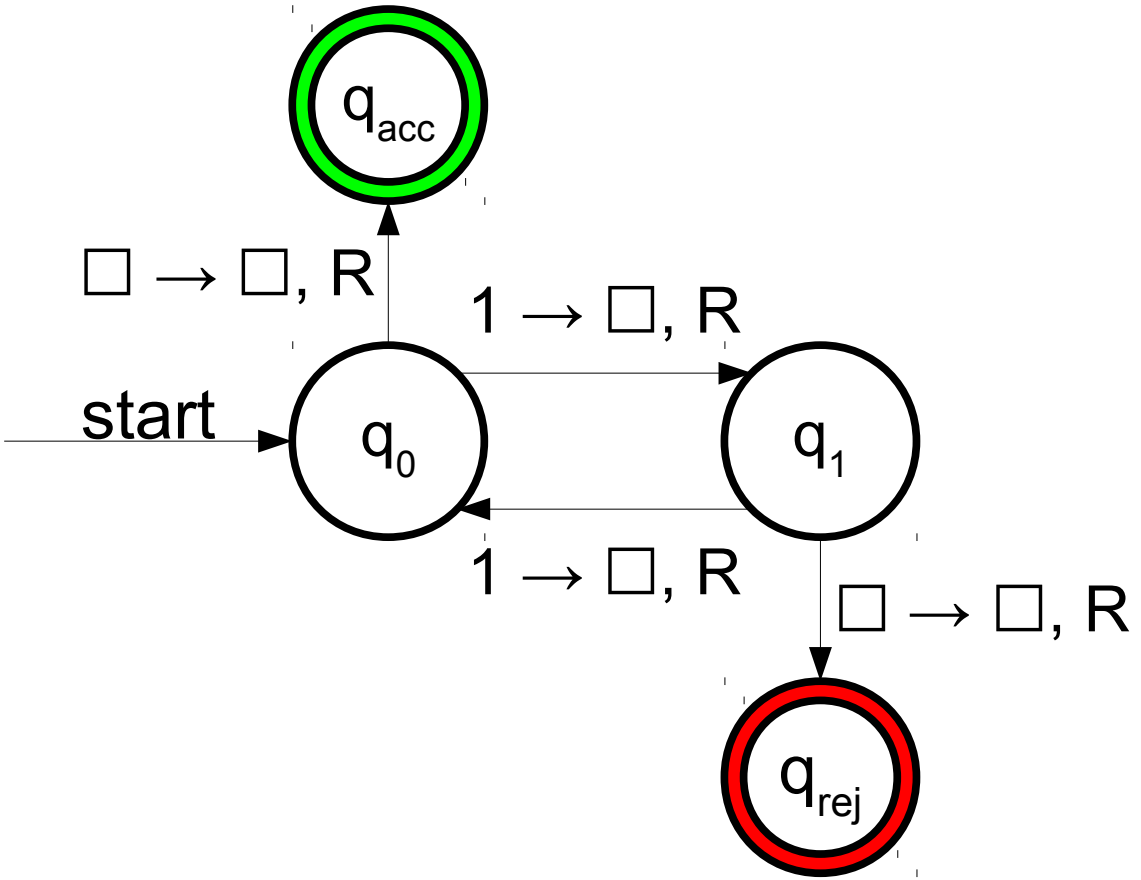

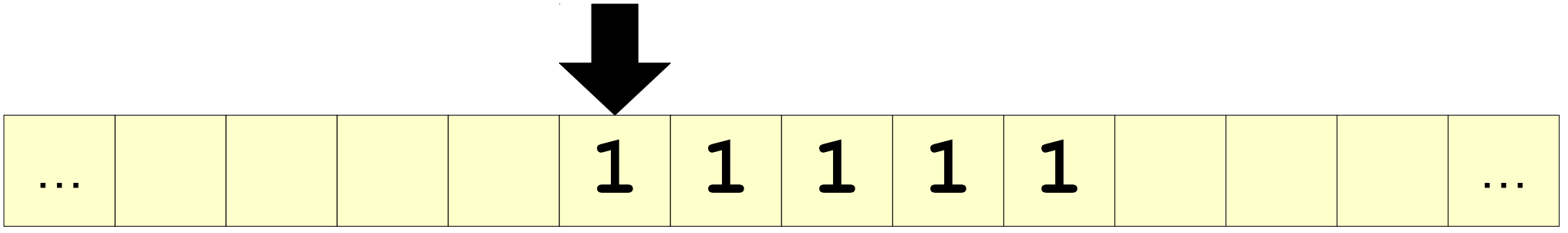

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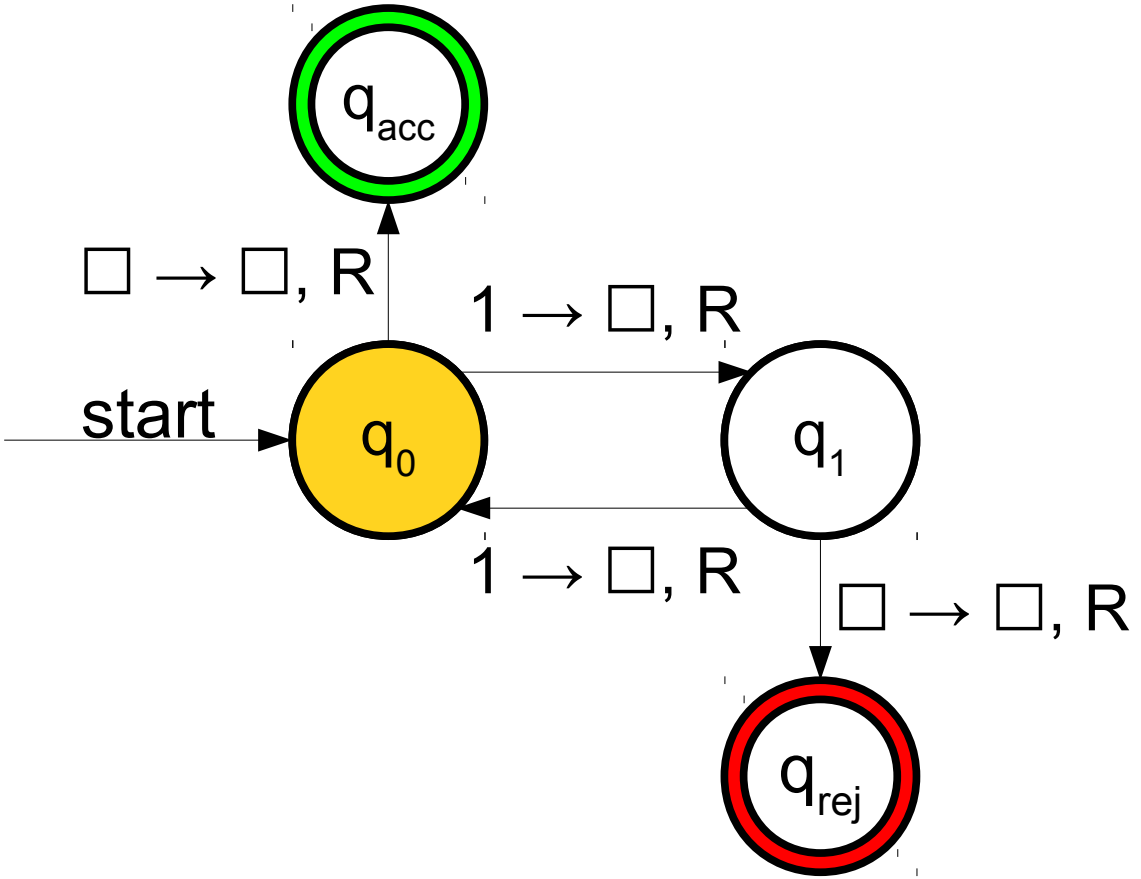

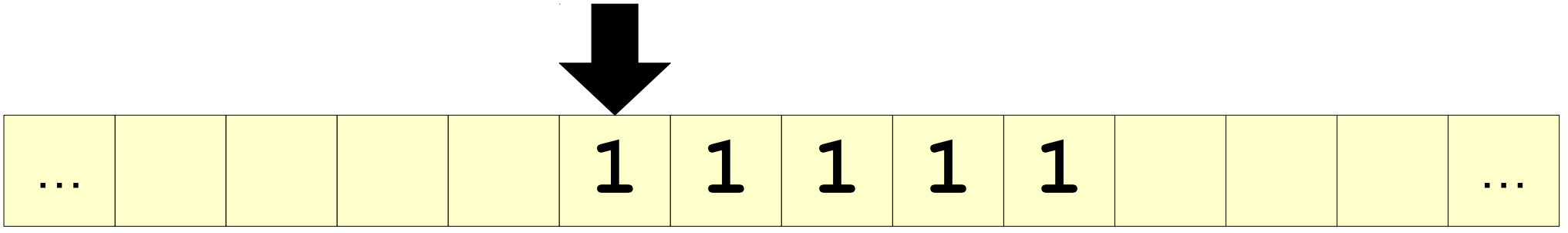

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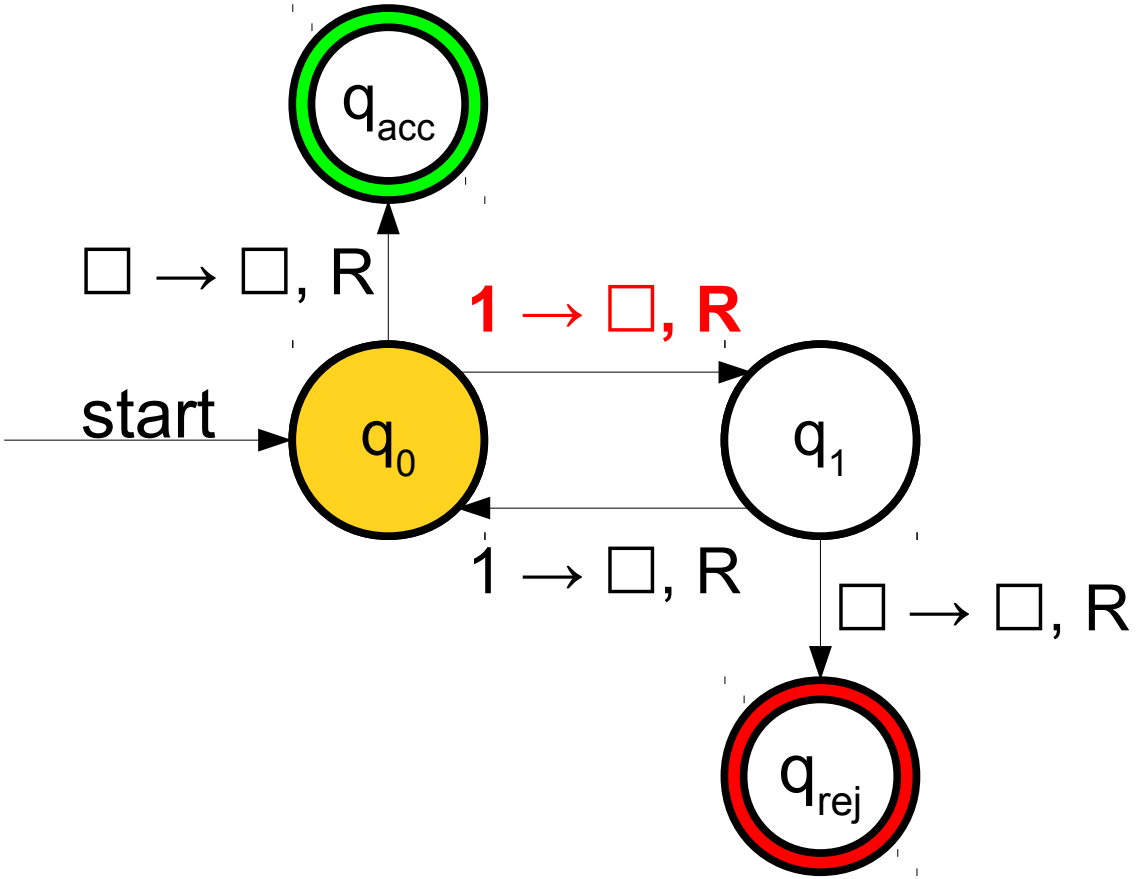

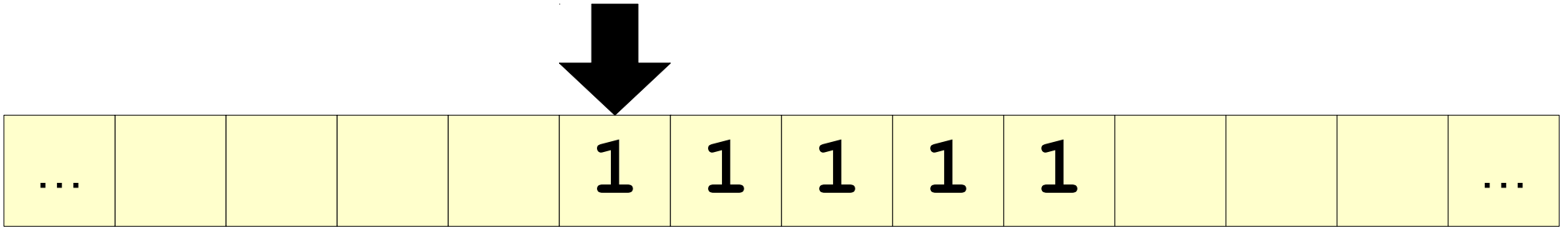

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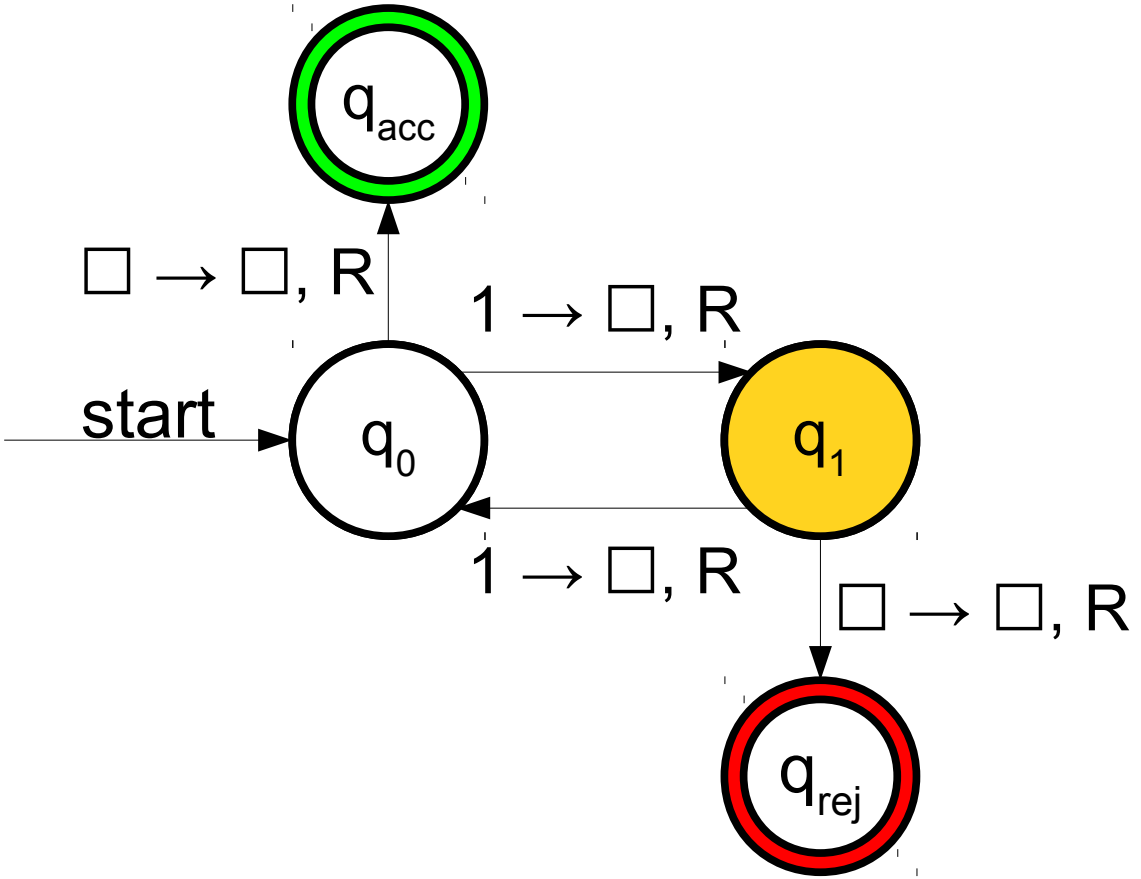

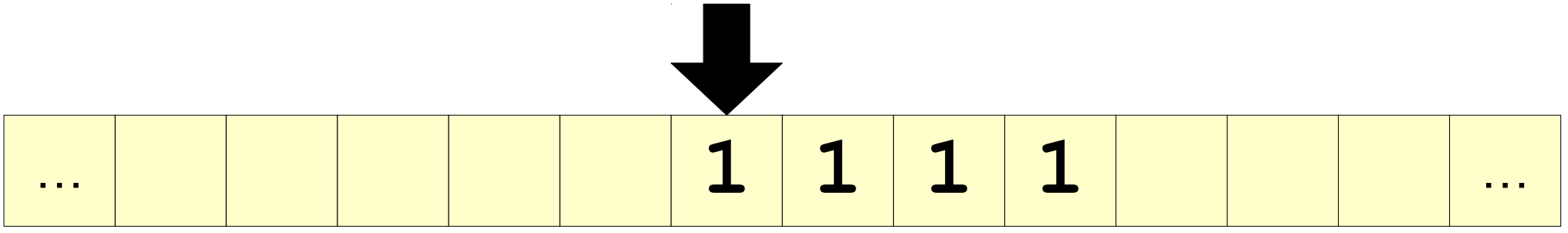

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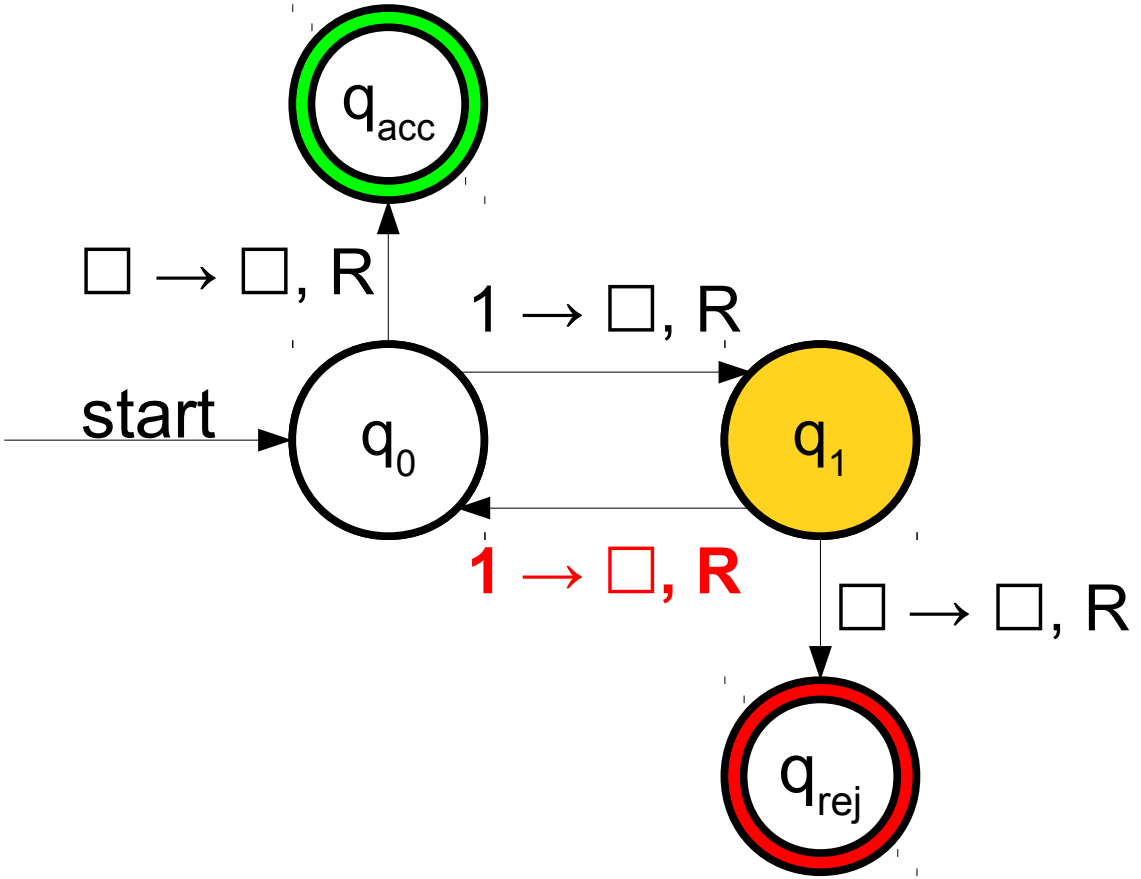

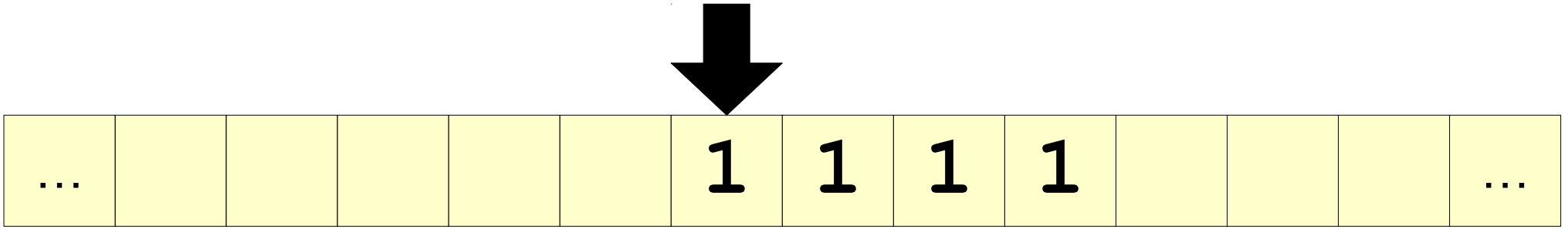

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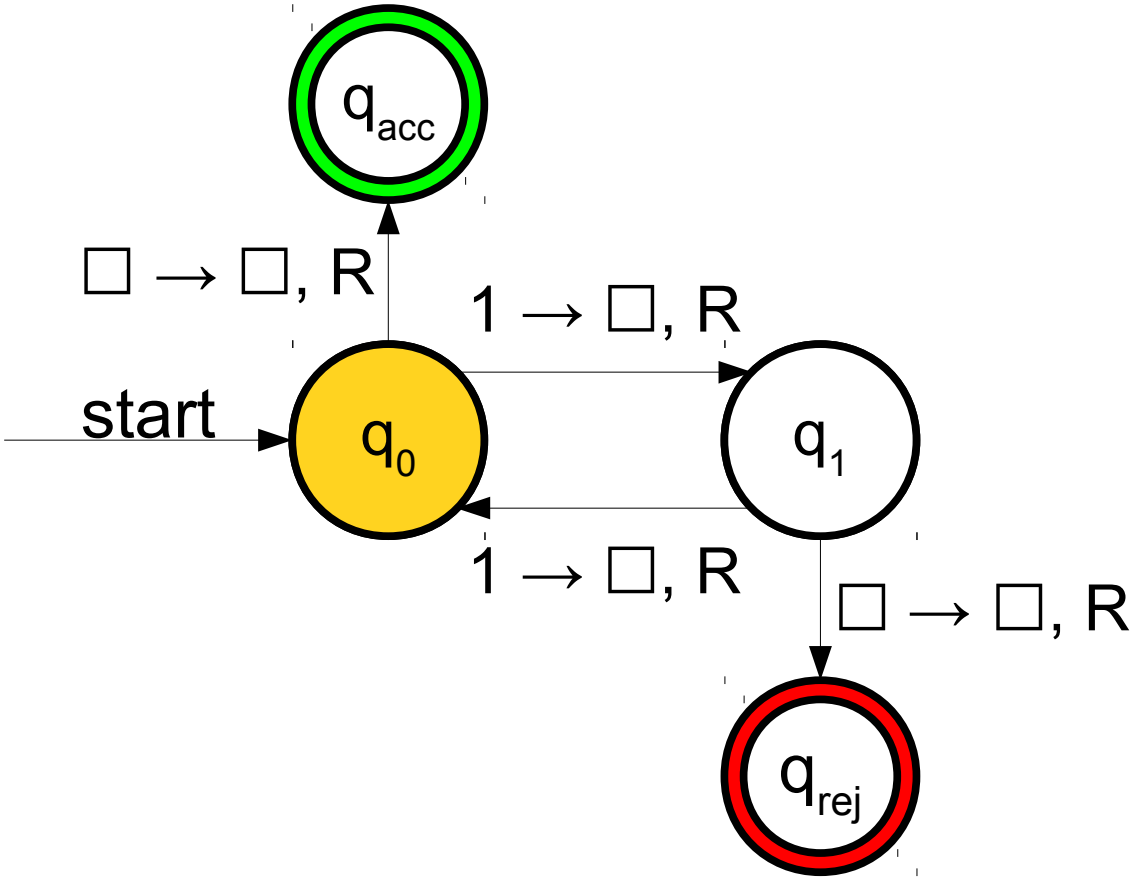

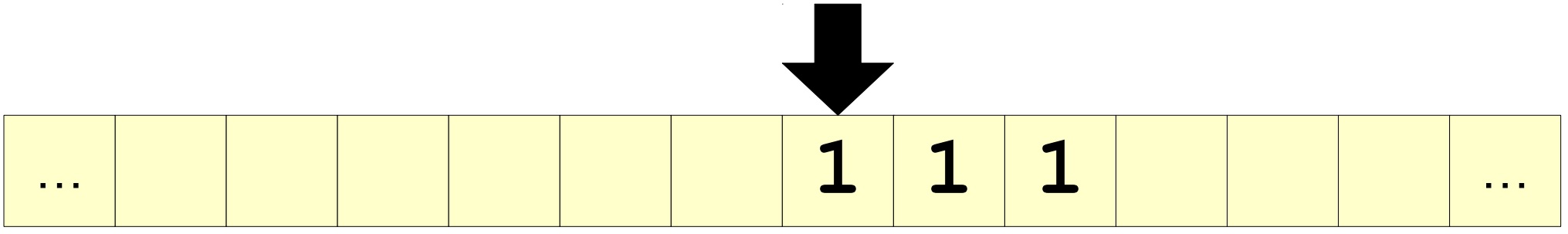

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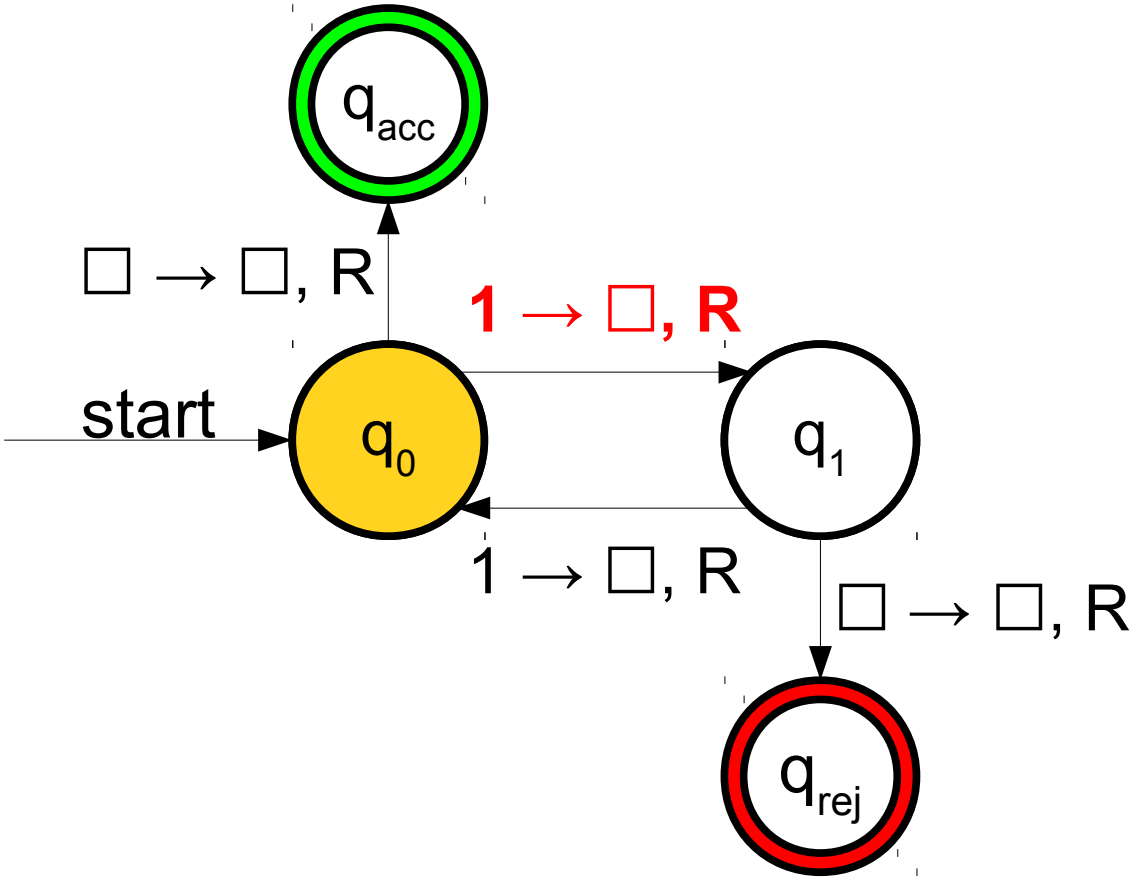

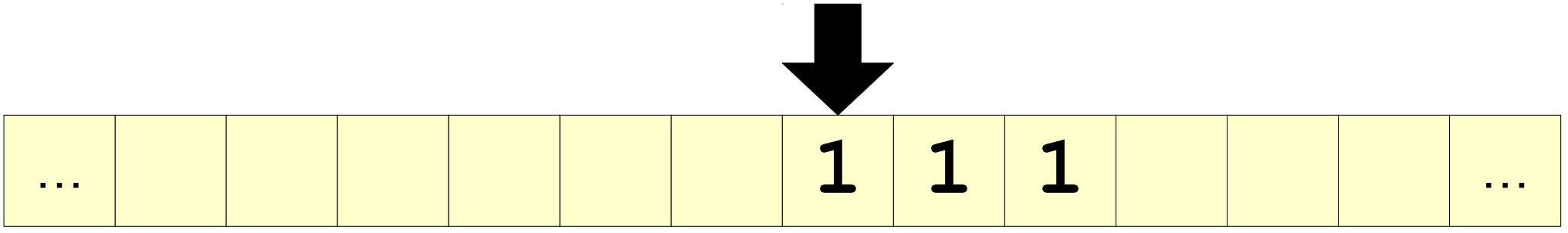

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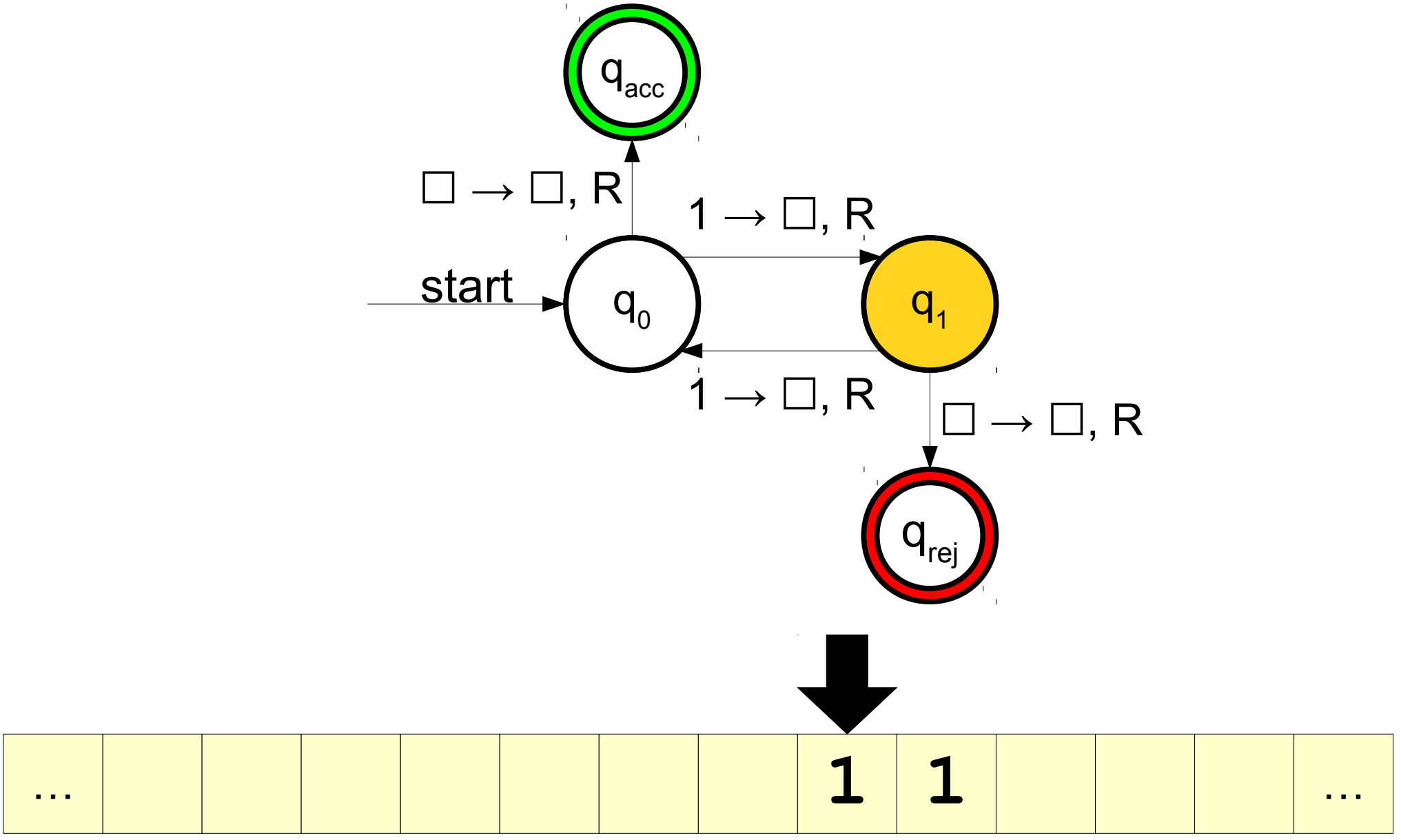

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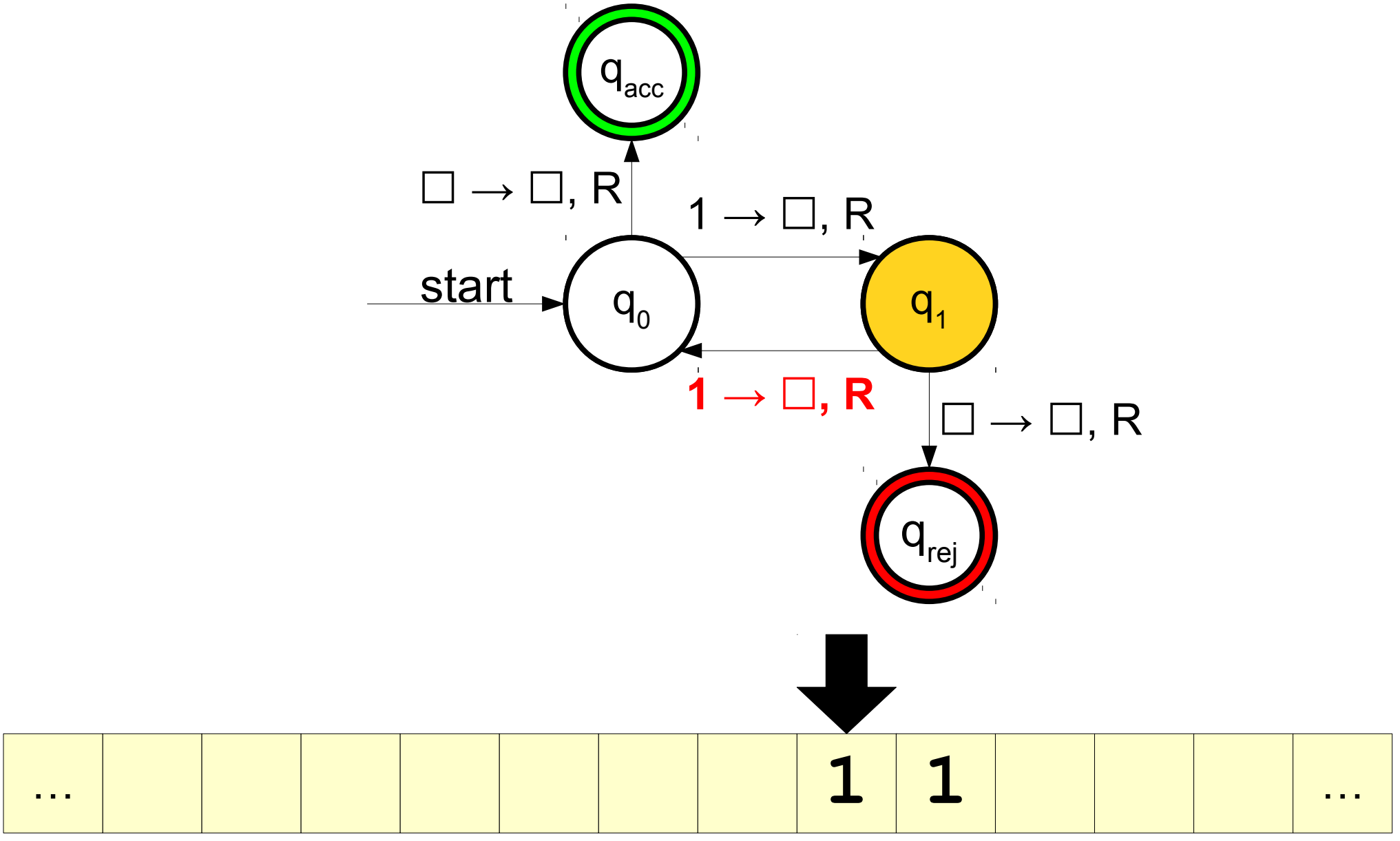

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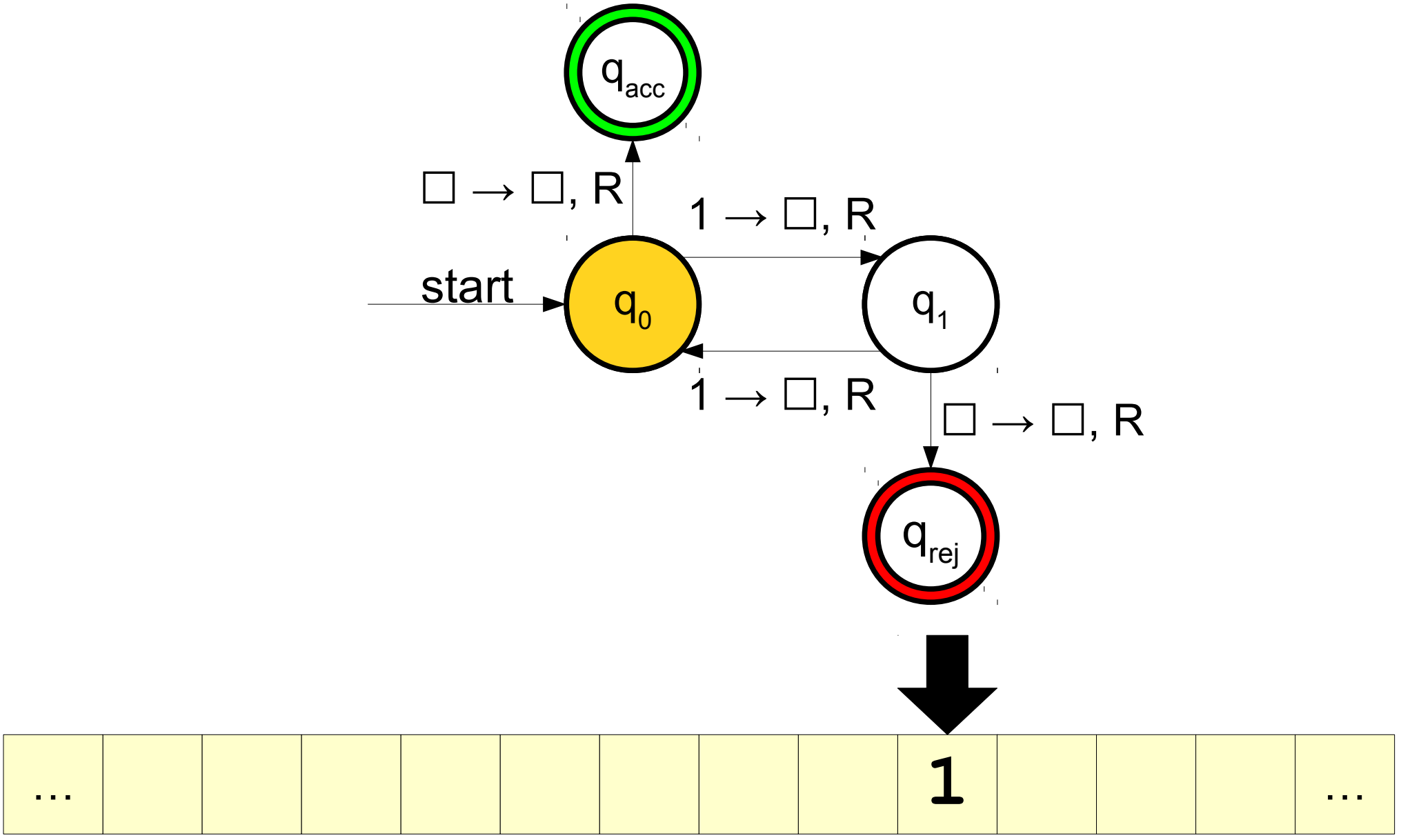

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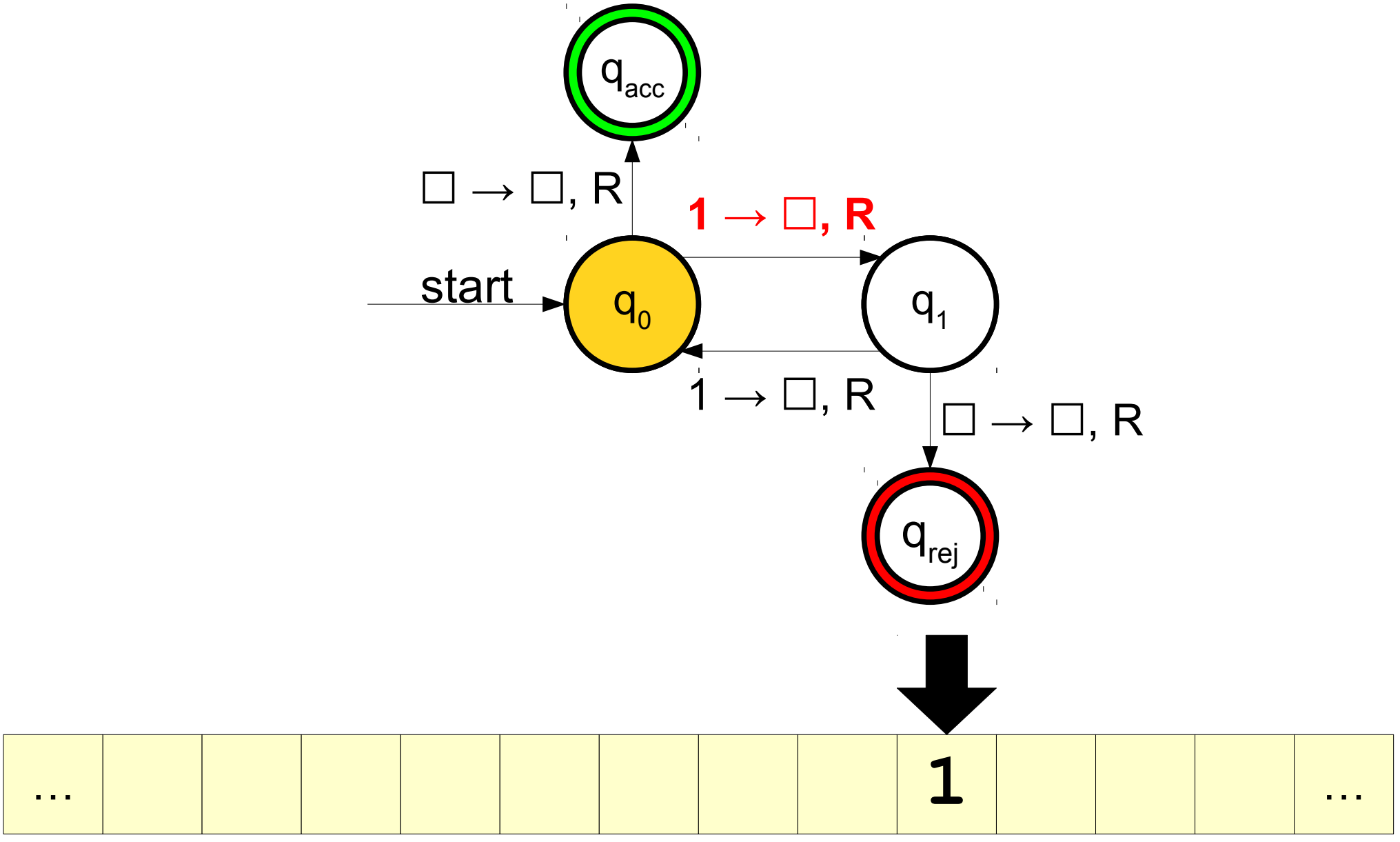

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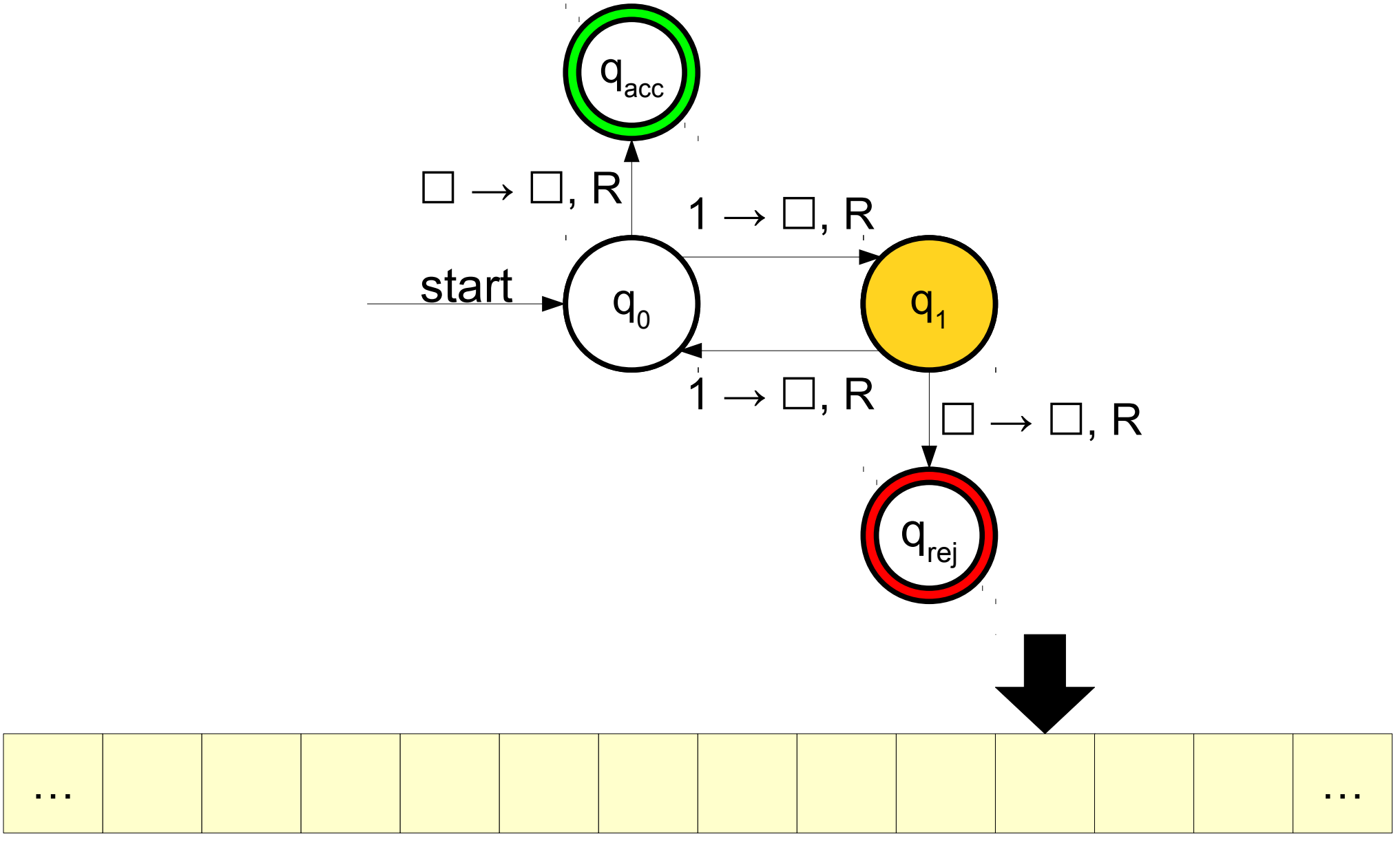

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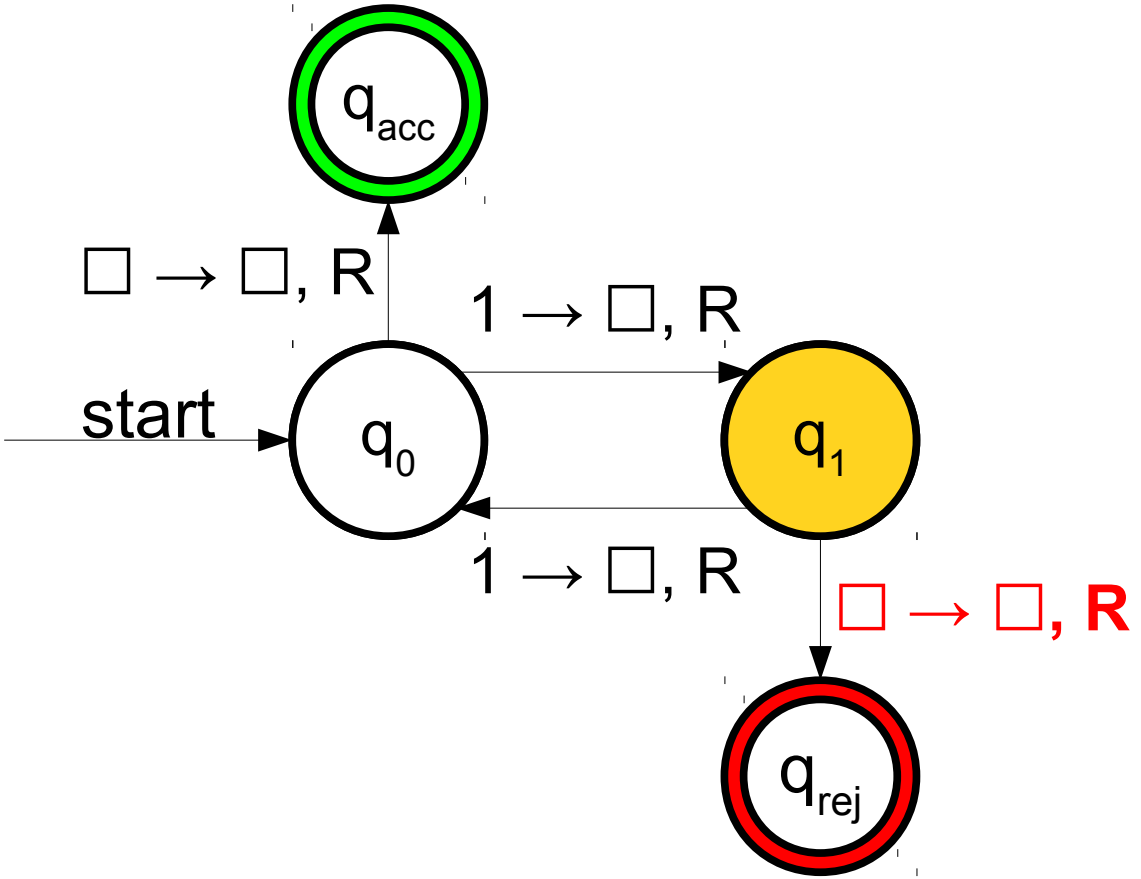

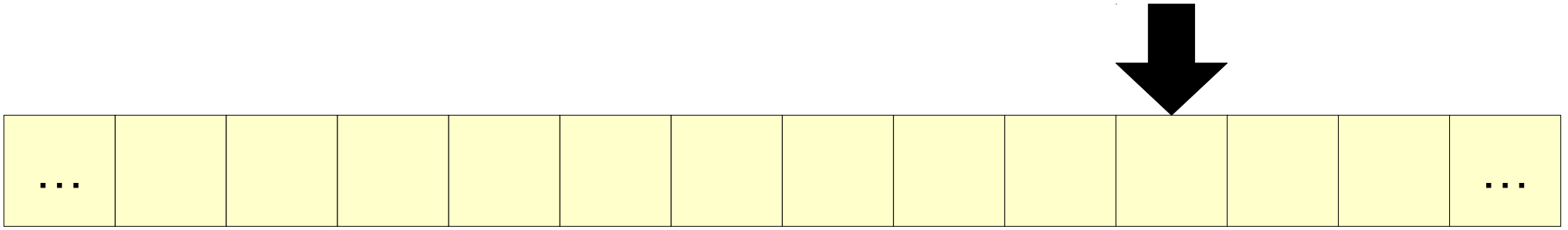

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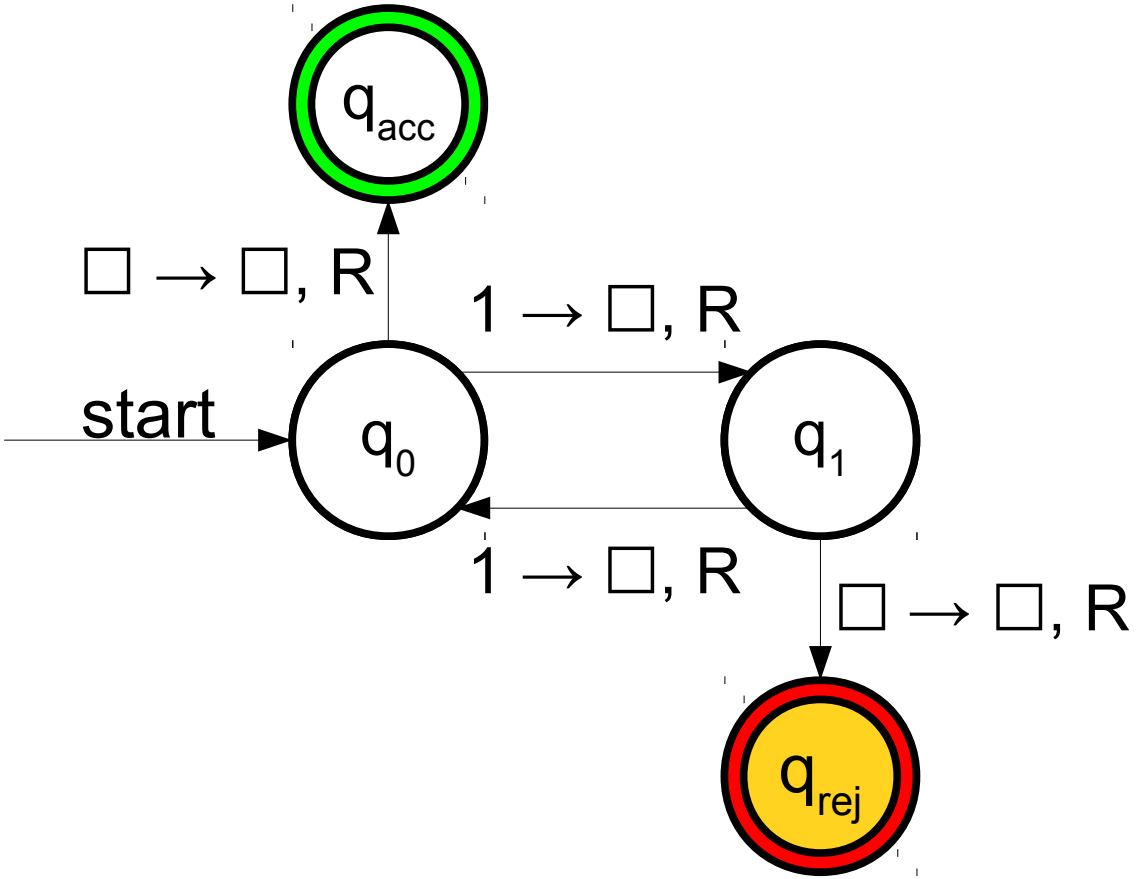

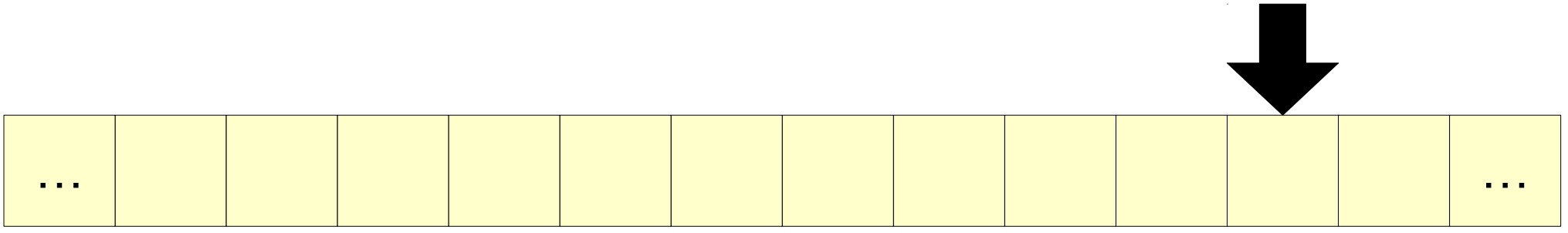

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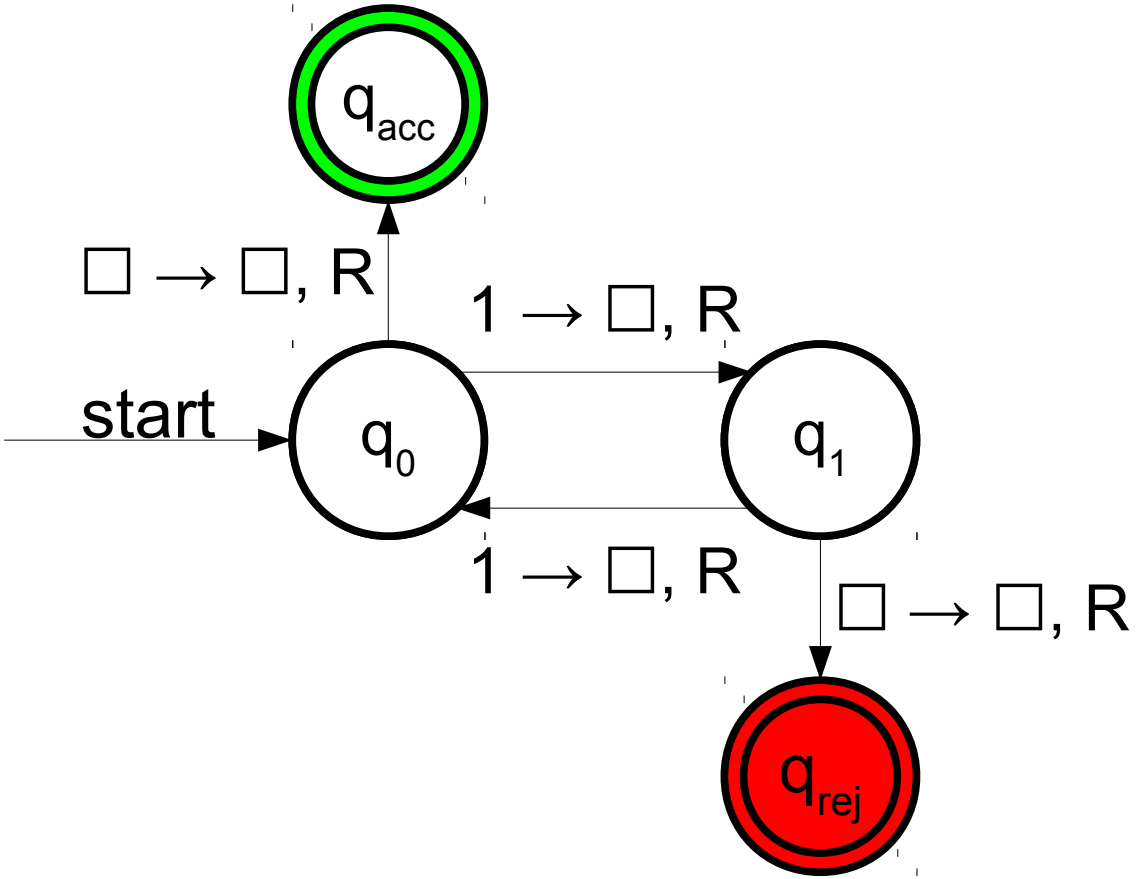

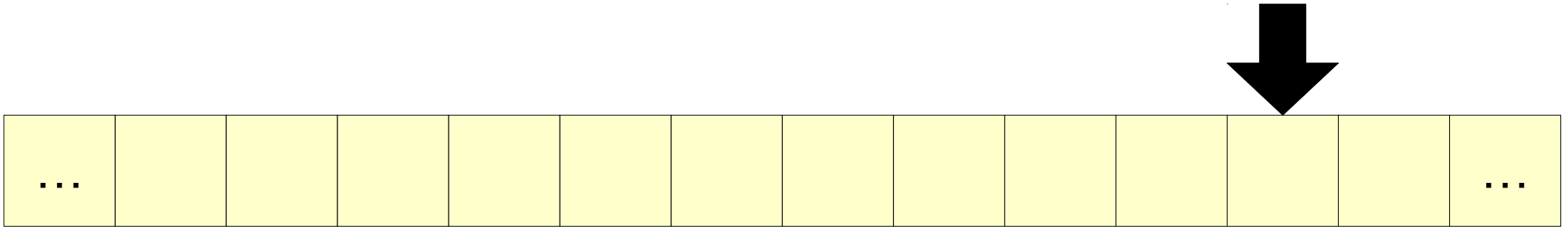

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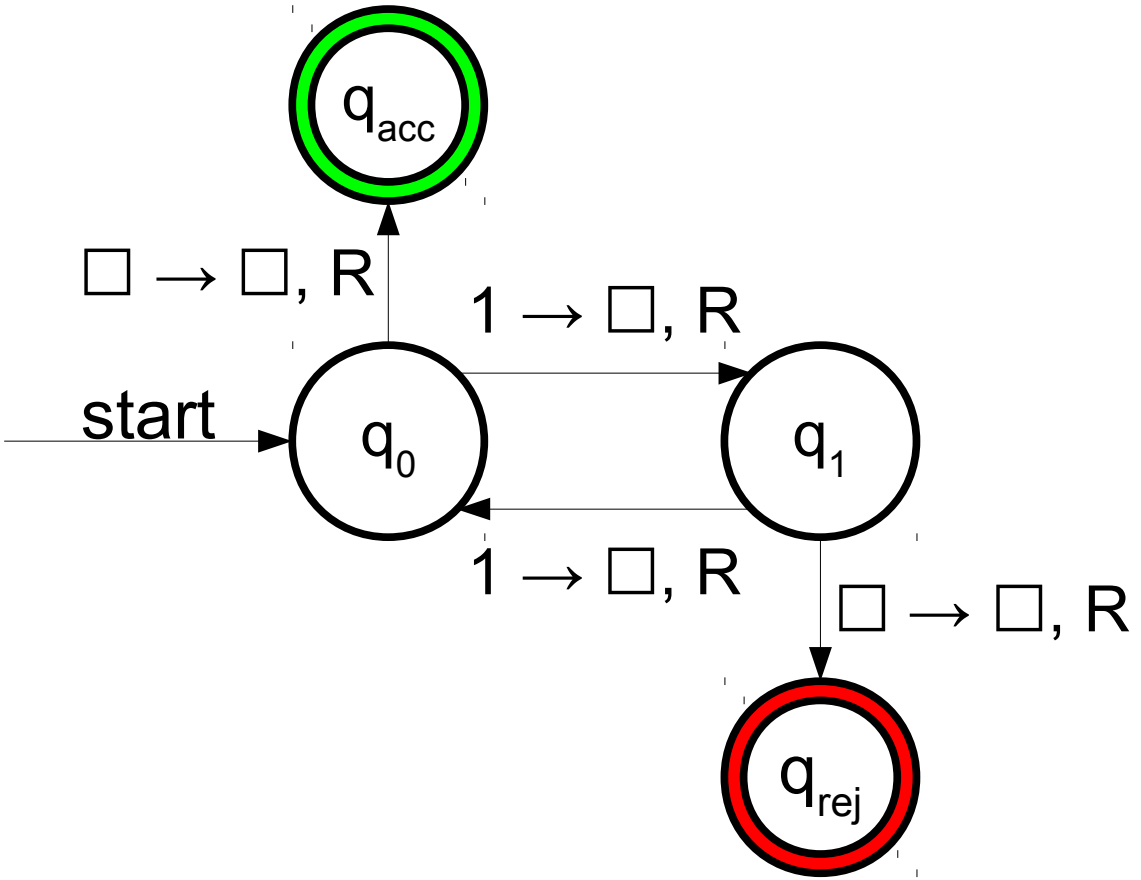

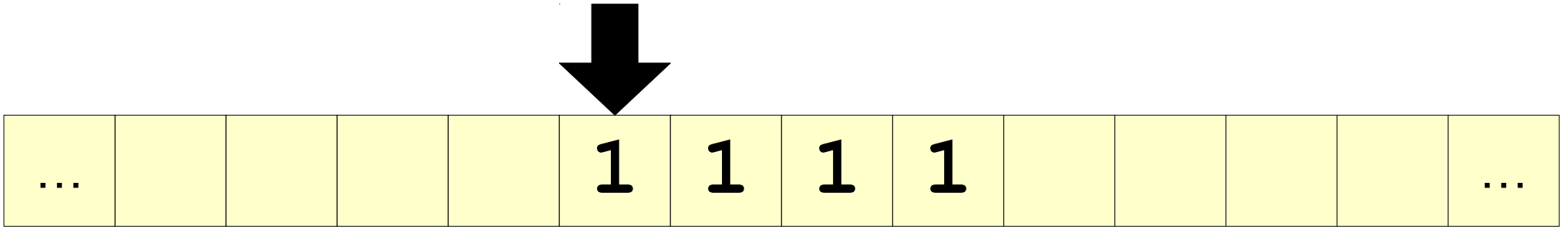

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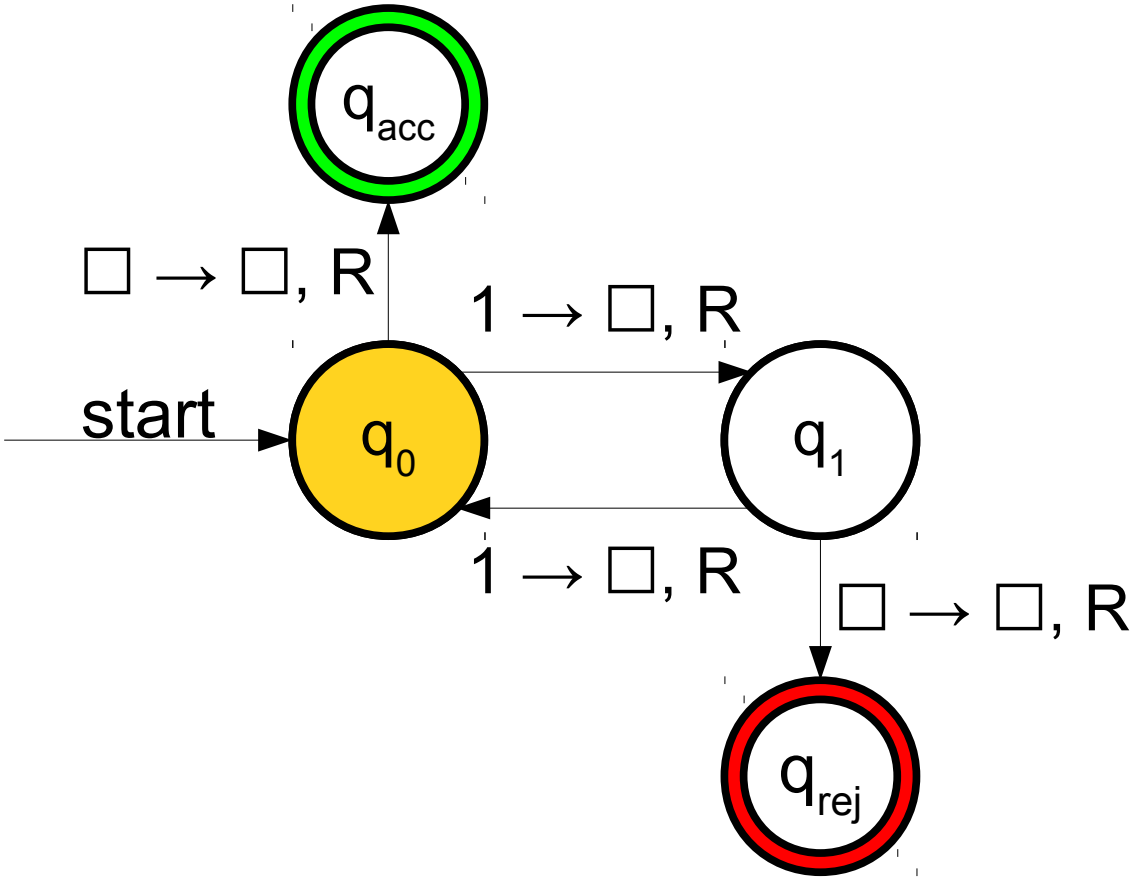

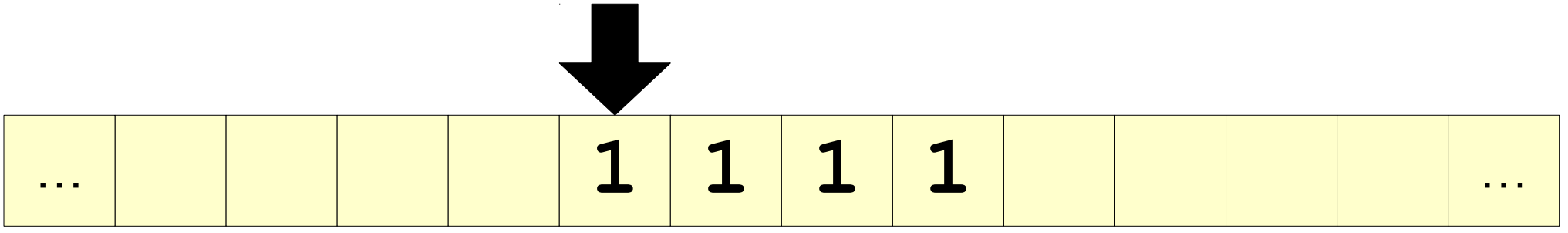

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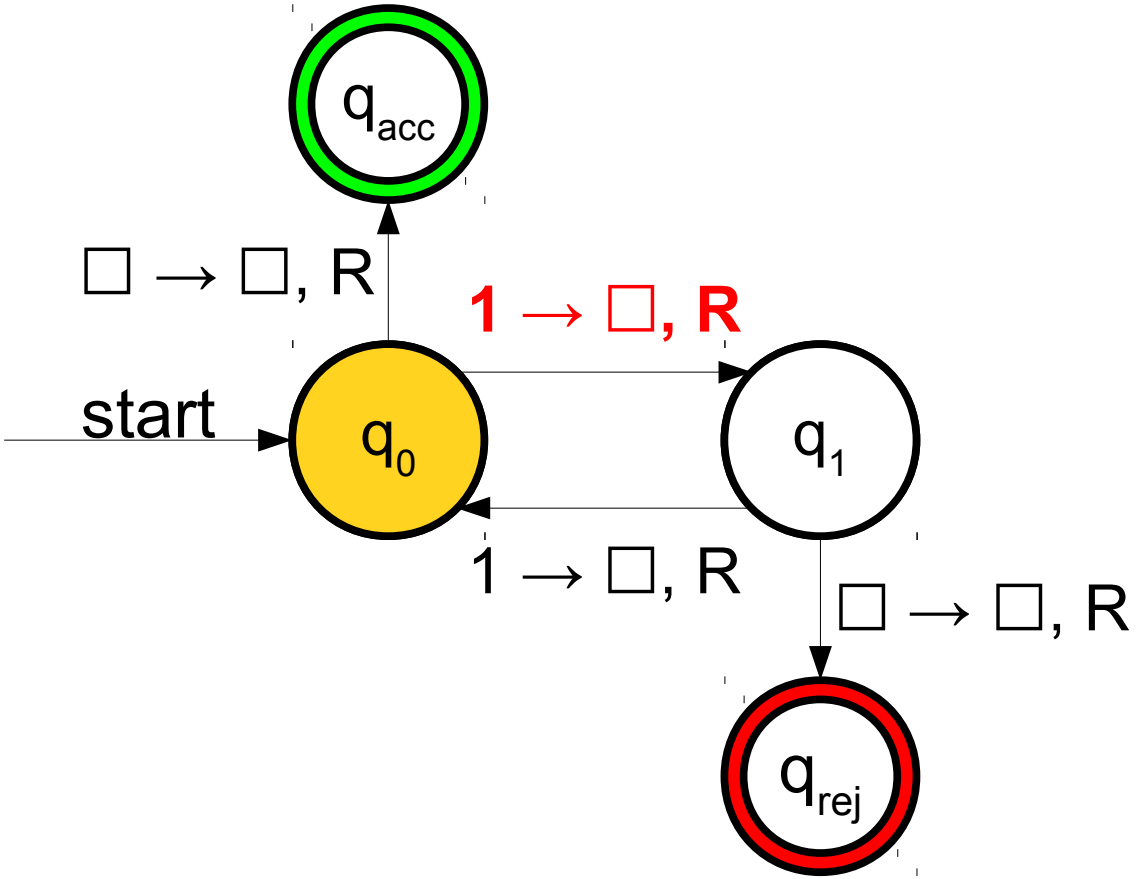

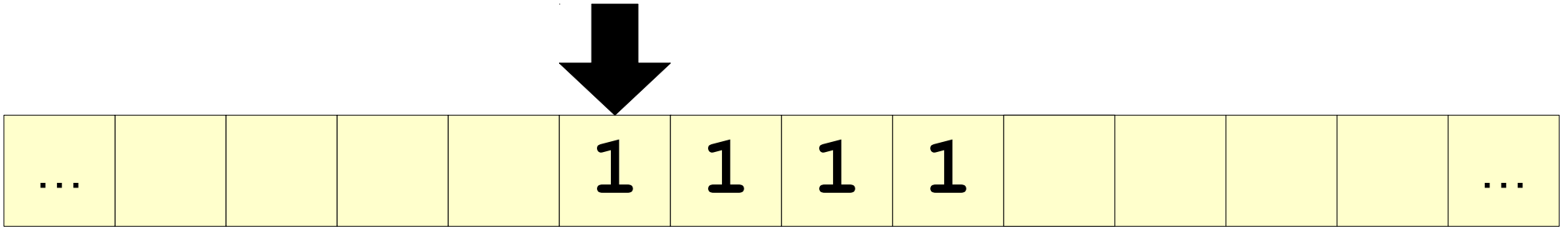

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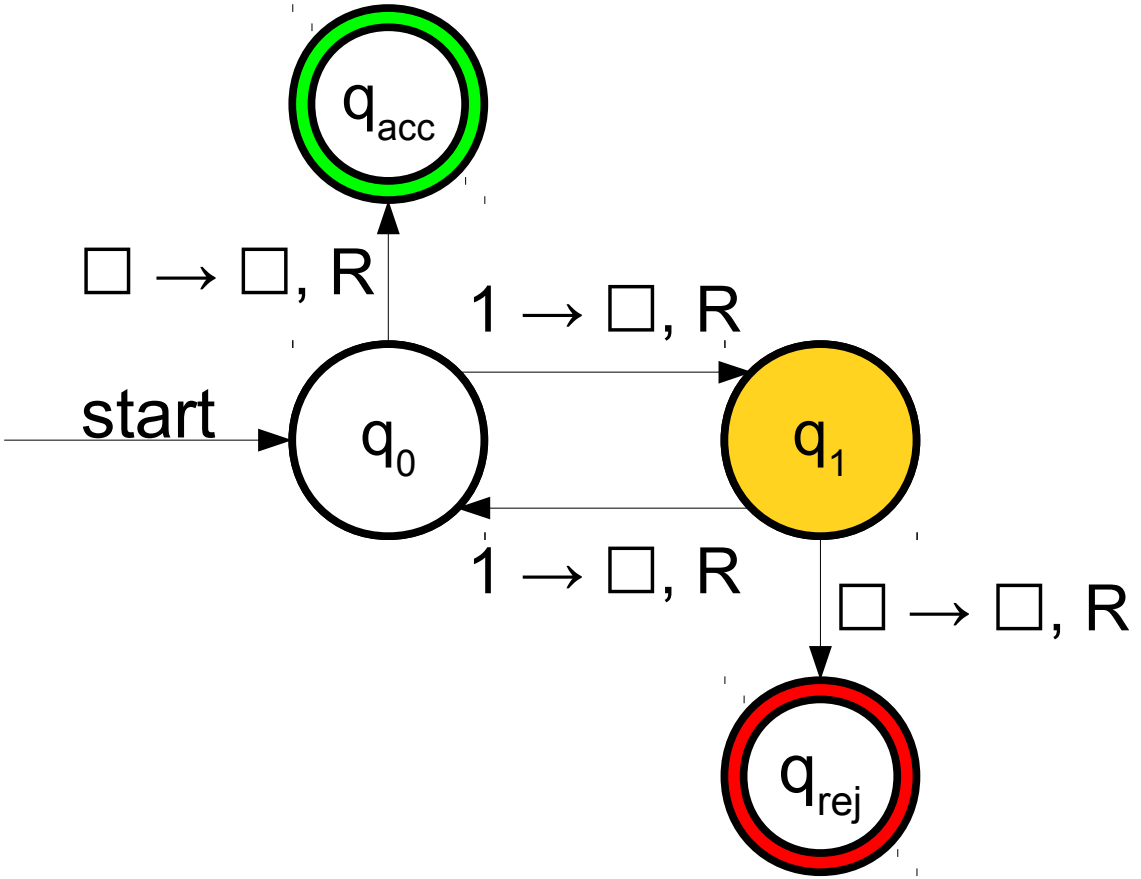
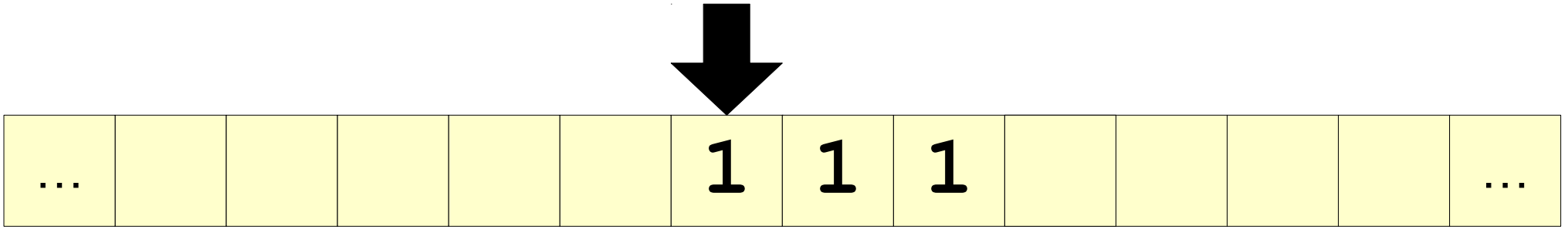
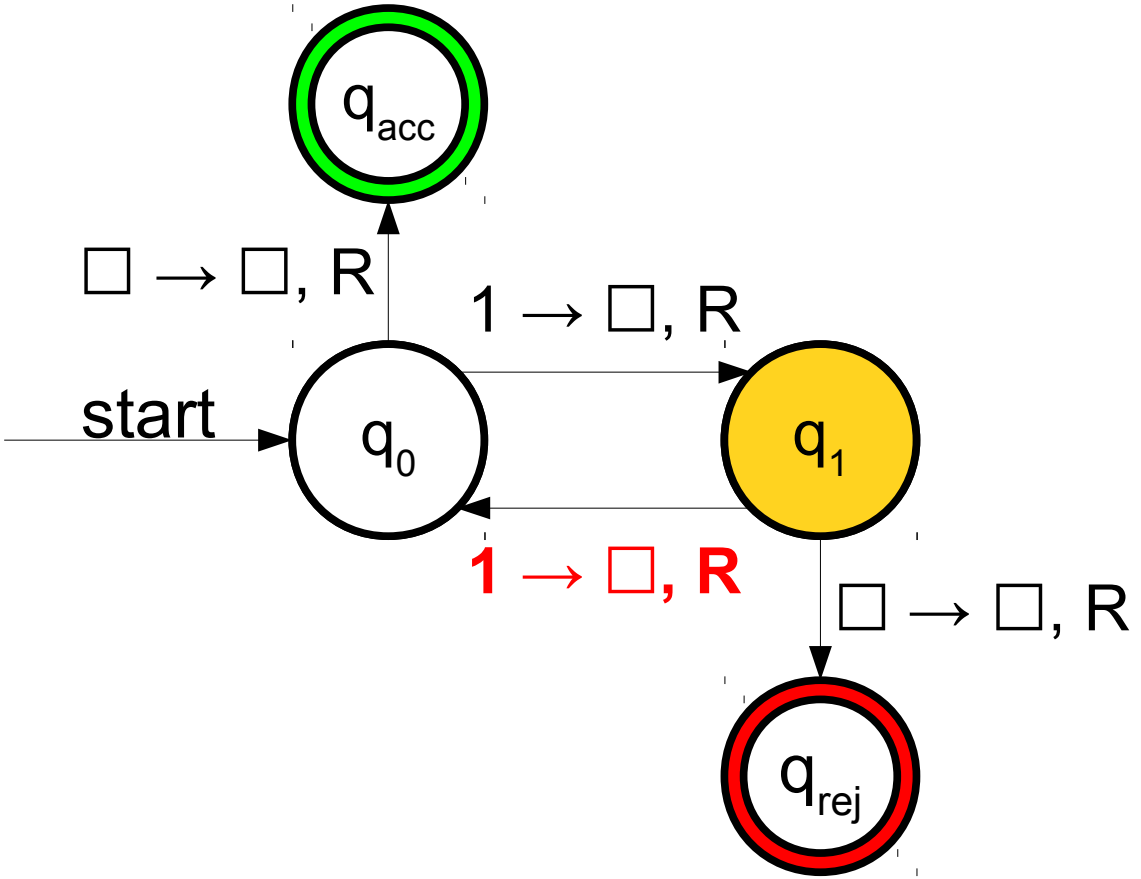
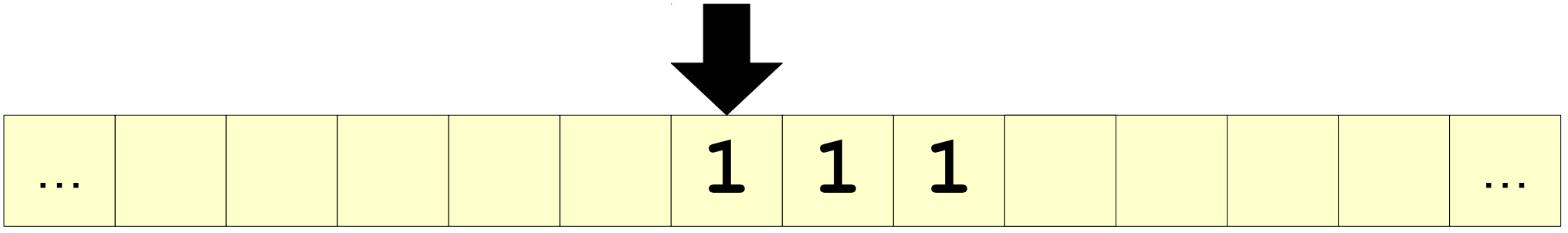




A Simple Turing Machine





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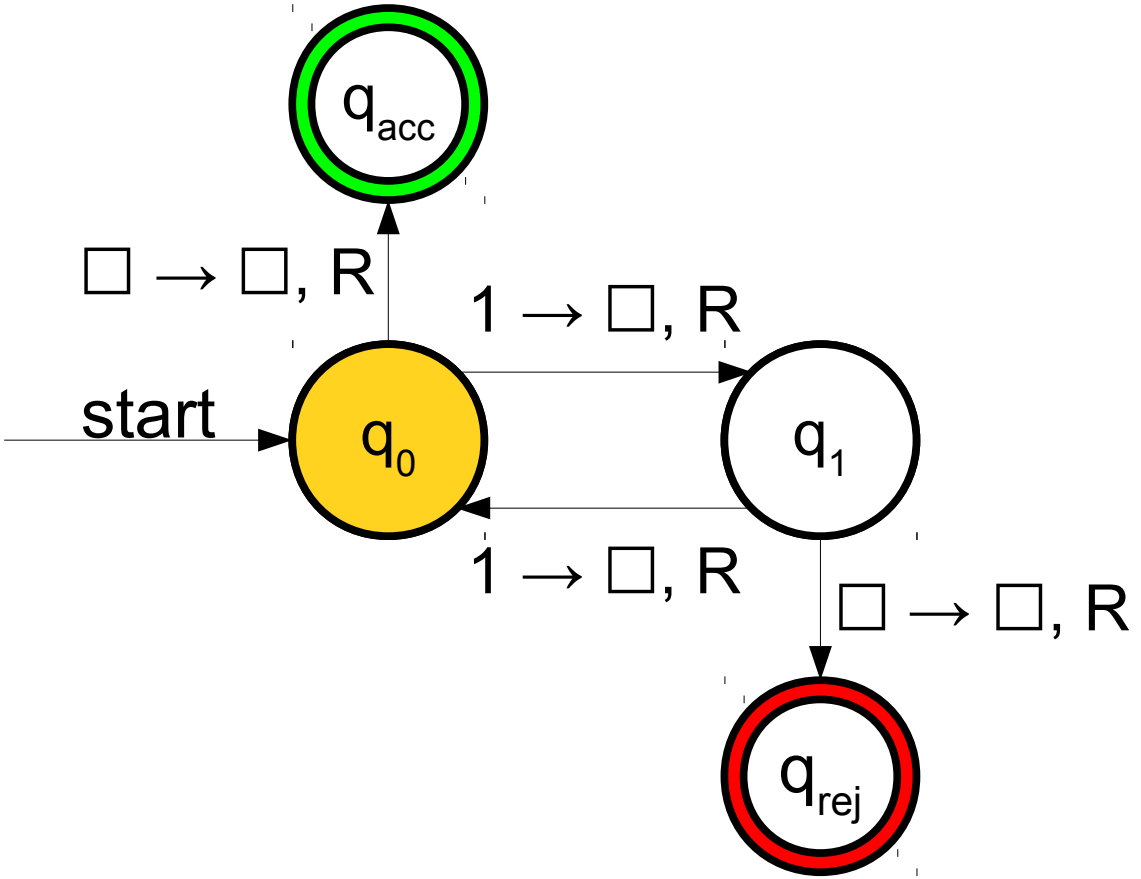

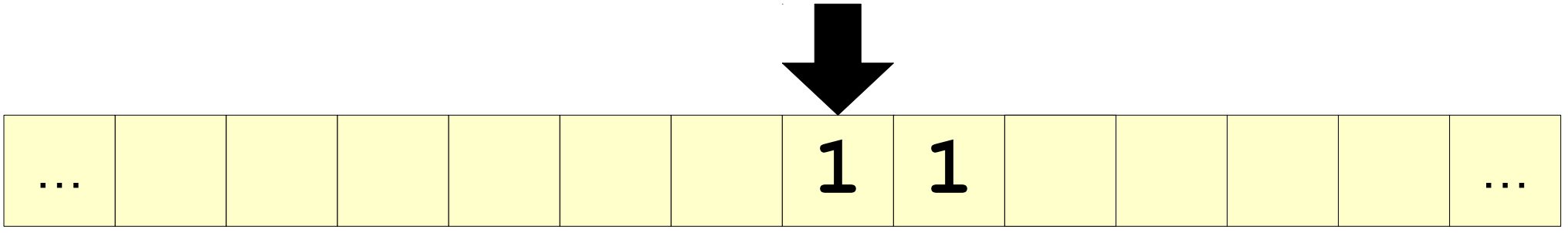

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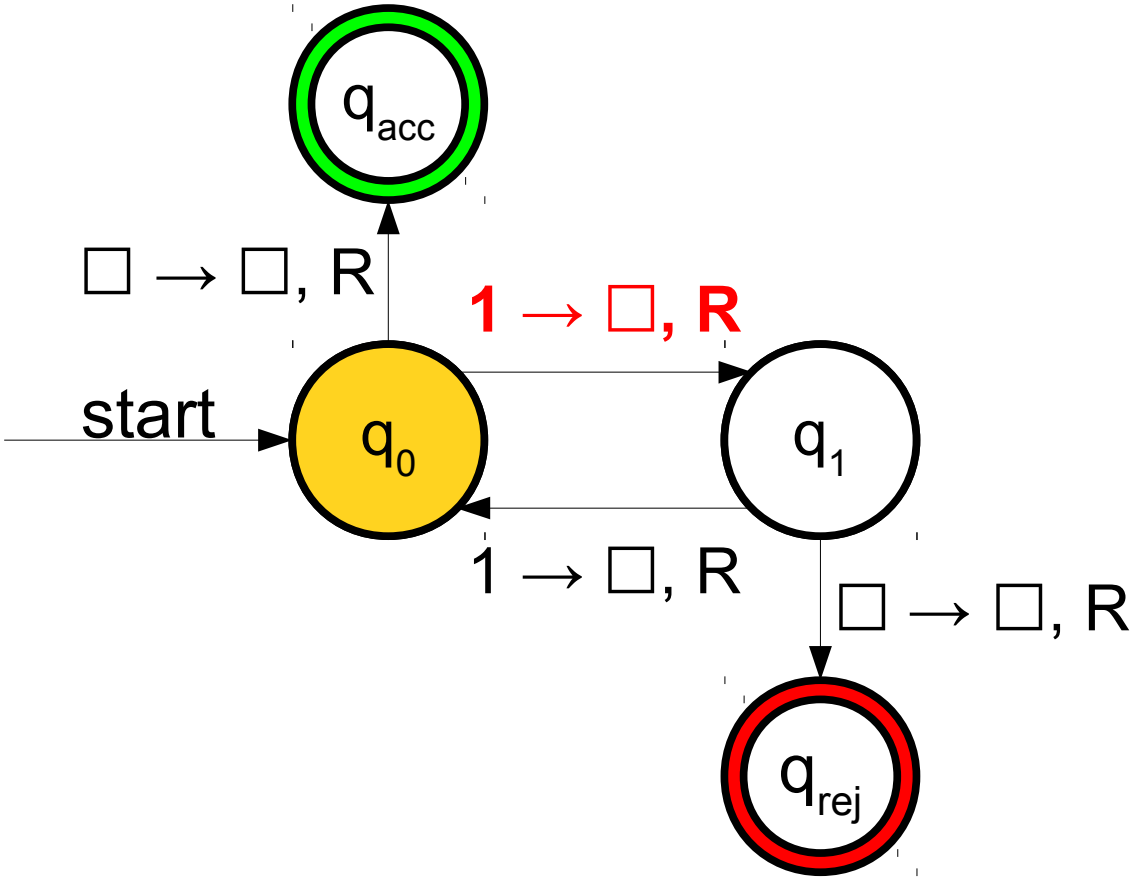

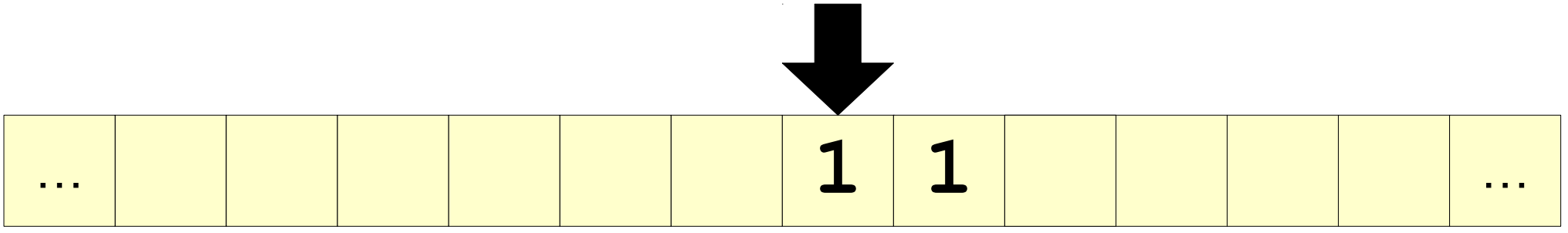

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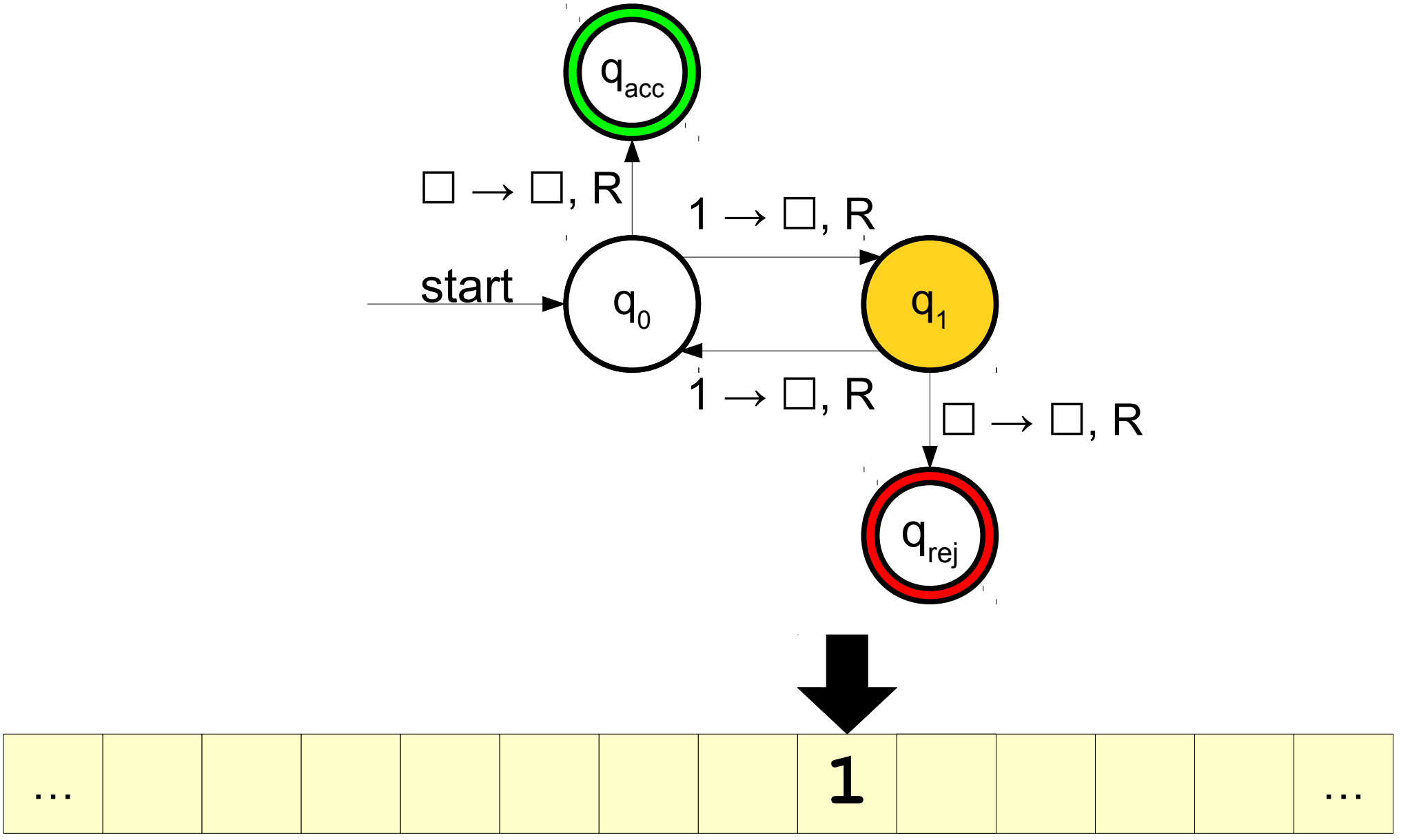

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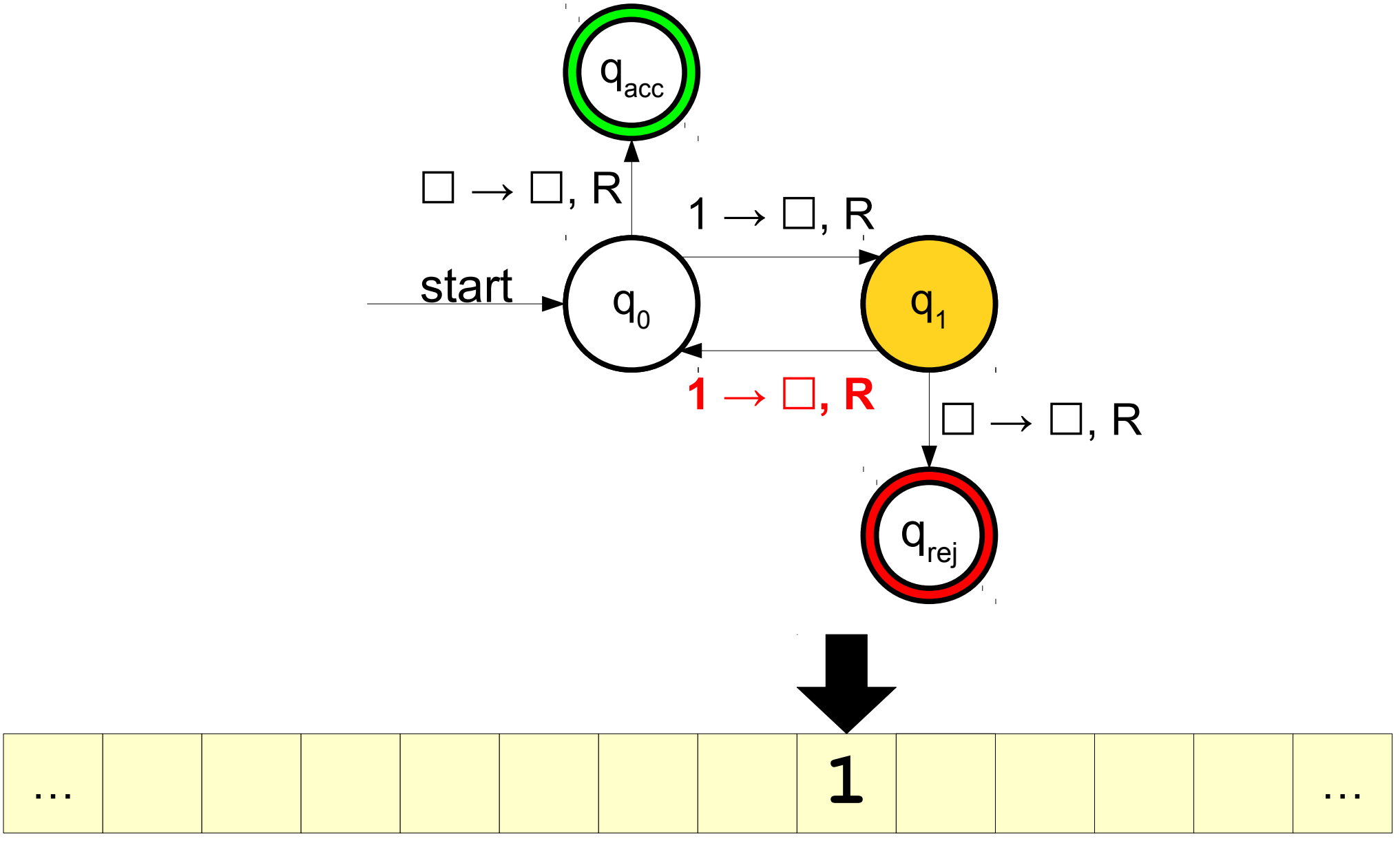

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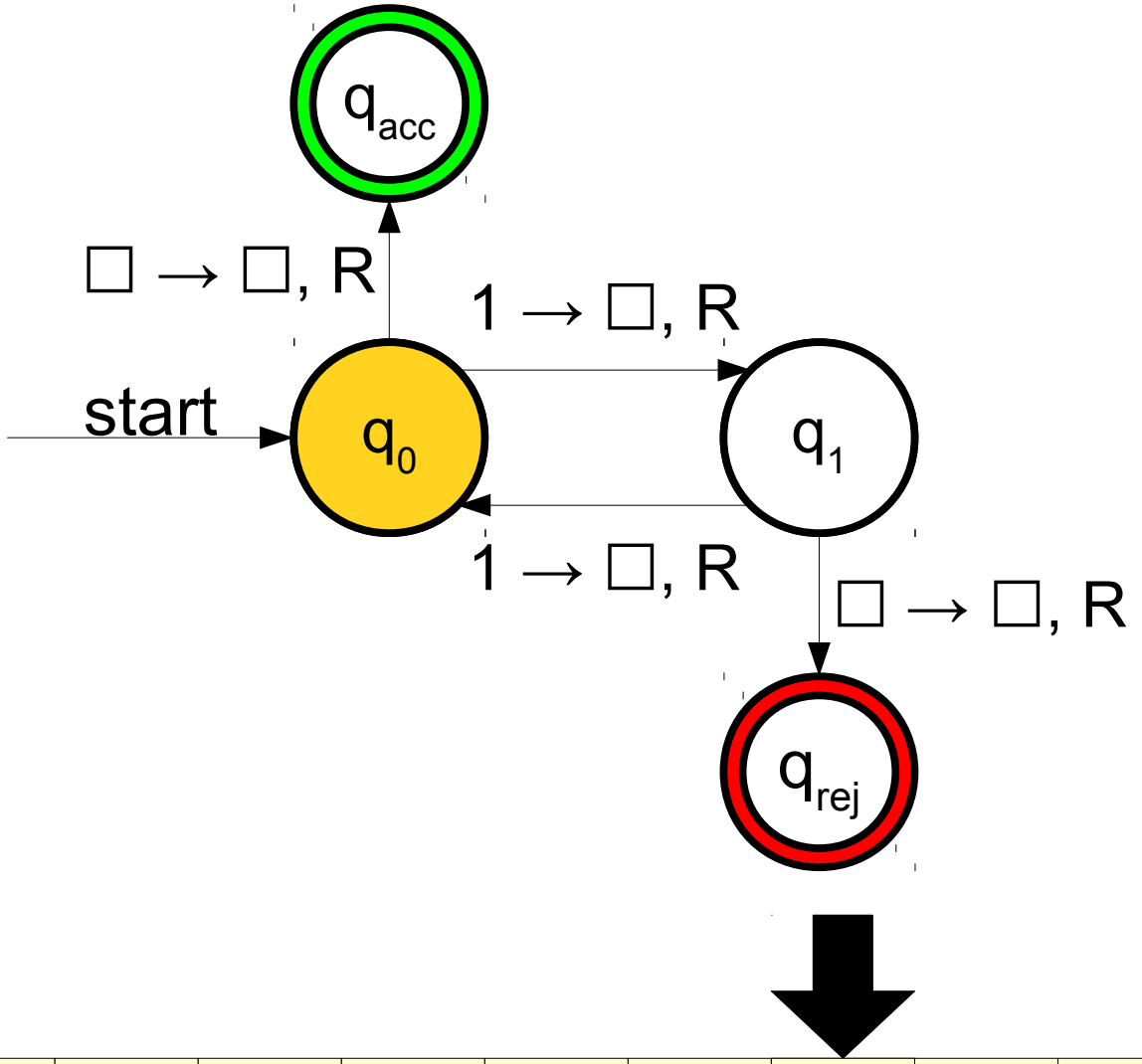

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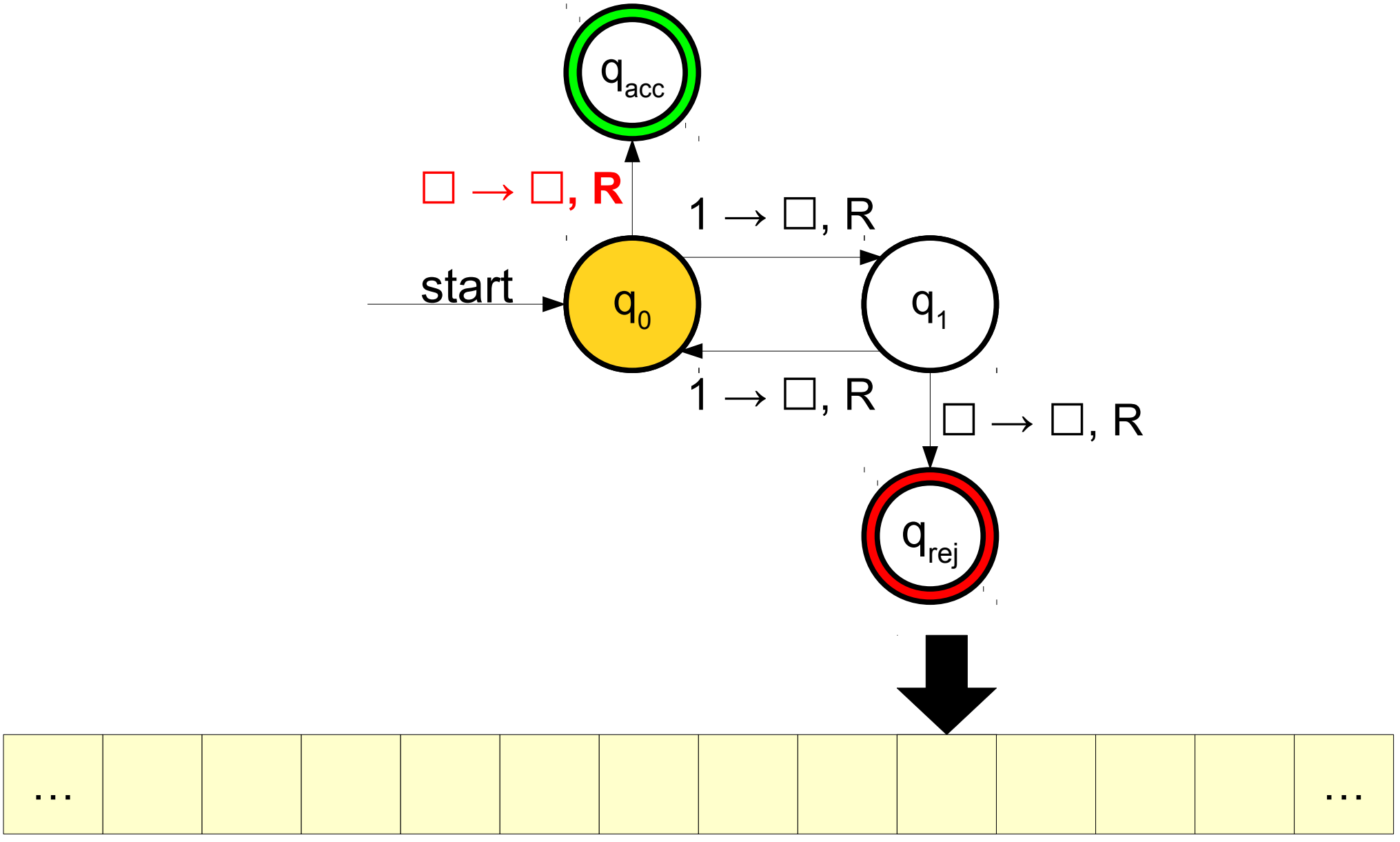

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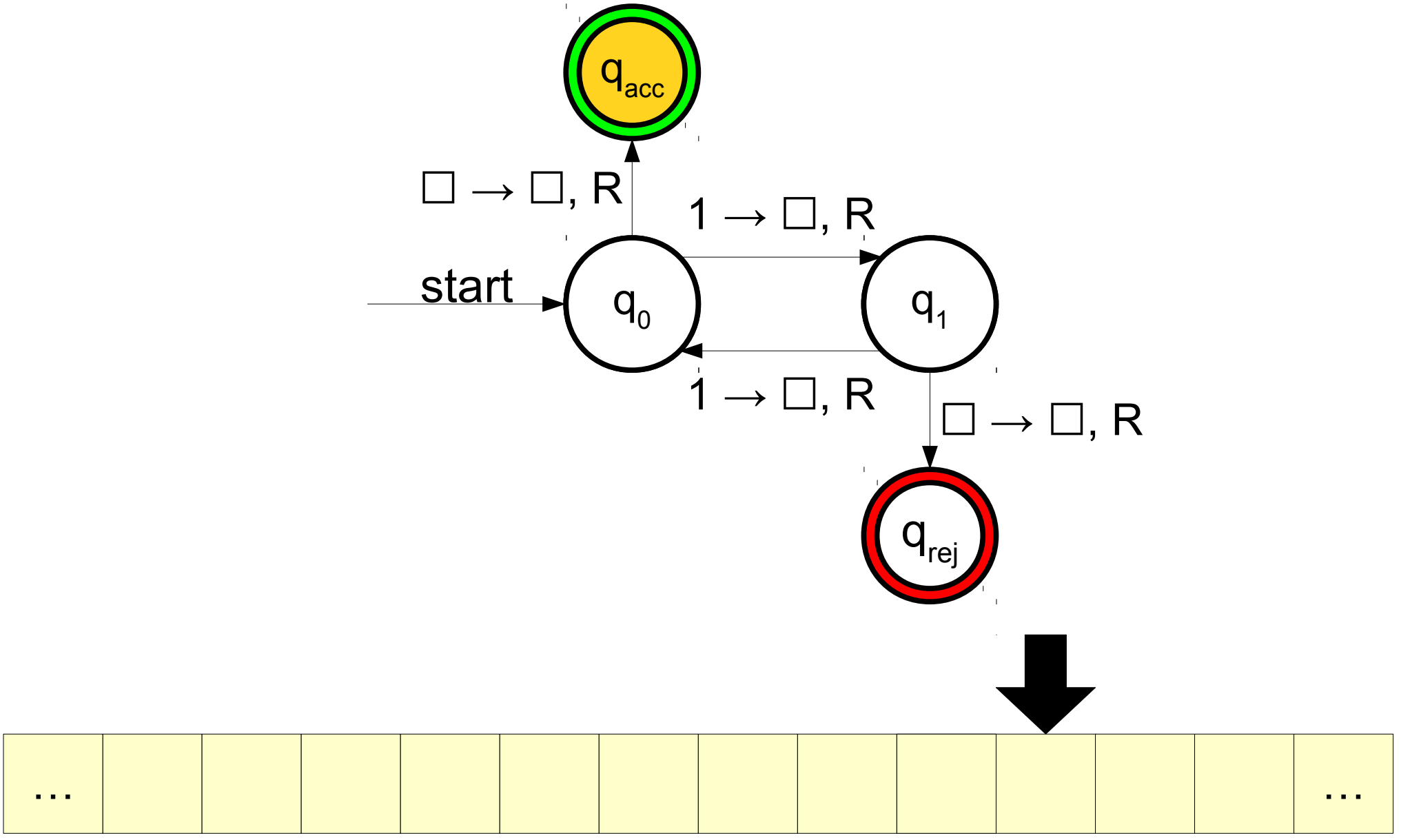

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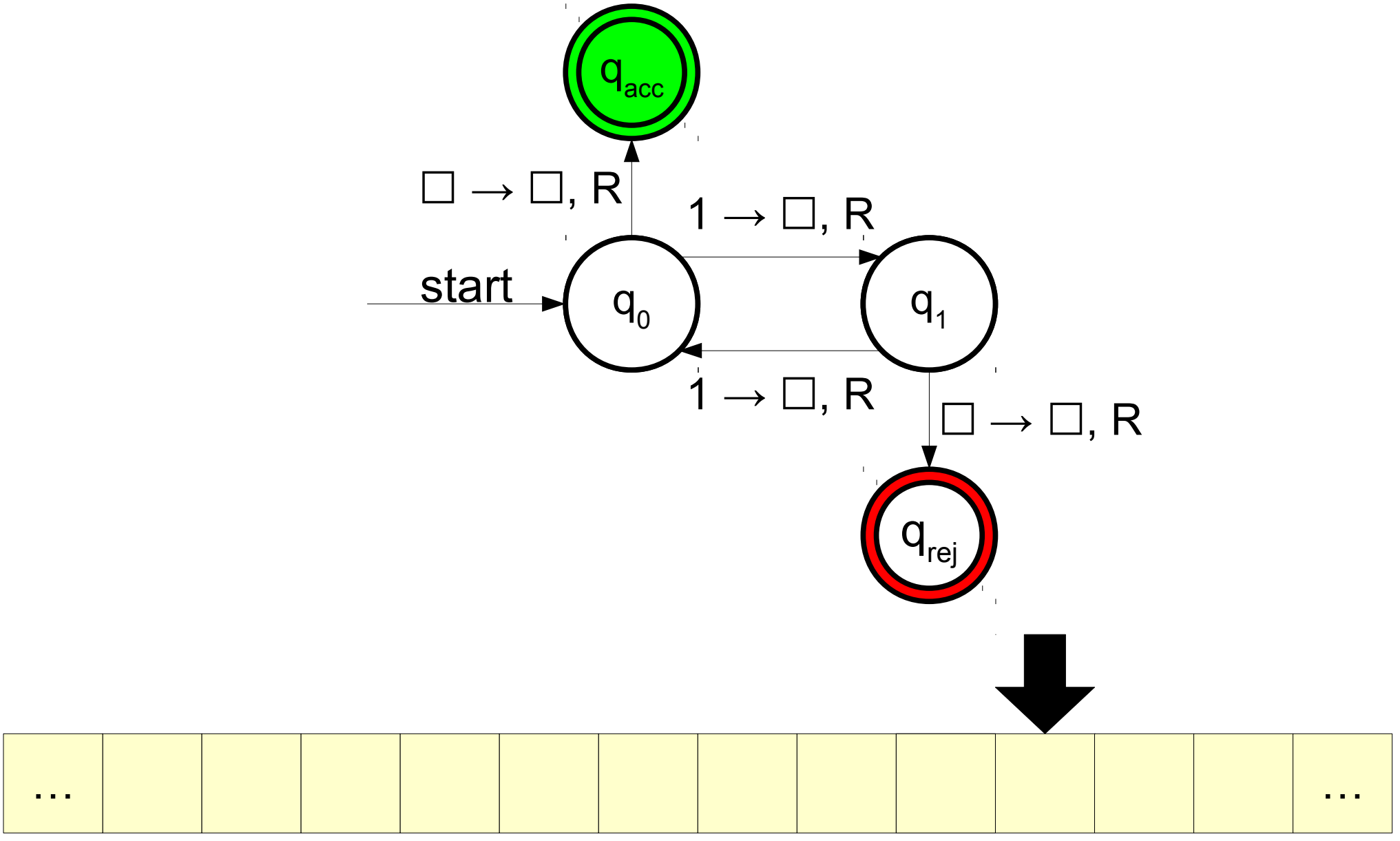


Accepting and Rejecting States

- Unlike DFAs, Turing machines do not stop processing the input when they finish reading it.
- Turing machines decide when (and if!) they will accept or reject their input.
- Turing machines can enter infinite loops and never accept or reject; more on that later...

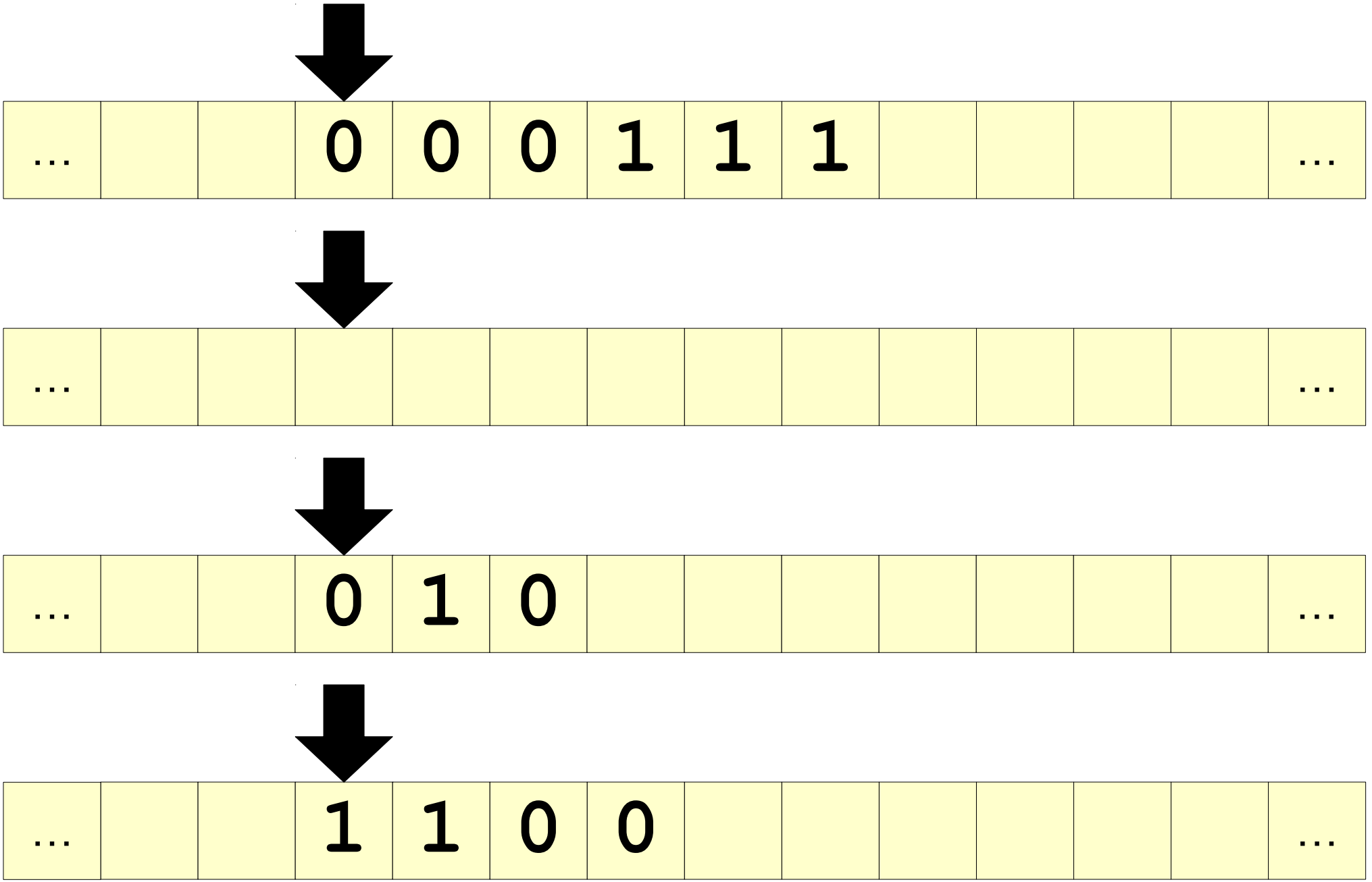
Designing Turing Machines

- Despite their simplicity, Turing machines are very powerful computing devices.
- Today's lecture explores how to design Turing machines for various languages.

Designing Turing Machines

- Let $\Sigma = \{\texttt{0}, \texttt{1}\}$ and consider the language $L = \{\texttt{0}^n\texttt{1}^n \mid n \in \mathbb{N}\}$.
- We know that L is context-free.
- How might we build a Turing machine for it?

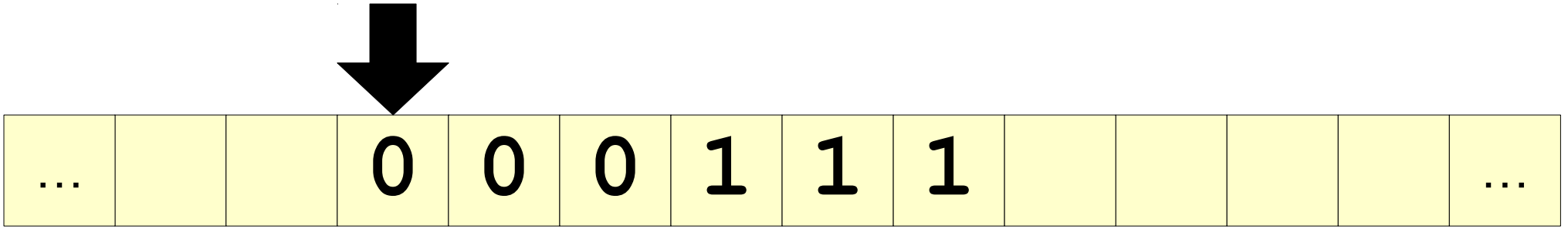
$$L = \{ \mathtt{0}^n \mathtt{1}^n \mid n \in \mathbb{N} \}$$



A Recursive Approach

- The string ε is in L.
- The string `0`w`1` is in L iff w is in L.
- Any string starting with `1` is not in L.
- Any string ending with `0` is not in L.

A Sketch of the TM



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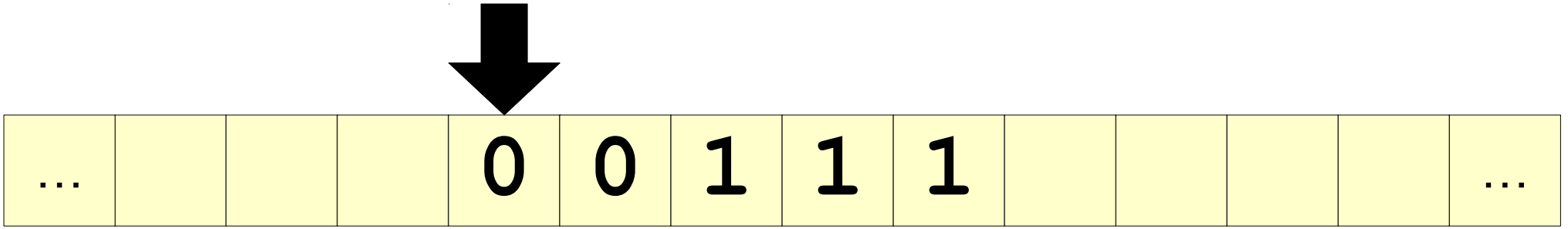

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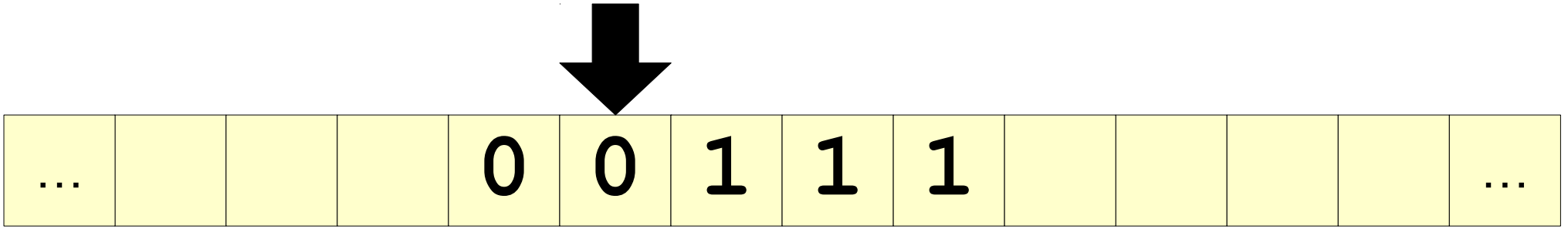

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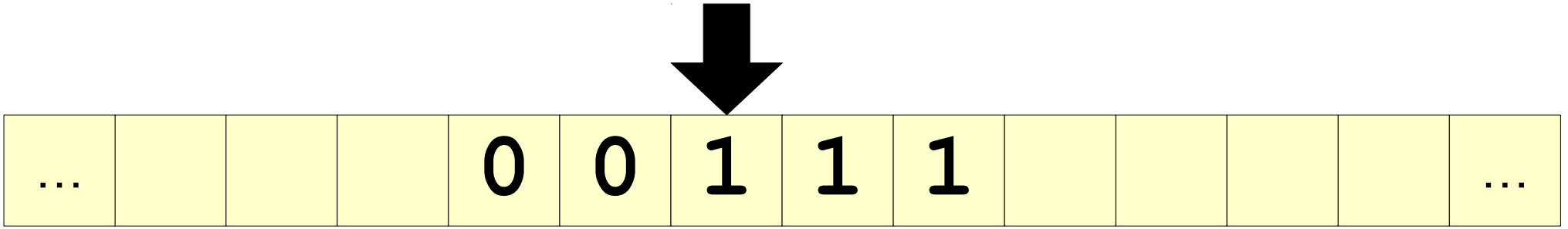

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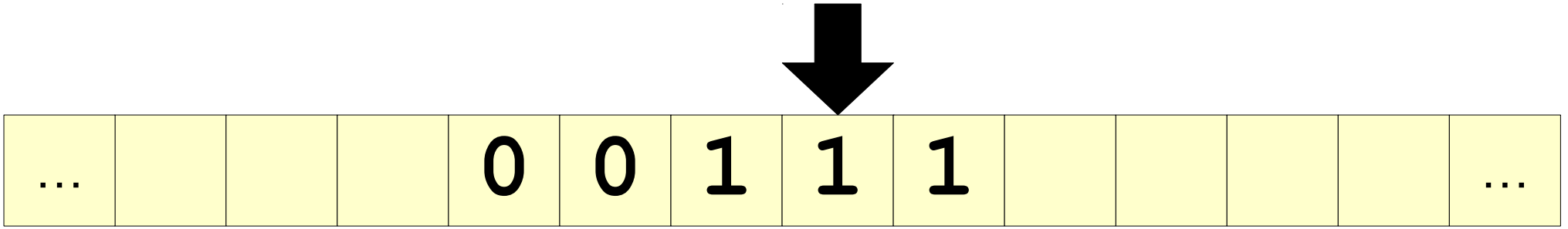

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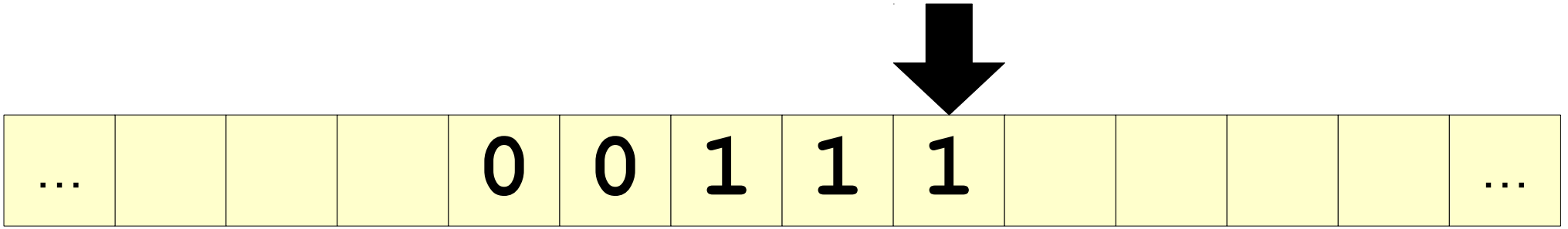

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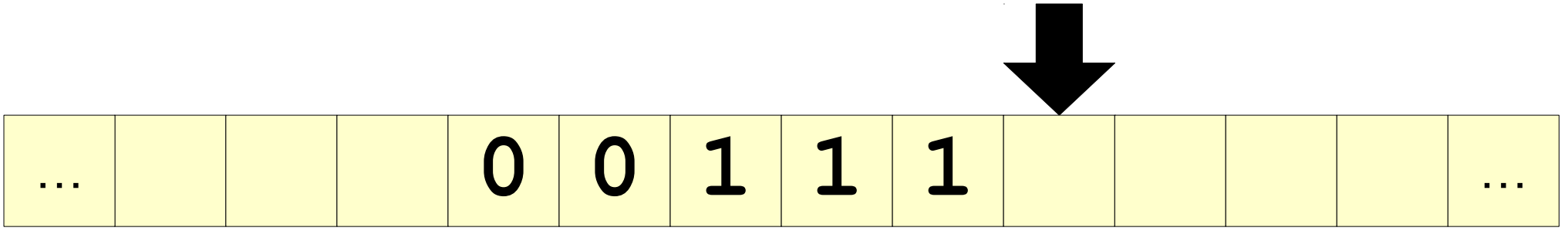

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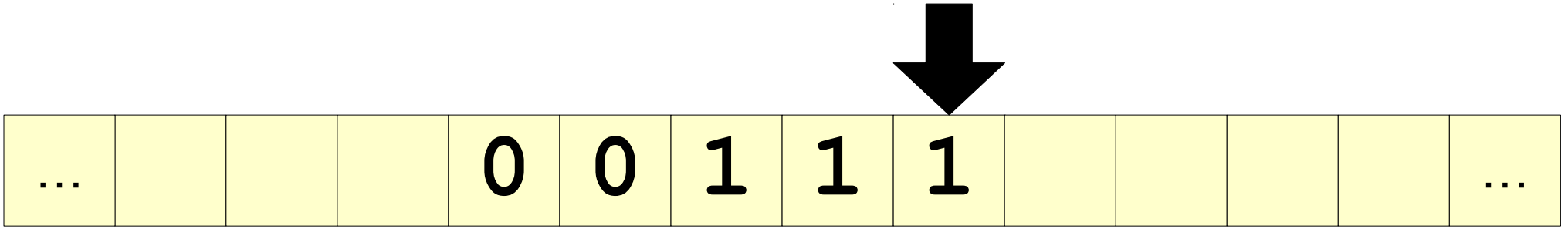

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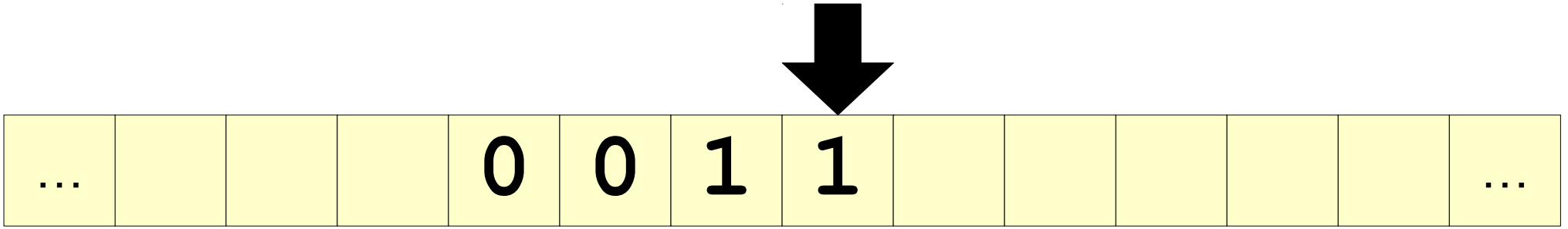

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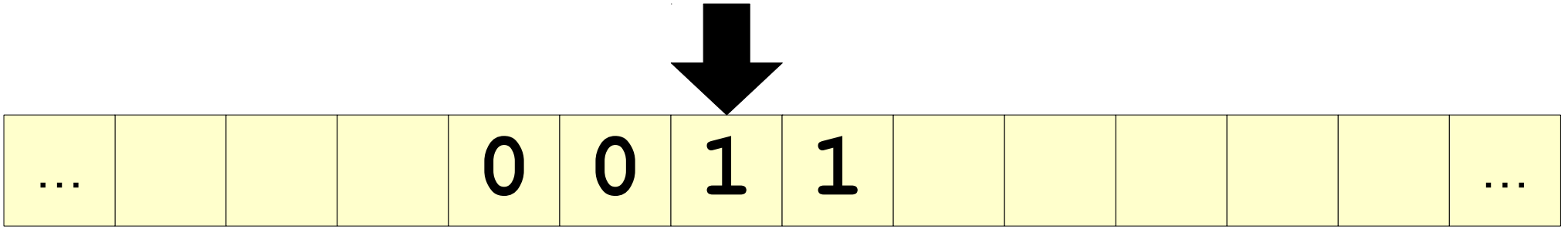

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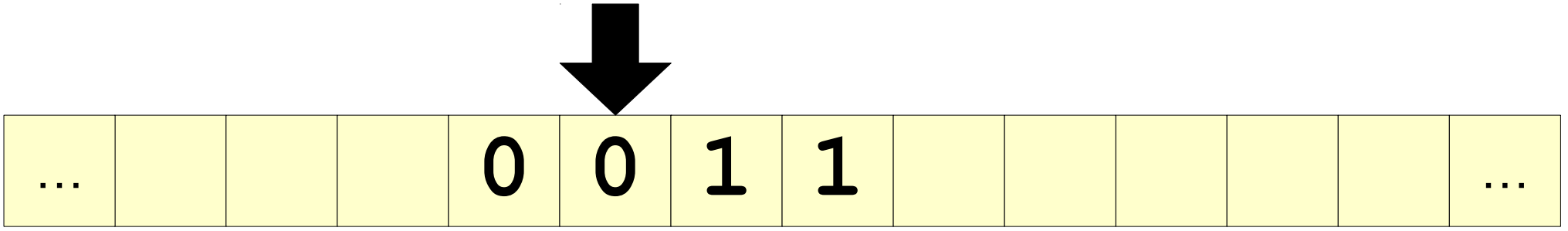

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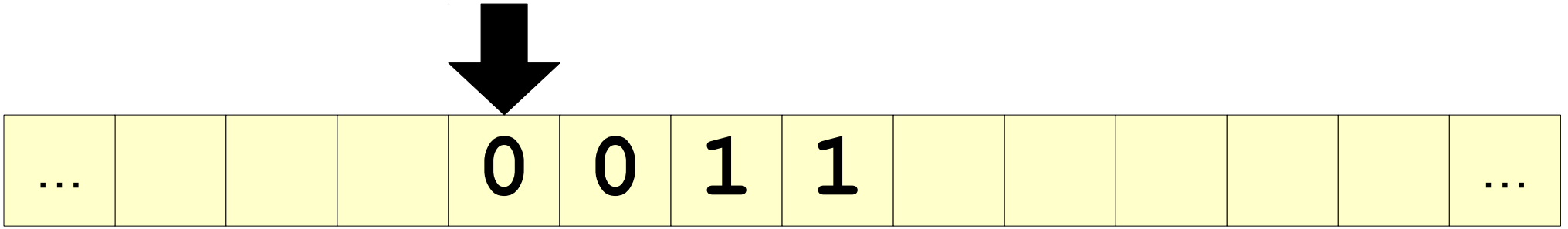

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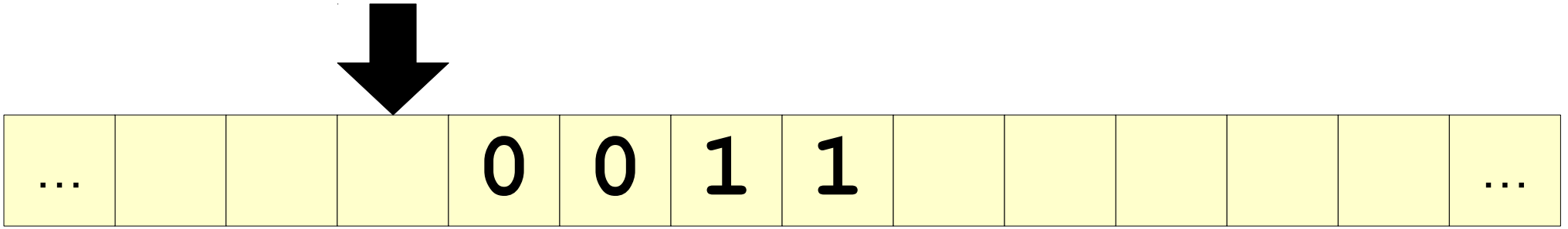

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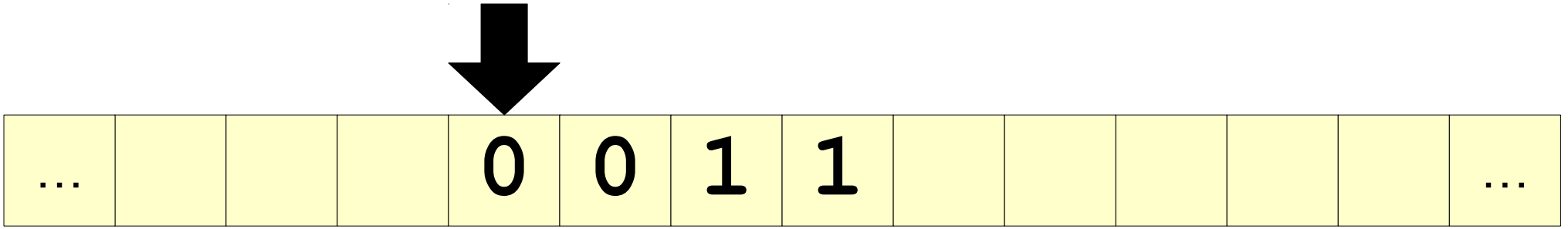

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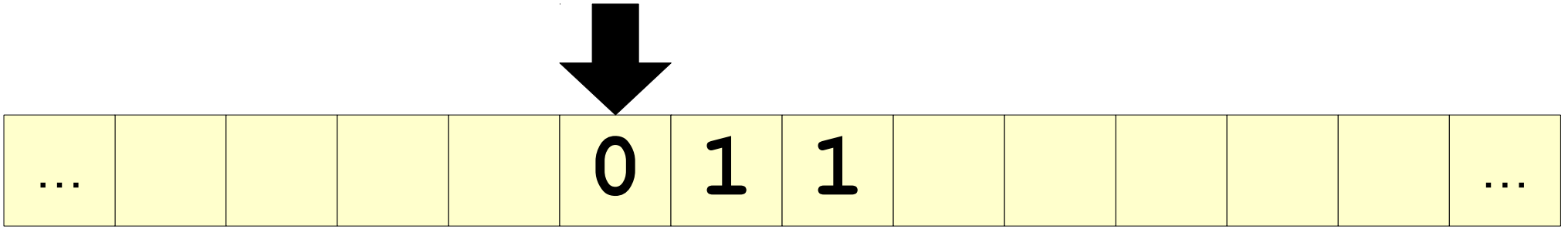

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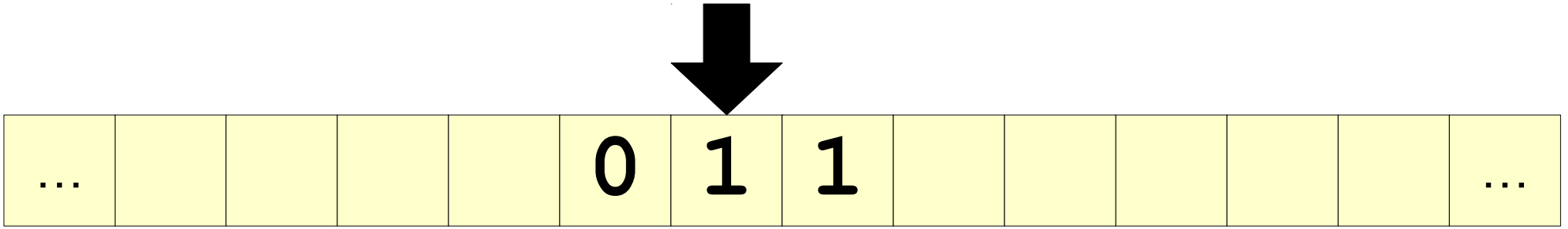

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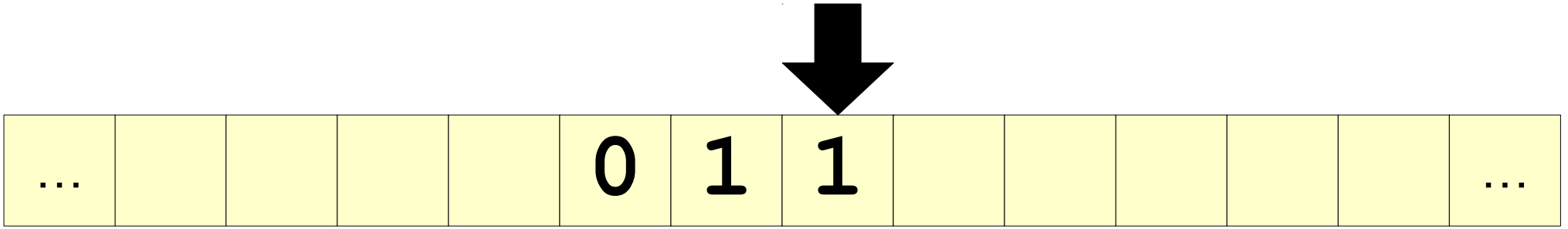

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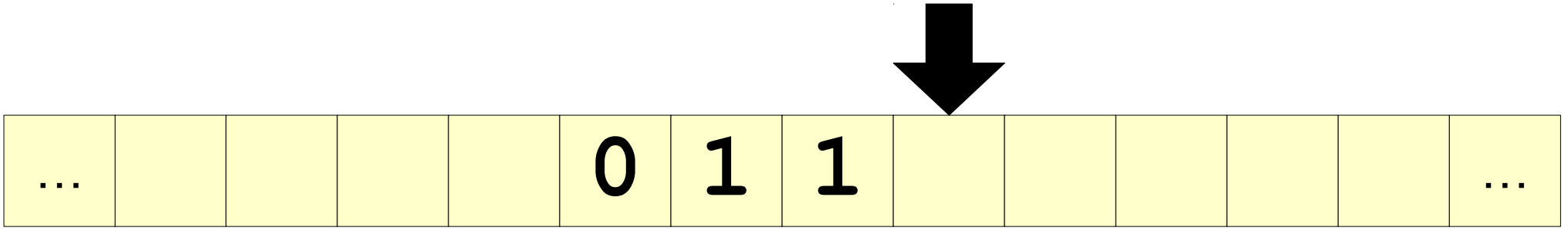

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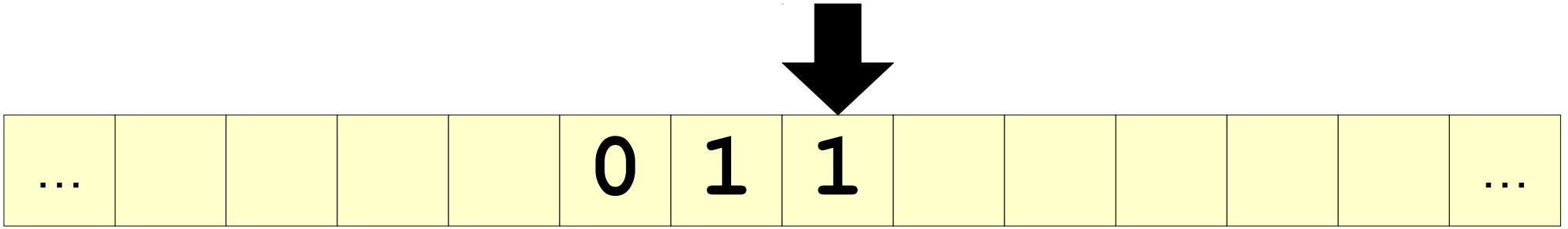

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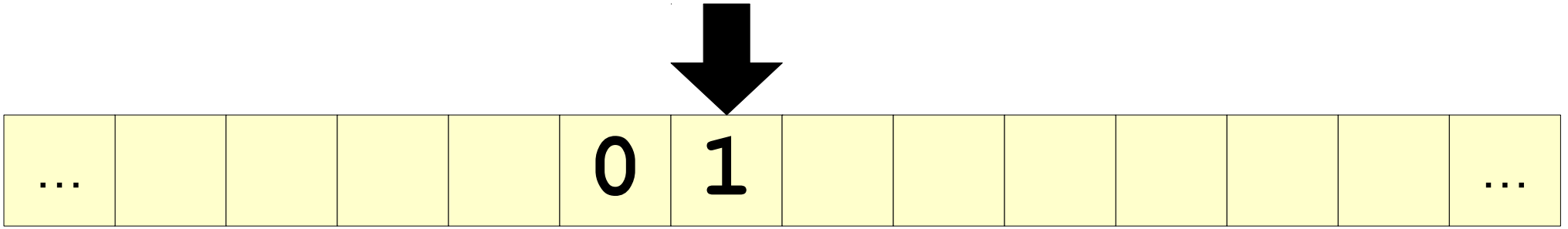

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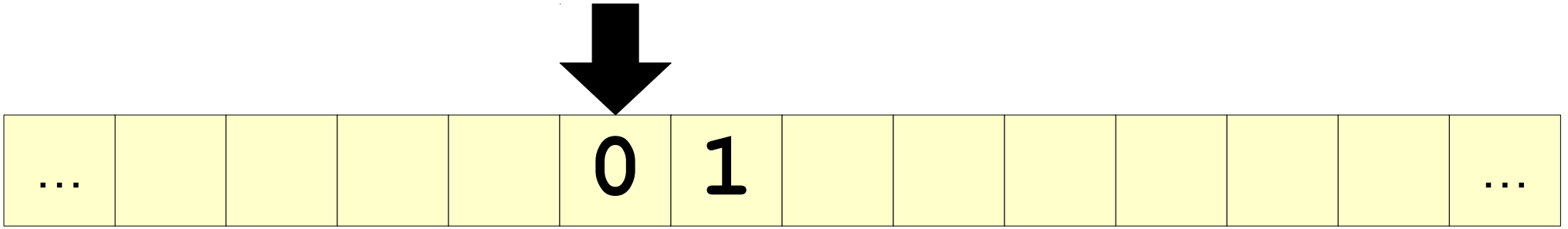

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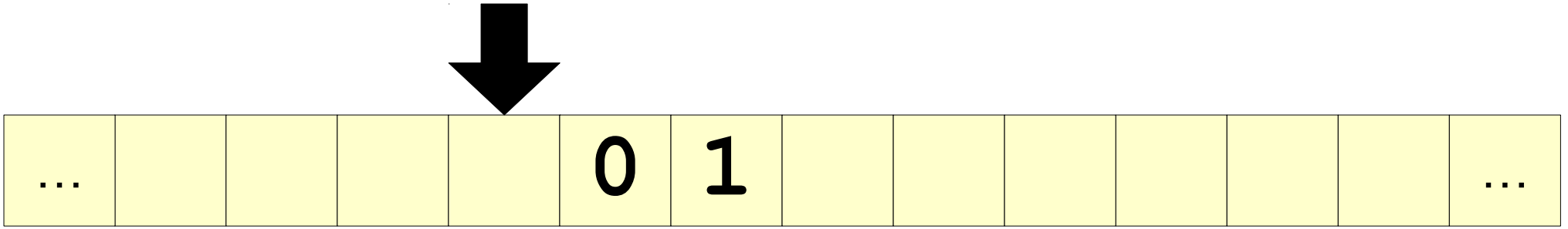

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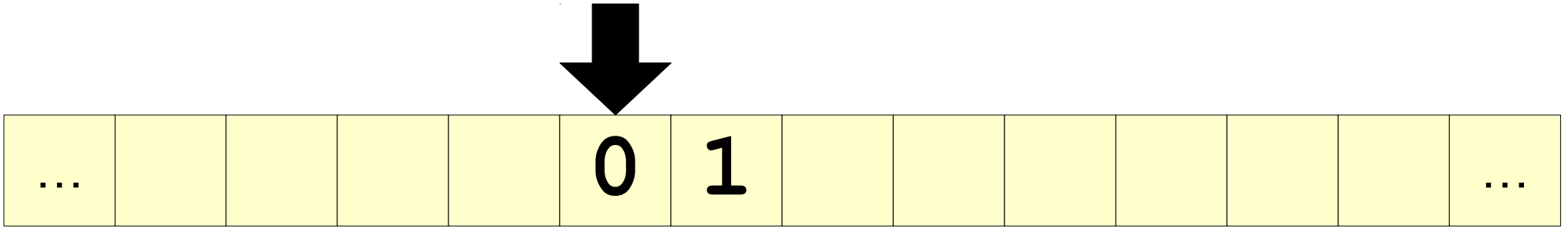

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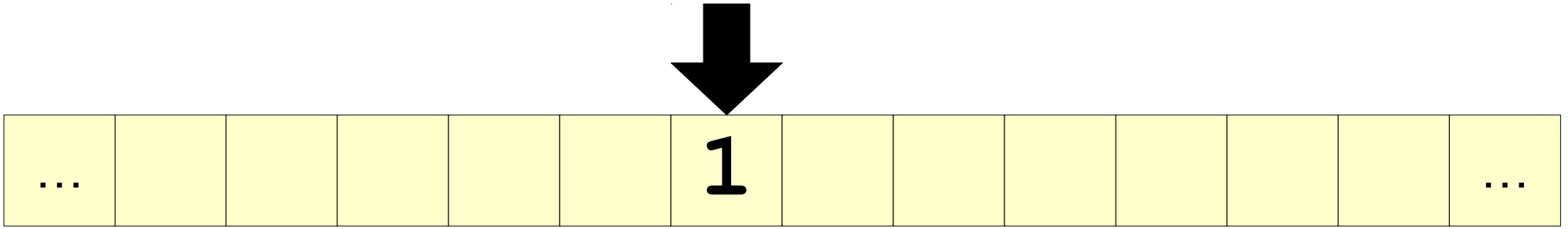

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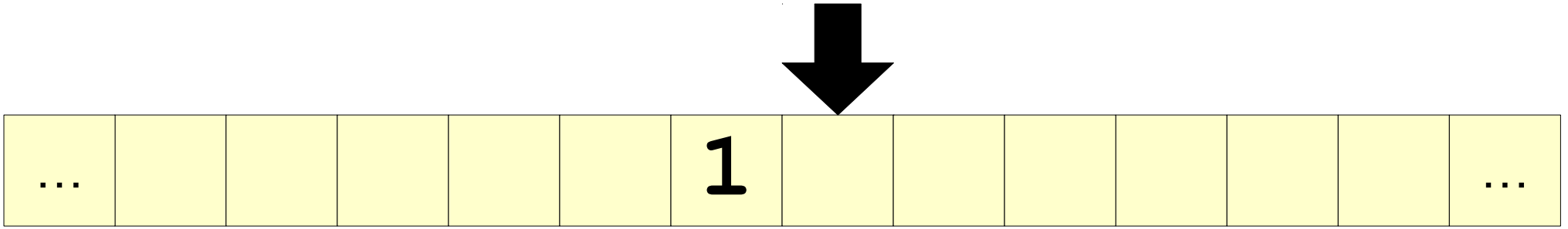

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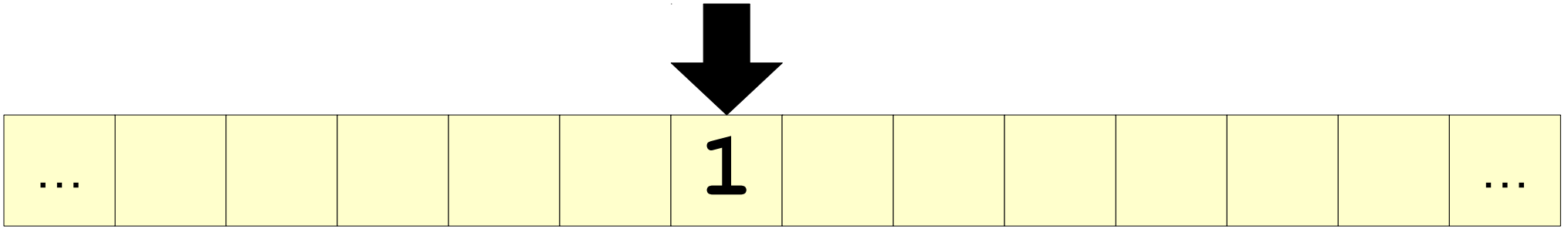

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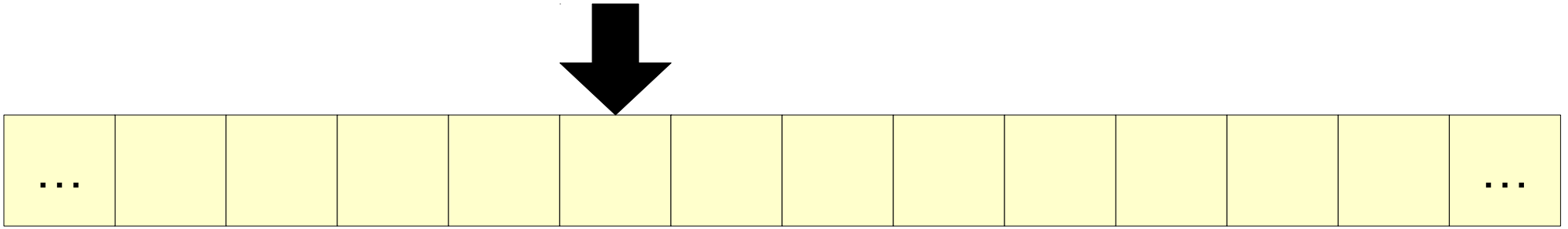

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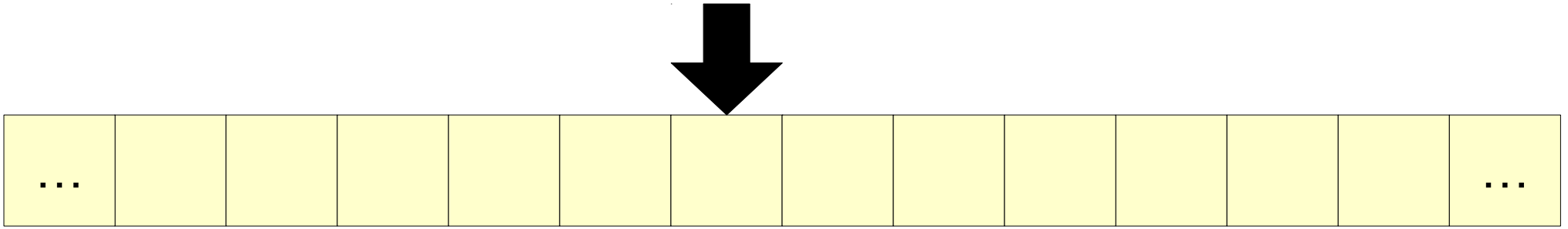

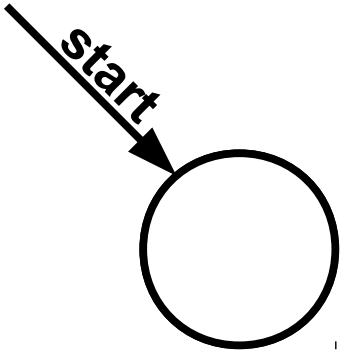
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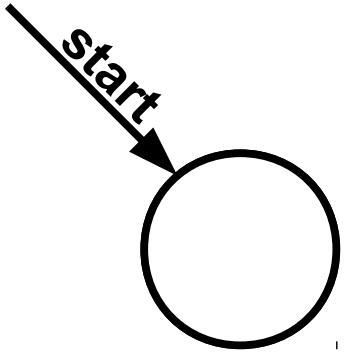
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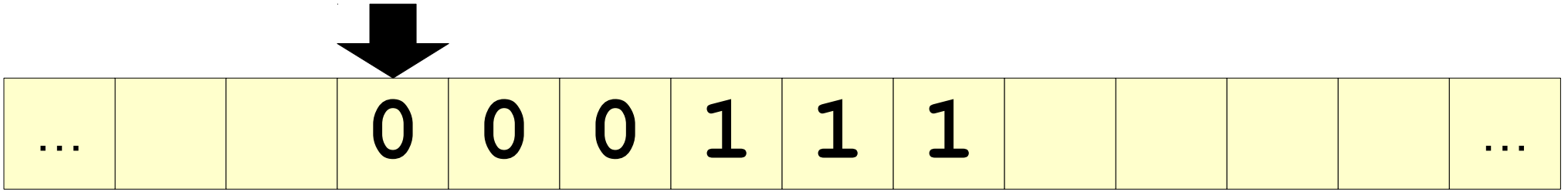
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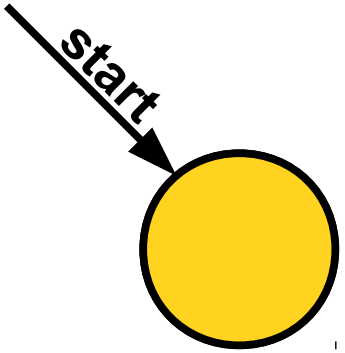
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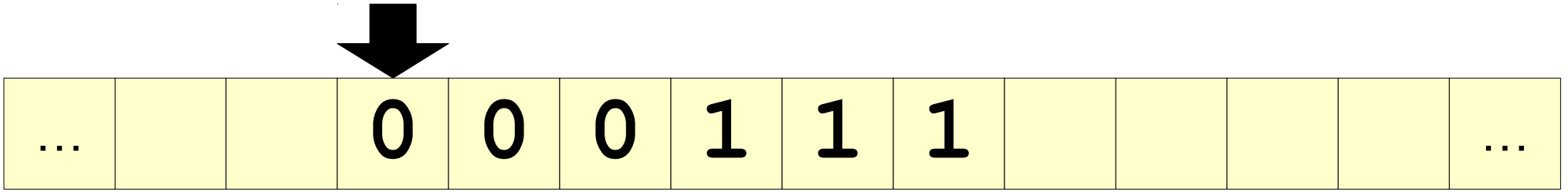
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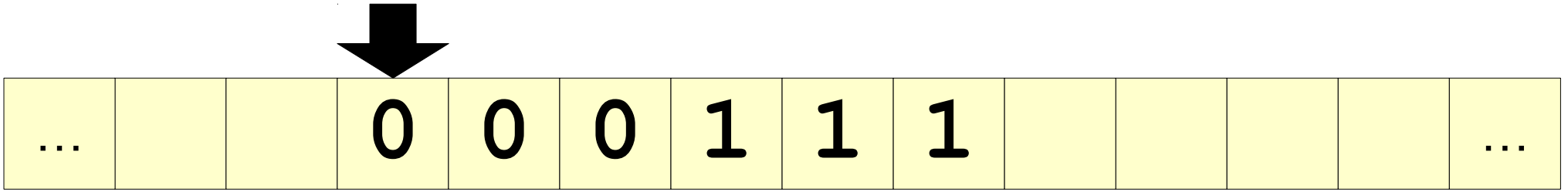
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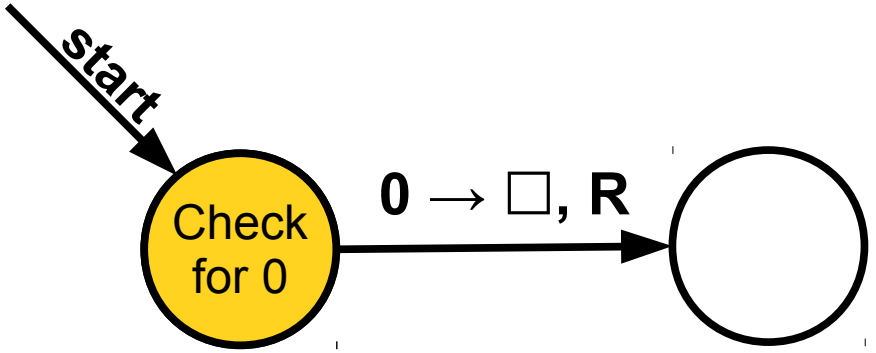
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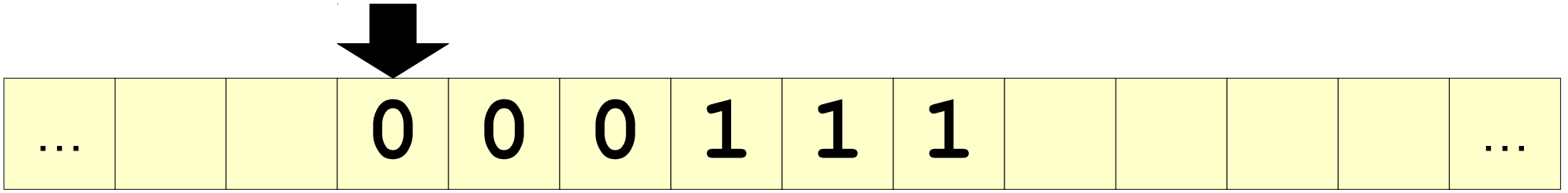
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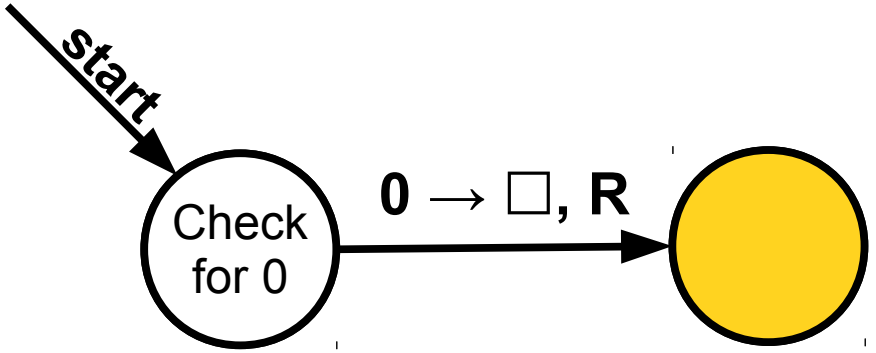
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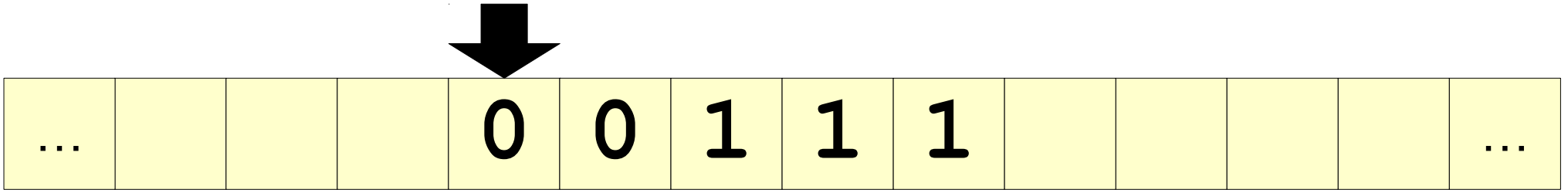
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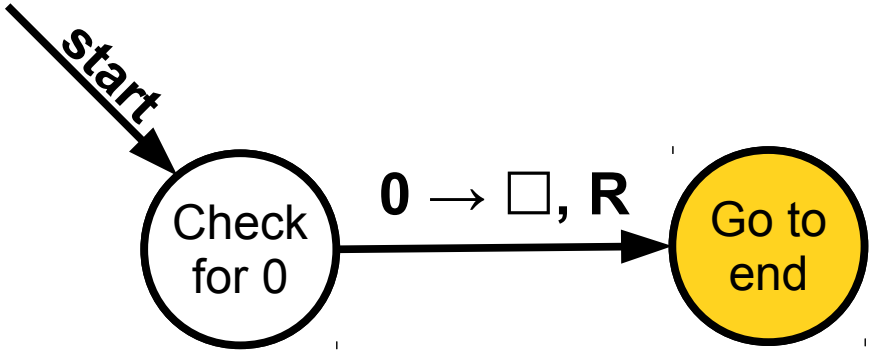
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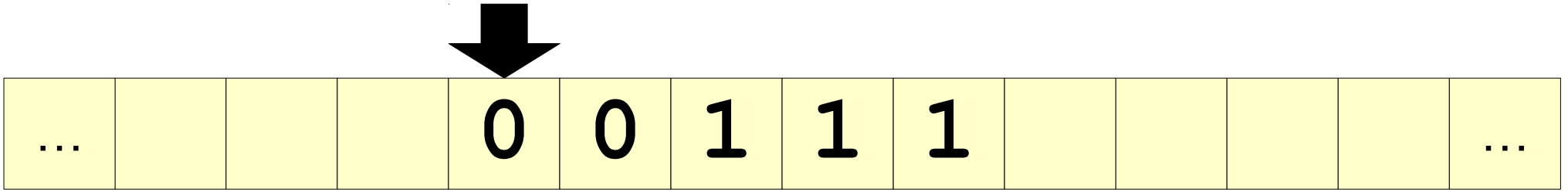
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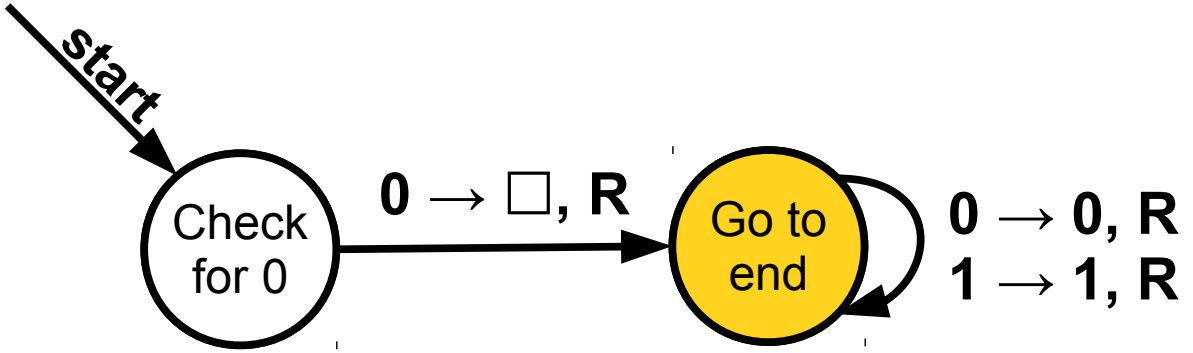
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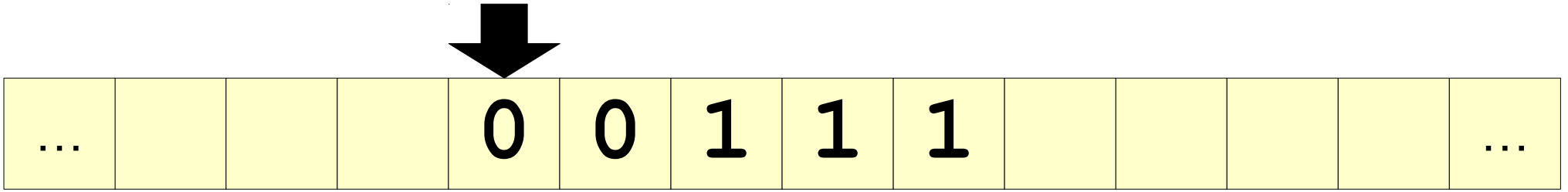
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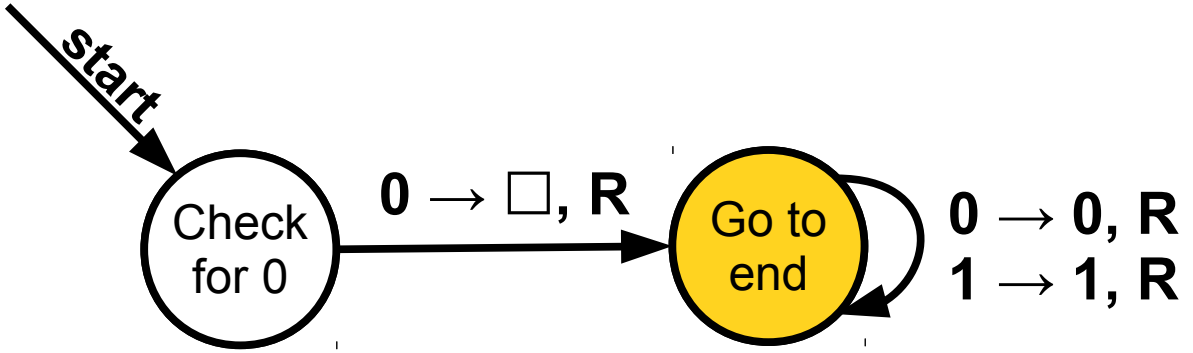
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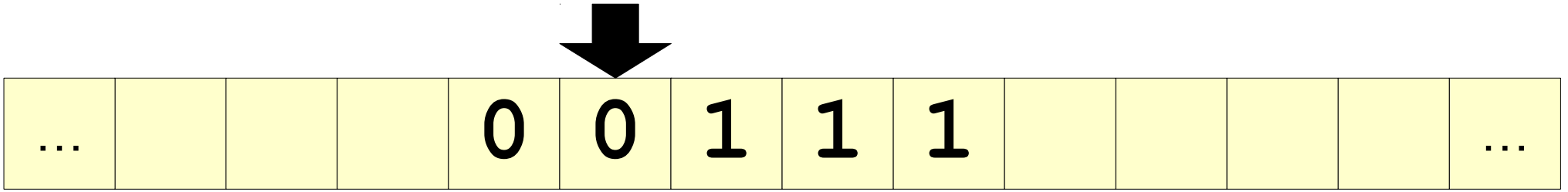
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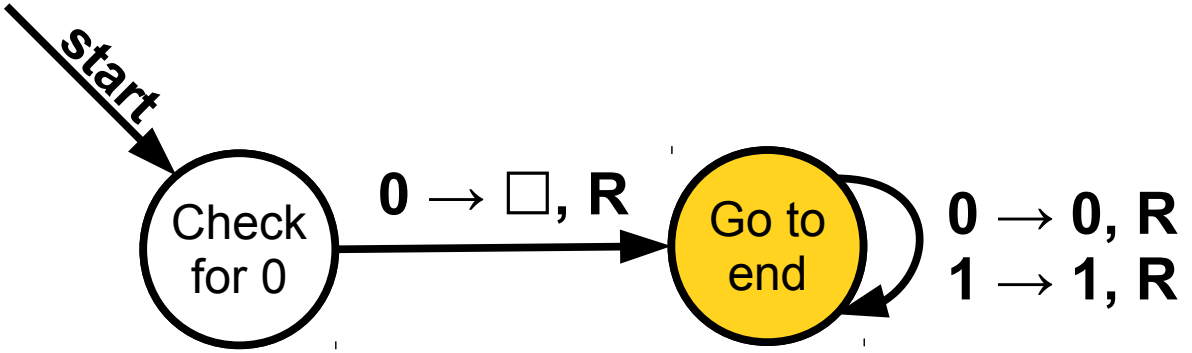
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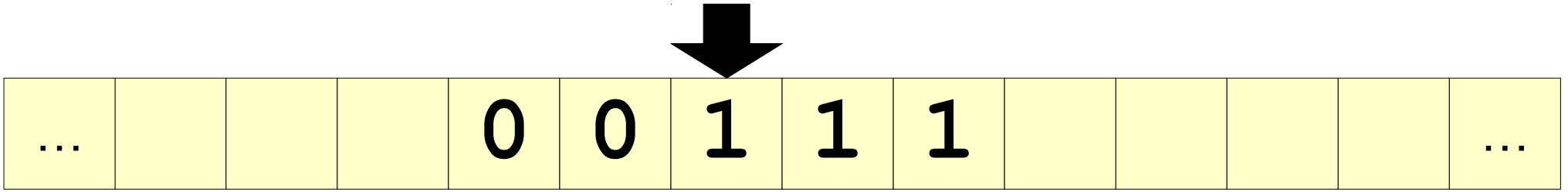
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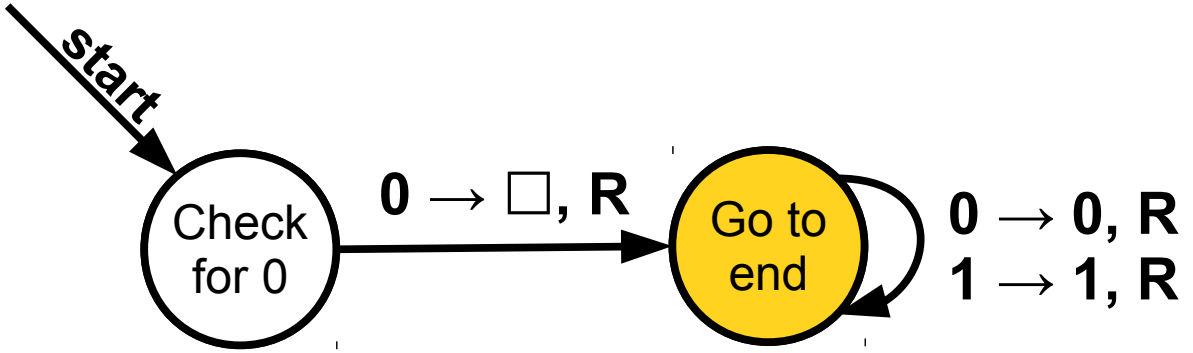
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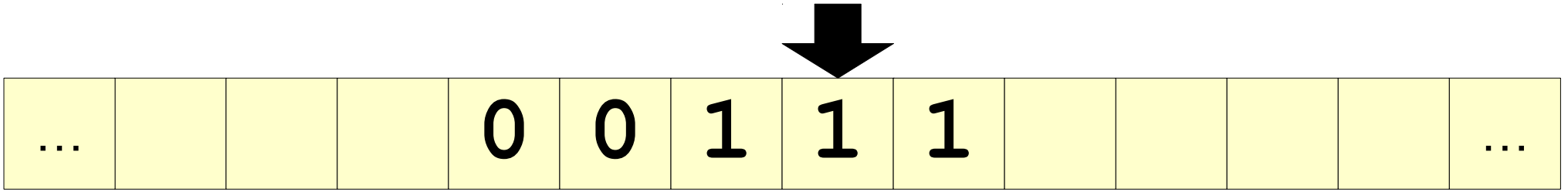
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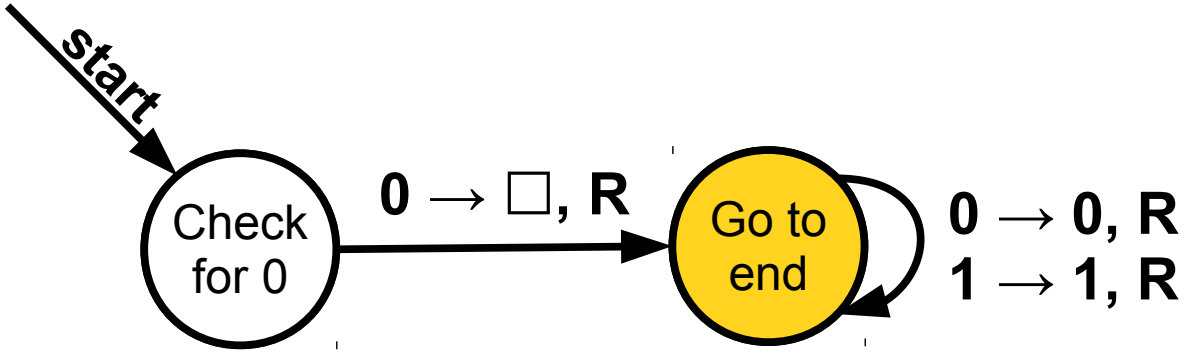
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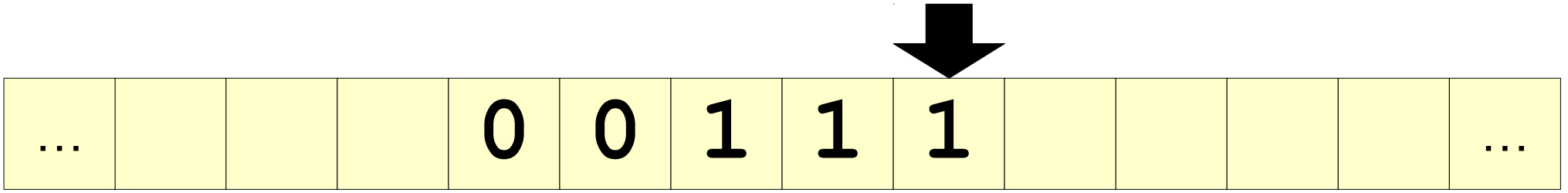
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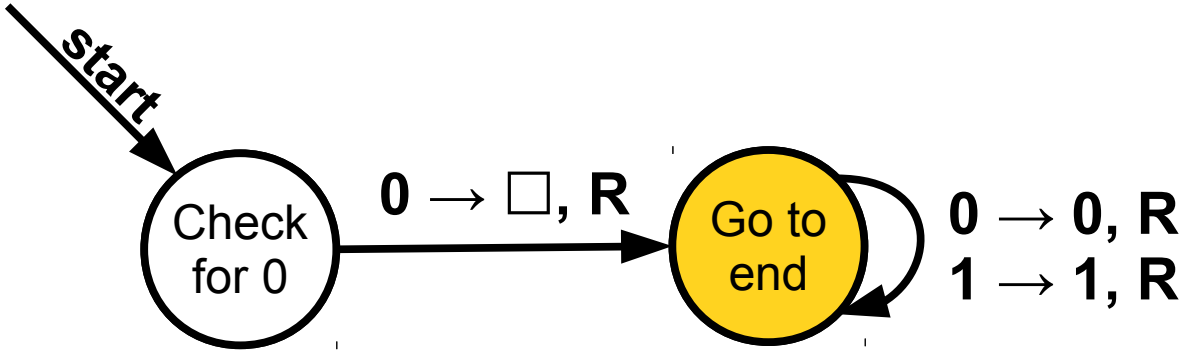
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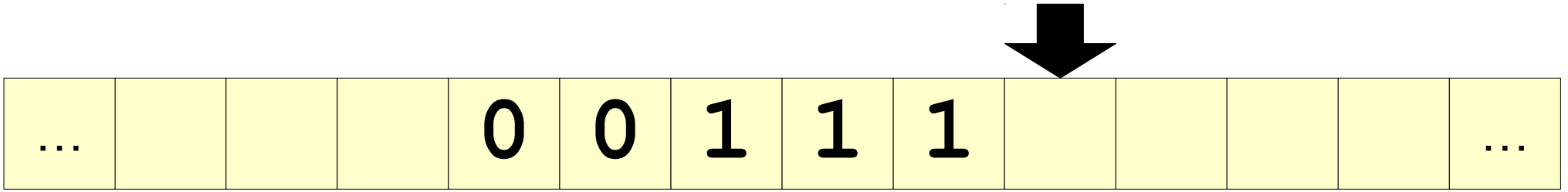
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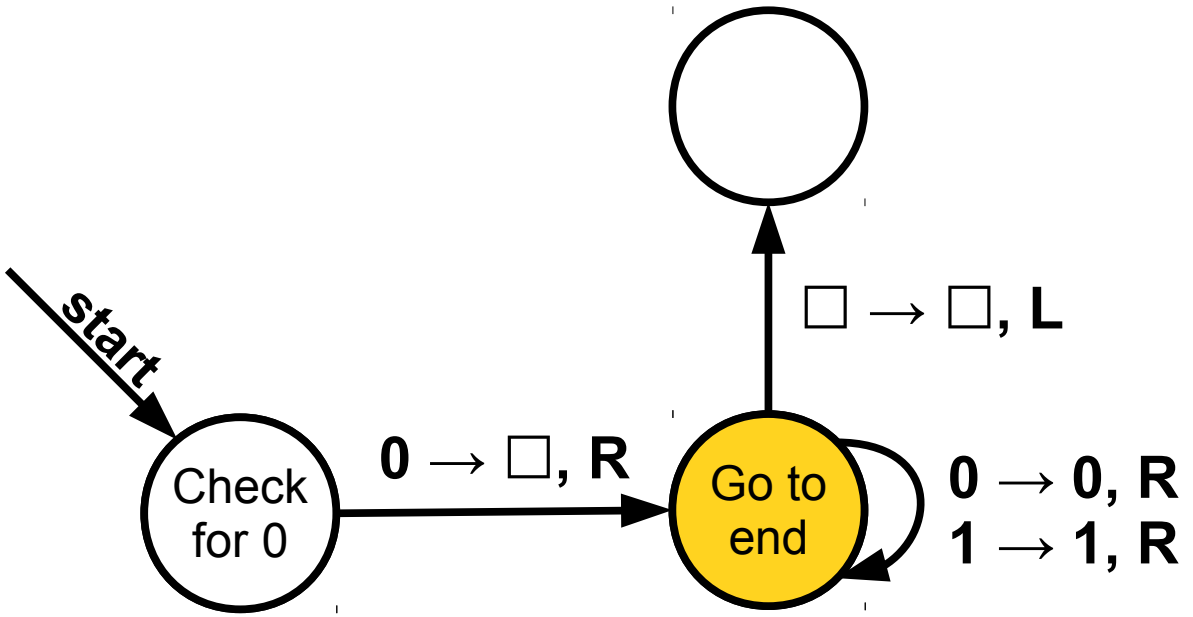
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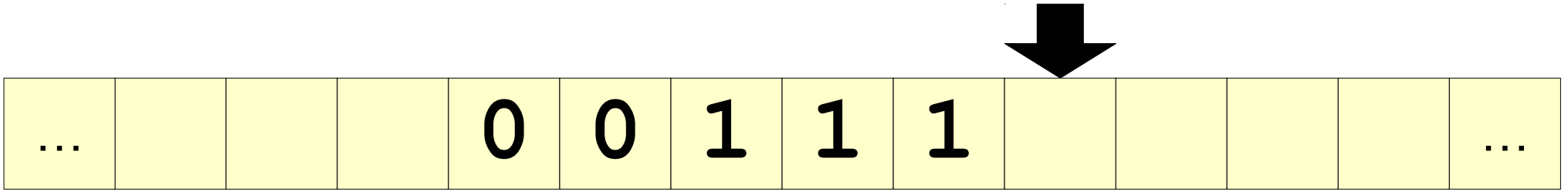
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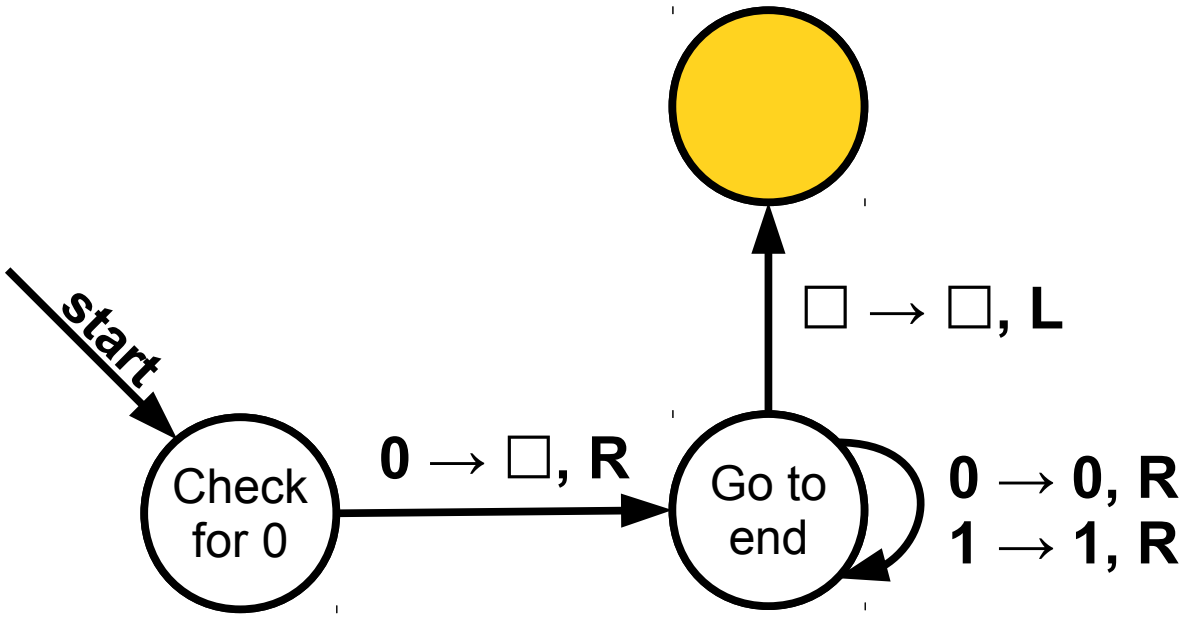
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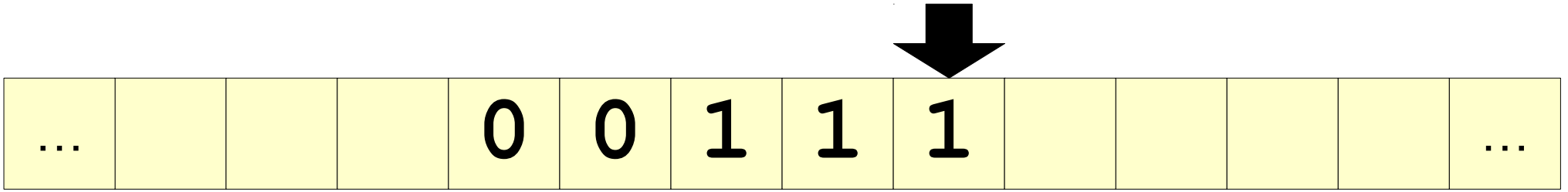
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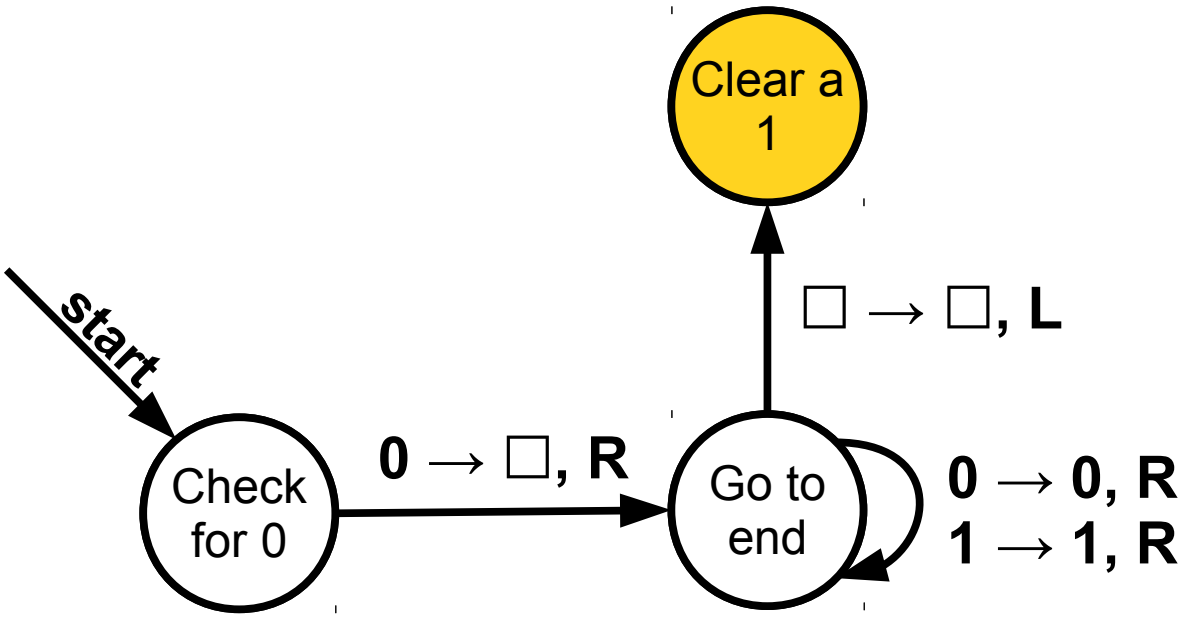
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Go to end
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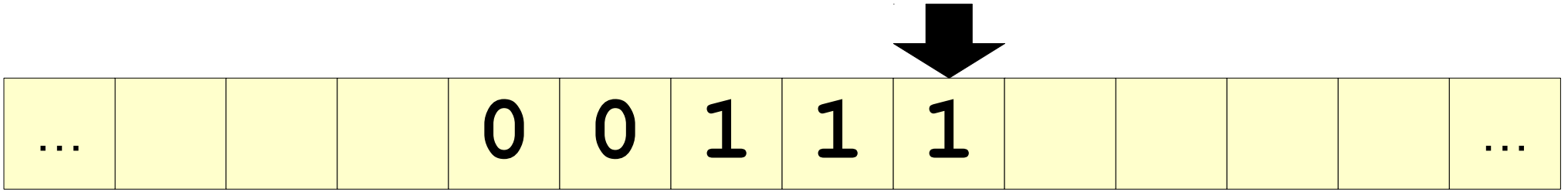
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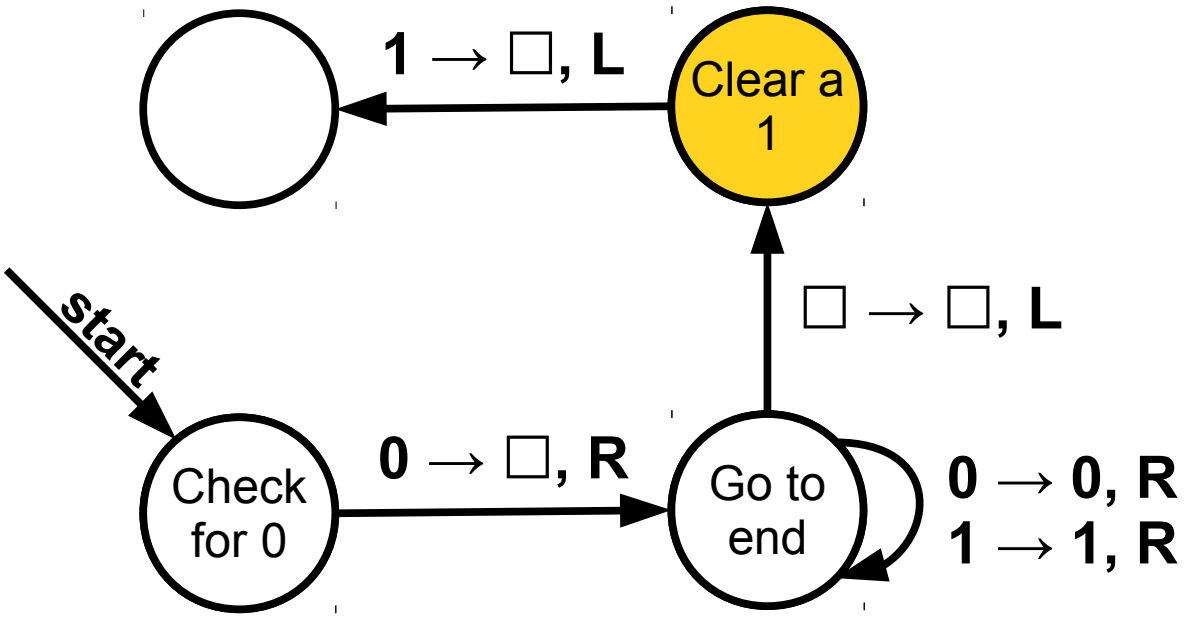
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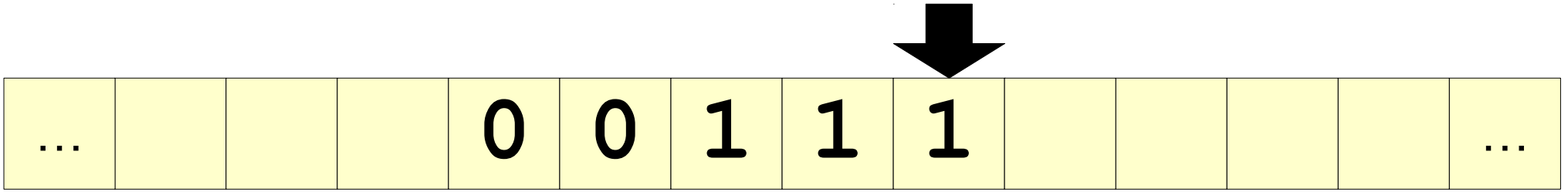
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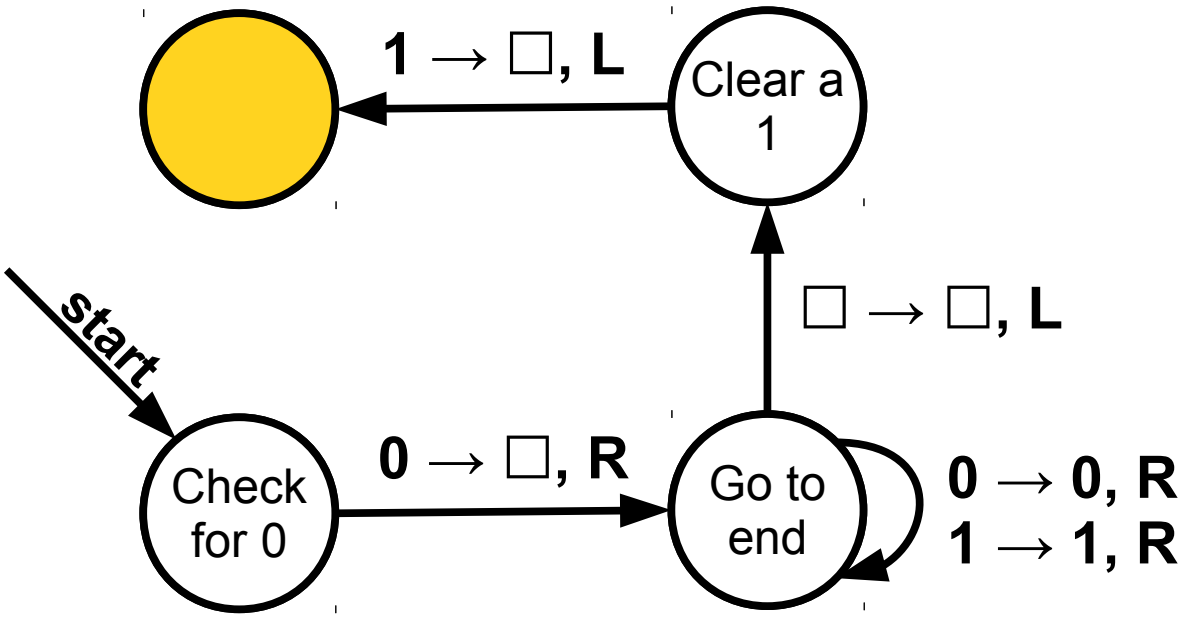
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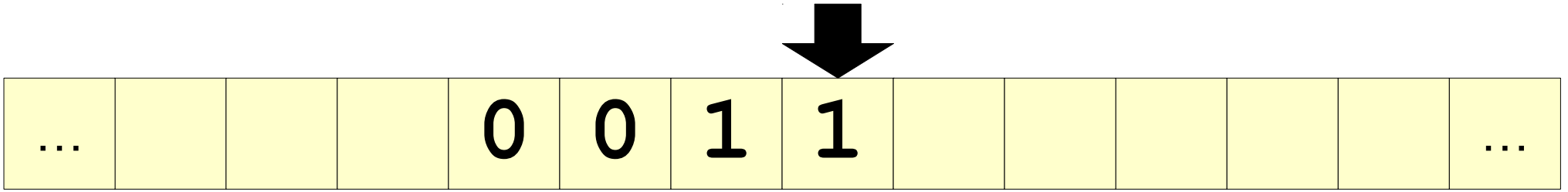
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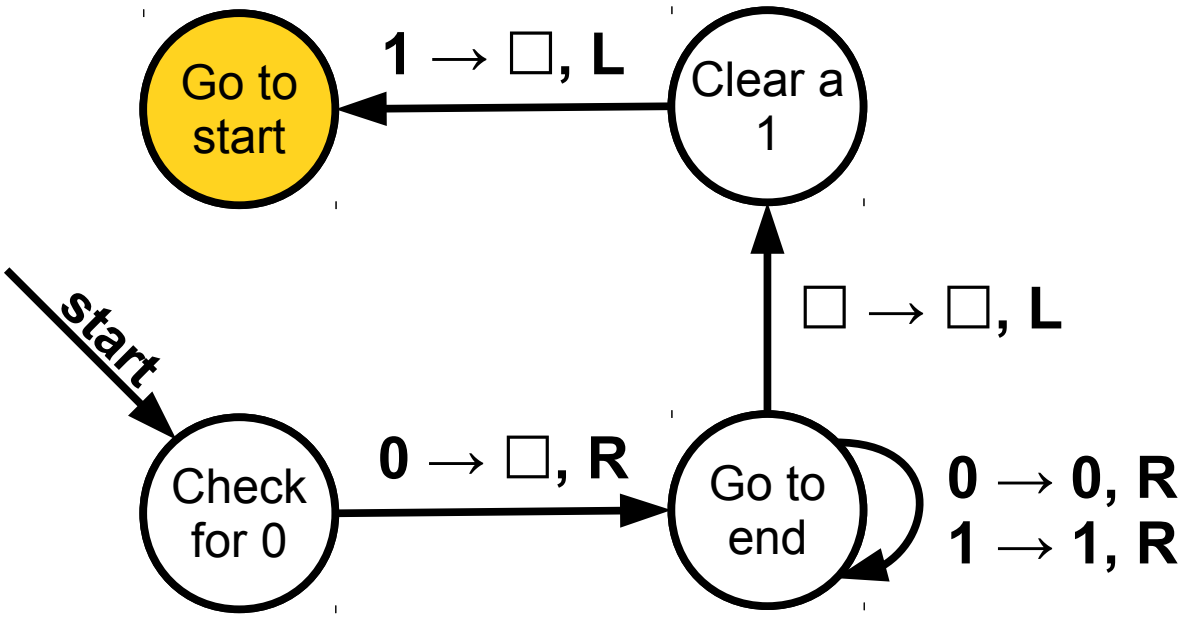
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start
Check for 0
0 → □, R
Go to end
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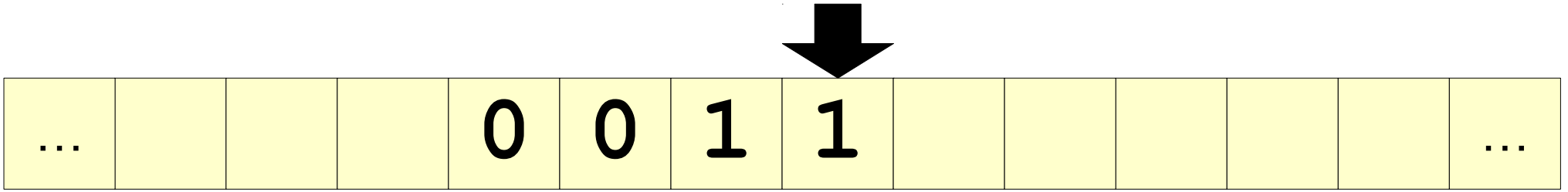
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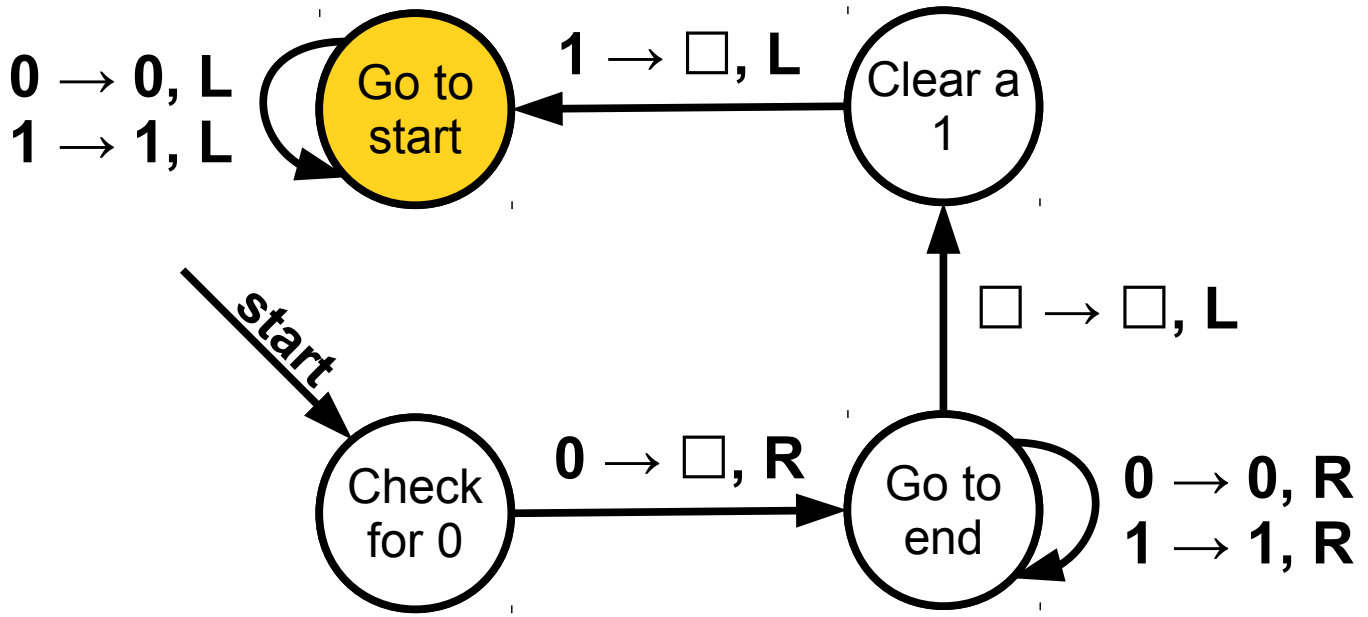
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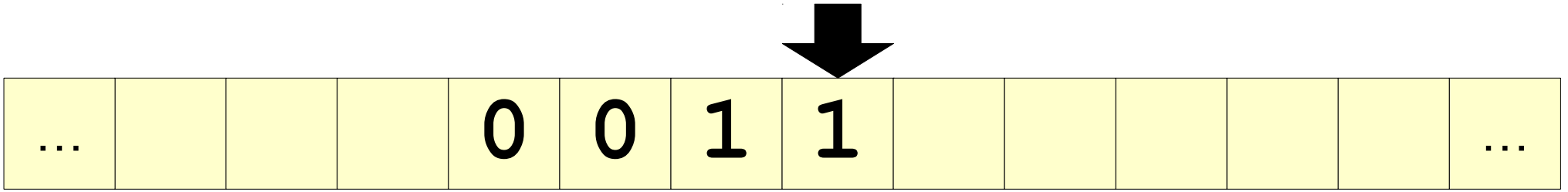
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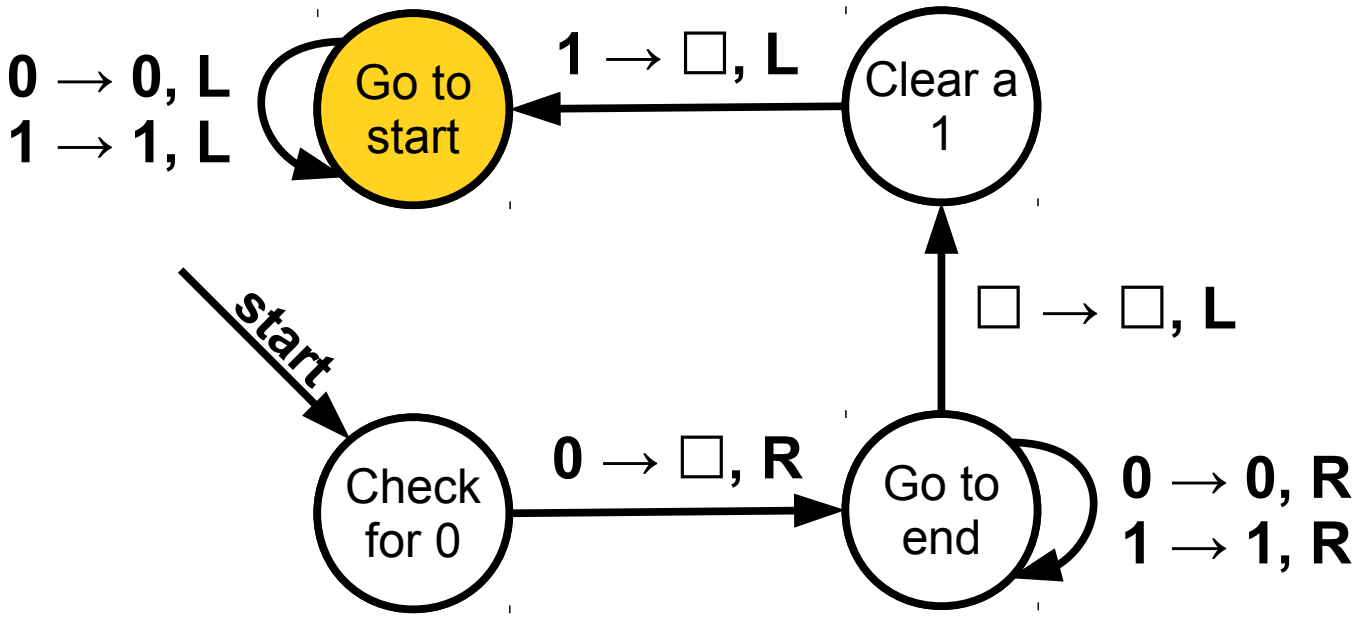
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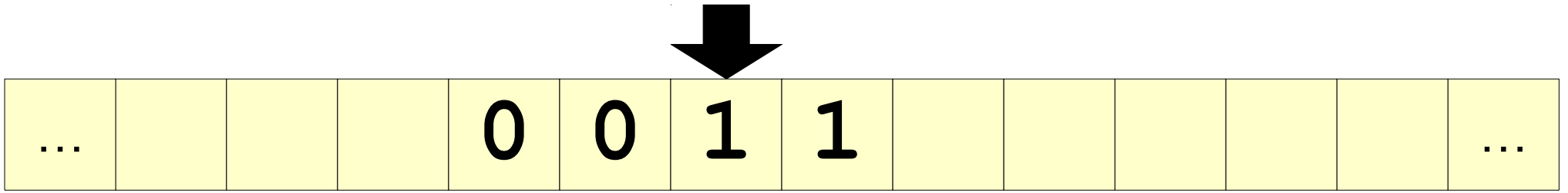
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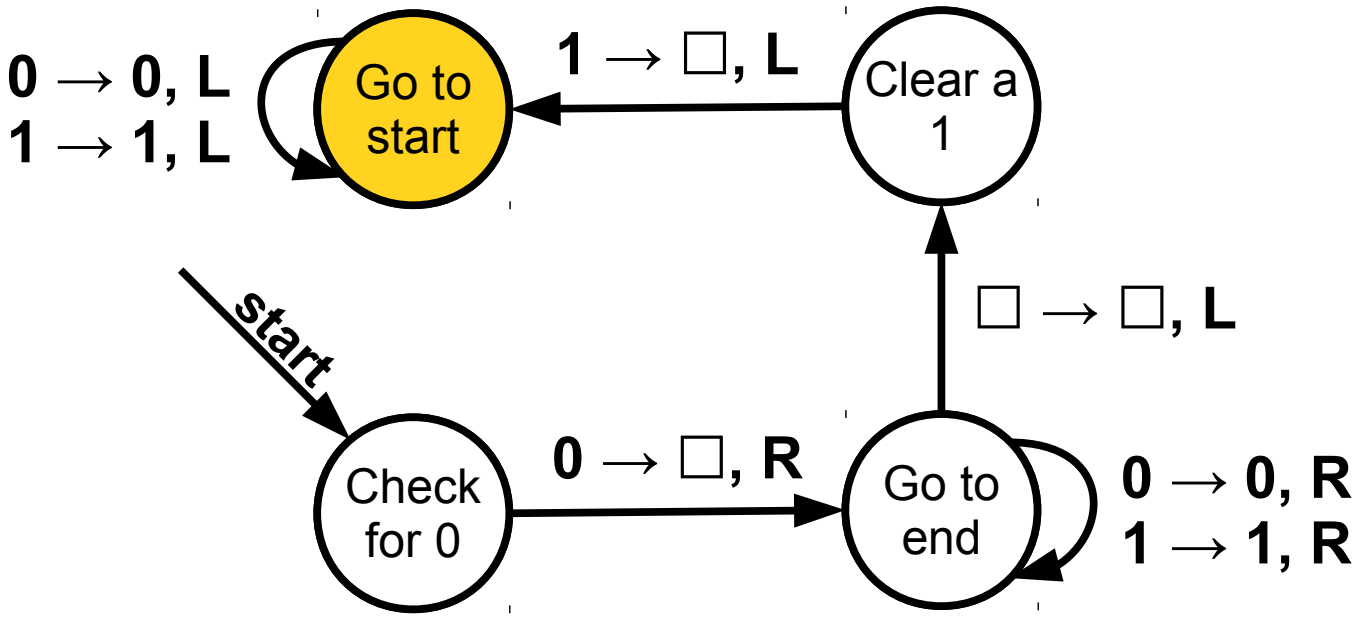
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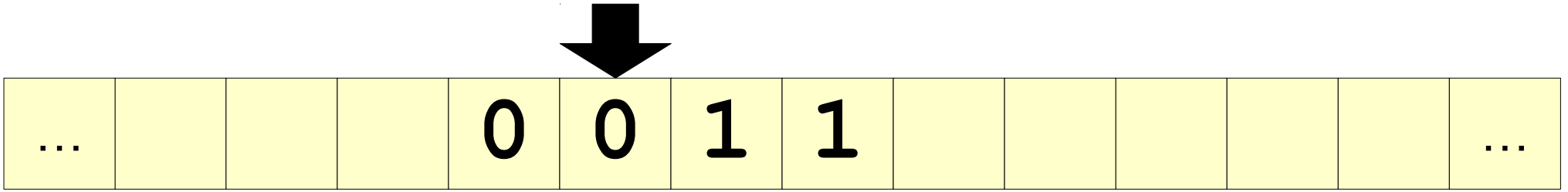
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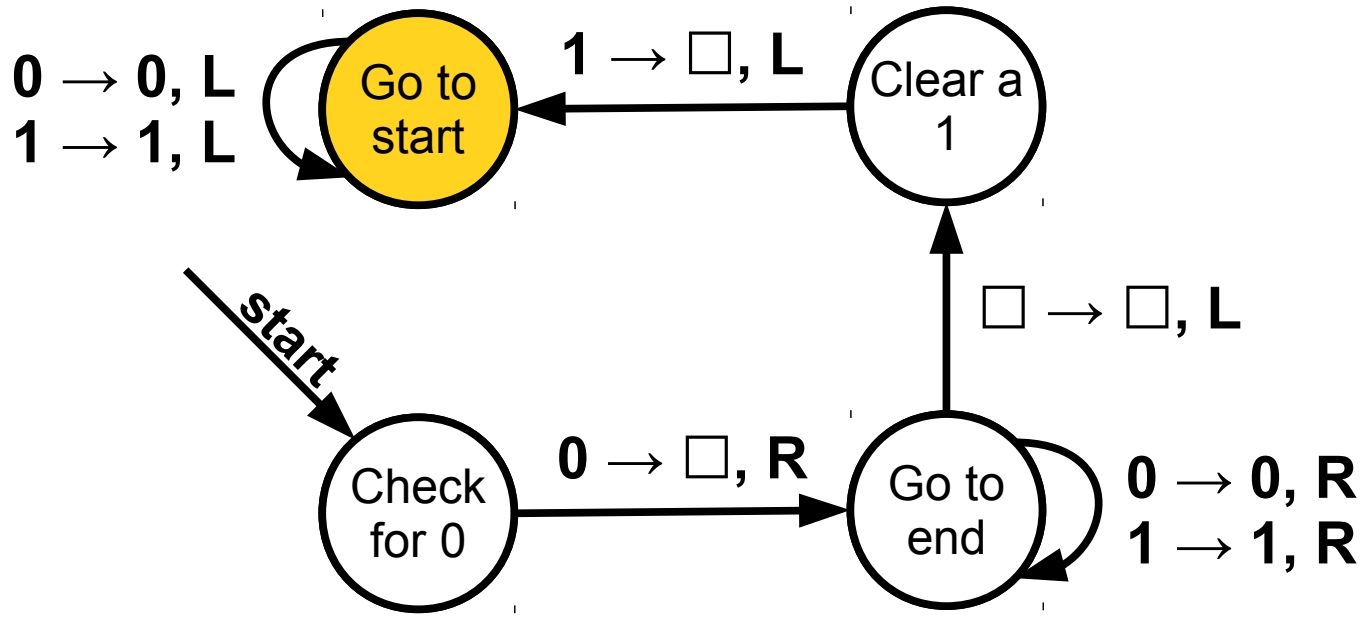
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Go to end
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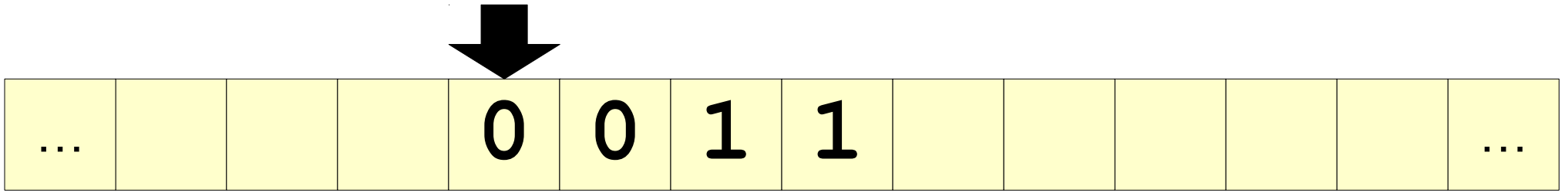
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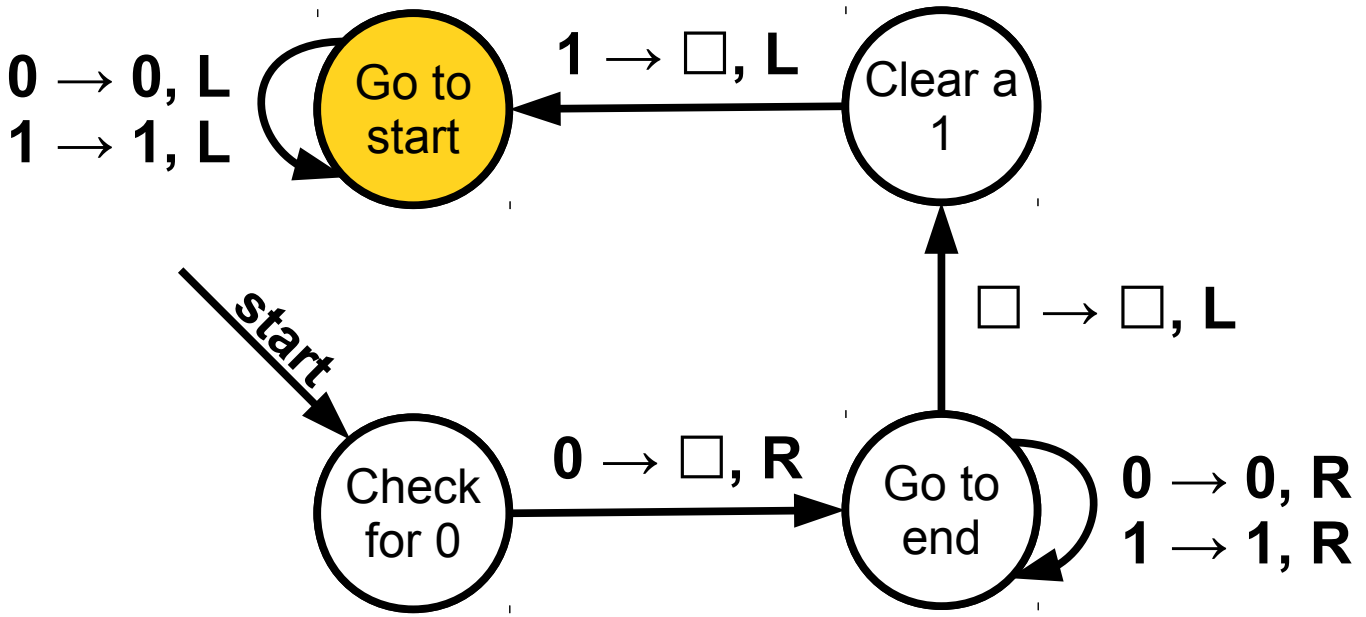
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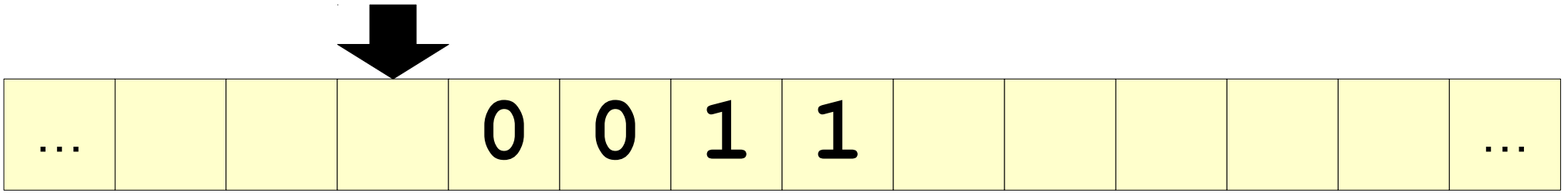
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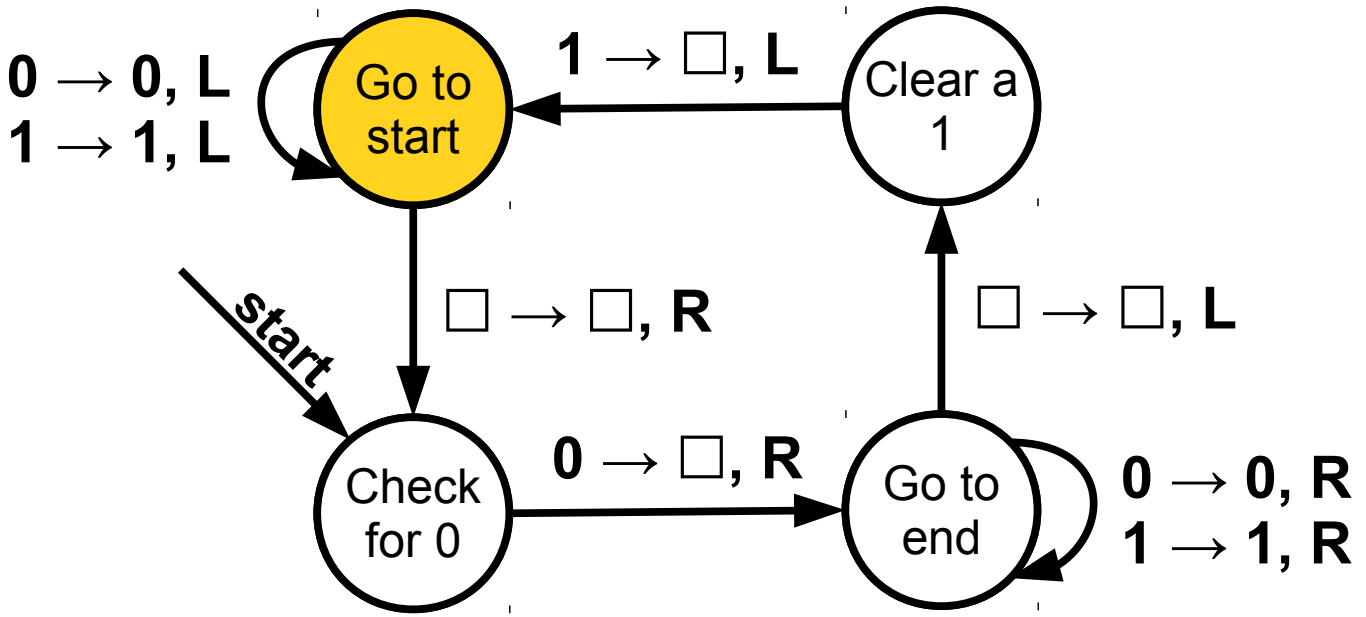
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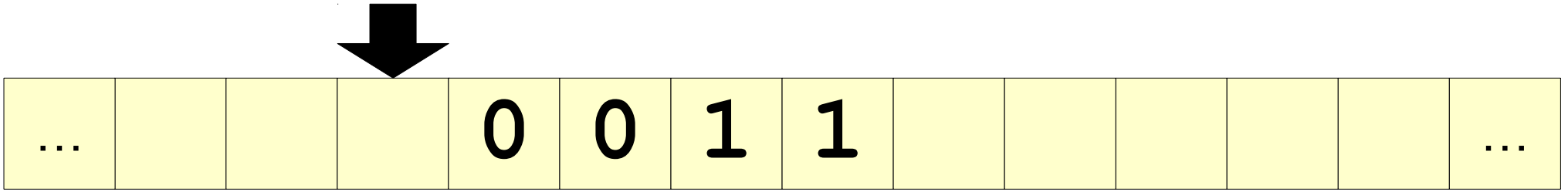
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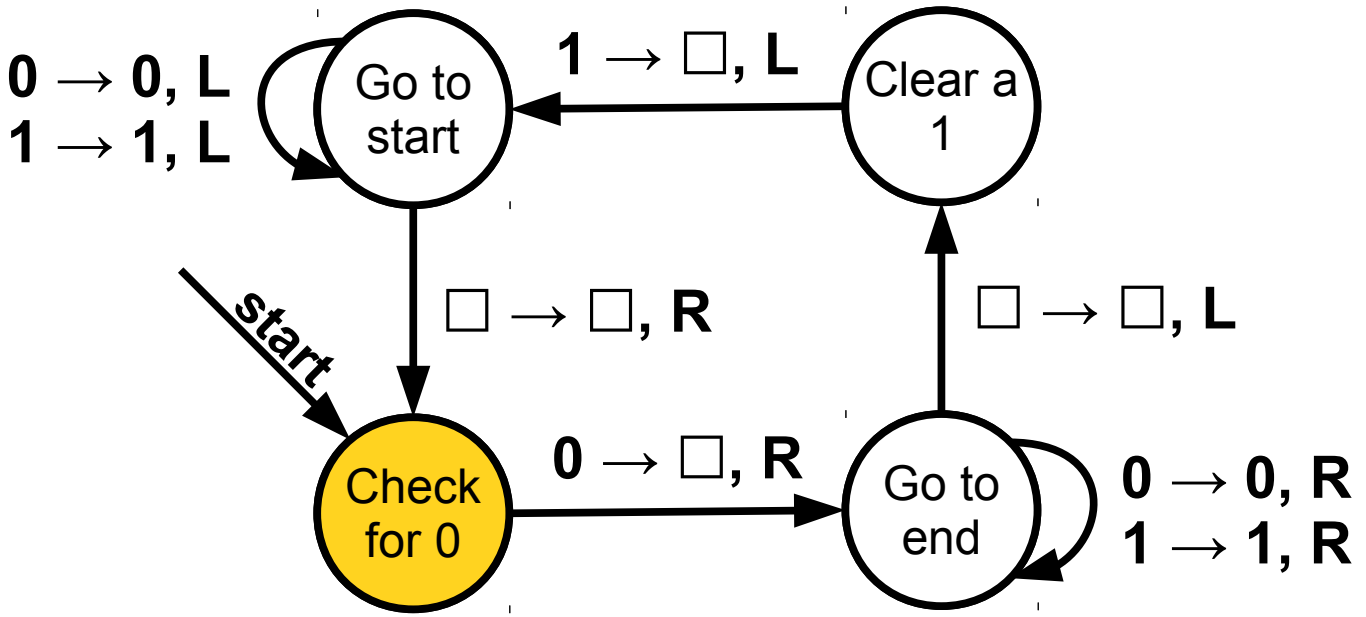
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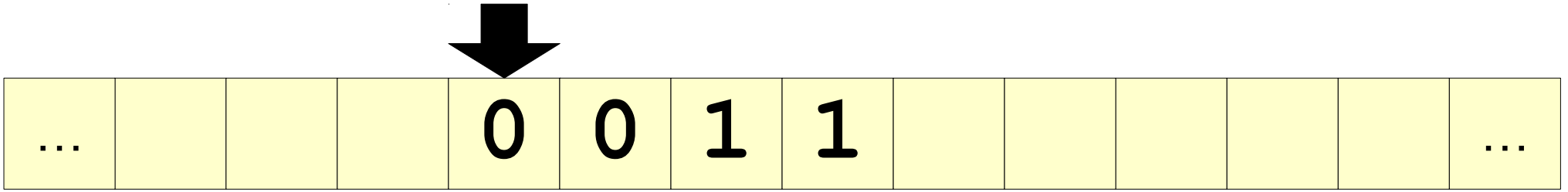
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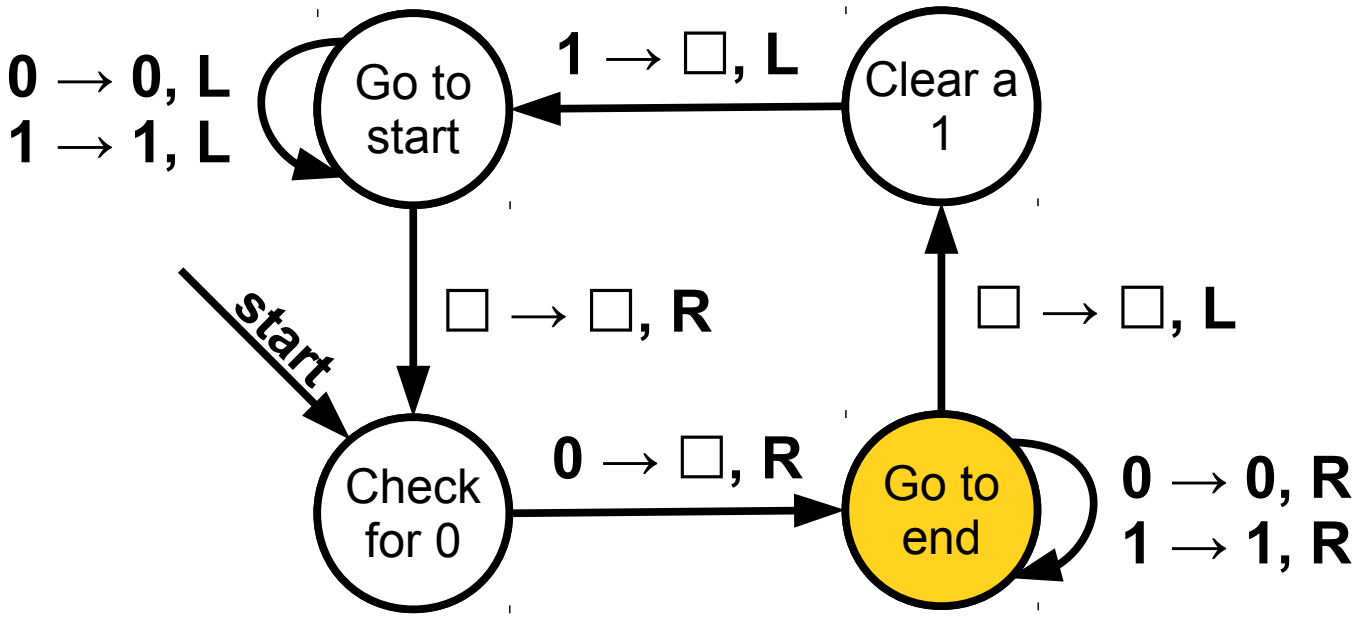
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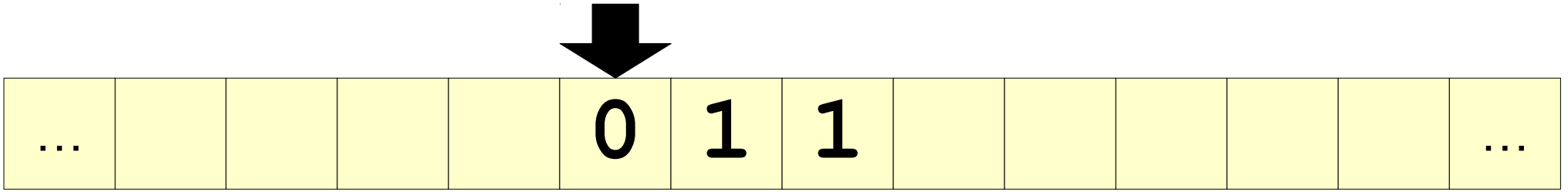
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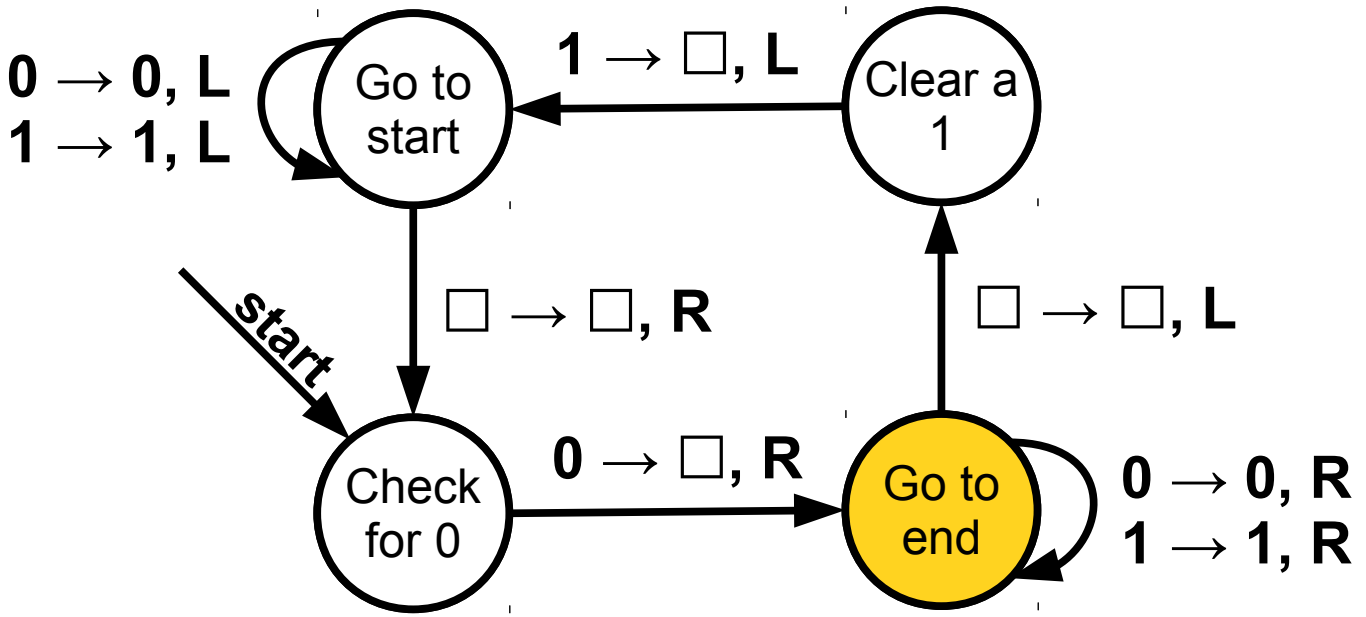
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Clear a 1
start
□ → □, R
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Check for 0
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Go to end
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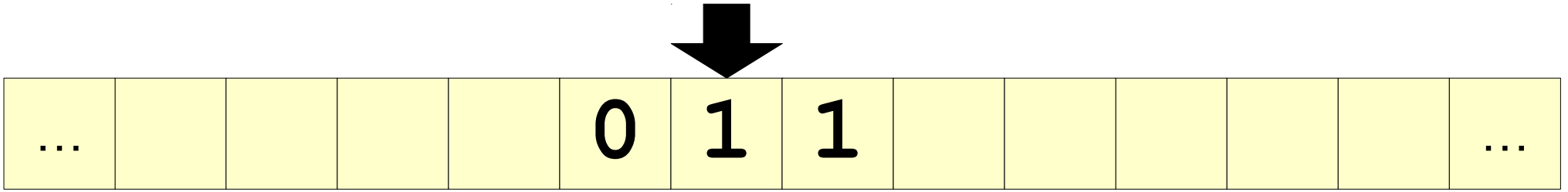
1 → 1, R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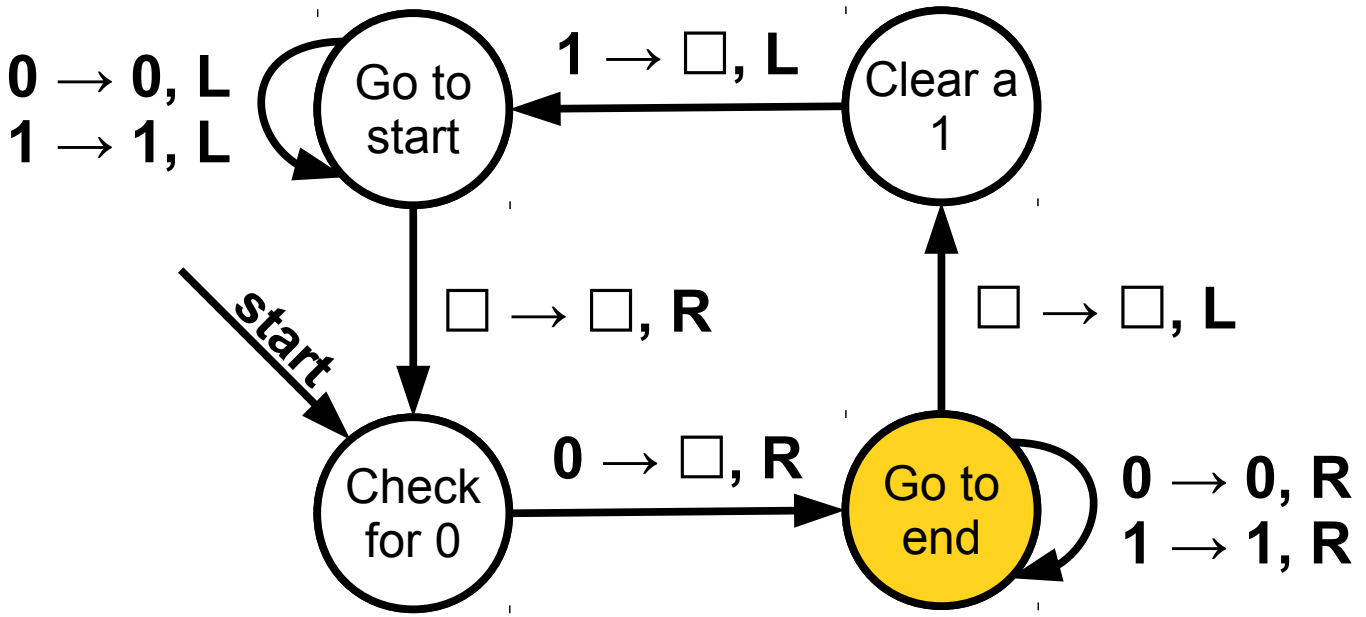
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1 → 1, L
Go to start
1 → □, L
Clear a 1
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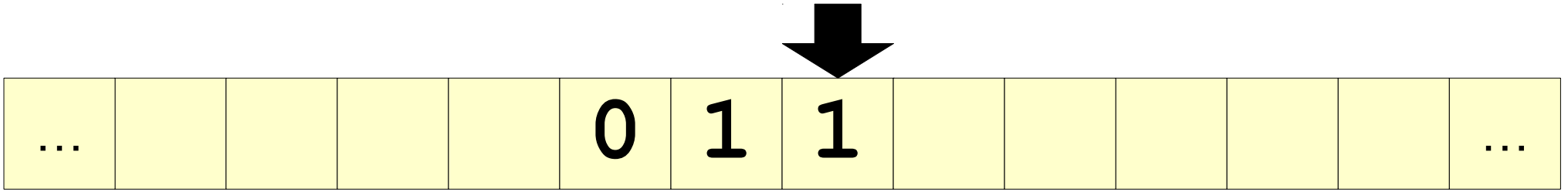
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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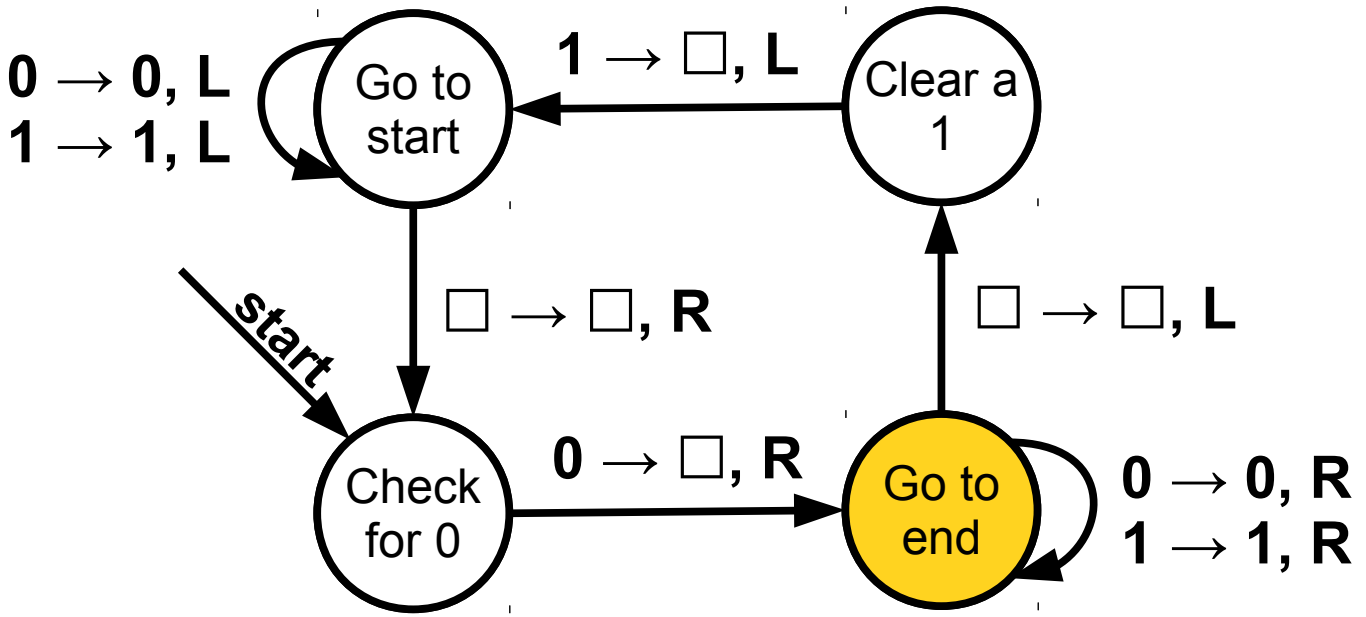
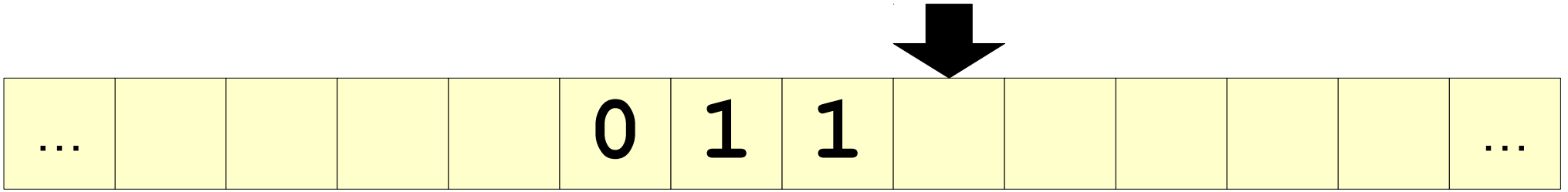

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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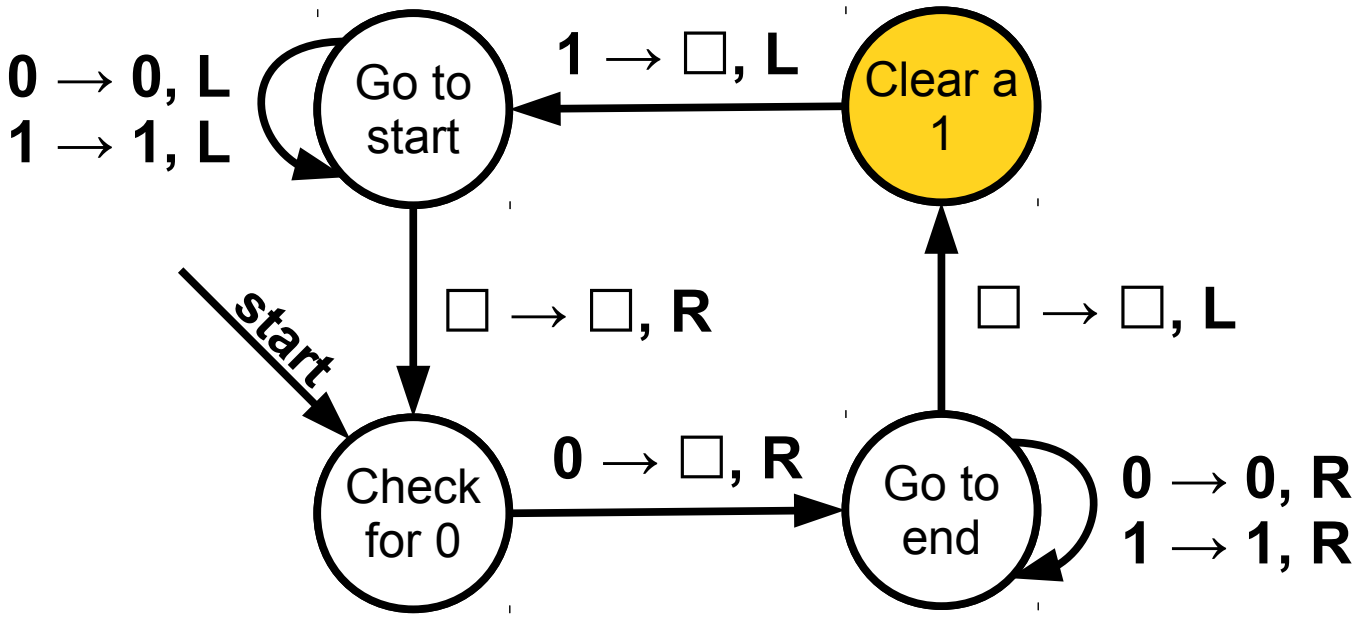
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Go to start
1 → □, L
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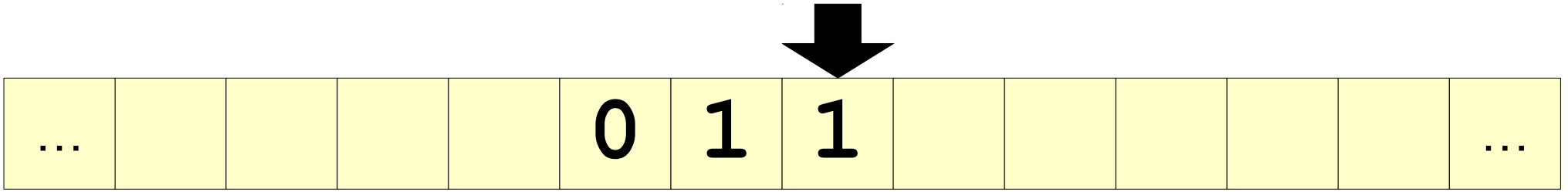
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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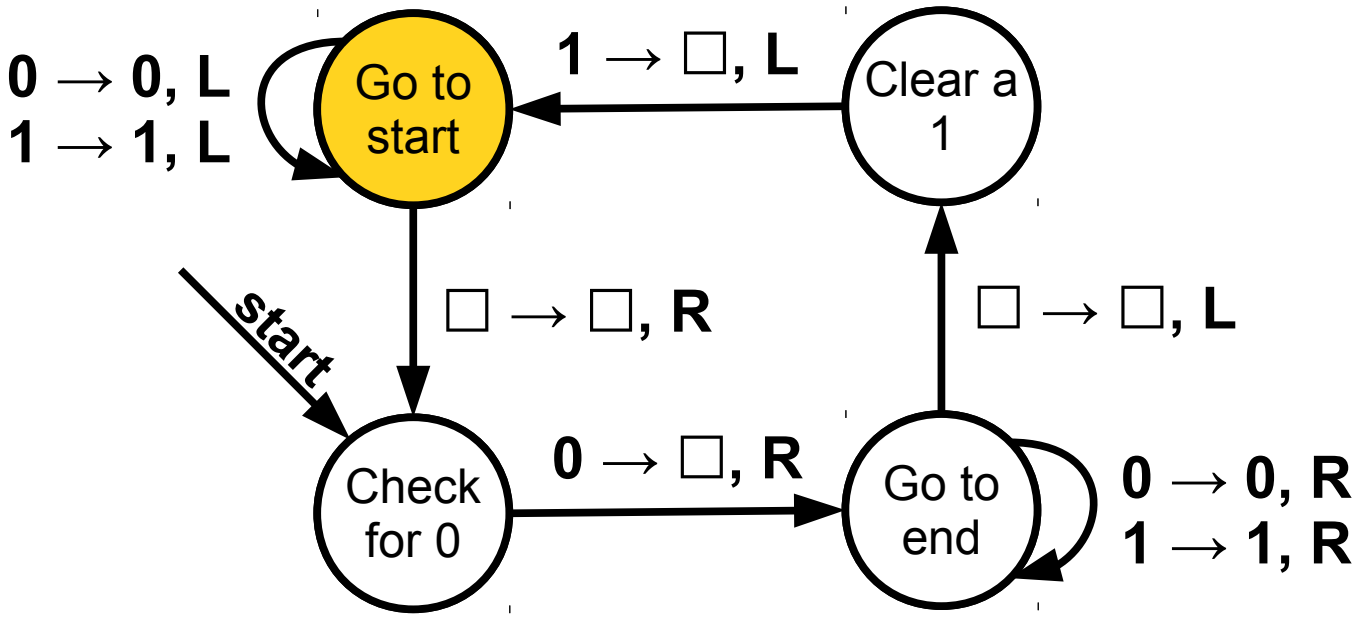
0 → 0, L
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Go to start
1 → □, L
Clear a 1
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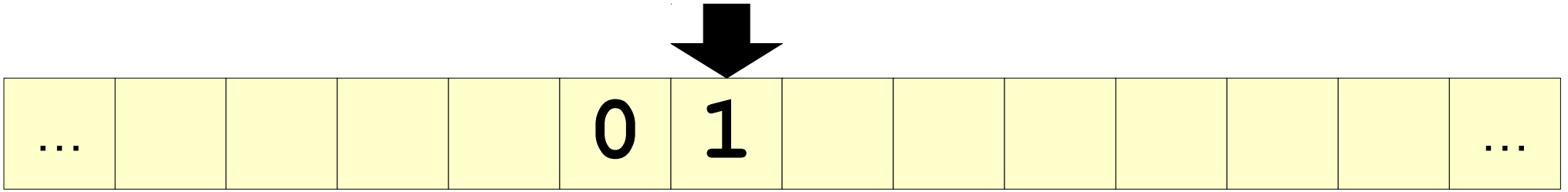
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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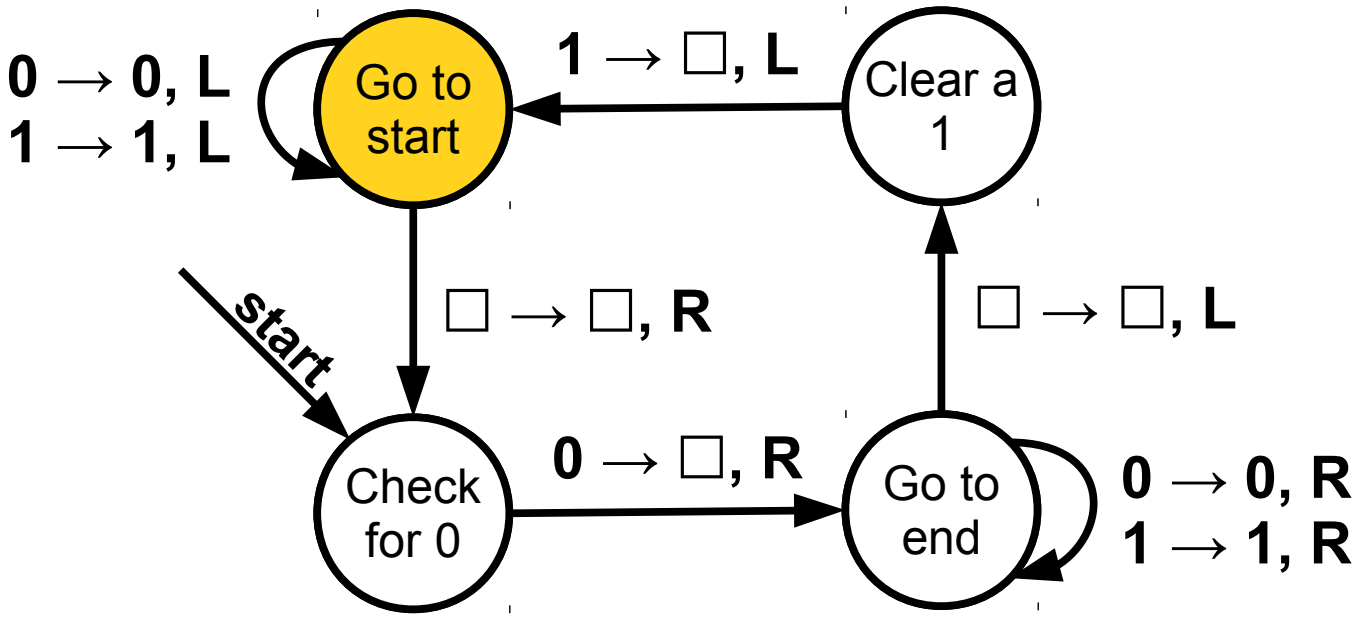
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Go to start
1 → □, L
Clear a 1
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□ → □, L
Check for 0
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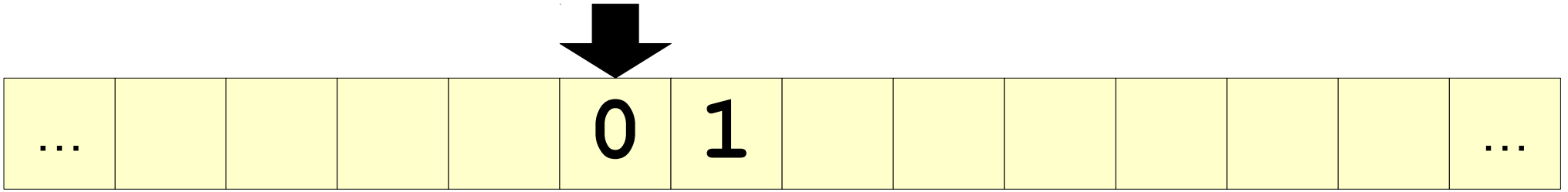
Go to end
0 → 0, R
1 → 1, R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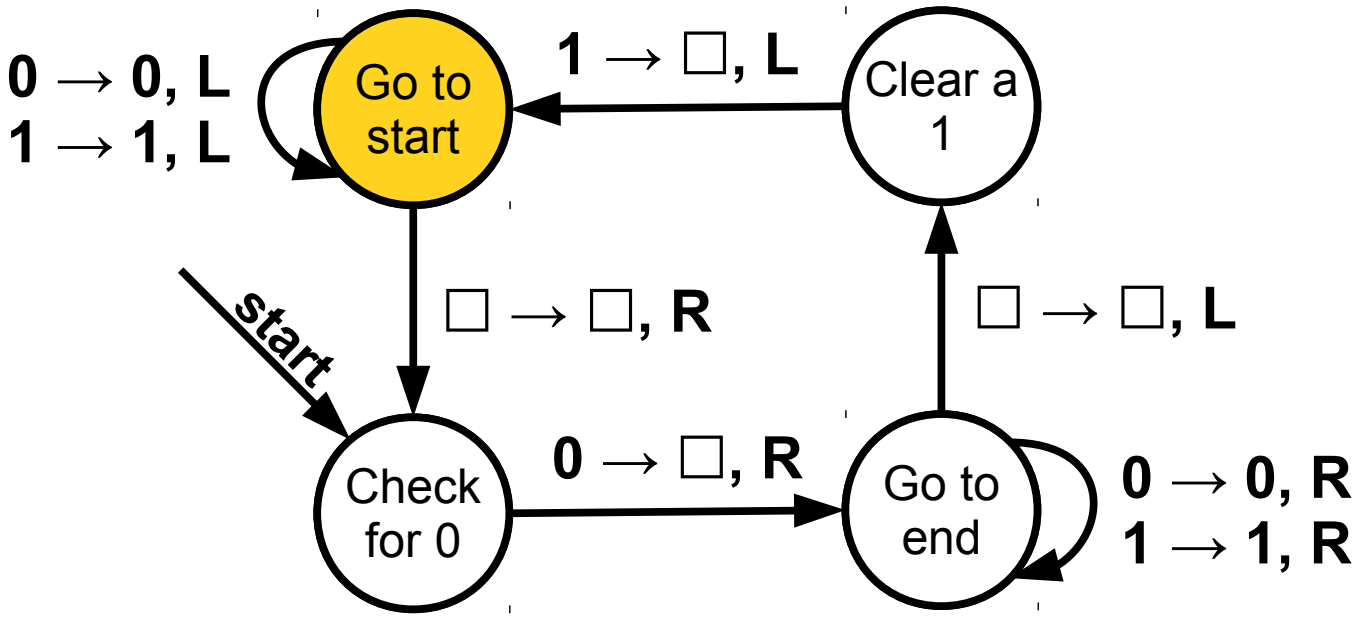
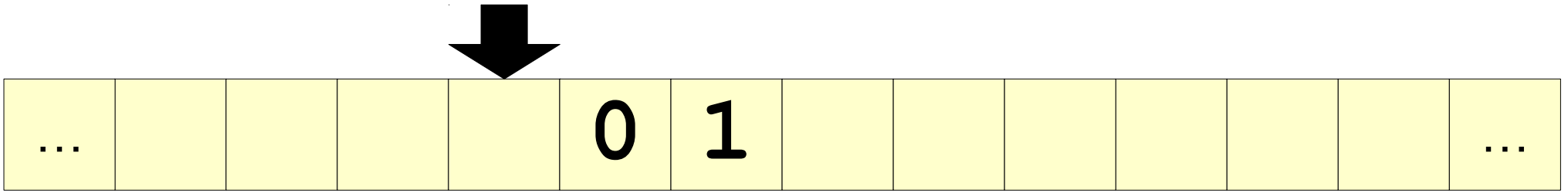

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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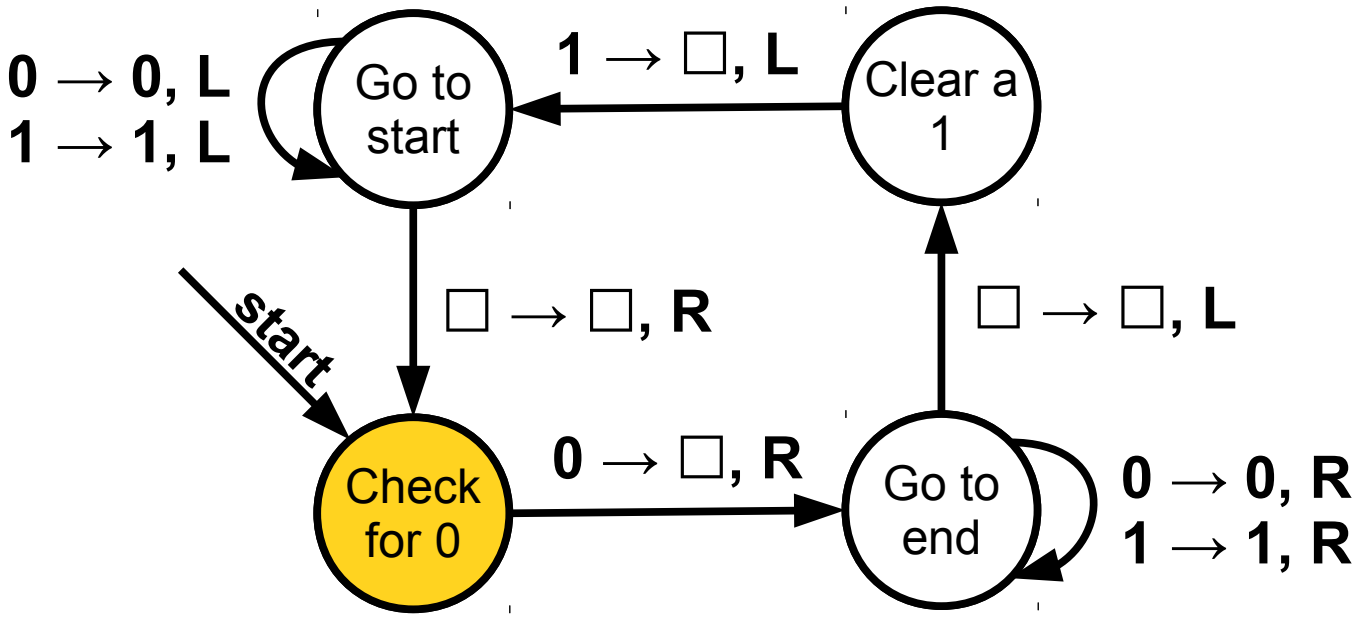
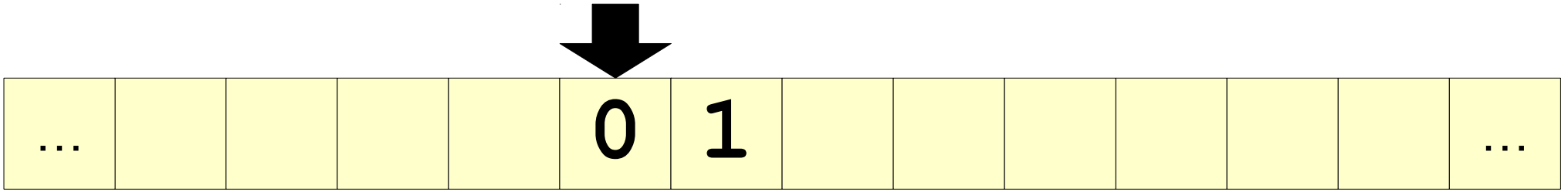

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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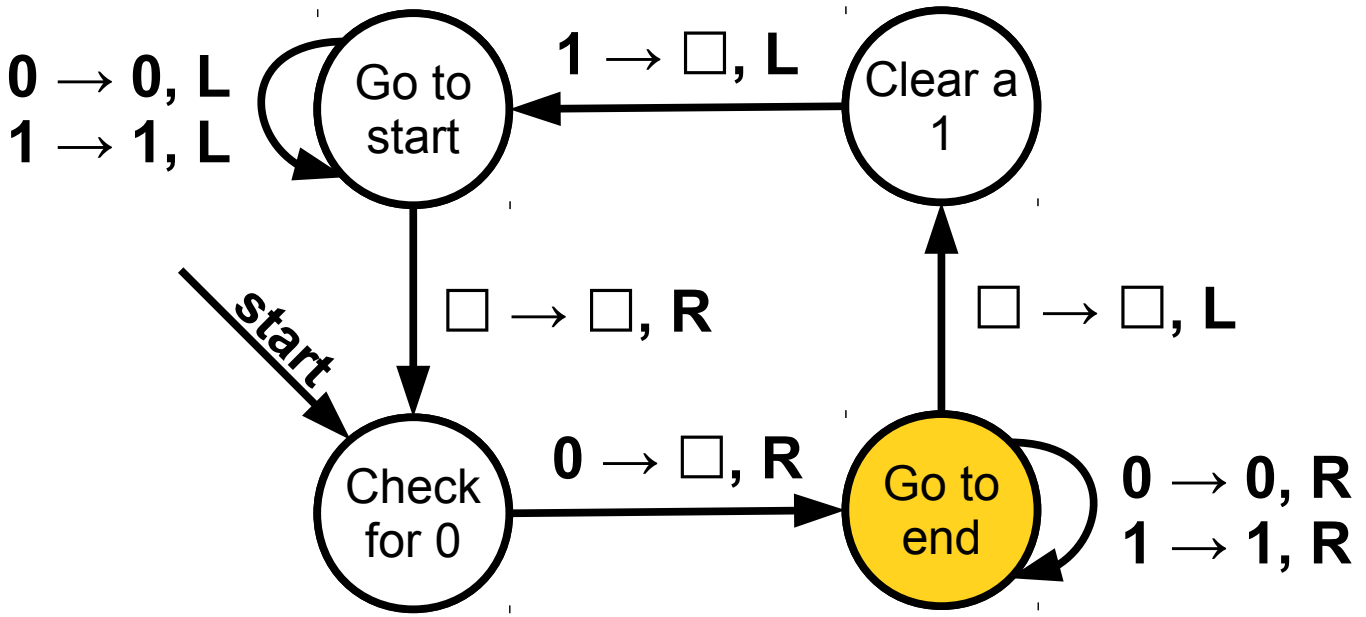
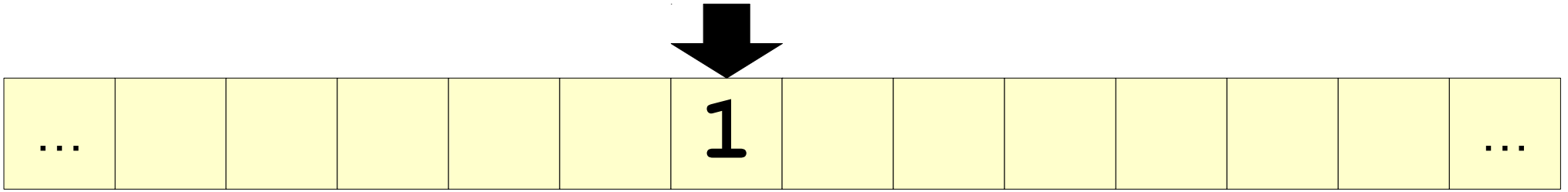

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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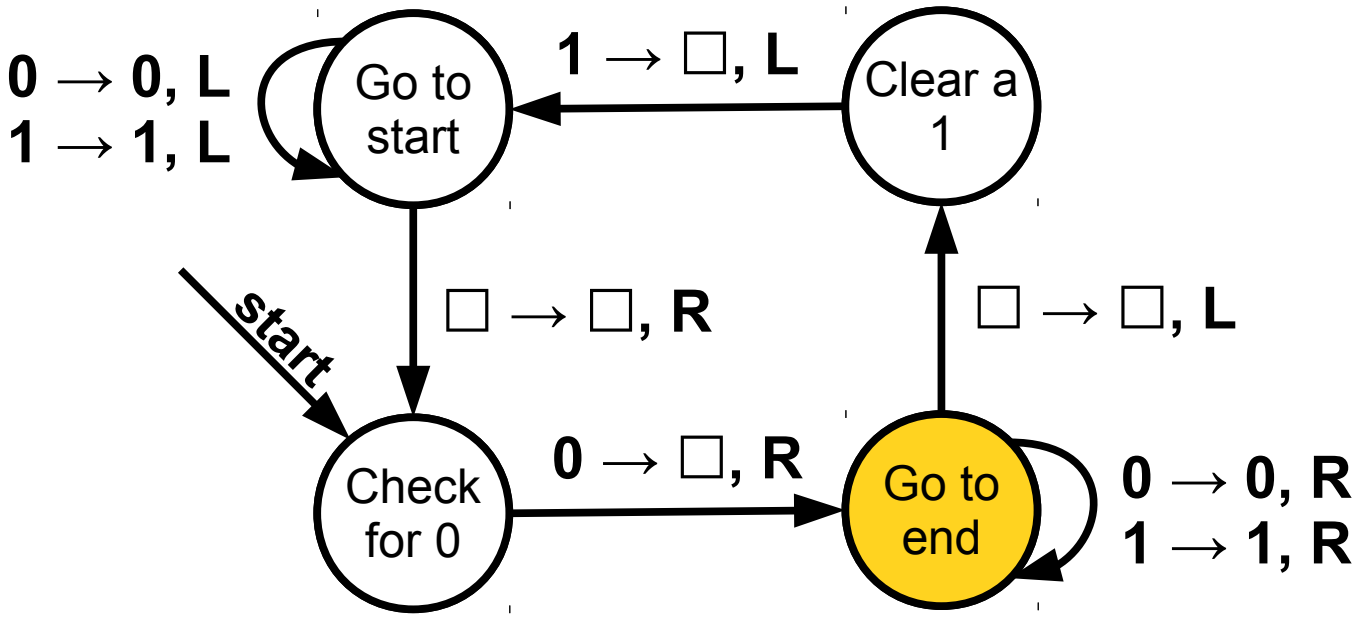
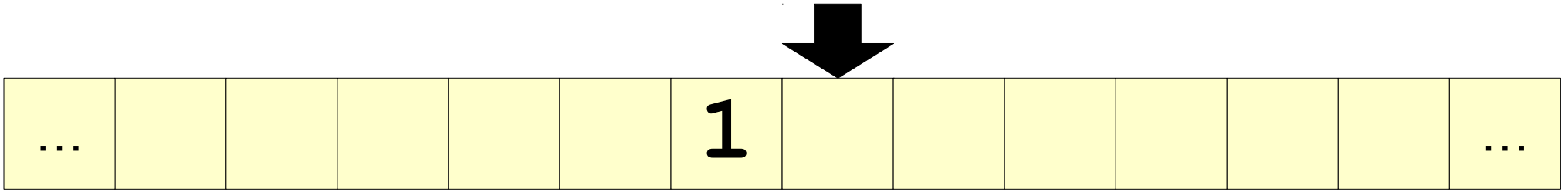

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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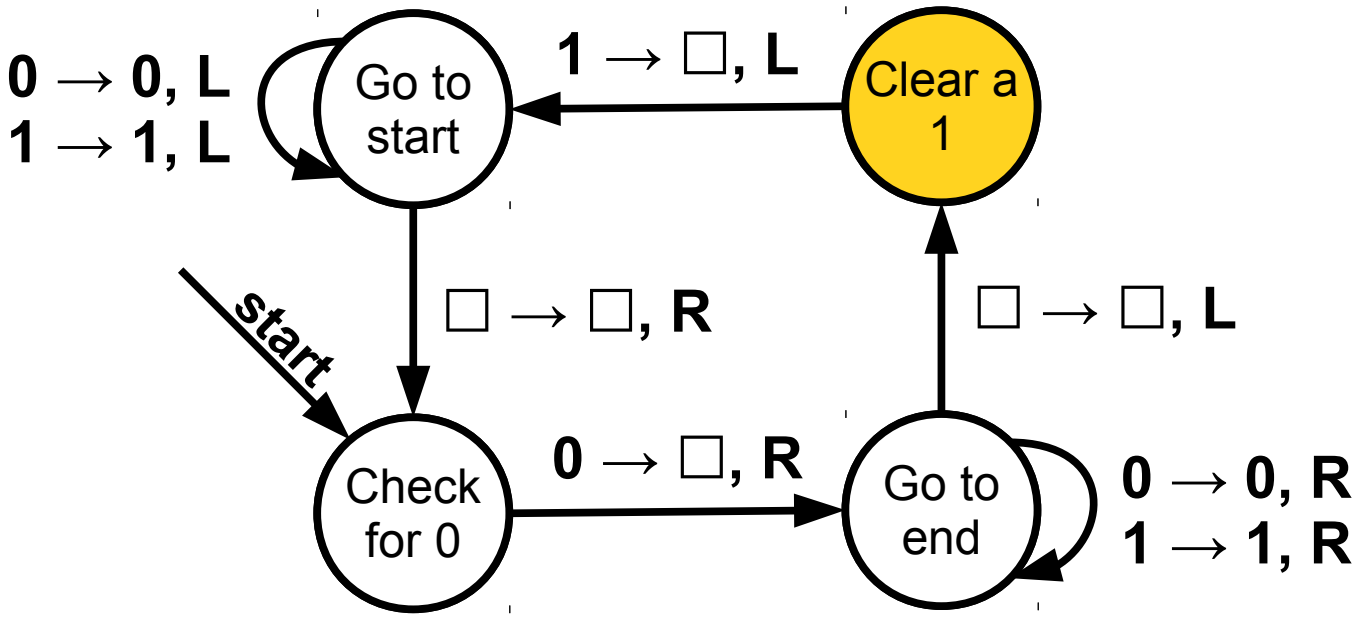
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
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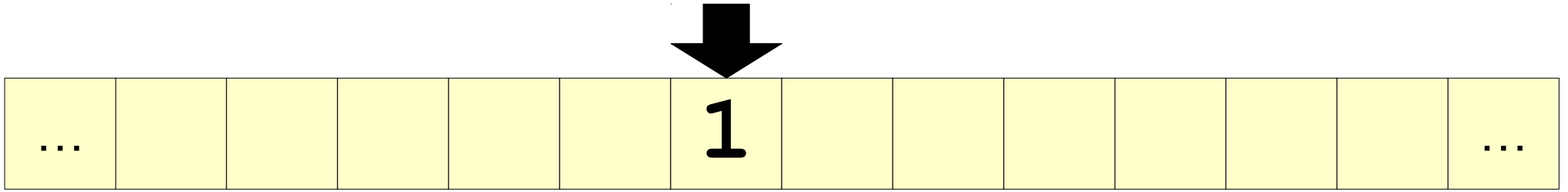
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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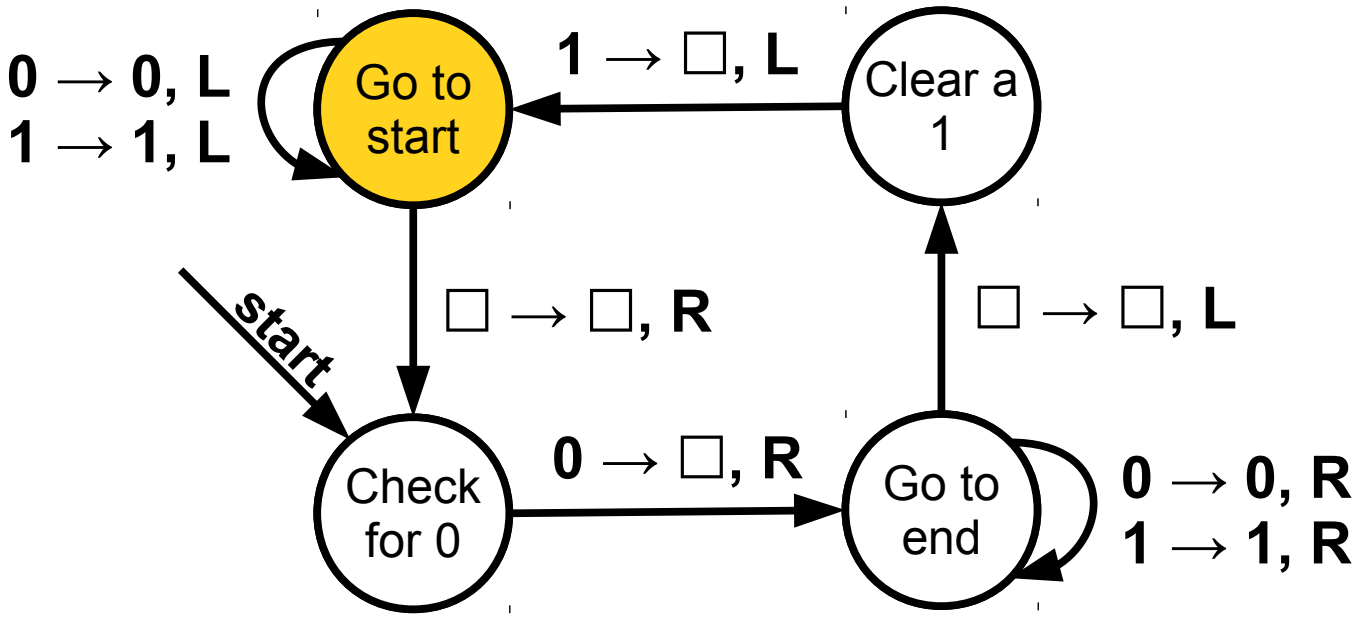
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
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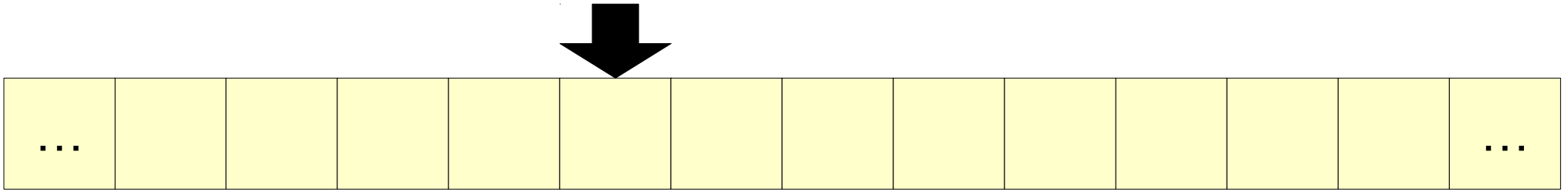
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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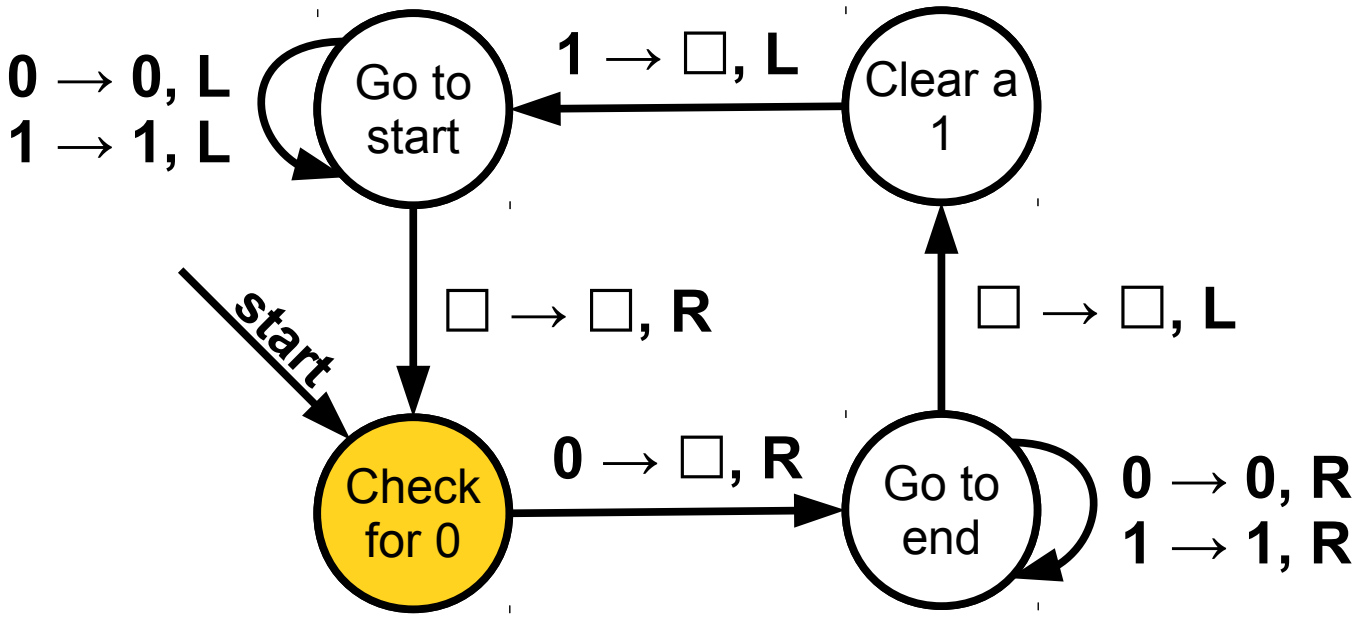
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
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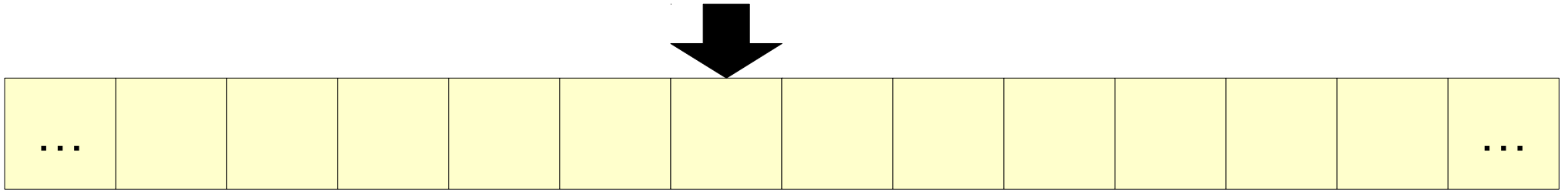
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R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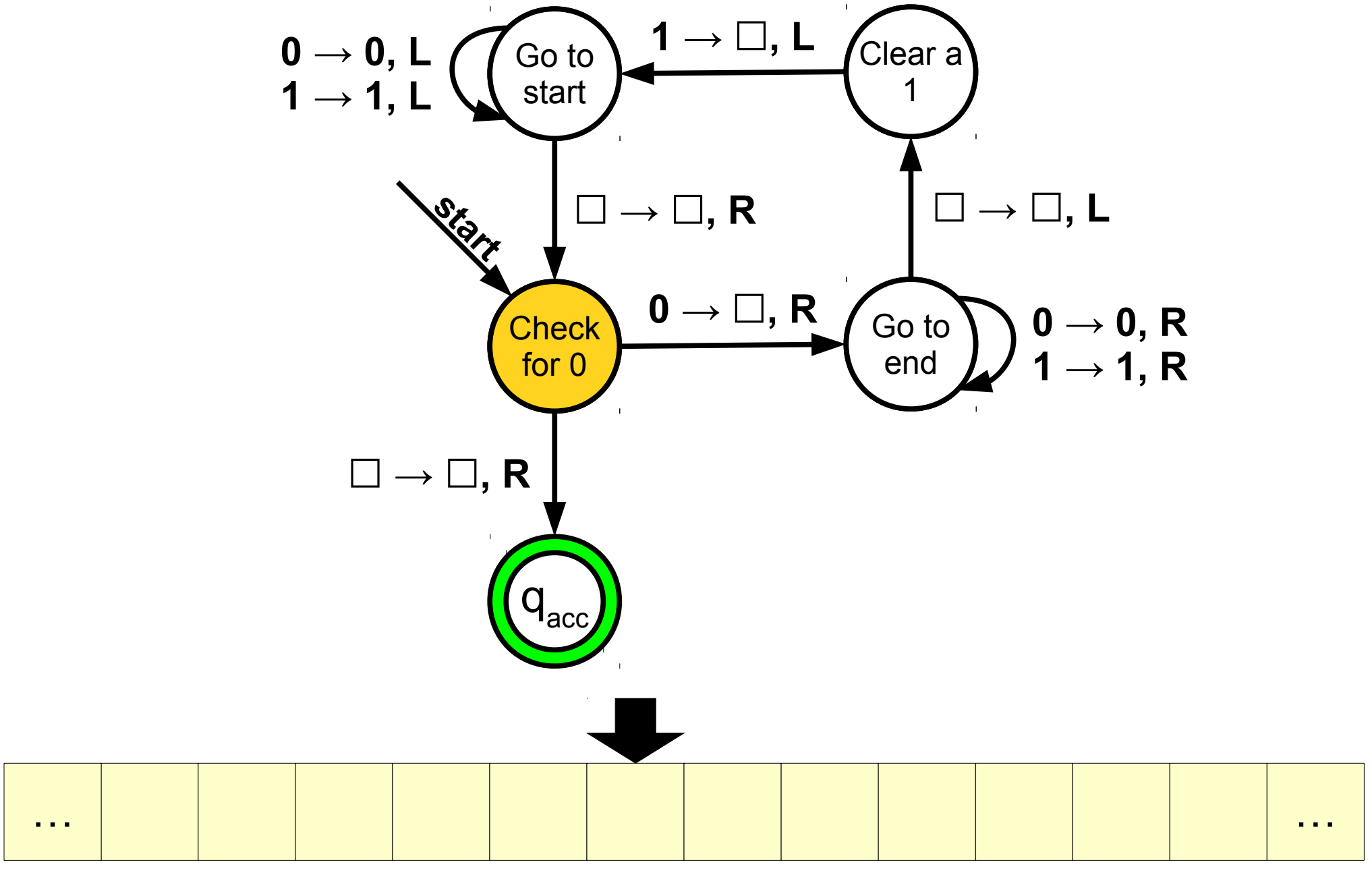
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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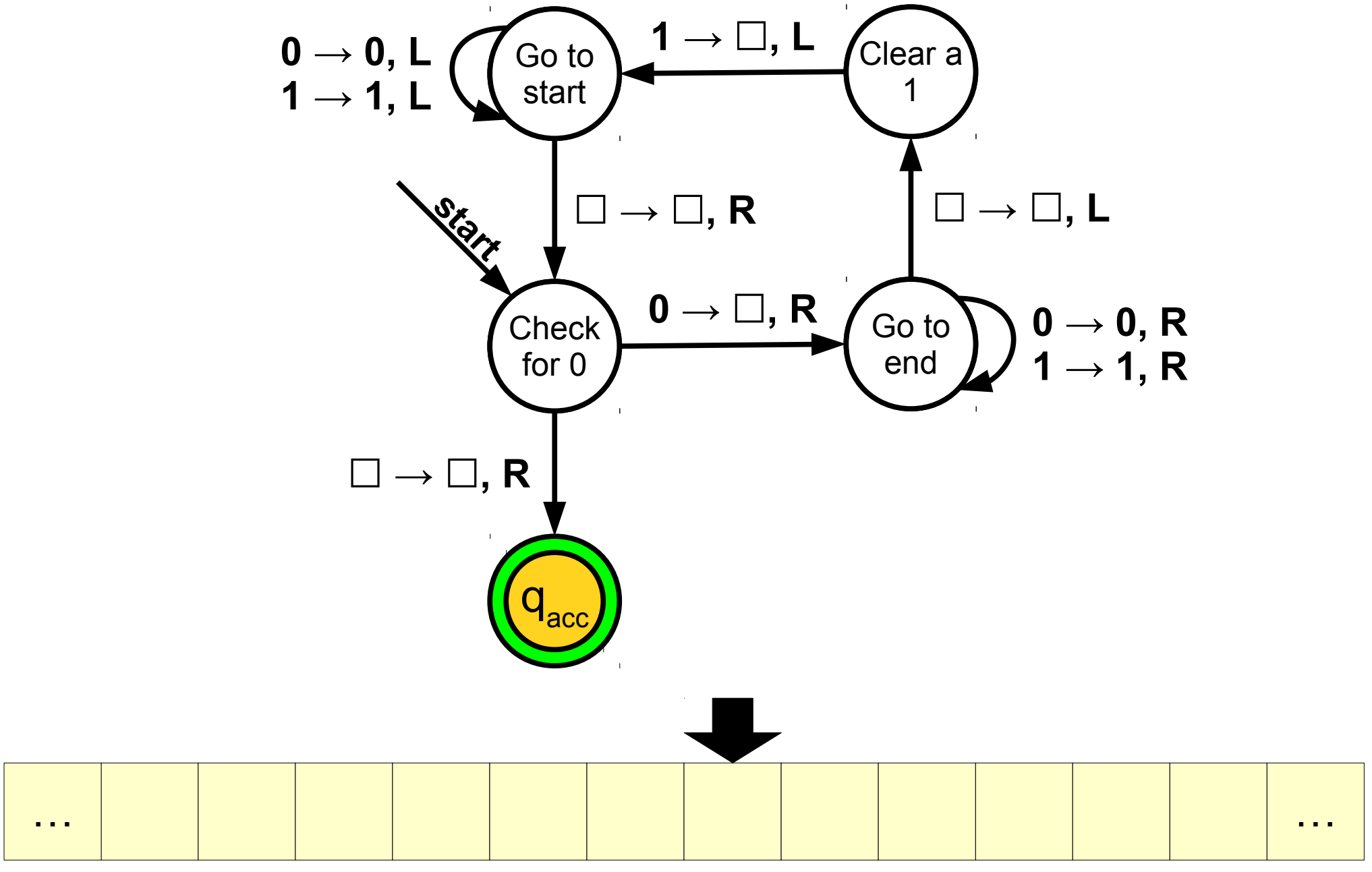
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
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0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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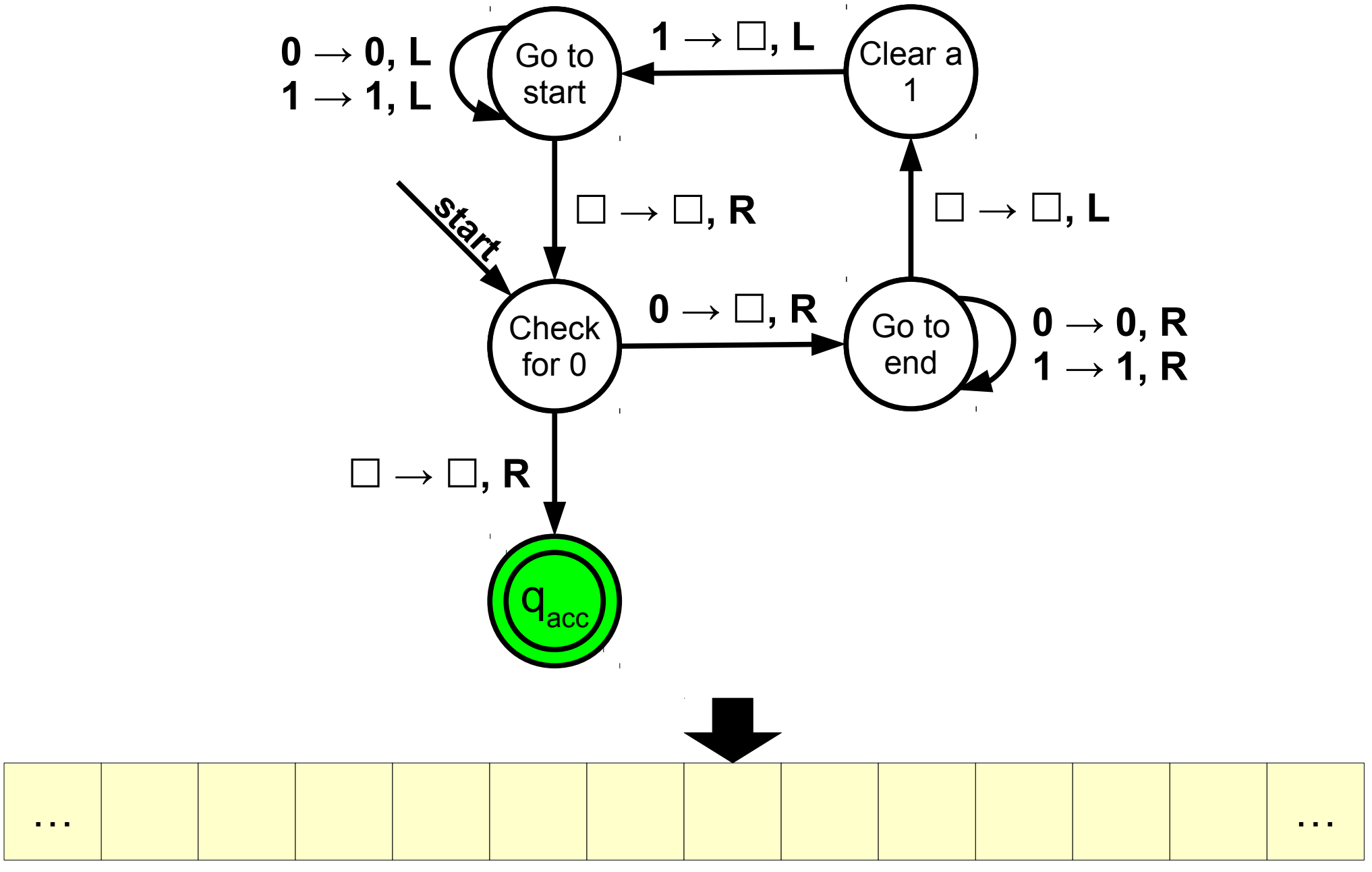
0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
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Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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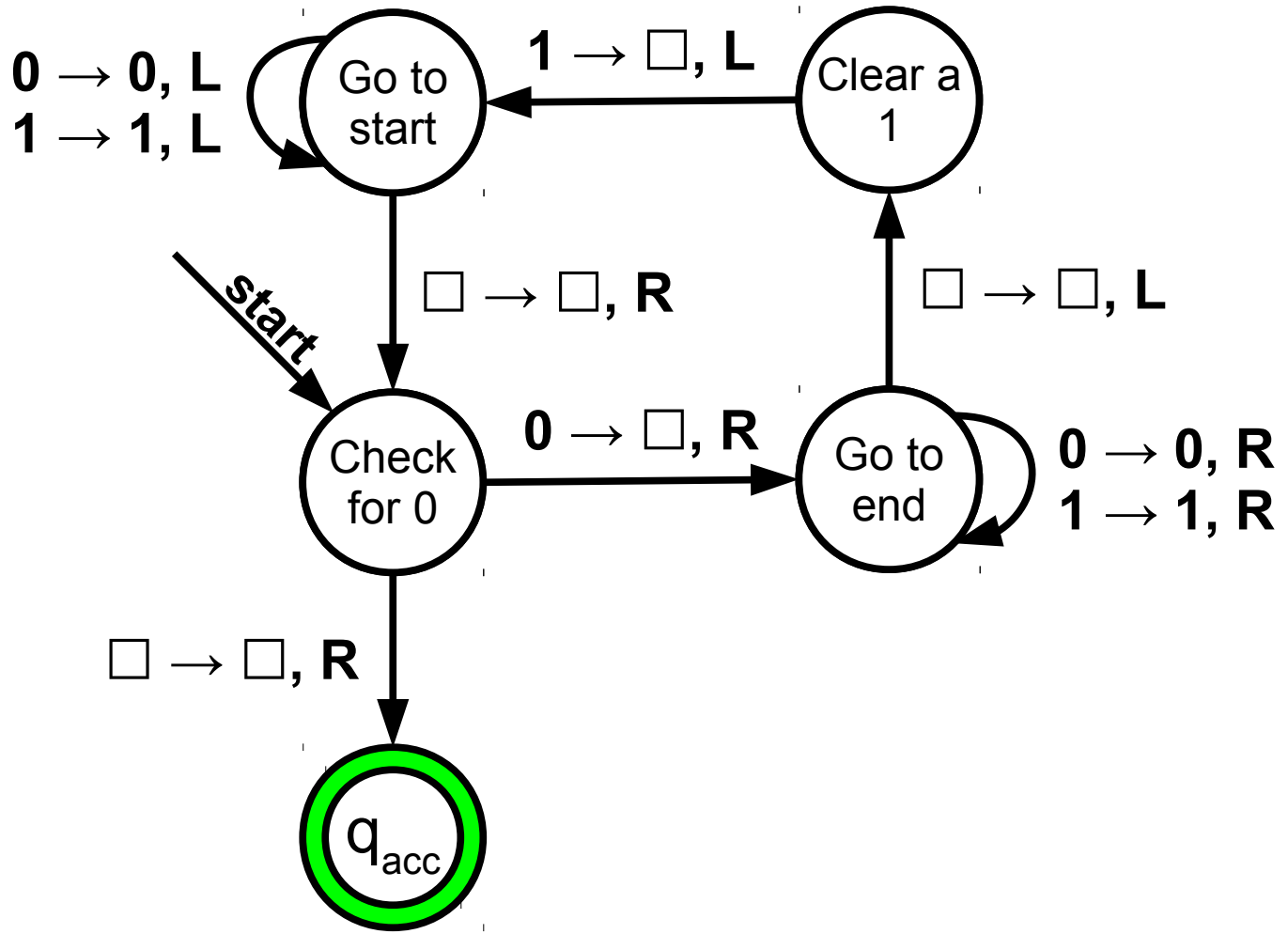
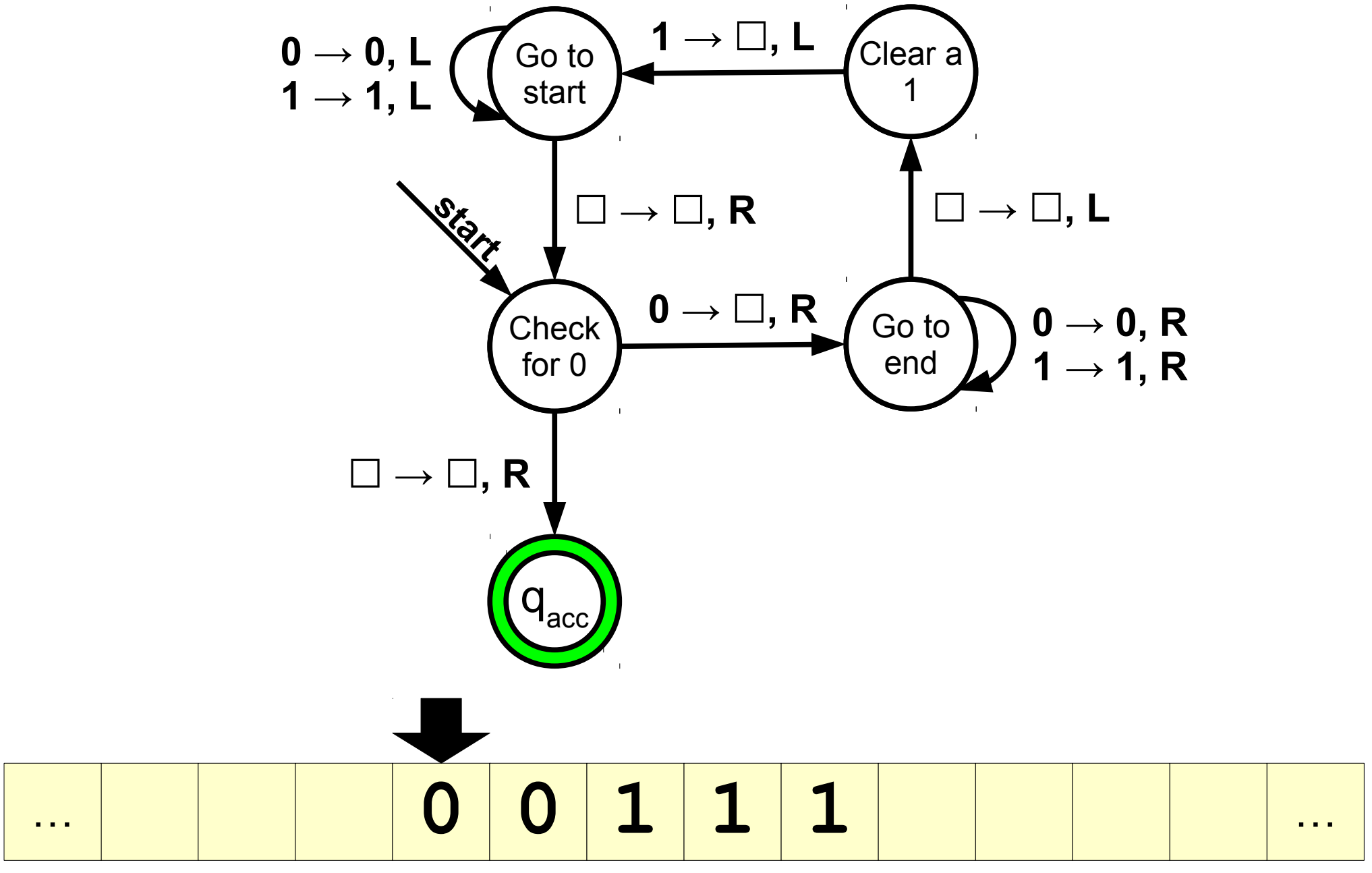

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}


0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
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1 → 1, R
□ → □, R
q_{acc}
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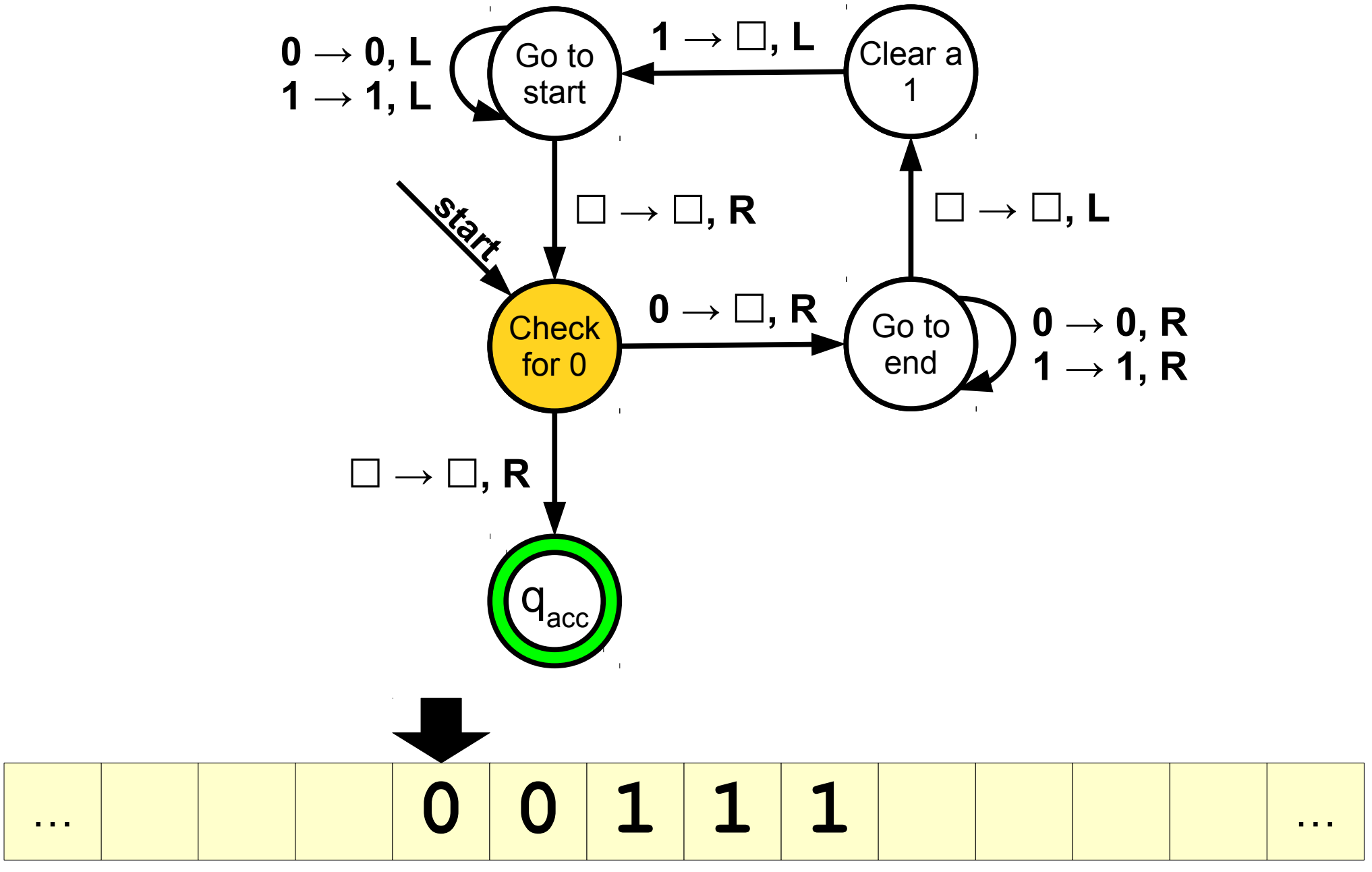
0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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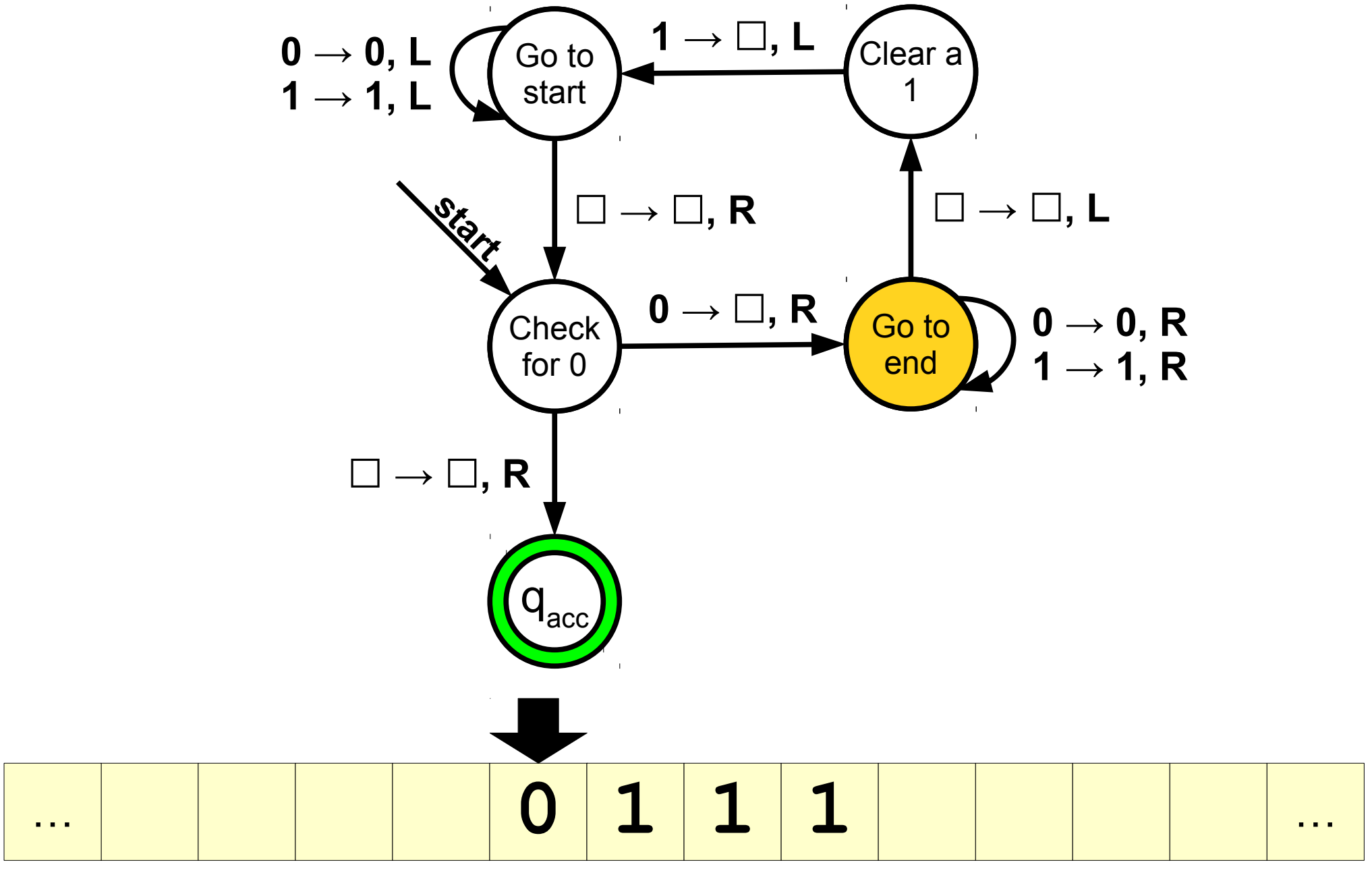
Go to start
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Check for 0
Go to end
q_{acc}
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□ → □, R
□ → □, L
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0 → 0, R
1 → 1, R
□ → □, R
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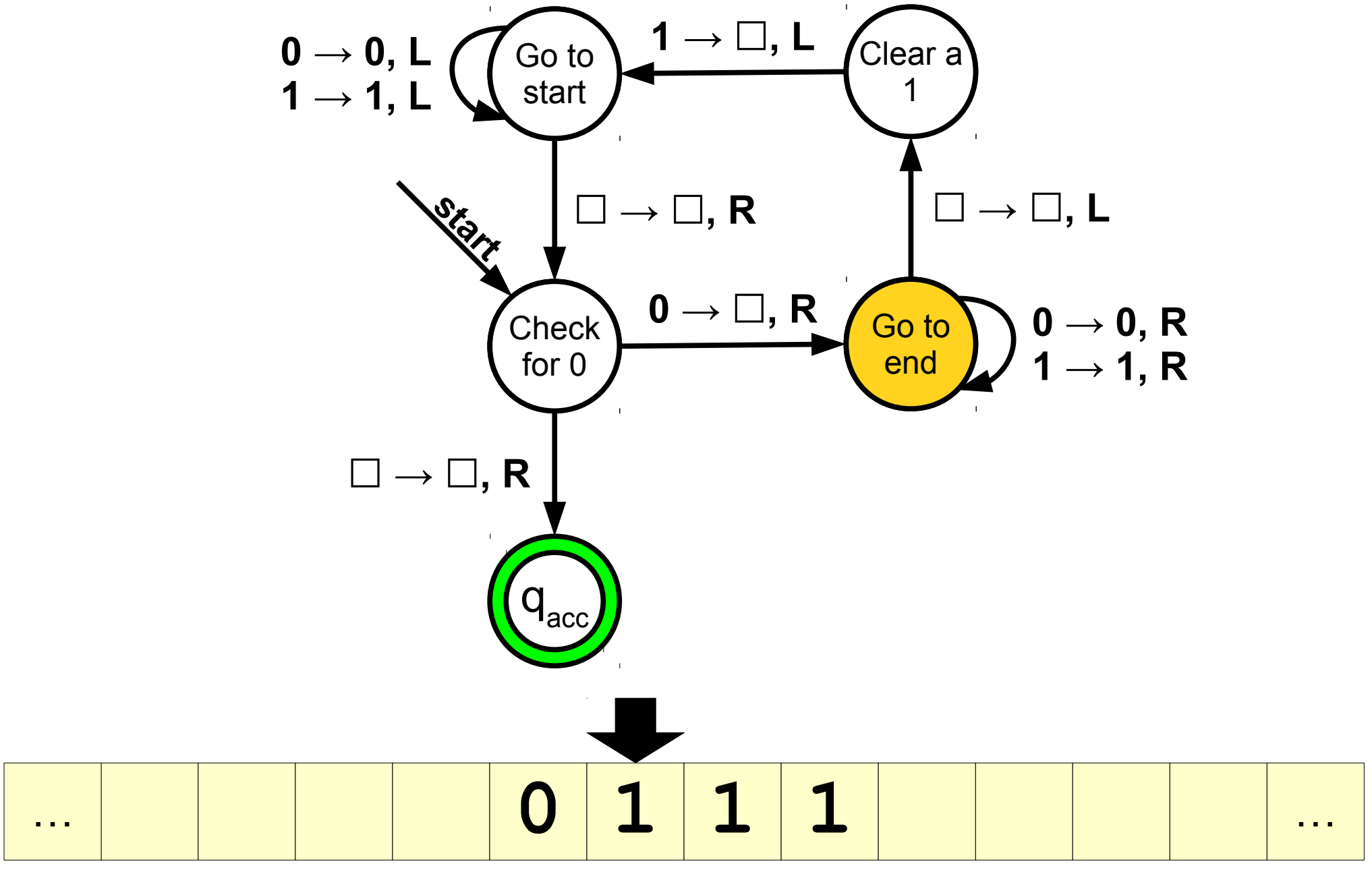
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
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1 → 1, R
□ → □, R
q_{acc}
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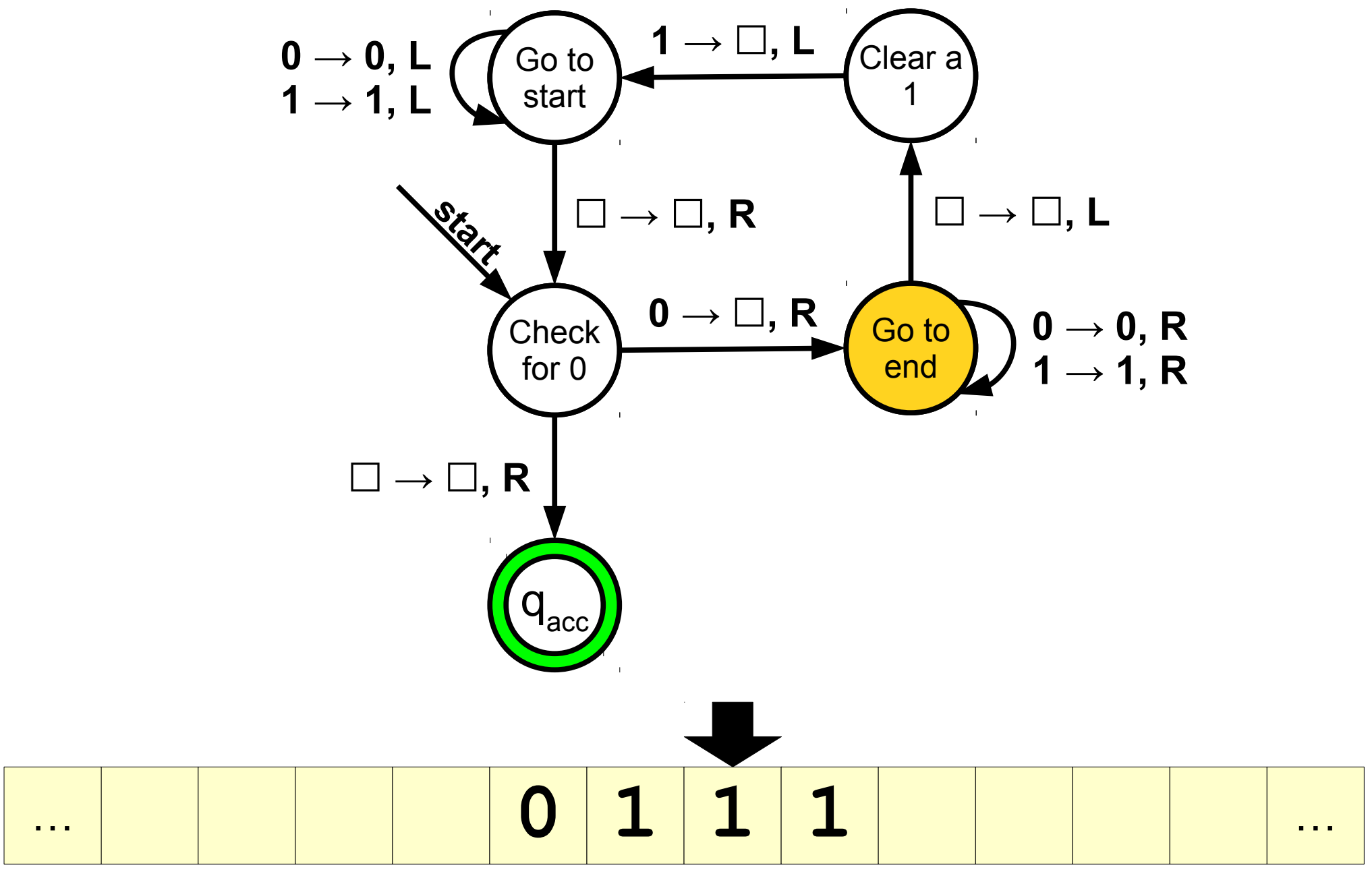
0 → 0, L
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Go to start
1 → □, L
Clear a 1
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Check for 0
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q_{acc}
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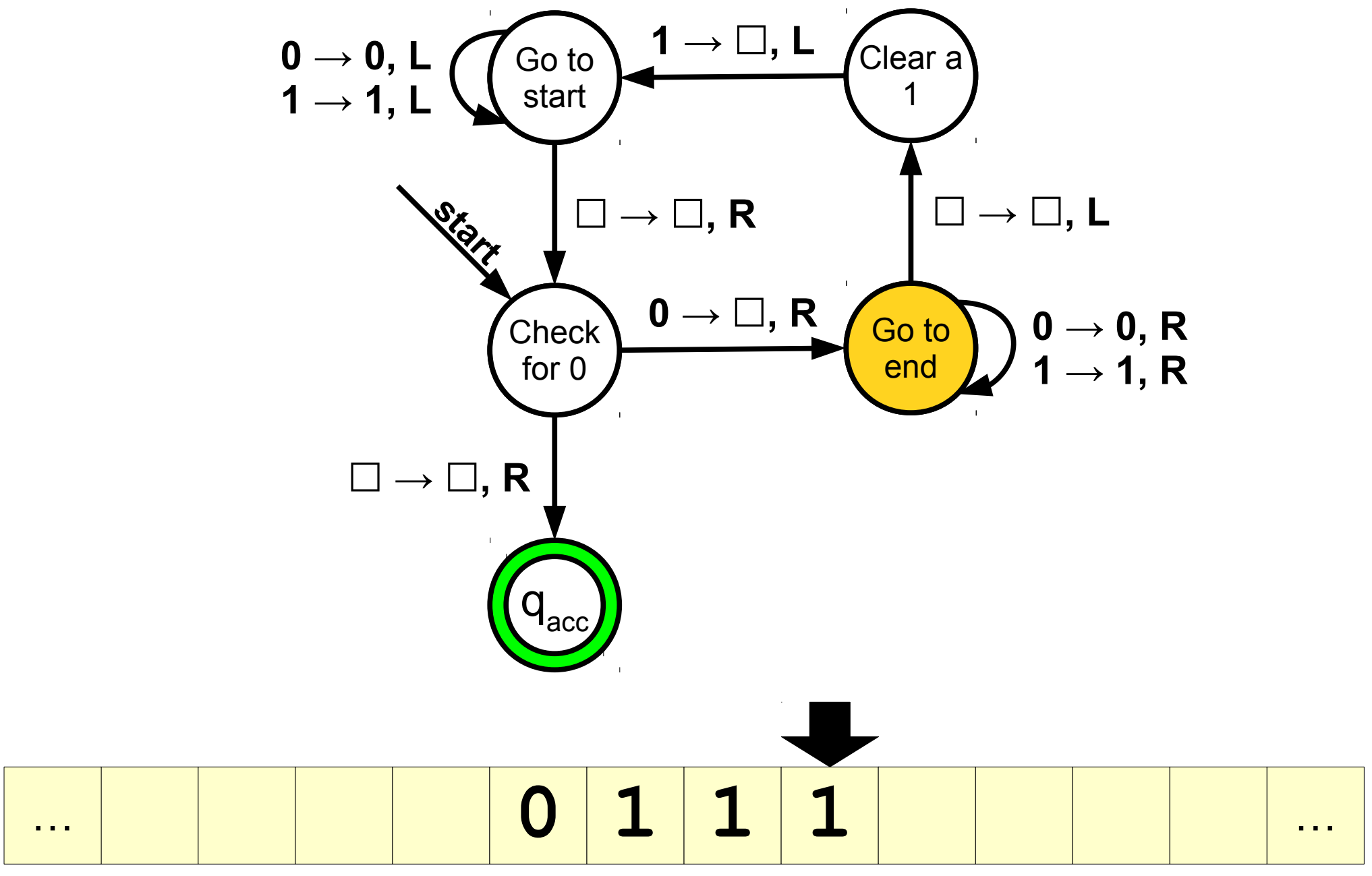
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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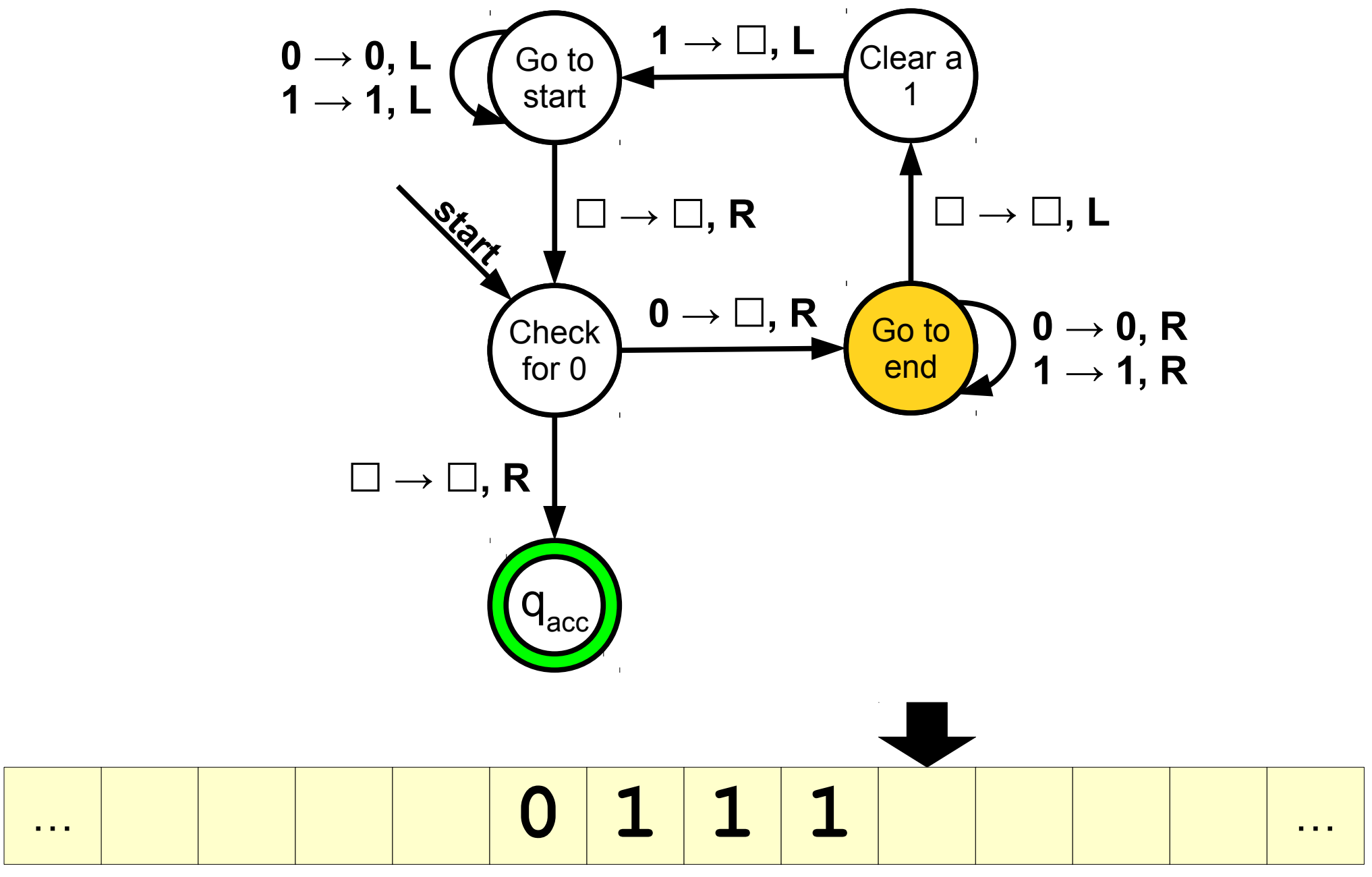
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
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Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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0 1 1 1
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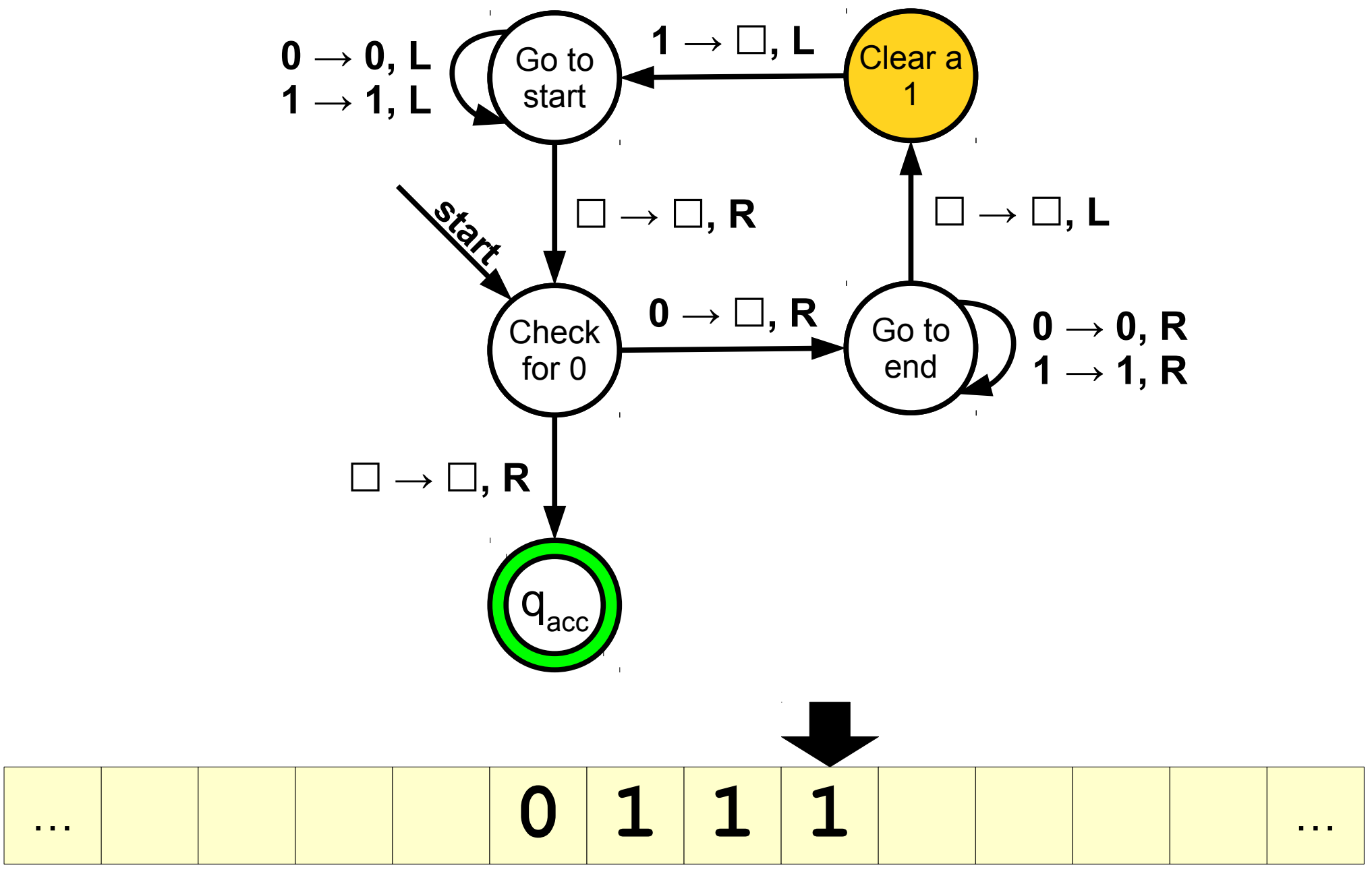
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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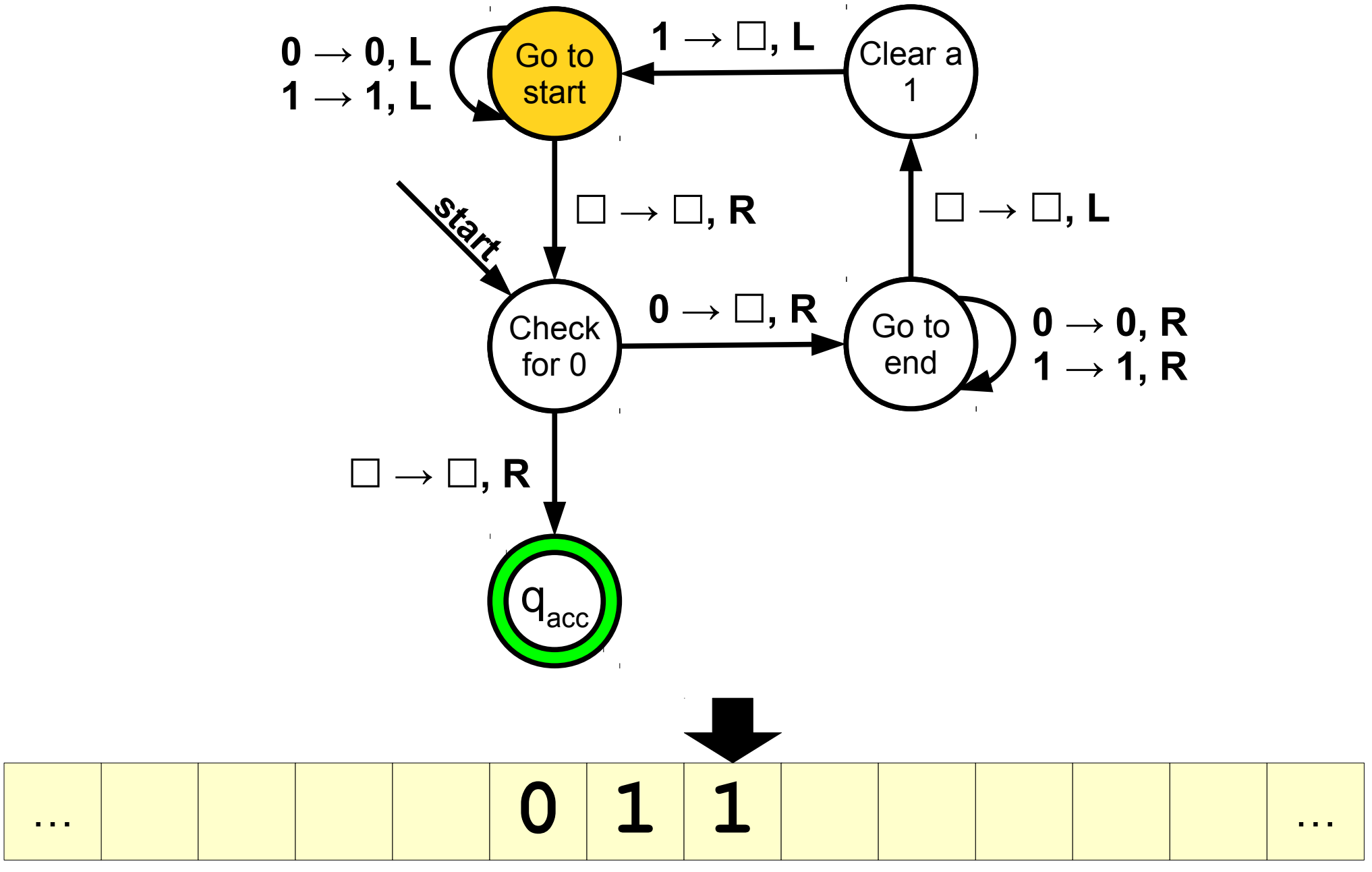
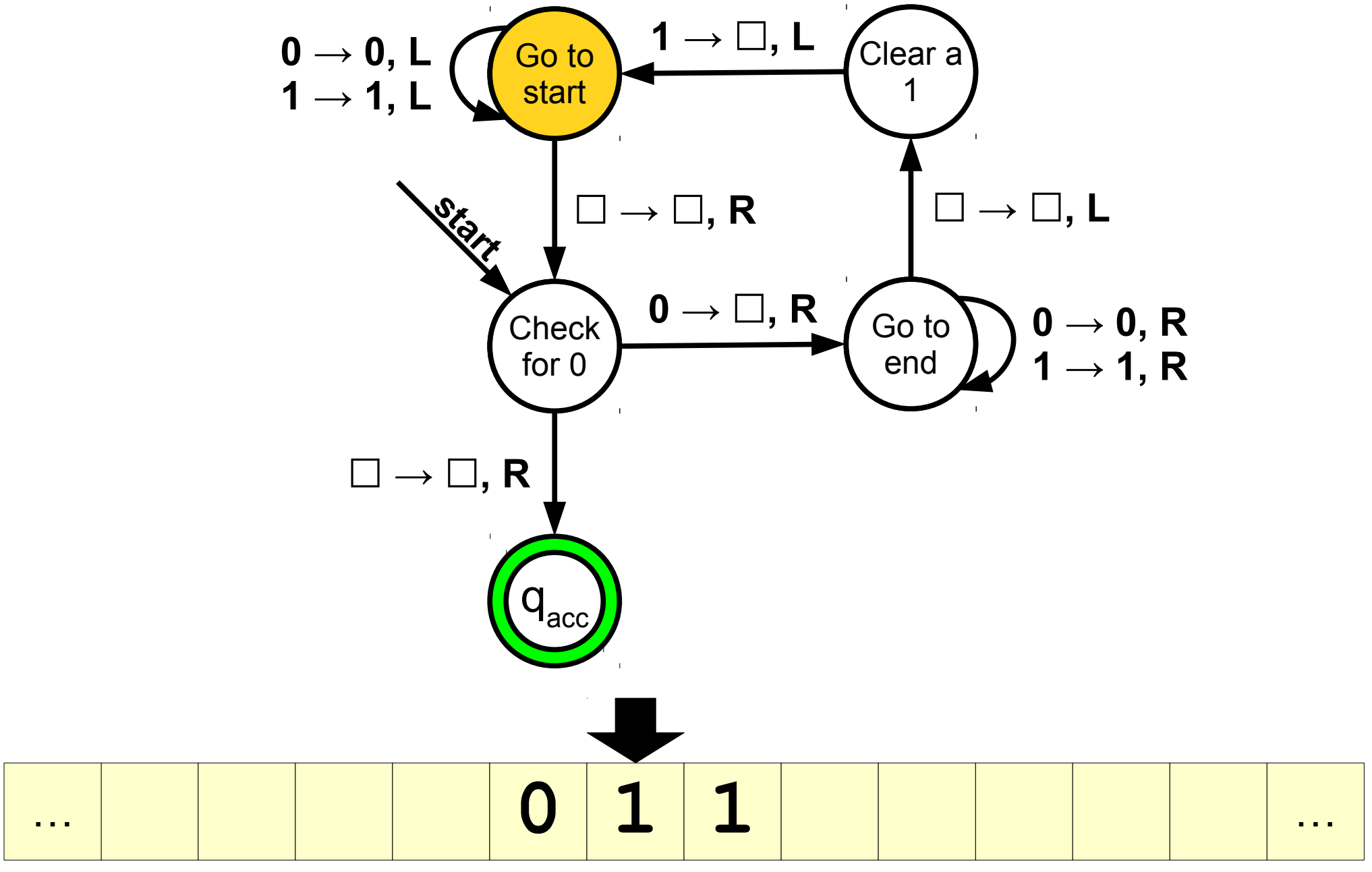

0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
…
0
1
1
…


0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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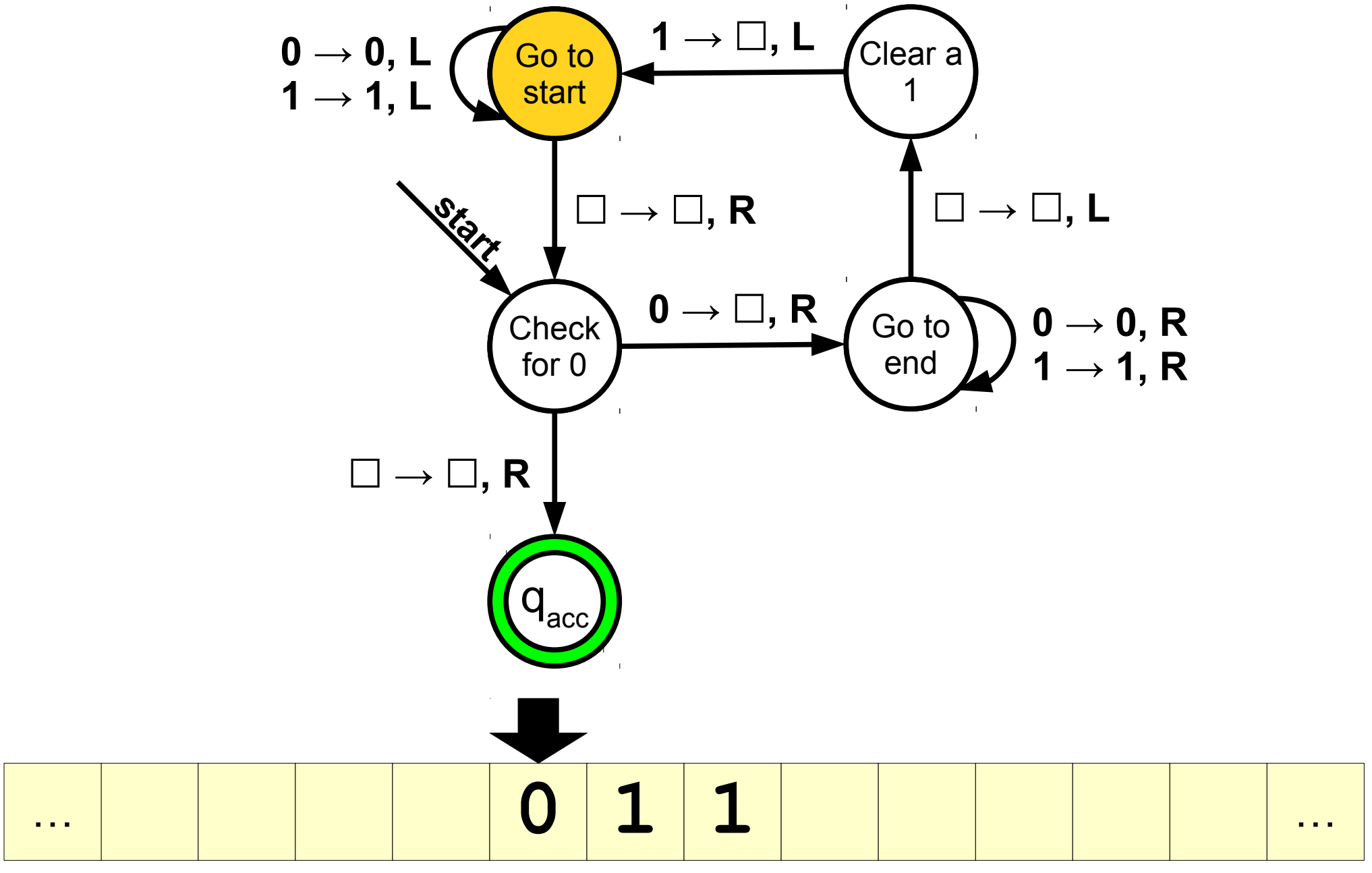
1
…


0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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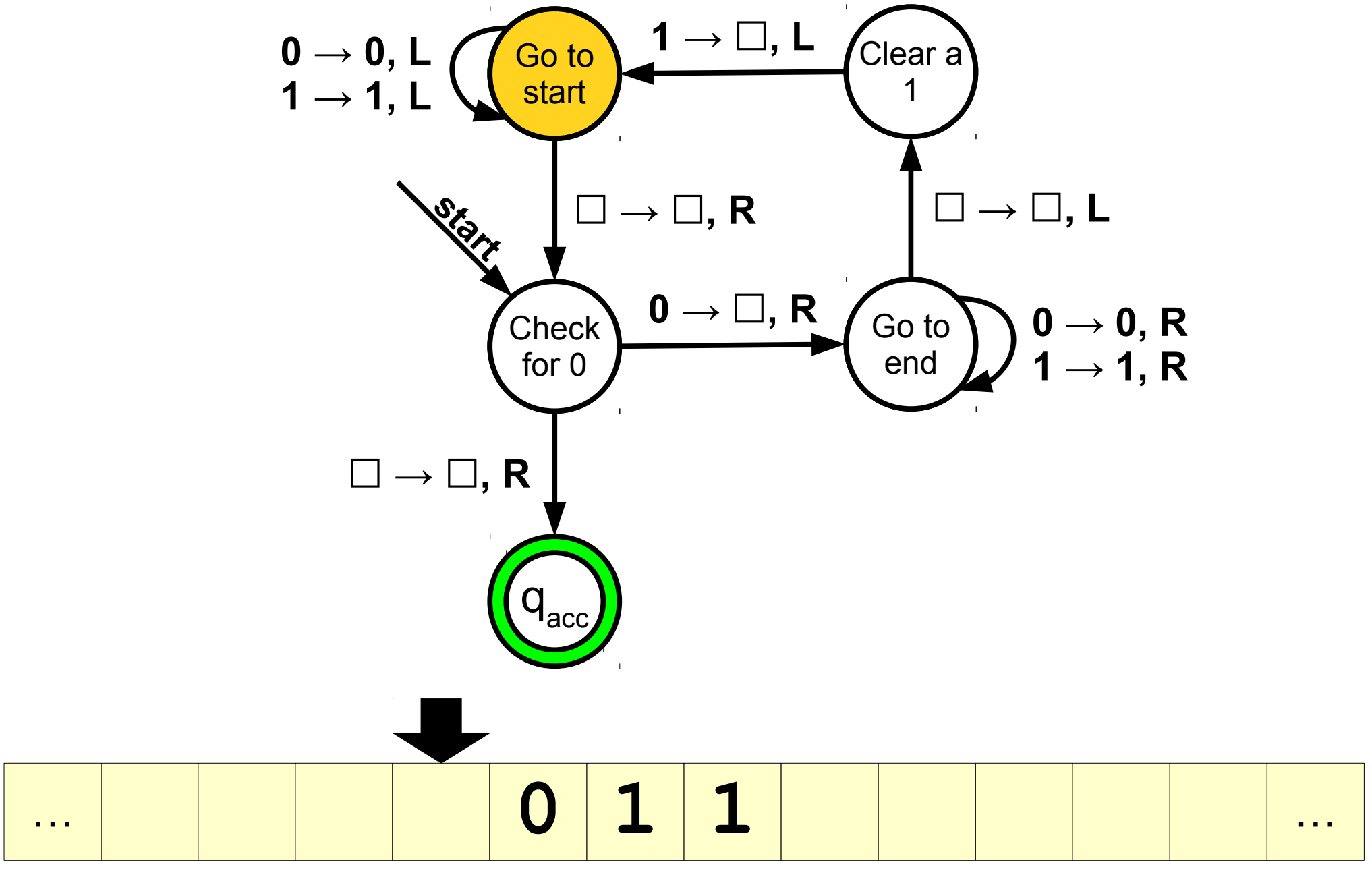
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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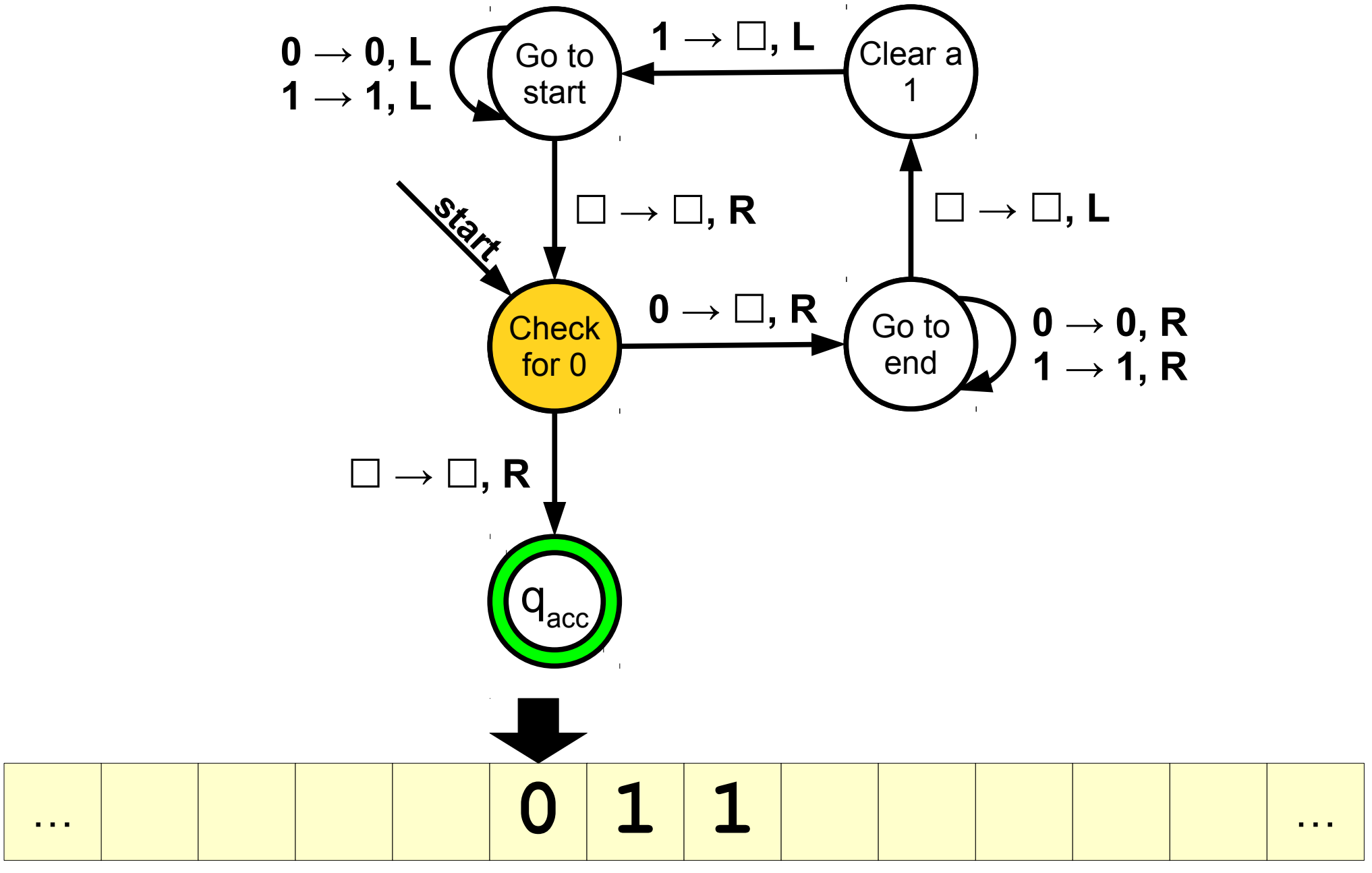
0 → 0, L
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Go to start
1 → □, L
Clear a 1
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□ → □, R
□ → □, L
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_acc
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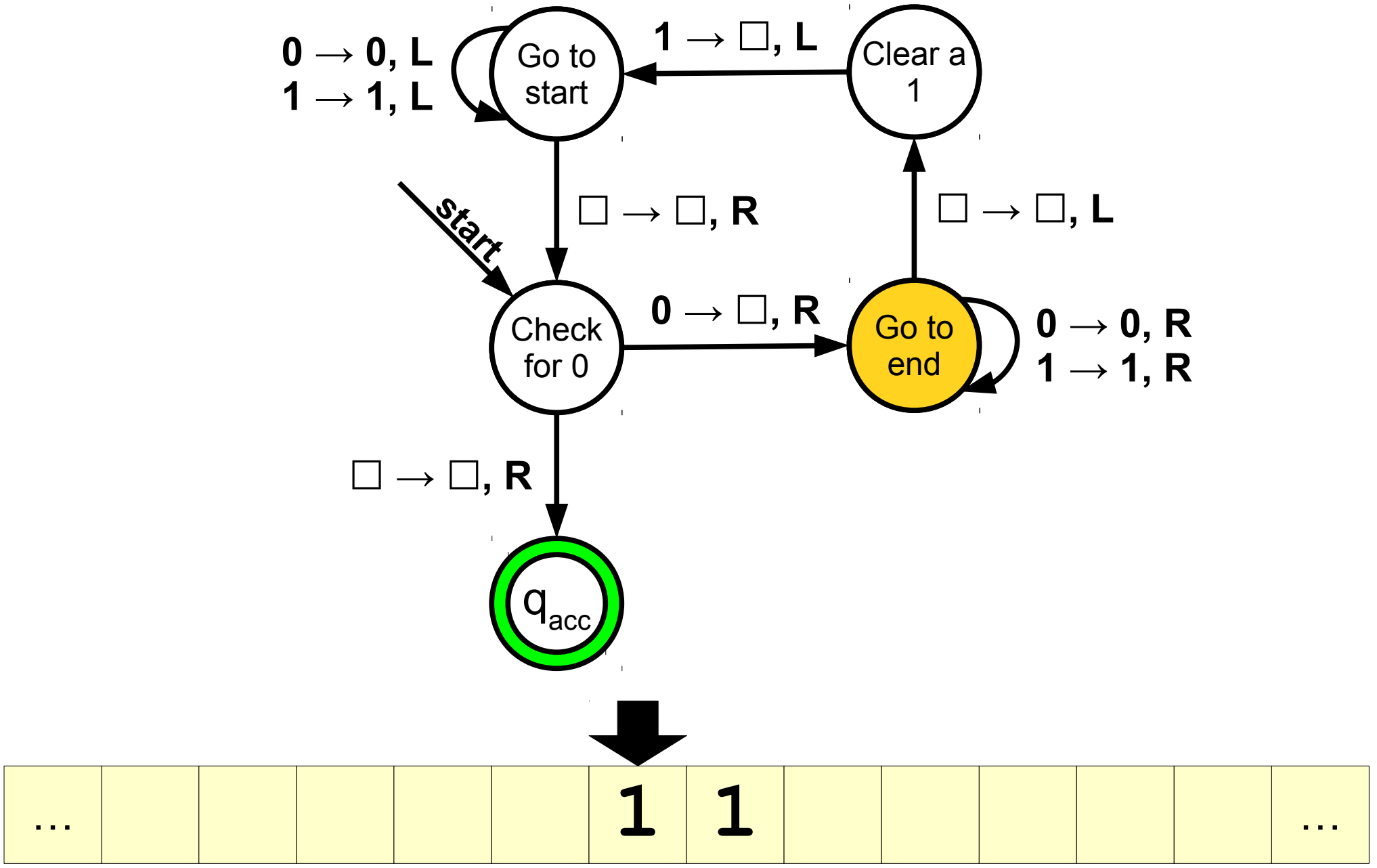
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_acc
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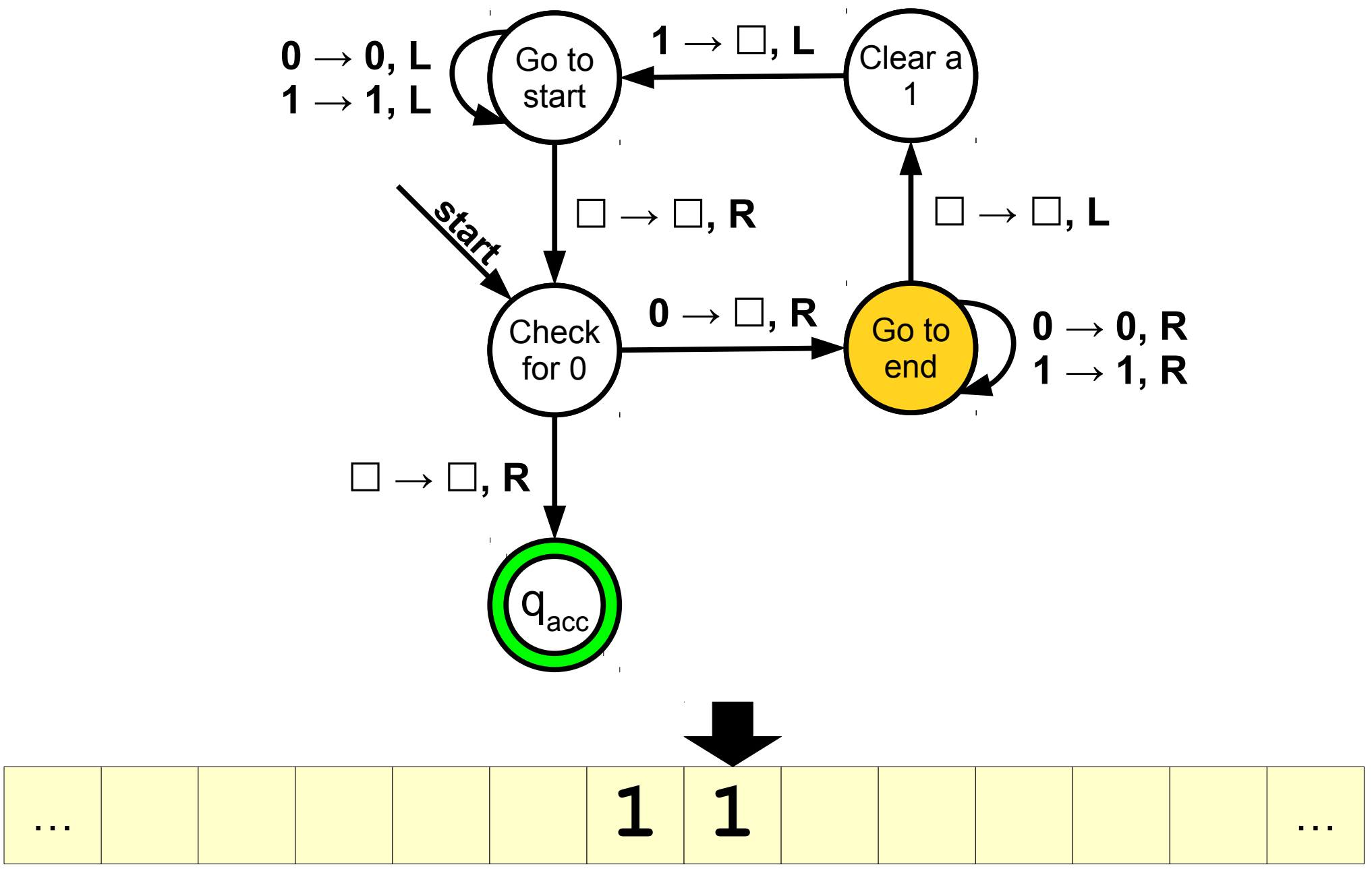
0 → 0, L
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Go to start
1 → □, L
Clear a 1
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□ → □, R
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Check for 0
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Go to end
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1 → 1, R
□ → □, R
q_{acc}
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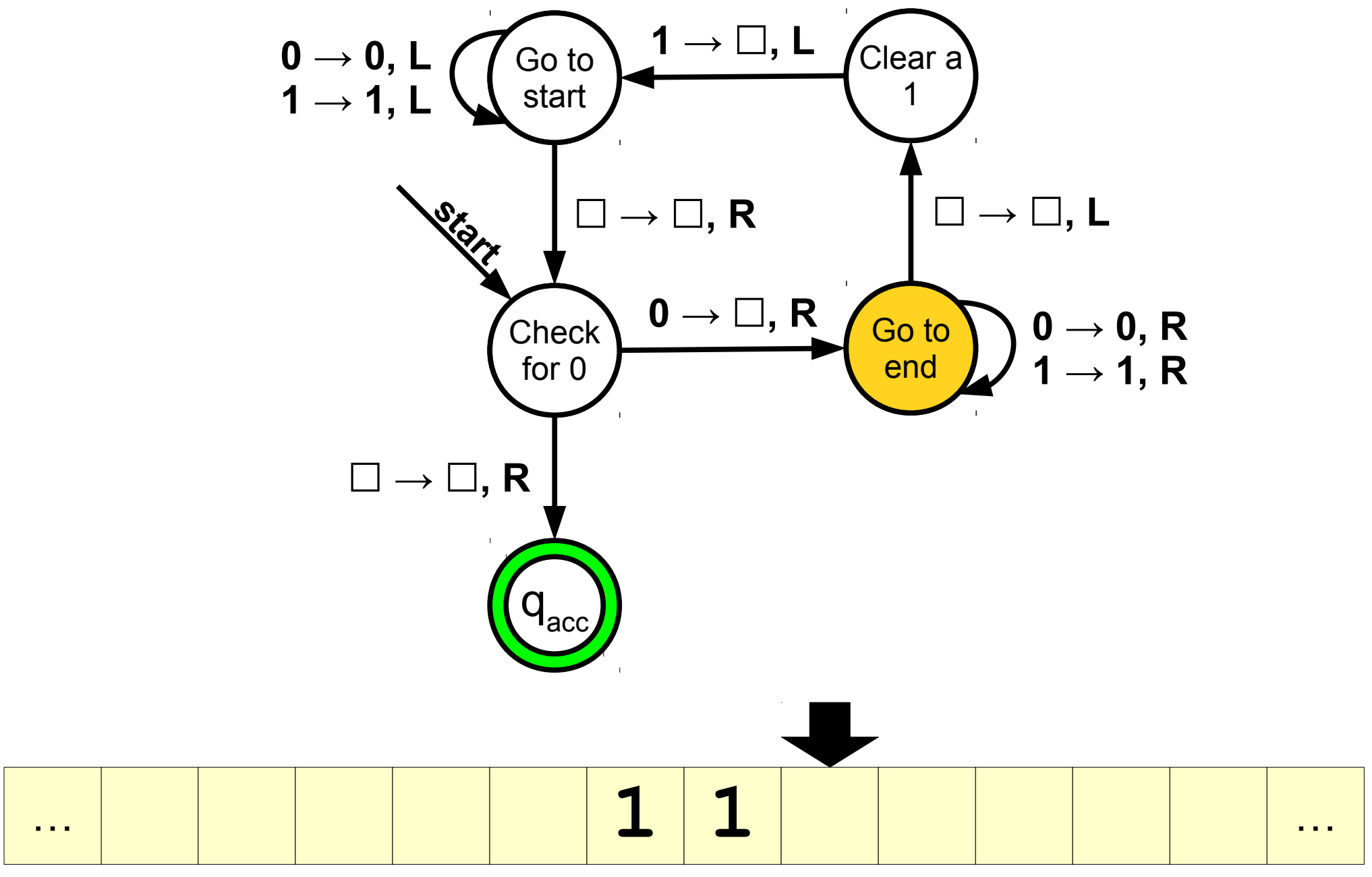
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1 → 1, L
Go to start
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Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{acc}
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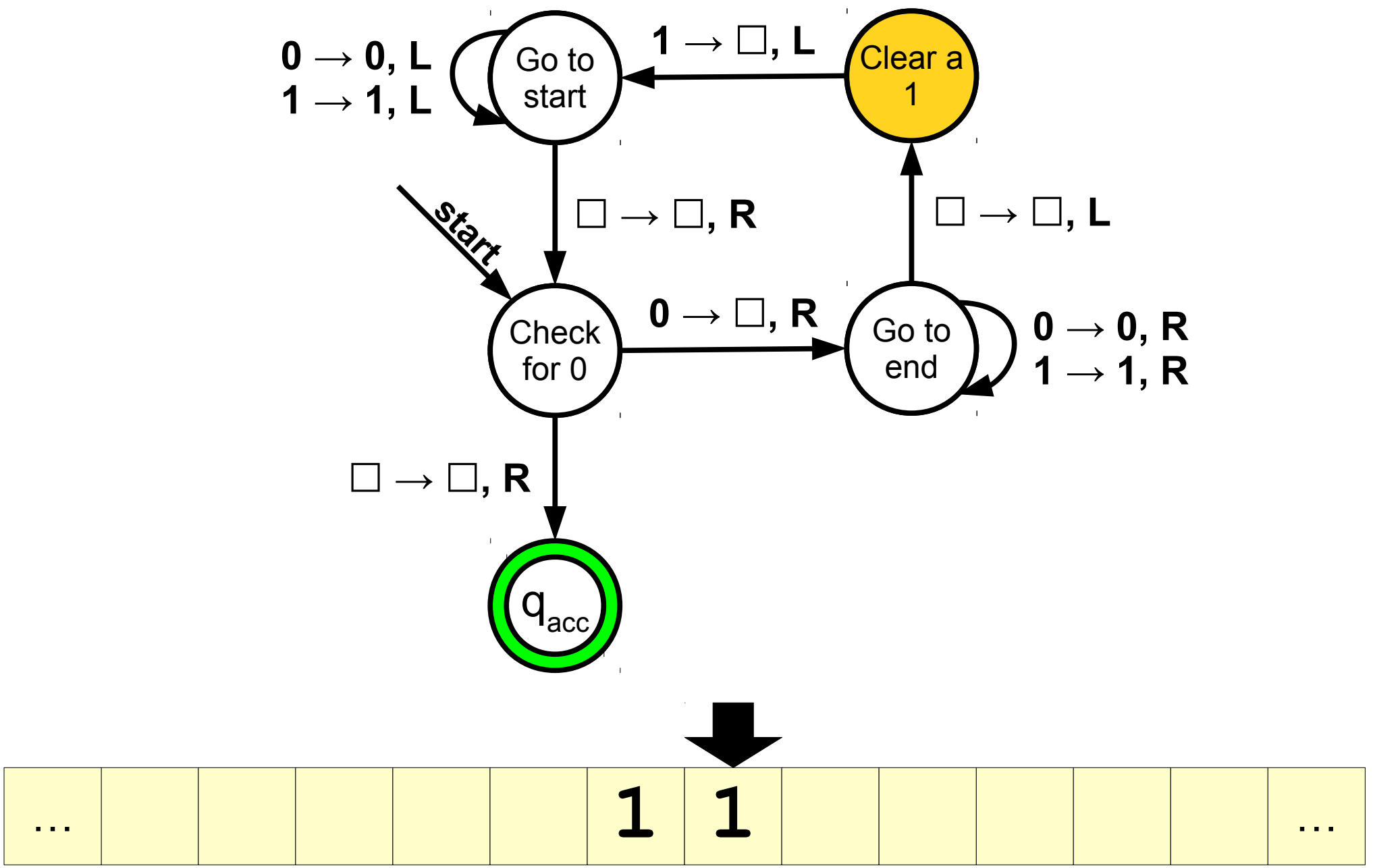
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1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
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Go to end
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1 → 1, R
□ → □, R
q_{acc}
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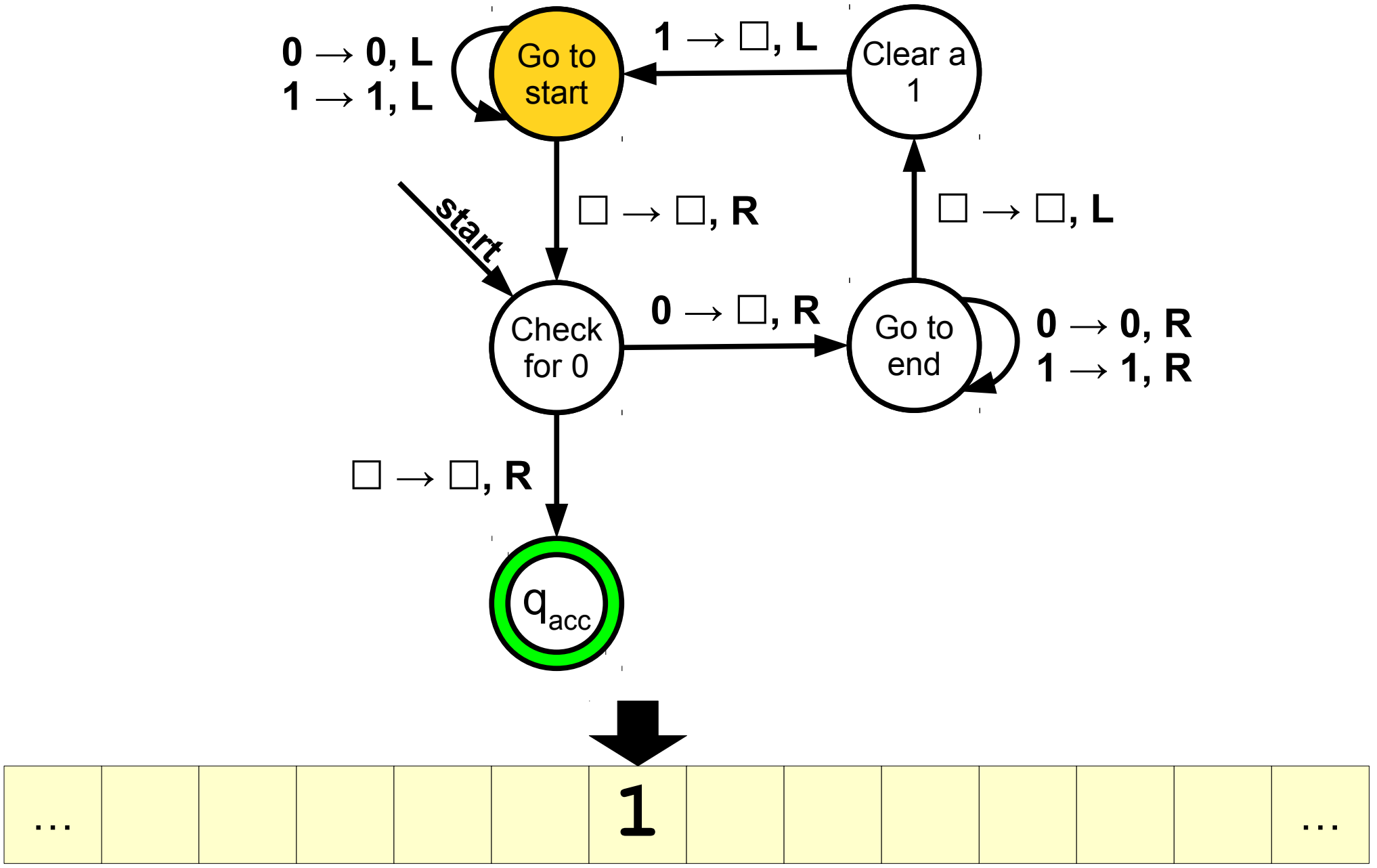
0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
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1 → 1, R
□ → □, R
q_acc
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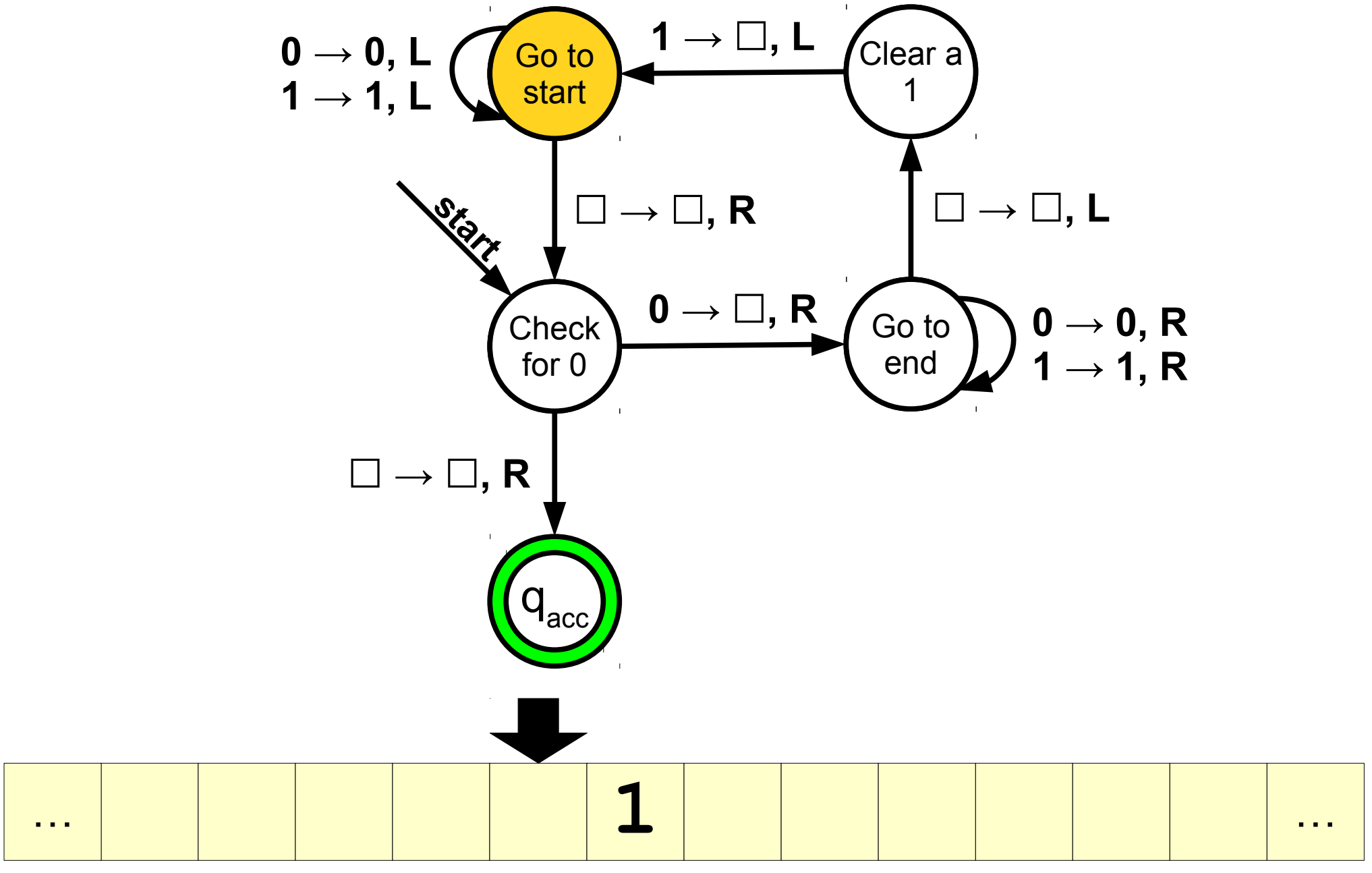
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
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□ → □, L
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Go to end
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1 → 1, R
□ → □, R
q_acc
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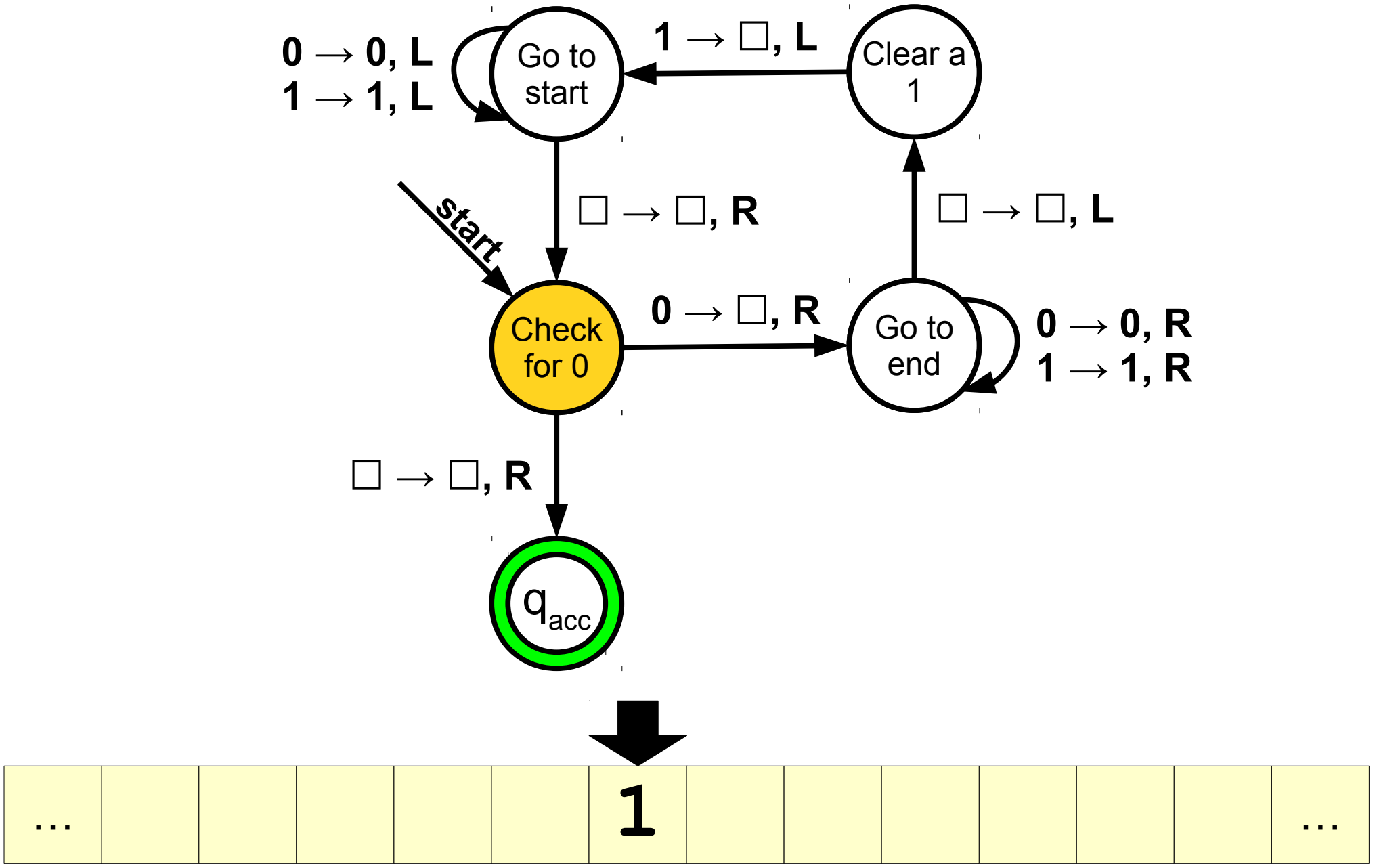
0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
Check for 0
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Go to end
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□ → □, R
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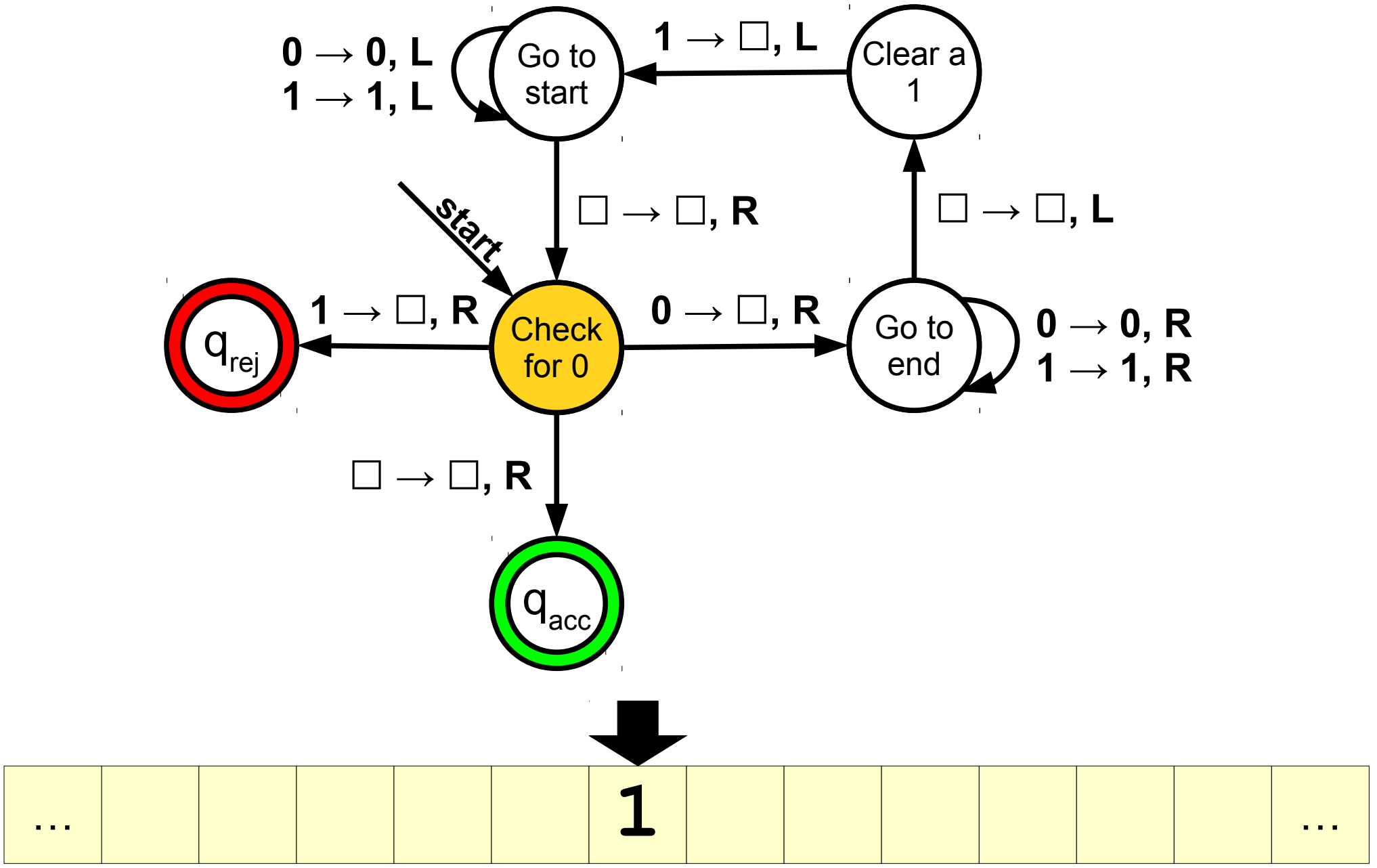
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
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□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
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1 → 1, R
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□ → □, R
q_acc
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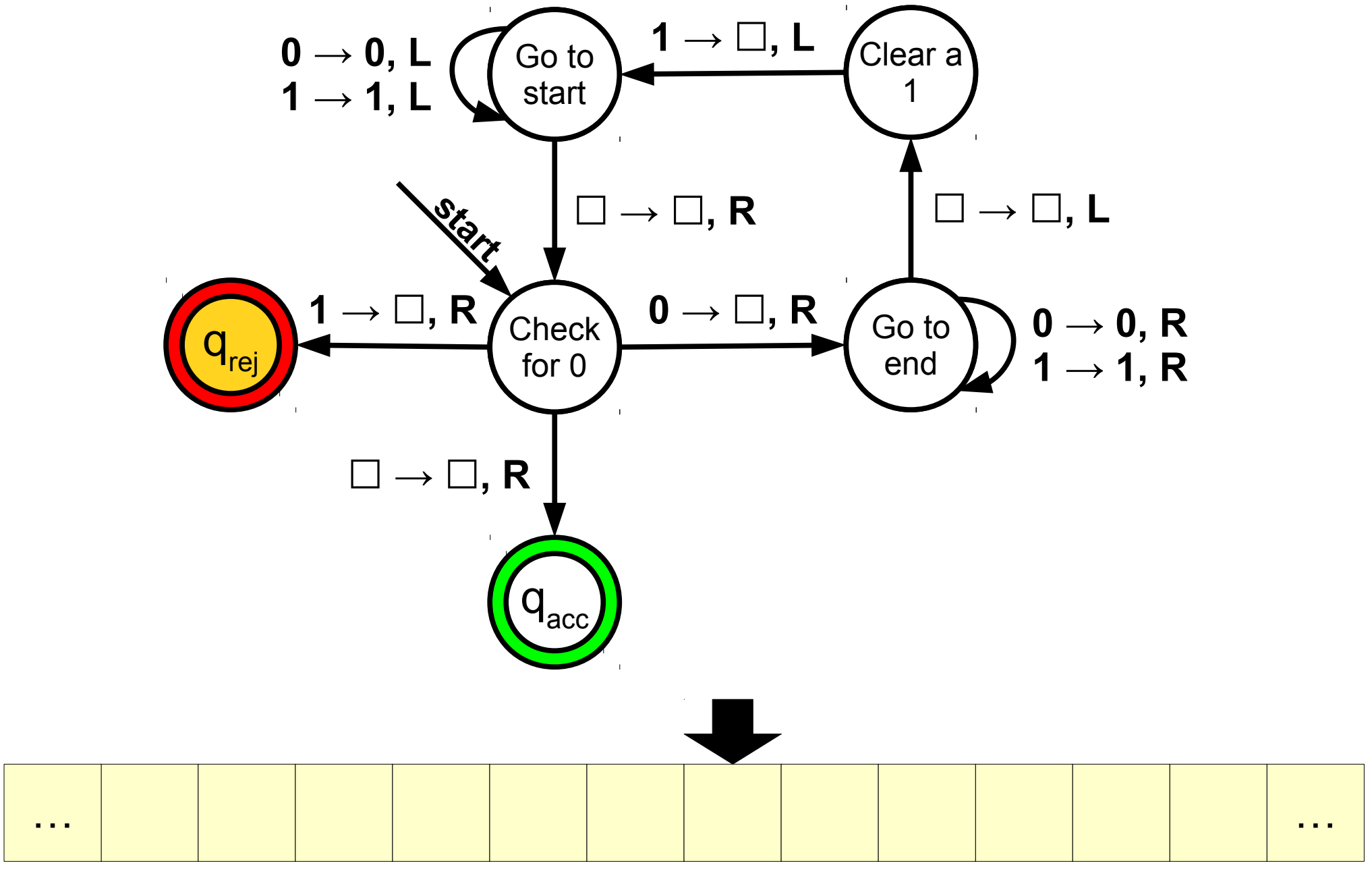
0 → 0, L
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Go to start
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Clear a 1
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□ → □, L
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Check for 0
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1 → 1, R
q_rej
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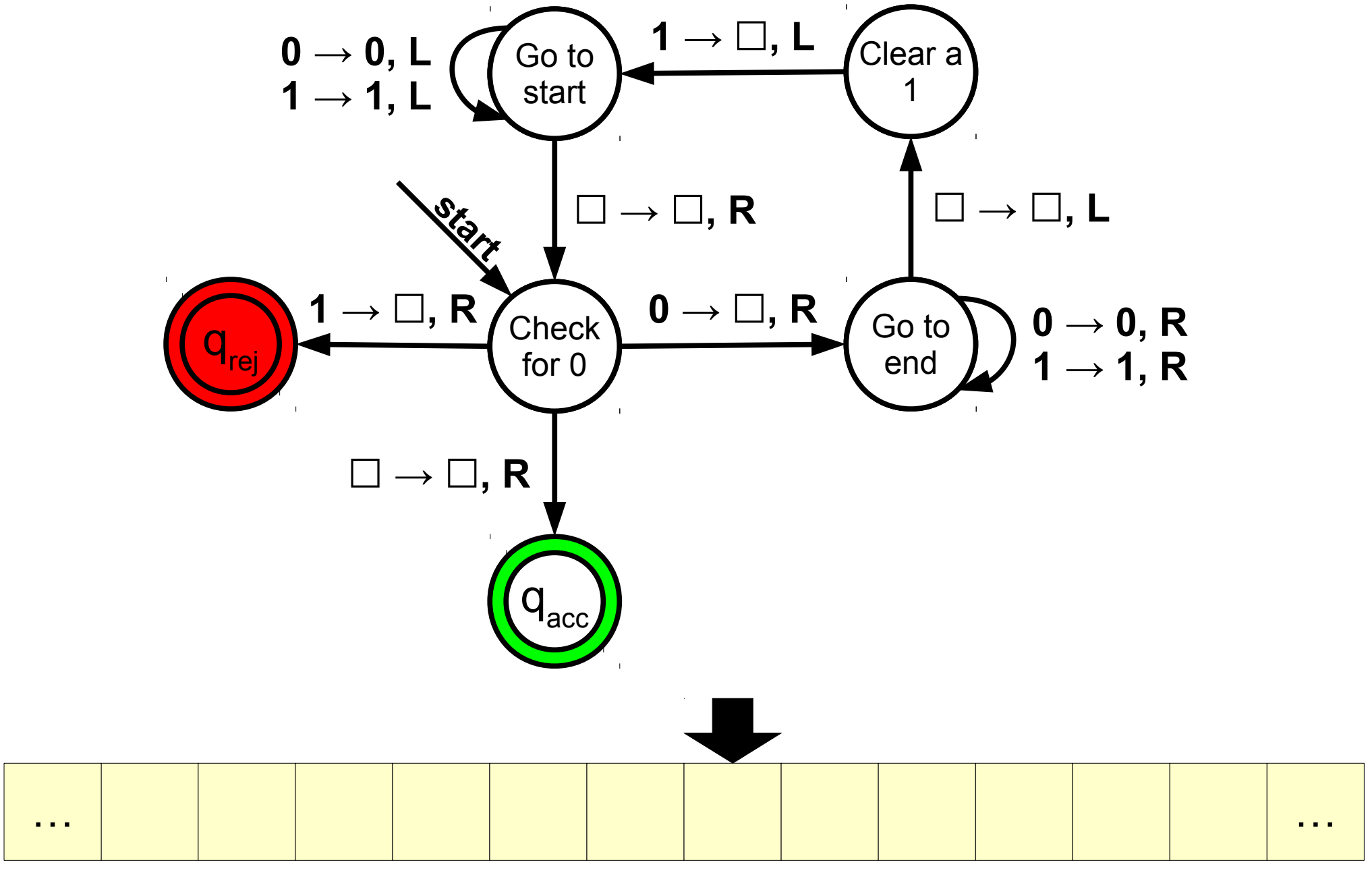
0 → 0, L
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Go to start
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Clear a 1
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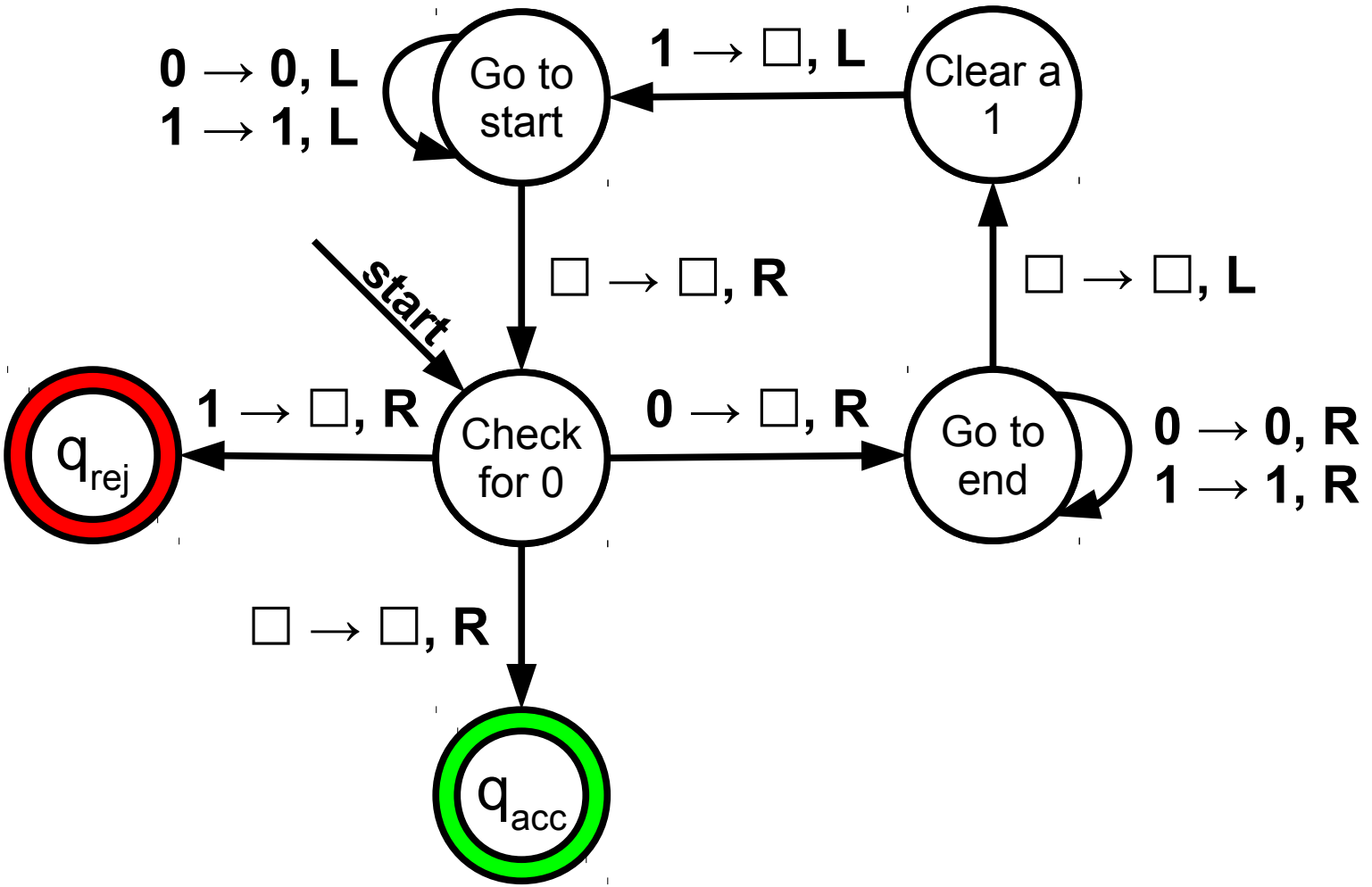
0 → 0, L
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Clear a 1
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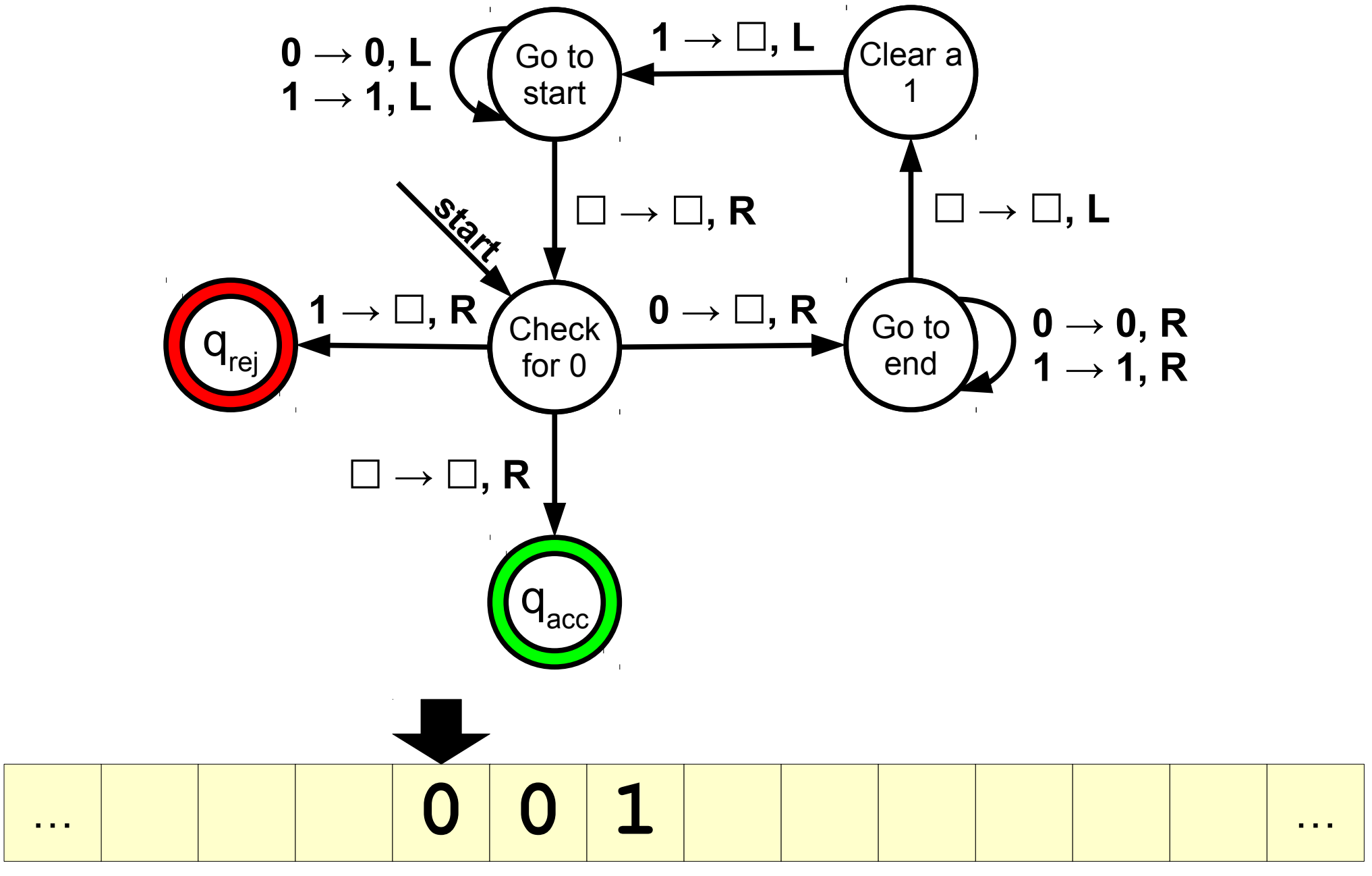
0 → 0, L
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Go to start
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Clear a 1
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□ → □, L
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Check for 0
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Go to end
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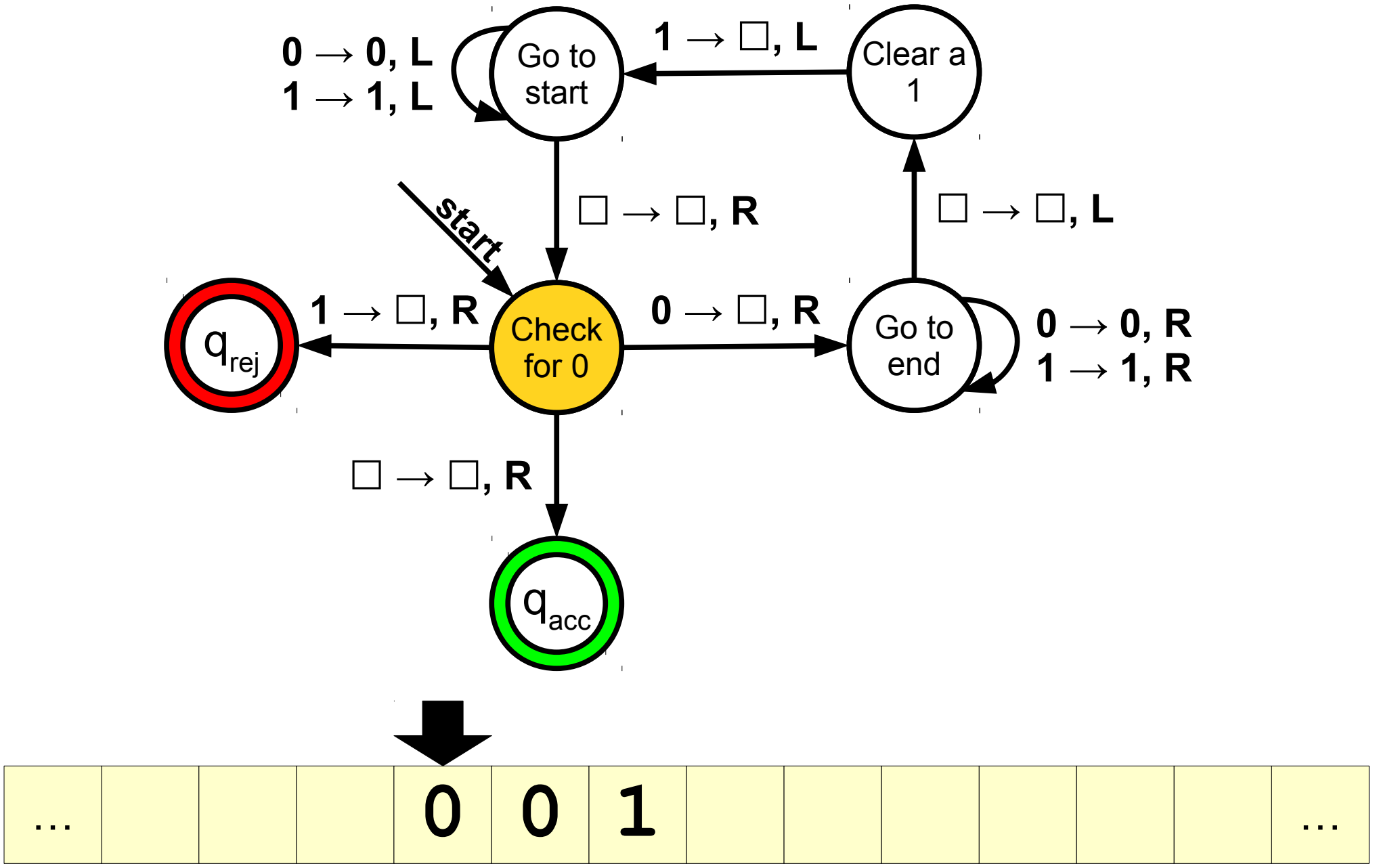
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
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□ → □, R
□ → □, L
1 → □, R
Check for 0
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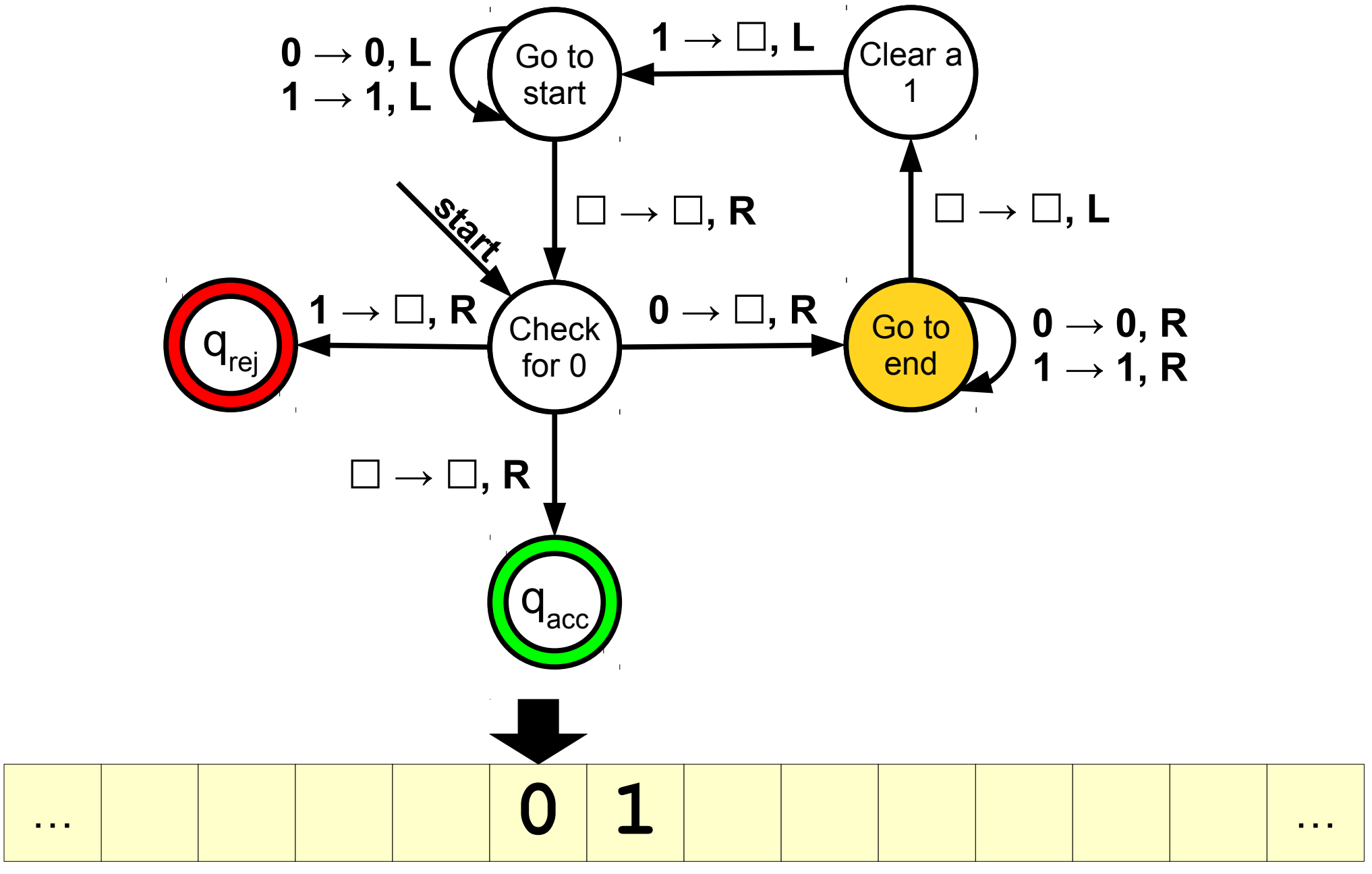
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
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Go to end
0 → 0, R
1 → 1, R
q_rej
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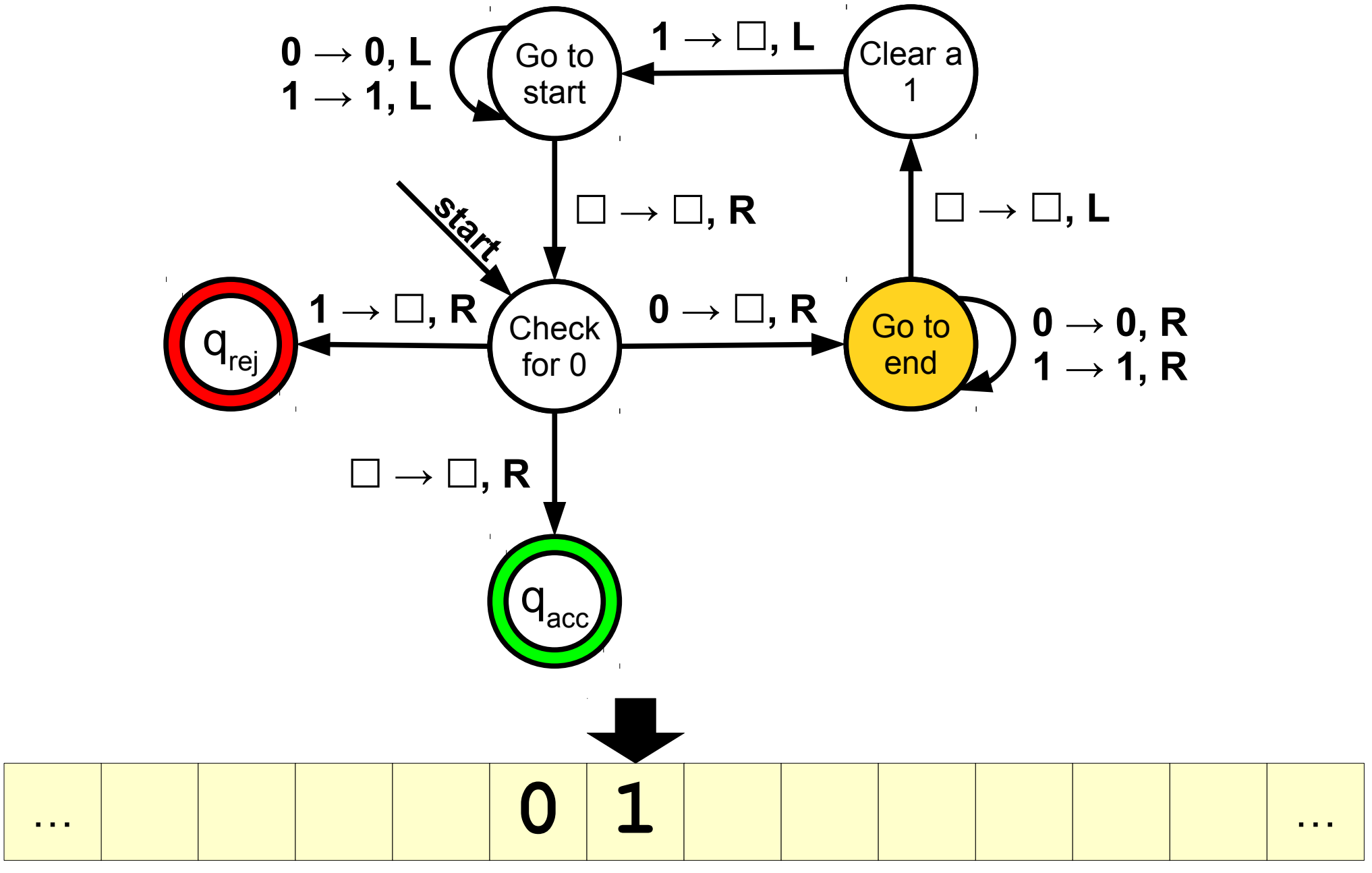
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
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Check for 0
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Go to end
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1 → 1, R
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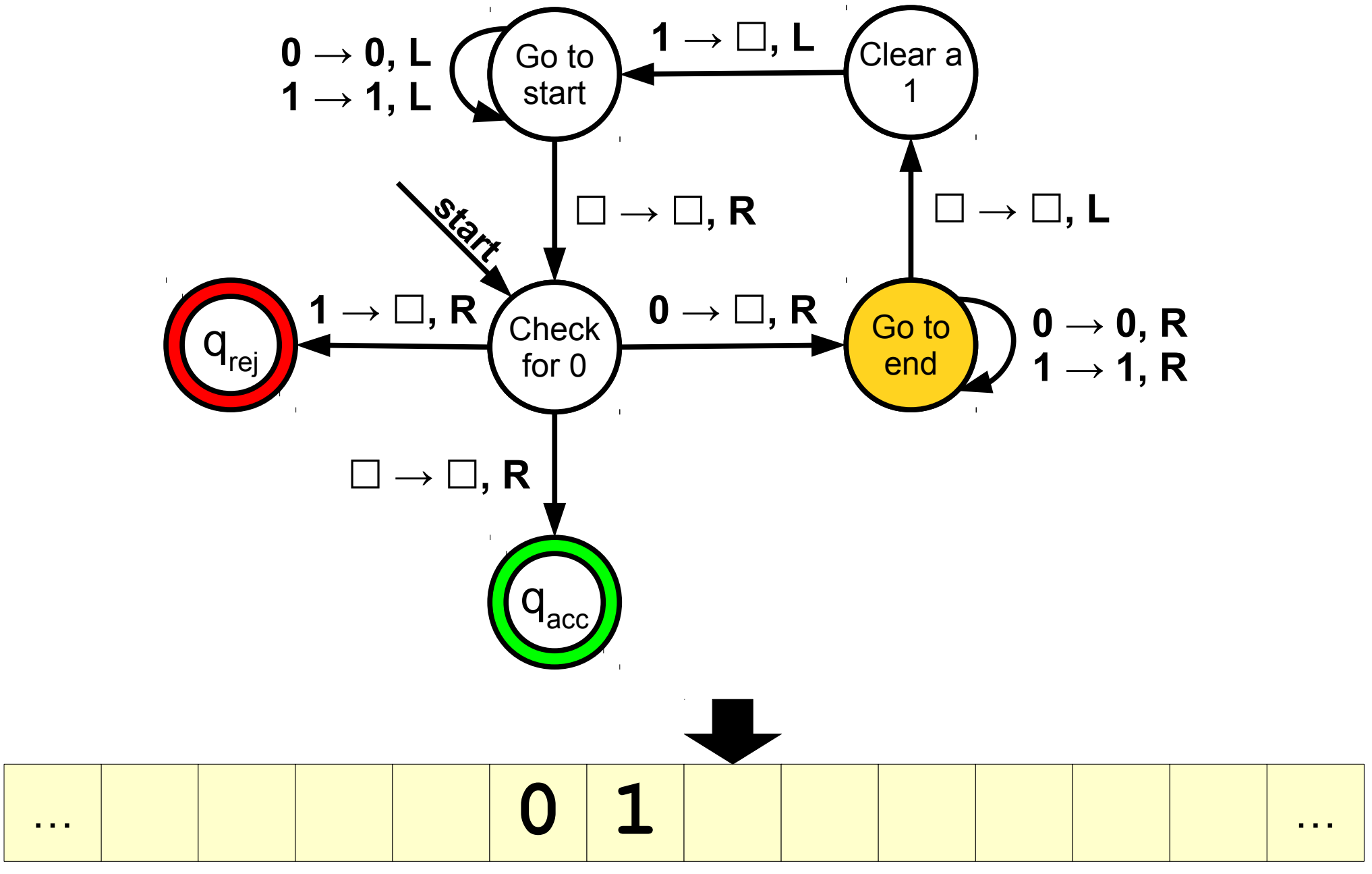
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
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Go to end
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1 → 1, R
q_rej
□ → □, R
q_acc
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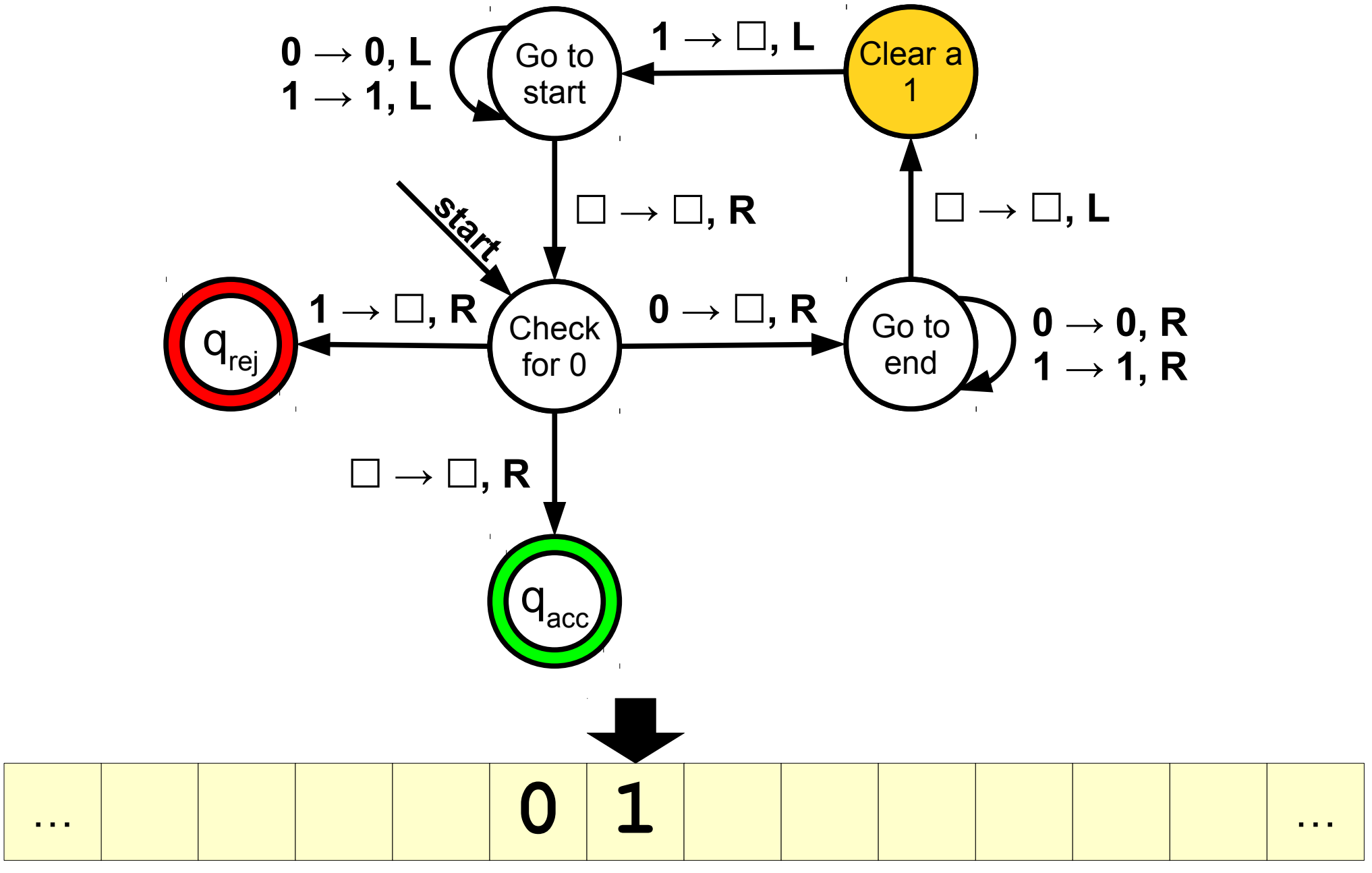
0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
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Go to end
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1 → 1, R
q_rej
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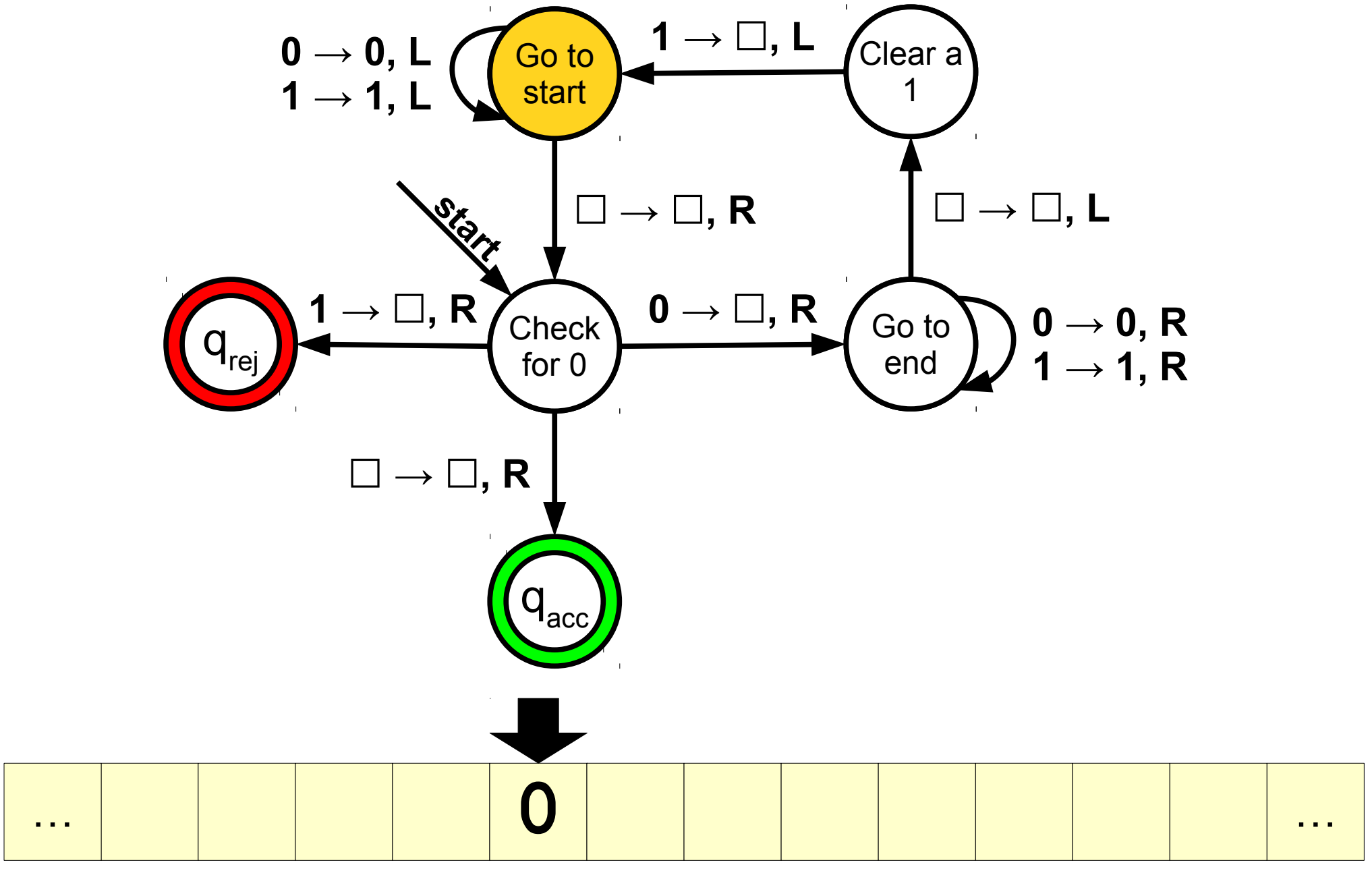
0 → 0, L
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Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
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Check for 0
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Go to end
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1 → 1, R
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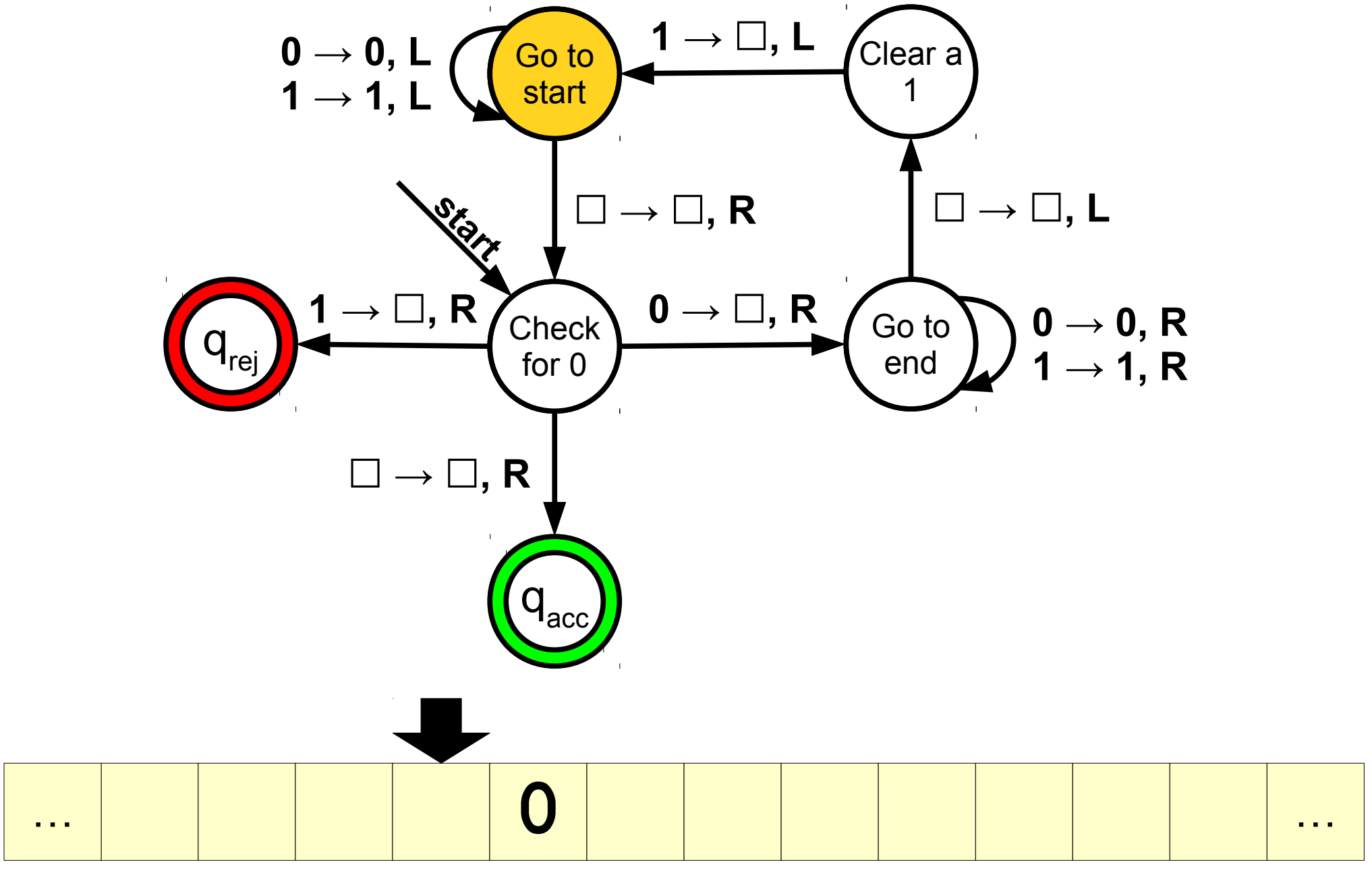
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
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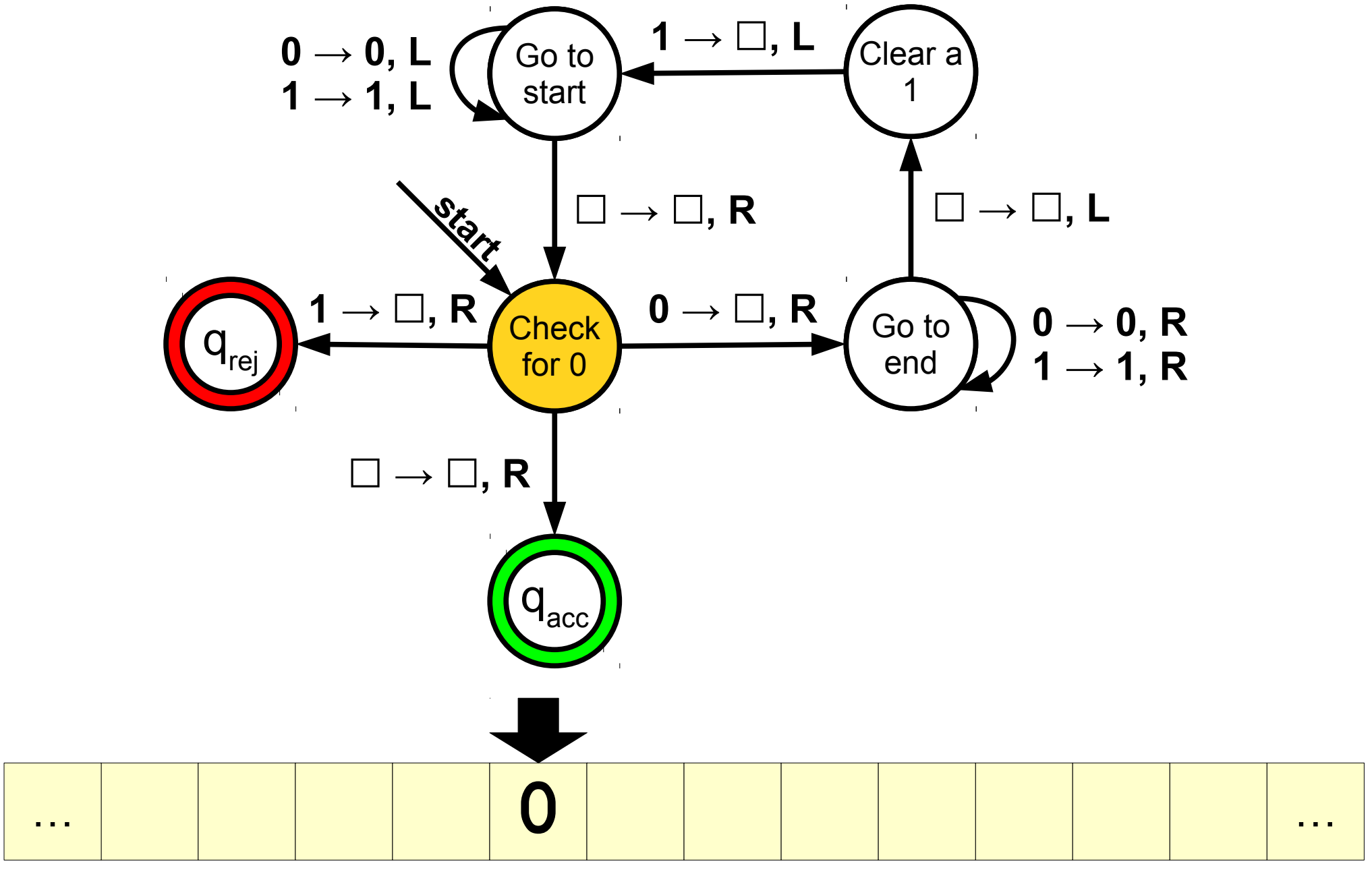
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
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Check for 0
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Go to end
0 → 0, R
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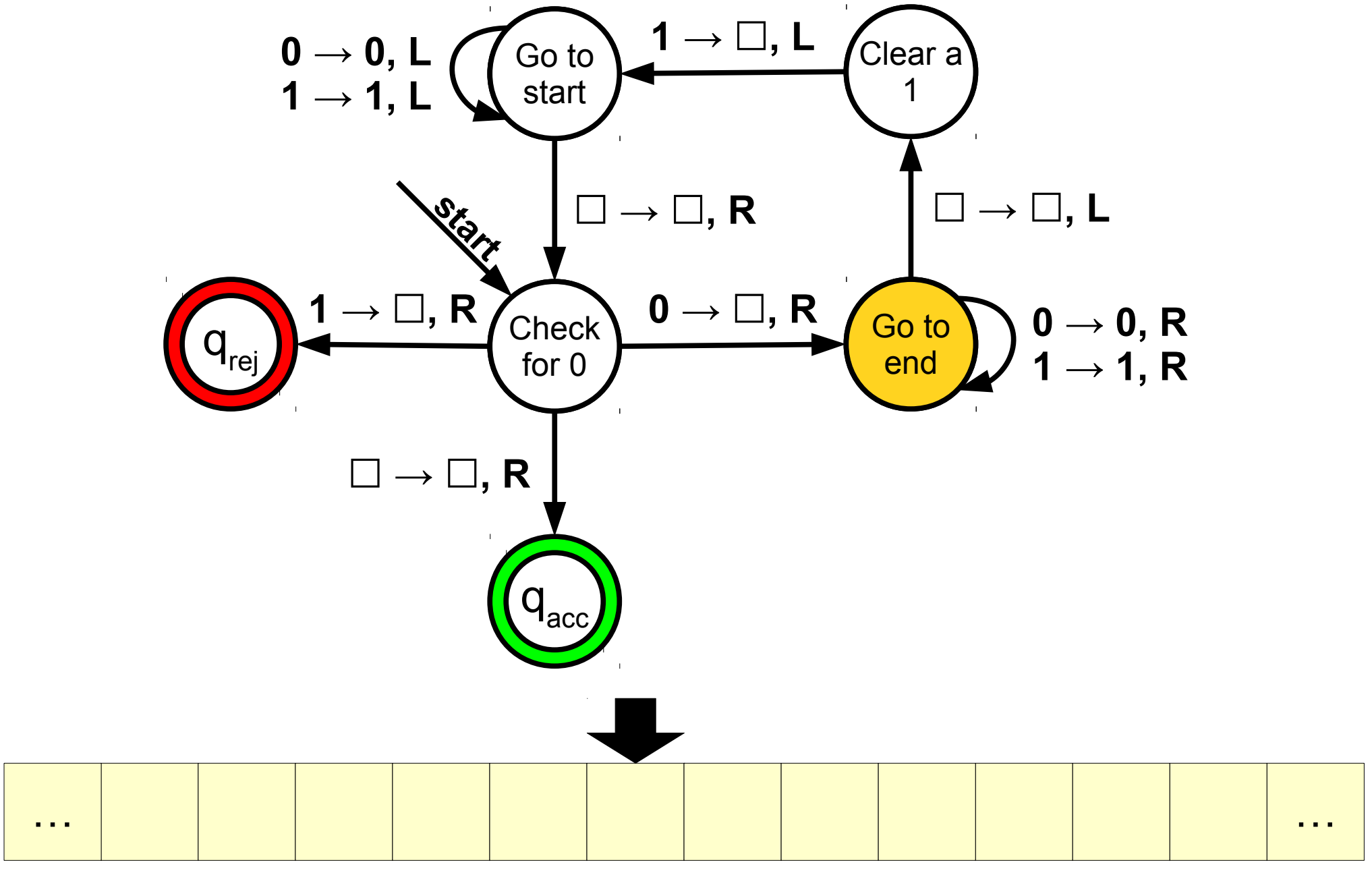
0 → 0, L
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Go to start
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Clear a 1
start
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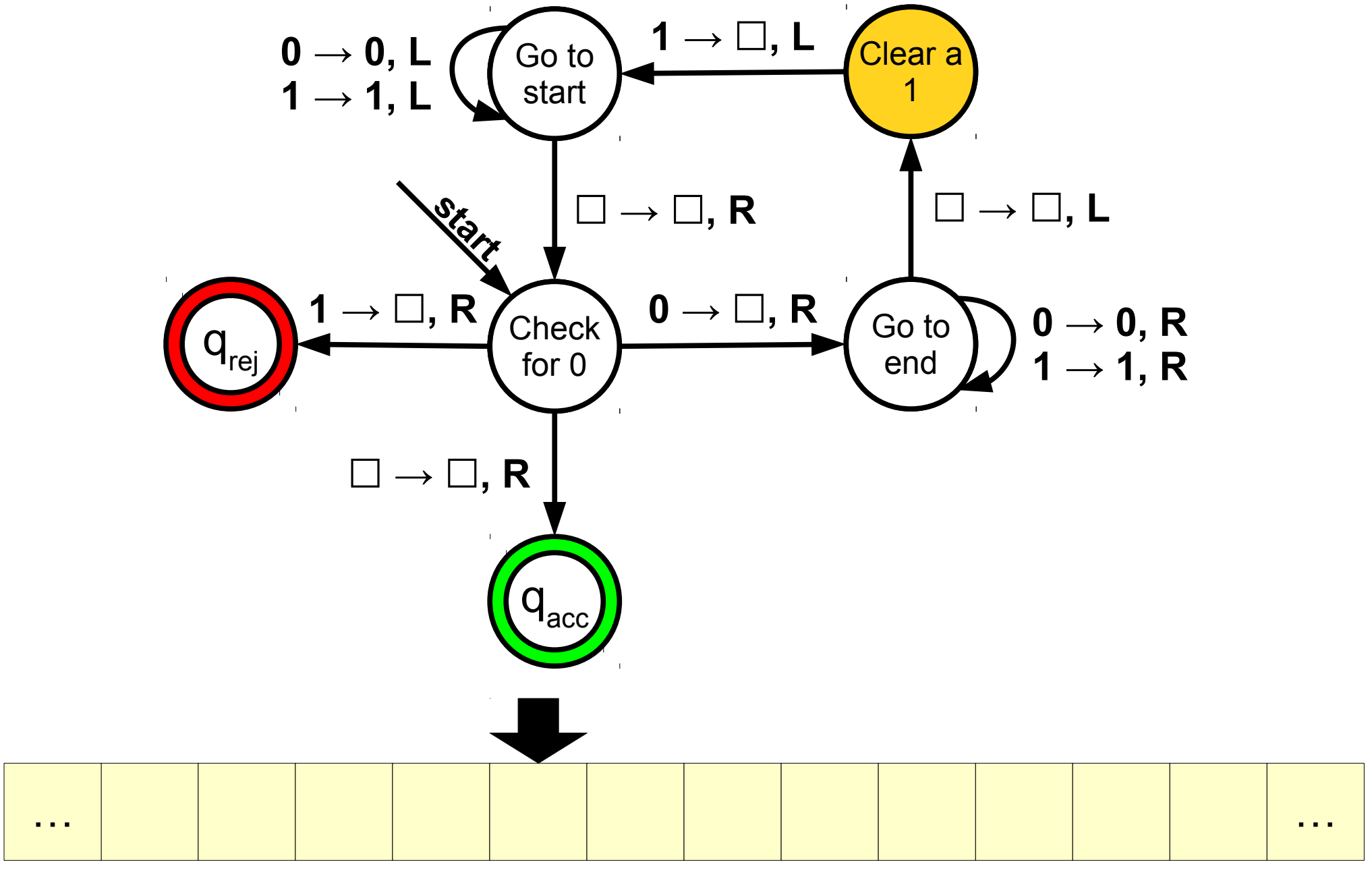
0 → 0, L
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Go to start
1 → □, L
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Check for 0
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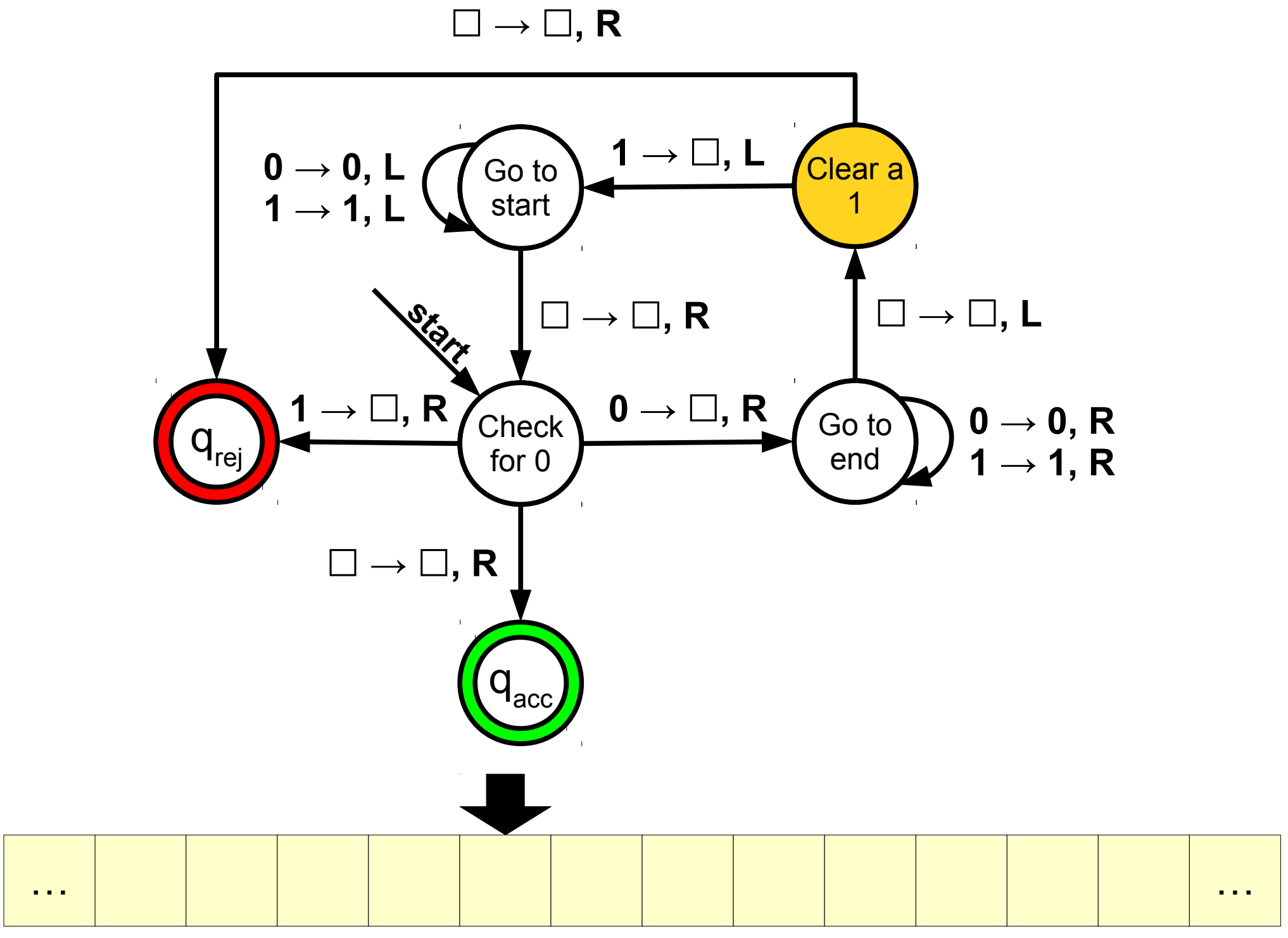
□ → □, R
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q_rej
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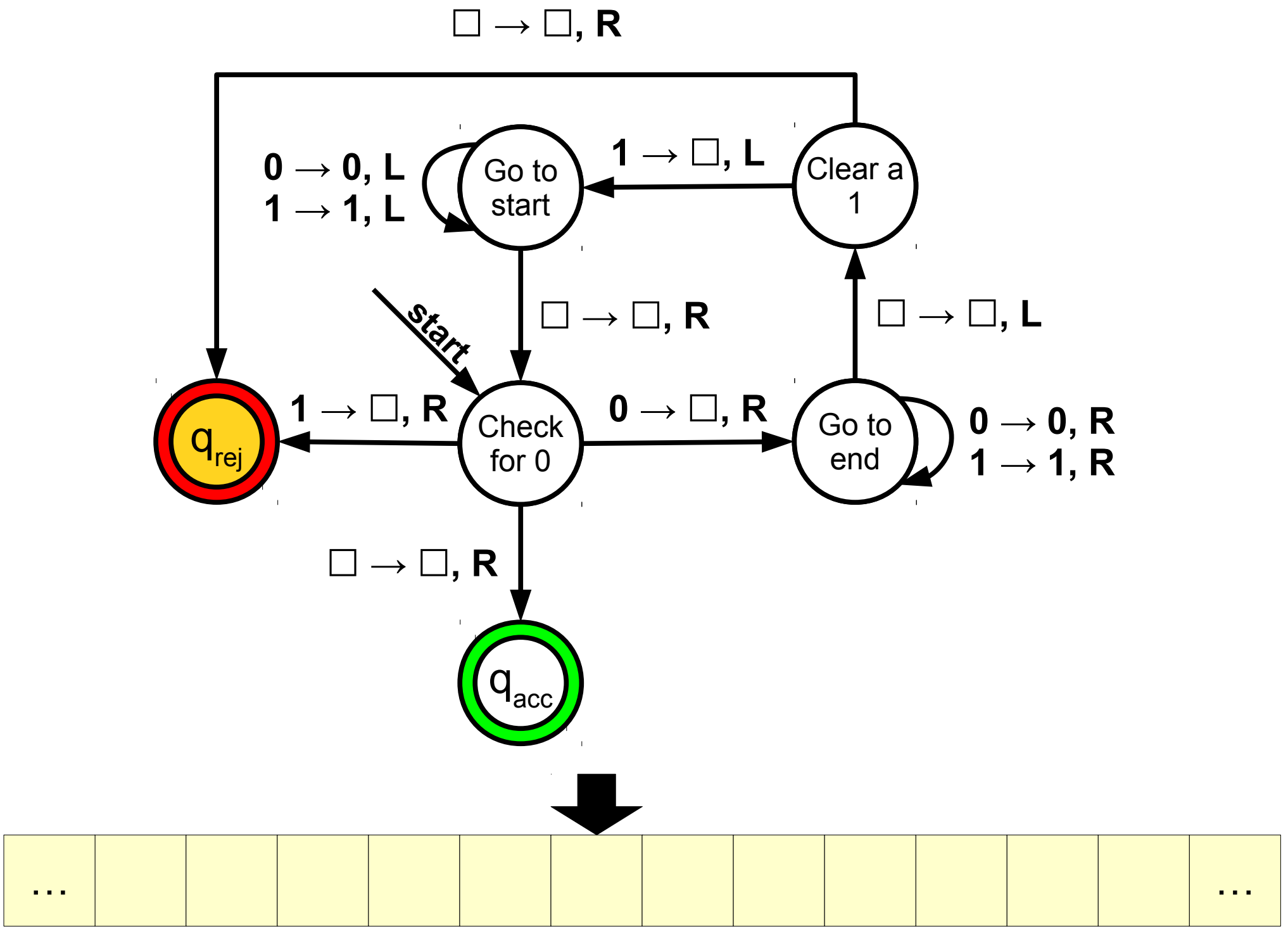
□ → □, R
0 → 0, L
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Go to start
1 → □, L
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Go to end
0 → 0, R
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q_rej
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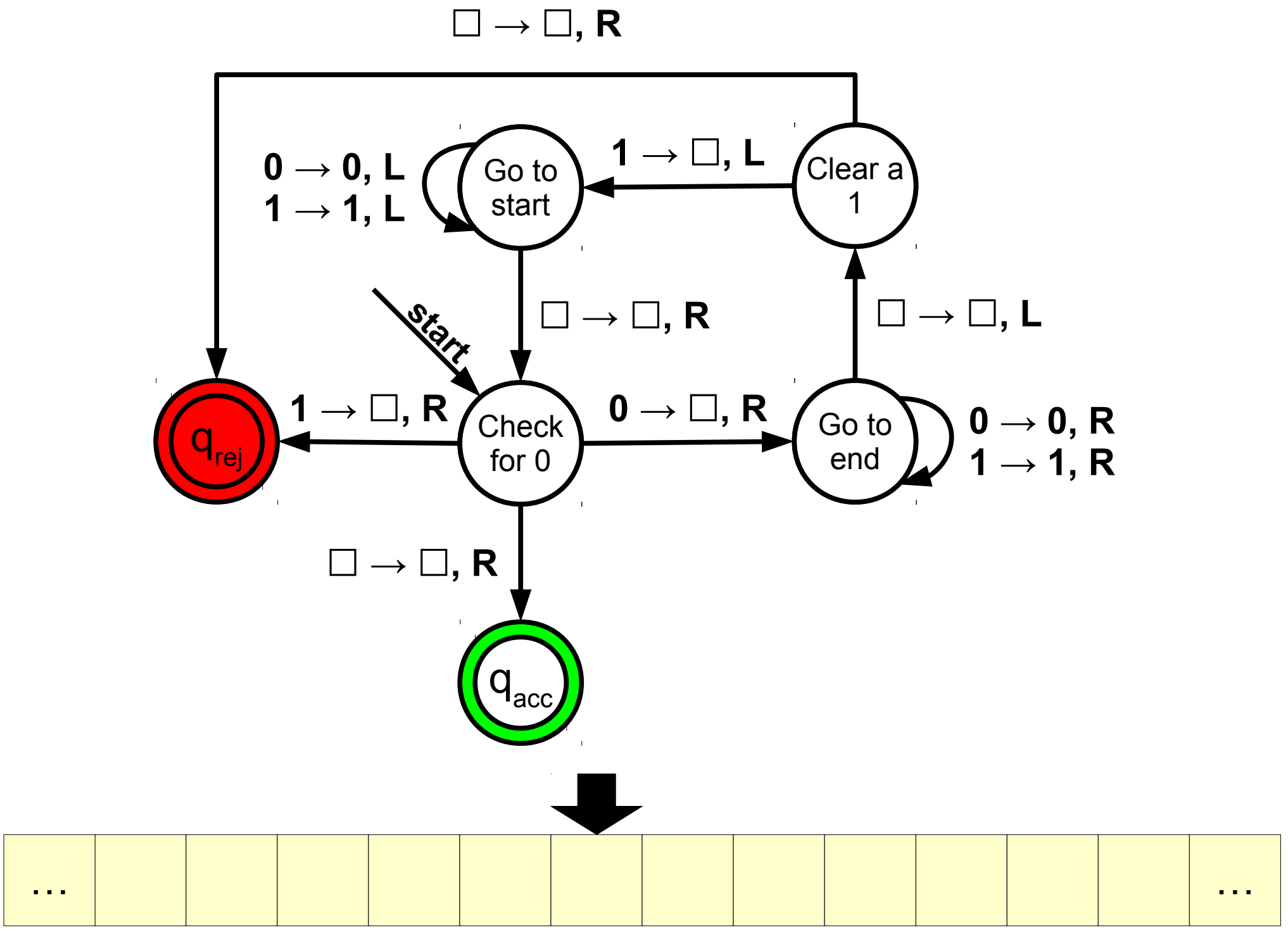
□ → □, R
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1 → 1, L
Go to start
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Check for 0
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q_rej
□ → □, R
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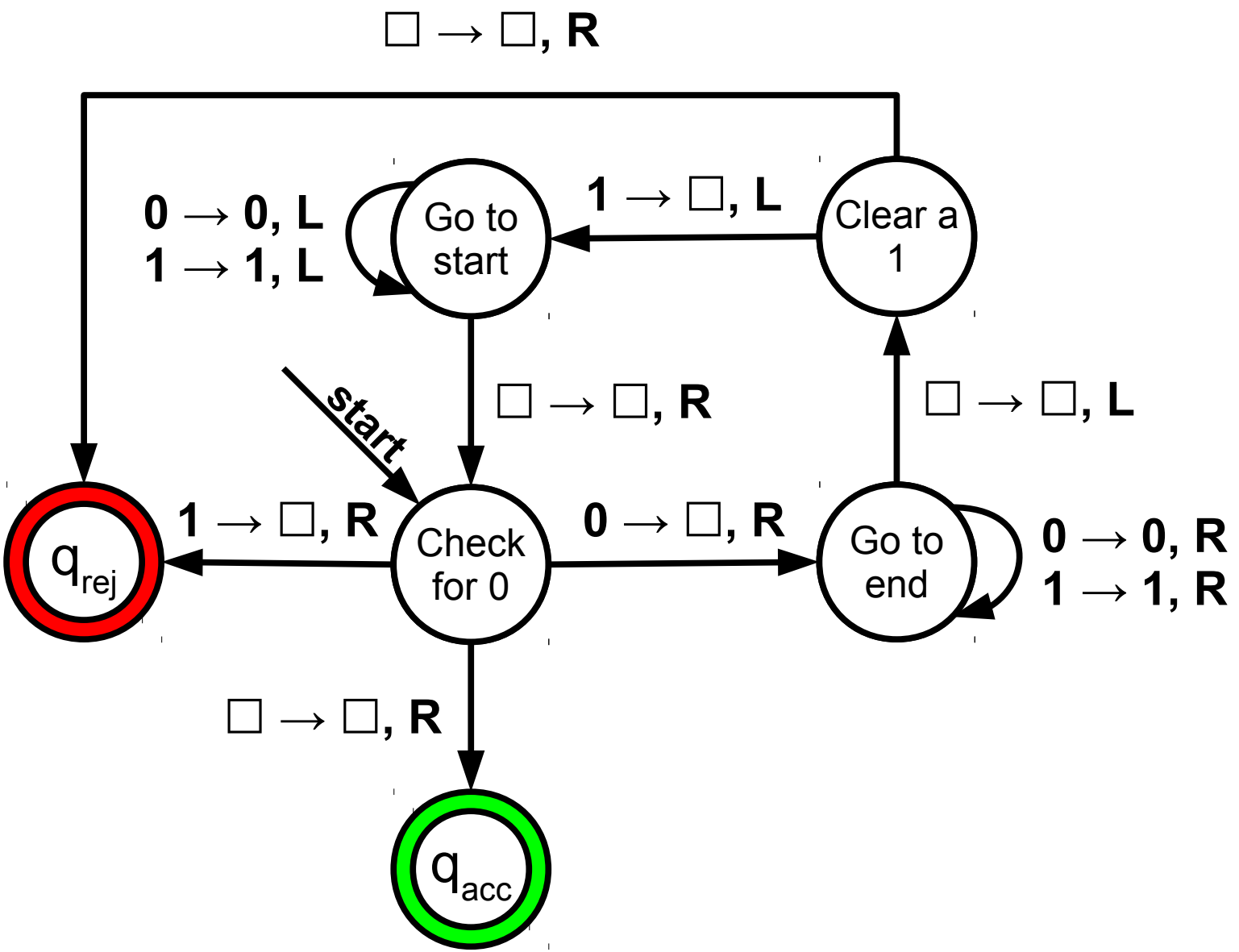
□ → □, R
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Go to start
1 → □, L
Clear a 1
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Go to end
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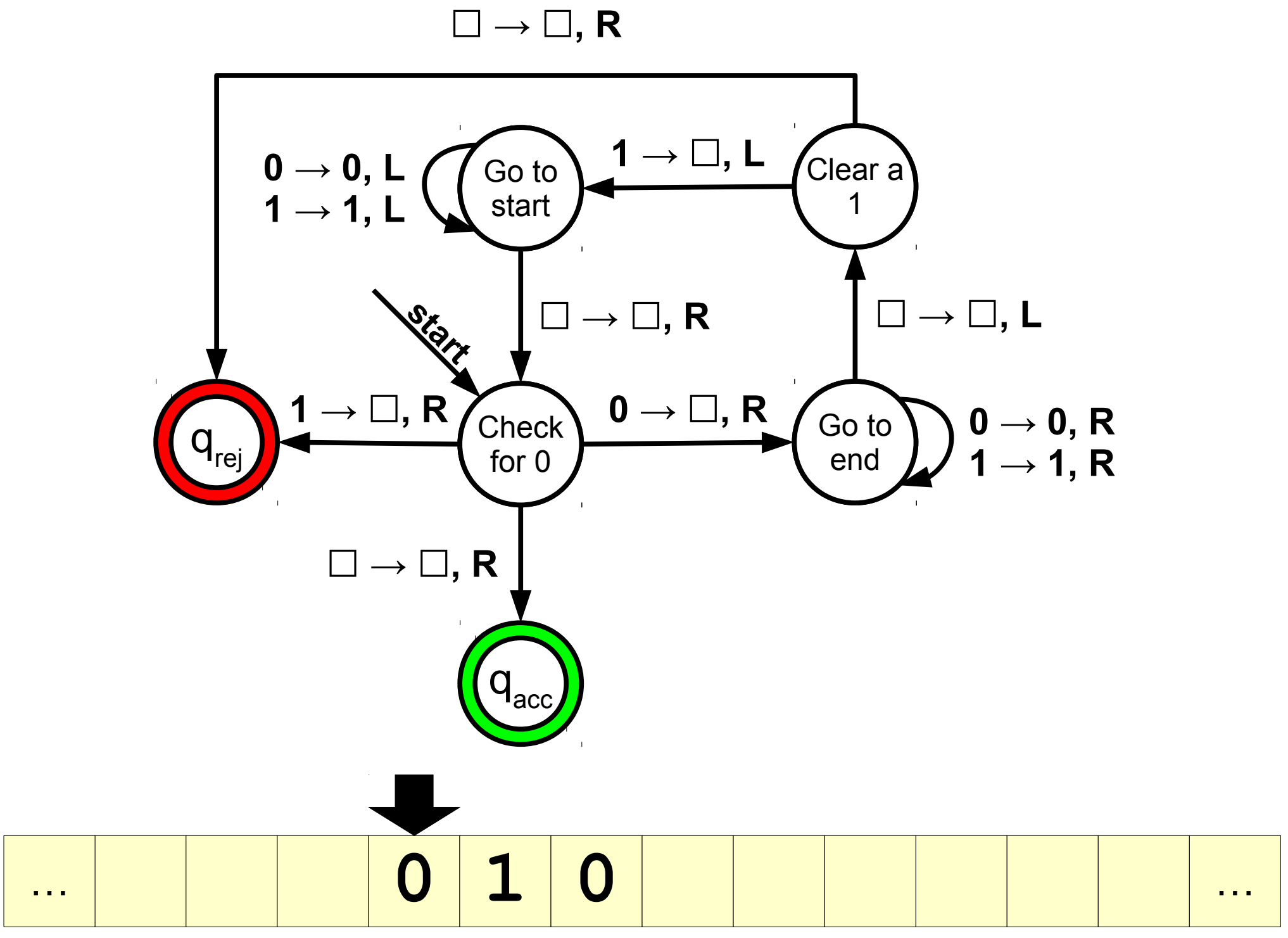
1 → 1, R
q_rej
□ → □, R
q_acc


□ → □, R
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Go to start
1 → □, L
Clear a 1
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□ → □, R
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Check for 0
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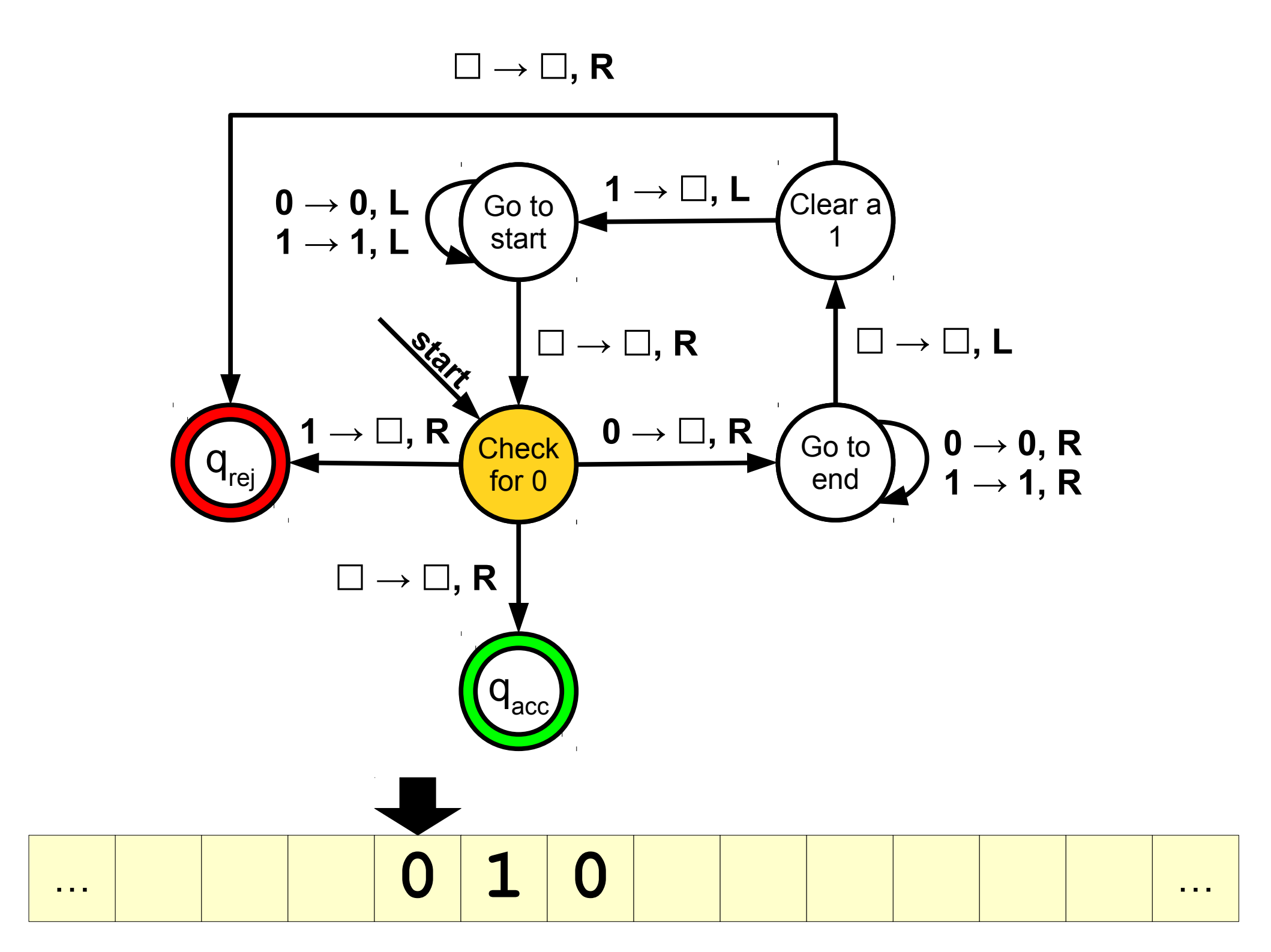
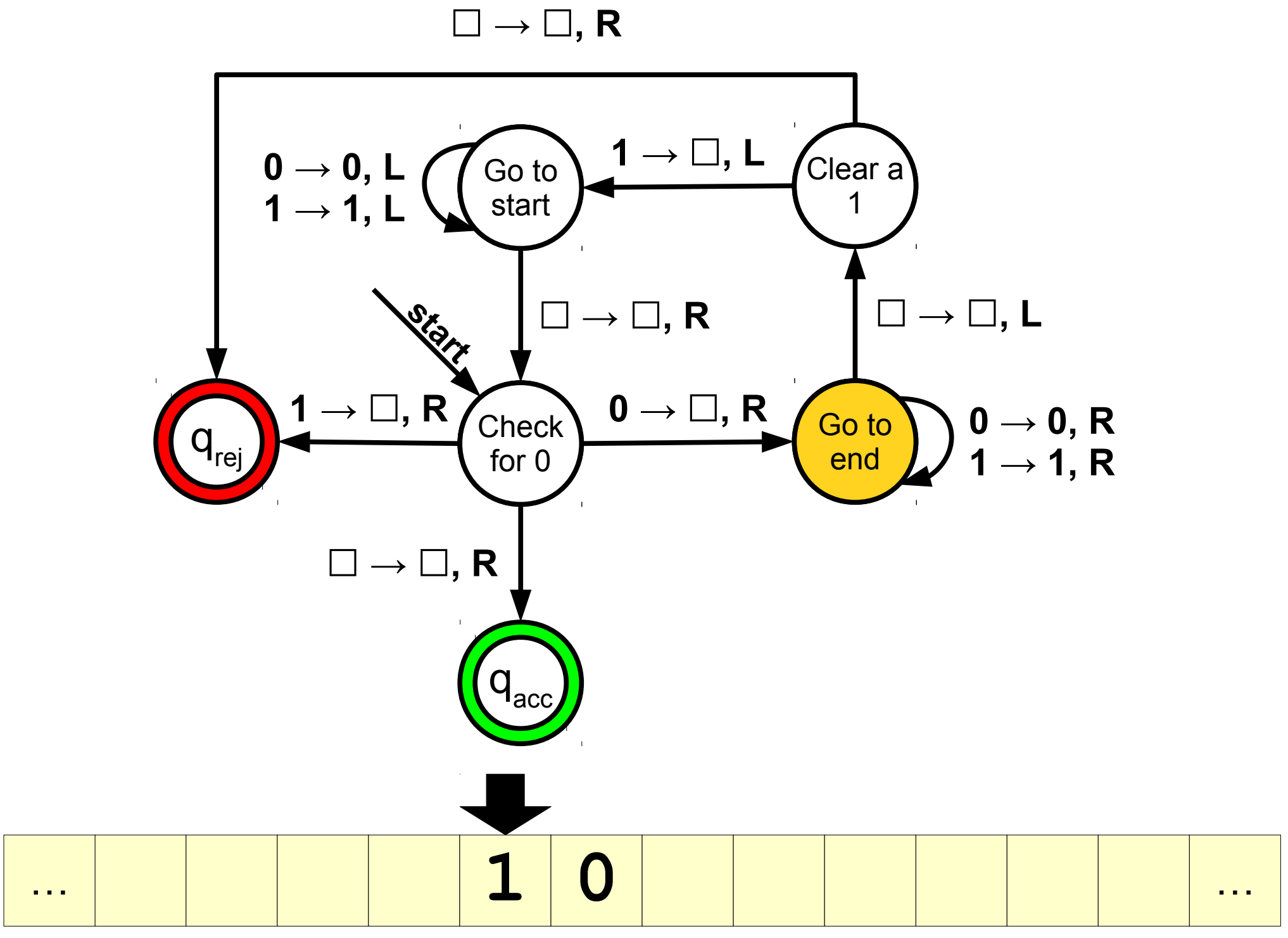
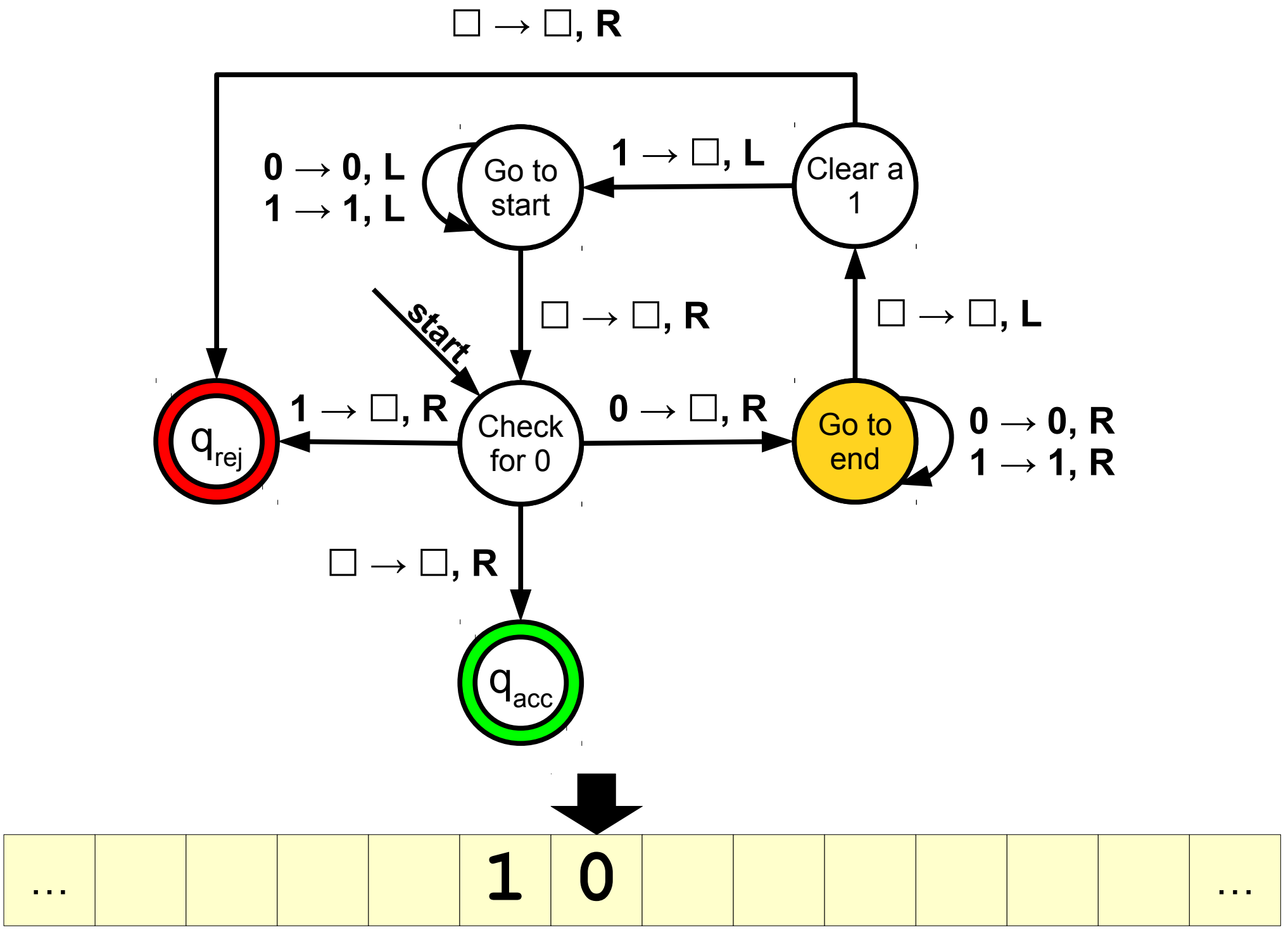
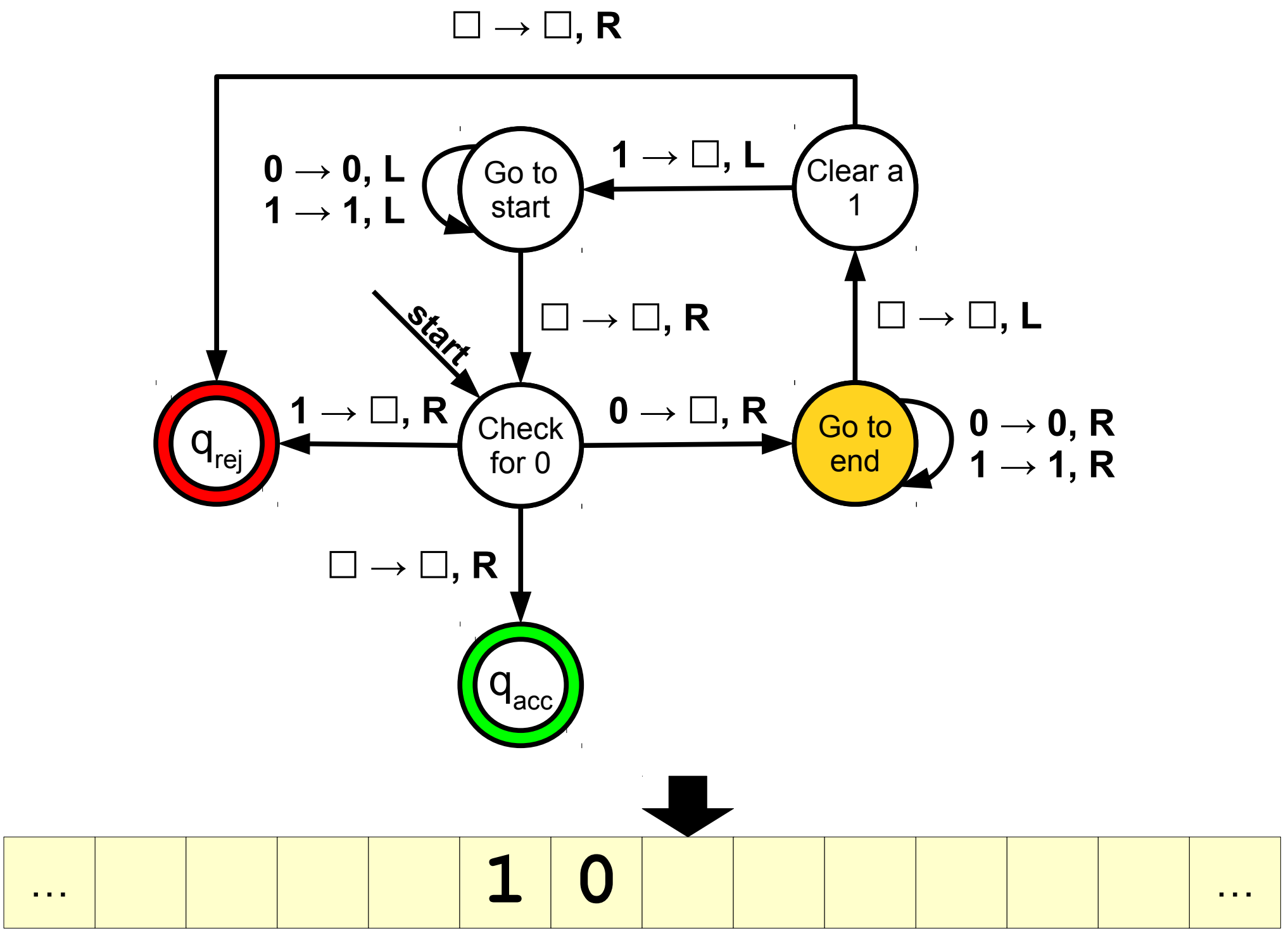
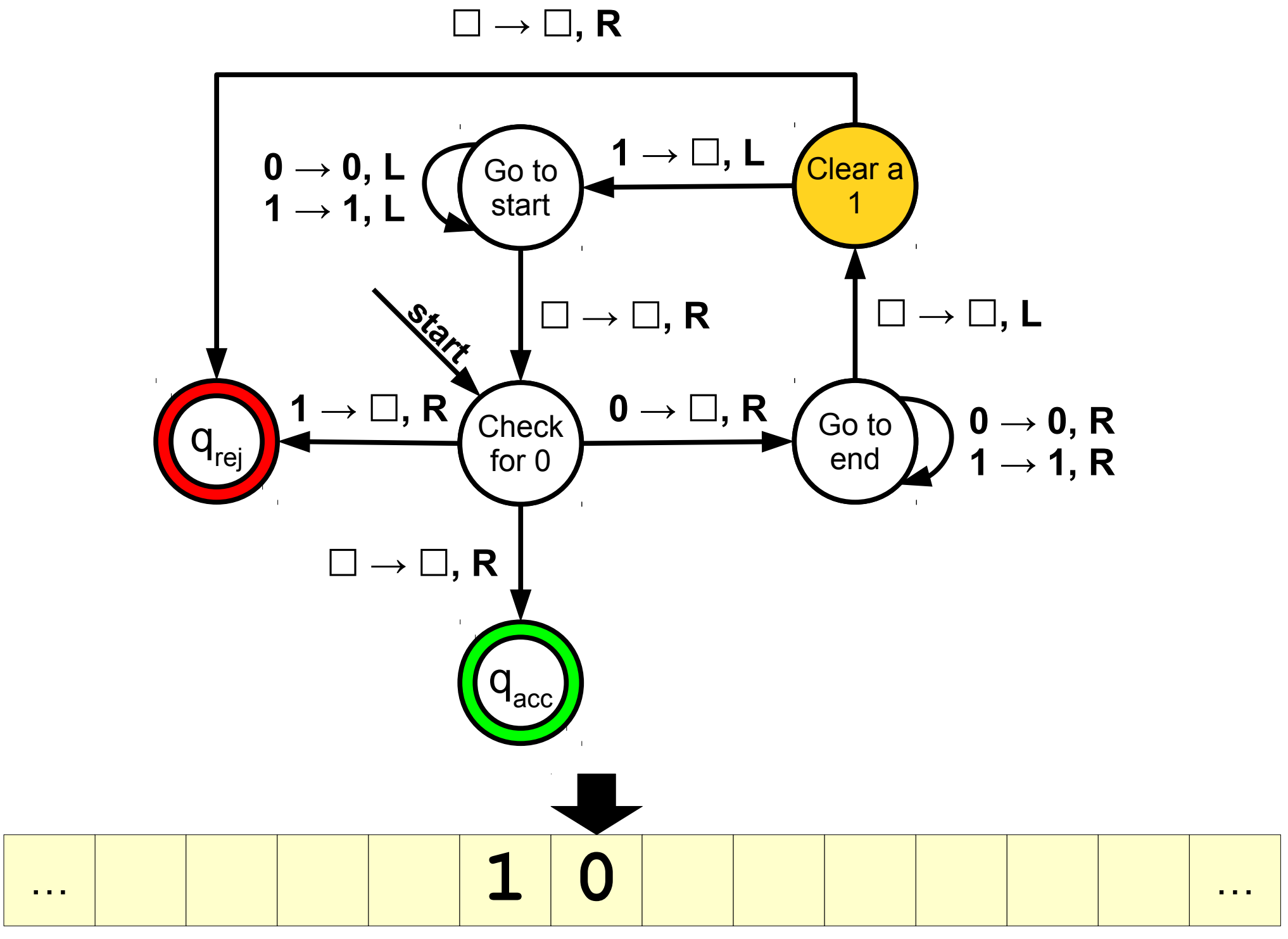
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
0 1 0
...


□ → □, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
0 1 0
...


□ → □, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
1
0
...


□ → □, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
1
0
...


□ → □, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
1
0
...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0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
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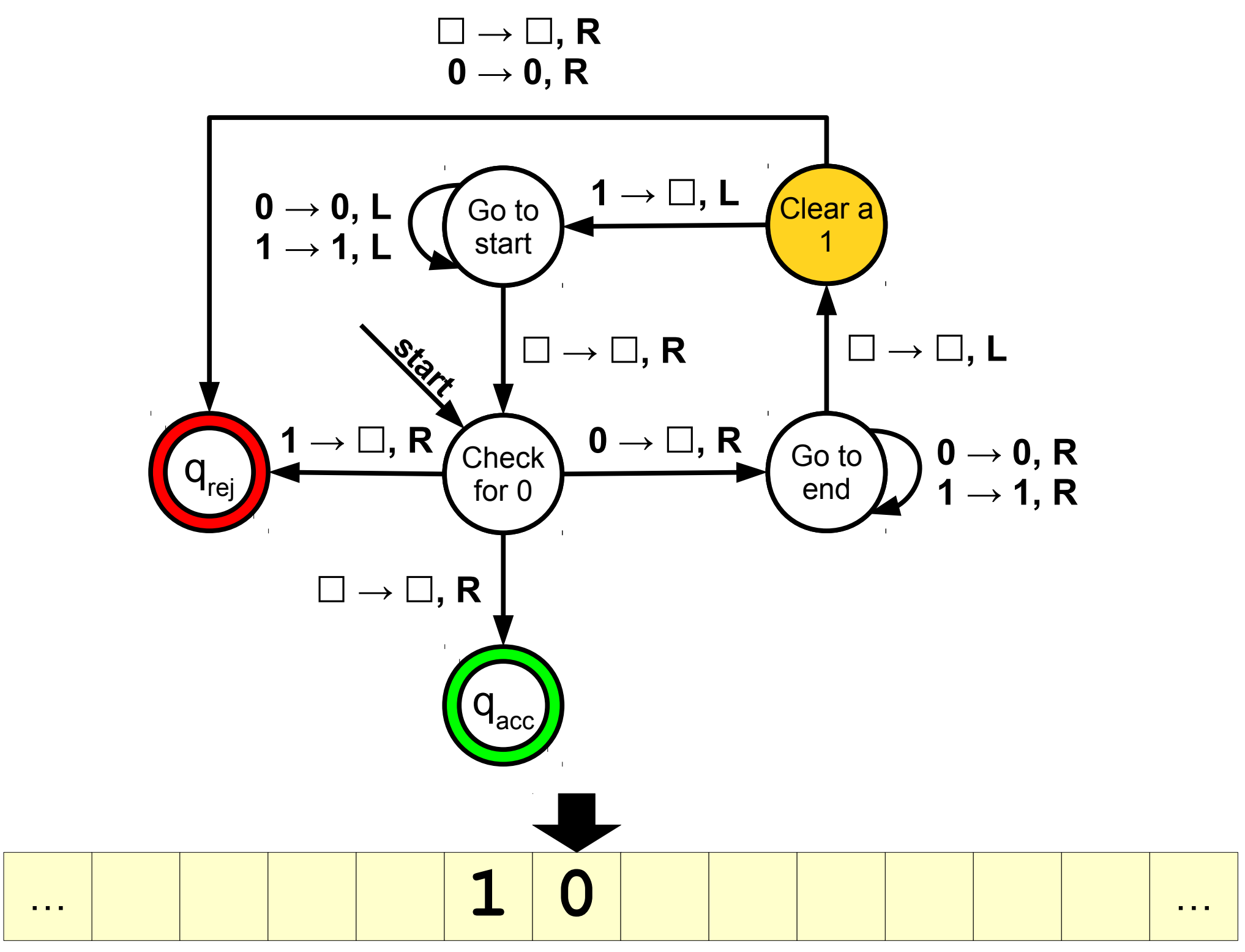
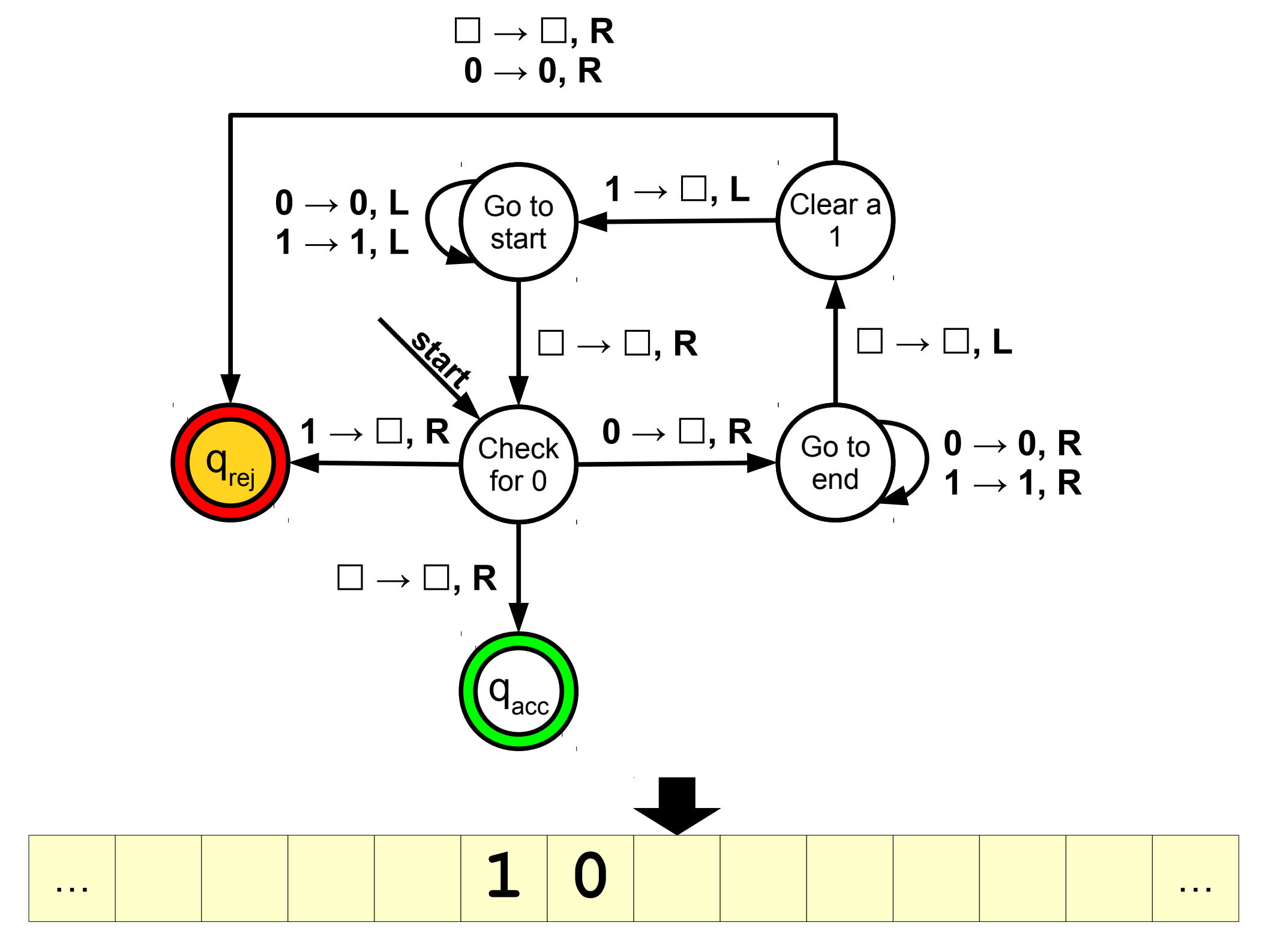
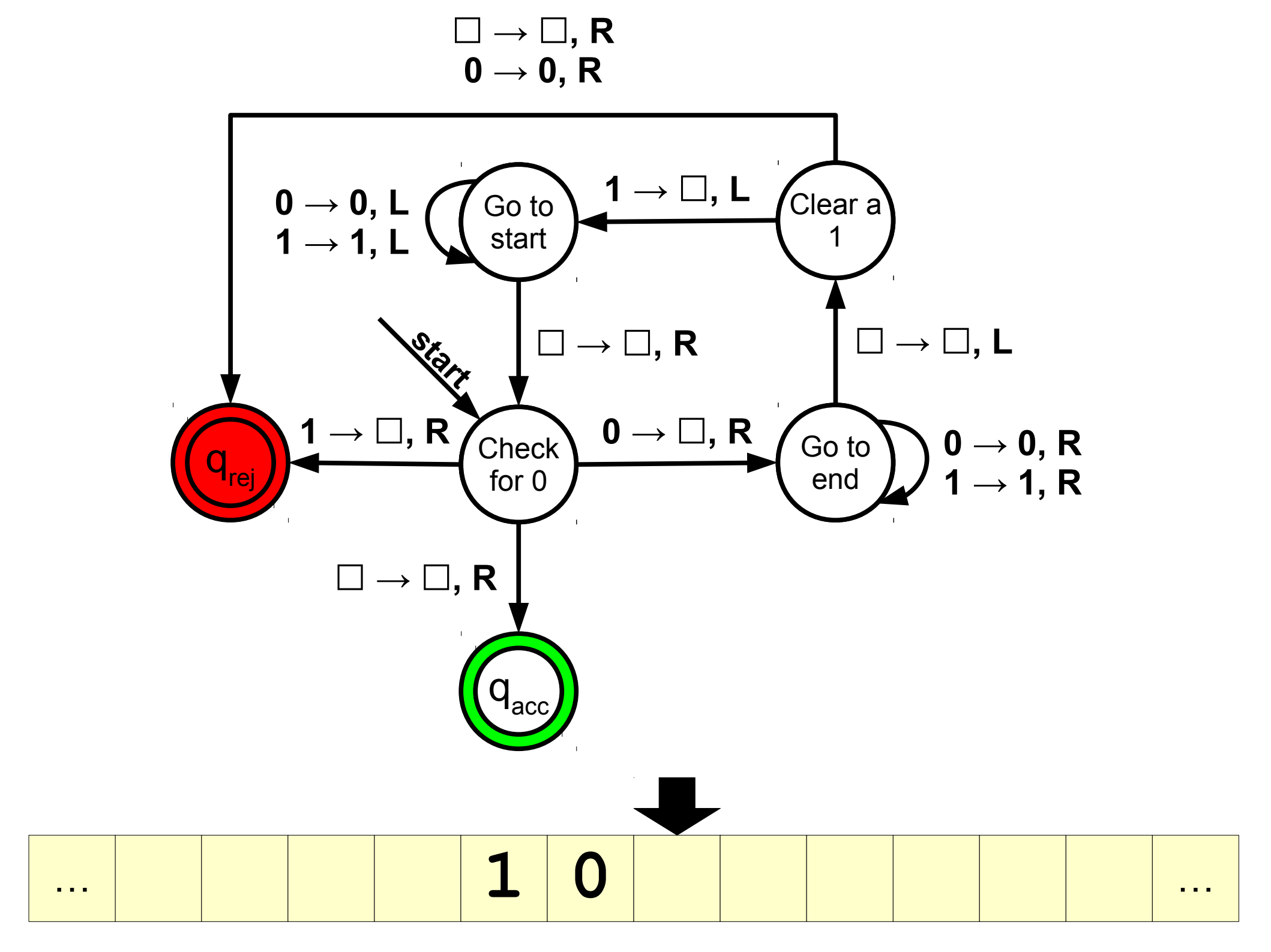
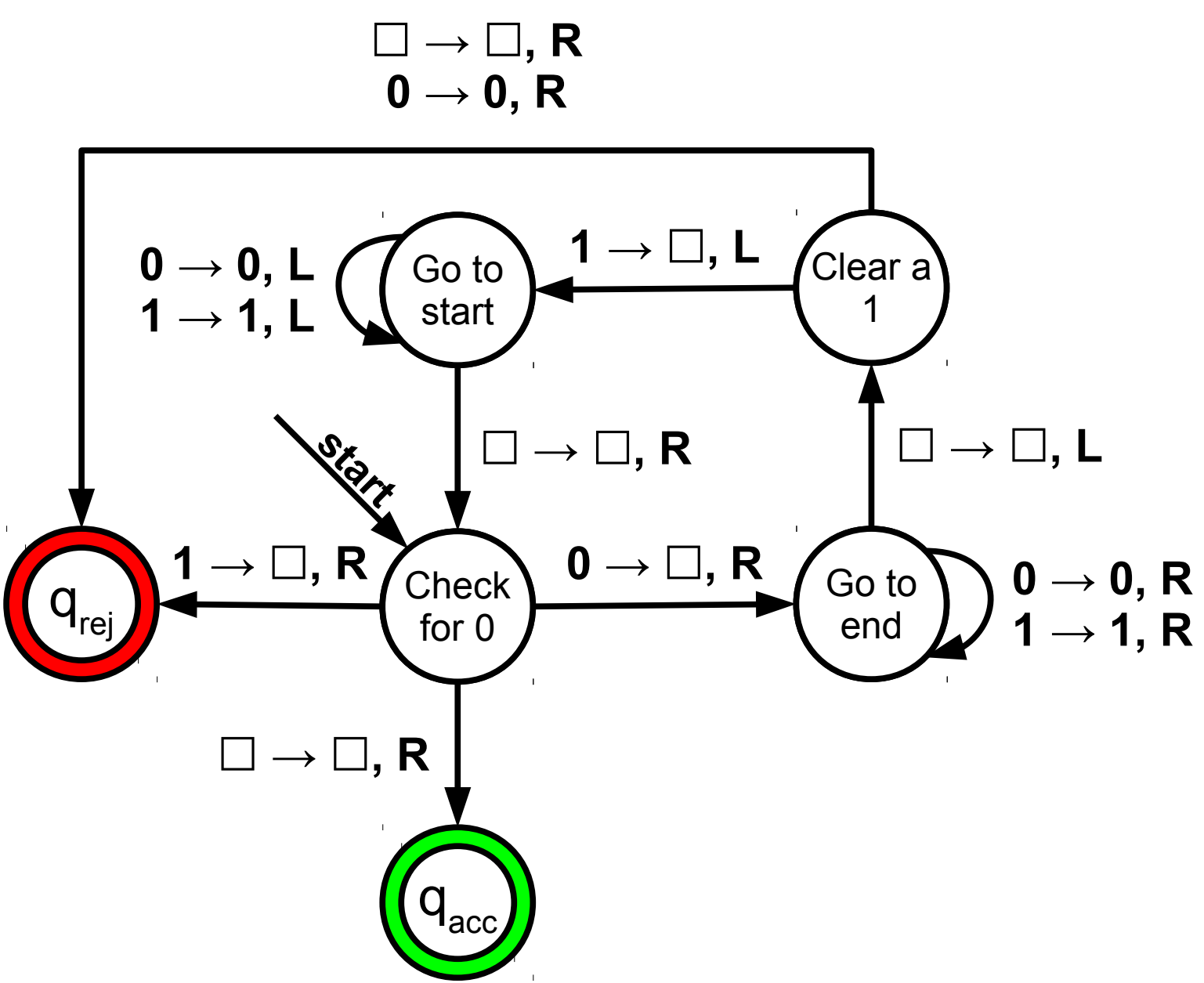
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
1
0
...


□ → □, R
0 → 0, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
1
0
...


□ → □, R
0 → 0, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc
...
1
0
...


□ → □, R
0 → 0, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
□ → □, R
q_{rej}
q_{acc}
…
1
0
…


□ → □, R
0 → 0, R
0 → 0, L
1 → 1, L
Go to start
1 → □, L
Clear a 1
start
□ → □, R
□ → □, L
1 → □, R
Check for 0
0 → □, R
Go to end
0 → 0, R
1 → 1, R
q_rej
□ → □, R
q_acc

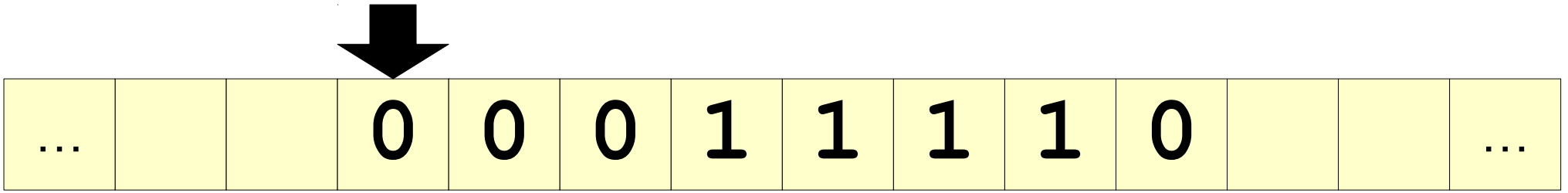
Another TM Design

- We've designed a TM for $\{ \mathtt{0}^n\mathtt{1}^n \mid n \in \mathbb{N} \}$.
- Consider this language over $\Sigma = \{ \mathtt{0}, \mathtt{1} \}$:

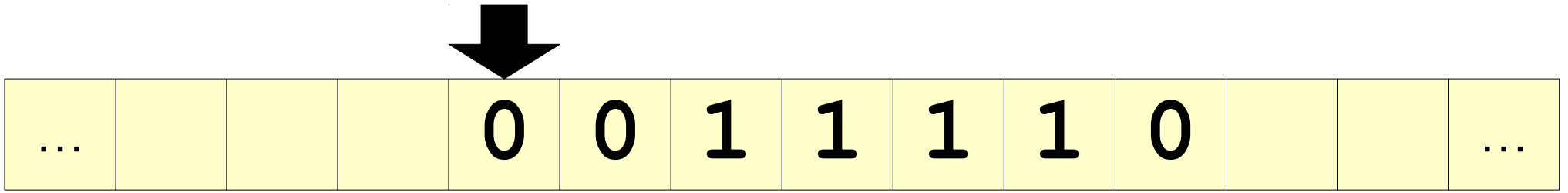
$$L = \{ w \in \Sigma^* \mid w \text{ has the same number of } \mathtt{0}\text{s and } \mathtt{1}\text{s} \}$$

- This language is also not regular, but it is context-free.
- How might we design a TM for it?

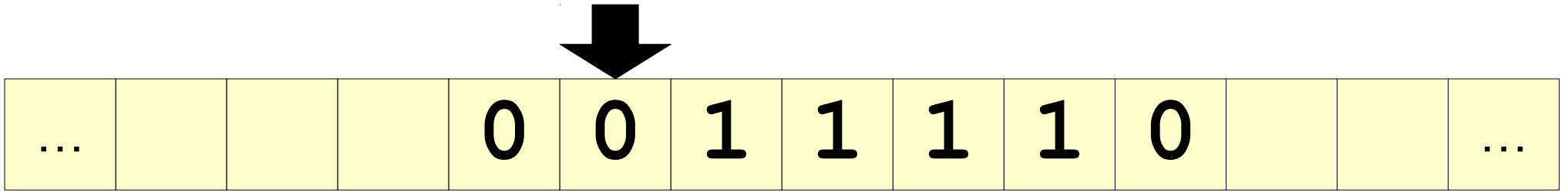
A Caveat



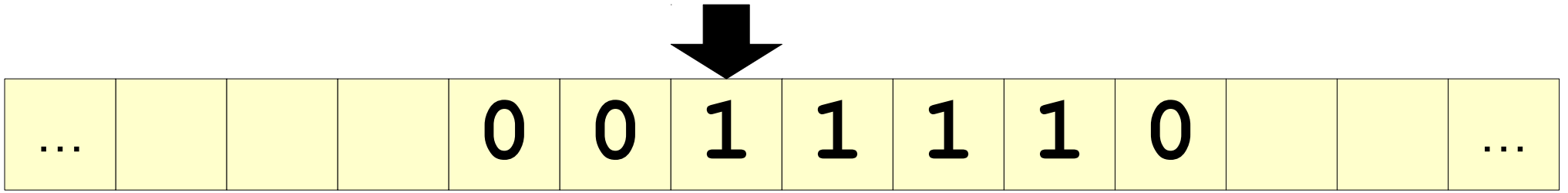
A Caveat



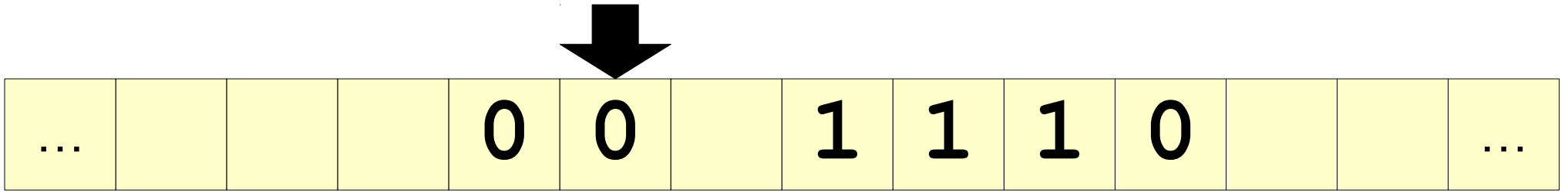
A Caveat



A Caveat



A Caveat



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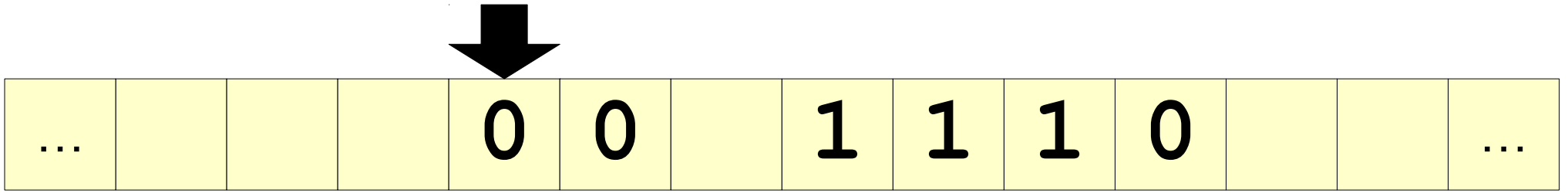

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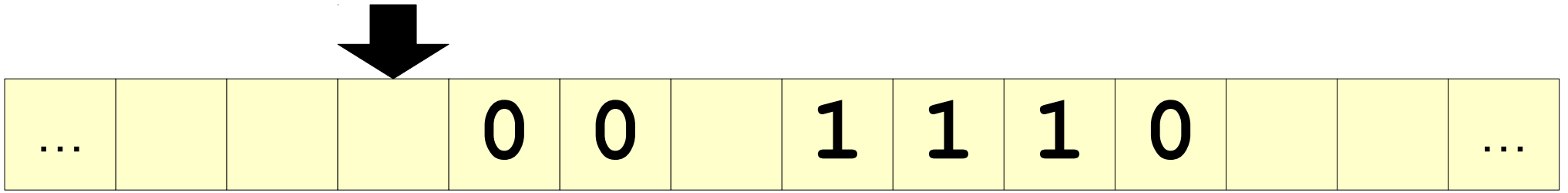

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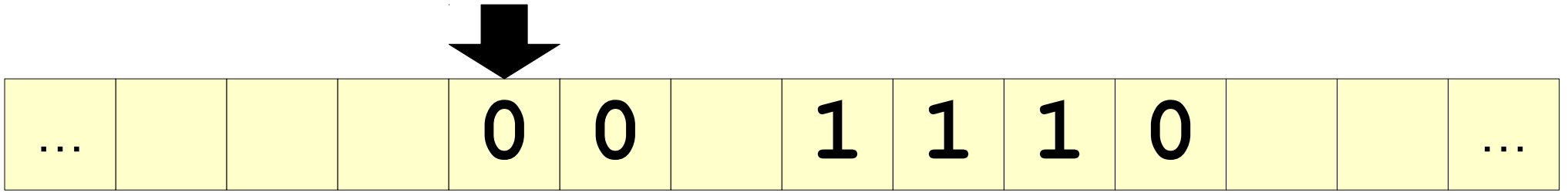

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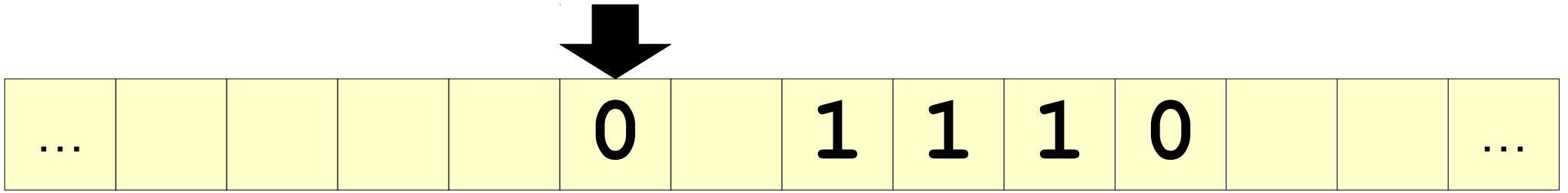

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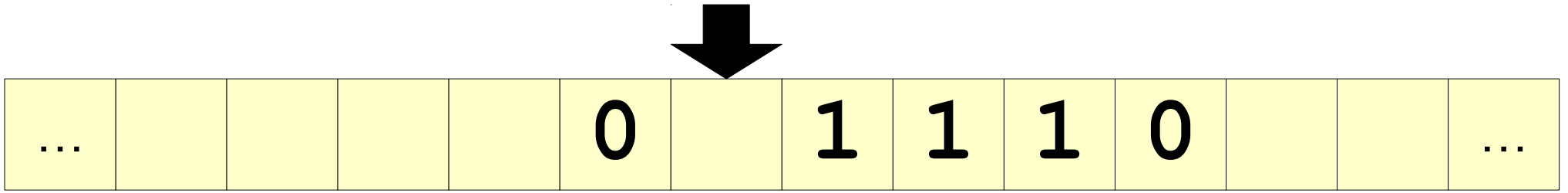
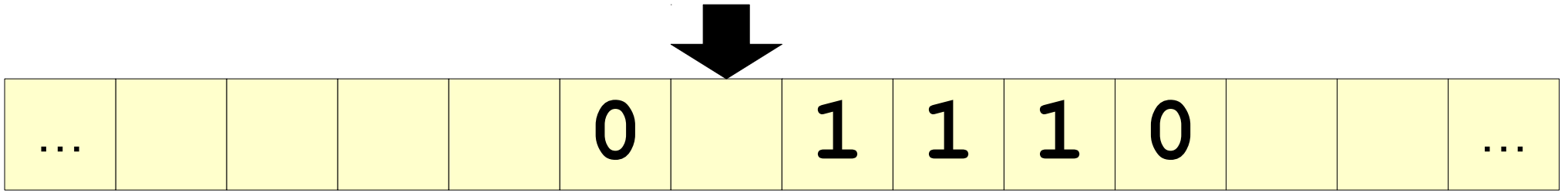
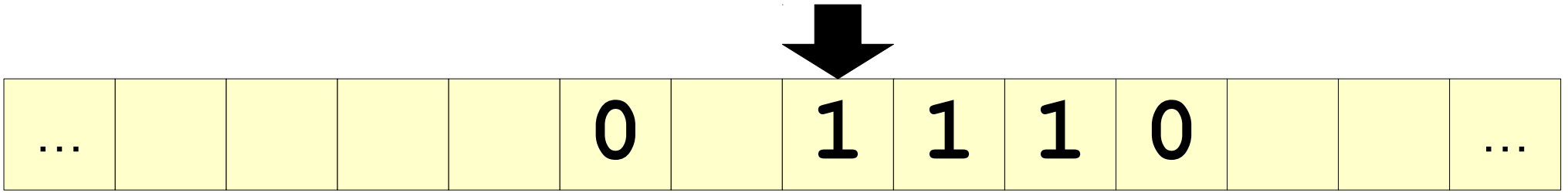


A Caveat

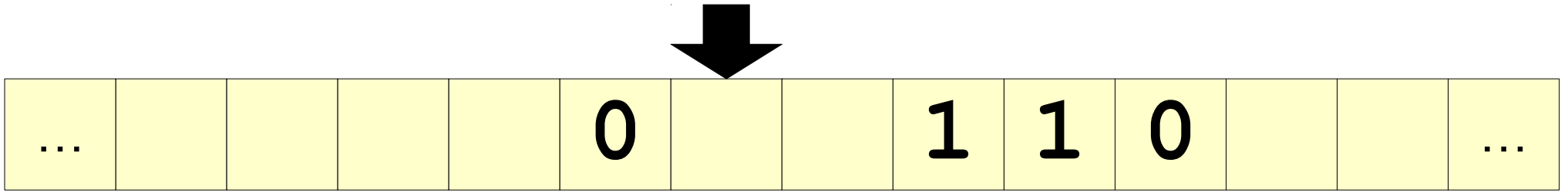


How do we know that this blank isn't one of the infinitely many blanks after our input string?

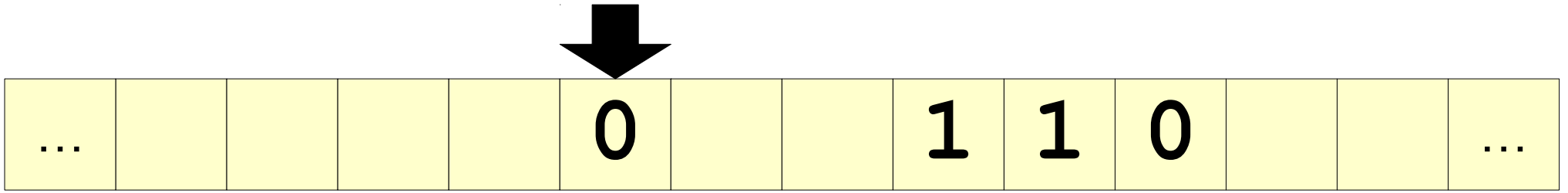
A Caveat



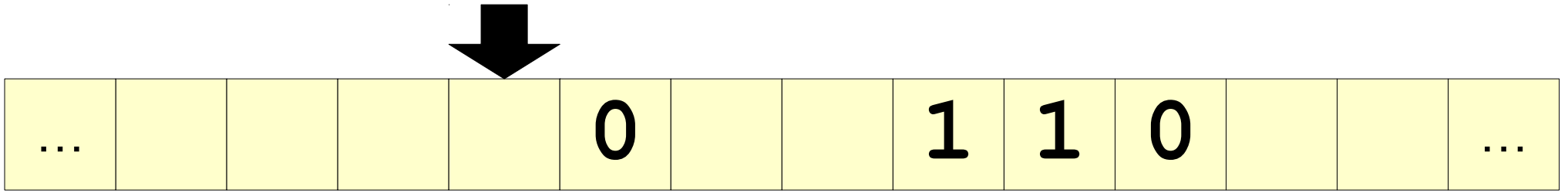
A Caveat



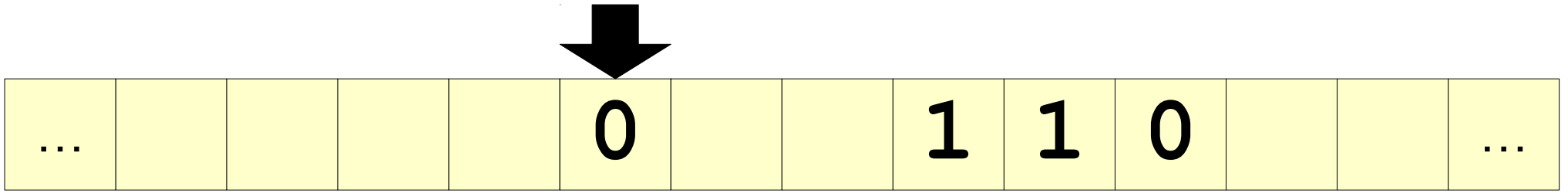
A Caveat



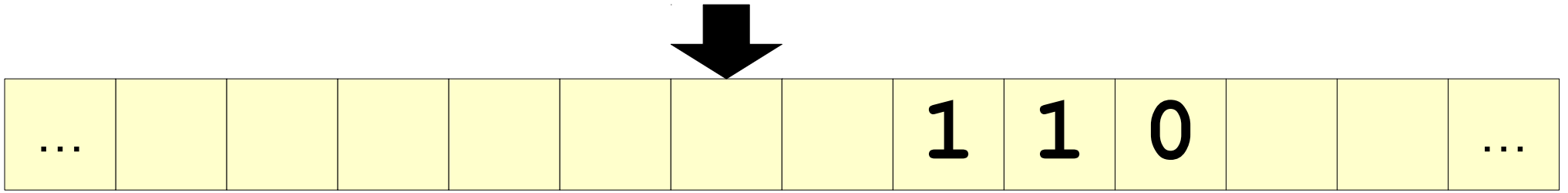
A Caveat



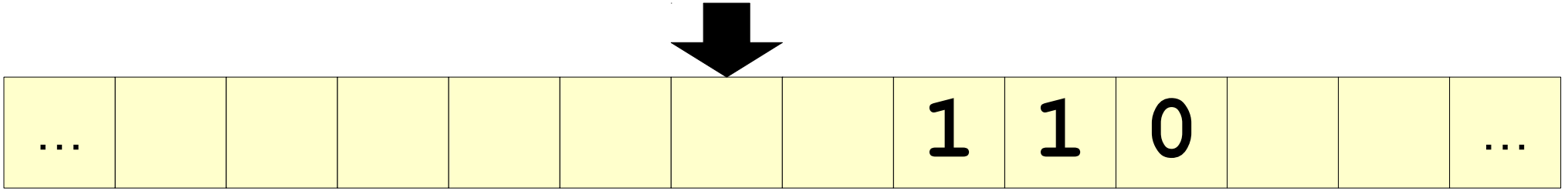
A Caveat



A Caveat

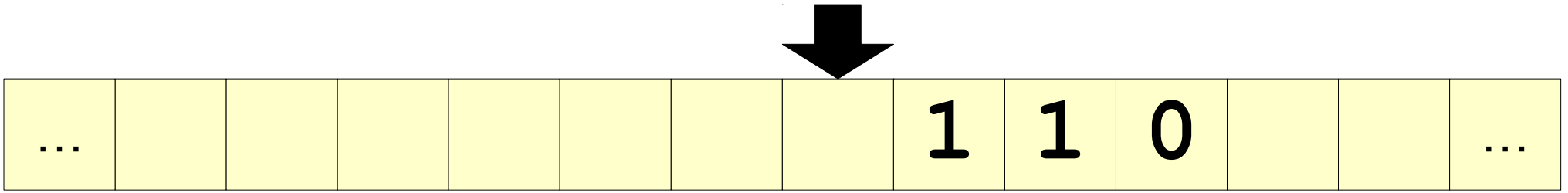


A Caveat

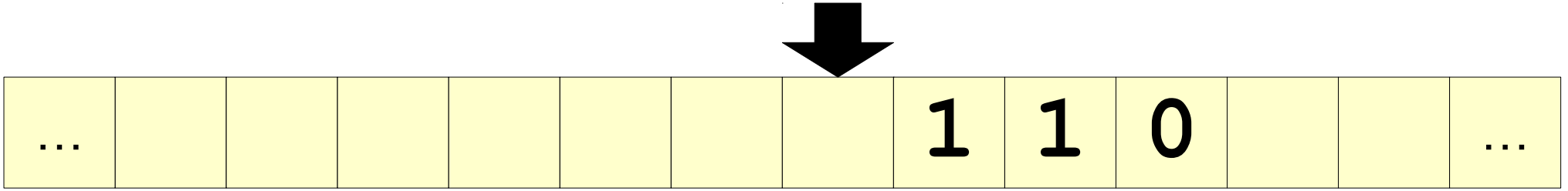


How do we know that this blank isn't one of the infinitely many blanks after our input string?

A Caveat

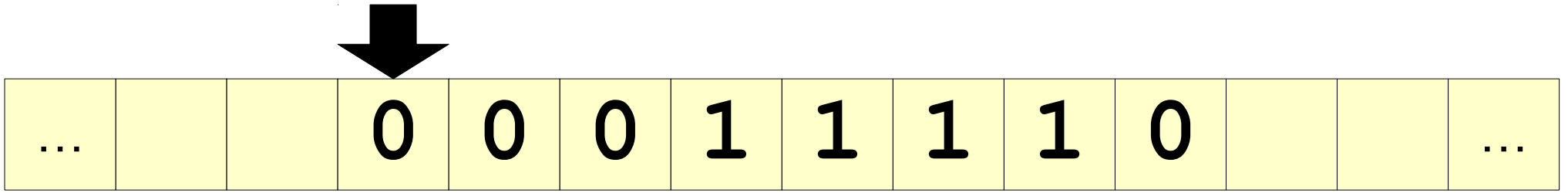


A Caveat

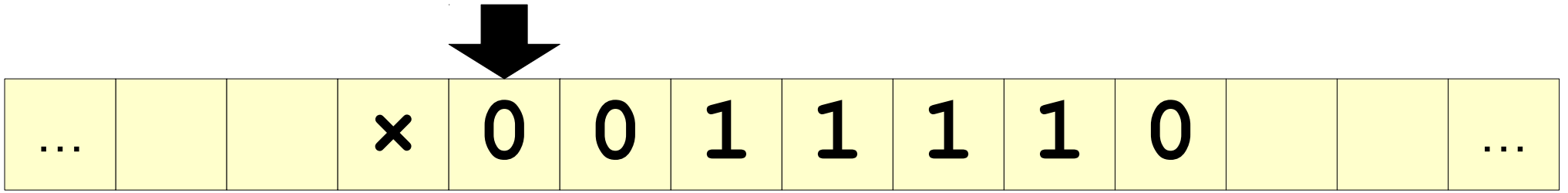


How do we know that this blank isn't one of the infinitely many blanks after our input string?

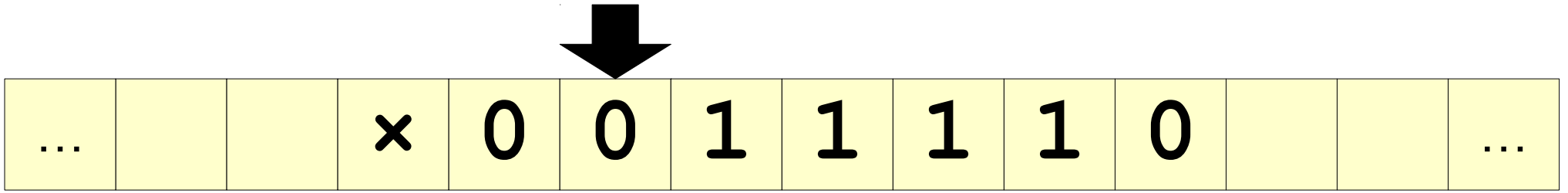
The Solution



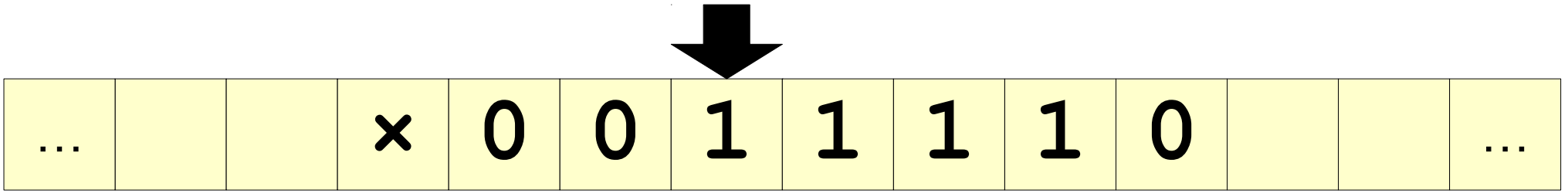
The Solution



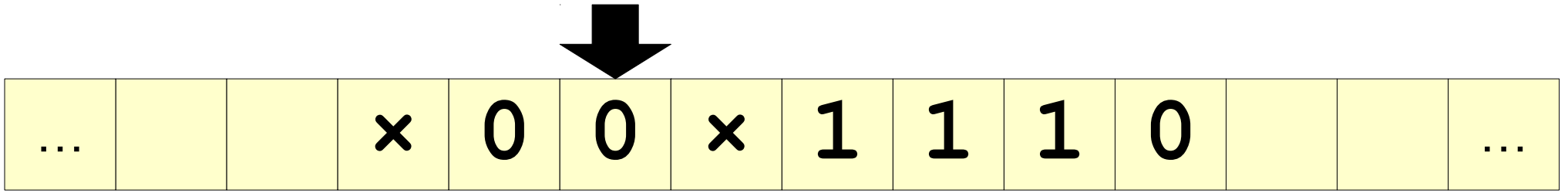
The Solution



The Solution



The Solution



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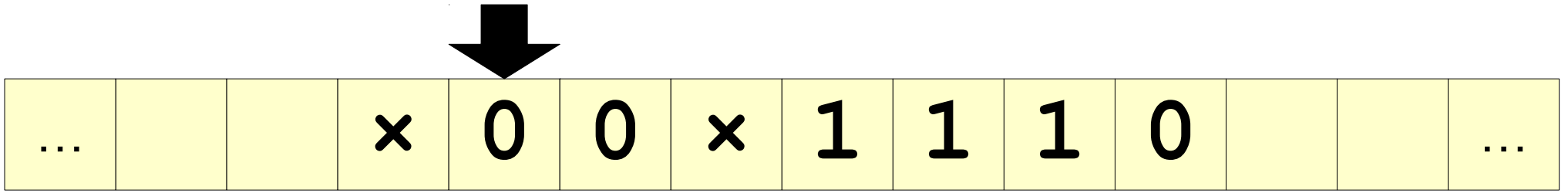
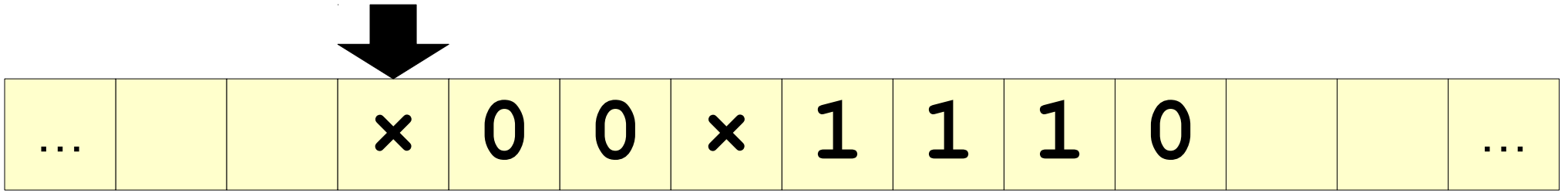
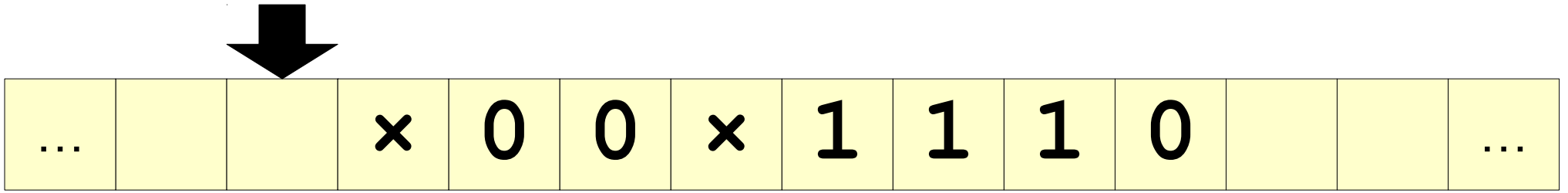


The Solution



The Solution



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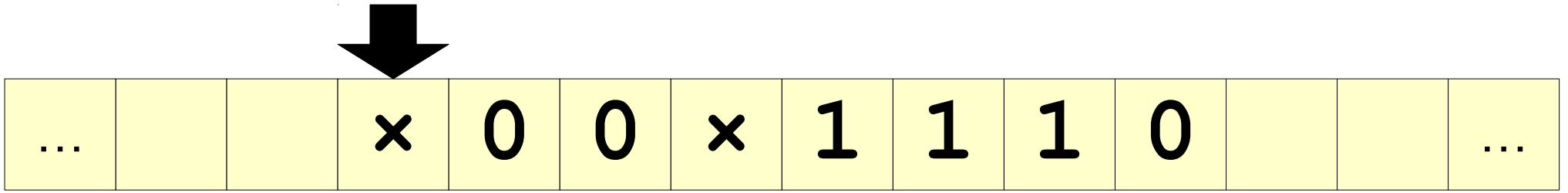
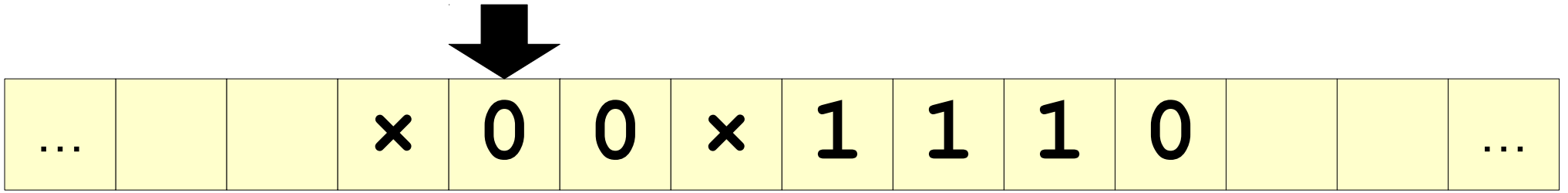
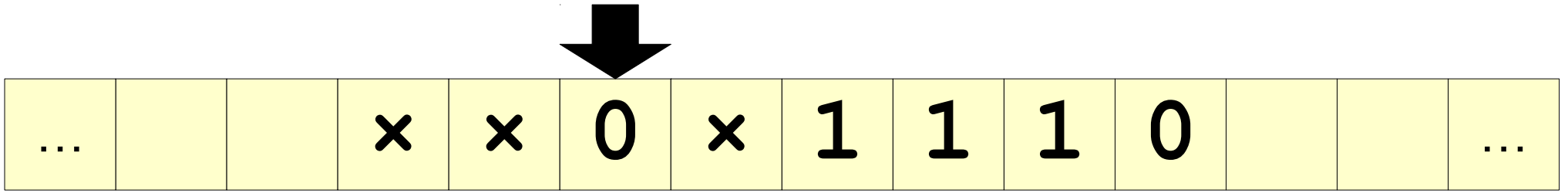


The Solution



The Solution



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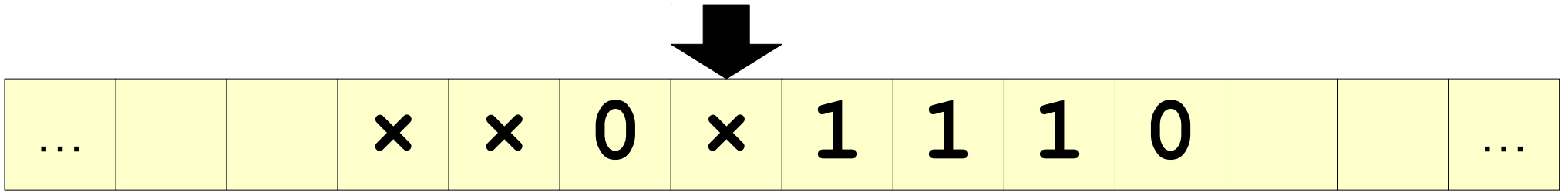

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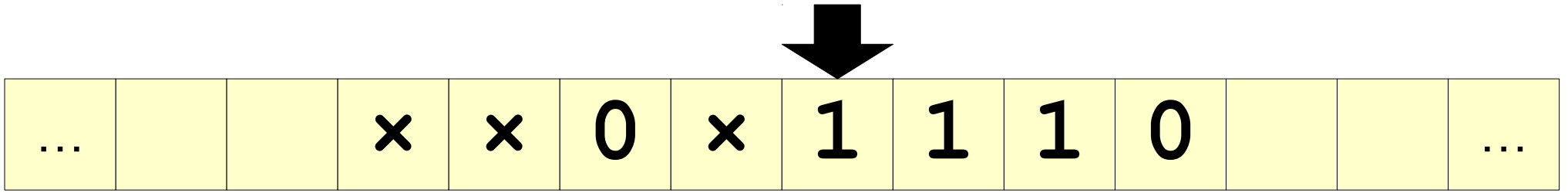

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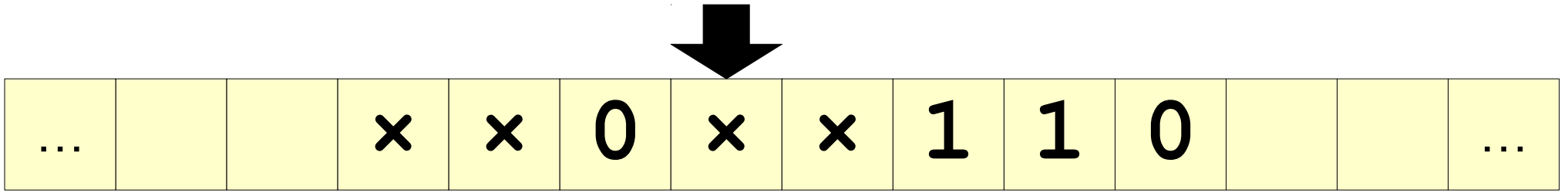

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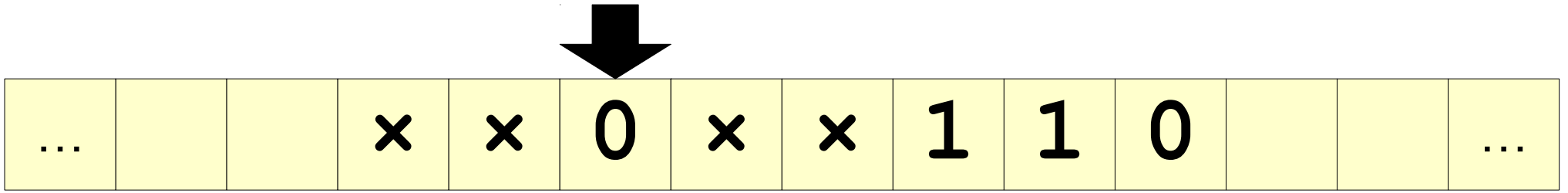

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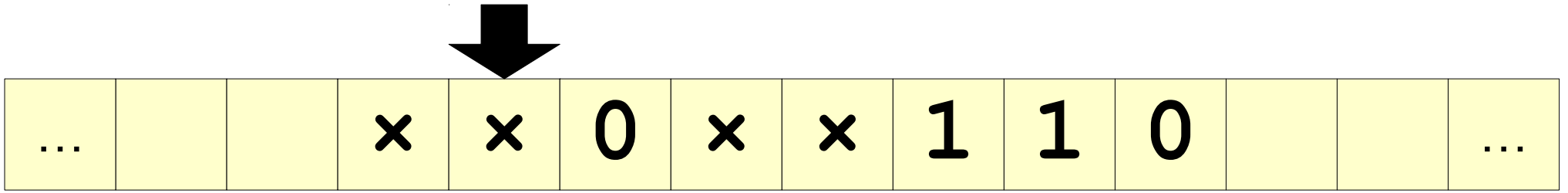
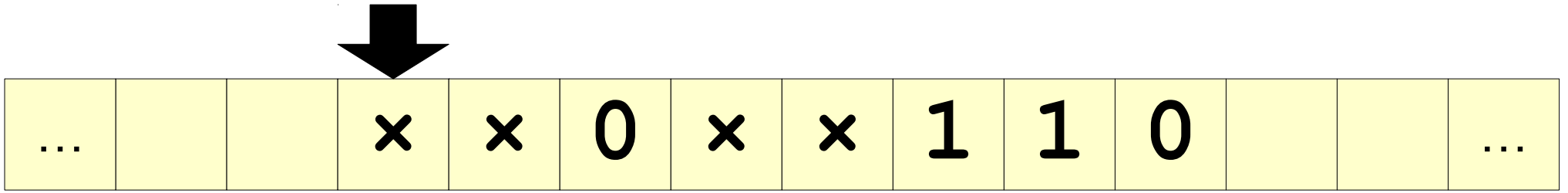


The Solution



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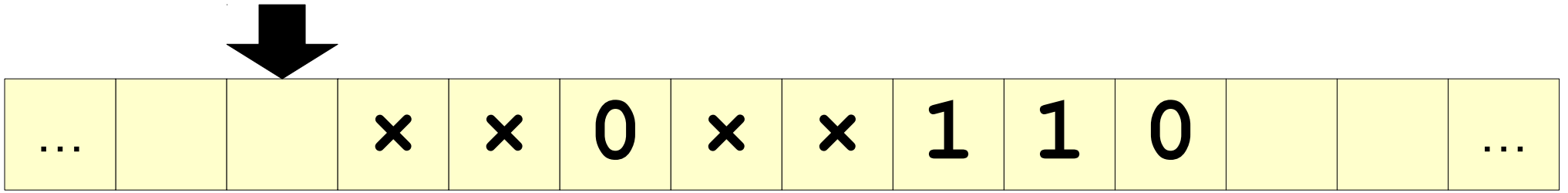

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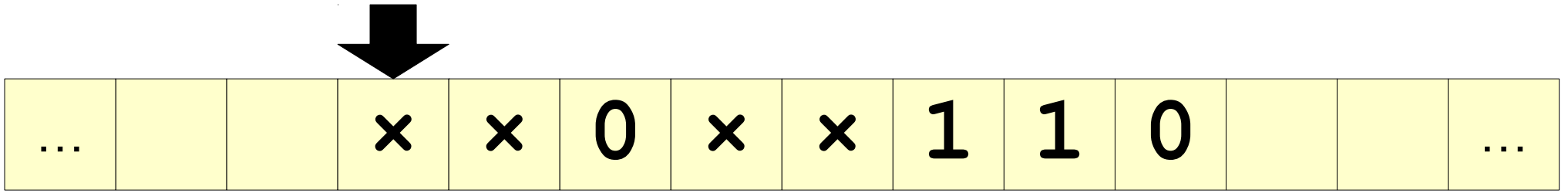
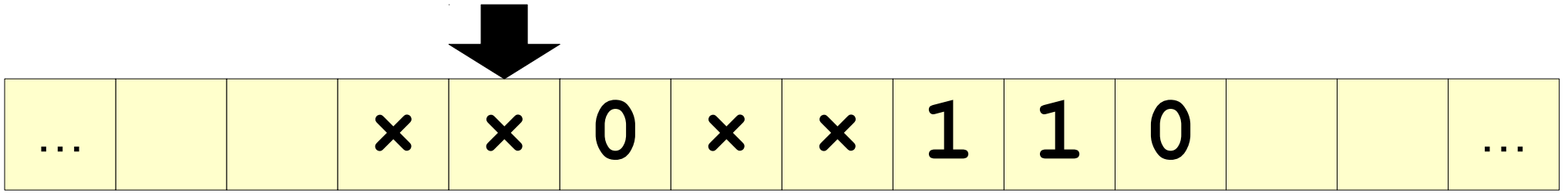
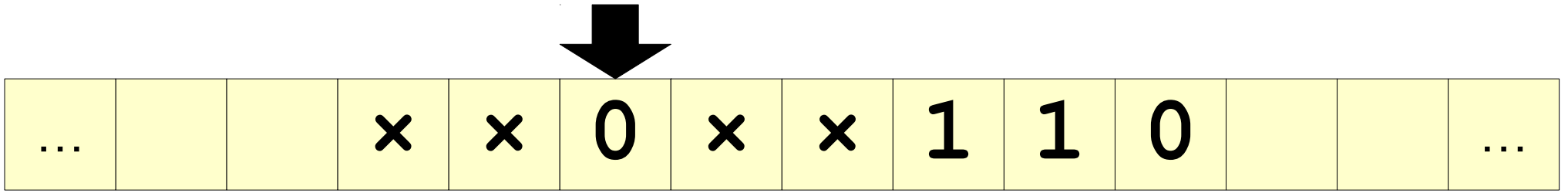


The Solution



The Solution



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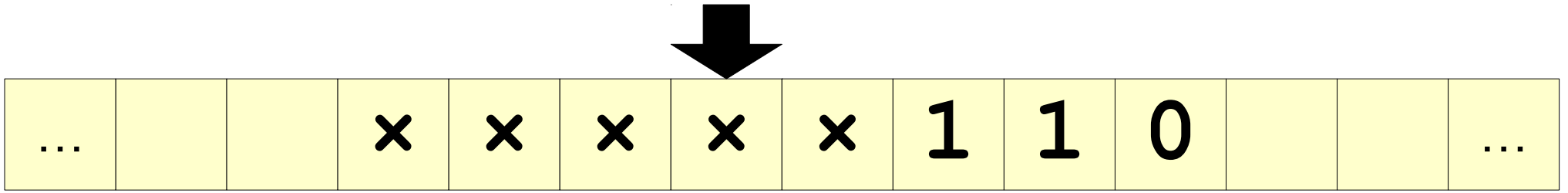

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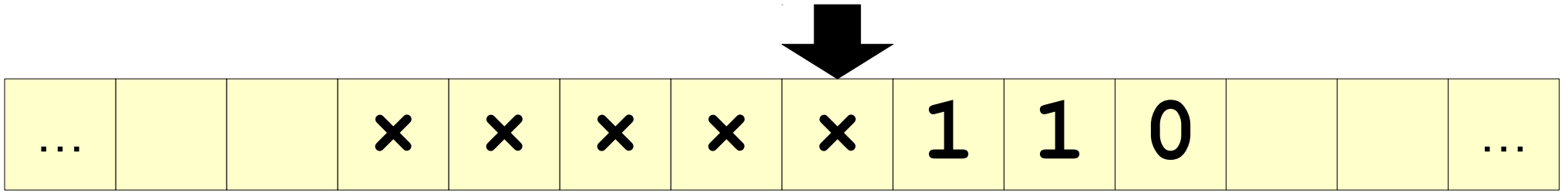

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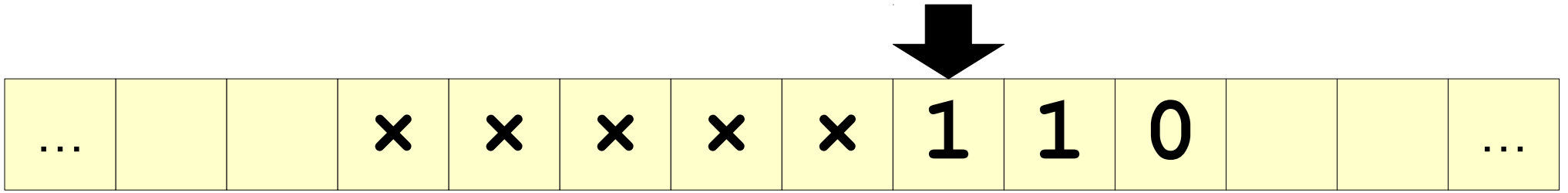

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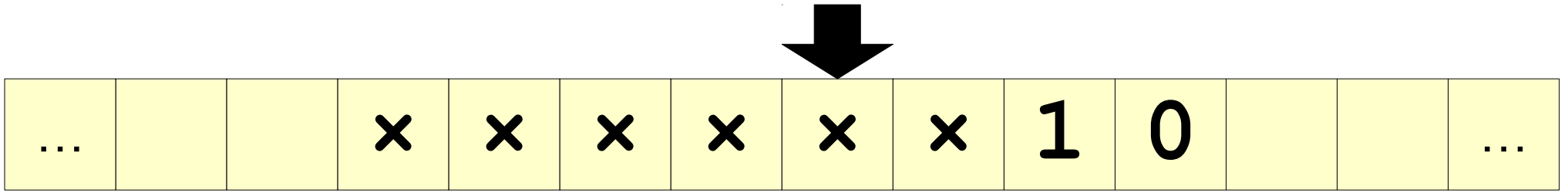

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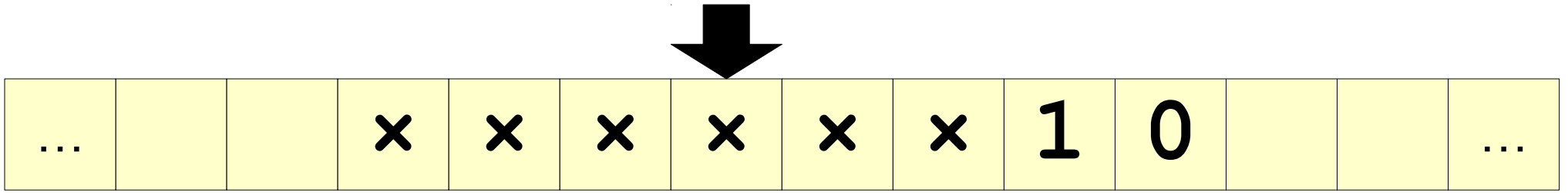

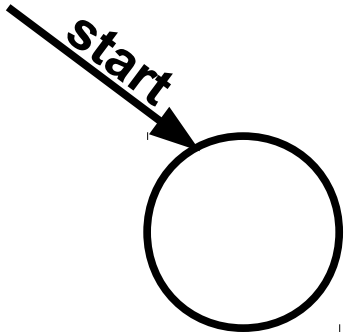
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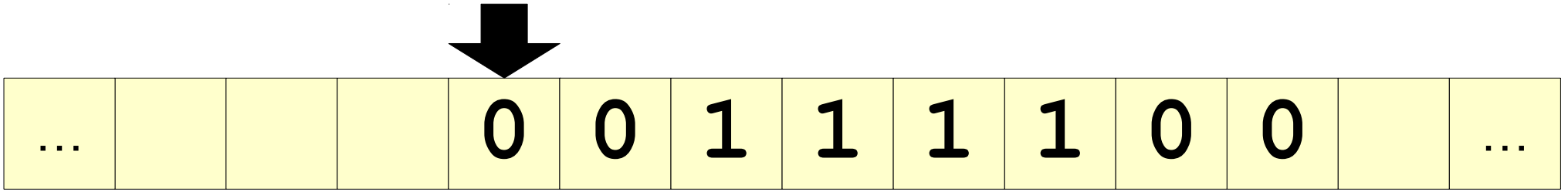
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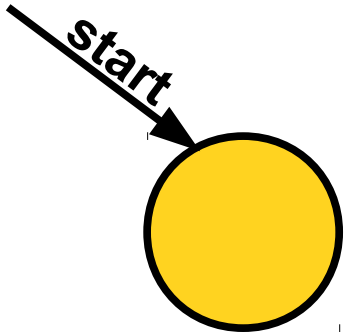
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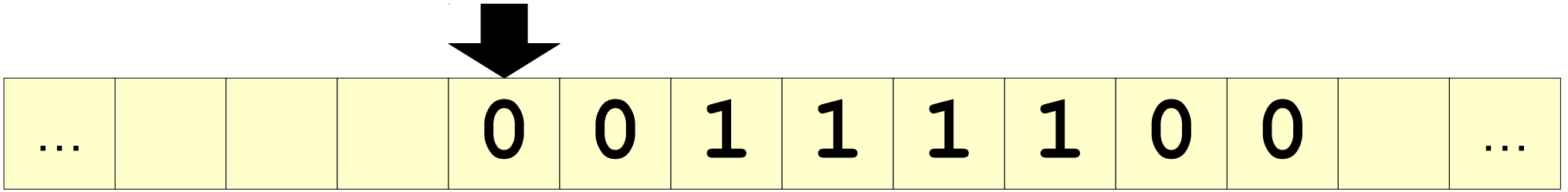
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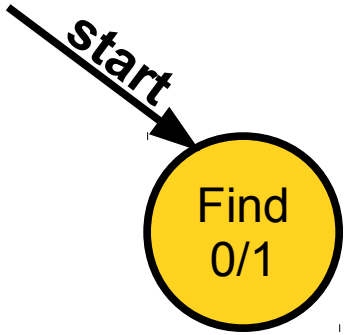
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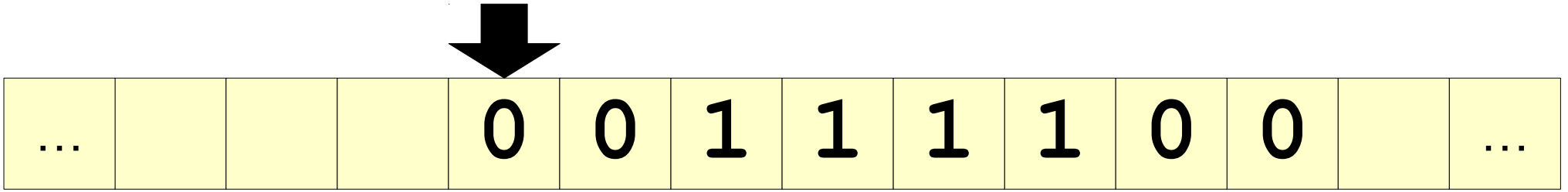
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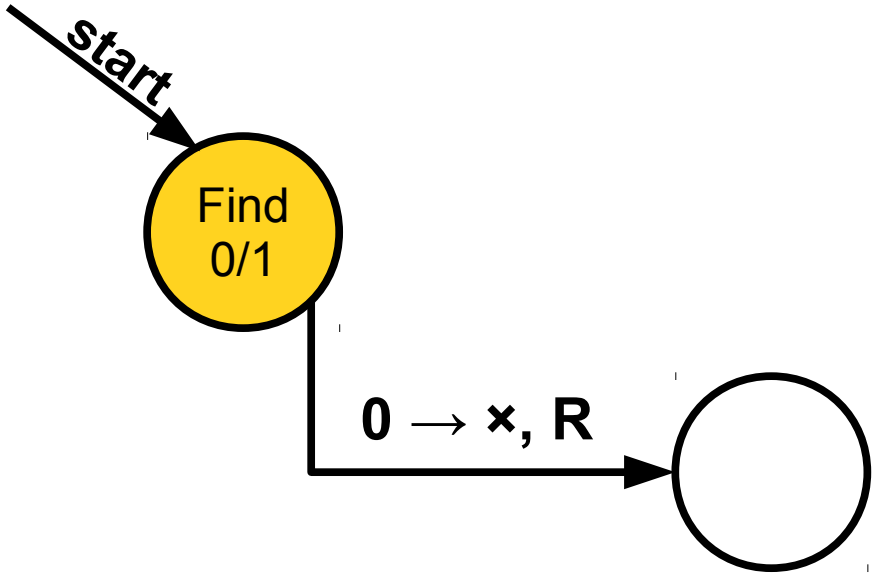
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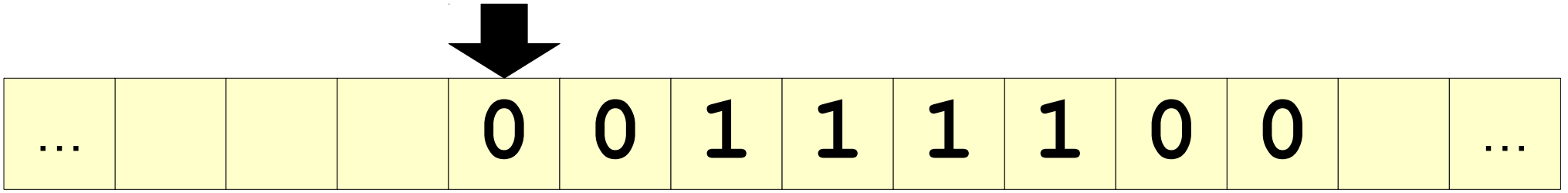
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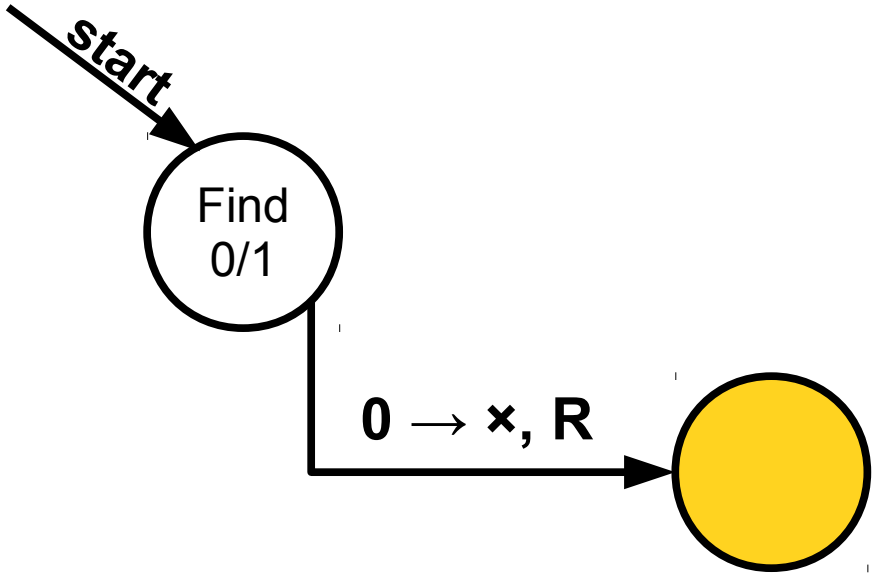
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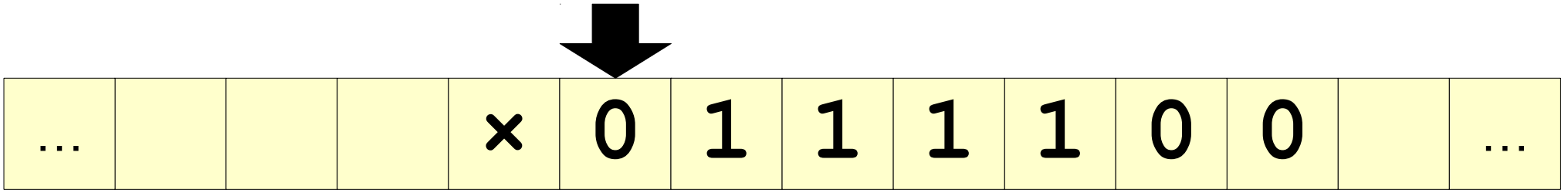
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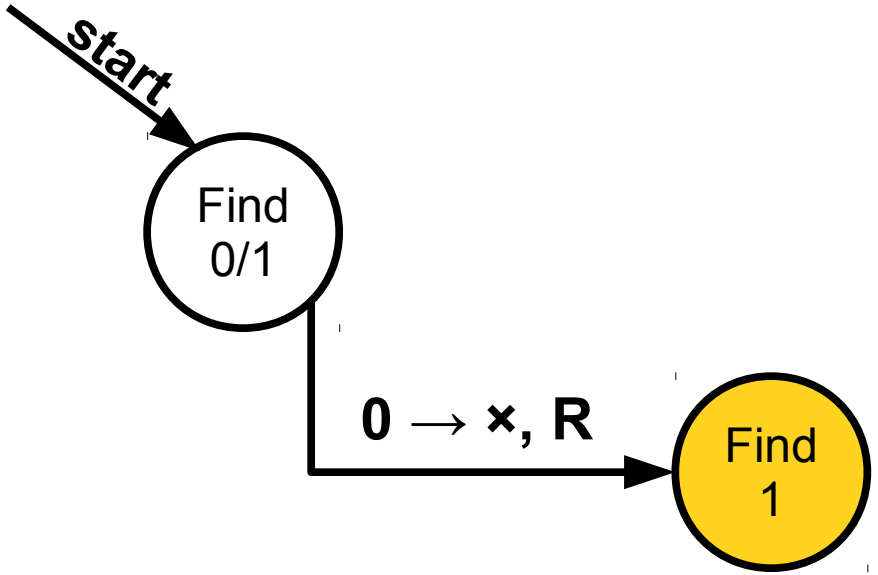
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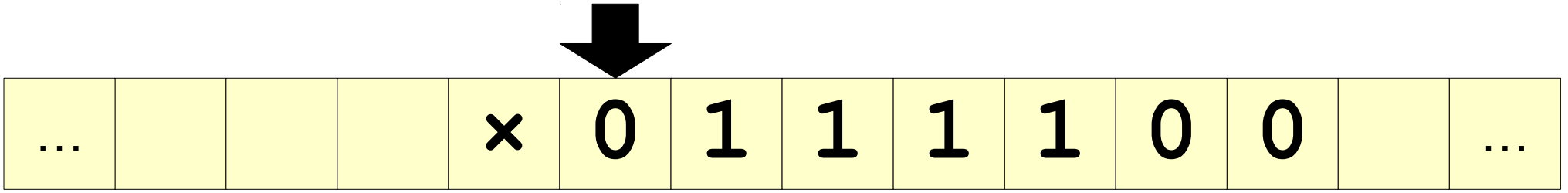
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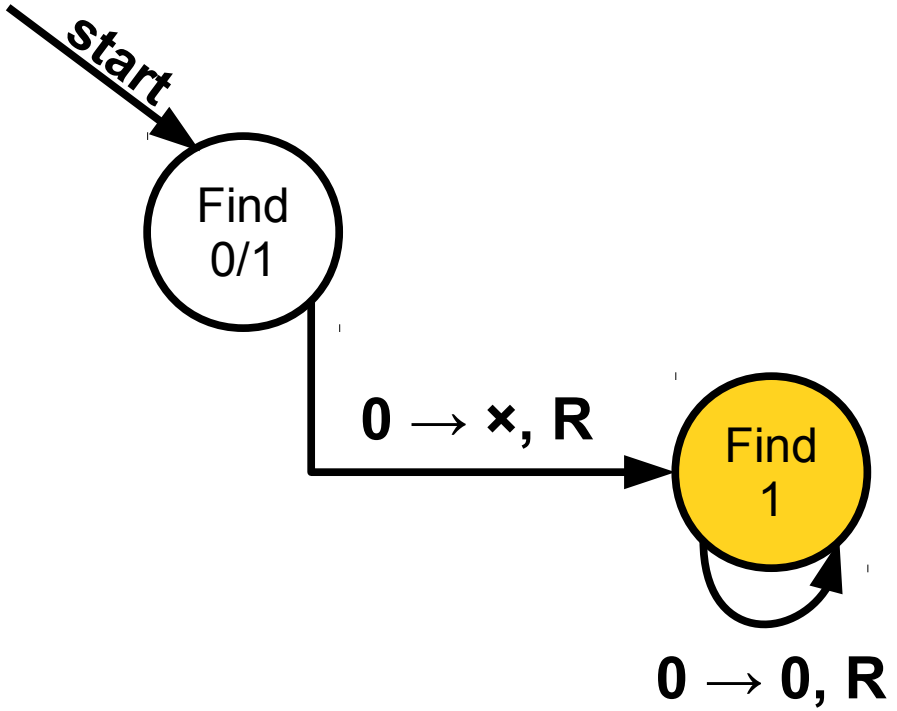
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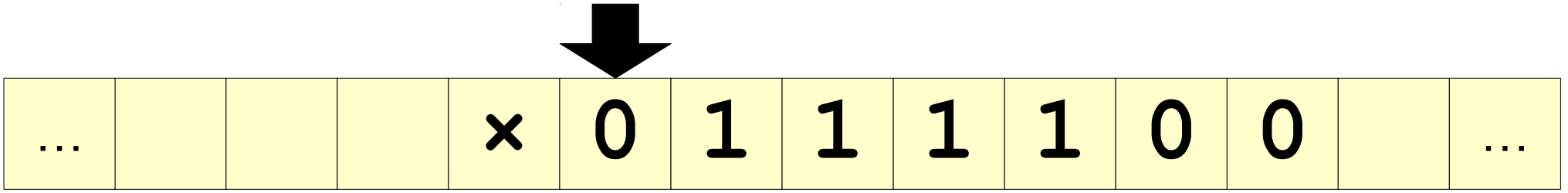
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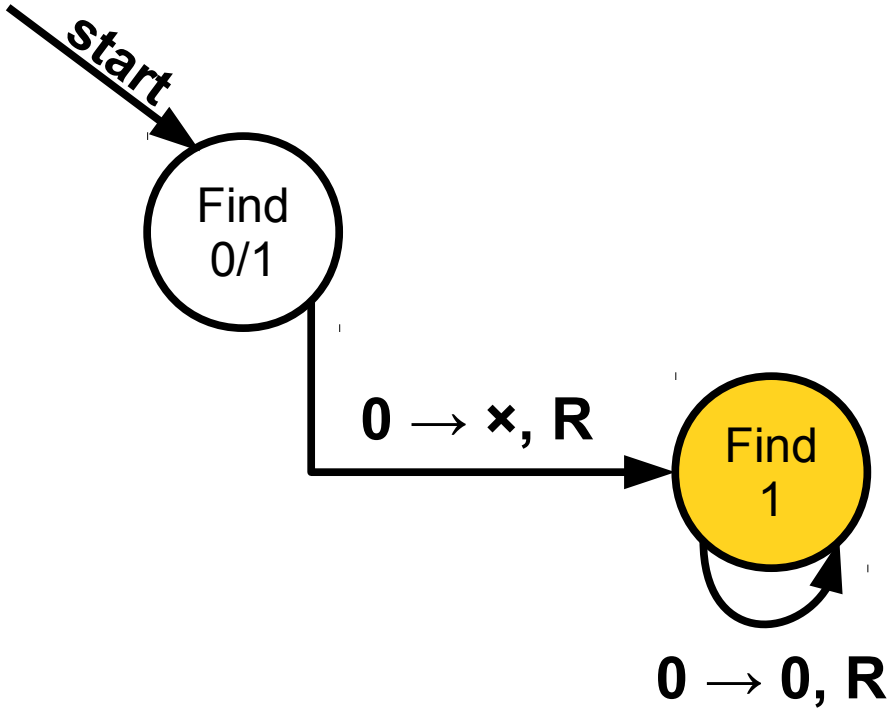
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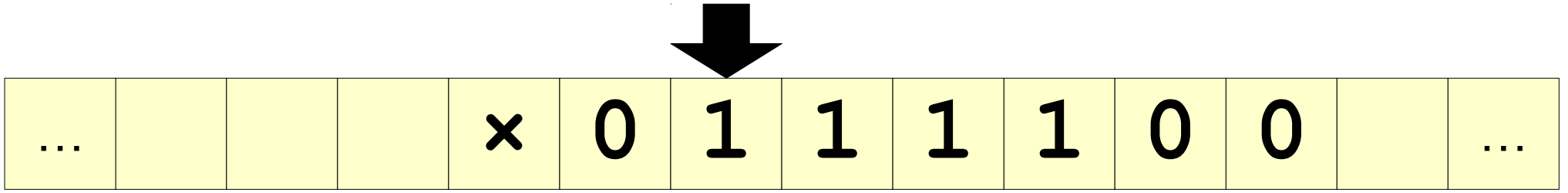
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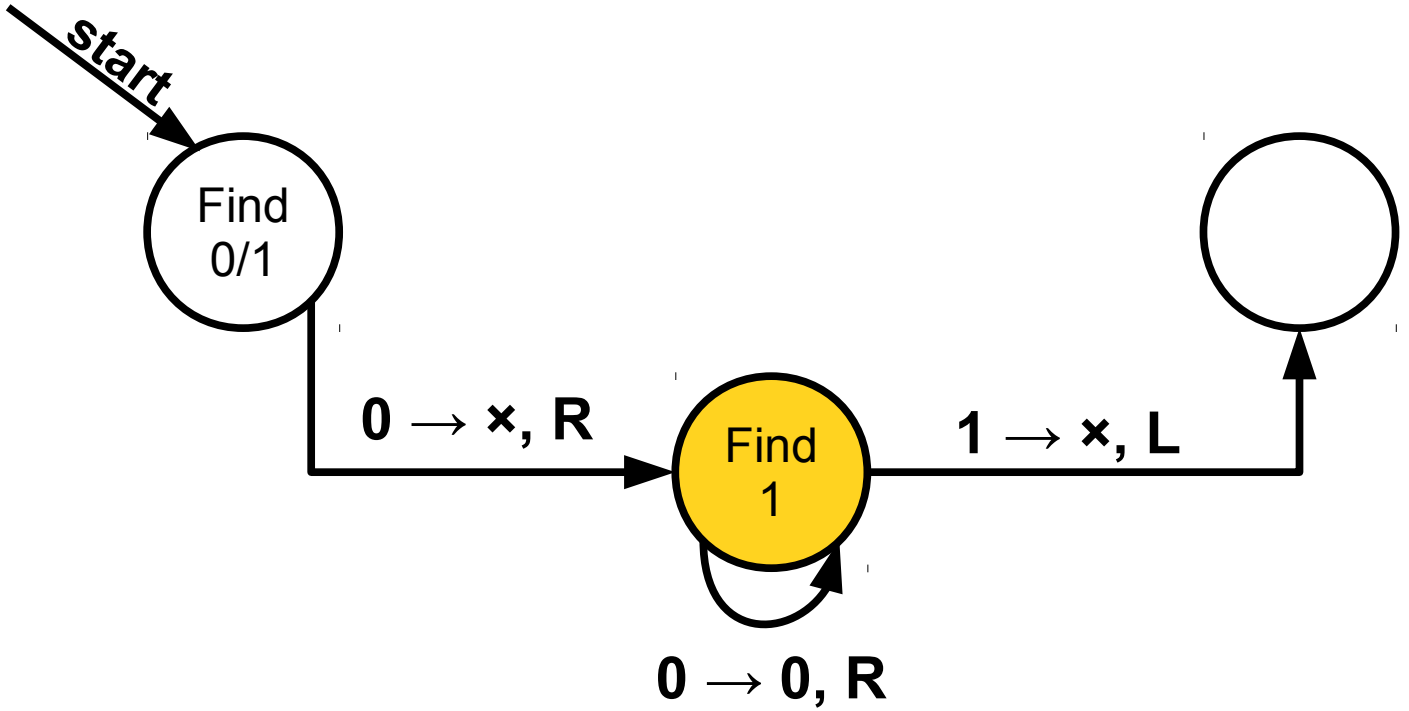
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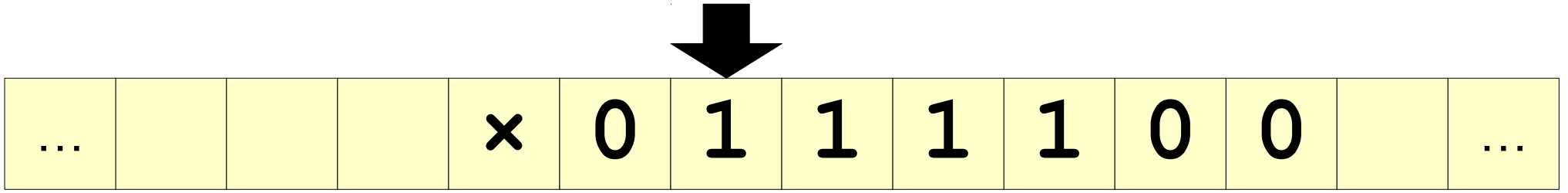
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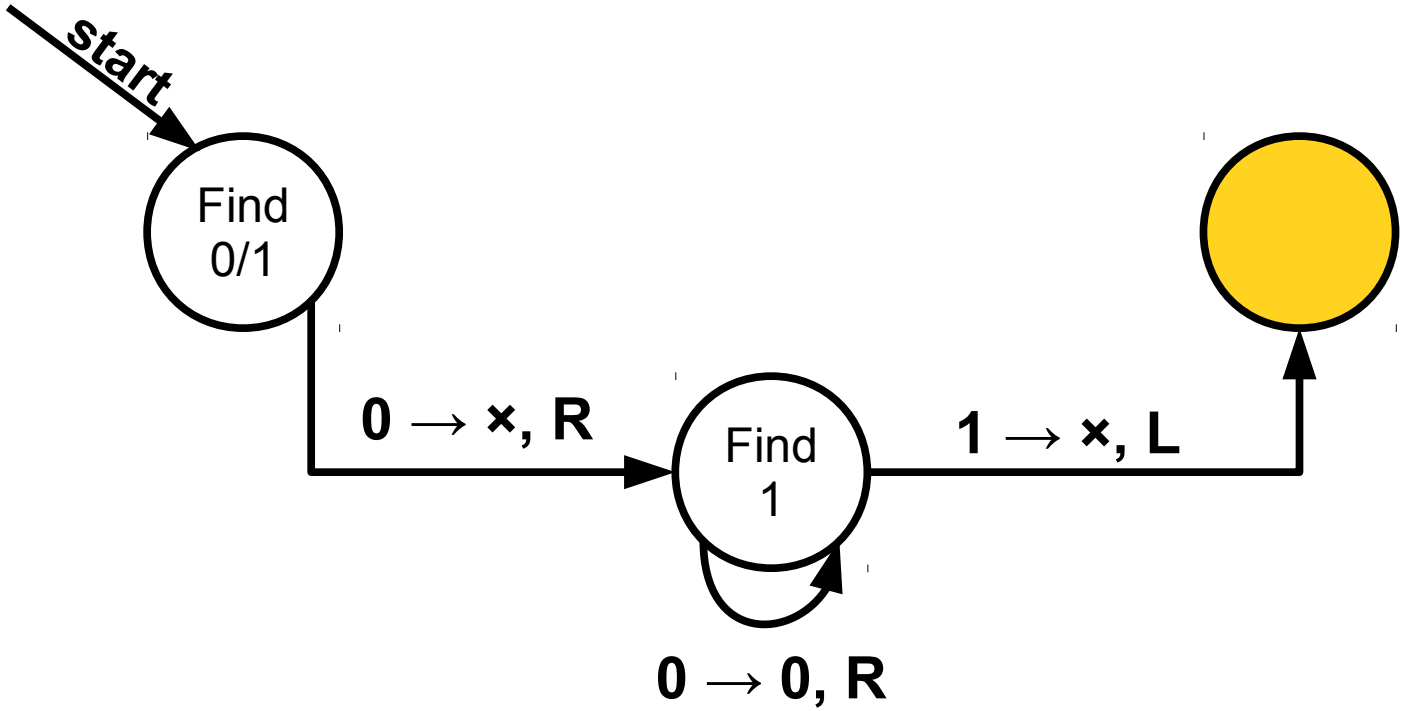
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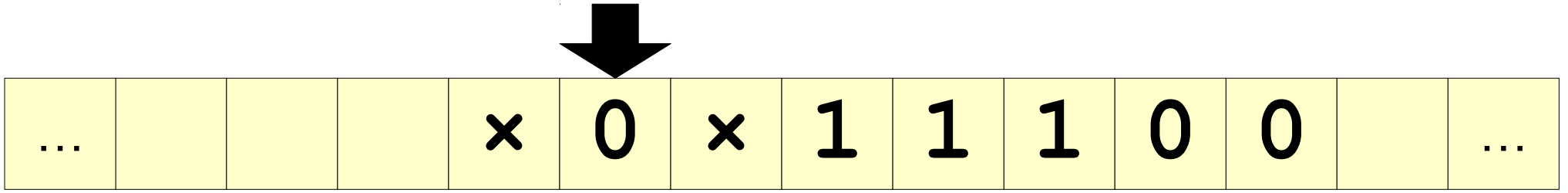
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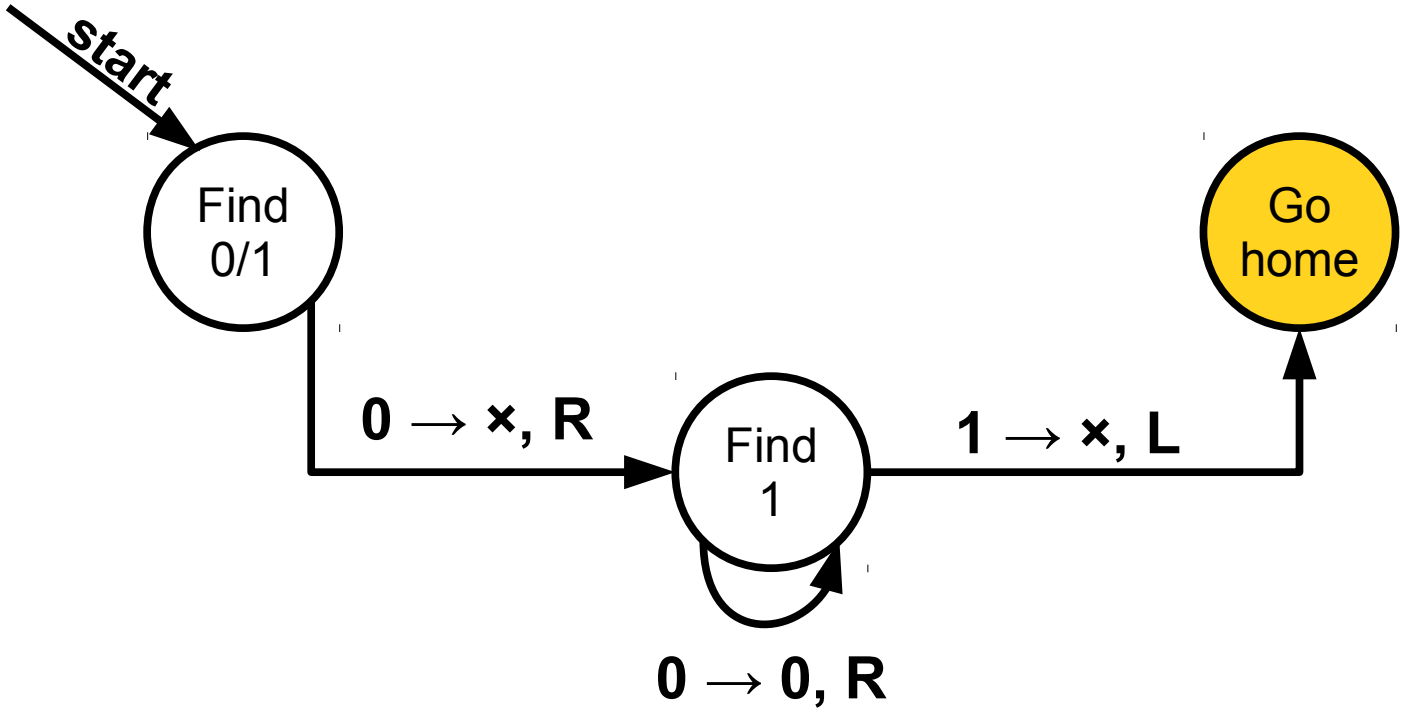
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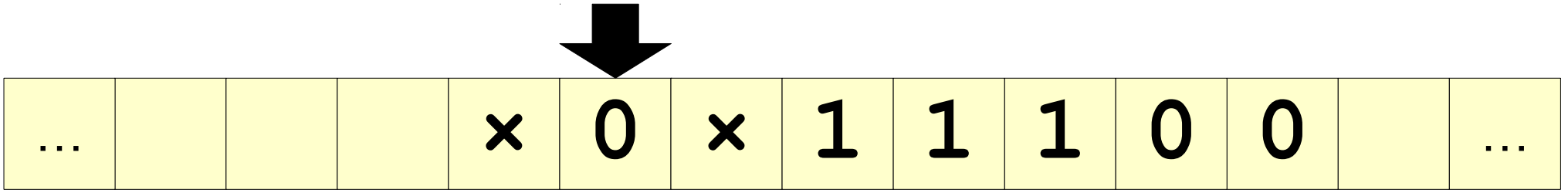
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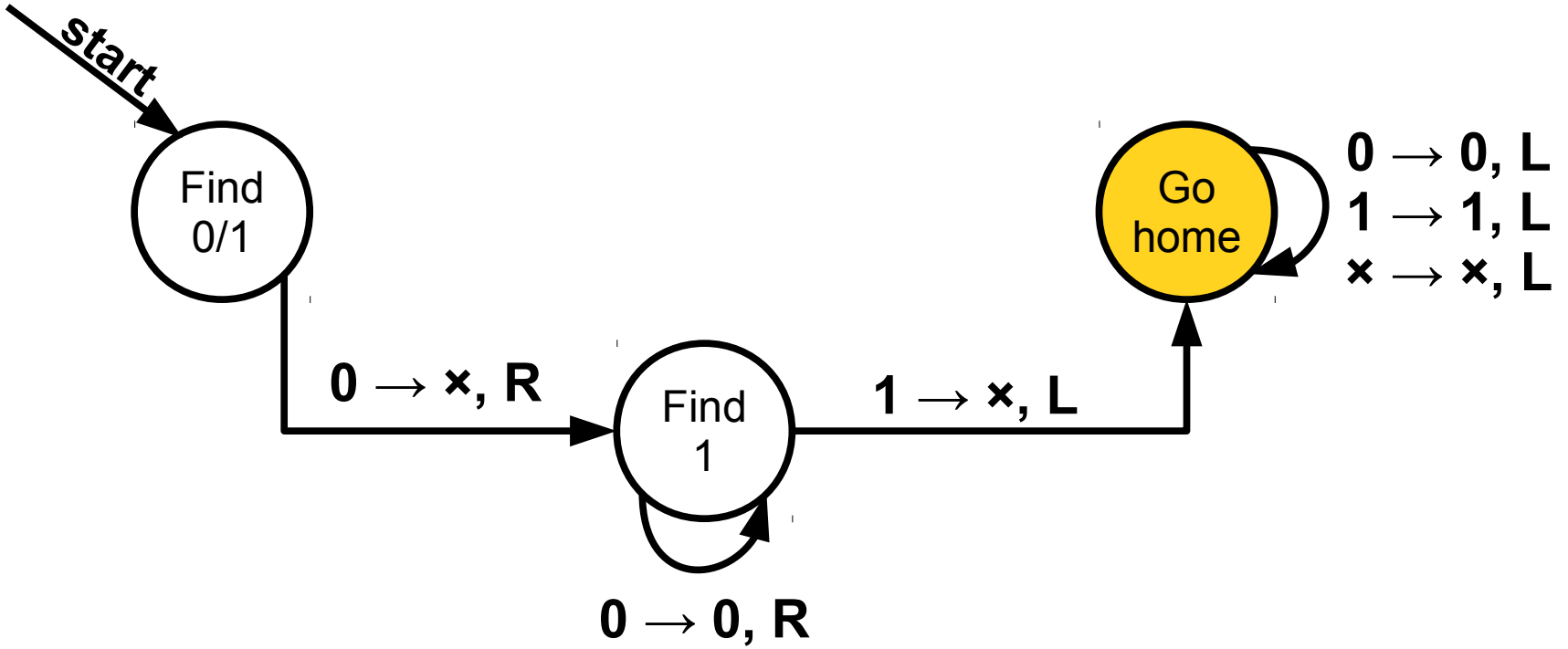
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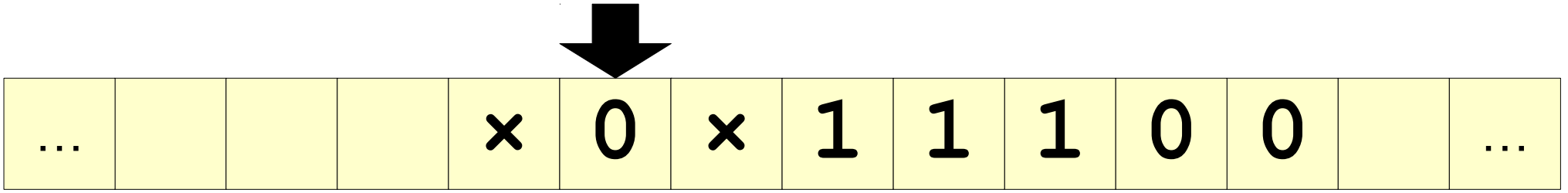
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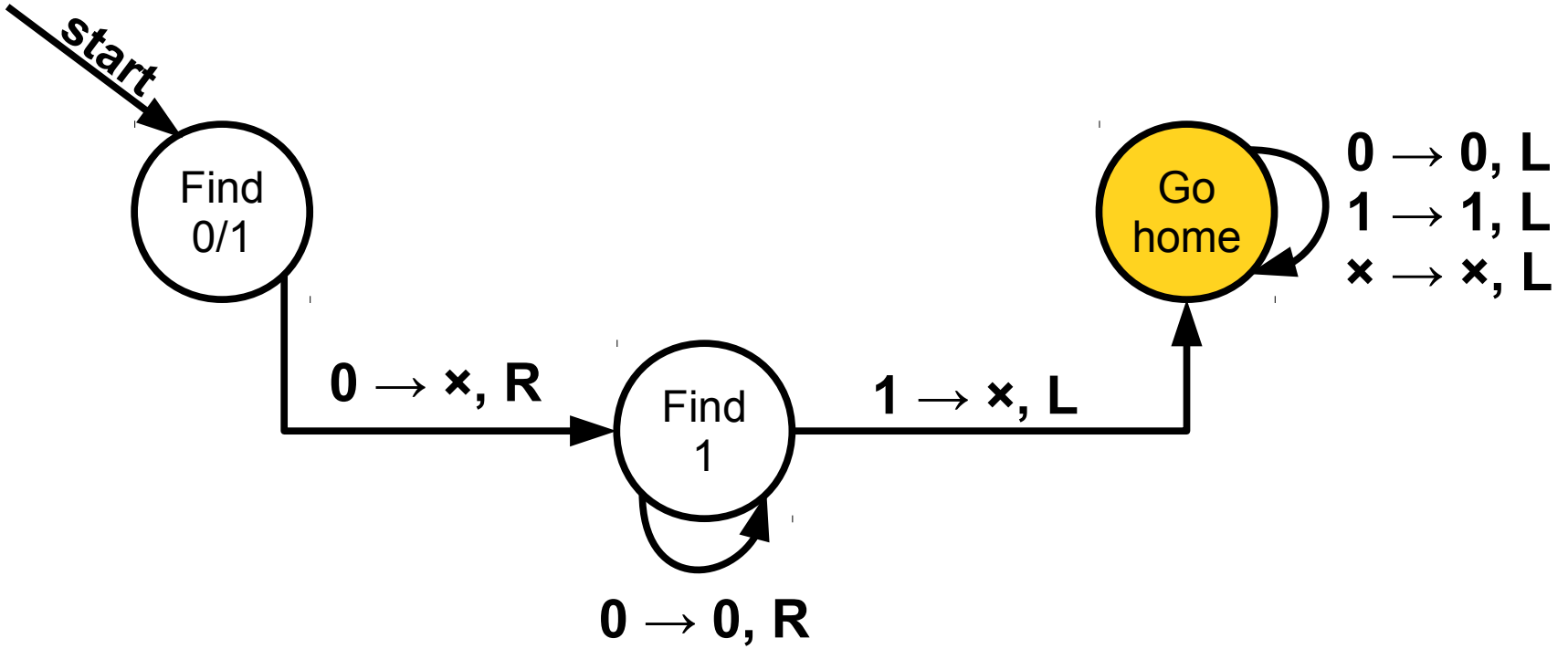
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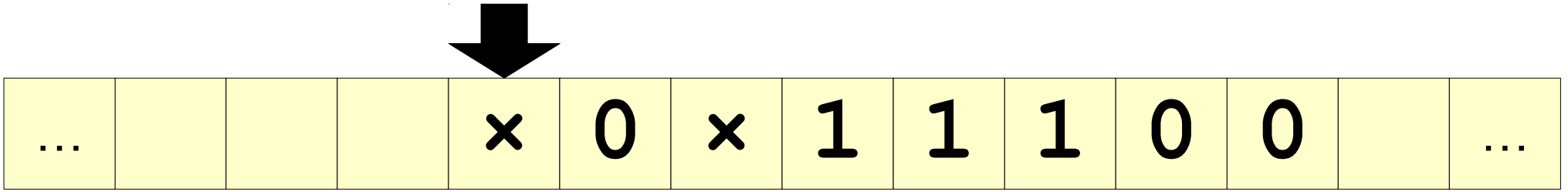
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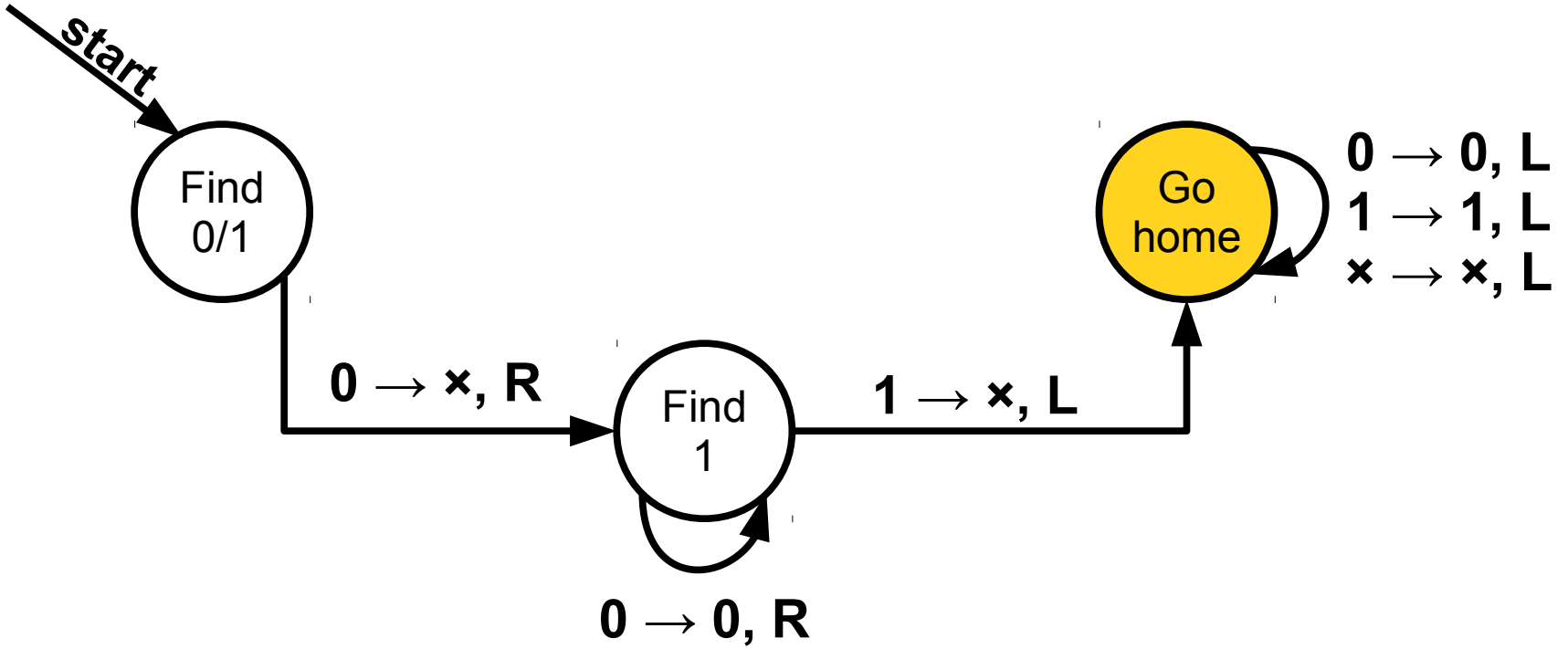
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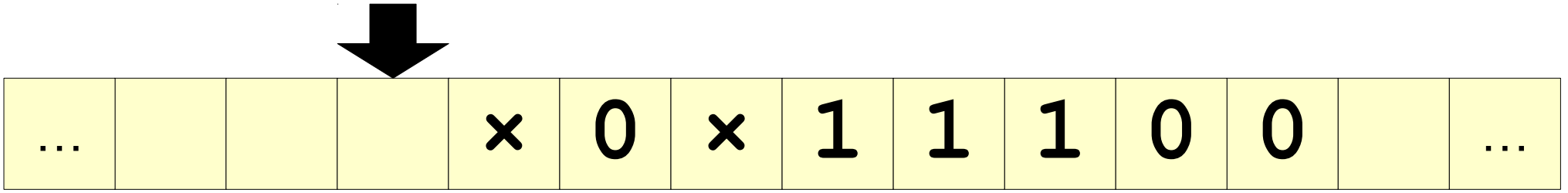
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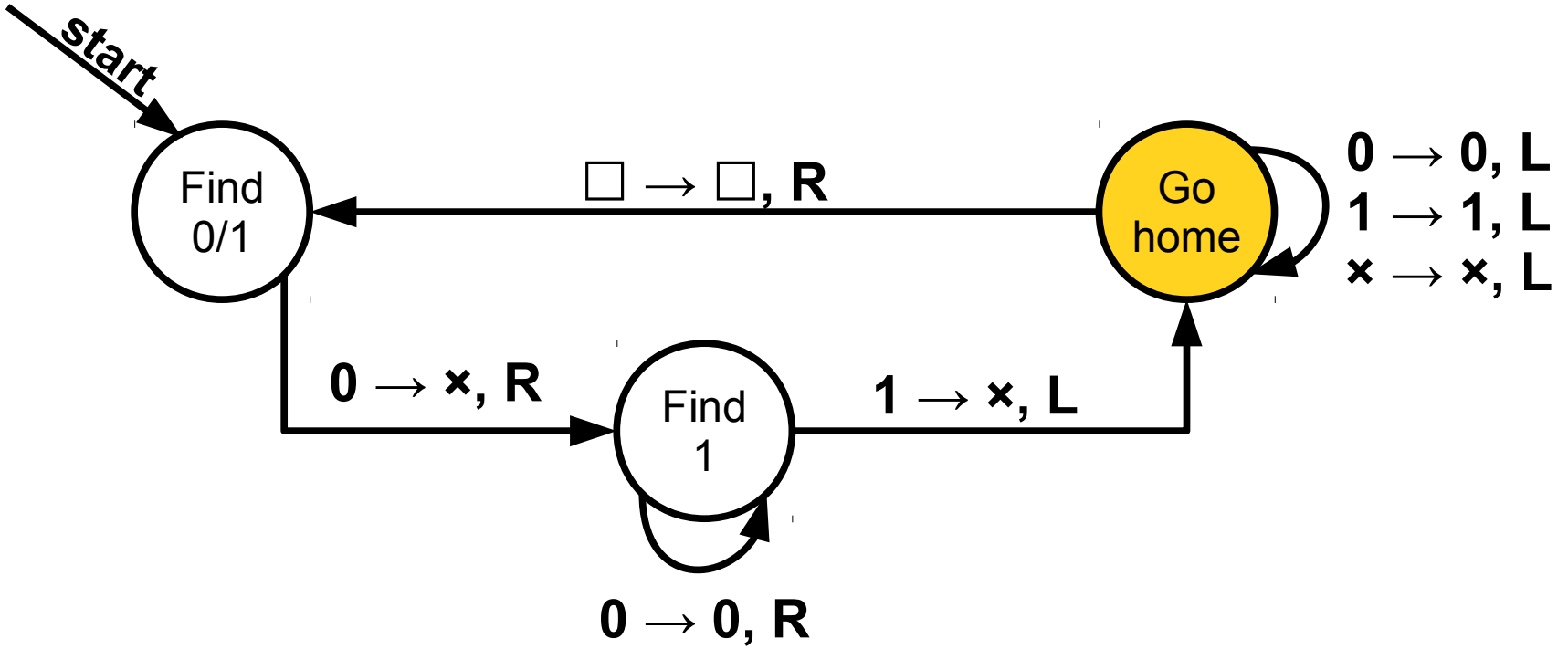
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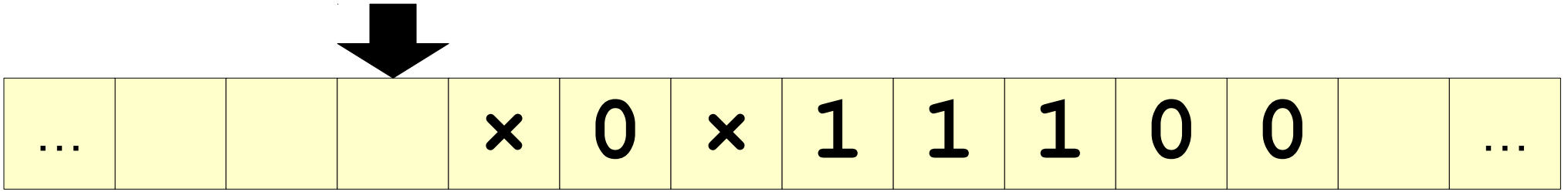
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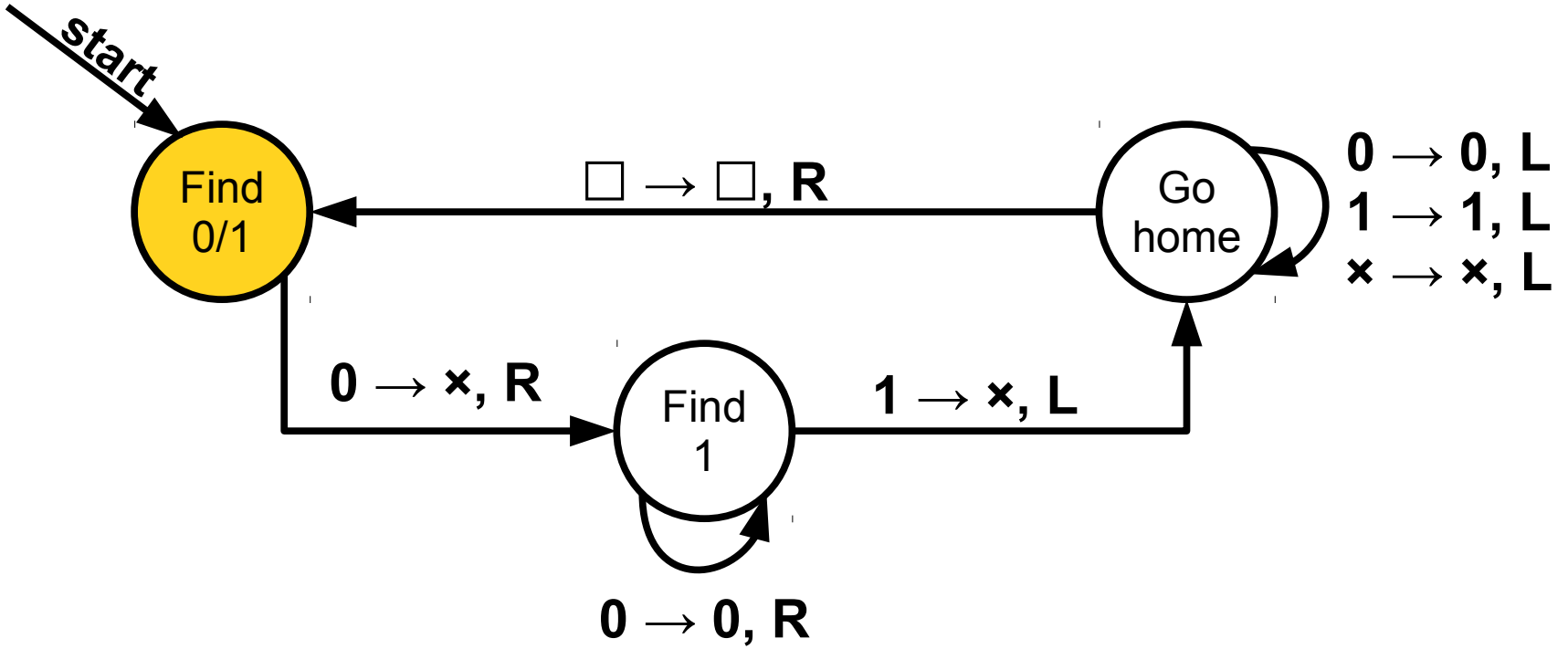
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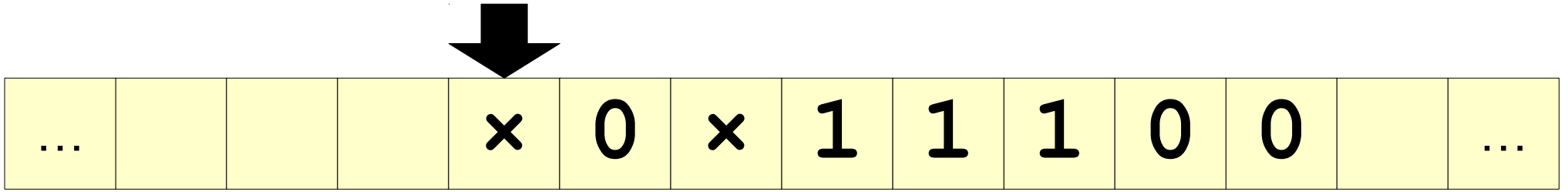
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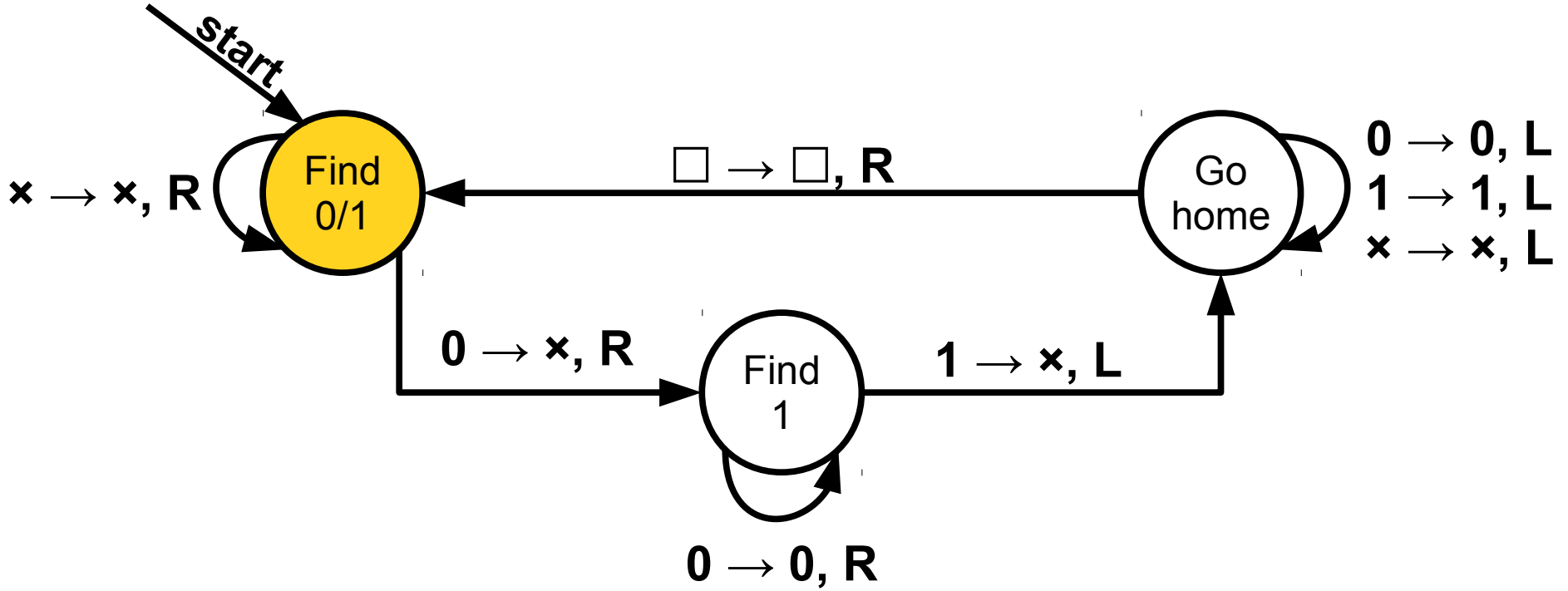
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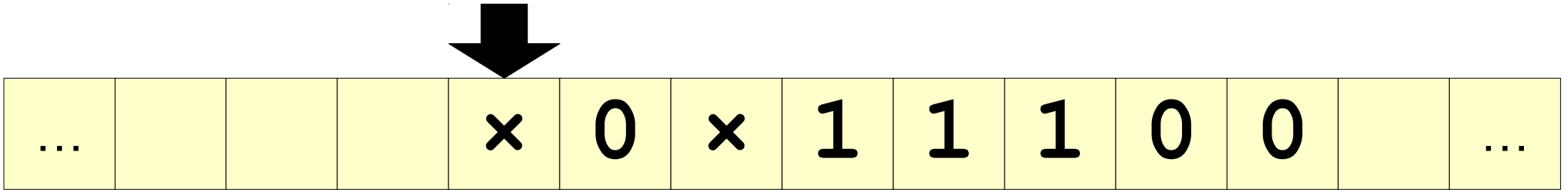
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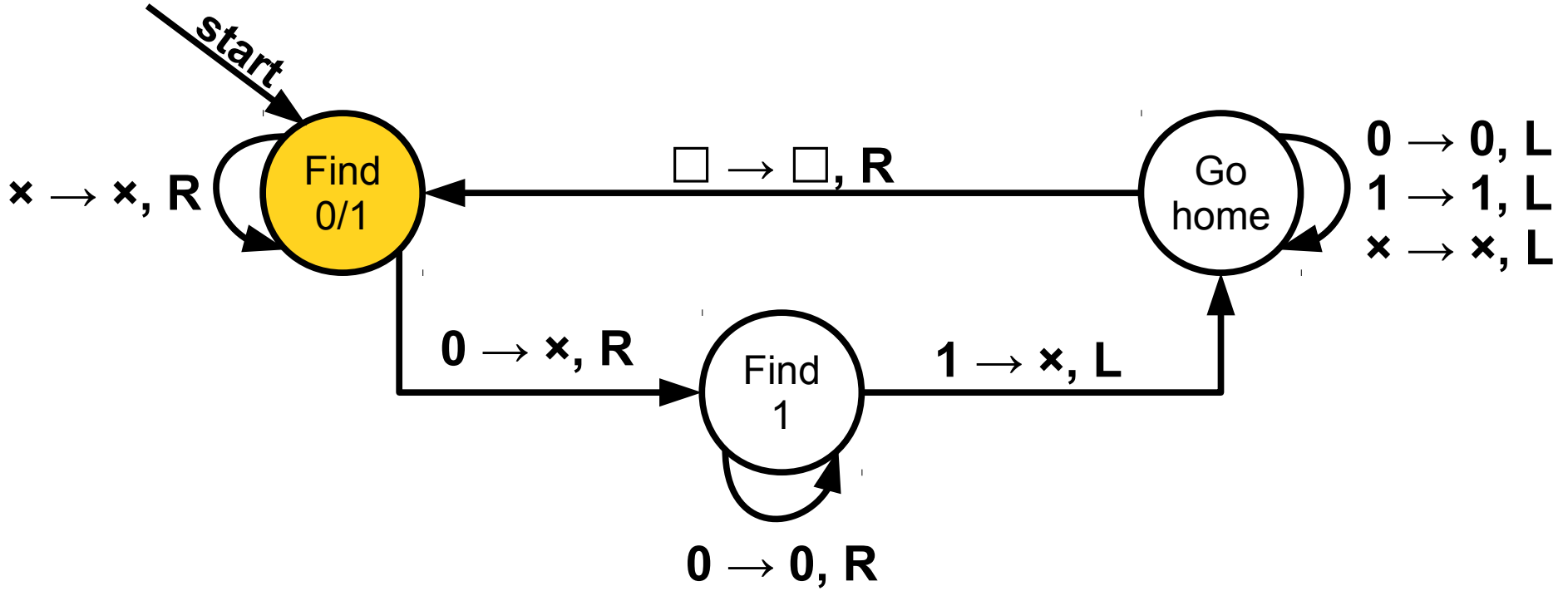
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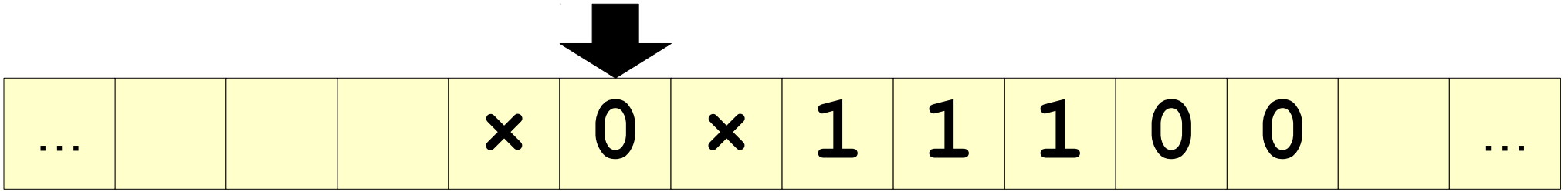
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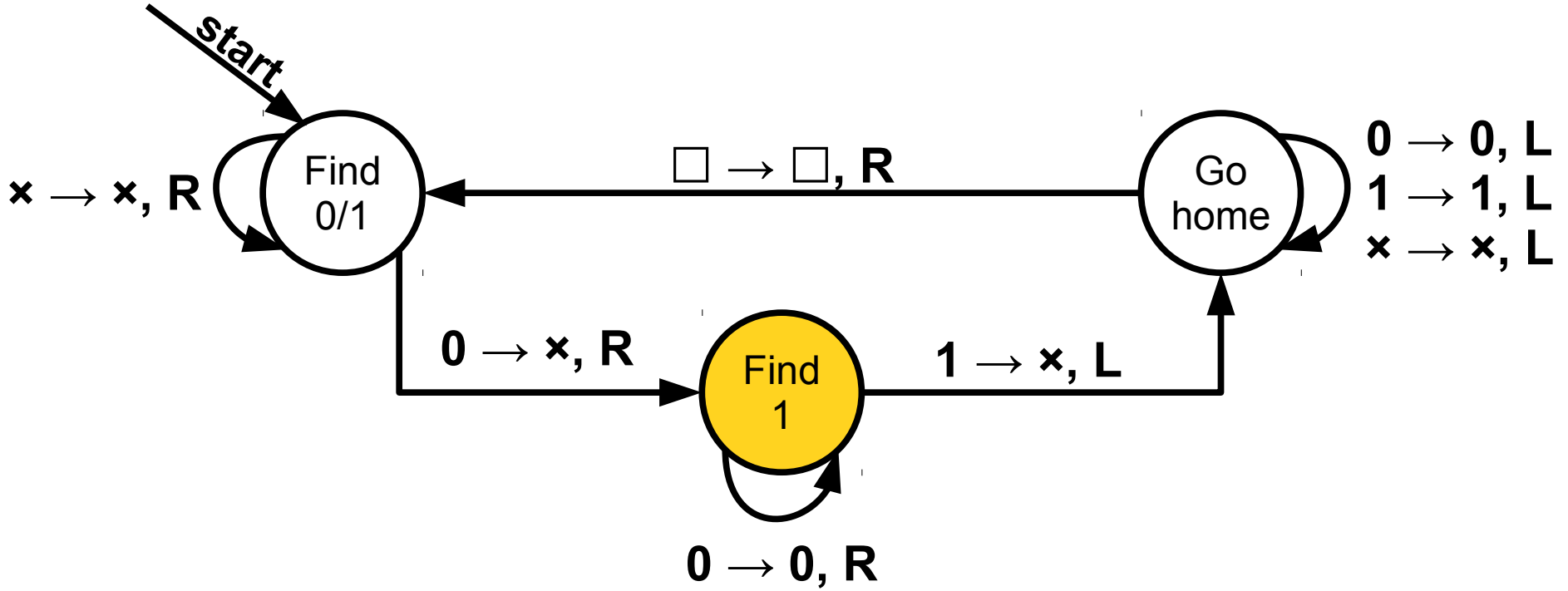
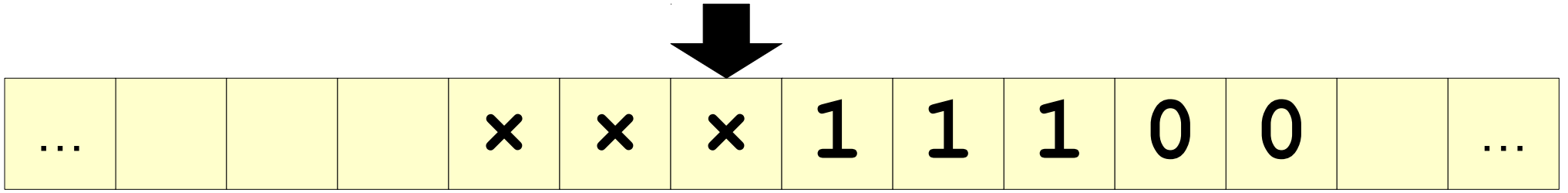
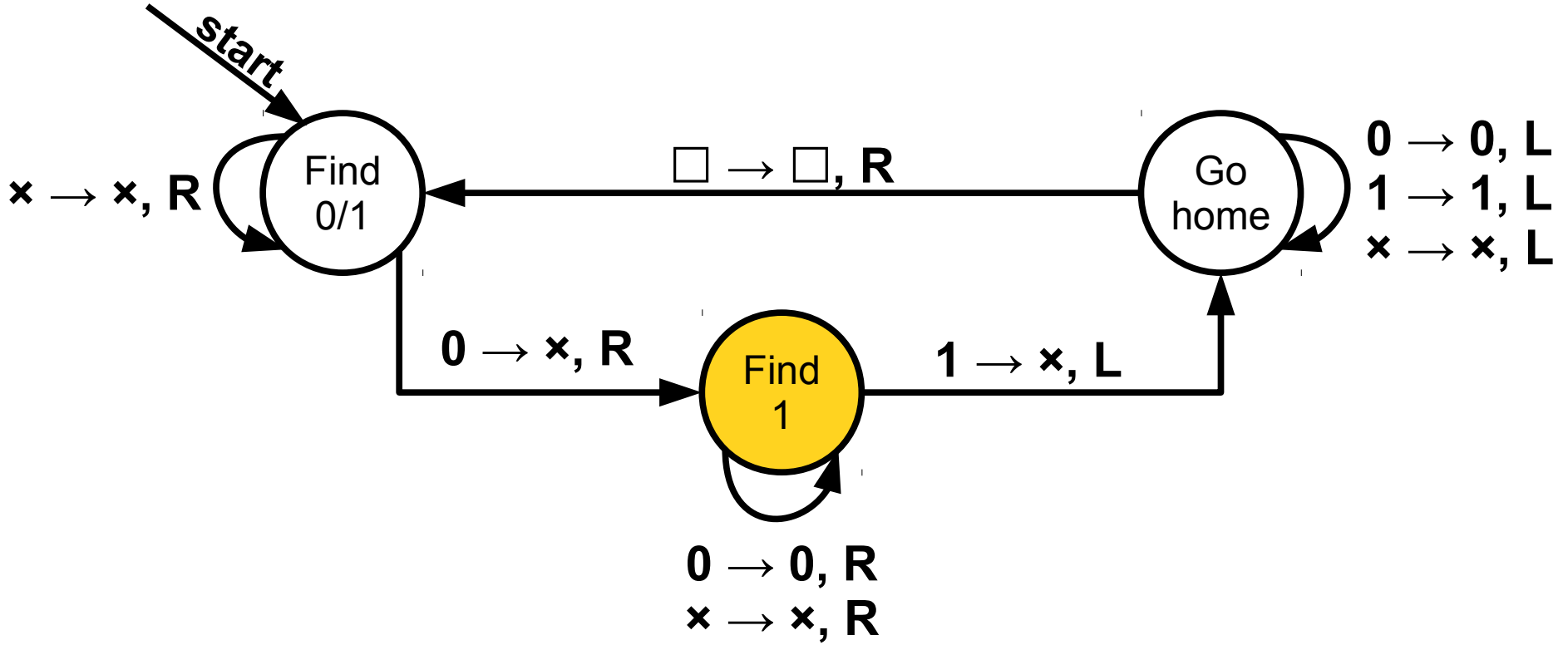
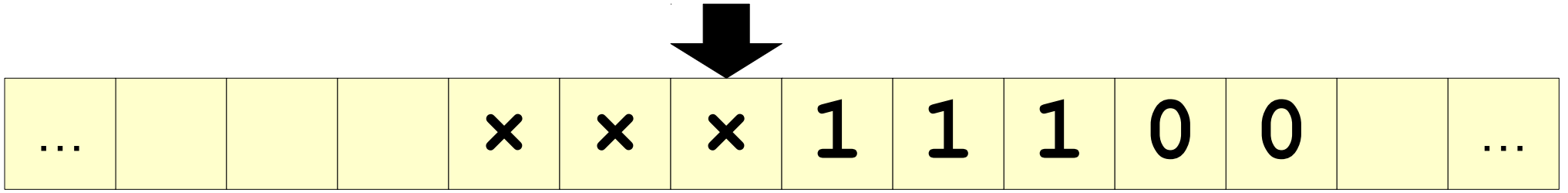
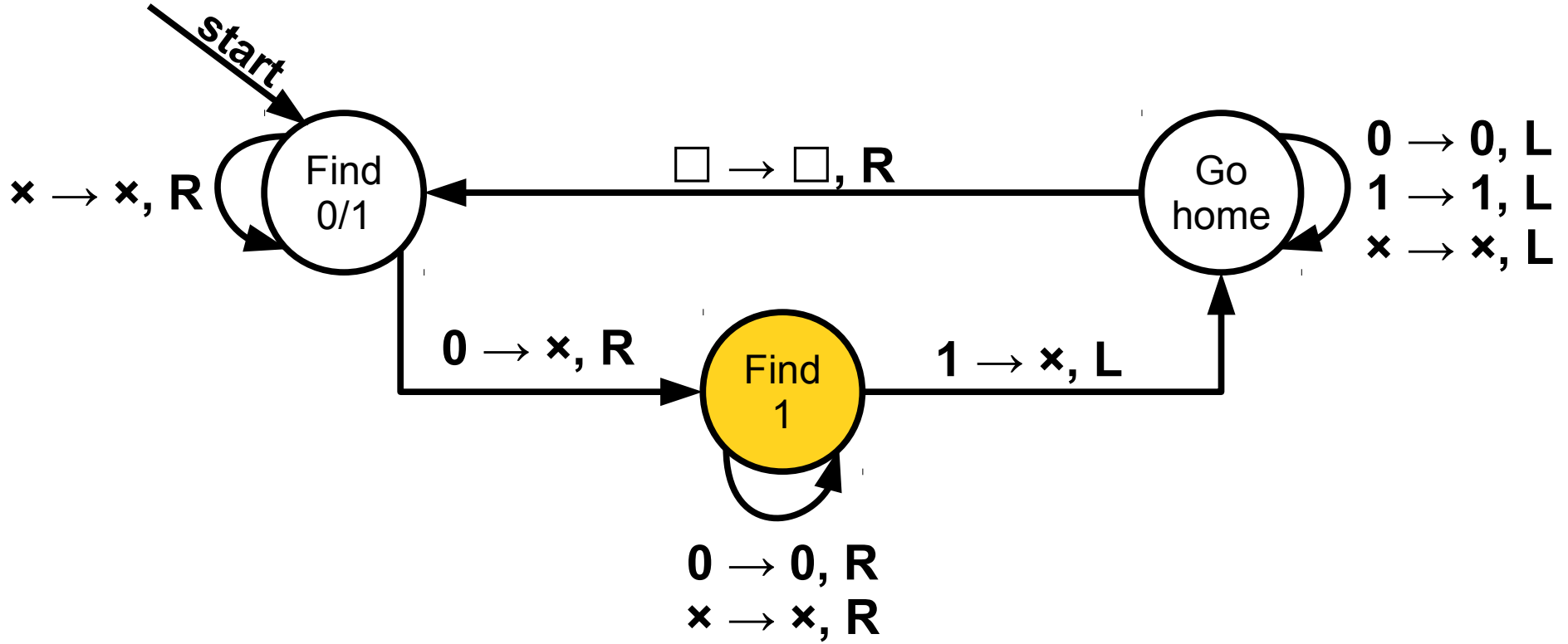
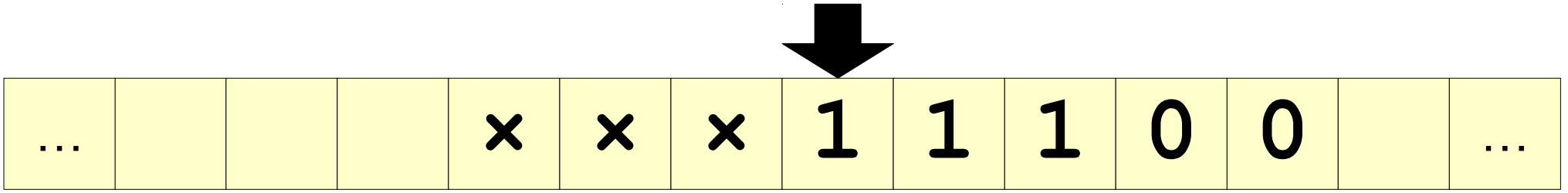

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R

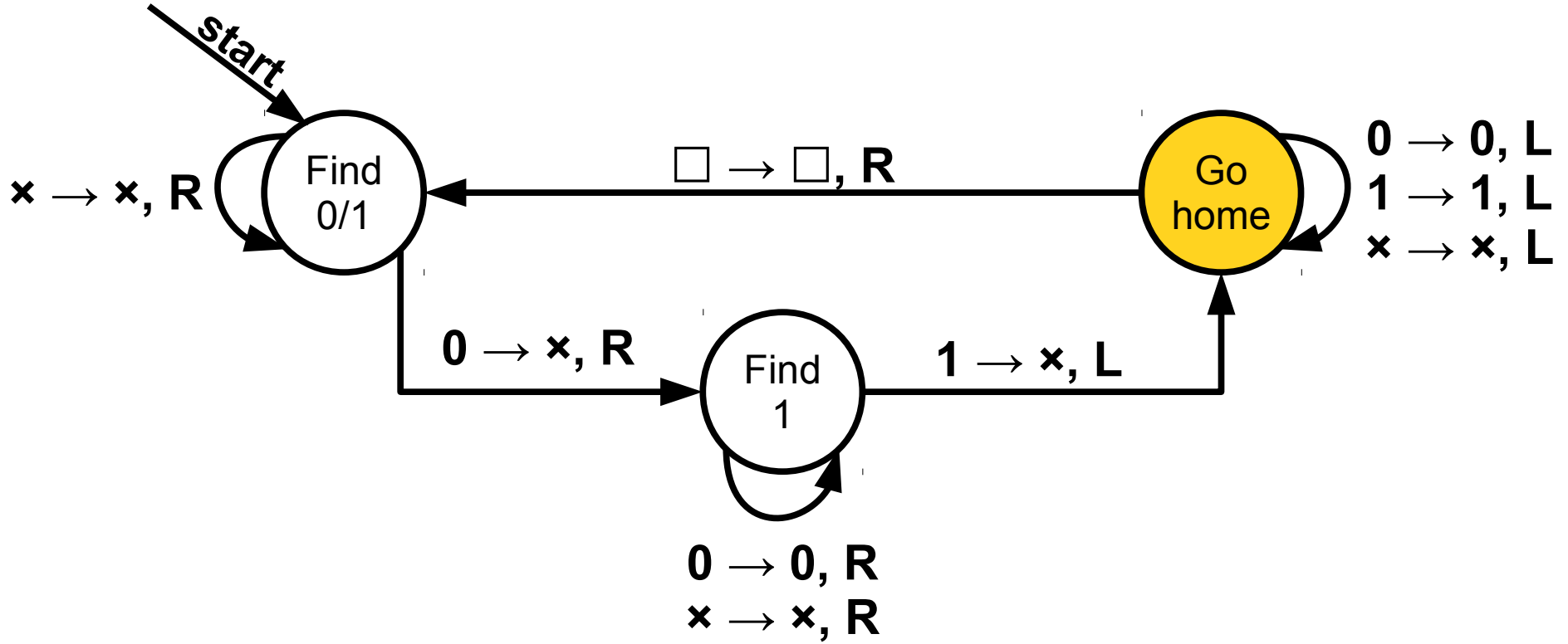

…
×
×
×
1
1
1
0
0
…

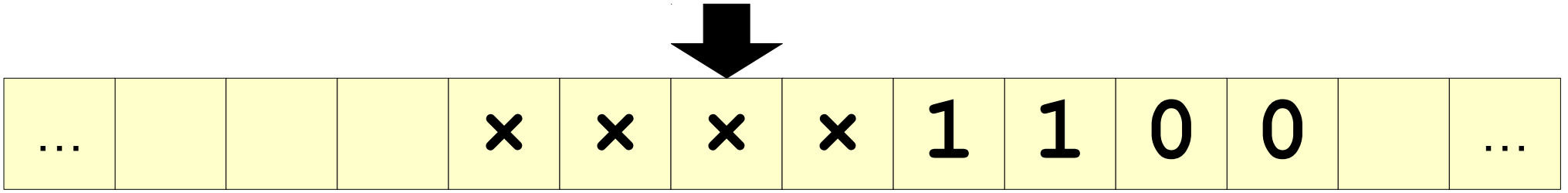

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

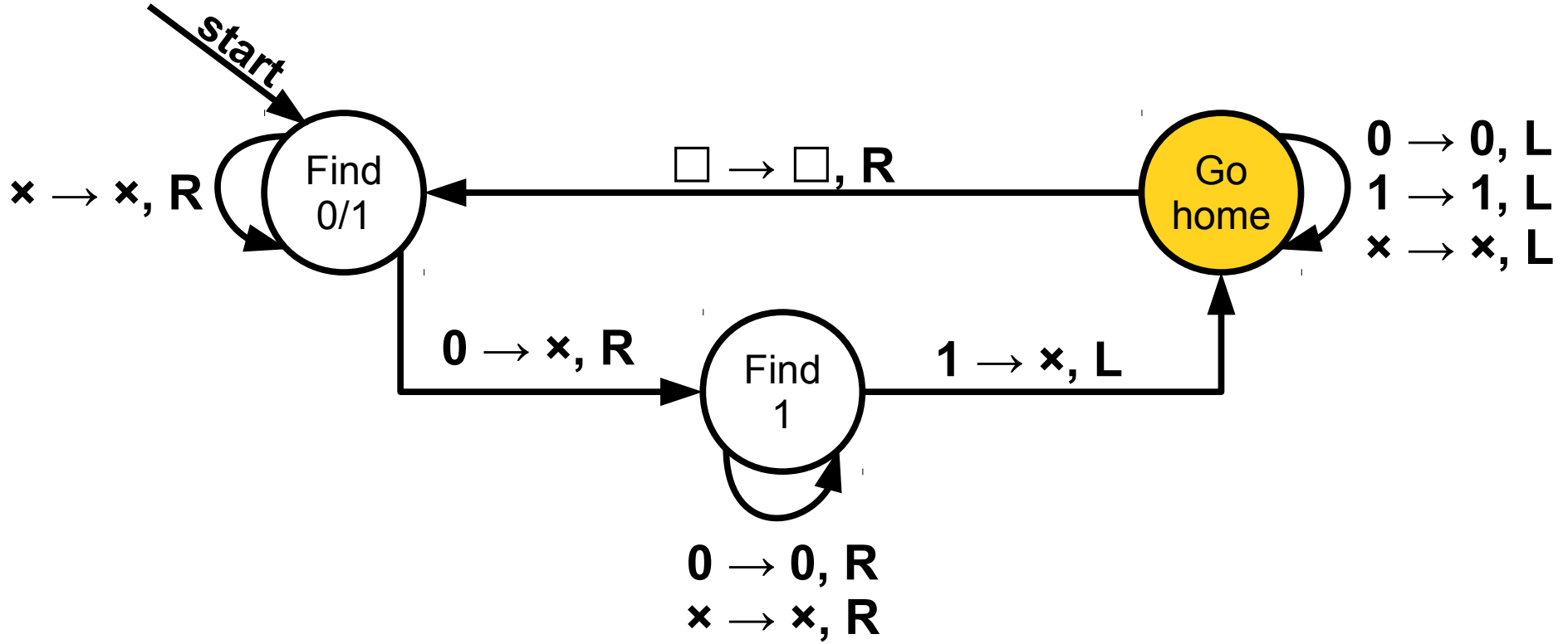

…
×
×
×
1
1
1
0
0
…

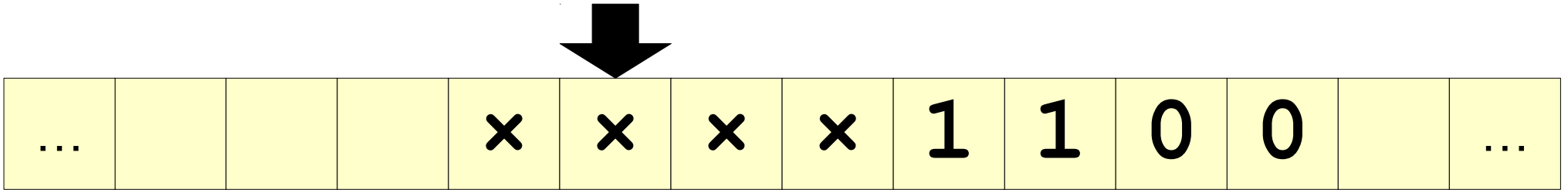

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

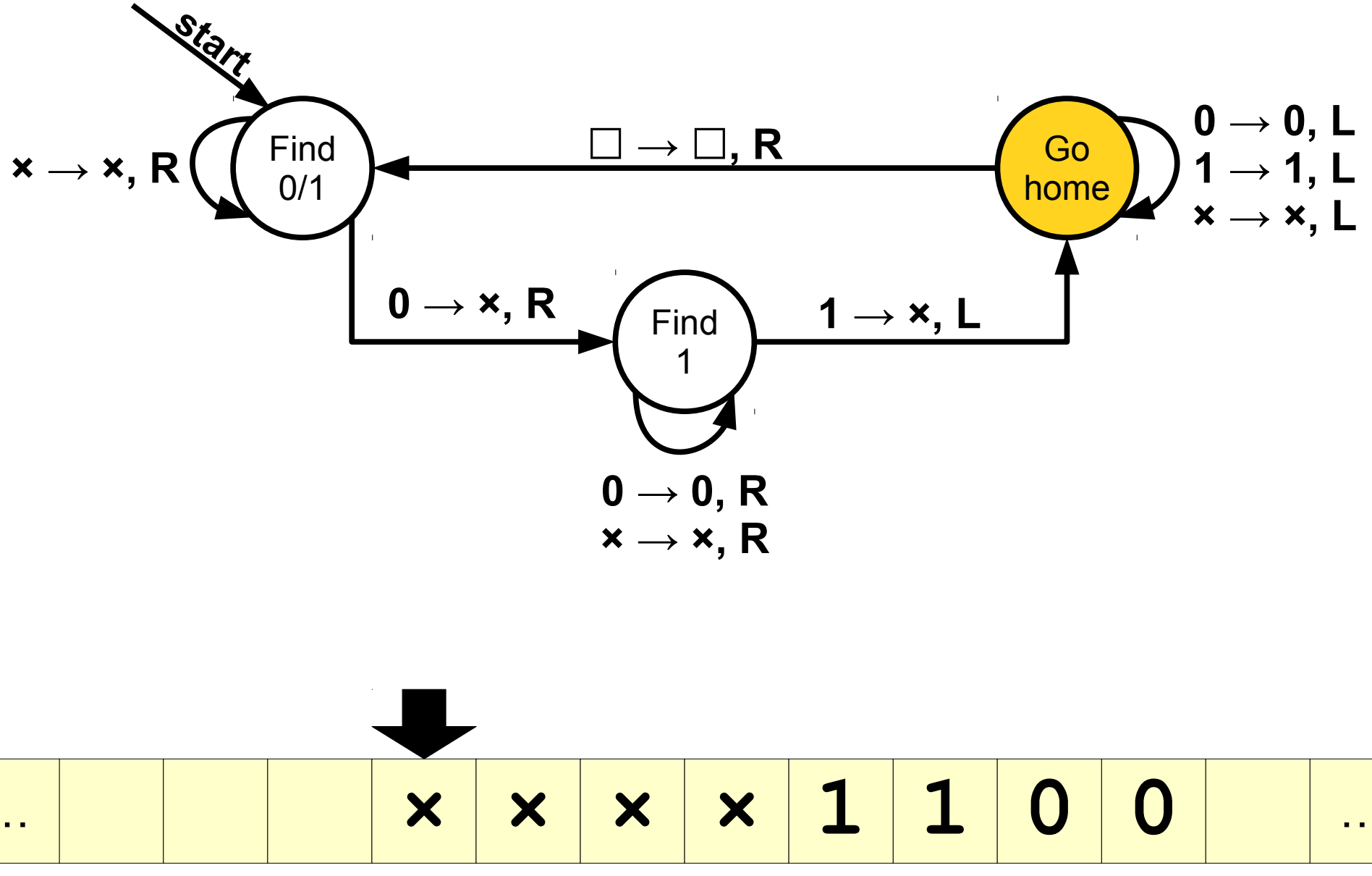

…
×
×
×
1
1
1
0
0
…

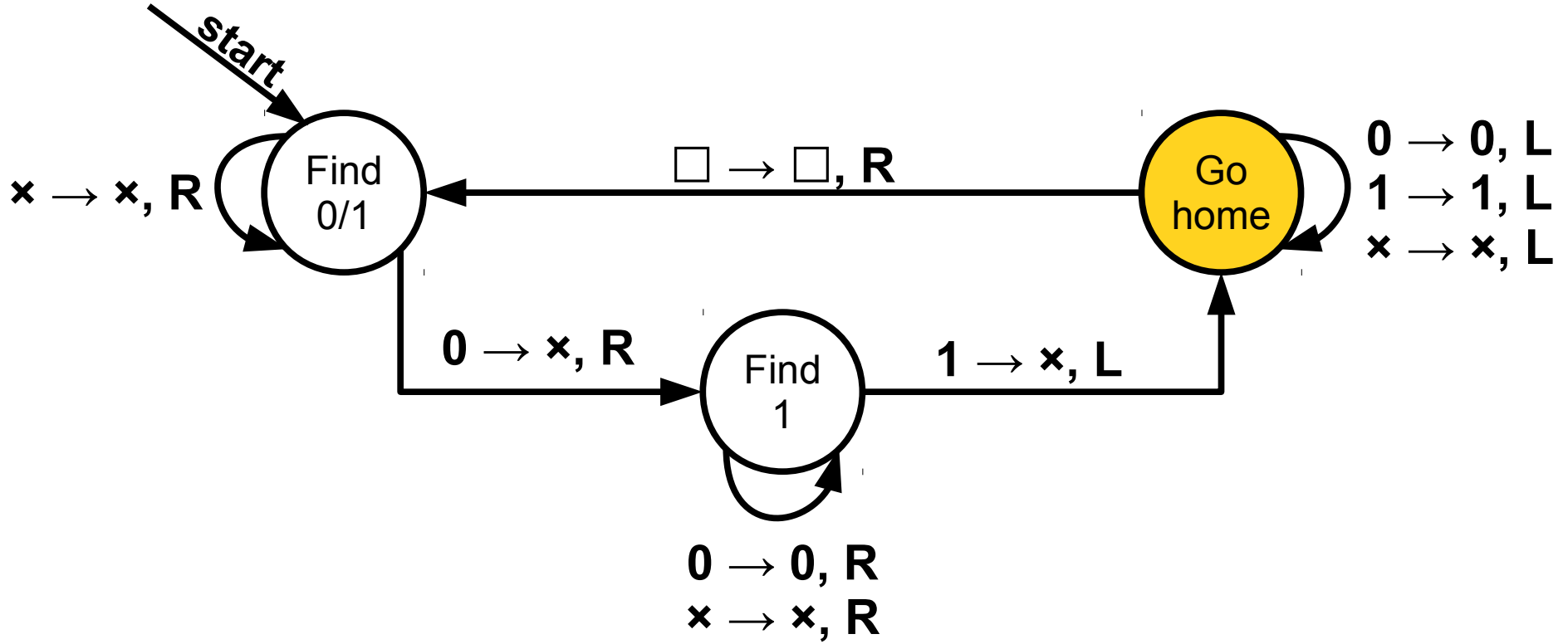

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

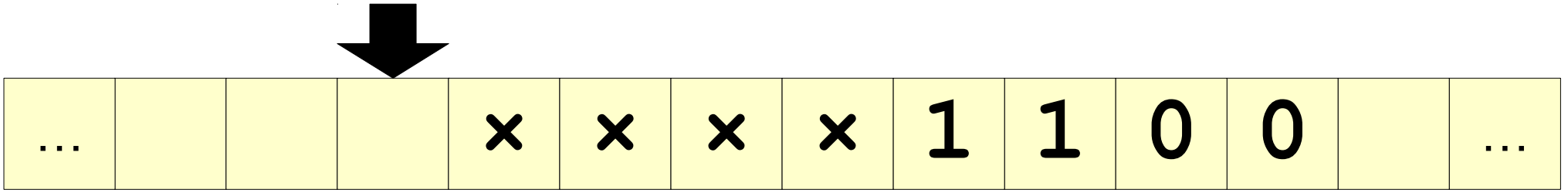

…
×
×
×
×
1
1
0
0
…

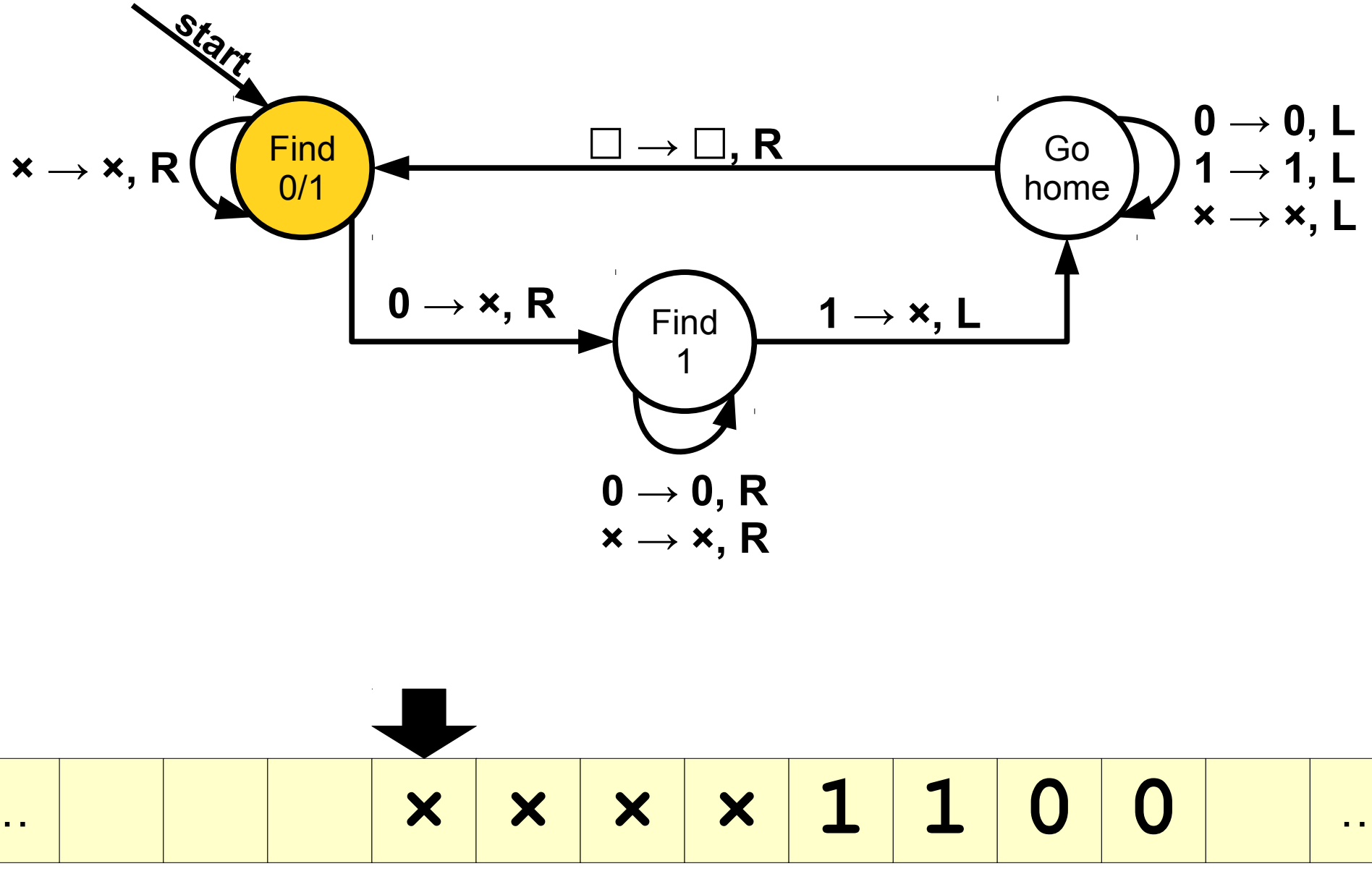

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

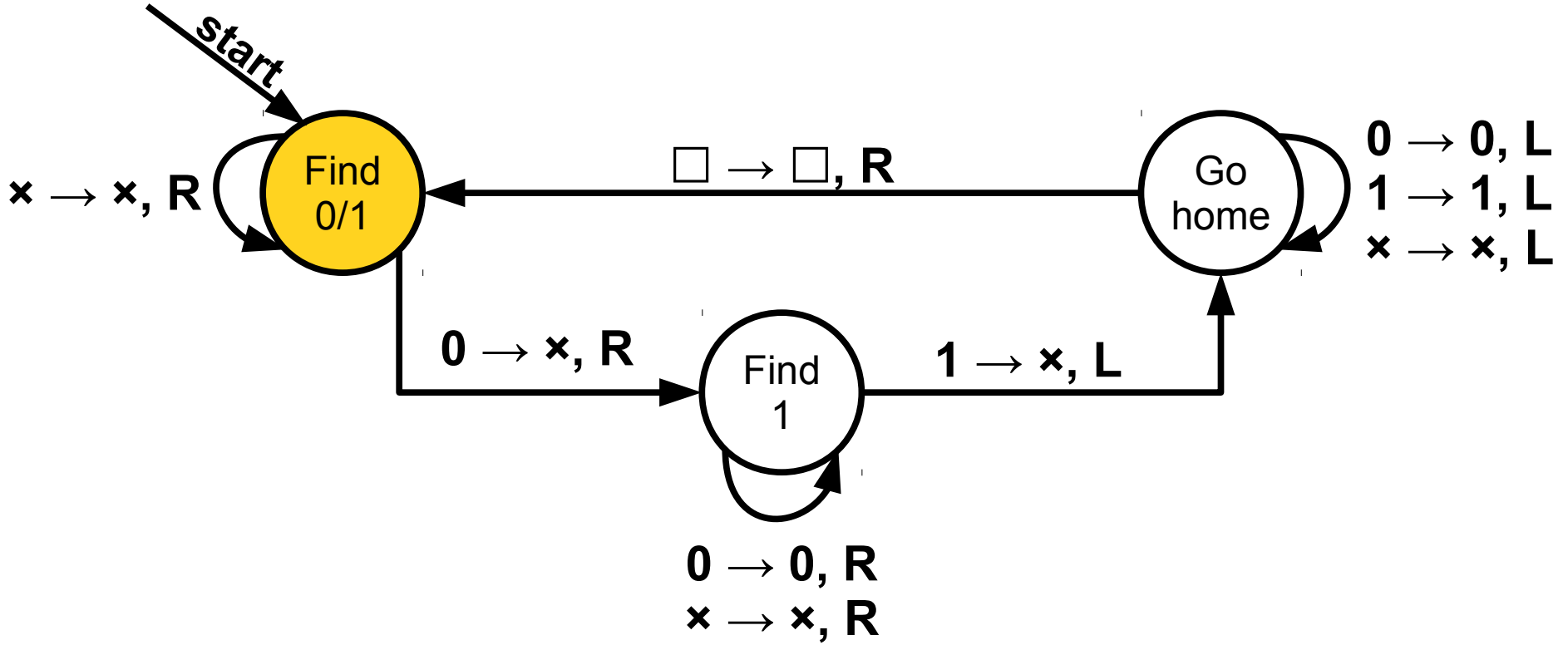

…
×
×
×
×
1
1
0
0
…

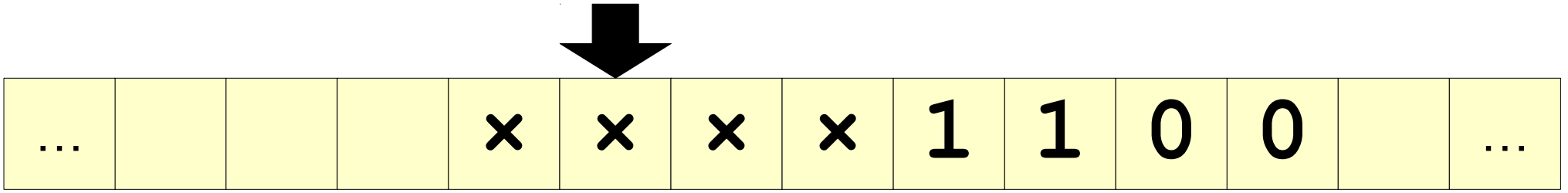

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R
… × × × × 1 1 0 0 …

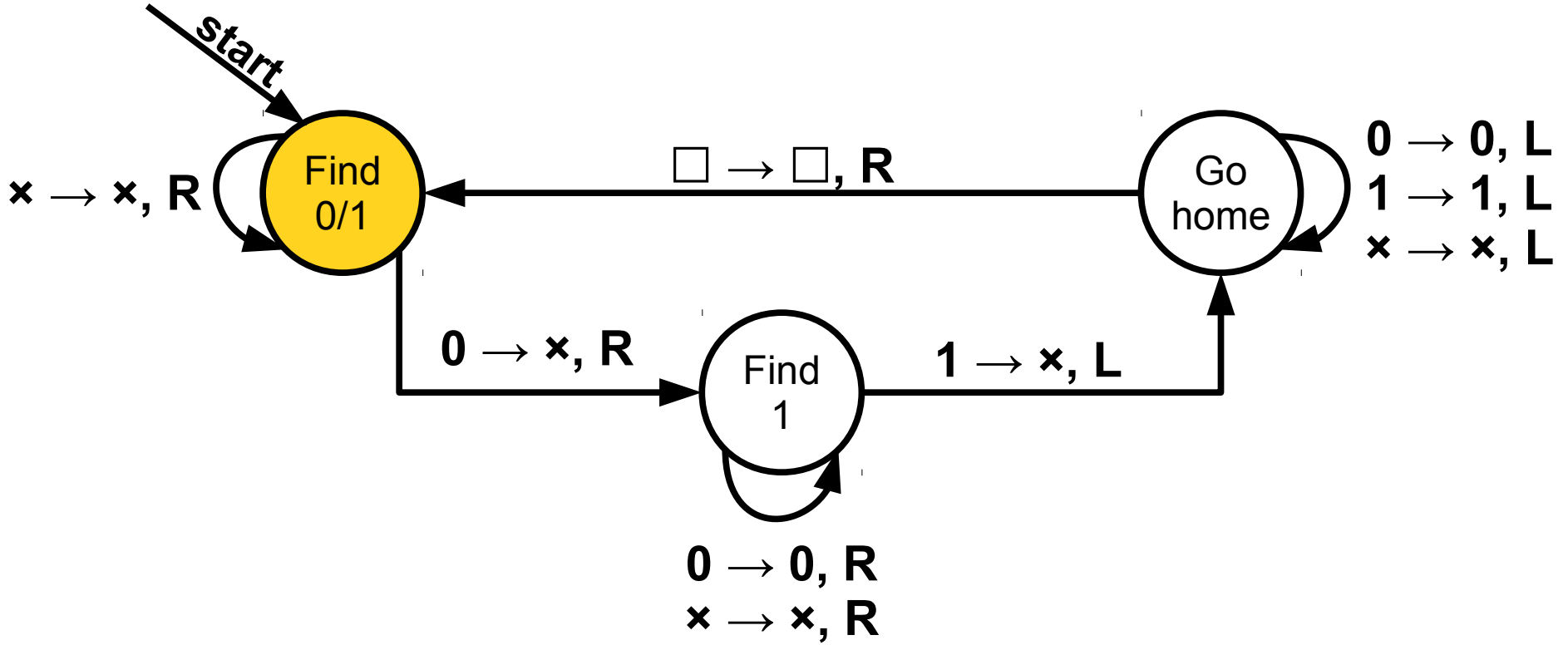

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

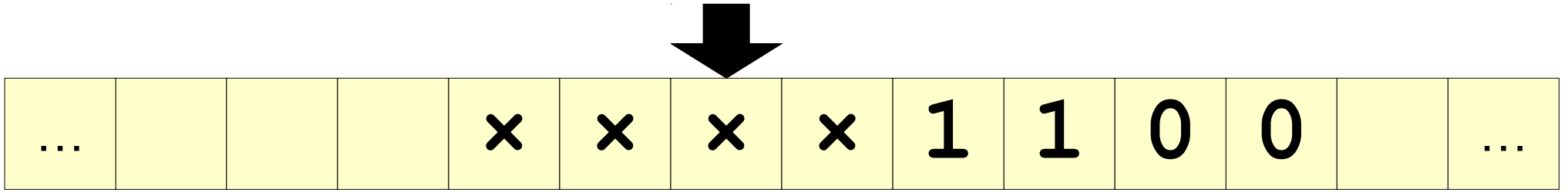

…
×
×
×
×
1
1
0
0
…

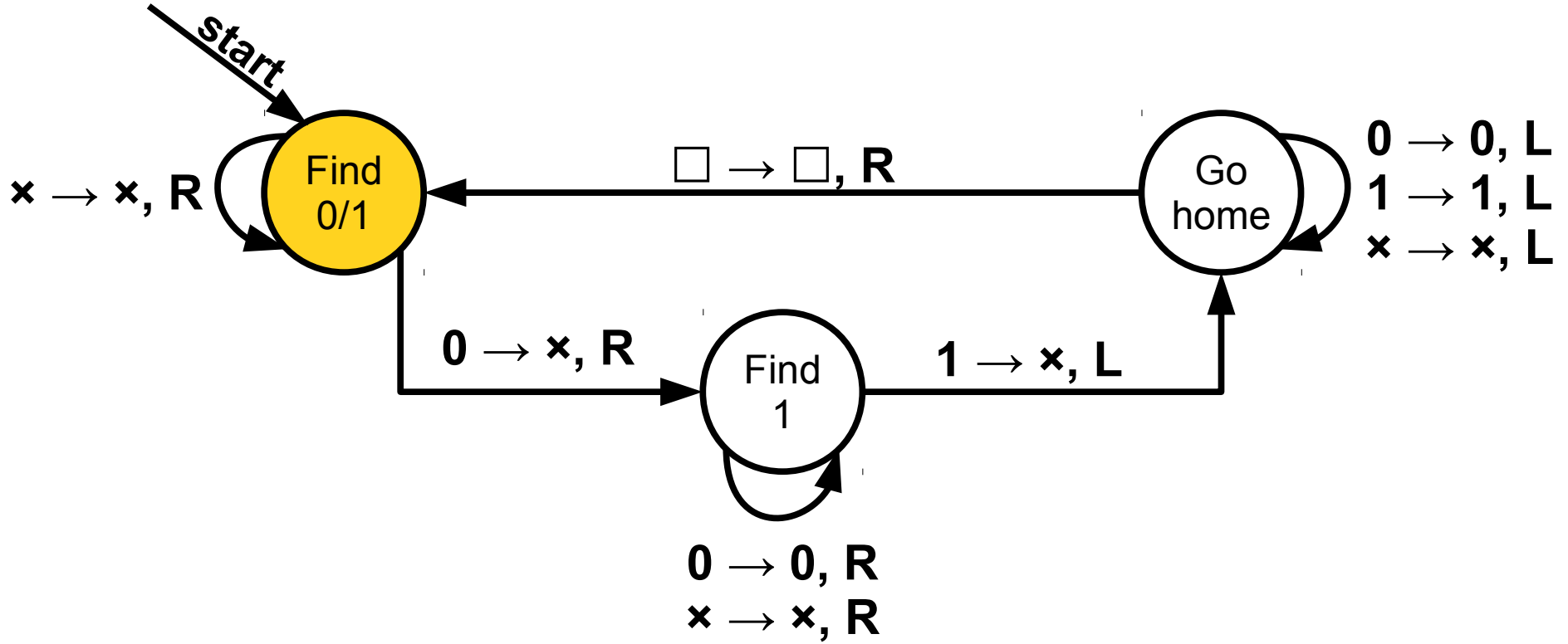

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R
… × × × × 1 1 0 0 …

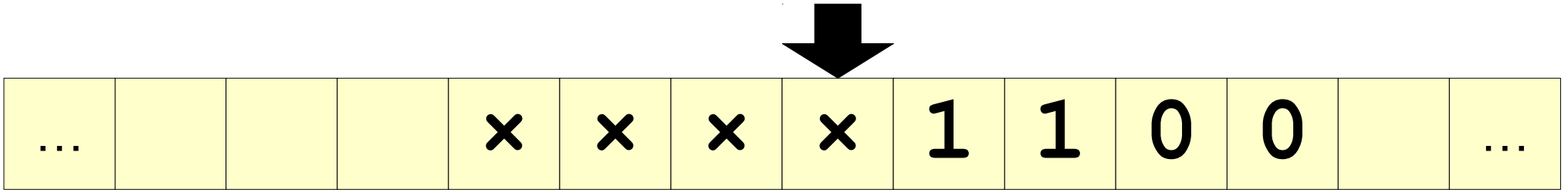

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

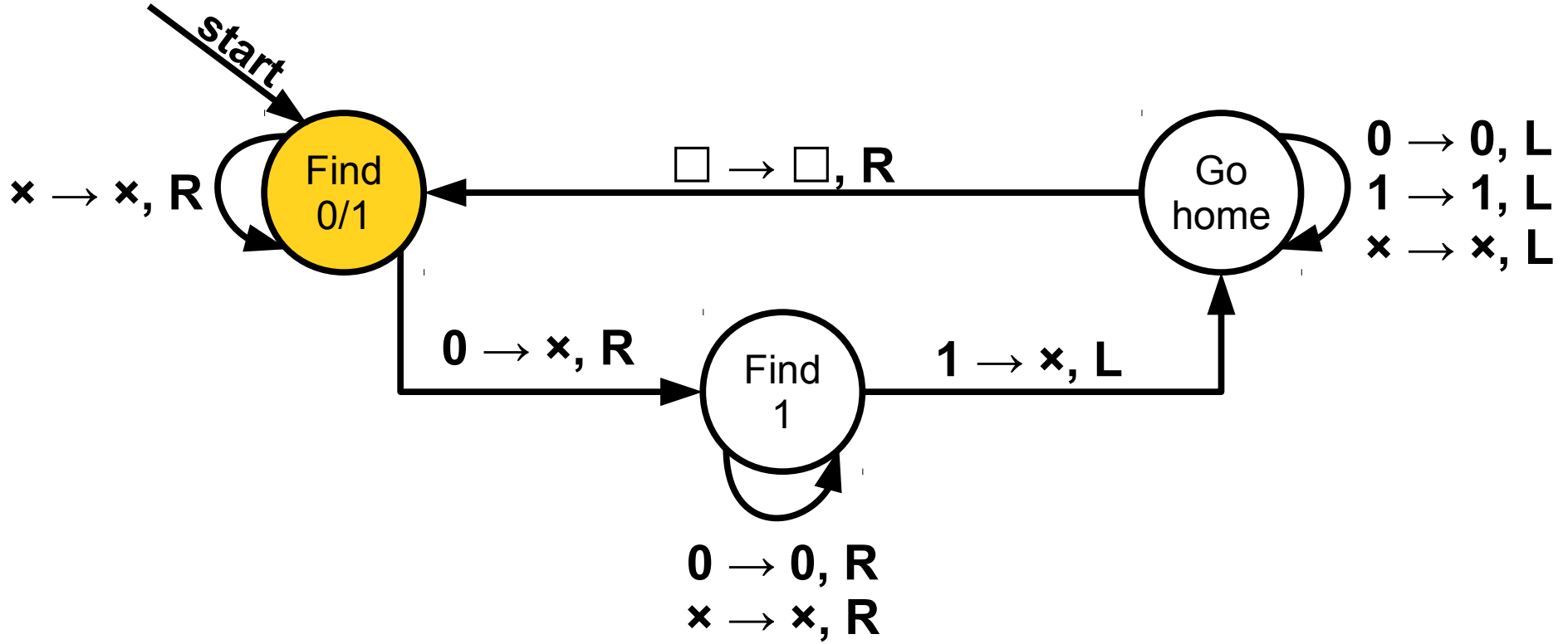

…
×
×
×
×
1
1
0
0
…

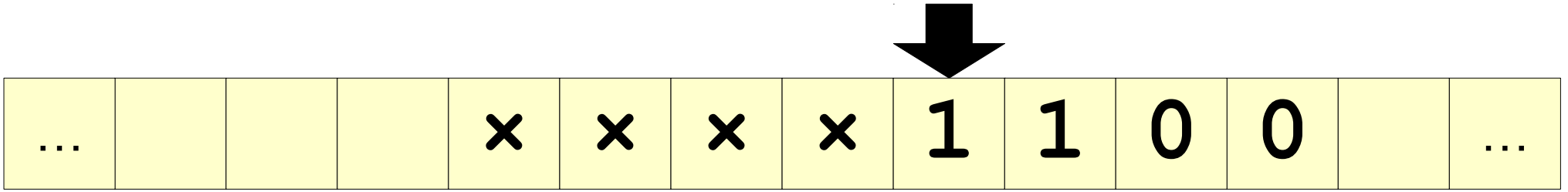

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

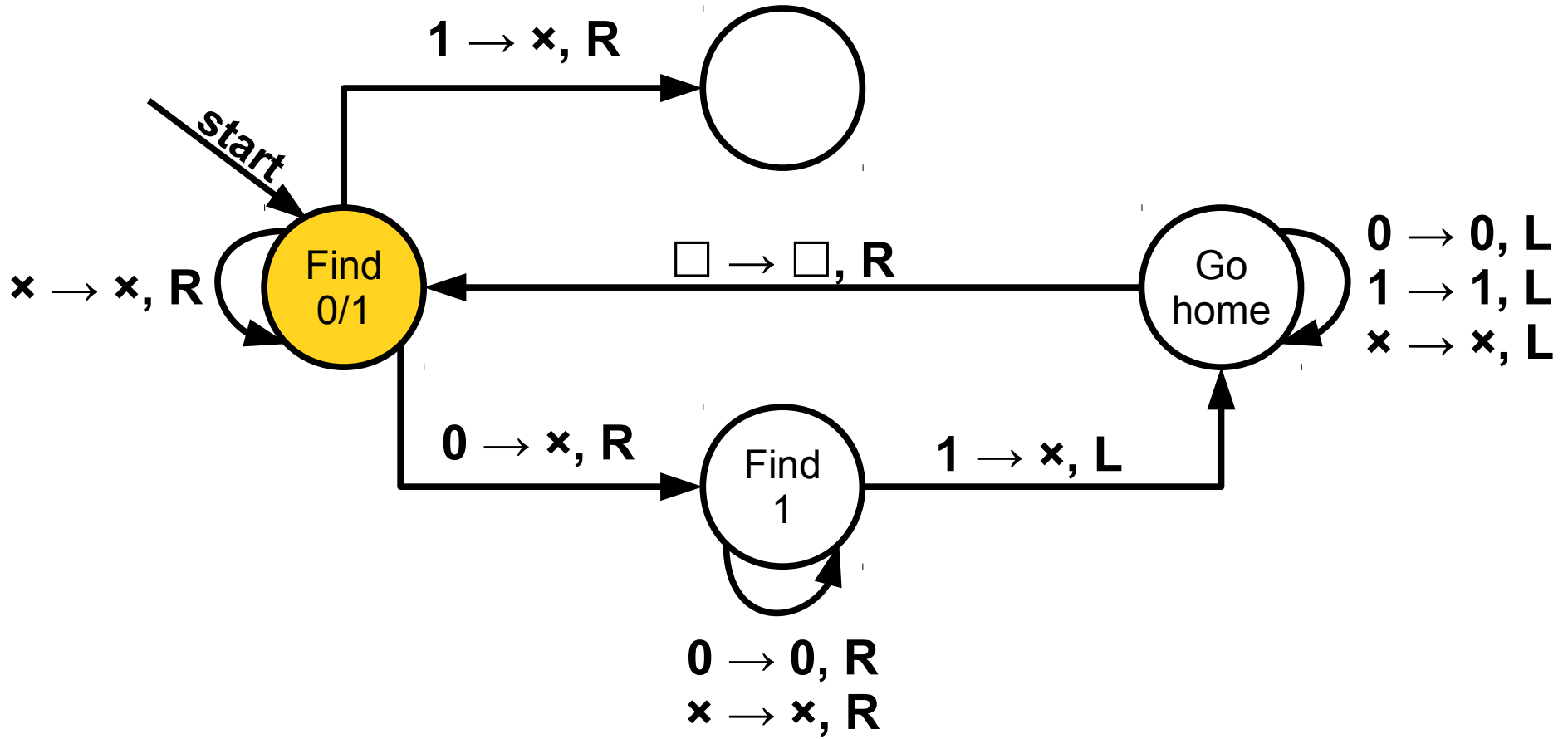

…
×
×
×
×
1
1
0
0
…

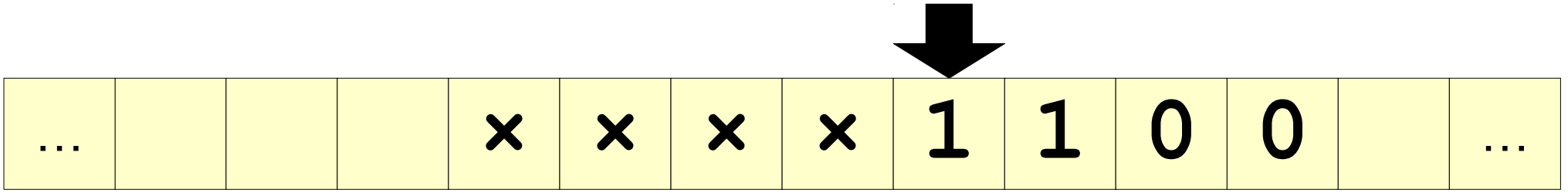

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

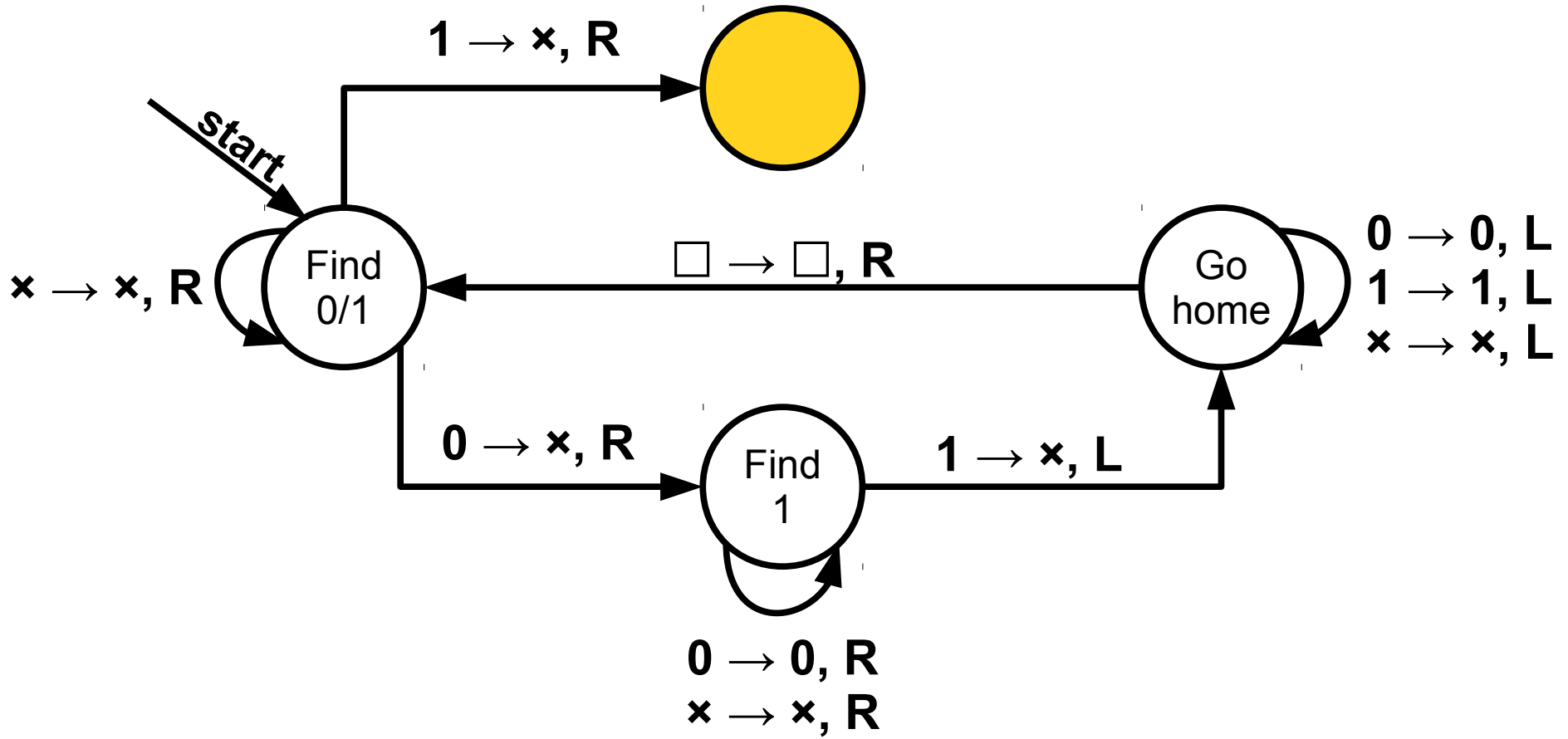

…
×
×
×
×
1
1
0
0
…

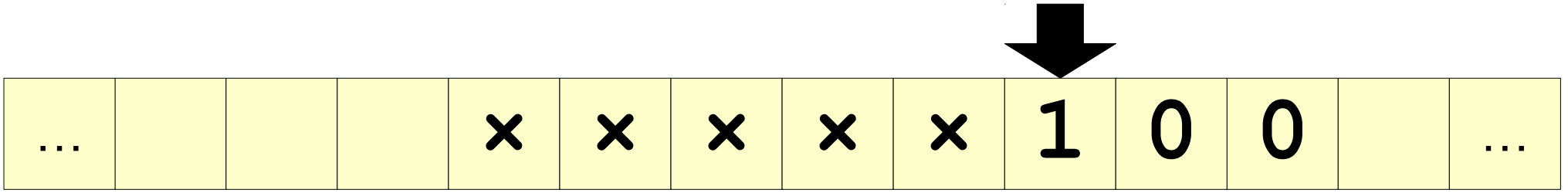

start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

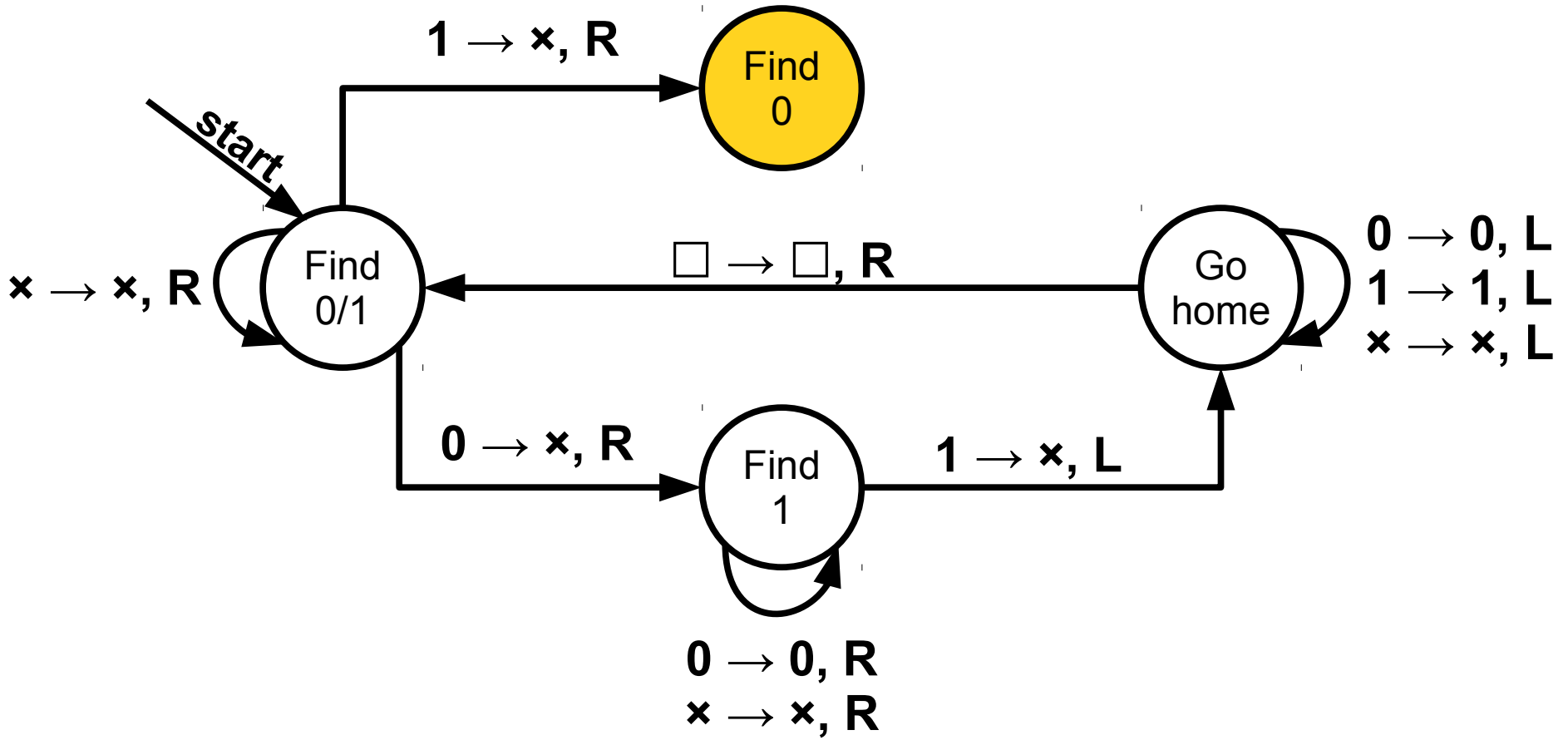

…
×
×
×
×
1
1
0
0
…

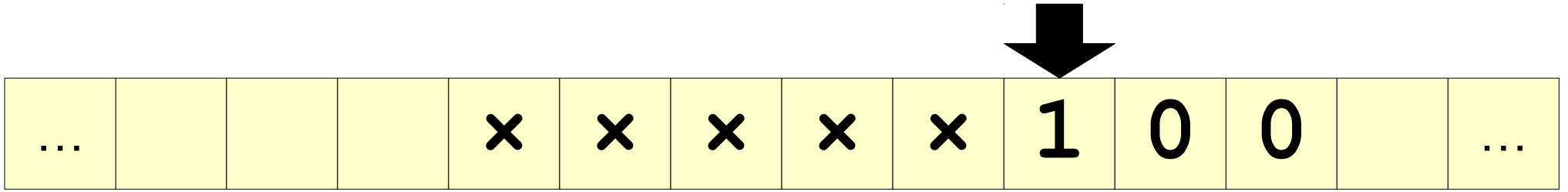

1 → ×, R
start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

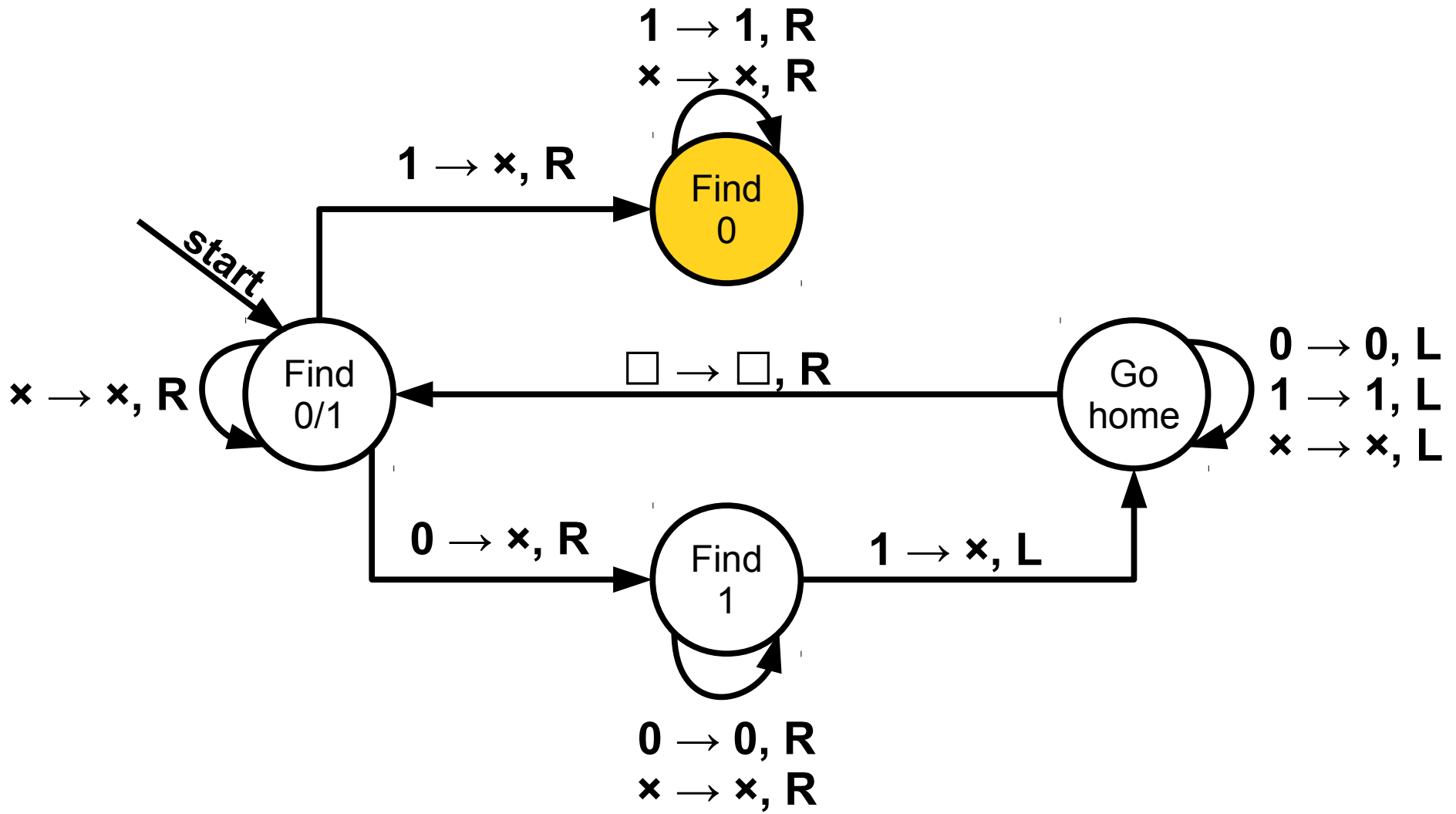

…
×
×
×
×
1
1
0
0
…

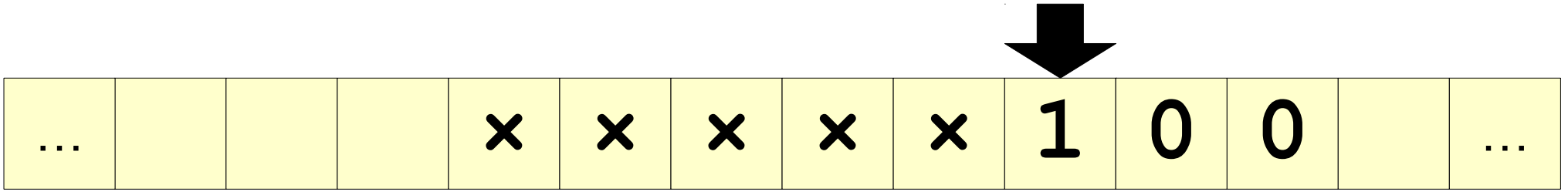

1 → ×, R
start
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

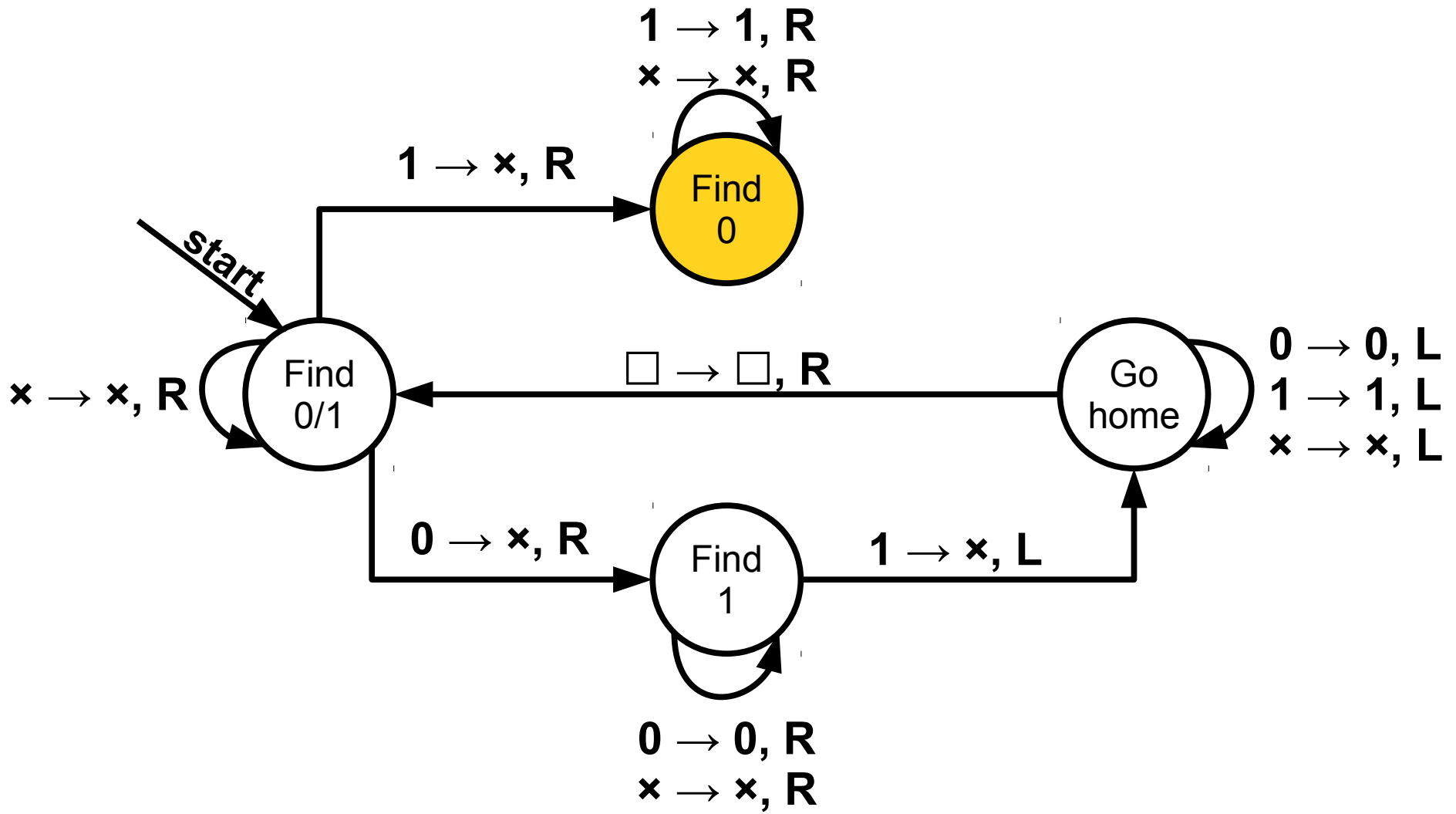

…
×
×
×
×
×
1
0
0
…

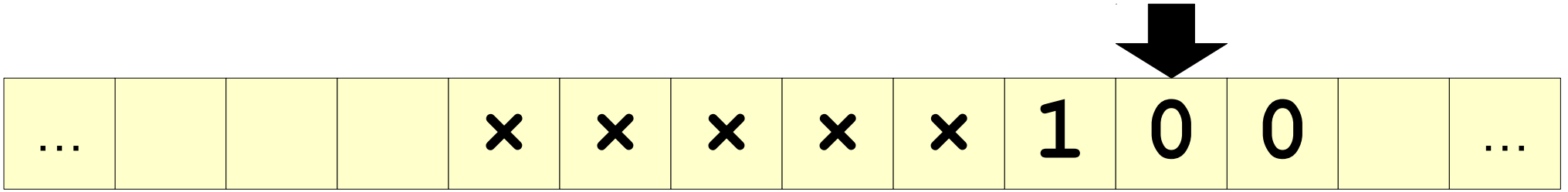

1 → ×, R
Find 0
start
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find 1
1 → ×, L
0 → 0, R
× → ×, R

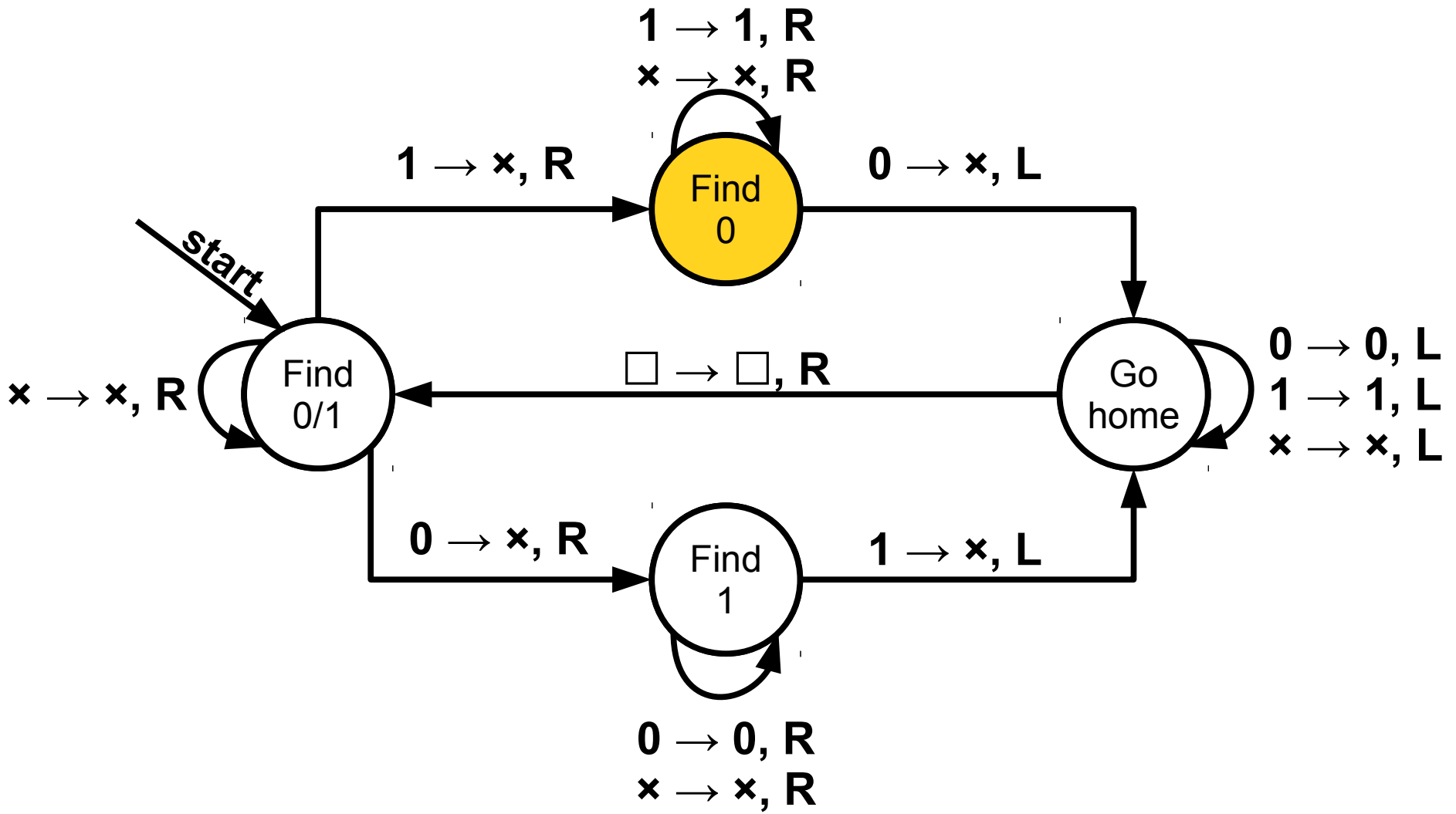

…
×
×
×
×
×
1
0
0
…

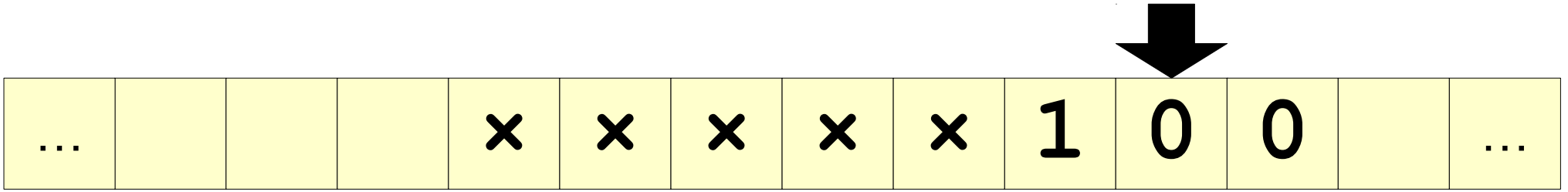

1 → 1, R
× → ×, R
1 → ×, R
Find 0
start
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find 1
1 → ×, L
0 → 0, R
× → ×, R

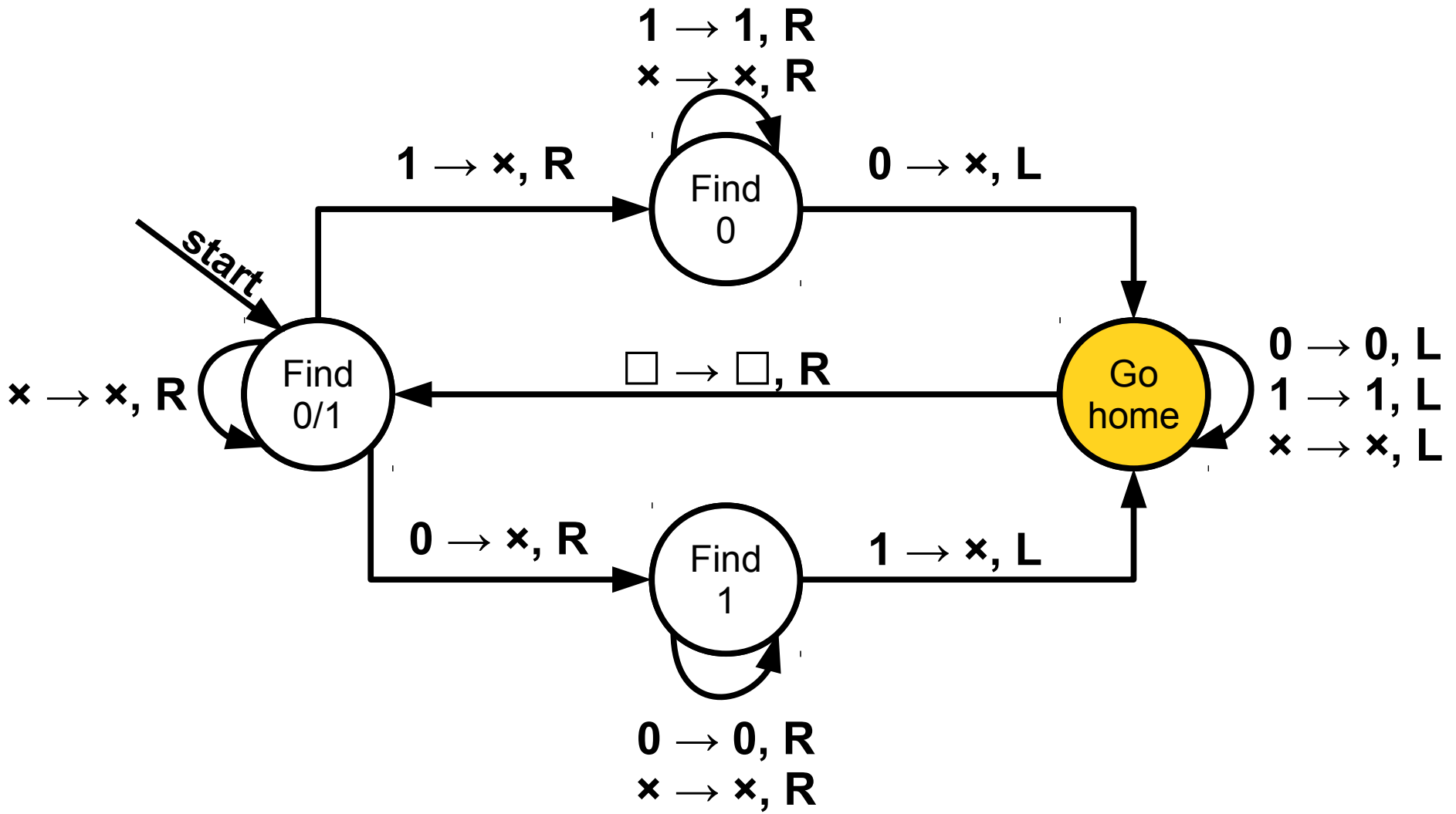

…
×
×
×
×
×
1
0
0
…

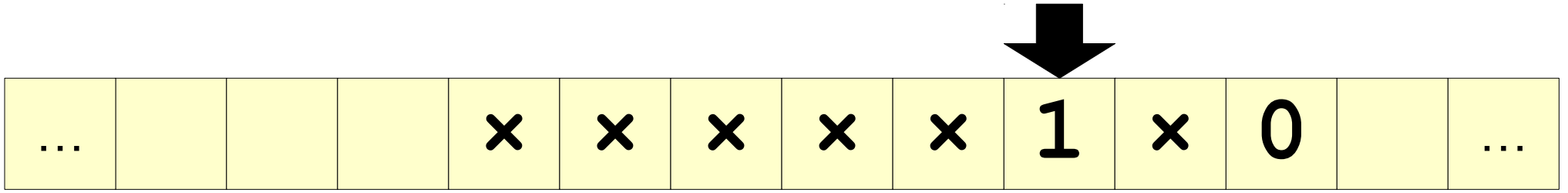

1 → 1, R
× → ×, R
1 → ×, R
Find 0
start
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find 1
1 → ×, L
0 → 0, R
× → ×, R

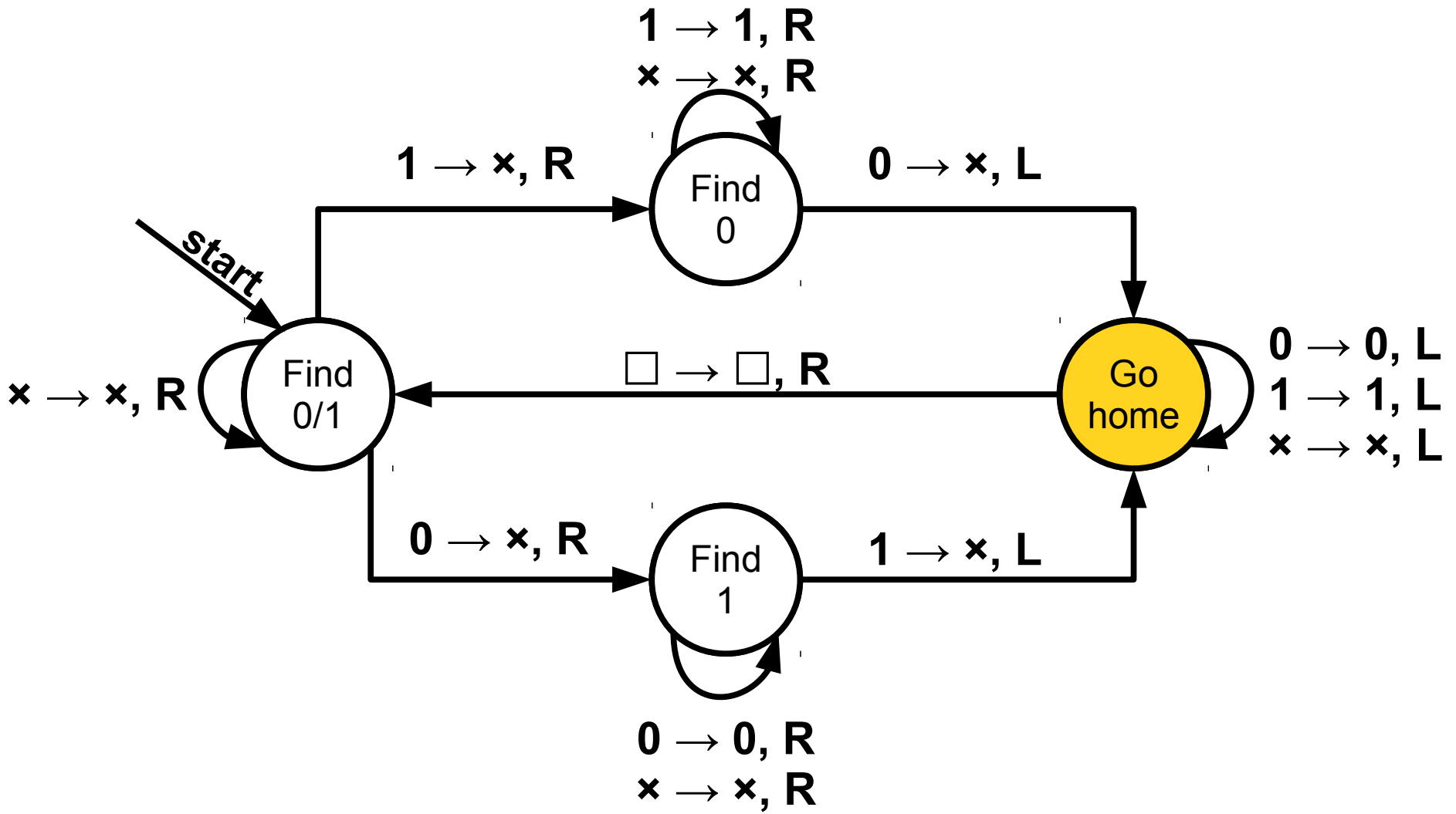

…
×
×
×
×
×
1
0
0
…

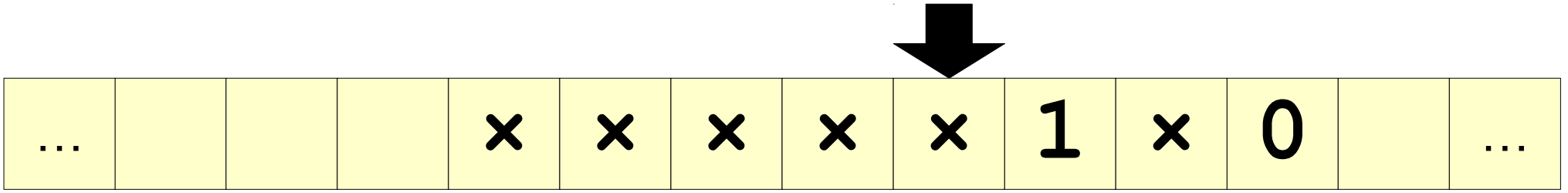

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

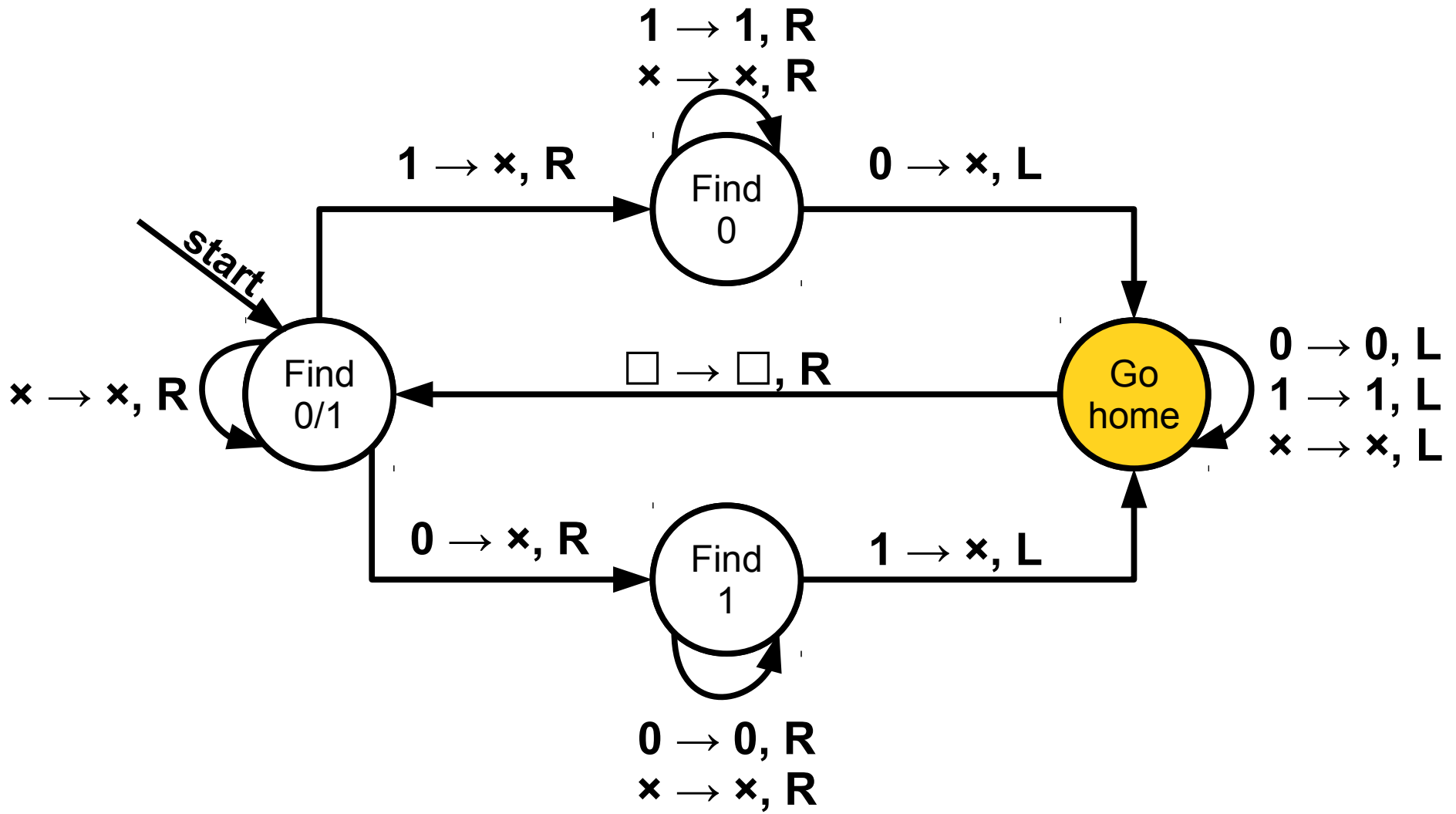

…
×
×
×
×
×
1
0
0
…

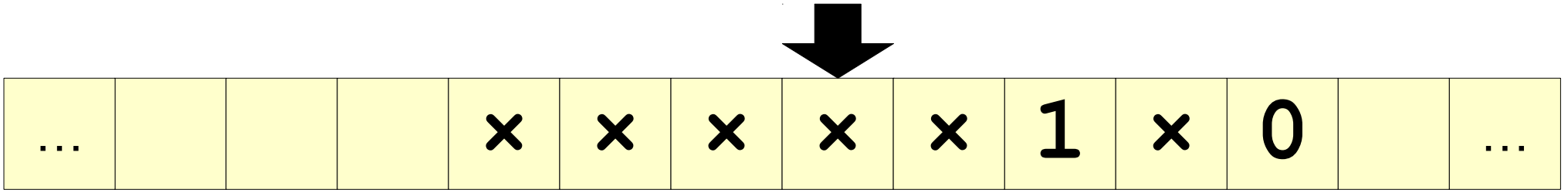

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

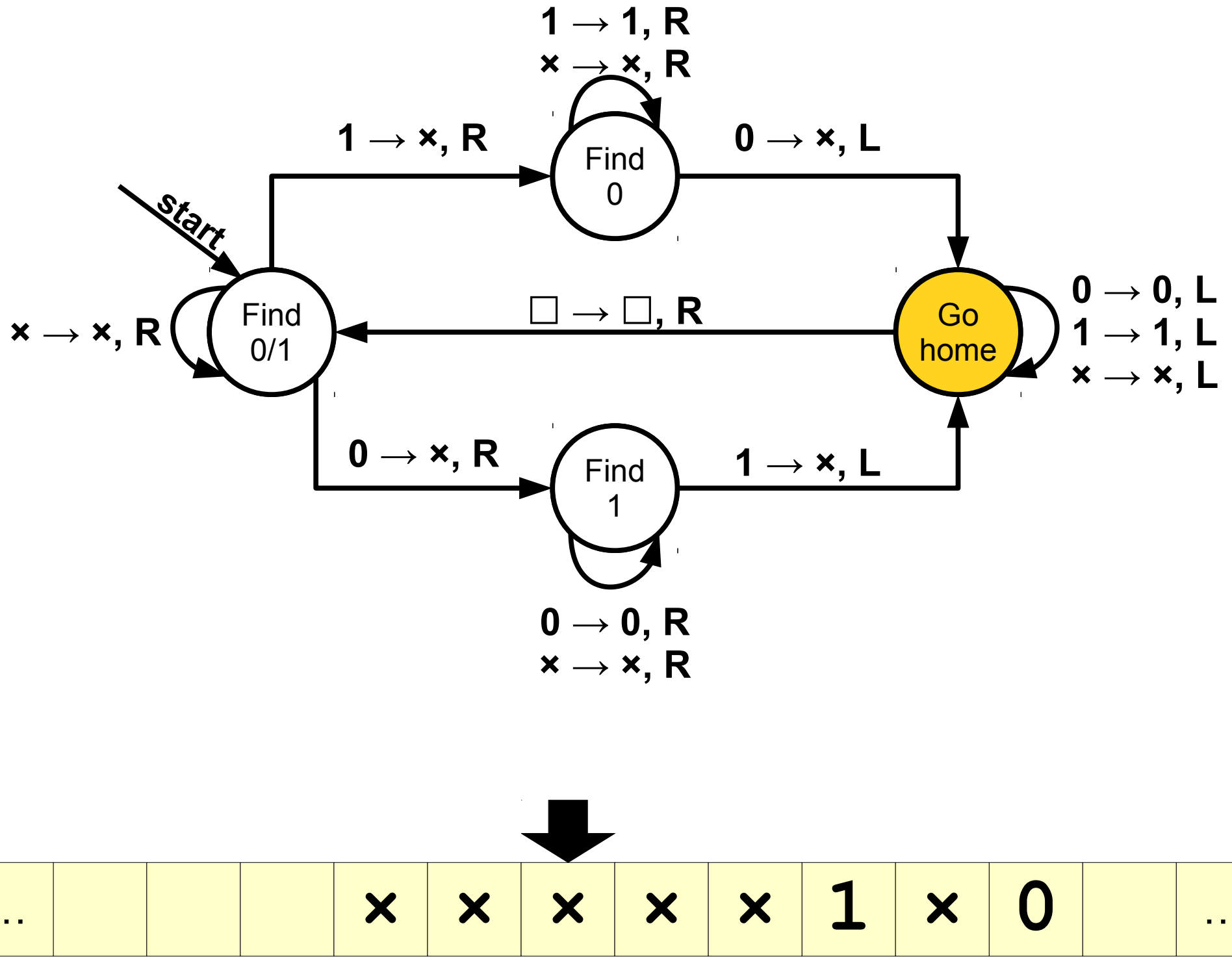

…
×
×
×
×
×
1
×
0
…

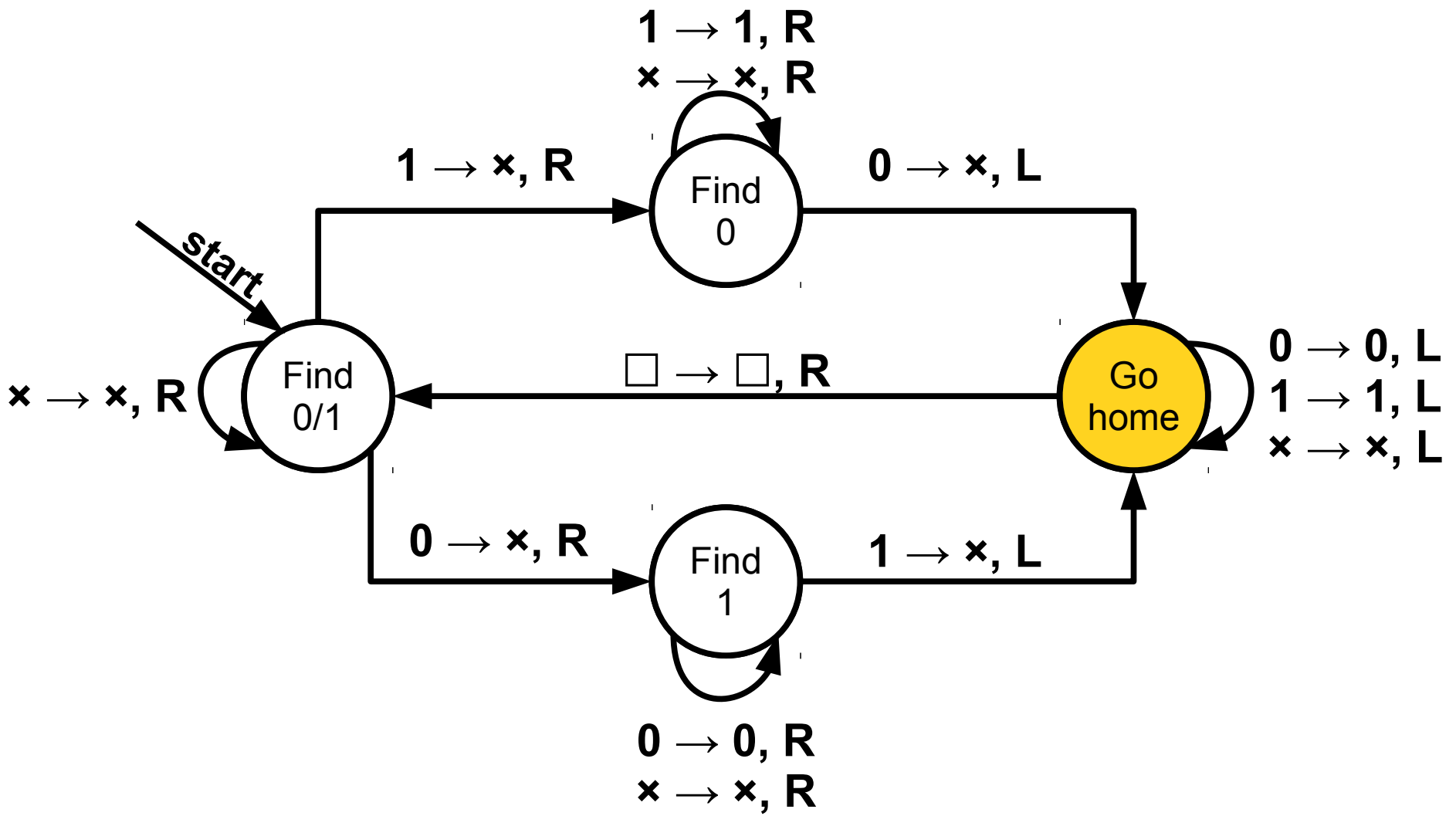

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

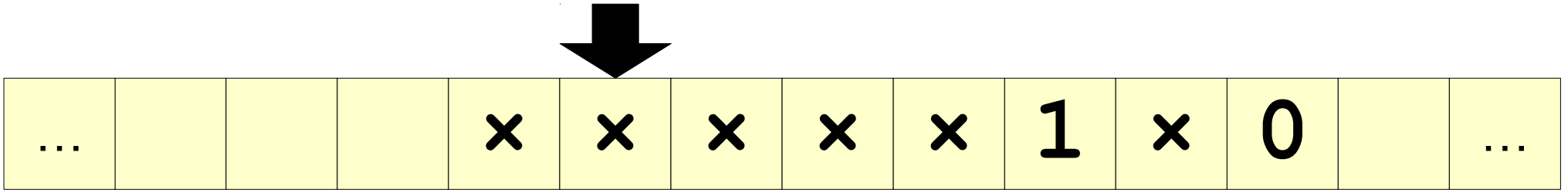

…
×
×
×
×
×
1
×
0
…

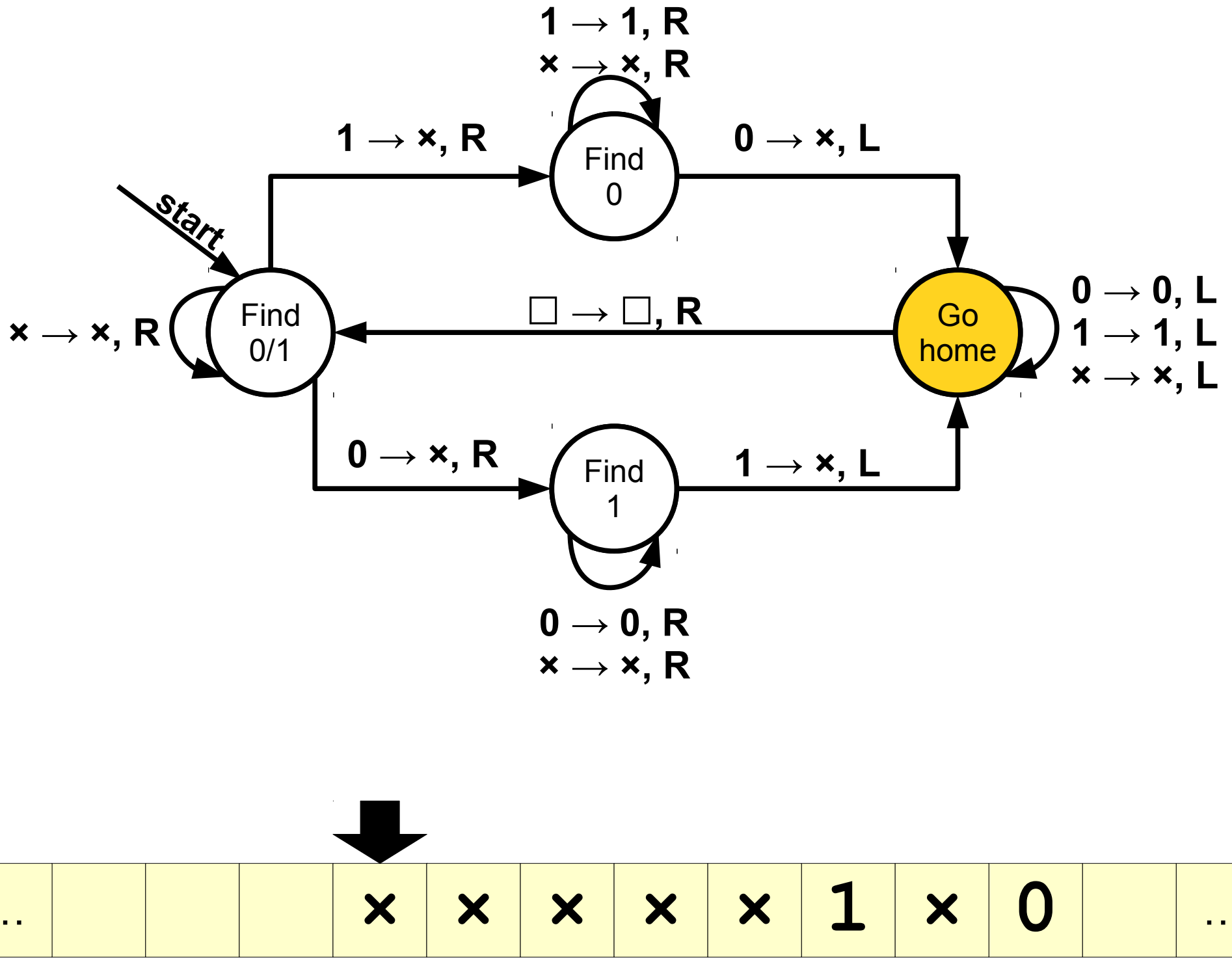

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find
1
0 → 0, R
× → ×, R

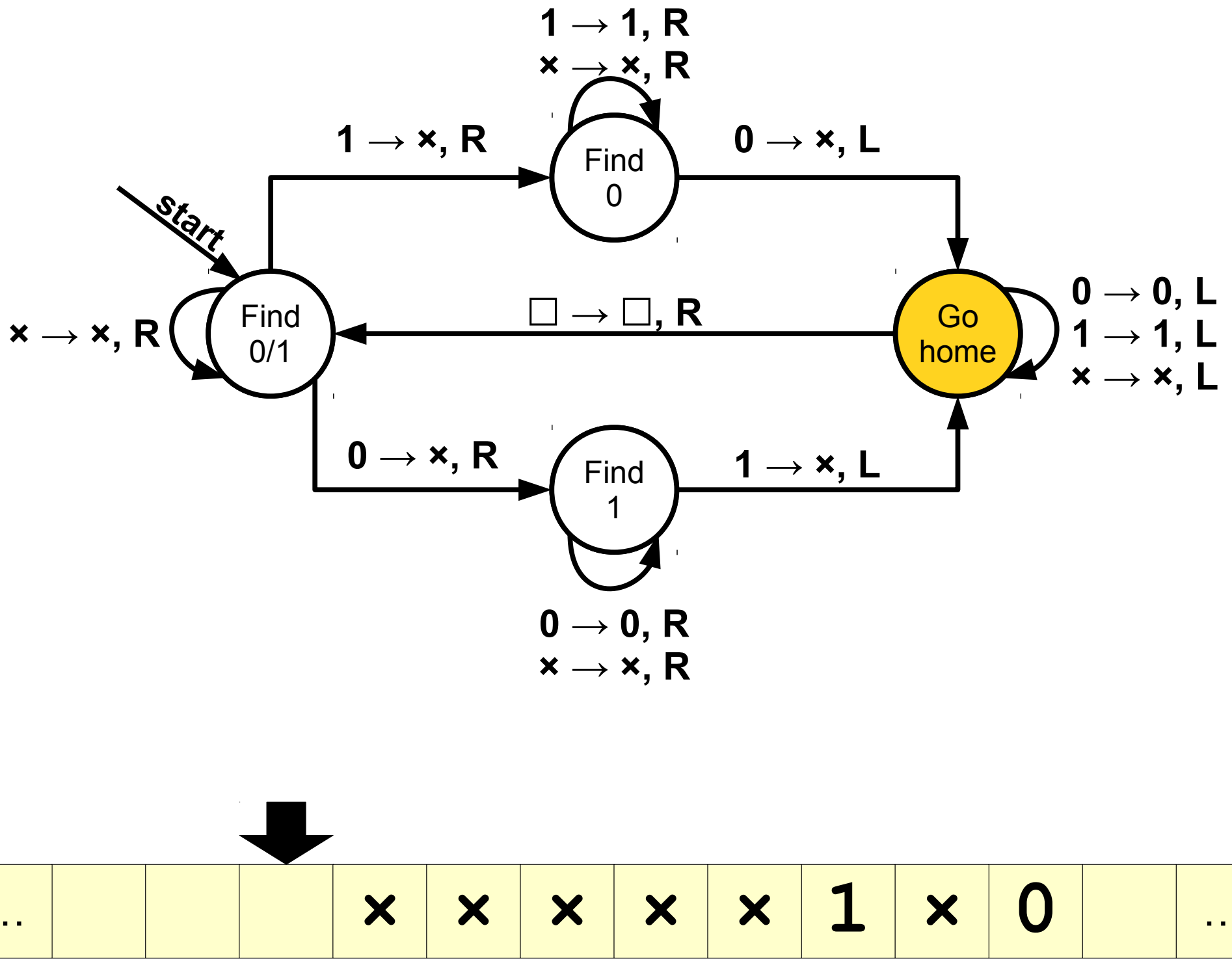

…
×
×
×
×
×
1
×
0
…

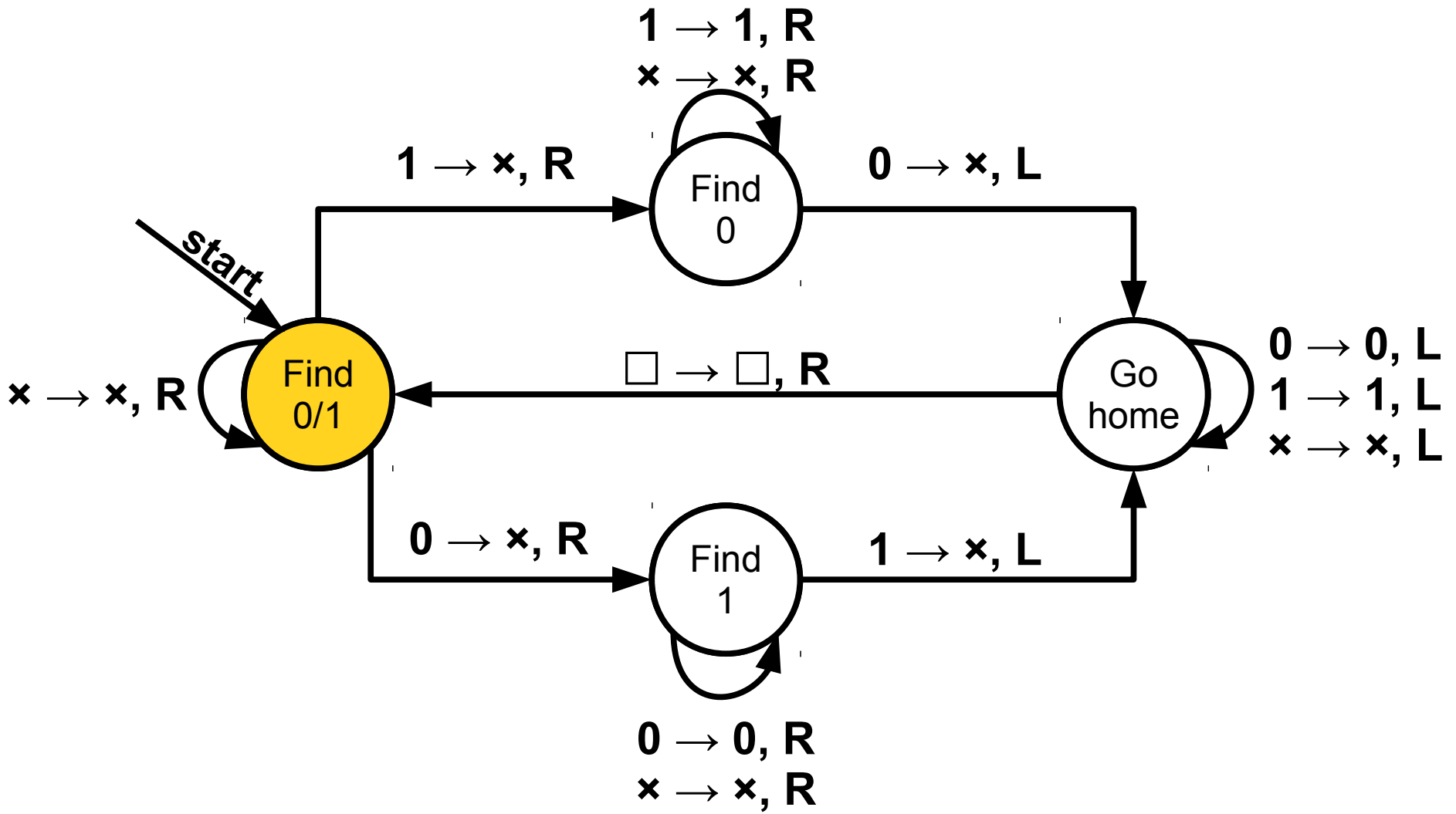

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R
… × × × × × 1 × 0 …

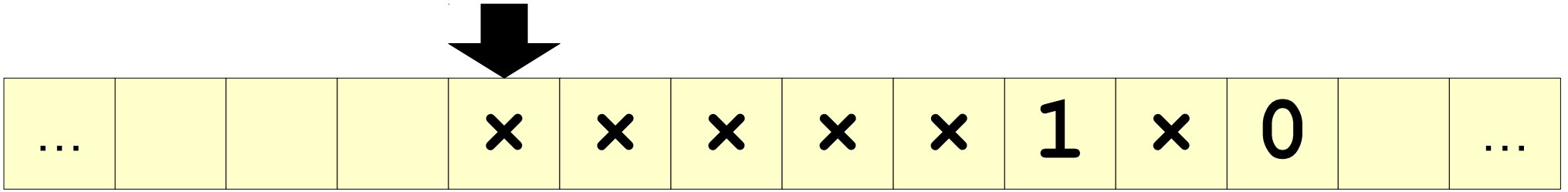

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

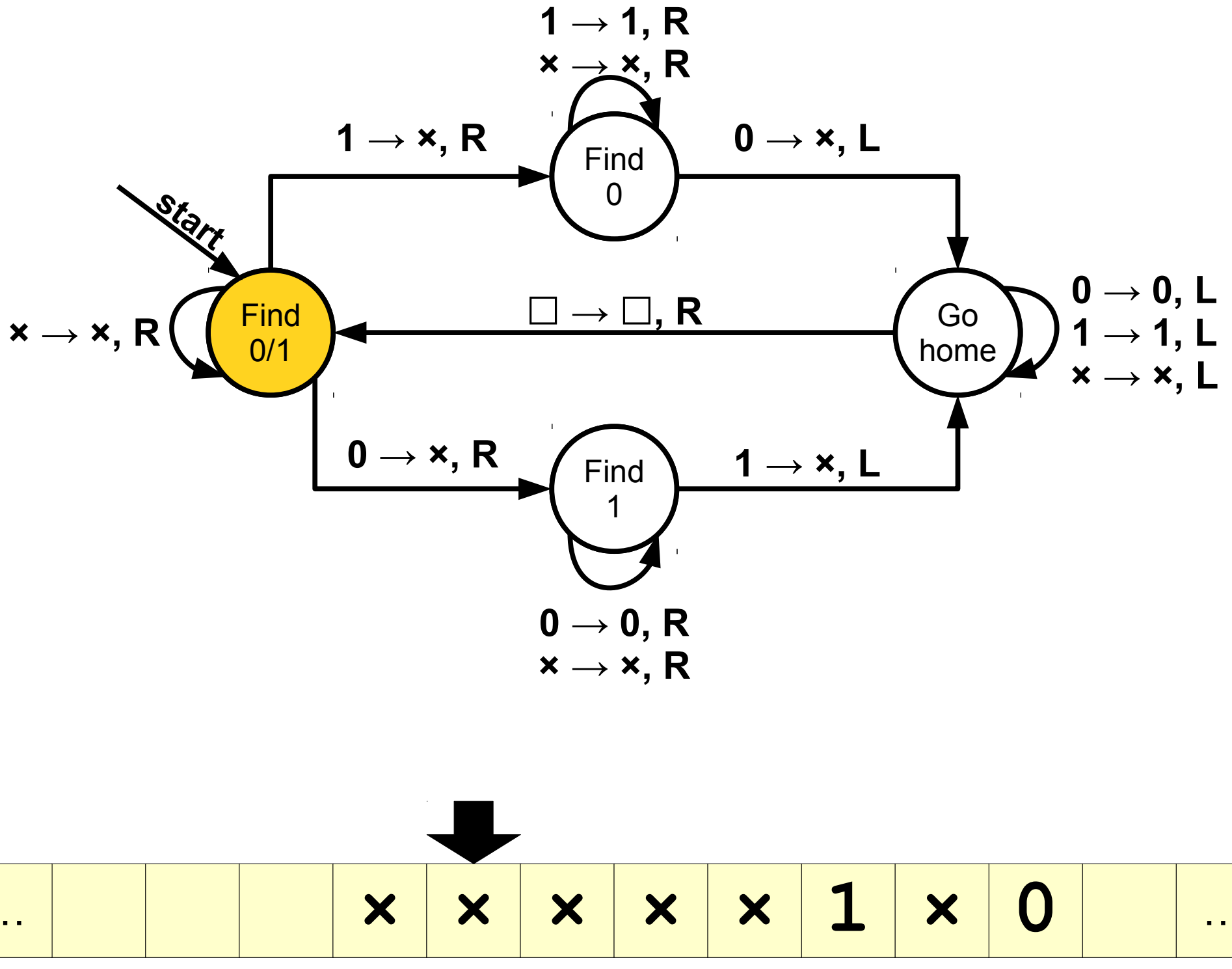

…
×
×
×
×
×
1
×
0
…

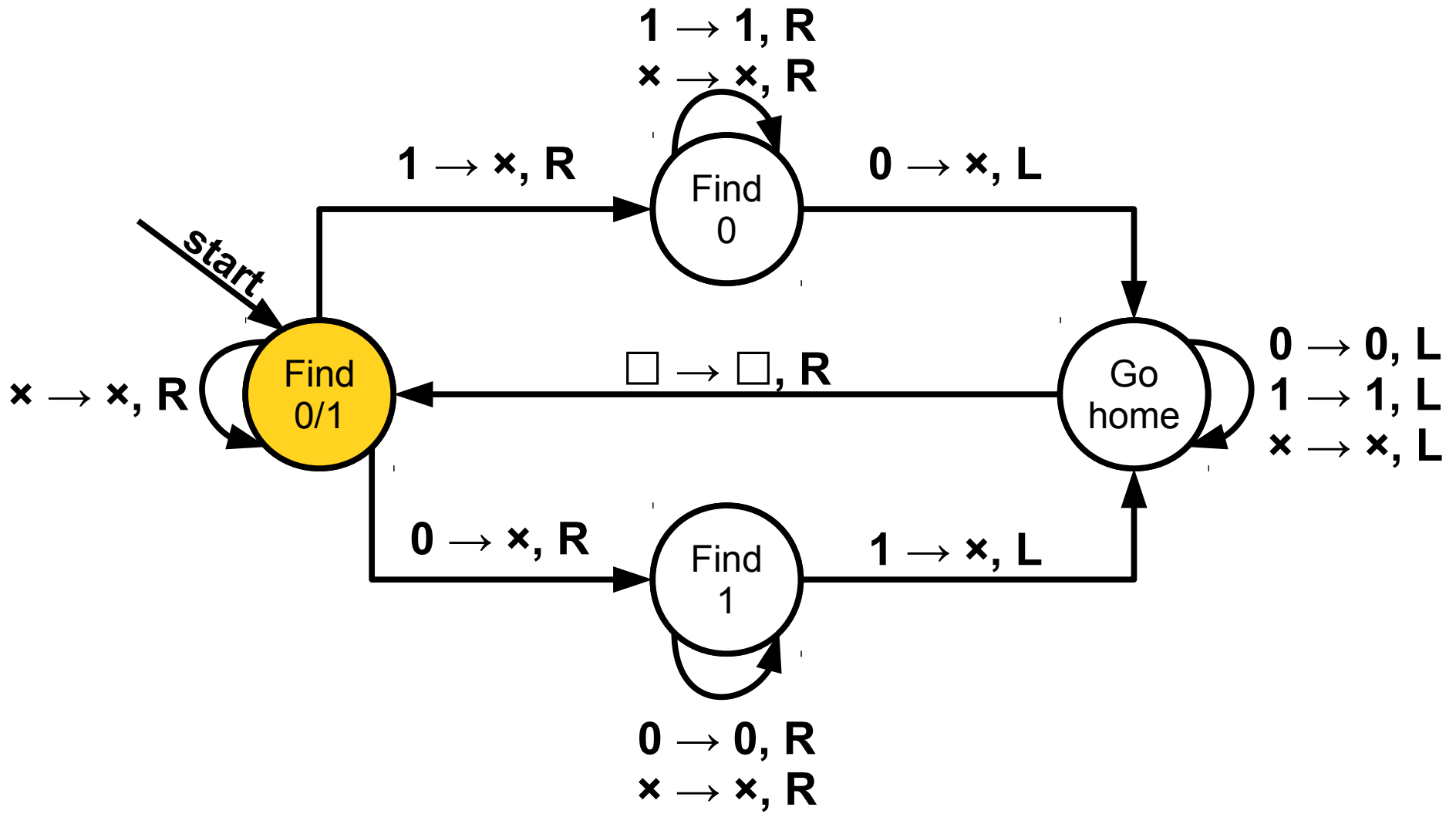

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R
…
×
×
×
×
×
1
×
0
…

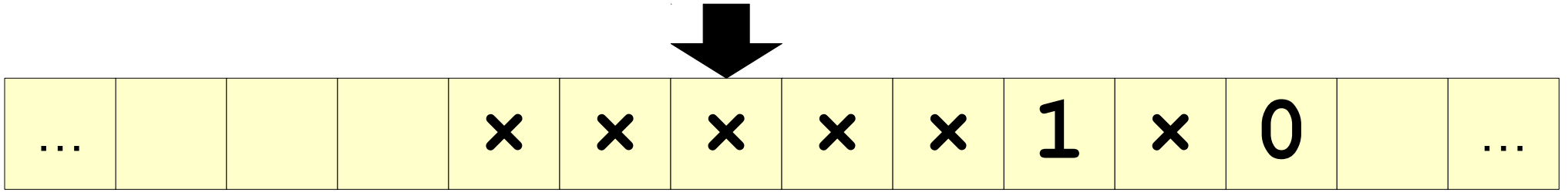

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R
…
×
×
×
×
×
1
×
0
…

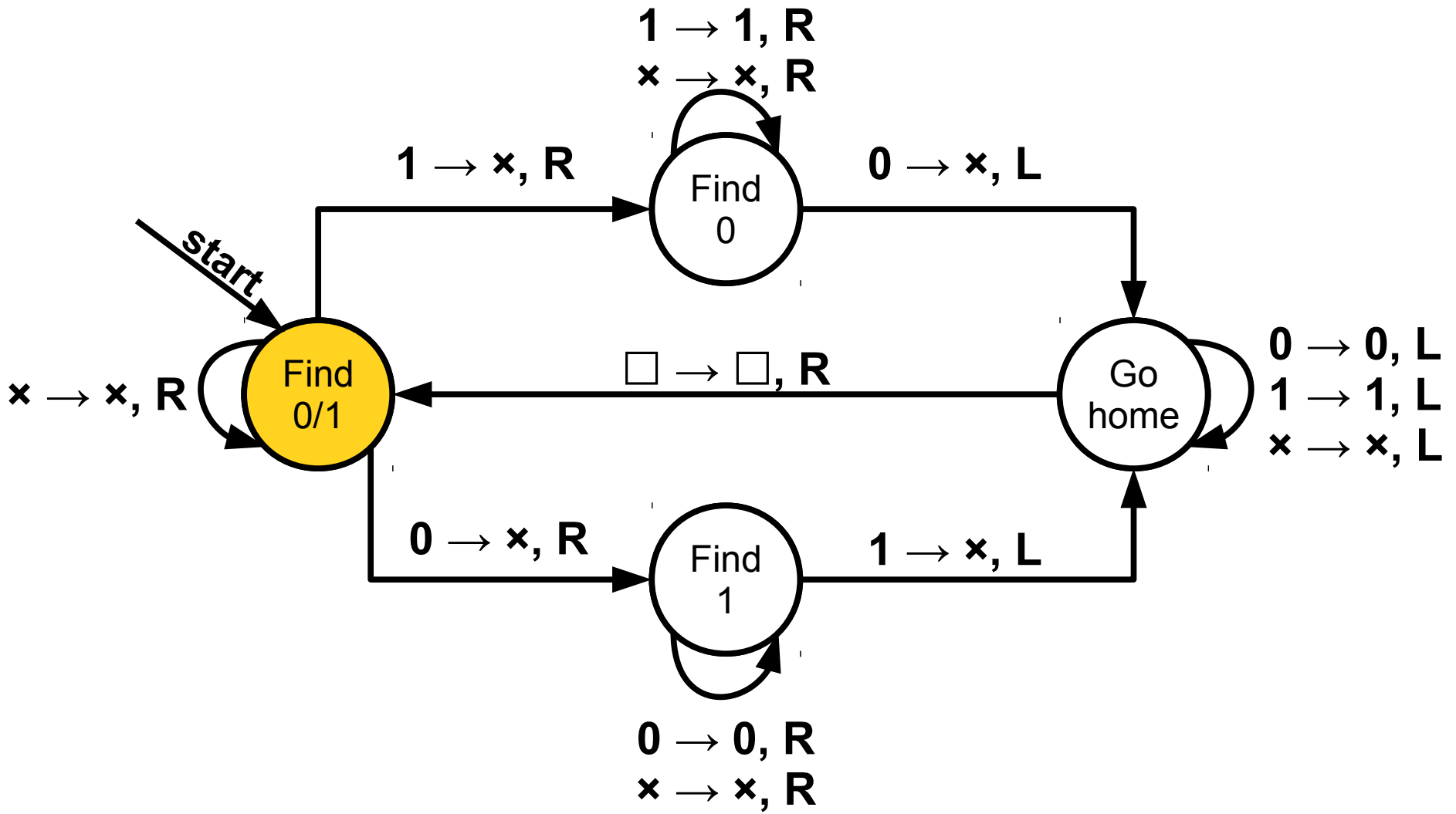

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find 1
1 → ×, L
0 → 0, R
× → ×, R

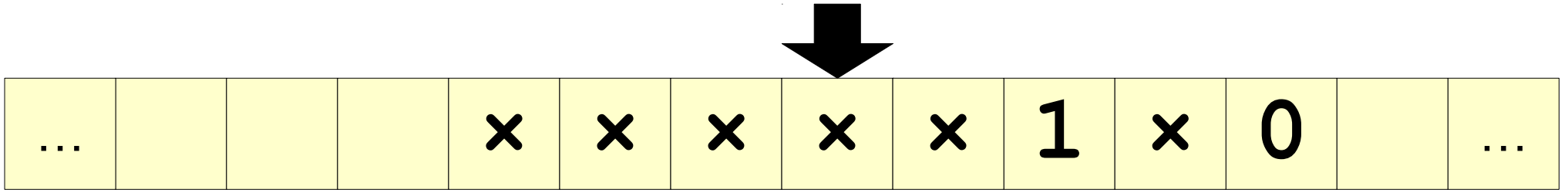

…
×
×
×
×
×
1
×
0
…

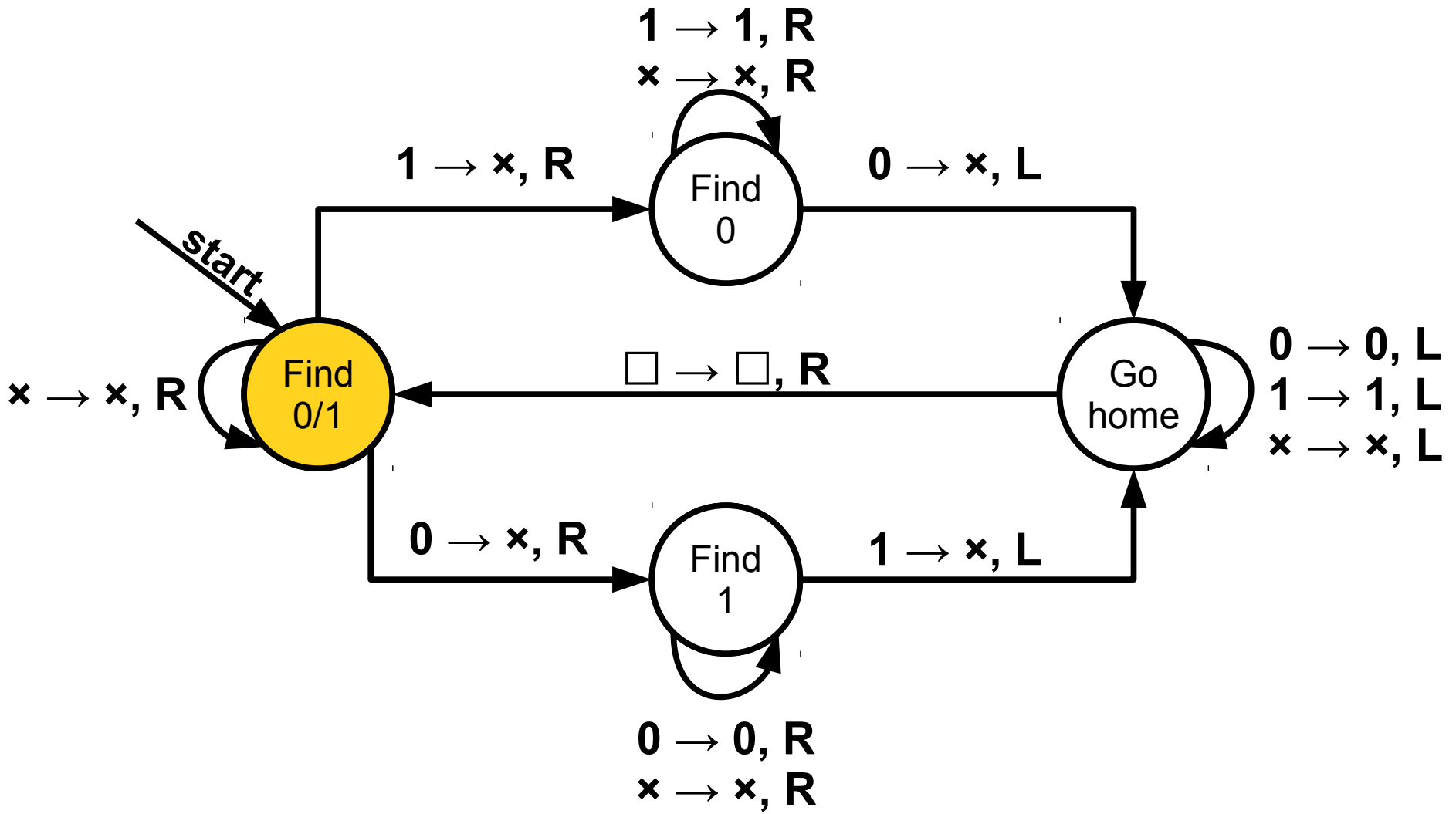

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R
… × × × × × 1 × 0 …

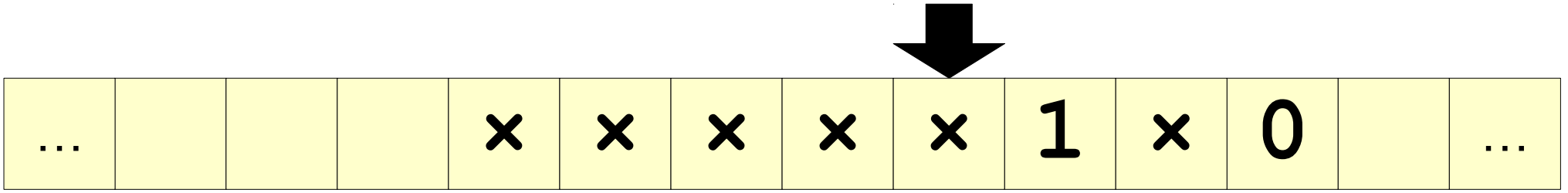

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

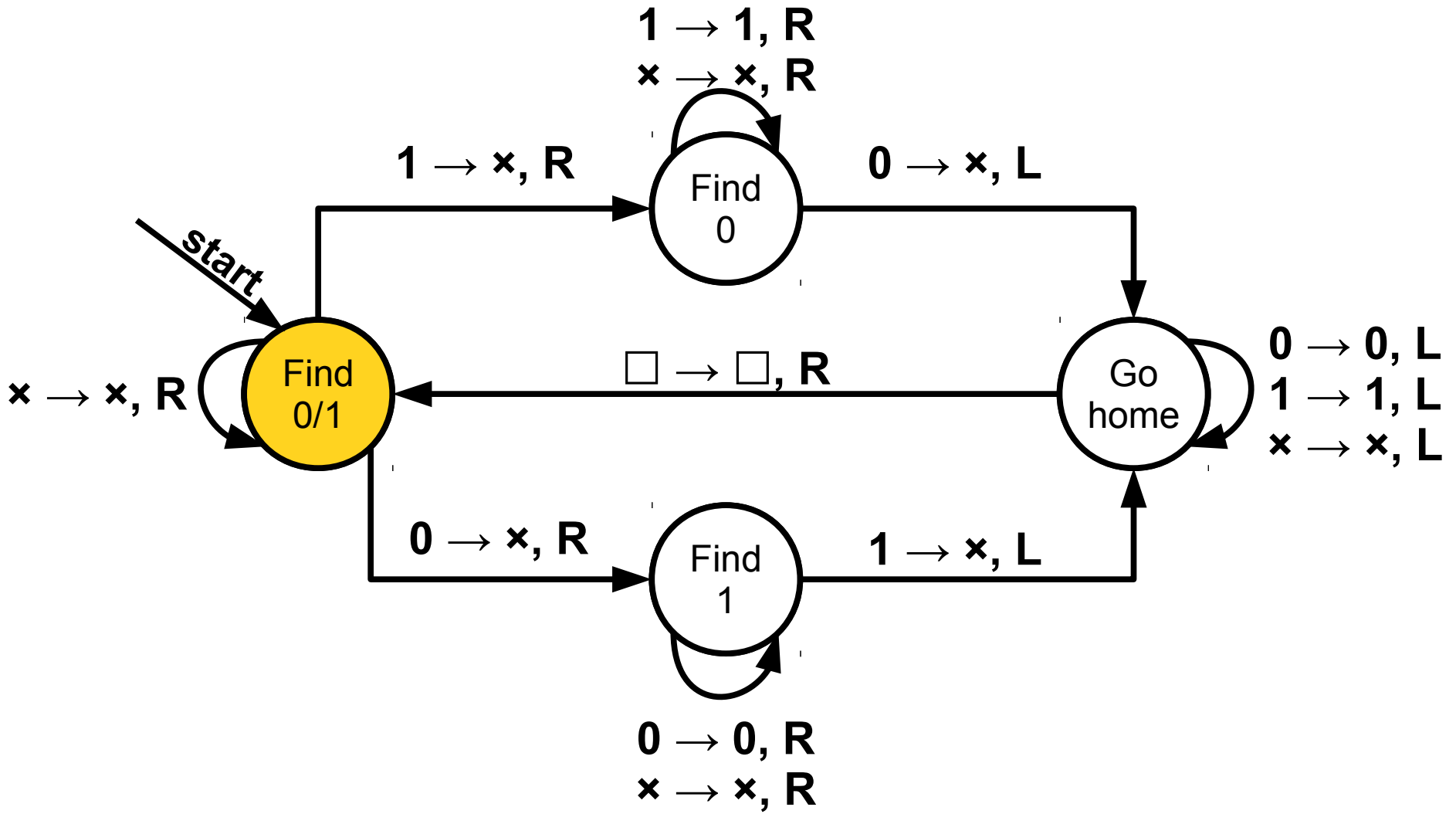

…
× × × × × 1 × 0
…

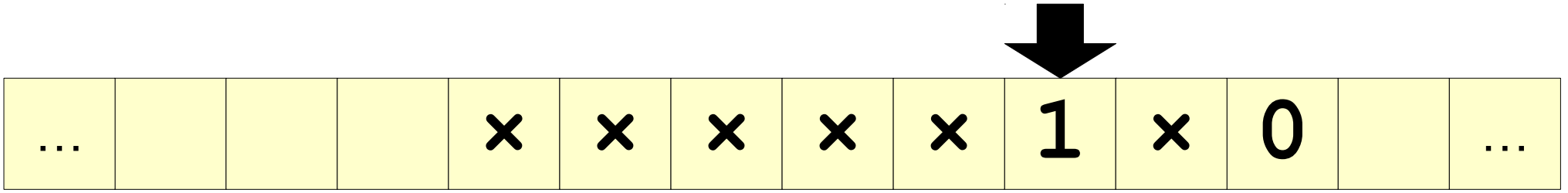

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

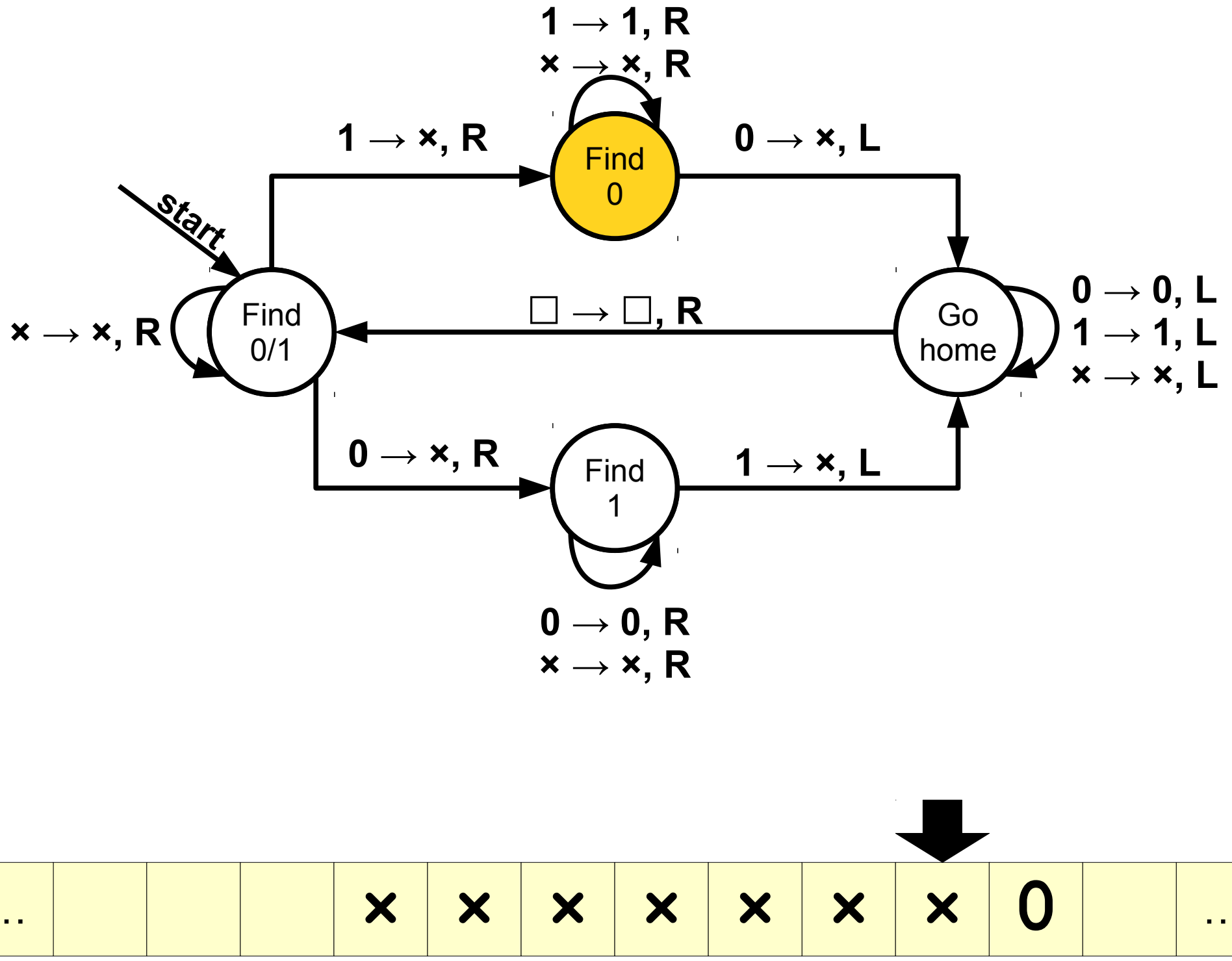

…
×
×
×
×
×
1
×
0
…

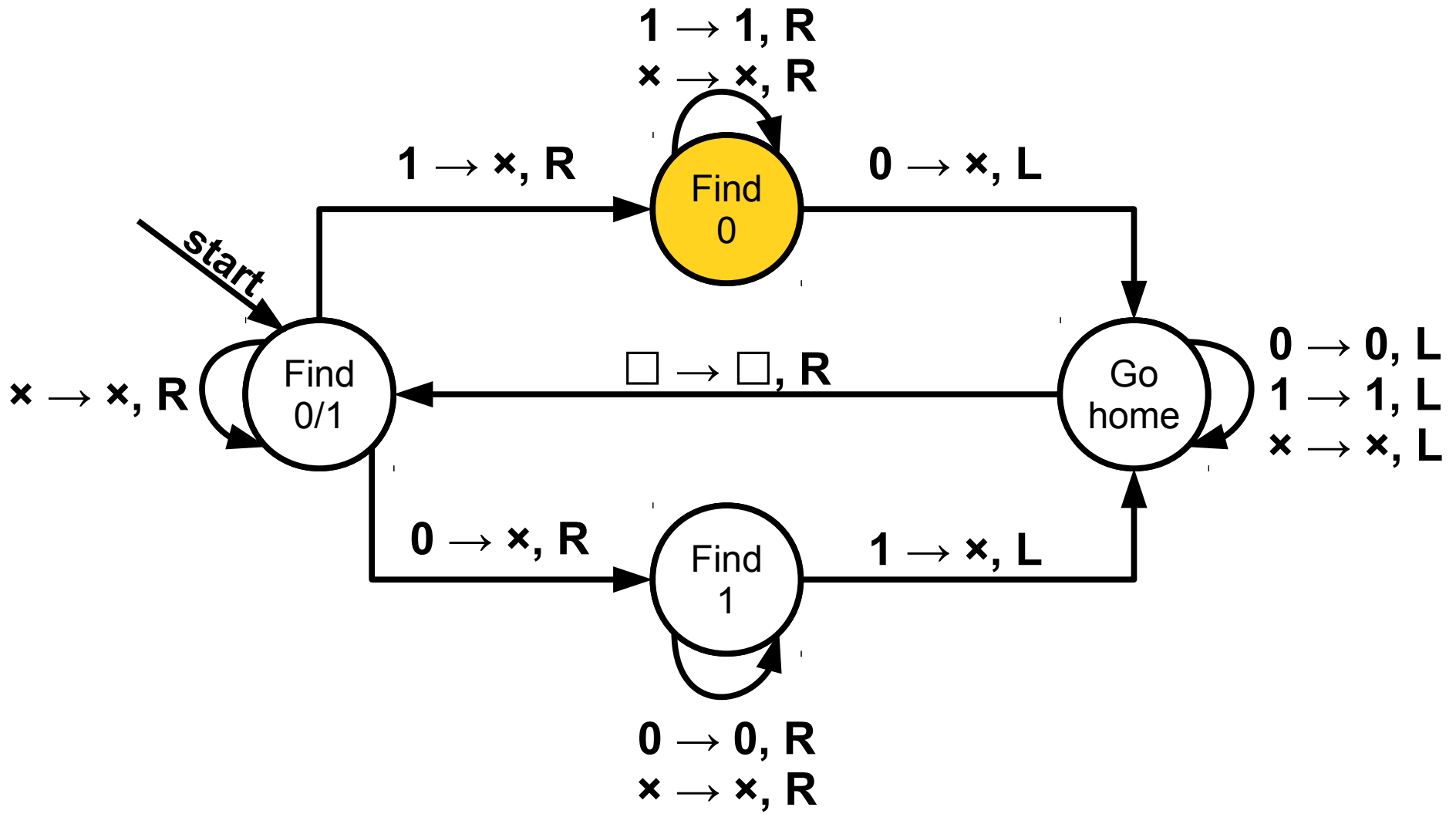

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

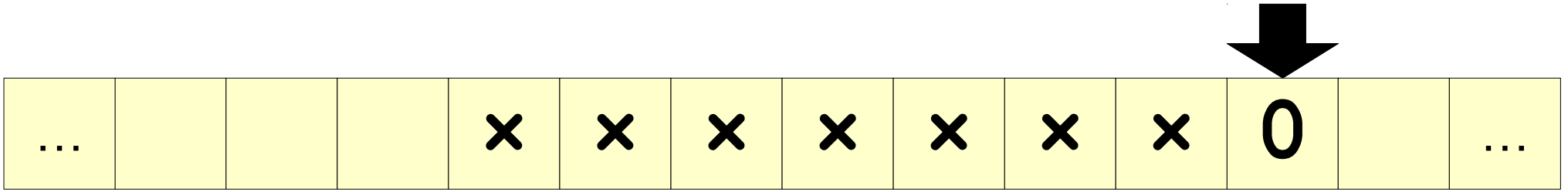

…
×
×
×
×
×
1
×
0
…

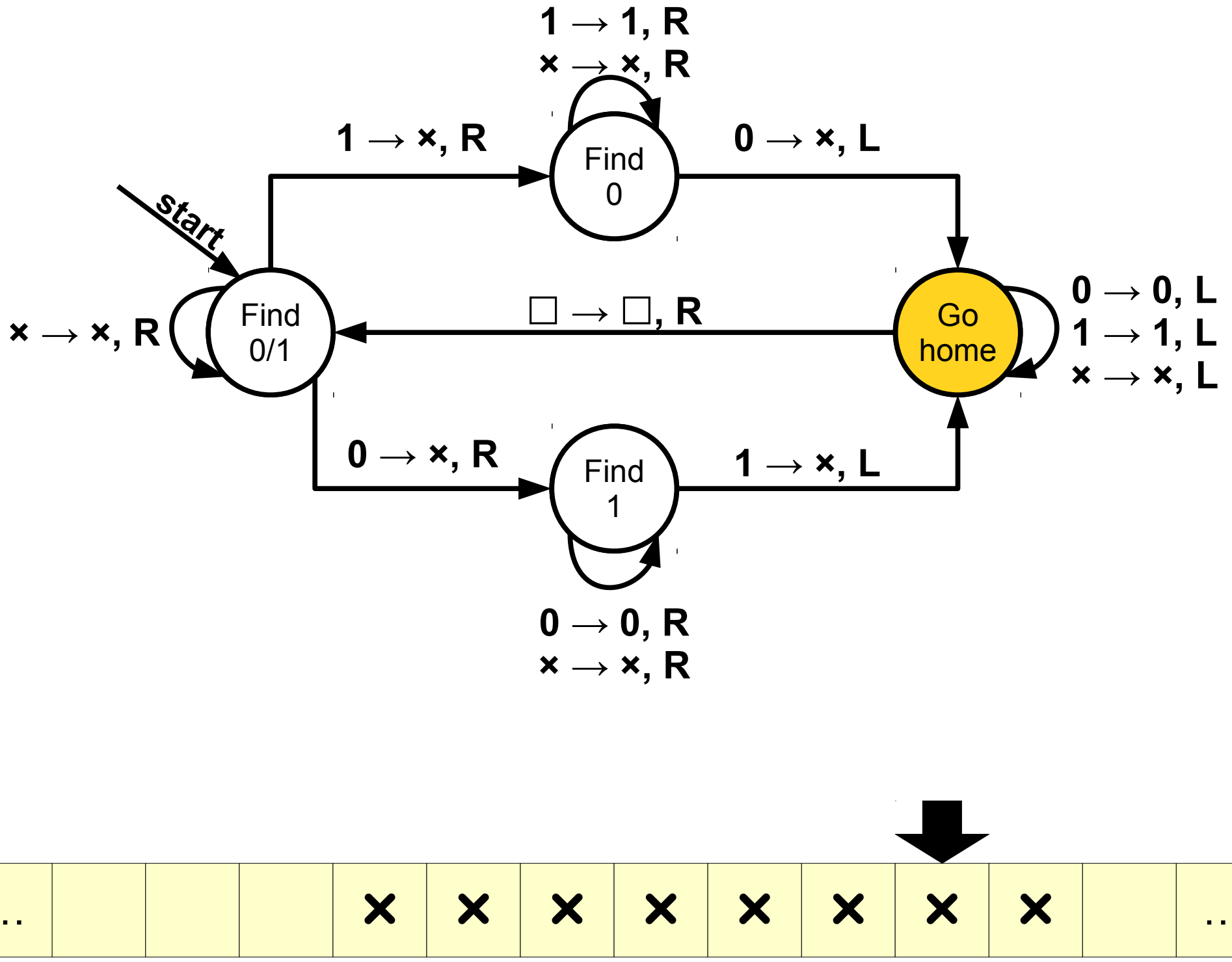

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

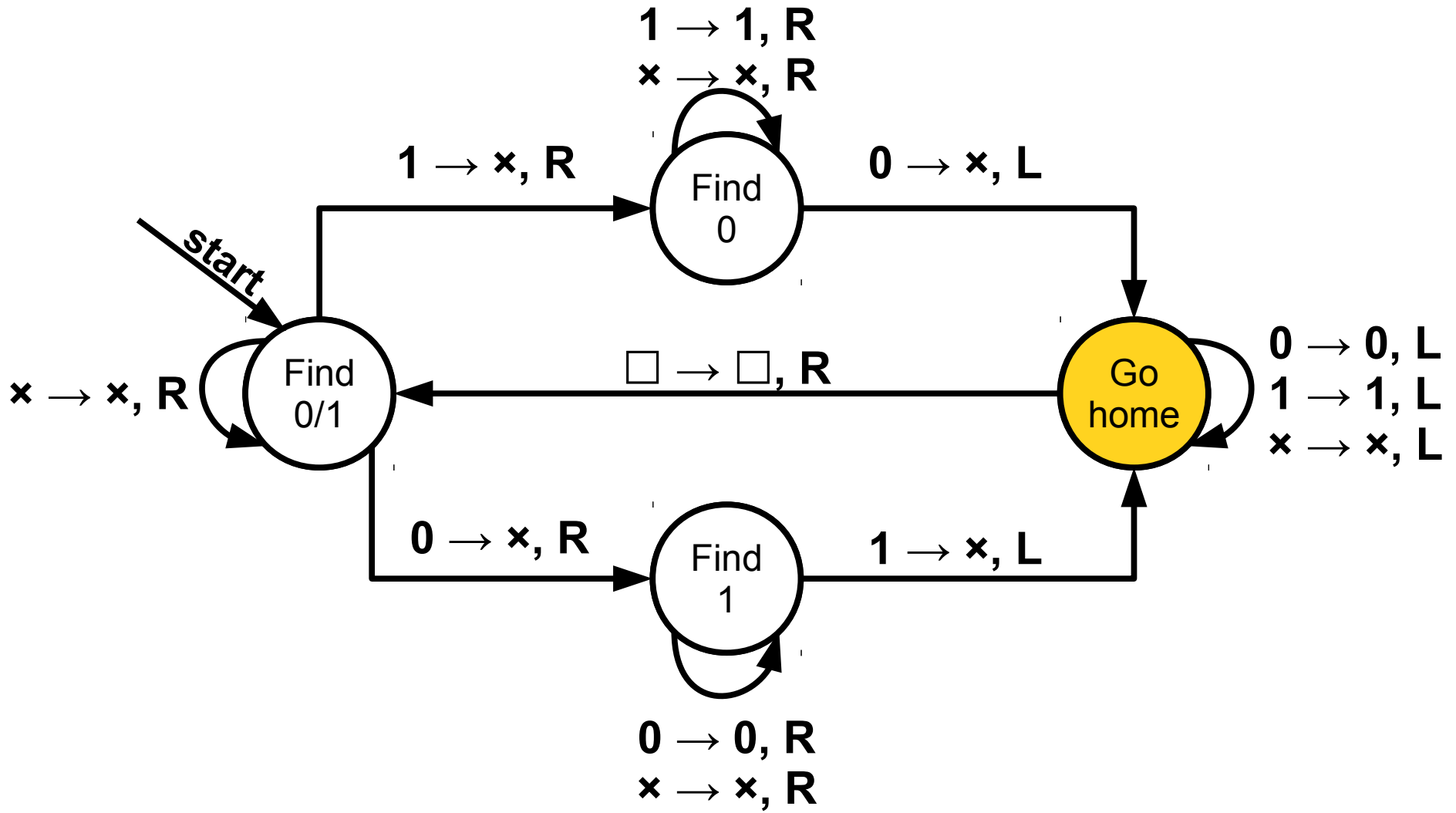

…
×
×
×
×
×
1
×
0
…

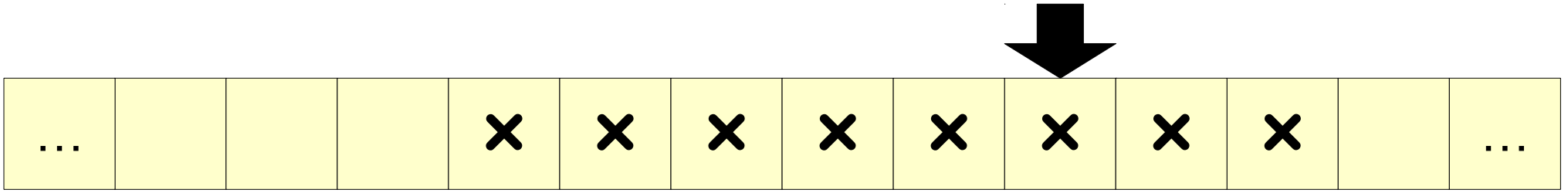

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find
1
0 → 0, R
× → ×, R
…
×
×
×
×
×
×
×
0
…

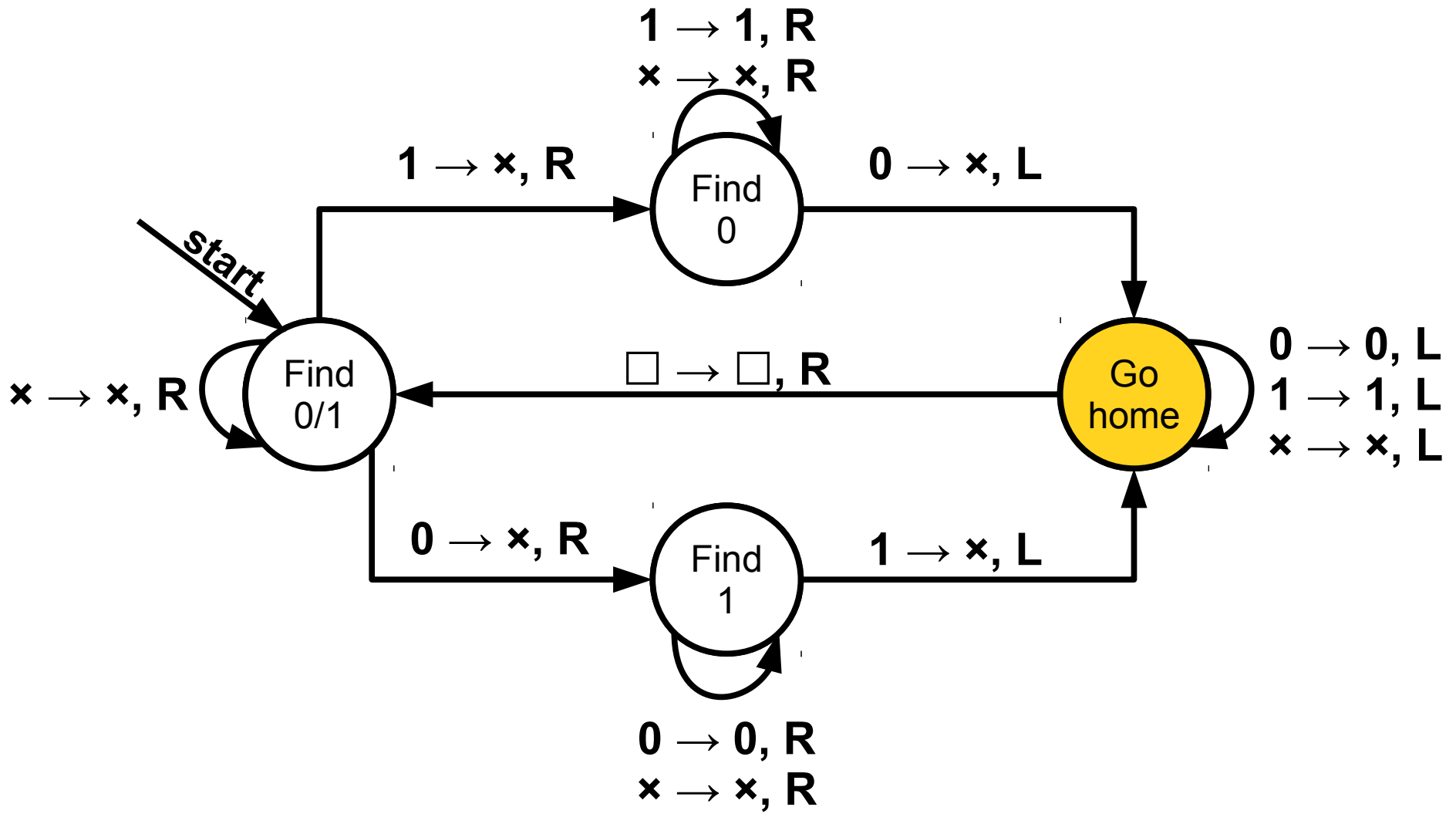

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find
1
1 → ×, L
0 → 0, R
× → ×, R

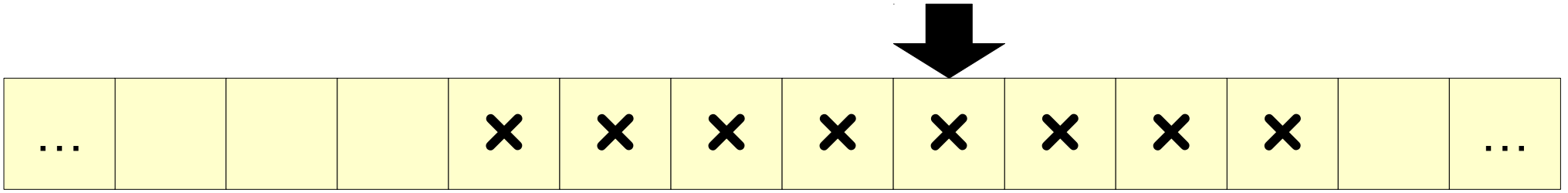

…
×
×
×
×
×
×
×
0
…

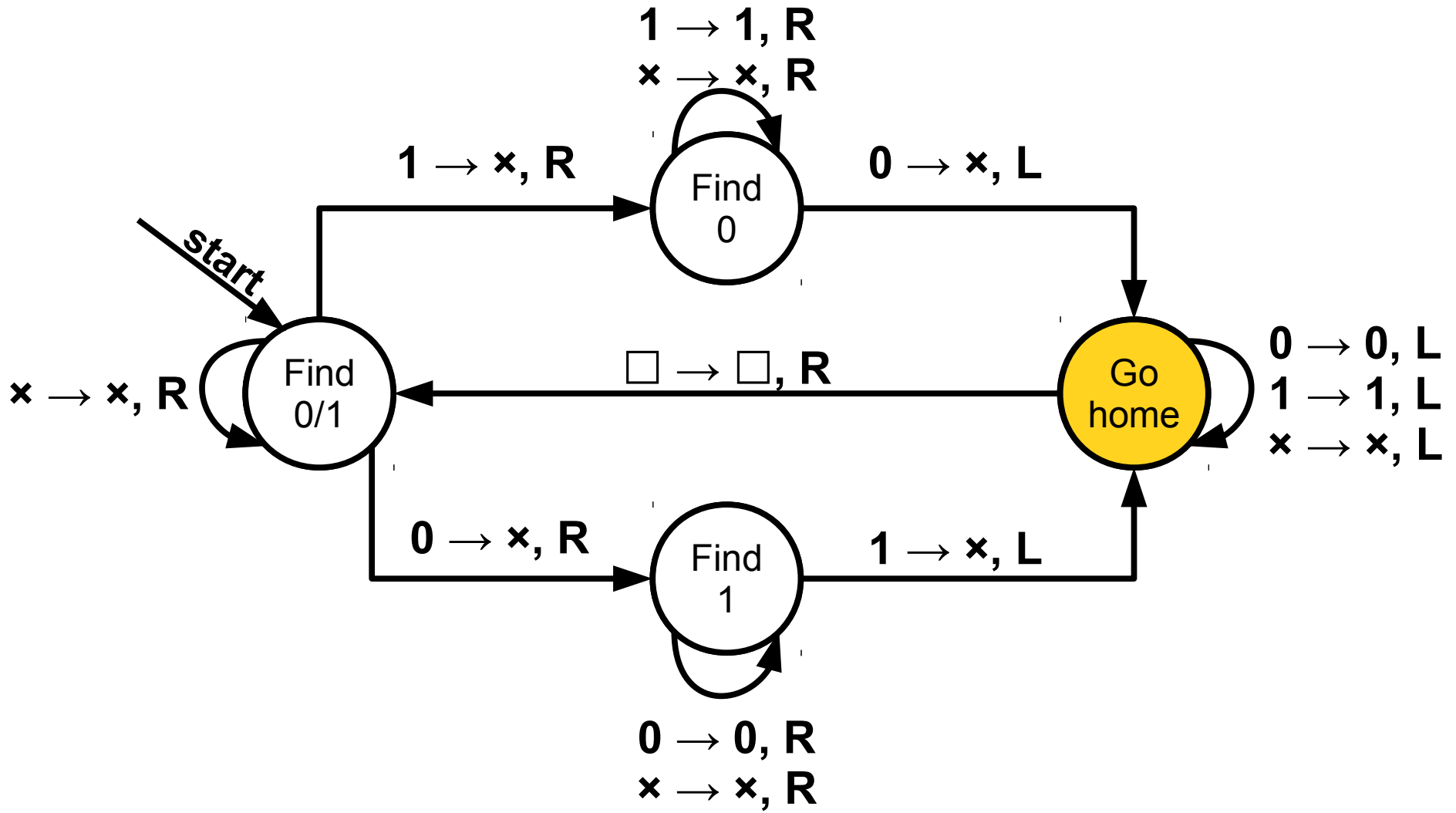

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R
…
…

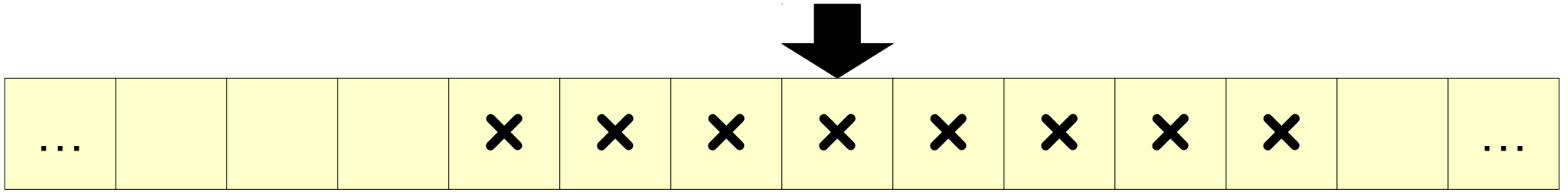

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

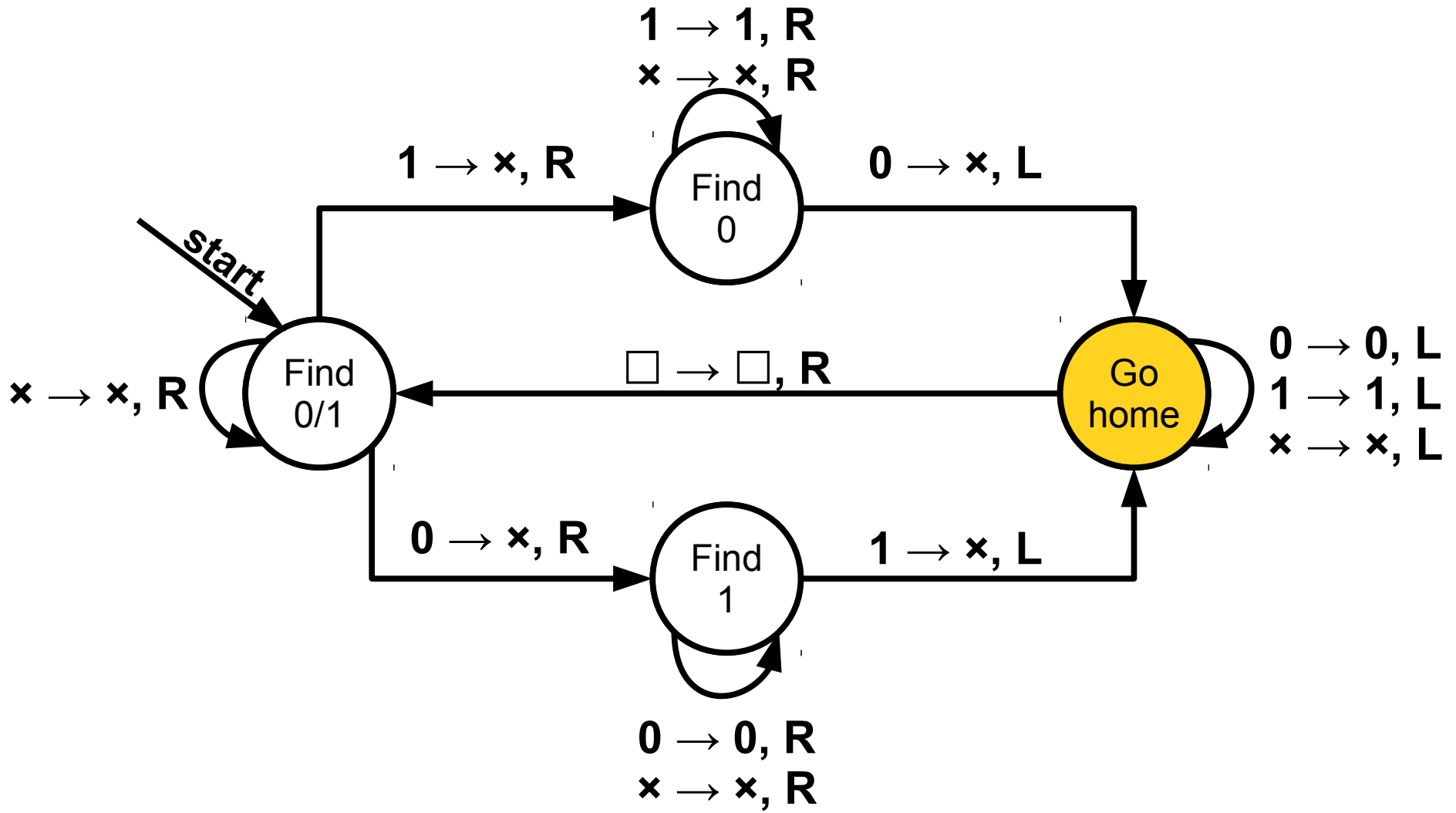

…
×
×
×
×
×
×
×
×
…

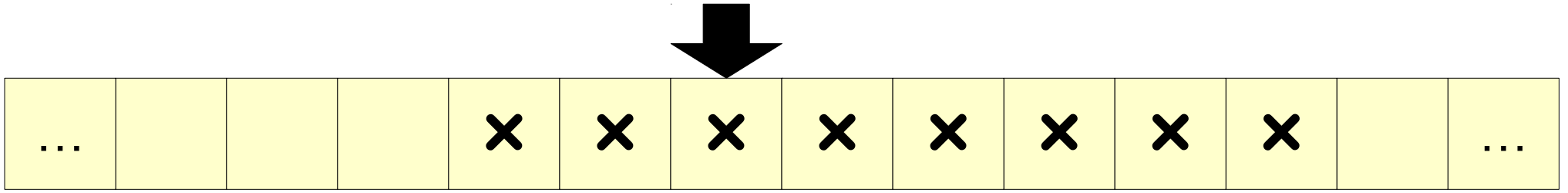

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

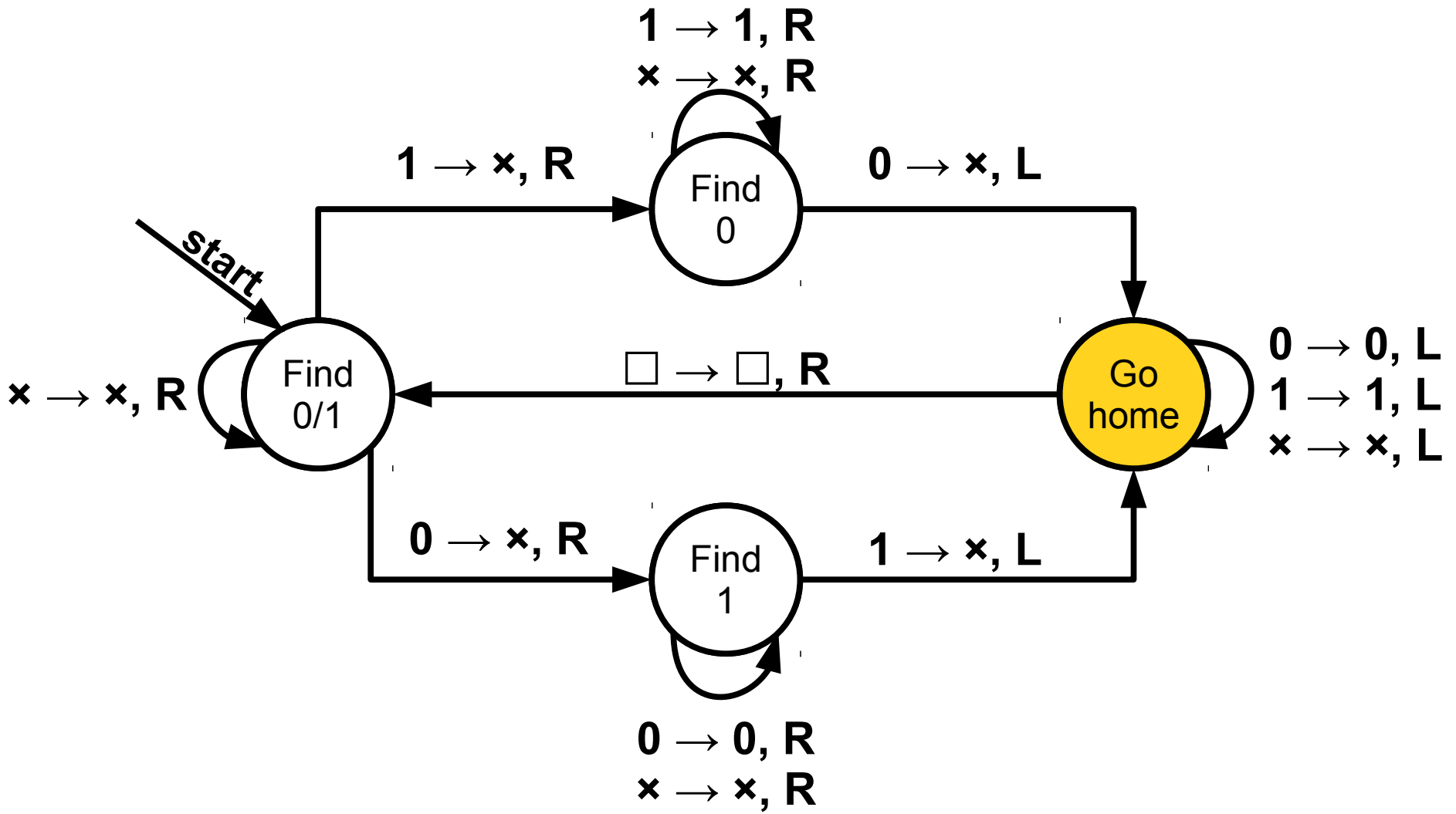

…
×
×
×
×
×
×
×
×
…

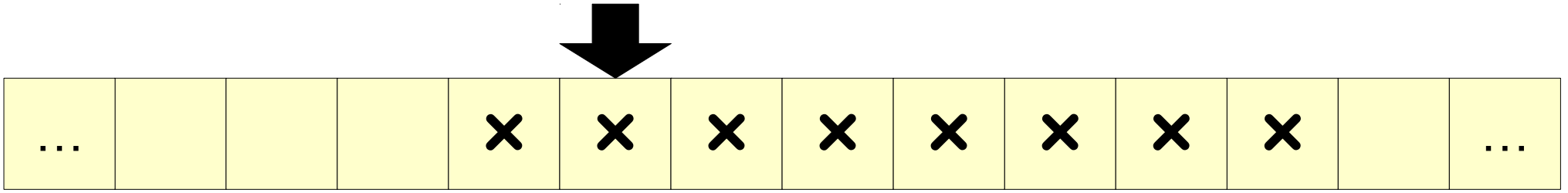

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

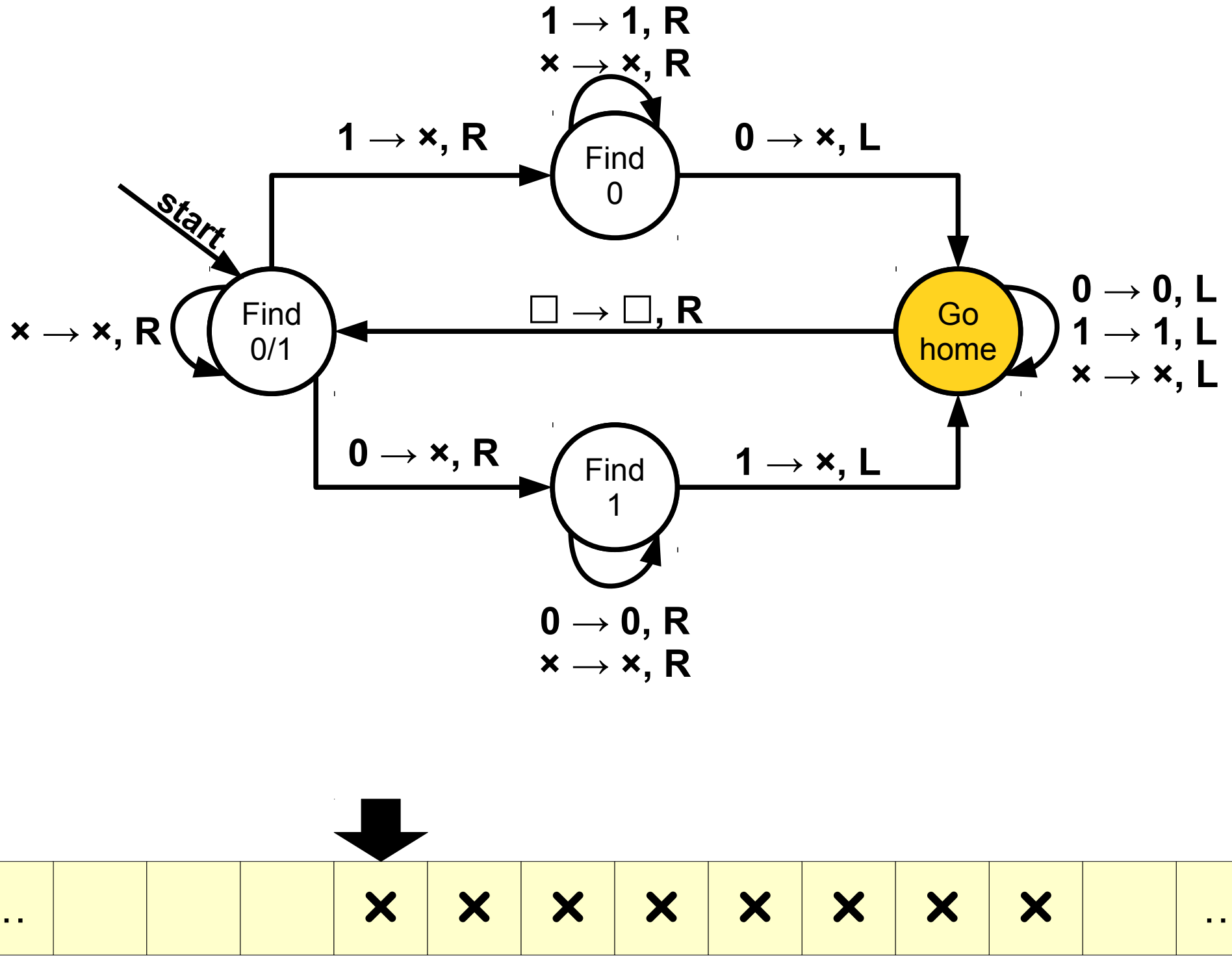

…
×
×
×
×
×
×
×
×
…

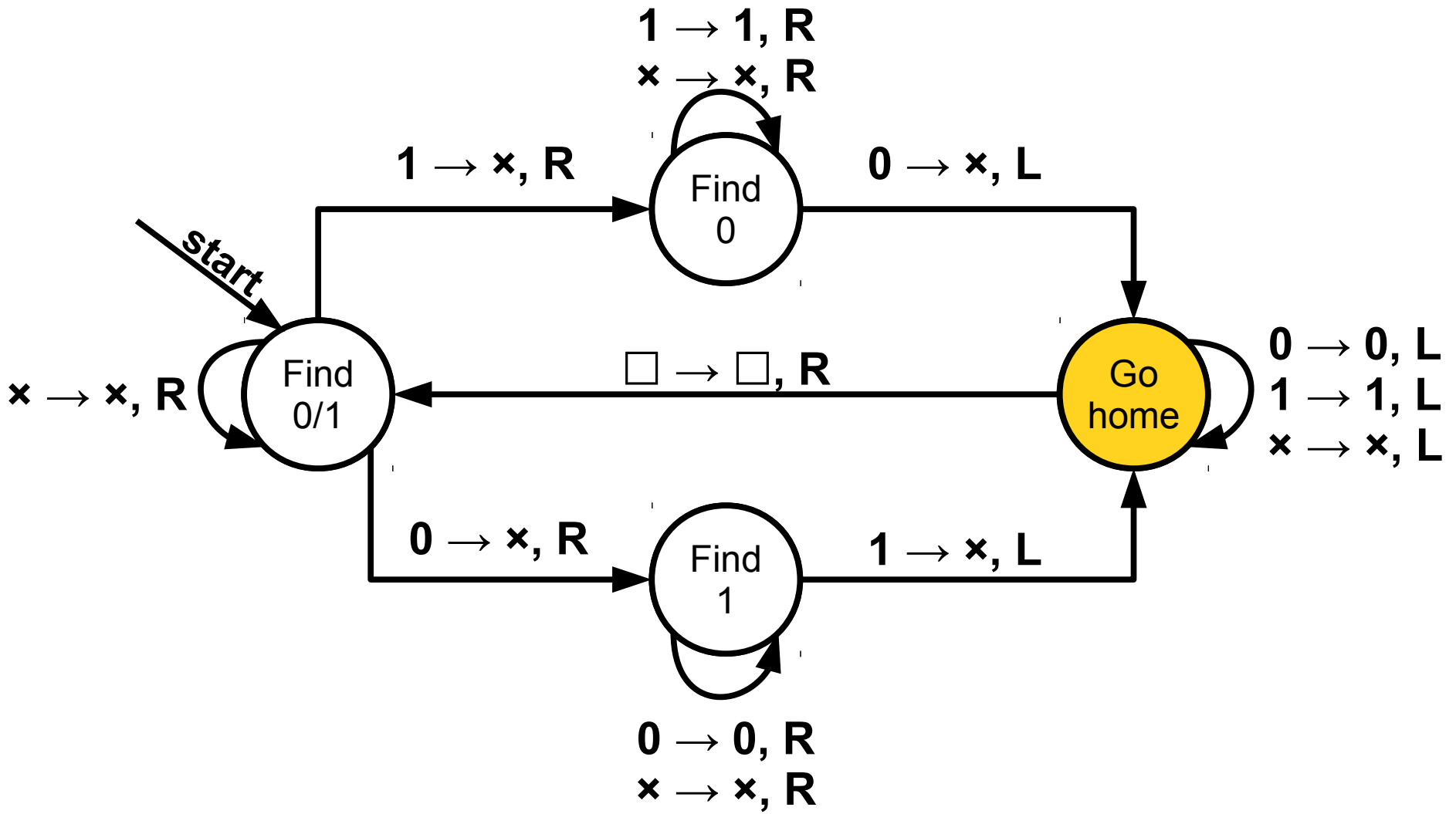

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R

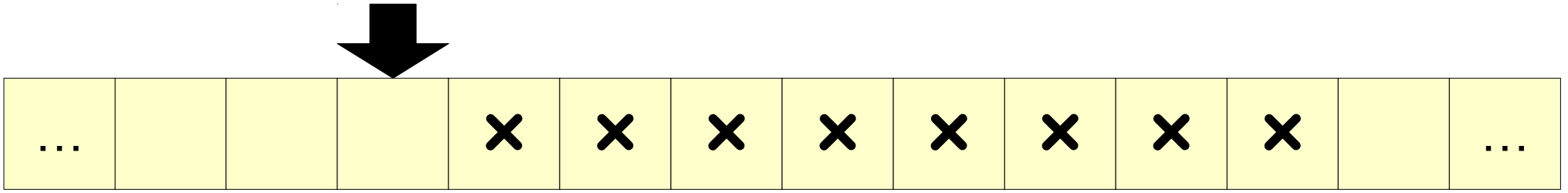

…
×
×
×
×
×
×
×
×
…

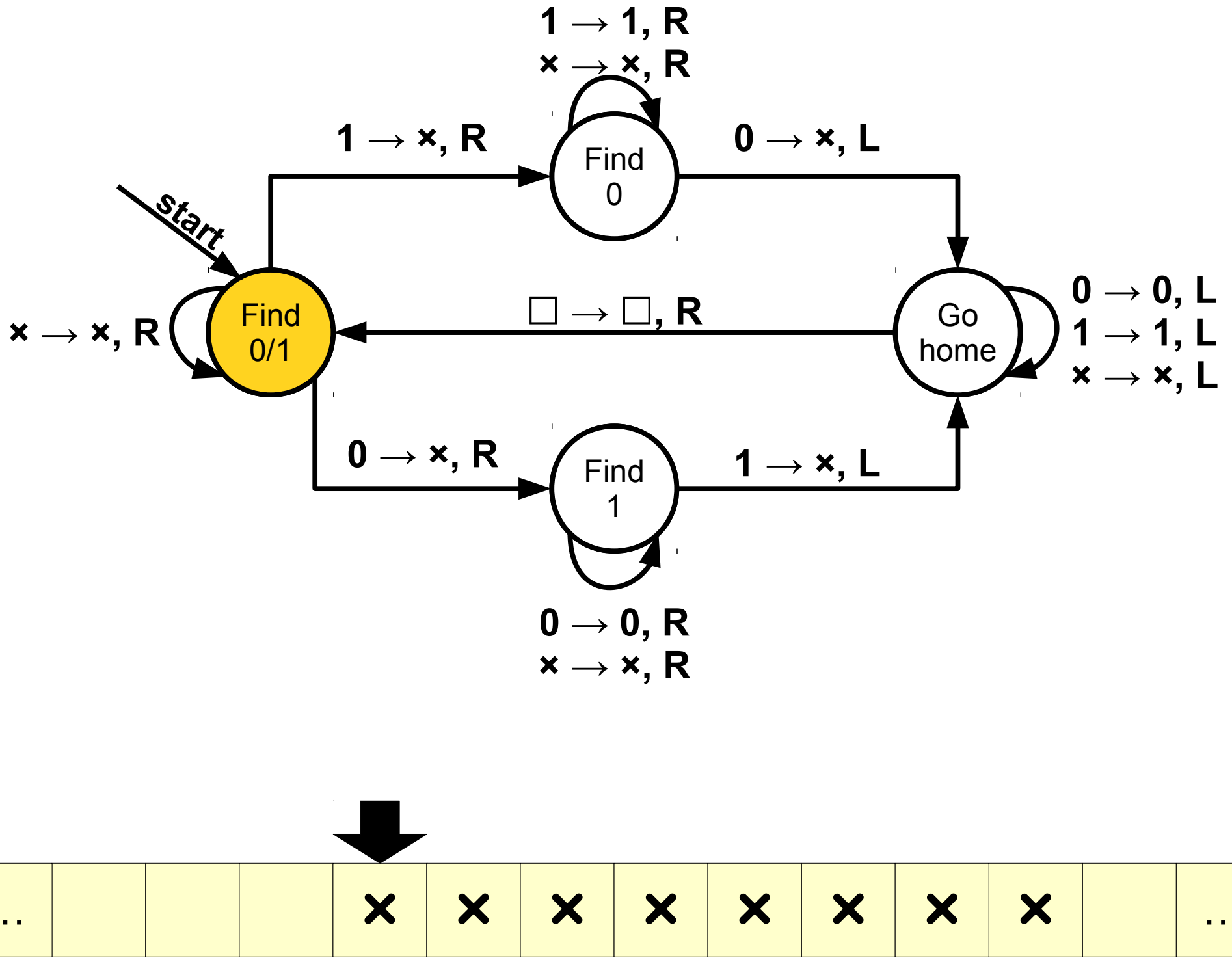

1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R


…
×
×
×
×
×
×
×
×
…


1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
Find 1
1 → ×, L
0 → 0, R
× → ×, R
…
×
×
×
×
×
×
×
×
…


1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find
0
Find
0/1
× → ×, R
□ → □, R
Go
home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find
1
0 → 0, R
× → ×, R


…
×
×
×
×
×
×
×
×
…


1 → 1, R
× → ×, R
1 → ×, R
0 → ×, L
start
Find 0
Find 0/1
× → ×, R
□ → □, R
Go home
0 → 0, L
1 → 1, L
× → ×, L
0 → ×, R
1 → ×, L
Find 1
0 → 0, R
× → ×, R
…
×
×
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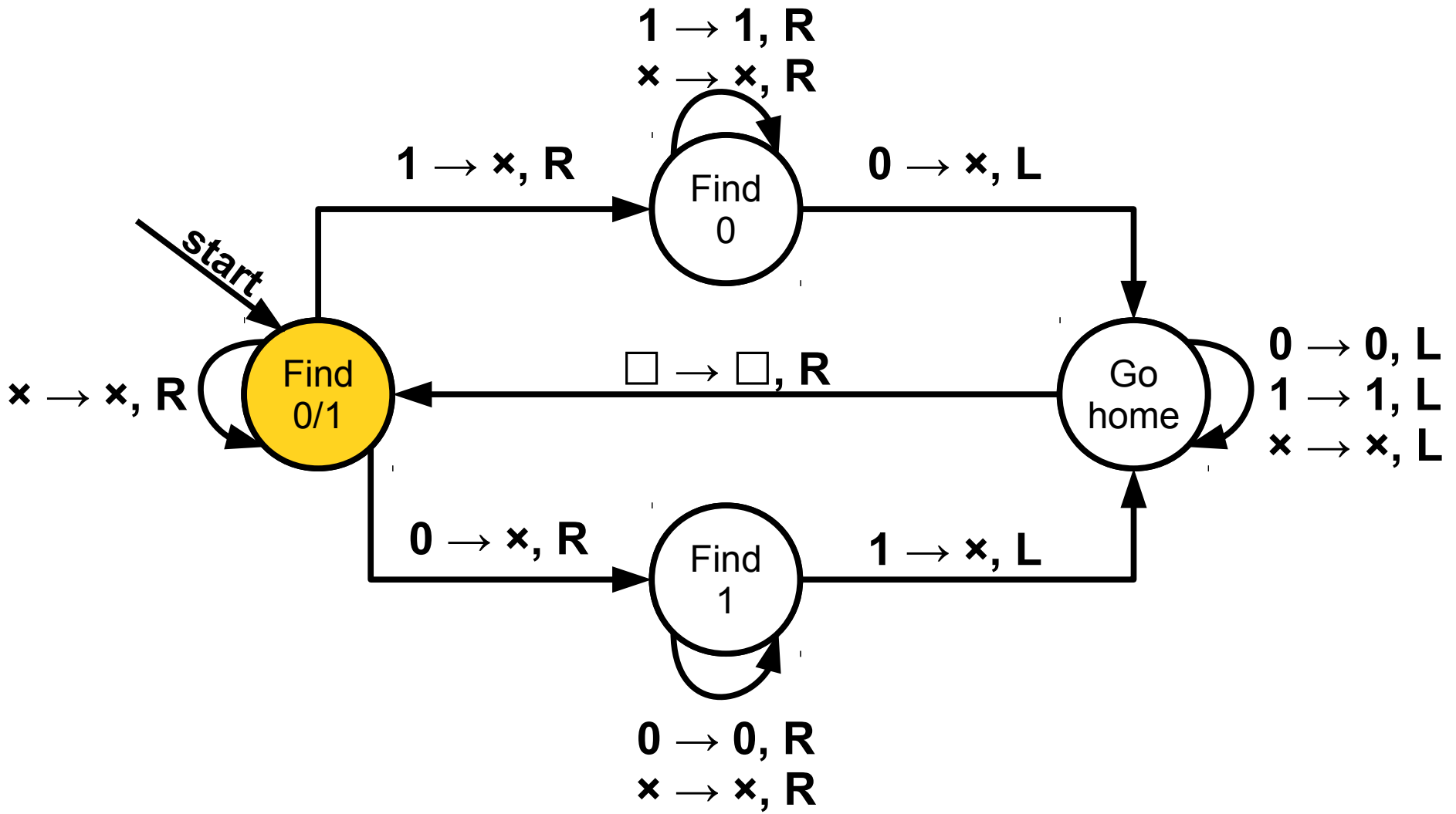
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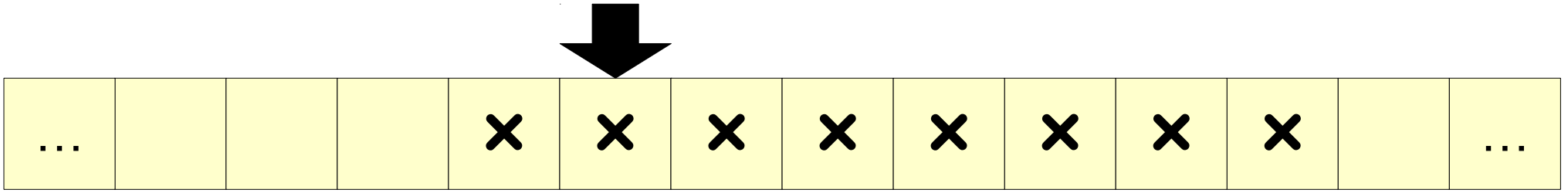
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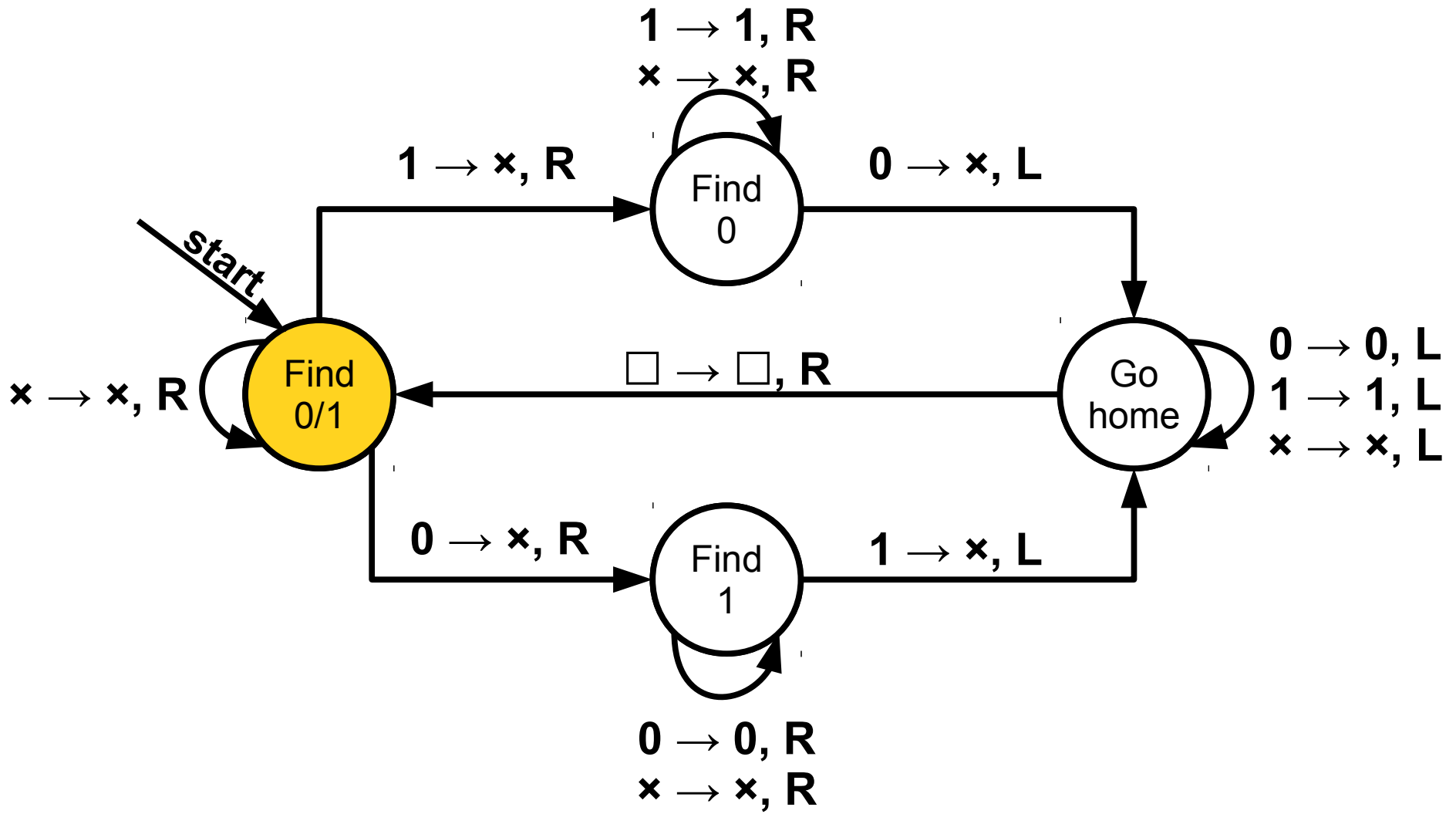
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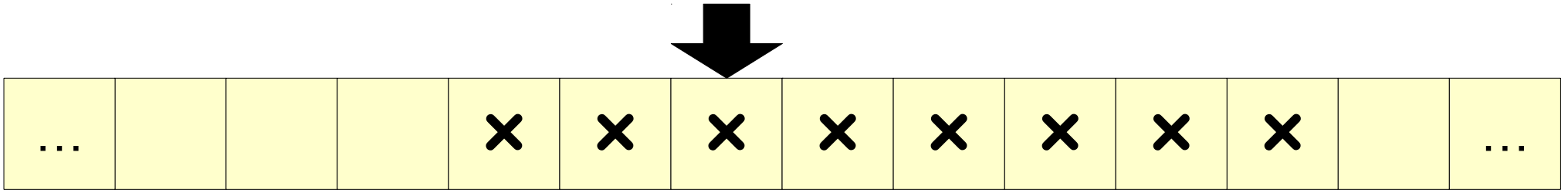
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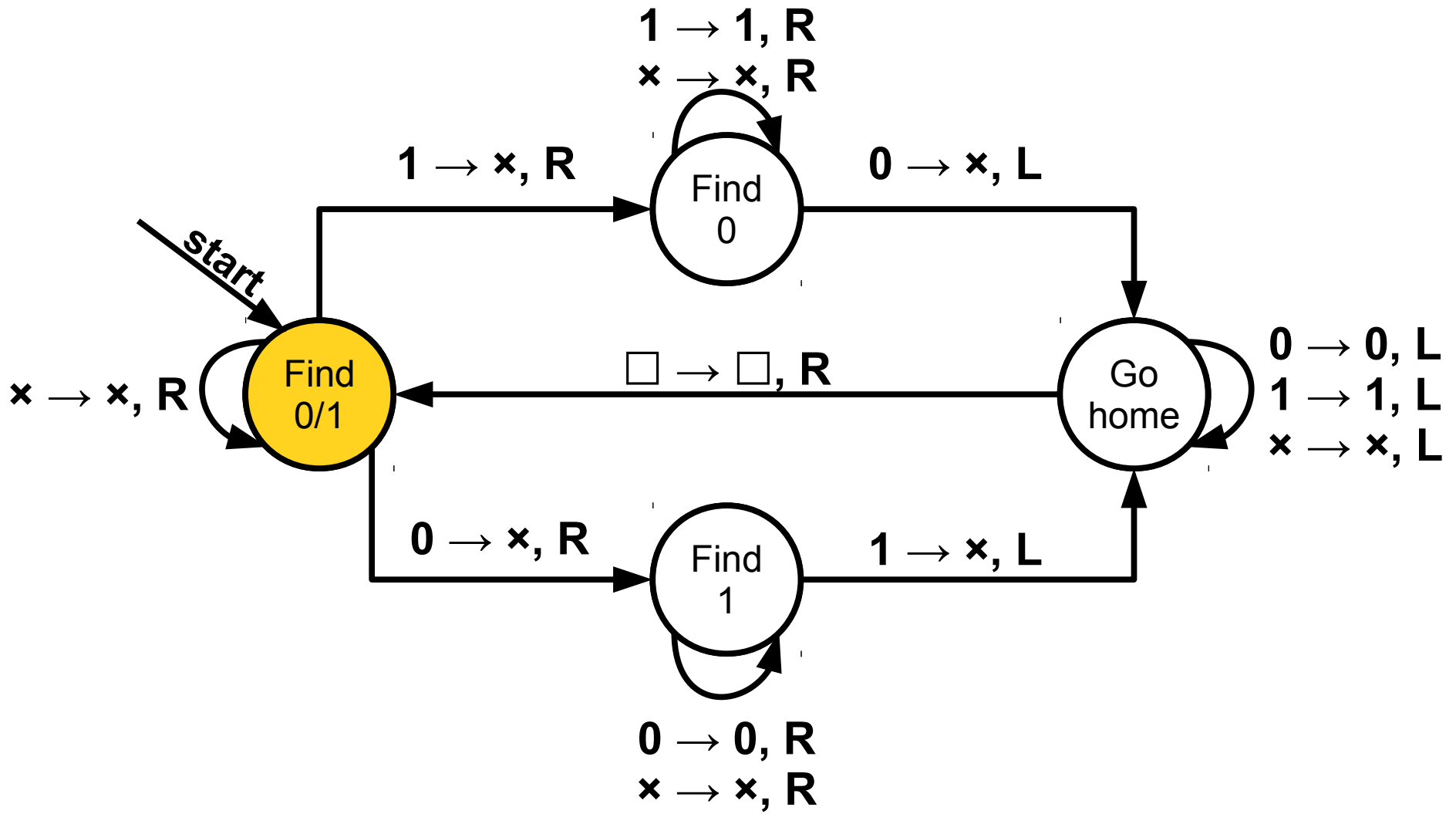
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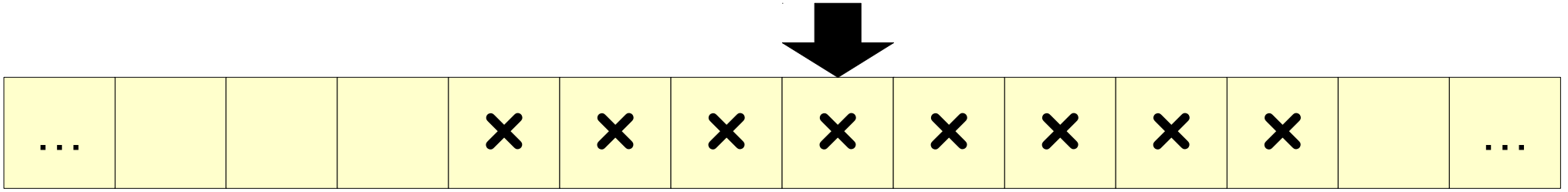
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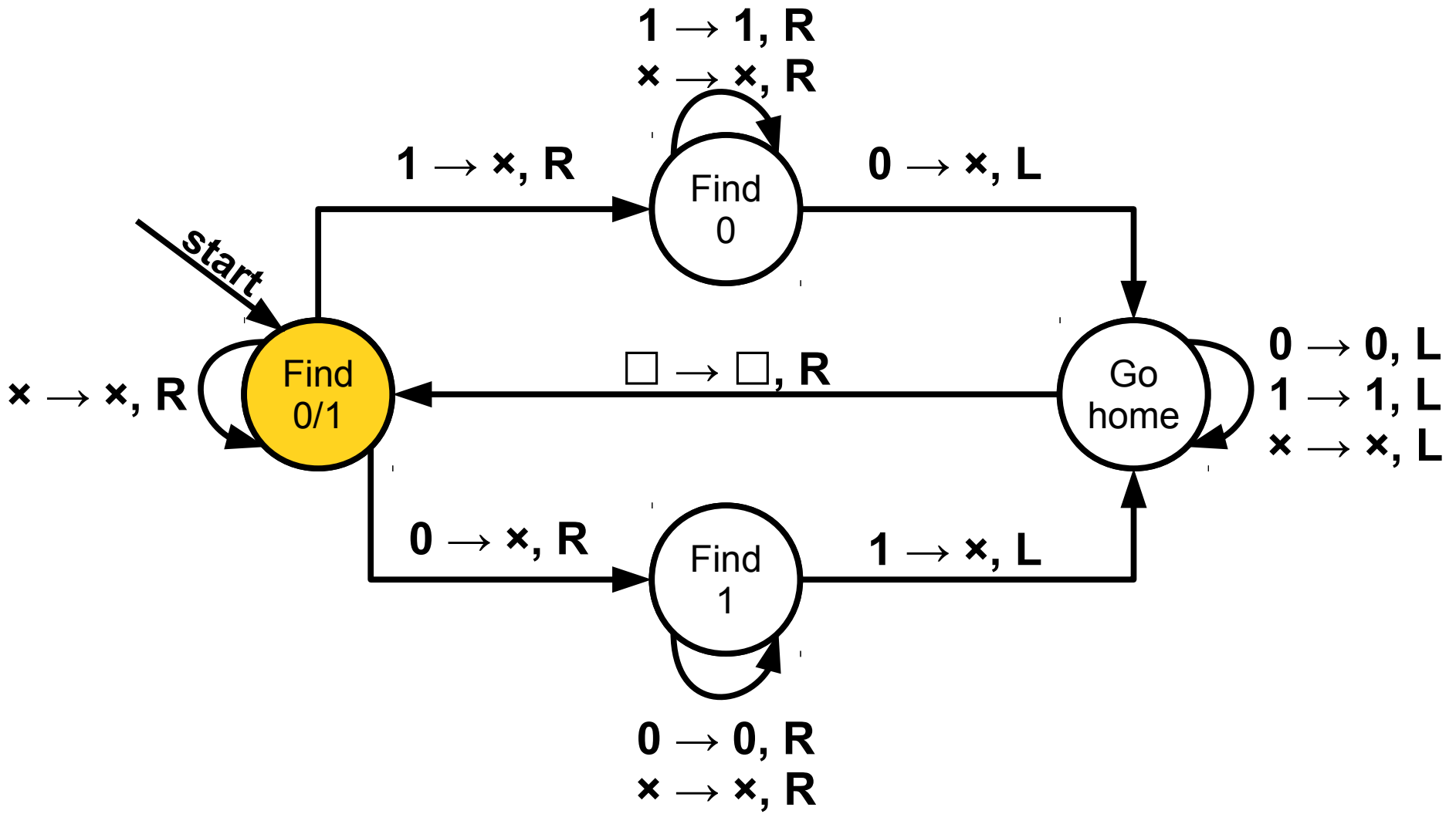
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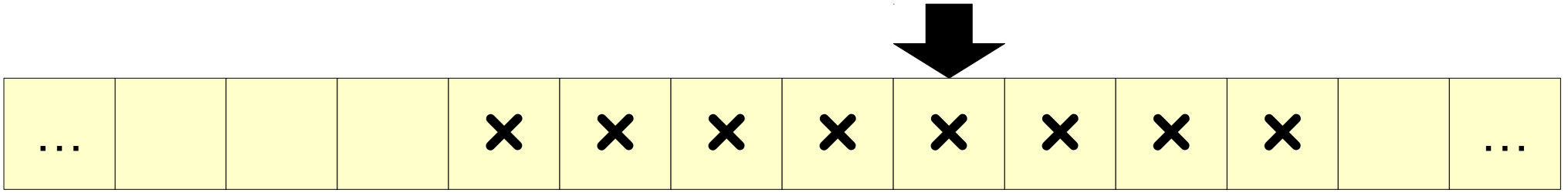
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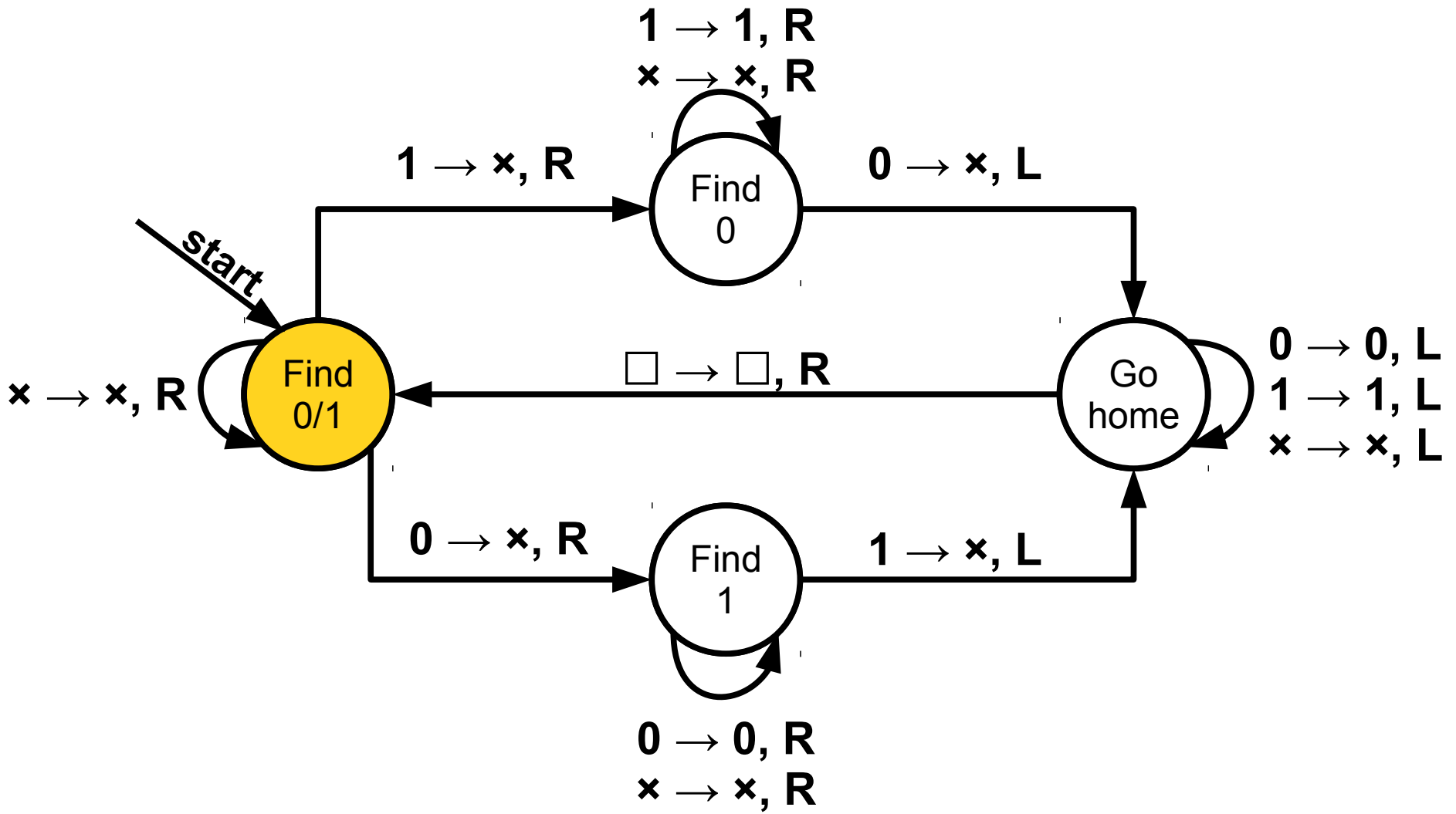
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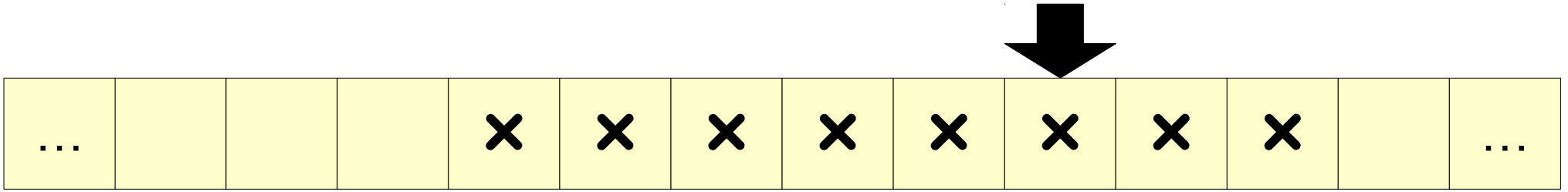
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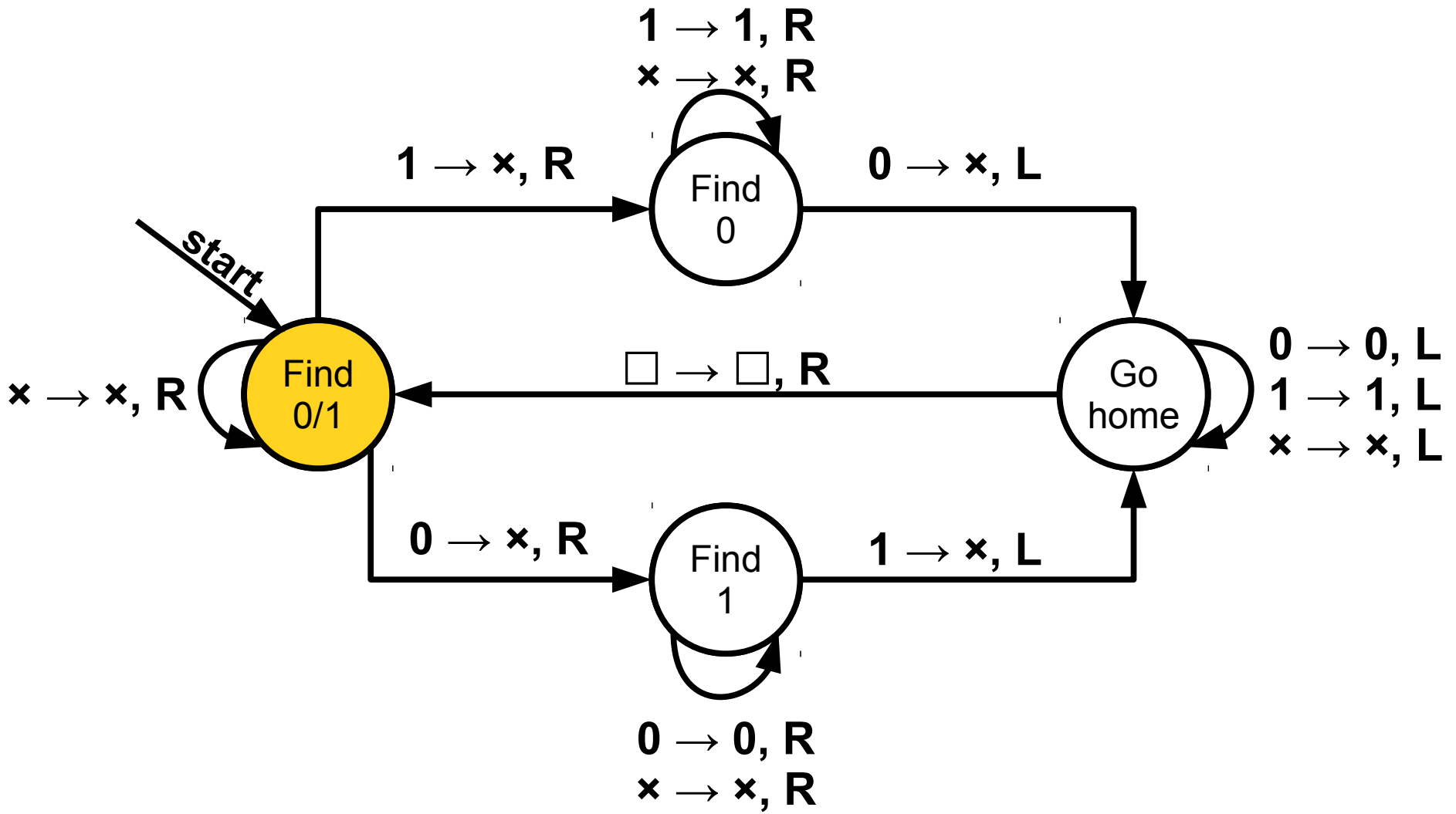
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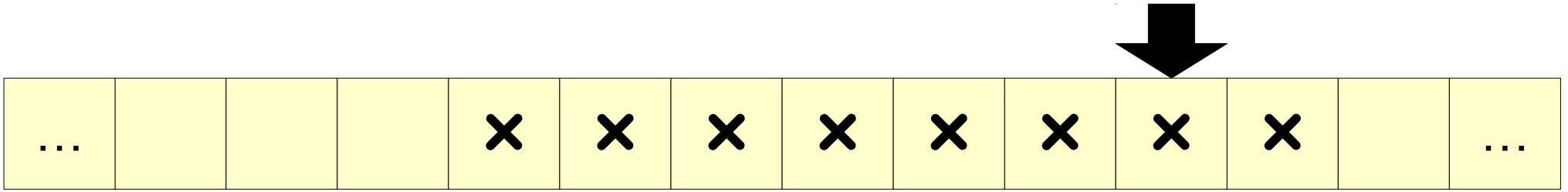
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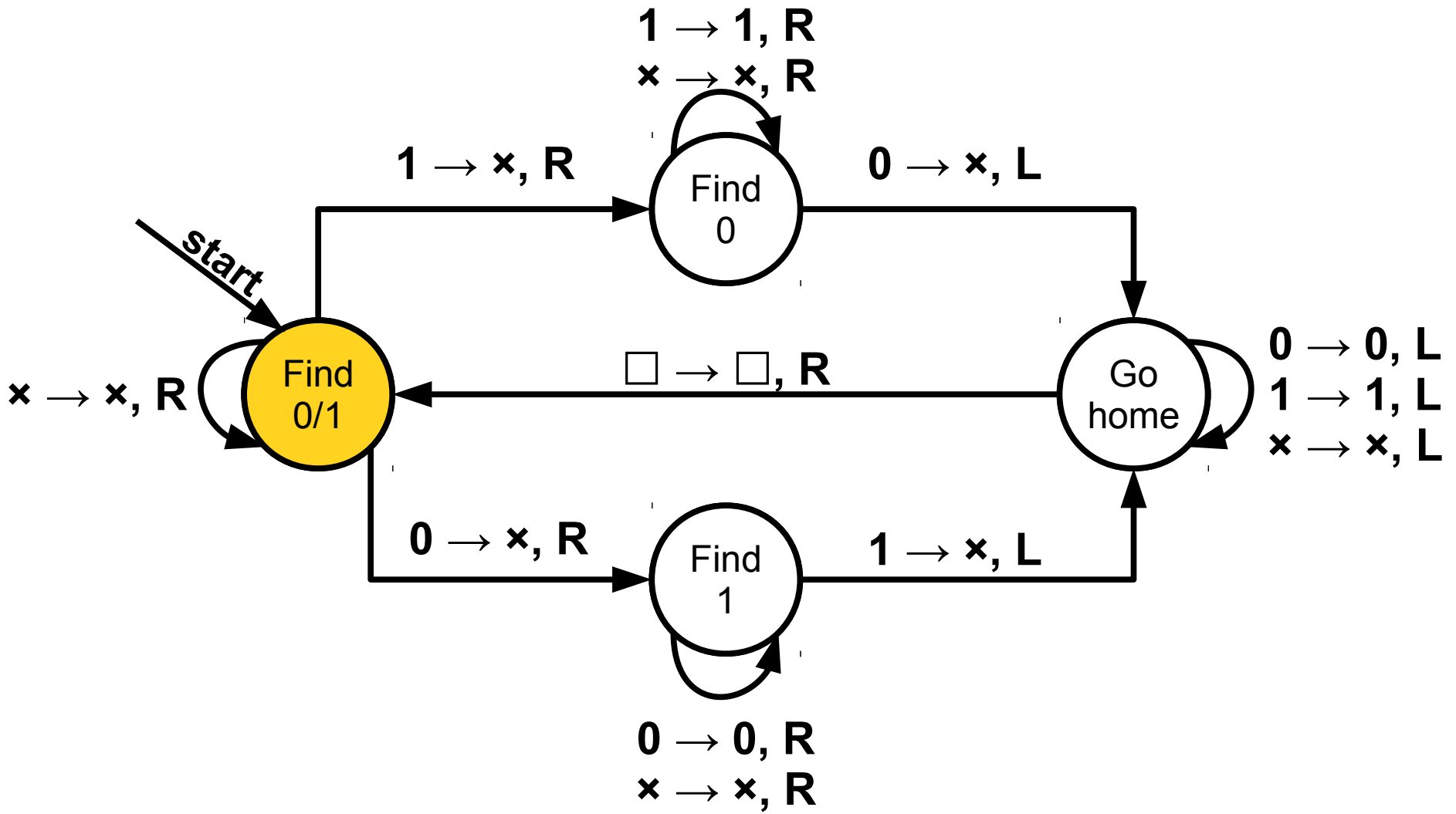
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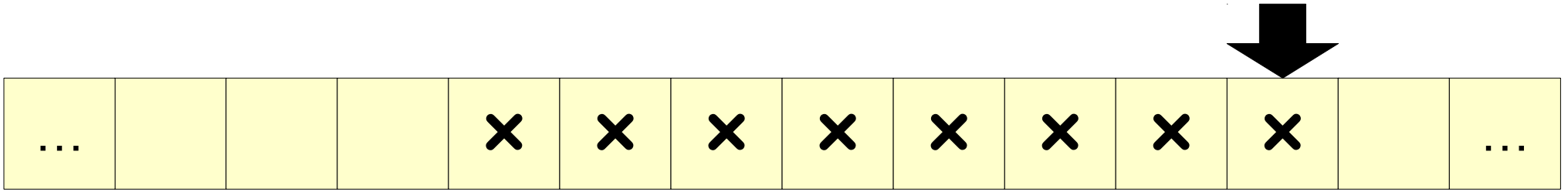
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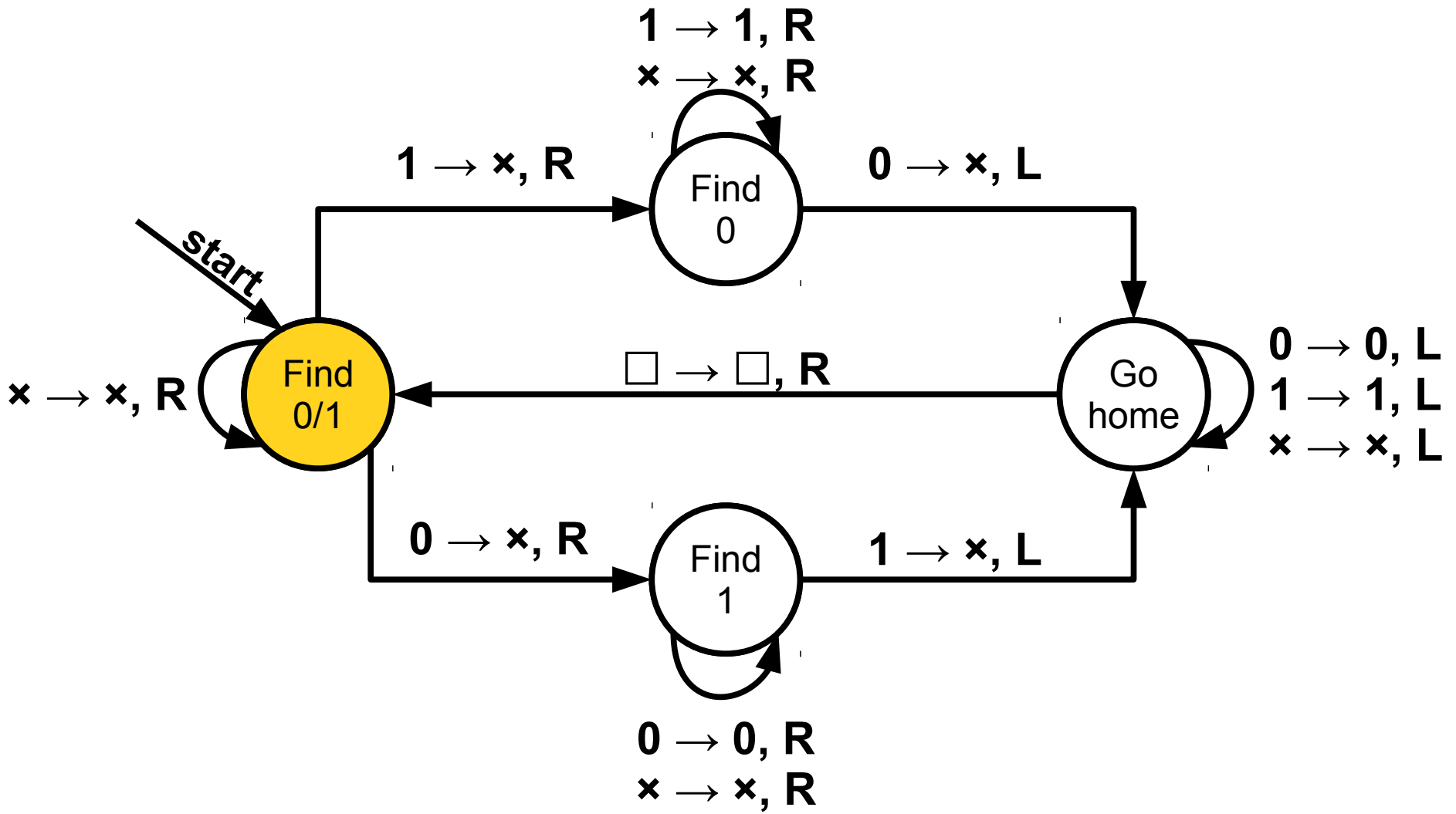
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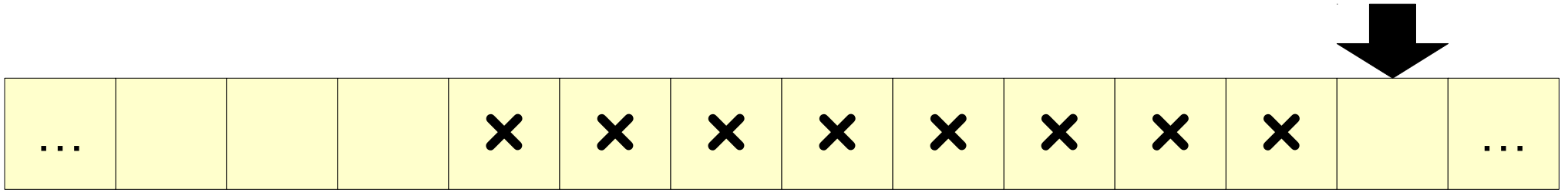
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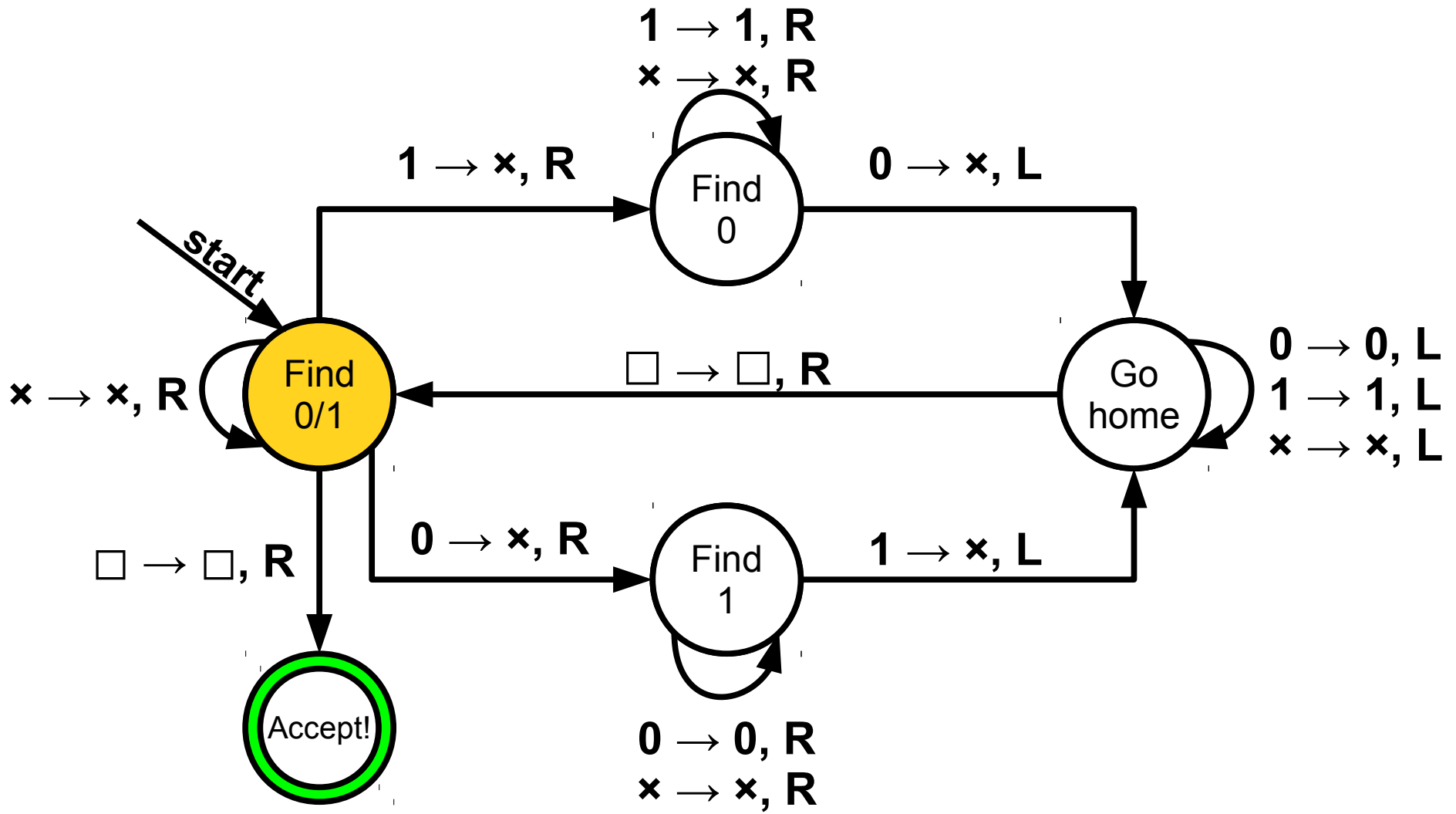
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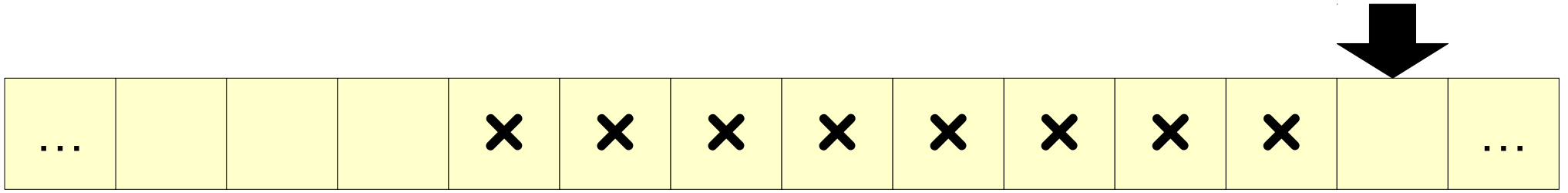
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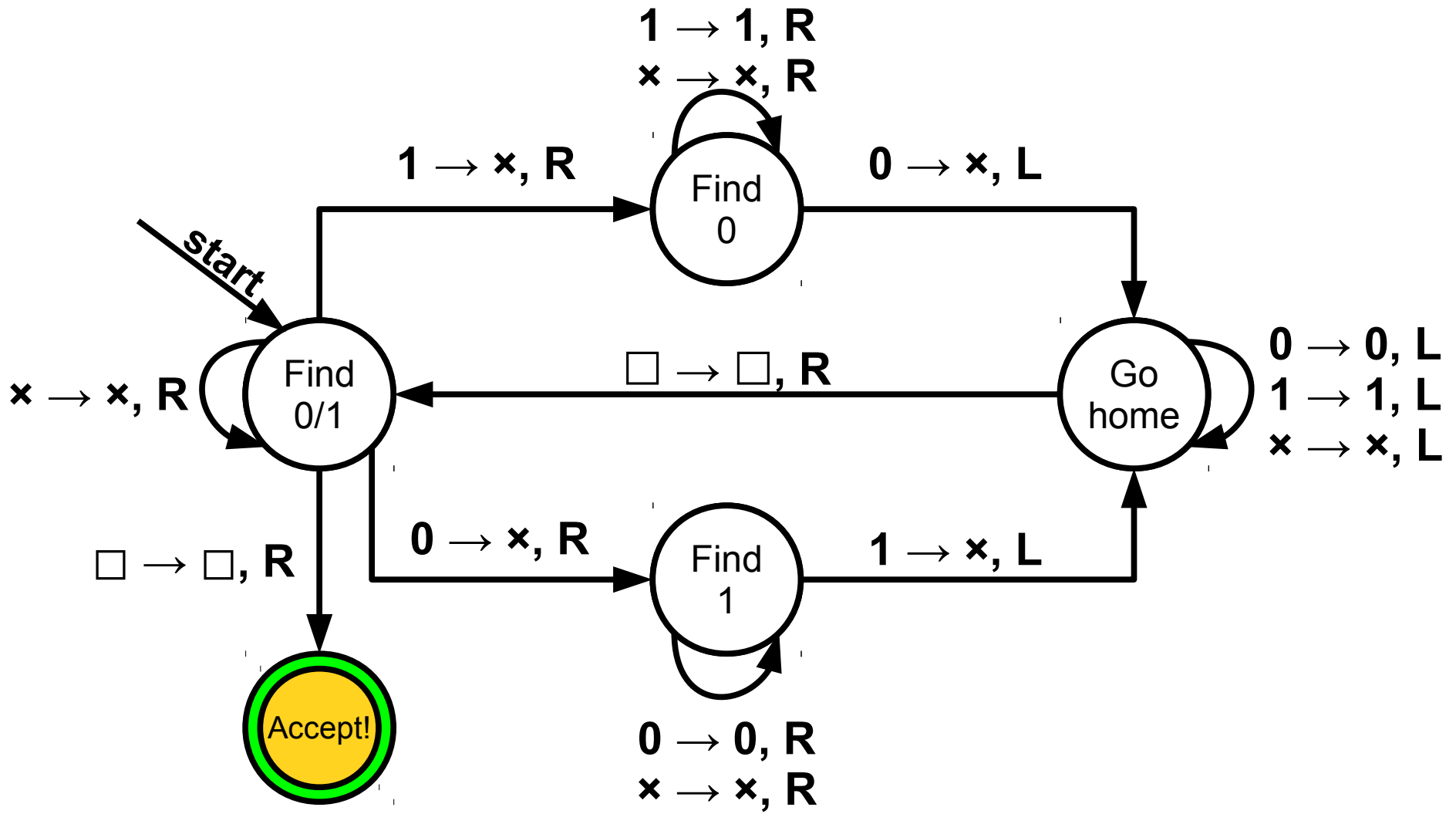
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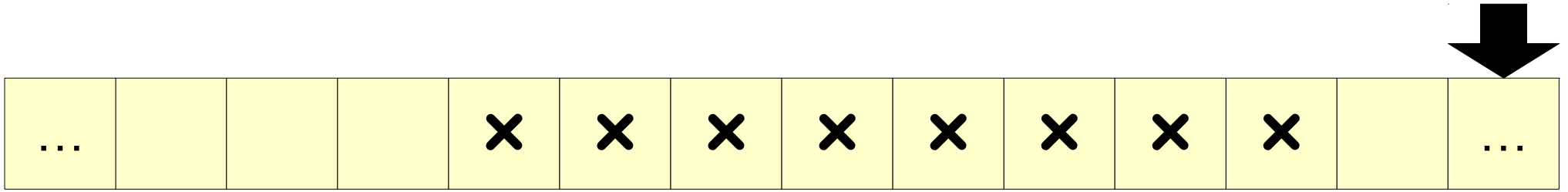
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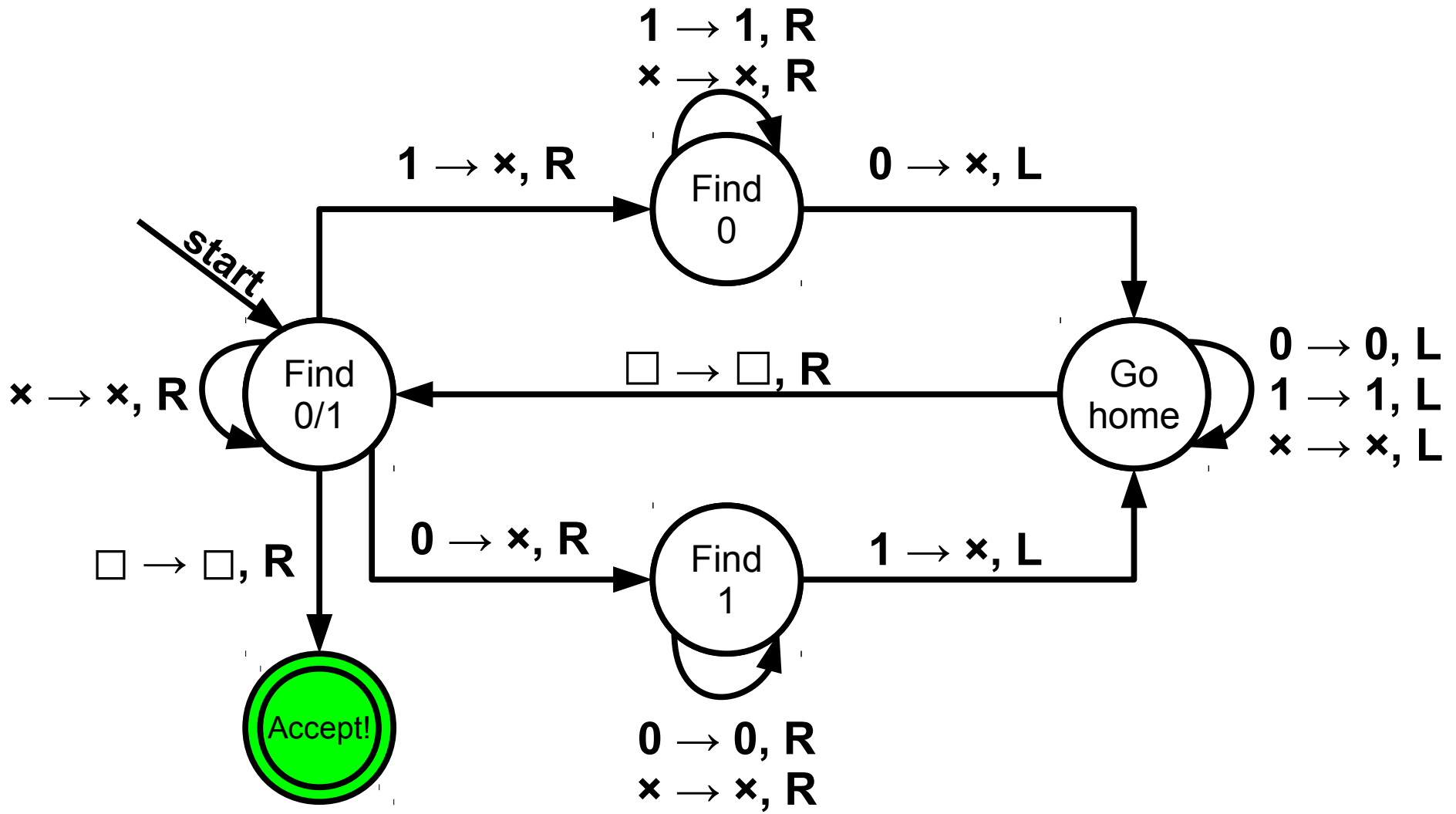
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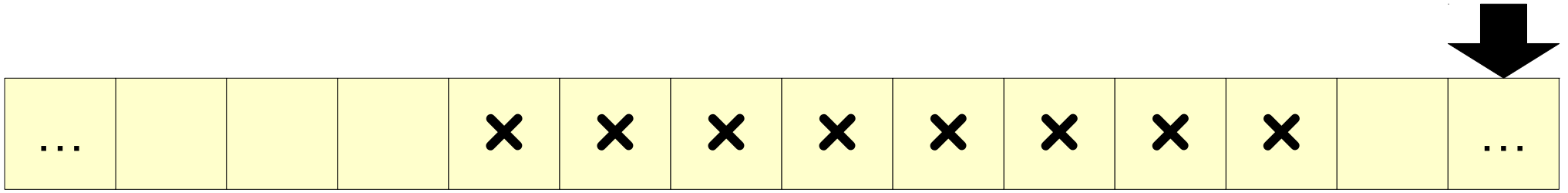
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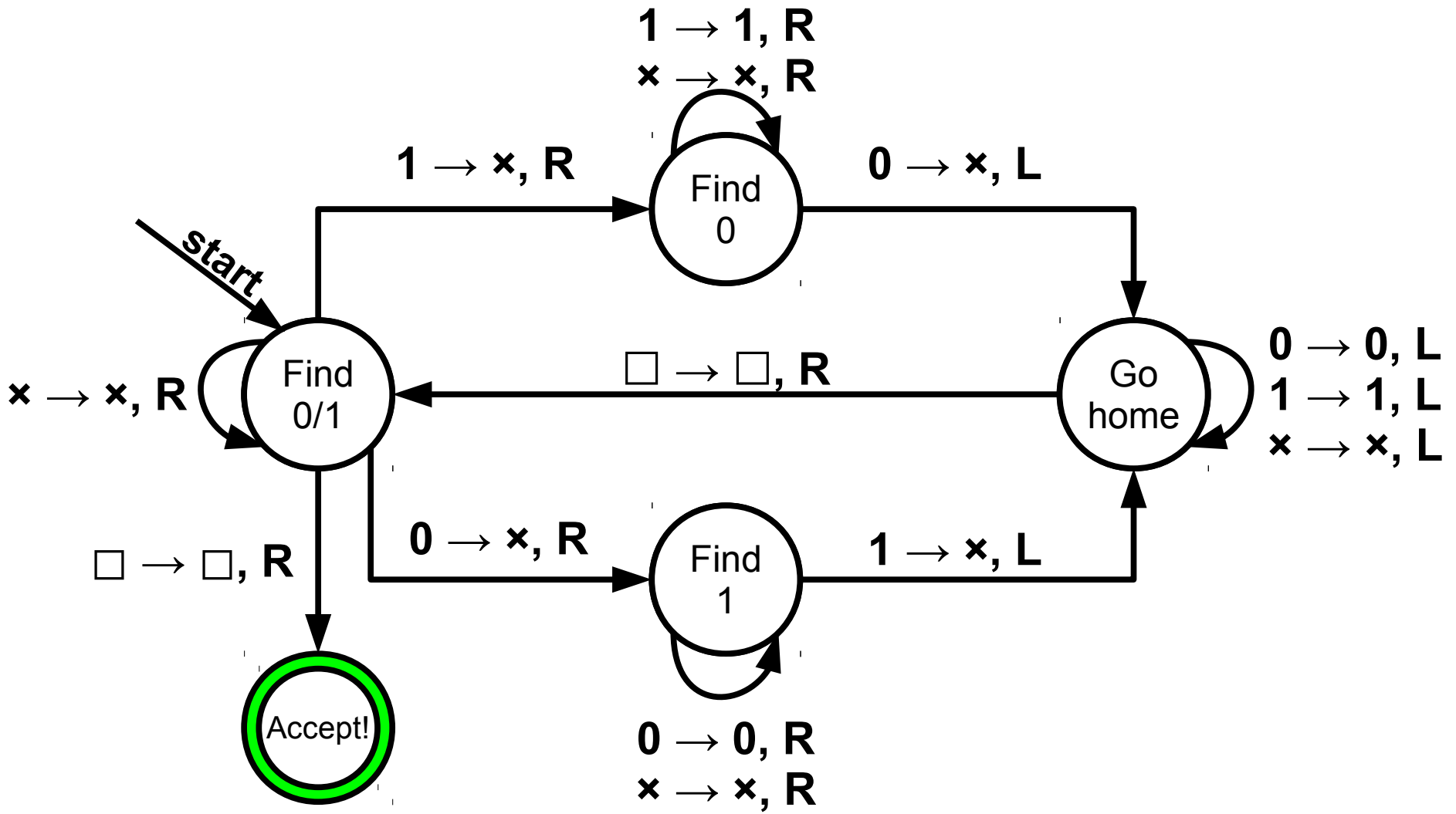
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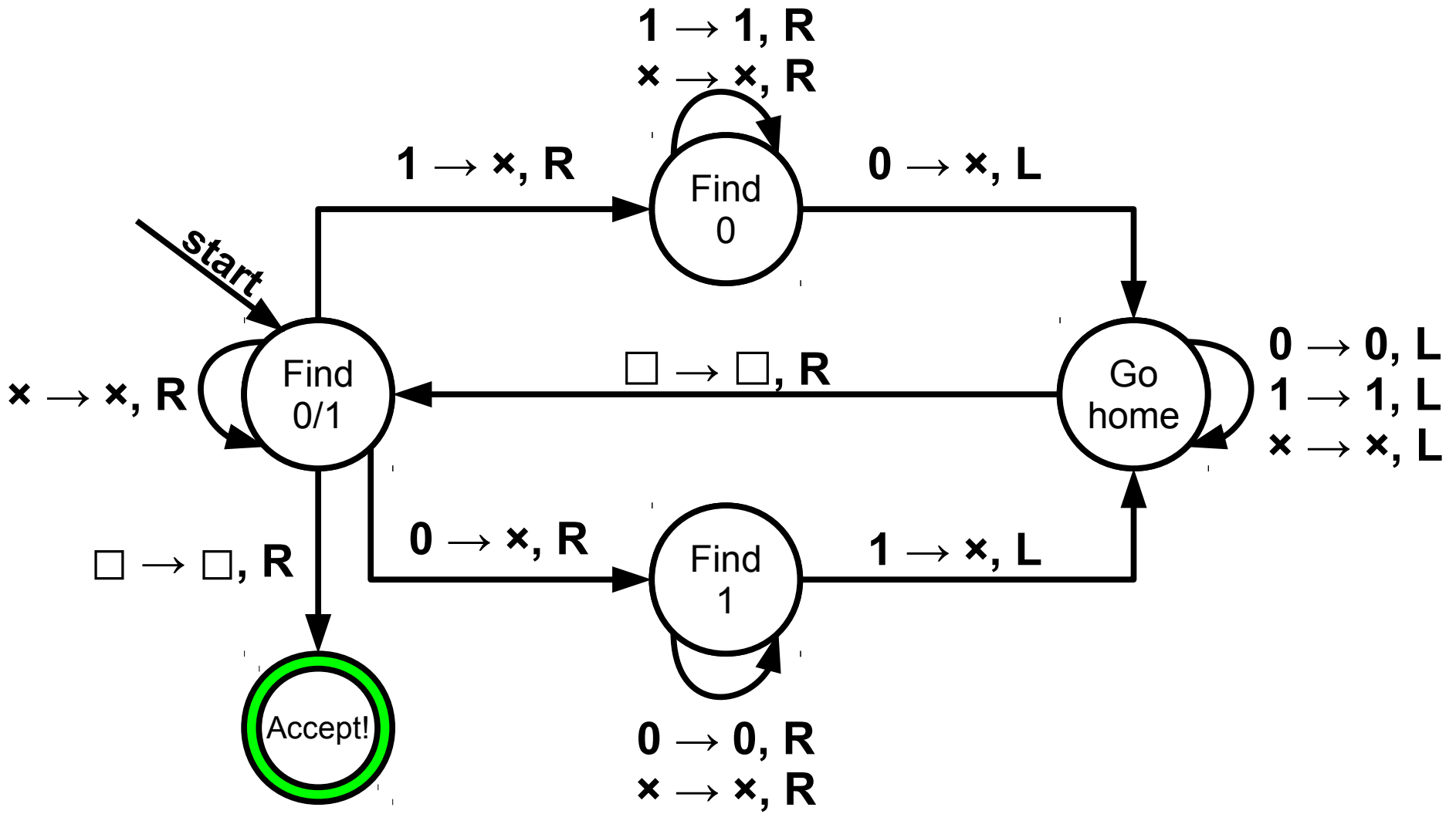
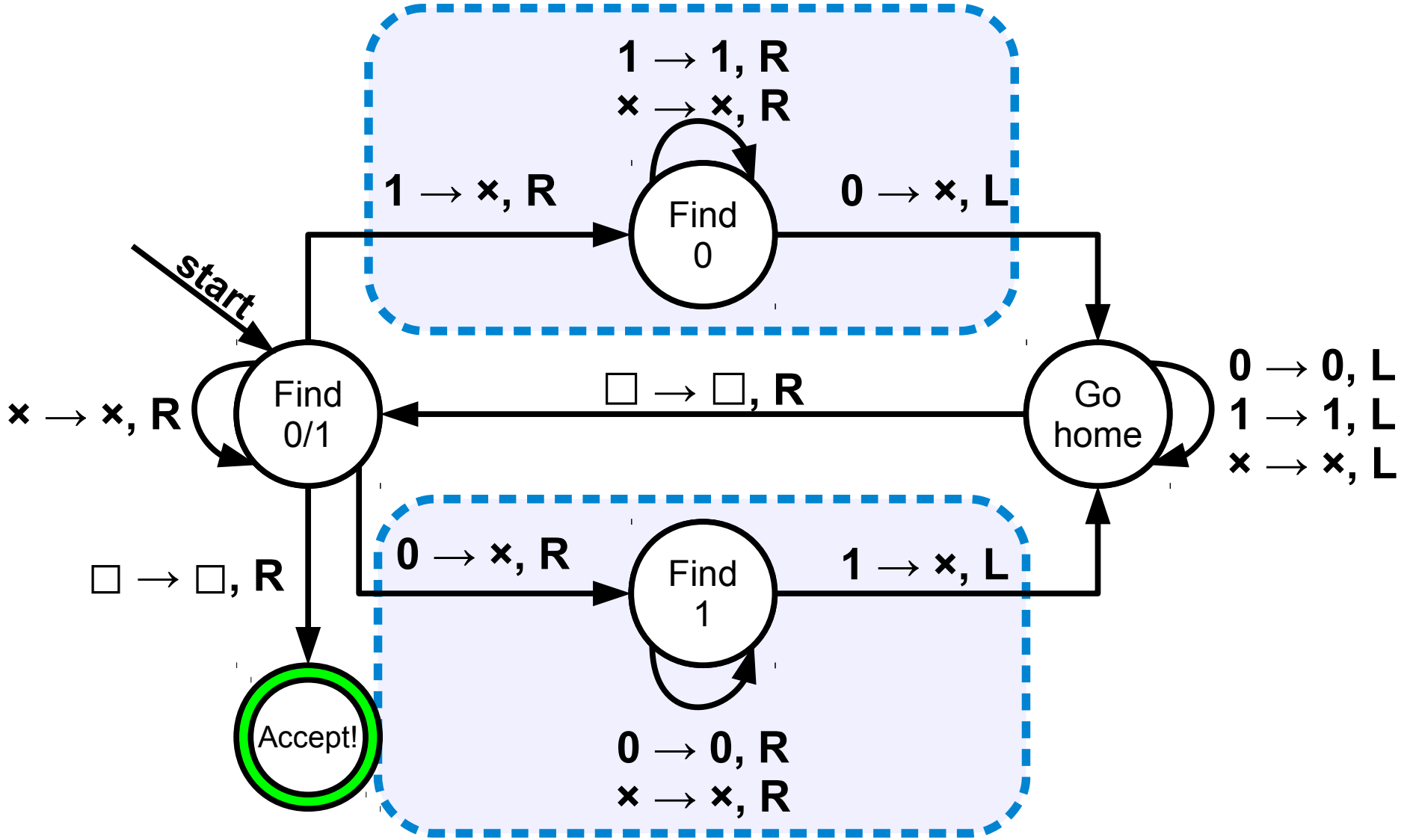


For now, let's ignore the missing transitions and pretend that they implicitly reject.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Constant Storage

- Sometimes, a TM needs to remember some additional information that can't be put on the tape.
- In this case, you can use similar techniques from DFAs and introduce extra states into the TM's finite-state control.
- The finite-state control can only remember one of finitely many things, but that might be all that you need!

Time-Out for Announcements!

Midterm Logistics

- Second midterm exam is next **Thursday, November 13** from **7PM – 10PM**, locations TBA.
  - Covers material up through and including PS6, with a focus on topics from PS4 – PS6.
  - Closed-book, closed-computer. You can have one 8.5” × 11” sheet of notes with you when you take the exam.
- Practice midterm is next **Monday, November 10** from 7PM – 10PM in **Annenberg Auditorium** (same time and place as last time.)
- We'll release a second set of practice problems on Friday.

Your Questions

“I find myself routinely falling below the median on homework submissions. The issue is not a lack of understanding the material, but rather losing points here and there due to wording. Do you have any suggestions on how I can improve?”

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“I sometimes feel like I am bad test-taker because I like to think through everything before starting a problem and sometimes allocate too much time on a single problem. So, how do you become a good test-taker? (and become a faster test-taker?)”

“What are benefits of doing research here vs summer internships? You mentioned CURIS and am interested, but am weighing options.”

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“I'm currently in the process of interviewing for summer internships. I usually do pretty well on the online coding tests, but not so well on phone interviews. How do I practice coding so that I'll do better when a real person asks me a question?”

Back to CS103!

Another TM Design

- Consider the following language over $\Sigma = \{\mathtt{0}, \mathtt{1}\}$:

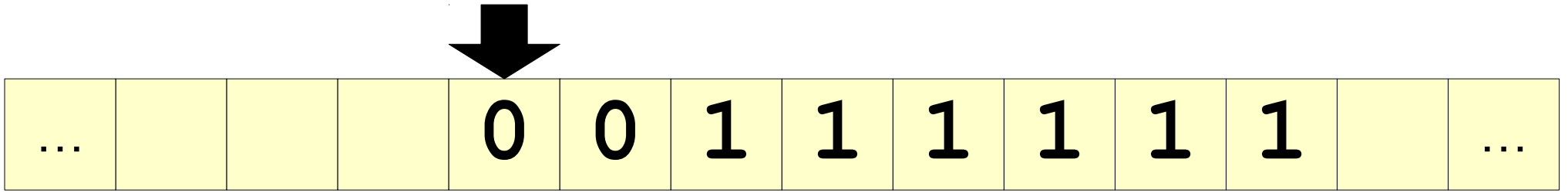
$$L = \{\mathtt{0}^n\mathtt{1}^m \mid n, m \in \mathbb{N} \text{ and } m \text{ is a multiple of } n\}$$

- Is this language regular?
- How might we design a TM for this language?

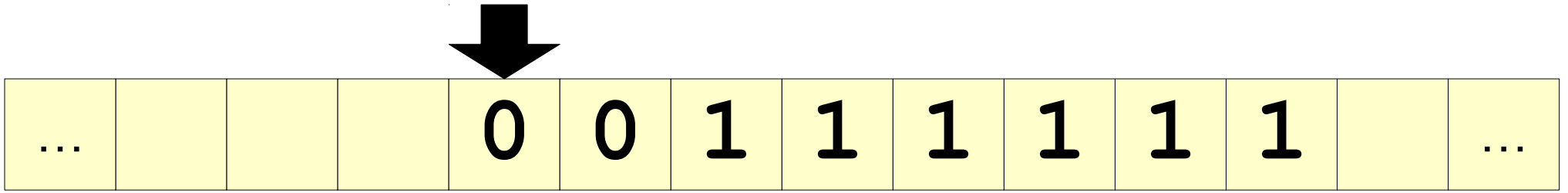
An Observation

- We can recursively describe when one number m is a multiple of n:
  - If $m = 0$, then m is a multiple of n.
  - Otherwise, m is a multiple of n iff $m - n$ is a multiple of n.
- **Idea:** Repeatedly subtract n from m until m becomes zero (good!) or drops below zero (bad!)

The Challenge



One Solution



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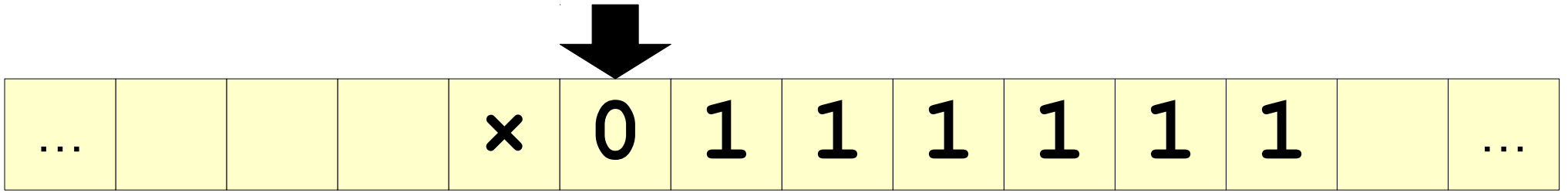

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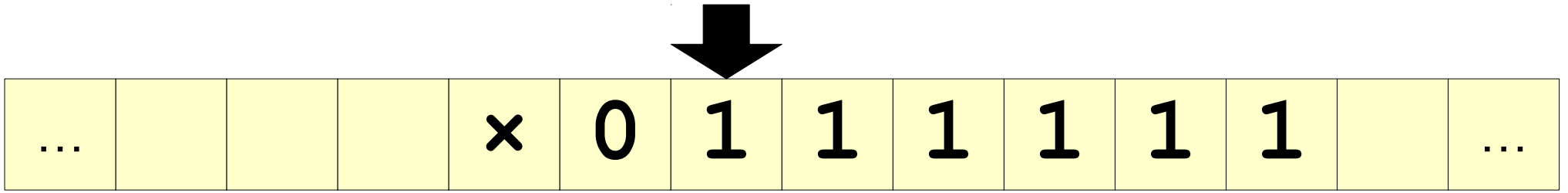

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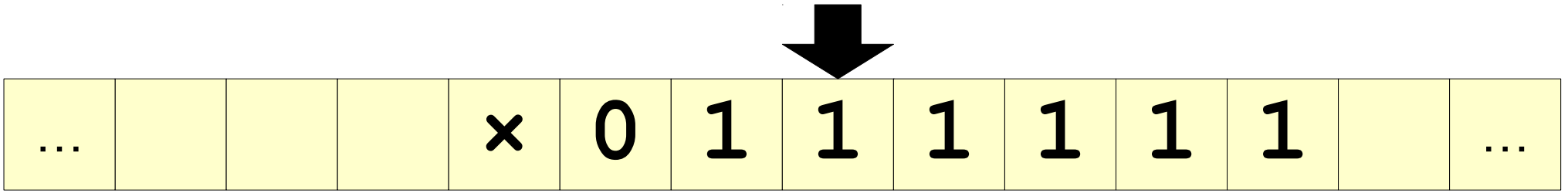

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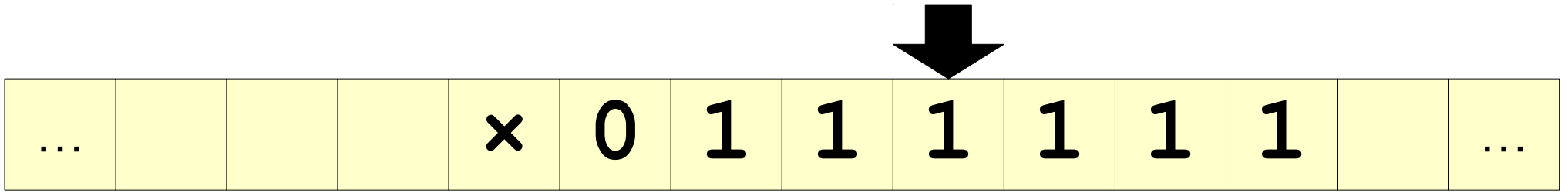

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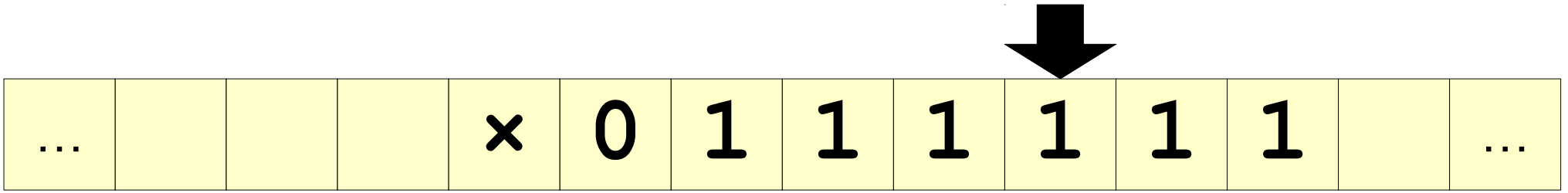

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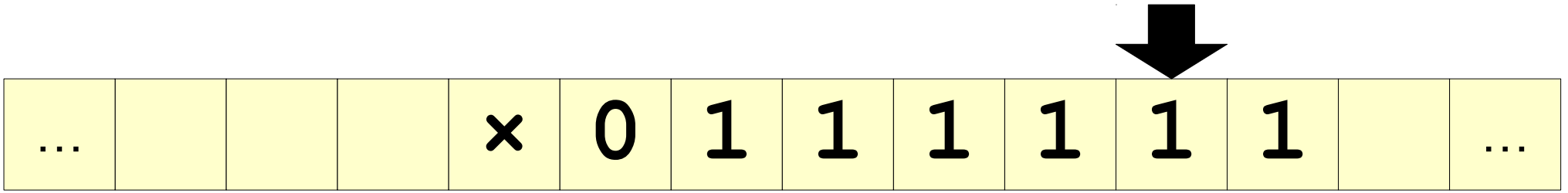

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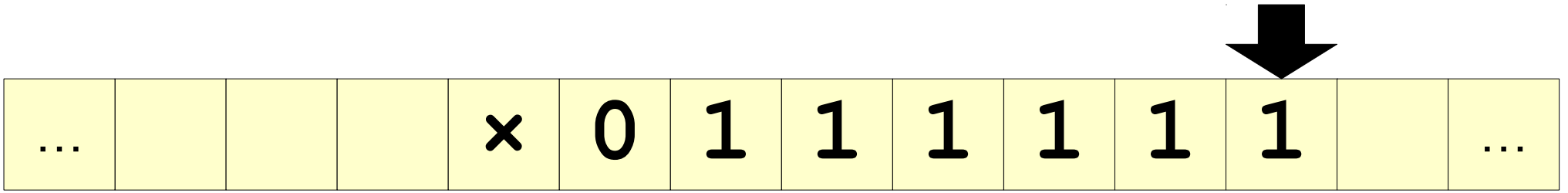

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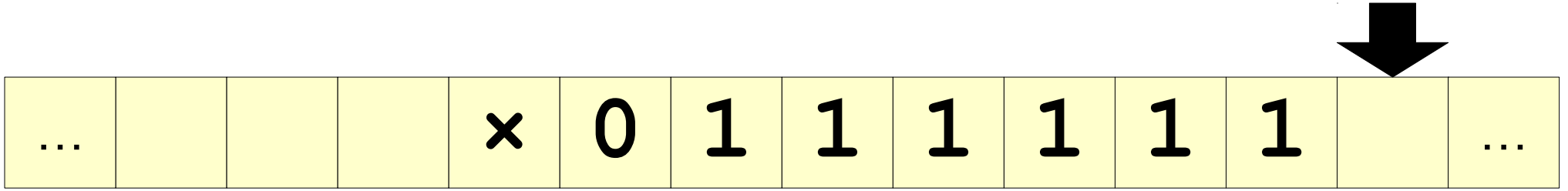
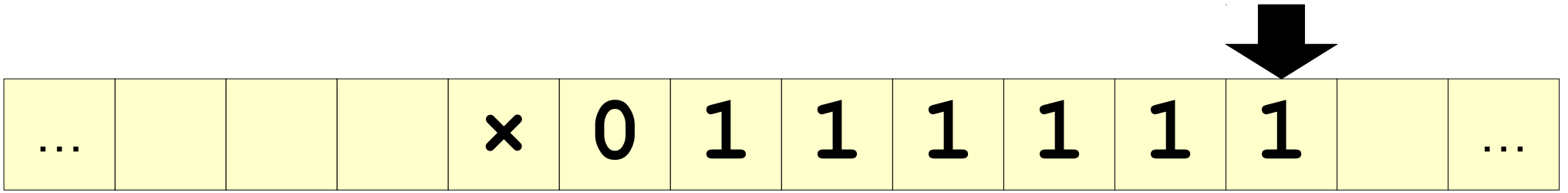


One Solution



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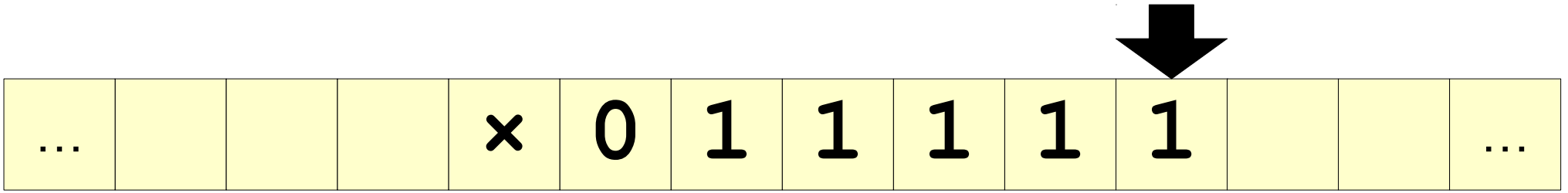

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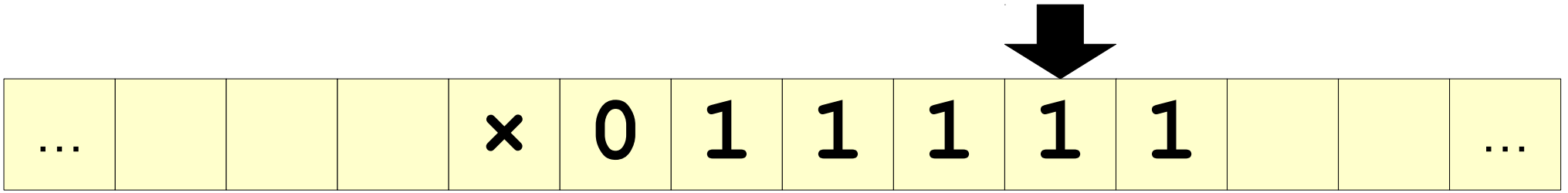

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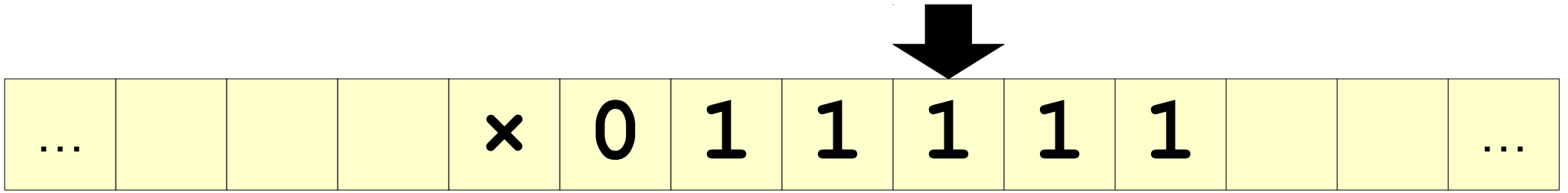

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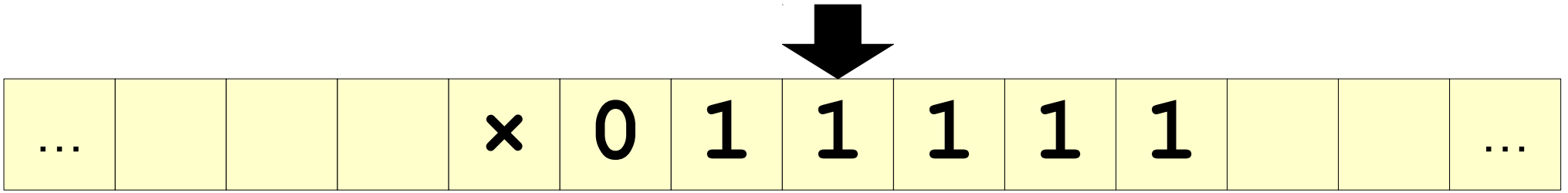

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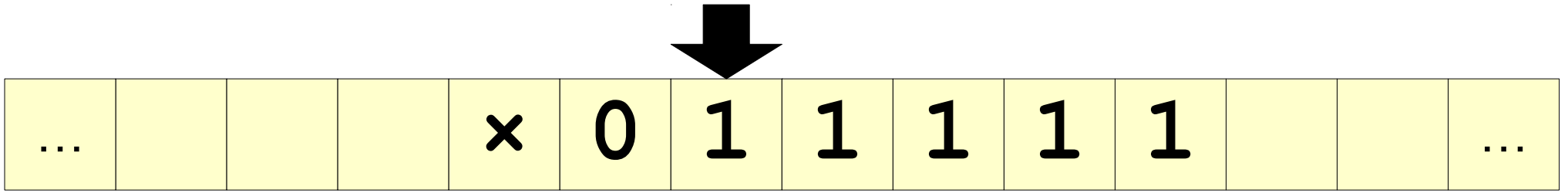

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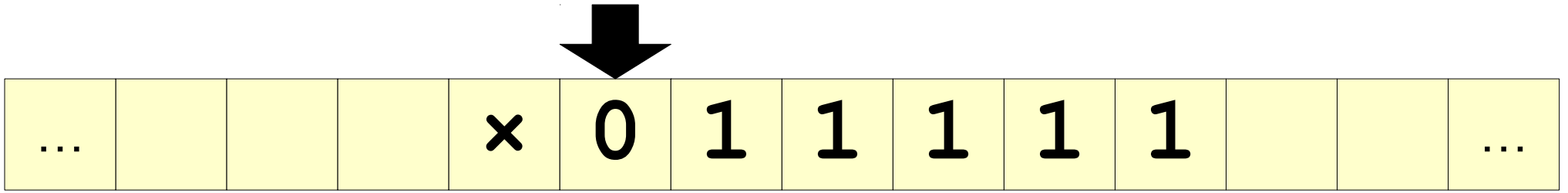

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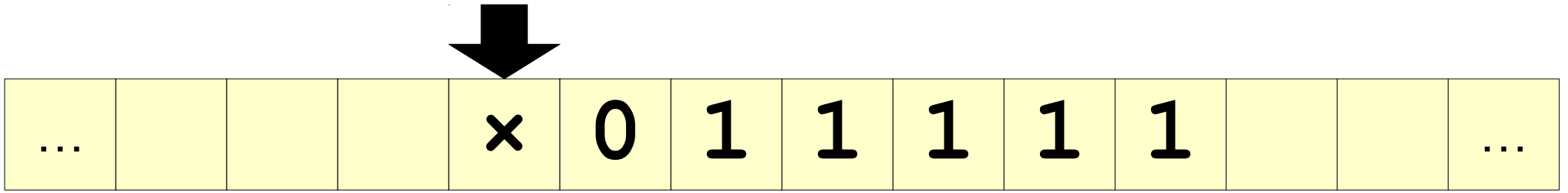

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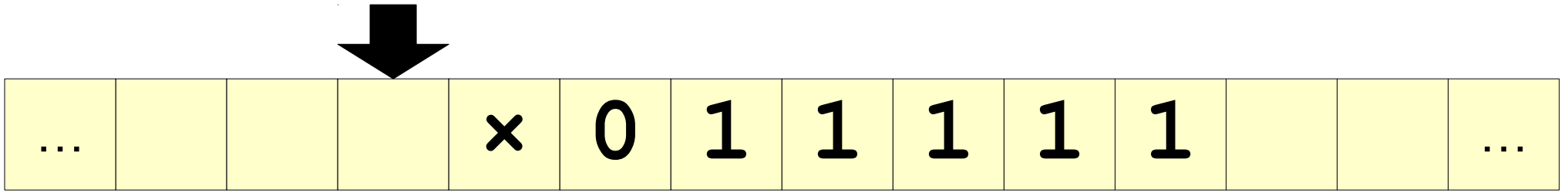

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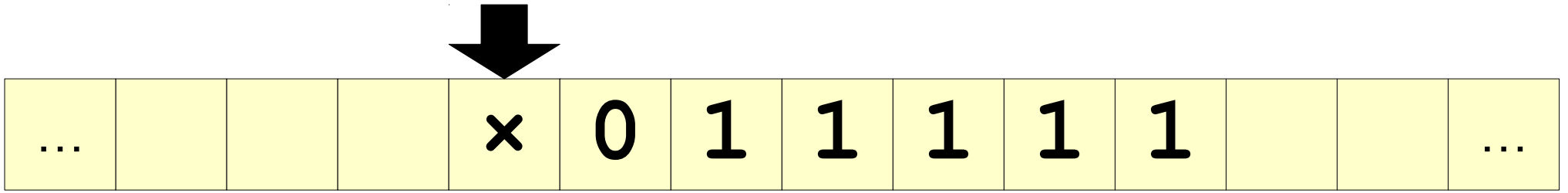

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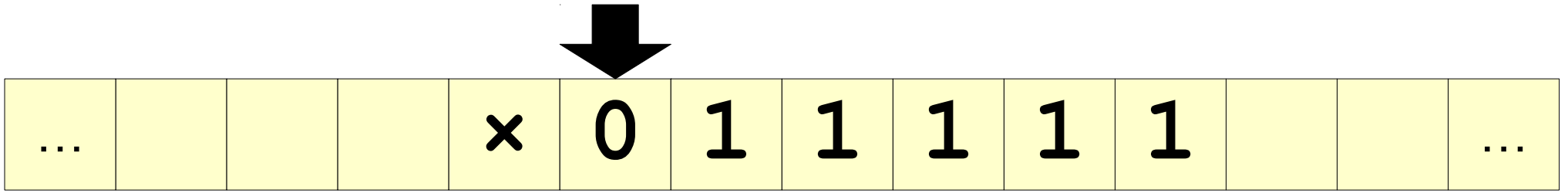

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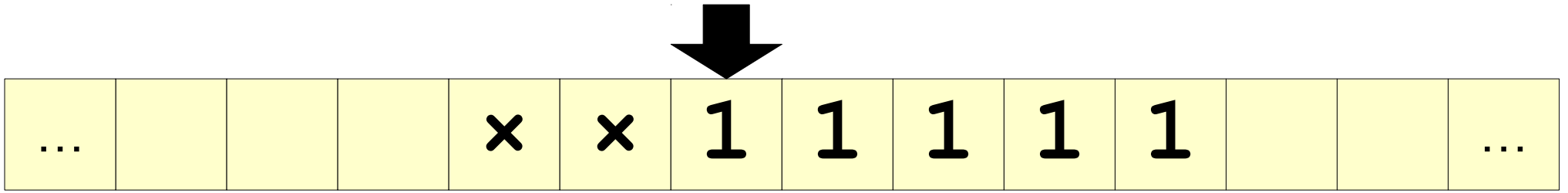

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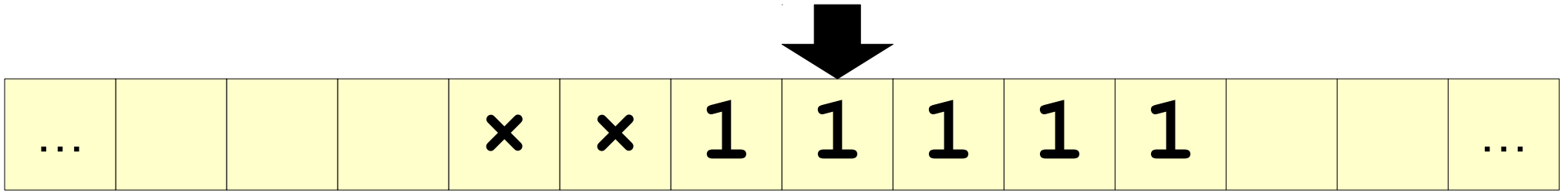

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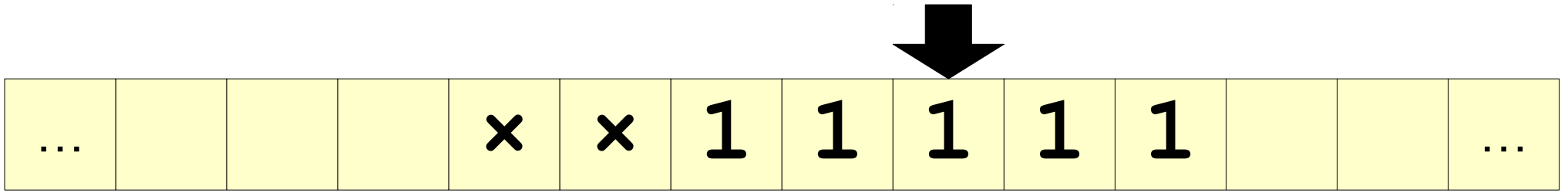

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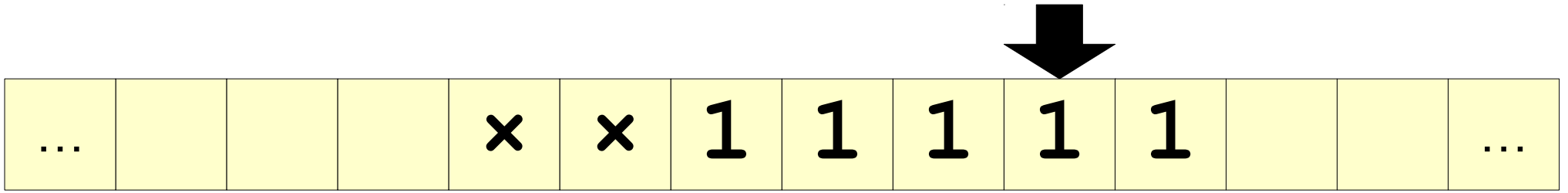

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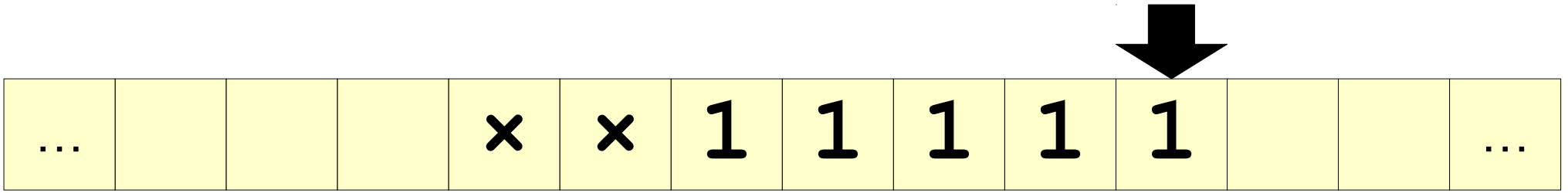

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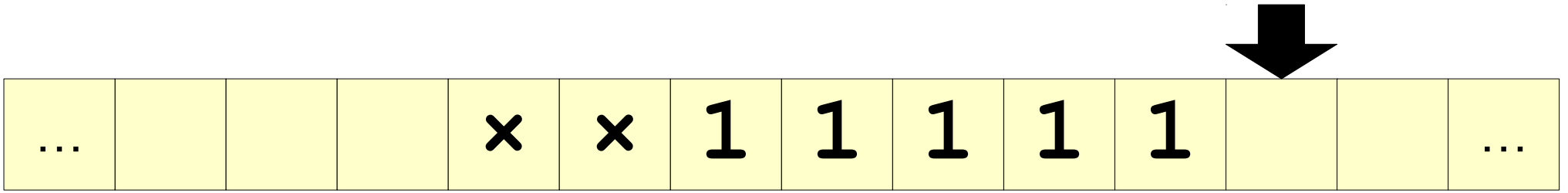

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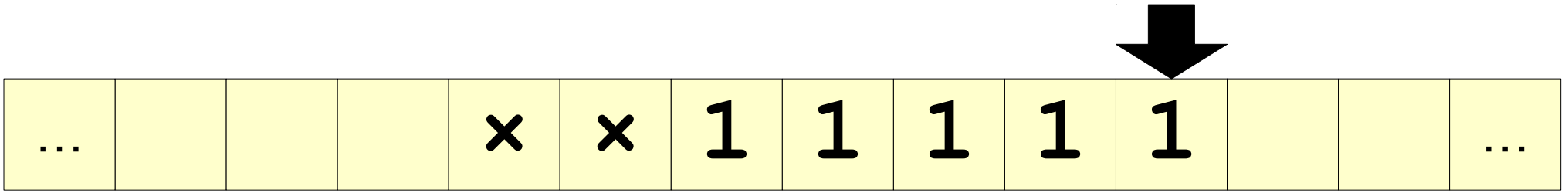

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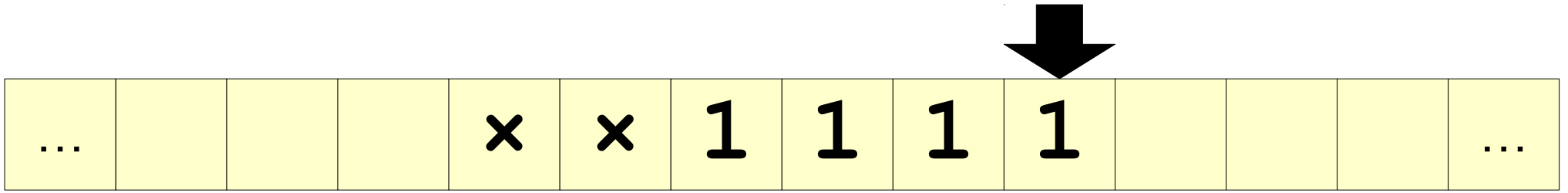

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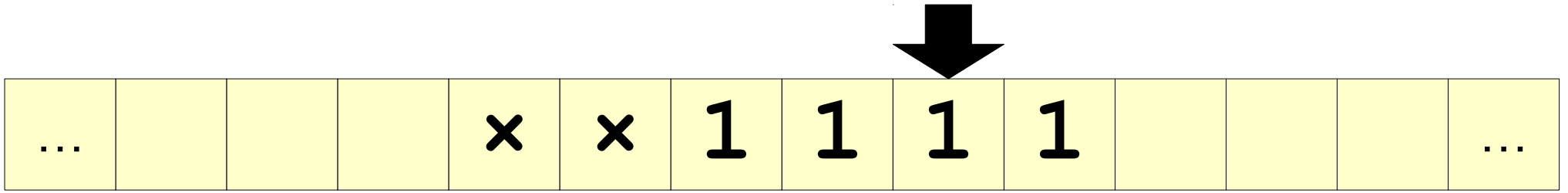

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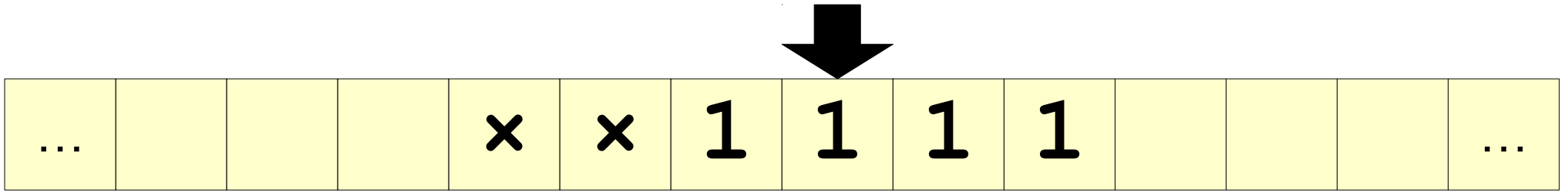

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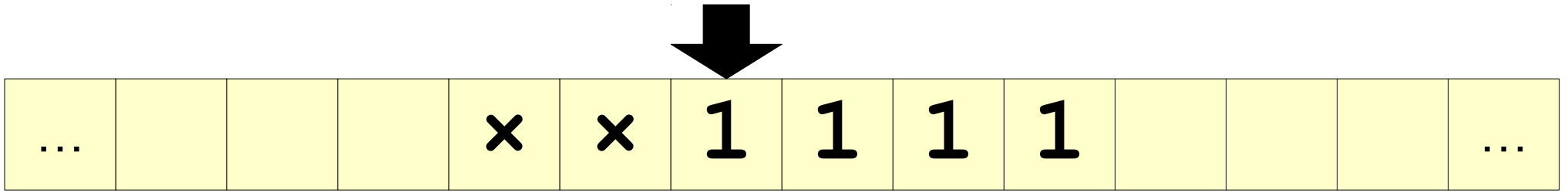

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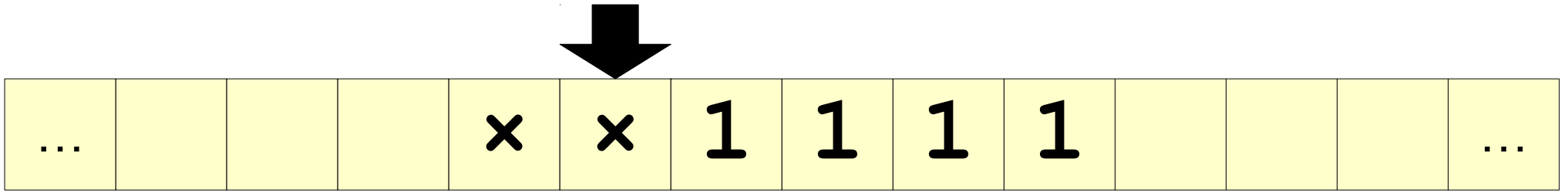

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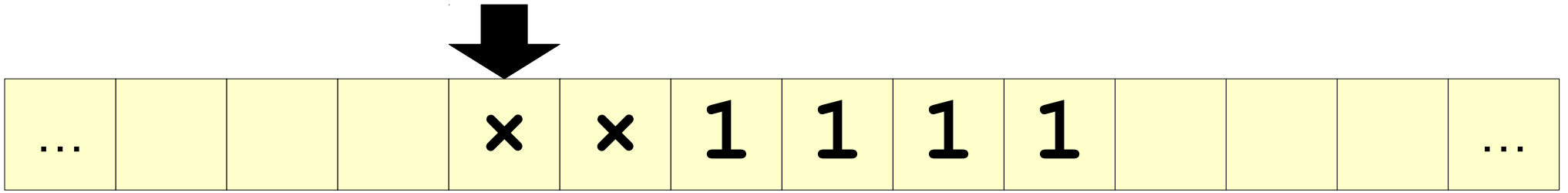

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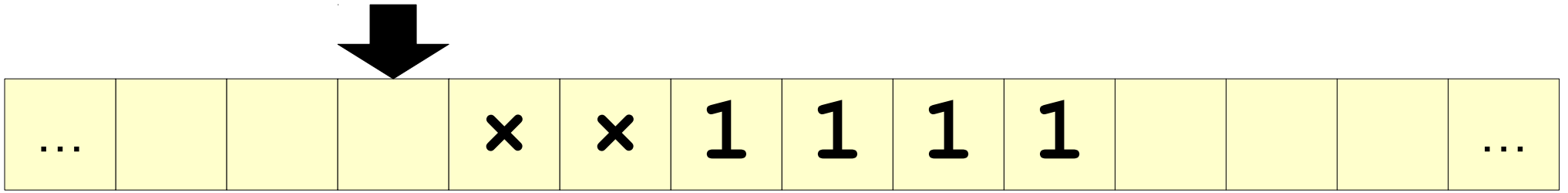

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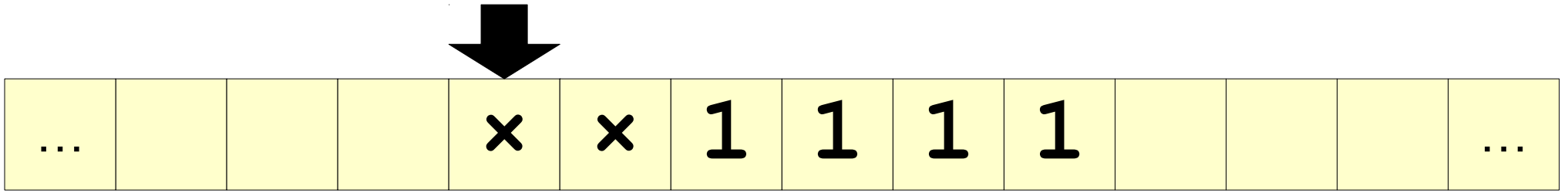

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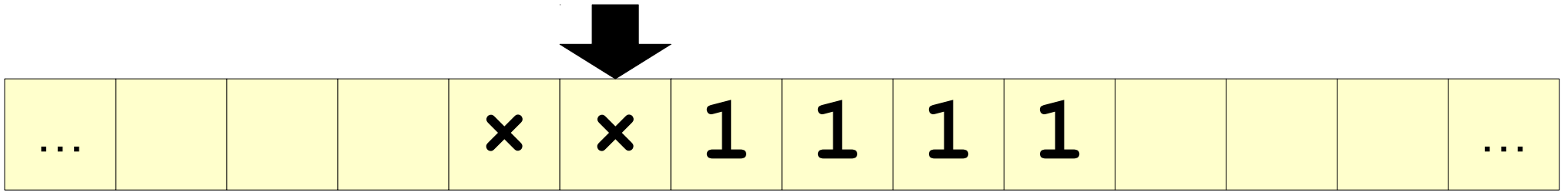

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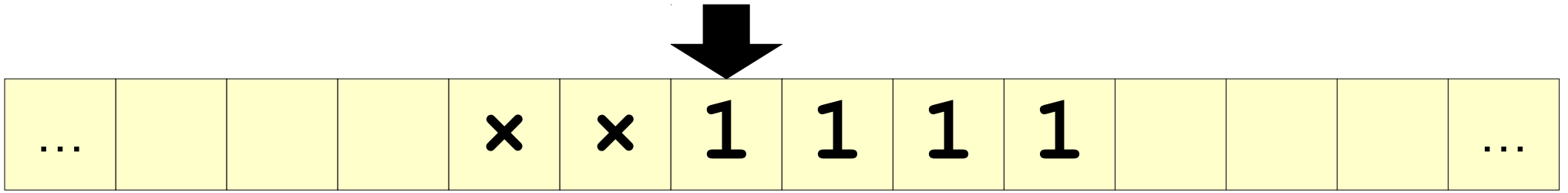

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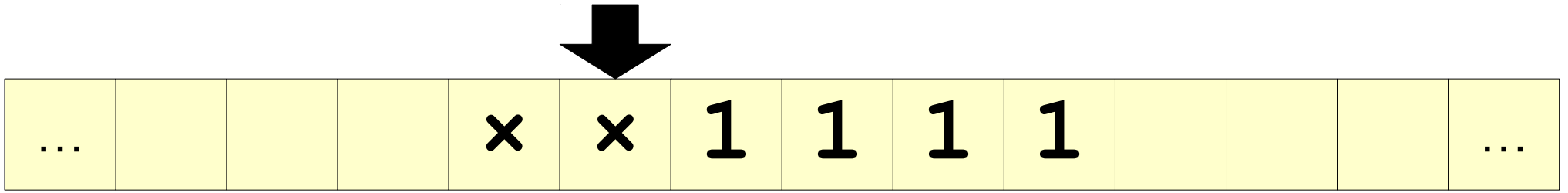

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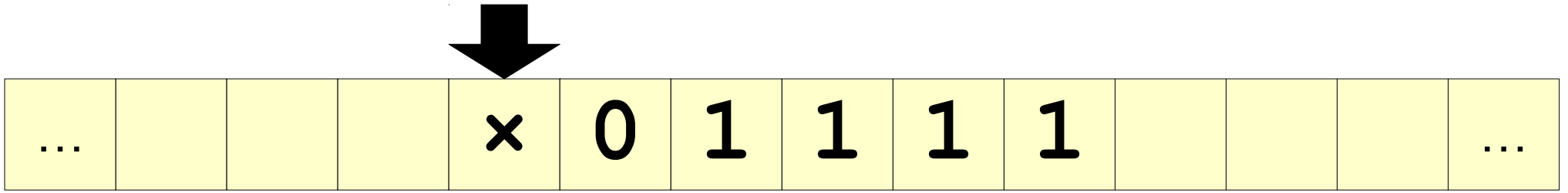

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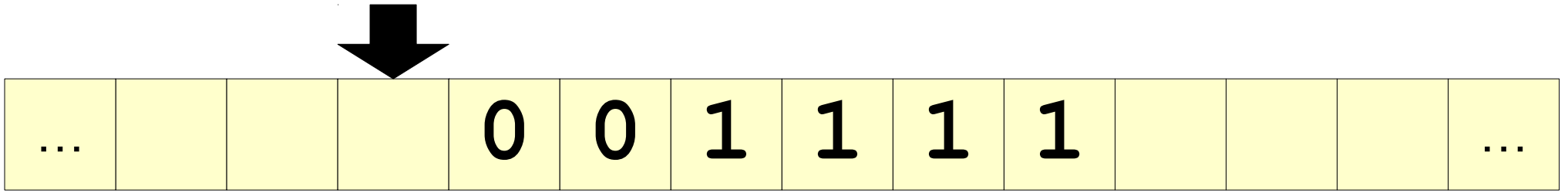

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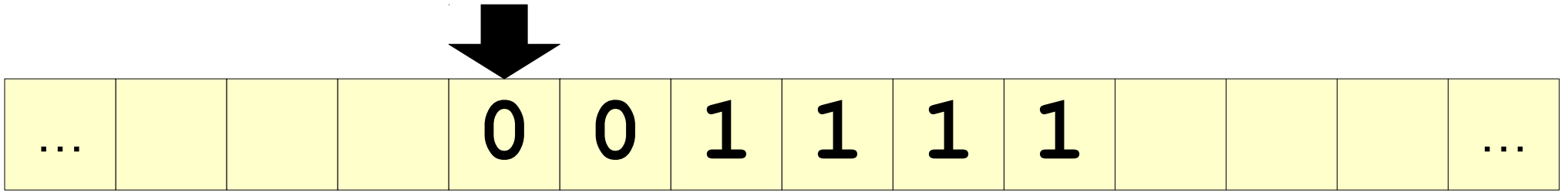

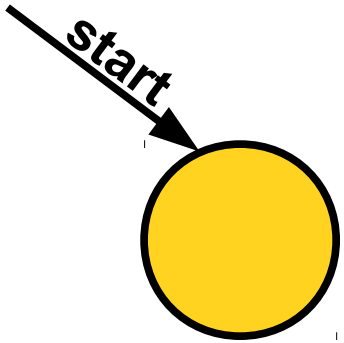
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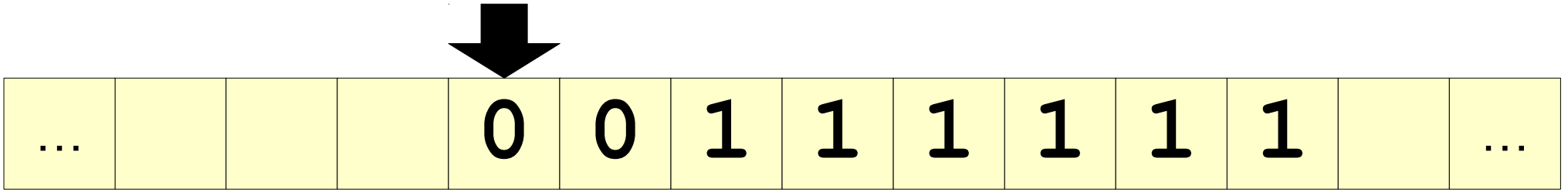
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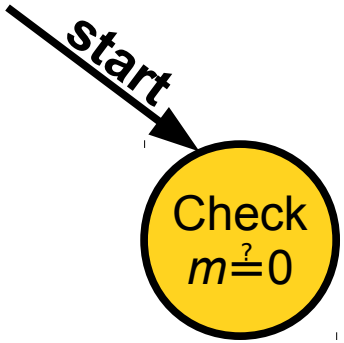
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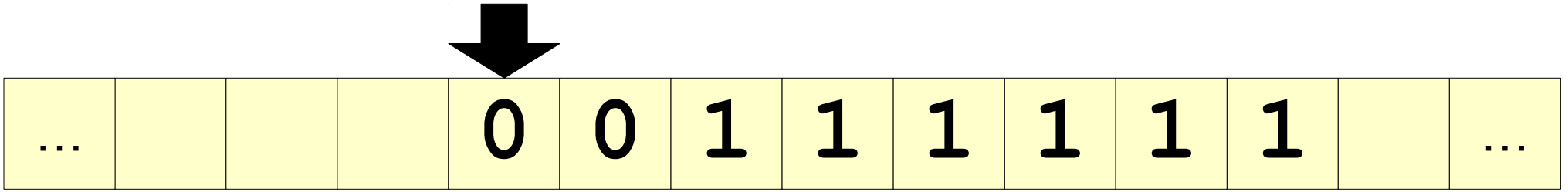
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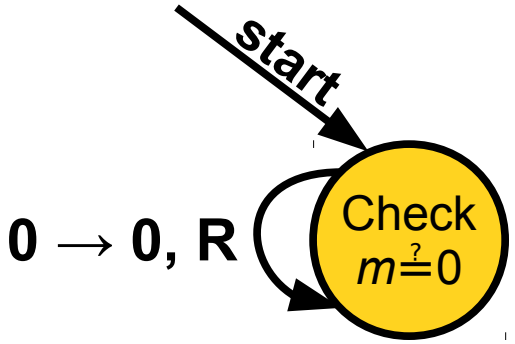
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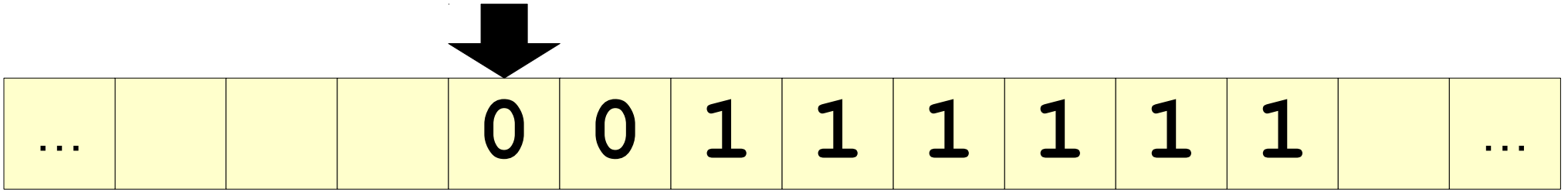
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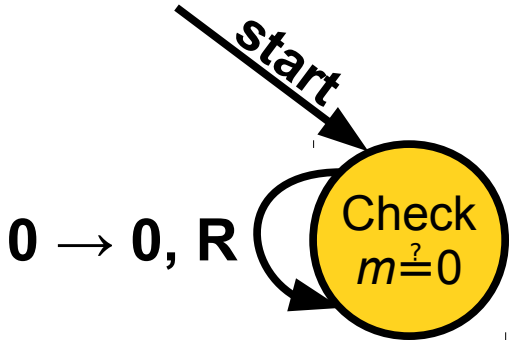
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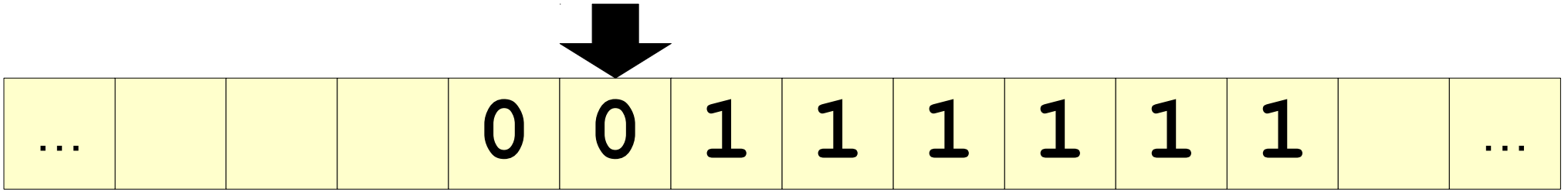
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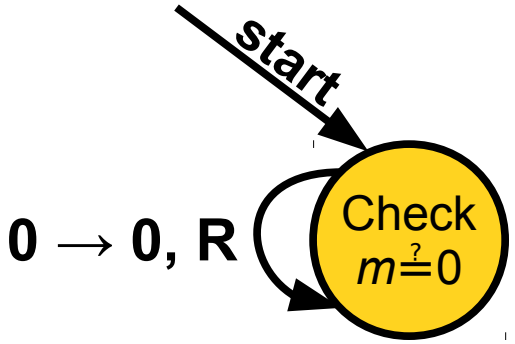
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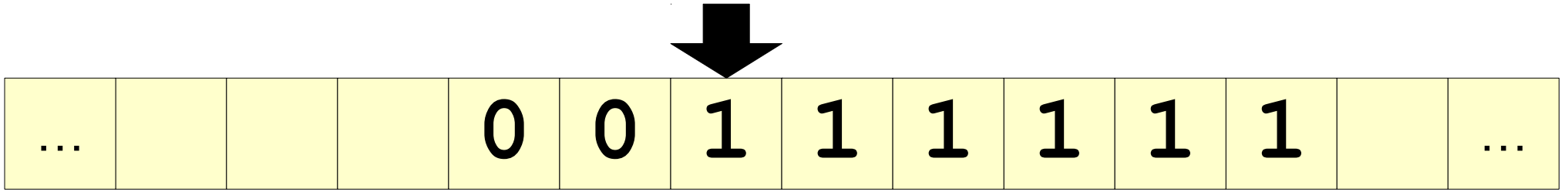
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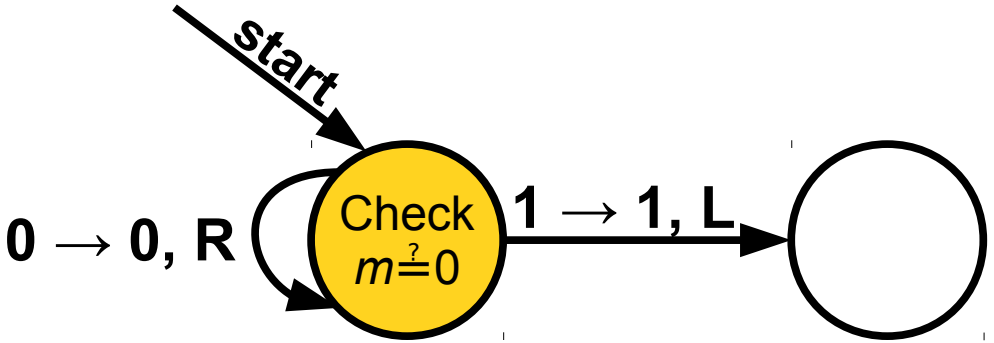
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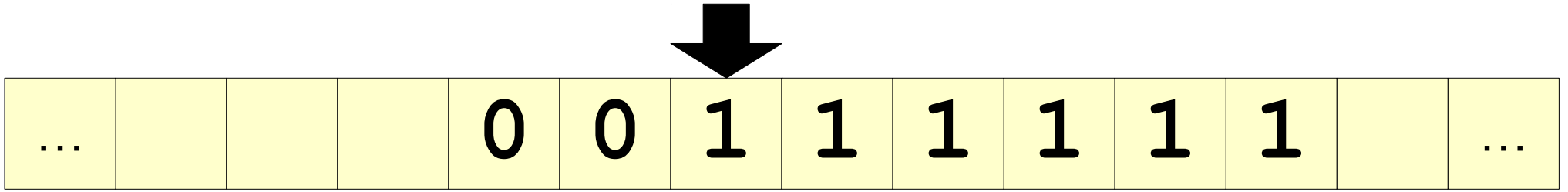
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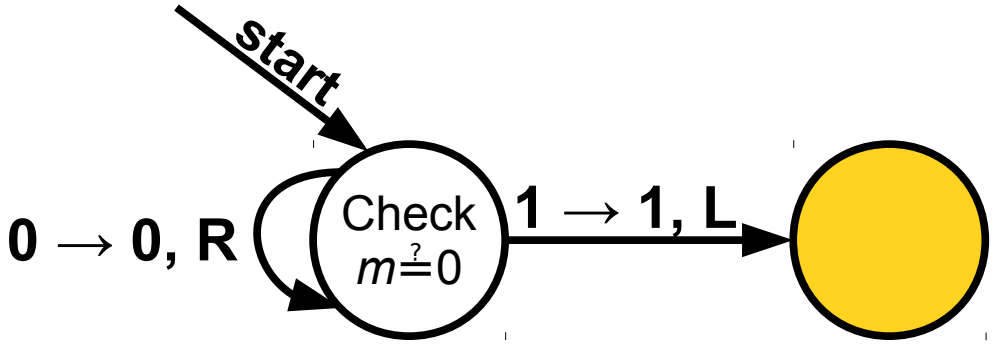
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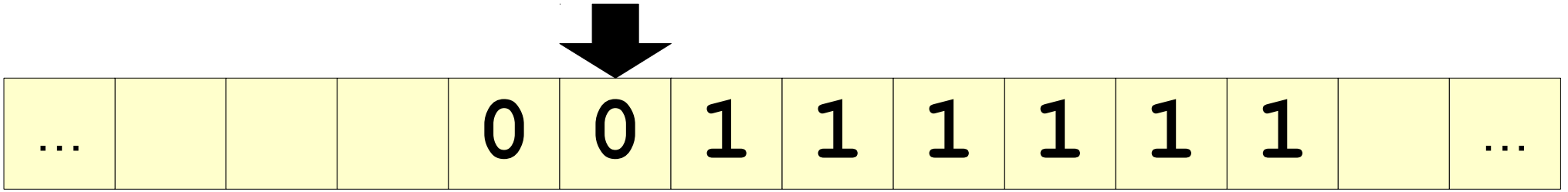
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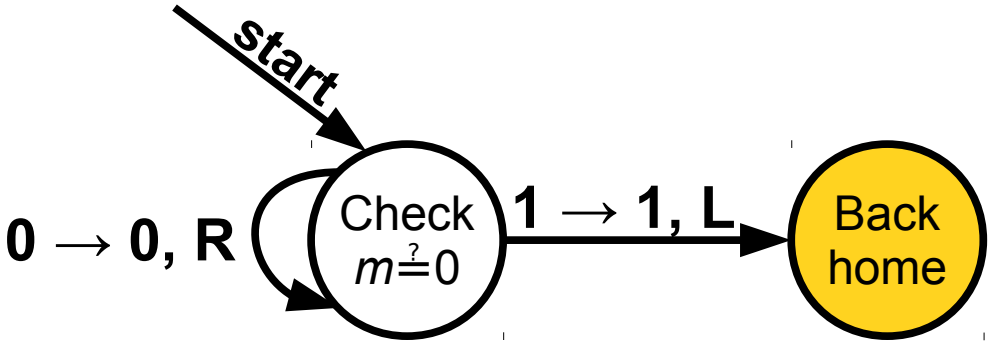
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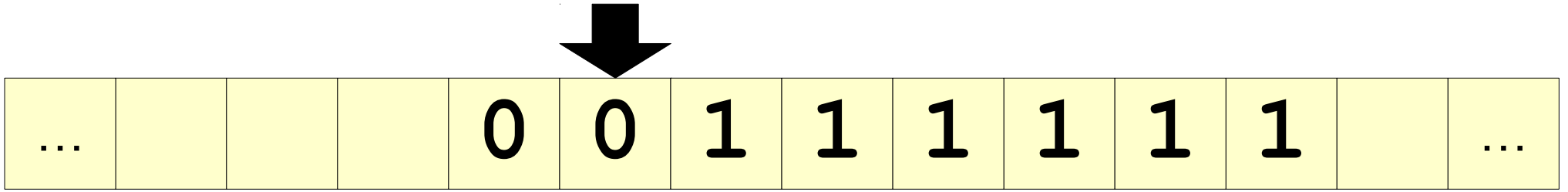
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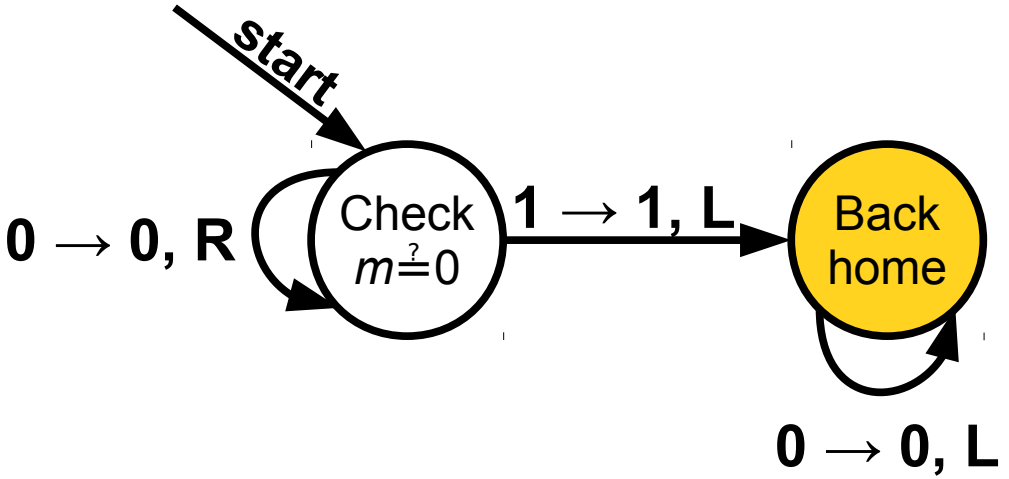
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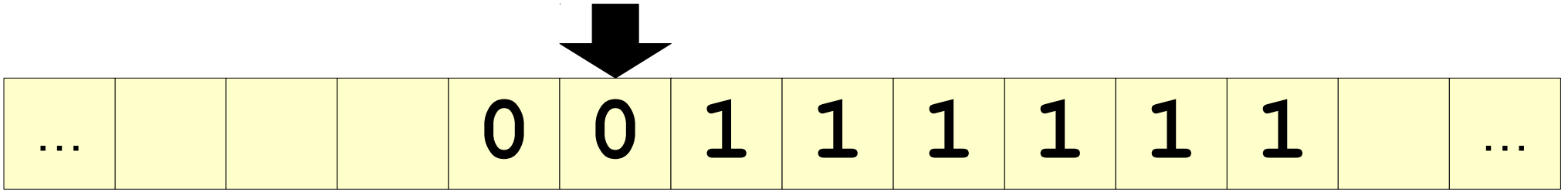
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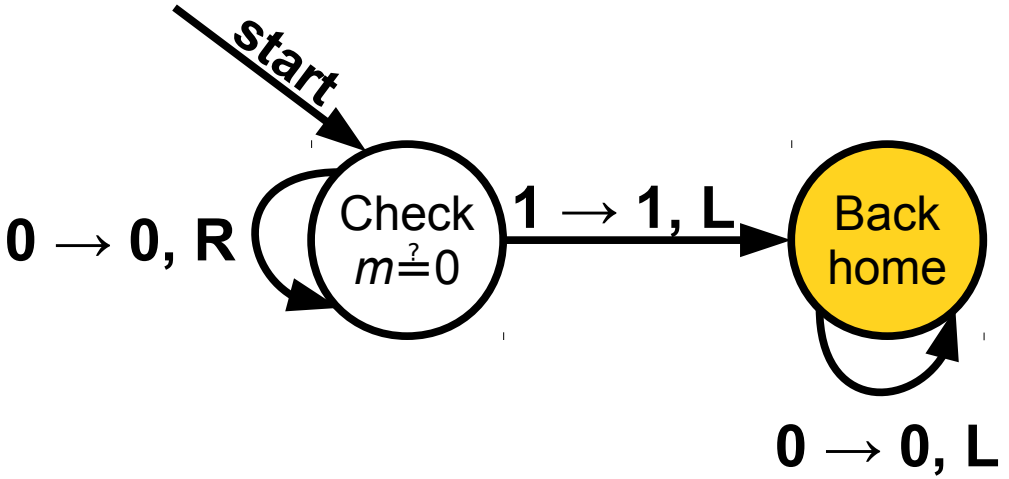
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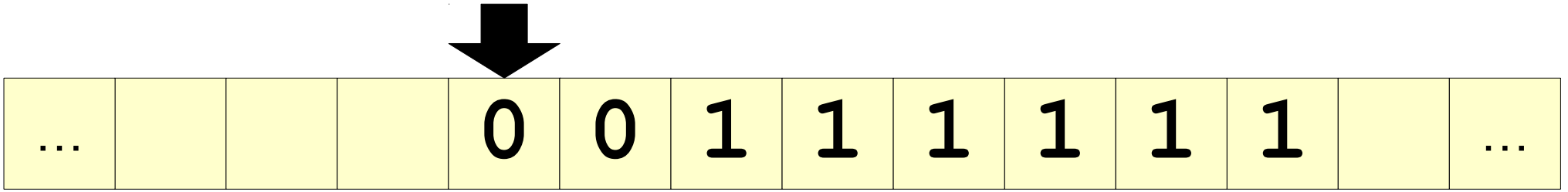
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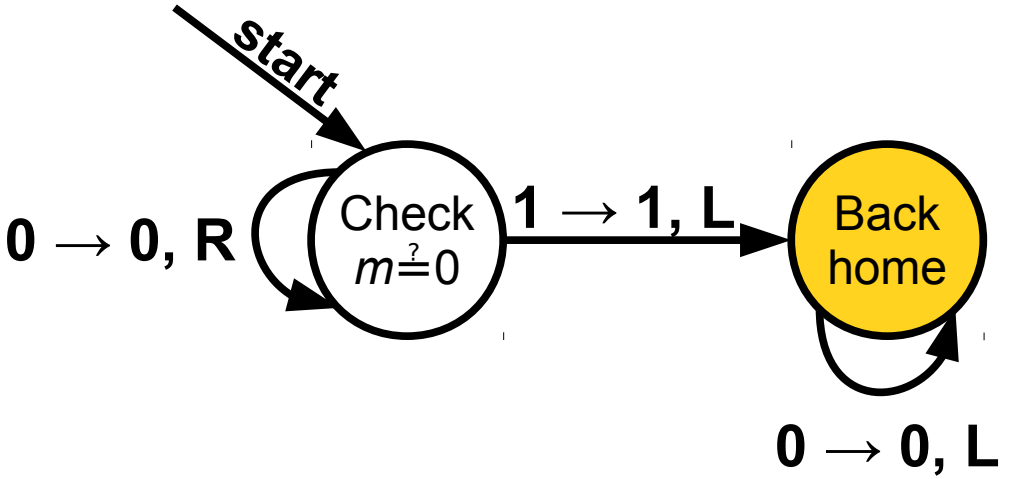
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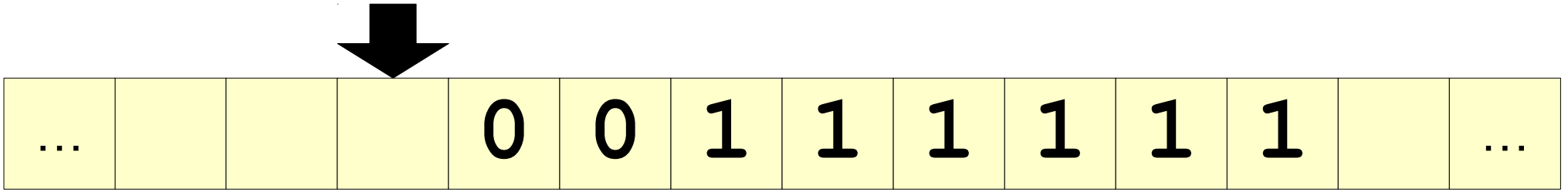
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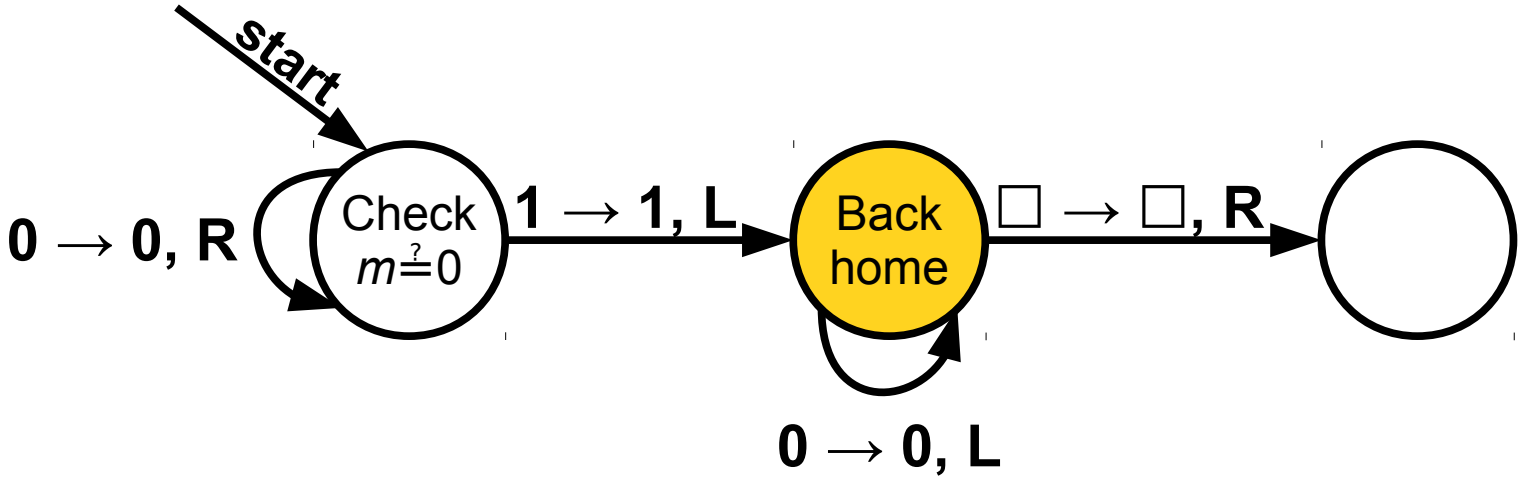
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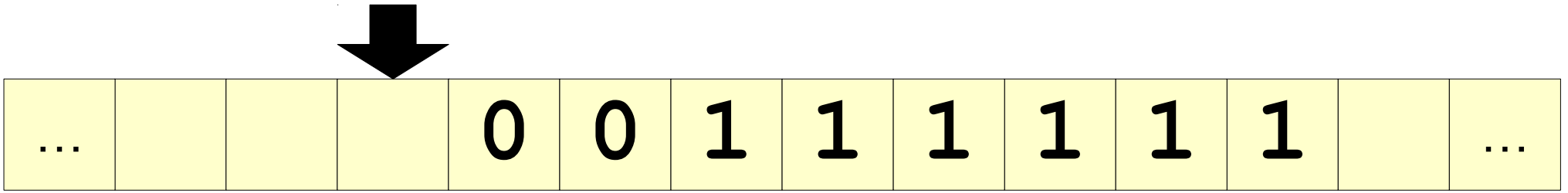
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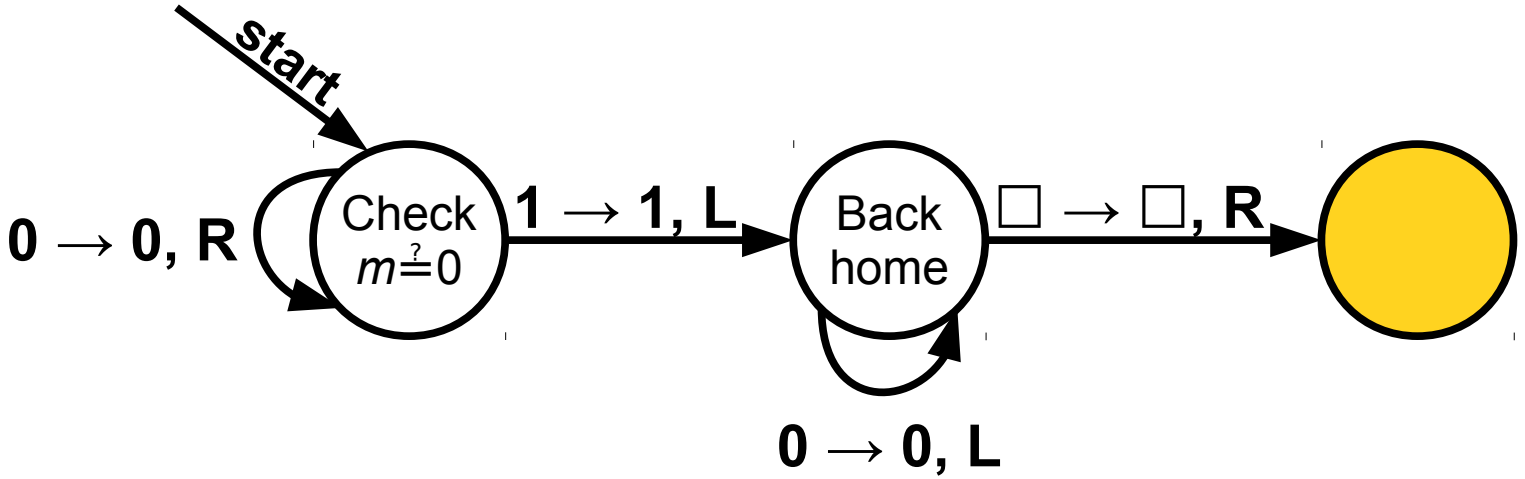
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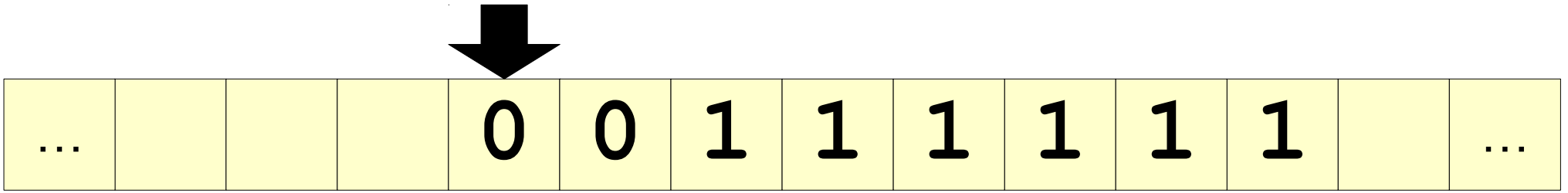
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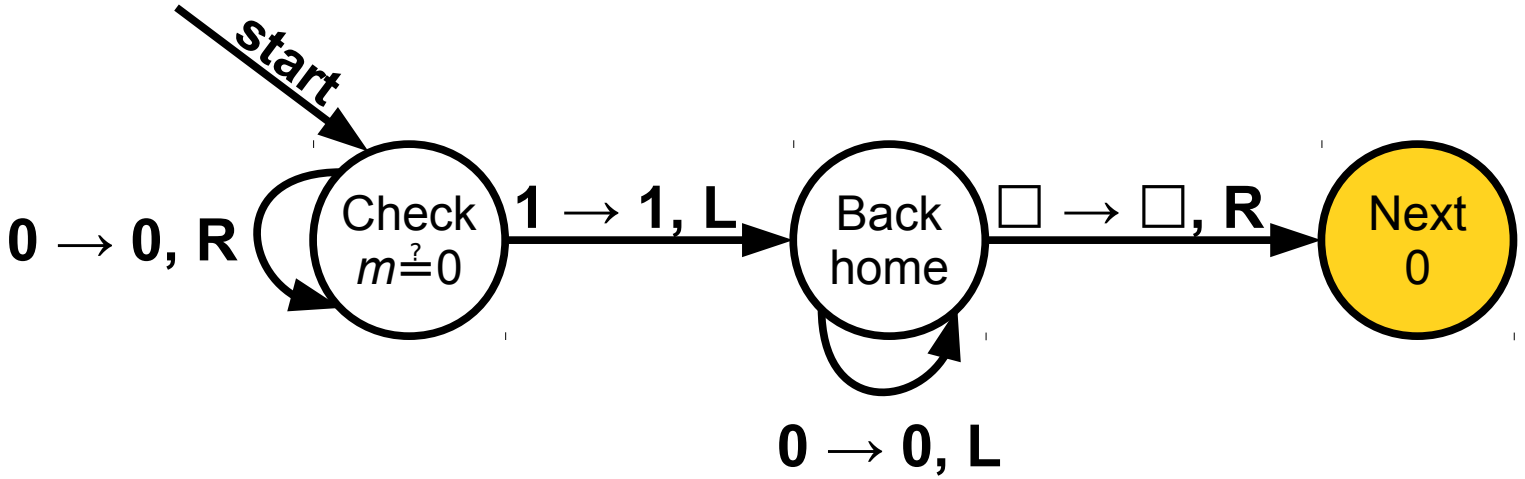
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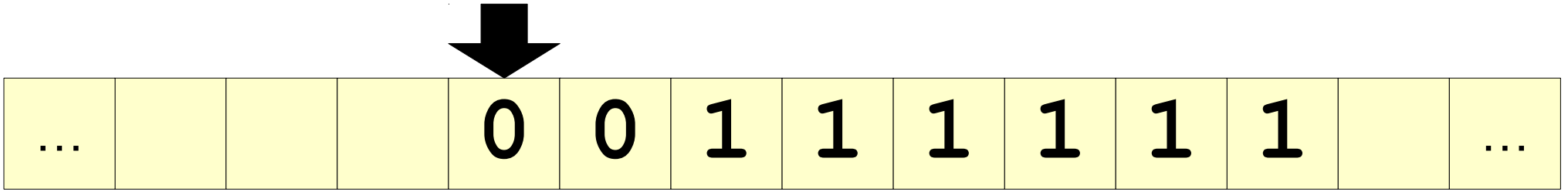
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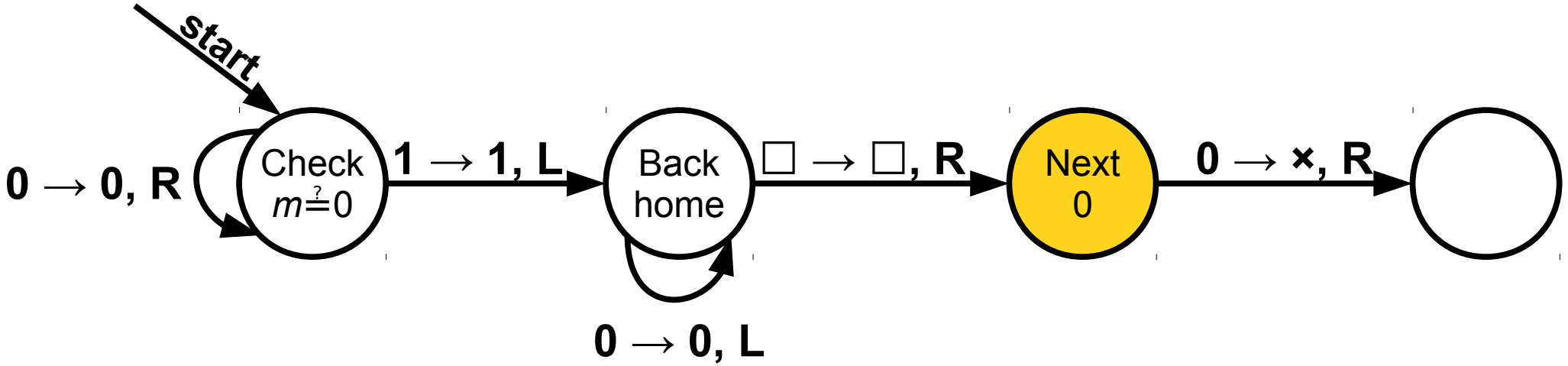
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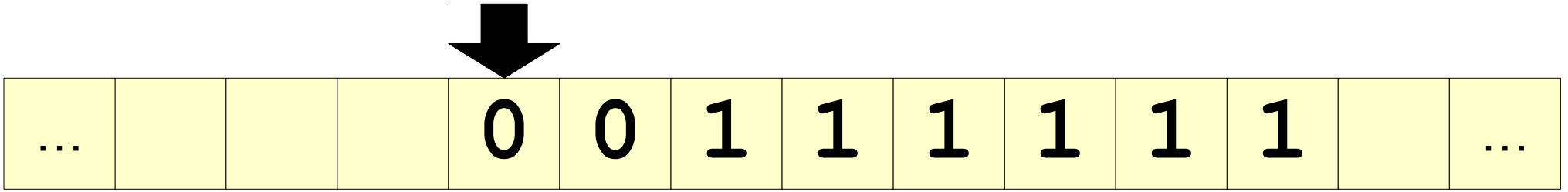
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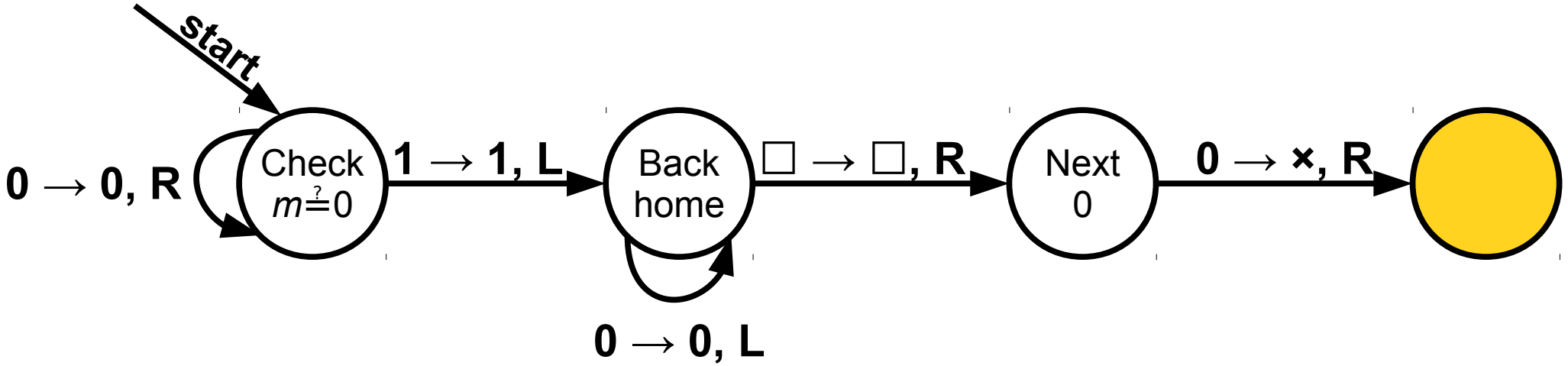
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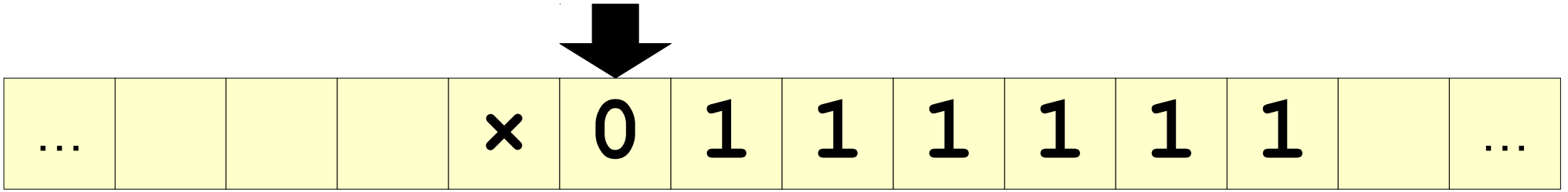
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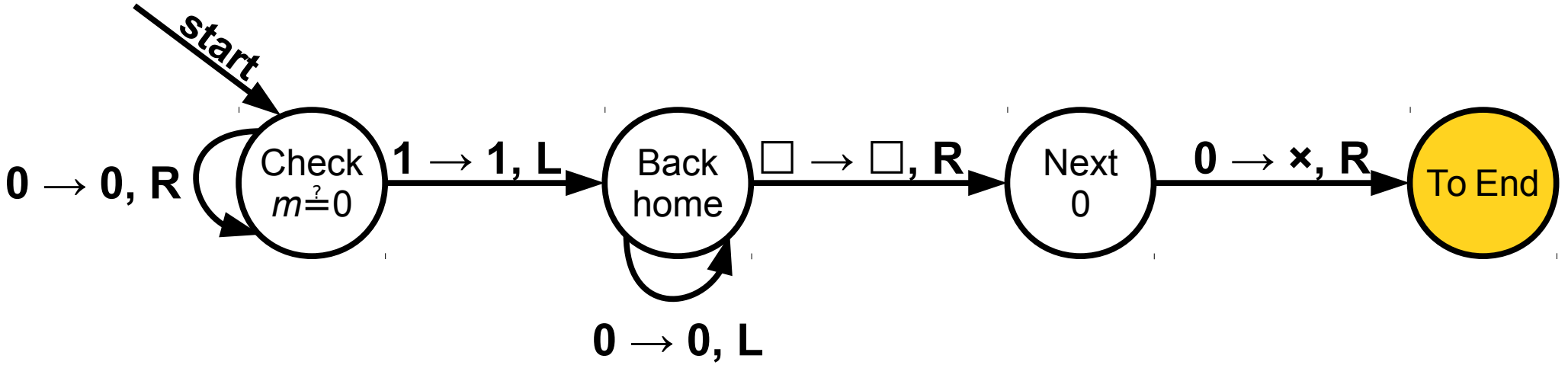
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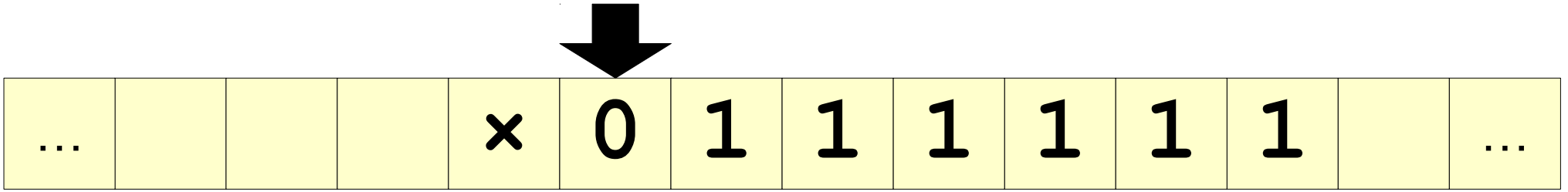
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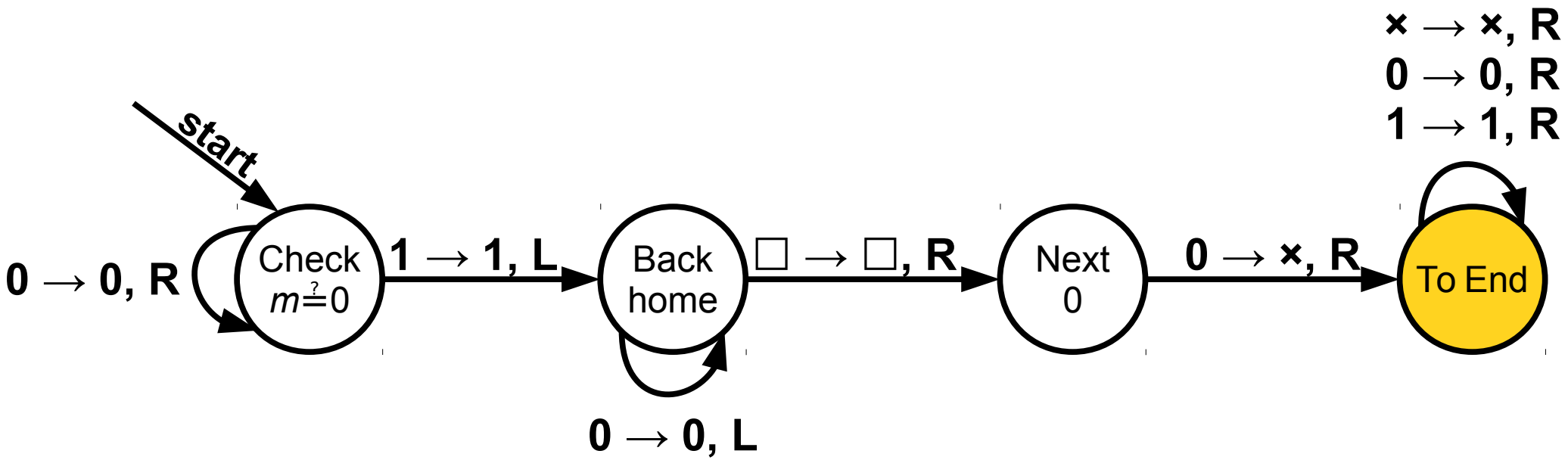
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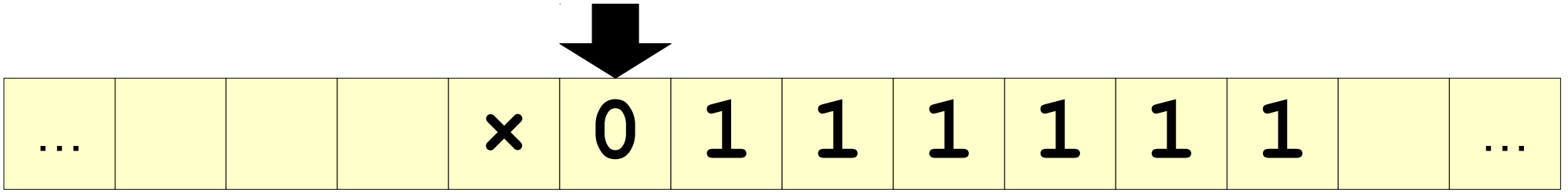
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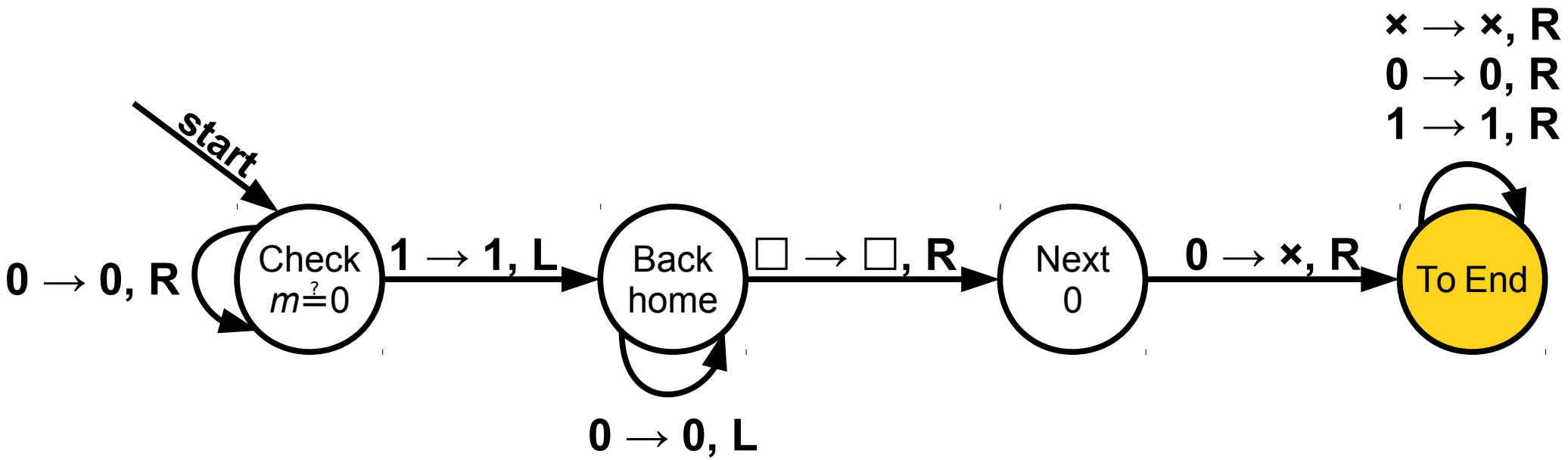
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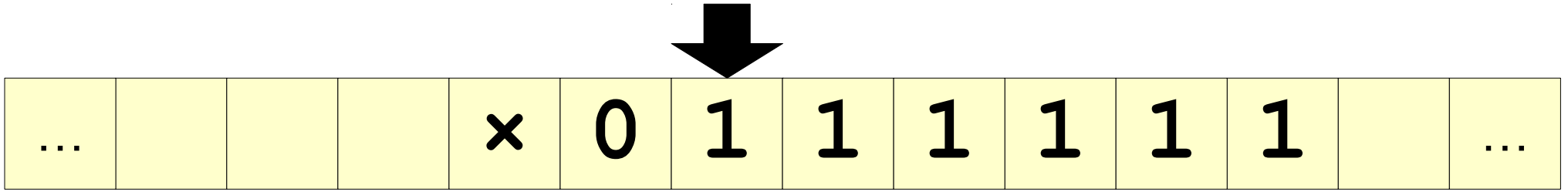
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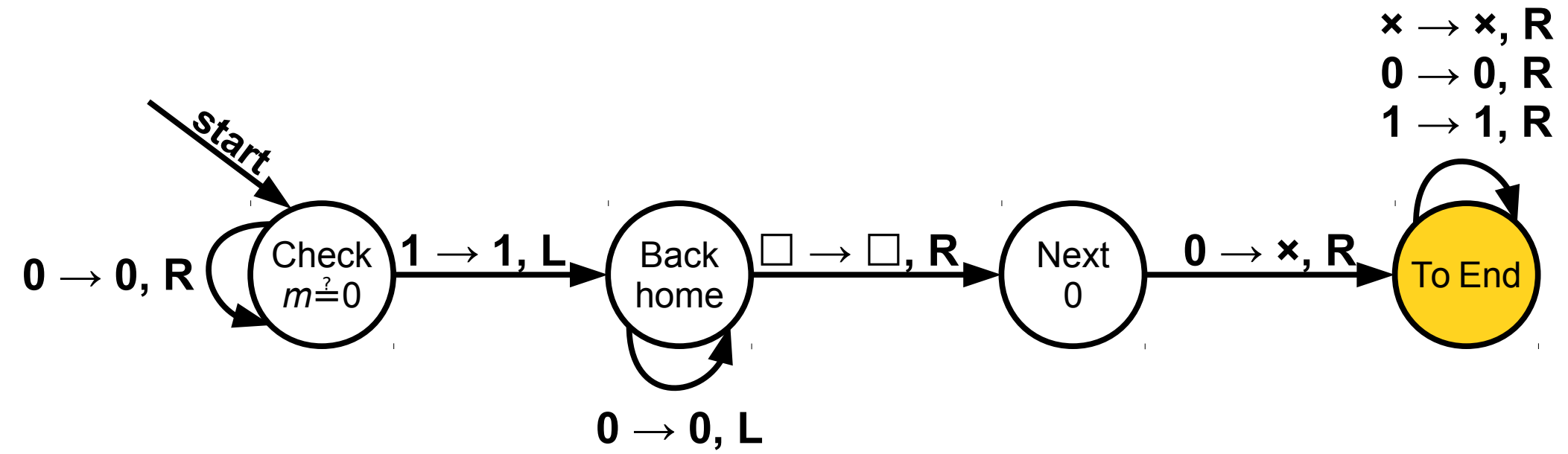
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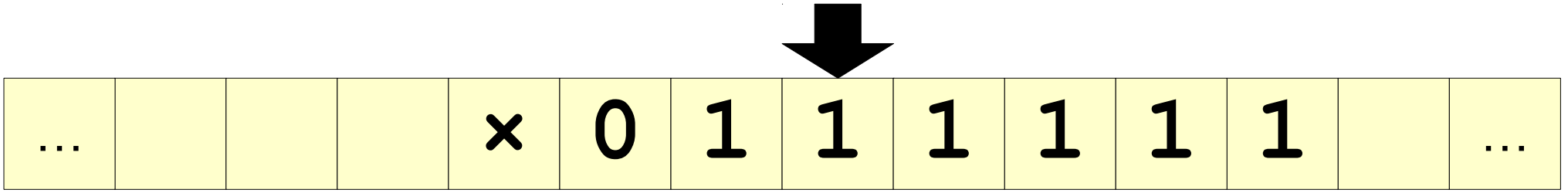
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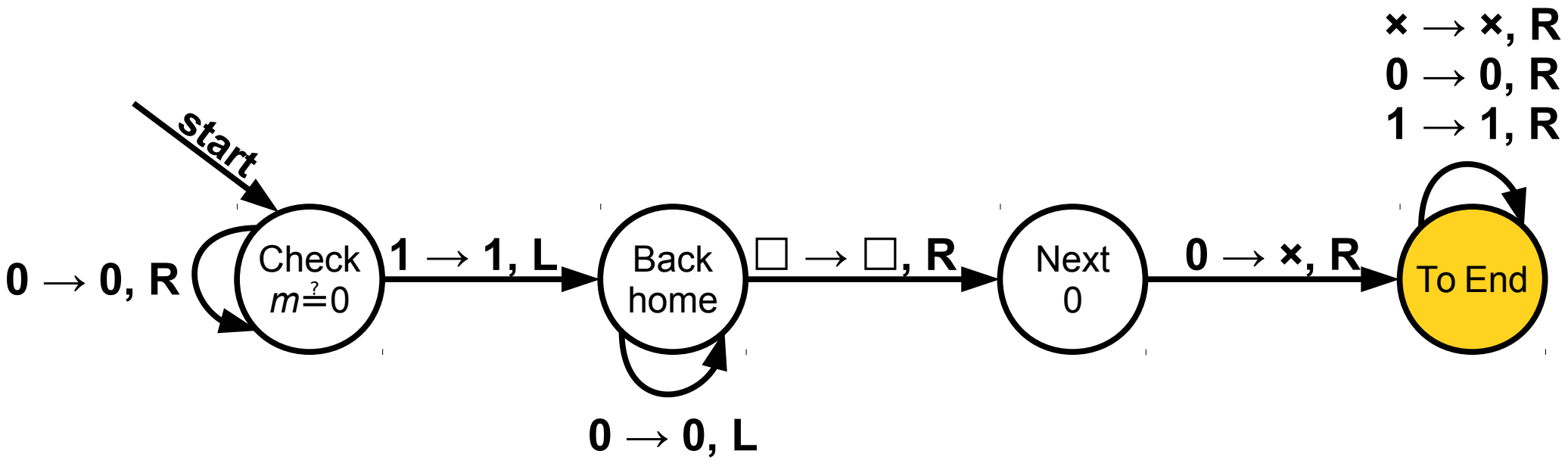
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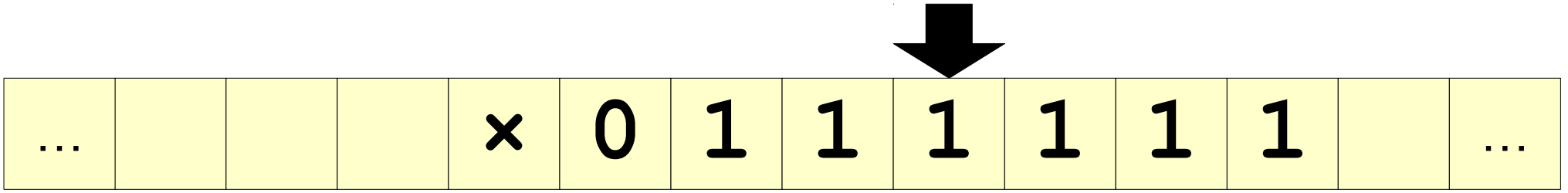
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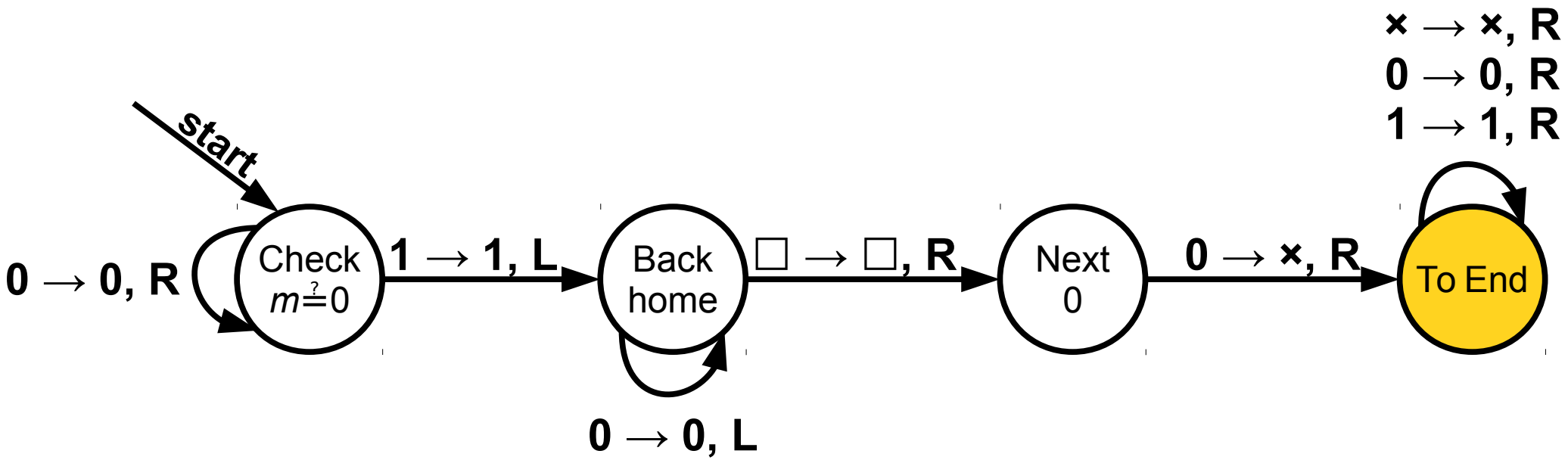
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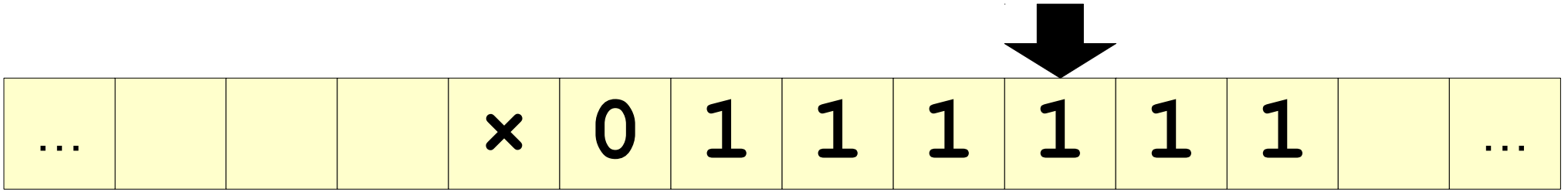
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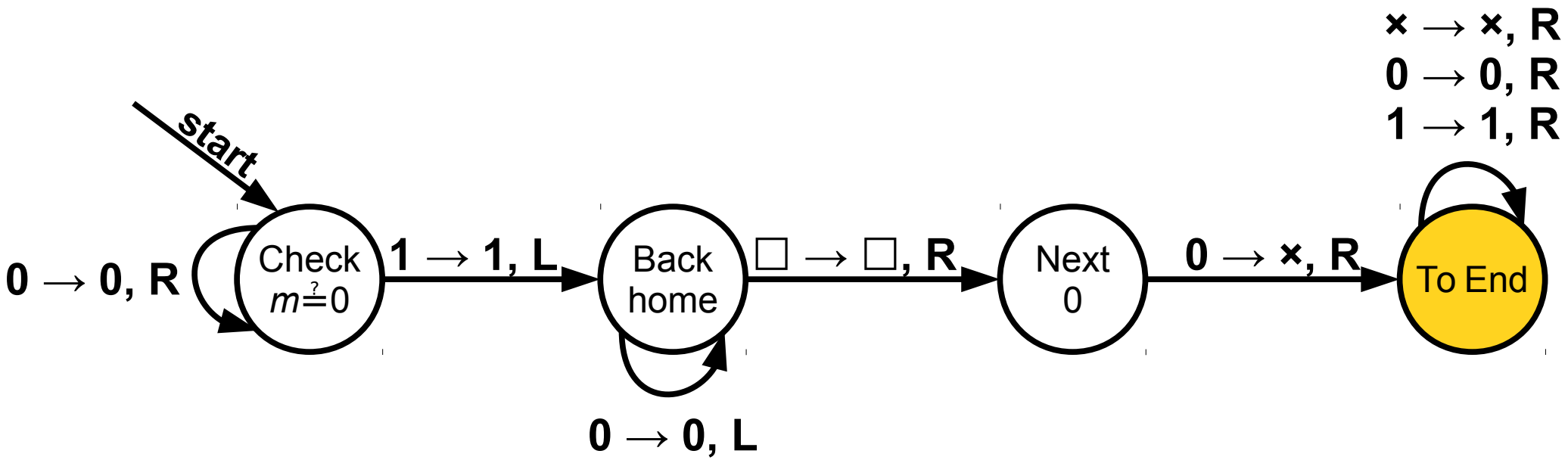
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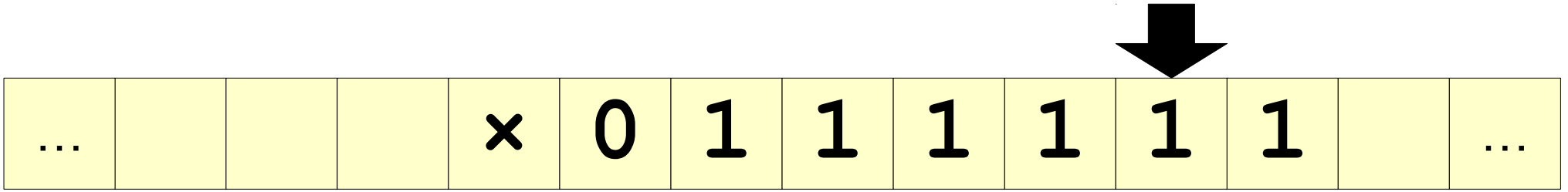
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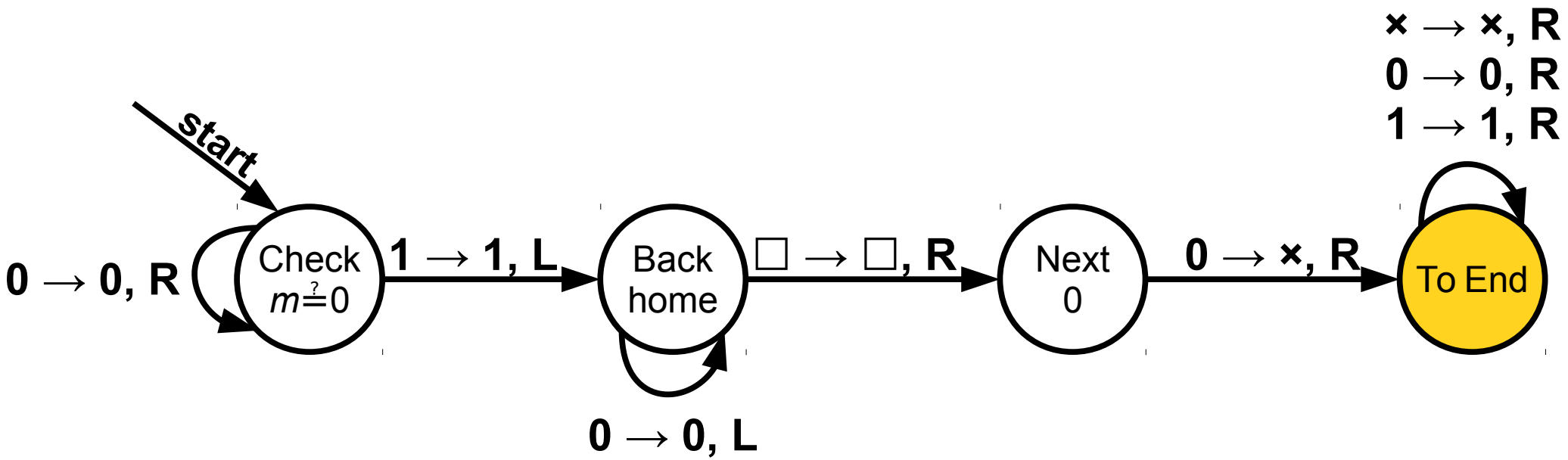
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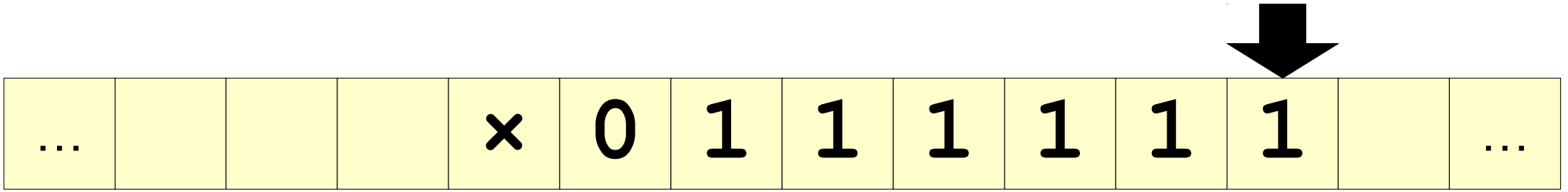
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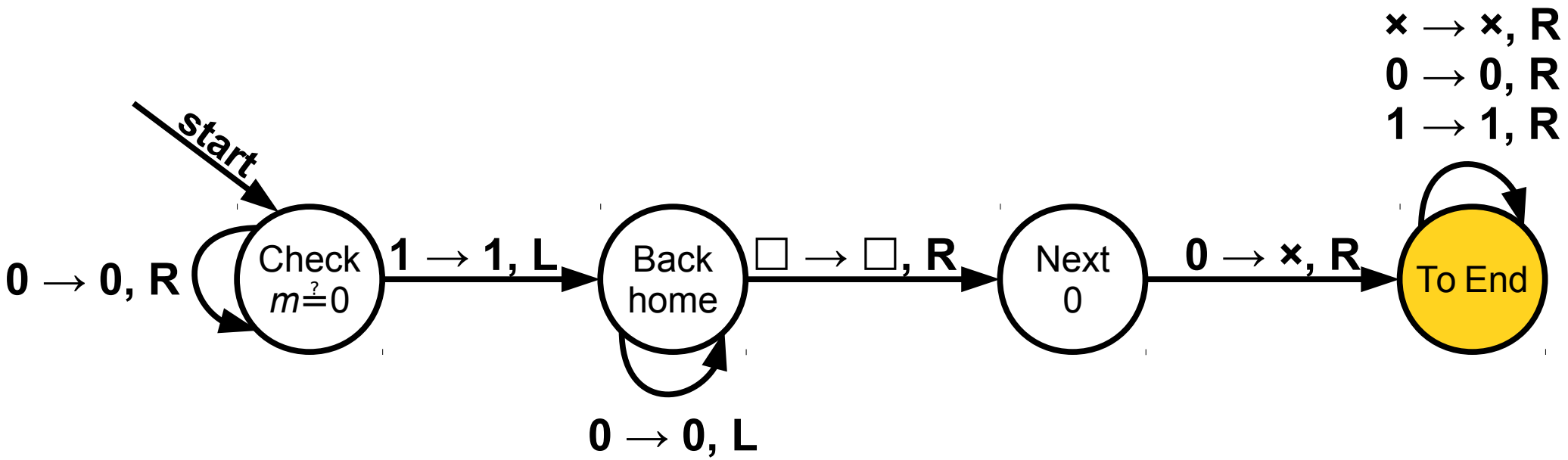
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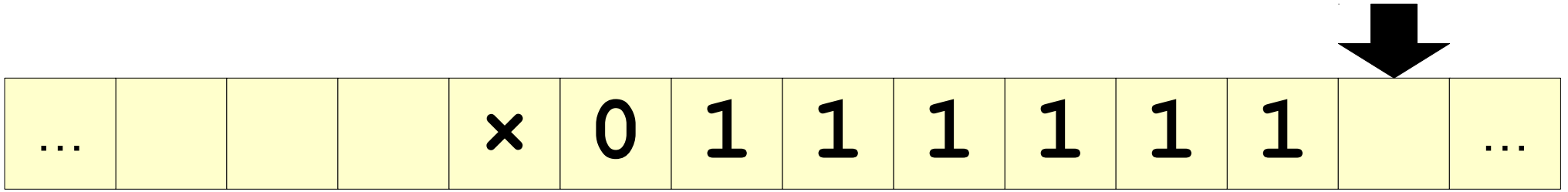
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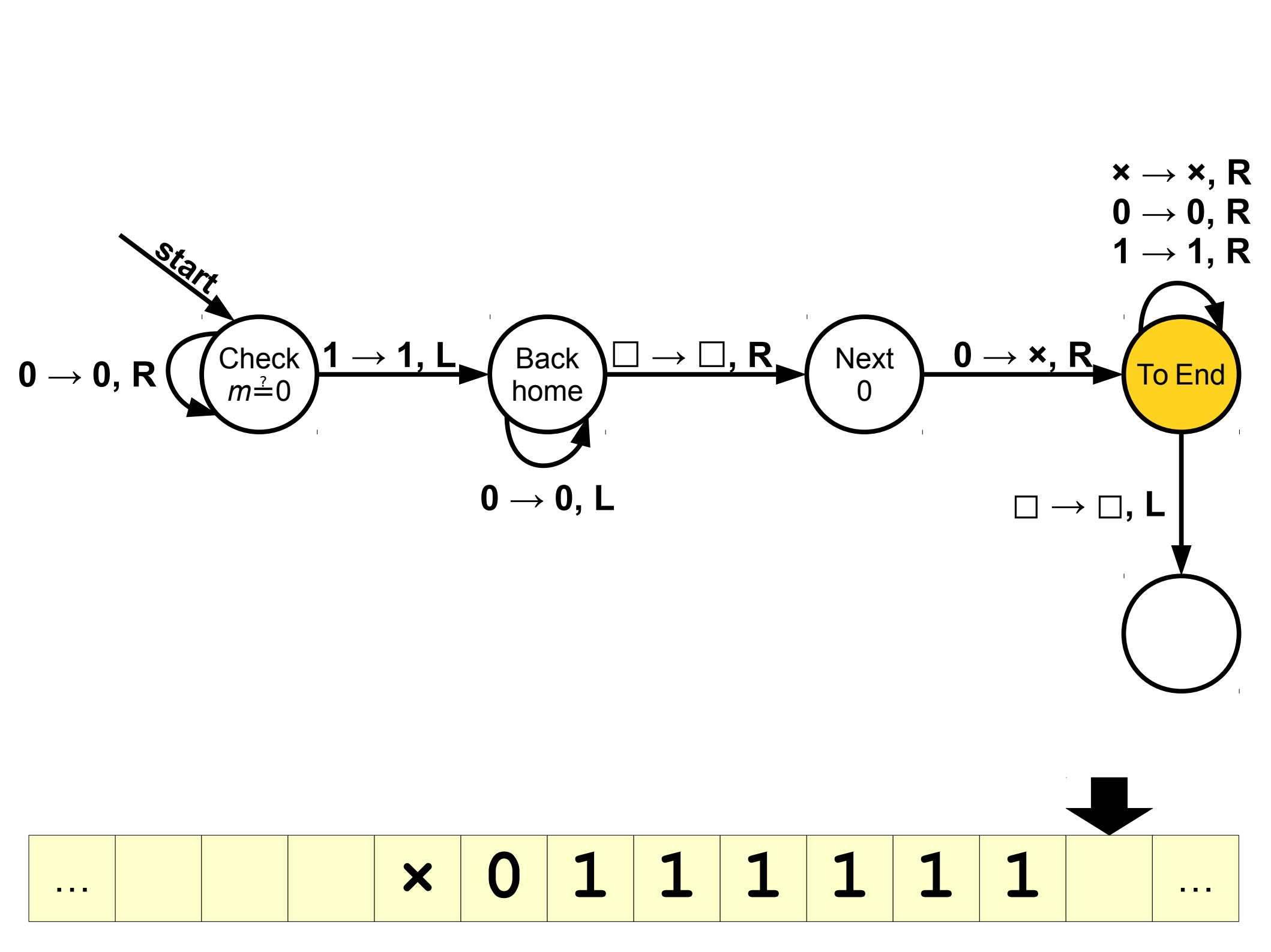
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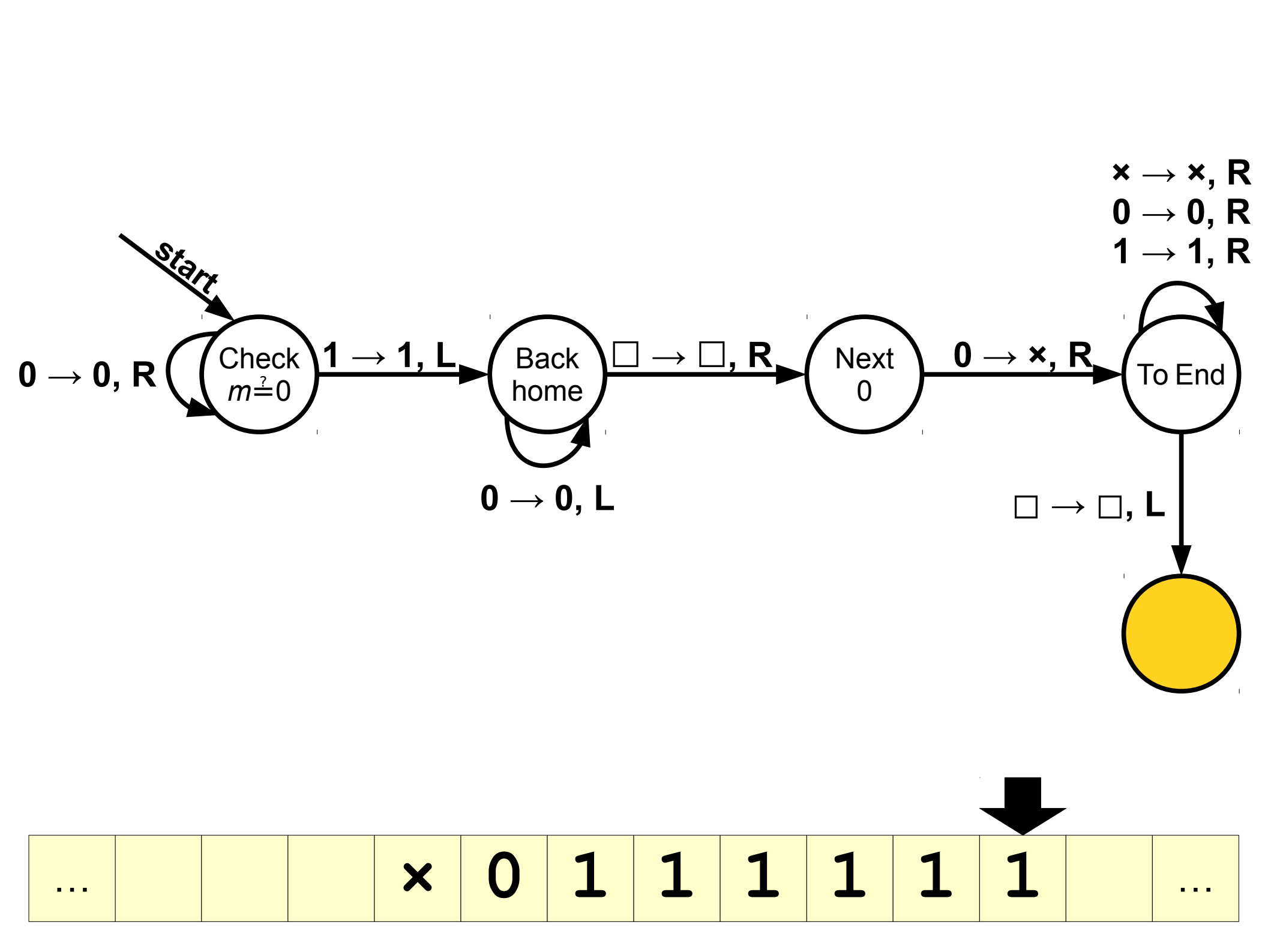
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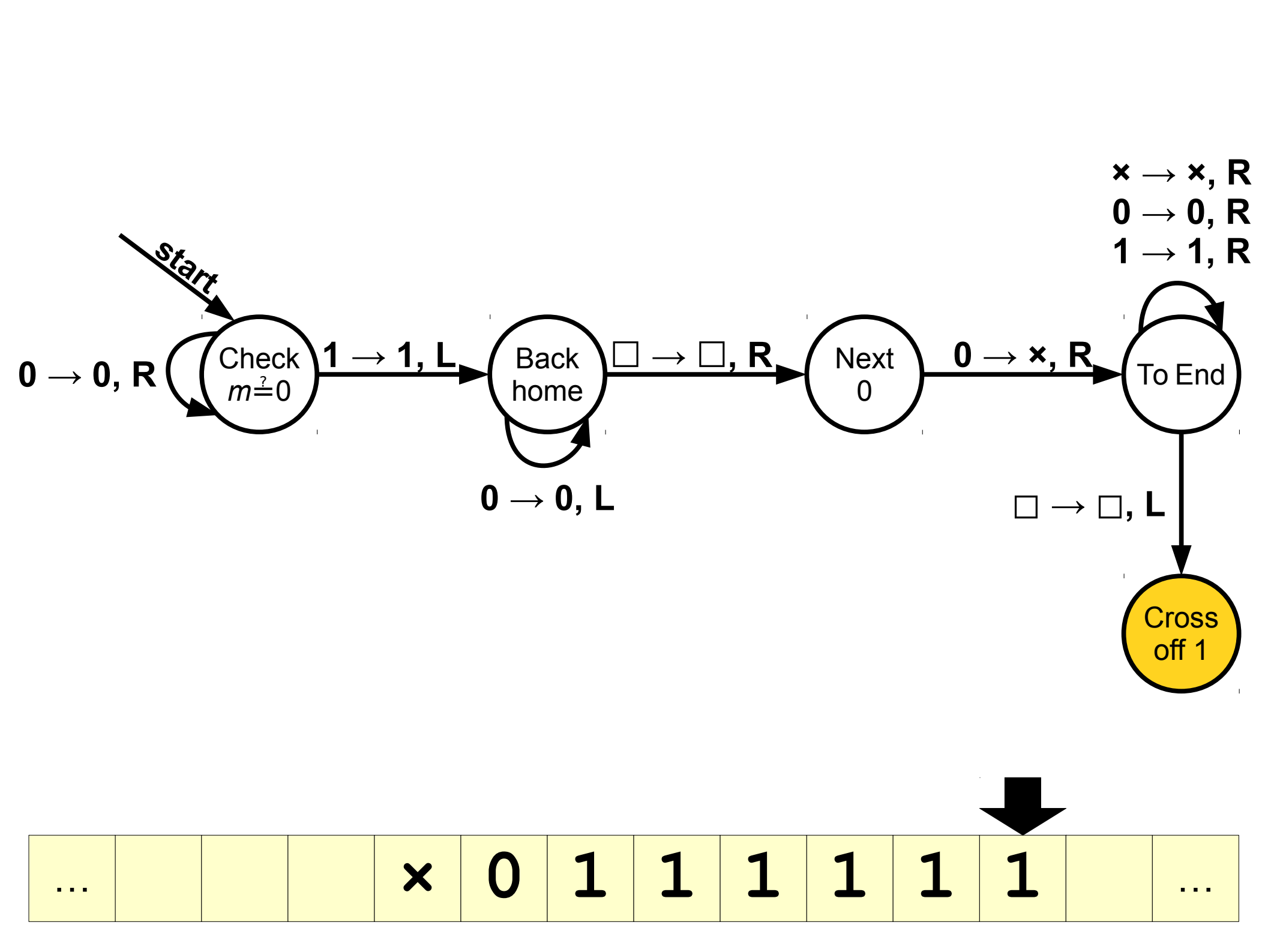
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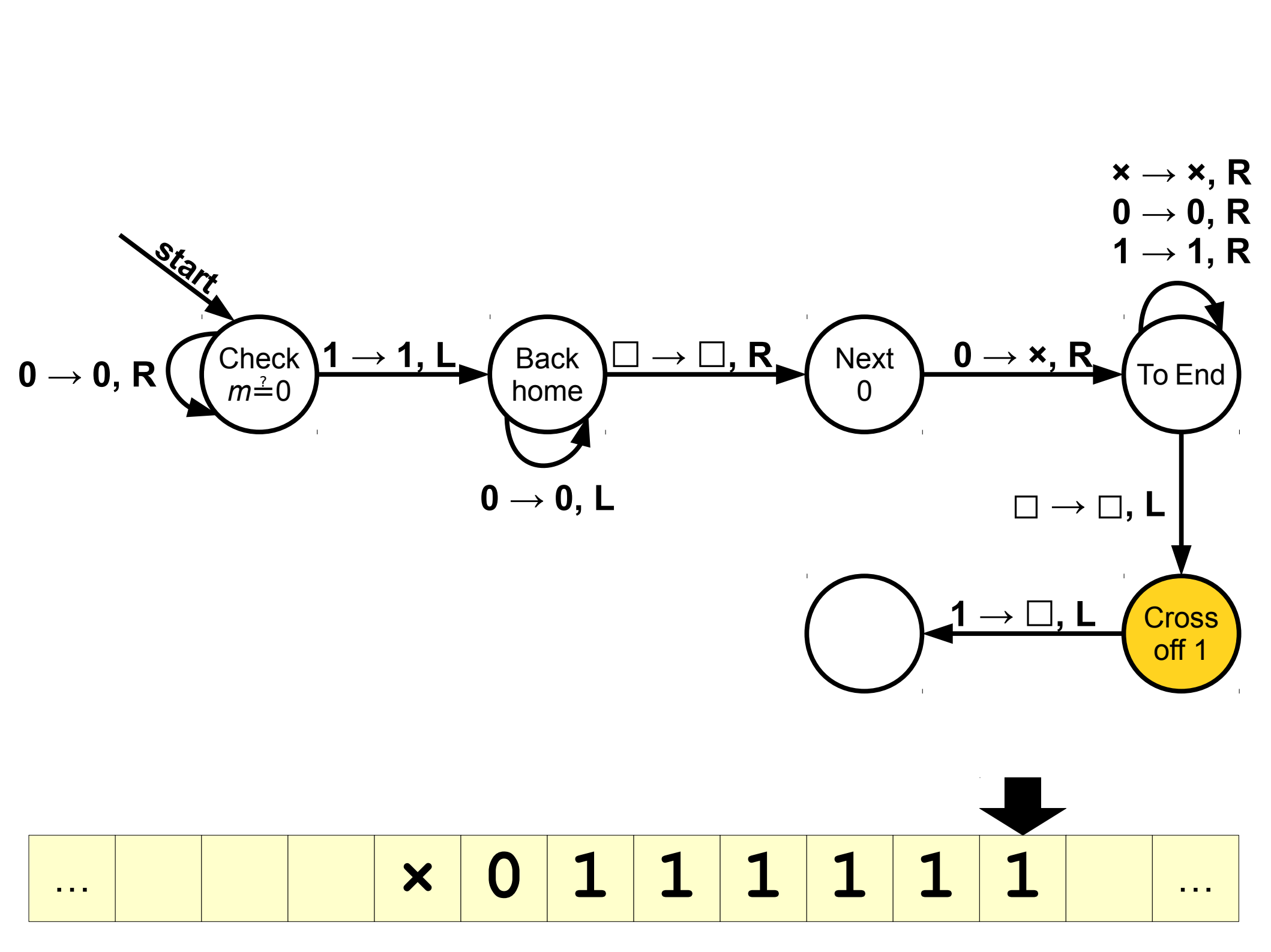
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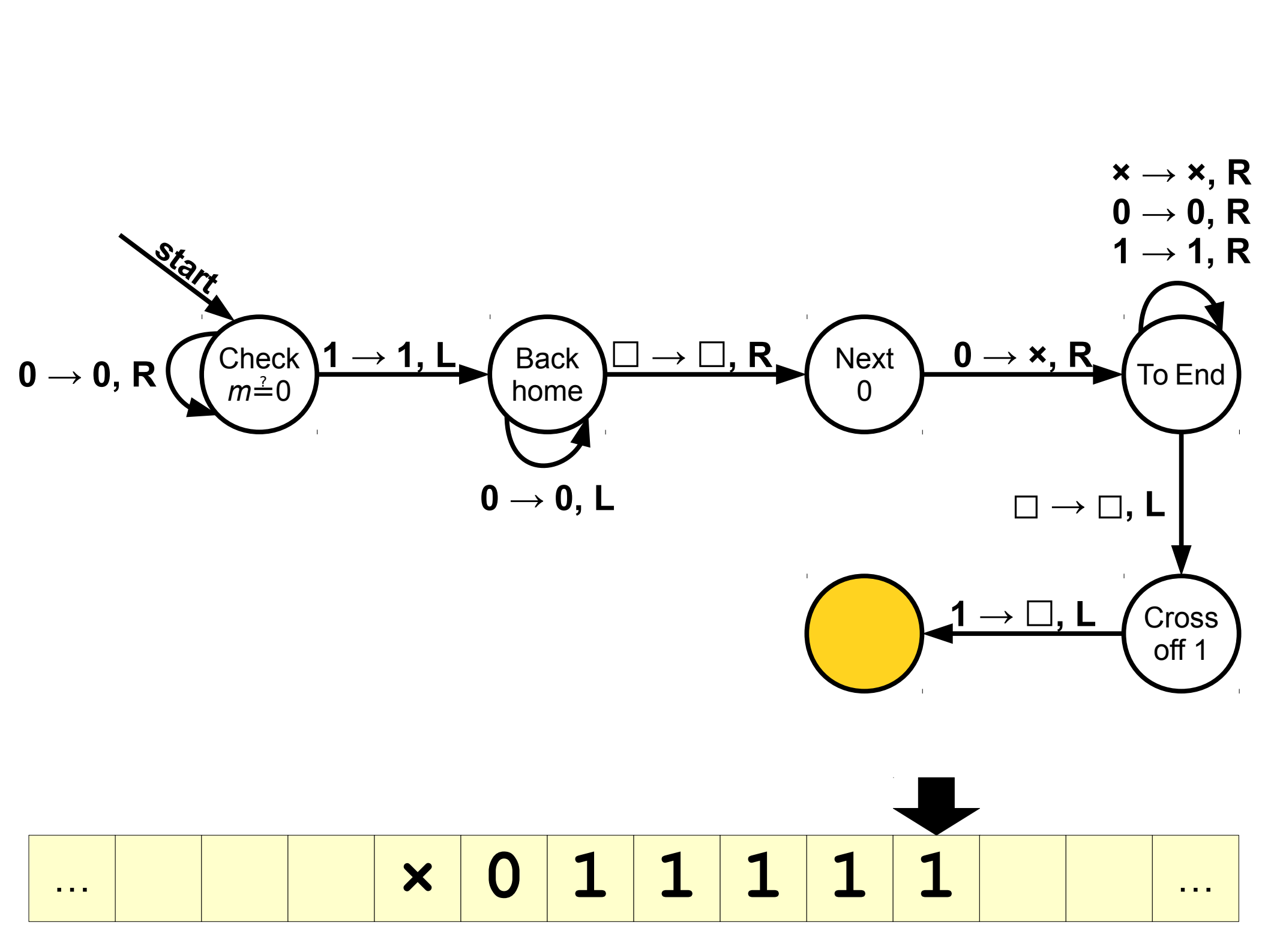
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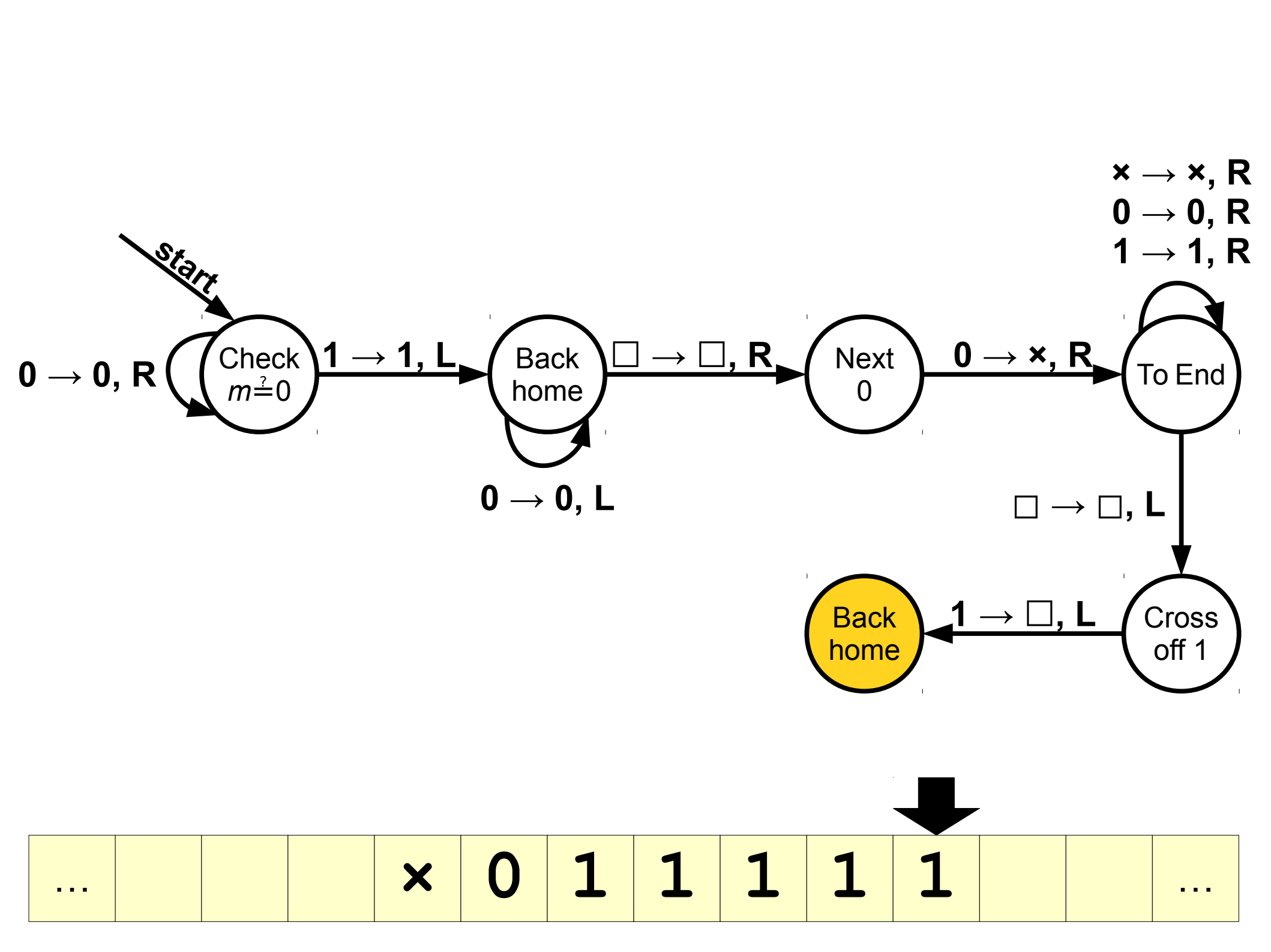
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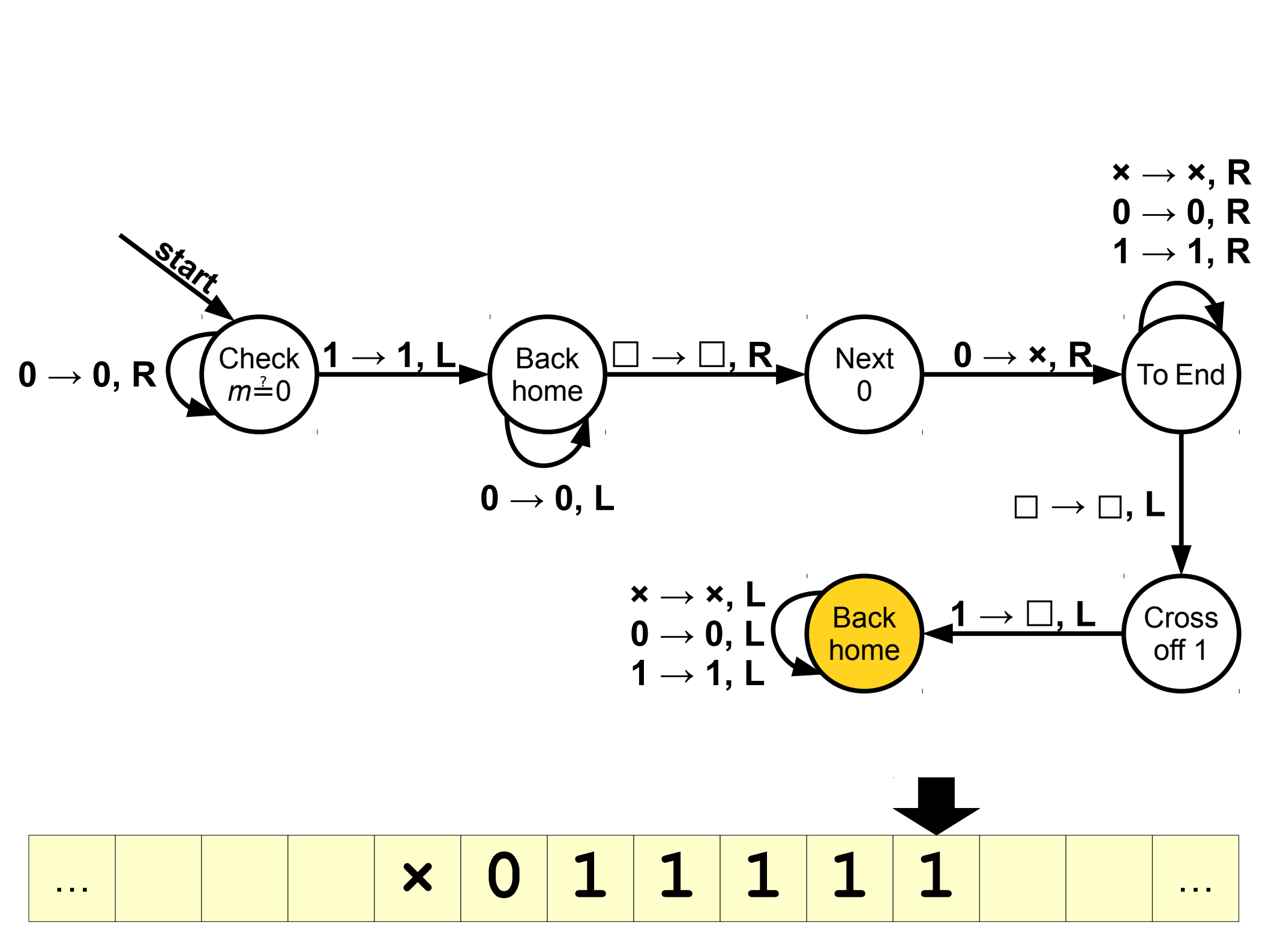
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Next
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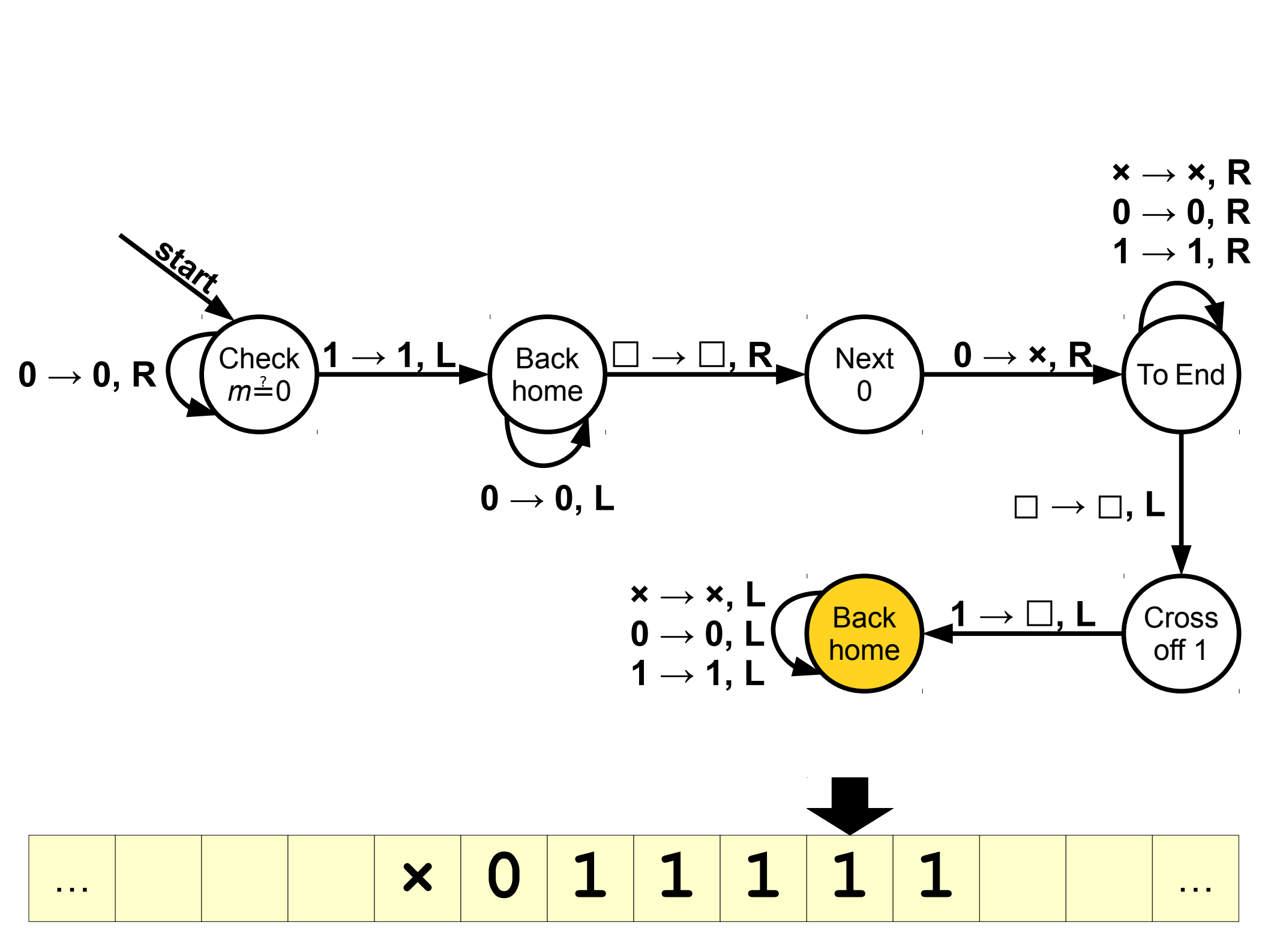
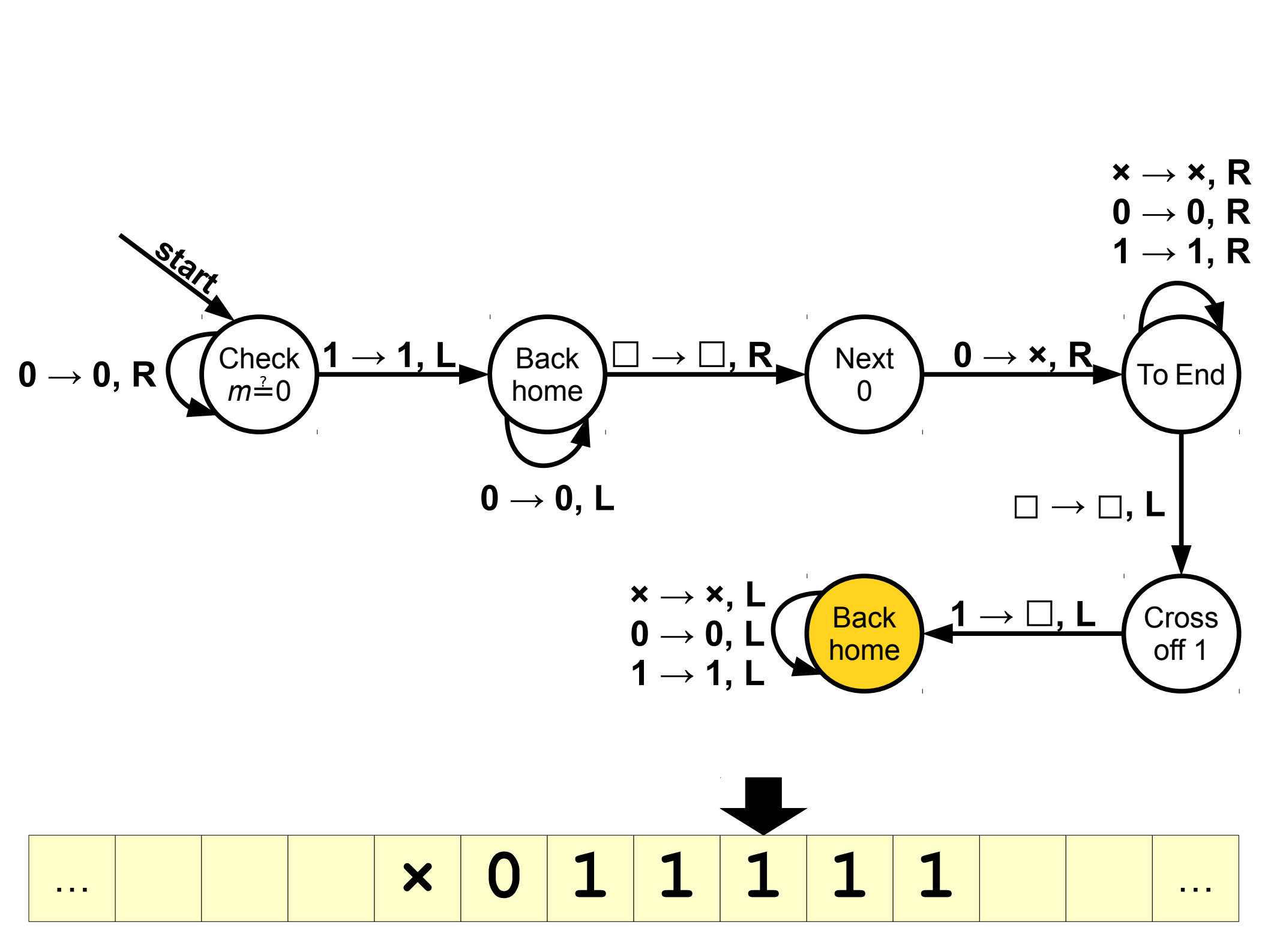
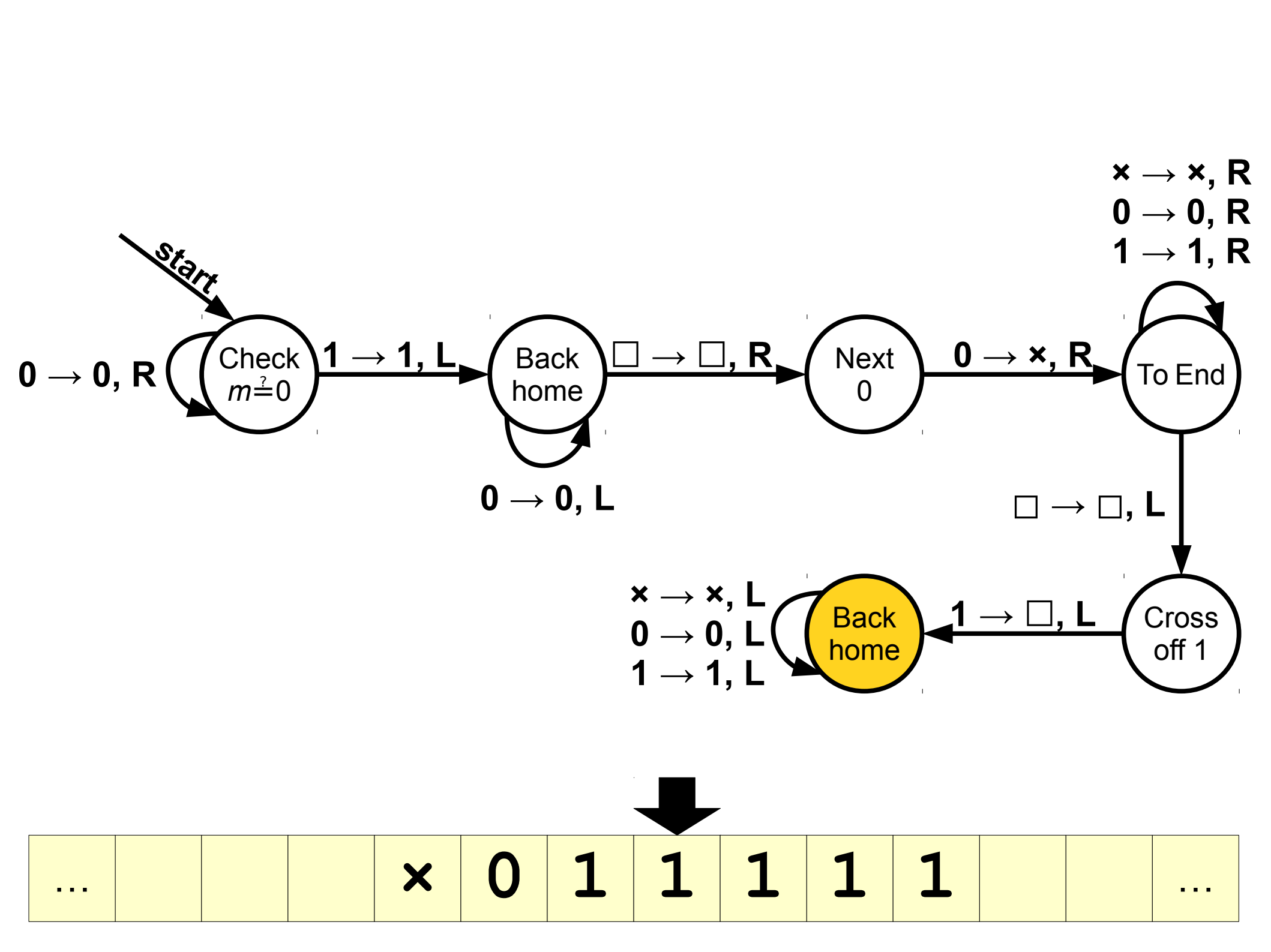
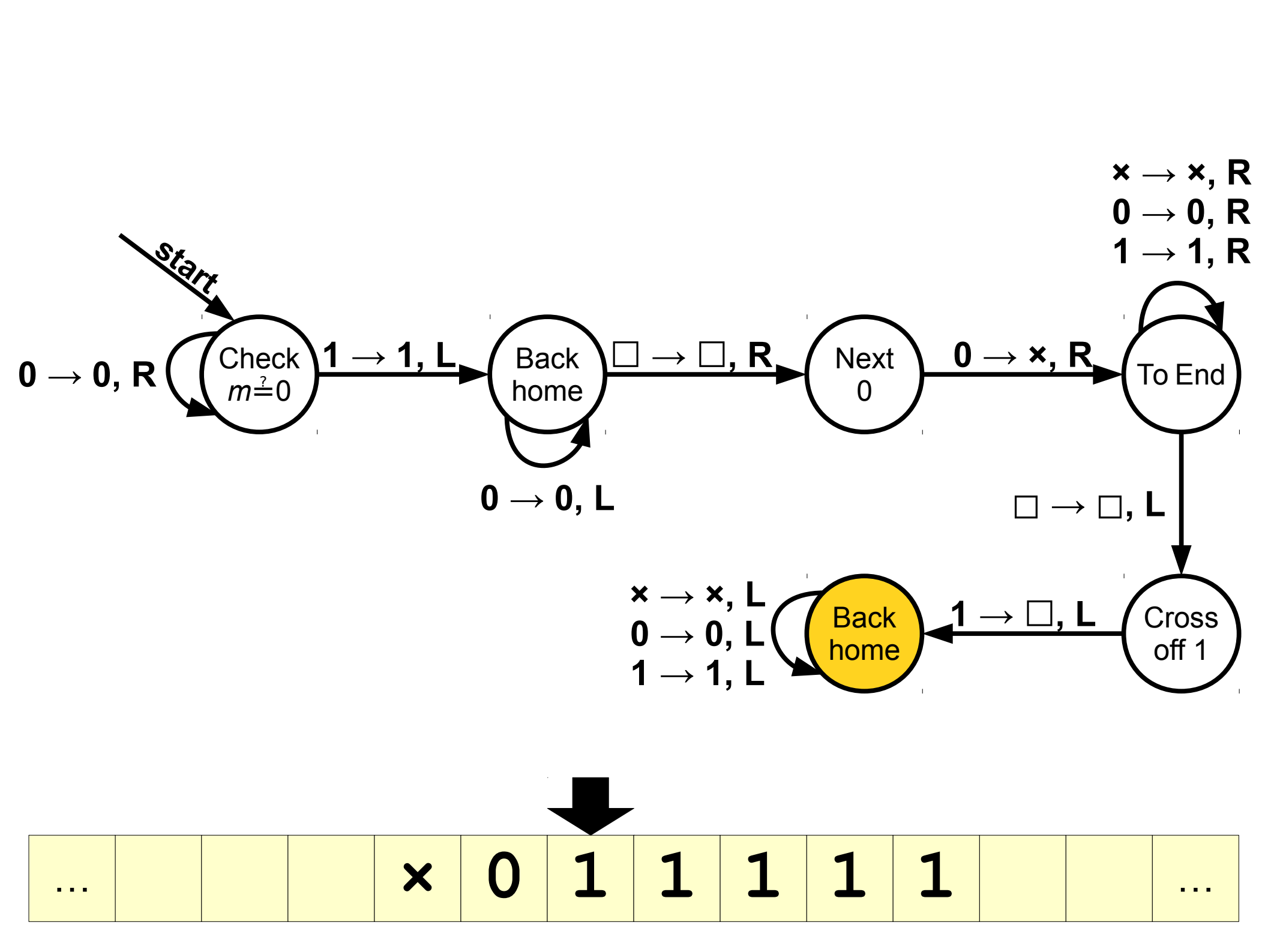
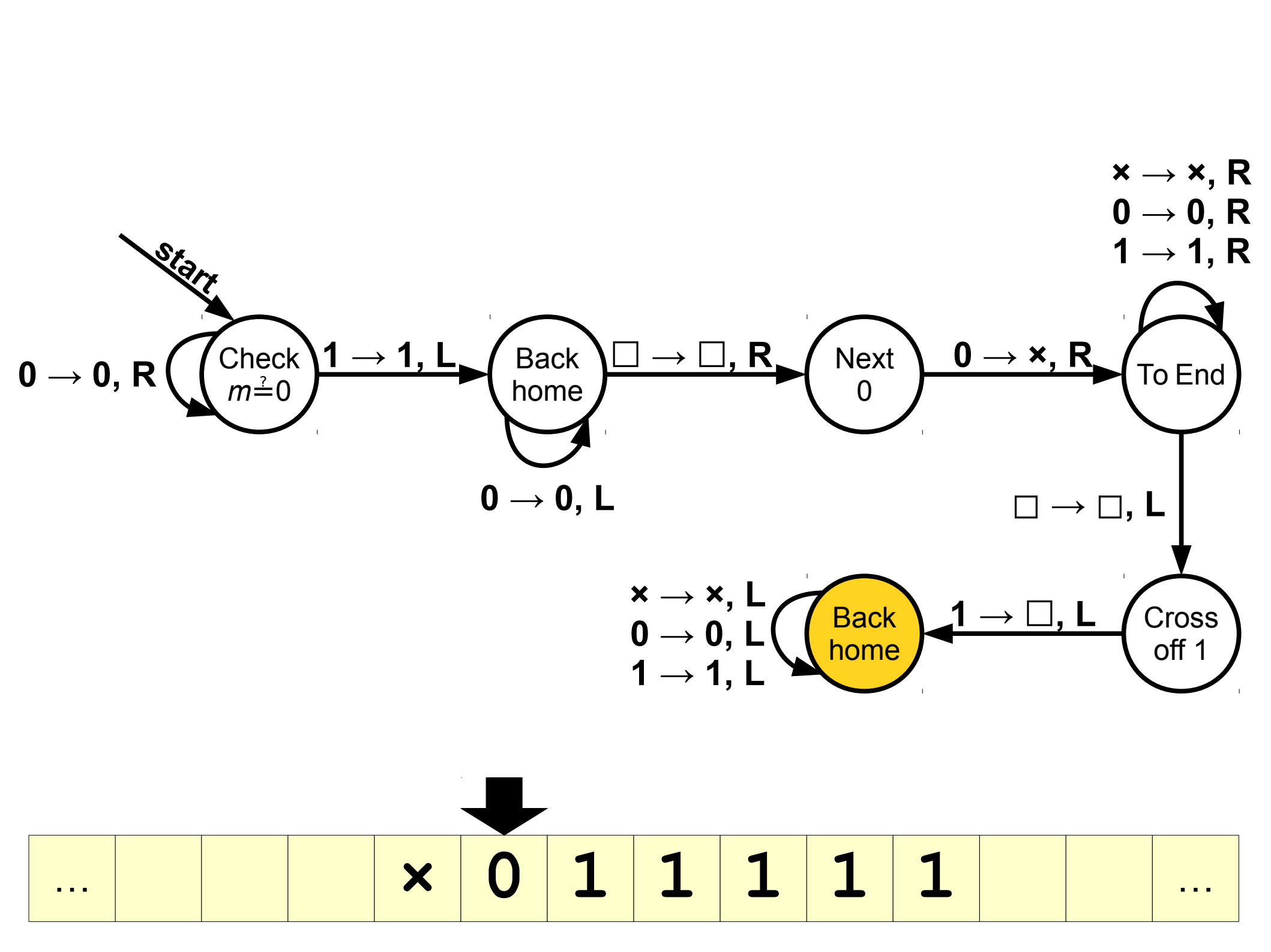
To End
Cross
off 1
Back
home
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
1 → □, L
× → ×, L
0 → 0, L
1 → 1, L
…
×
0
1
1
1
1
1
…

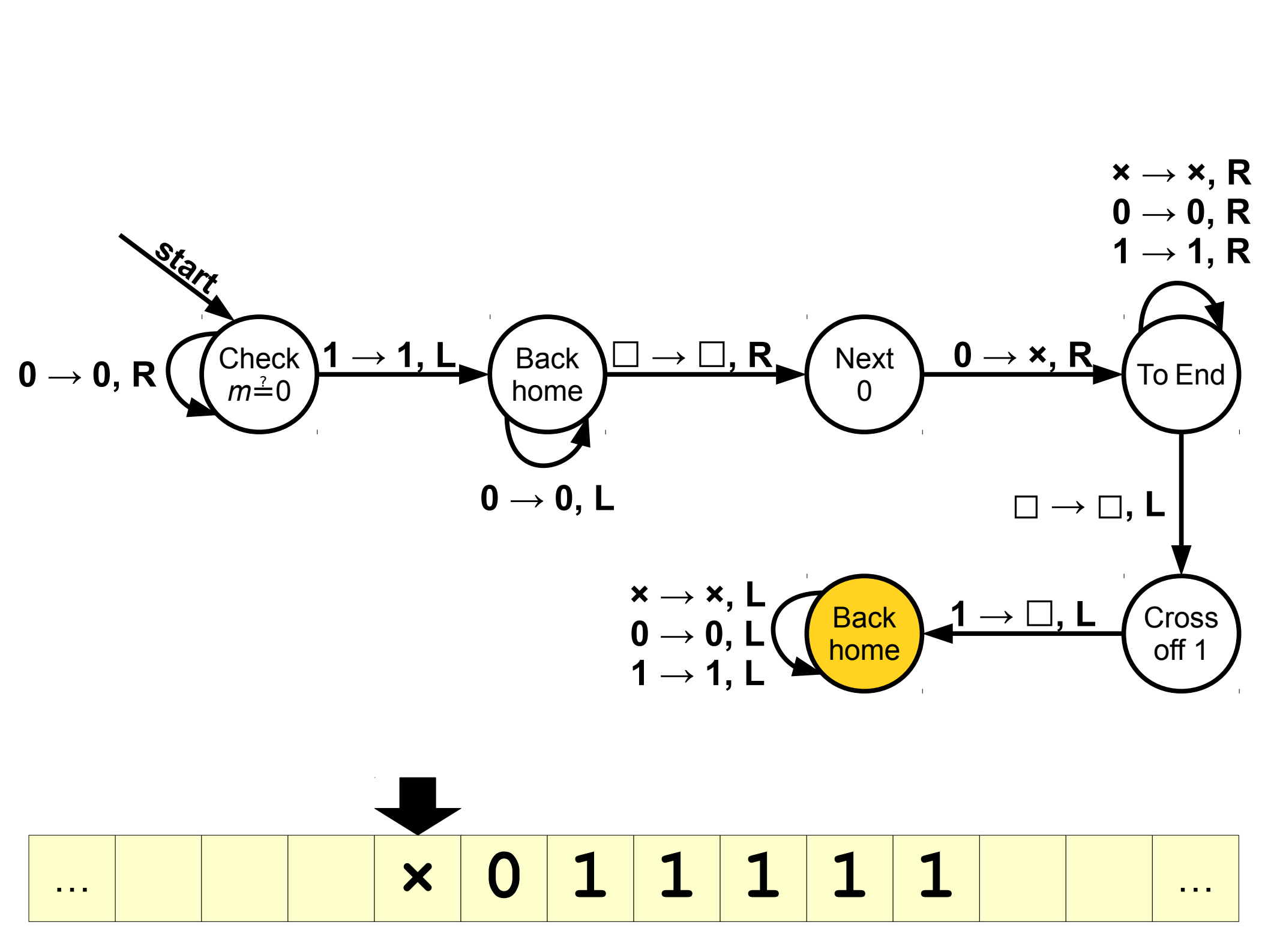

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Cross
off 1
Back
home
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
1 → □, L
× → ×, L
0 → 0, L
1 → 1, L
… × 0 1 1 1 1 1 …

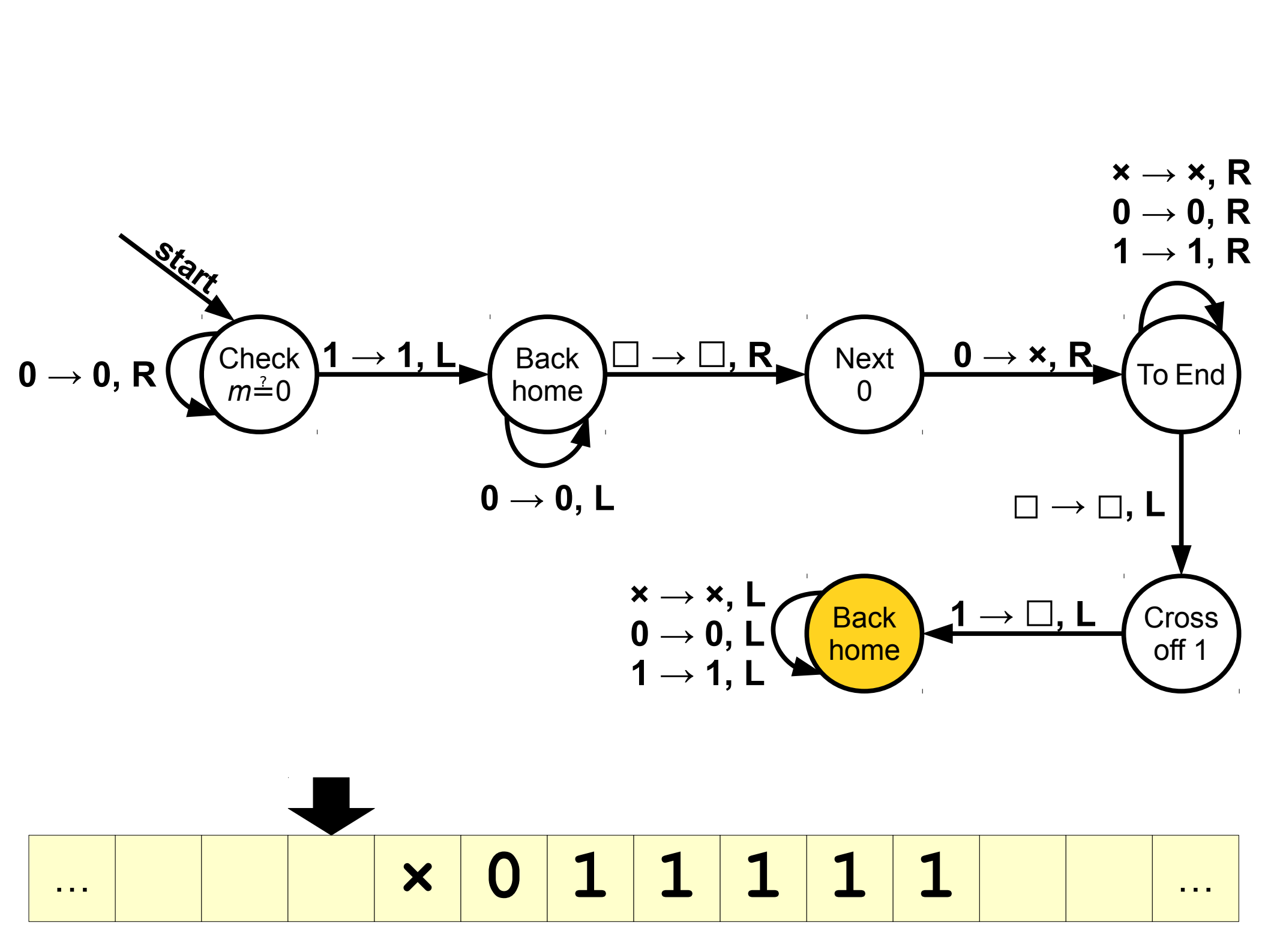

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Cross
off 1
Back
home
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
1 → □, L
× → ×, L
0 → 0, L
1 → 1, L
… × 0 1 1 1 1 1 …

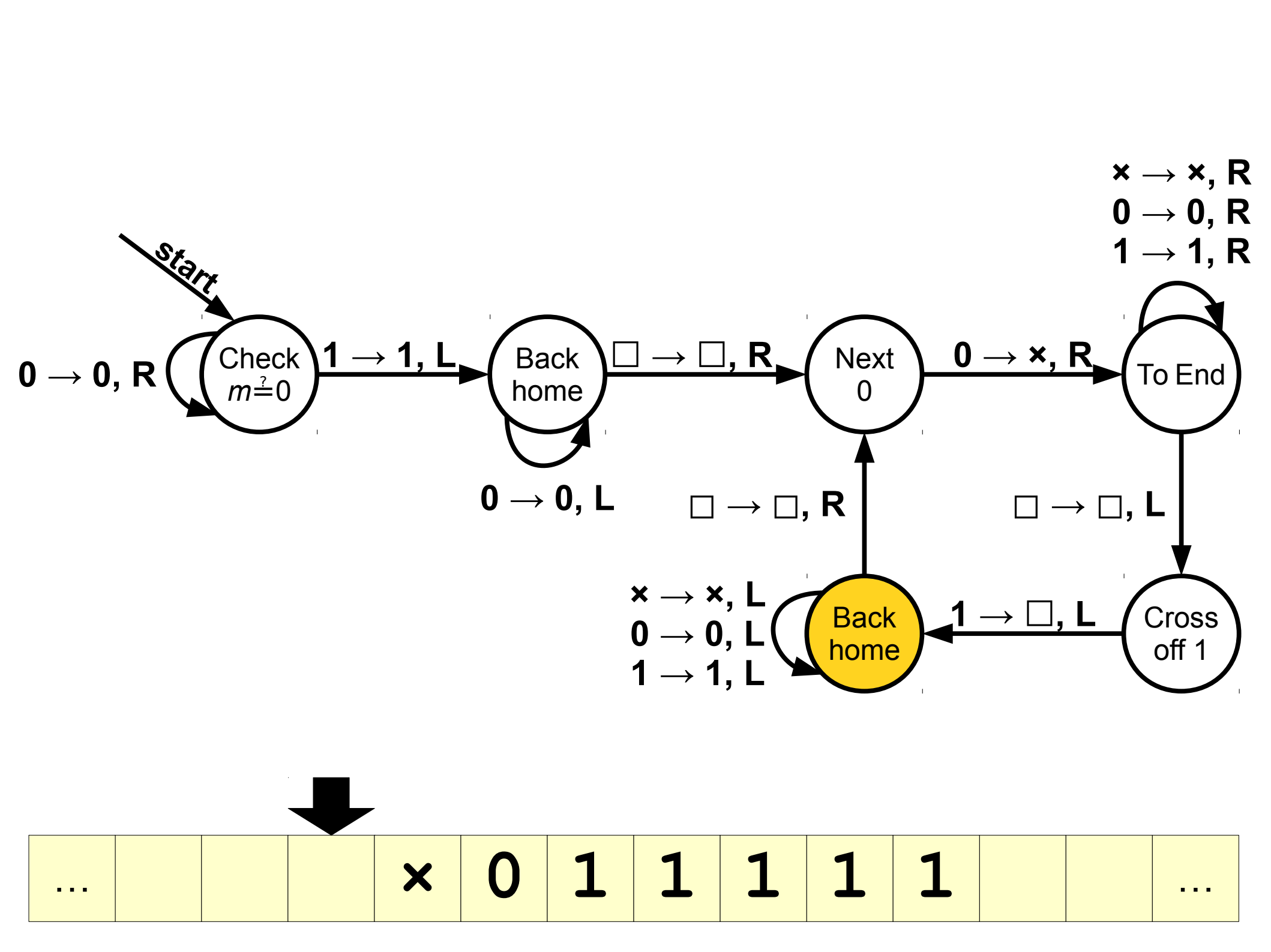

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Cross
off 1
Back
home
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
1 → □, L
× → ×, L
0 → 0, L
1 → 1, L
… × 0 1 1 1 1 1 …

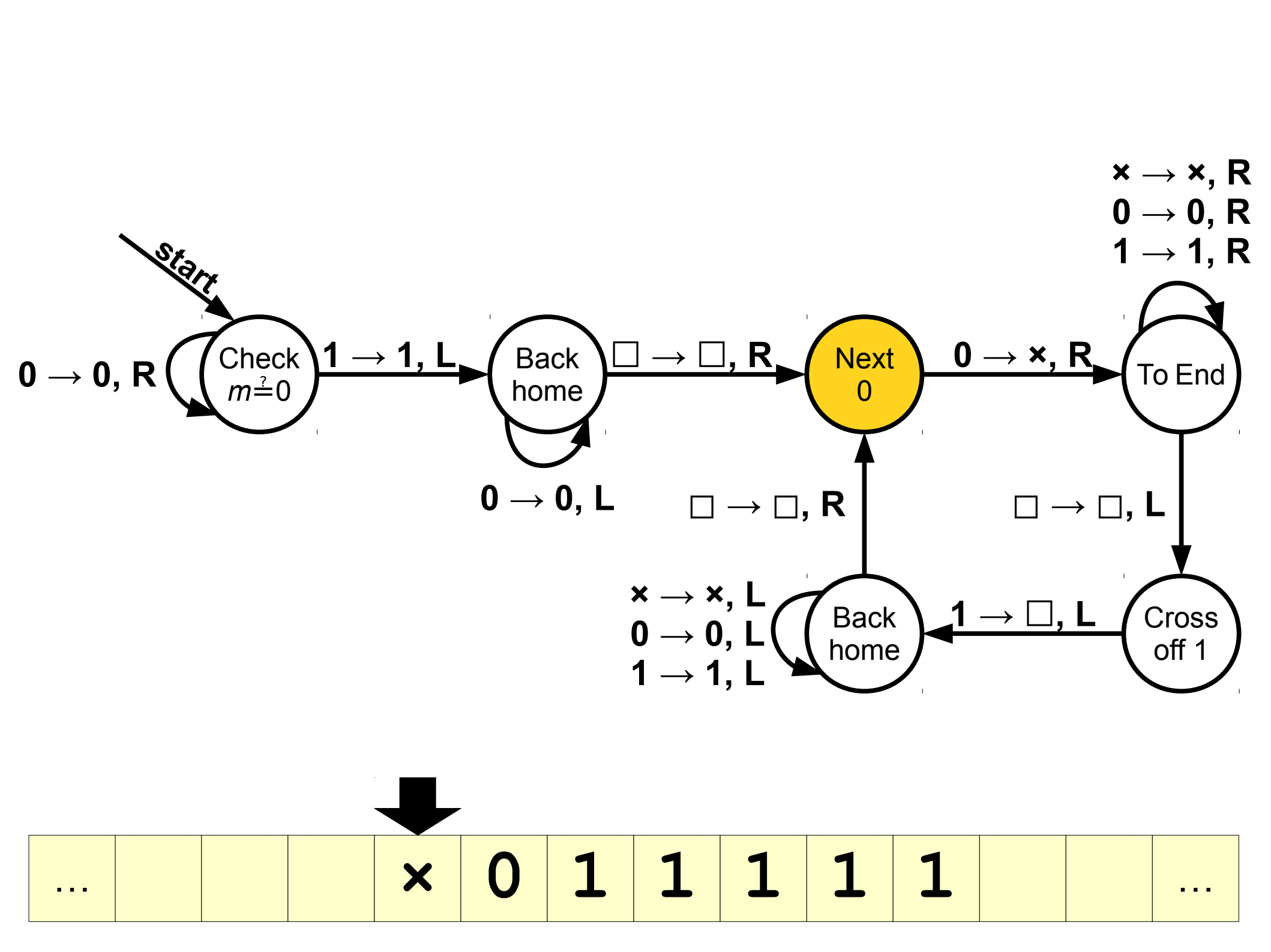

start
Check
m ≟ 0
0 → 0, R
1 → 1, L
Back
home
0 → 0, L
□ → □, R
Next
0
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
… × 0 1 1 1 1 1 …

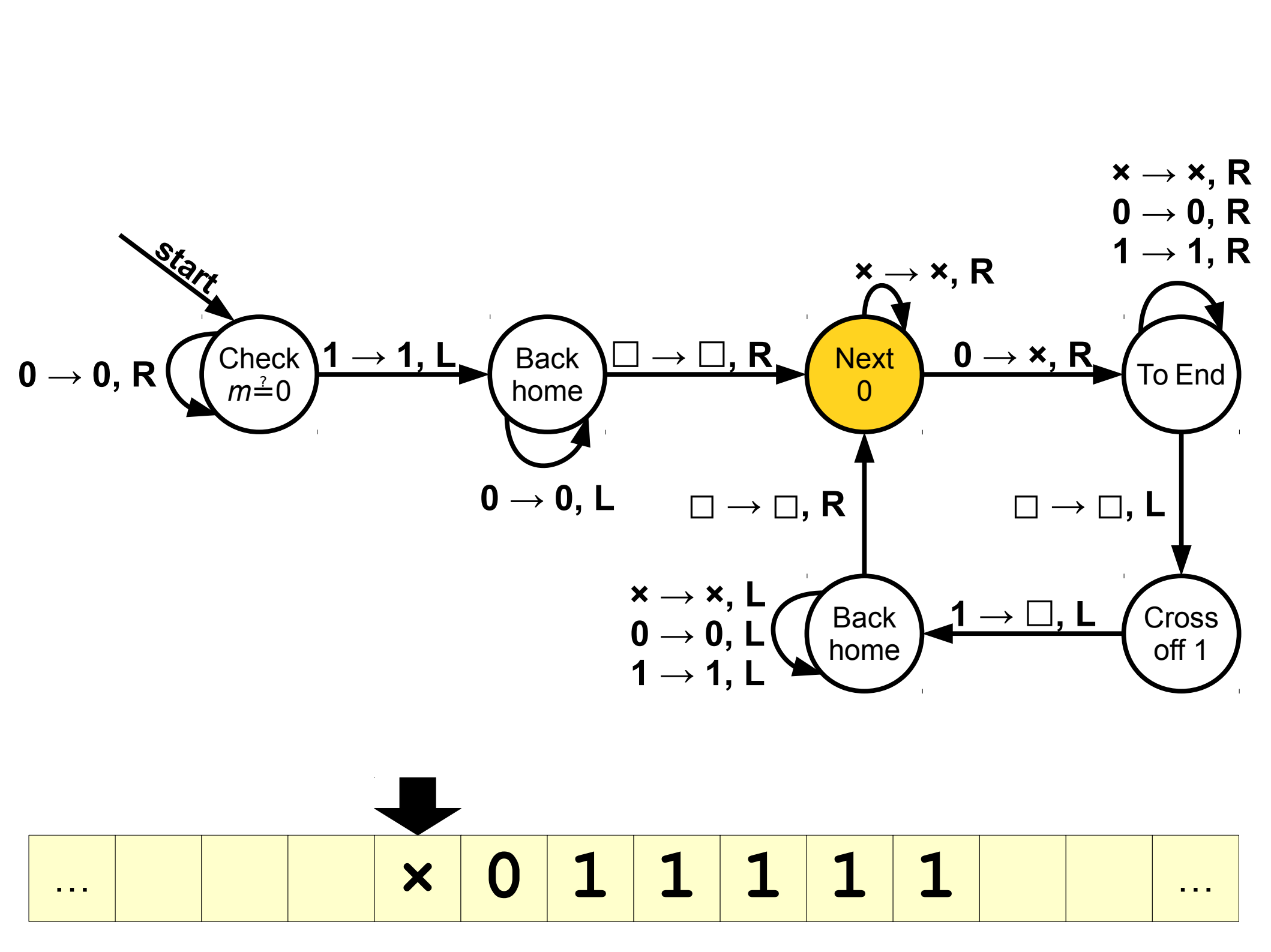

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Cross
off 1
Back
home
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
1 → □, L
× → ×, L
0 → 0, L
1 → 1, L
…
×
0
1
1
1
1
1
…

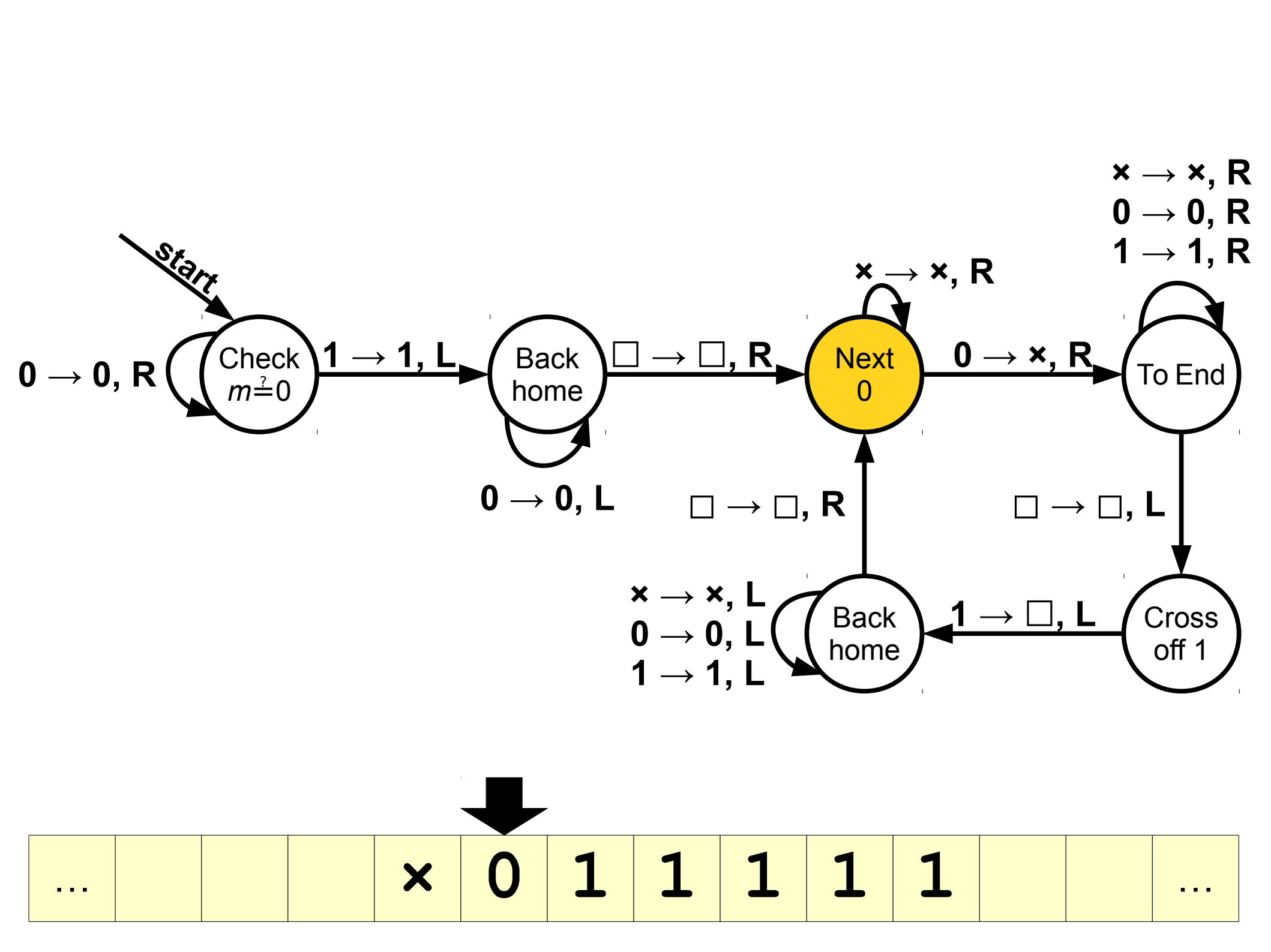

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × 0 1 1 1 1 1 …

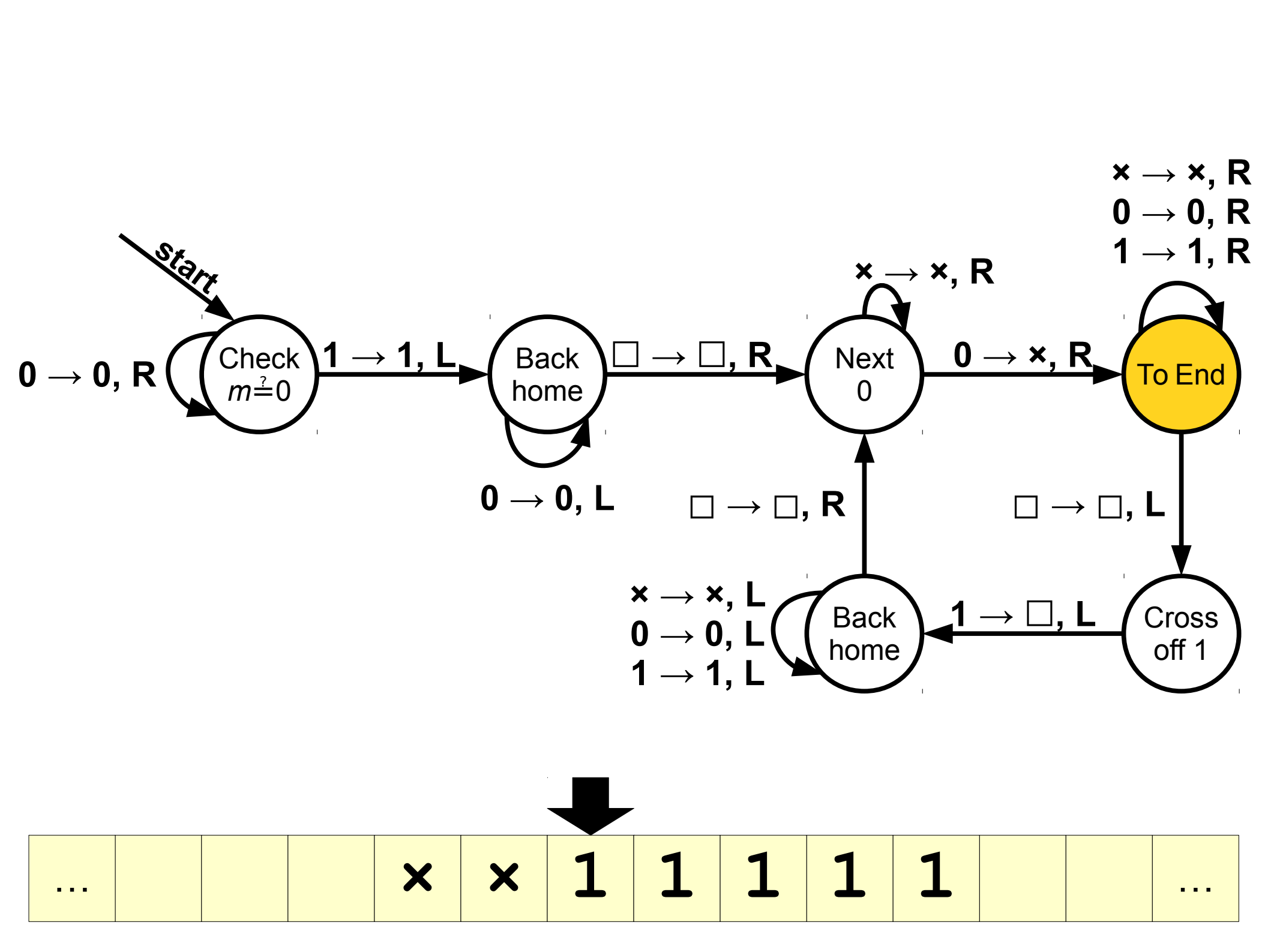

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
…
×
0
1
1
1
1
1
…

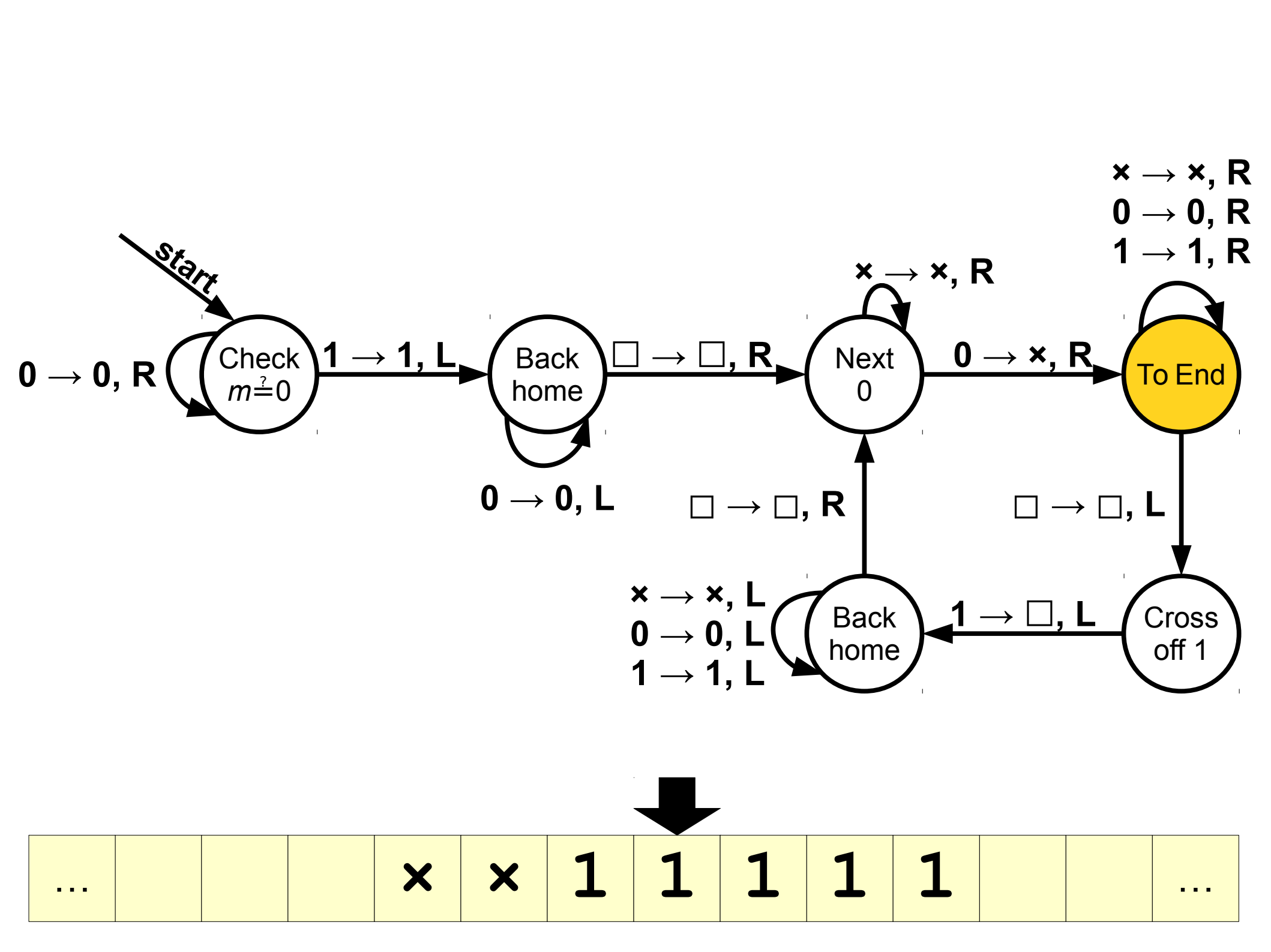

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × 0 1 1 1 1 1 …

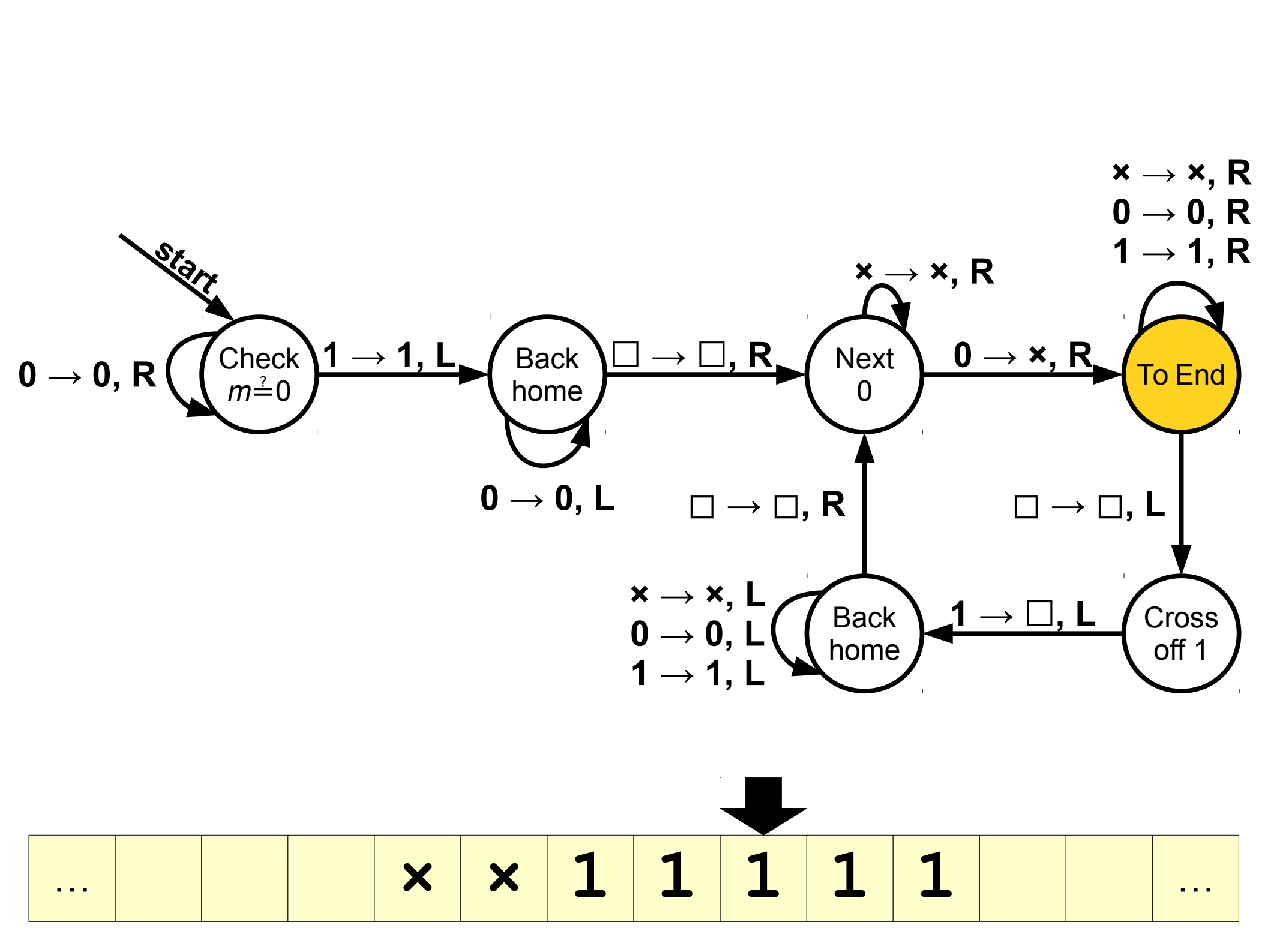

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × 0 1 1 1 1 1 …

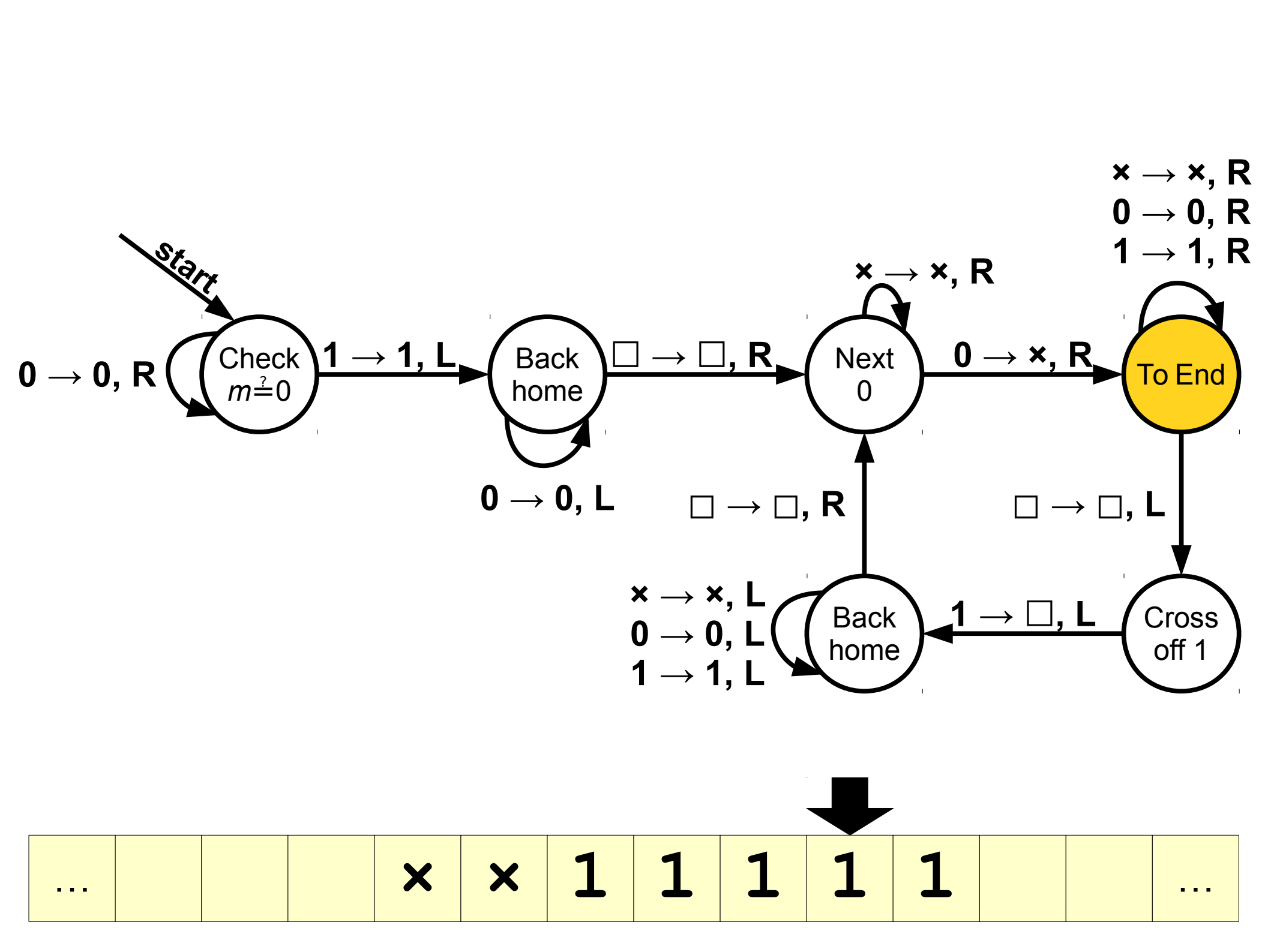

start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × 0 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × 0 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
Back
home
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To End
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home
Cross
off 1
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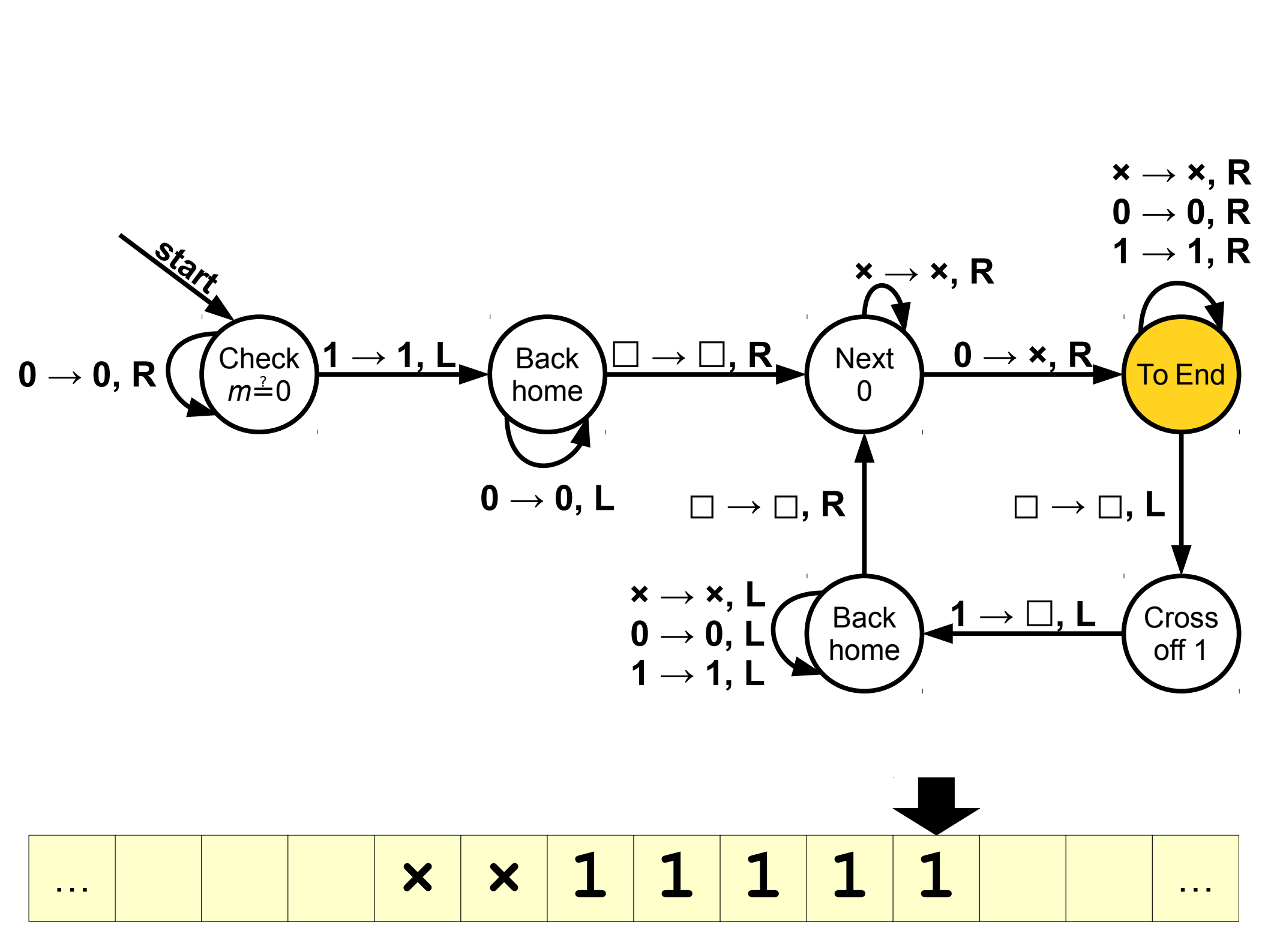
1 → 1, L
□ → □, R
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
Back
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Next
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To End
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home
Cross
off 1
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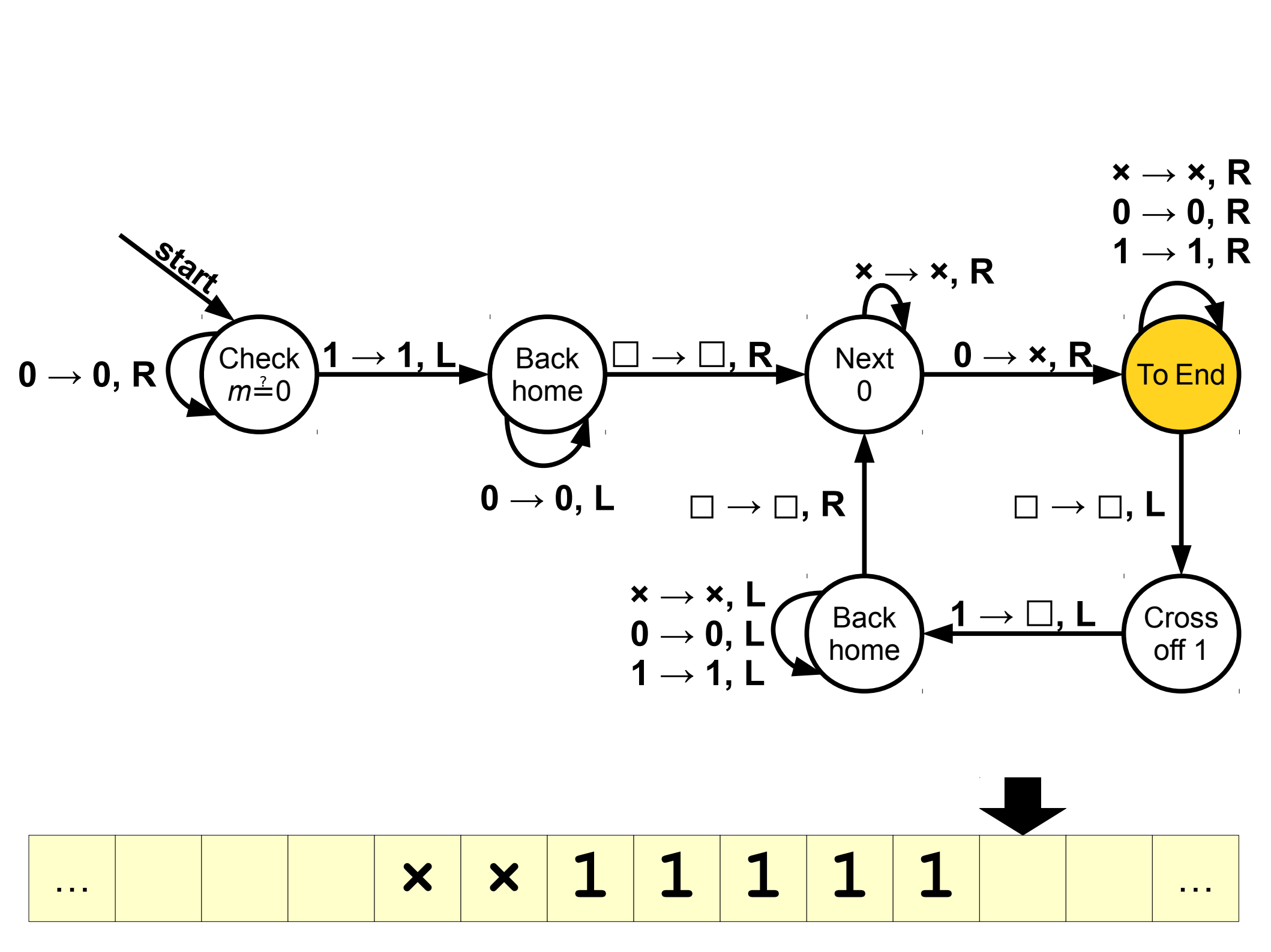
1 → 1, L
□ → □, R
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
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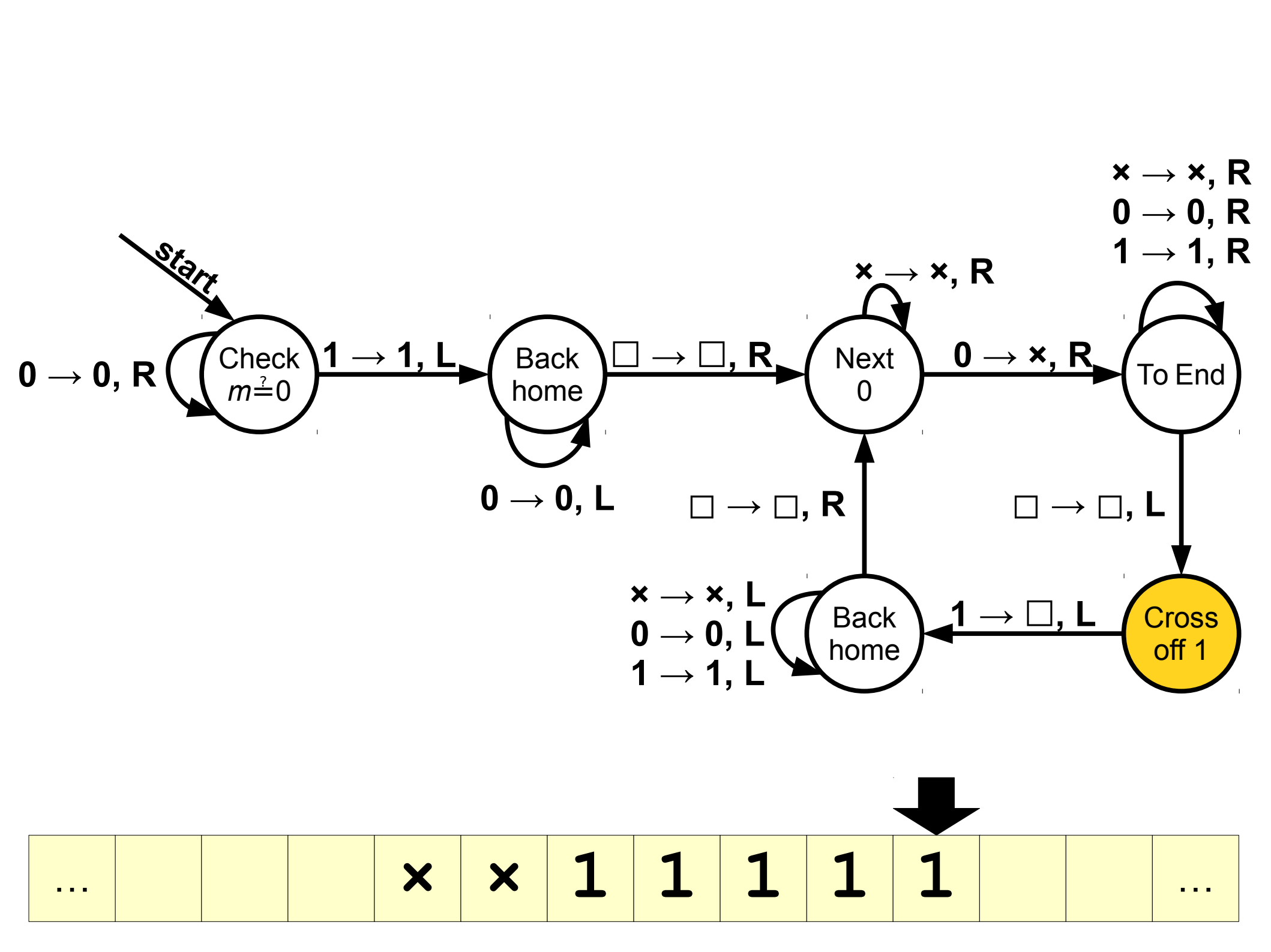
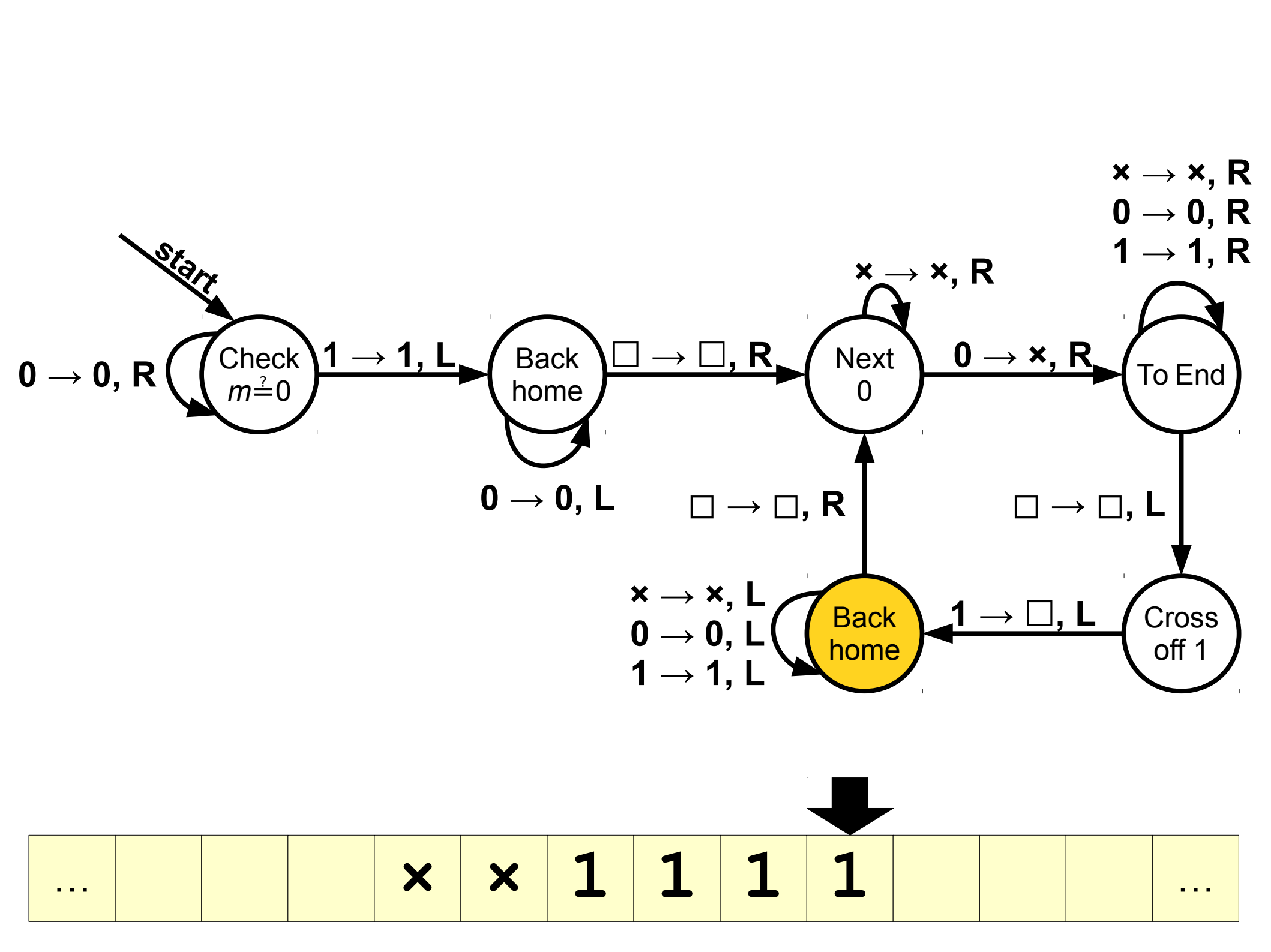
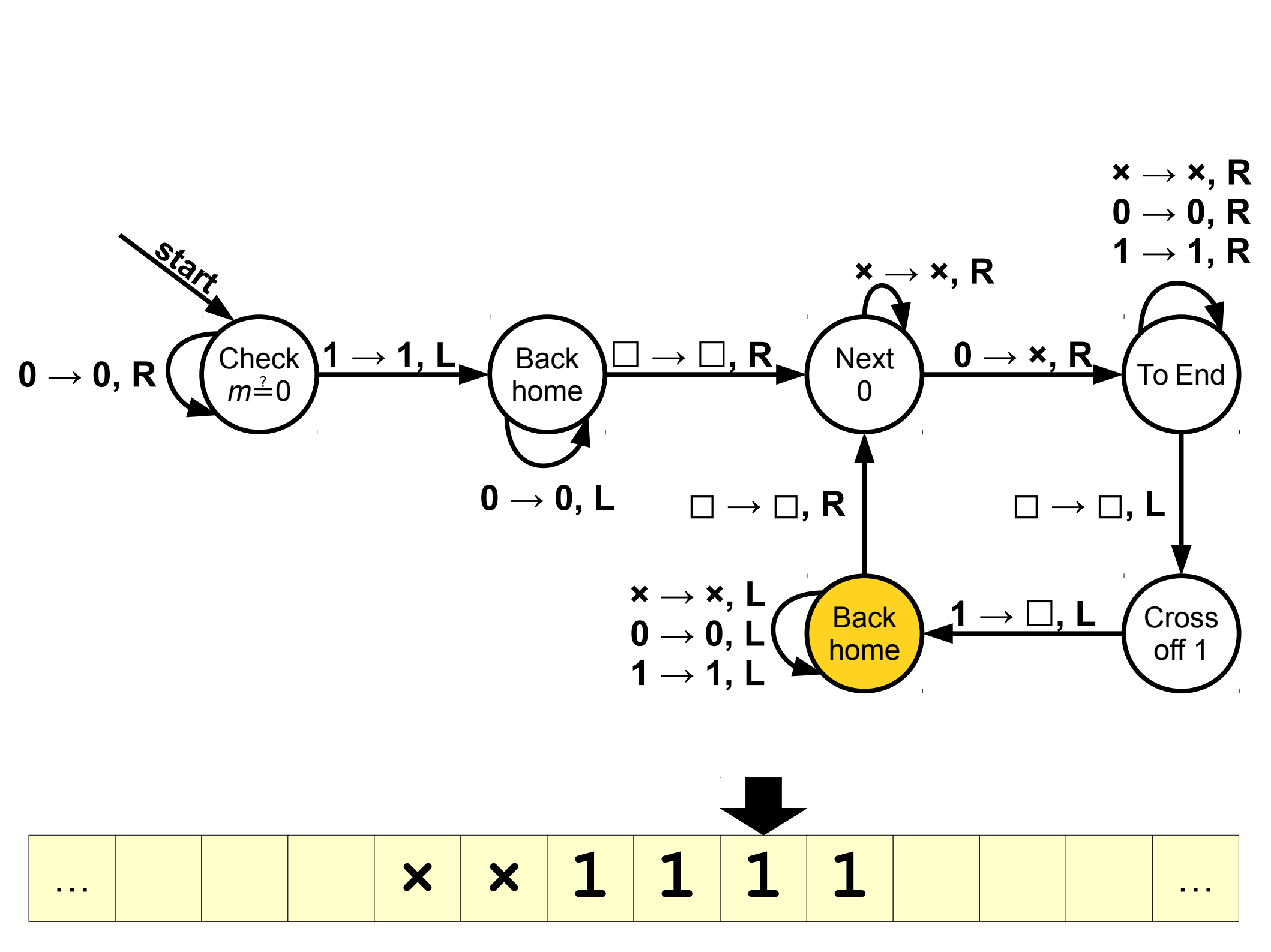
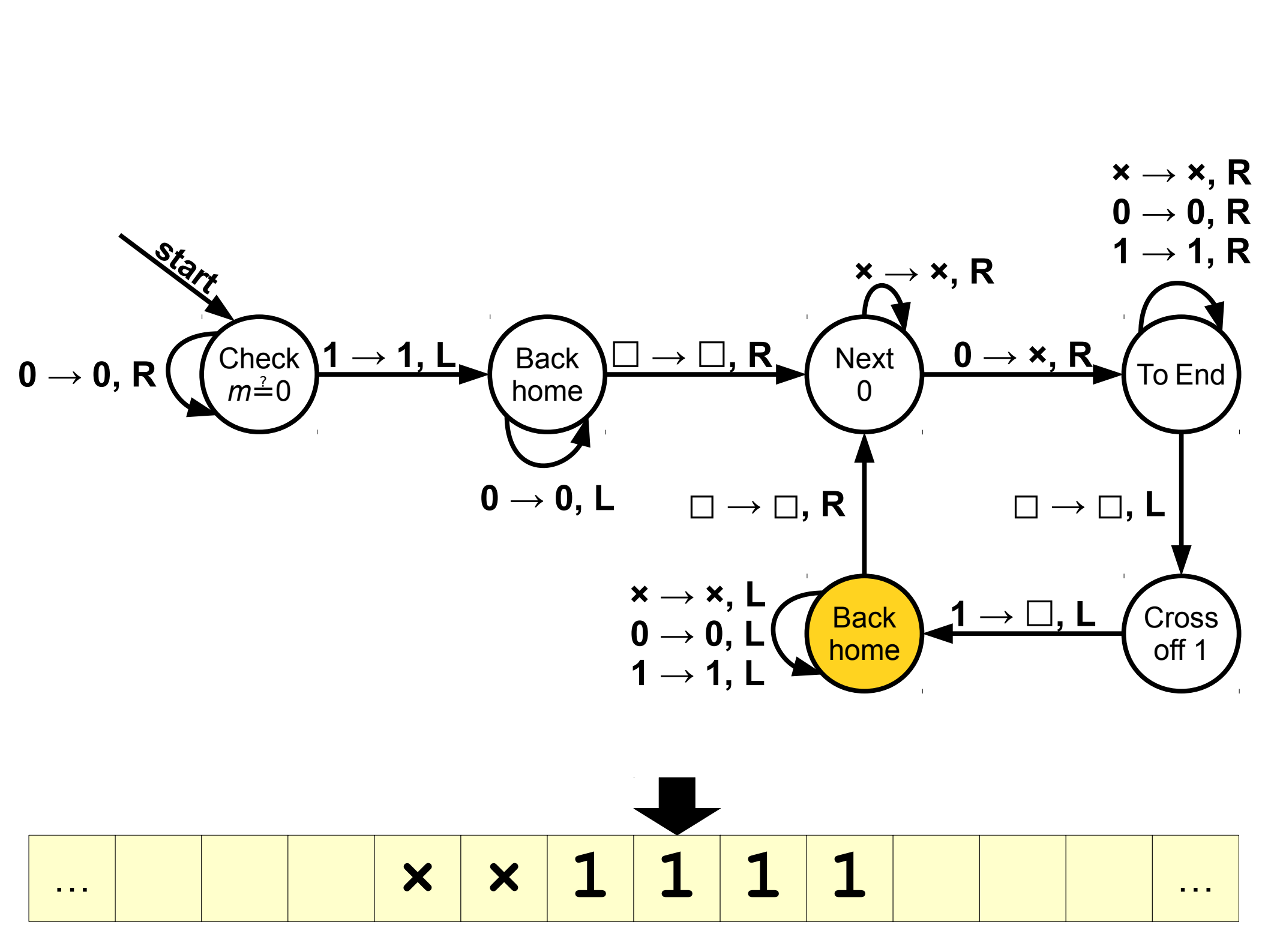
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × × 1 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
□ → □, R
× → ×, L
0 → 0, L
1 → 1, L
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
□ → □, R
× → ×, L
0 → 0, L
1 → 1, L
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
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home
□ → □, R
0 → 0, L
Next
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× → ×, R
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To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
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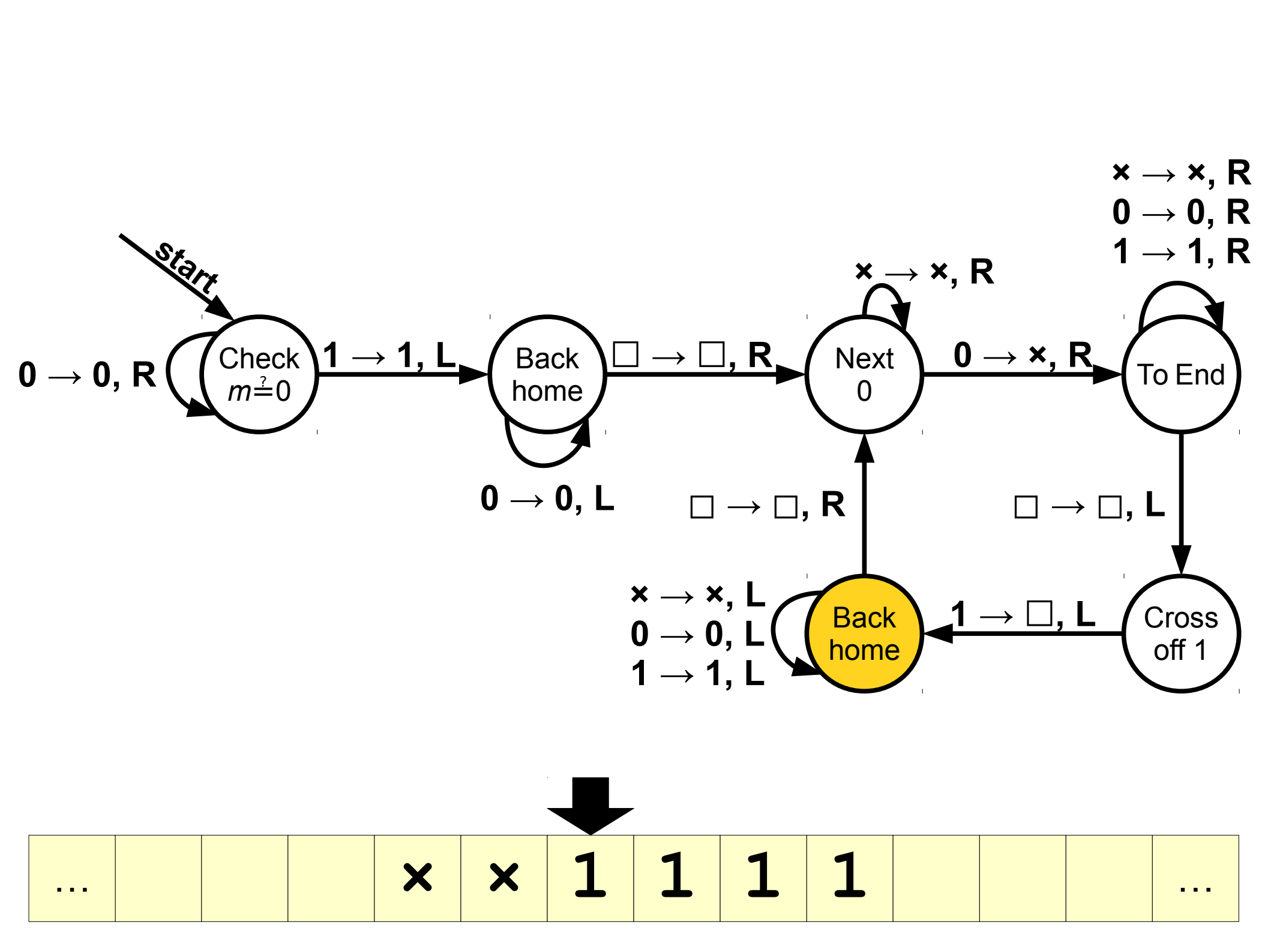
home
□ → □, R
× → ×, L
0 → 0, L
1 → 1, L
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
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home
□ → □, R
0 → 0, L
Next
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× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
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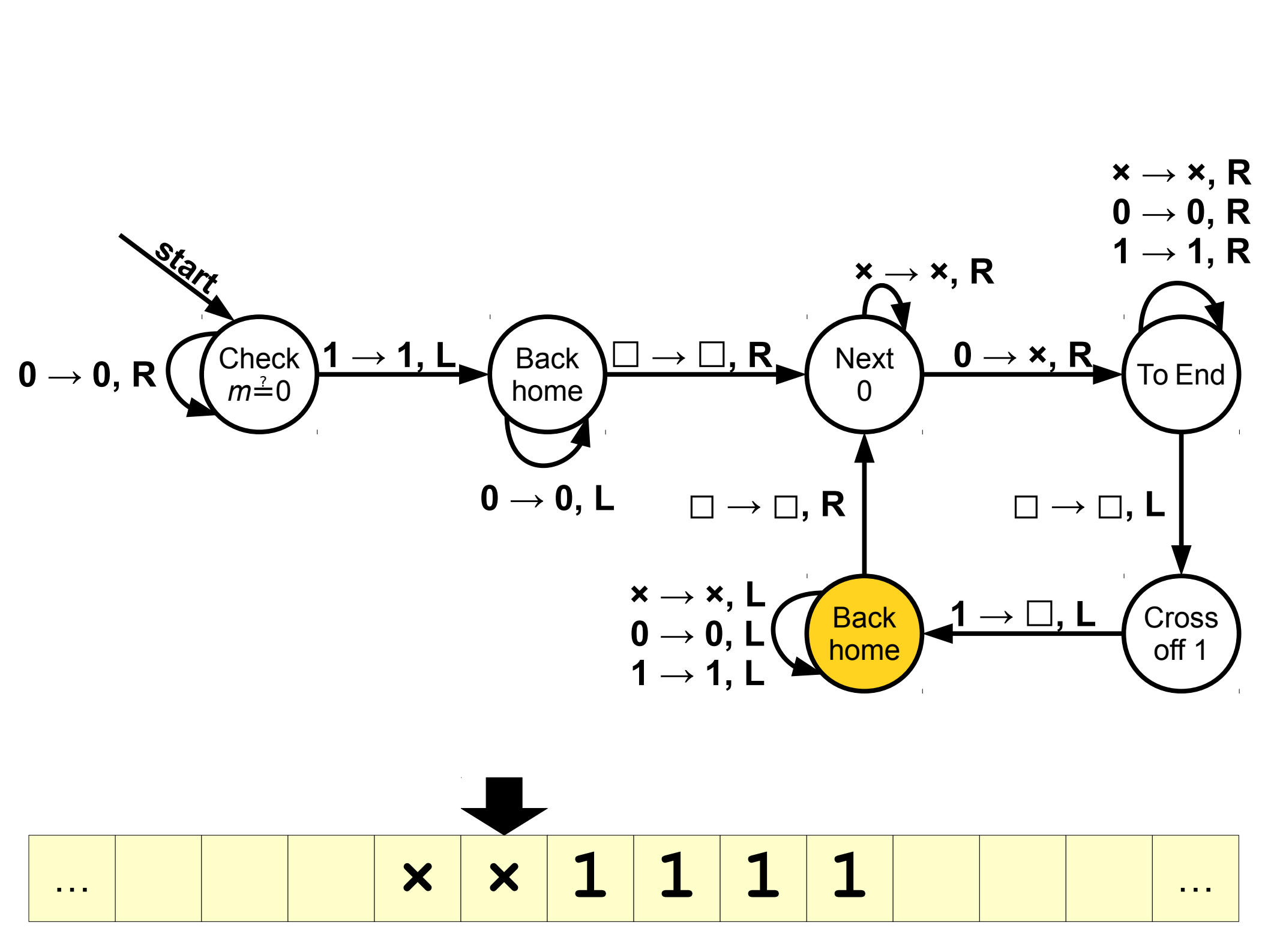
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
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home
□ → □, R
0 → 0, L
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× → ×, R
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To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
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home
□ → □, R
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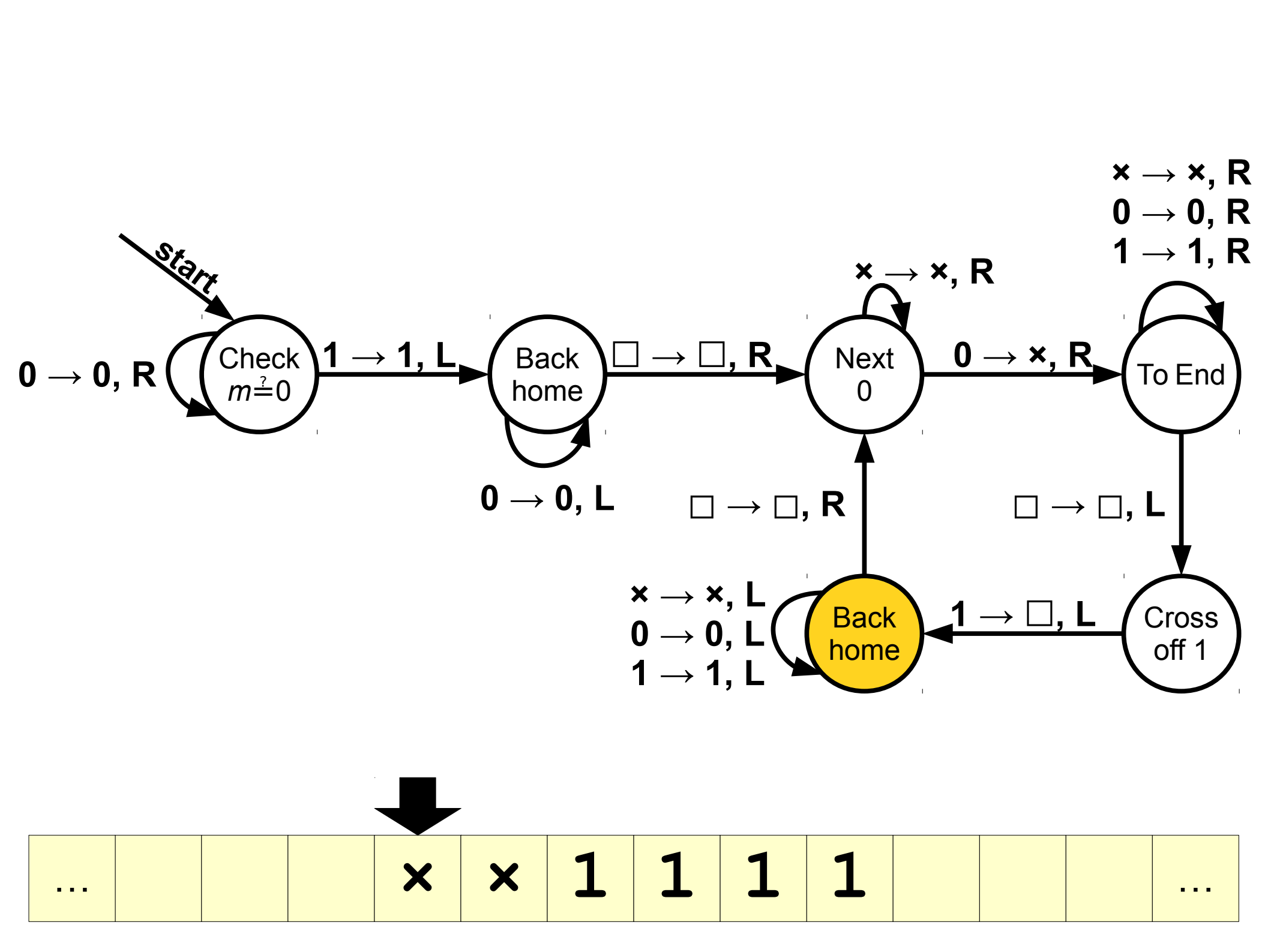
0 → 0, L
1 → 1, L
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
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home
□ → □, R
0 → 0, L
Next
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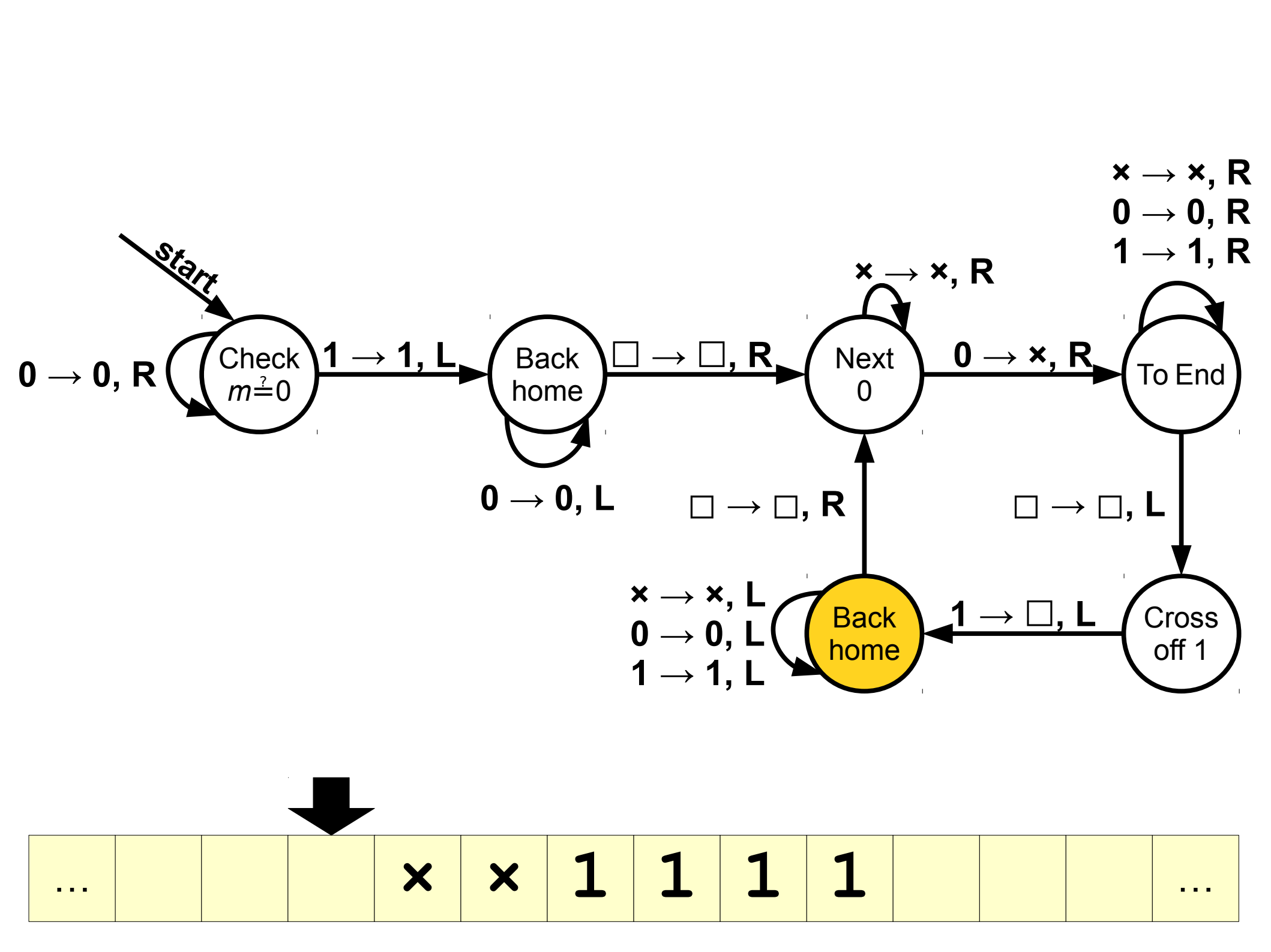
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
□ → □, R
× → ×, L
0 → 0, L
1 → 1, L
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
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home
□ → □, R
0 → 0, L
Next
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× → ×, R
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To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
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1 → □, L
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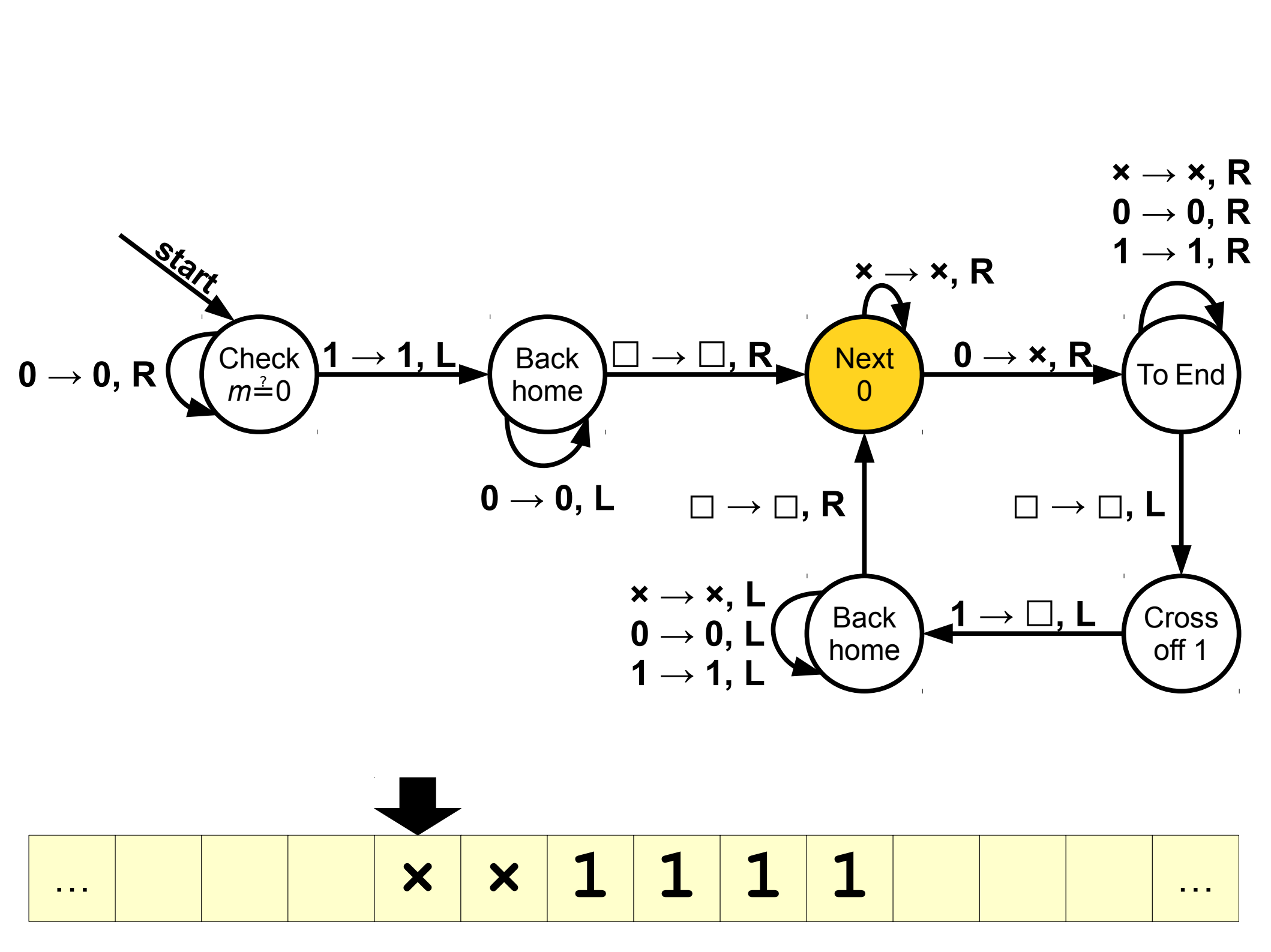
home
□ → □, R
× → ×, L
0 → 0, L
1 → 1, L
… × × 1 1 1 1 …


start
Check
$m \stackrel{?}{=} 0$
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home
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To End
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home
Cross
off 1
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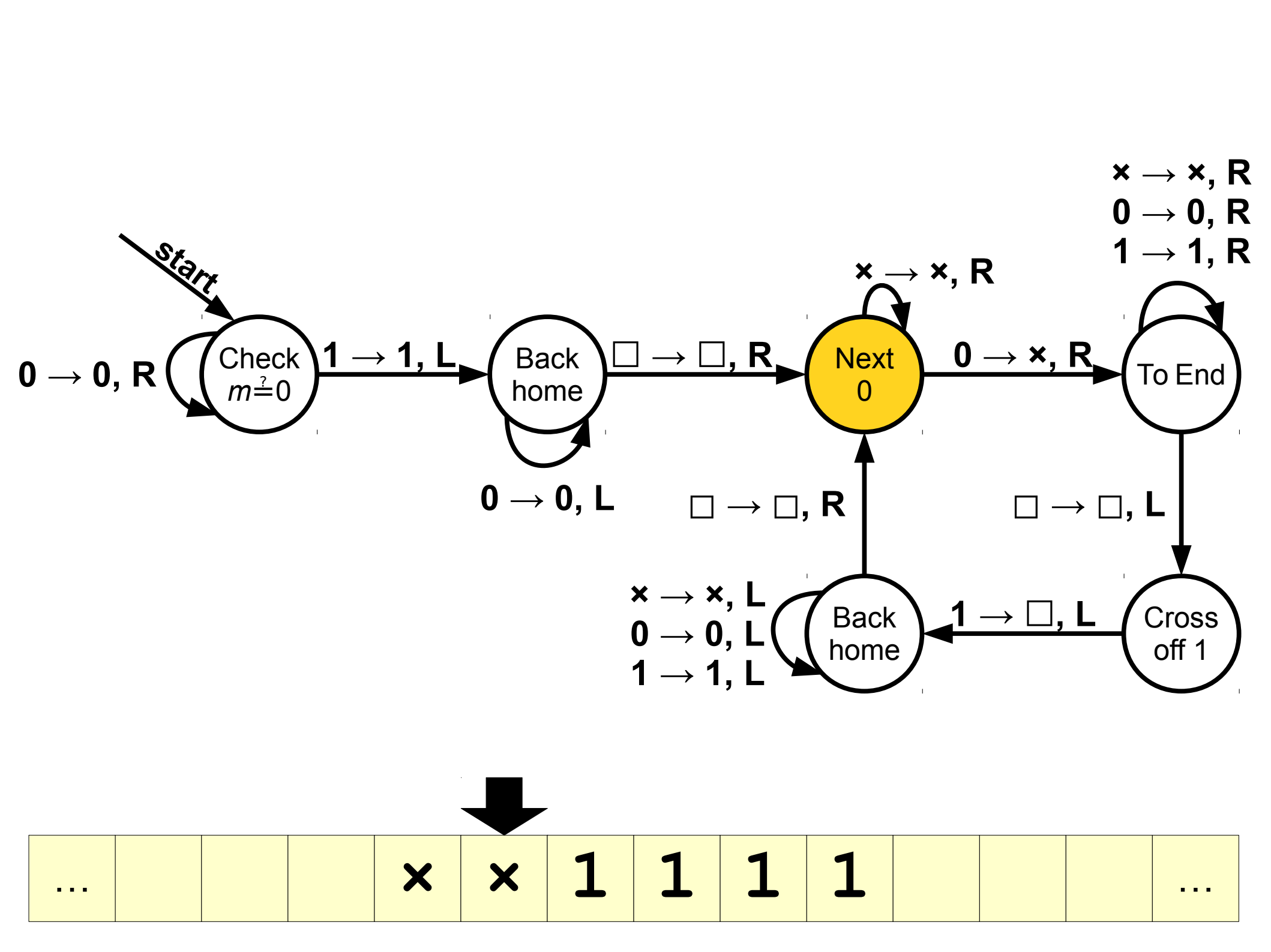
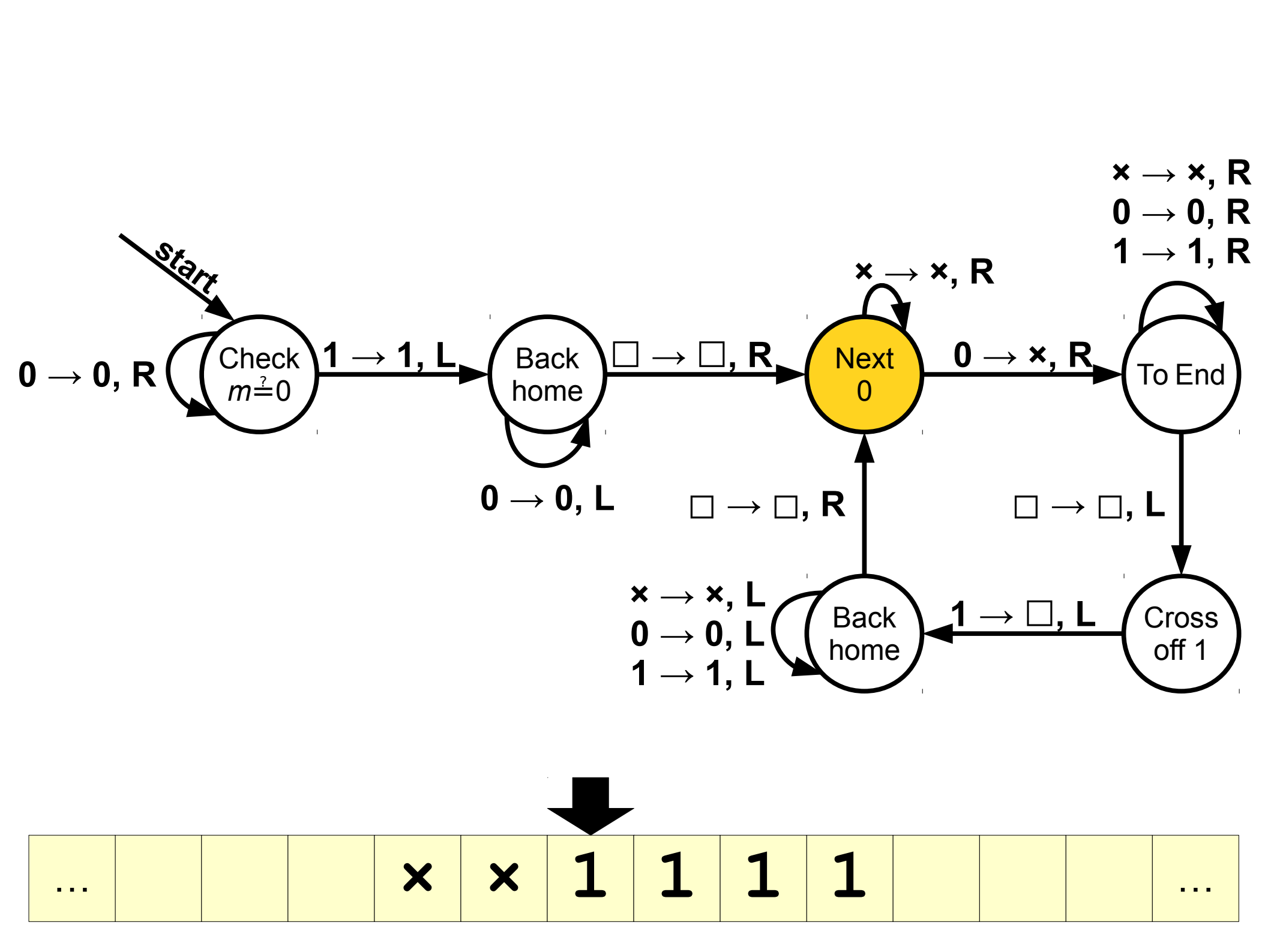
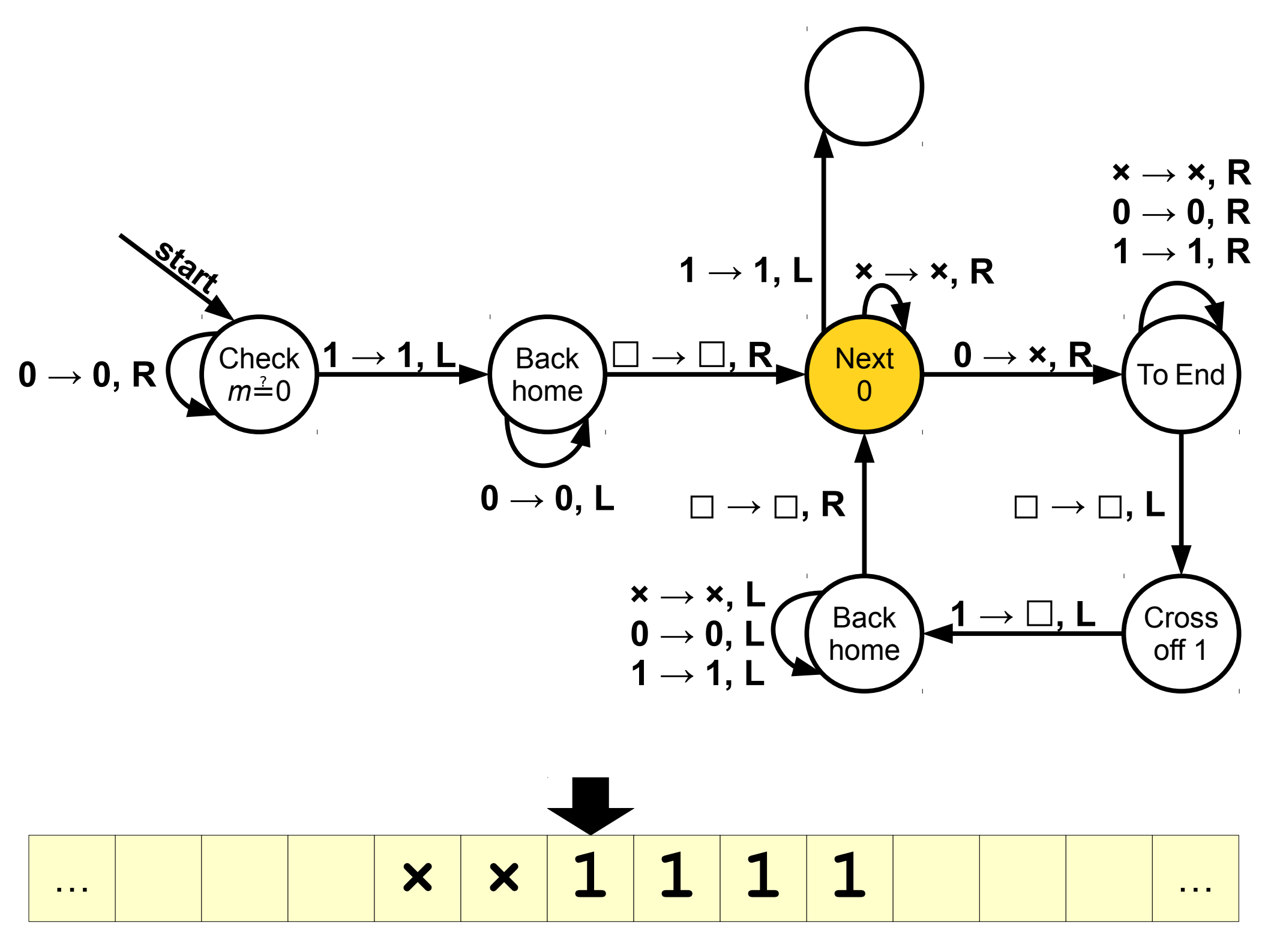
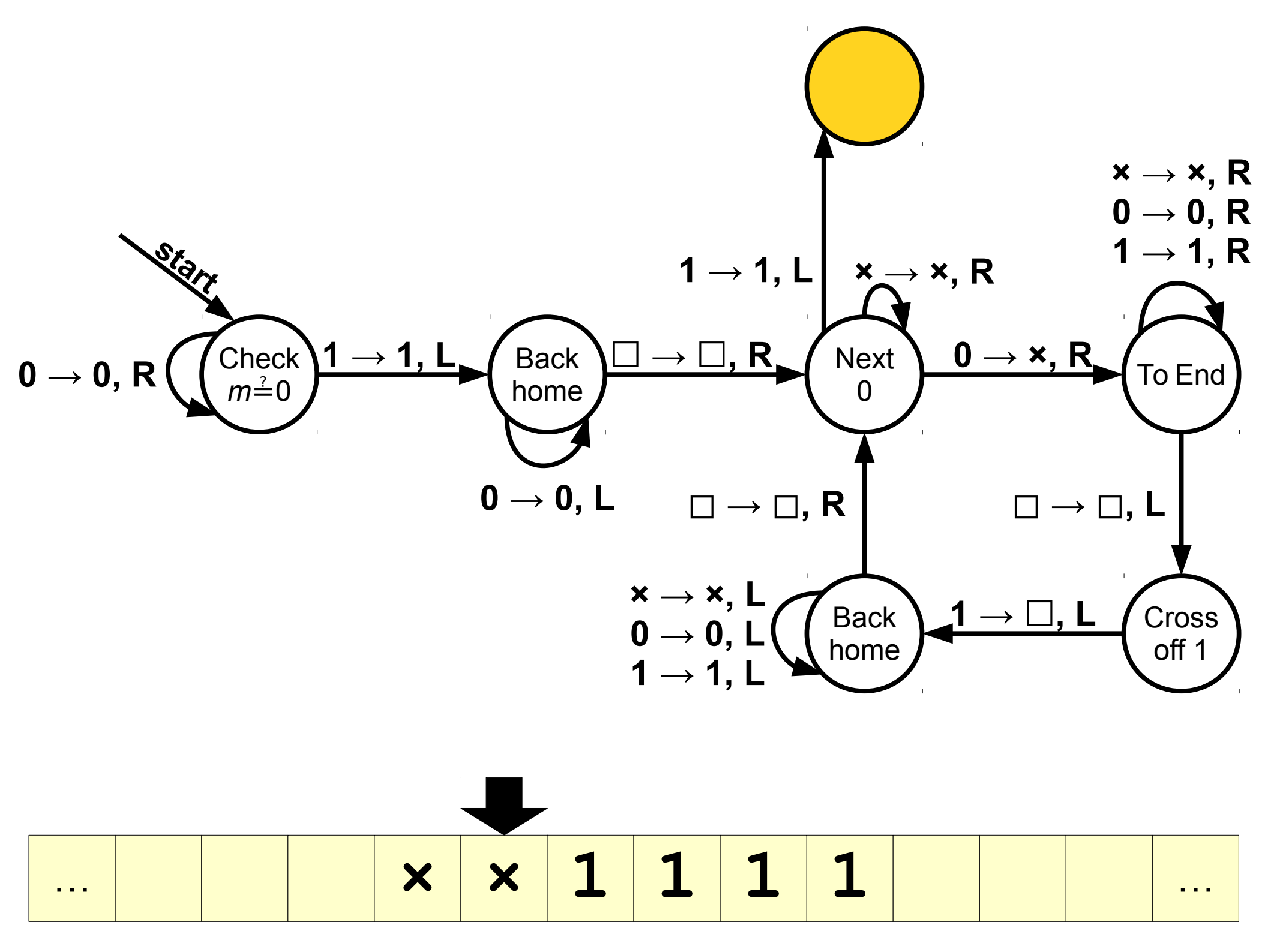
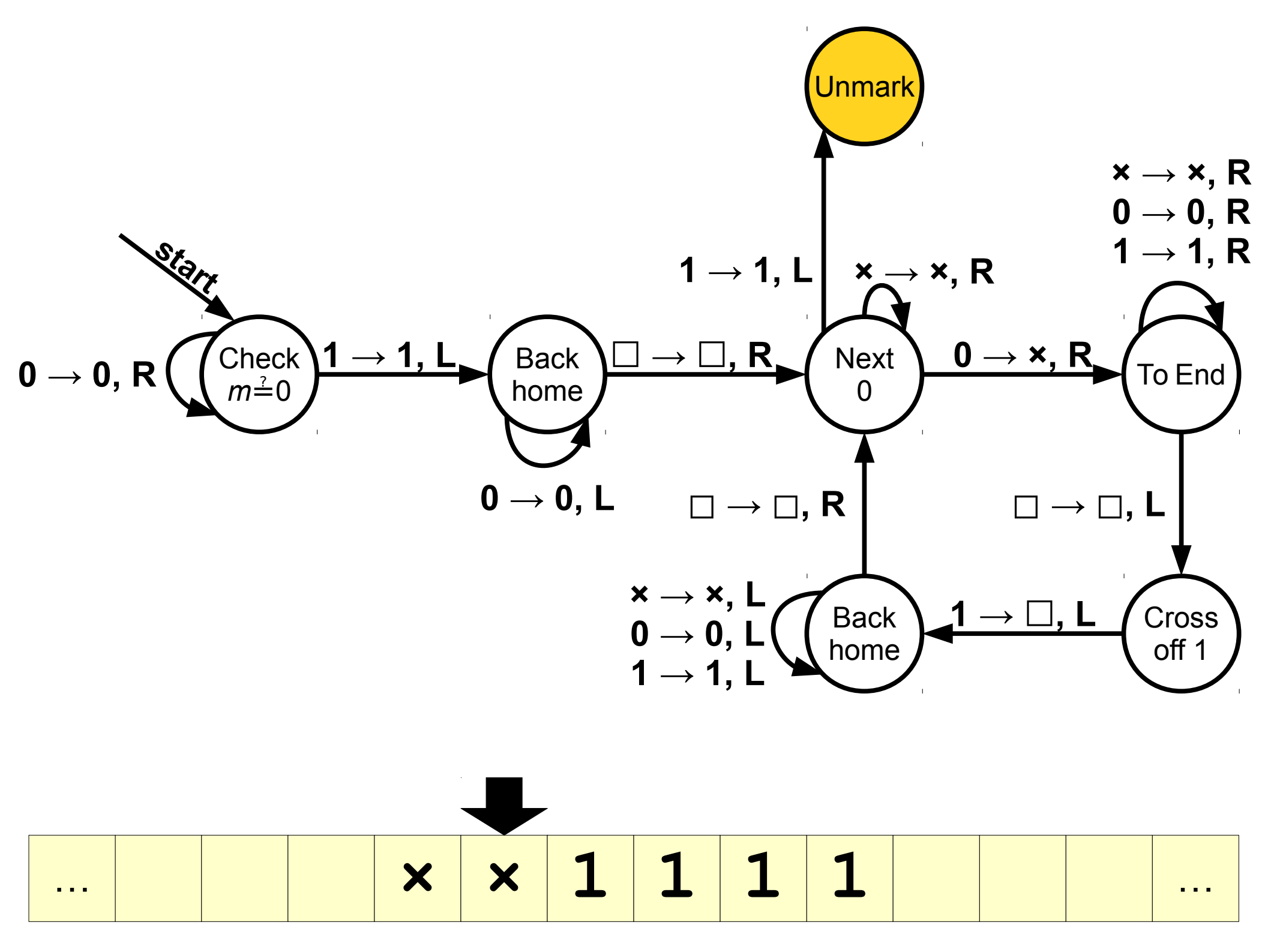
1 → 1, L
□ → □, R
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 …

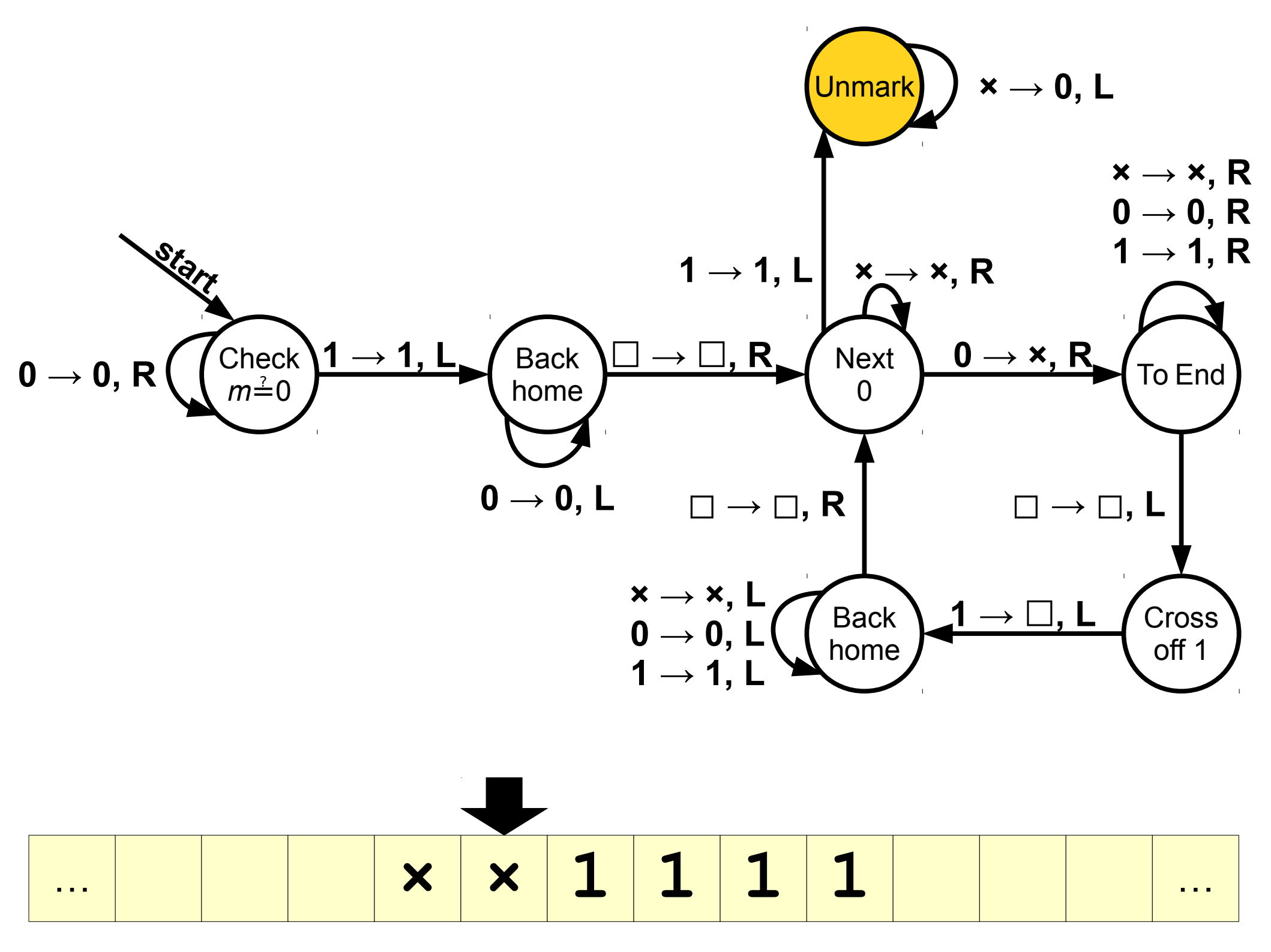

start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × × 1 1 1 1 …

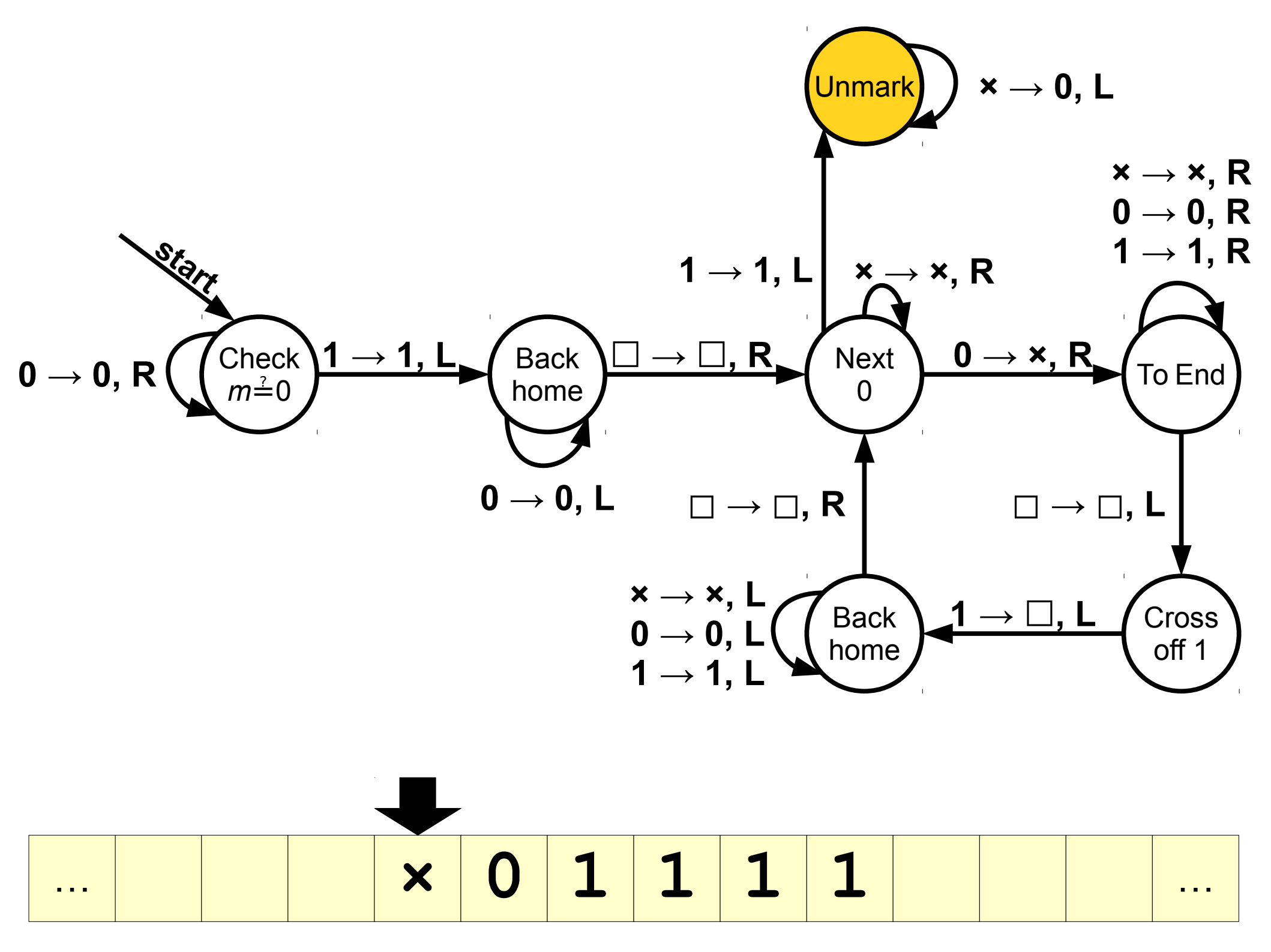

start
Check
$m \stackrel{?}{=} 0$
0 → 0, R
1 → 1, L
Back
home
□ → □, R
0 → 0, L
Next
0
× → ×, R
0 → ×, R
To End
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
Cross
off 1
1 → □, L
Back
home
× → ×, L
0 → 0, L
1 → 1, L
□ → □, R
… × × 1 1 1 1 …

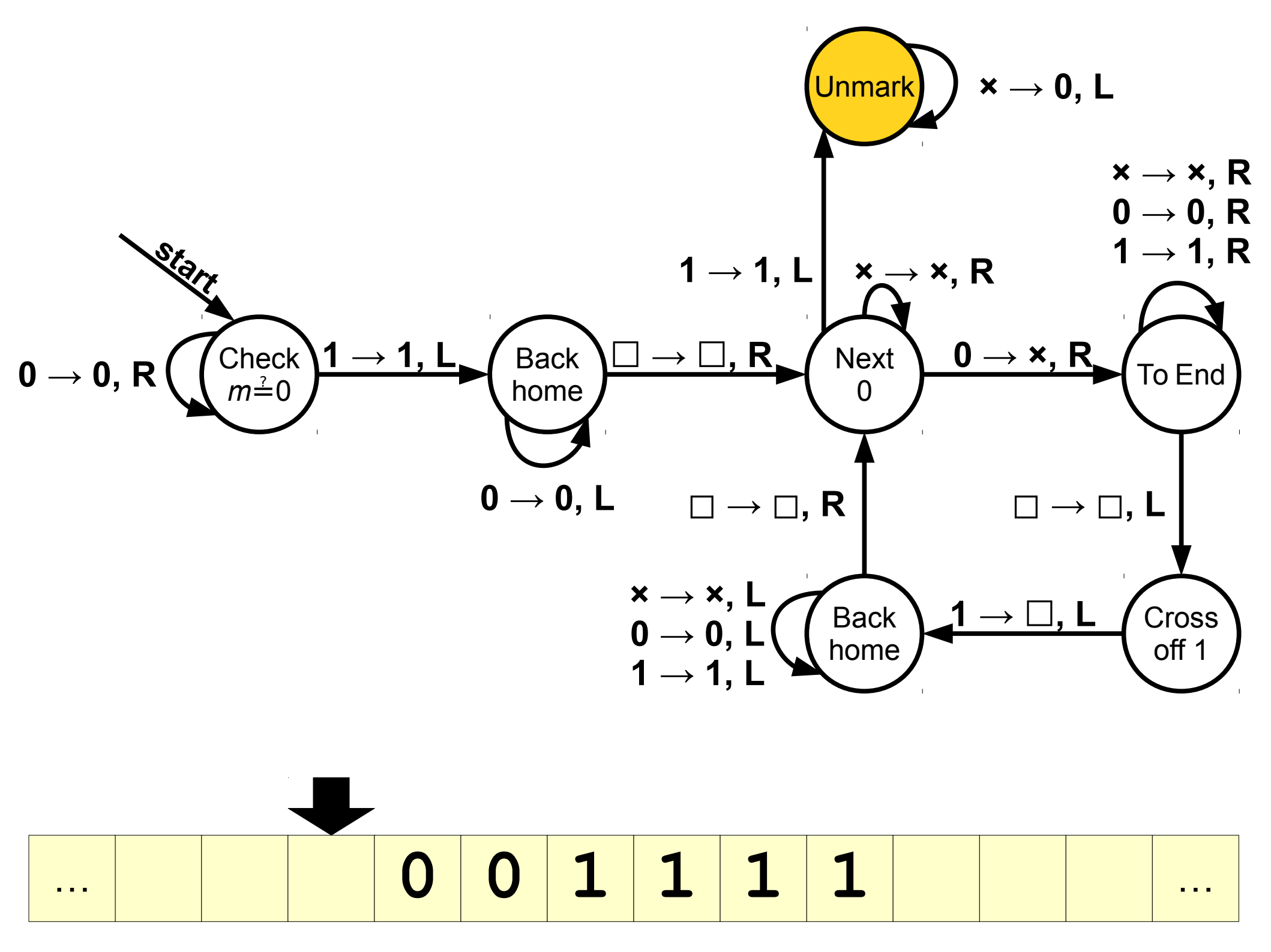

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
1 → 1, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 …

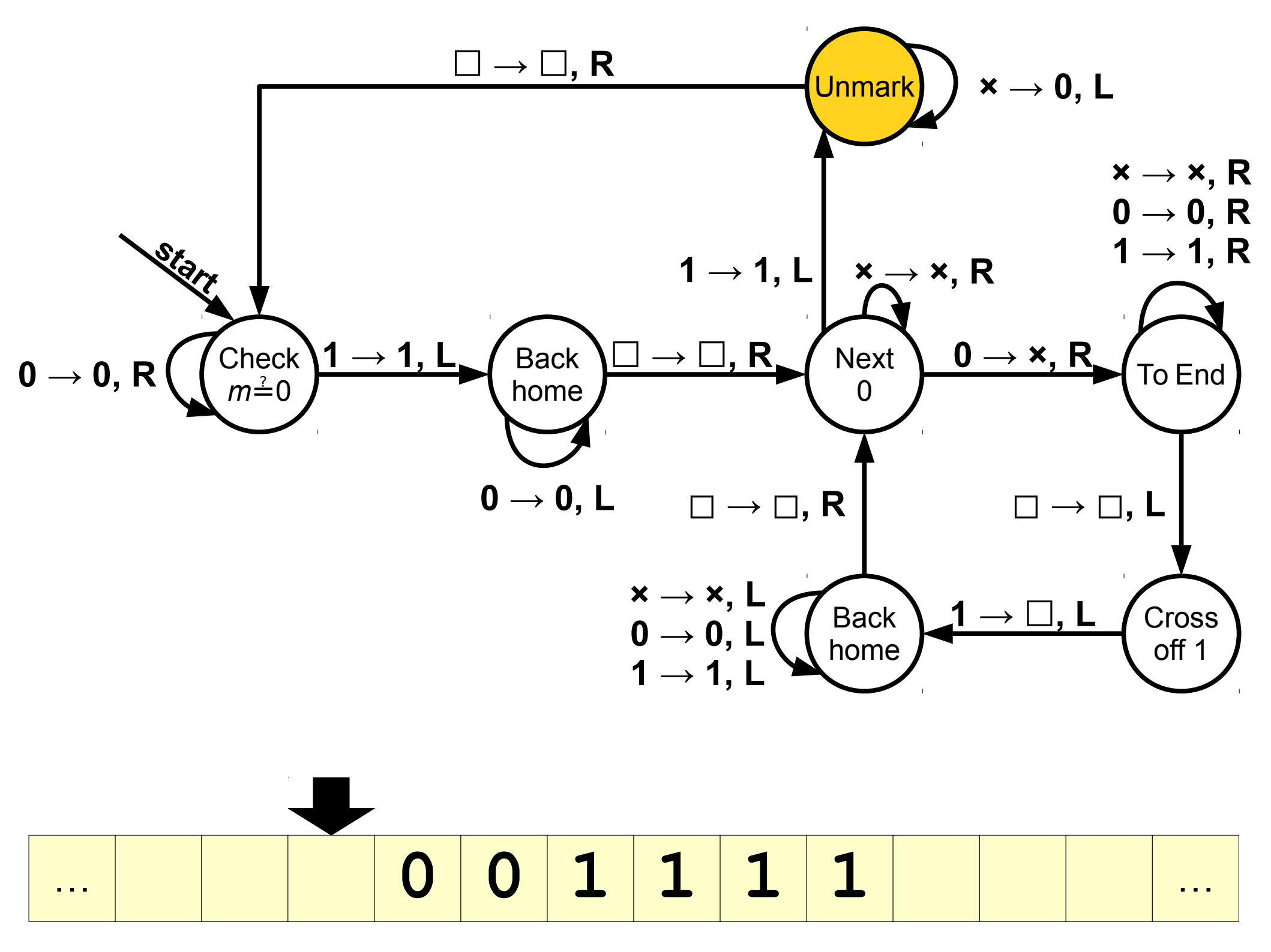

start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
1 → 1, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 …

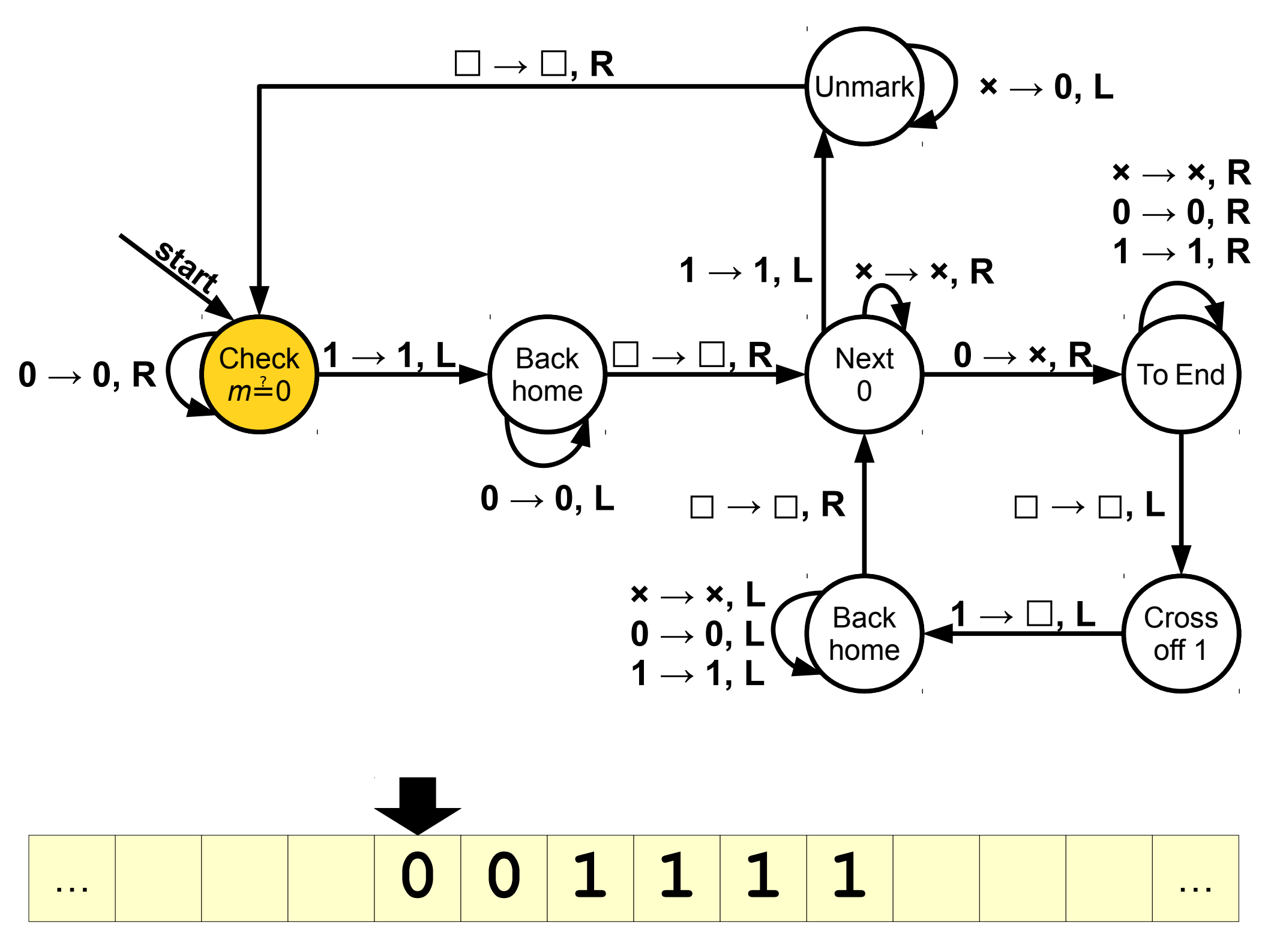

Unmark
start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
1 → 1, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 1 1 …


Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m=?0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 1 1 …


Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
1
1
1
…


Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… 0 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0 0 1 1 1 1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
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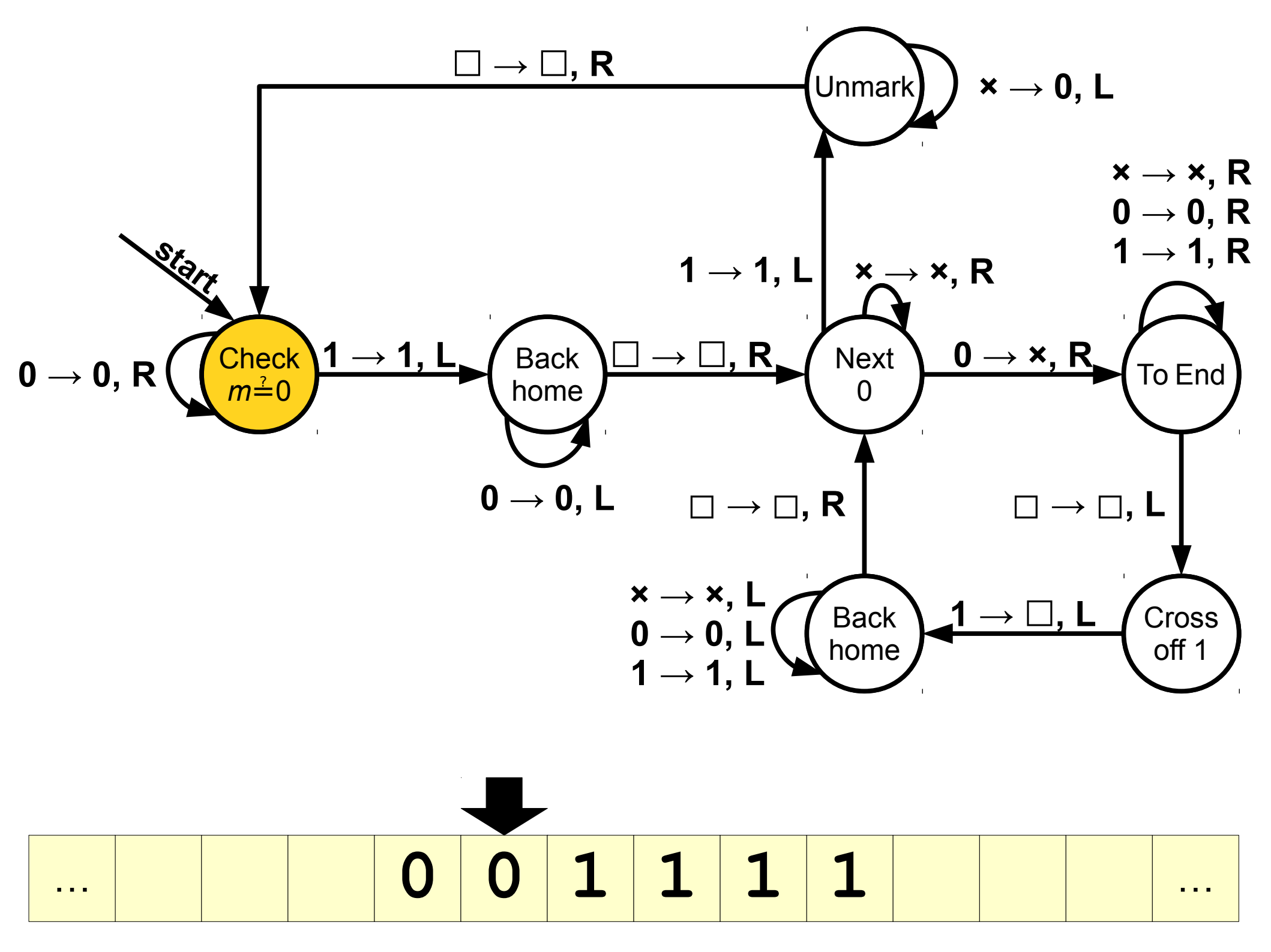
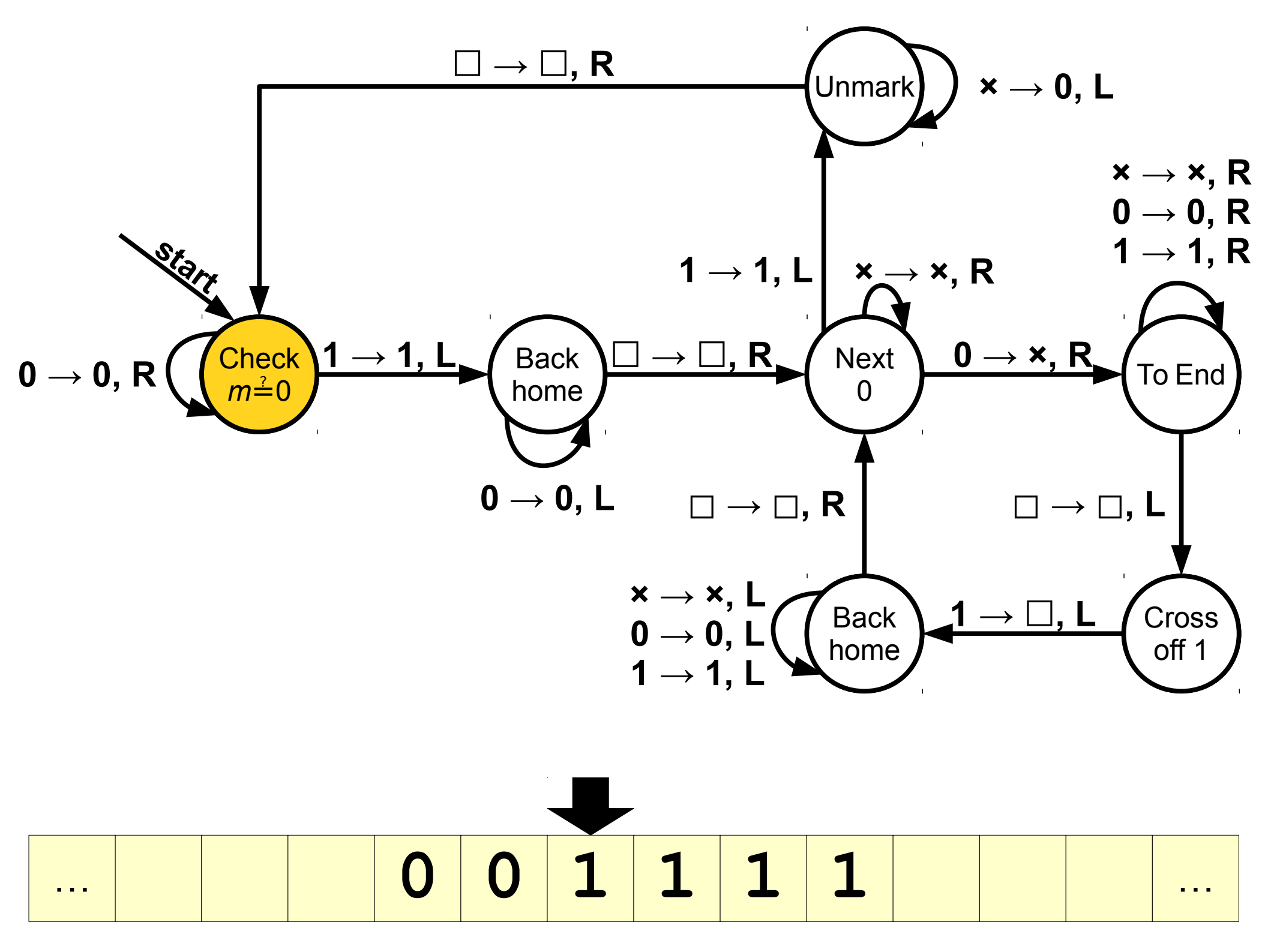
1
1
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0 0 1 1 1 1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
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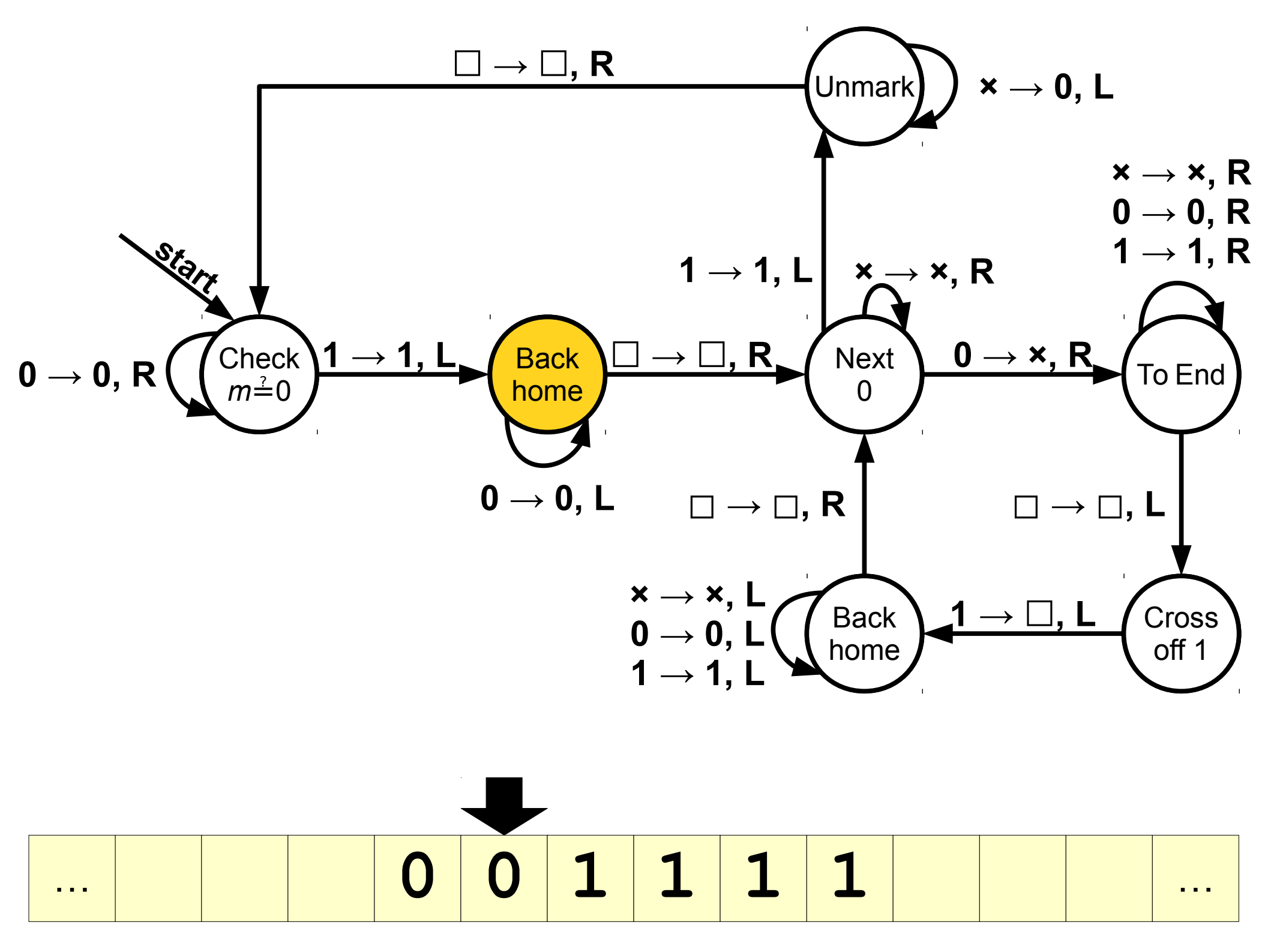
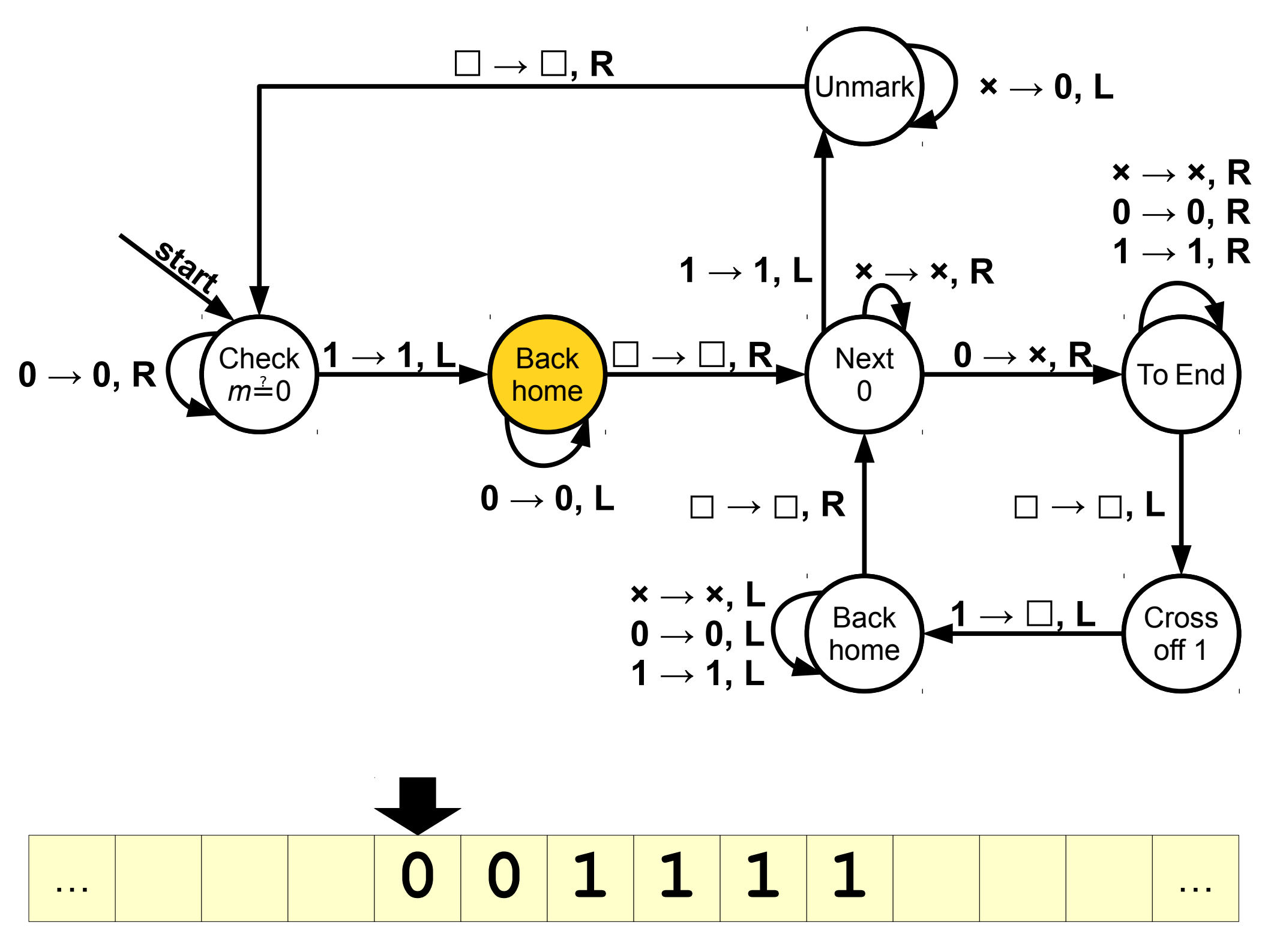
1
1
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0 0 1 1 1 1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
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0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
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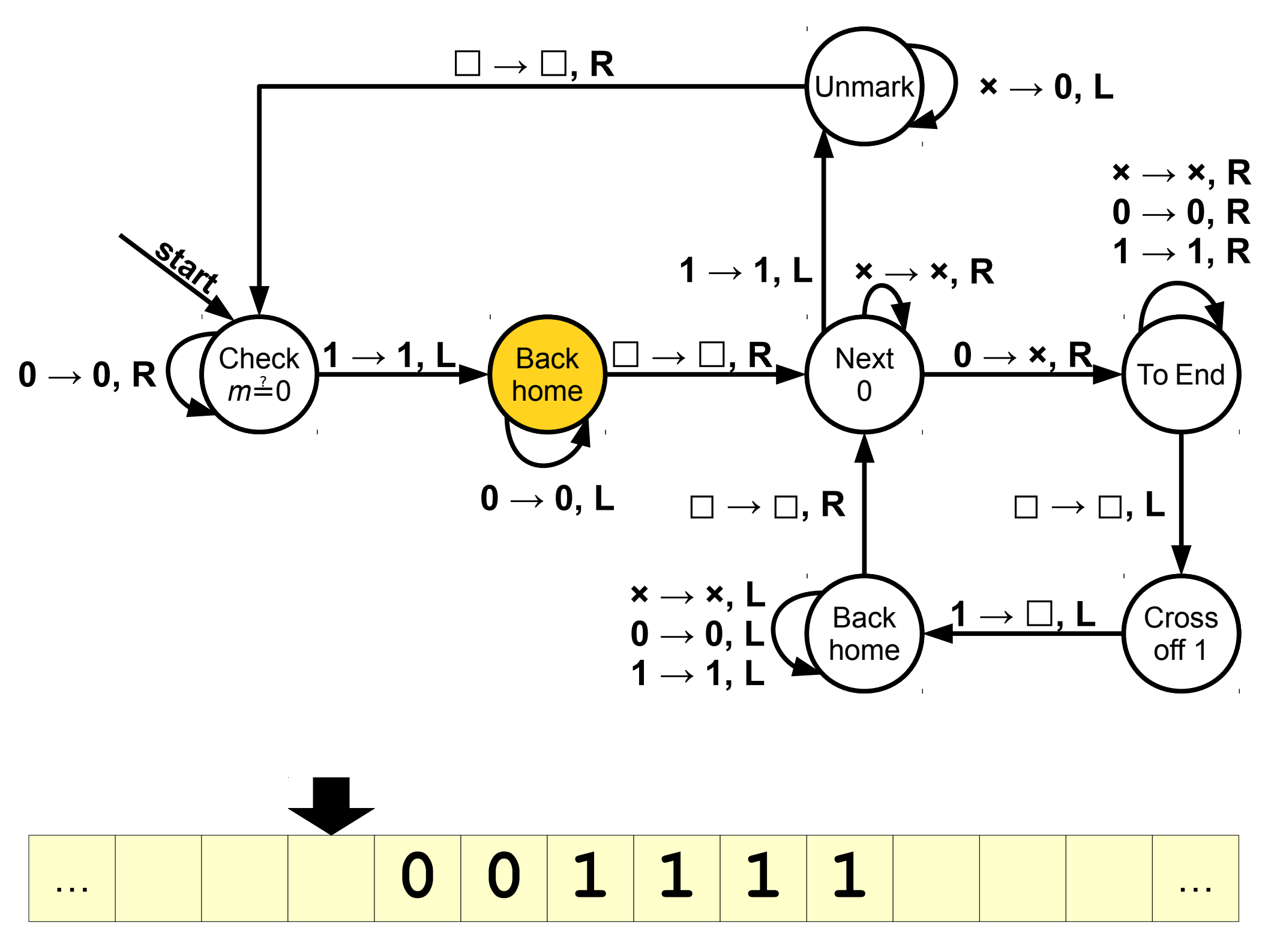
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
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1
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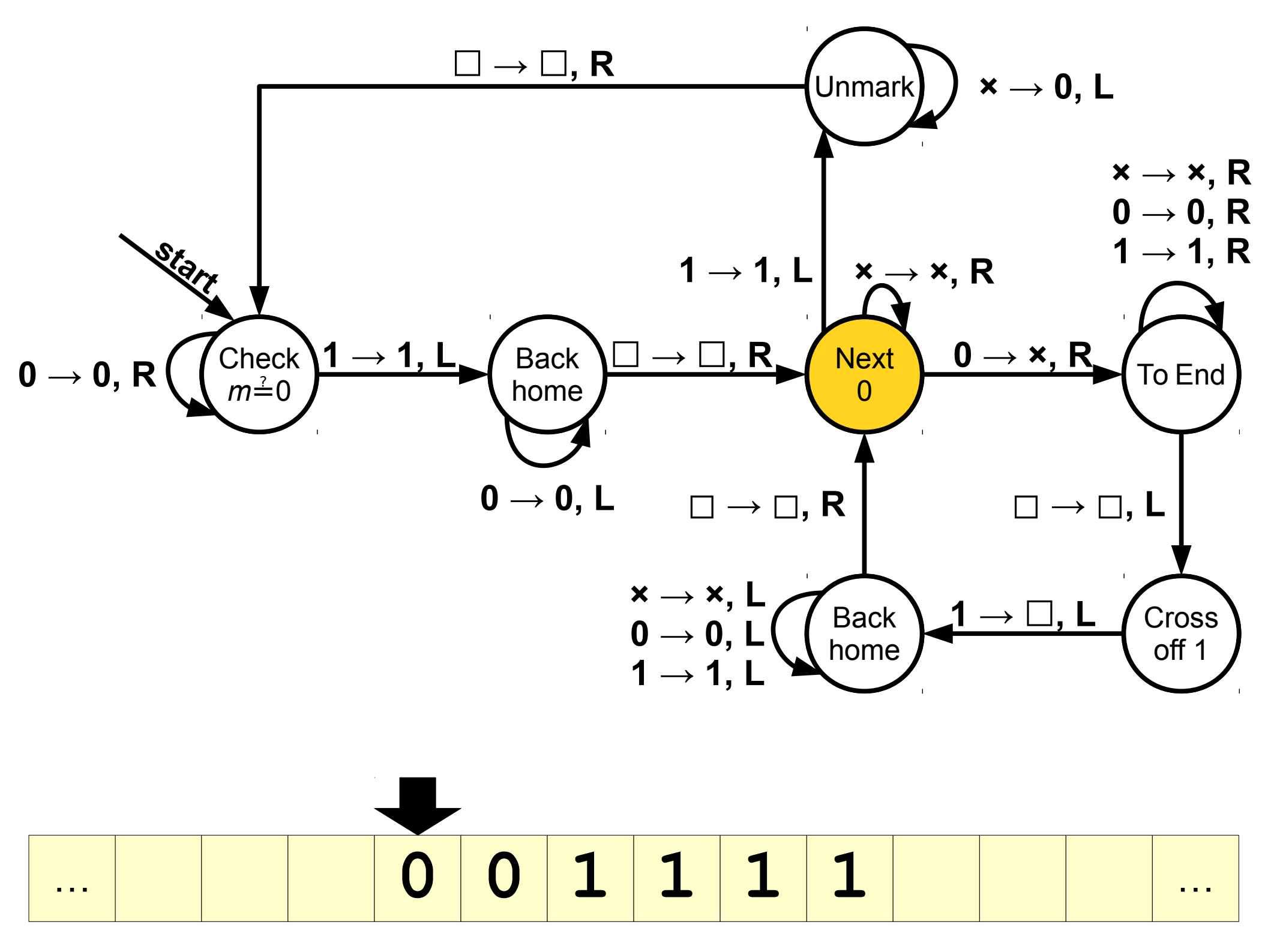
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
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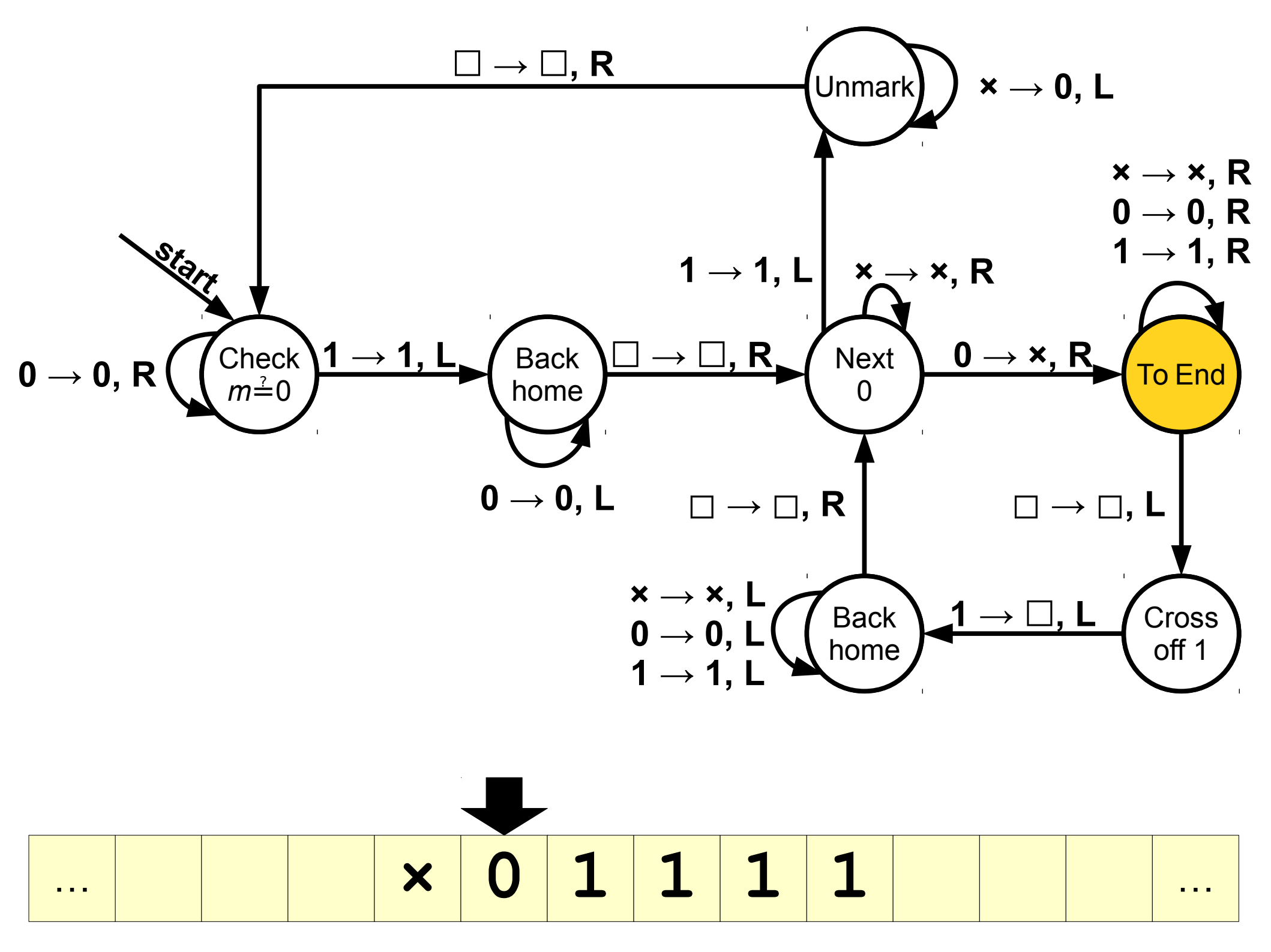
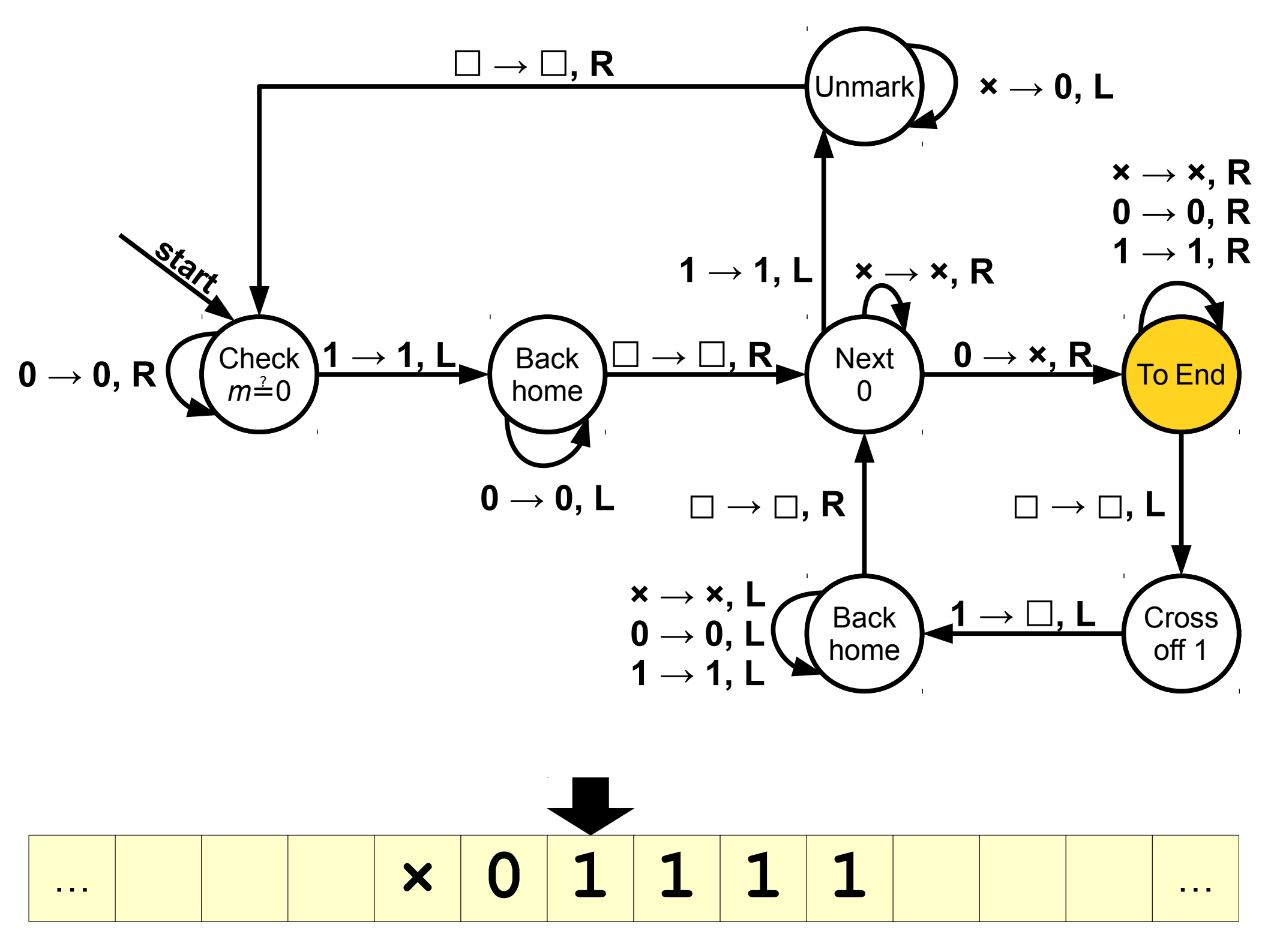
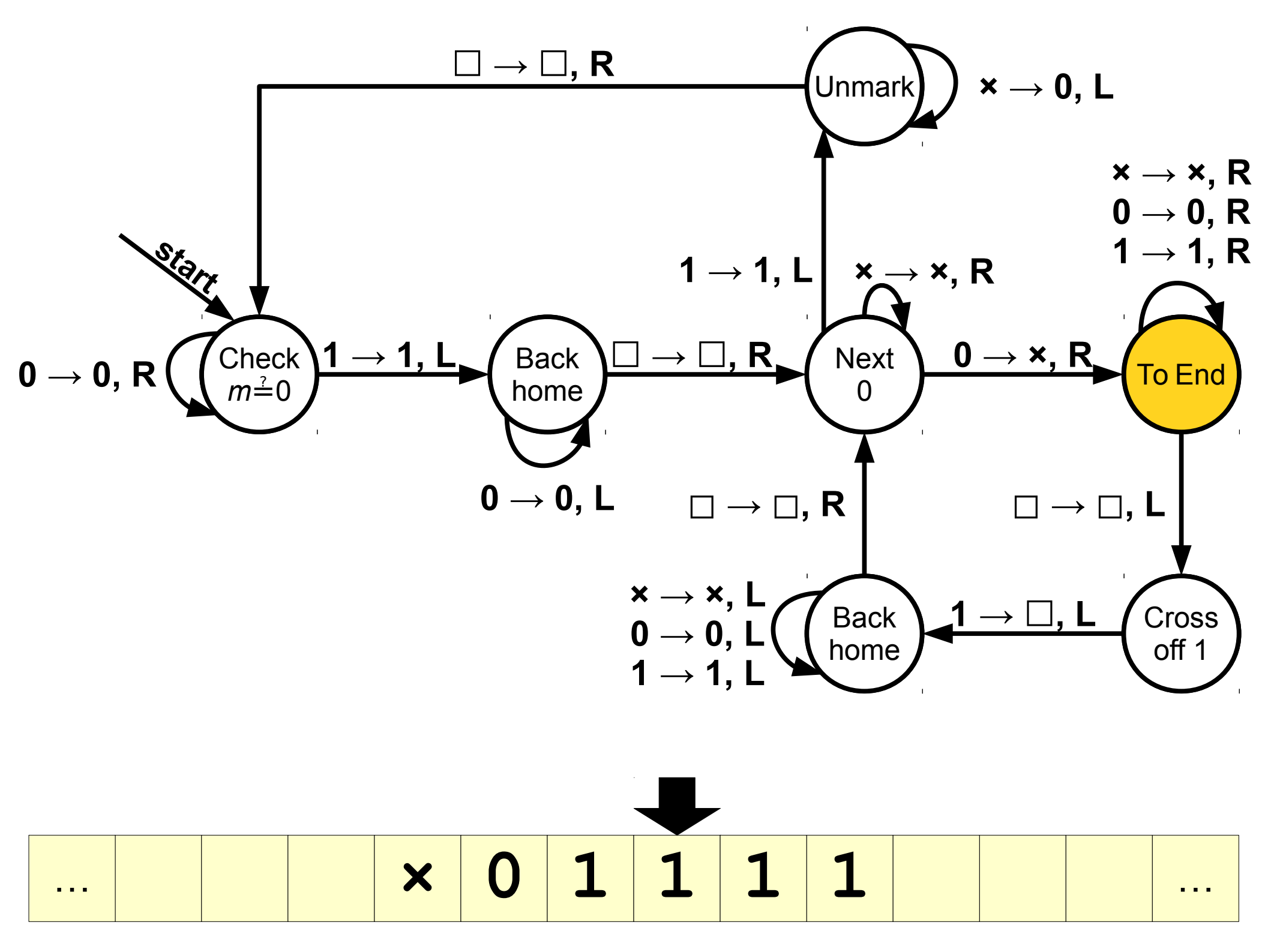
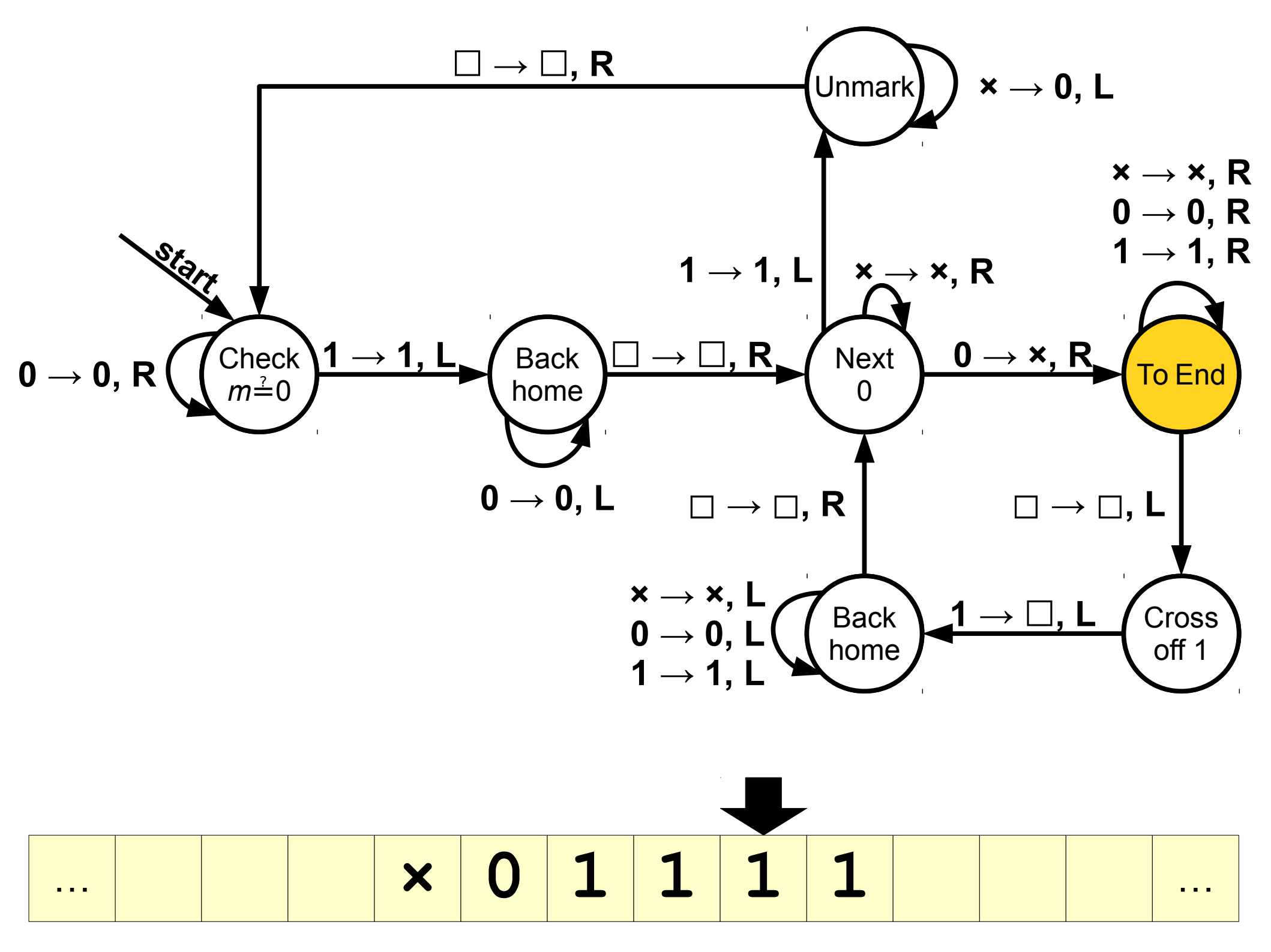
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
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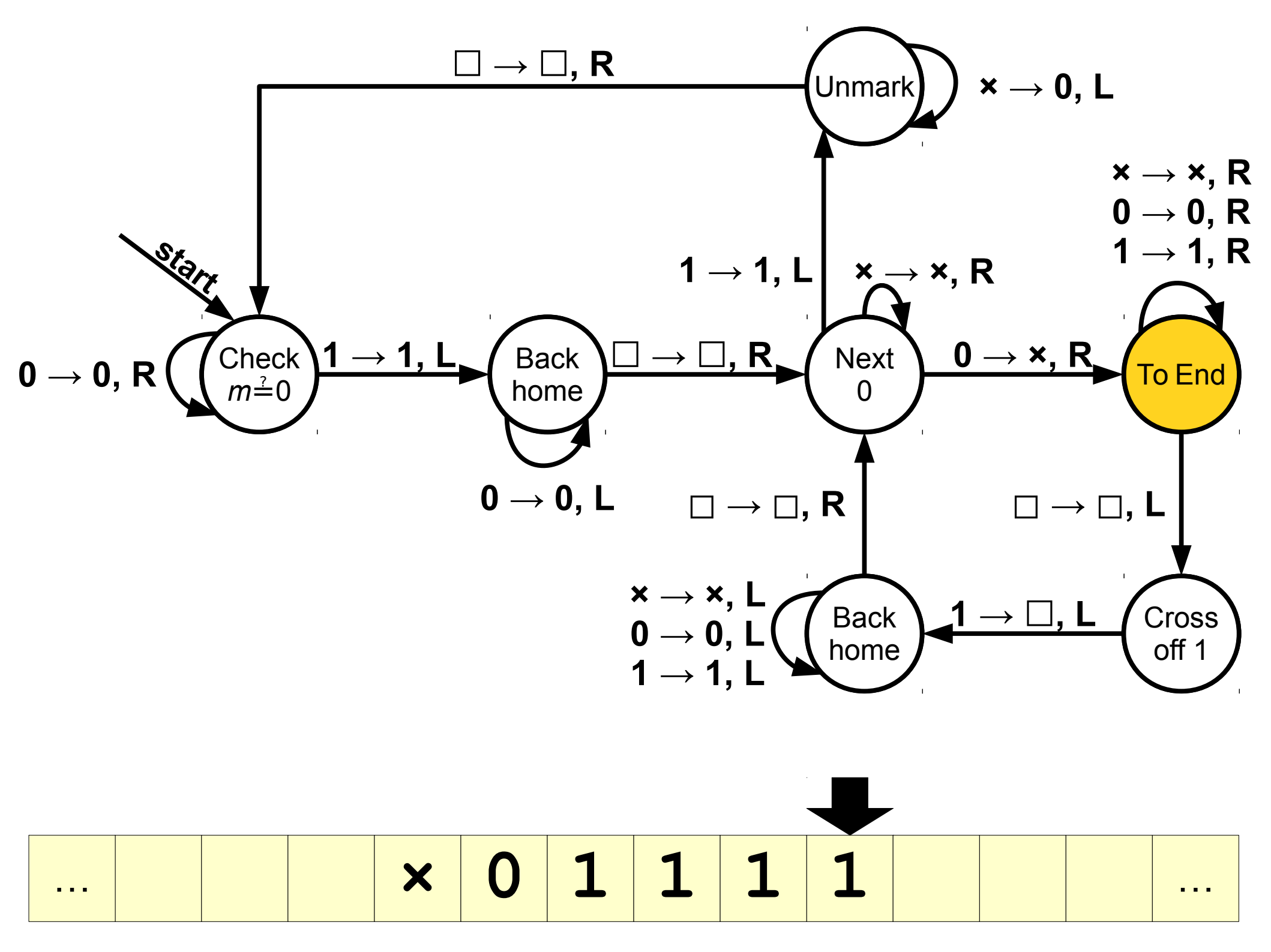
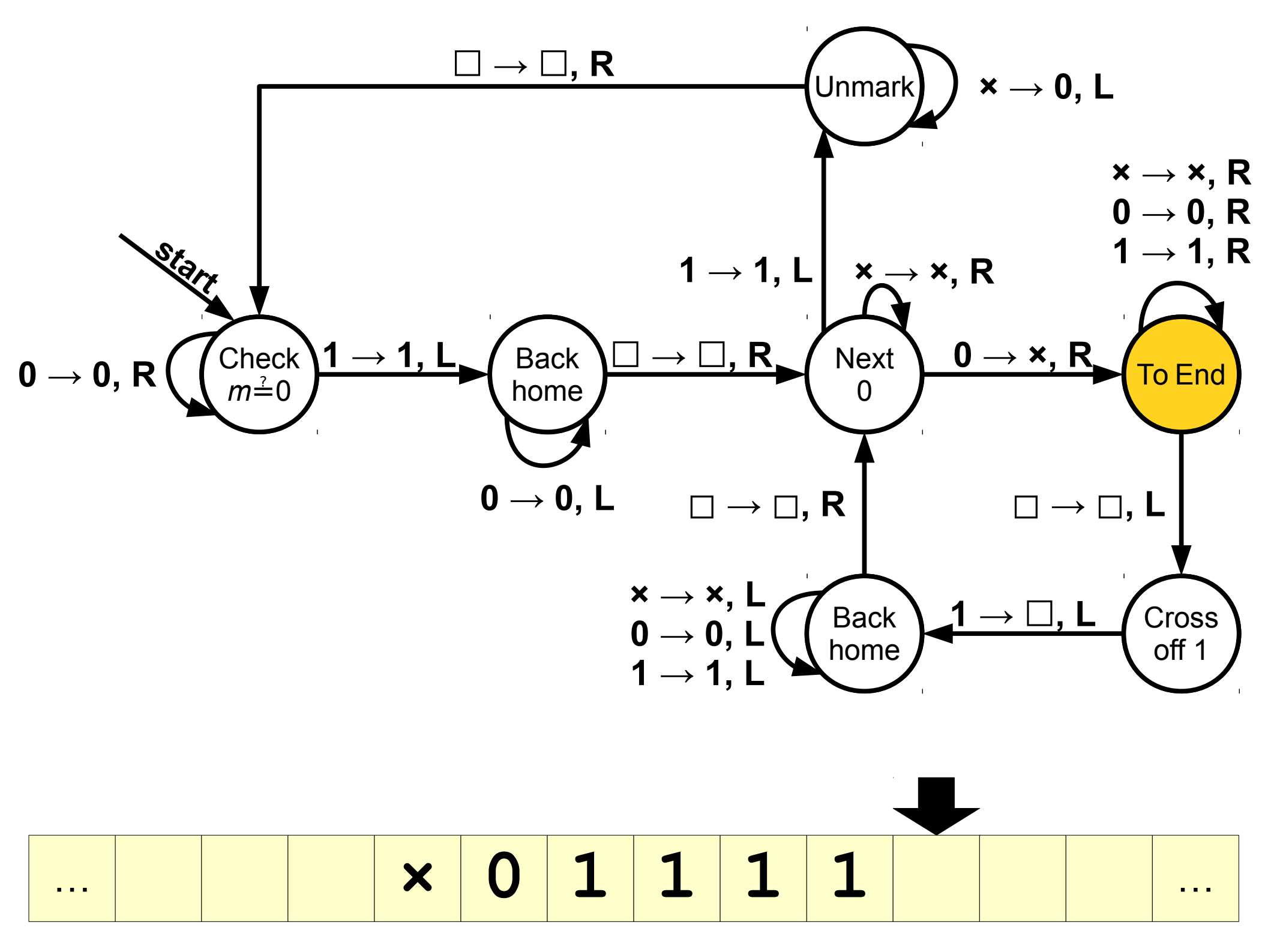
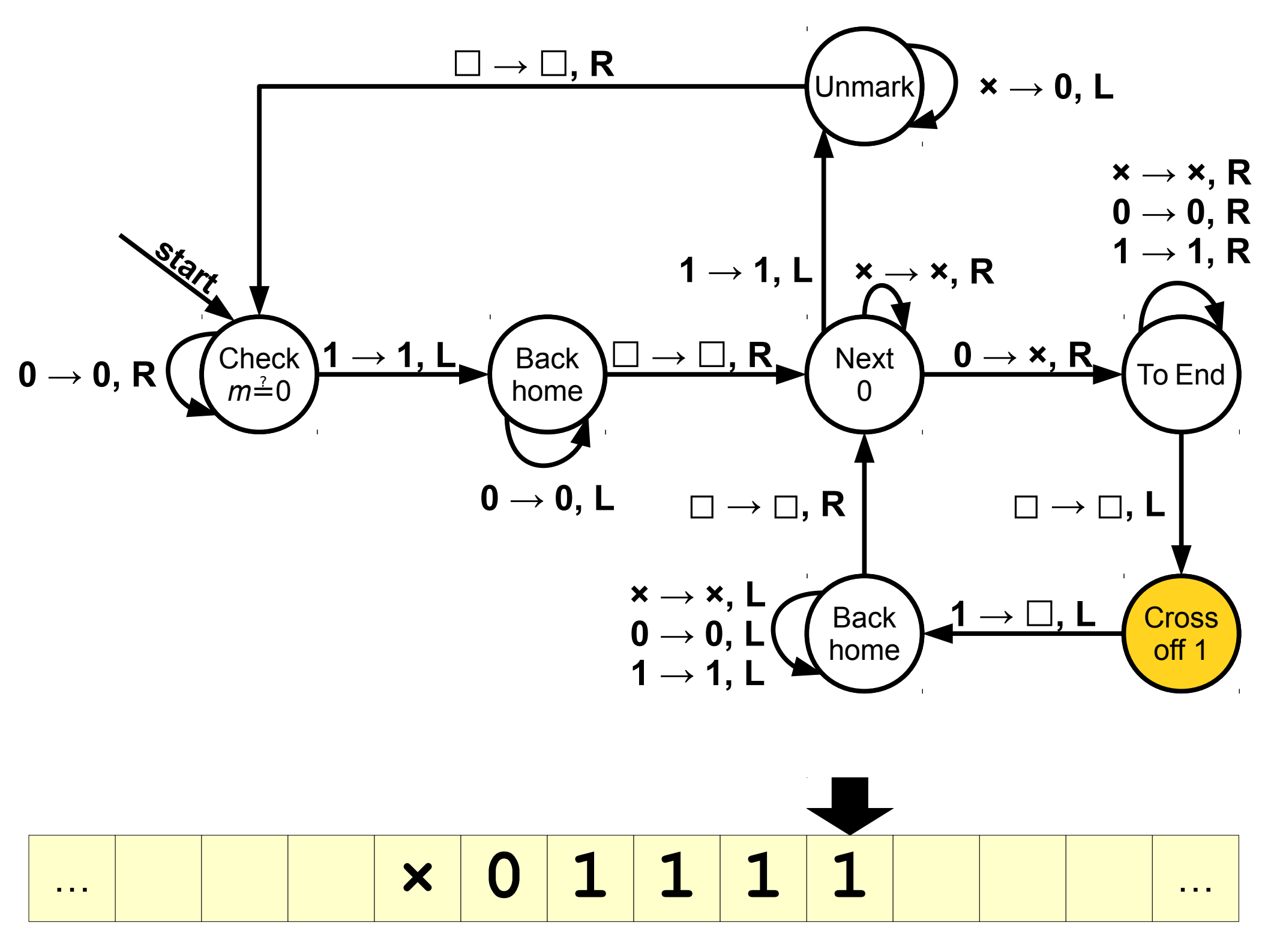
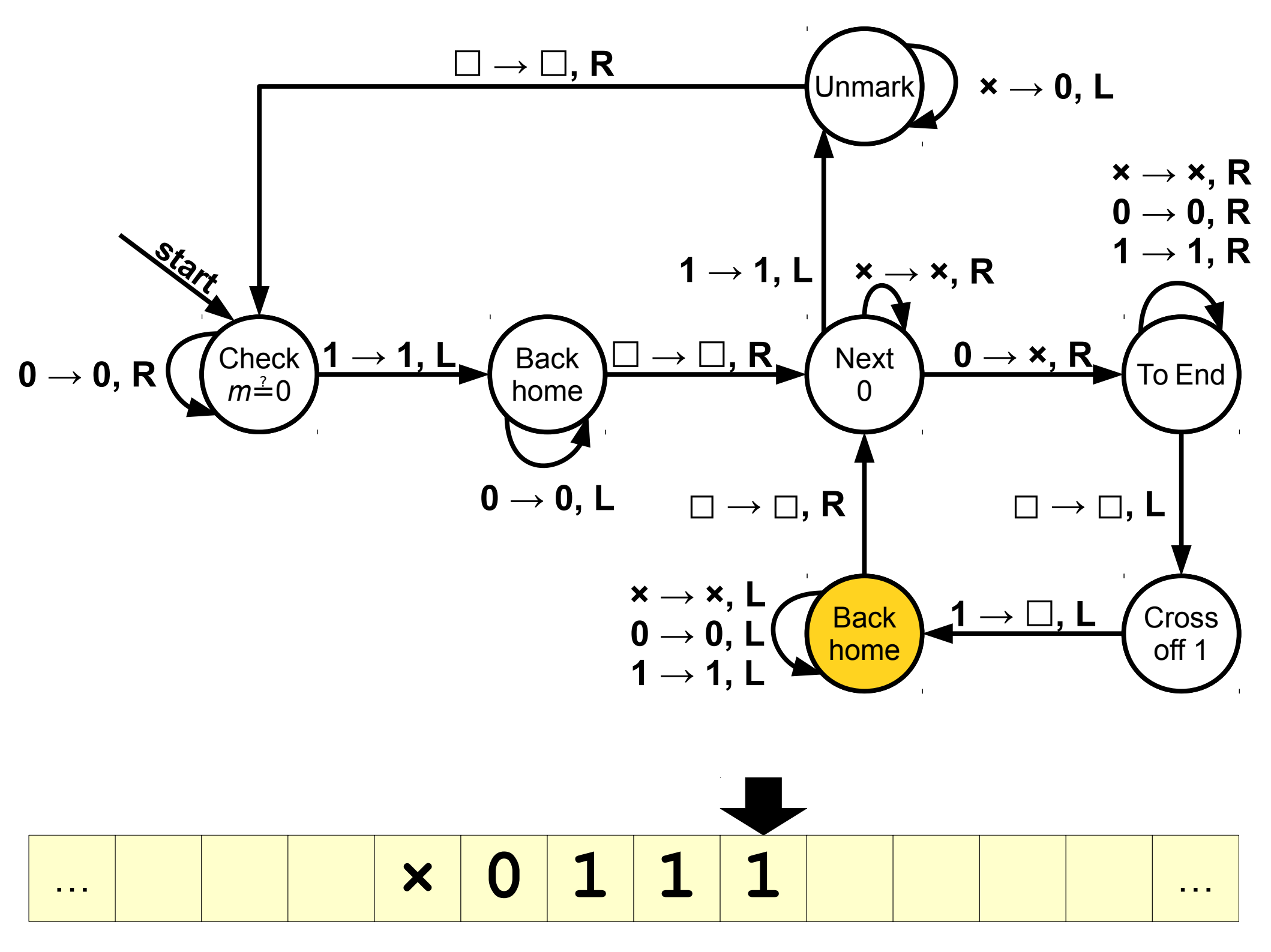
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
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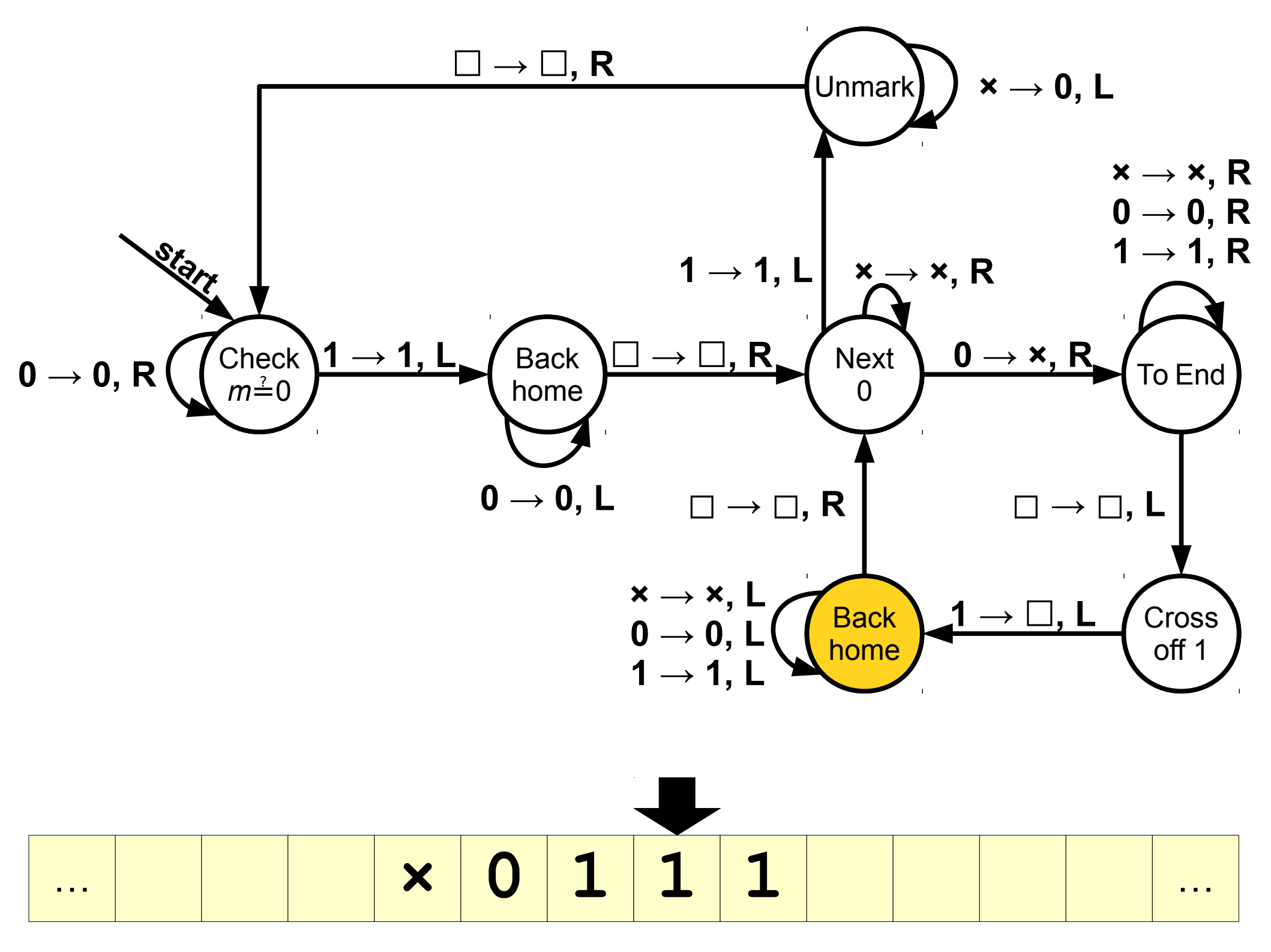
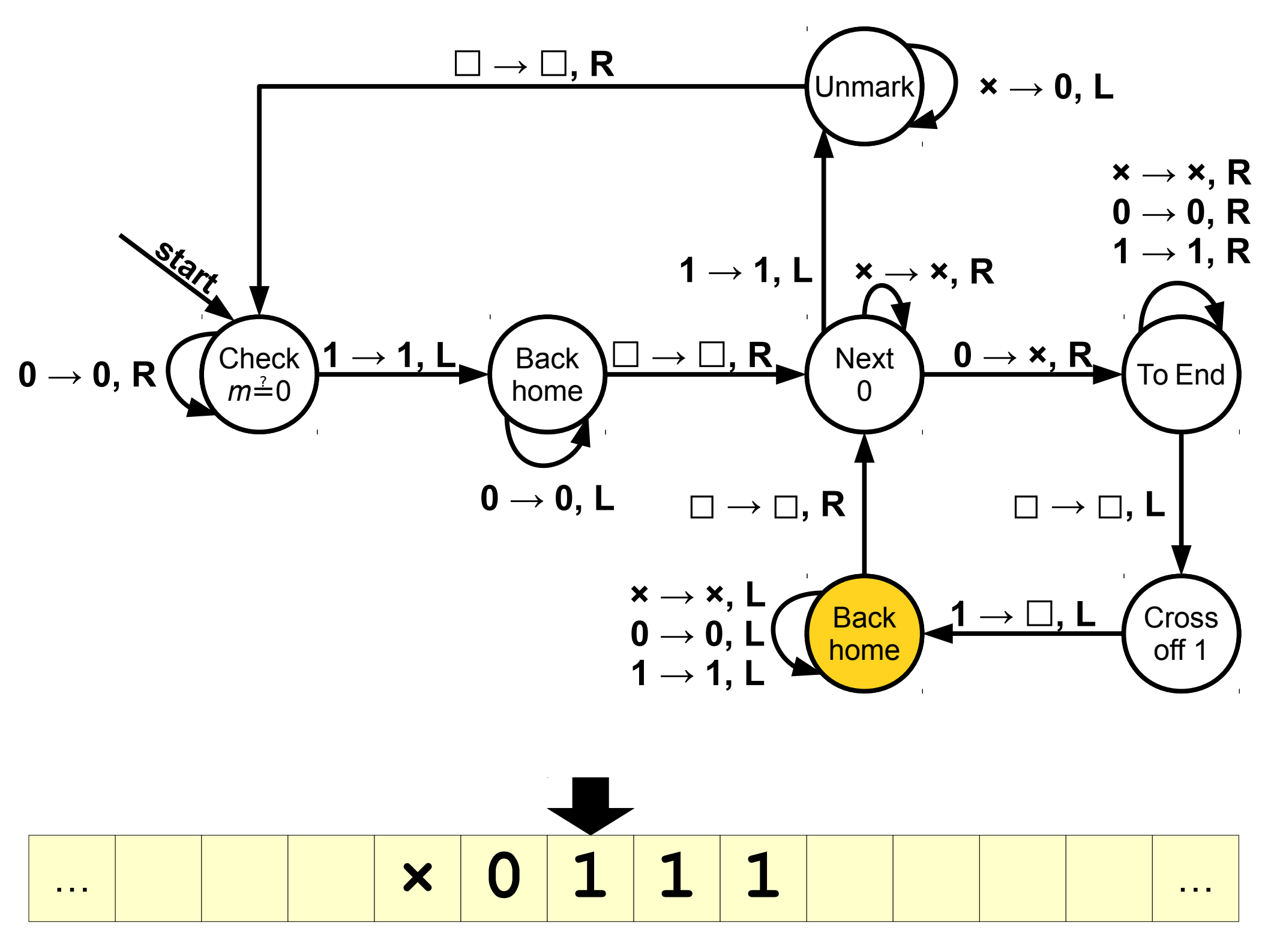
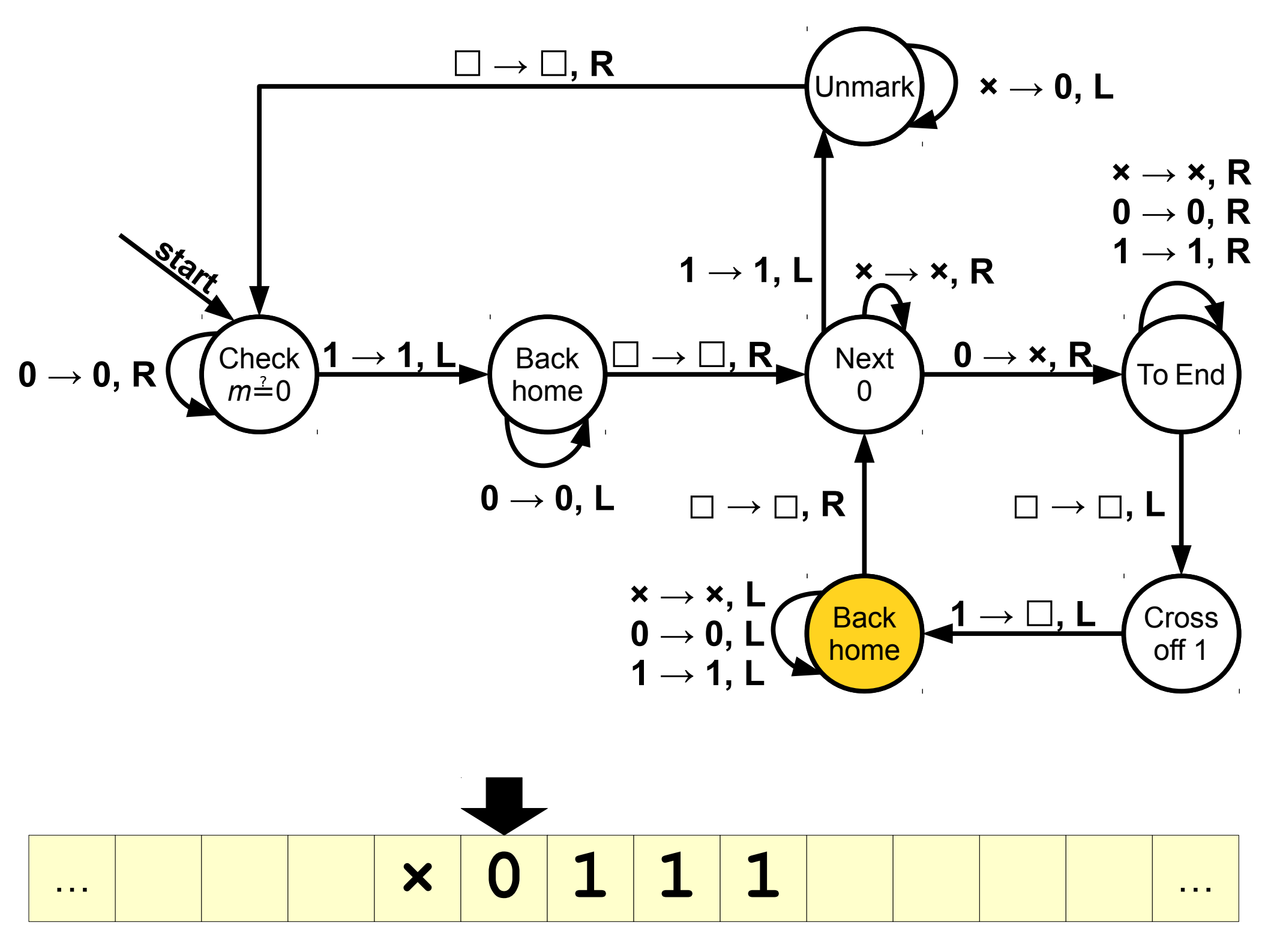
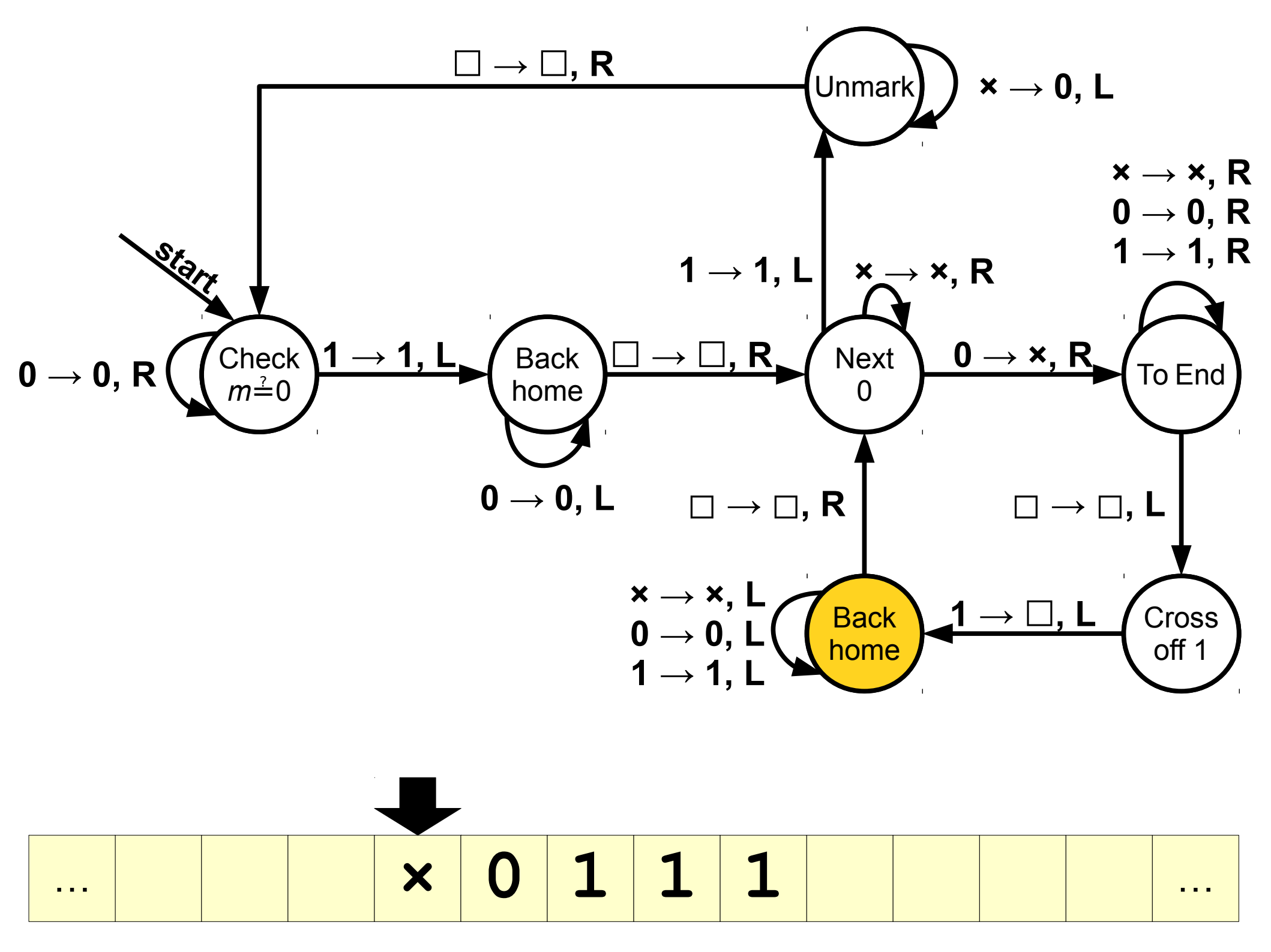
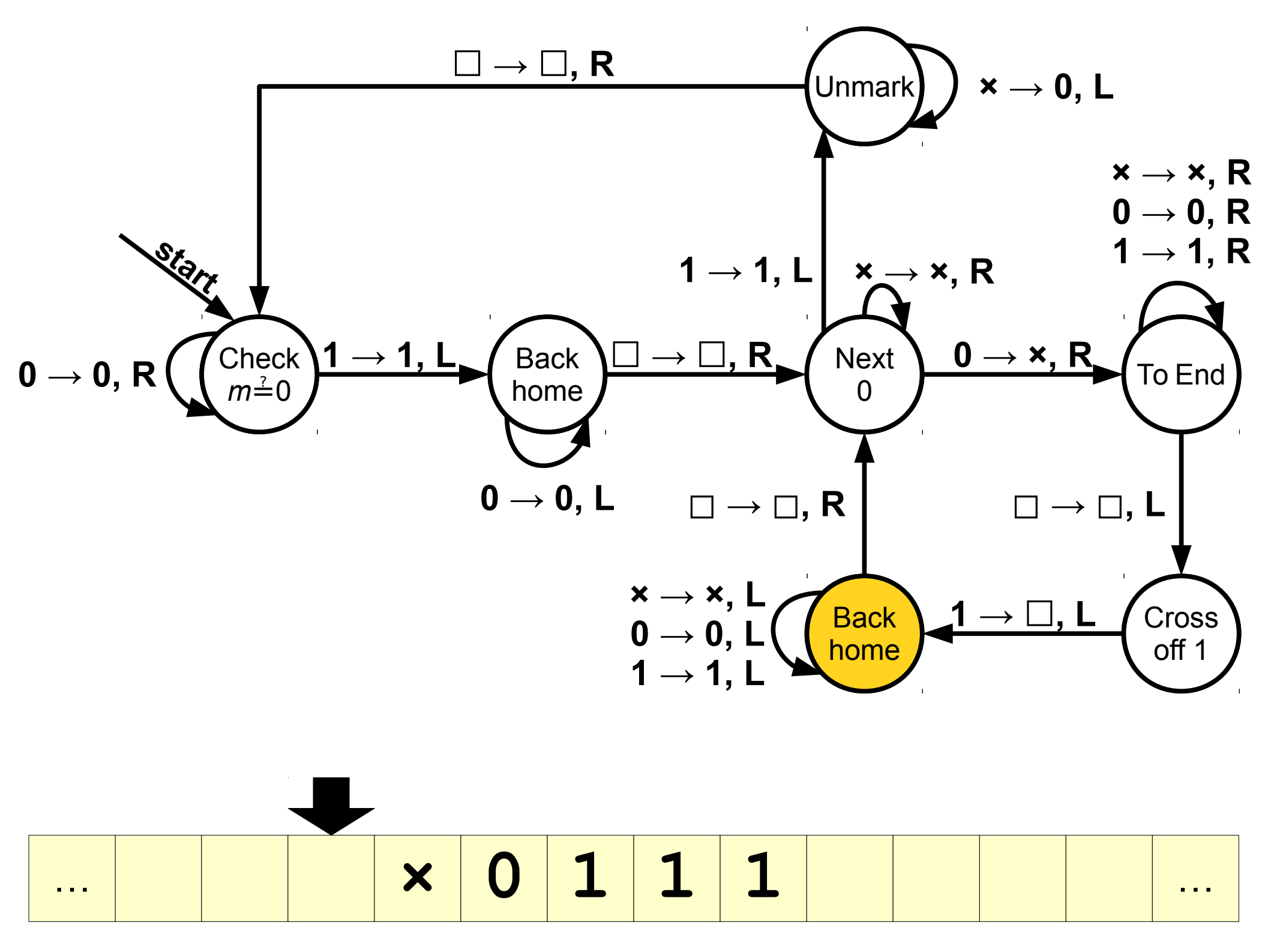
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
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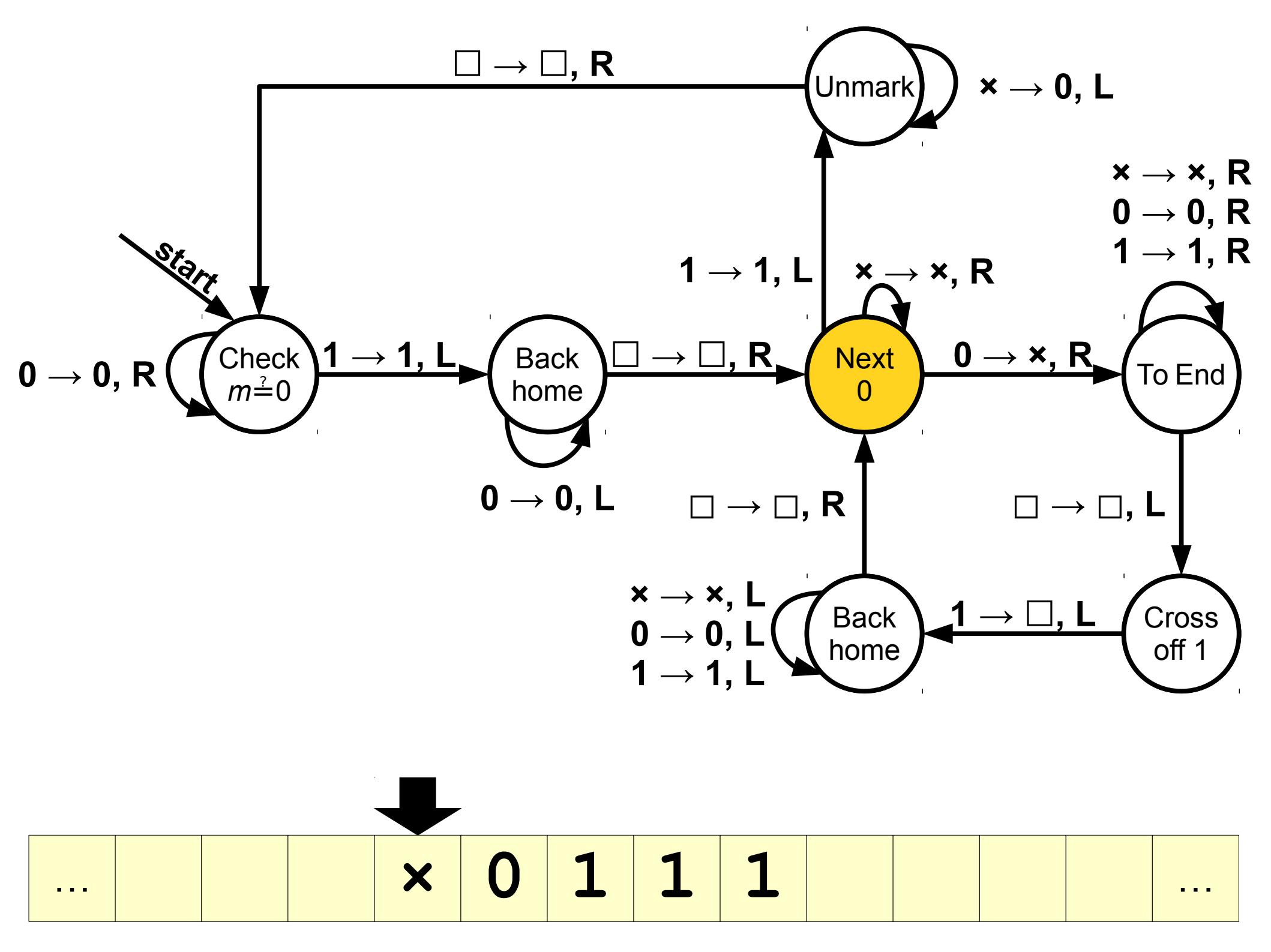
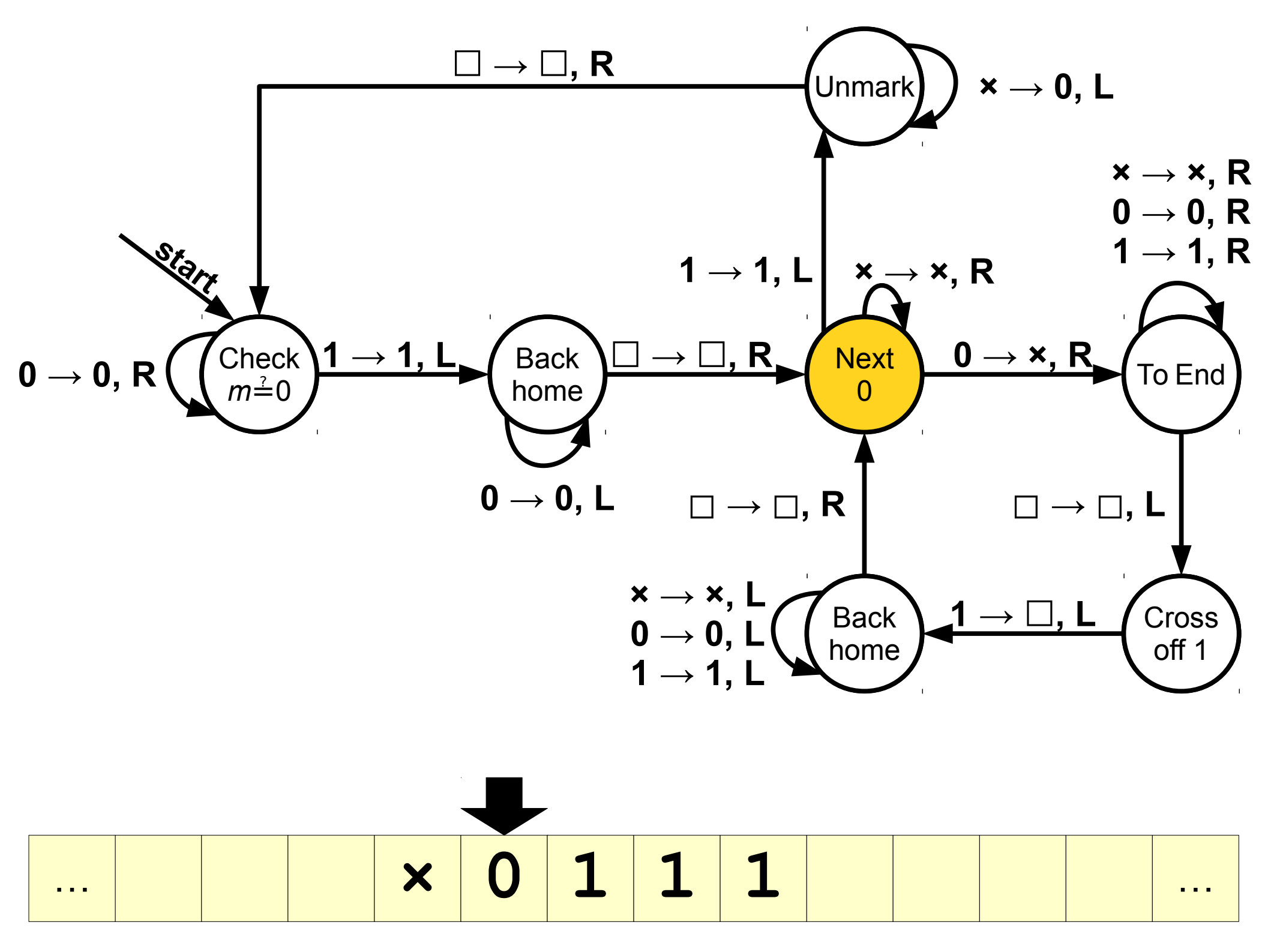
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
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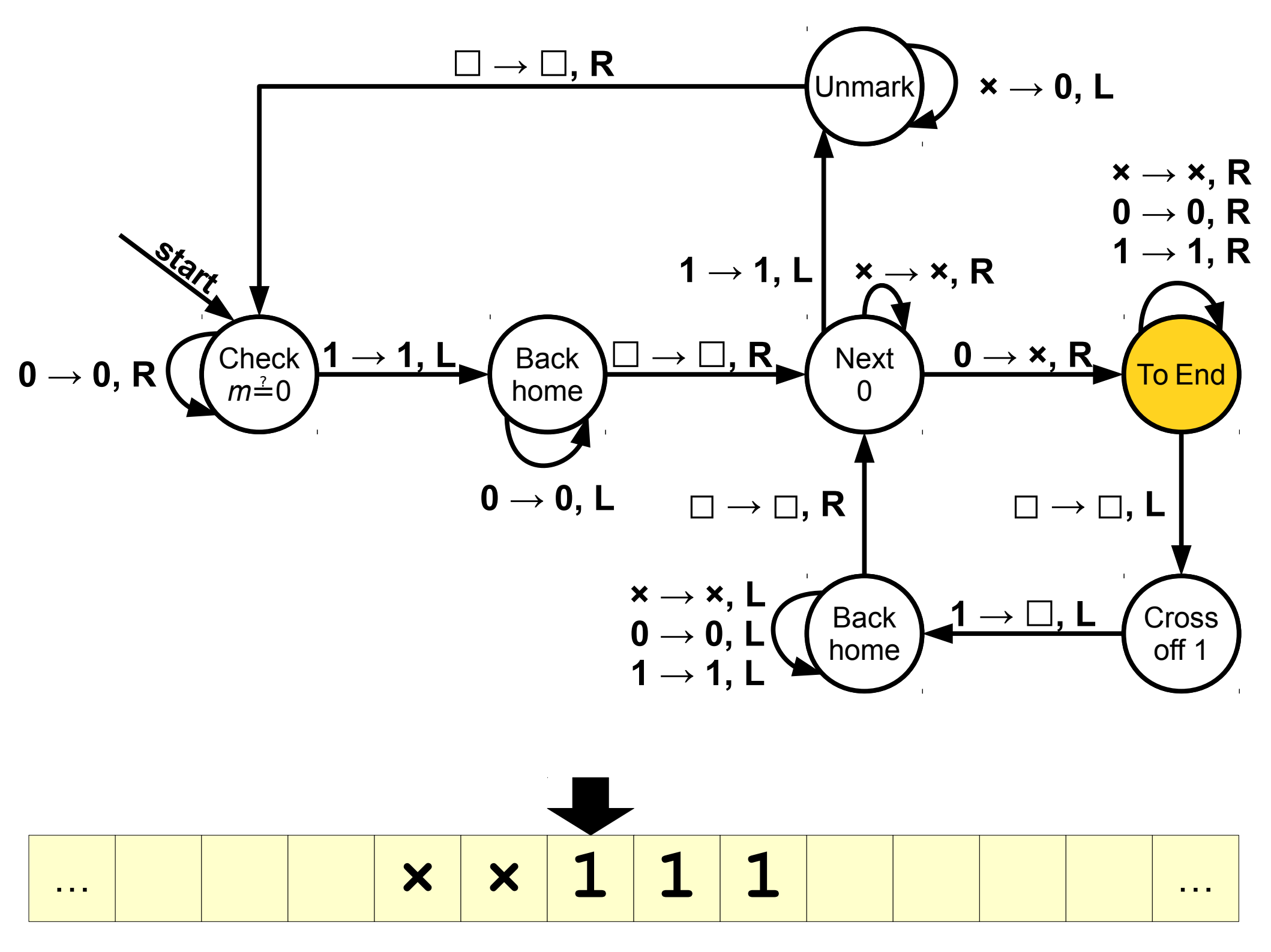
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
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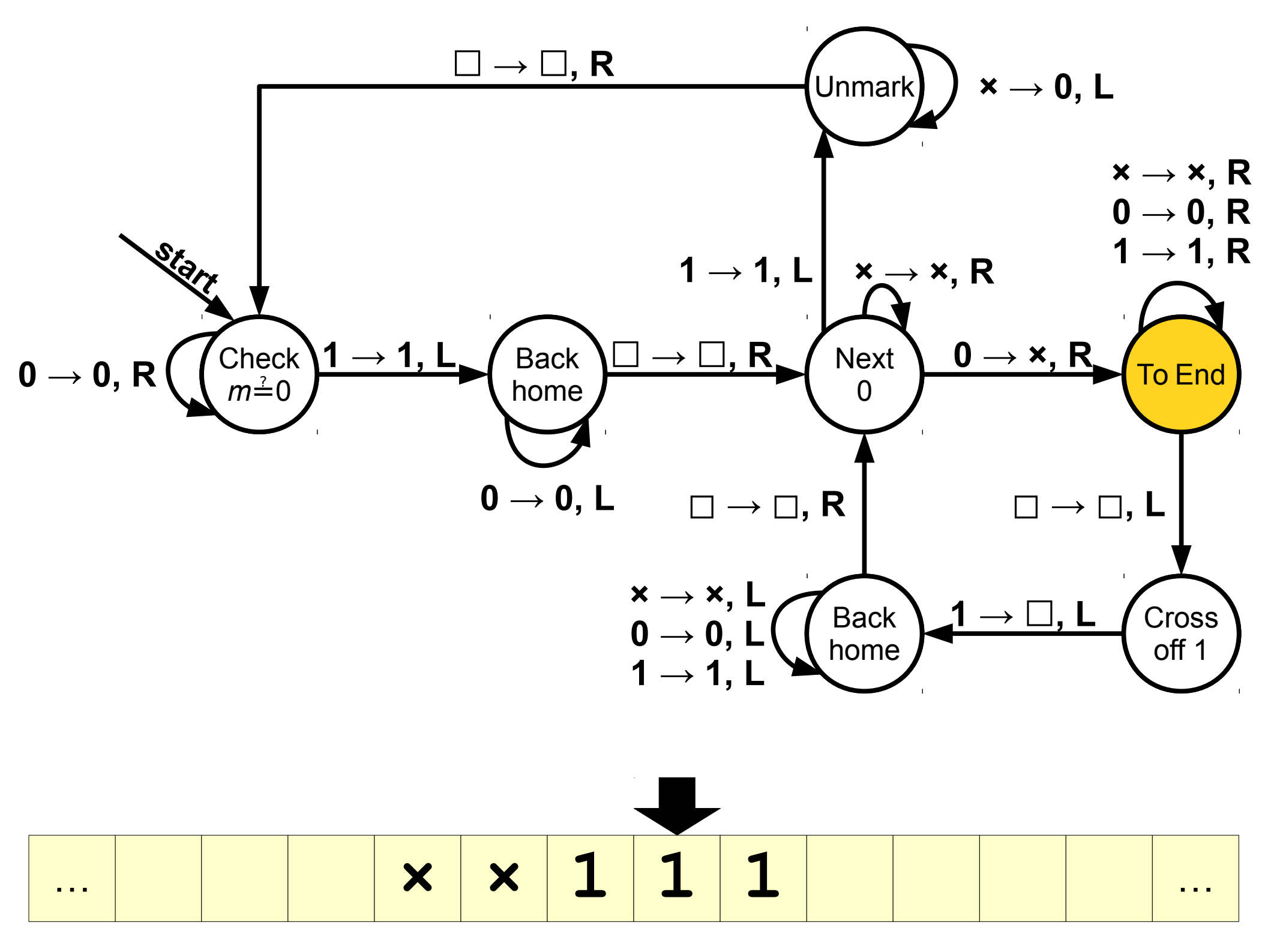
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
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home
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To End
0 → 0, L
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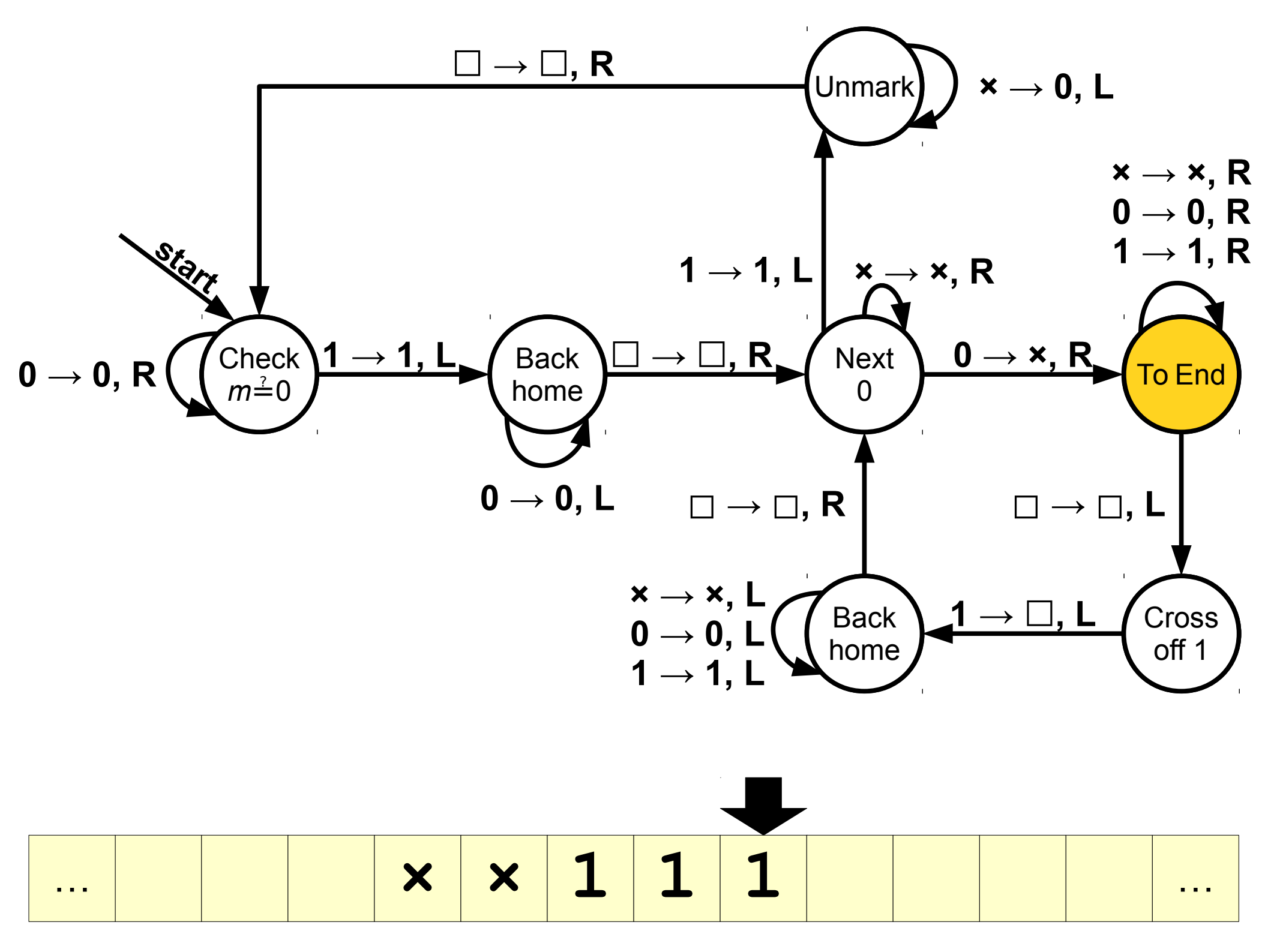
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
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Check
m≟0
0 → 0, R
1 → 1, L
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home
□ → □, R
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To End
0 → 0, L
□ → □, R
□ → □, L
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1 → 1, L
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home
1 → □, L
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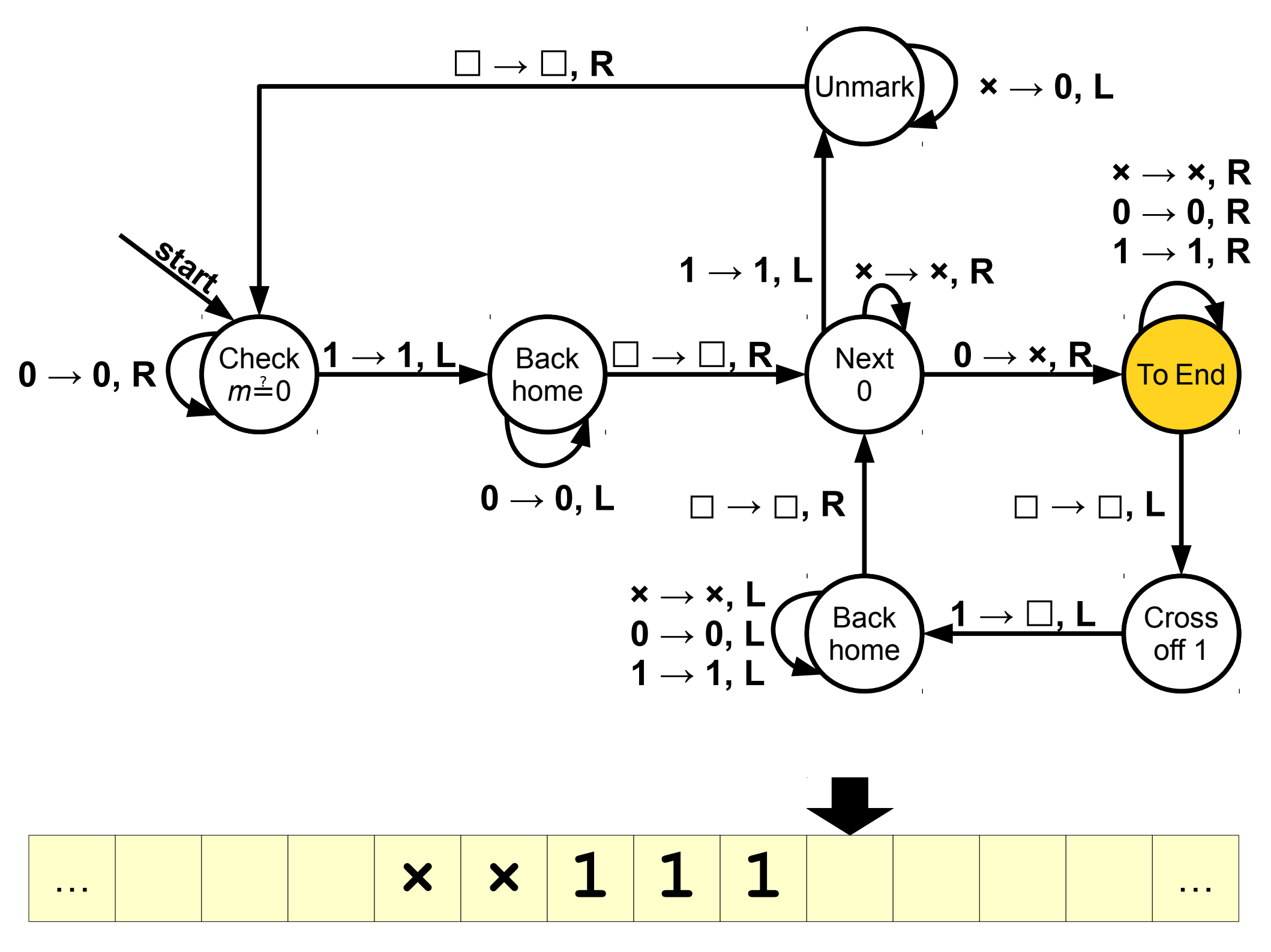
off 1
… × × 1 1 1 …


□ → □, R
Unmark
× → 0, L
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0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
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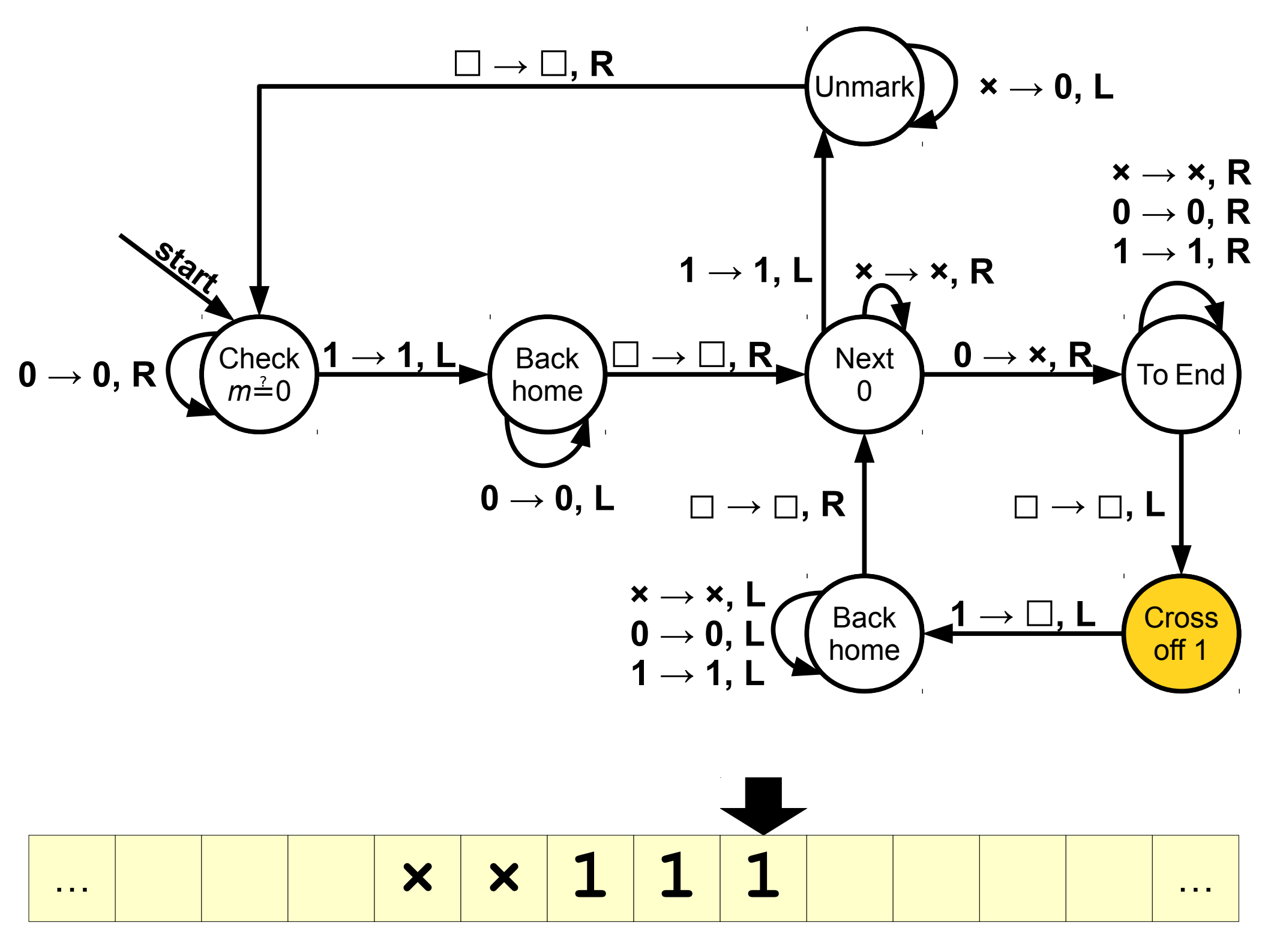
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 1 …


□ → □, R
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× → 0, L
× → ×, R
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□ → □, R
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Back
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1 → □, L
Cross
off 1
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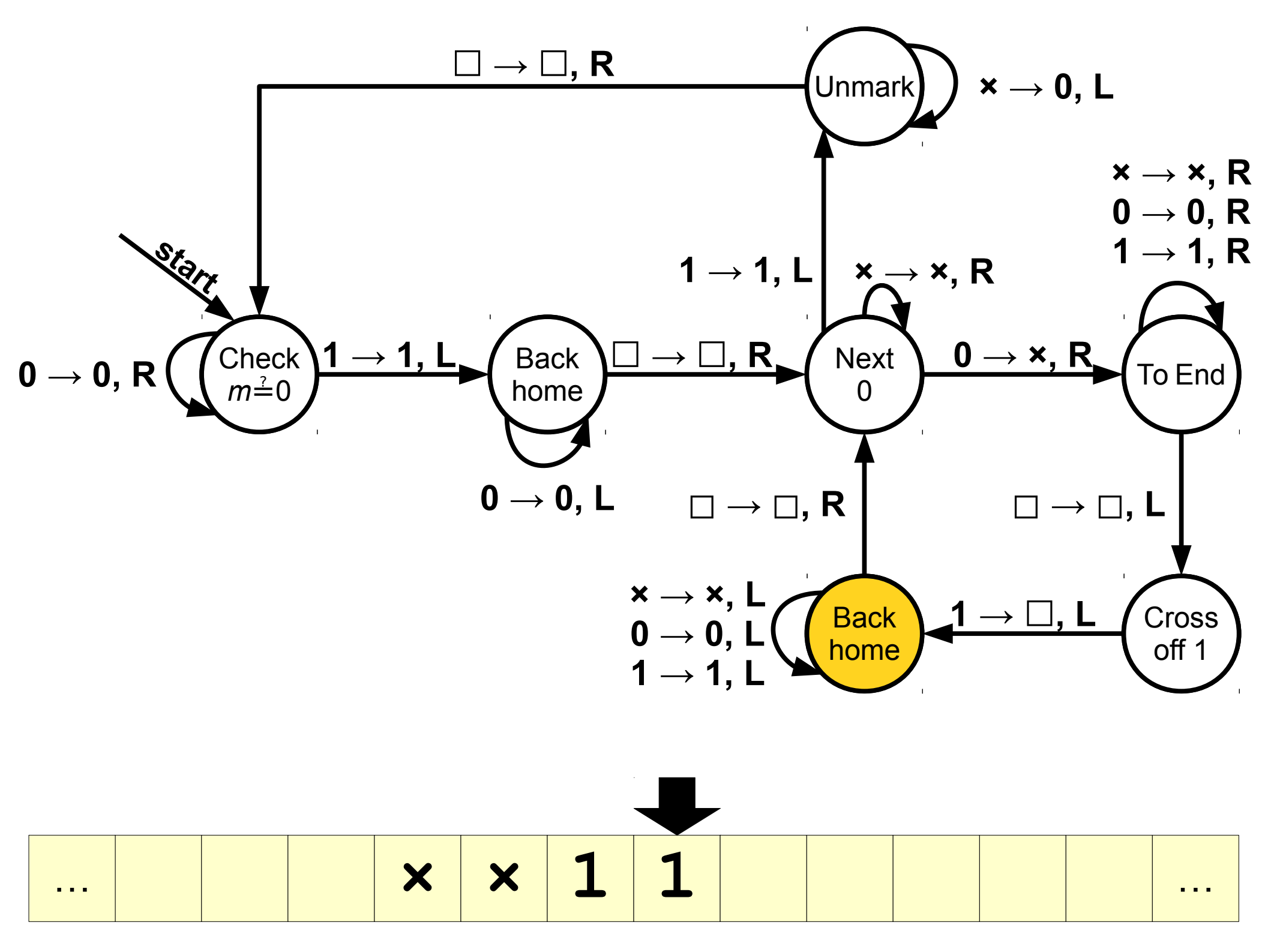
□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
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Check
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To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
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1 → 1, L
Back
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Cross
off 1
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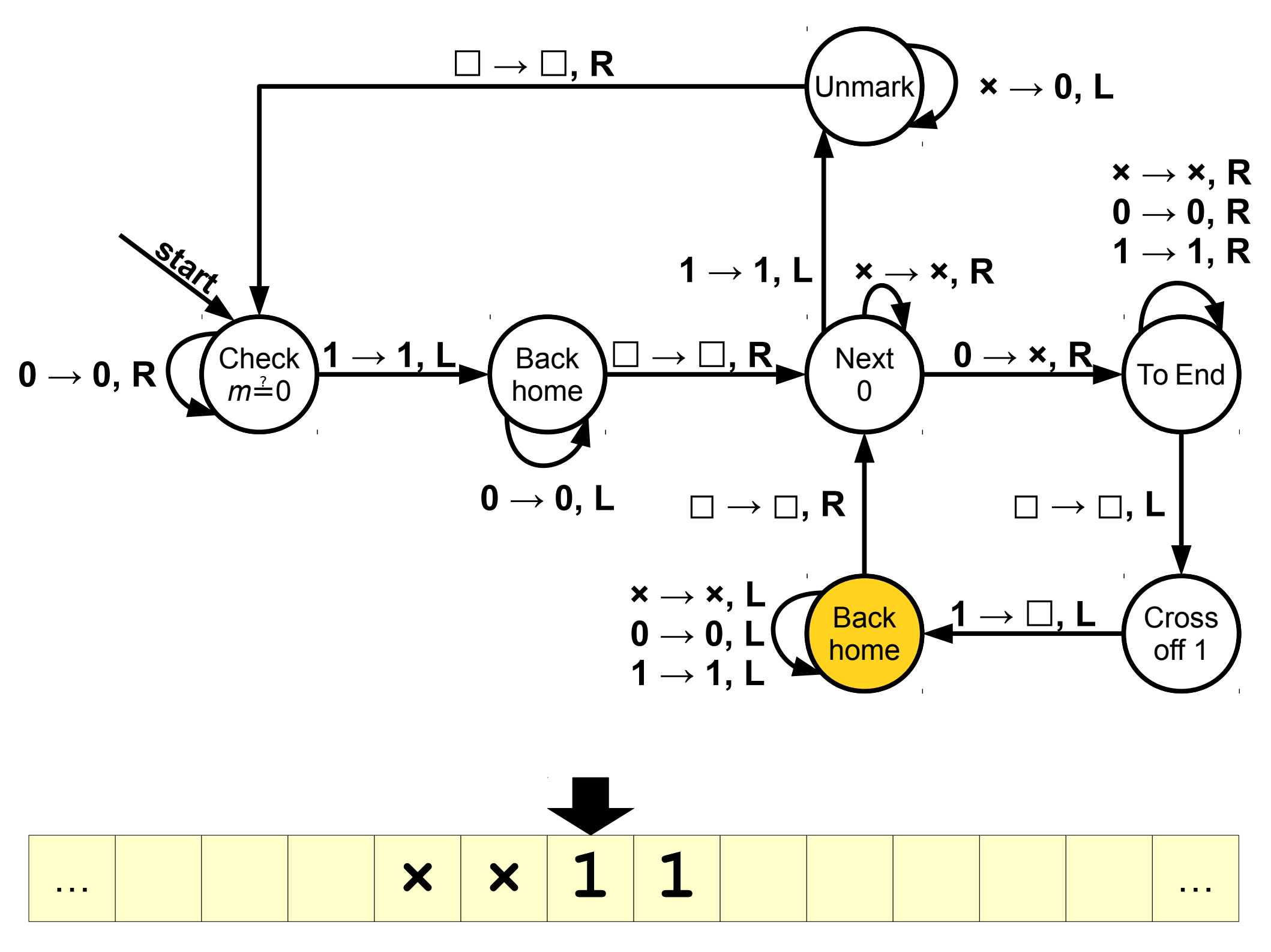
□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
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0 → 0, R
Check
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1 → 1, L
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home
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To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
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off 1
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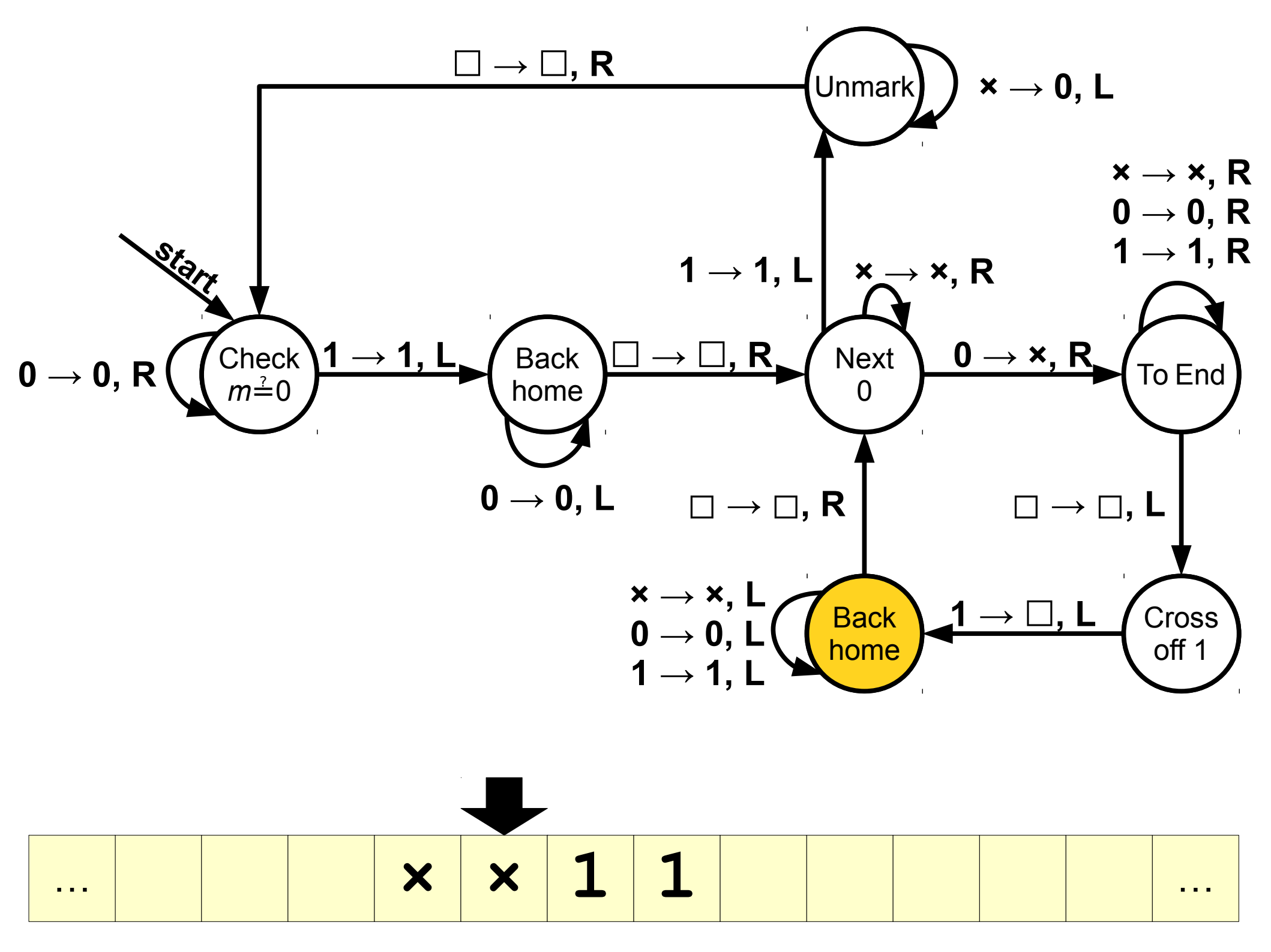
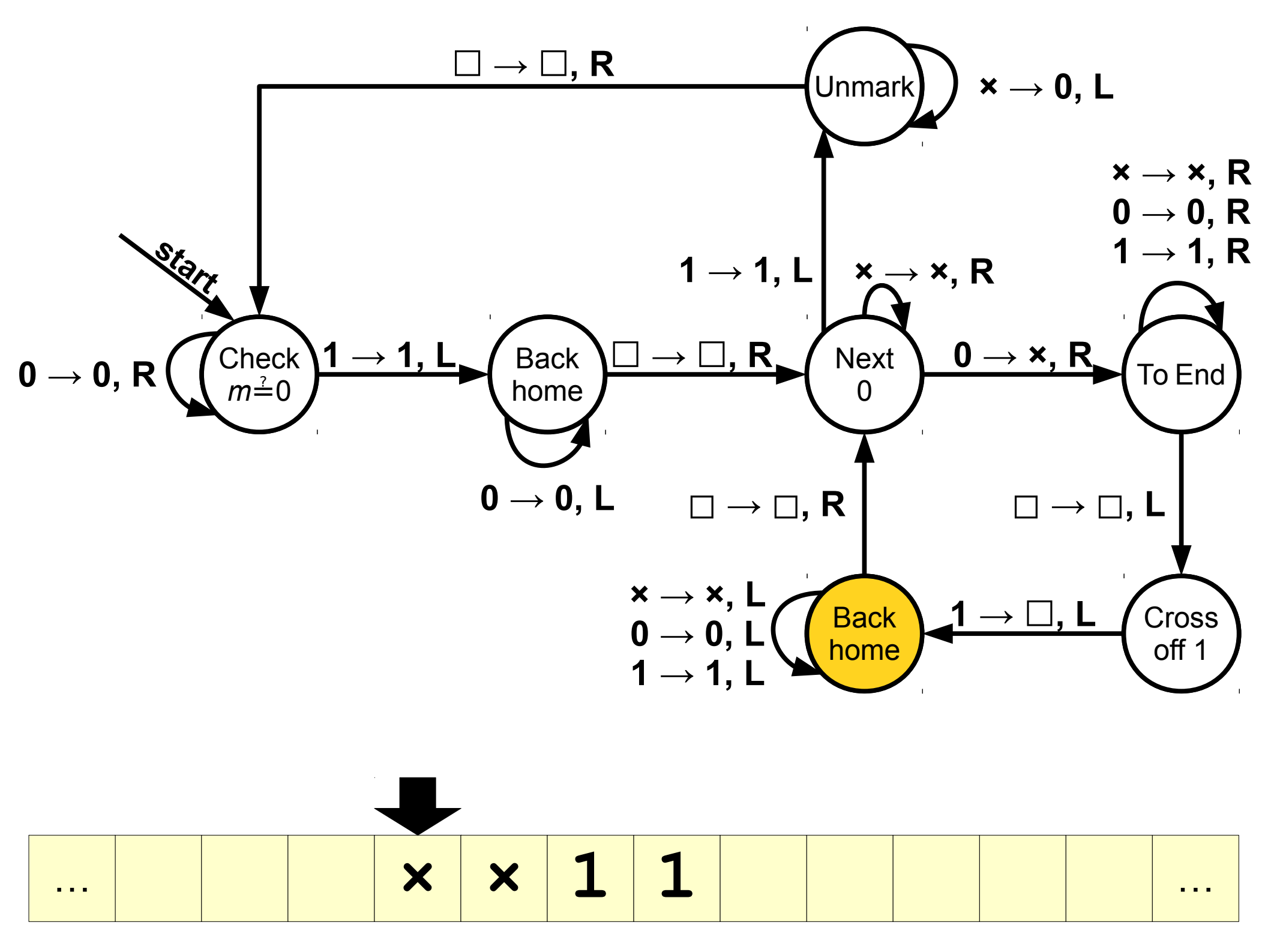

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
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0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
× × 1 1
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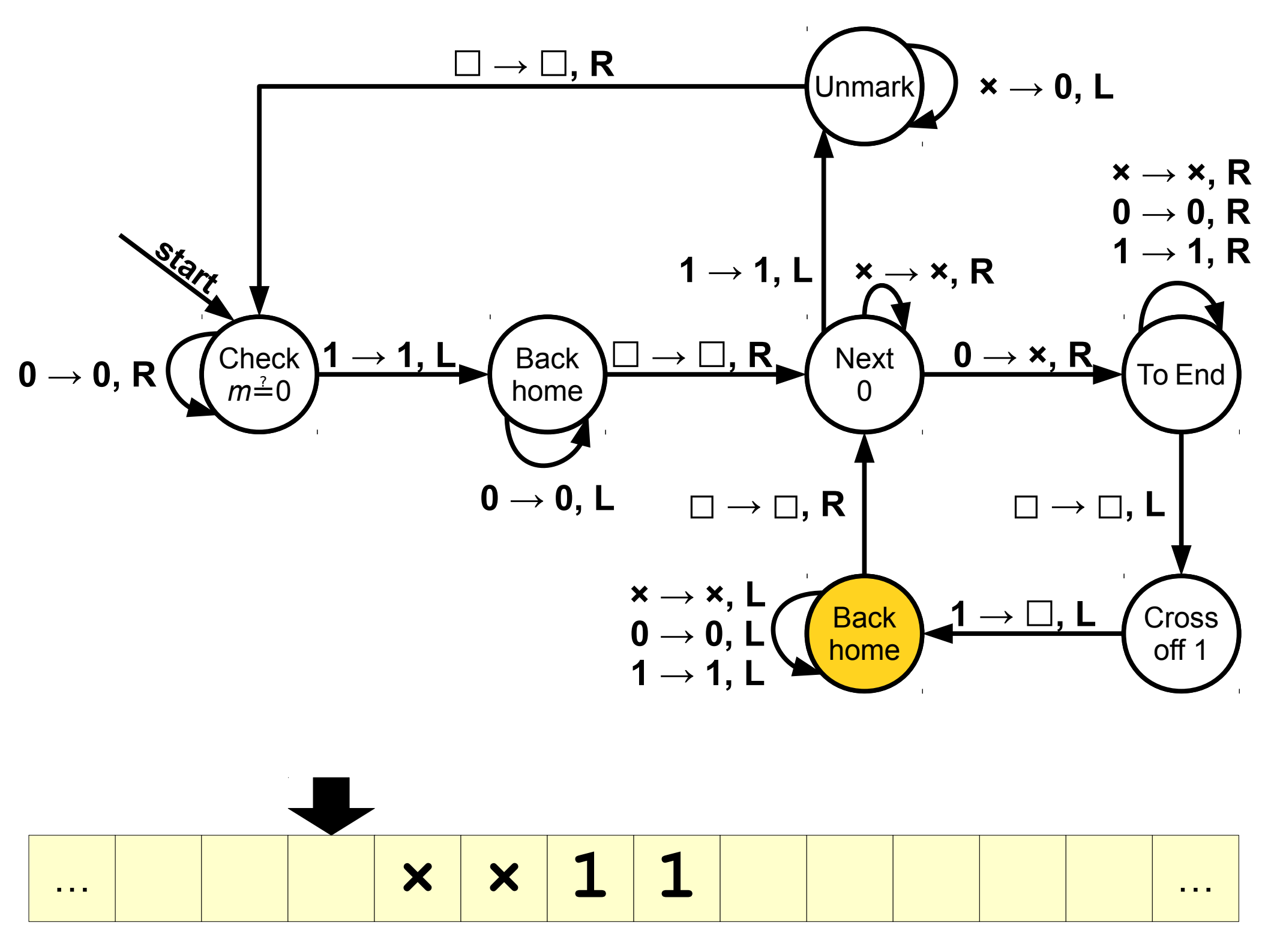
□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
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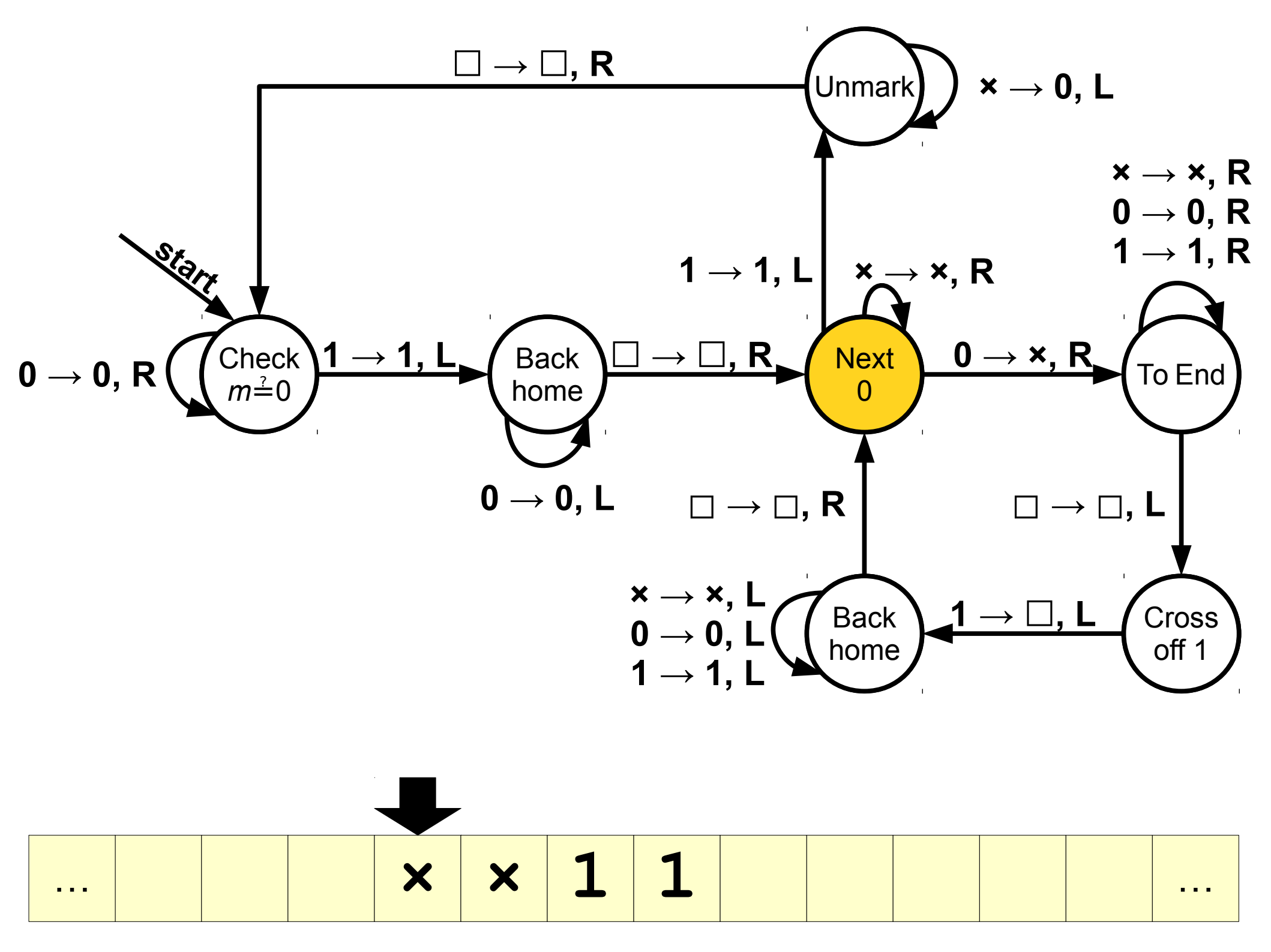
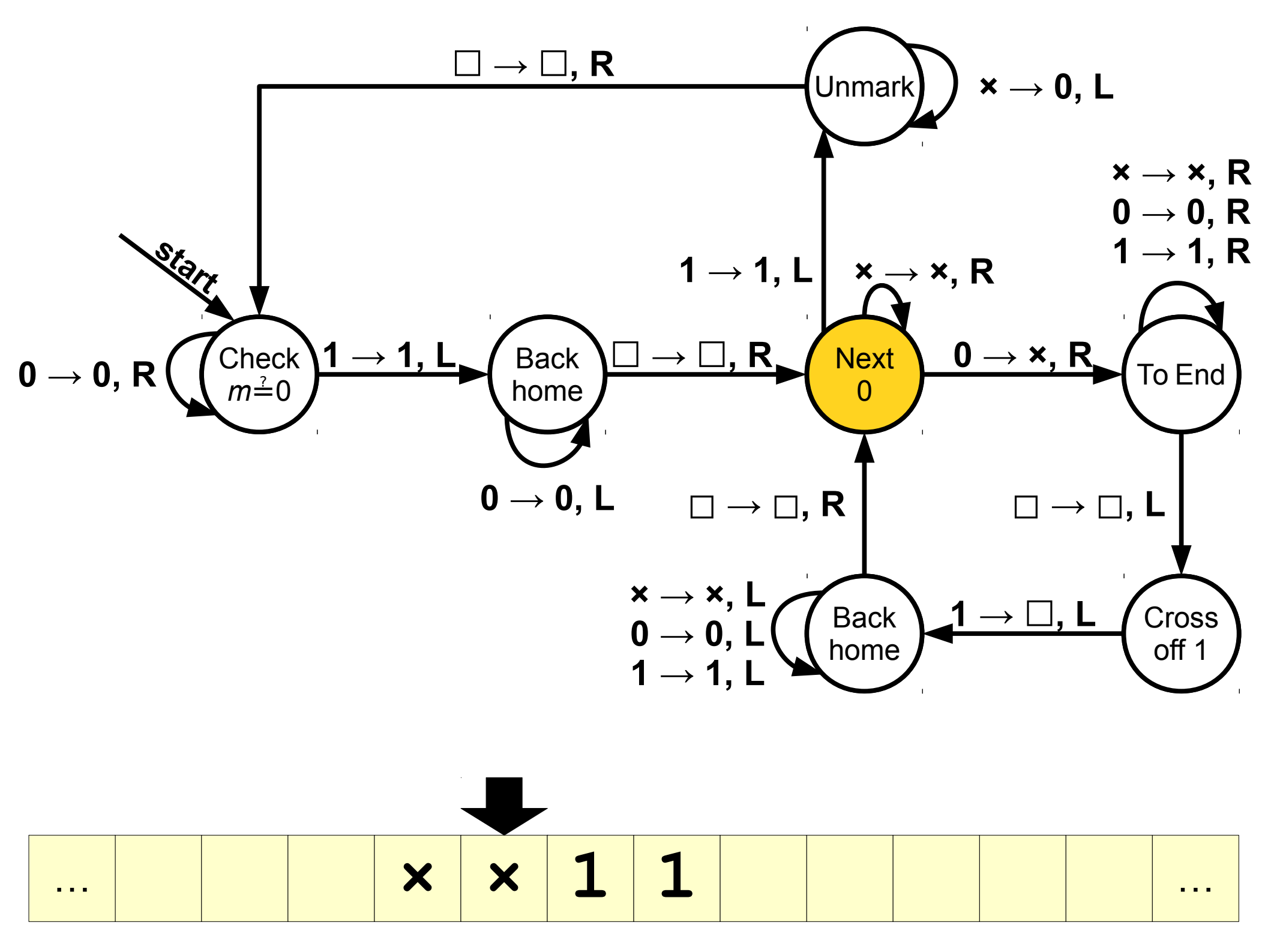
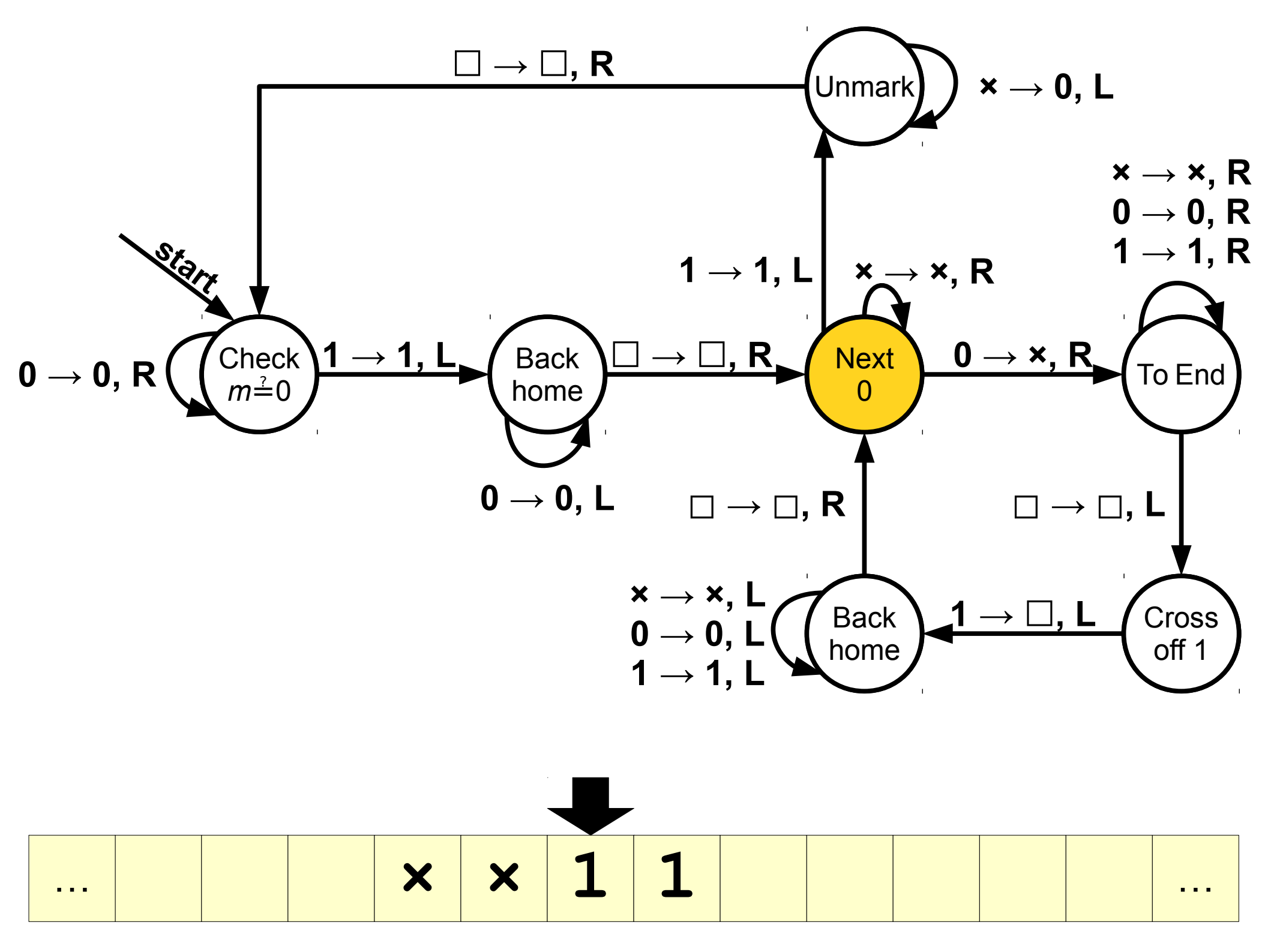
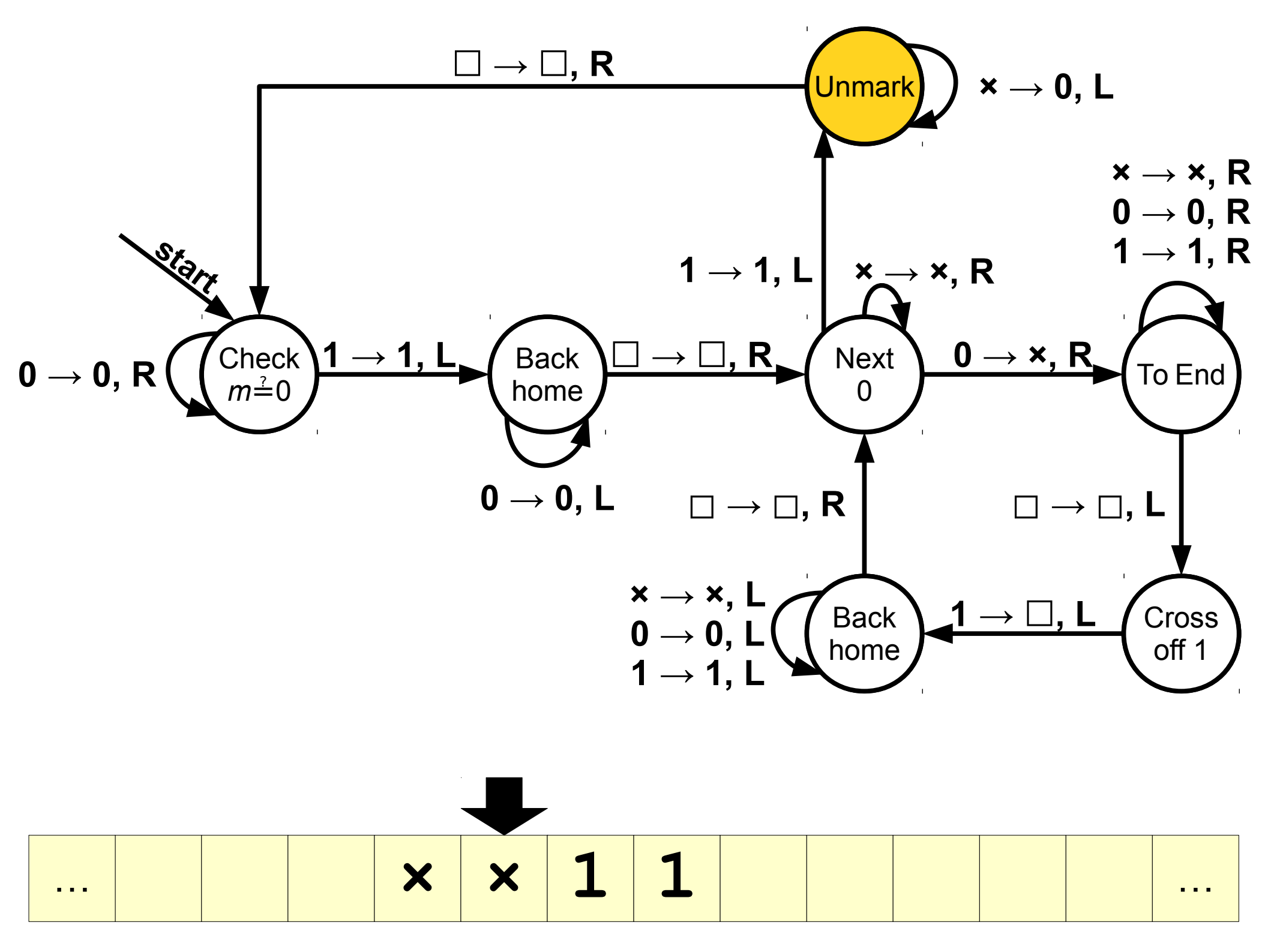
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
×
1
1
…


start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
To End
Unmark
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
1 → 1, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
… × × 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
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home
□ → □, R
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0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
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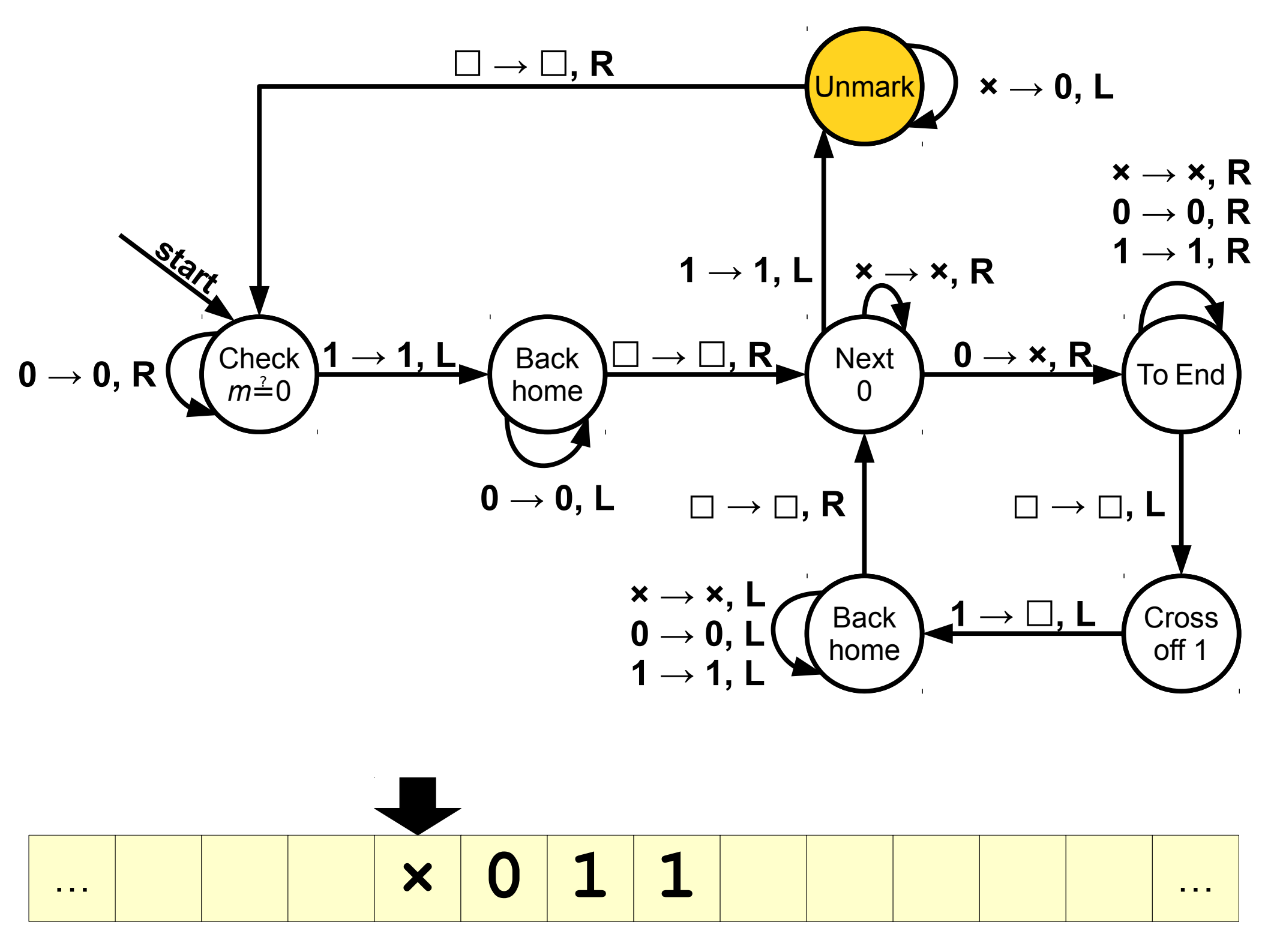
off 1
… × × 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
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0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
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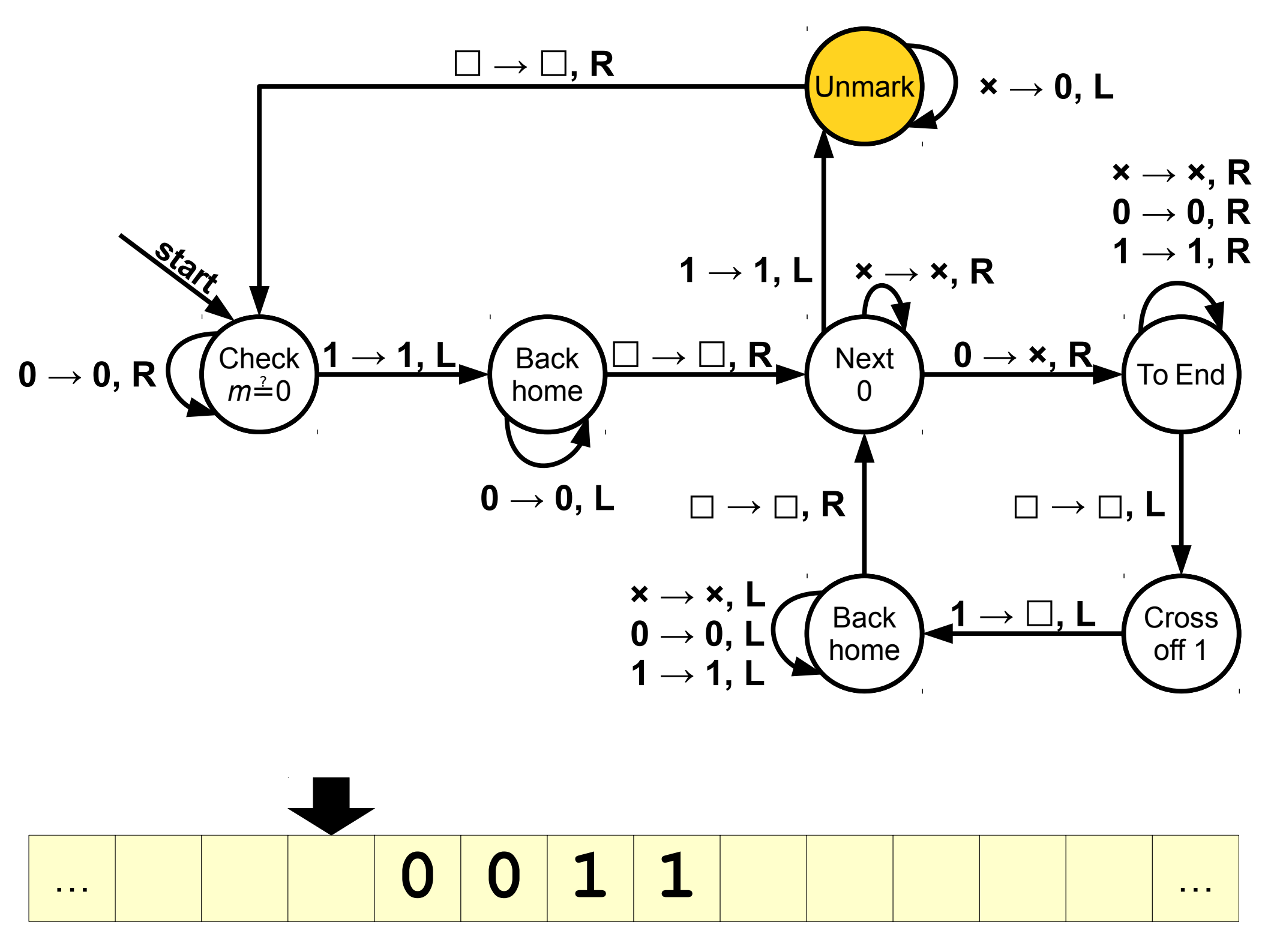
□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
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0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
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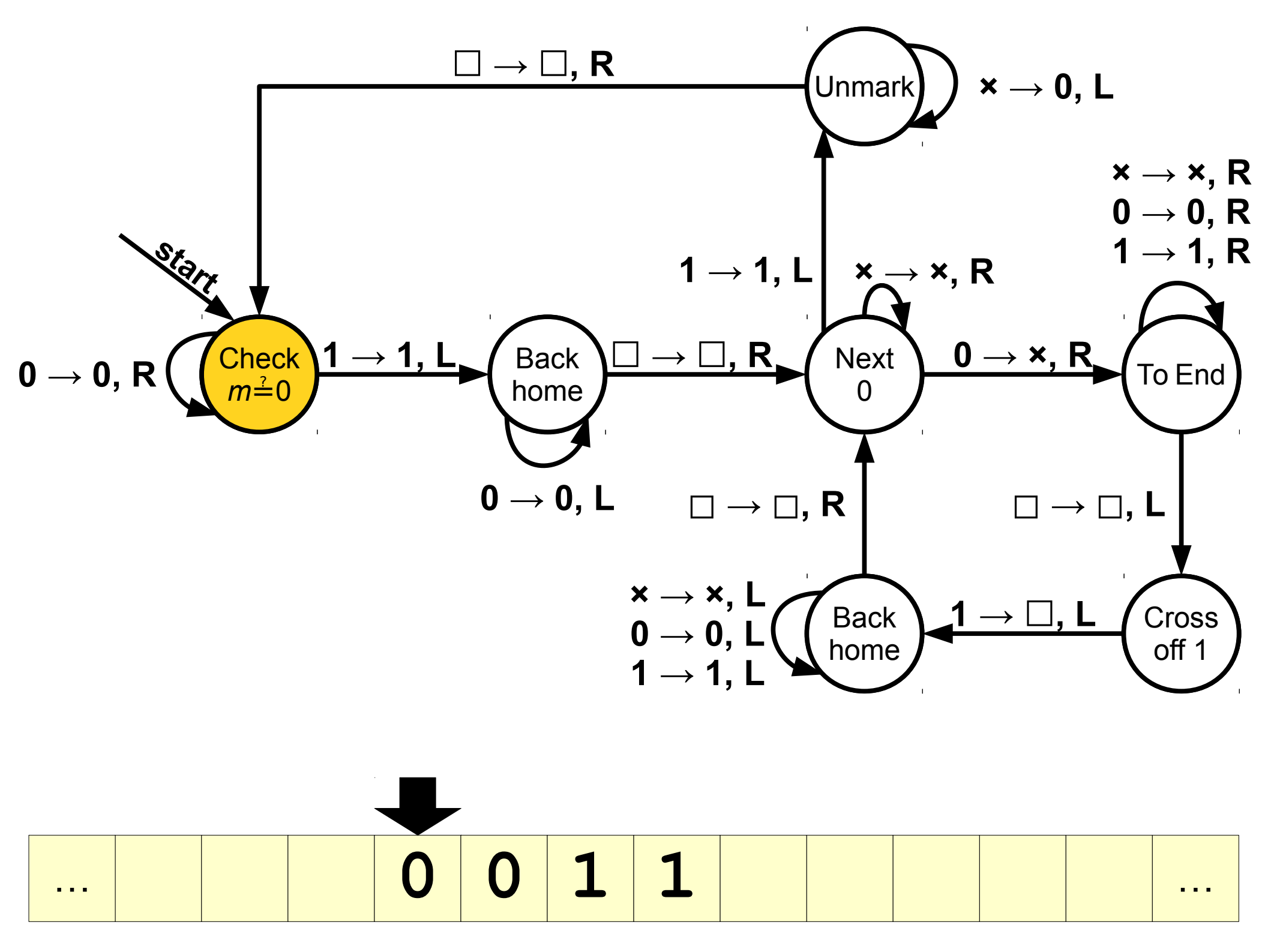
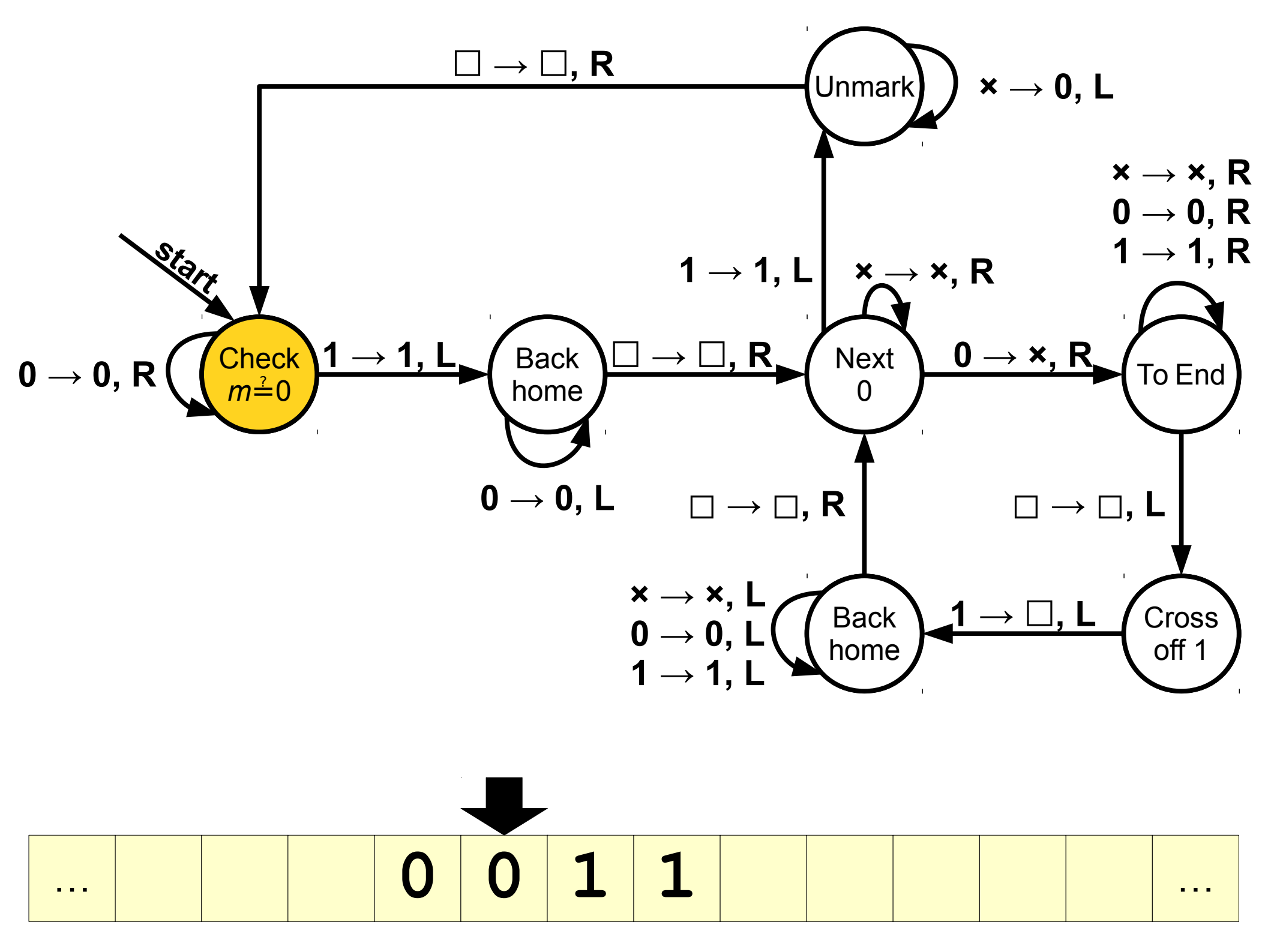
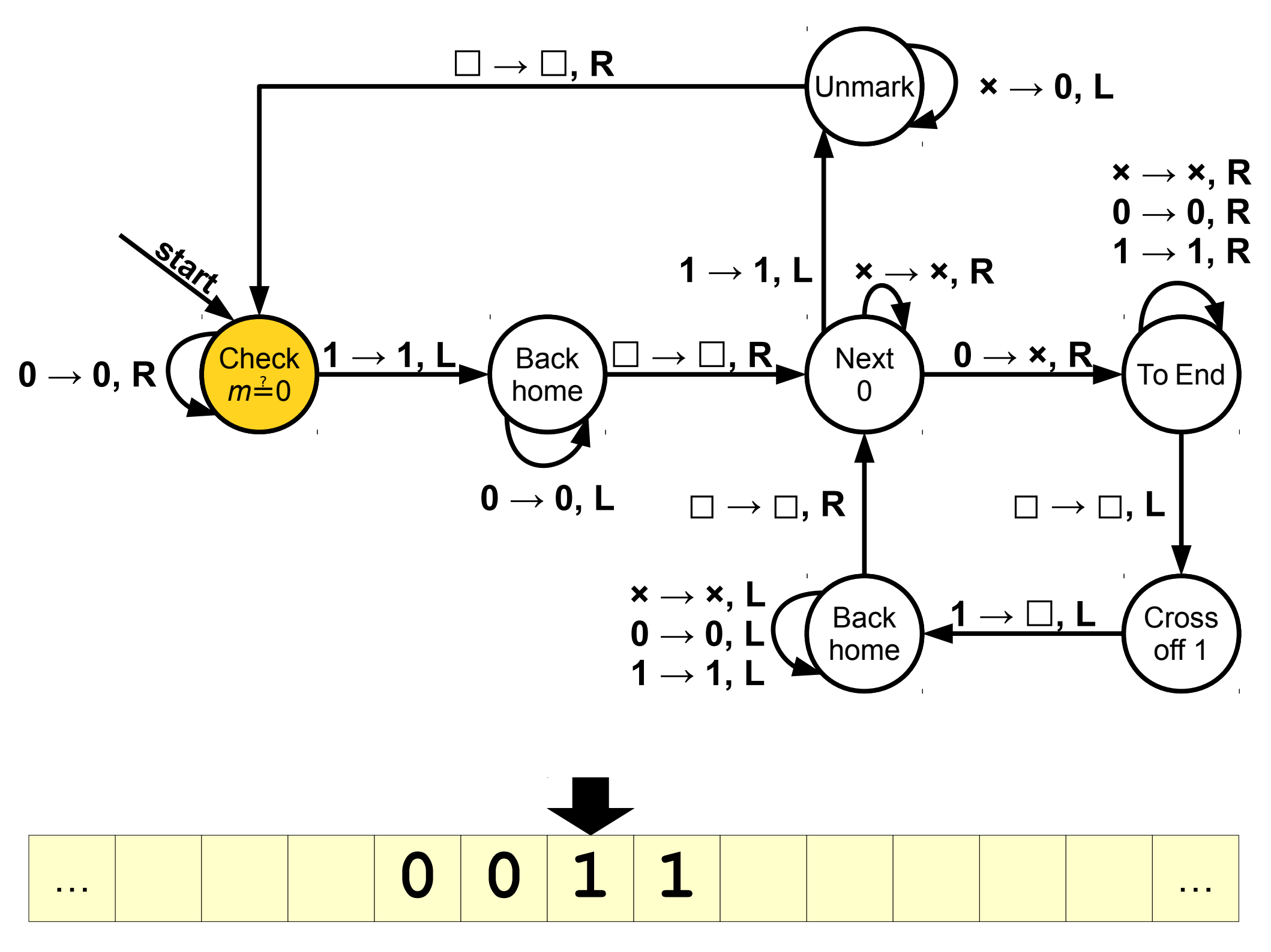
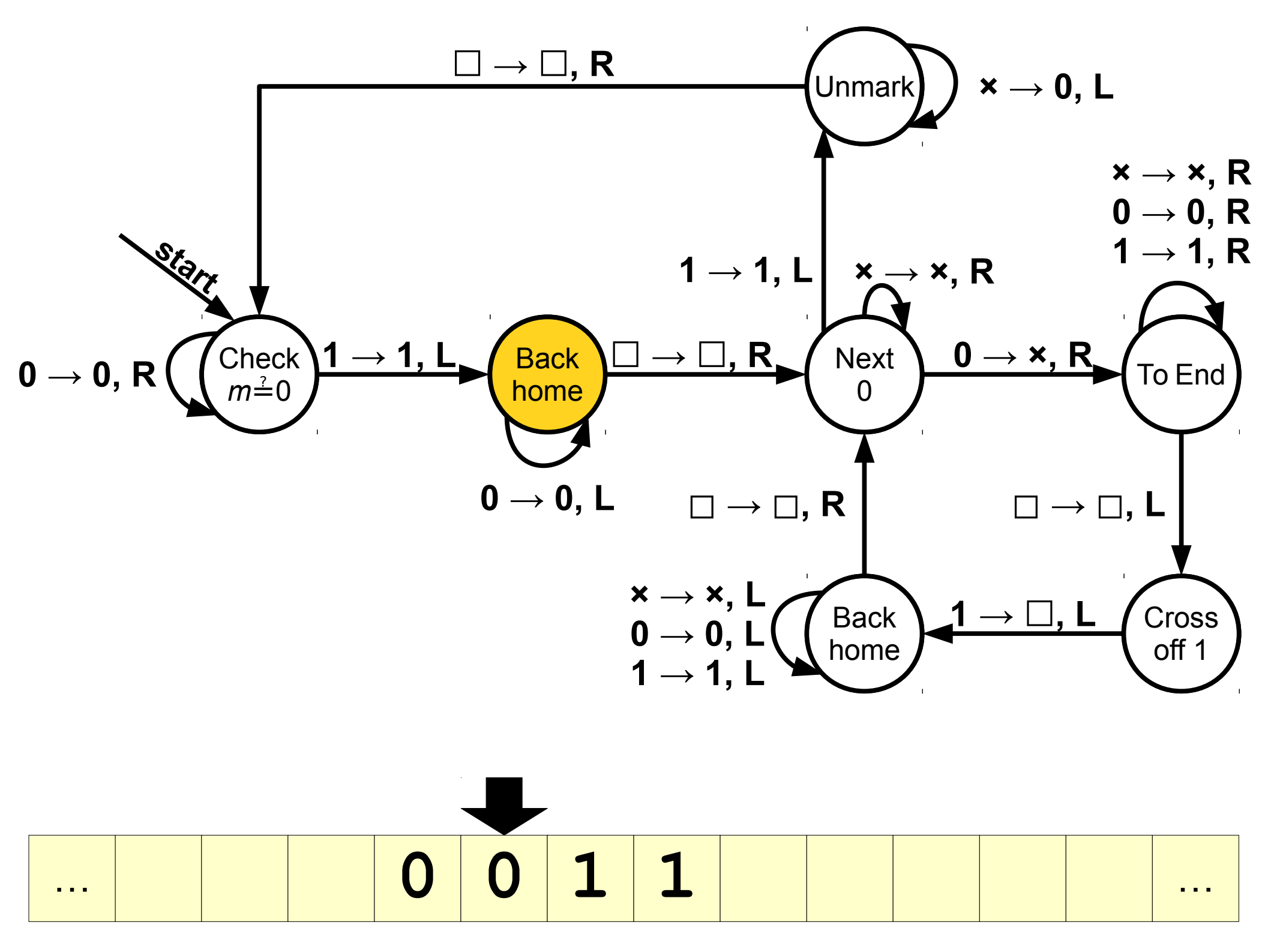
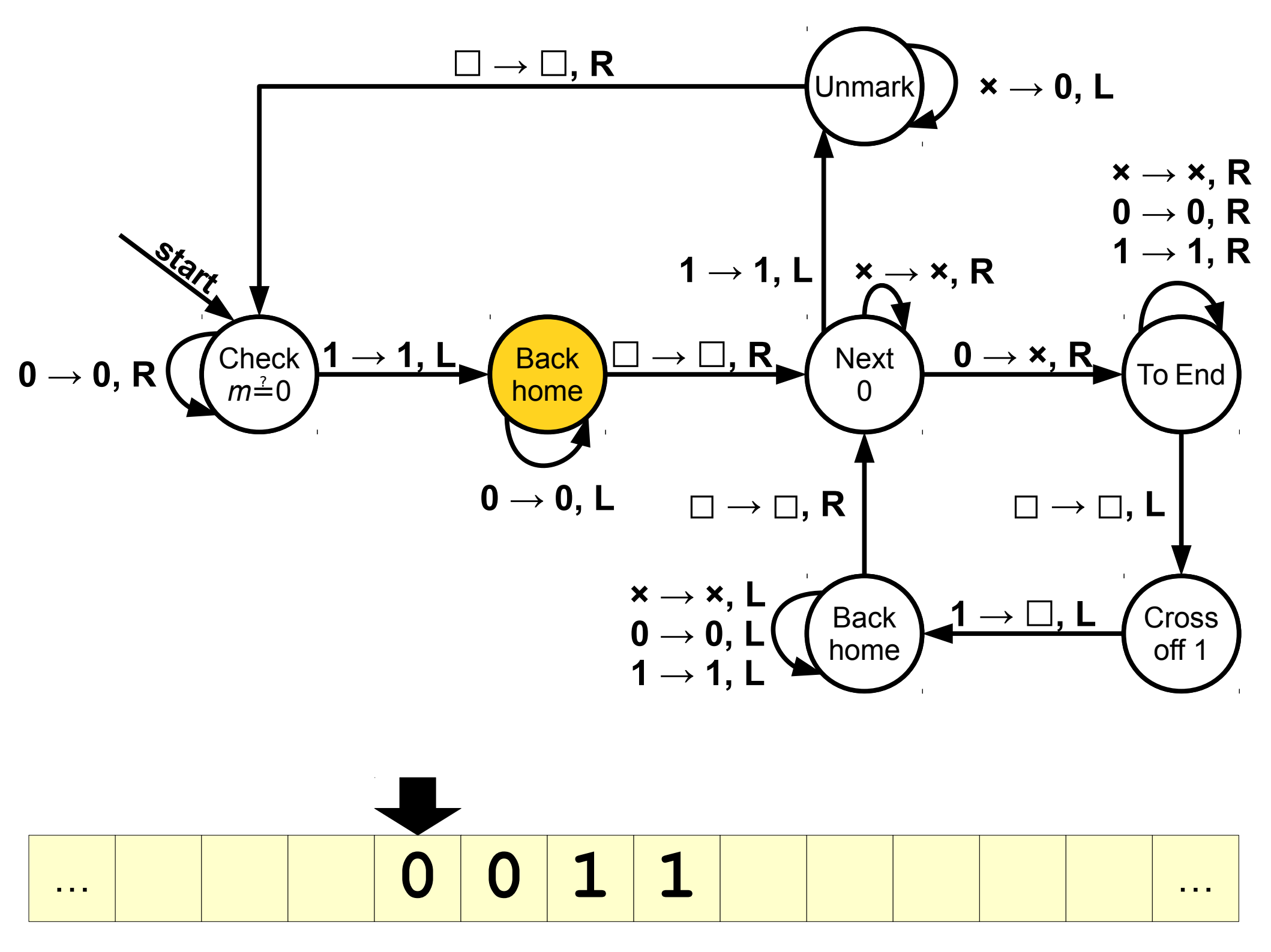
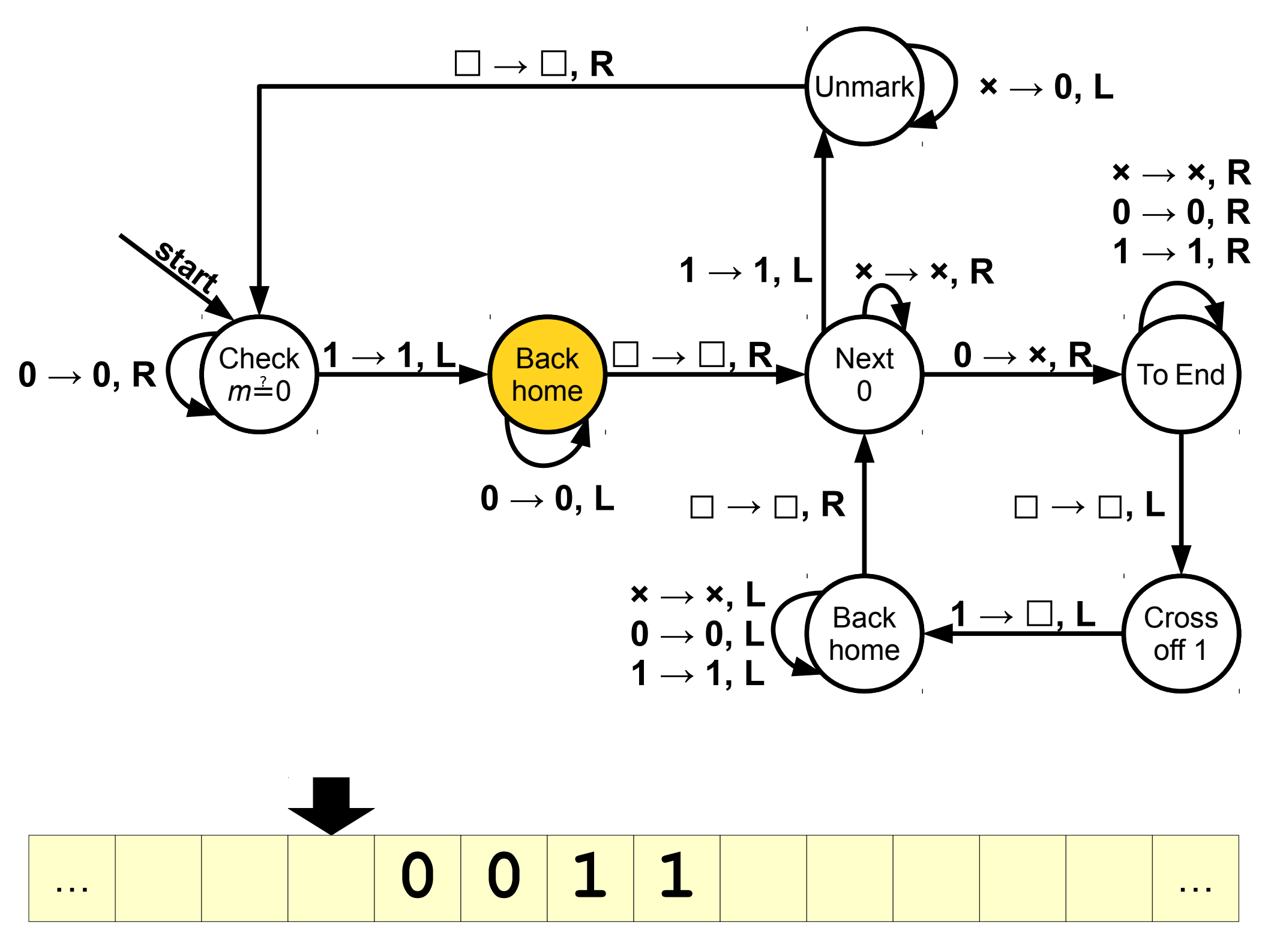

start
Check
m=?0
Back
home
Next
0
Unmark
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
1 → 1, L
□ → □, R
□ → □, L
1 → □, L
× → ×, L
0 → 0, L
1 → 1, L
… 0 0 1 1 …

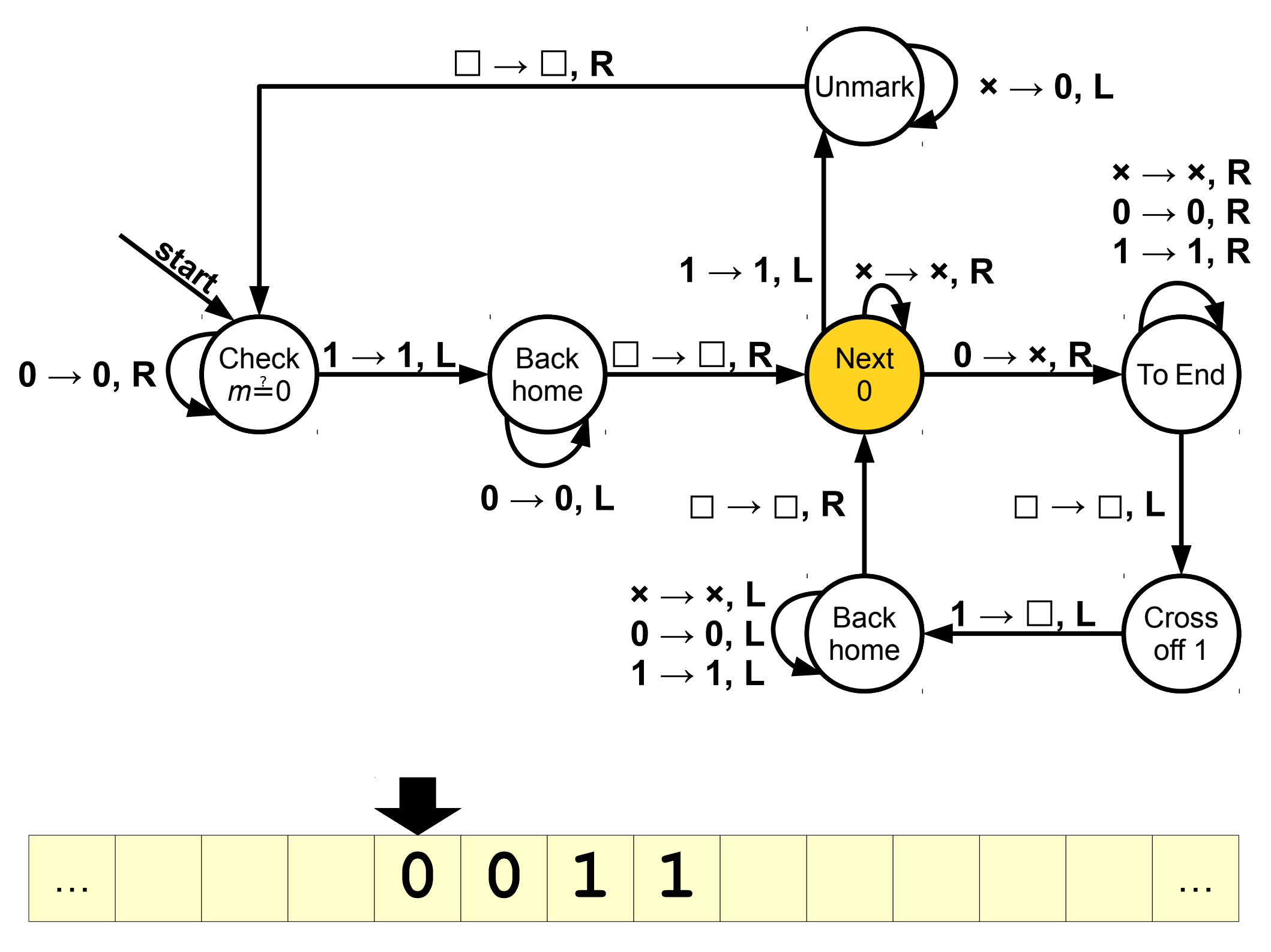

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
0
1
1
…

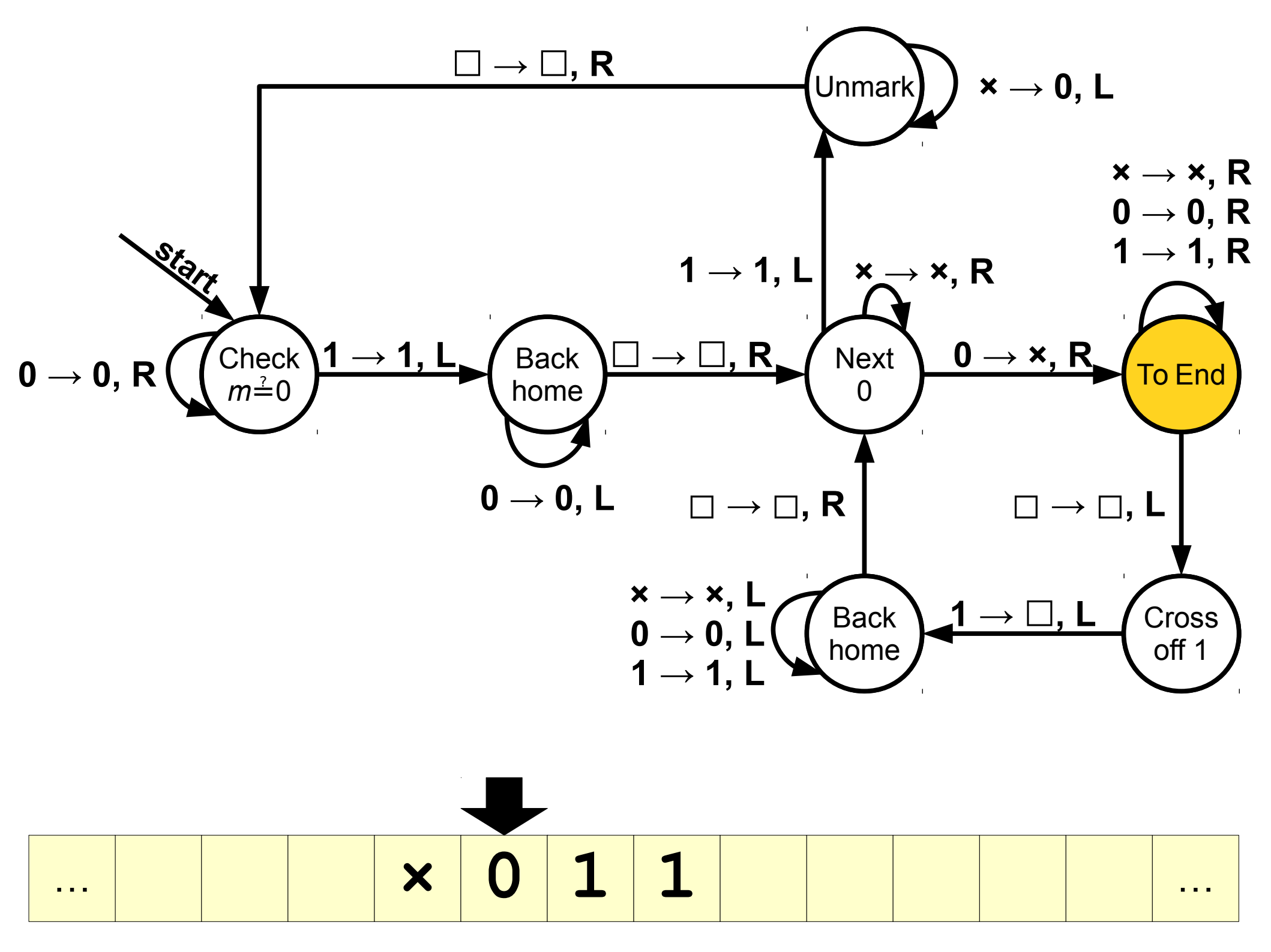

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
0
1
1
…

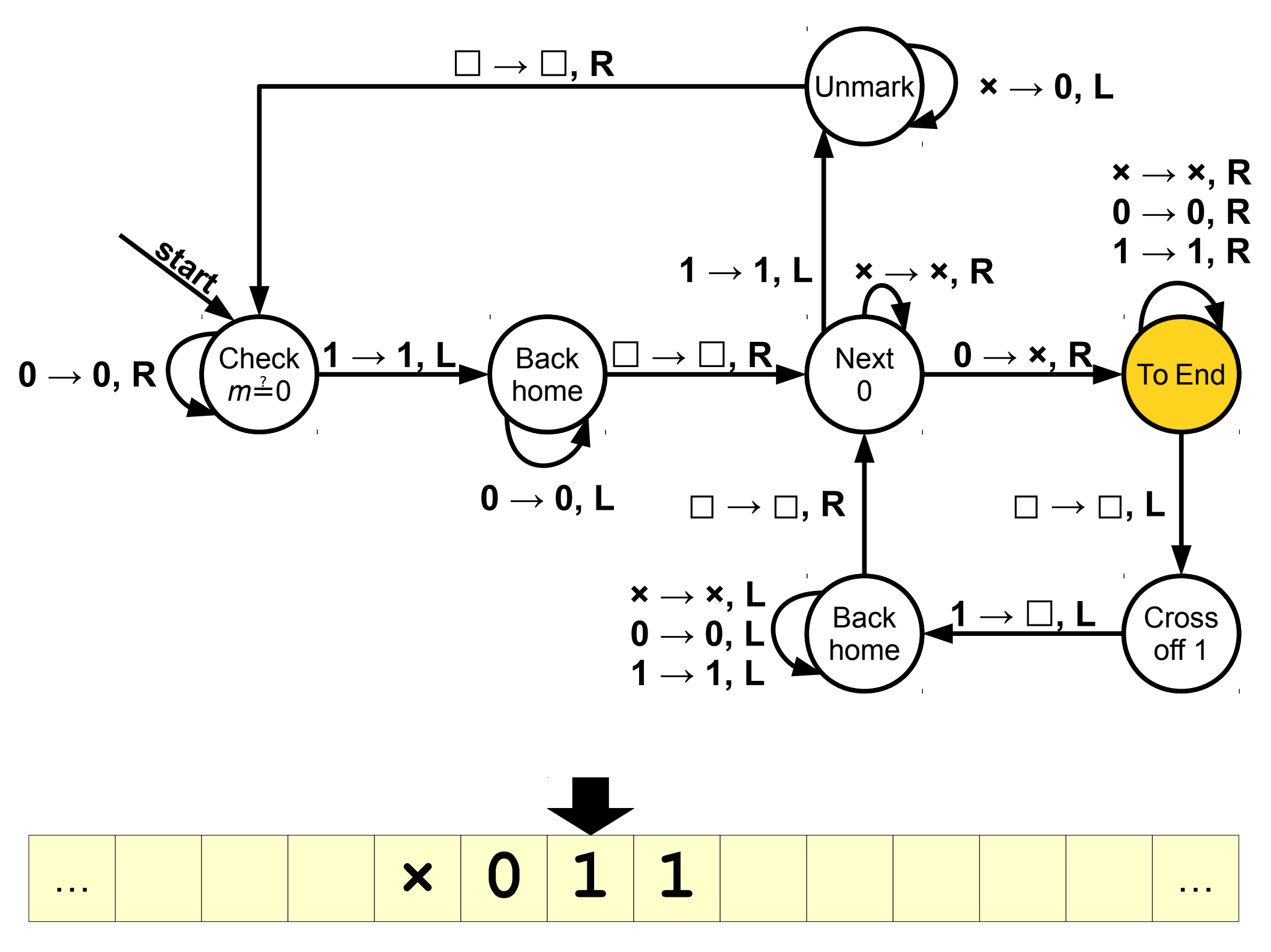

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
0
1
1
…

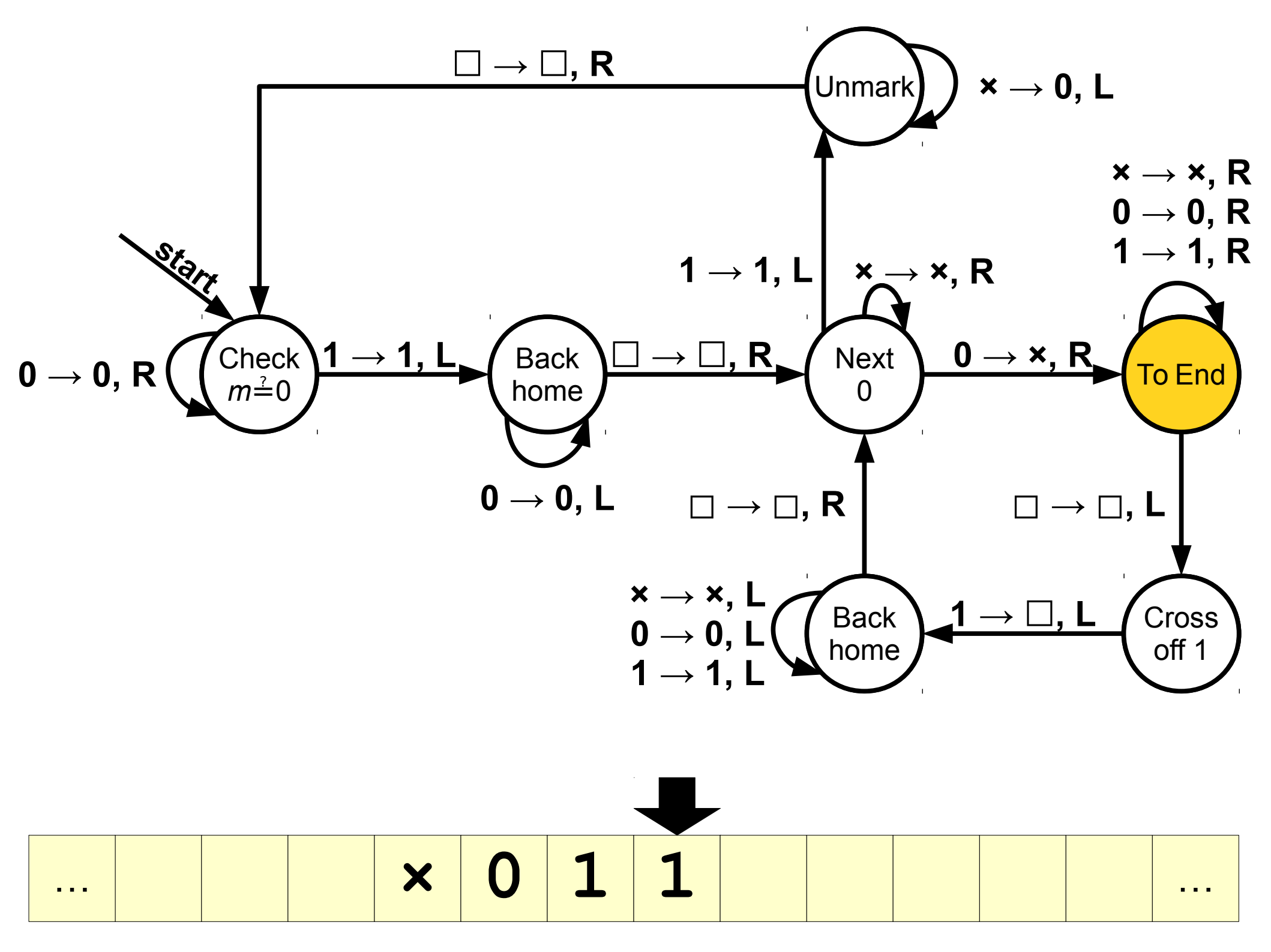

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
0
1
1
…

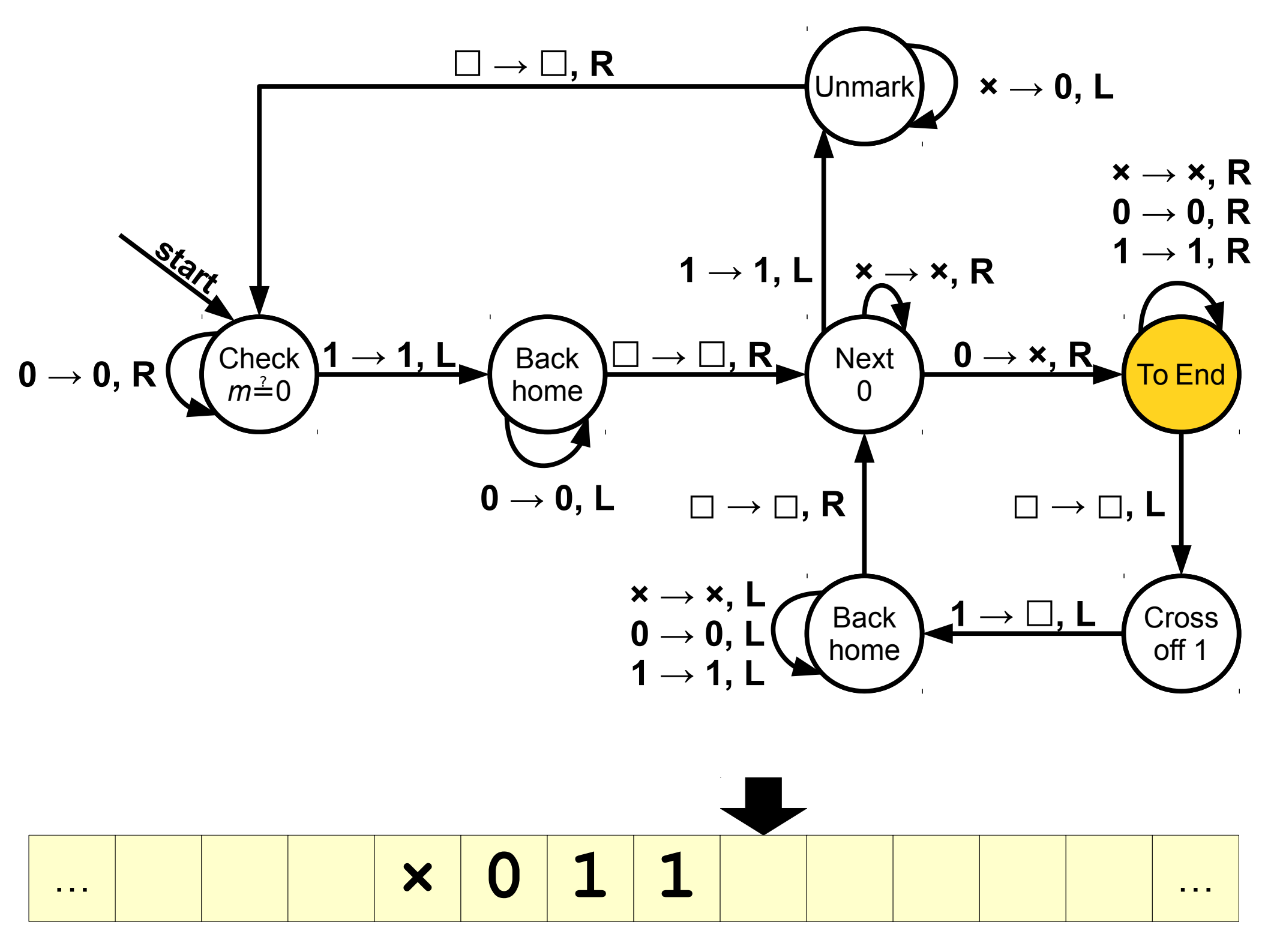

start
Check
$m \stackrel{?}{=} 0$
Back
home
Unmark
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
1 → 1, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
…
0 0 1 1
…

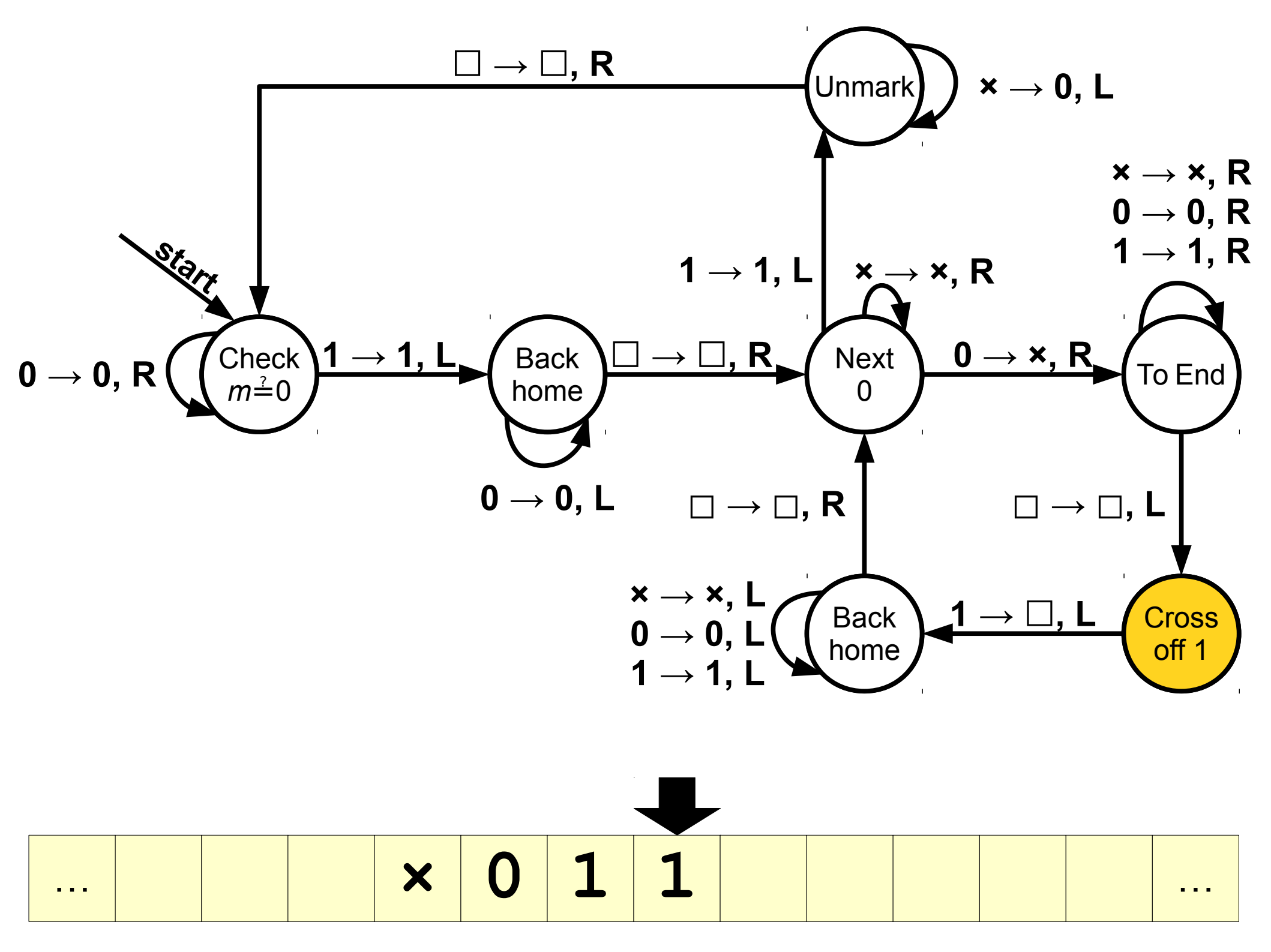

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m=0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
0
0
1
1
…

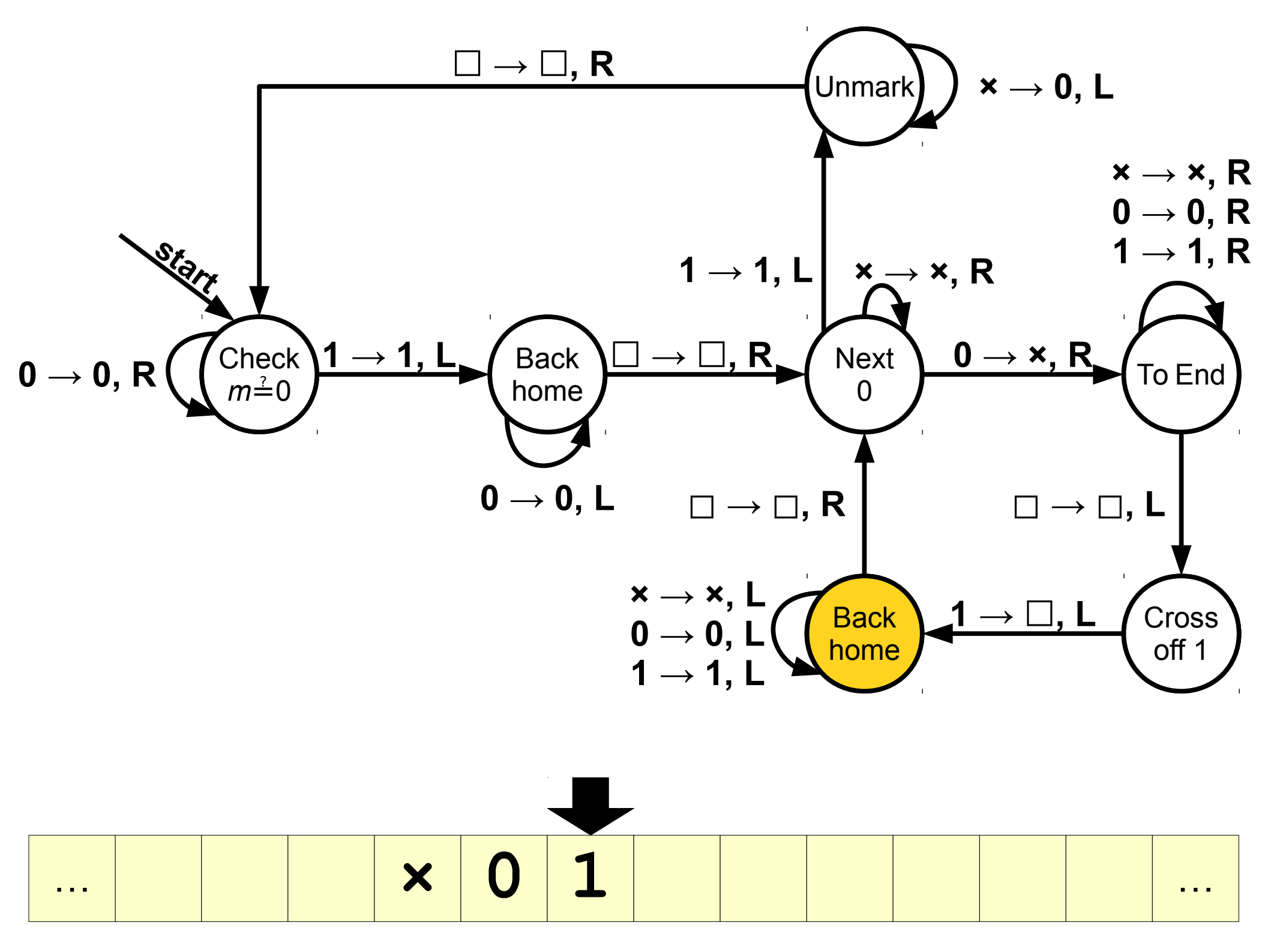

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 …


start
Check
$m \stackrel{?}{=} 0$
Back
home
Next
0
Unmark
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
0 → 0, L
1 → 1, L
× → ×, R
0 → ×, R
× → ×, R
0 → 0, R
1 → 1, R
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
…
×
0
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × 0 1 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
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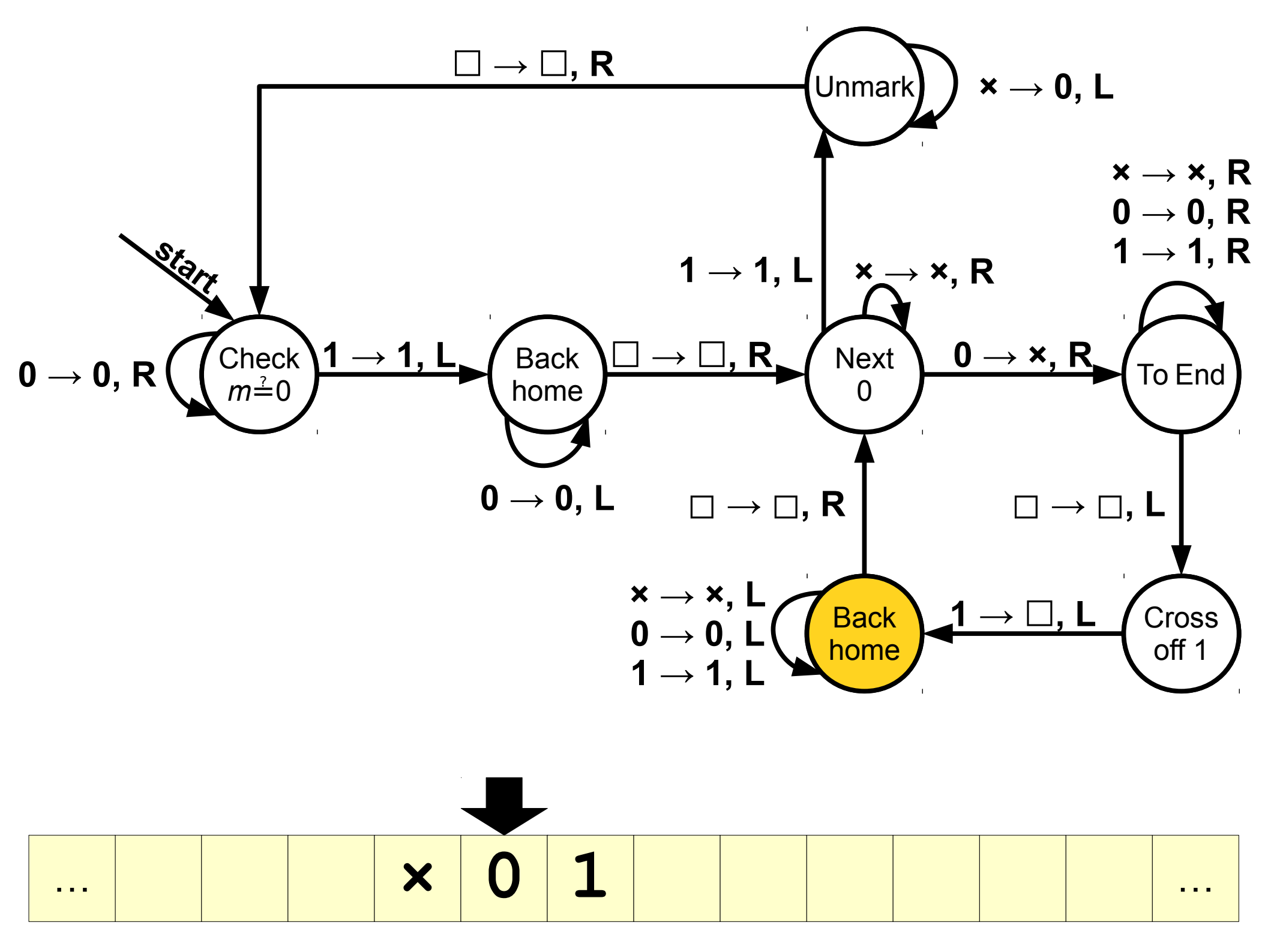
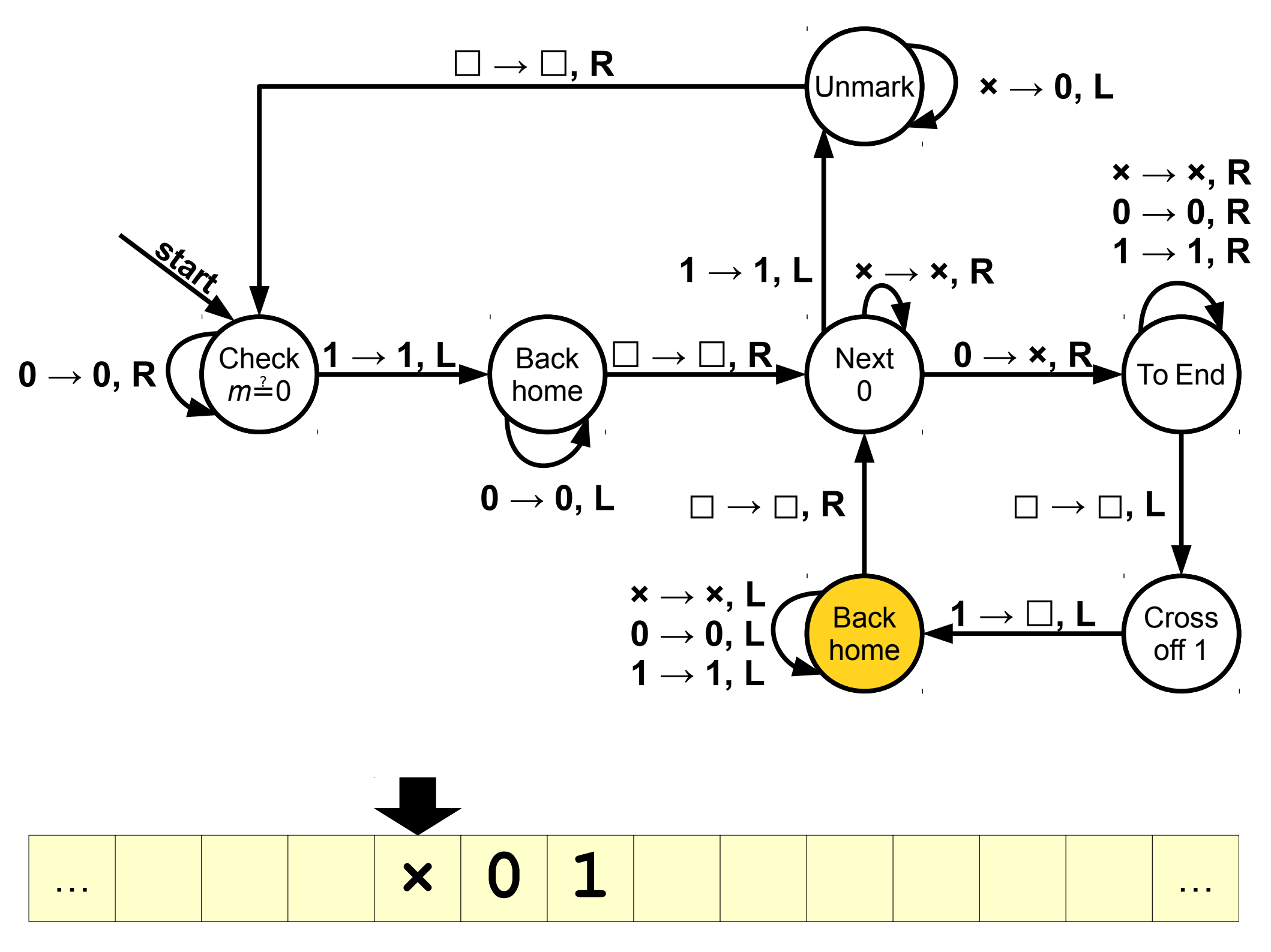
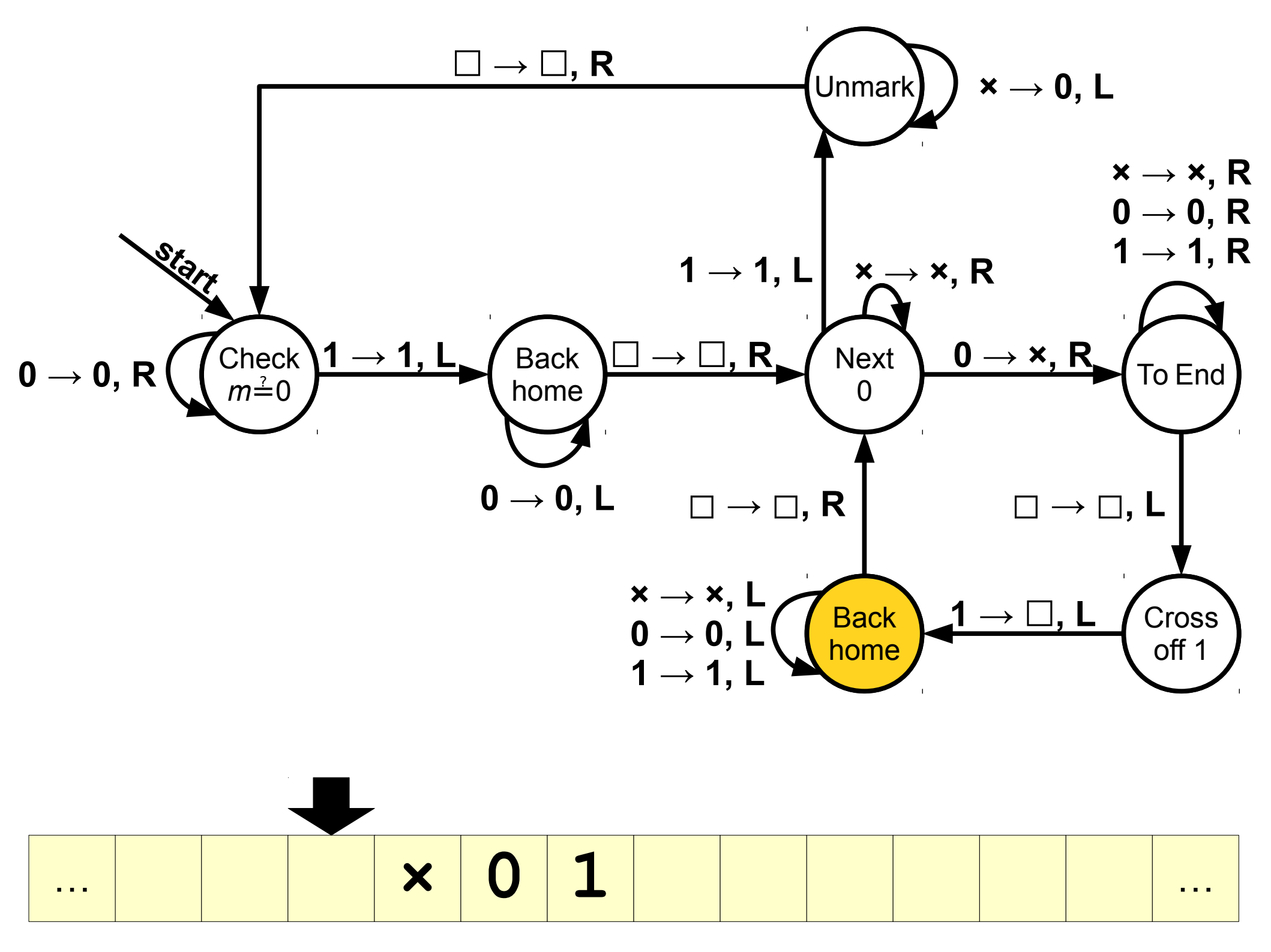
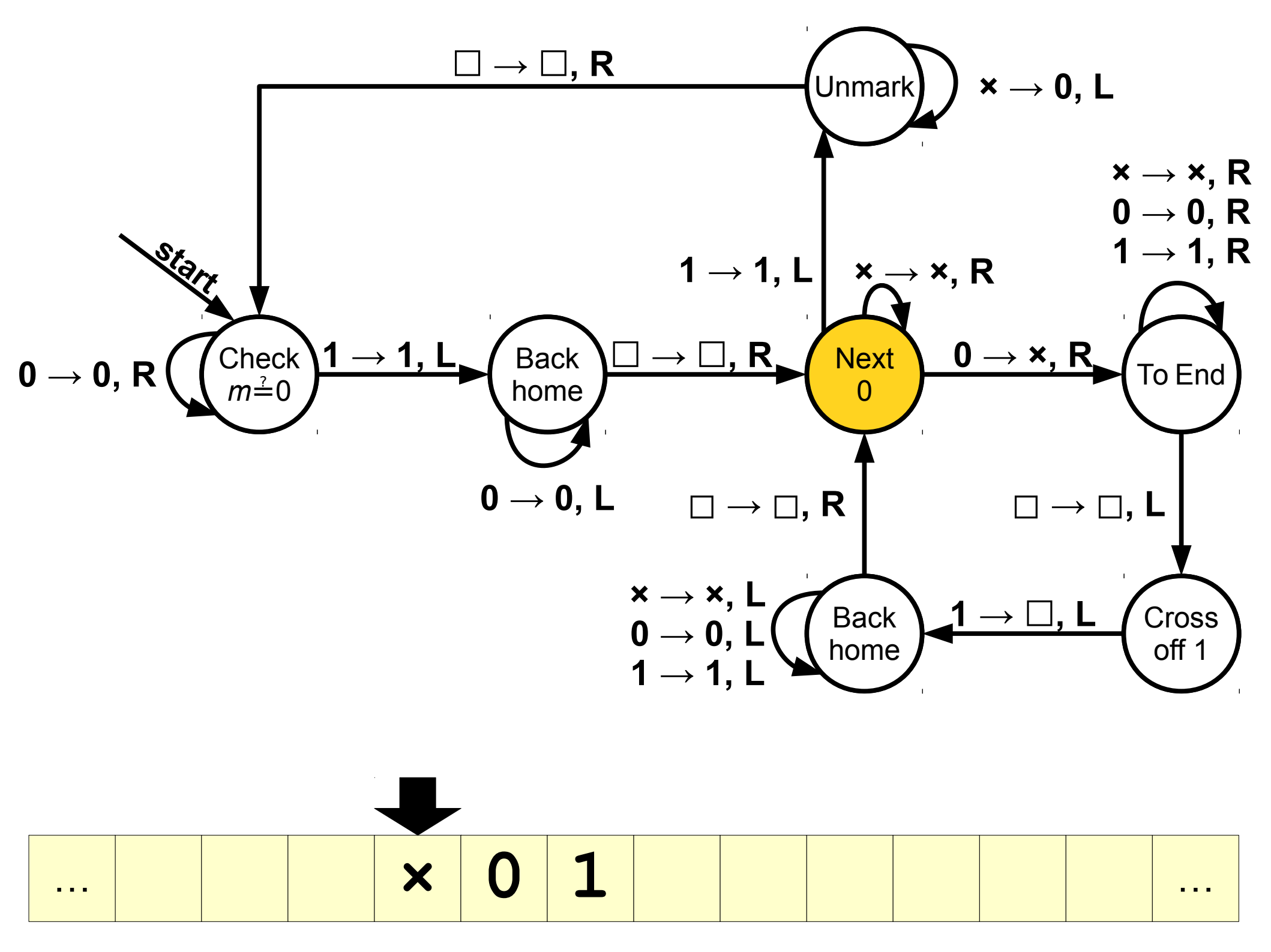
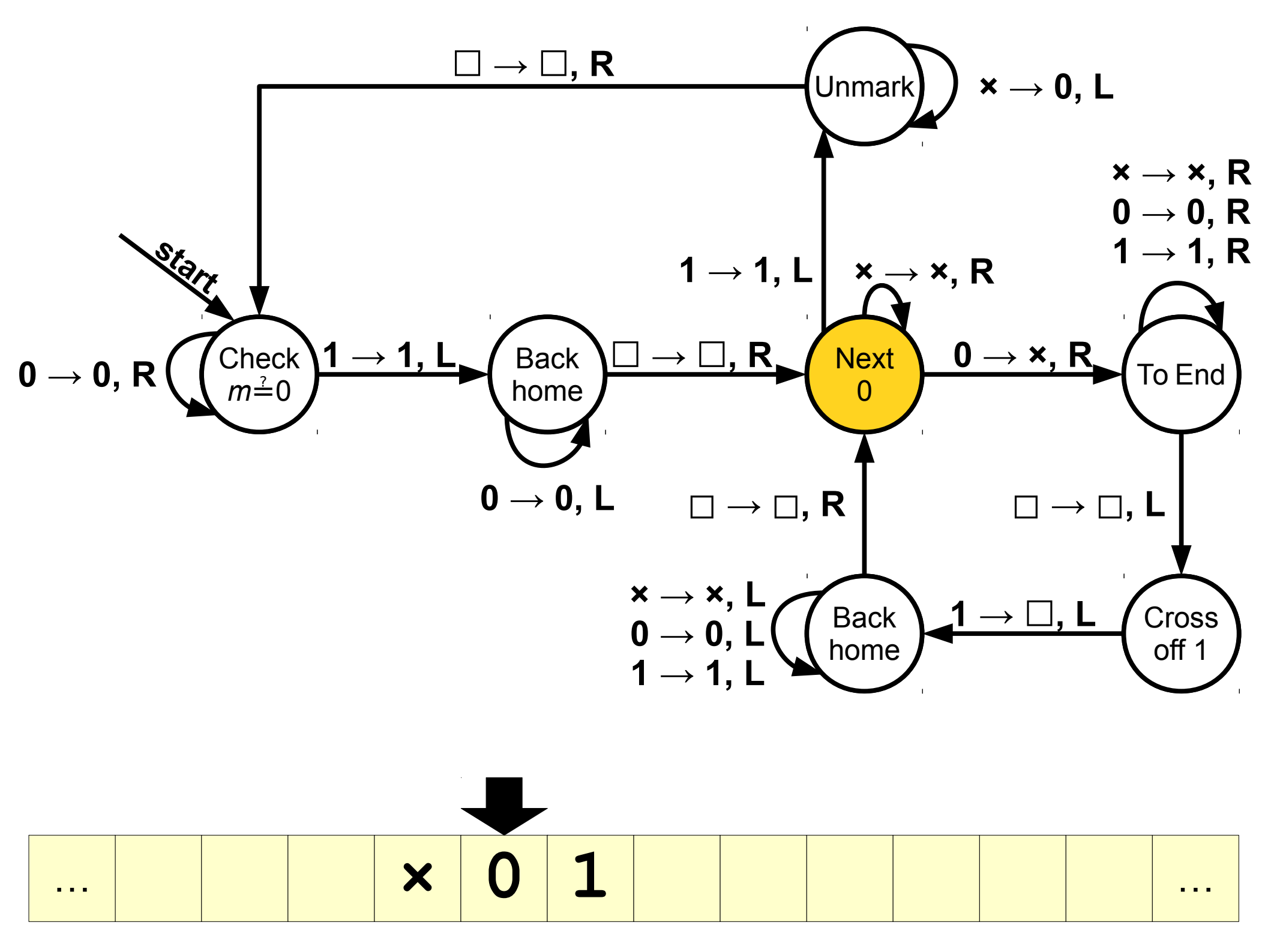
1
…

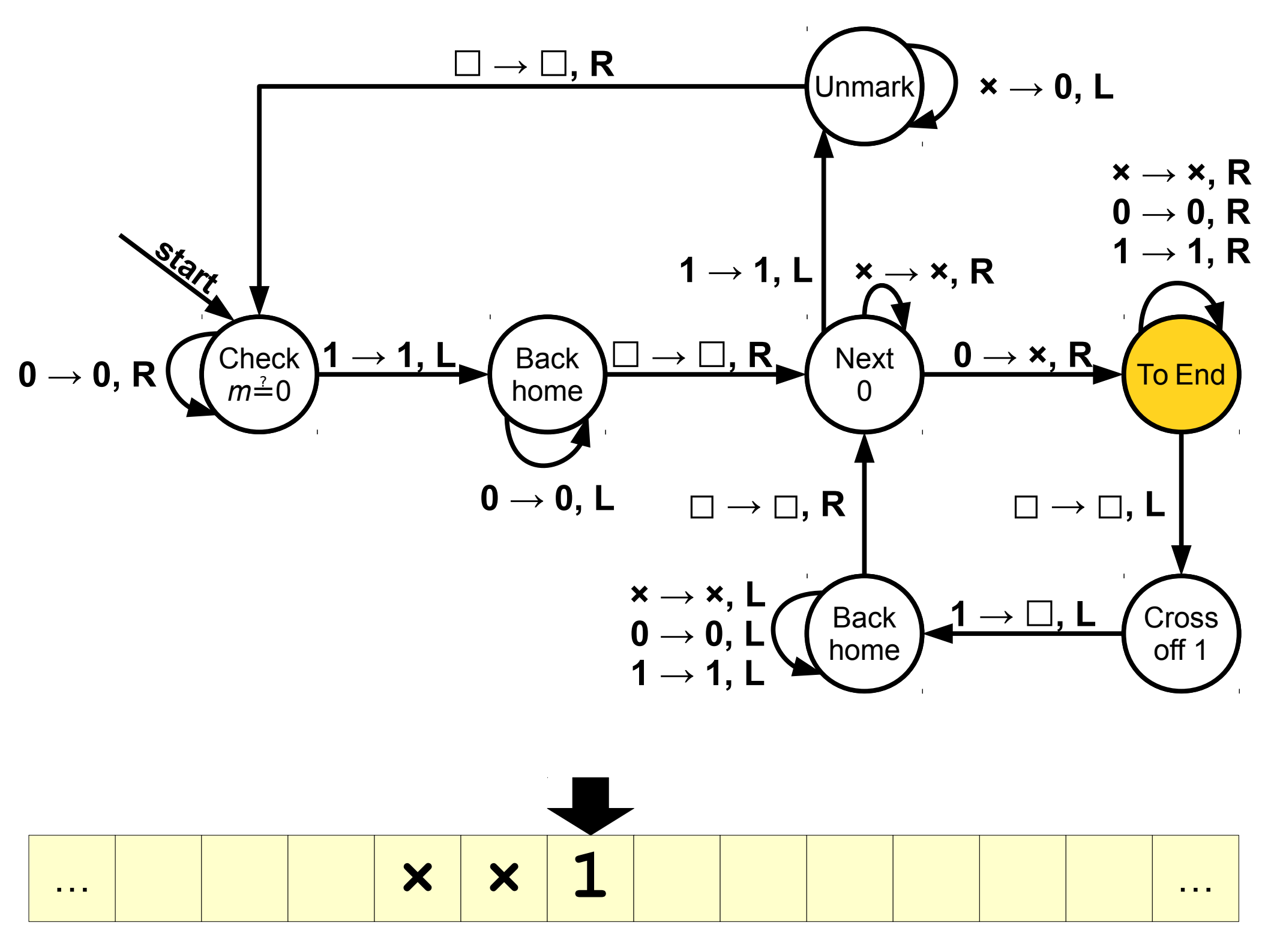

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
…

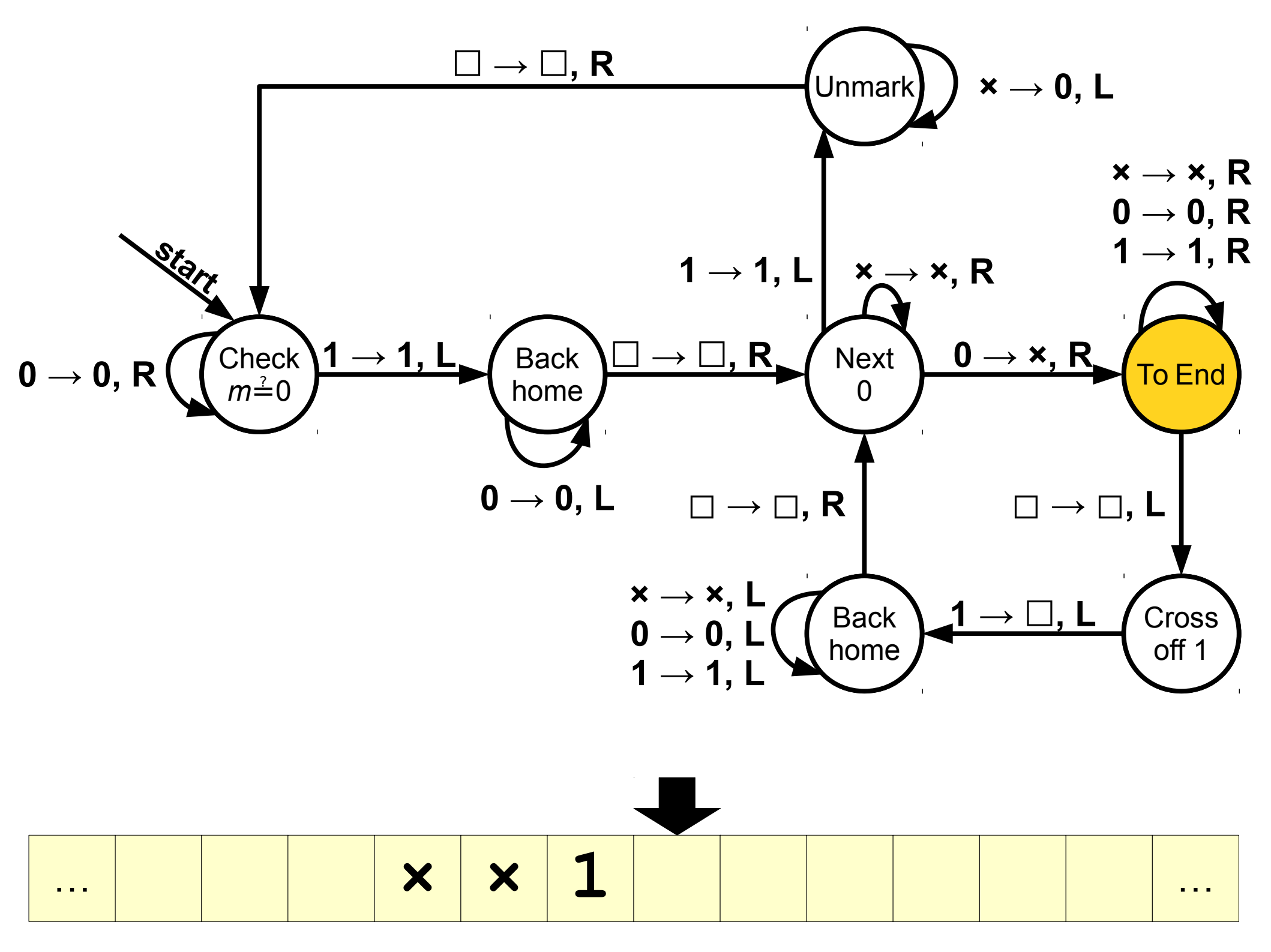

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
…

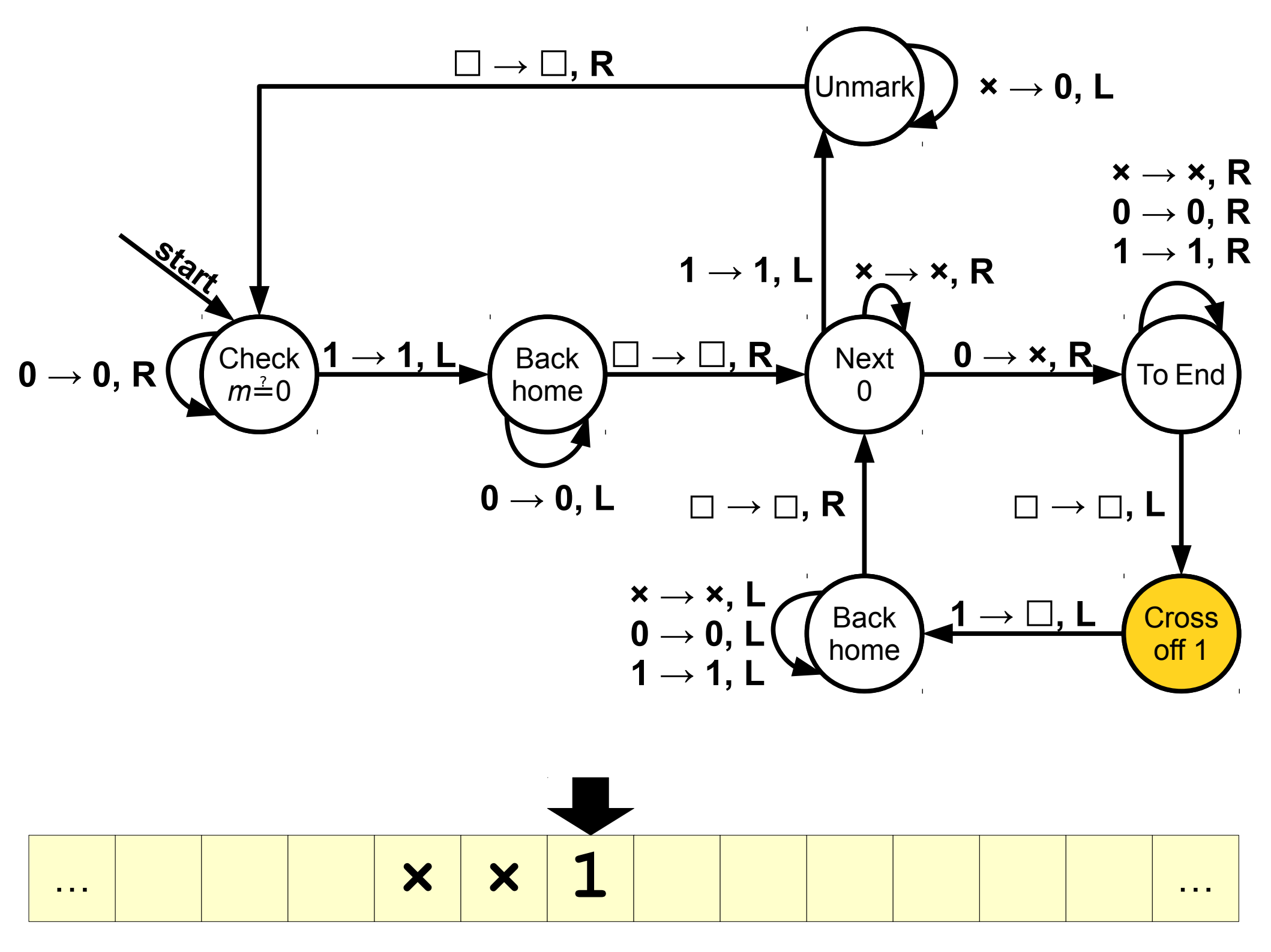

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, R
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
…

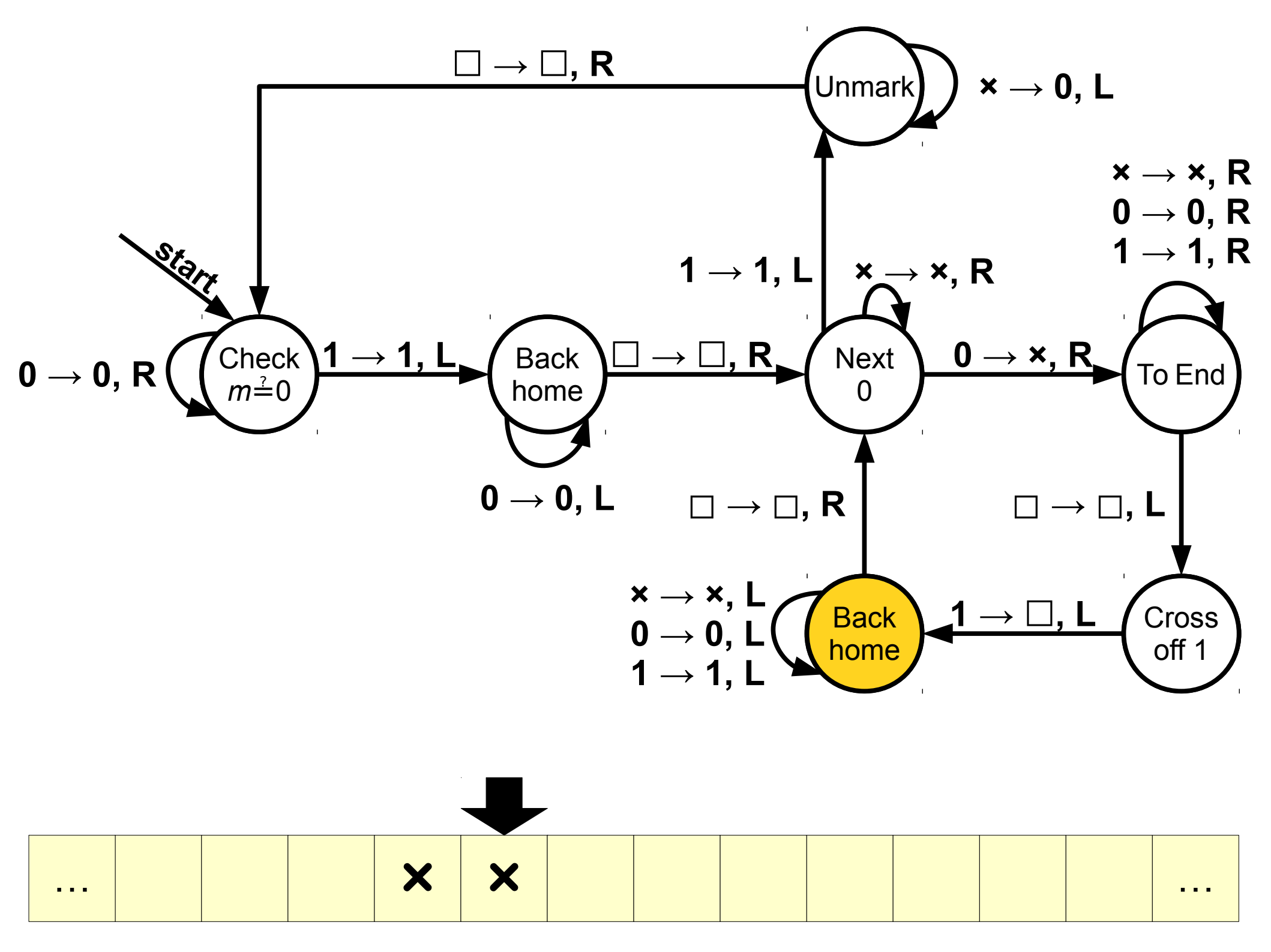

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
…

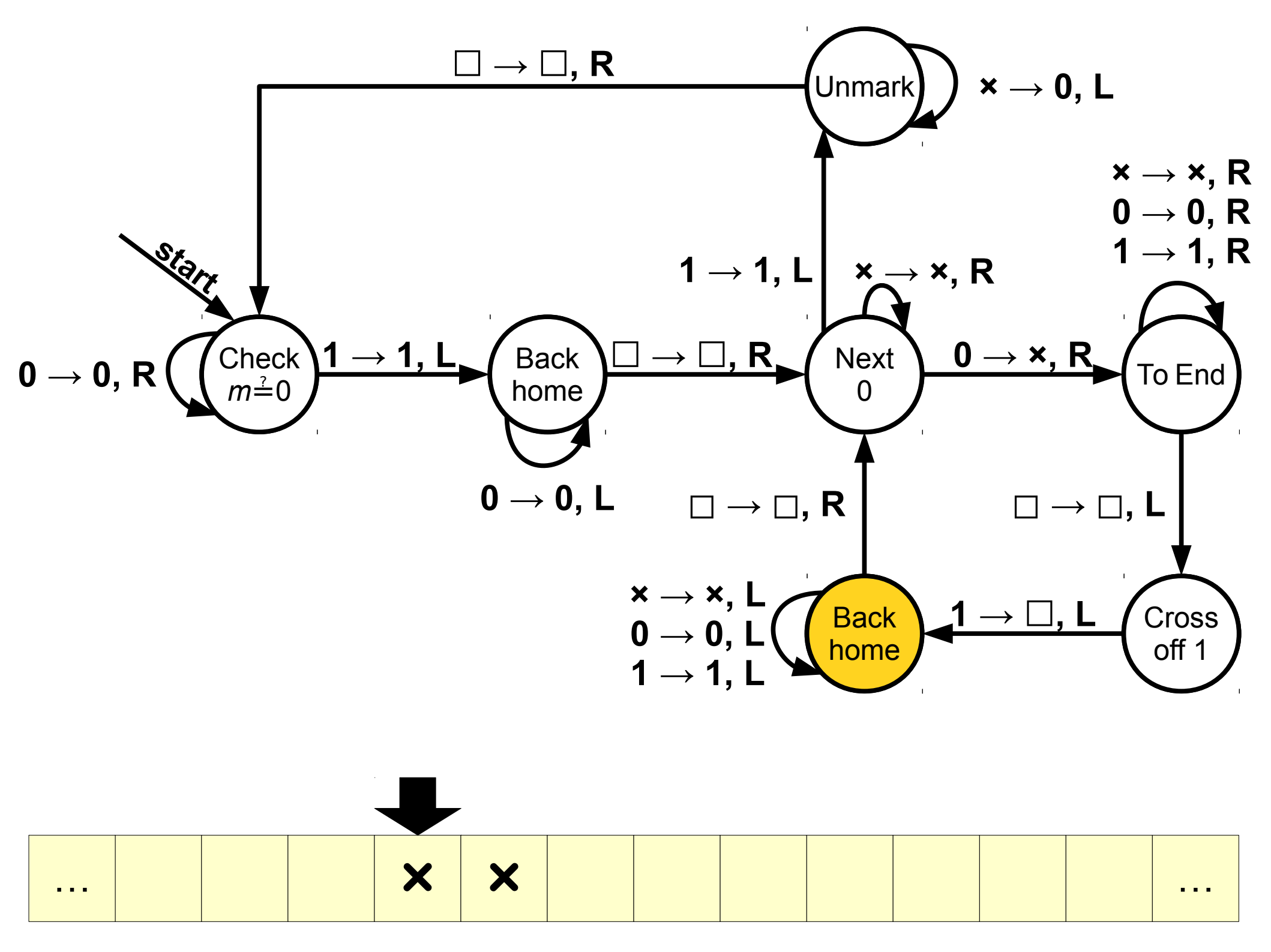

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
…

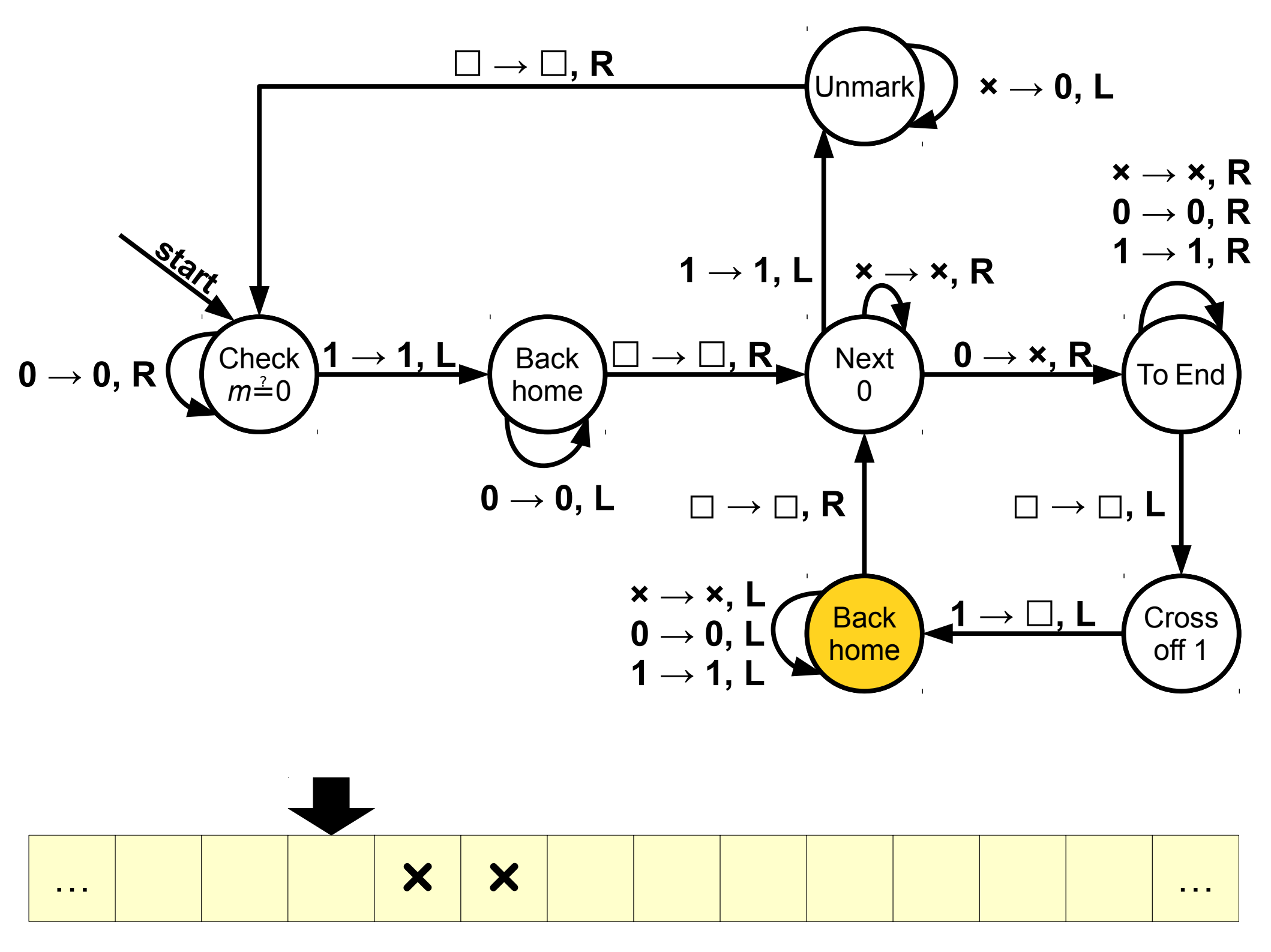

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
×
1
…

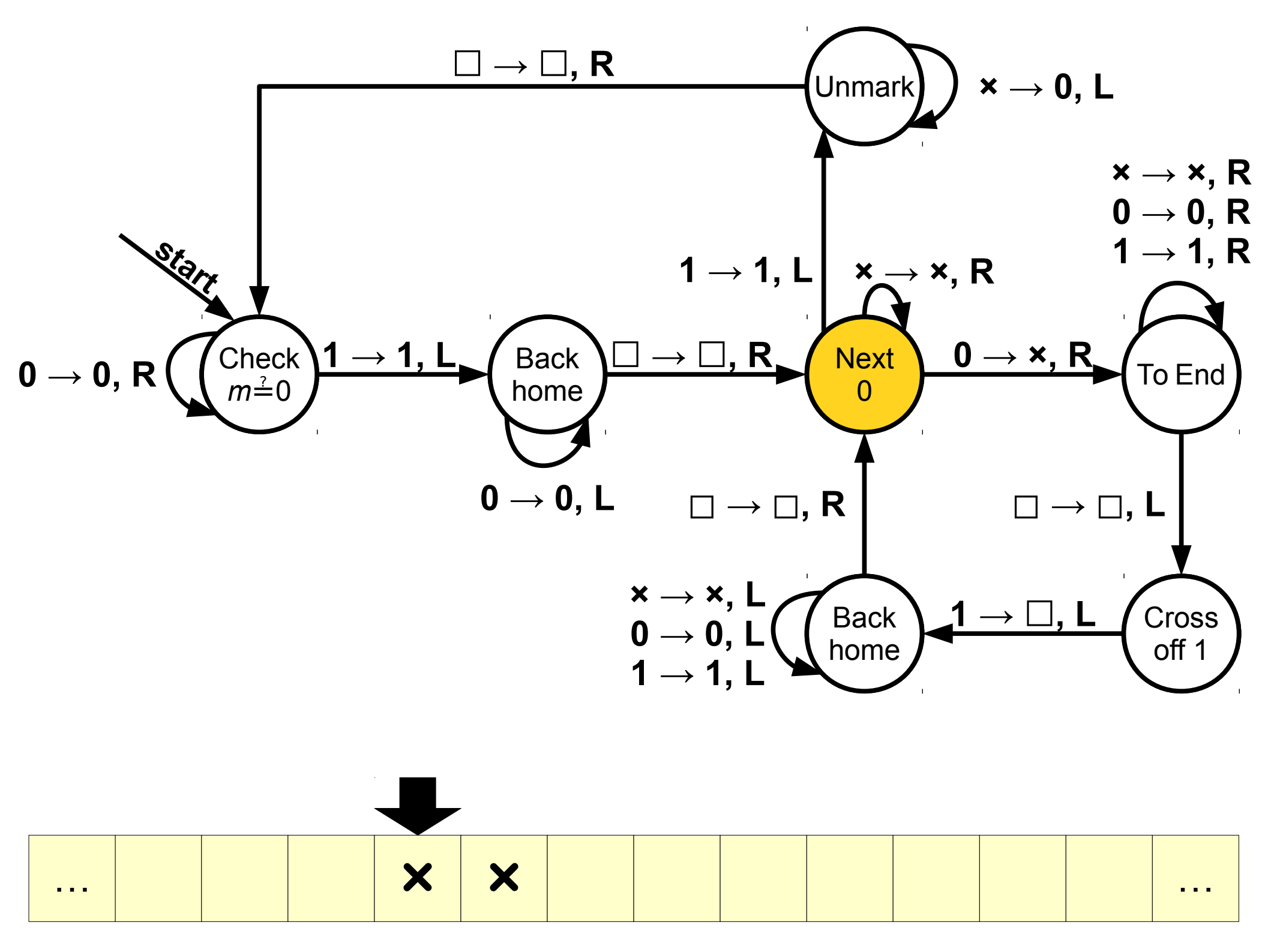

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m ≟ 0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
… × × 1 …


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
×
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
×
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
0 → 0, R
Check
m≟0
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
×
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
start
1 → 1, L
× → ×, R
Check
m≟0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
×
…


start
Check
m=0
Unmark
Back
home
Next
0
To End
Back
home
Cross
off 1
0 → 0, R
1 → 1, L
□ → □, R
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
0 → ×, R
0 → 0, L
□ → □, L
× → ×, L
0 → 0, L
1 → 1, L
1 → □, L
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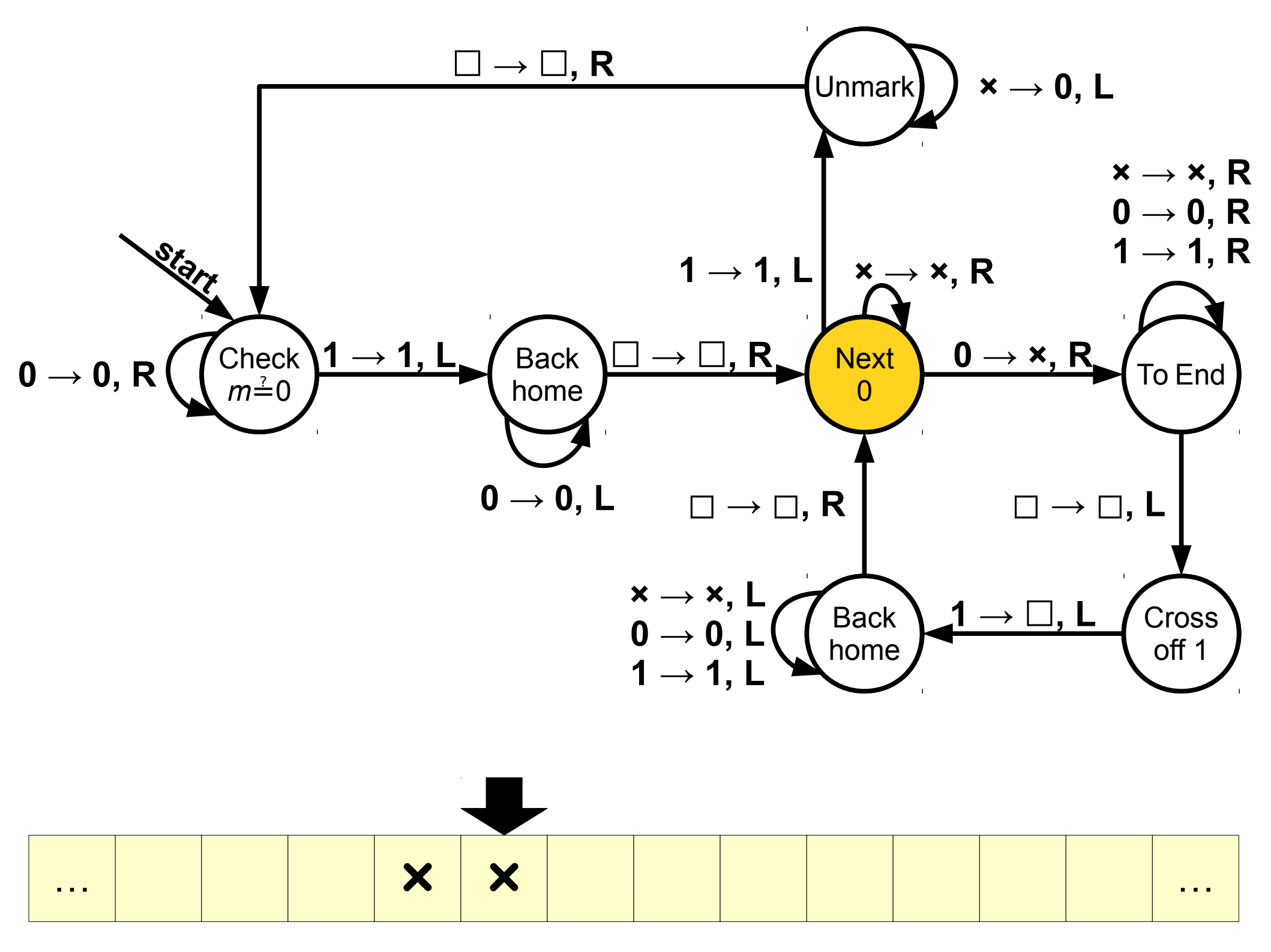
□ → □, R
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1 → 1, L
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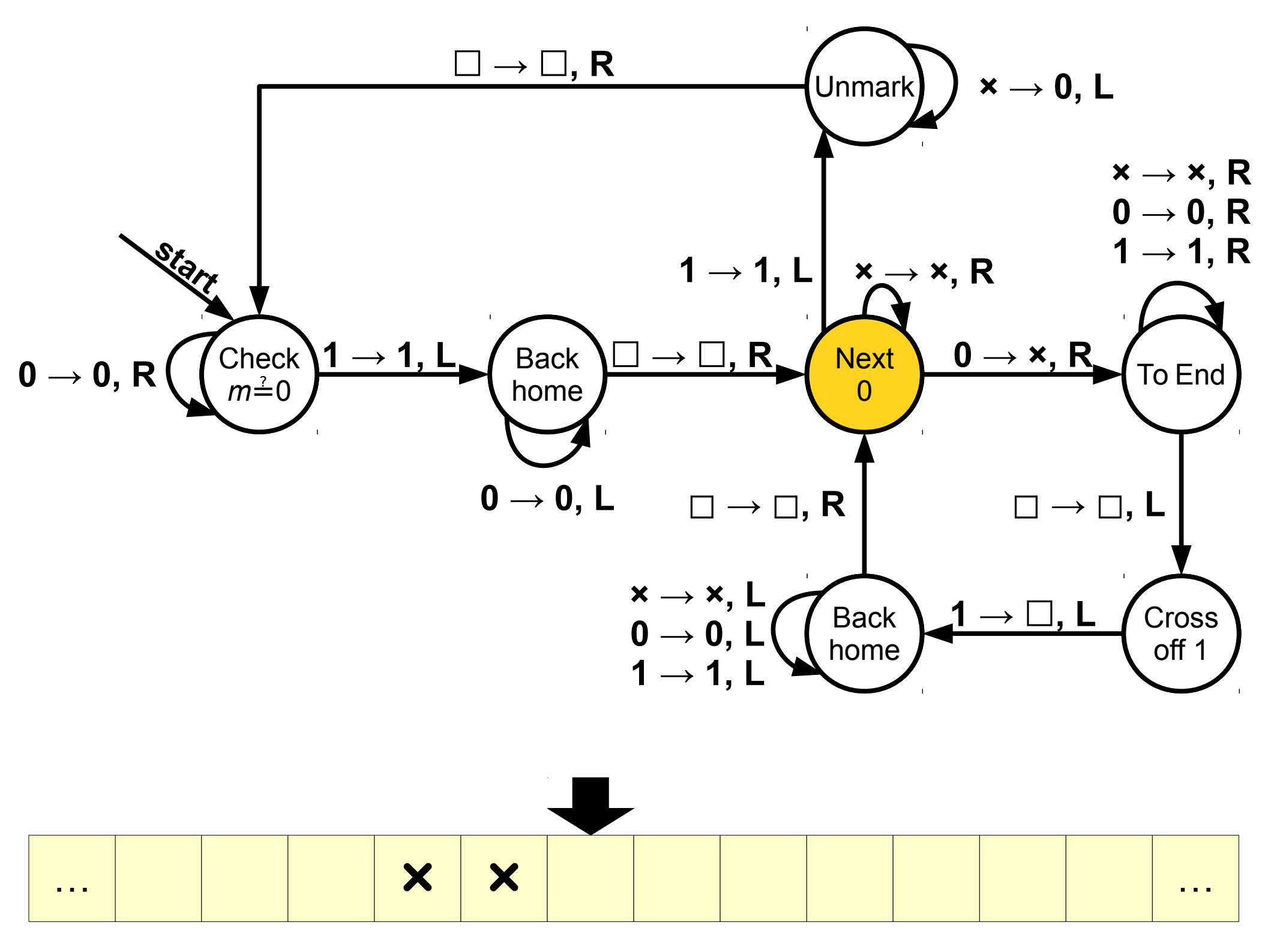
□ → □, R
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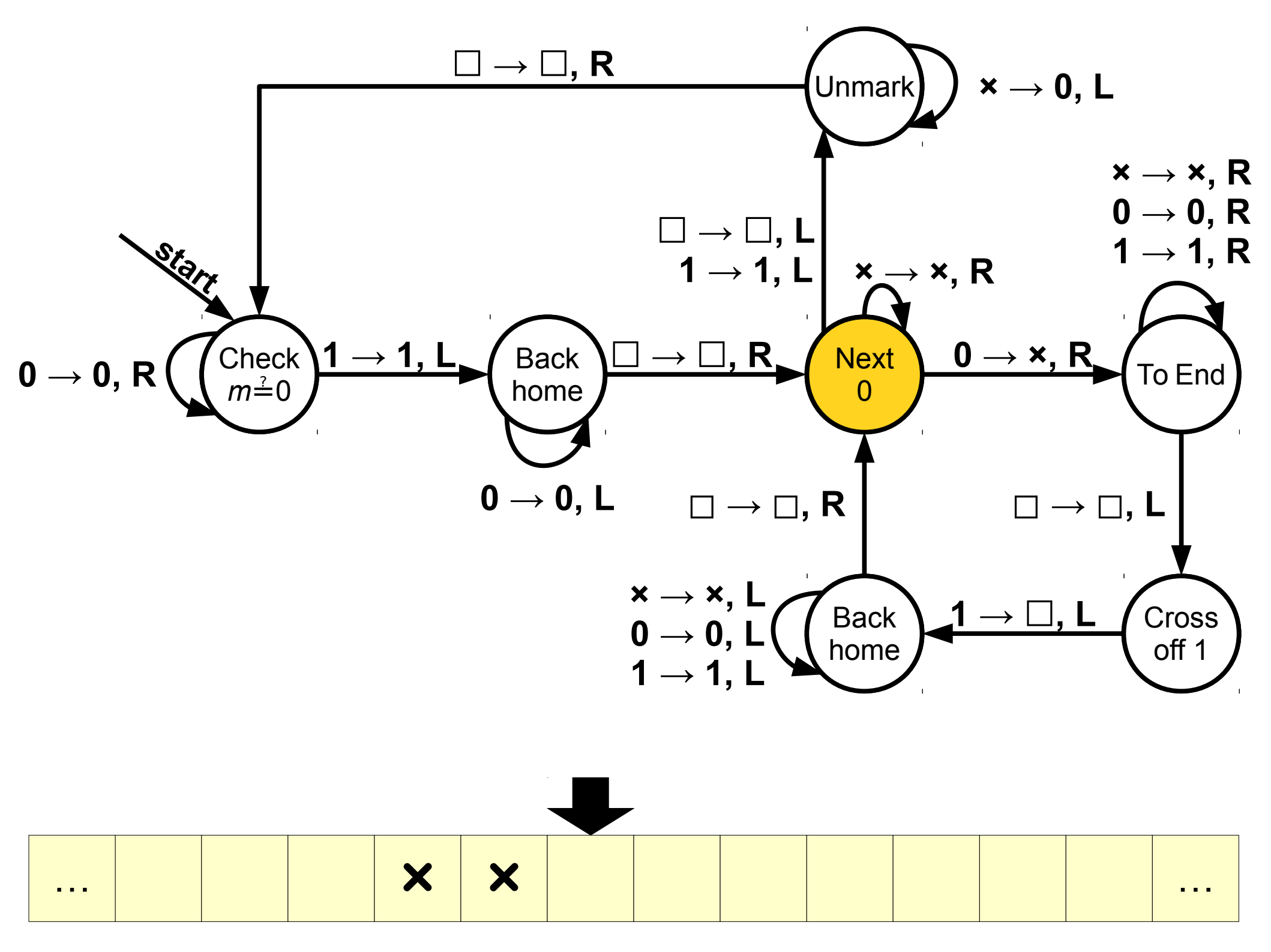
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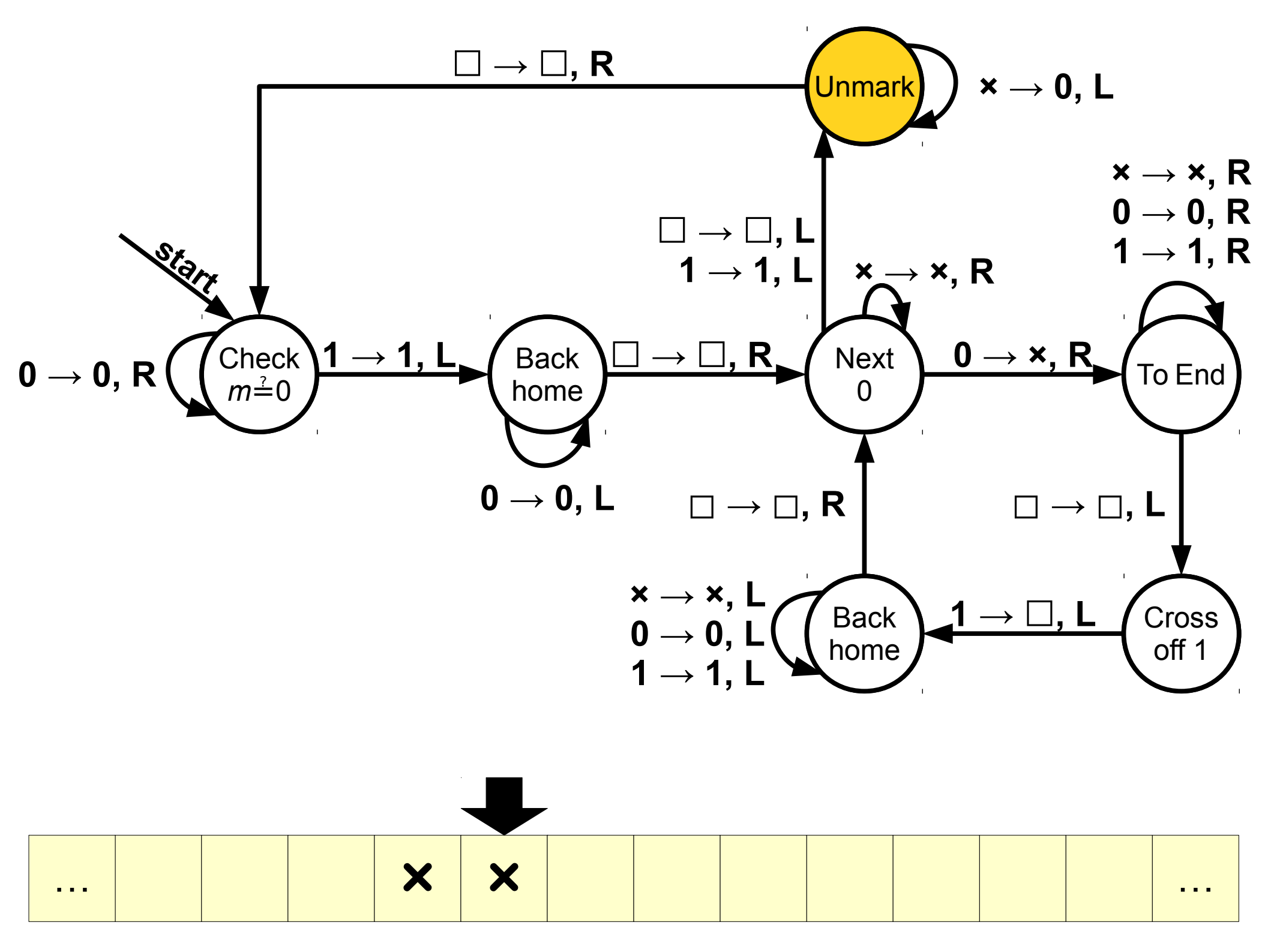
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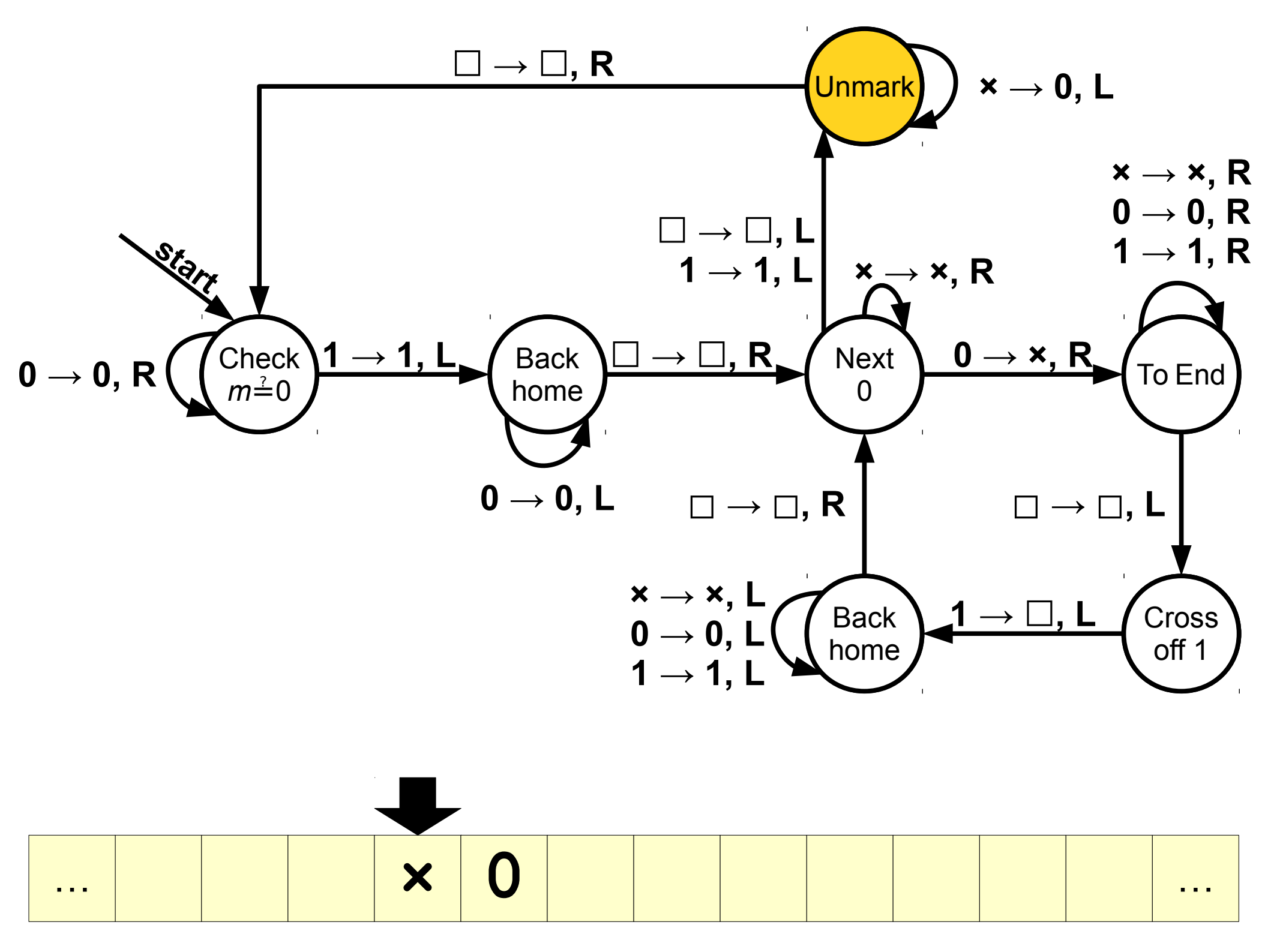
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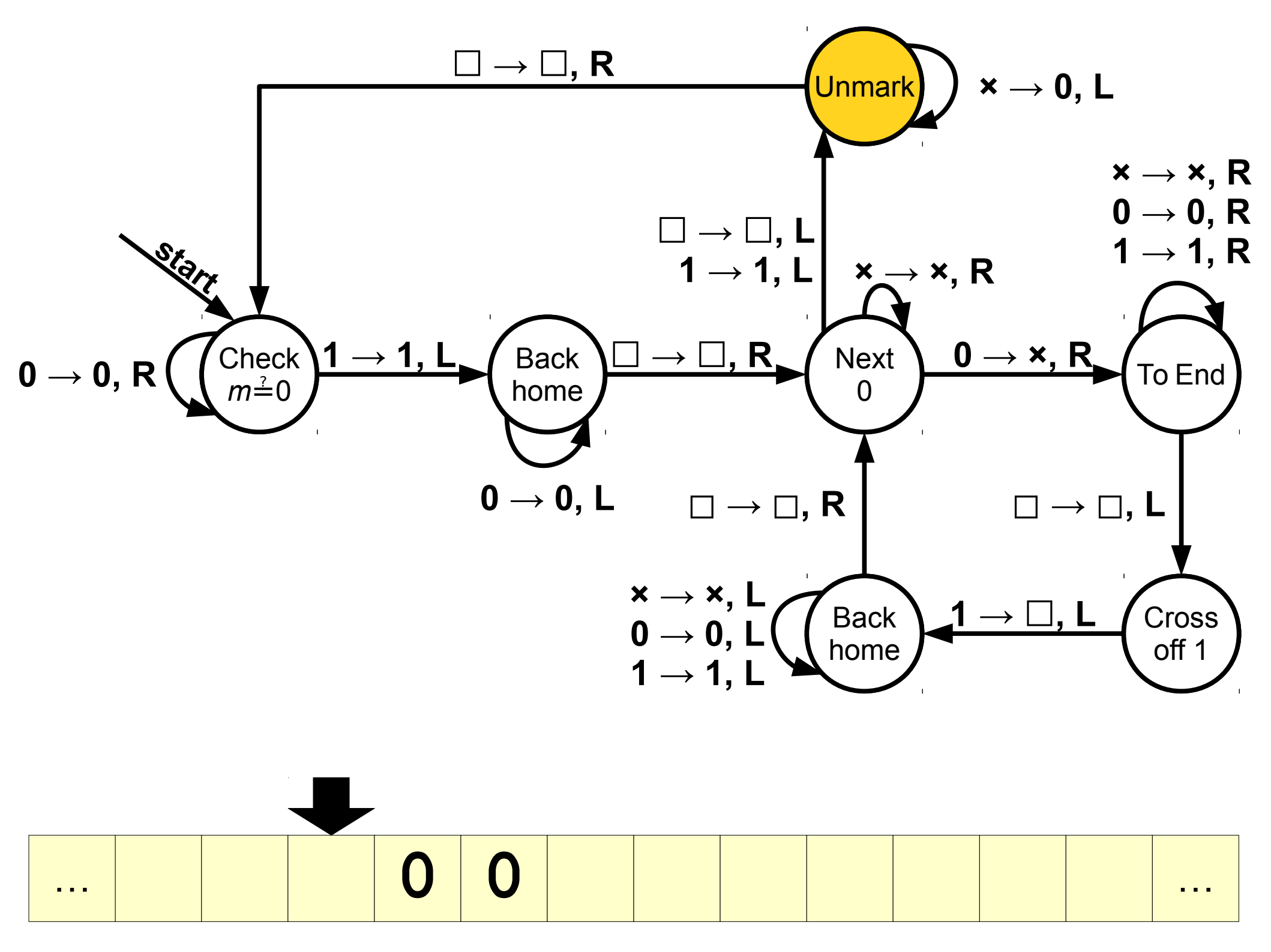
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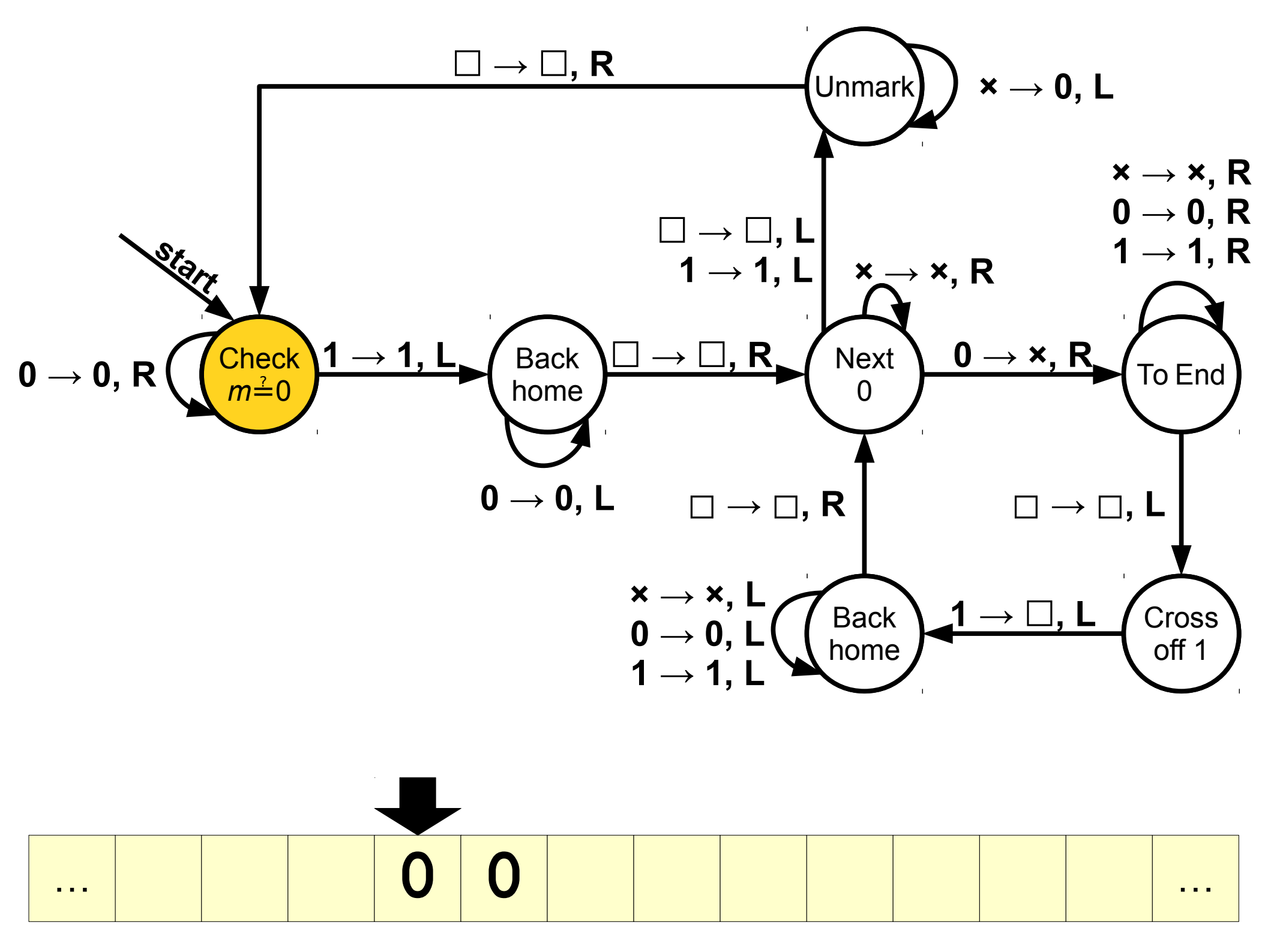
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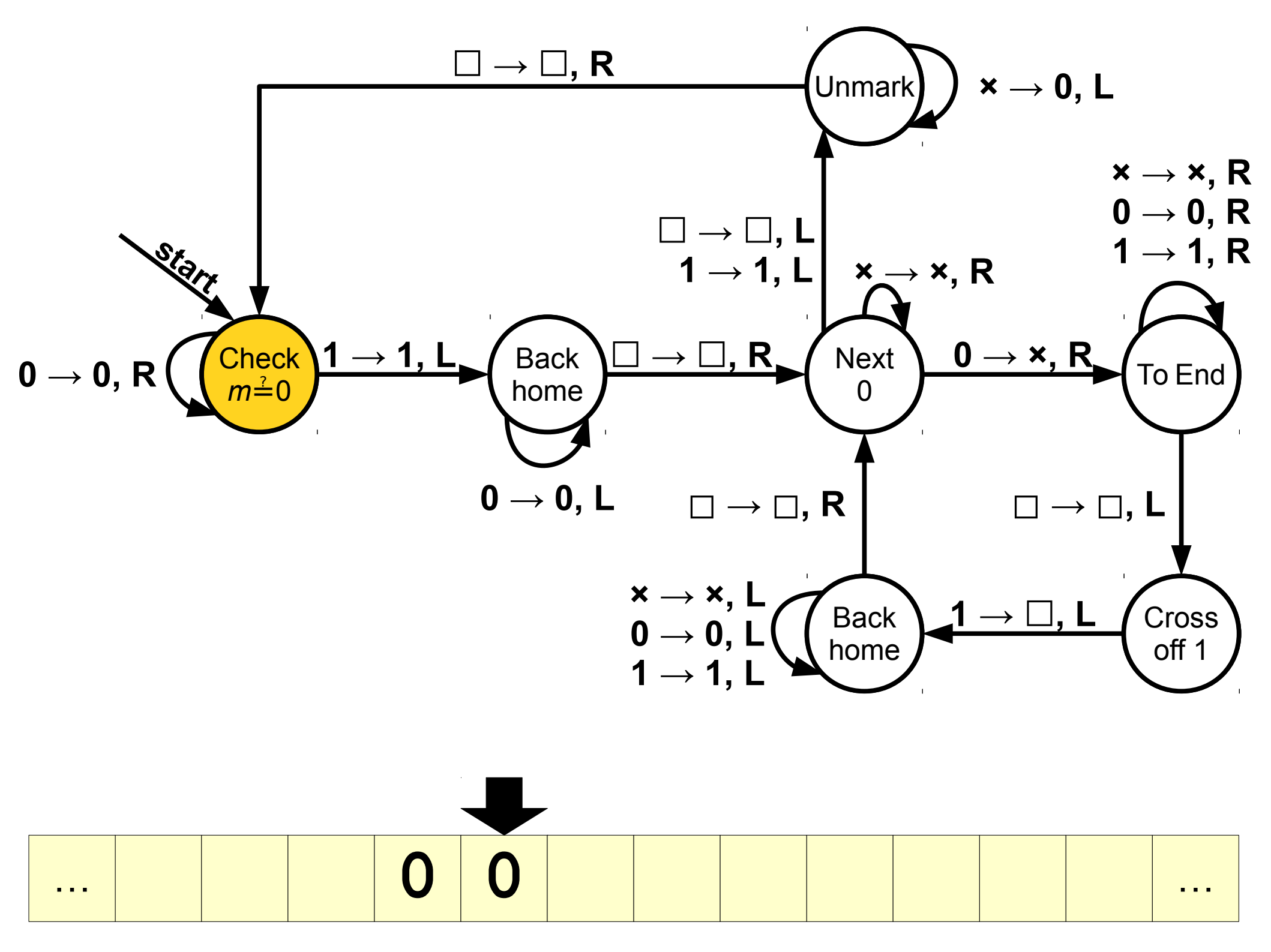
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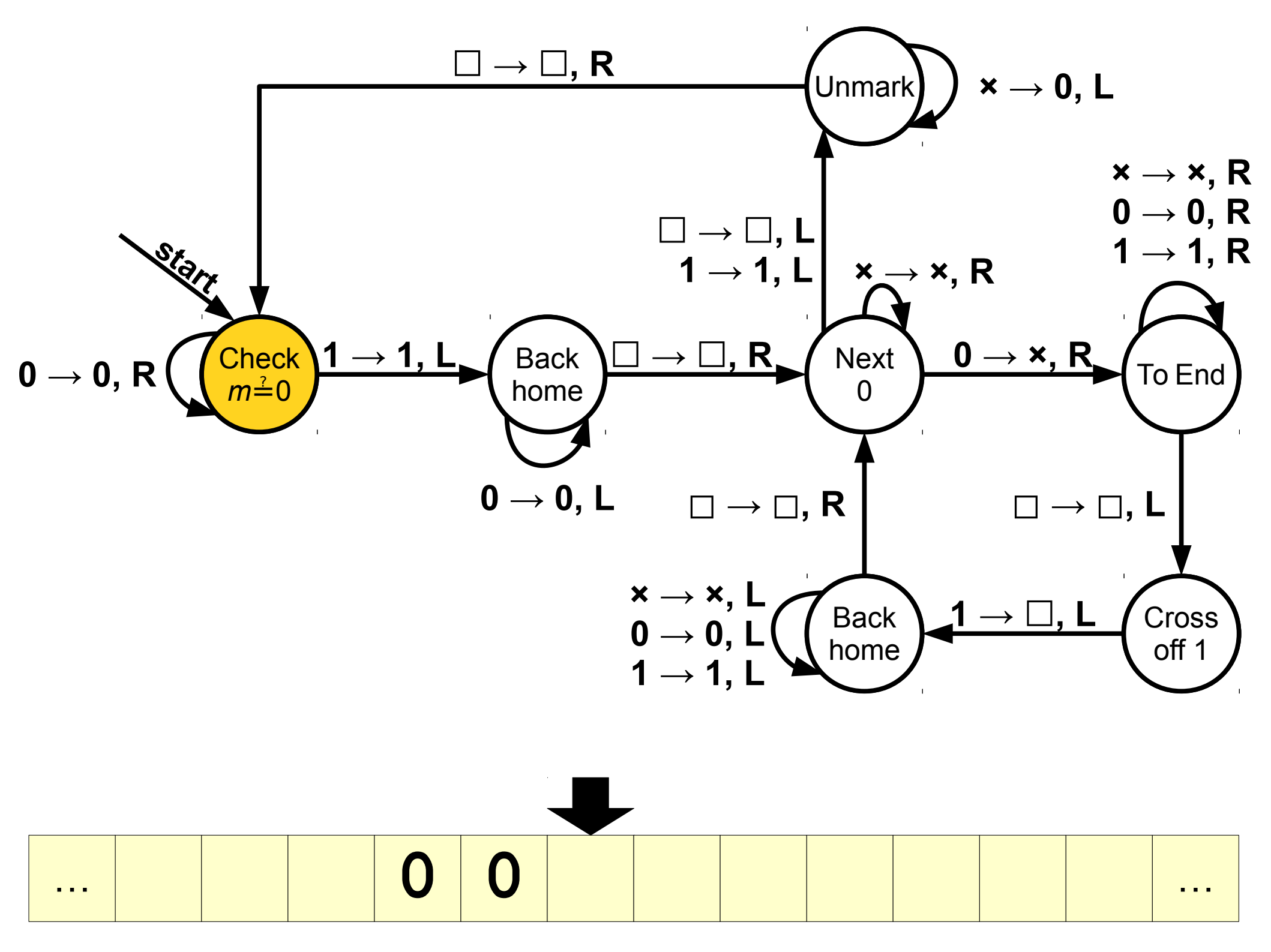
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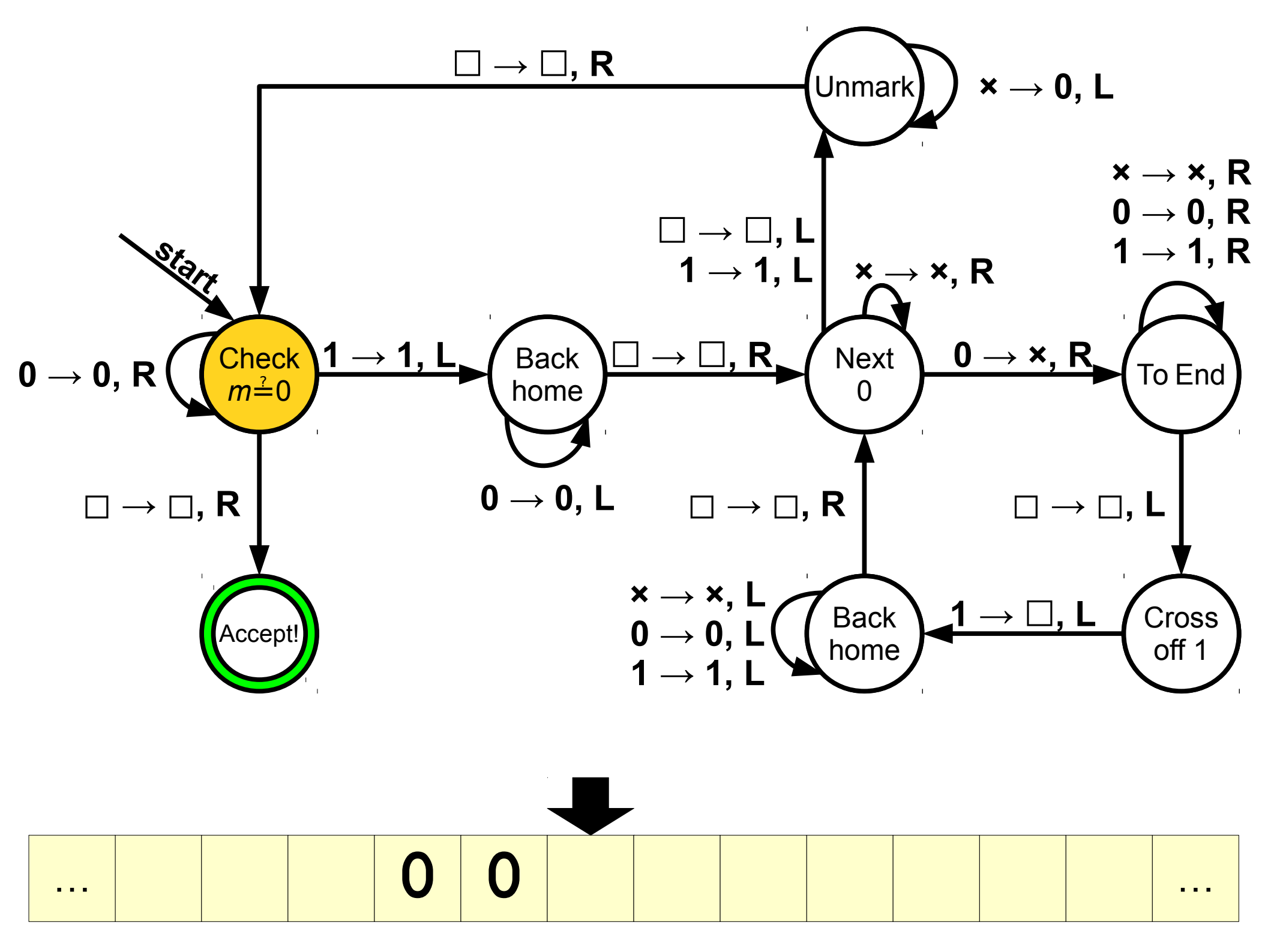
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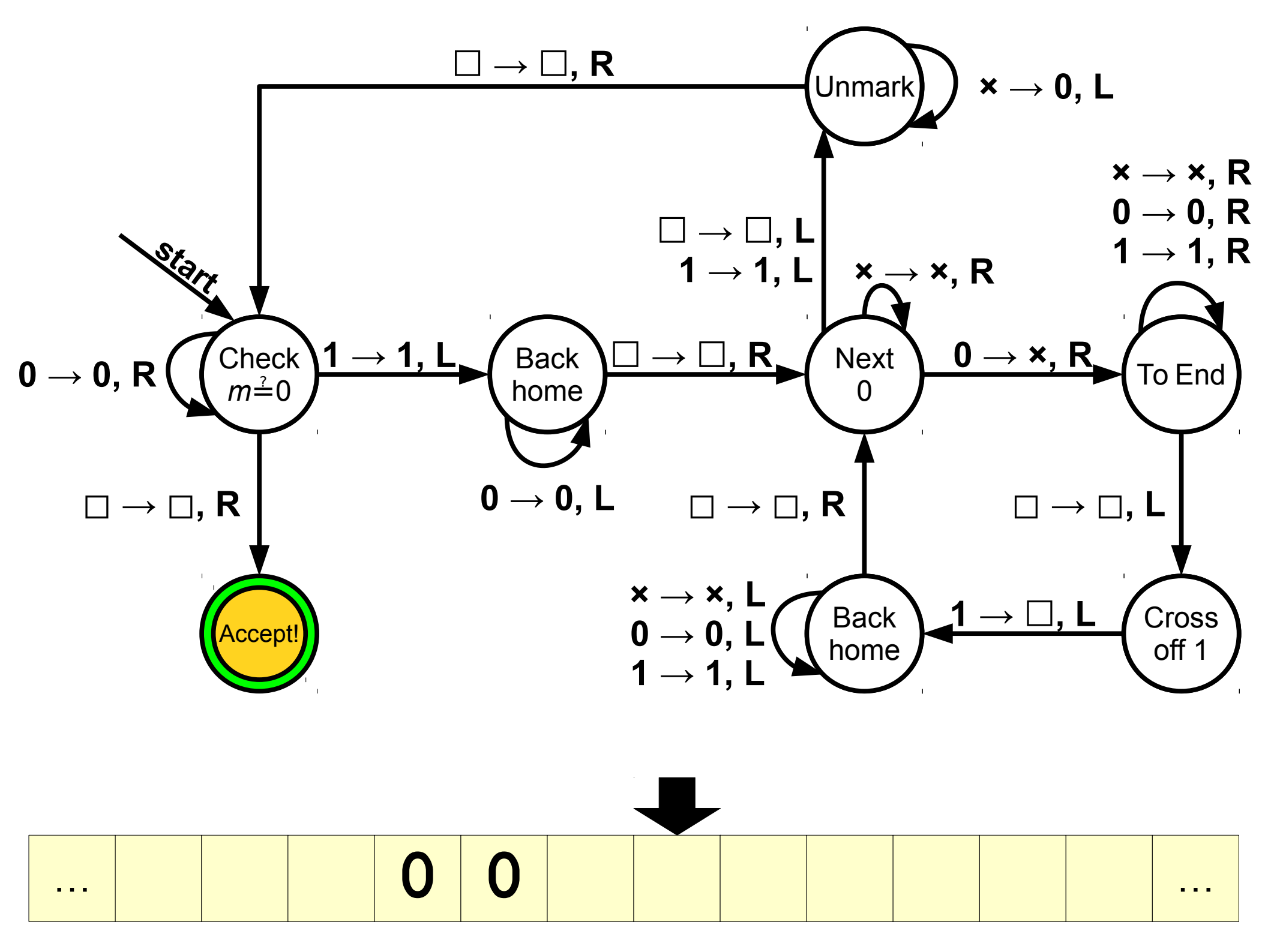
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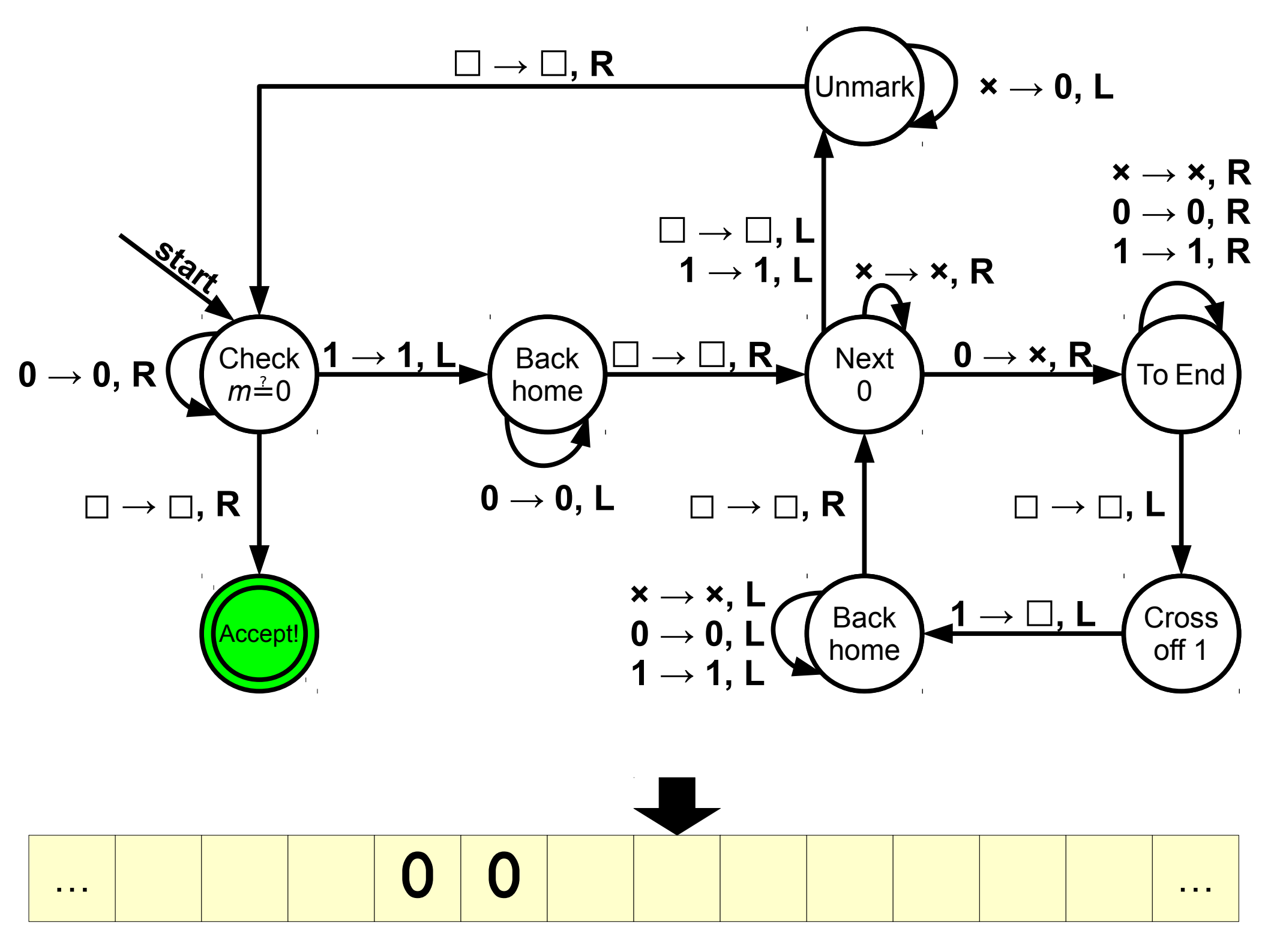
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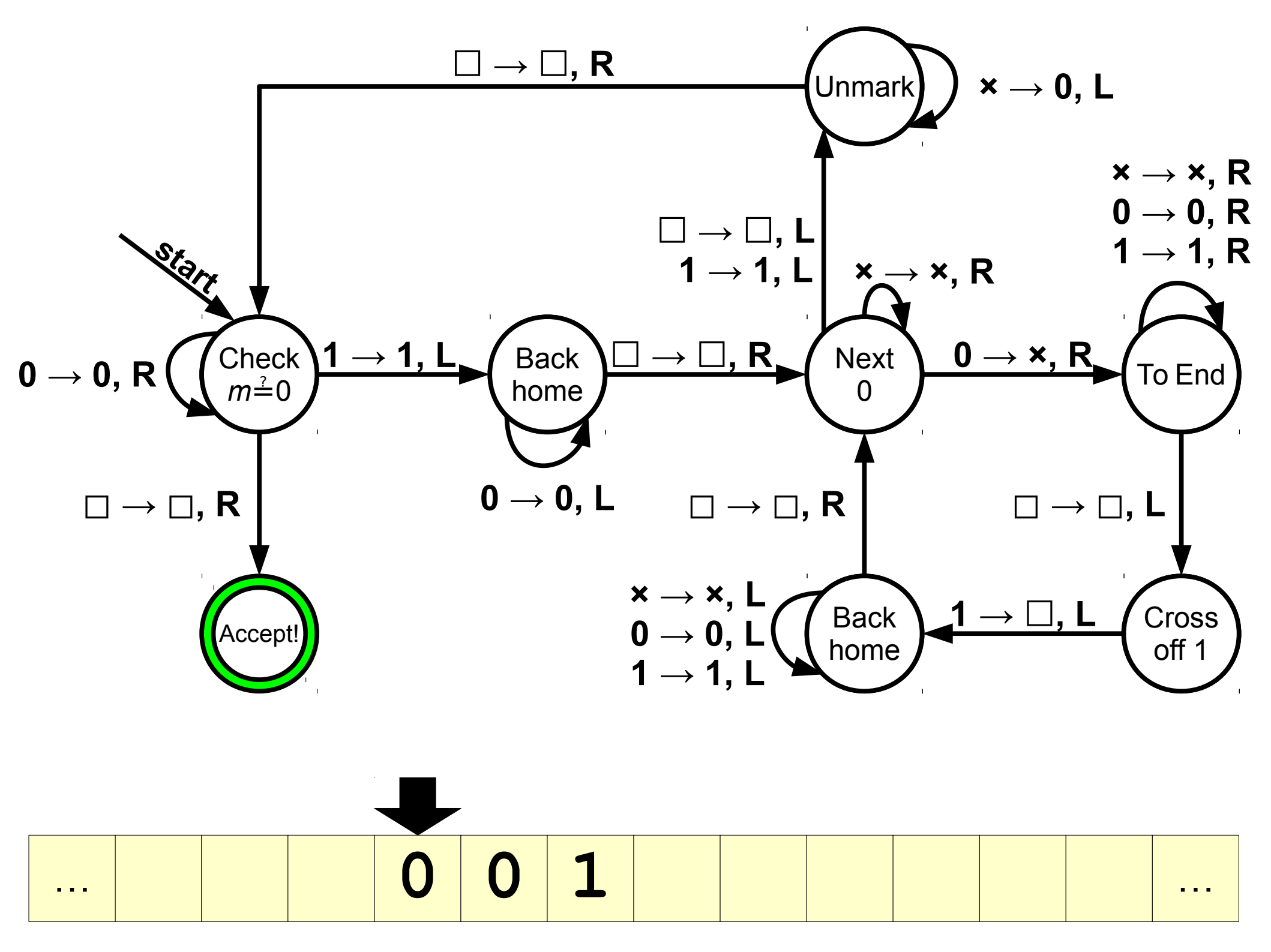
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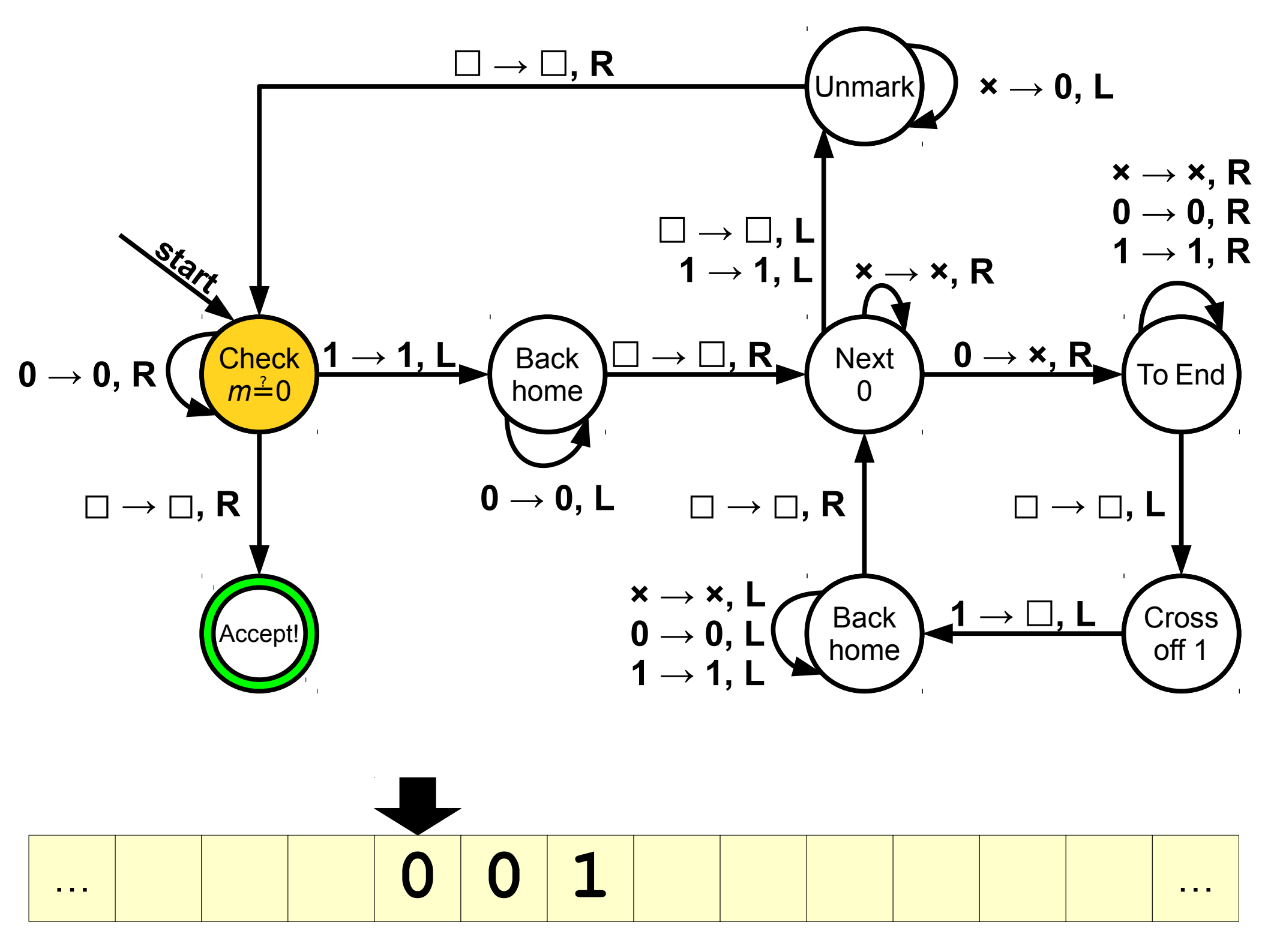
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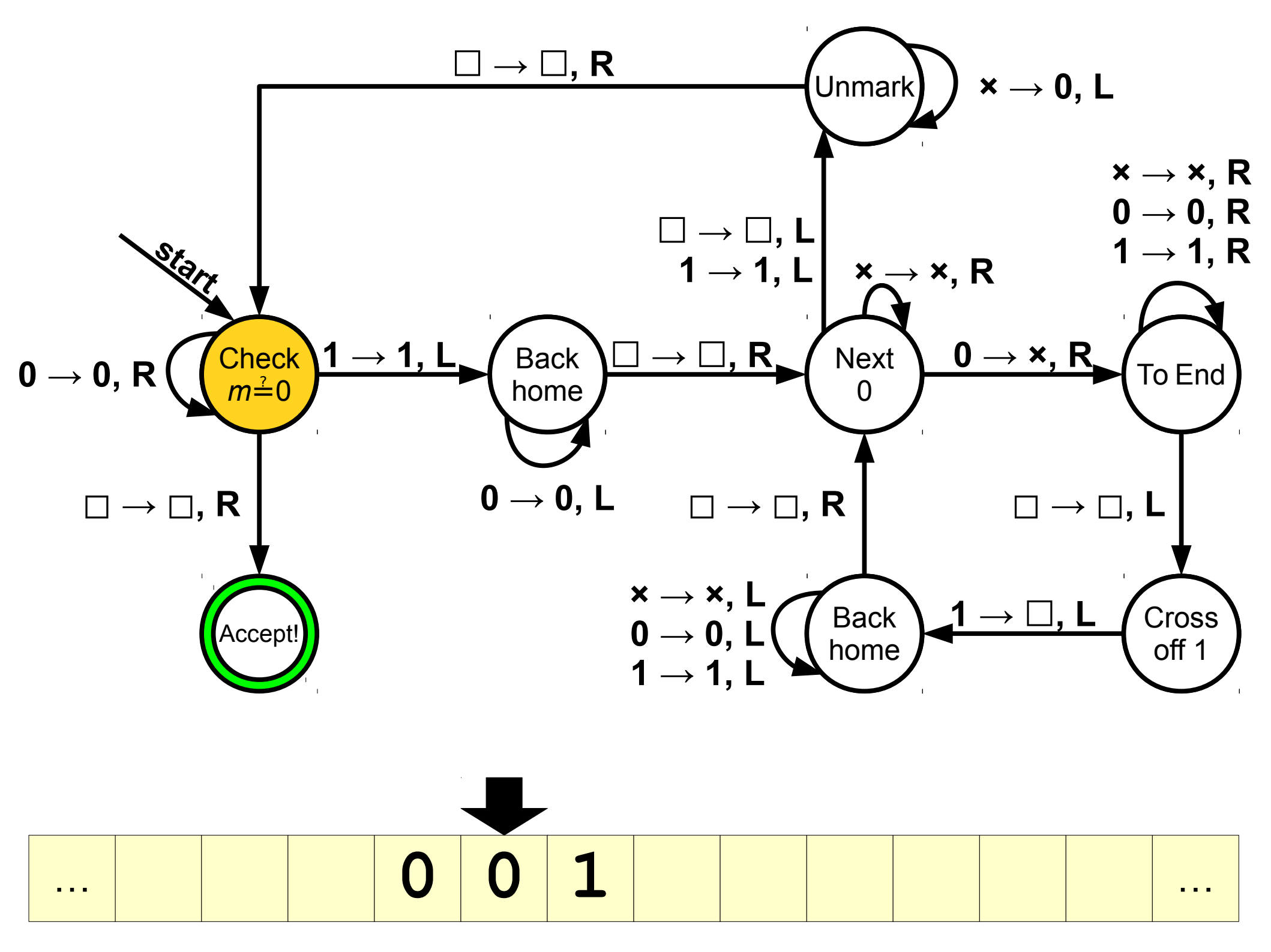
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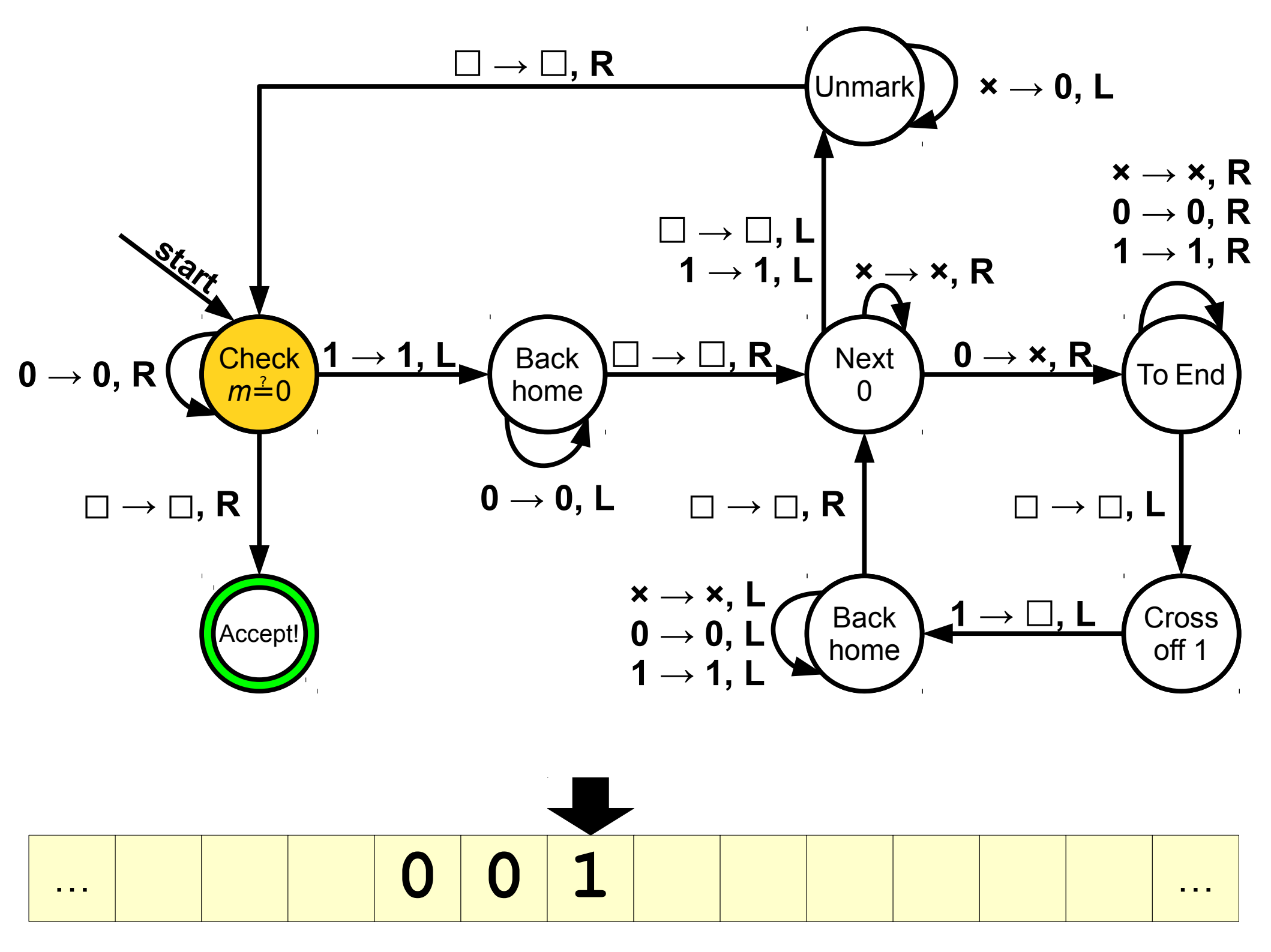
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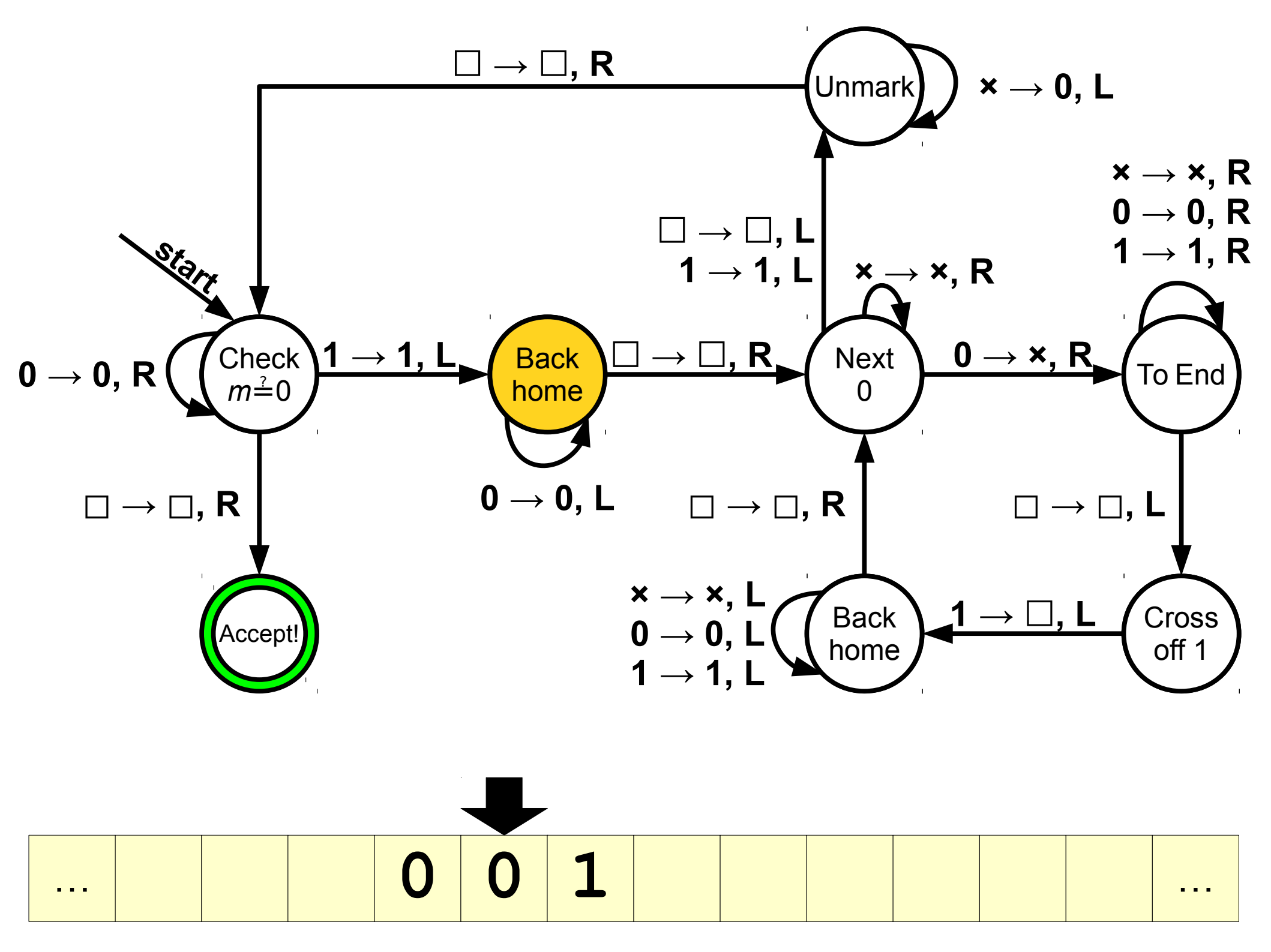
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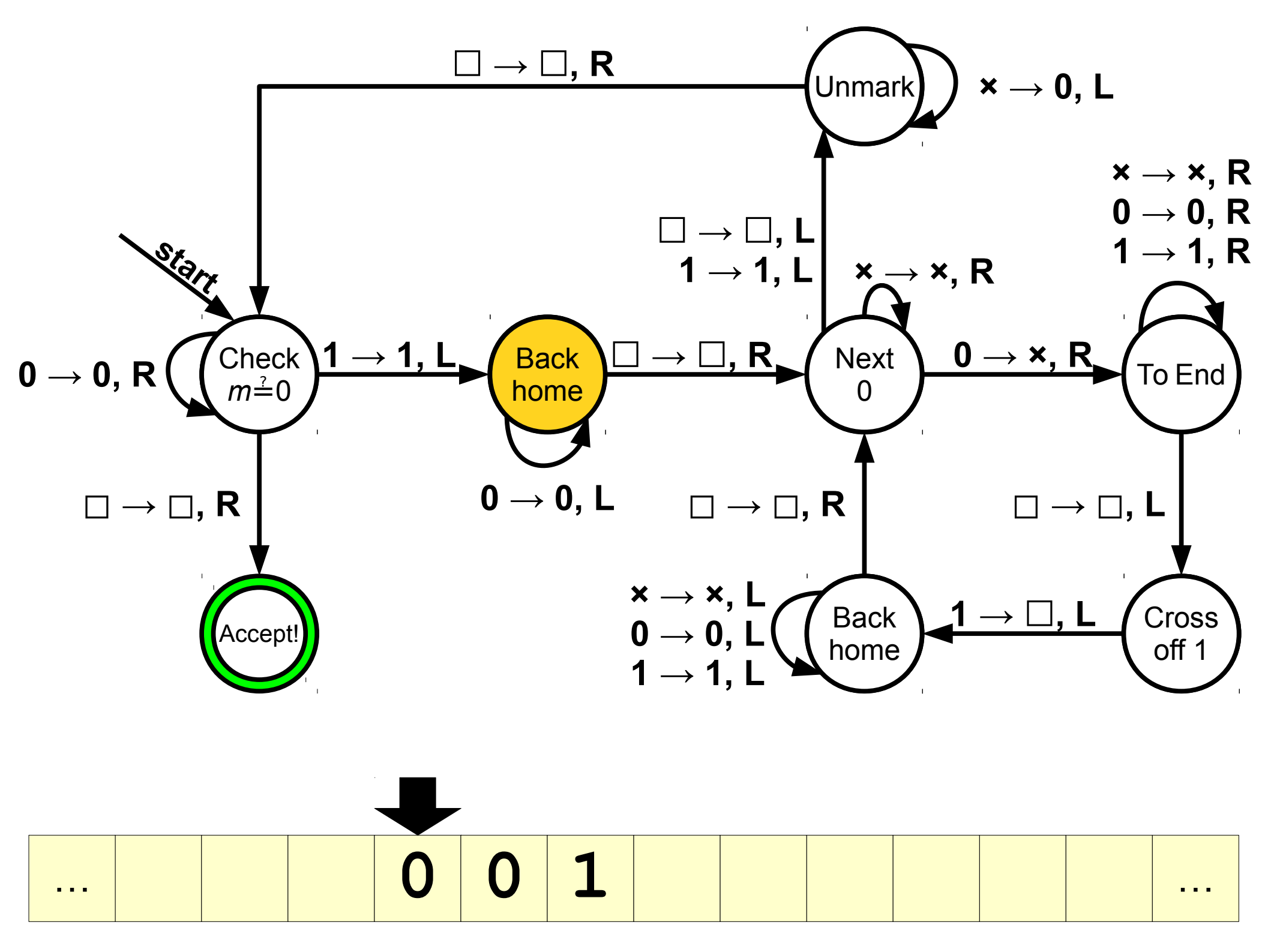
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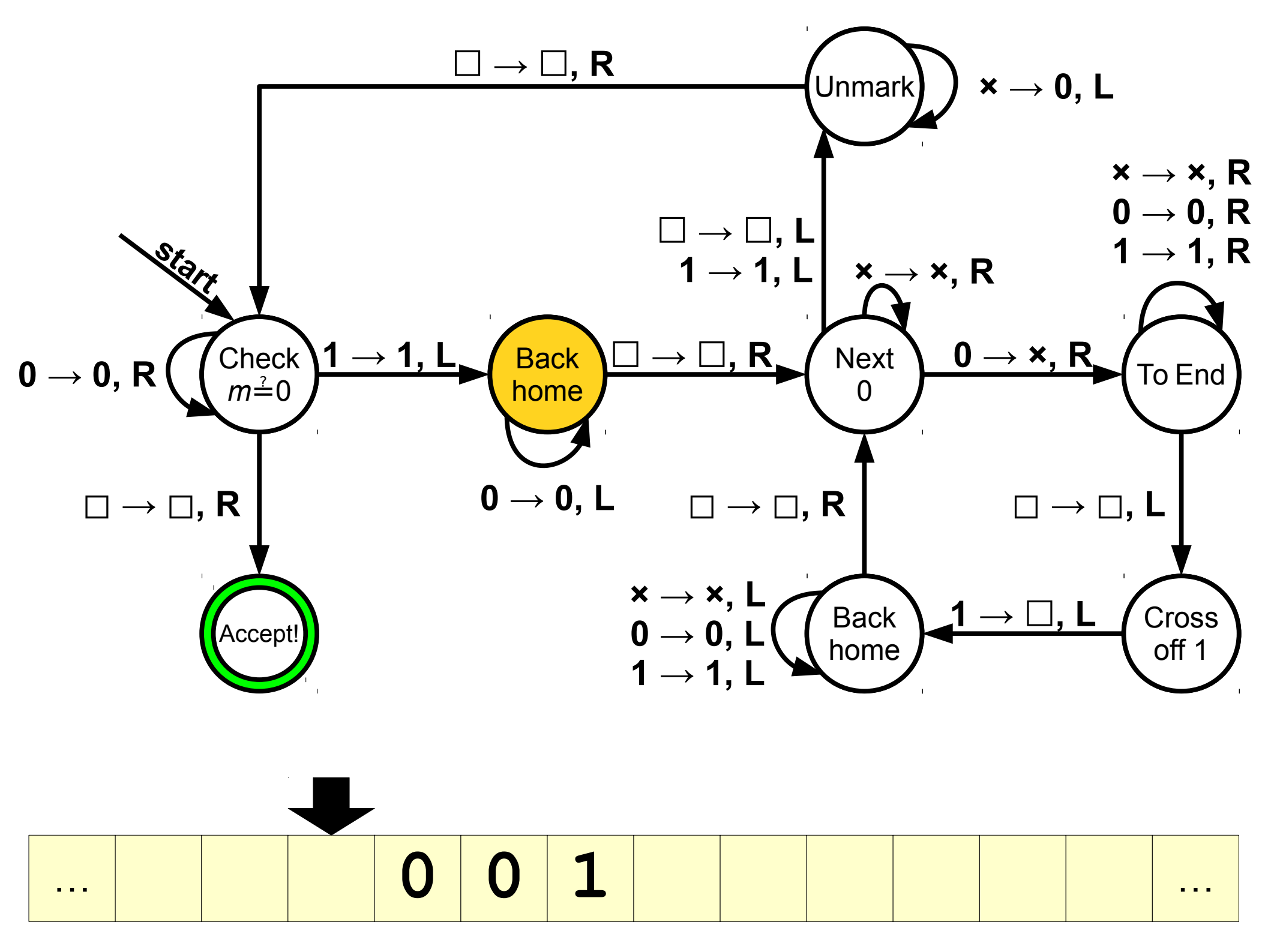
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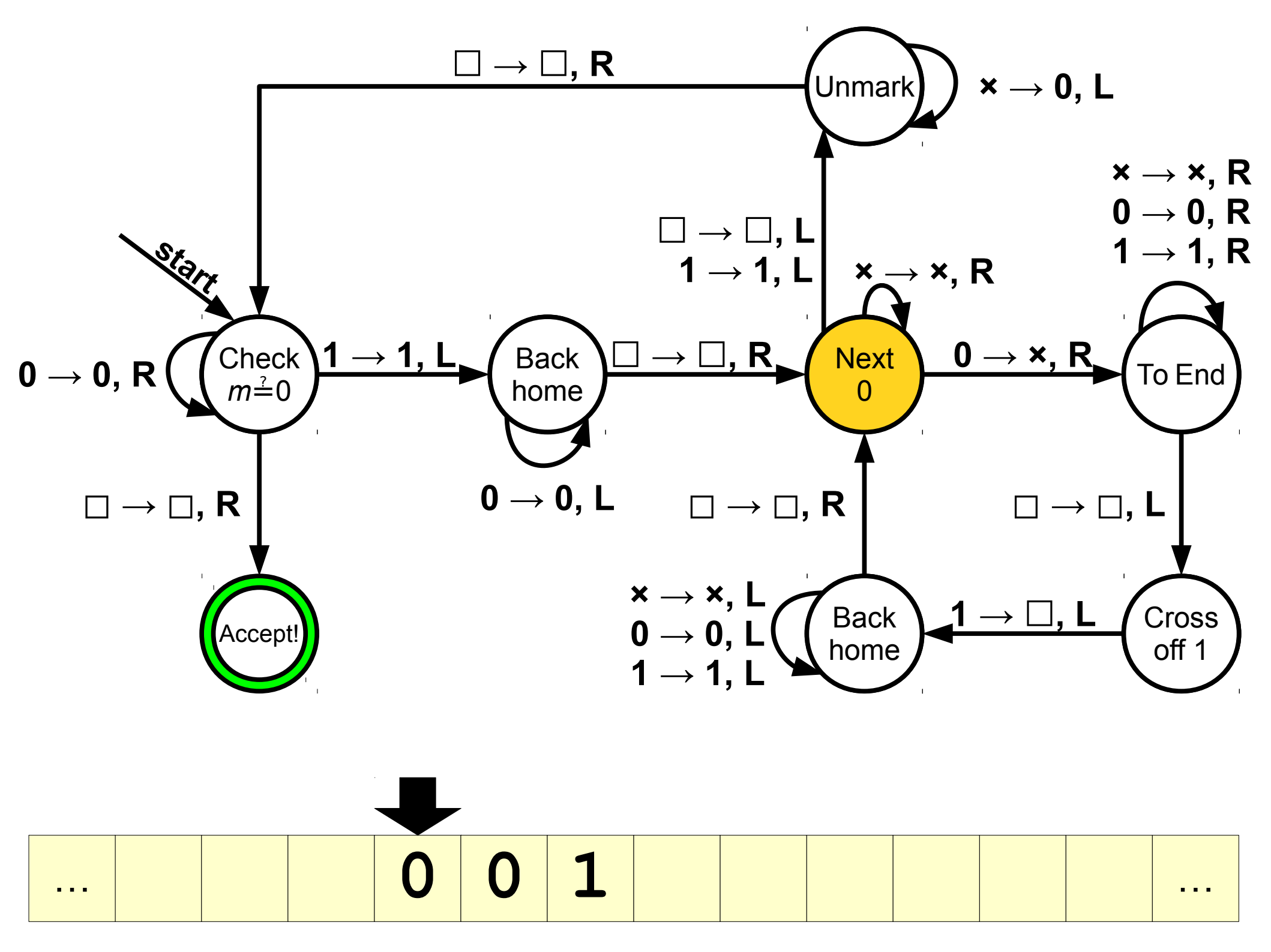
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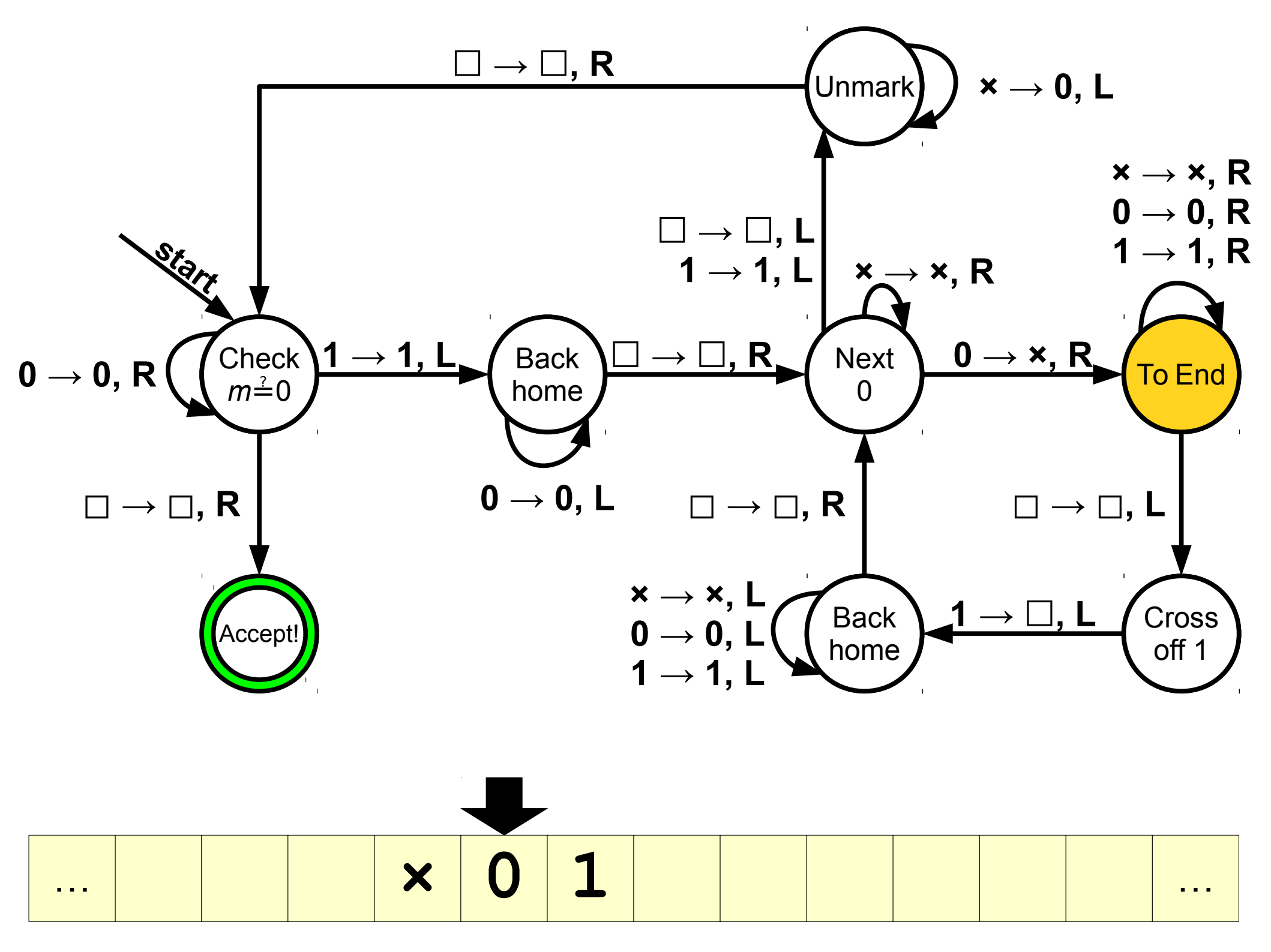
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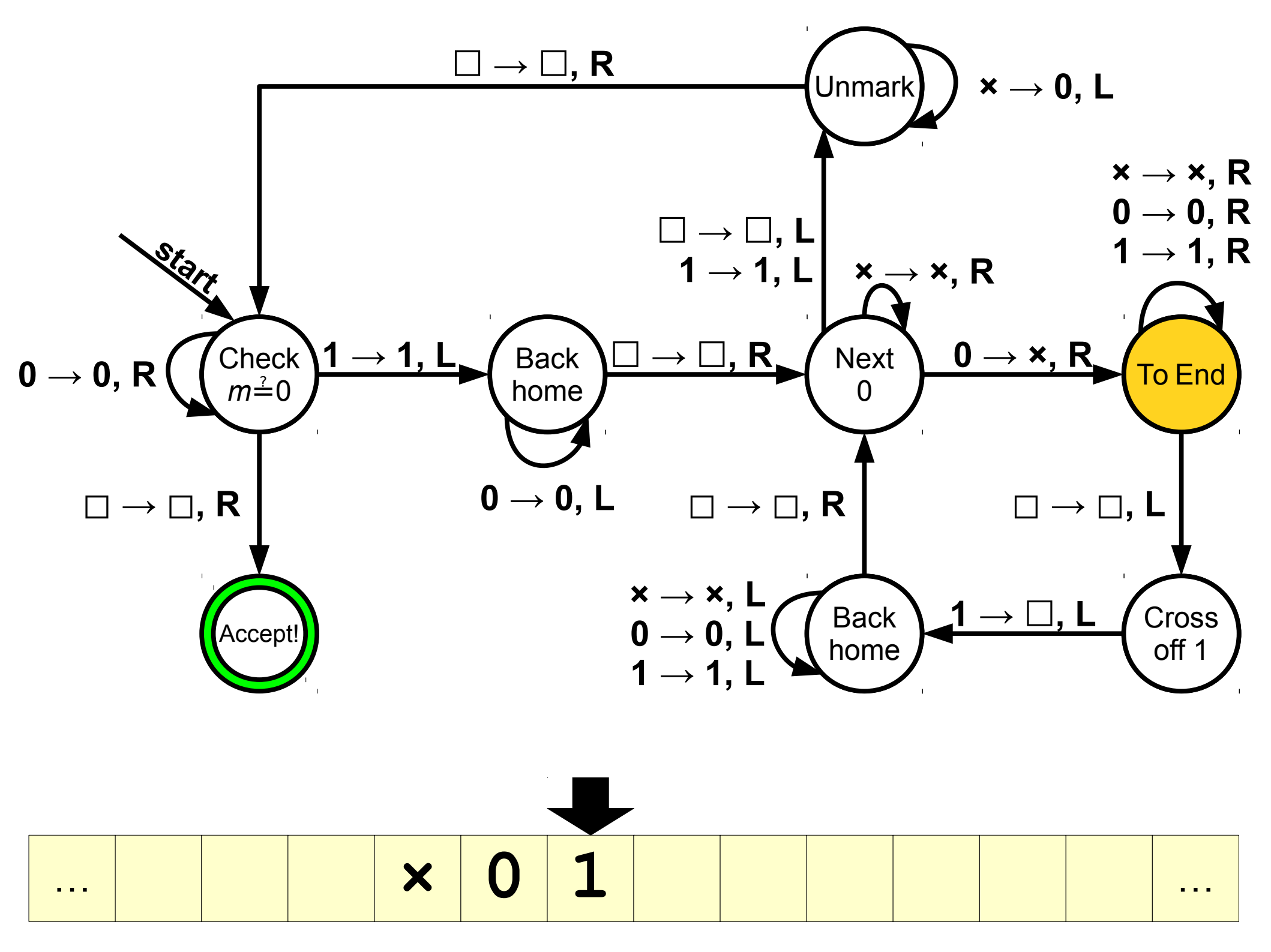
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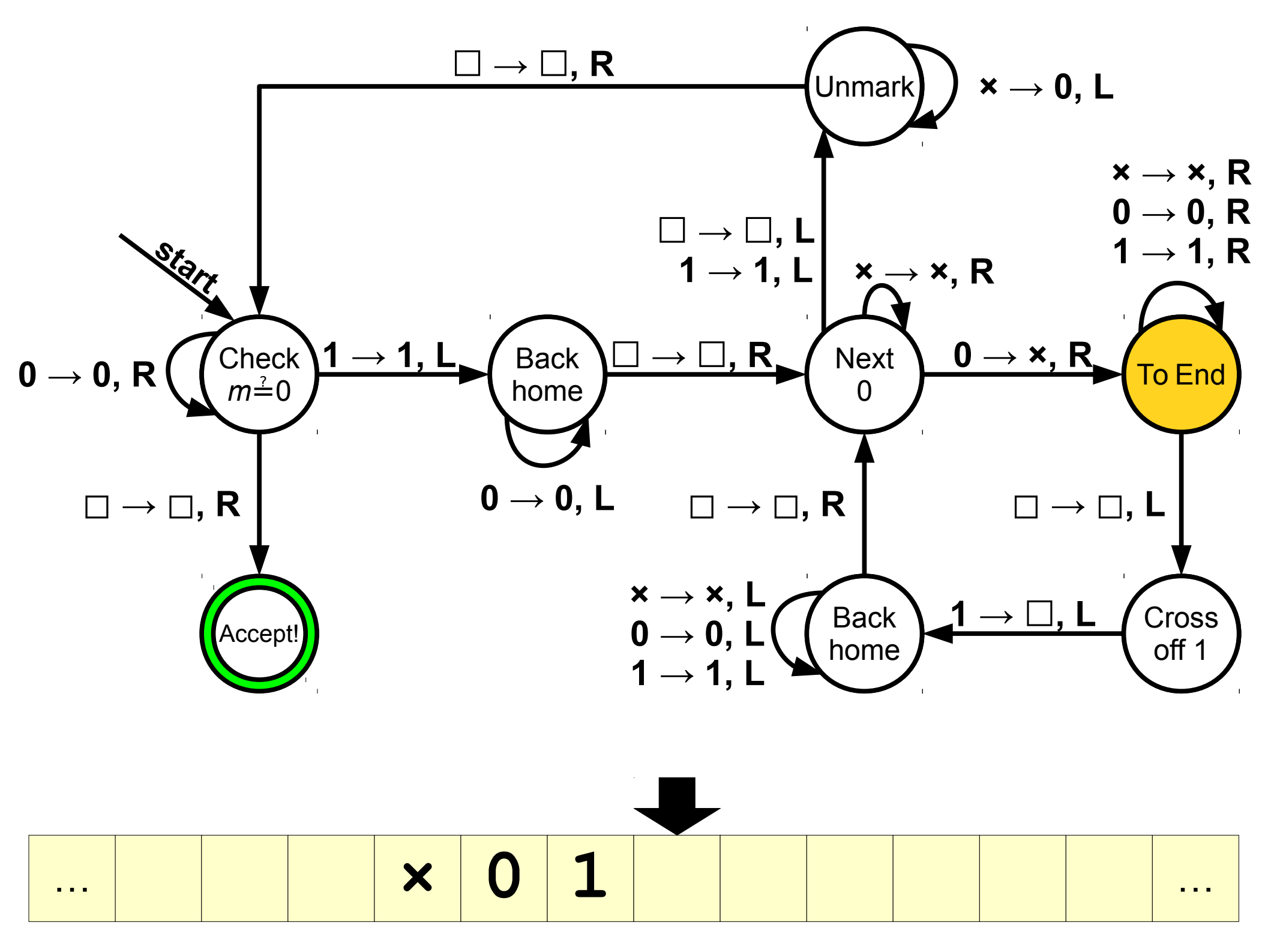
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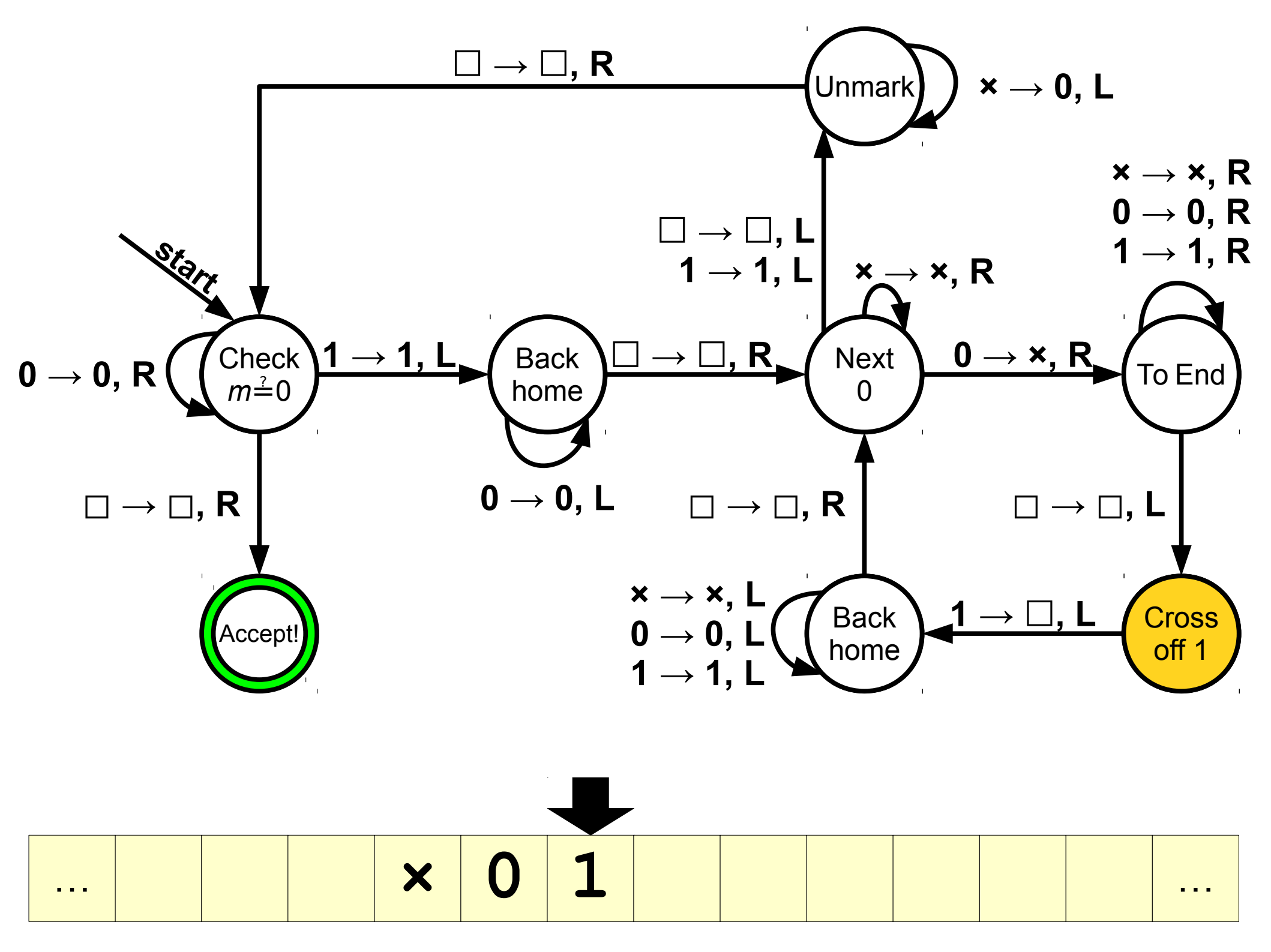
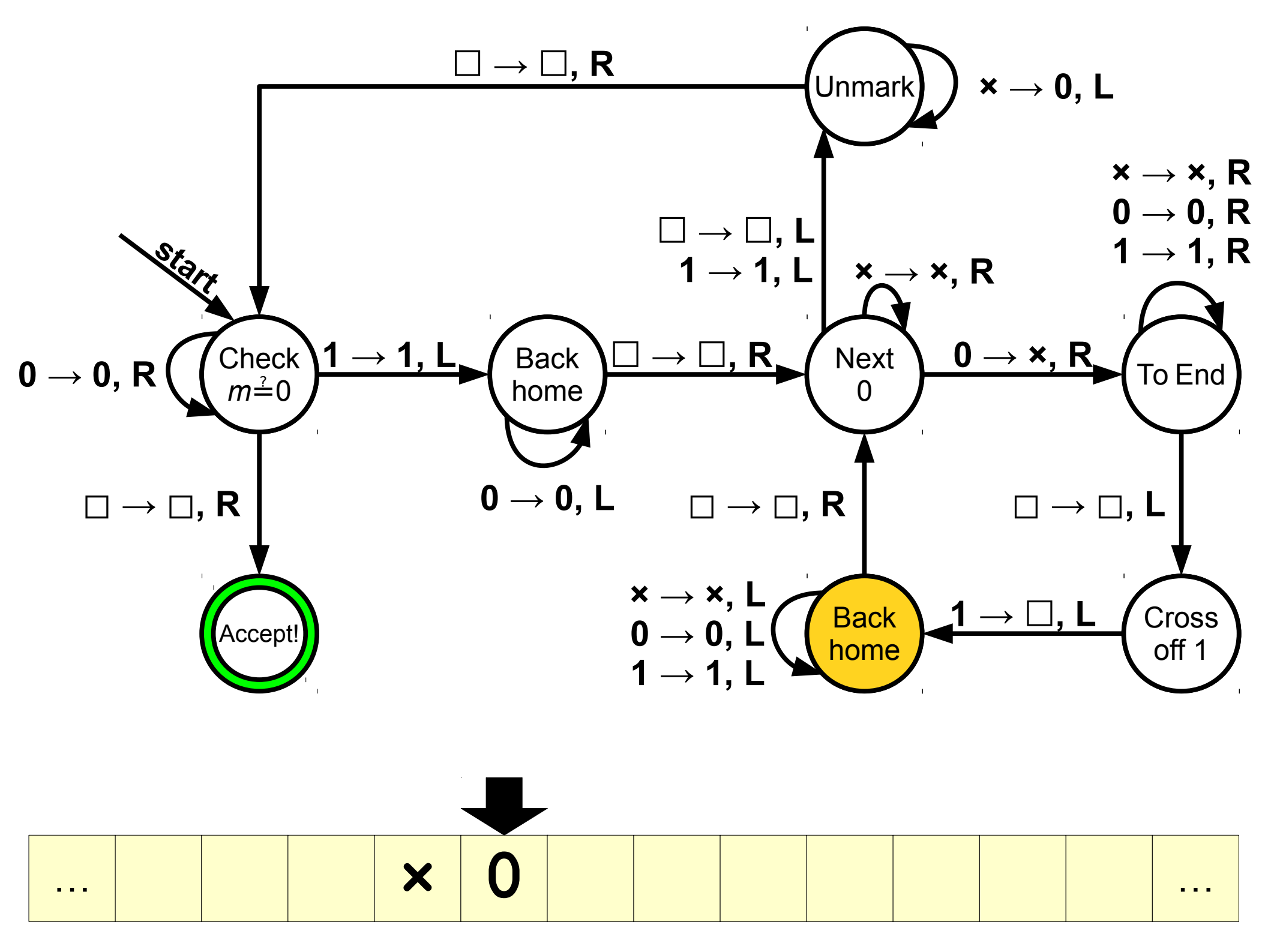

□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
1 → 1, L
× → ×, R
start
Check
m ≟ 0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, R
□ → □, L
Accept!
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
…
×
0
1
…


□ → □, R
Unmark
× → 0, L
× → ×, R
0 → 0, R
1 → 1, R
□ → □, L
1 → 1, L
× → ×, R
start
Check
m ≟ 0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
0
0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, R
□ → □, L
Accept!
× → ×, L
0 → 0, L
1 → 1, L
Back
home
1 → □, L
Cross
off 1
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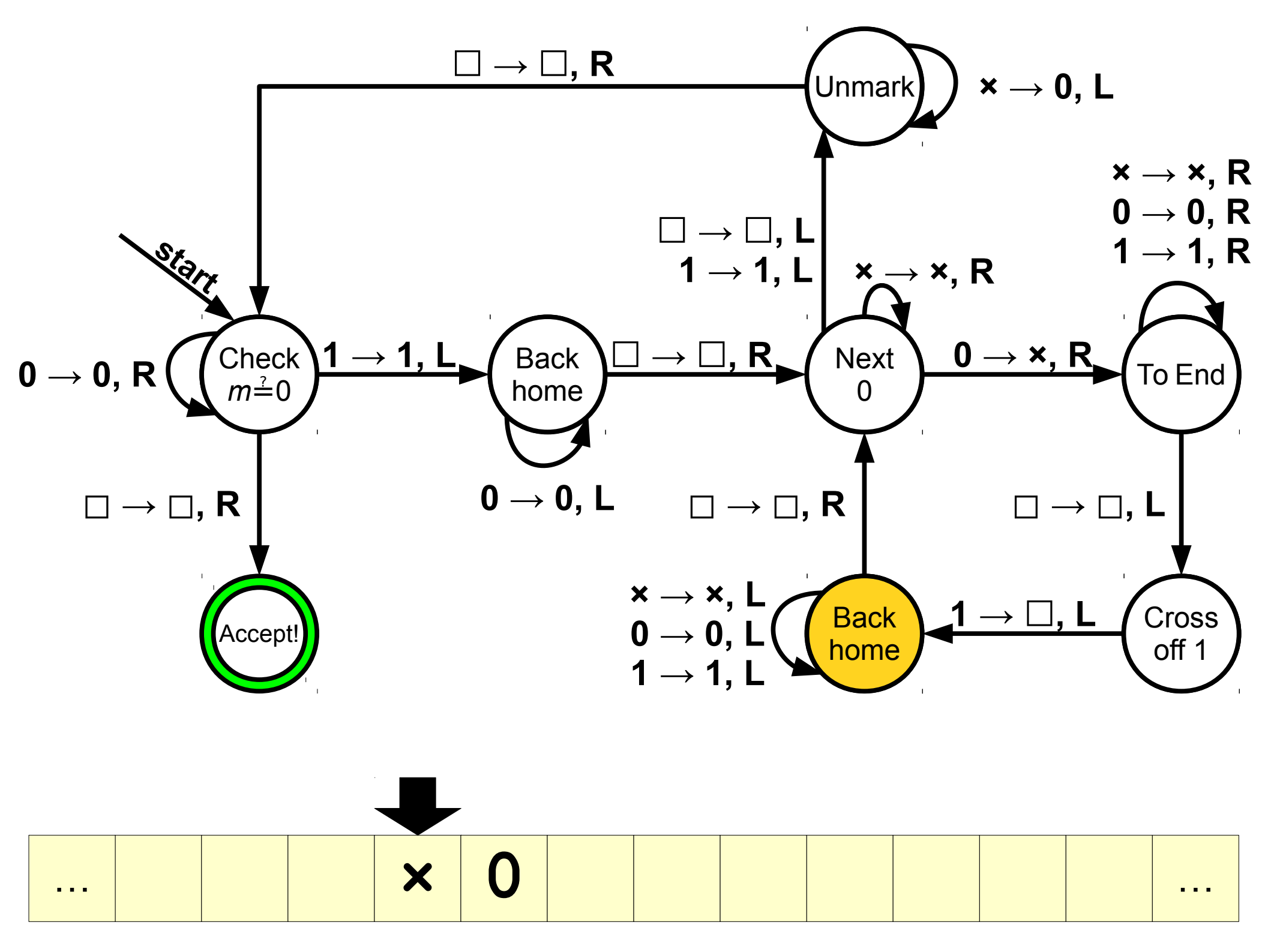
□ → □, R
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0 → 0, R
1 → 1, R
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start
Check
m ≟ 0
0 → 0, R
1 → 1, L
Back
home
□ → □, R
Next
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0 → ×, R
To End
0 → 0, L
□ → □, R
□ → □, R
□ → □, L
Accept!
× → ×, L
0 → 0, L
1 → 1, L
Back
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1 → □, L
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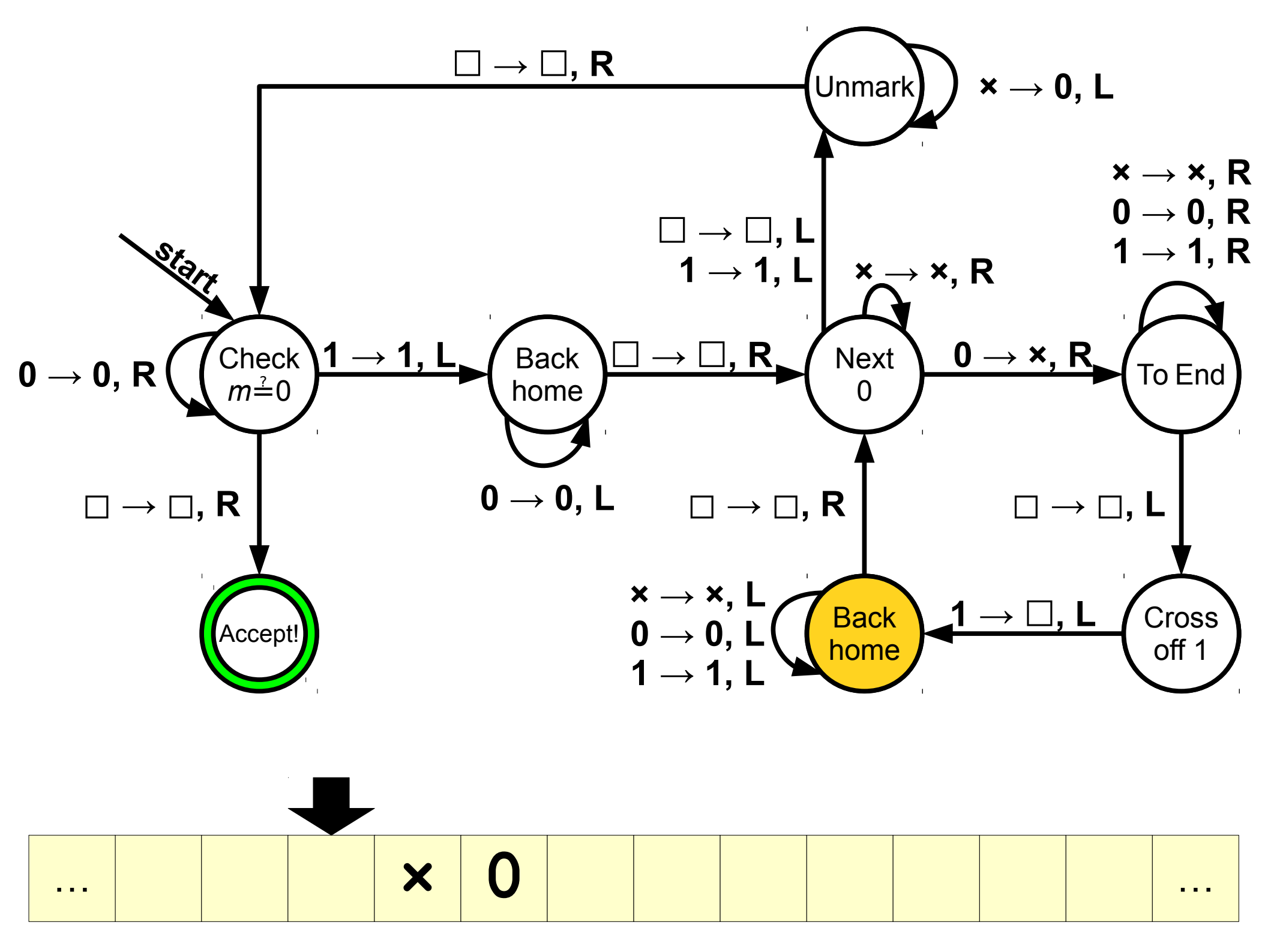
□ → □, R
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m ≟ 0
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Back
home
□ → □, R
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To End
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□ → □, R
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Accept!
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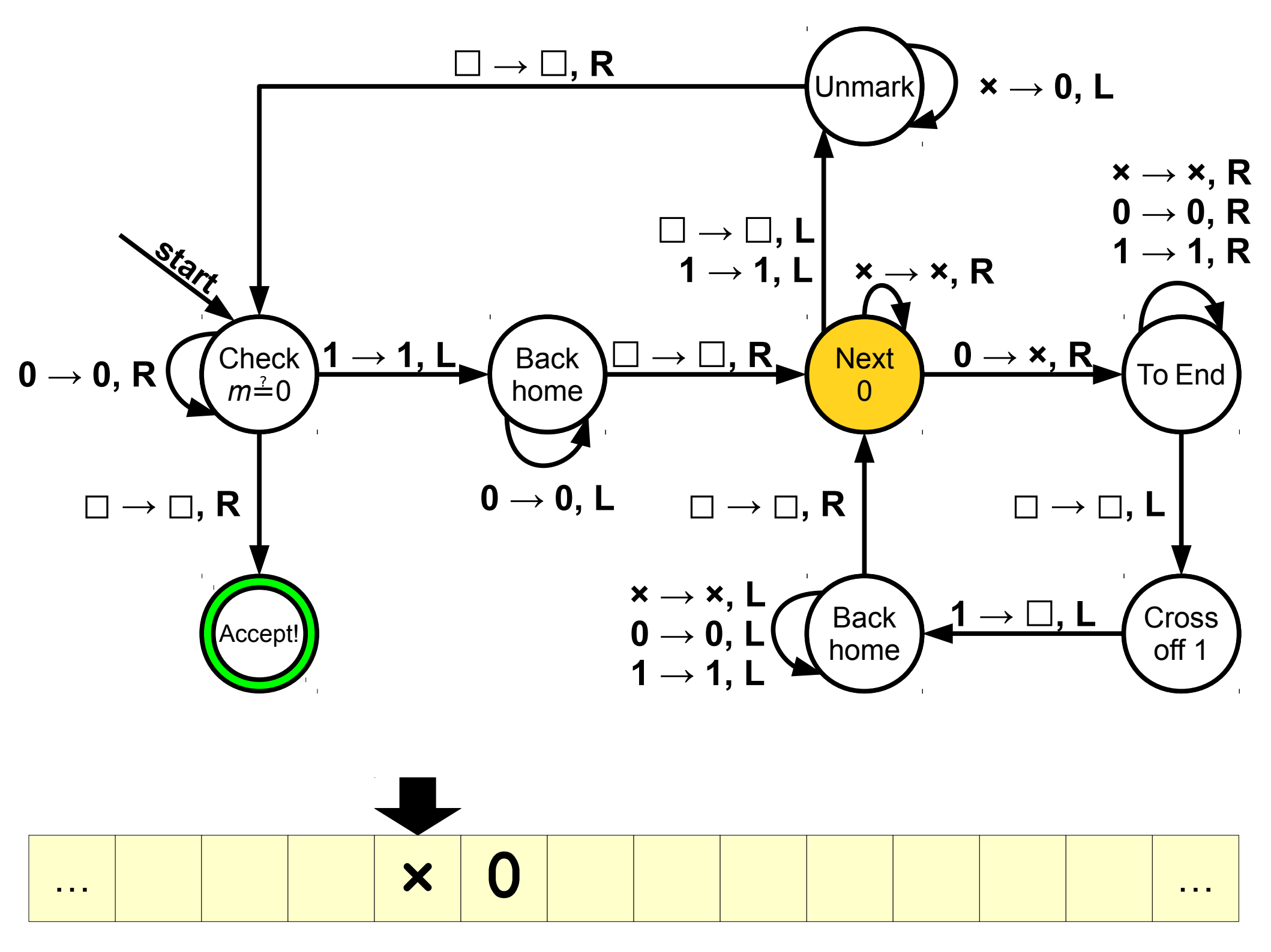
□ → □, R
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Accept!
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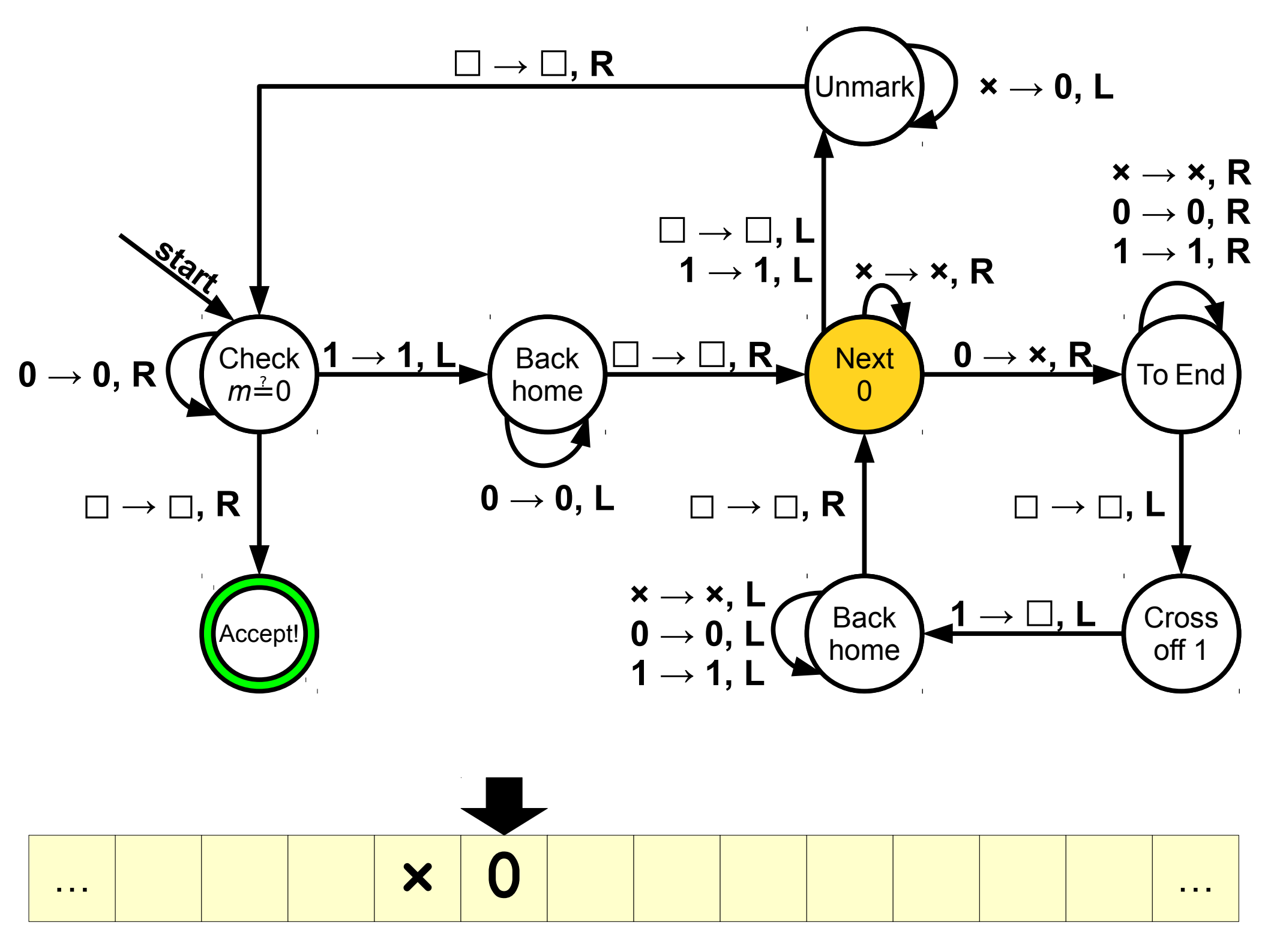
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Accept!
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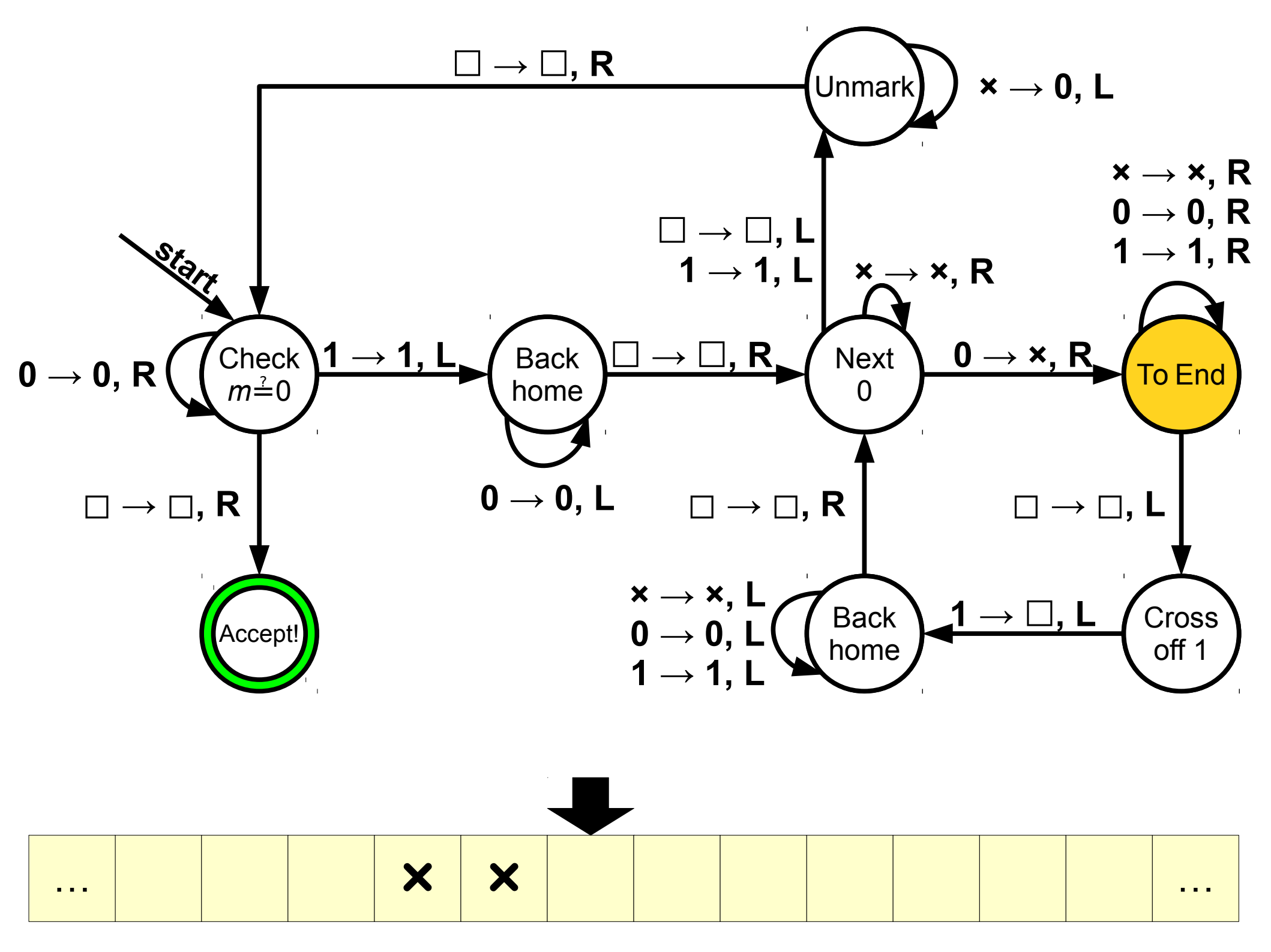
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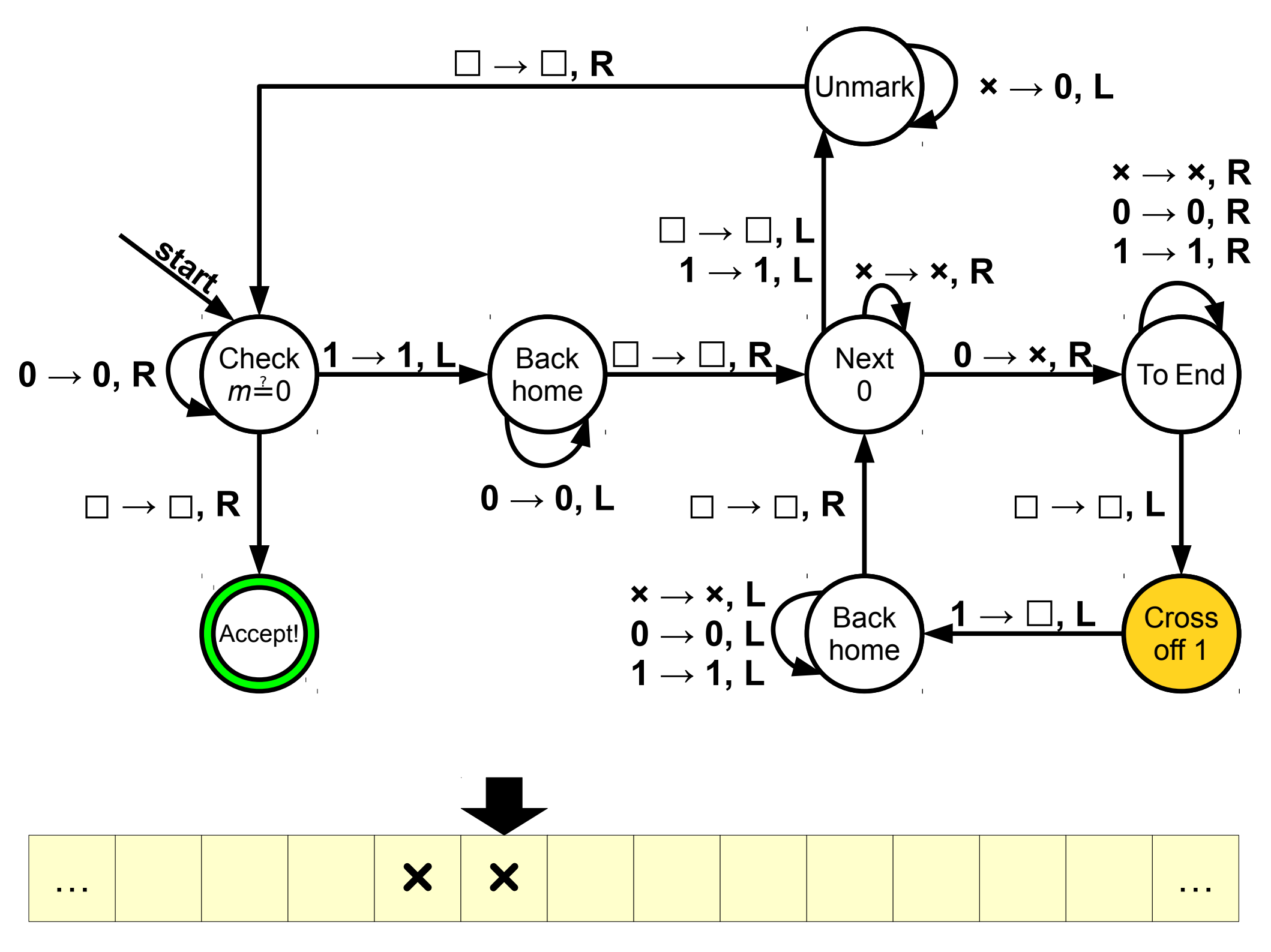
□ → □, R
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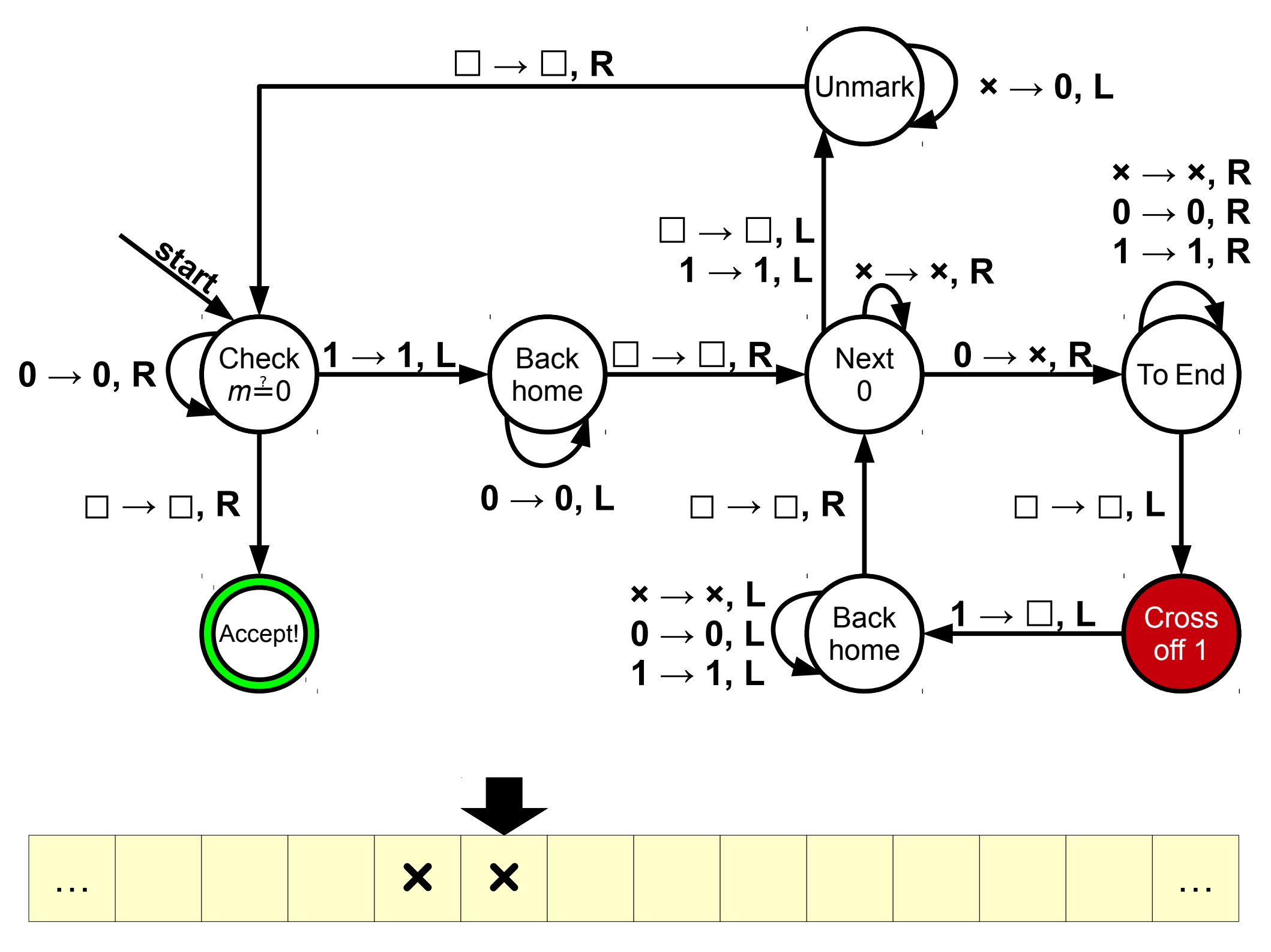
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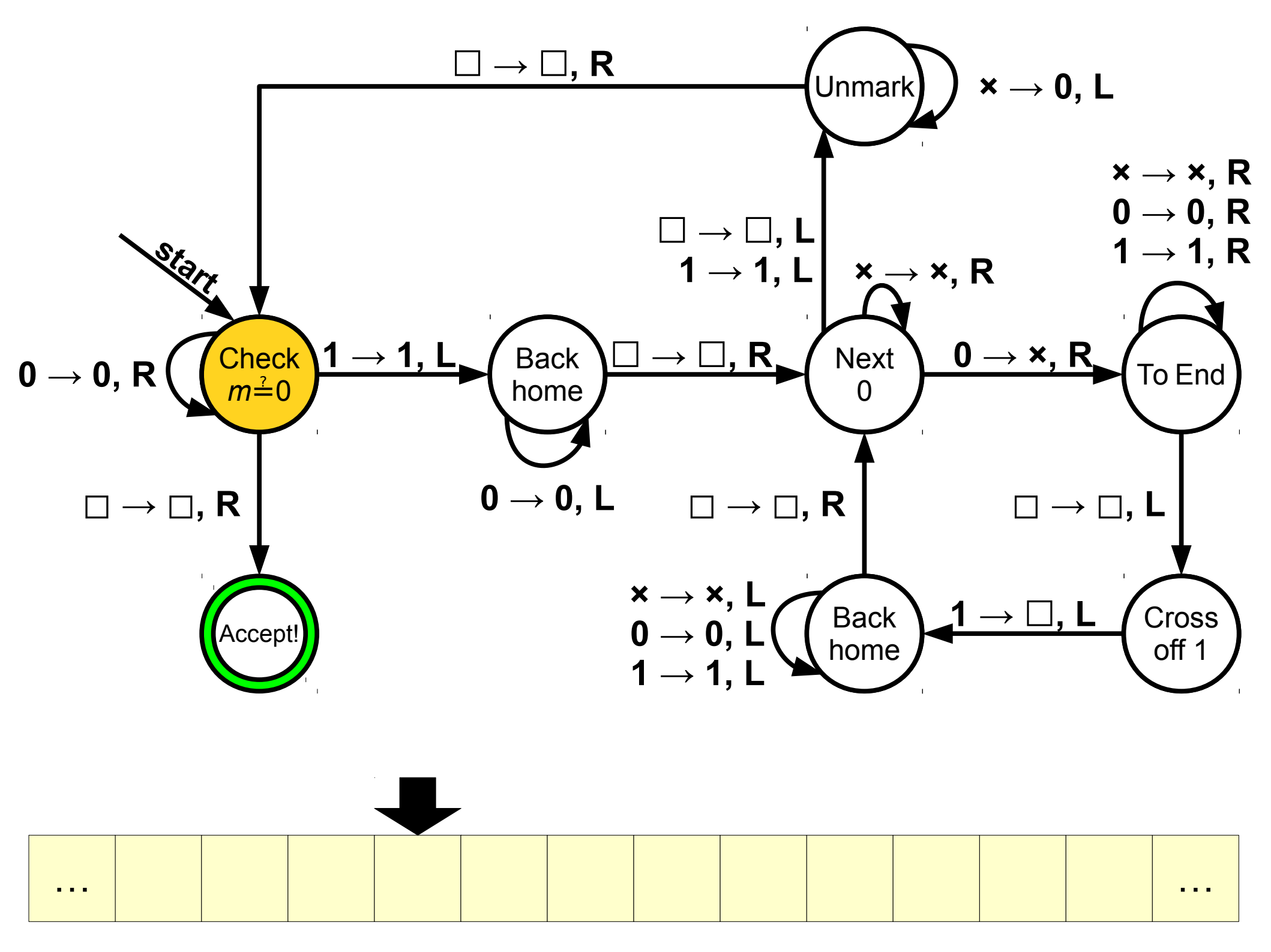
□ → □, R
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× → ×, R
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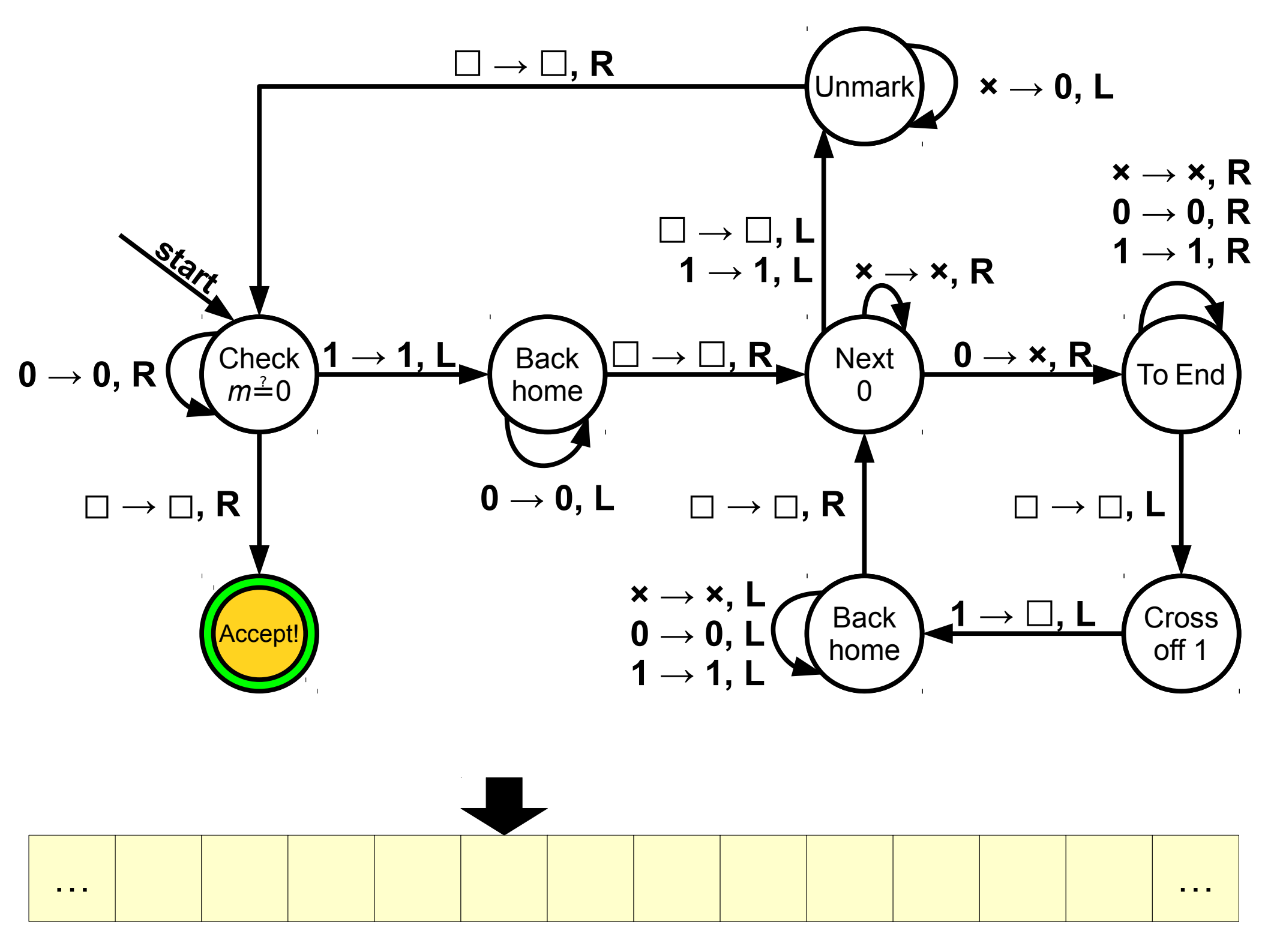
start
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Back
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Next
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To End
Unmark
Back
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Cross
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Accept!
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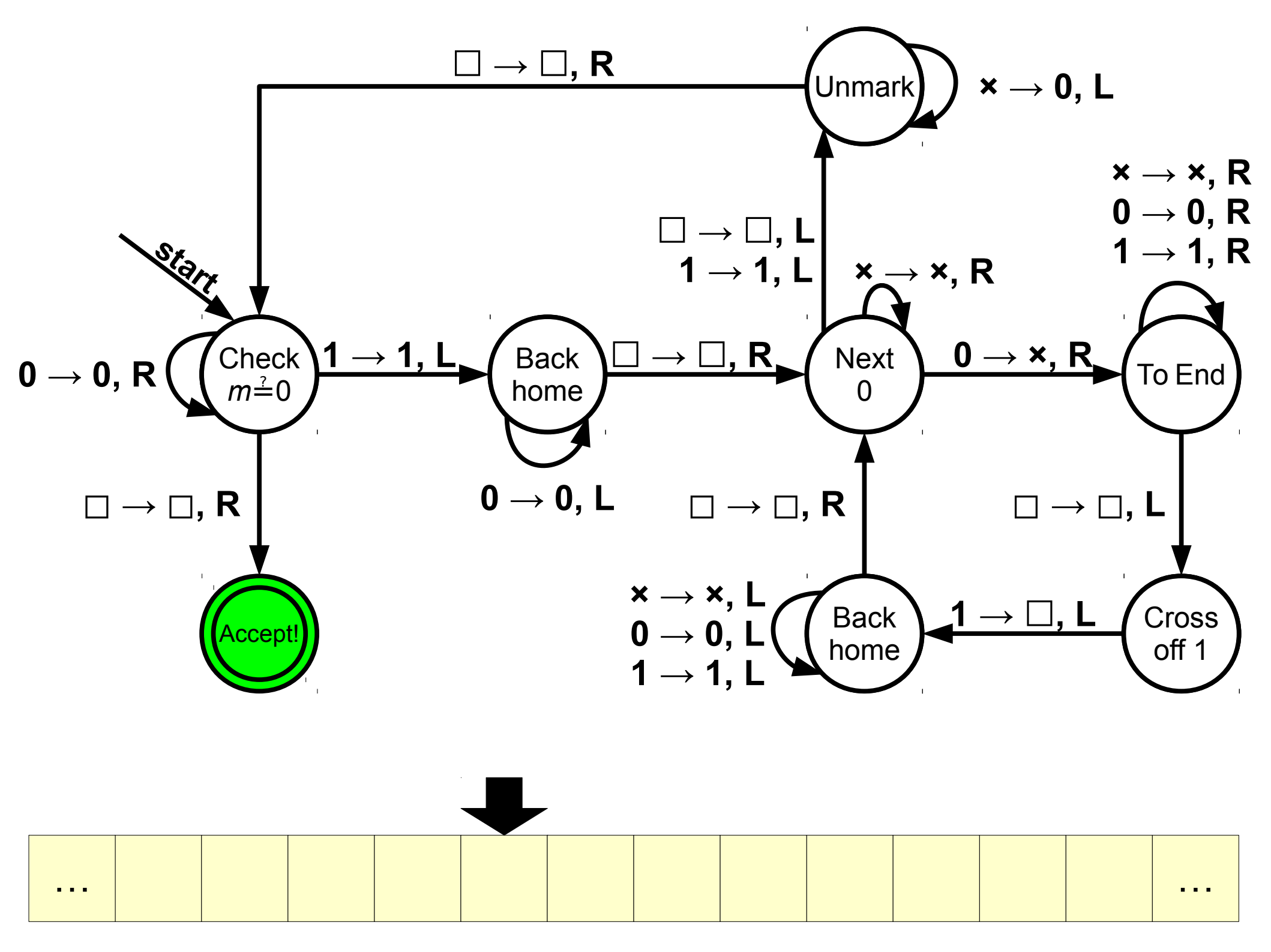
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