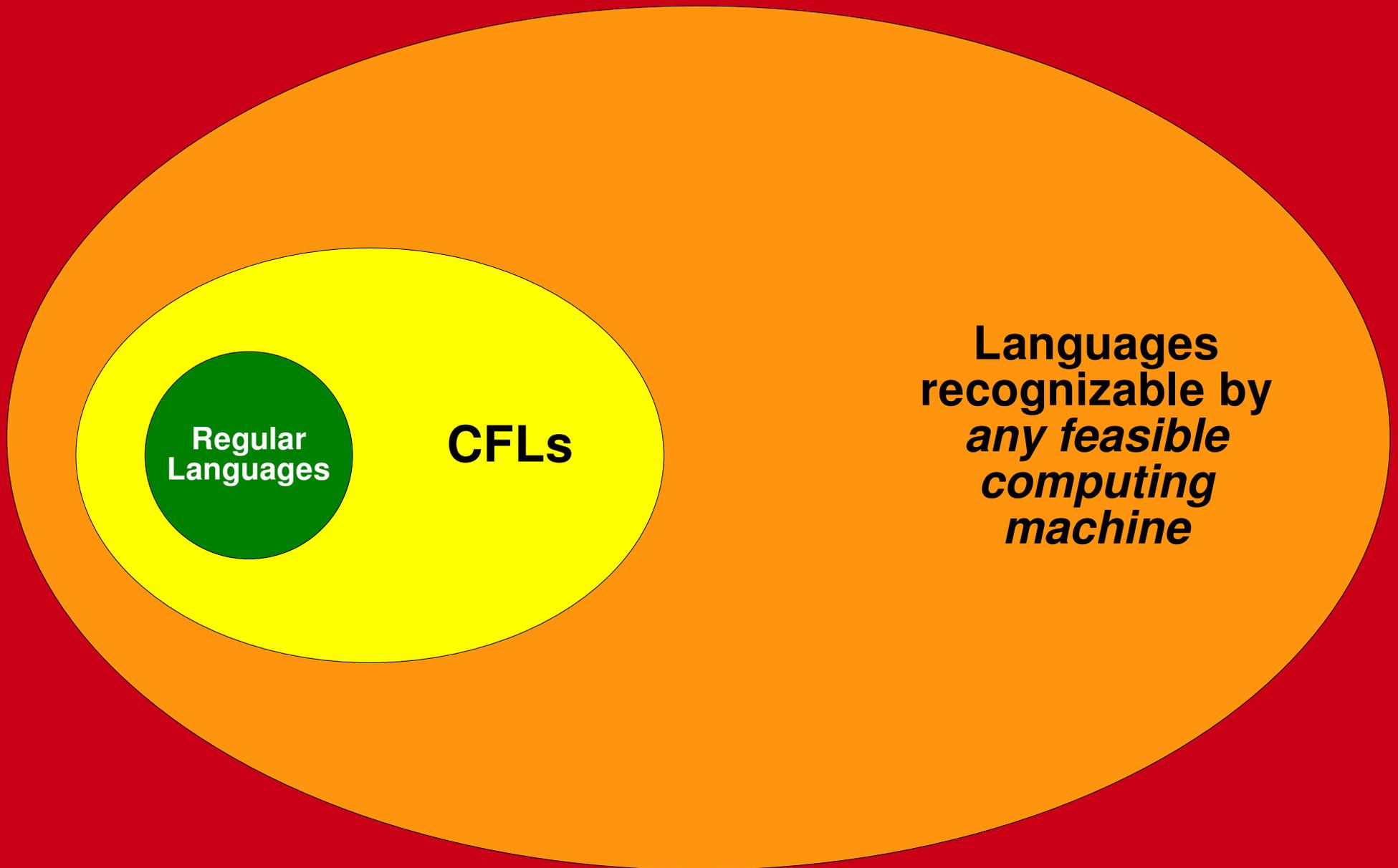


Turing Machines

Part One

What problems can we solve with a computer?



**Regular
Languages**

CFLs

**Languages
recognizable by
*any feasible
computing
machine***

All Languages

That same drawing, to scale.

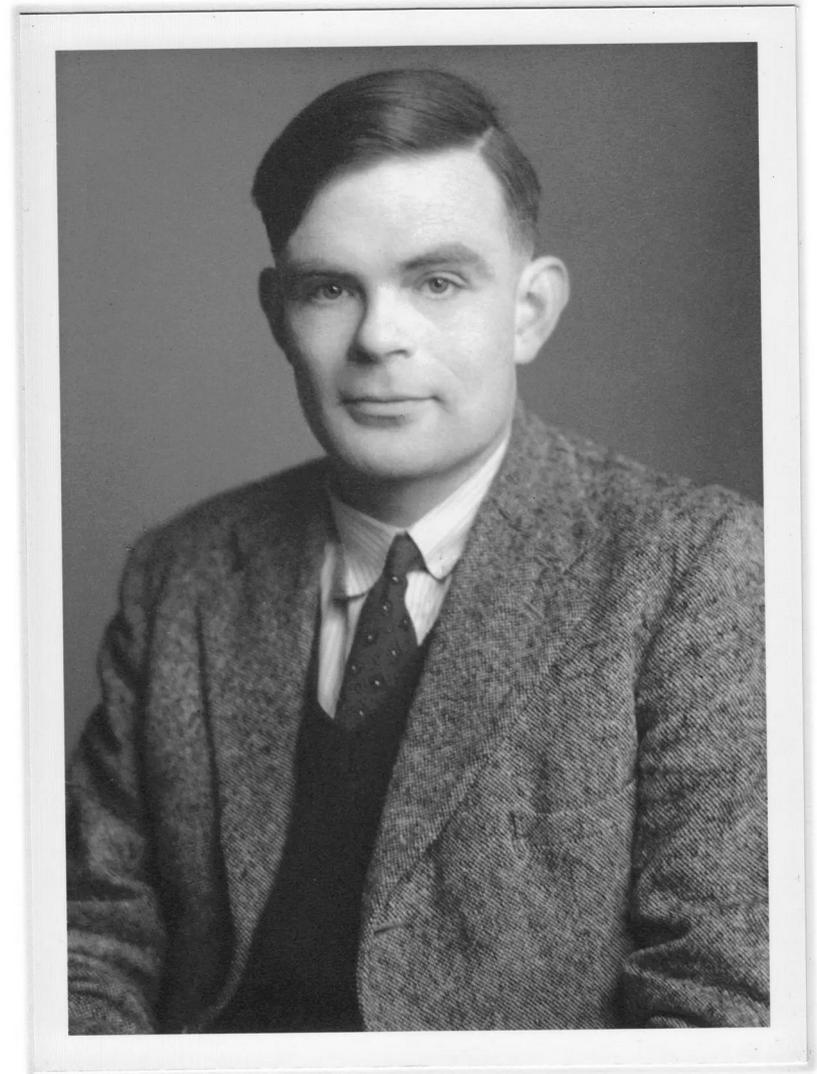
The Problem

- Finite automata accept precisely the regular languages.
- We may need unbounded memory to recognize context-free languages.
 - e.g. $\{ a^n b^n \mid n \in \mathbb{N} \}$ requires unbounded counting.
- How do we model a computing device that has unbounded memory?

A Brief History Lesson

Turing Machines

- In March 1936, Alan Turing (aged 23!) published a paper detailing the ***a-machine*** (for ***automatic machine***), an automaton for computing on real numbers.
- They're now more popularly referred to as ***Turing machines*** in his honor.
- He also later made contributions to computational biology, artificial intelligence, cryptography, etc. Seriously, Google this guy.



$$\begin{array}{r} 27182818284590 \\ + 31415926535897 \\ \hline \end{array}$$

$$\begin{array}{r} 27182818284590 \\ + 31415926535897 \\ \hline 7 \end{array}$$

$$\begin{array}{r} 271828182845\overset{1}{9}0 \\ + 314159265358\mathbf{9}7 \\ \hline 271828182845\mathbf{8}7 \end{array}$$

$$\begin{array}{r} 27182818284^1 590 \\ + 31415926535^1 897 \\ \hline 27182818284 590 \\ 31415926535 897 \\ \hline 585987447717717 \end{array}$$

$$\begin{array}{r} 2718281828 \\ + 3141592653 \\ \hline 2718281828 \\ + 3141592653 \\ \hline 5859874721 \end{array}$$

$$\begin{array}{r} 271828182 \\ + 314159265 \\ \hline 271828182 \\ 314159265 \\ \hline 585987447 \end{array}$$

$$\begin{array}{r} 27182818 \mathbf{2} 84590 \\ + 31415926 \mathbf{5} 35897 \\ \hline 27182818 \mathbf{8} 20487 \end{array}$$

$$\begin{array}{r} 2718281\mathbf{8}284590 \\ + 3141592\mathbf{6}535897 \\ \hline 2718281\mathbf{4}820487 \end{array}$$

$$\begin{array}{r} 271828\mathbf{1}8284590 \\ + 314159\mathbf{2}6535897 \\ \hline 271828\mathbf{4}4820487 \end{array}$$

$$\begin{array}{r} 27182\mathbf{8}18284590 \\ + 31415\mathbf{9}26535897 \\ \hline 744820487 \end{array}$$

$$\begin{array}{r} 2718 \mathbf{2}818284590 \\ + 3141 \mathbf{5}926535897 \\ \hline \mathbf{8}744820487 \end{array}$$

$$\begin{array}{r} 27182818284590 \\ + 31415926535897 \\ \hline 27182818284590 \\ 31415926535897 \\ \hline 98744820487 \end{array}$$

$$\begin{array}{r} 27\mathbf{1}82818284590 \\ + 31\mathbf{4}15926535897 \\ \hline \mathbf{5}98744820487 \end{array}$$

Carrying digits: 1, 1, 1, 1, 1, 1

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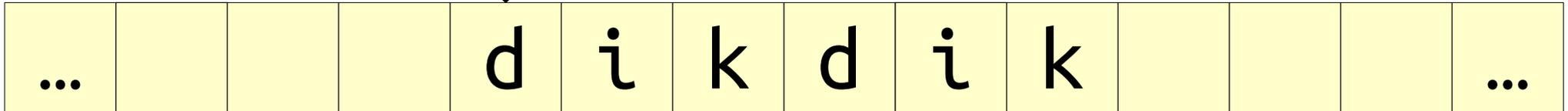
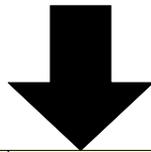
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Key Idea: Even if you need huge amounts of scratch space to perform a calculation, at each point in the calculation you only need access to a small amount of that scratch space.

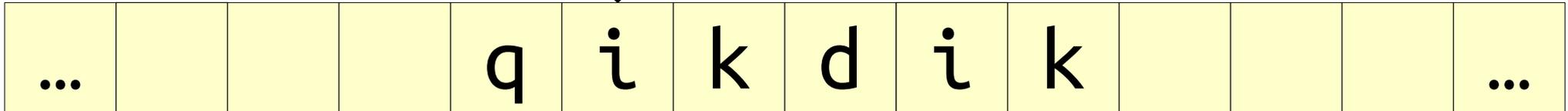
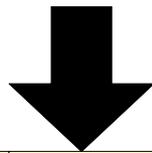
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- To provide his machines extra memory, Turing gave his machines access to an *infinite tape* subdivided into a number of *tape cells*.
- A Turing machine can only see one tape cell at a time, the one pointed at by the *tape head*.
- The Turing machine can
 - read the cell under the tape head,
 - (possibly) change which symbol was written under the tape head, and
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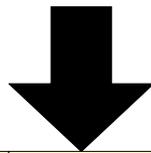
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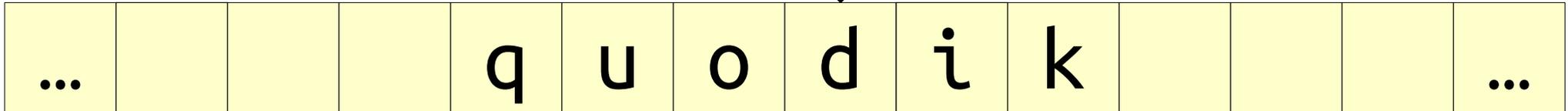
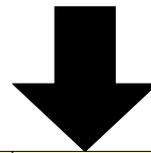
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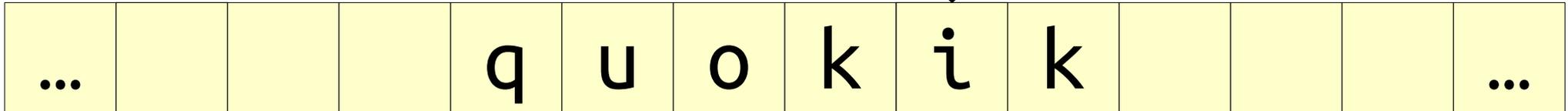
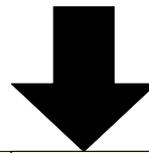
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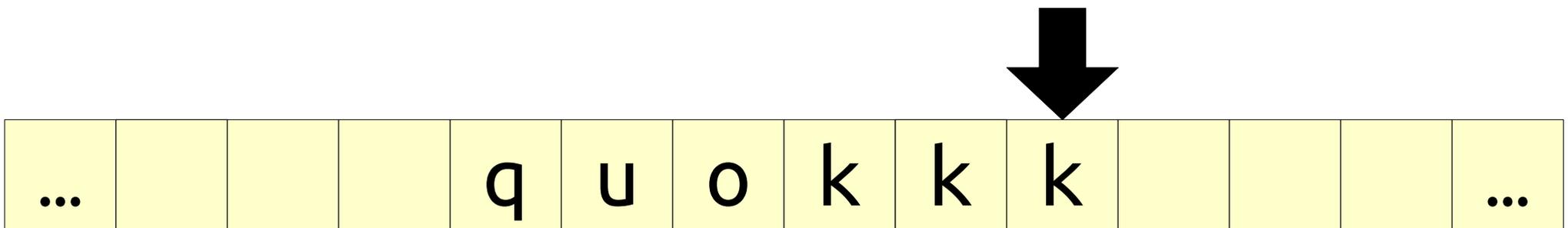
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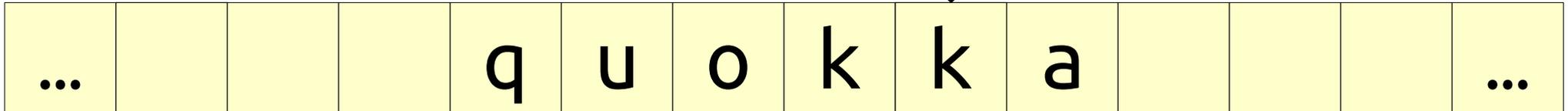
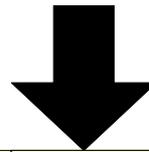
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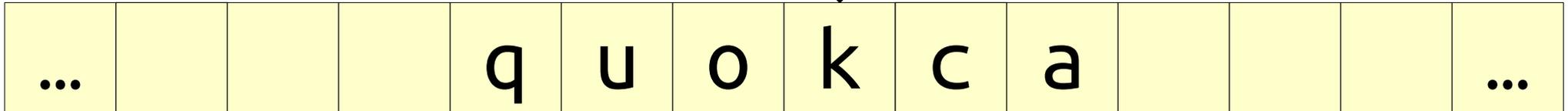
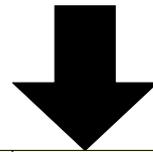
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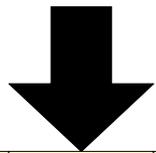
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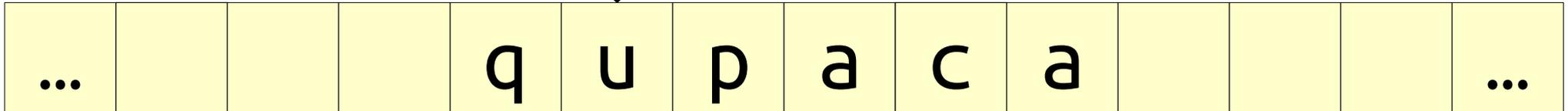
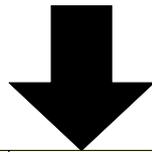
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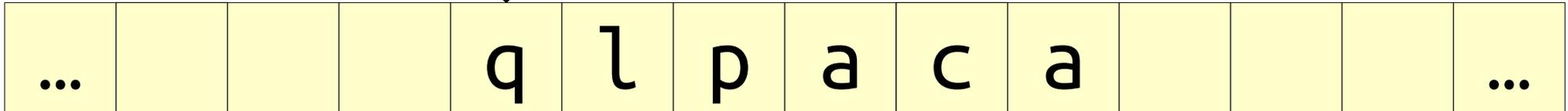
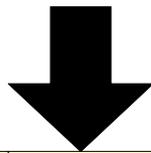
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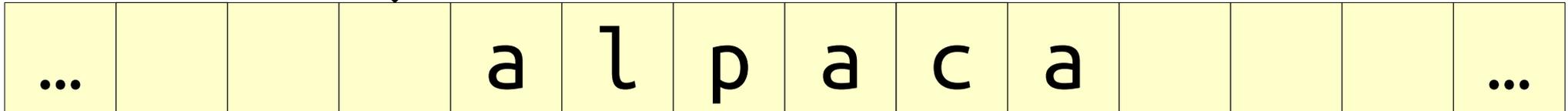
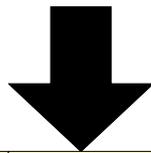
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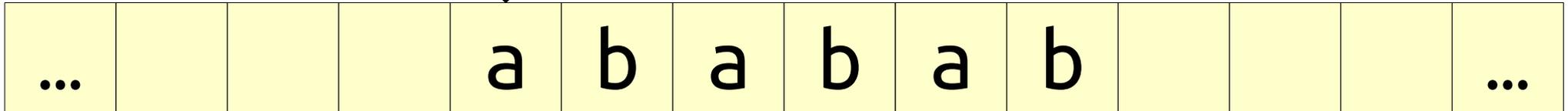
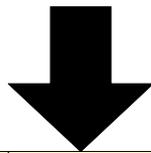
- Over the years, there have been many simplifications and edits to Turing's original automata.
 - In practice, electronic computers are written in terms of individual instructions rather than states and transitions.
 - Turing's original paper deals with computing individual real numbers; we typically want to compute functions of inputs.
- What we're going to present as "Turing machines" in this class differ significantly from Turing's original description, while retaining the core essential ideas.
 - (Our model is closer to Emil Post's *Formulation 1* and Hao Wang's *Basic Machine B*, for those of you who are curious.)
- If you'd like to learn more about Turing's original version of the Turing machine, come chat with me after class!

Turing Machines

- A TM is a series of instructions that control a tape head as it moves across an infinite tape.
- The tape begins with the input string written somewhere, surrounded by infinitely many blank cells.
 - Rule: The input string cannot contain blank cells.
- The tape head begins above the first character of the input. (If the input is ϵ , the tape head points somewhere on a blank tape.)

Start:

```
If Blank Return True
If 'b' Return False
Write 'x'
Move Right
If Not 'b' Return False
Write 'x'
Move Right
Goto Start
```

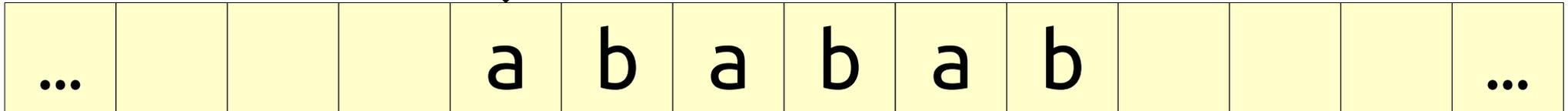
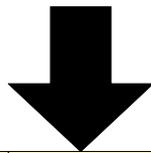


Turing Machines

- We begin at the Start label.
- Labels indicate different sections of code. The name Start is special and means “begin here.”
- Labels have no effect when executed. We just move to the next line.

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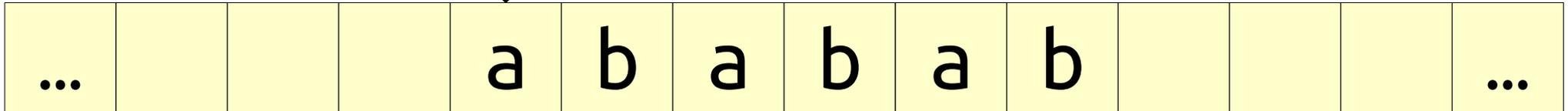
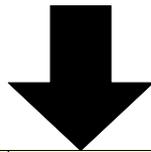


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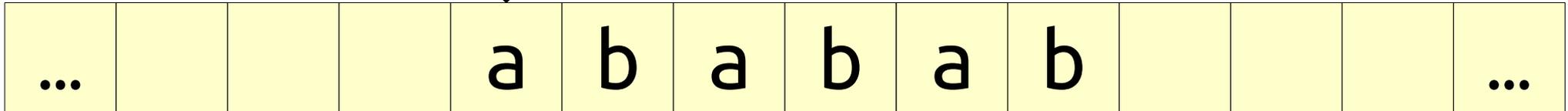
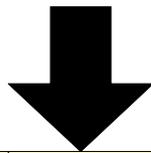
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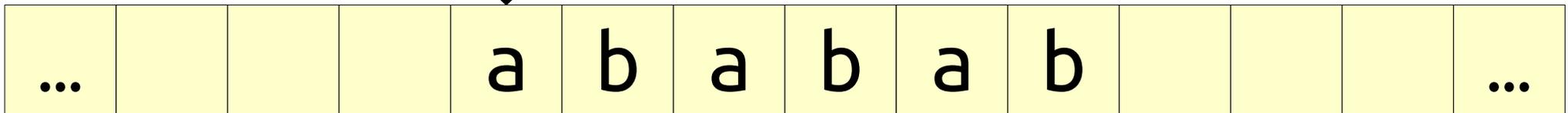
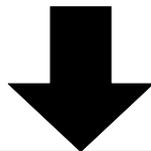
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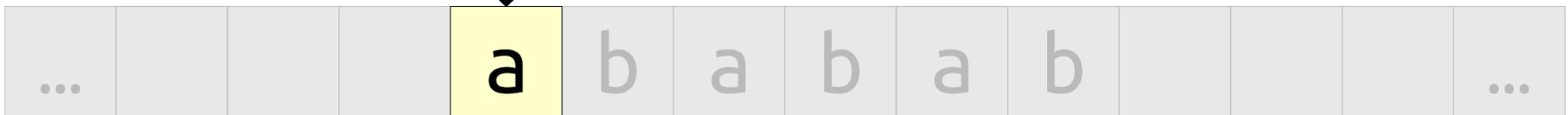
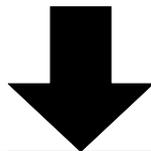
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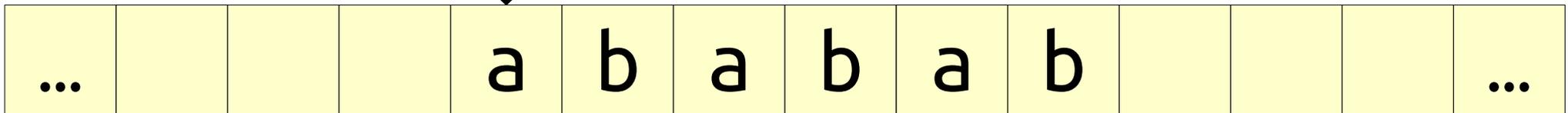
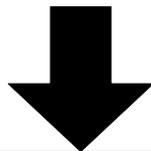
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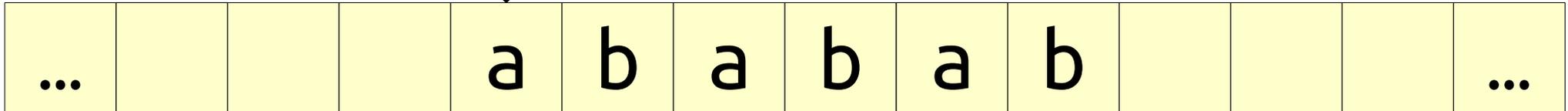
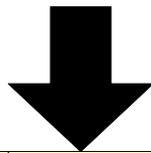
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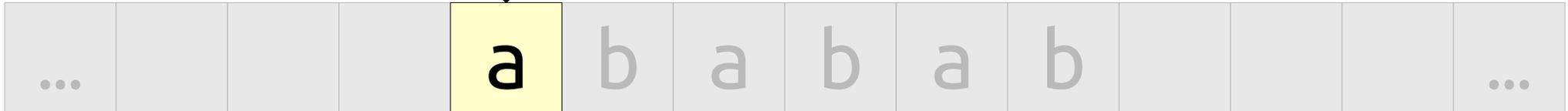
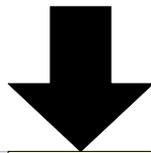
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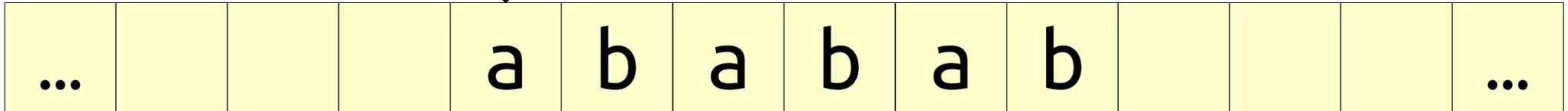
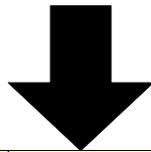
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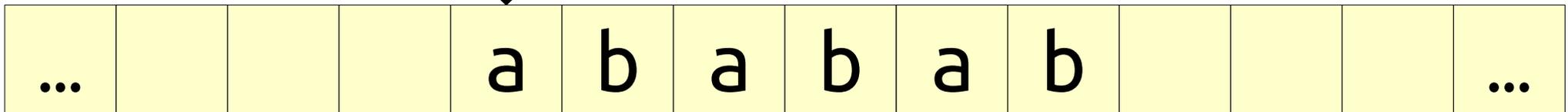
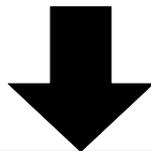
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Turing Machines

- The statement
Write *symbol*
writes *symbol* to the
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head.
- The *symbol* can
either be Blank or a
character in quotes.

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Write 'x'

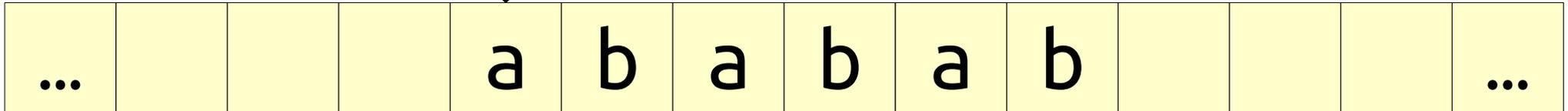
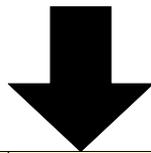
Move Right

If Not 'b' Return False

Write 'x'

Move Right

Goto Start



Turing Machines

- The statement
Write *symbol*
writes *symbol* to the
cell under the tape
head.
- The *symbol* can
either be Blank or a
character in quotes.

Start:

If Blank Return True

If 'b' Return False

Write 'x'

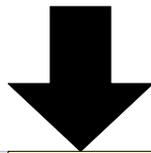
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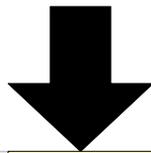
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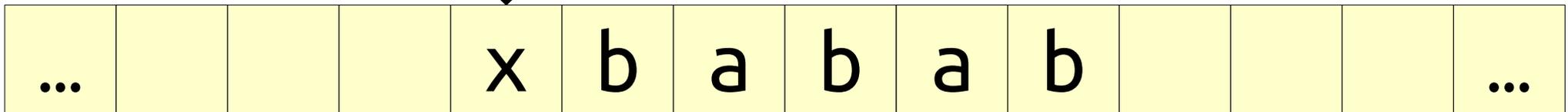
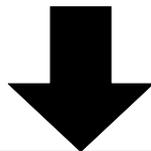
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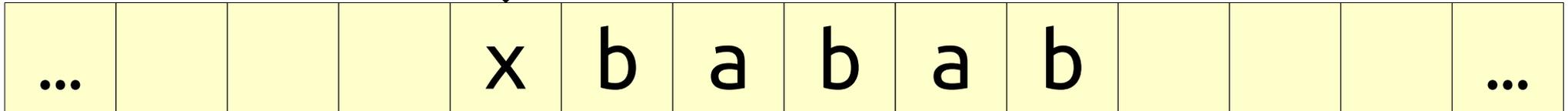
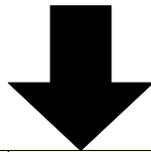
Move Right

If Not 'b' Return False

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Goto Start



Turing Machines

- The command
Move *direction*
moves the tape head one step in the indicated direction (either Left or Right).

Start:

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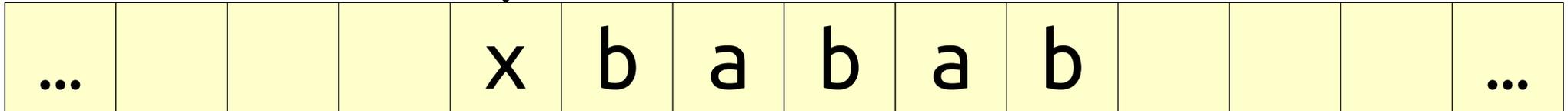
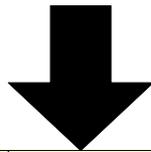
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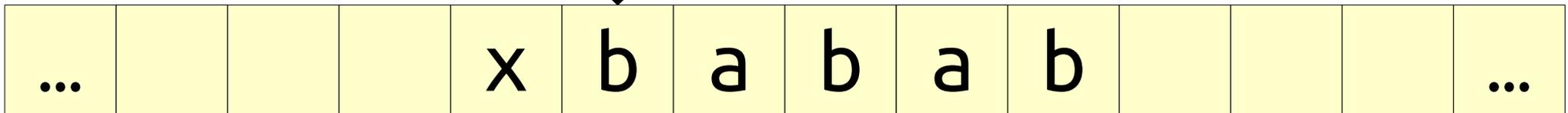
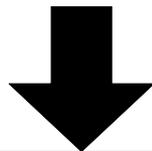
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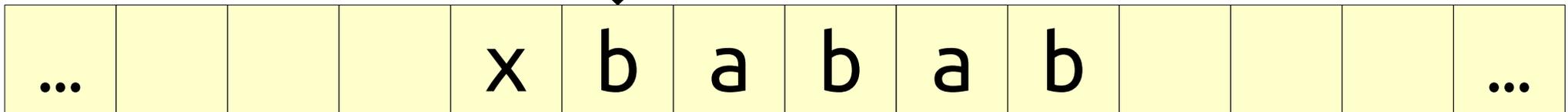
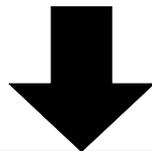
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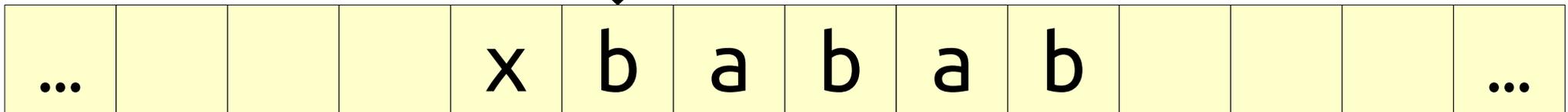
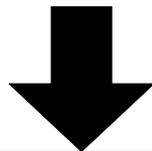
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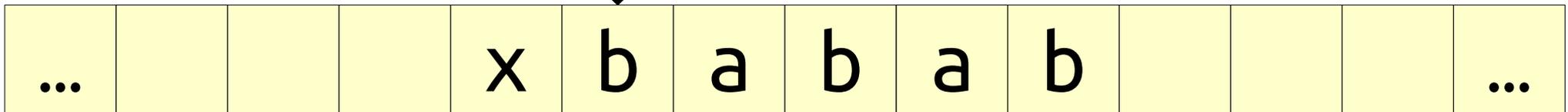
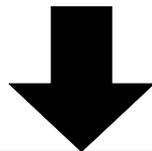
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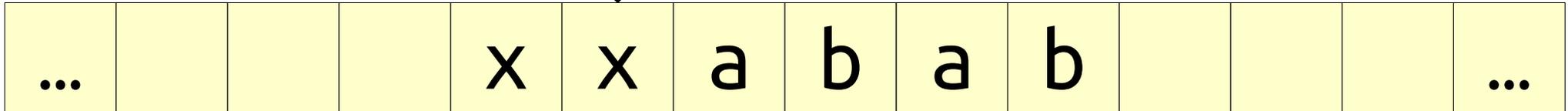
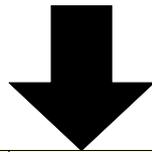
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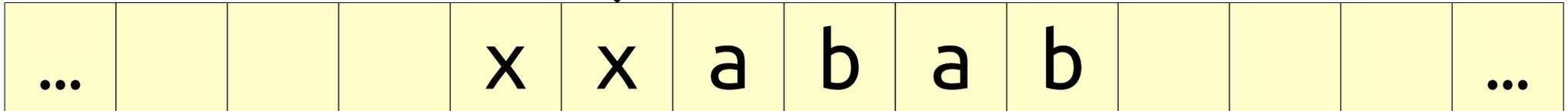
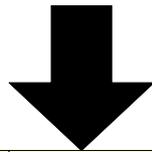


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Move Right
If Not 'b' Return False
Write 'x'
Move Right
Goto Start
```



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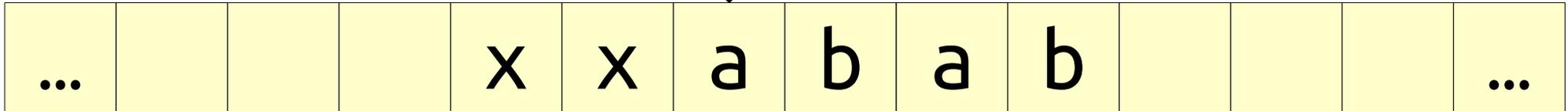
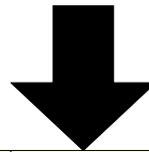
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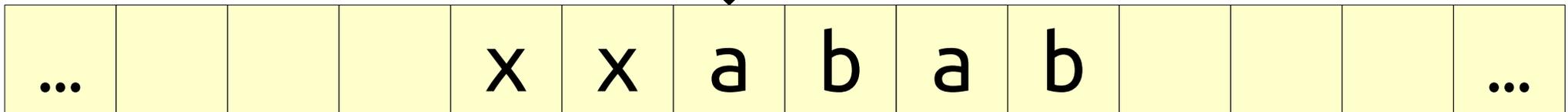
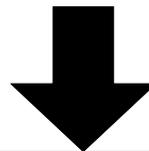


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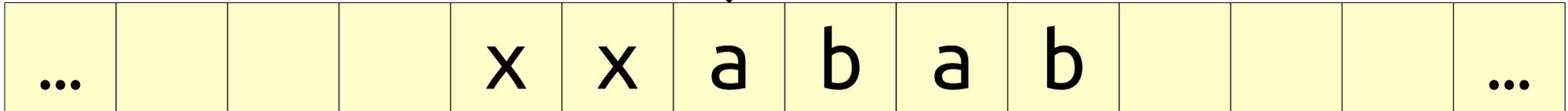
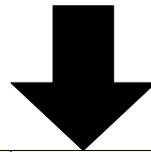


Turing Machines

- The command
Goto *label*
jumps to the indicated label.
- This program just has a Start label, but most interesting programs have other labels beyond this.

Start:

```
If Blank Return True  
If 'b' Return False  
Write 'x'  
Move Right  
If Not 'b' Return False  
Write 'x'  
Move Right  
Goto Start
```

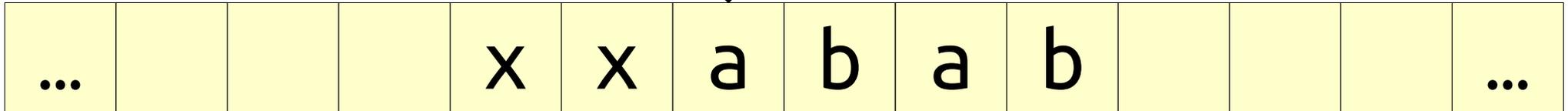
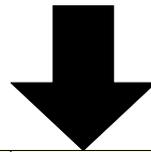


Turing Machines

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Goto *label*
jumps to the indicated label.
- This program just has a Start label, but most interesting programs have other labels beyond this.

Start:

```
If Blank Return True  
If 'b' Return False  
Write 'x'  
Move Right  
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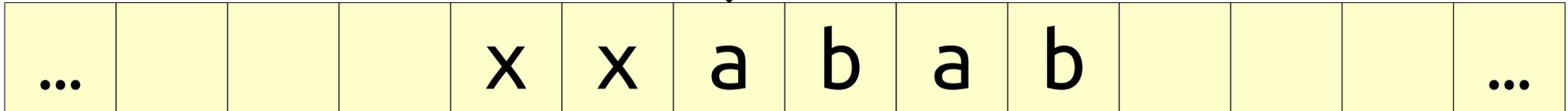
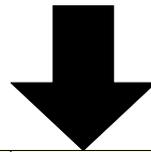


Turing Machines

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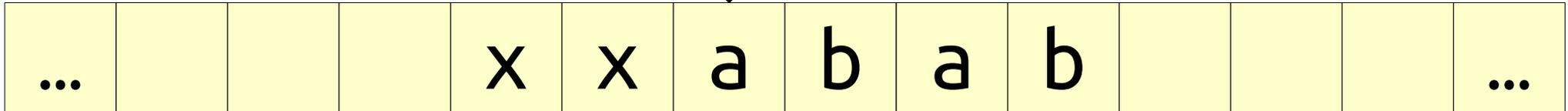
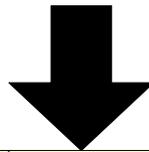


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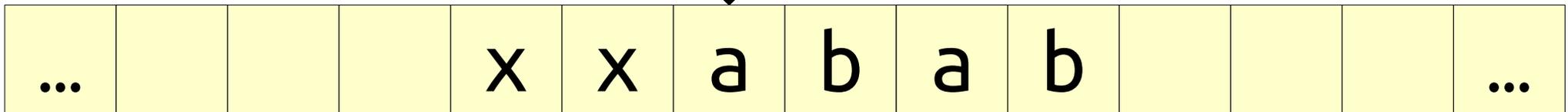
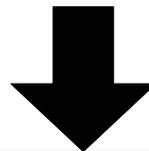
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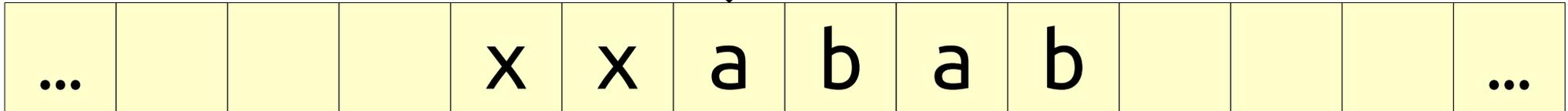
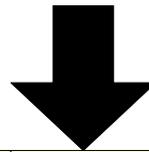
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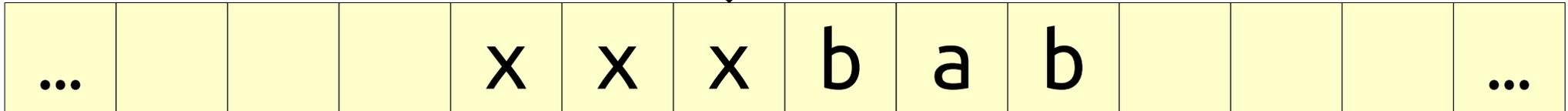
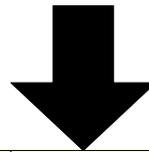
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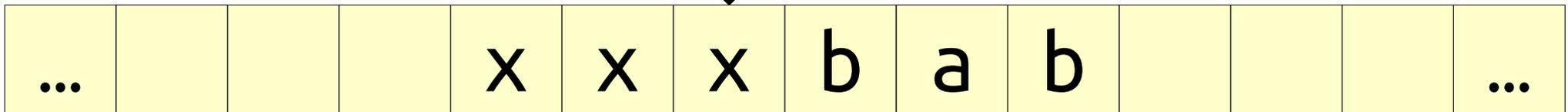
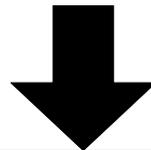
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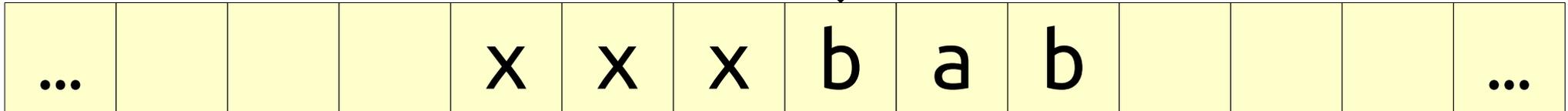
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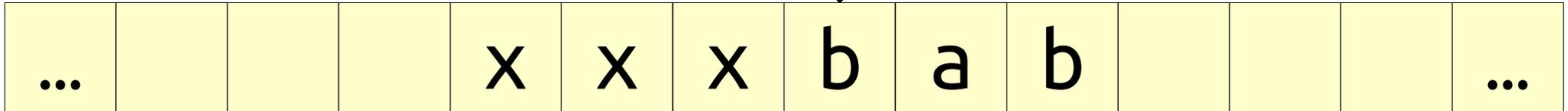
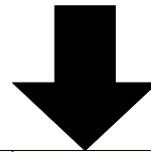
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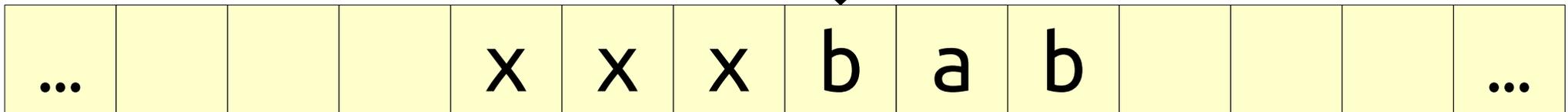
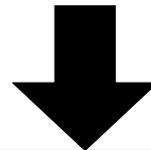
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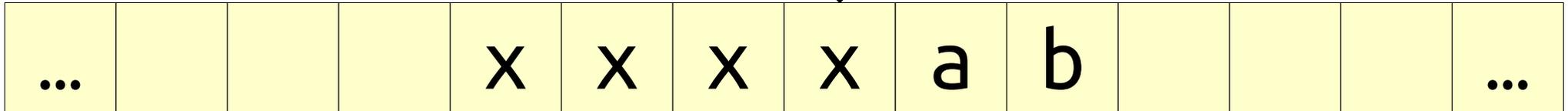
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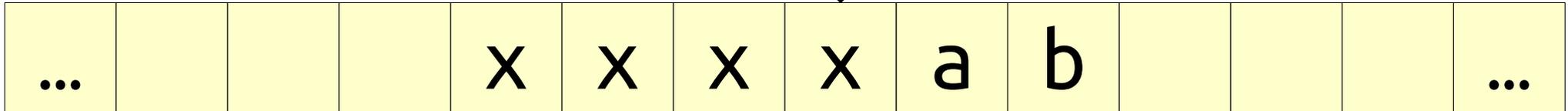
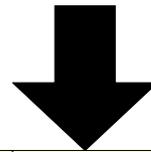
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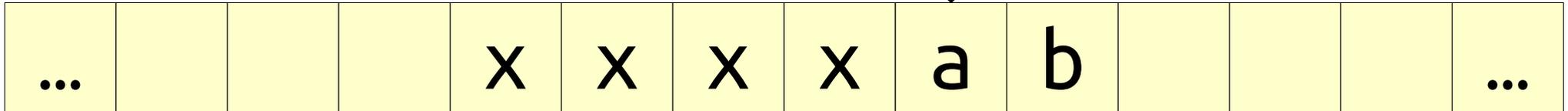


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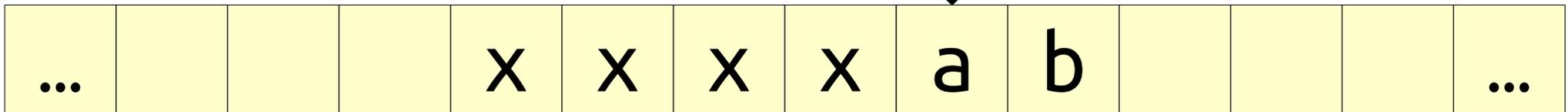
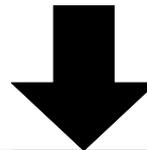


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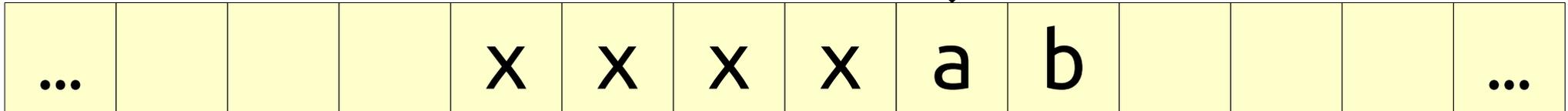
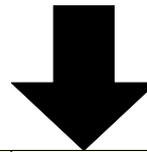


Turing Machines

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- (If we “fall off” the bottom of the program, the TM acts as though it executes the Return False command.)

Start:

```
If Blank Return True
If 'b' Return False
Write 'x'
Move Right
If Not 'b' Return False
Write 'x'
Move Right
Goto Start
```



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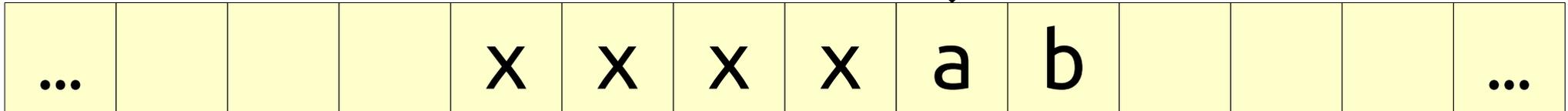
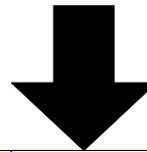
Move Right

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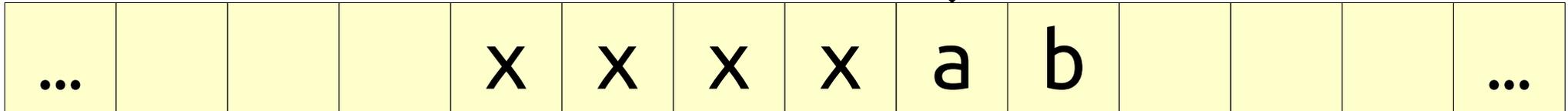
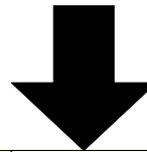
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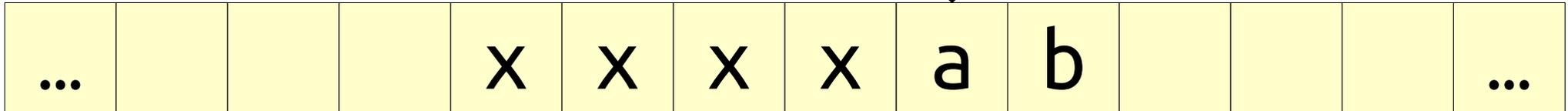
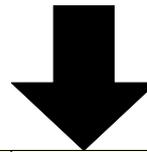
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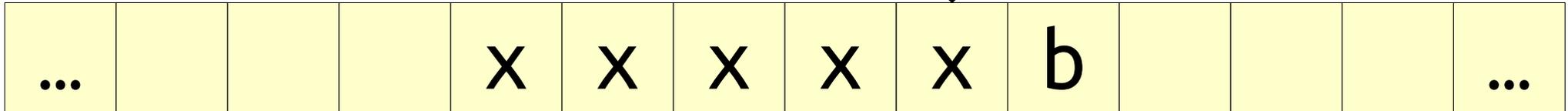
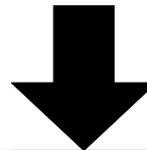
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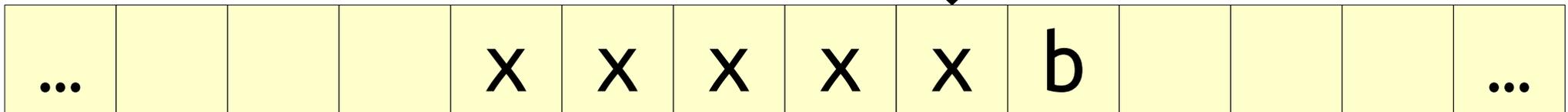
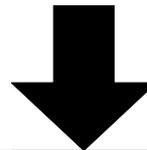
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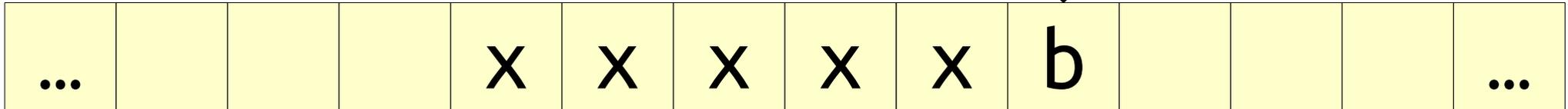
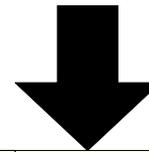
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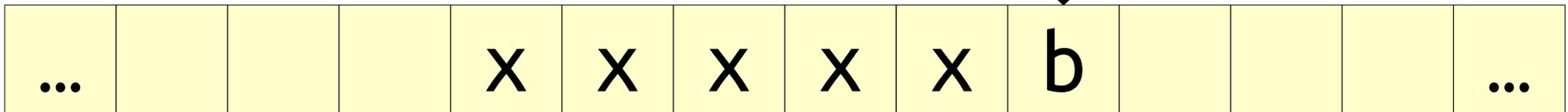
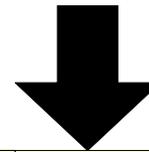
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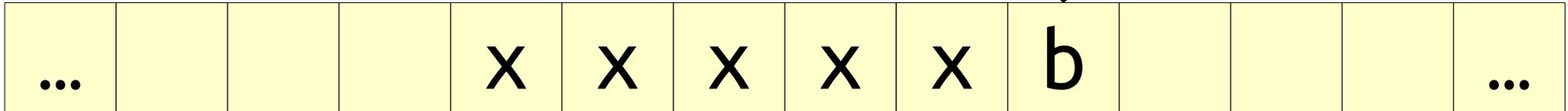
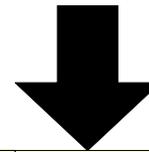
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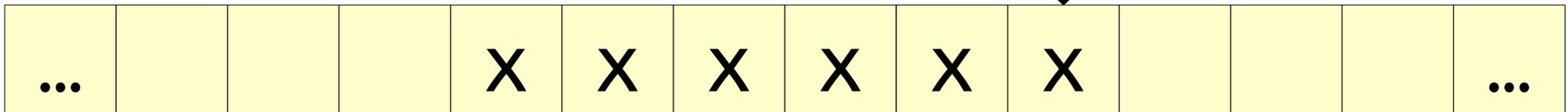
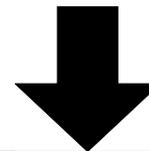
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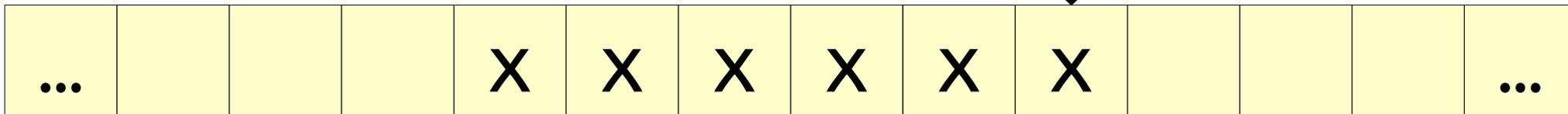
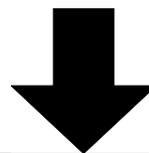
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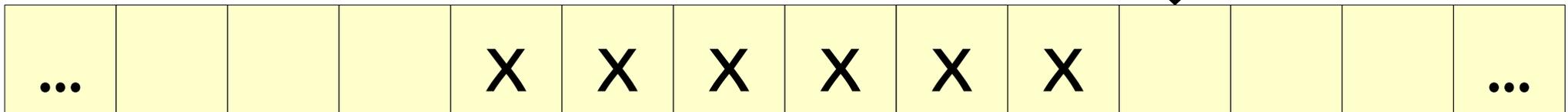
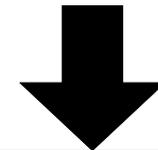
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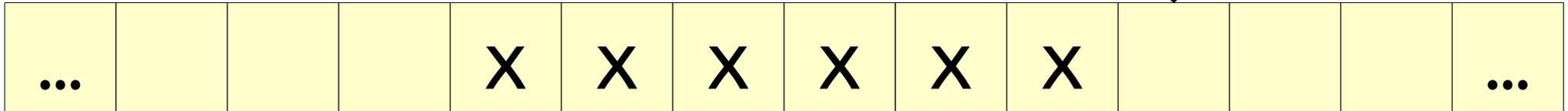


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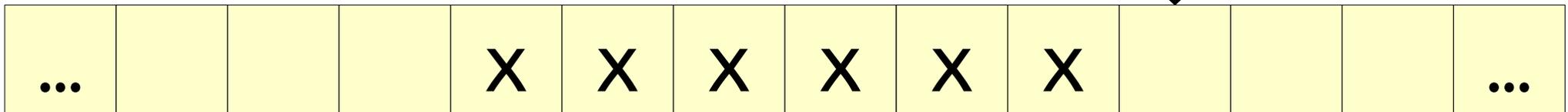
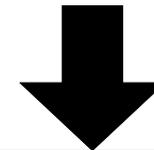


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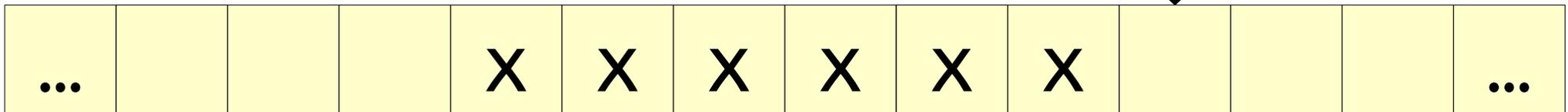
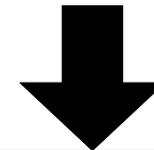
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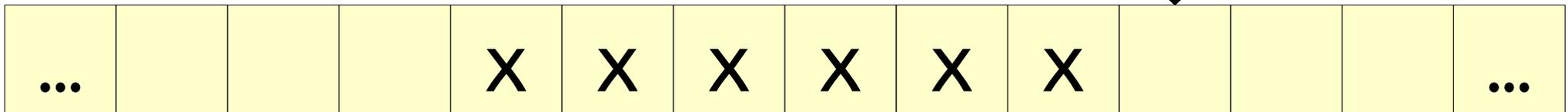
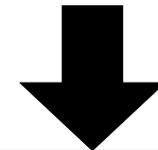
Move Right

If Not 'b' Return False

Write 'x'

Move Right

Goto Start



Turing Machines

- This TM initially started up with the string ababab on its tape, so this means that TM returns true on the input ababab, not xxxxxx.
- An intuition for this: we gave this program an input. It therefore returned true with respect to that input, not whatever internal data it generated in making its decision.

Start:

If Blank Return True

If 'b' Return False

Write 'x'

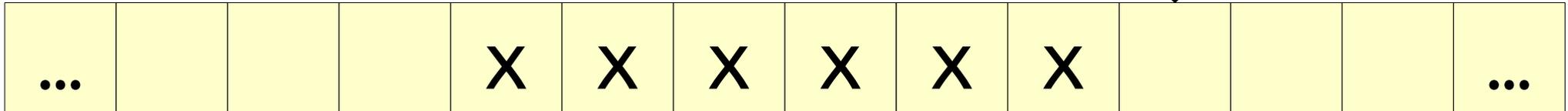
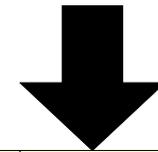
Move Right

If Not 'b' Return False

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Move Right

Goto Start

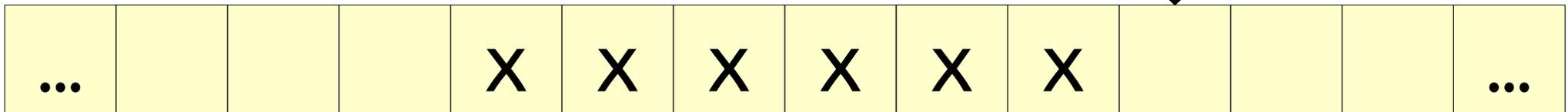
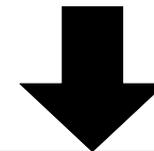


Turing Machines

- To summarize, we only have six commands:
 - Move *direction*
 - Write *symbol*
 - Goto *label*
 - Return *result*
 - If *symbol command*
 - If Not *symbol command*
- Despite their simplicity, TMs are *surprisingly* powerful. The rest of this lecture explores why.

Start:

```
If Blank Return True
If 'b' Return False
Write 'x'
Move Right
If Not 'b' Return False
Write 'x'
Move Right
Goto Start
```



Your Turn!

- Draw what the tape and tape head look like when this TM finishes running.
- Is the input bbaacc accepted or rejected?
- More generally, what does this TM do?

Start:

If 'a' Goto Mirth

If Blank Return False

Move Right

Goto Start

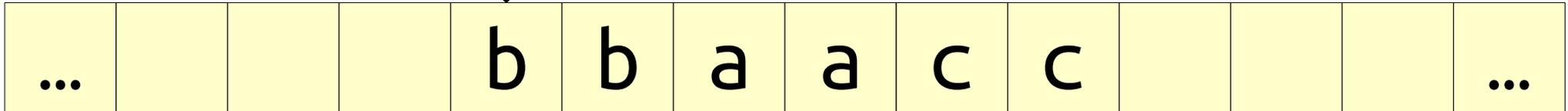
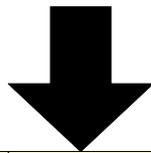
Mirth:

If 'b' Return True

If Blank Return False

Move Right

Goto Mirth



Programming Turing Machines

Our First Challenge

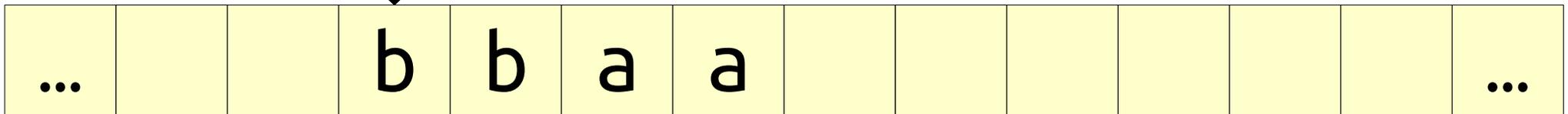
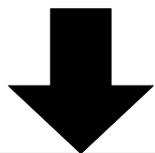
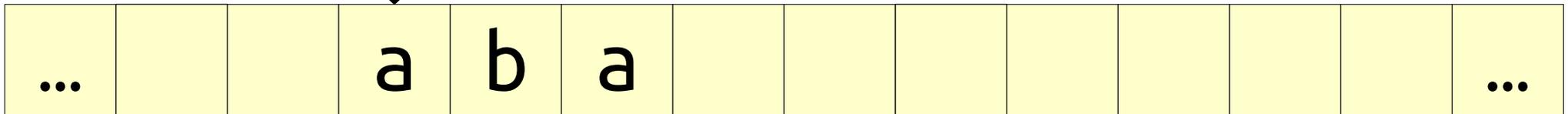
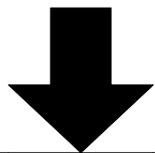
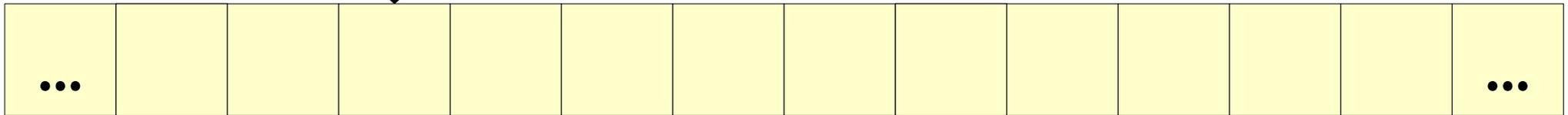
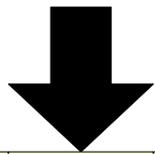
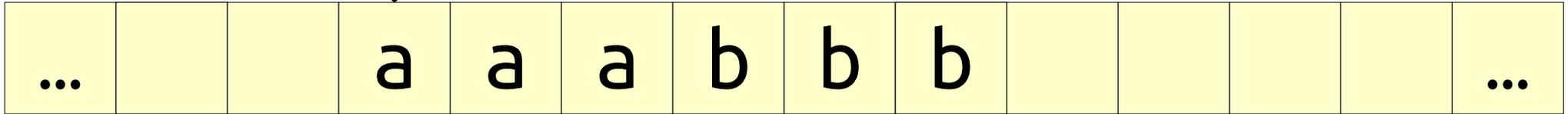
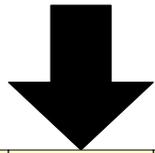
- The language

$$\{ \mathbf{a}^n \mathbf{b}^n \mid n \in \mathbb{N} \}$$

is a canonical example of a nonregular language. It's not possible to check if a string is in this language given only finite memory.

- Turing machines, however, are powerful enough to do this. Let's see how.

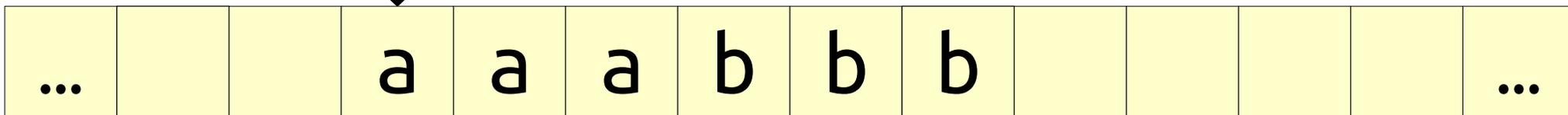
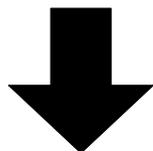
$$L = \{ \mathbf{a}^n \mathbf{b}^n \mid n \in \mathbb{N} \}$$



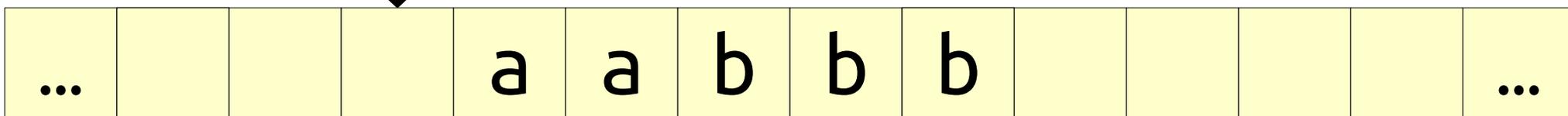
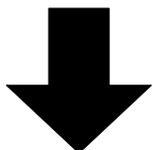
A Recursive Approach

- We can process our string using this recursive approach:
 - The string ε is in L .
 - The string **a** w **b** is in L if and only if w is in L .
 - Any string starting with **b** is not in L .
 - Any string ending with **a** is not in L .
- All that's left to do now is write a TM that implements this.

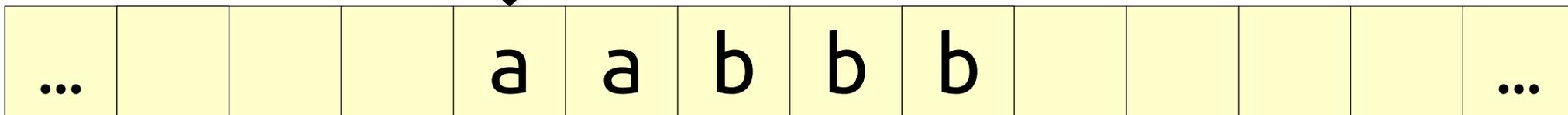
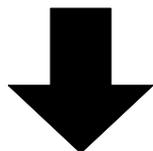
A Sketch of our TM



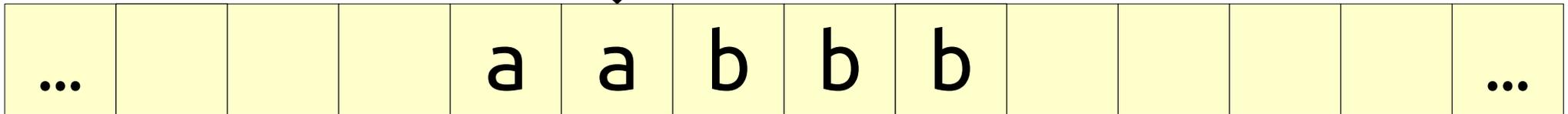
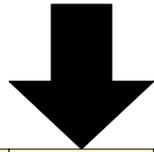
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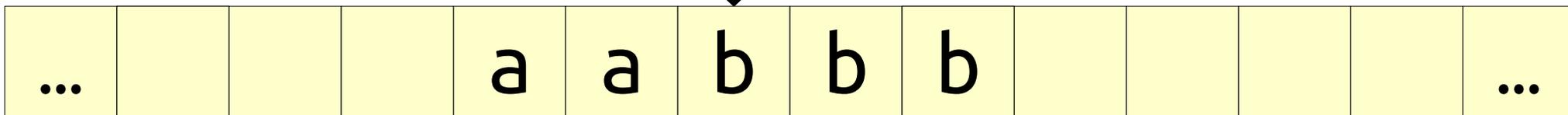
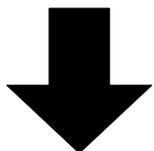
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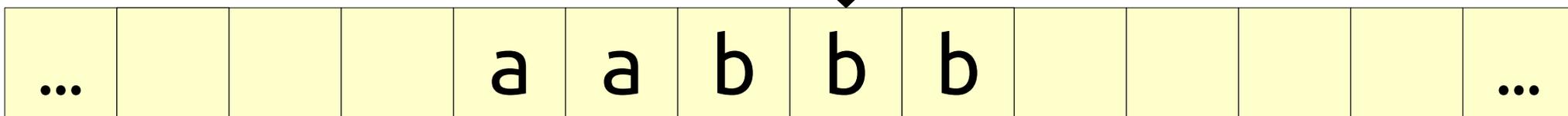
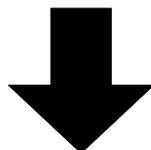
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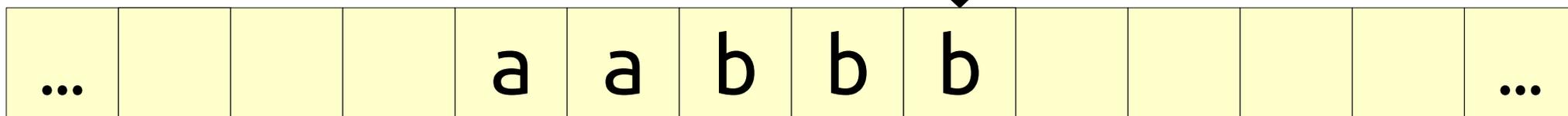
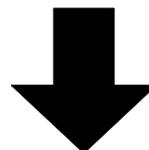
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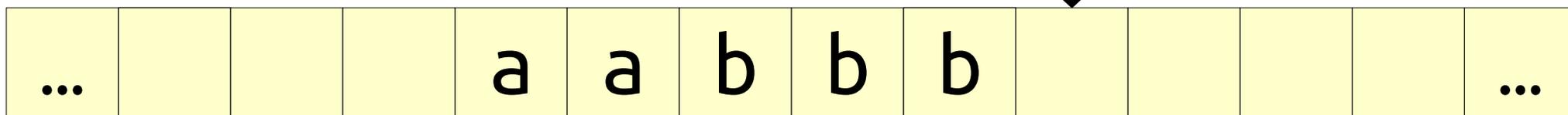
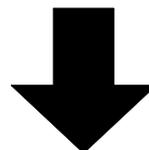
A Sketch of our TM



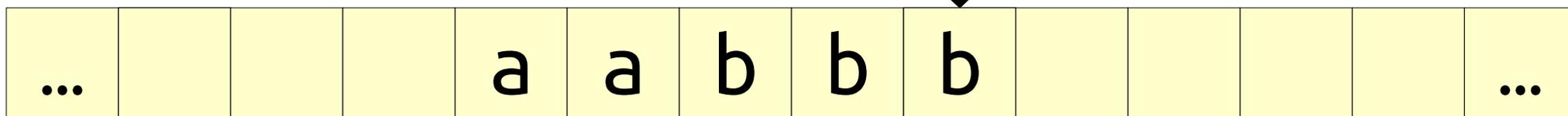
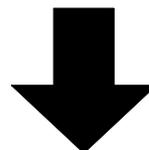
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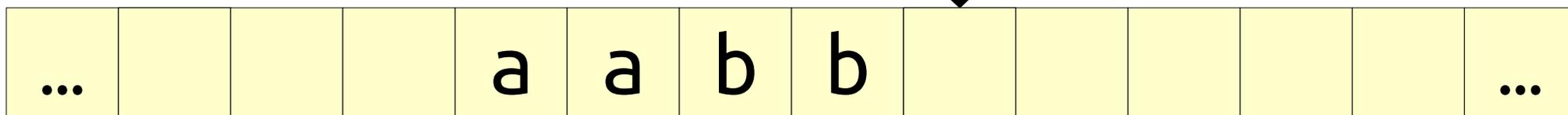
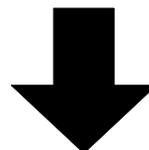
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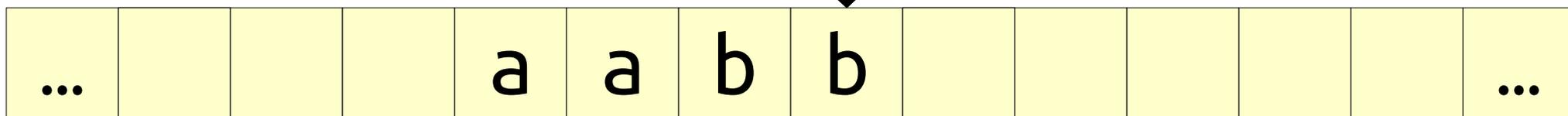
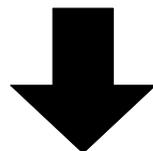
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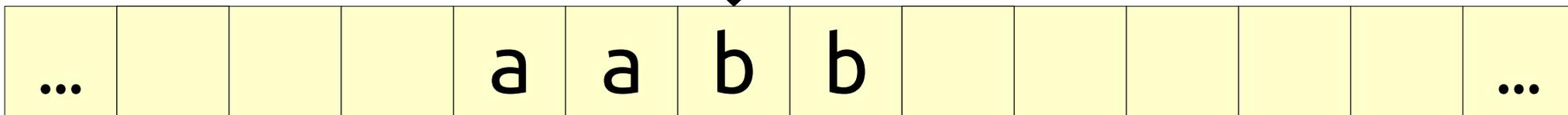
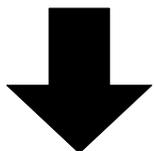
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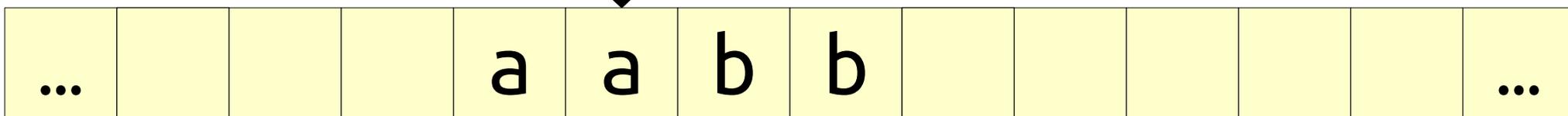
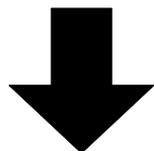
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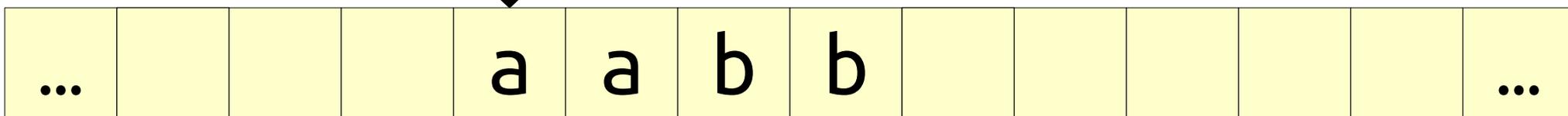
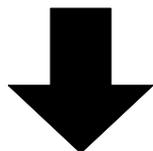
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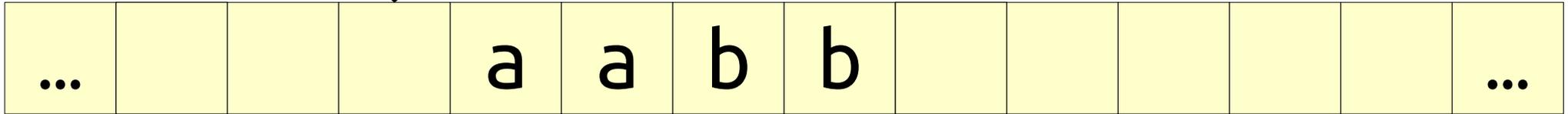
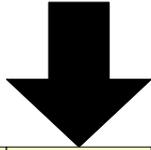
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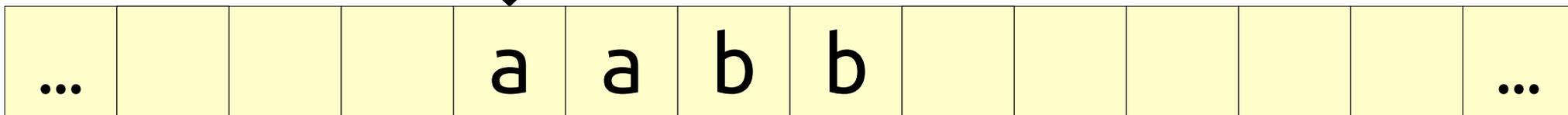
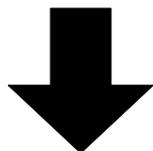
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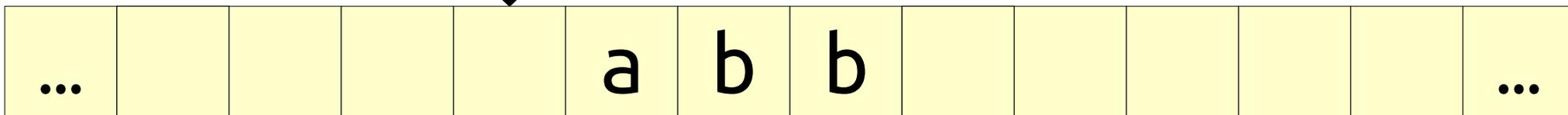
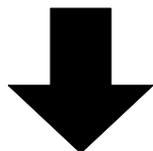
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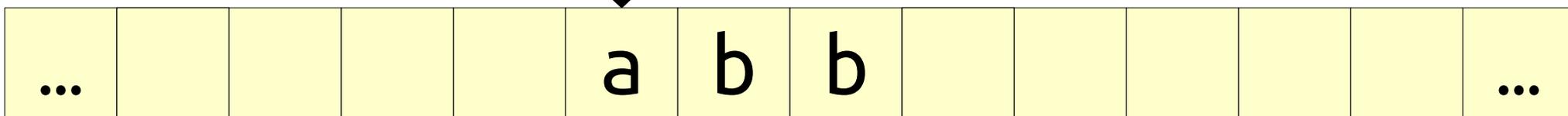
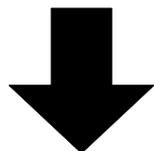
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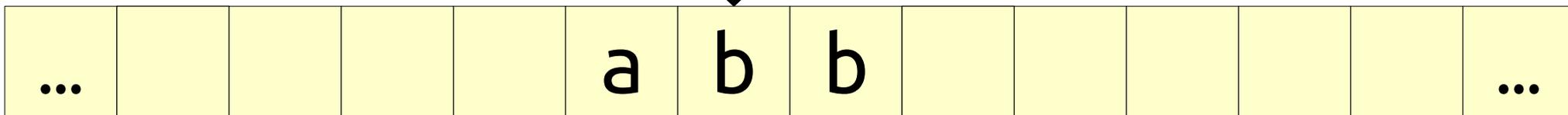
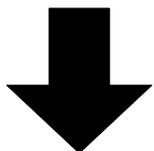
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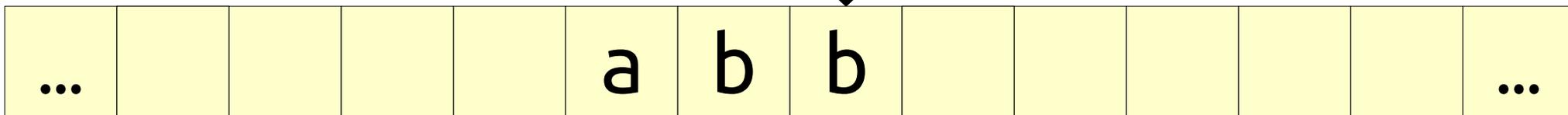
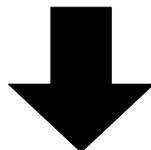
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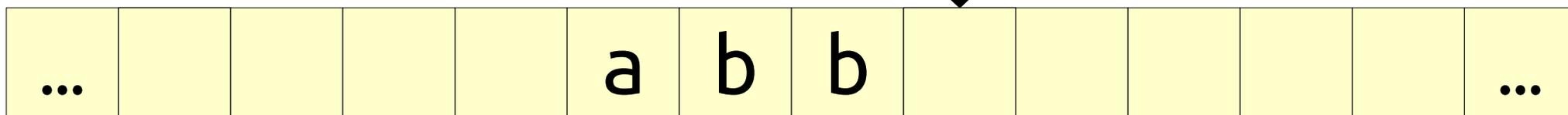
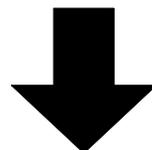
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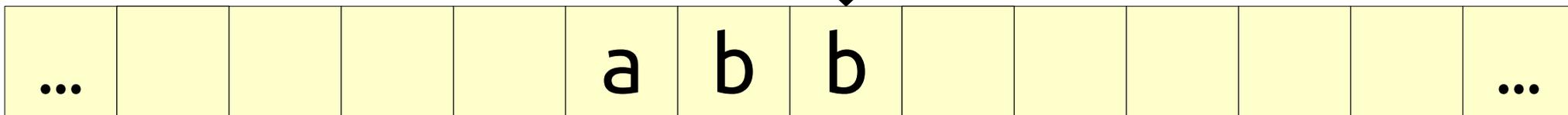
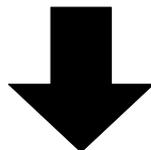
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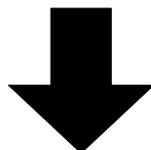
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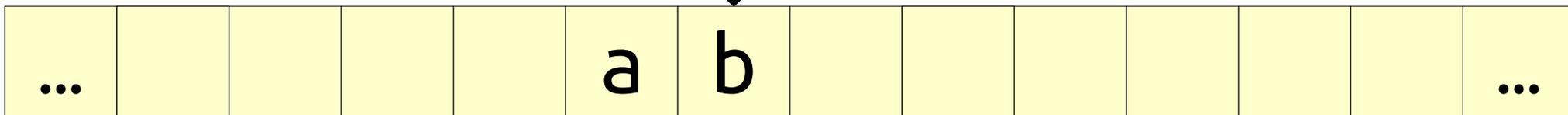
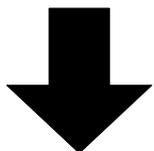
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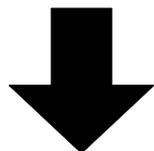
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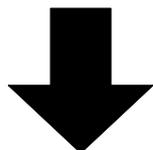
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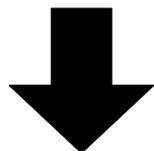
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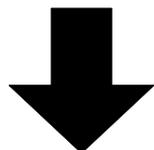
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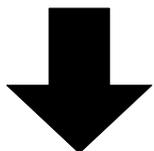
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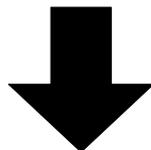
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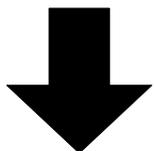
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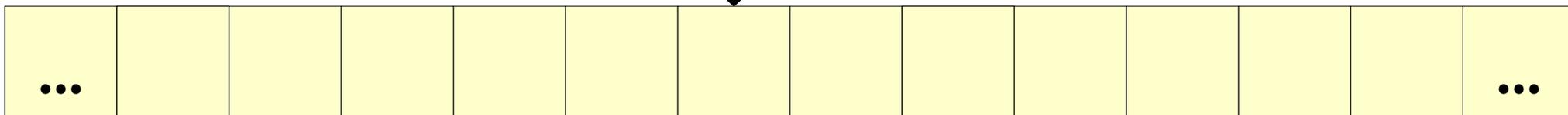
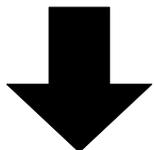
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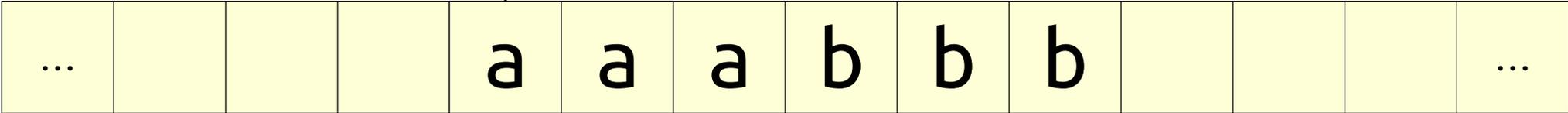
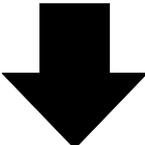


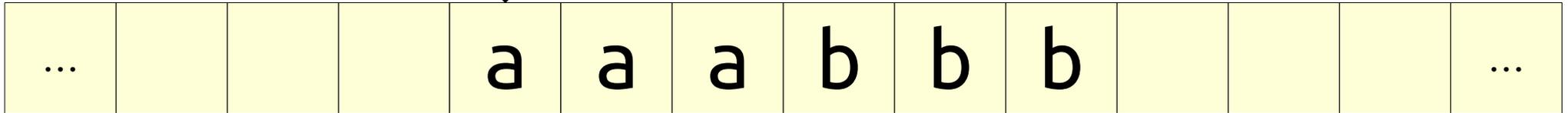
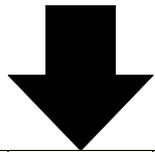
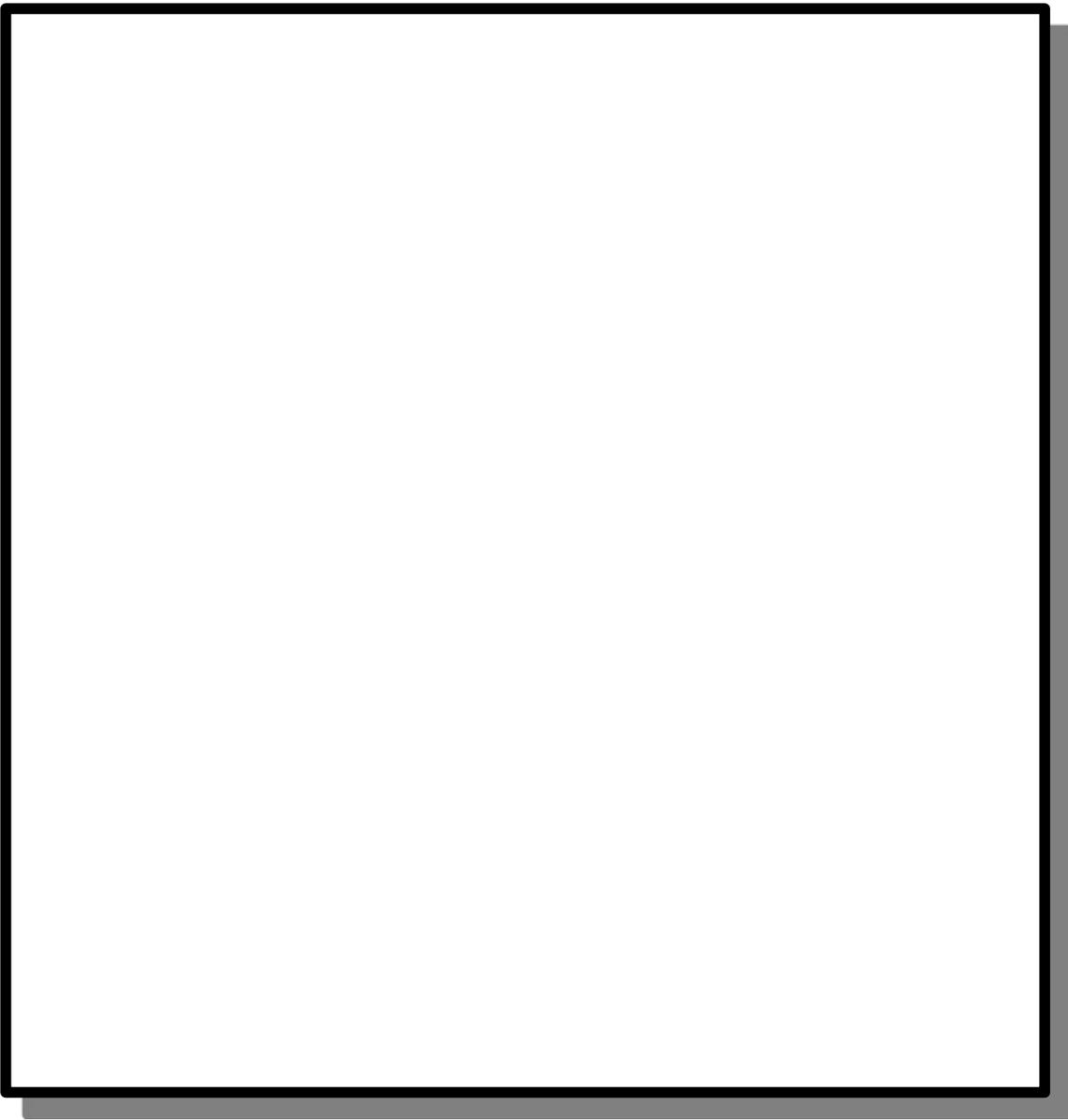
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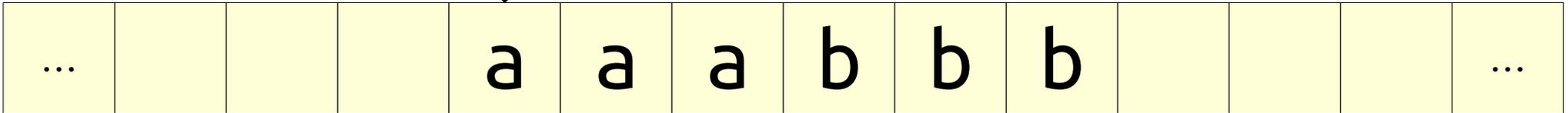
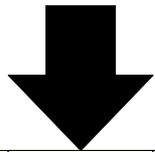
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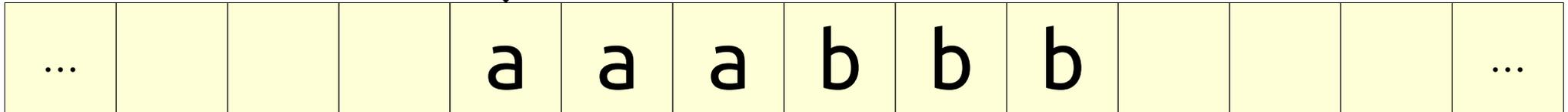
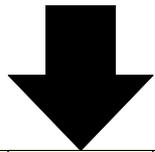




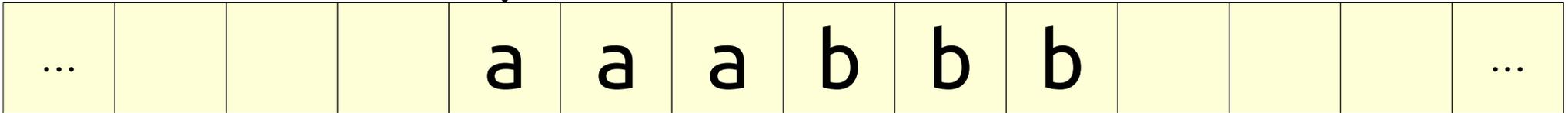
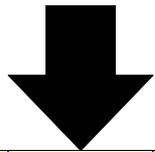
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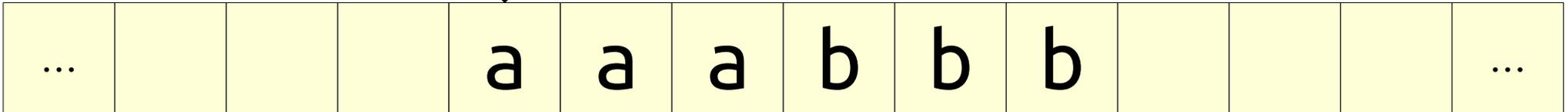
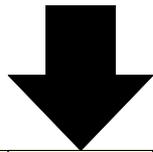


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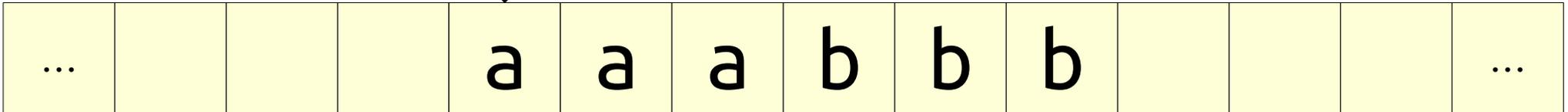
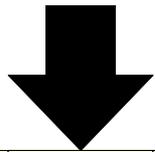


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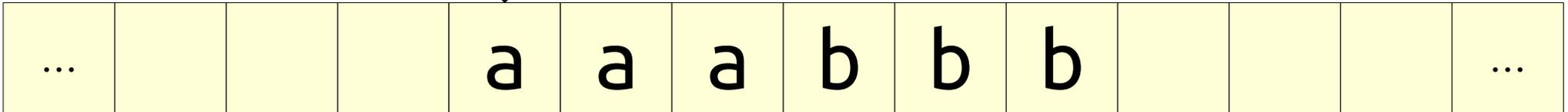
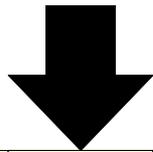
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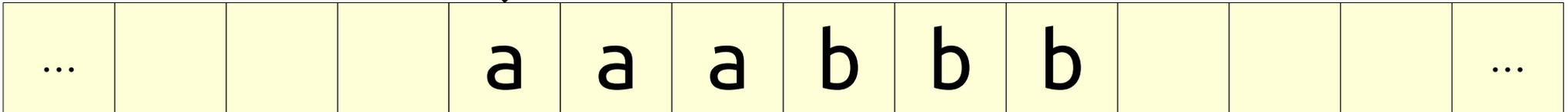
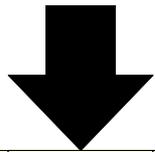
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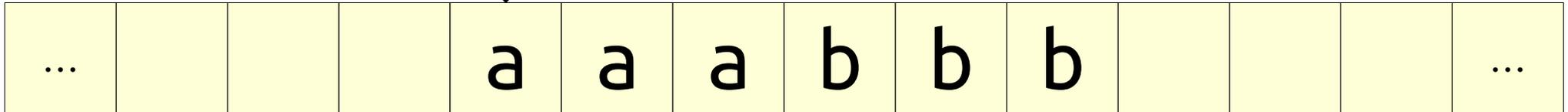
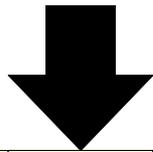


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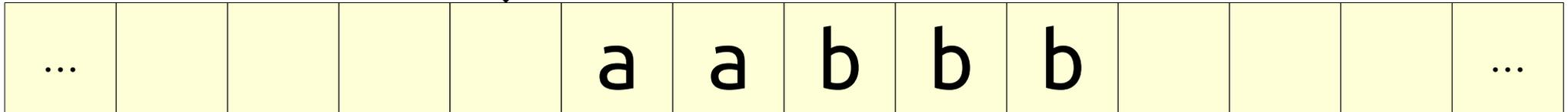
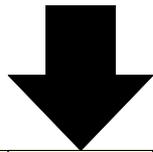


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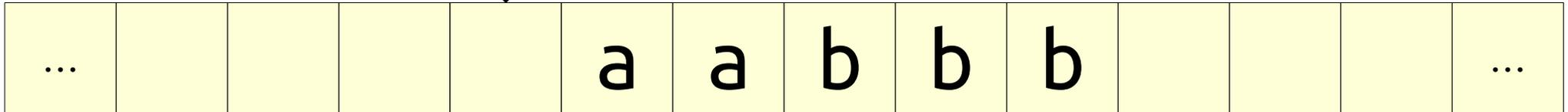
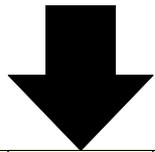


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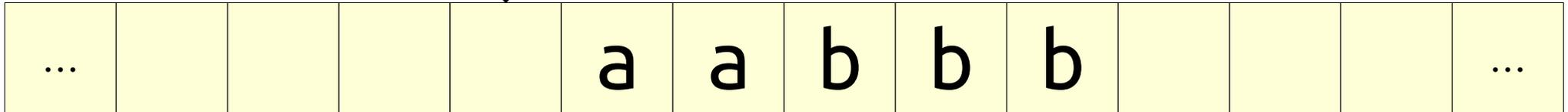
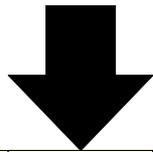
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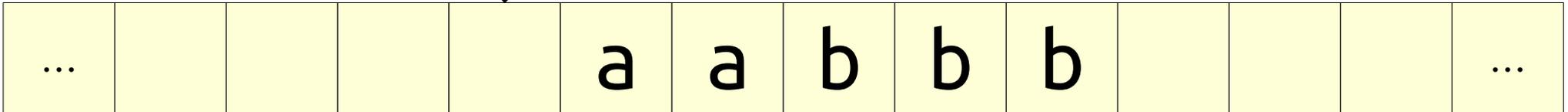
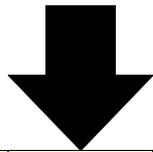
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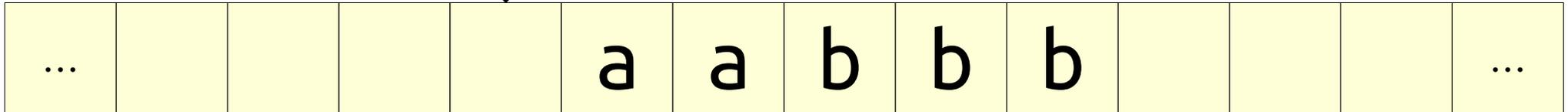
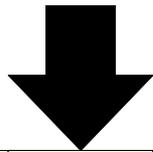
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Move Right



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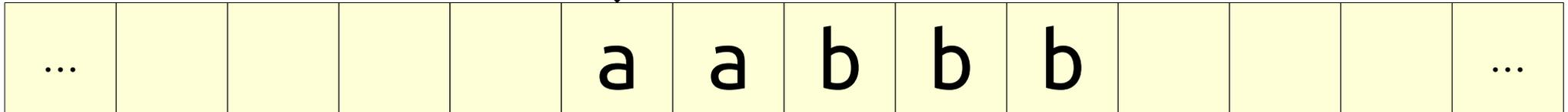
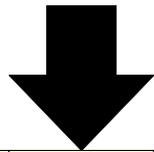
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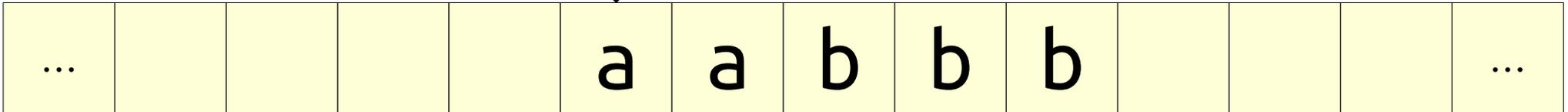
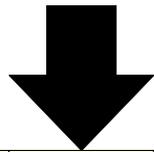
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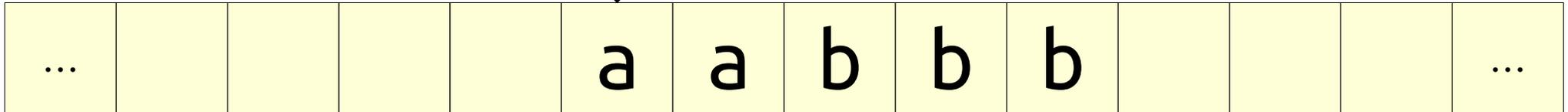
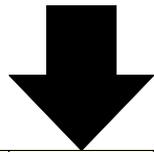
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If Not Blank Goto ZipRight



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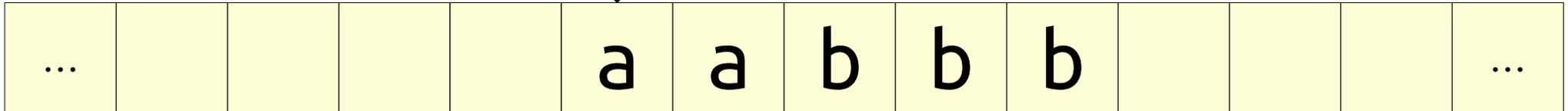
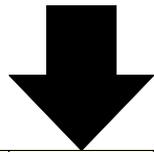
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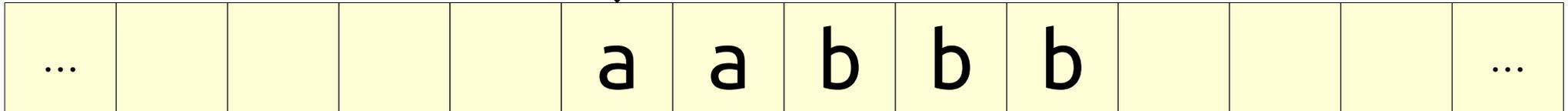
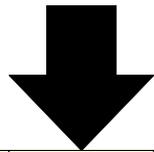
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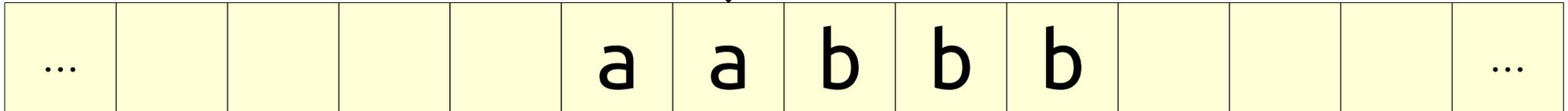
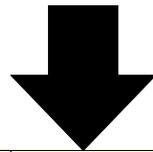
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Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight



Start:

If Blank Return True

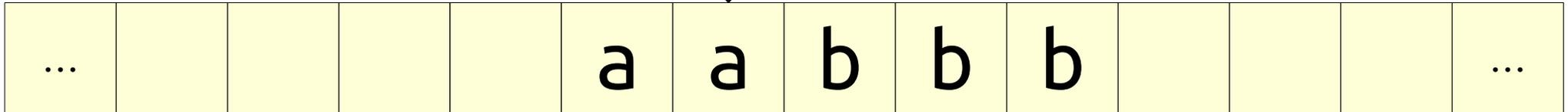
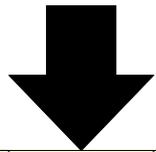
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ZipRight:

Move Right

If Not Blank Goto ZipRight



Start:

If Blank Return True

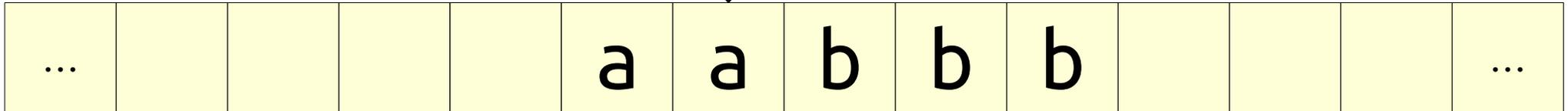
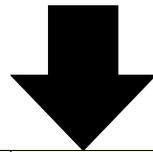
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Move Right

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Start:

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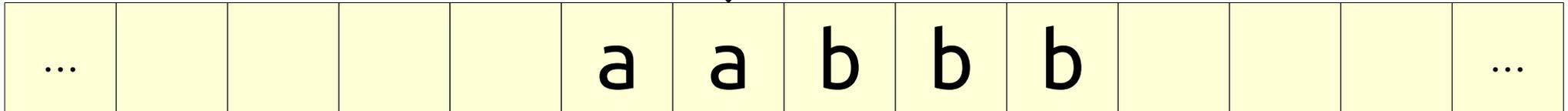
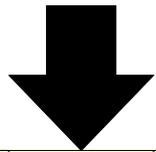
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Move Right

If Not Blank Goto ZipRight



Start:

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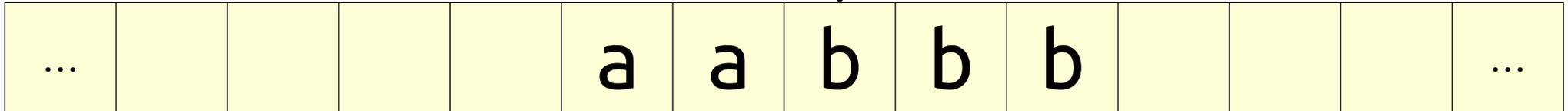
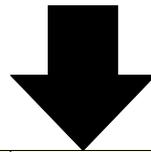
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Move Right

If Not Blank Goto ZipRight



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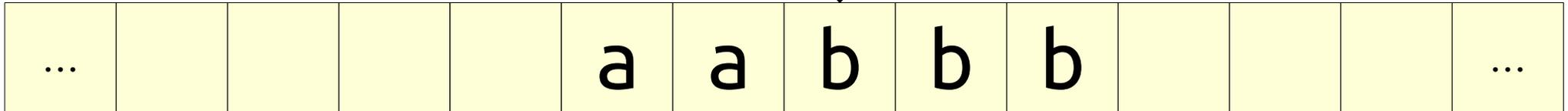
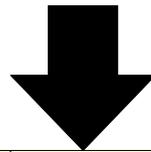
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Start:

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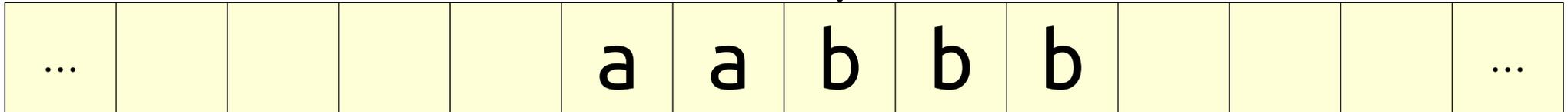
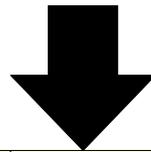
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Move Right

If Not Blank Goto ZipRight



Start:

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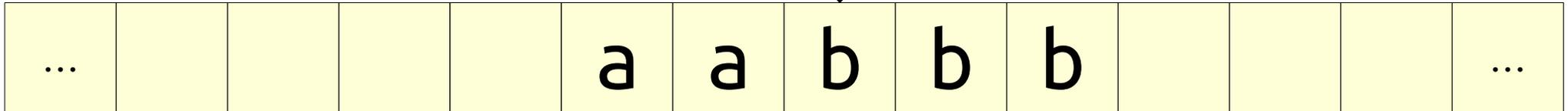
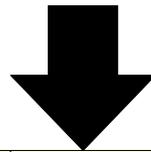
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Move Right

If Not Blank Goto ZipRight



Start:

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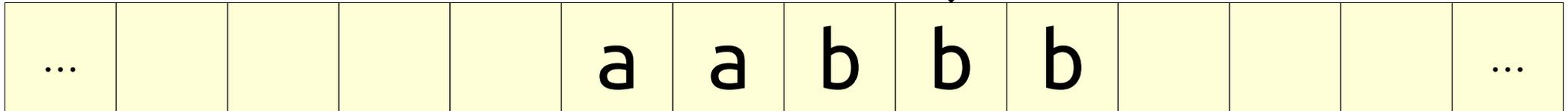
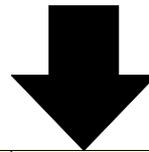
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ZipRight:

Move Right

If Not Blank Goto ZipRight



Start:

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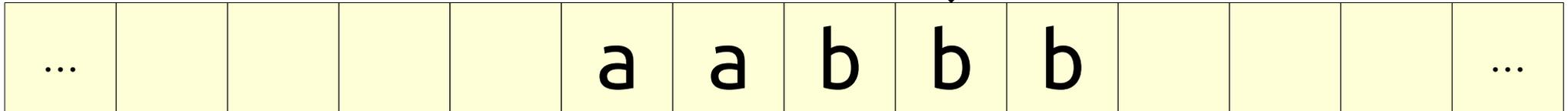
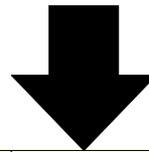
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ZipRight:

Move Right

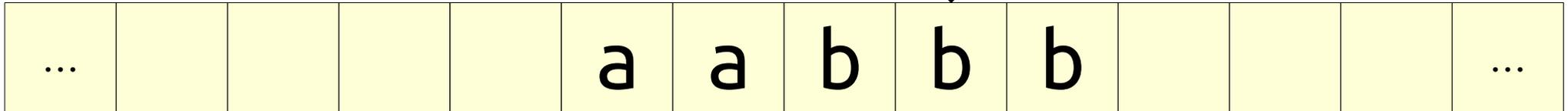
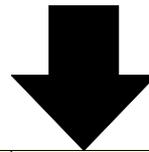
If Not Blank Goto ZipRight



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Start:  
  If Blank Return True  
  If 'b' Return False  
  Write Blank
```

```
ZipRight:
```

```
  Move Right  
  If Not Blank Goto ZipRight
```



Start:

If Blank Return True

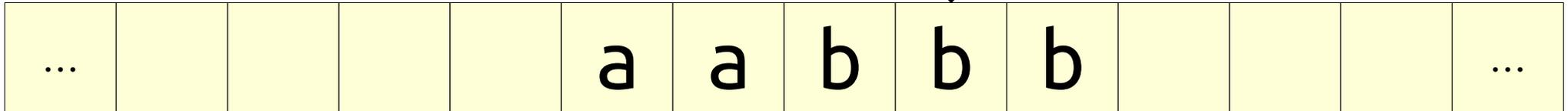
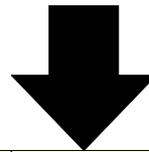
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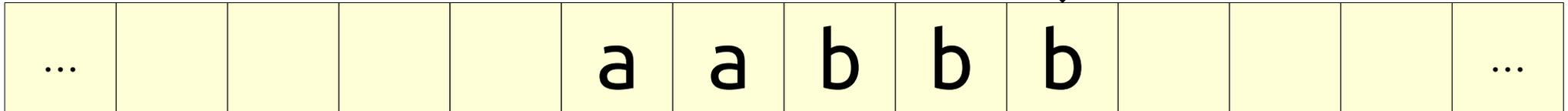
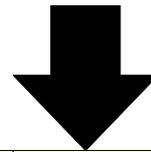
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ZipRight:

Move Right

If Not Blank Goto ZipRight



Start:

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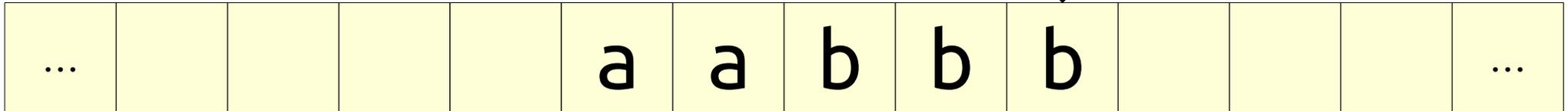
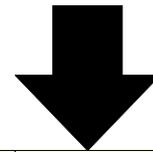
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Move Right

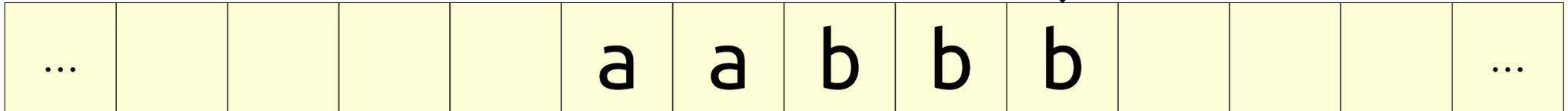
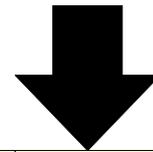
If Not Blank Goto ZipRight



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Start:  
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  If 'b' Return False  
  Write Blank
```

ZipRight:

```
  Move Right  
  If Not Blank Goto ZipRight
```



Start:

If Blank Return True

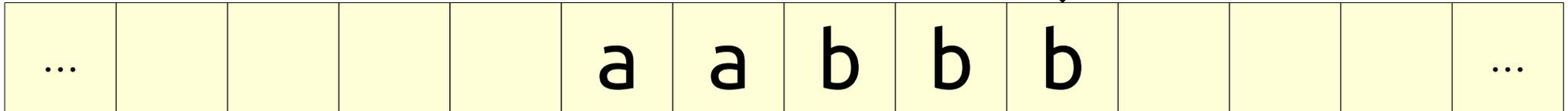
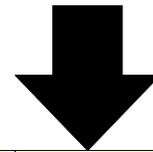
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ZipRight:

Move Right

If Not Blank Goto ZipRight



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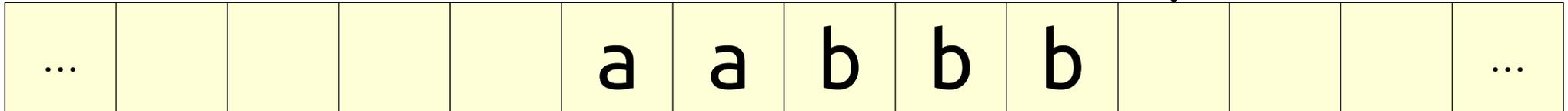
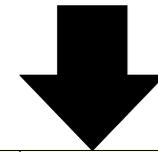
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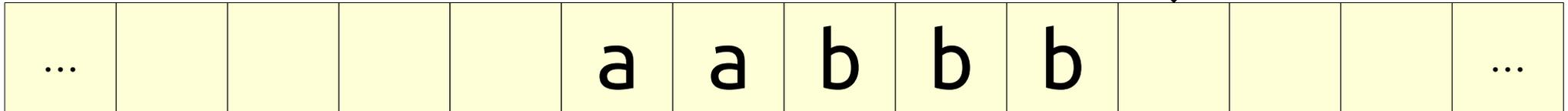
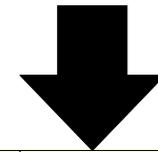
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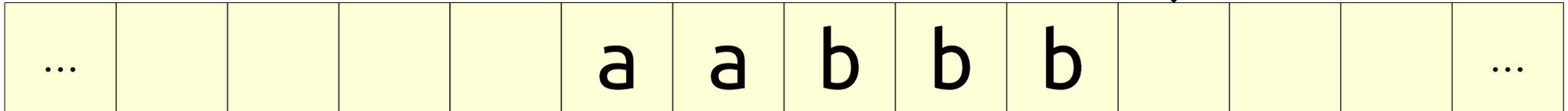
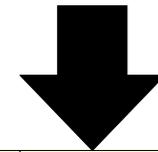
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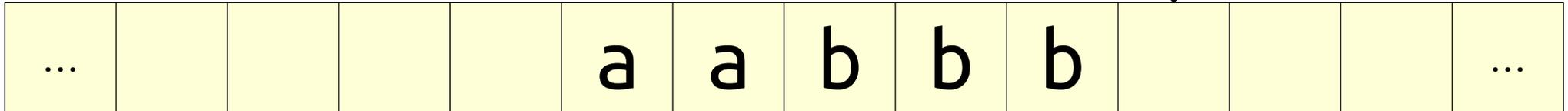
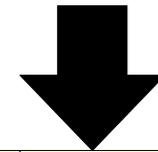
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If Not Blank Goto ZipRight

Move Left



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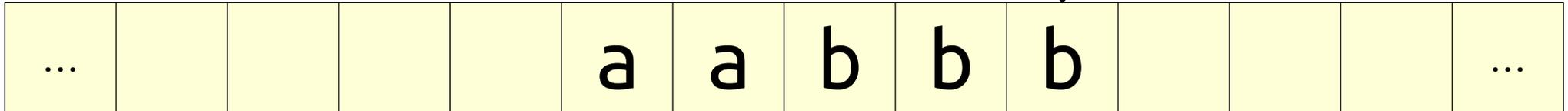
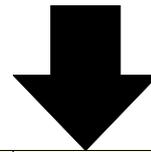
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Move Right

If Not Blank Goto ZipRight

Move Left



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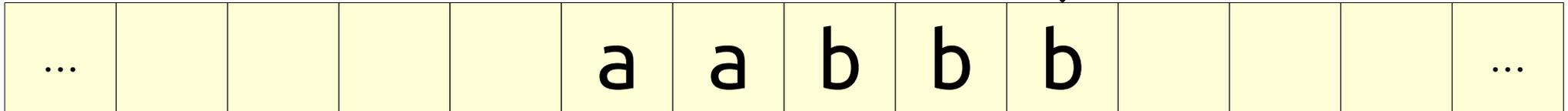
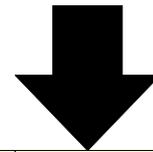
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If Not Blank Goto ZipRight

Move Left



Start:

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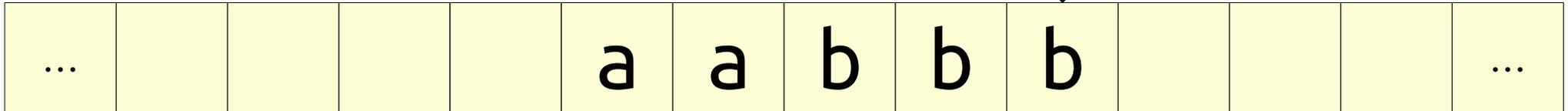
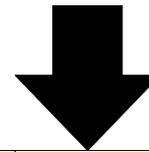
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Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False



Start:

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If 'b' Return False

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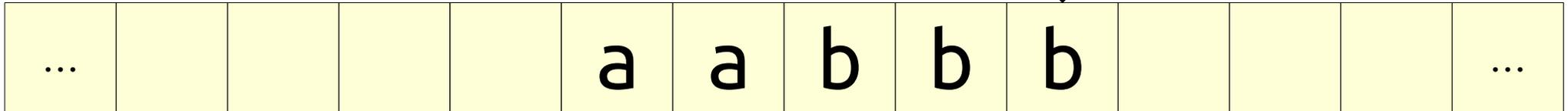
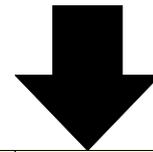
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If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False



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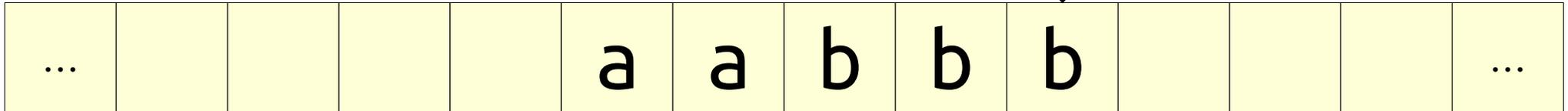
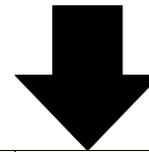
Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank



Start:

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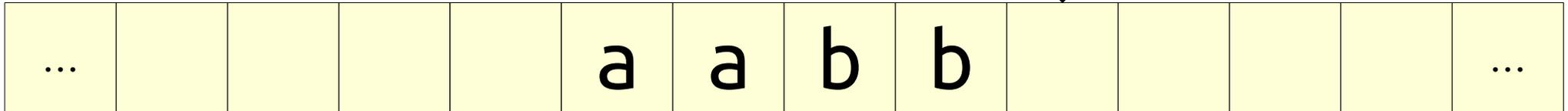
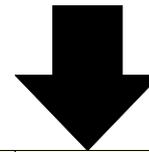
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Move Left

If Not 'b' Return False

Write Blank



Start:

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ZipRight:

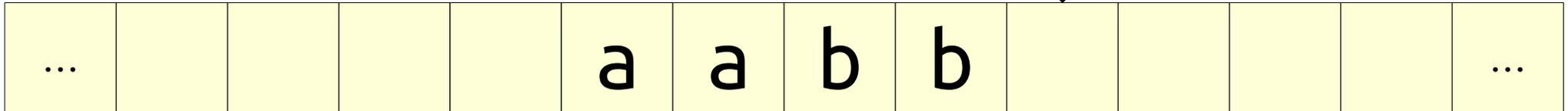
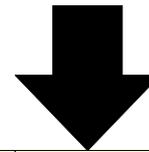
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Move Left

If Not 'b' Return False

Write Blank



Start:

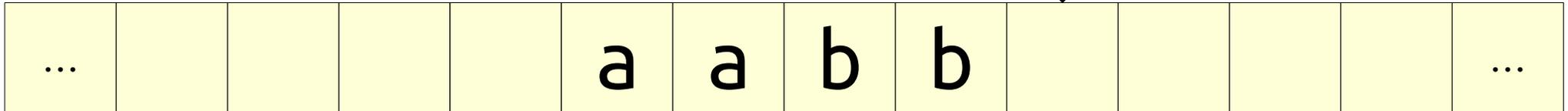
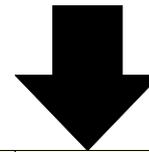
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

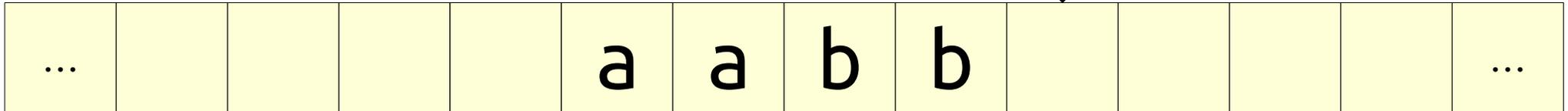
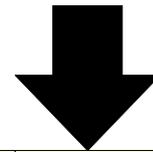
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

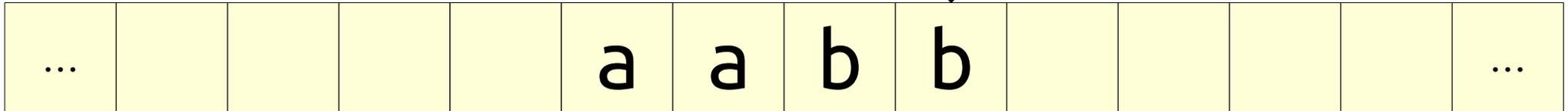
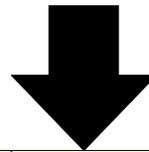
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

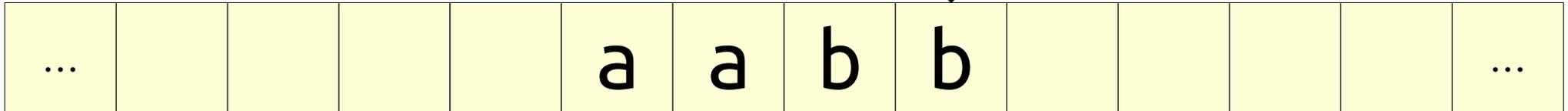
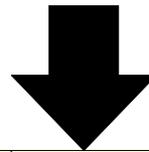
If Not 'b' Return False

Write Blank

ZipLeft:

Move Left

If Not Blank Goto ZipLeft



Start:

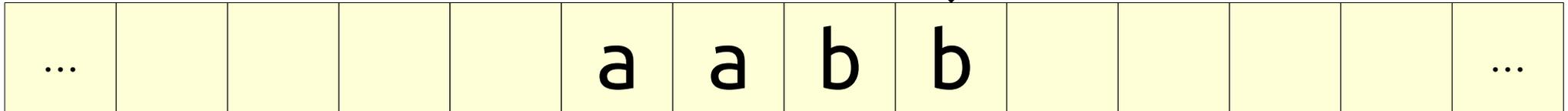
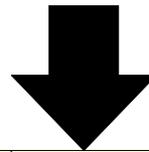
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

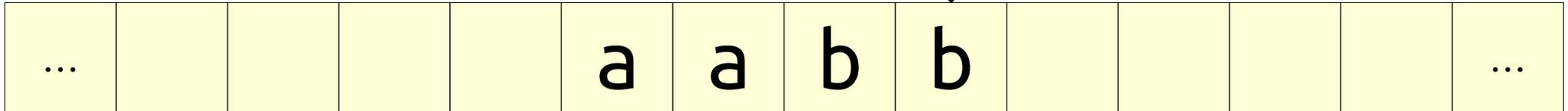
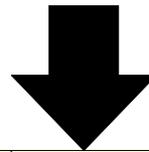
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

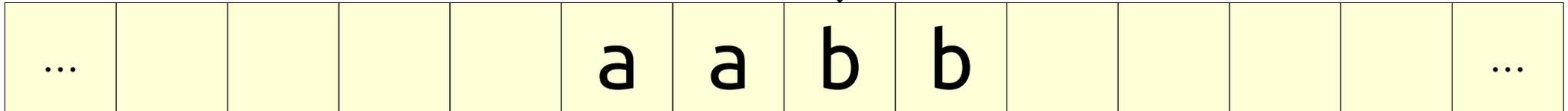
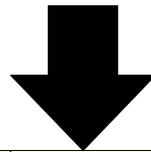
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

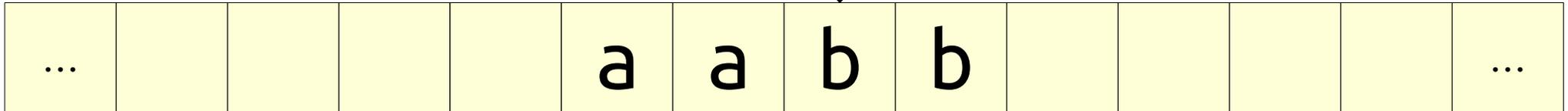
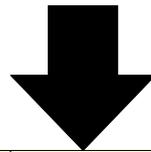
If Not 'b' Return False

Write Blank

ZipLeft:

Move Left

If Not Blank Goto ZipLeft



Start:

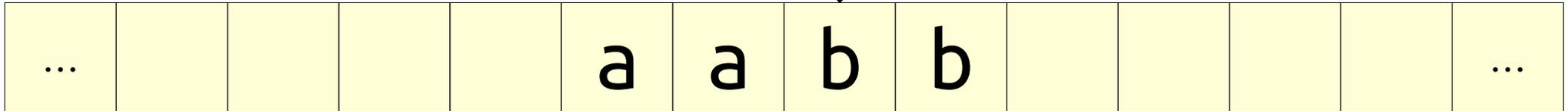
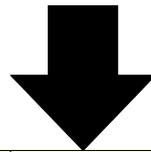
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

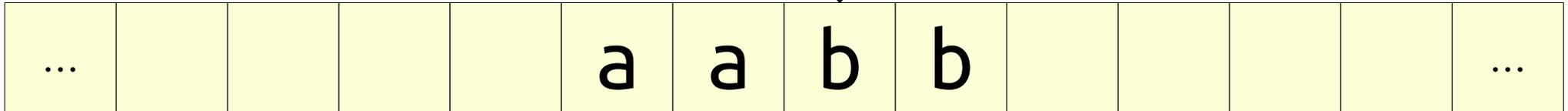
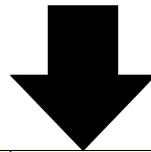
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

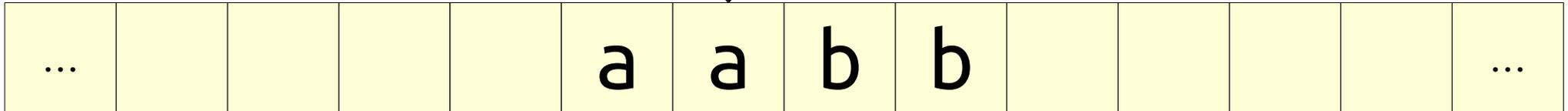
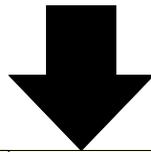
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

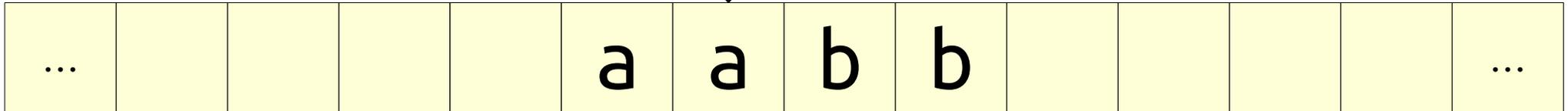
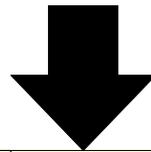
If Not 'b' Return False

Write Blank

ZipLeft:

Move Left

If Not Blank Goto ZipLeft



Start:

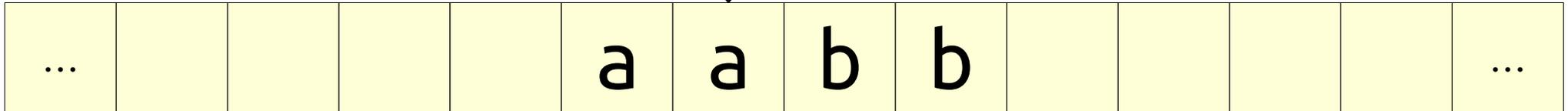
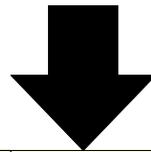
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

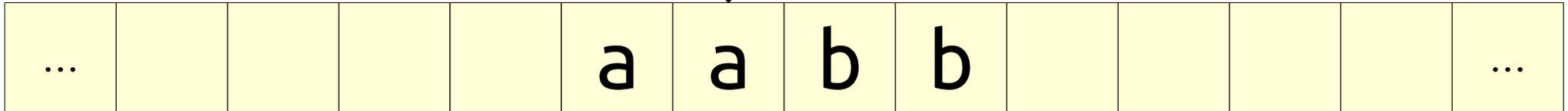
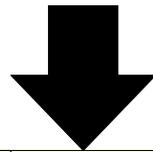
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

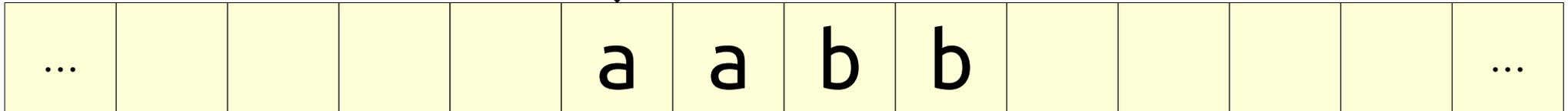
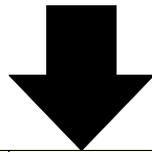
If Not 'b' Return False

Write Blank

ZipLeft:

Move Left

If Not Blank Goto ZipLeft



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

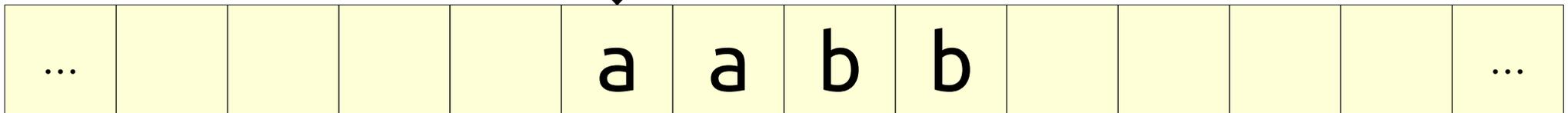
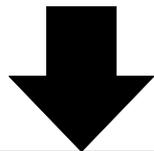
If Not 'b' Return False

Write Blank

ZipLeft:

Move Left

If Not Blank Goto ZipLeft



Start:

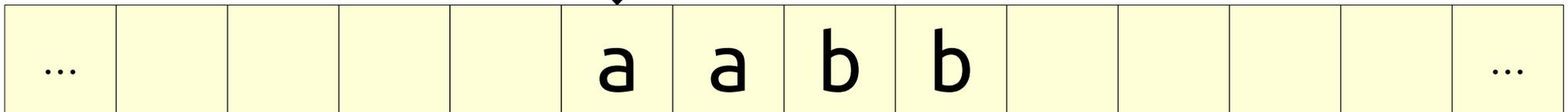
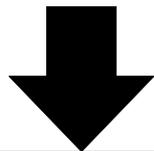
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

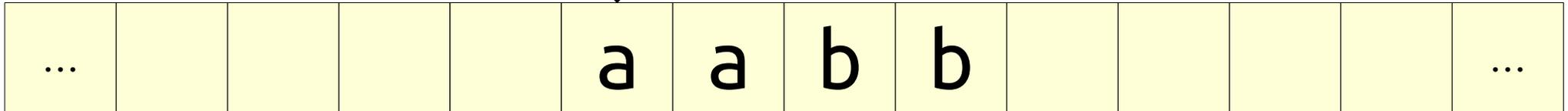
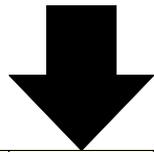
If Not 'b' Return False

Write Blank

ZipLeft:

Move Left

If Not Blank Goto ZipLeft



Start:

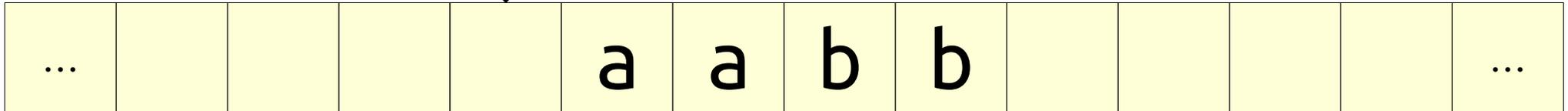
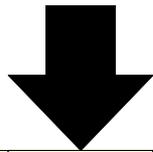
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

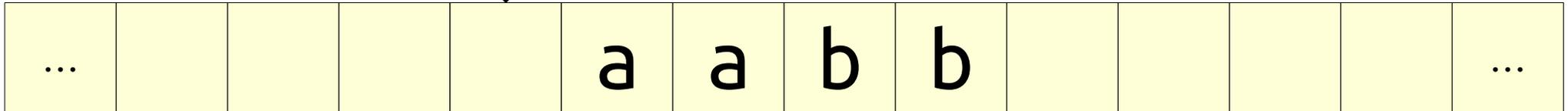
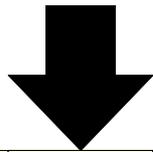
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

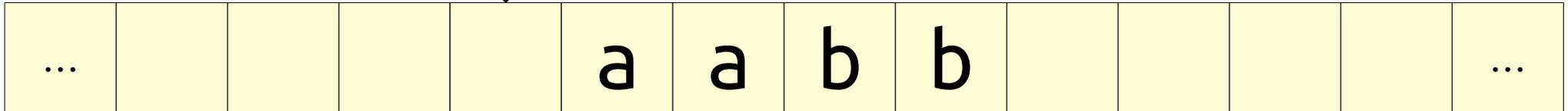
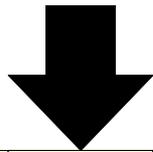
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft
```



Start:

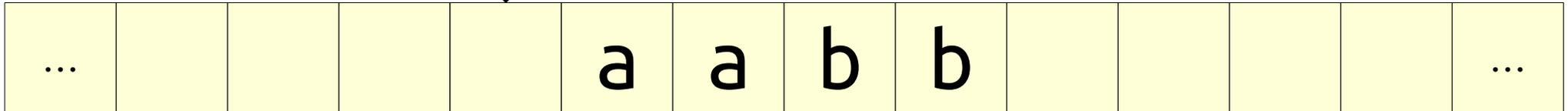
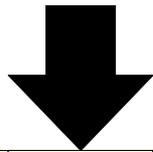
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right
```



Start:

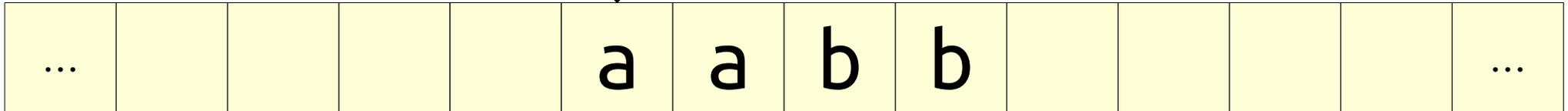
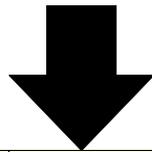
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right
```



Start:

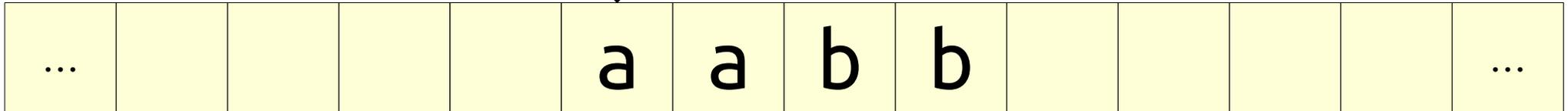
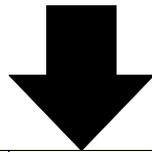
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right
```



Start:

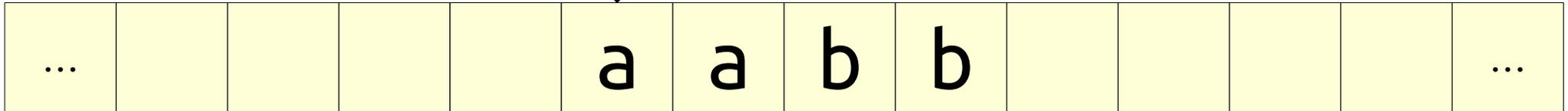
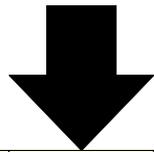
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

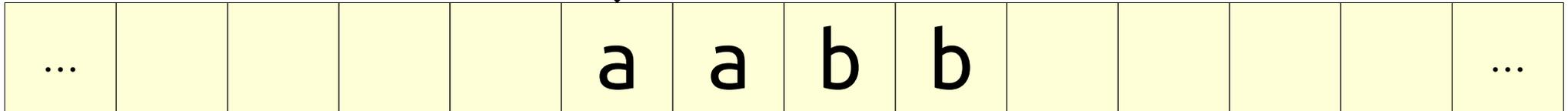
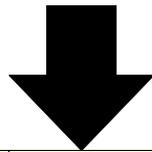
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

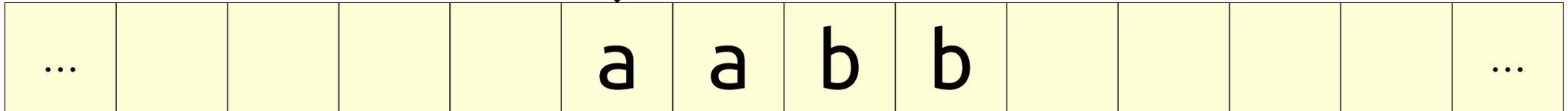
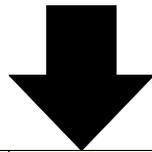
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

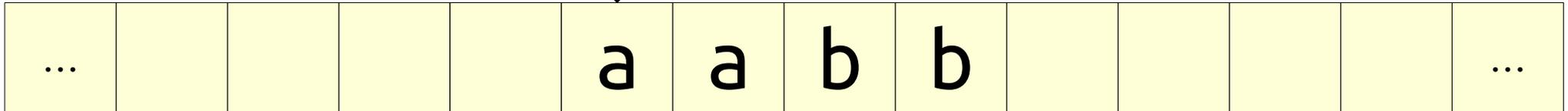
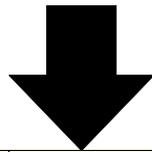
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

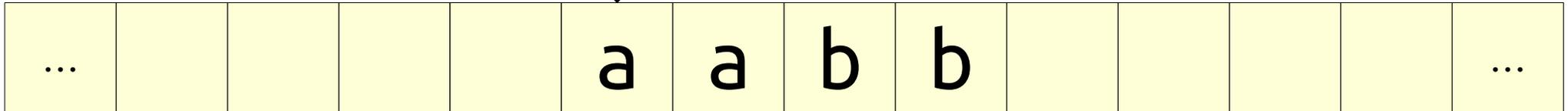
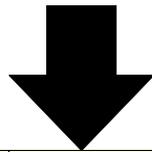
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

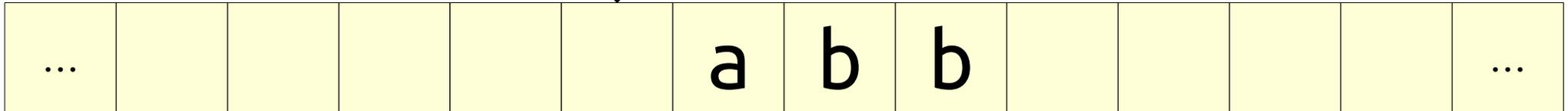
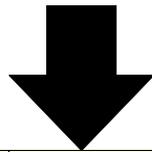
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



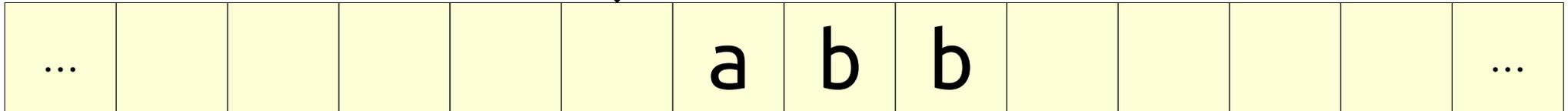
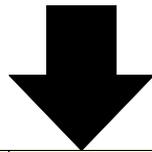
```
Start:  
  If Blank Return True  
  If 'b' Return False  
  Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
If 'b' Return False  
Write Blank
```

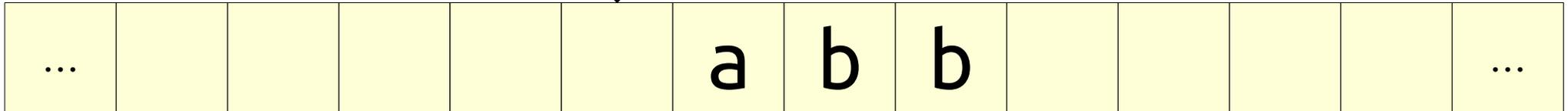
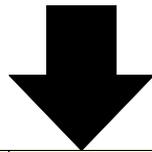
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
If 'b' Return False  
Write Blank
```

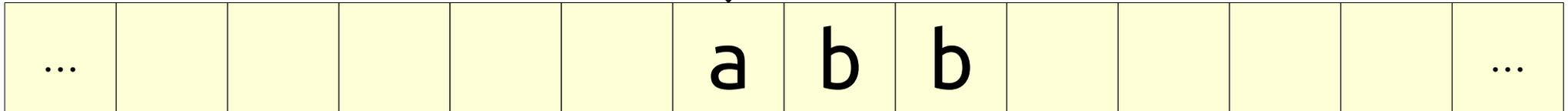
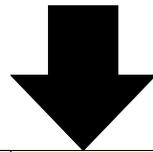
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

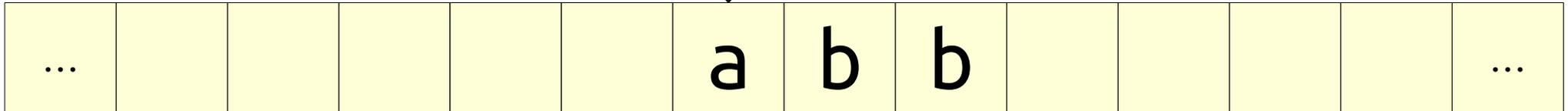
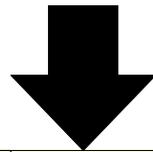
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

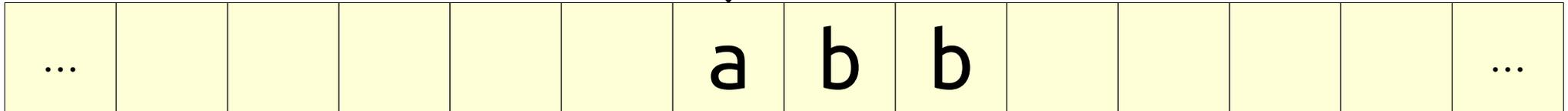
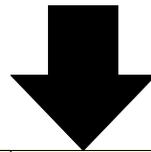
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

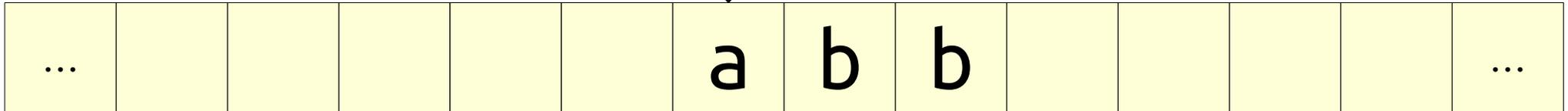
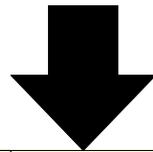
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
If 'b' Return False  
Write Blank
```

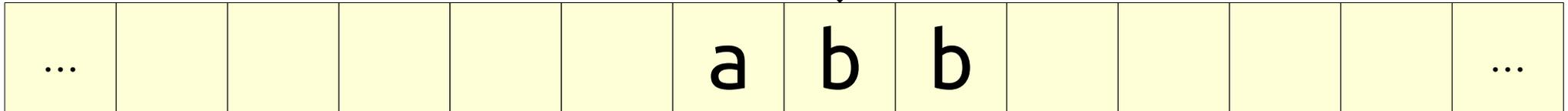
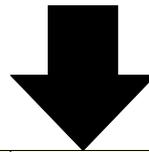
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

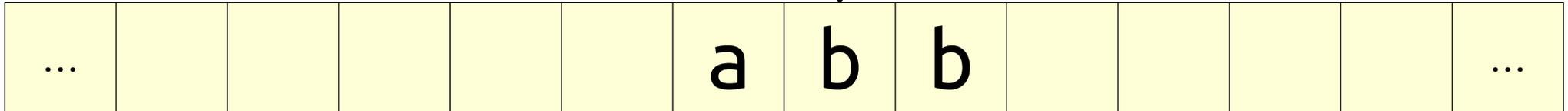
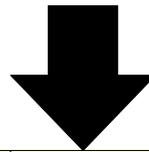
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



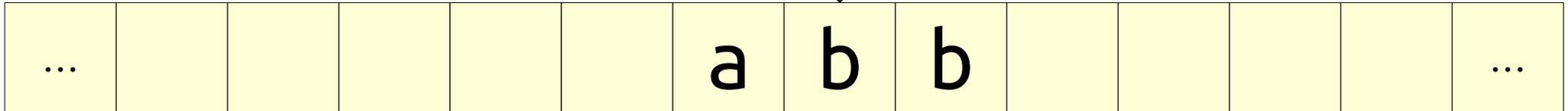
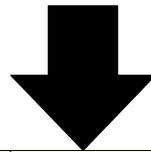
```
Start:  
  If Blank Return True  
  If 'b' Return False  
  Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
If 'b' Return False  
Write Blank
```

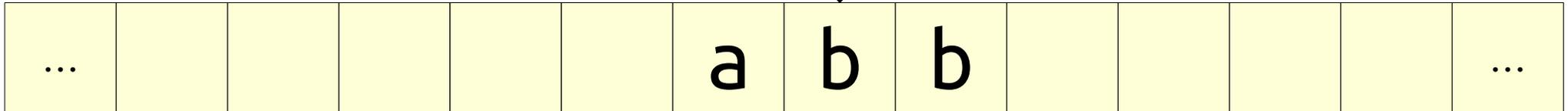
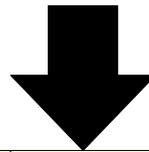
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
If 'b' Return False  
Write Blank
```

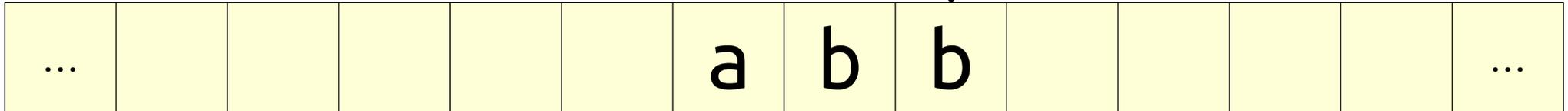
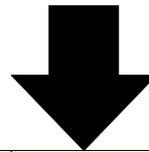
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

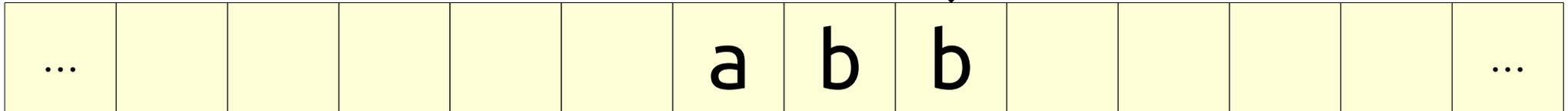
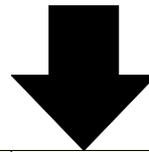
```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



```
Start:  
  If Blank Return True  
  If 'b' Return False  
  Write Blank
```

```
ZipRight:  
  Move Right  
  If Not Blank Goto ZipRight  
  Move Left  
  If Not 'b' Return False  
  Write Blank
```

```
ZipLeft:  
  Move Left  
  If Not Blank Goto ZipLeft  
  Move Right  
  Goto Start
```

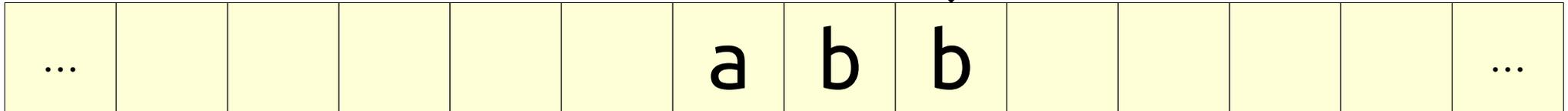
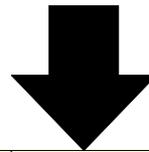


```
Start:  
  If Blank Return True  
  If 'b' Return False  
  Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

```
ZipLeft:  
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

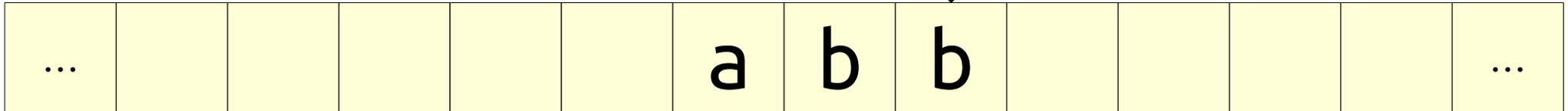
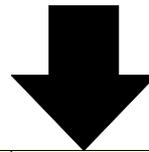
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

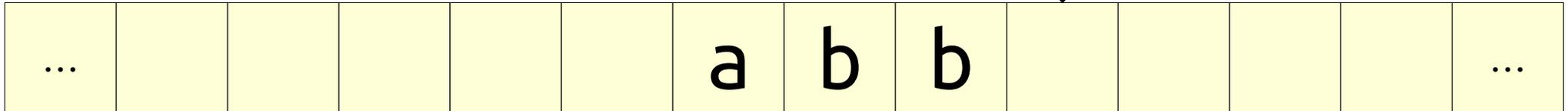
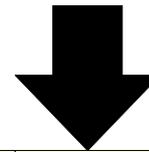
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

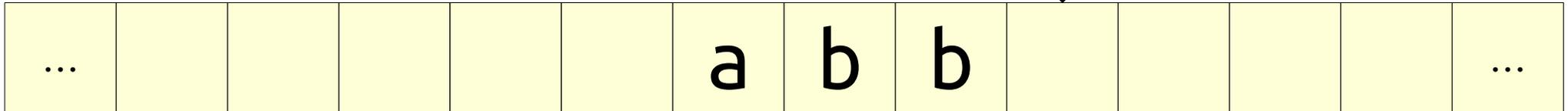
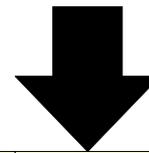
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Start:

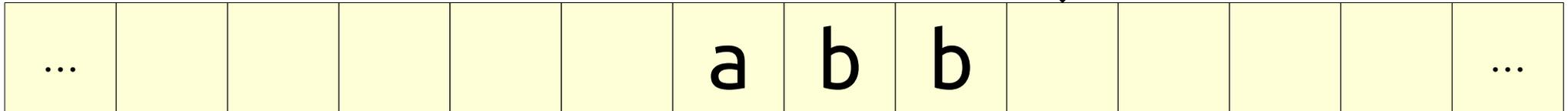
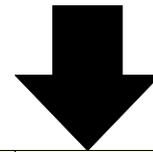
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

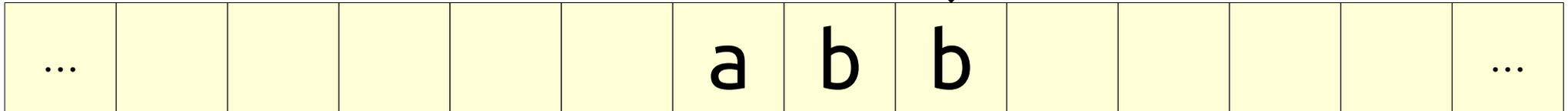
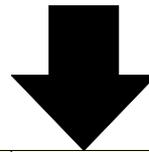
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

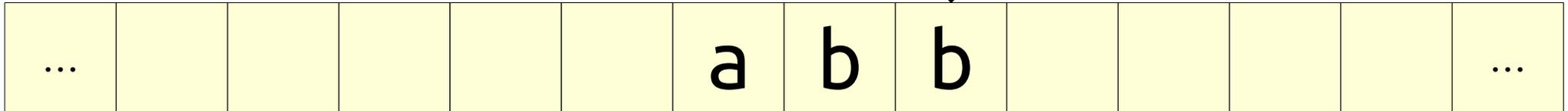
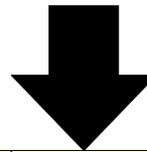
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

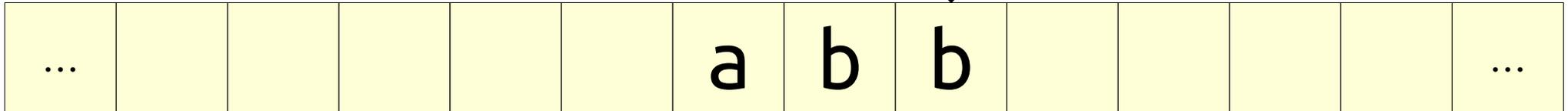
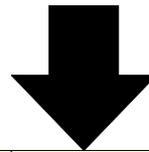
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

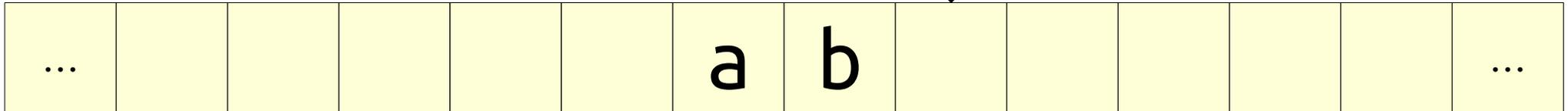
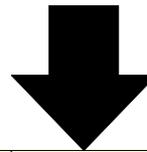
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

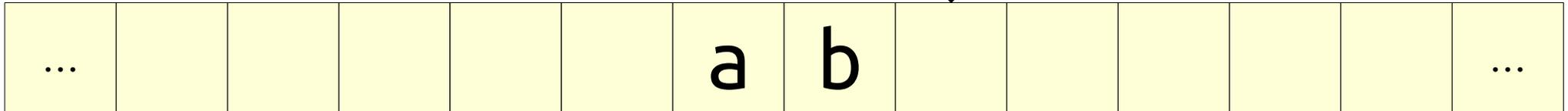
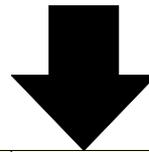
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

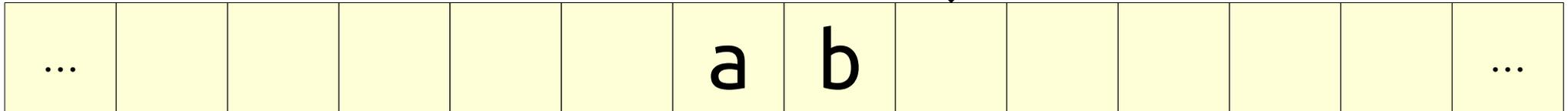
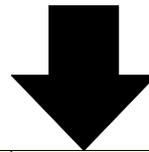
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

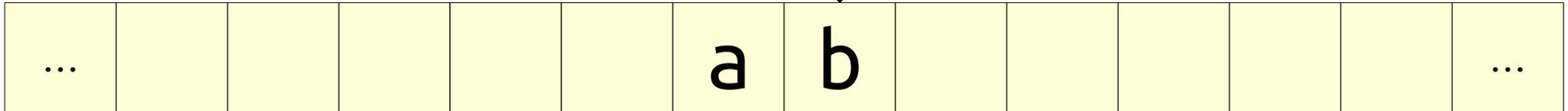
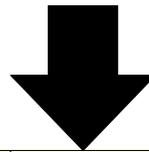
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

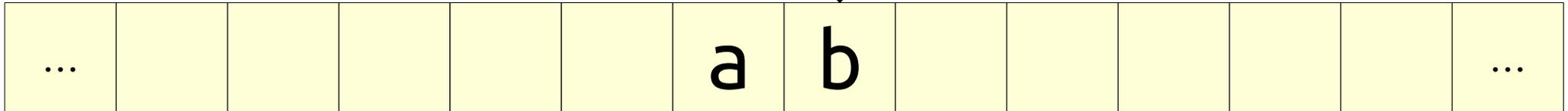
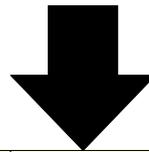
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

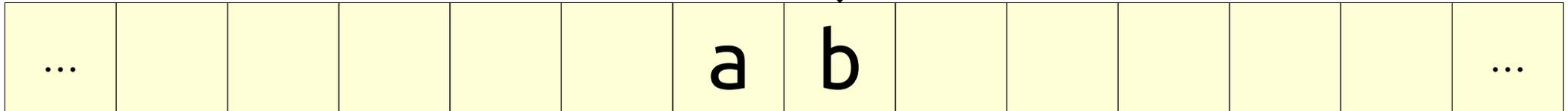
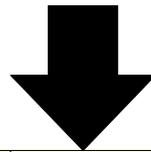
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

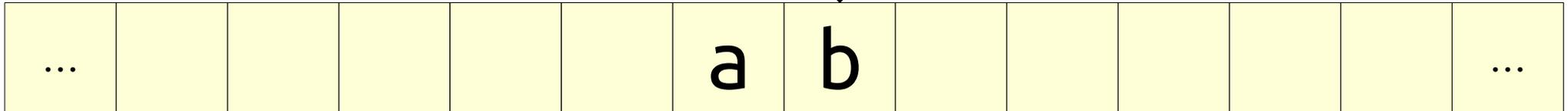
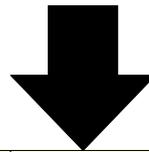
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

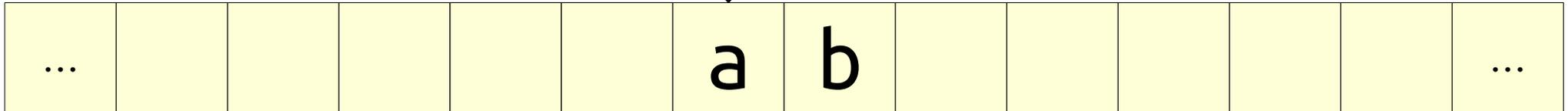
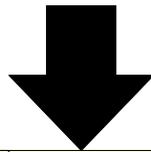
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

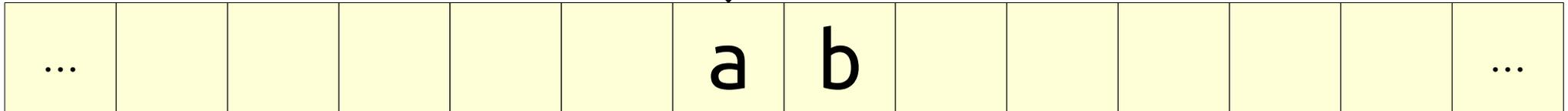
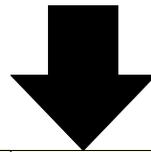
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

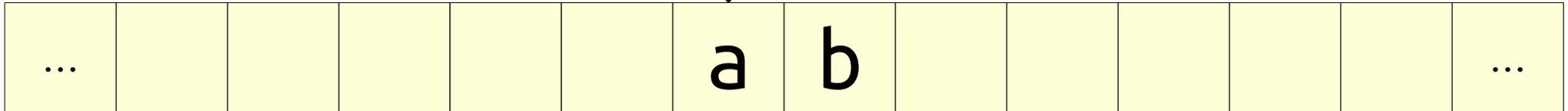
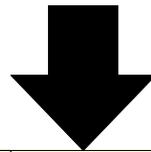
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

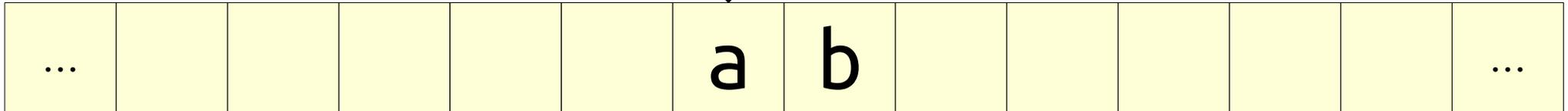
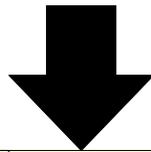
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

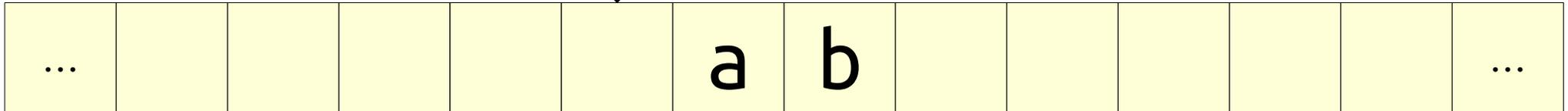
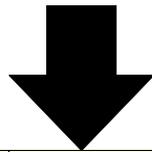
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

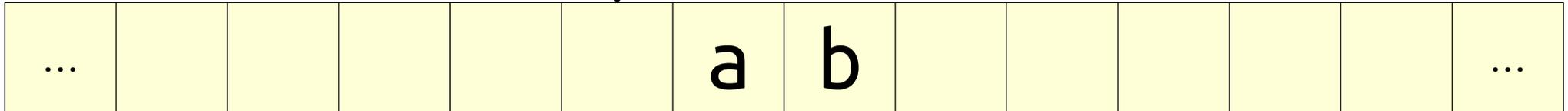
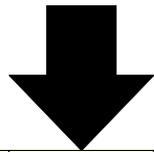
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

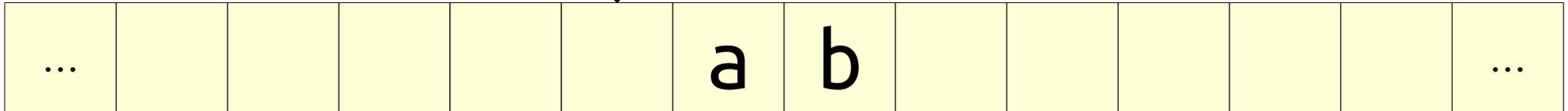
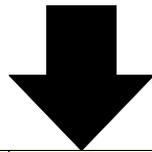
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

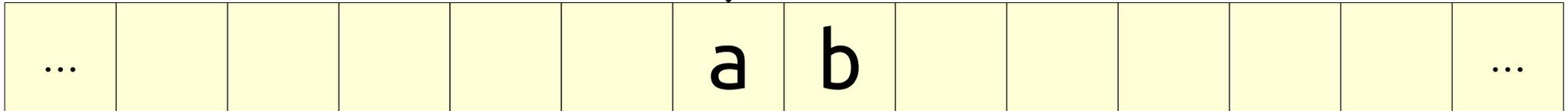
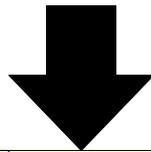
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

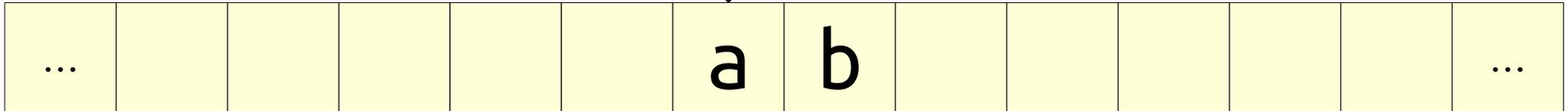
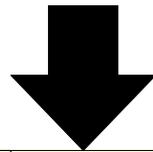
```
If Blank Return True  
If 'b' Return False  
Write Blank
```

ZipRight:

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Move Right  
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

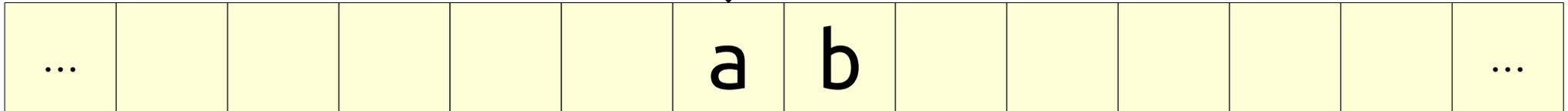
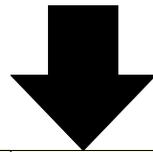
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ZipLeft:

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Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

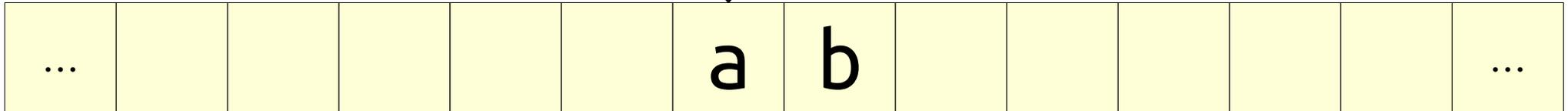
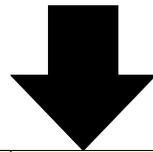
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

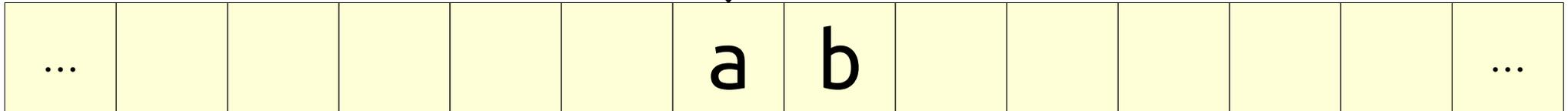
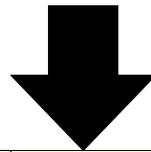
ZipLeft:

Move Left

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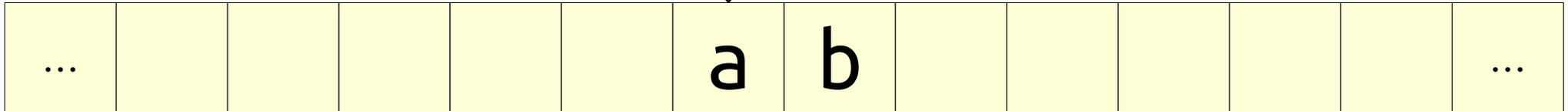
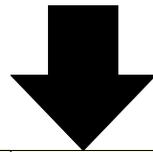
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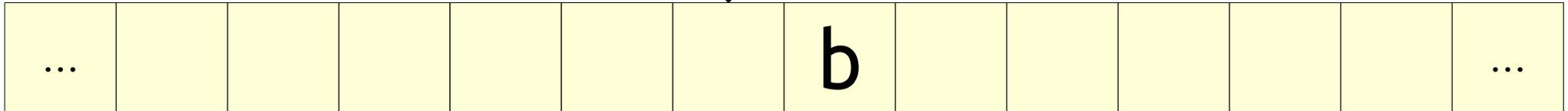
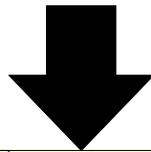
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



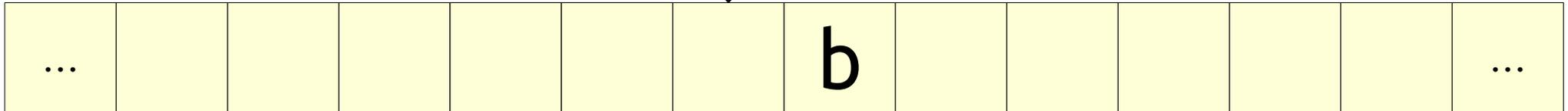
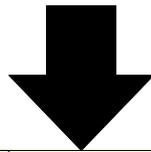
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Start:  
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ZipLeft:

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Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
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Write Blank
```

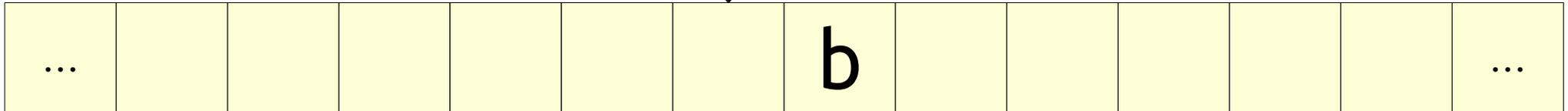
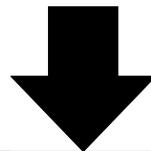
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

```
If Blank Return True  
If 'b' Return False  
Write Blank
```

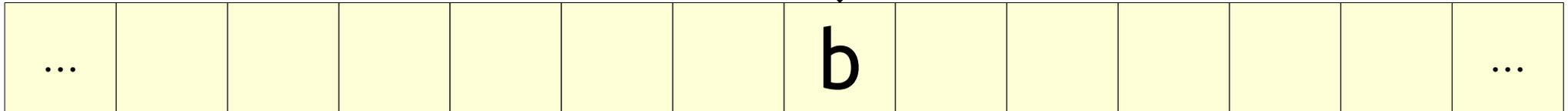
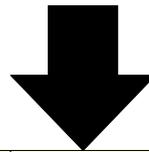
ZipRight:

Move Right

```
If Not Blank Goto ZipRight  
Move Left  
If Not 'b' Return False  
Write Blank
```

ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
```



Start:

If Blank Return True

If 'b' Return False

Write Blank

ZipRight:

Move Right

If Not Blank Goto ZipRight

Move Left

If Not 'b' Return False

Write Blank

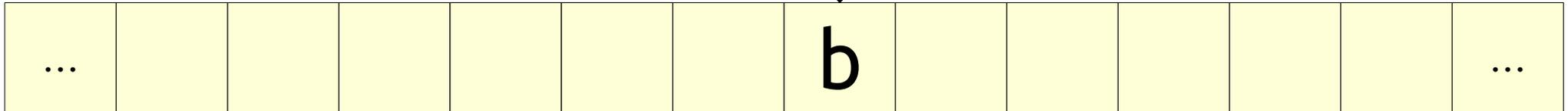
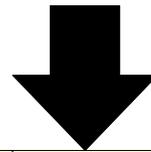
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start

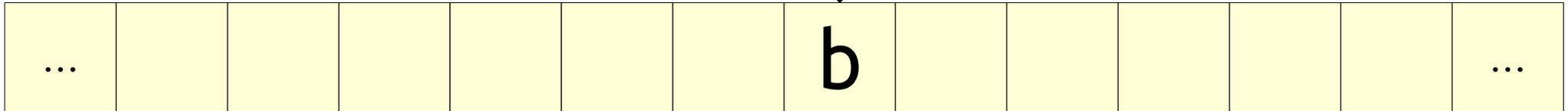
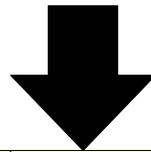


```
Start:  
  If Blank Return True  
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  Write Blank
```

ZipRight:

```
Move Right  
If Not Blank Goto ZipRight  
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If Not 'b' Return False  
Write Blank
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ZipLeft:  
Move Left  
If Not Blank Goto ZipLeft  
Move Right  
Goto Start
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Start:

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If Blank Return True  
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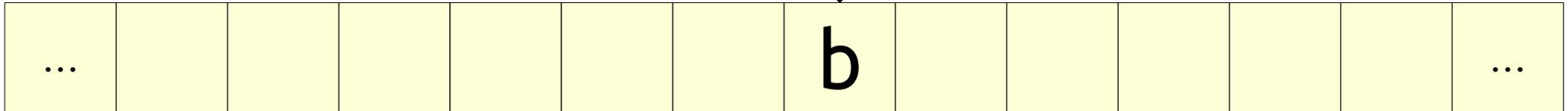
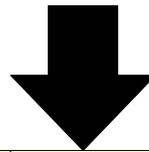
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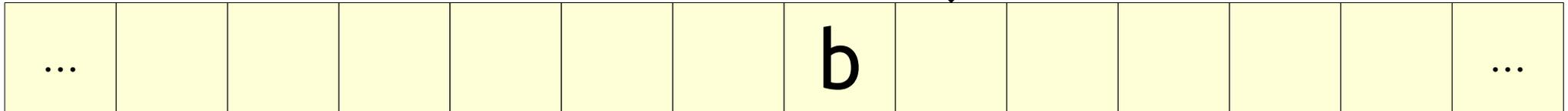
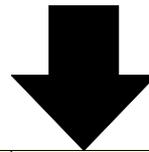
ZipRight:

Move Right

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If Not Blank Goto ZipRight  
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ZipLeft:

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Move Left  
If Not Blank Goto ZipLeft  
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Start:

If Blank Return True

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ZipRight:

Move Right

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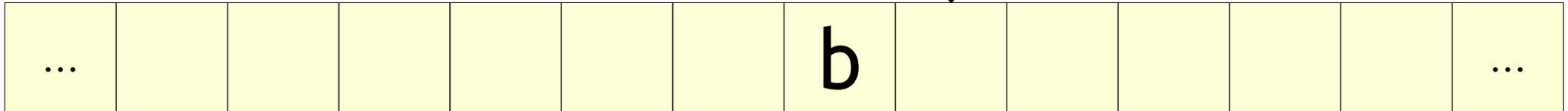
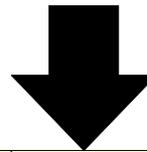
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Start:

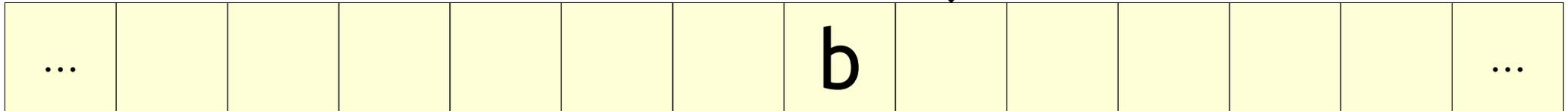
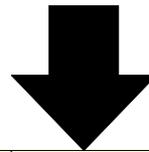
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Start:

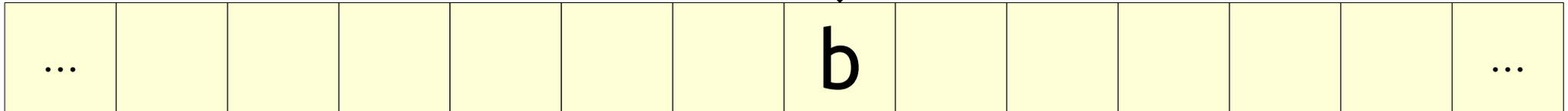
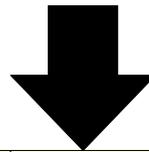
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Start:

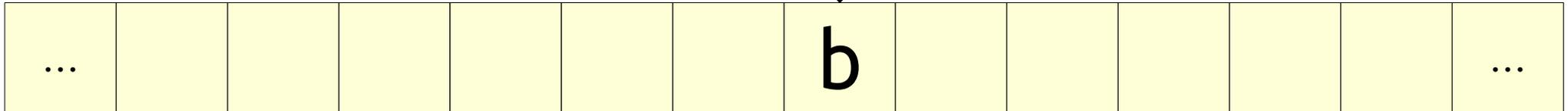
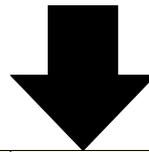
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Start:

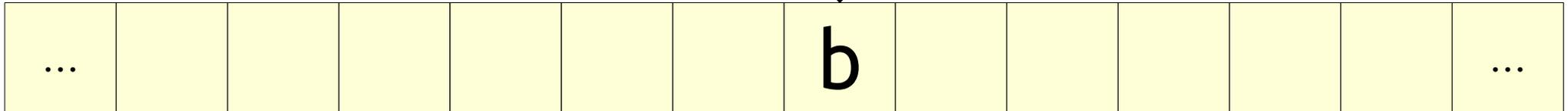
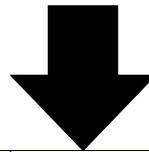
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Start:

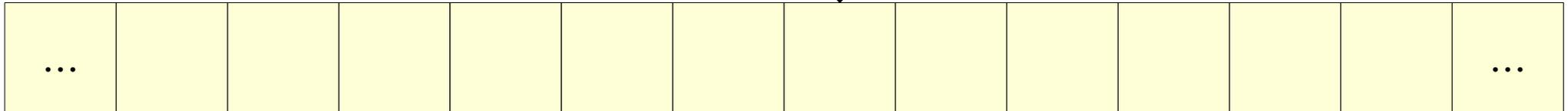
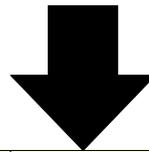
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ZipLeft:

```
Move Left  
If Not Blank Goto ZipLeft  
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Start:

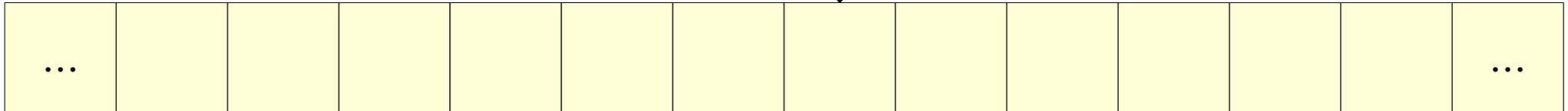
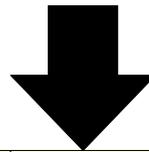
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ZipLeft:

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Start:

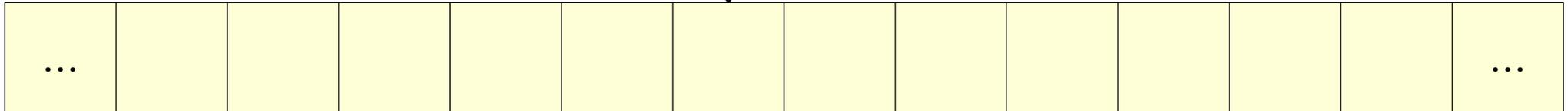
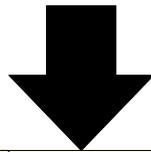
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Move Right  
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Start:

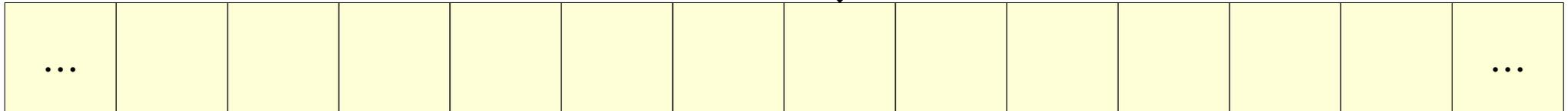
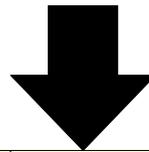
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Move Left  
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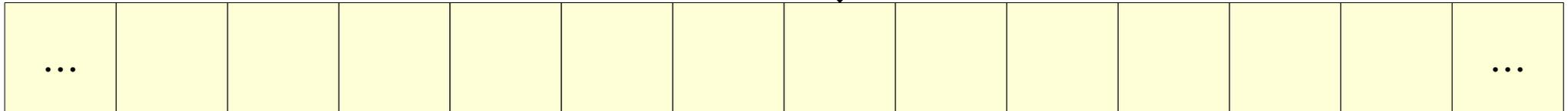
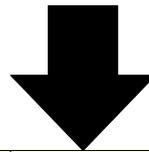
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```



Start:

If Blank Return True

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ZipRight:

Move Right

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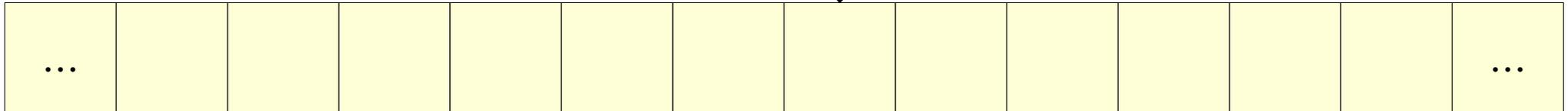
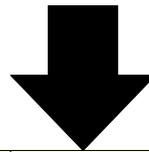
ZipLeft:

Move Left

If Not Blank Goto ZipLeft

Move Right

Goto Start



Time-Out for Announcements!

Second Midterm Complete

- You're done with the second midterm exam – congratulations!
- We will be grading the exam over the weekend and will get back to you with scores as soon as it's ready.
- Solutions are up online, along with information about historical grade cutoff markers.
- ***Do not withdraw or change your grading basis*** unless you have run some projections about your raw score! Check what the numbers say first.

Problem Set Six

- The TAs are currently finishing grading PS6. We'll release scores as soon as they're ready.
- Solutions are up on the course website. Feel free to read over them in the meantime.

Your Questions

“What is your favorite bike route
in the Bay Area?”

There are some beautiful, beautiful trails near Crystal Springs Reservoir – it’s really incredible there. The “Bayway” goes from SF to Mountain View and is a great way to tour around the area.

Back to CS103!

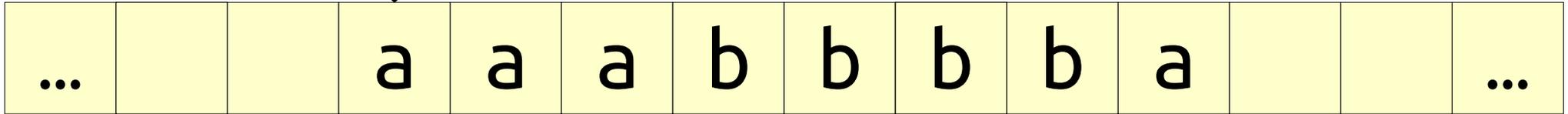
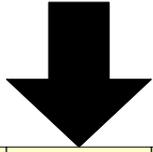
Our Next Challenge

- Let's now take aim at this more general language:

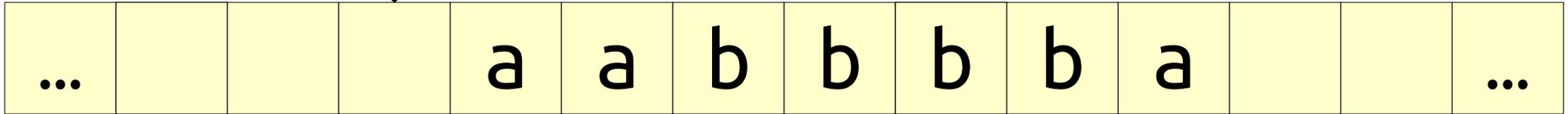
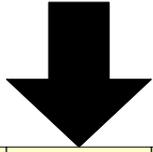
$$\{ w \in \{a, b\}^* \mid w \text{ has an equal number of } a\text{'s and } b\text{'s} \}$$

- This language is not regular (do you see why?)
- It is context-free, but it's a bit tricky to write a CFG for it. (See PS8!)
- Let's see how to design a TM for it.

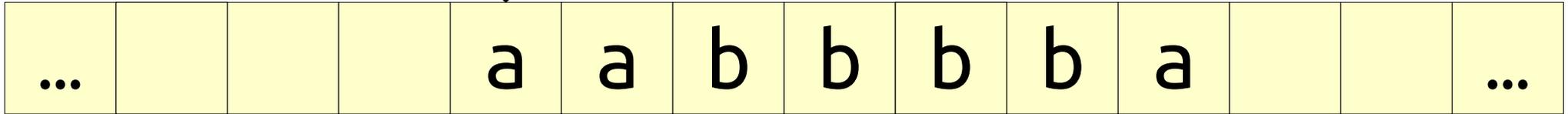
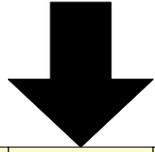
A Caveat



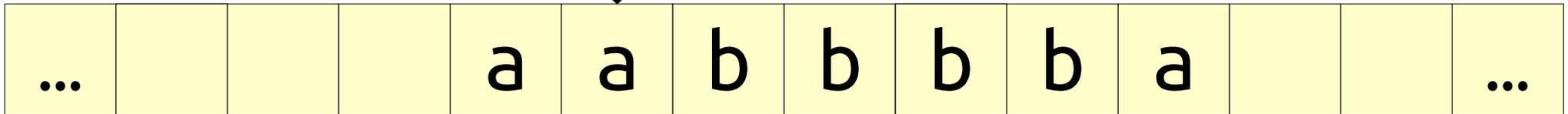
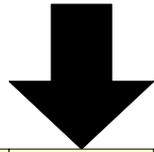
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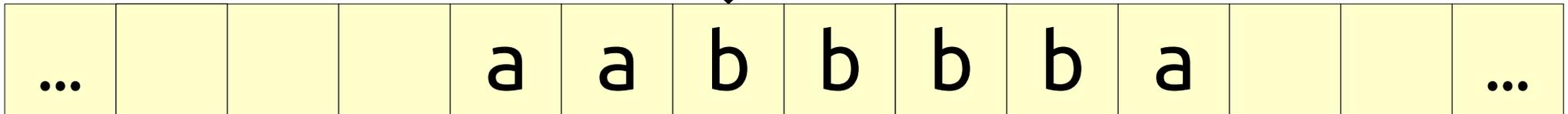
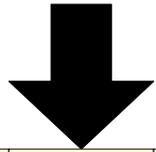
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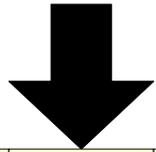
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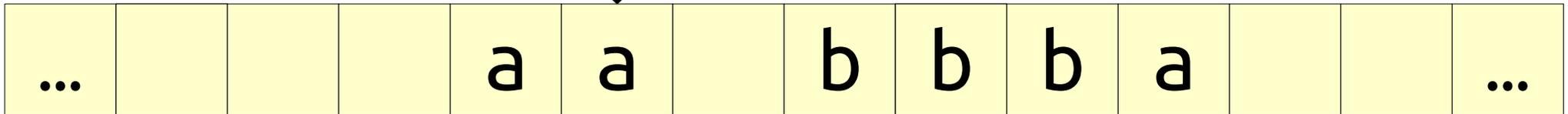
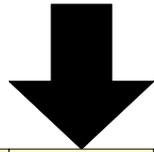
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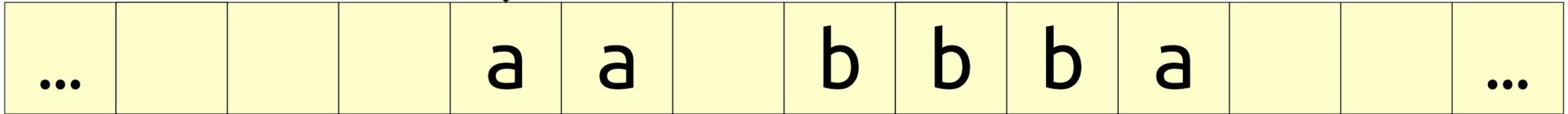
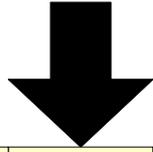
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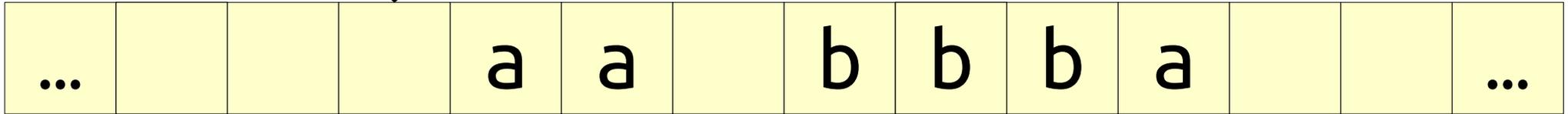
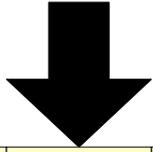
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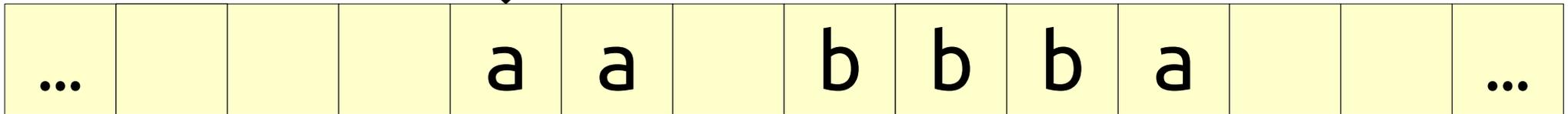
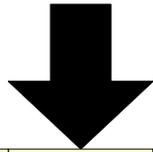
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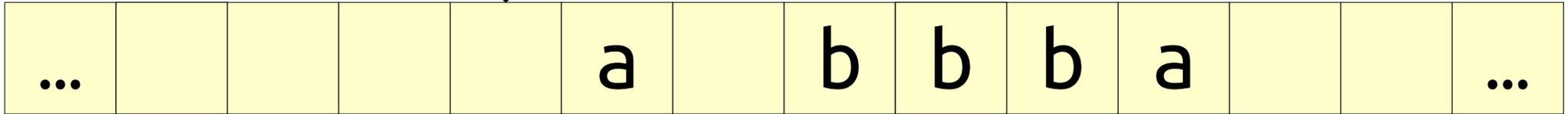
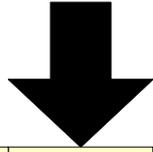
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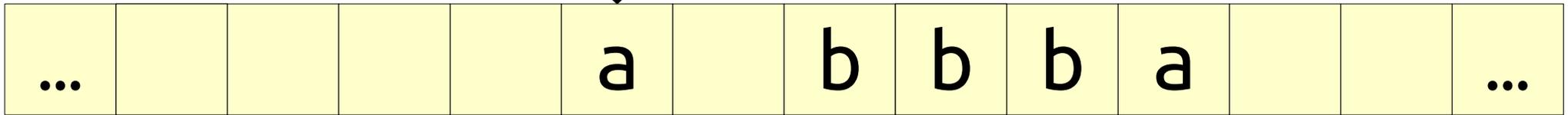
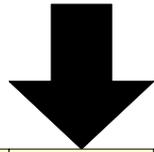
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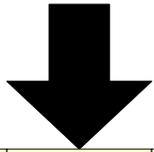
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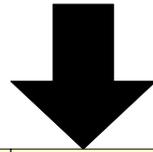
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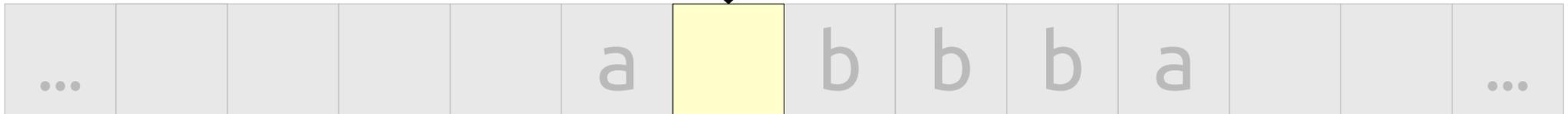


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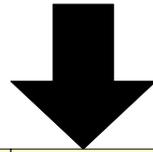
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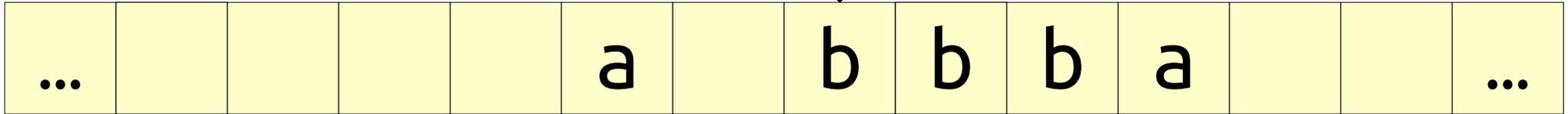
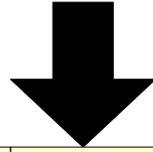
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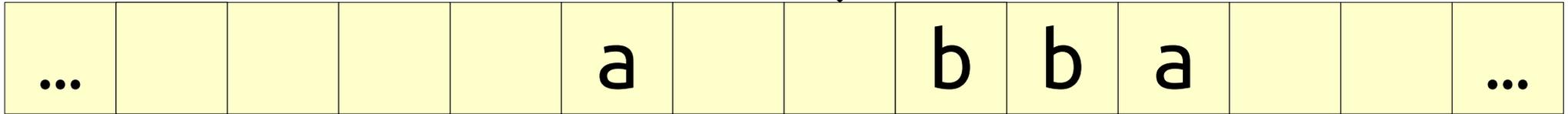
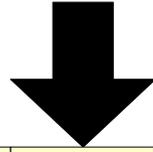


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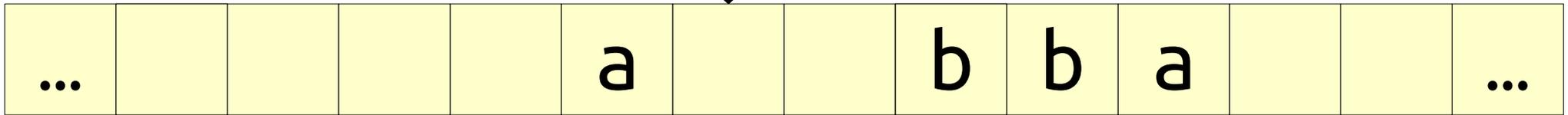
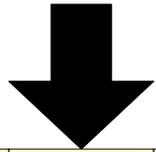
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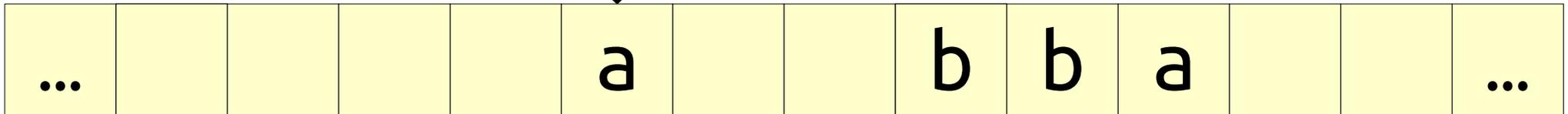
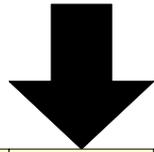
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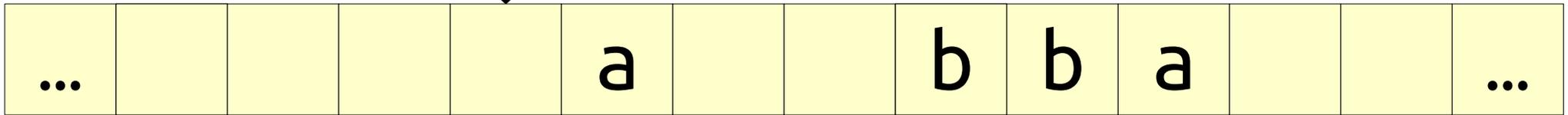
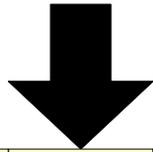
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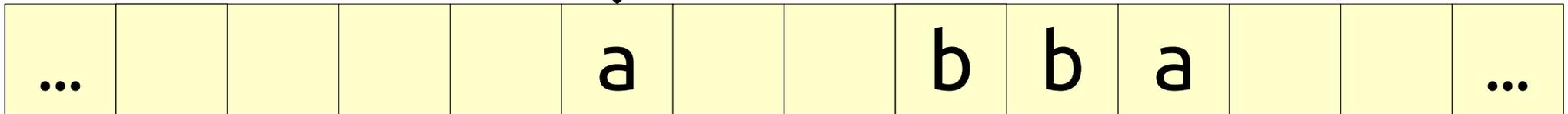
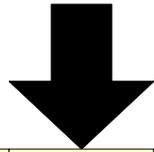
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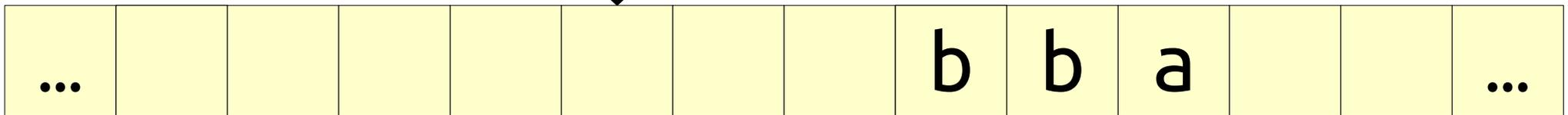
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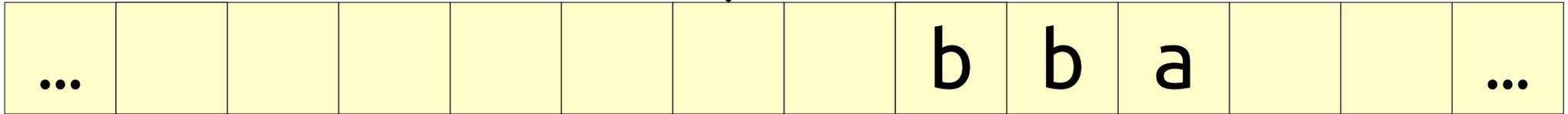
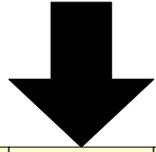
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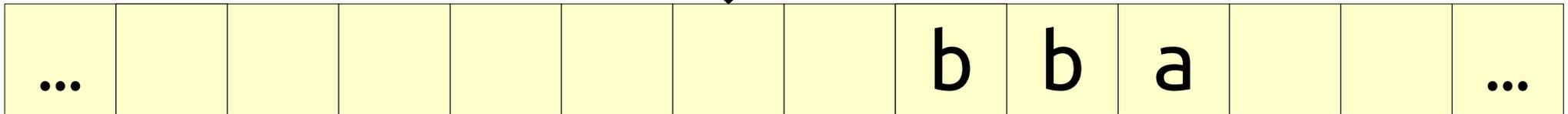
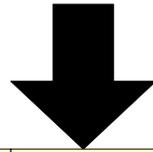
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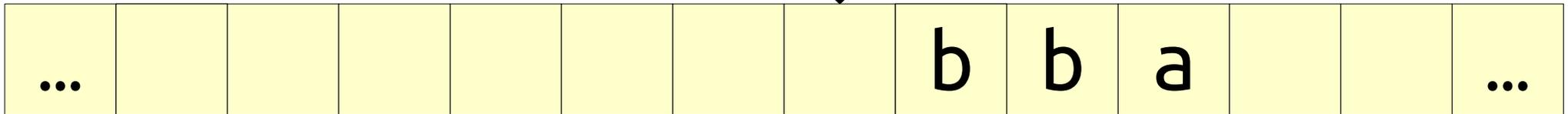
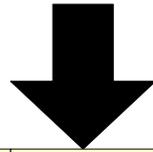


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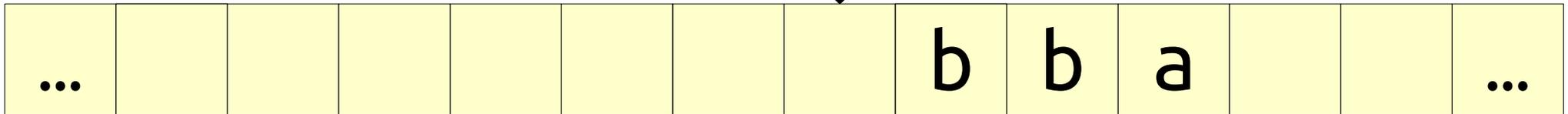
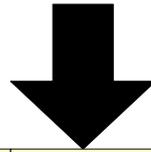


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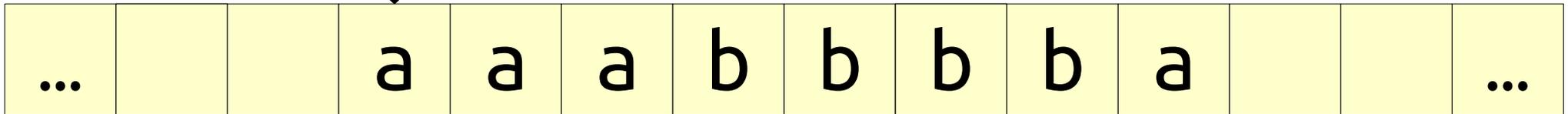
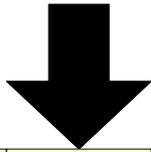


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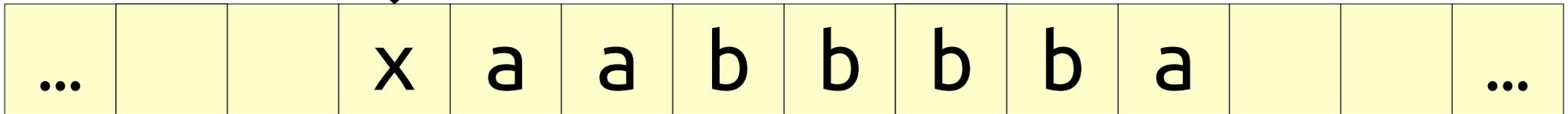
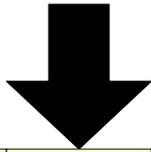


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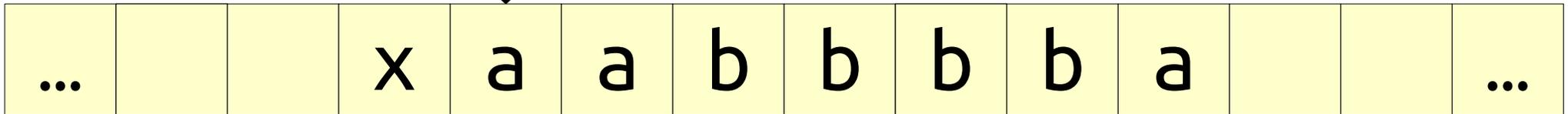
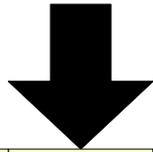
One Solution



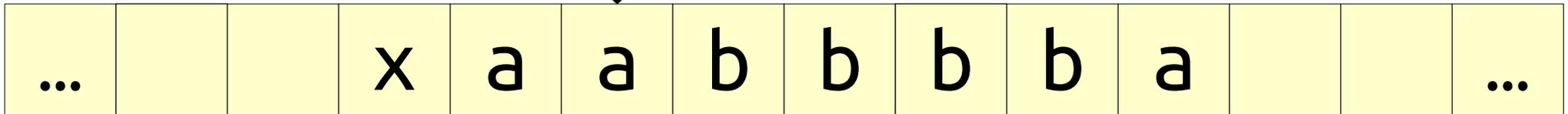
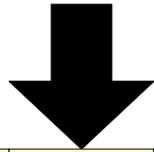
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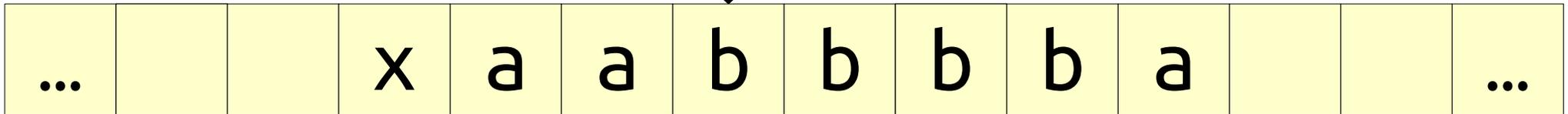
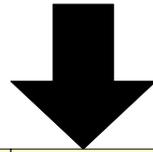
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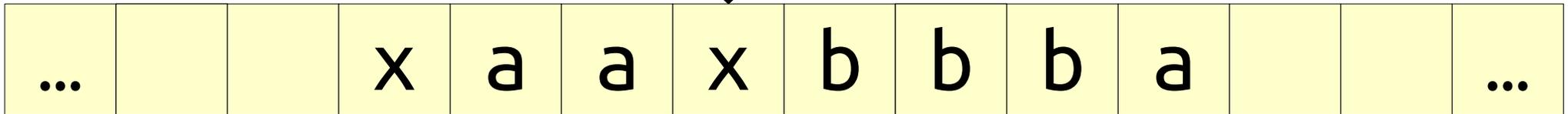
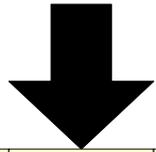
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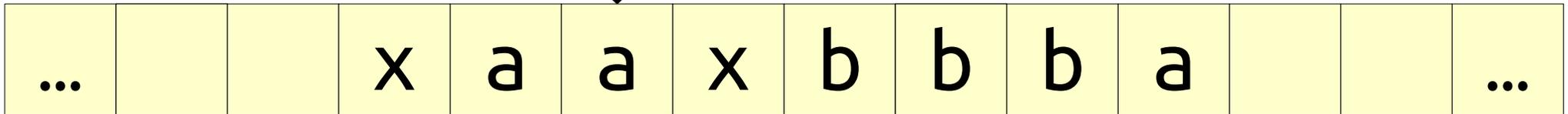
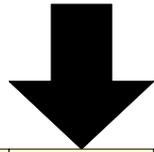
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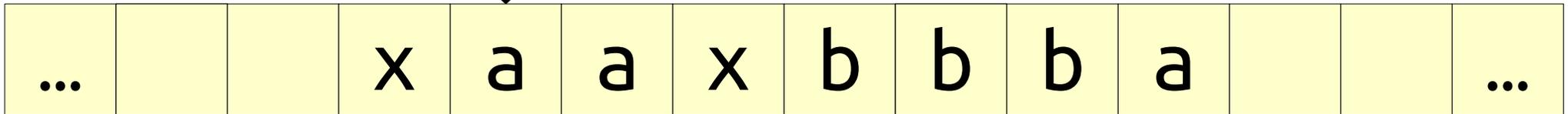
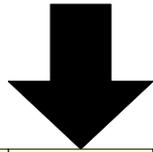
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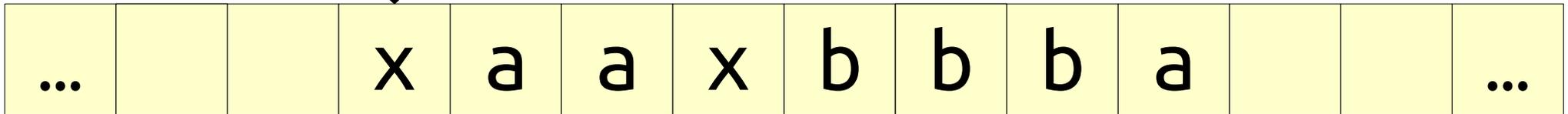
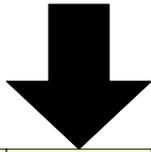
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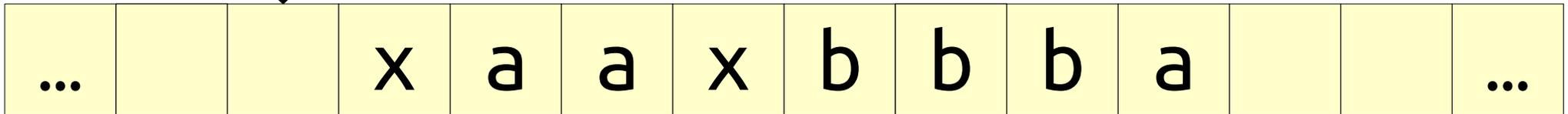
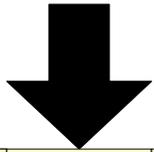
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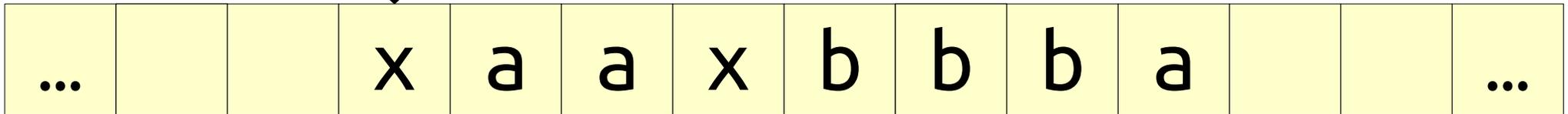
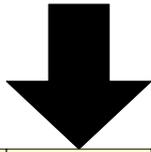
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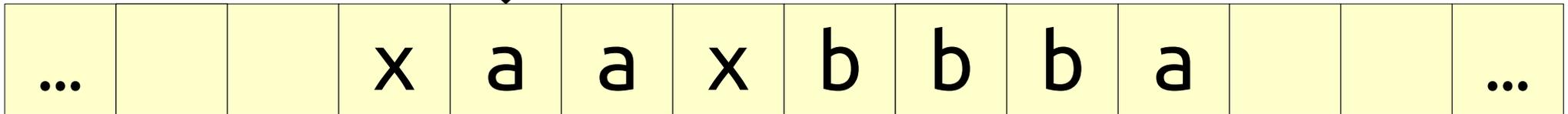
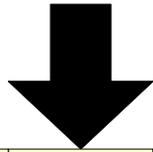
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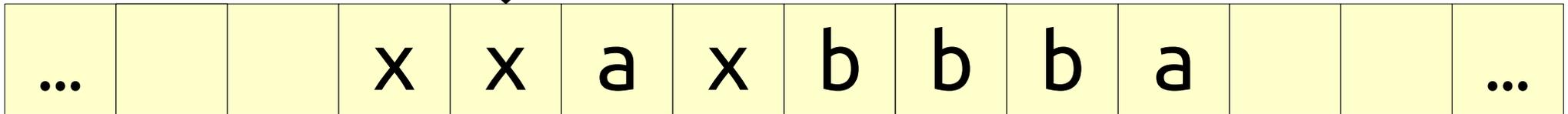
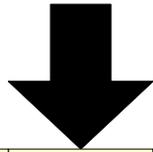
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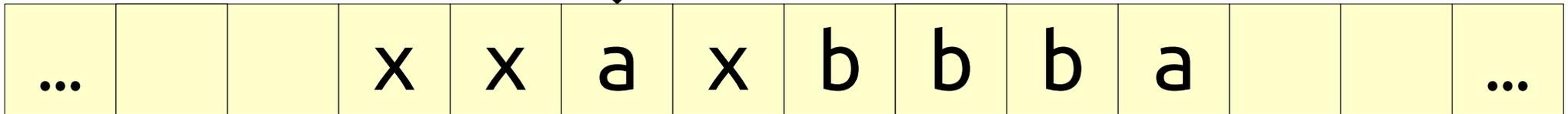
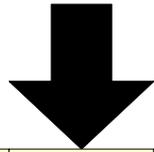
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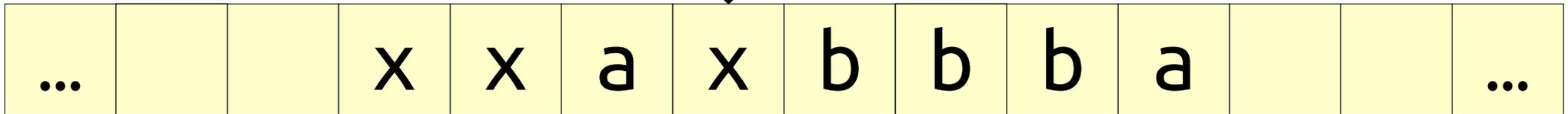
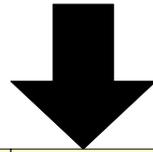
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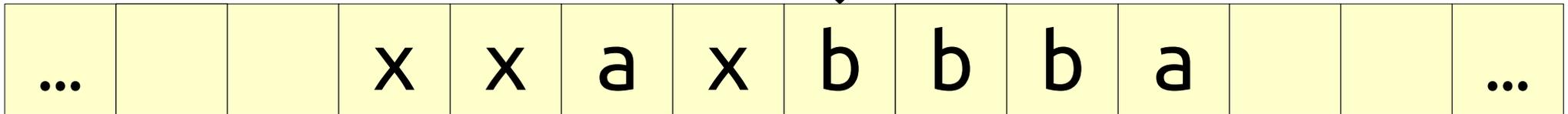
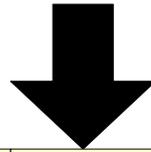
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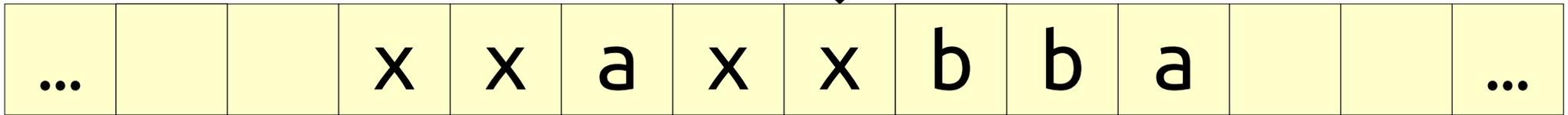
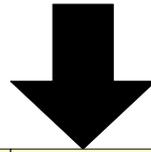
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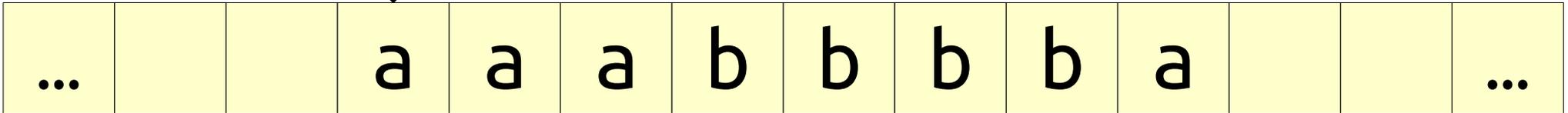
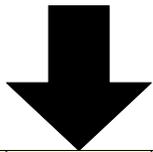
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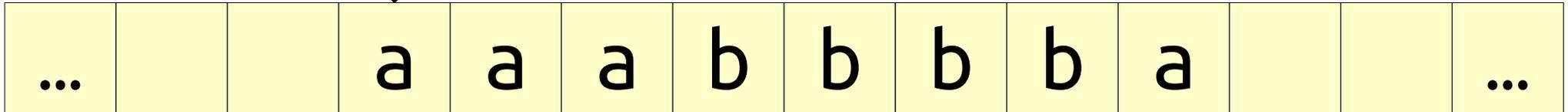
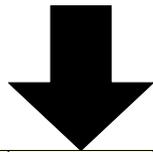
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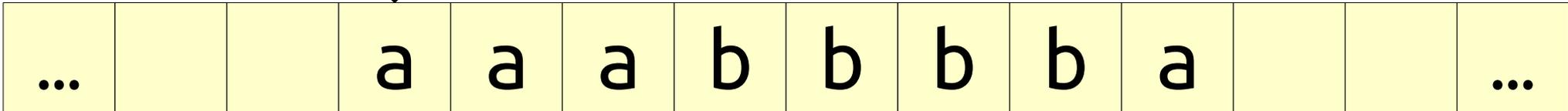
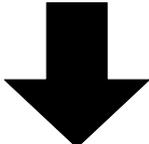
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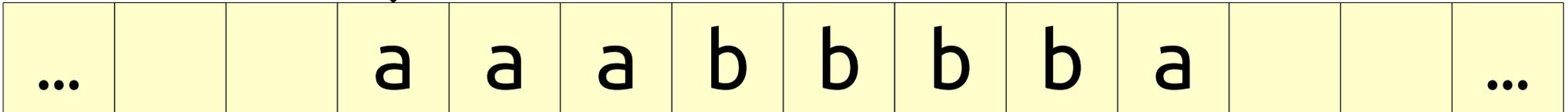
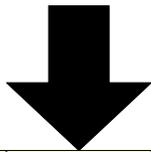


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Start:

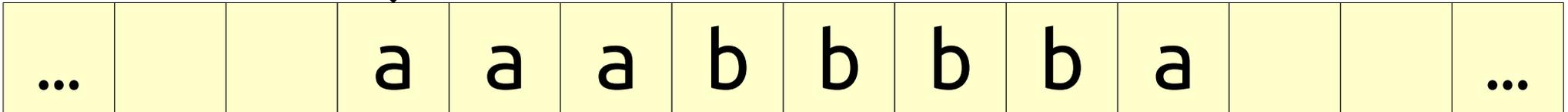
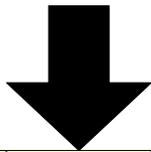
If 'a' Goto FoundA



Start:

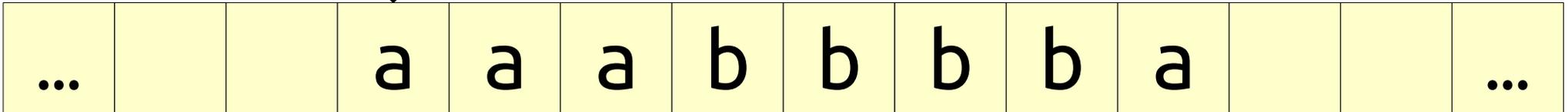
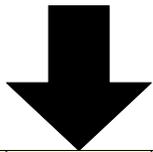
If 'a' Goto FoundA

FoundA:



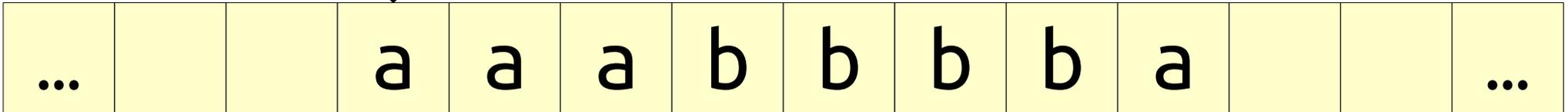
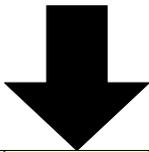
Start:
If 'a' Goto FoundA

FoundA:



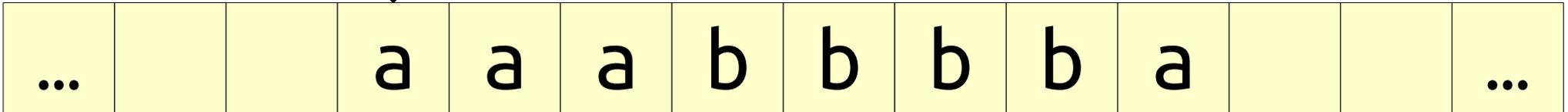
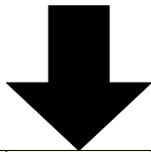
Start:
If 'a' Goto FoundA

FoundA:



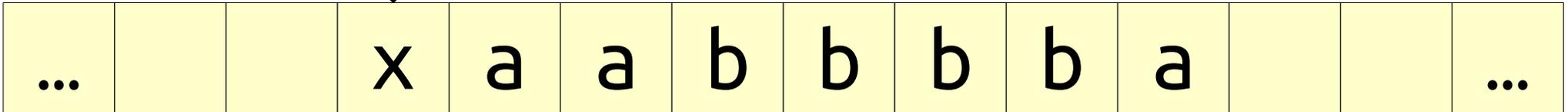
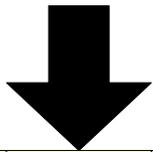
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
Write 'x'
```



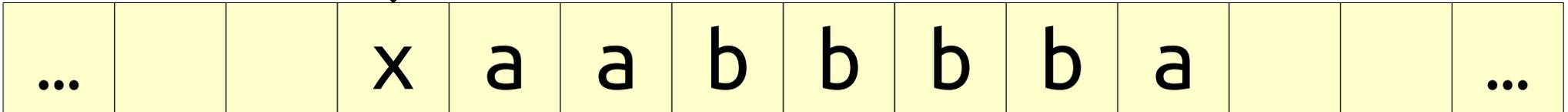
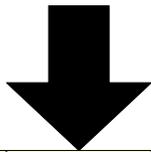
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
Write 'x'
```



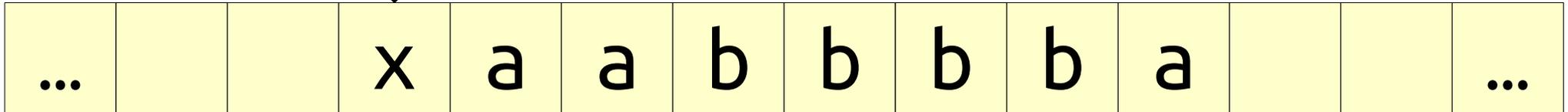
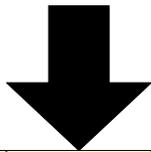
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```



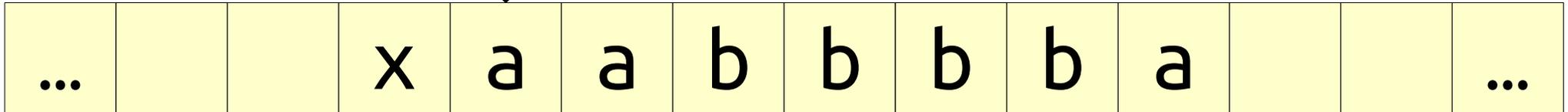
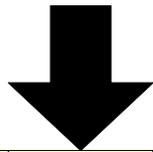
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'  
  Move Right
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'  
  Move Right
```



Start:

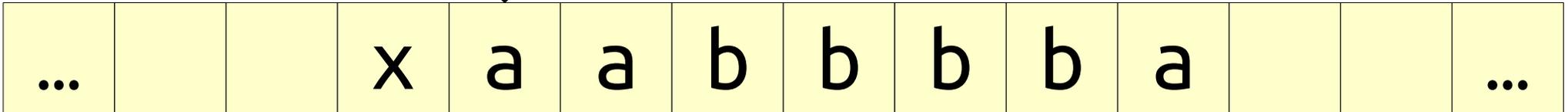
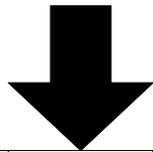
If 'a' Goto FoundA

FoundA:

Write 'x'

Move Right

If 'a' ?

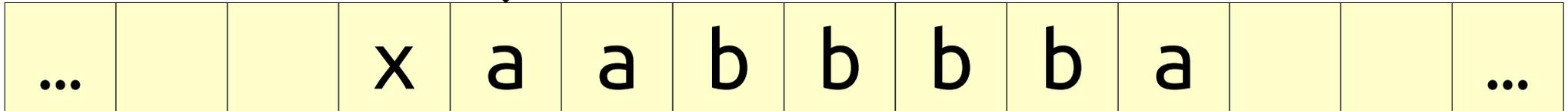
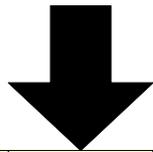


```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
Move Right
```

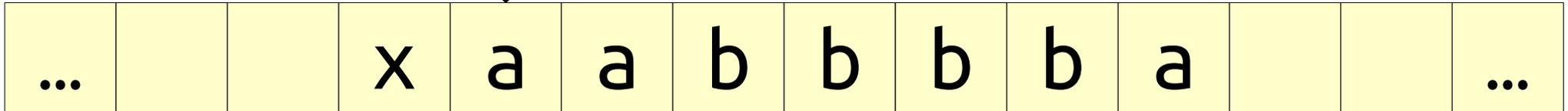
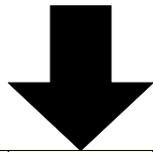
```
If 'a' ?
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

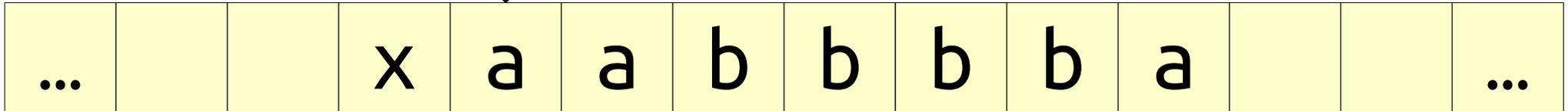
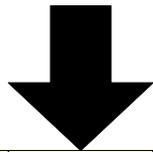
```
LoopA:  
  Move Right  
  If 'a' ?
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

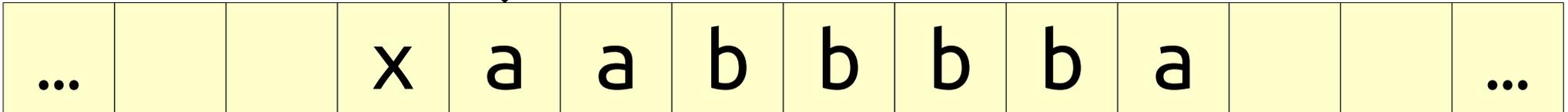
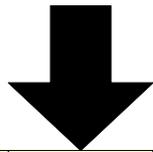
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LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

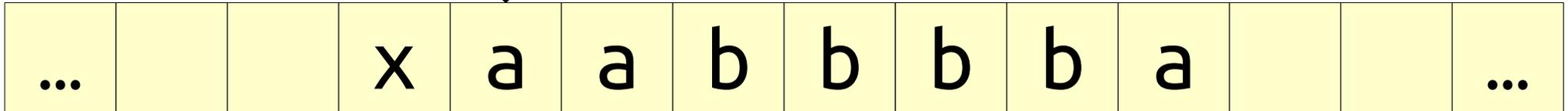
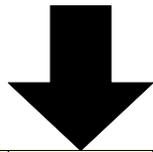
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LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

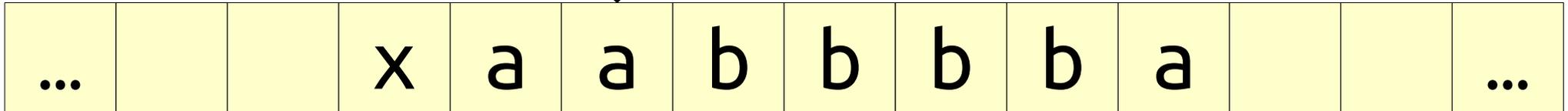
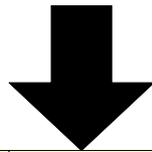
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

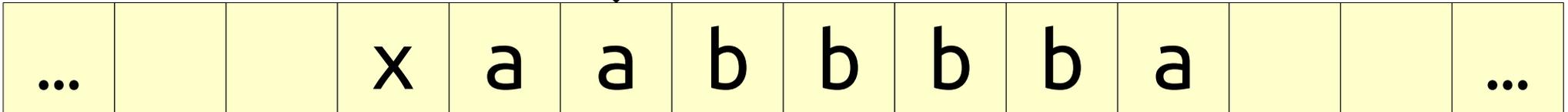
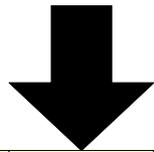
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

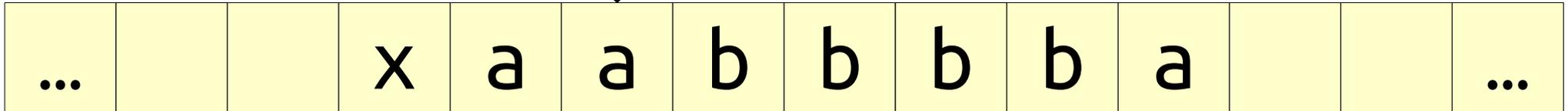
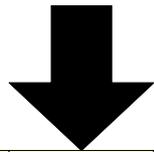
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

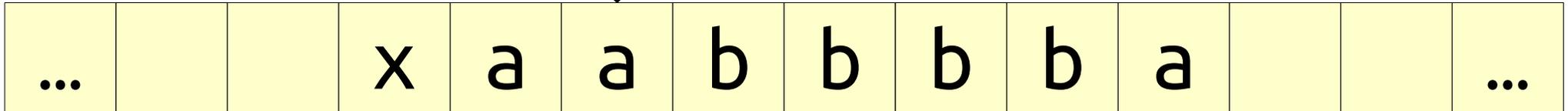
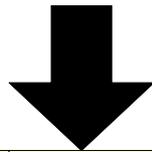
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

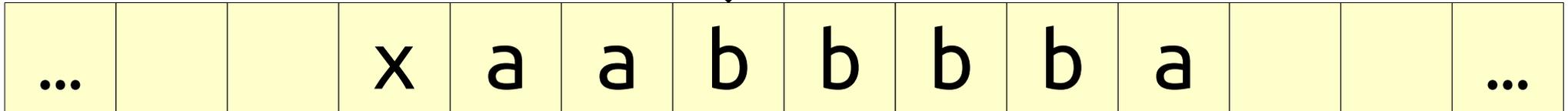
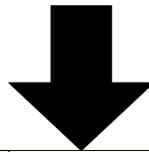
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

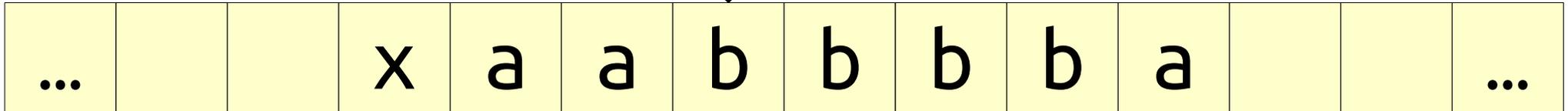
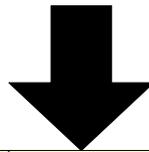
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

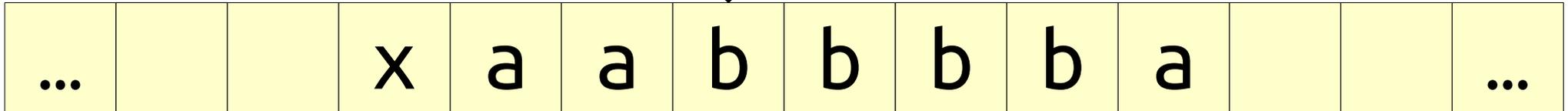
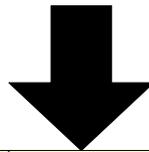
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

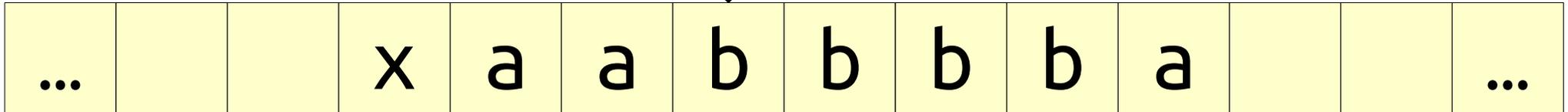
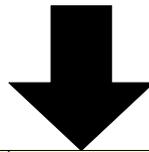
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA
```



```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

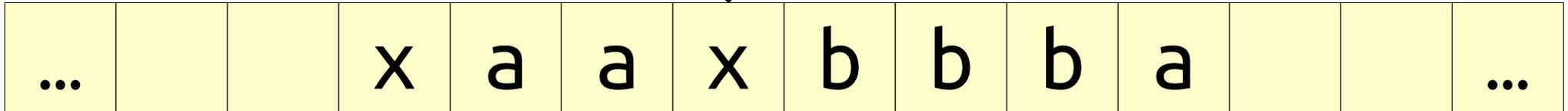
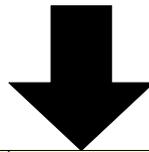
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'
```



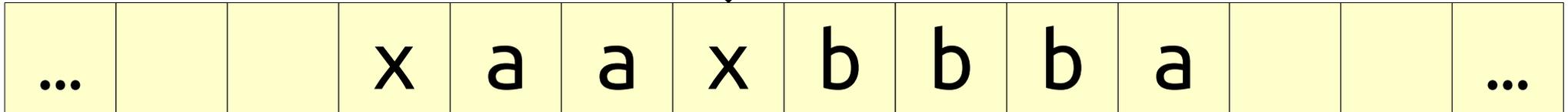
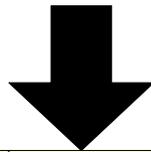
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

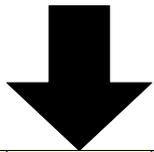
```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'
```



```
Start:  
  If 'a' Goto FoundA  
  
FoundA:  
  Write 'x'  
  
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'
```



```
Start:  
  If 'a' Goto FoundA  
  
FoundA:  
  Write 'x'  
  
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```



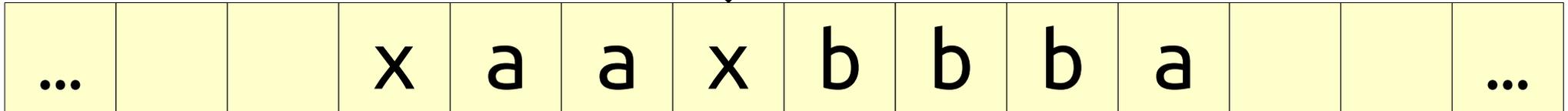
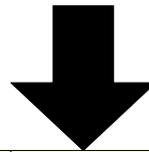
...			x	a	a	x	b	b	b	a			...
-----	--	--	---	---	---	---	---	---	---	---	--	--	-----

```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```



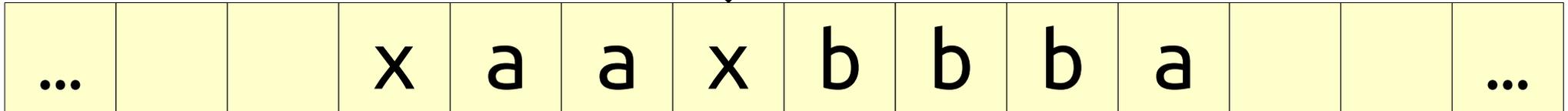
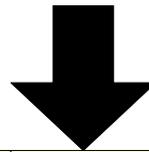
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:
```

```
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

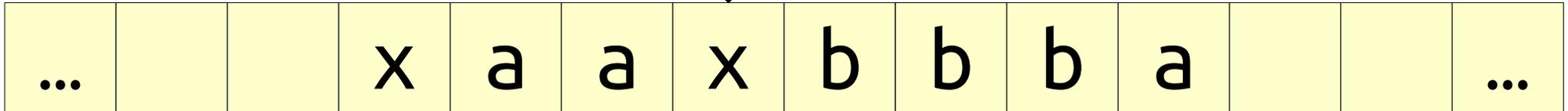
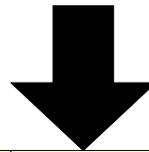


```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

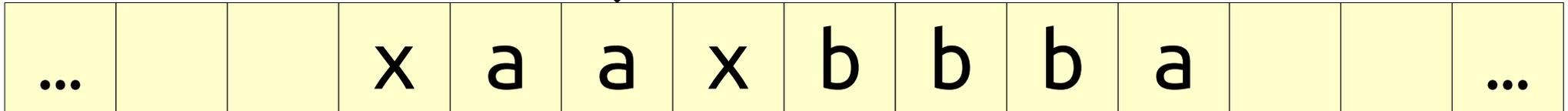
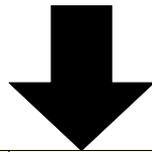


```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

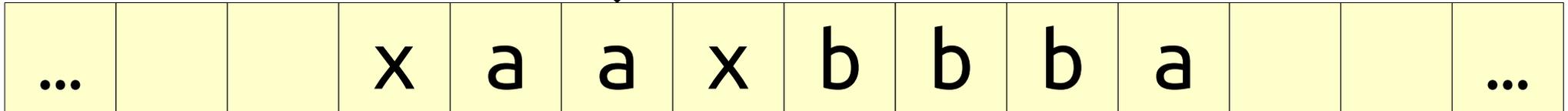
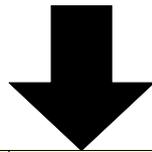


```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```



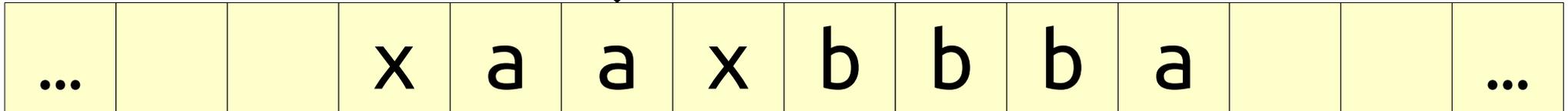
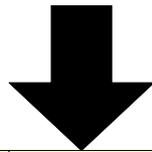
```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:
```

```
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

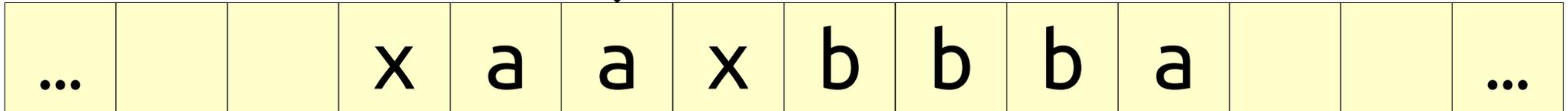
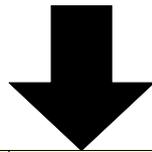


```
Start:  
  If 'a' Goto FoundA
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

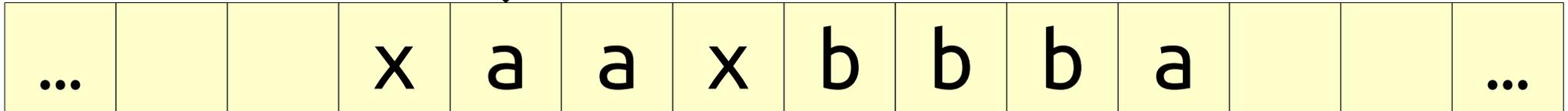
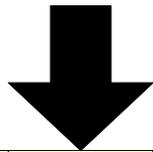


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LoopA:  
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  If 'a' Goto LoopA  
  Write 'x'  
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```

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GoHome:  
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  Move Right  
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```

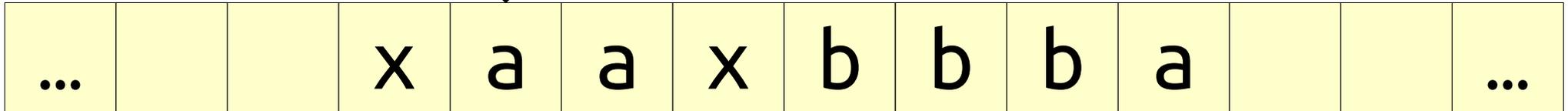
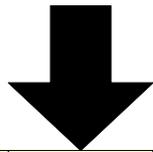


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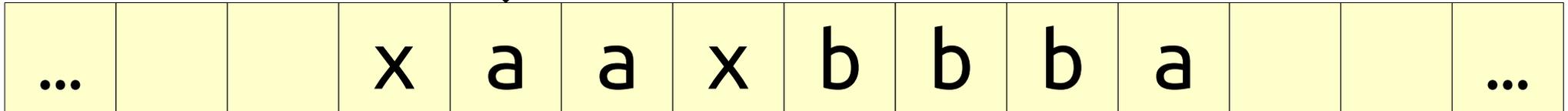
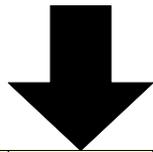
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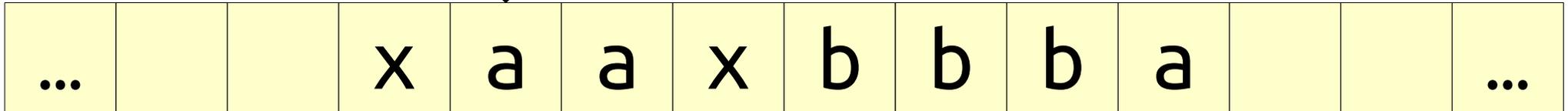
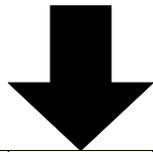


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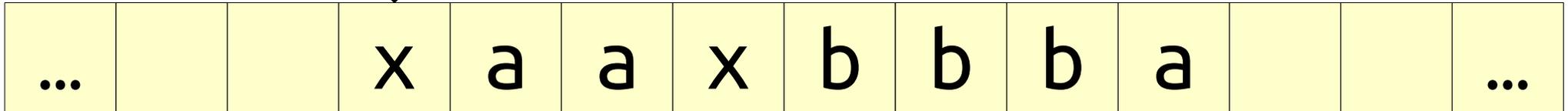
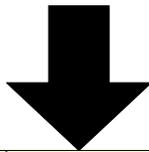


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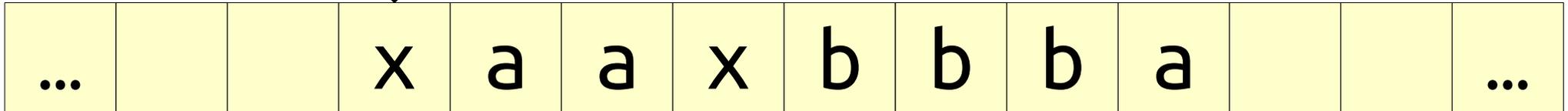
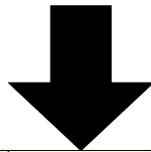


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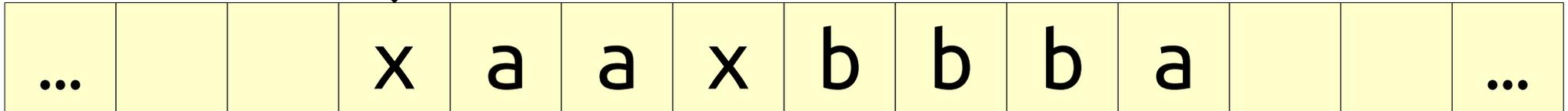
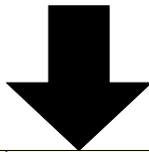
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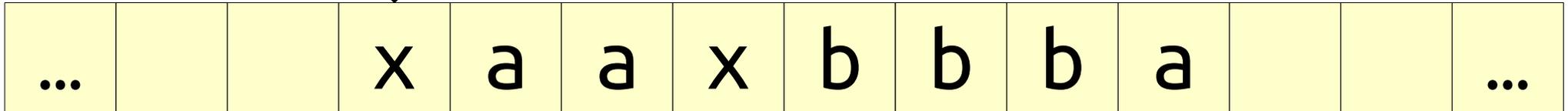
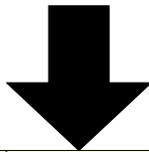


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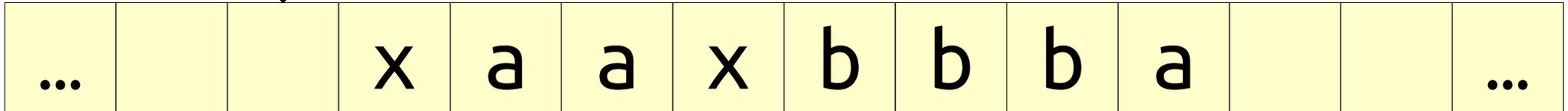
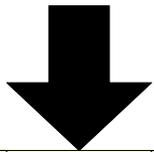


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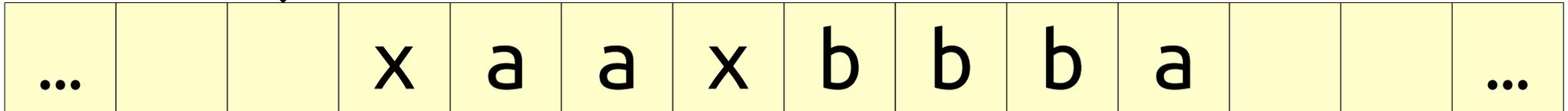
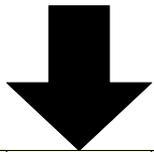


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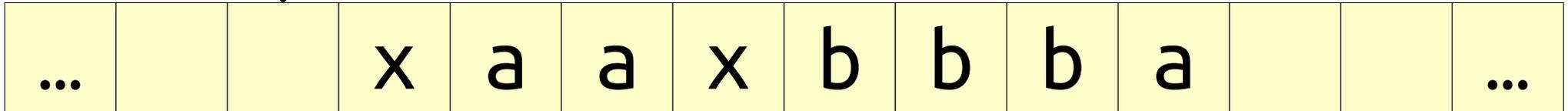
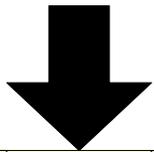


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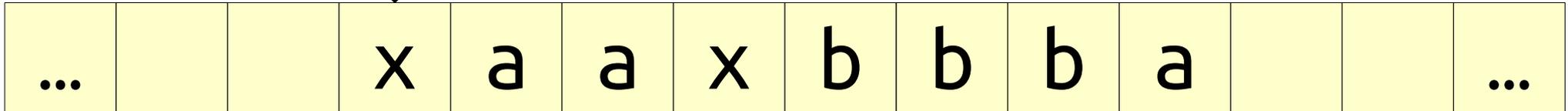
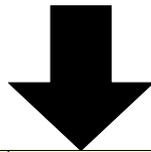


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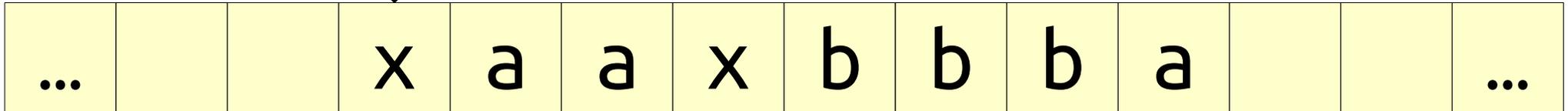
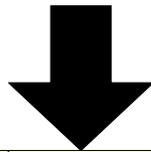


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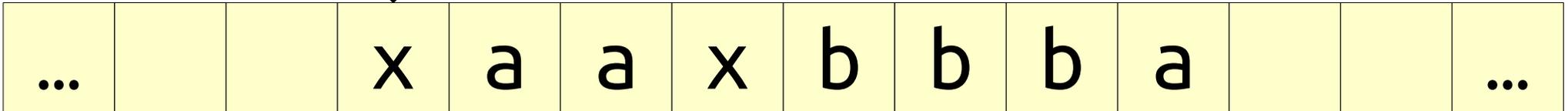
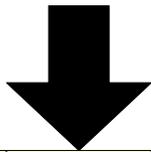
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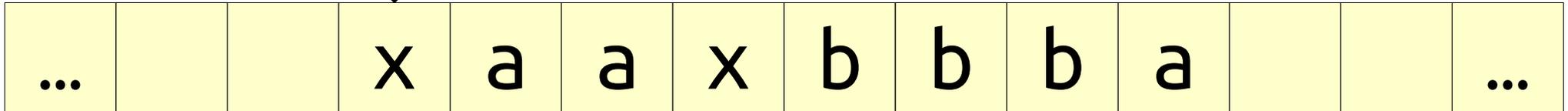
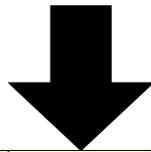
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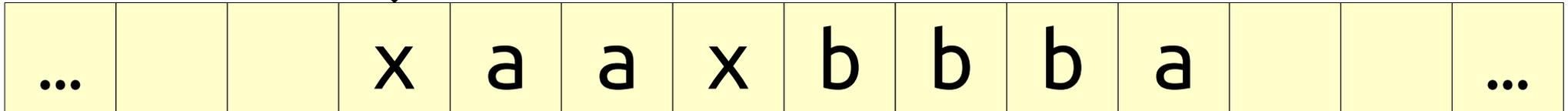
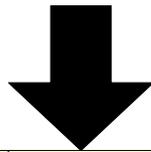


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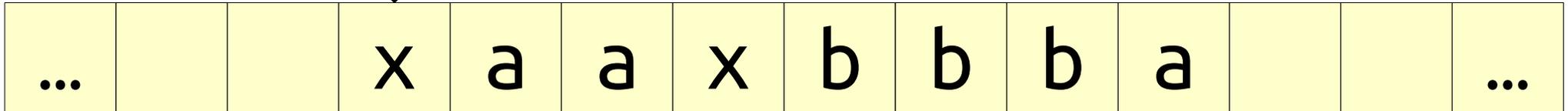
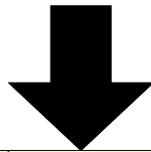
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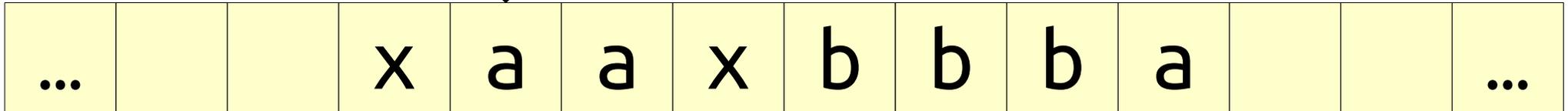
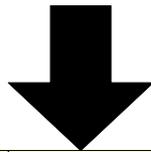
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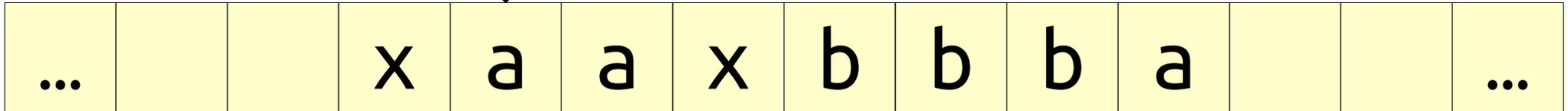
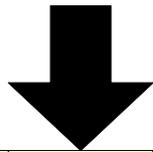
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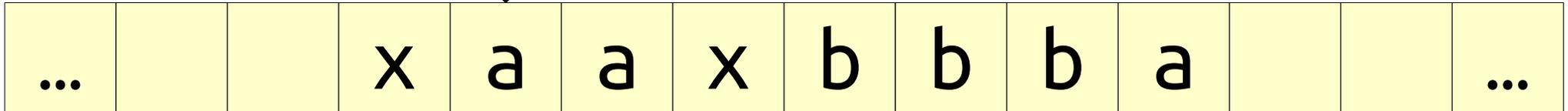
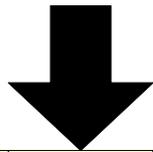
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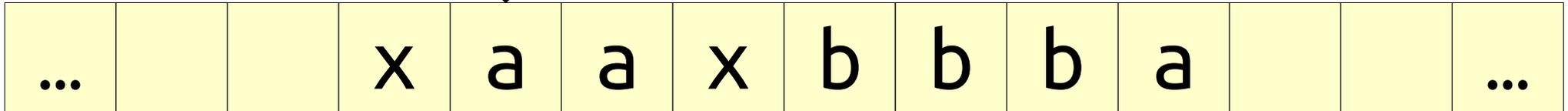
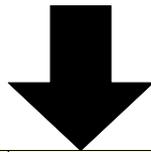
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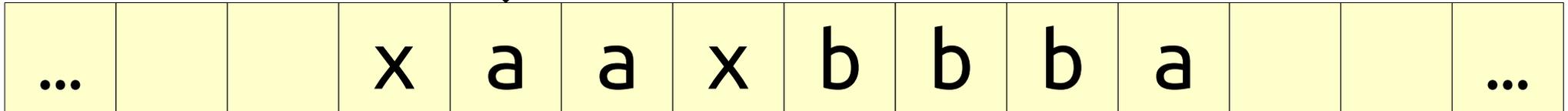
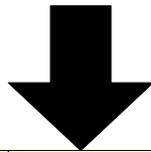
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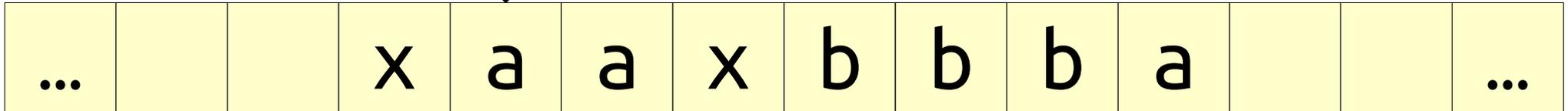
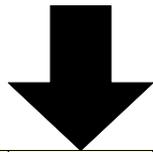


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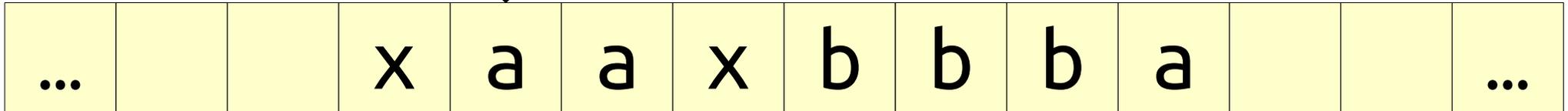
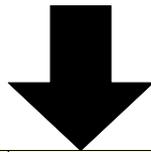
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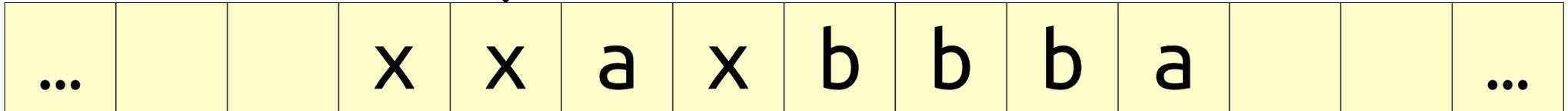
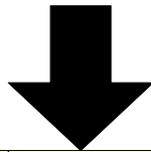


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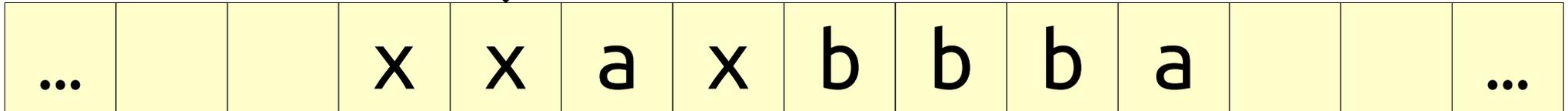
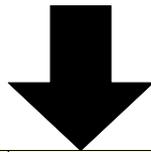


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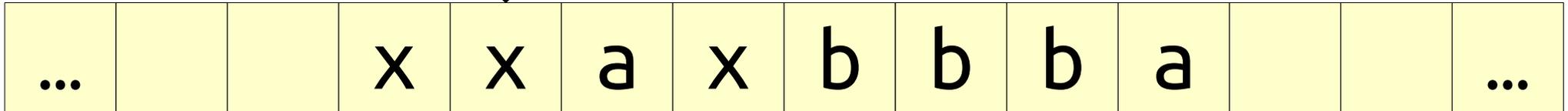
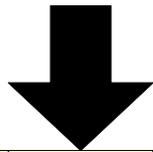


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  Move Right  
  Goto Start
```

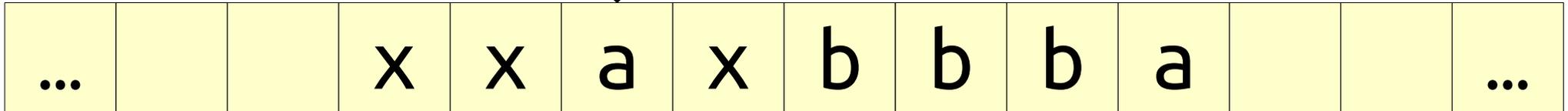
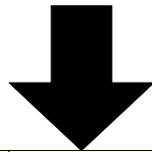


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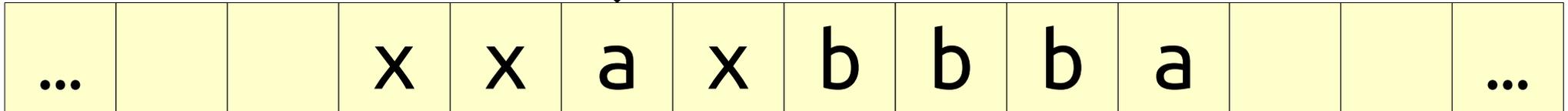
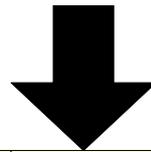
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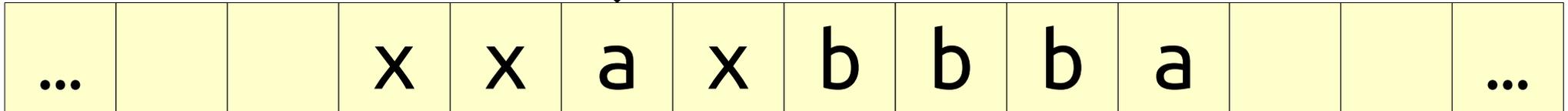
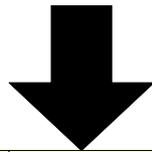


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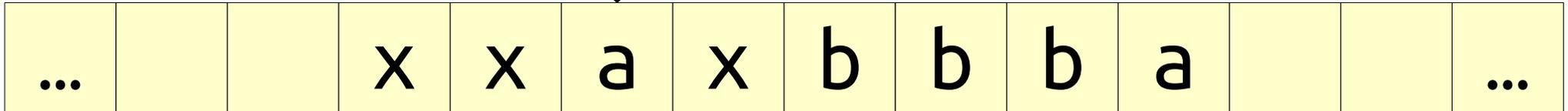
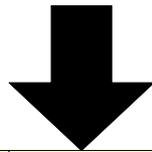


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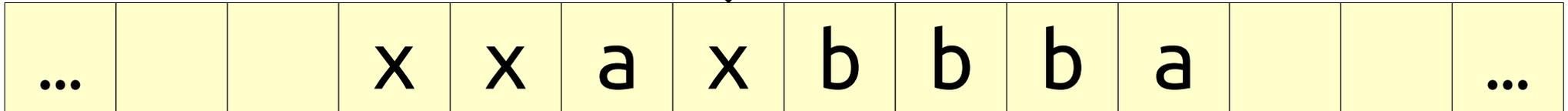
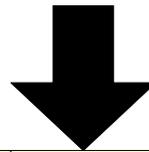


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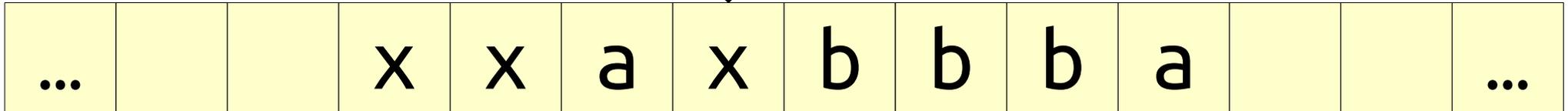
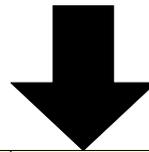


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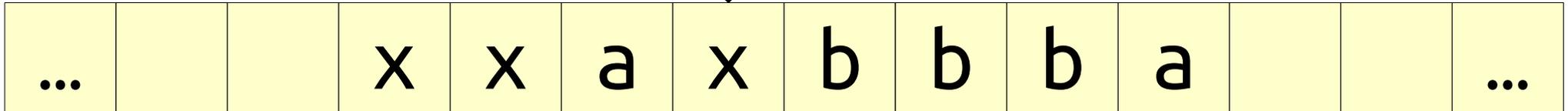
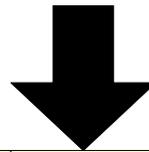
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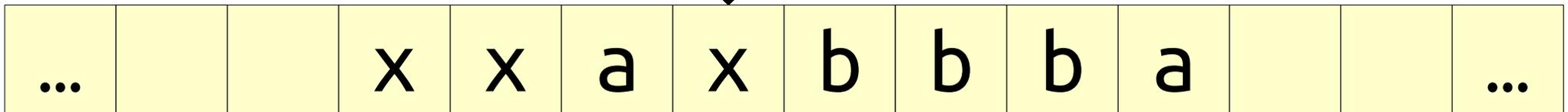
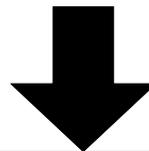
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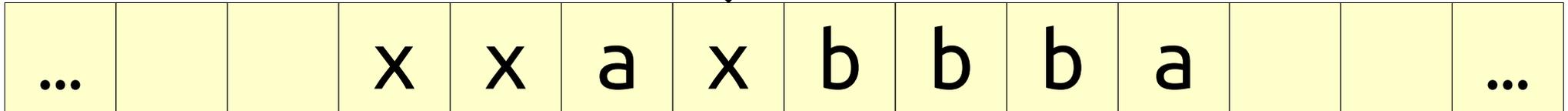
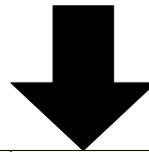
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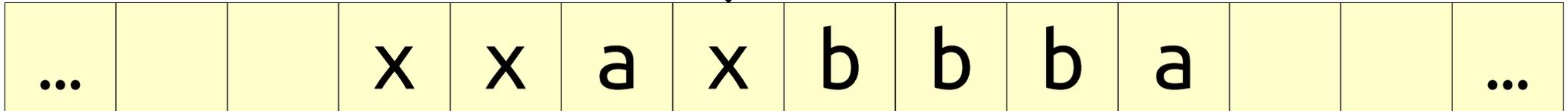
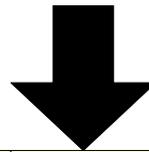


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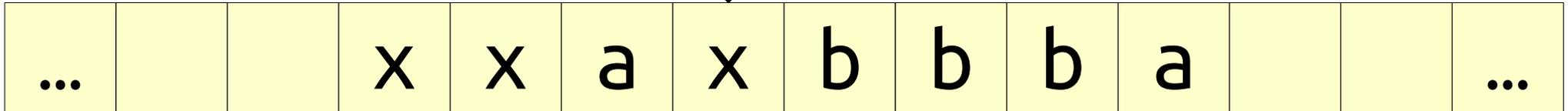
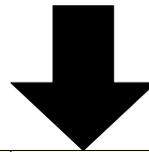


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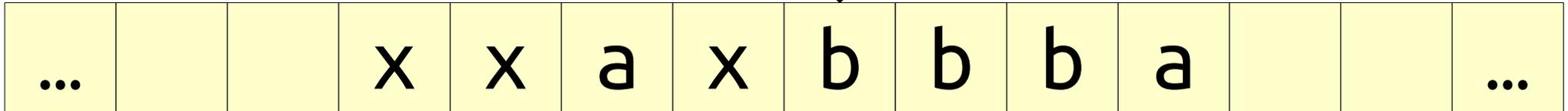
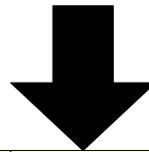


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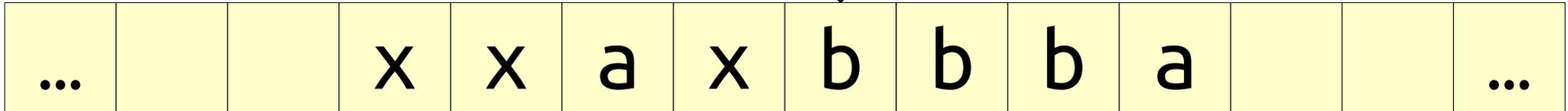
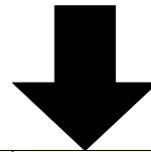


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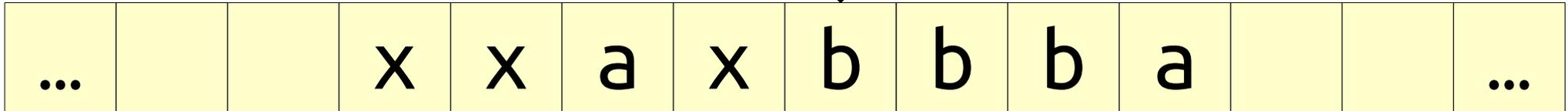
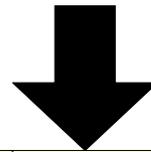


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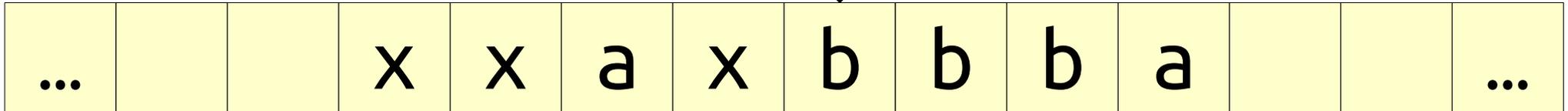
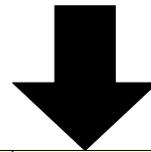


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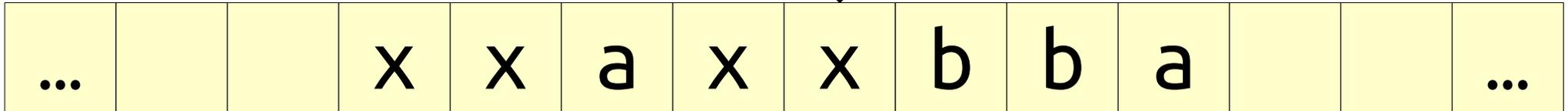
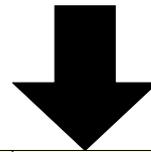


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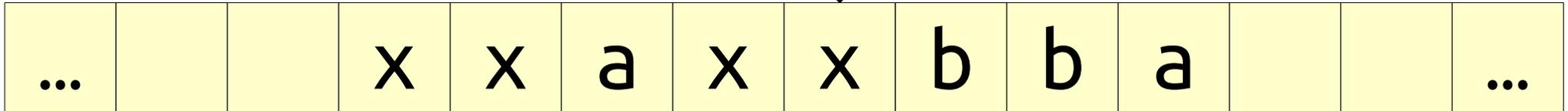
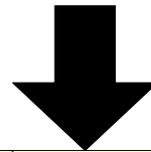


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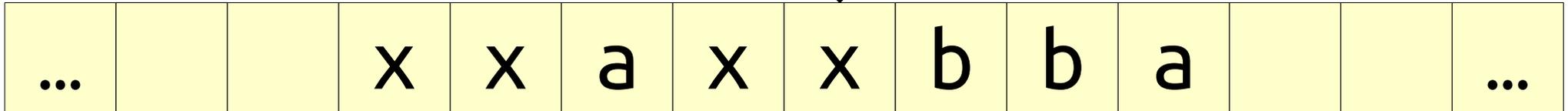
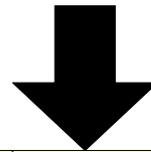


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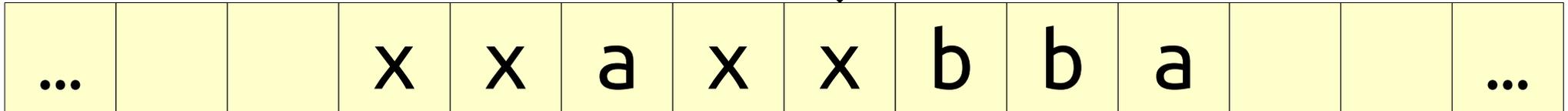
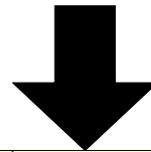


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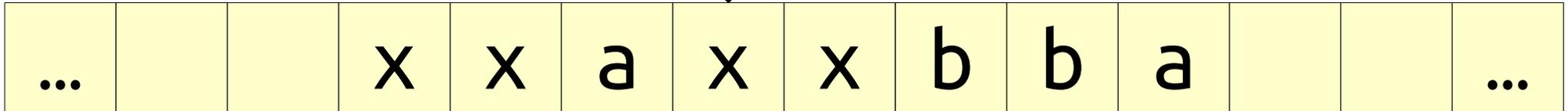
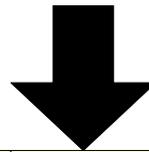


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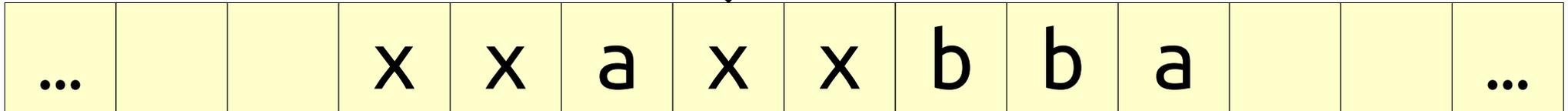
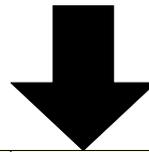


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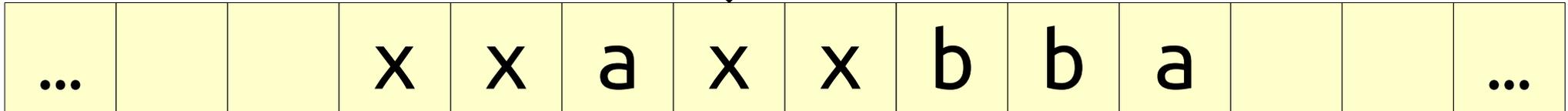
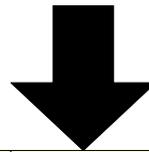


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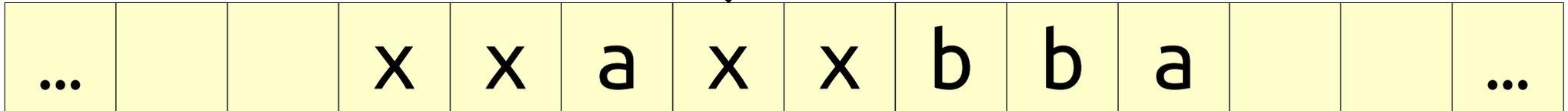
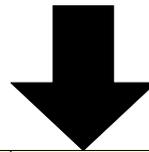


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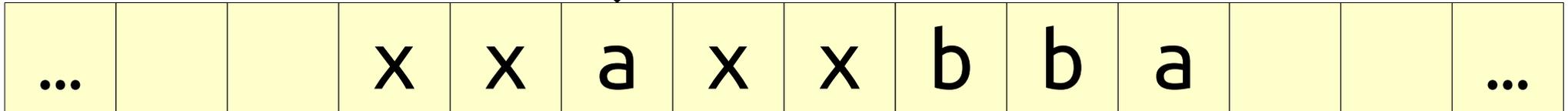
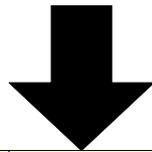


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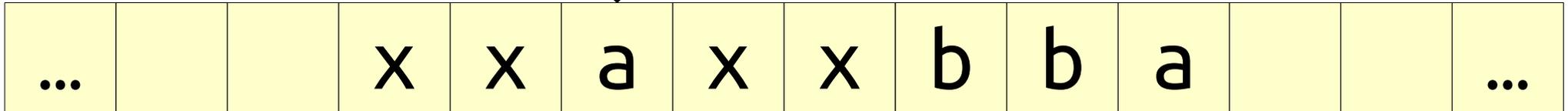
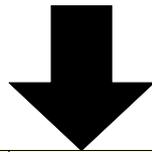


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  If 'x' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```



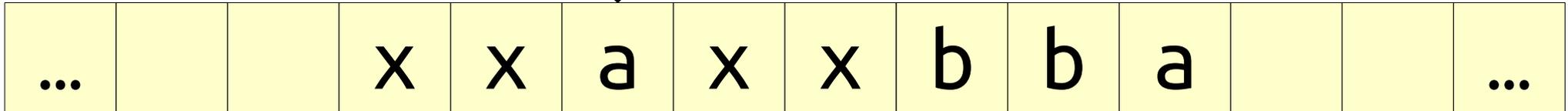
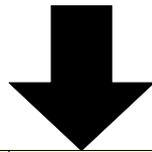
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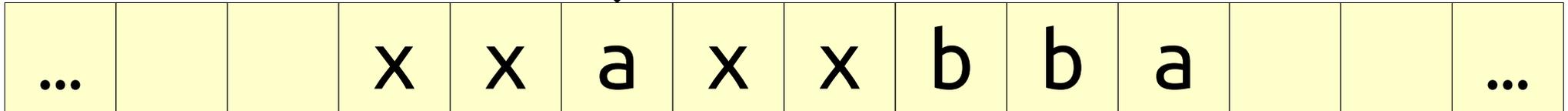
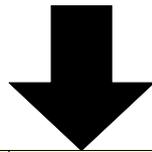


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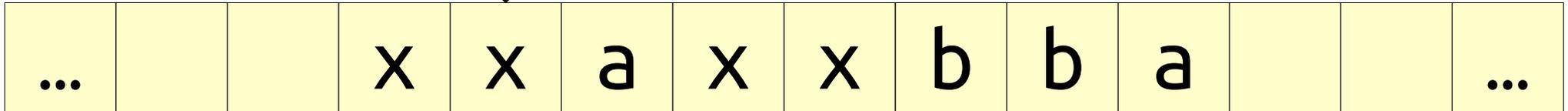
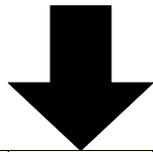


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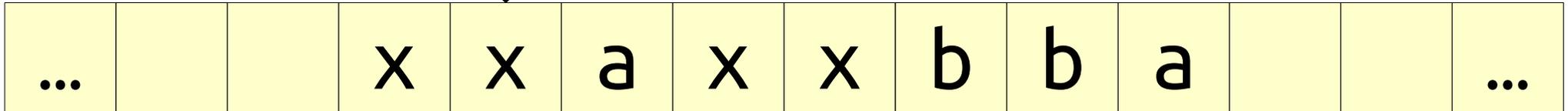
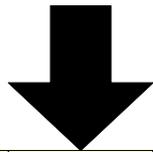


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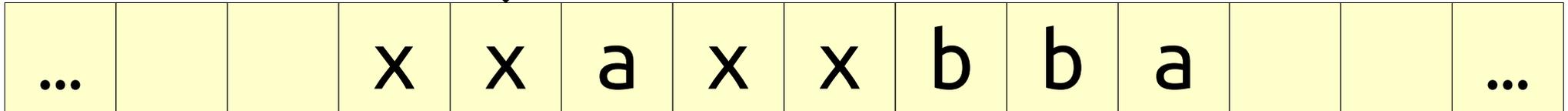
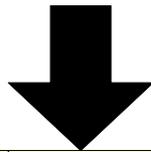
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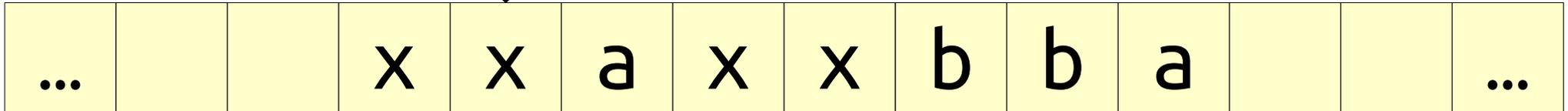
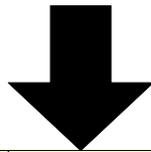


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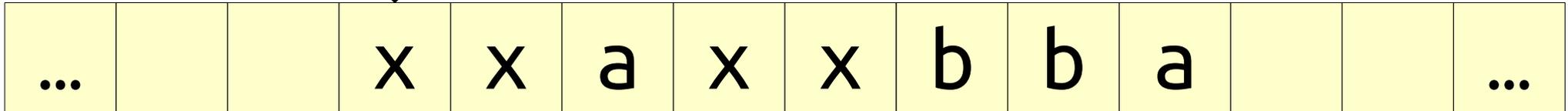
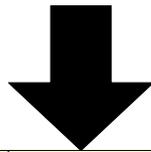
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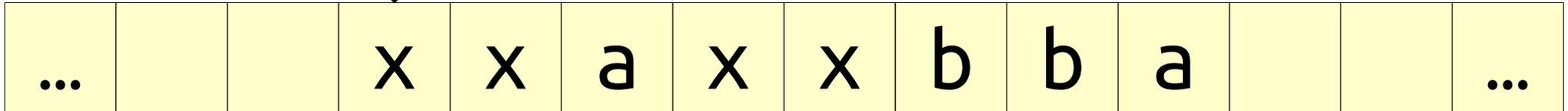
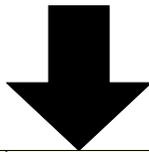


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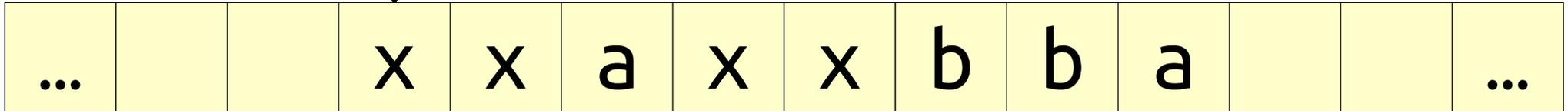
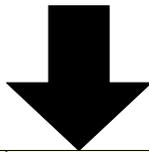
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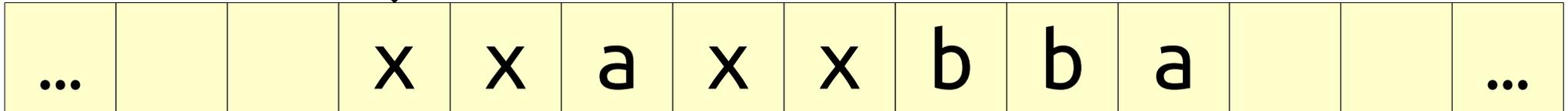
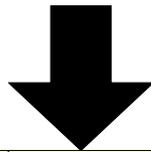
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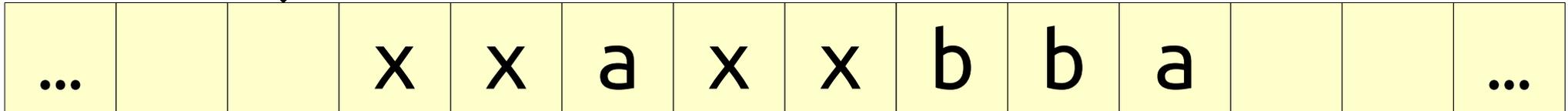
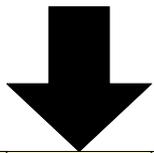
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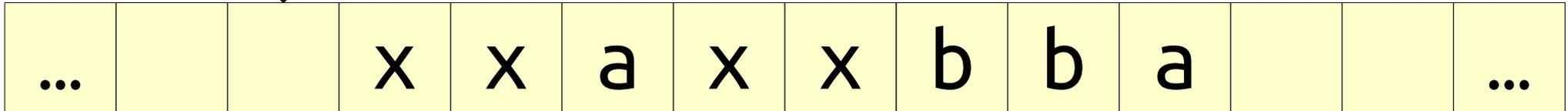
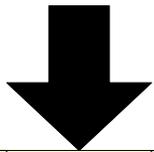


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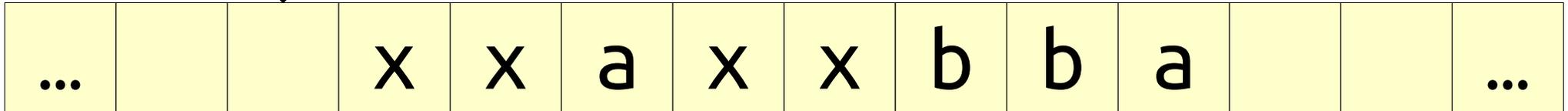
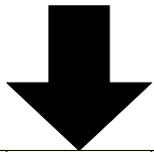


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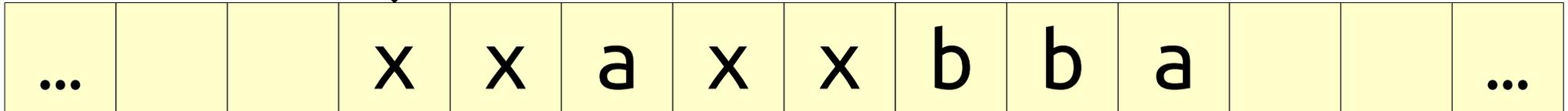
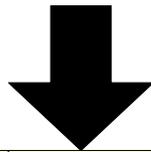
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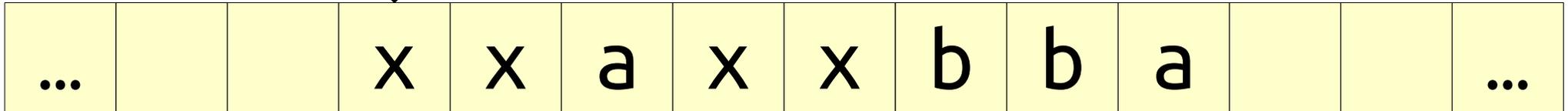
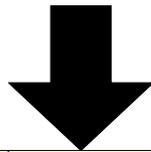


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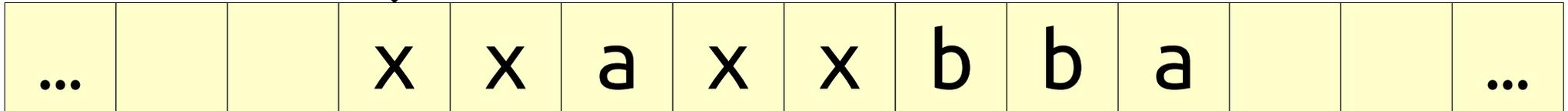
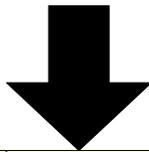
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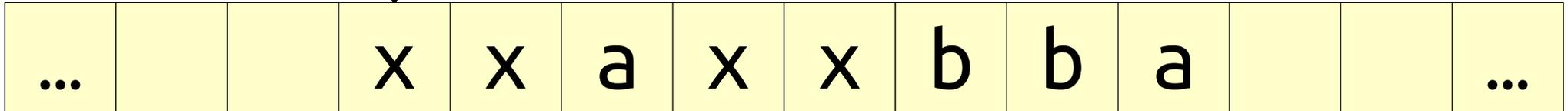
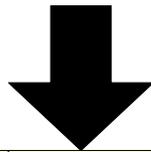
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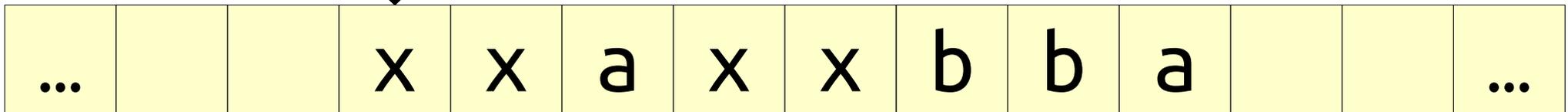
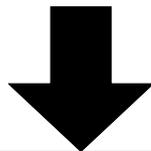
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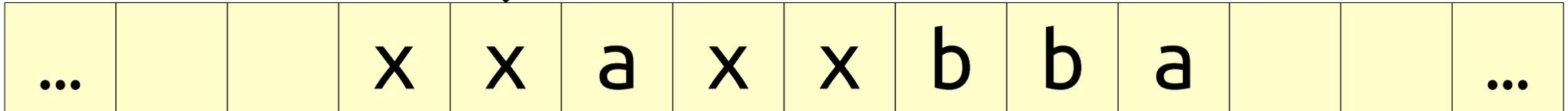
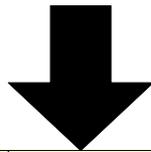


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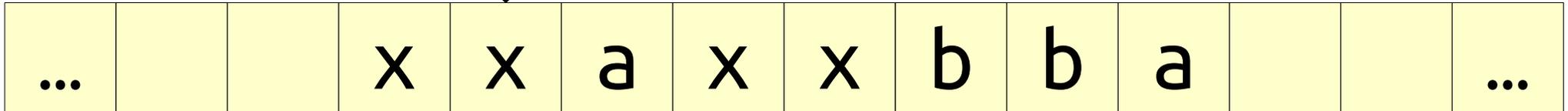
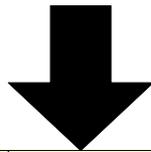


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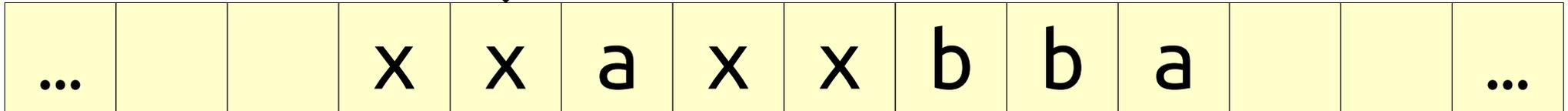
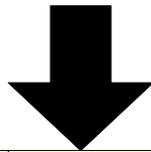
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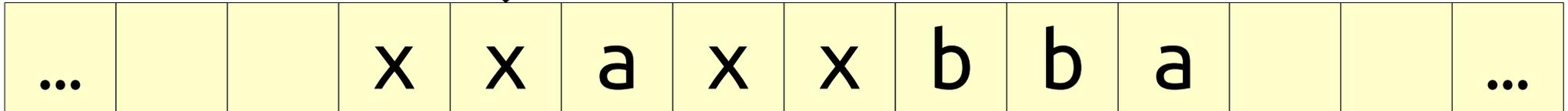
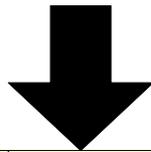
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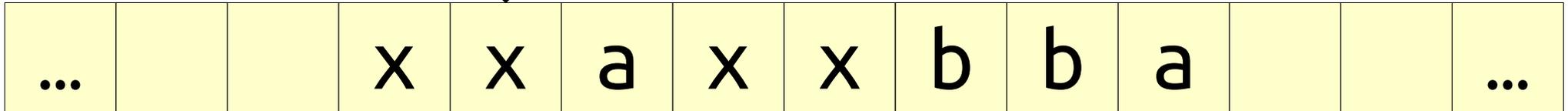
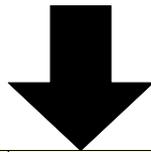


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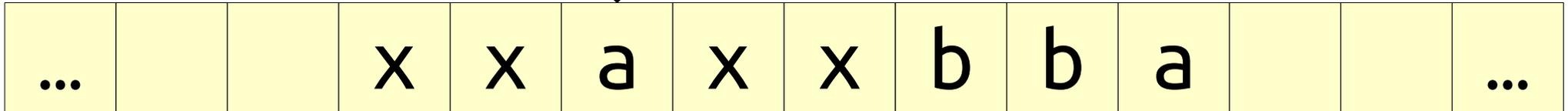
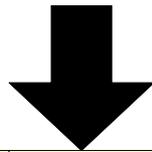


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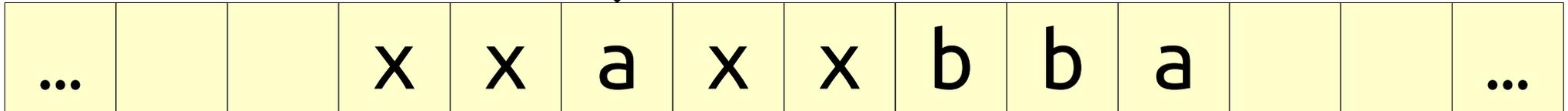
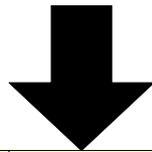


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  Goto Start
```



Start:

```
If 'a' Goto FoundA  
Move Right  
Goto Start
```

FoundA:

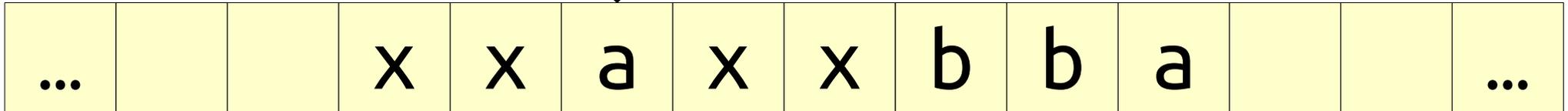
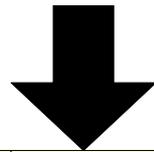
```
Write 'x'
```

LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
```

GoHome:

```
Move Left  
If Not Blank Goto GoHome  
Move Right  
Goto Start
```



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

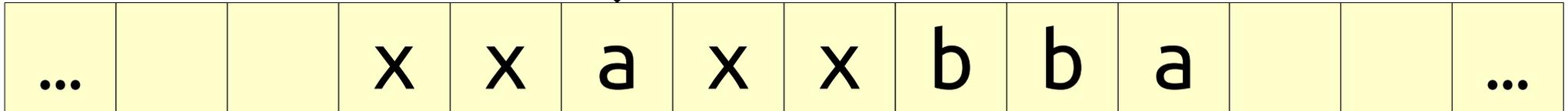
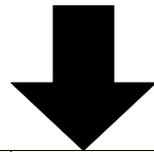
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start

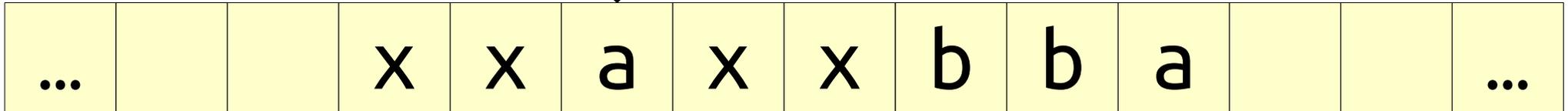
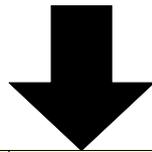


```
Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

FoundA:

```
  Write 'x'  
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

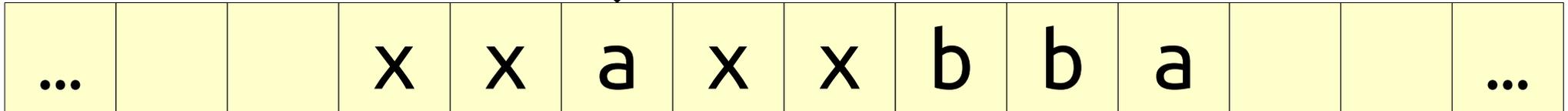
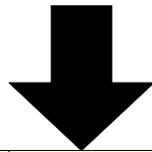


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Start:  
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  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
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  If 'a' Goto LoopA  
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GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
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  Goto Start
```



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Goto Start
```

FoundA:

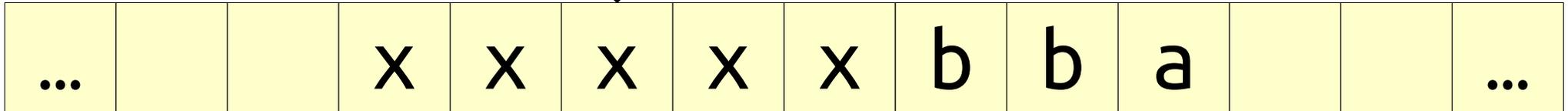
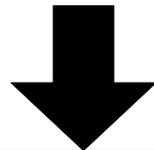
```
Write 'x'
```

LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
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GoHome:

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If Not Blank Goto GoHome  
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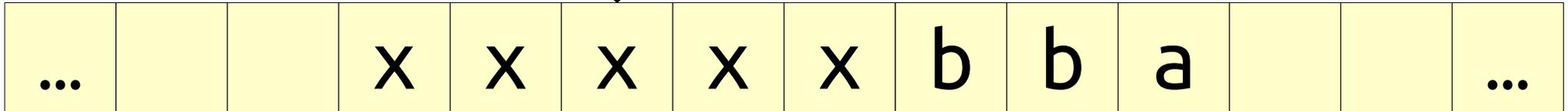
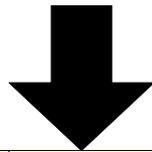


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```

```
FoundA:  
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```

```
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```
GoHome:  
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  If Not Blank Goto GoHome  
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  Goto Start
```

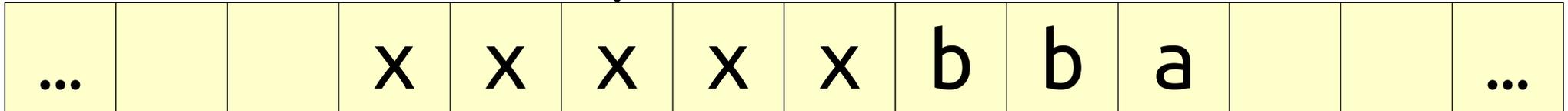
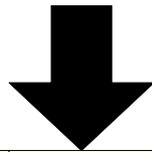


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  Goto Start
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FoundA:  
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LoopA:  
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  If 'a' Goto LoopA  
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```
GoHome:  
  Move Left  
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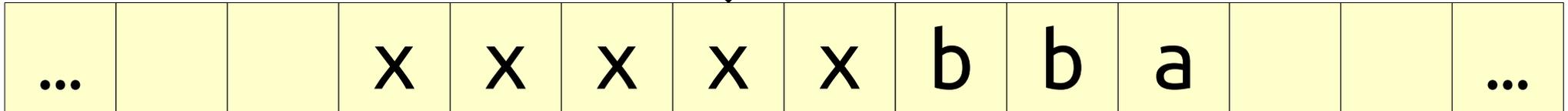
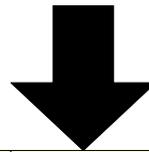


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  If 'a' Goto FoundA  
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  Goto Start
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FoundA:  
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  If Not Blank Goto GoHome  
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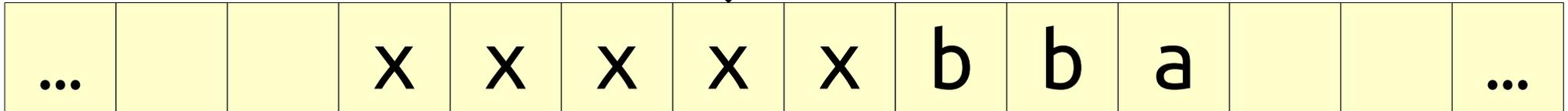
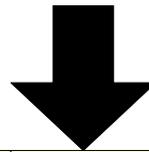


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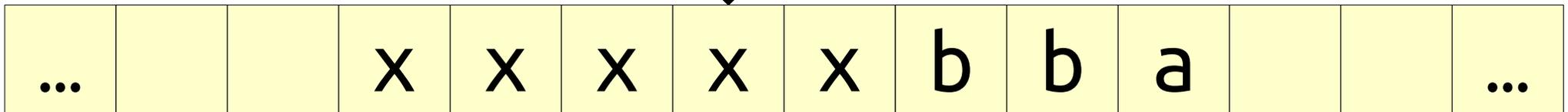
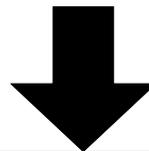
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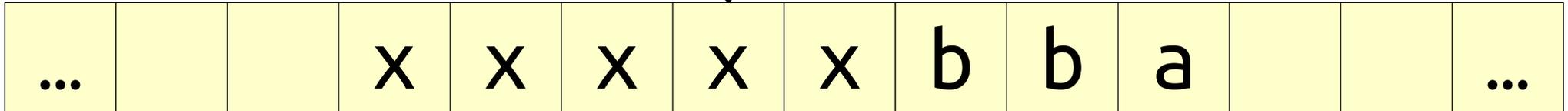
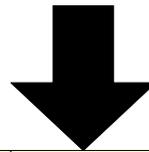


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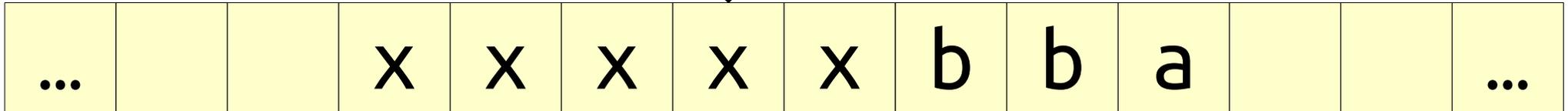
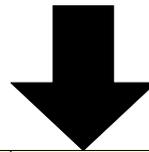


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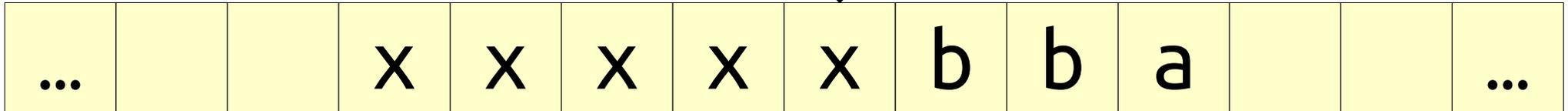
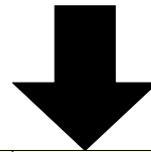


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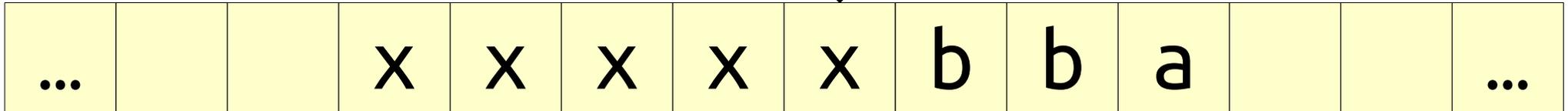
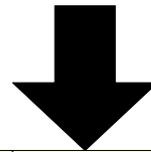


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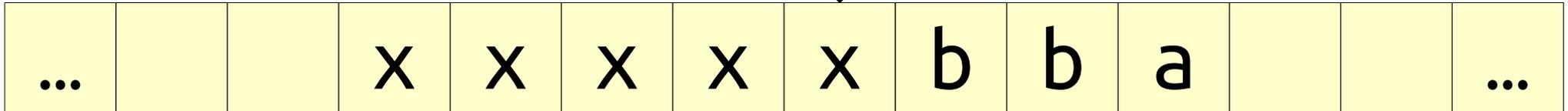
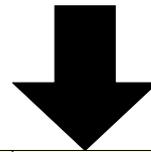


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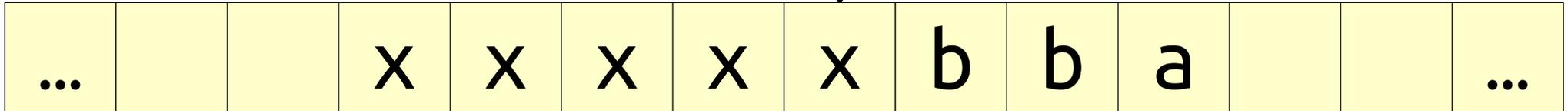
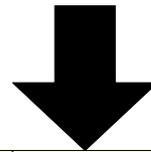


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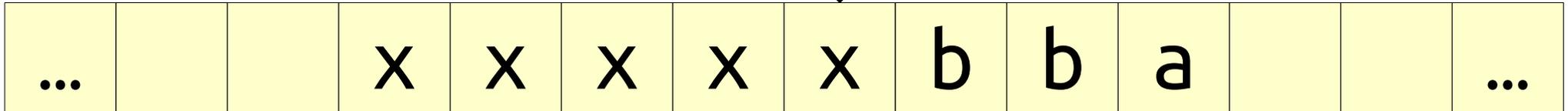
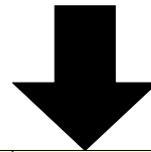


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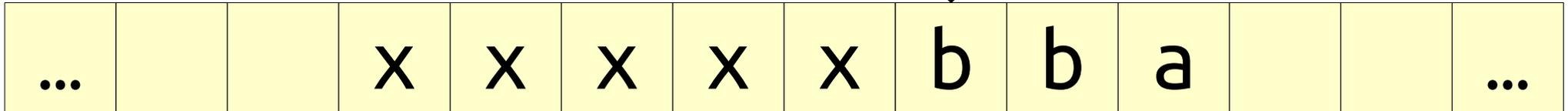
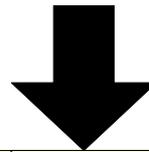


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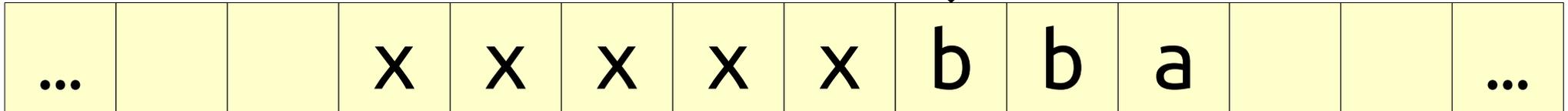
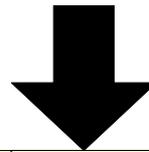


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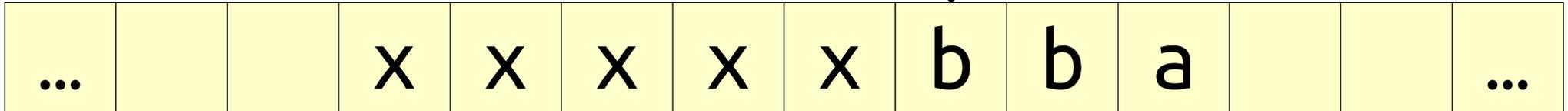
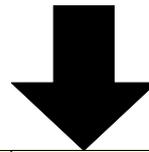


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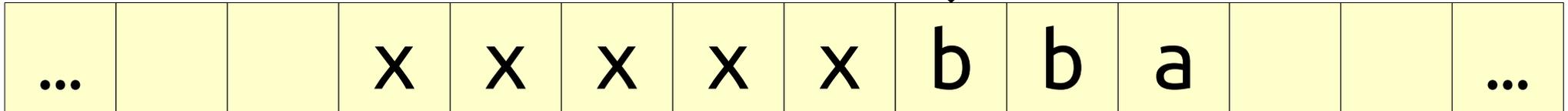
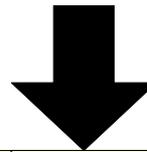
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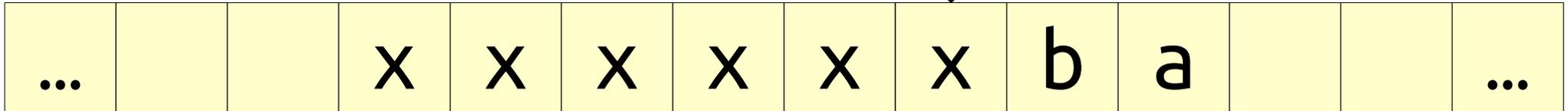
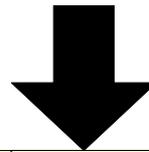


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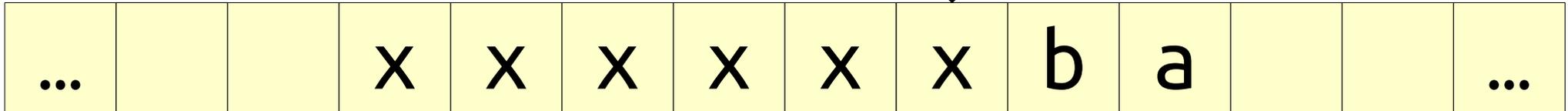
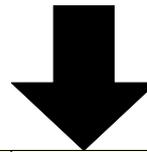
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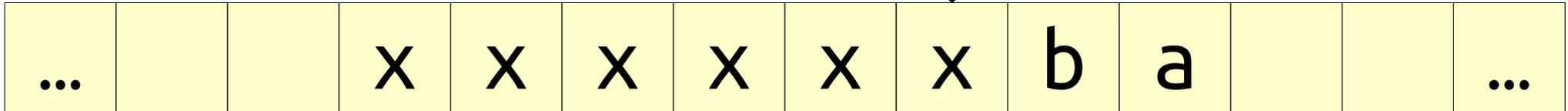
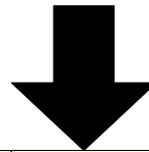
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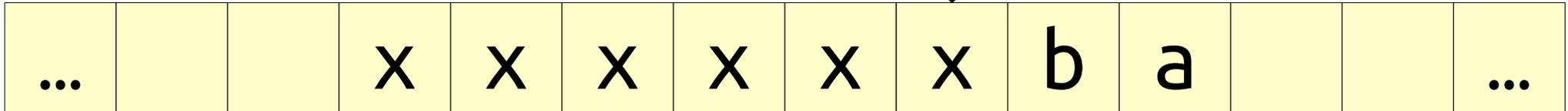
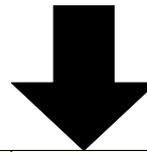
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```
If Not Blank Goto GoHome  
Move Right  
Goto Start
```



Start:

```
If 'a' Goto FoundA  
Move Right  
Goto Start
```

FoundA:

```
Write 'x'
```

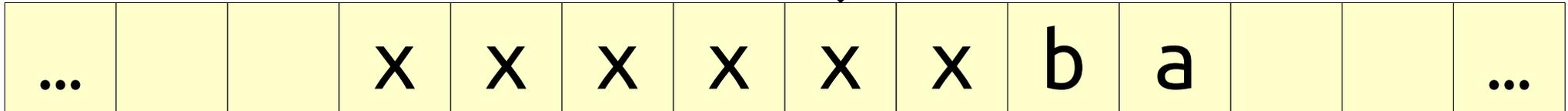
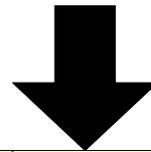
LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
```

GoHome:

```
Move Left
```

```
If Not Blank Goto GoHome  
Move Right  
Goto Start
```

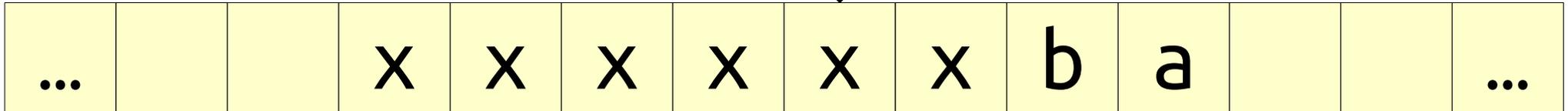
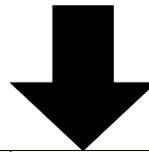


```
Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```



Start:

```
If 'a' Goto FoundA  
Move Right  
Goto Start
```

FoundA:

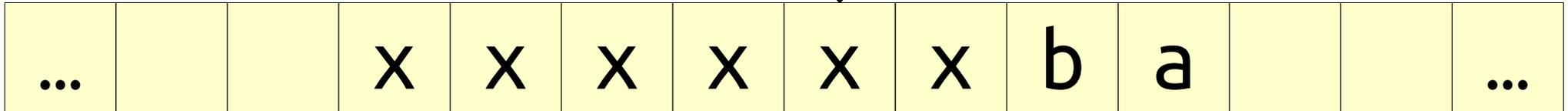
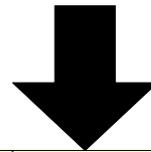
```
Write 'x'
```

LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
```

GoHome:

```
Move Left  
If Not Blank Goto GoHome  
Move Right  
Goto Start
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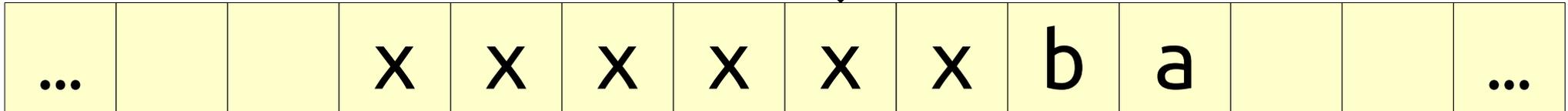
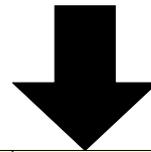


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GoHome:  
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  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
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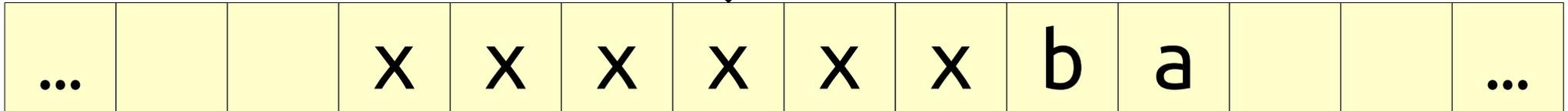
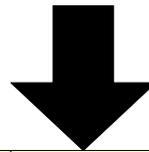


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  Goto Start
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FoundA:  
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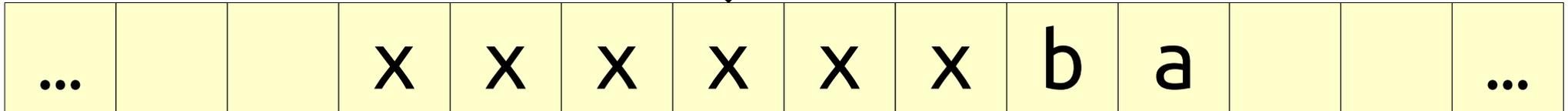
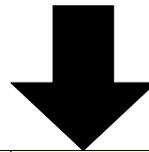


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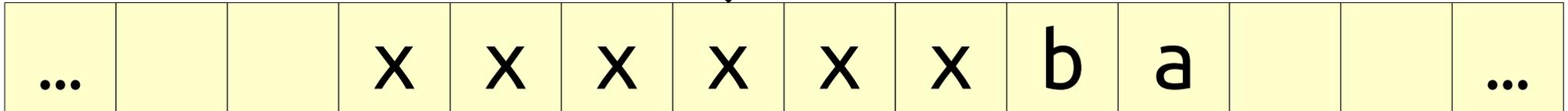
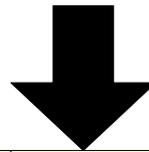


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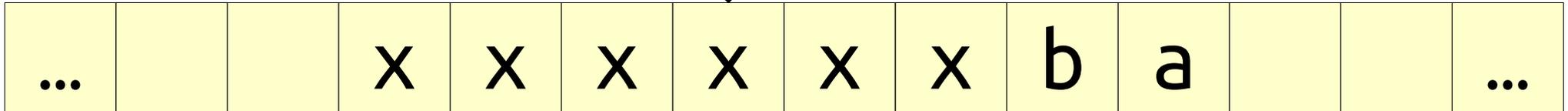
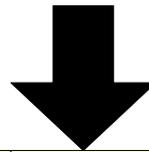


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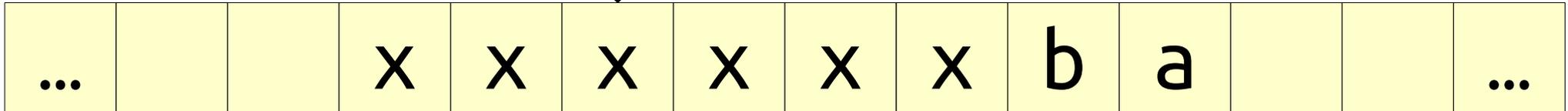
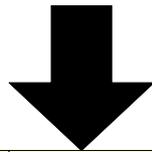


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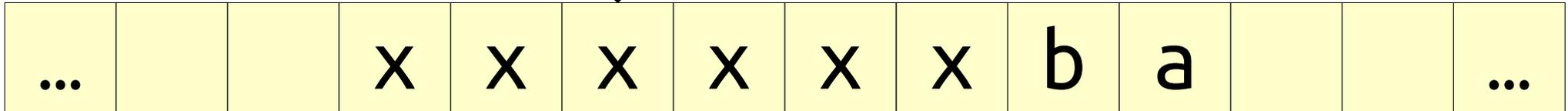
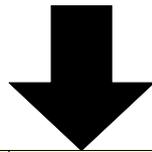


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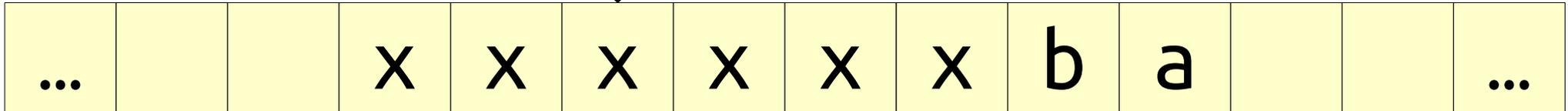
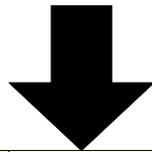


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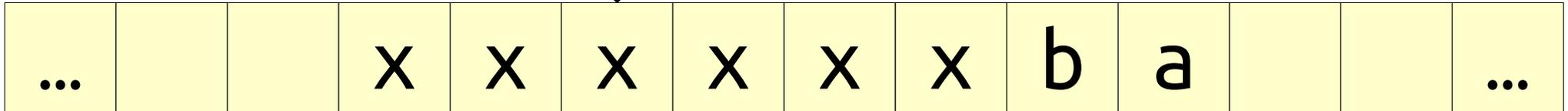
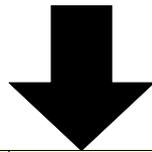


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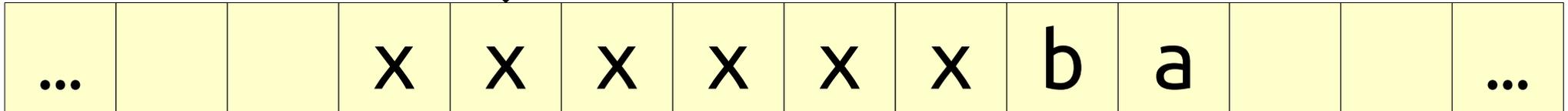
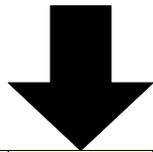


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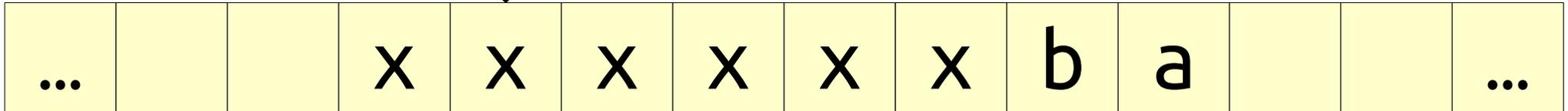
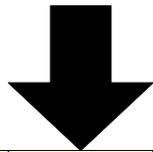


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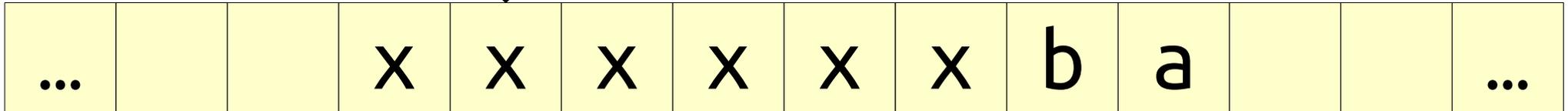
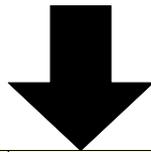
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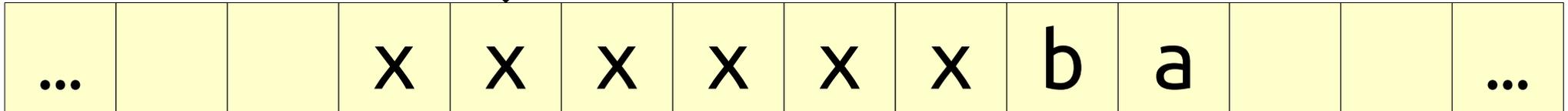
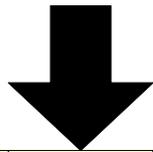


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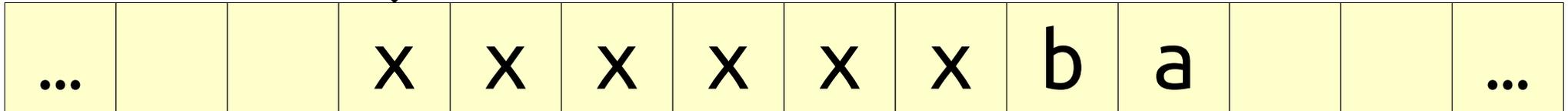
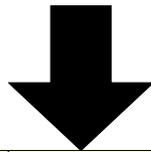
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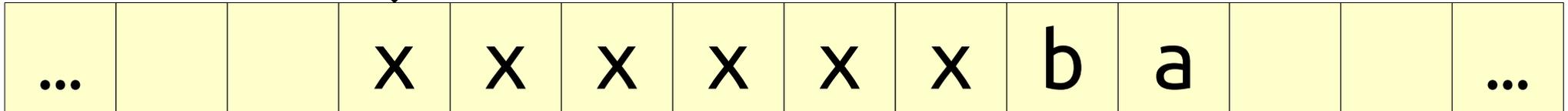
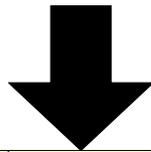


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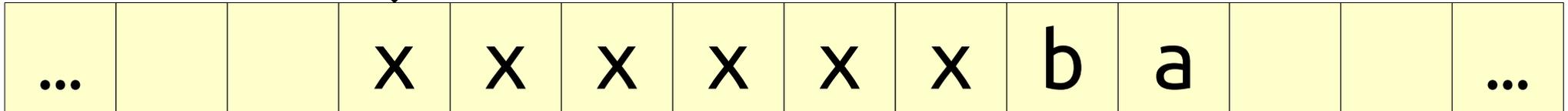
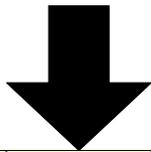
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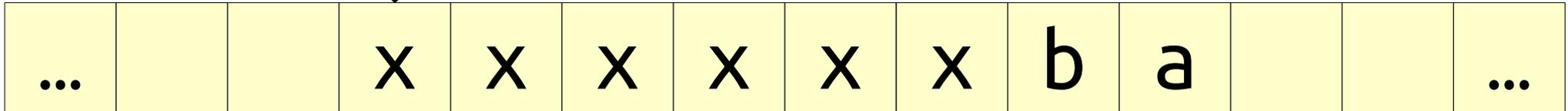
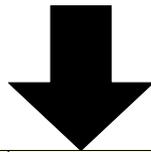
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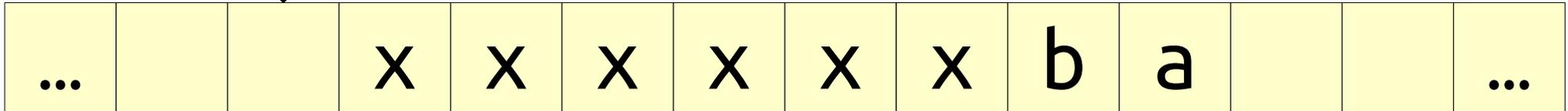
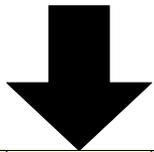
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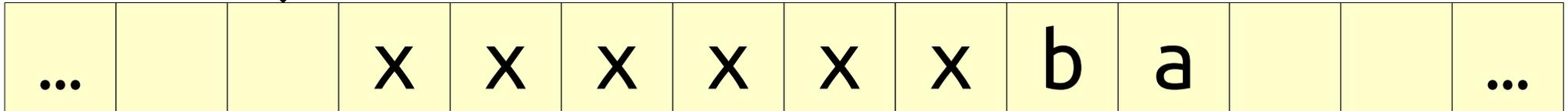
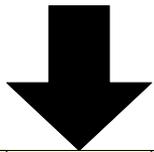


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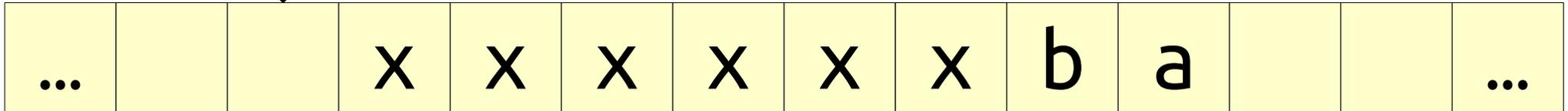
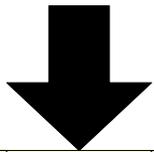


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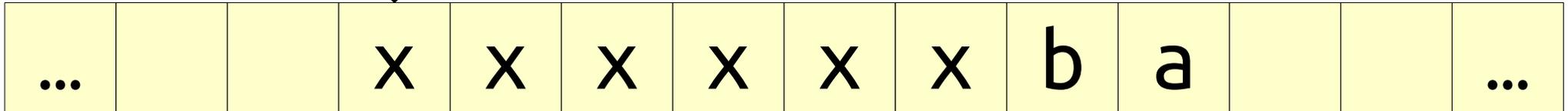
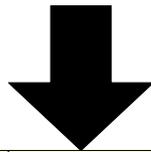
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FoundA:

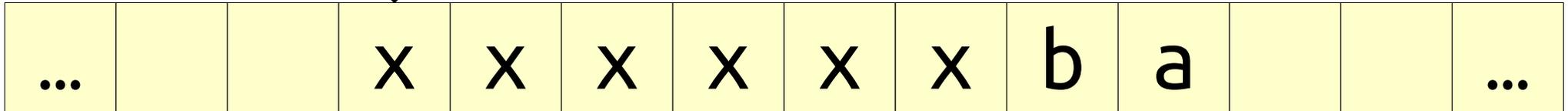
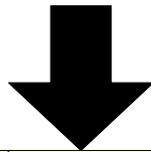
```
Write 'x'
```

LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
```

GoHome:

```
Move Left  
If Not Blank Goto GoHome  
Move Right  
Goto Start
```



Start:

```
If 'a' Goto FoundA  
Move Right  
Goto Start
```

FoundA:

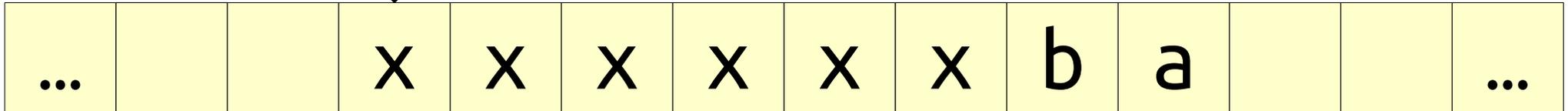
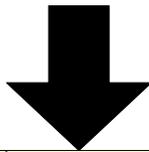
```
Write 'x'
```

LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
```

GoHome:

```
Move Left  
If Not Blank Goto GoHome  
Move Right  
Goto Start
```



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

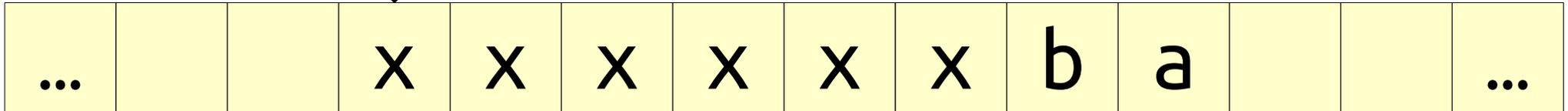
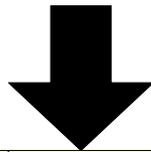
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

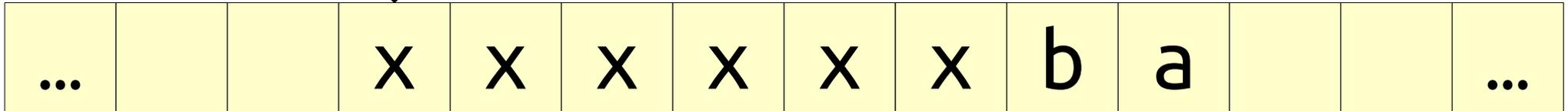
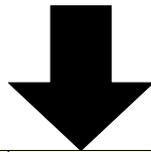
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

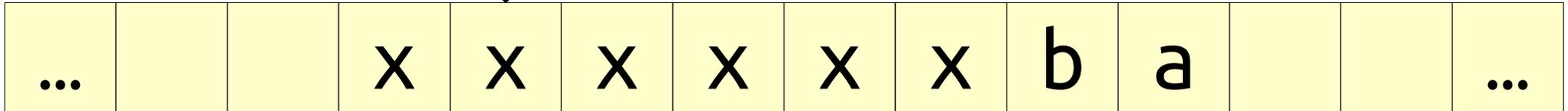
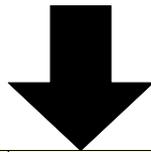
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start

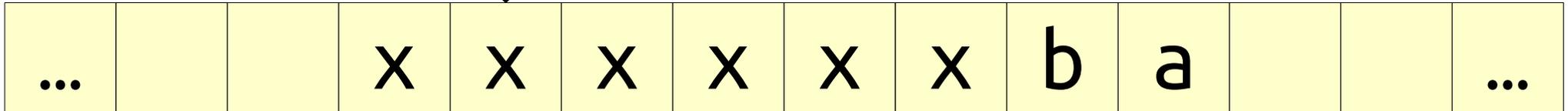
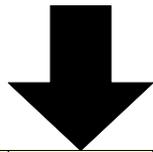


```
Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```



Start:

```
If 'a' Goto FoundA  
Move Right  
Goto Start
```

FoundA:

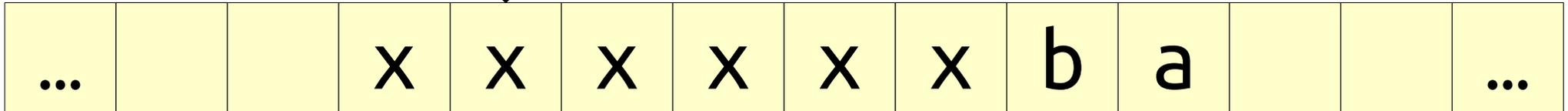
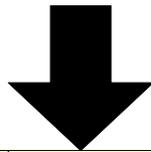
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If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

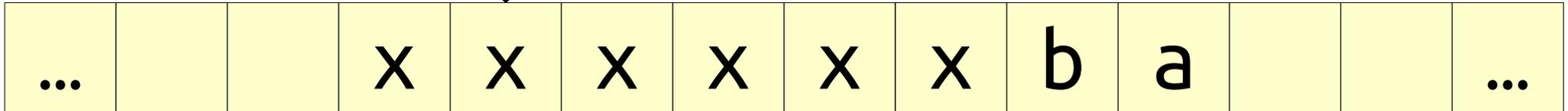
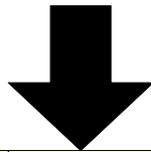
GoHome:

Move Left

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Write 'x'

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Move Right

If 'a' Goto LoopA

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Write 'x'

Goto GoHome

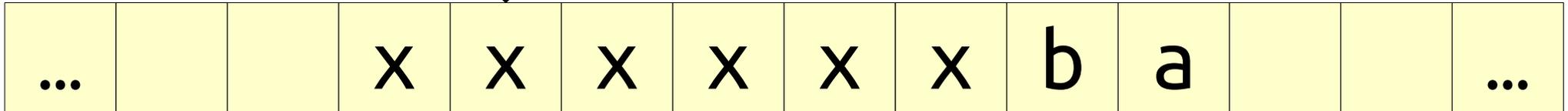
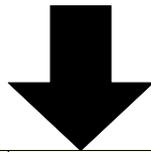
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If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

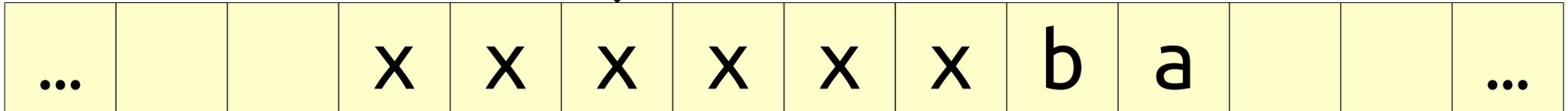
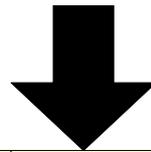
GoHome:

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If Not Blank Goto GoHome

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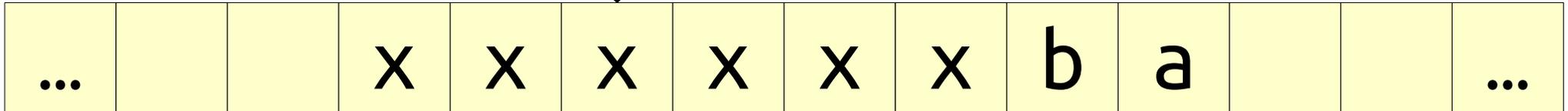
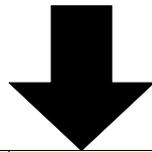


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Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

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FoundA:  
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LoopA:  
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  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
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  Goto Start
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Start:

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If 'a' Goto FoundA  
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```

FoundA:

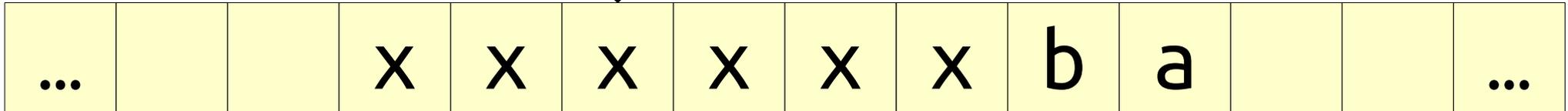
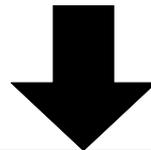
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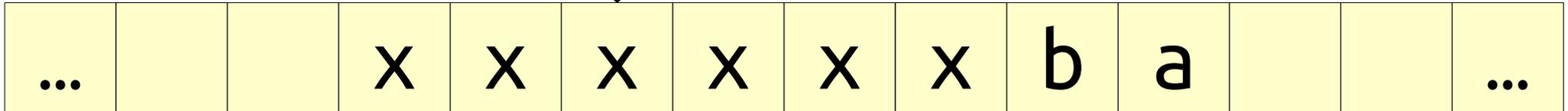
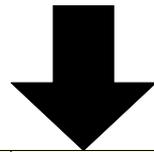
GoHome:

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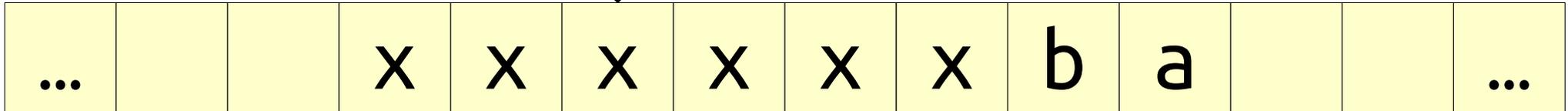
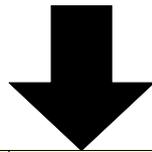
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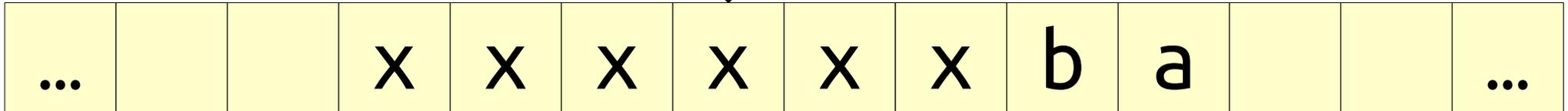
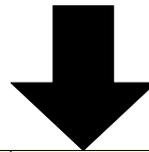
GoHome:

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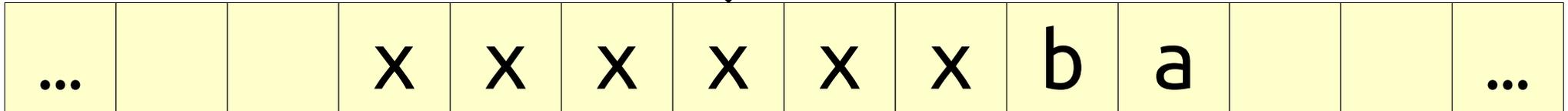
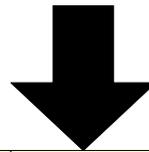


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Start:  
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  Goto Start
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FoundA:  
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LoopA:  
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  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
  Write 'x'  
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GoHome:  
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Start:

```
If 'a' Goto FoundA  
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Goto Start
```

FoundA:

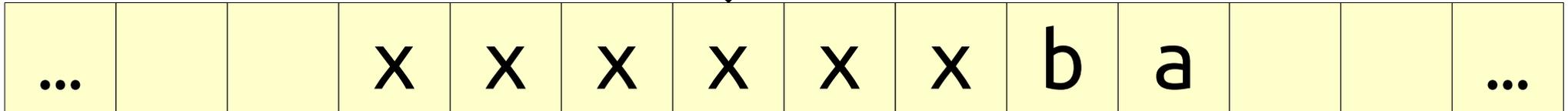
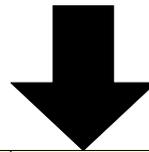
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LoopA:

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If 'a' Goto LoopA  
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GoHome:

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Move Left  
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Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

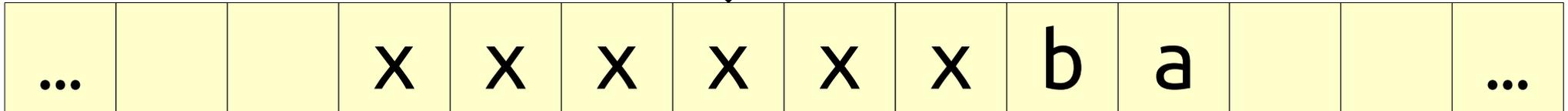
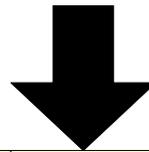
GoHome:

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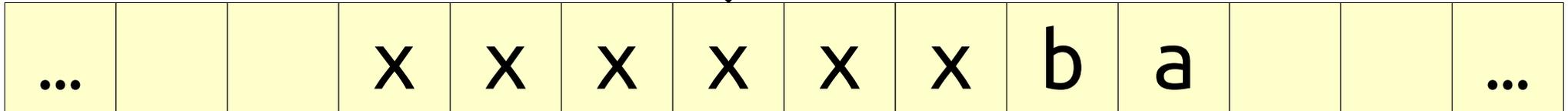
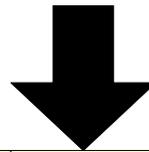
GoHome:

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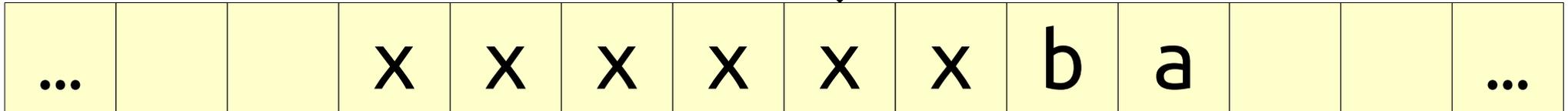
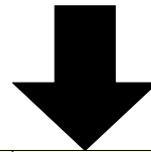


```
Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
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GoHome:  
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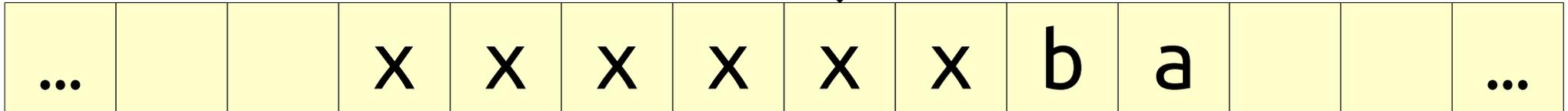
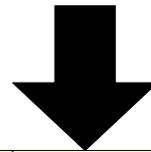


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  If 'a' Goto FoundA  
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Start:

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If 'a' Goto FoundA  
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FoundA:

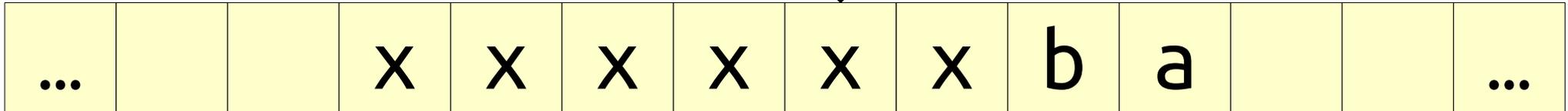
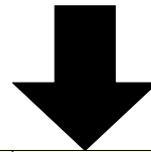
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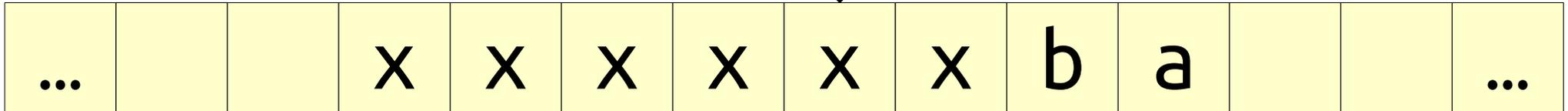
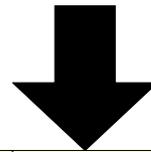
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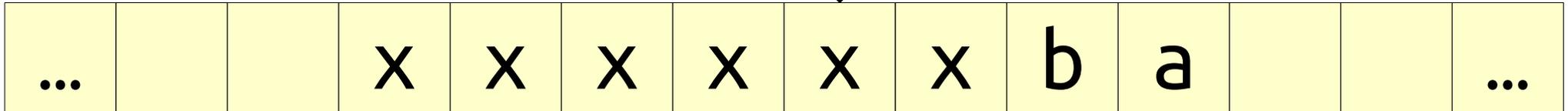
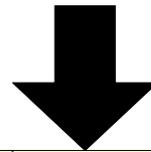


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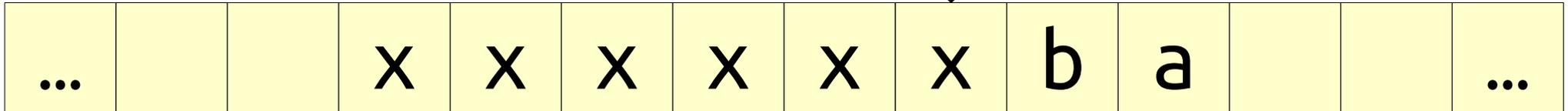
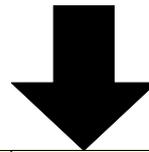


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  If 'a' Goto FoundA  
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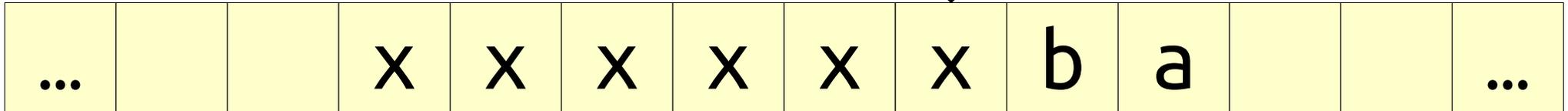
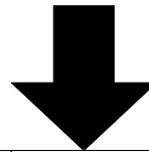


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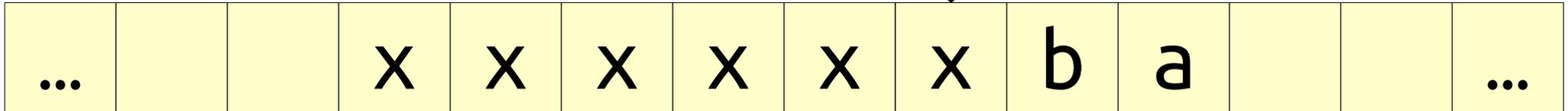
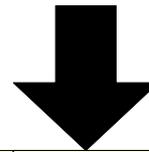
```
Write 'x'
```

LoopA:

```
Move Right  
If 'a' Goto LoopA  
If 'x' Goto LoopA  
Write 'x'  
Goto GoHome
```

GoHome:

```
Move Left  
If Not Blank Goto GoHome  
Move Right  
Goto Start
```



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

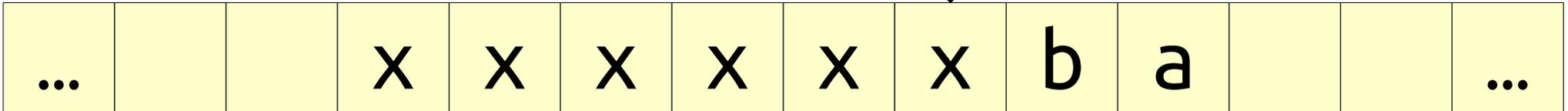
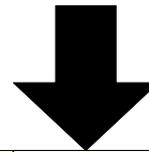
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start

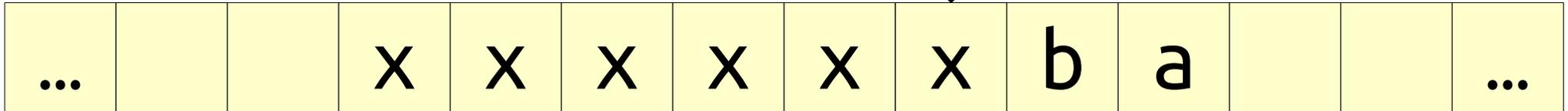
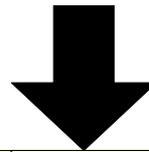


```
Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

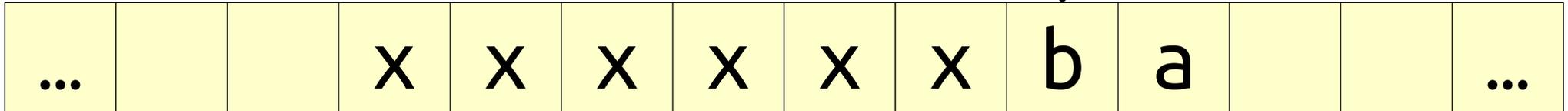
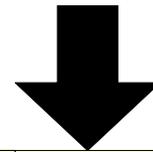


```
Start:  
  If 'a' Goto FoundA  
  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'
```

```
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
  Write 'x'  
  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```



Start:

```
If 'a' Goto FoundA  
Move Right  
Goto Start
```

FoundA:

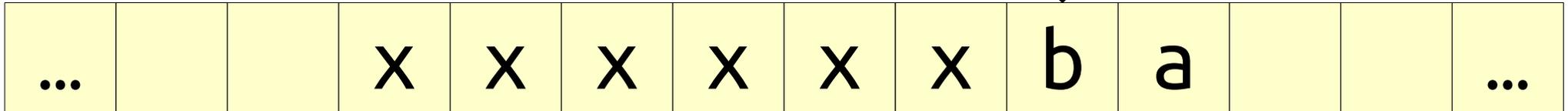
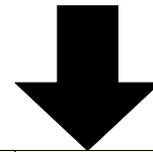
```
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```

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```
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```



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

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LoopA:

Move Right

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If 'x' Goto LoopA

Write 'x'

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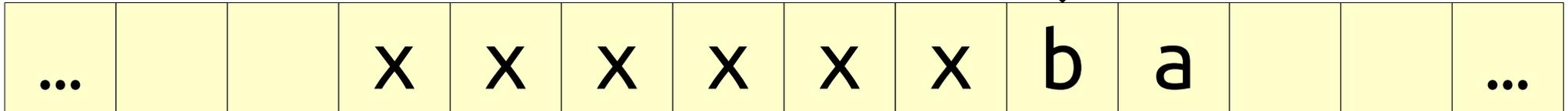
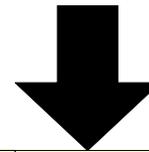
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start



Start:

If 'a' Goto FoundA

Move Right
Goto Start

FoundA:

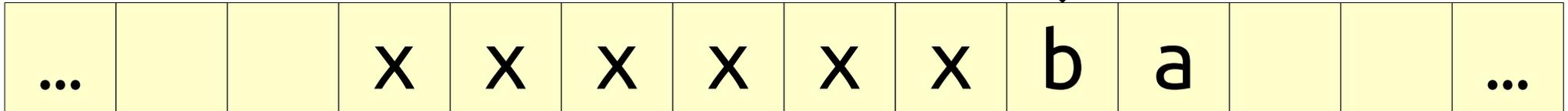
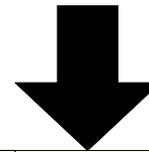
Write 'x'

LoopA:

Move Right
If 'a' Goto LoopA
If 'x' Goto LoopA
Write 'x'
Goto GoHome

GoHome:

Move Left
If Not Blank Goto GoHome
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Goto Start



Start:

If 'a' Goto FoundA

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

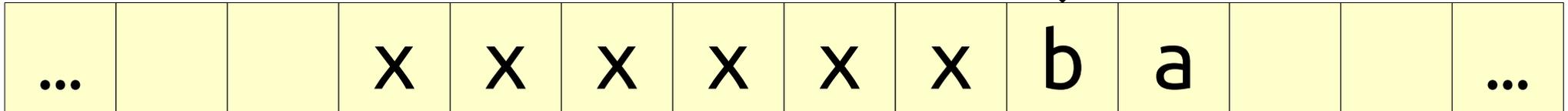
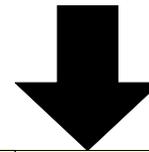
GoHome:

Move Left

If Not Blank Goto GoHome

Move Right

Goto Start



Start:

If 'a' Goto FoundA

If 'b' Goto FoundB

Move Right

Goto Start

FoundA:

Write 'x'

LoopA:

Move Right

If 'a' Goto LoopA

If 'x' Goto LoopA

Write 'x'

Goto GoHome

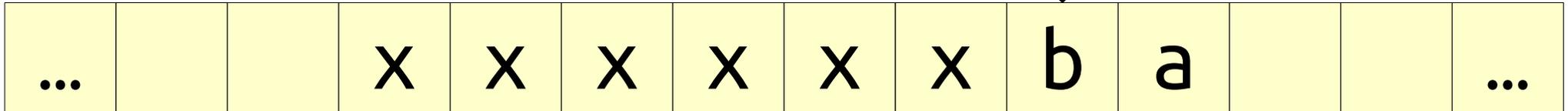
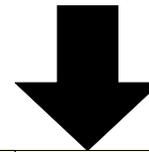
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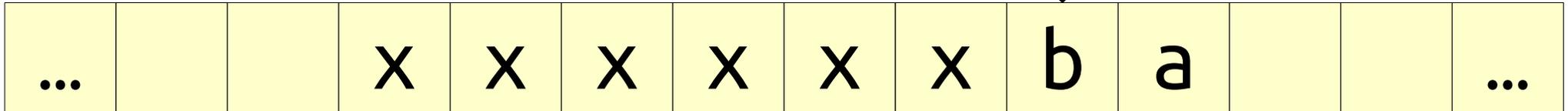
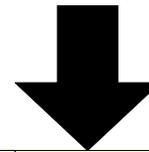


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  Move Right
  Goto Start
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FoundA:
  Write 'x'
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  If 'x' Goto LoopA
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  Goto GoHome
```

```
GoHome:
  Move Left
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  Goto Start
```

```
FoundB:
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LoopB:
  Move Right
  If 'b' Goto LoopB
  If 'x' Goto LoopB
  Write 'x'
  Goto GoHome
```

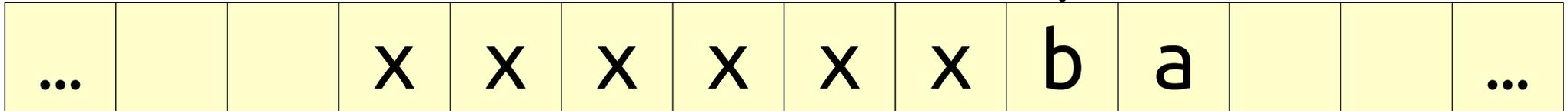
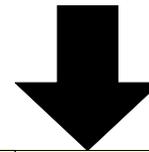


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```

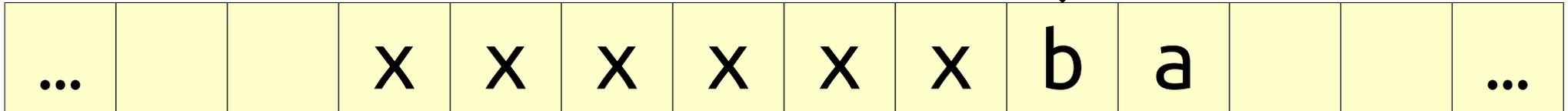
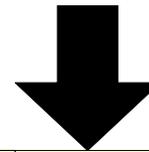


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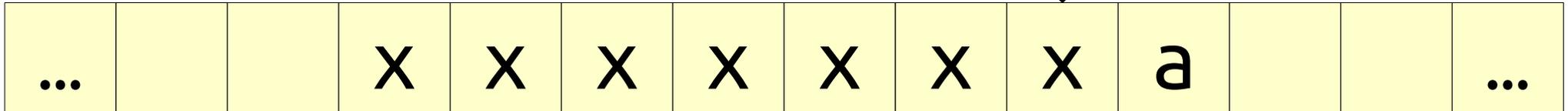
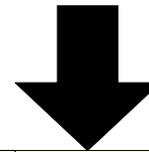


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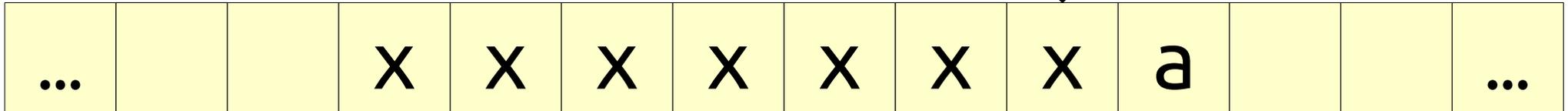
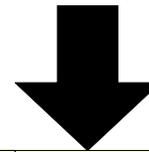


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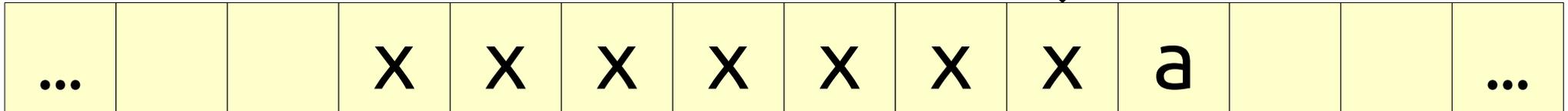
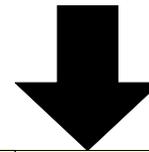


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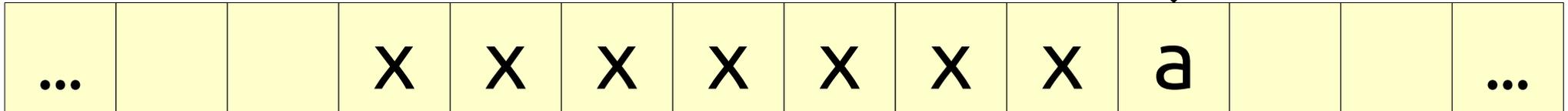
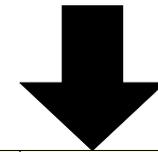


```
Start:
  If 'a' Goto FoundA
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  Move Right
  Goto Start
```

```
FoundA:
  Write 'x'
LoopA:
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GoHome:
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FoundB:
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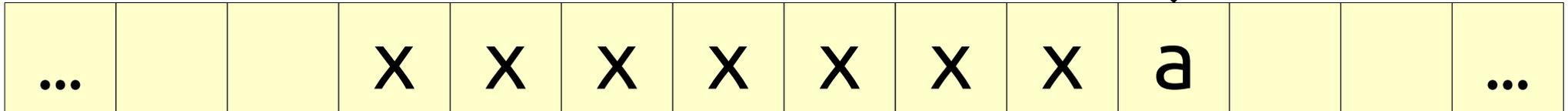
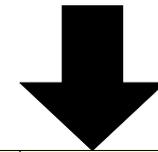


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```
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```
FoundB:
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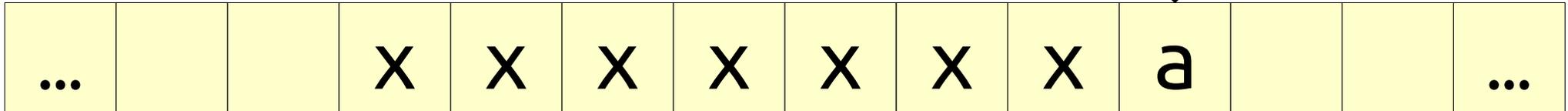
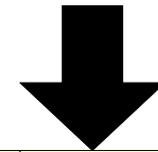


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  If 'a' Goto FoundA
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```
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  Write 'x'
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```
GoHome:
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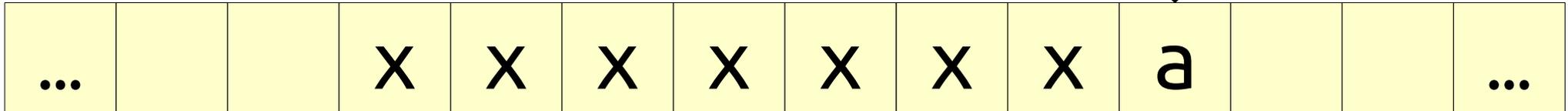
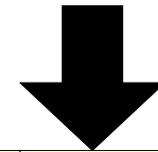


```
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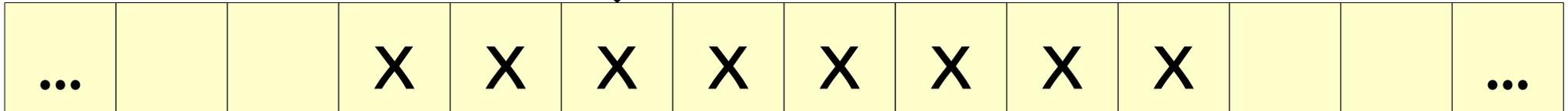
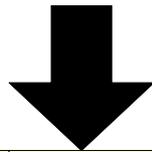



```
Start:  
  If 'a' Goto FoundA  
  If 'b' Goto FoundB  
  Move Right  
  Goto Start
```

```
FoundA:  
  Write 'x'  
LoopA:  
  Move Right  
  If 'a' Goto LoopA  
  If 'x' Goto LoopA  
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  Goto GoHome
```

```
GoHome:  
  Move Left  
  If Not Blank Goto GoHome  
  Move Right  
  Goto Start
```

```
FoundB:  
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  Move Right  
  If 'b' Goto LoopB  
  If 'x' Goto LoopB  
  Write 'x'  
  Goto GoHome
```



Start:

```
If 'a' Goto FoundA
If 'b' Goto FoundB
If Blank Return True
Move Right
Goto Start
```

FoundA:

```
Write 'x'
```

LoopA:

```
Move Right
If 'a' Goto LoopA
If 'x' Goto LoopA
Write 'x'
Goto GoHome
```

GoHome:

```
Move Left
If Not Blank Goto GoHome
Move Right
Goto Start
```

FoundB:

```
Write 'x'
```

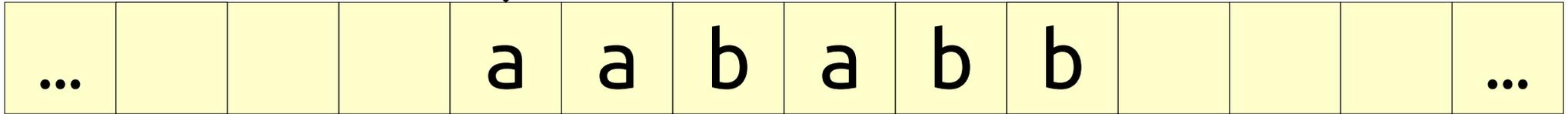
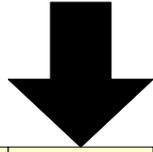
LoopB:

```
Move Right
If 'b' Goto LoopB
If 'x' Goto LoopB
Write 'x'
Goto GoHome
```

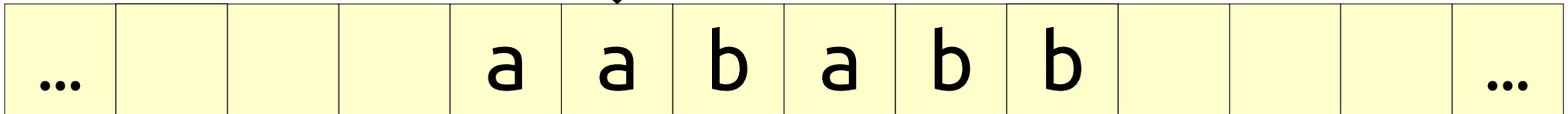
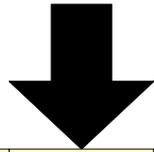

Another Idea

- We just built a TM for the language
 $\{ w \in \{a, b\}^* \mid w \text{ has the same number of } a\text{'s and } b\text{'s} \}$.
- An observation: this would be a *lot* easier to test for if all the **a**'s came before all the **b**'s.
 - In fact, that would turn this into checking if the string has the form $a^n b^n$, which we already know how to do!
- **Idea:** Could we sort the characters of our input string?

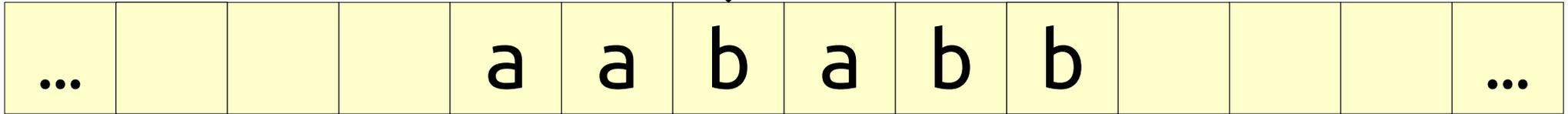
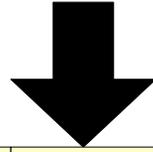
The Idea



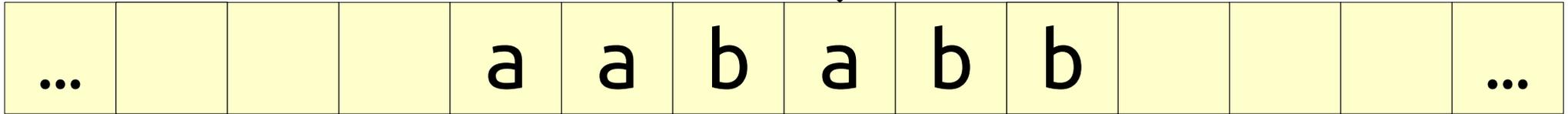
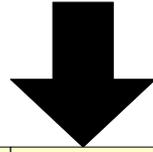
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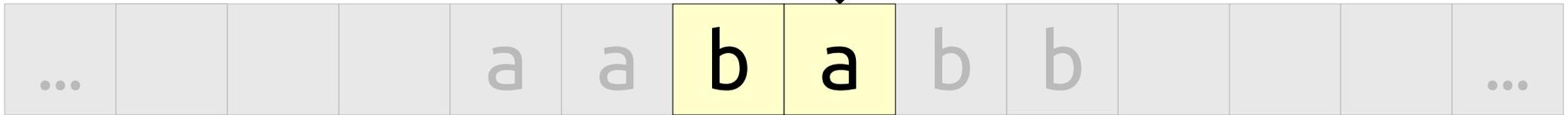
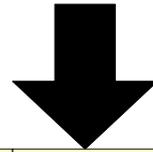
The Idea



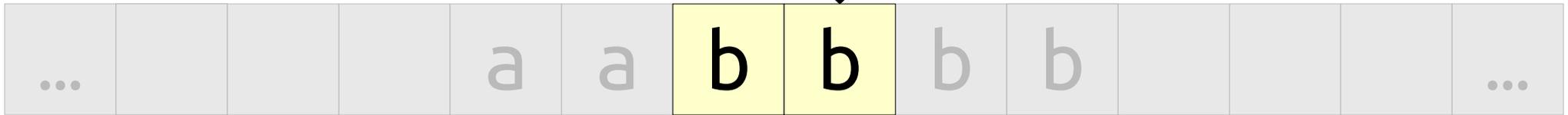
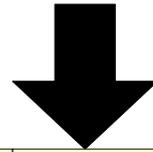
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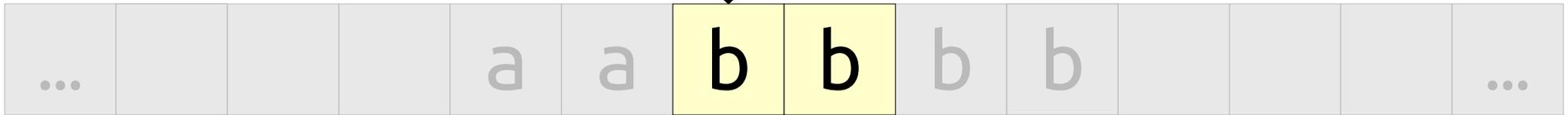
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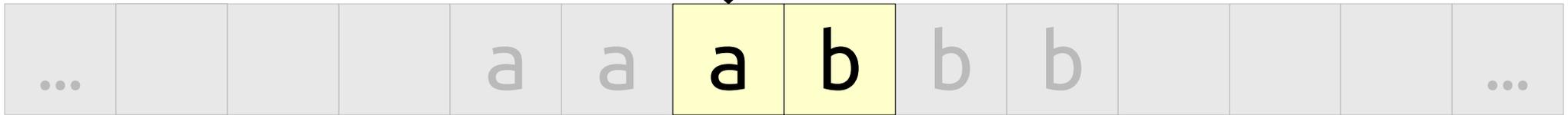
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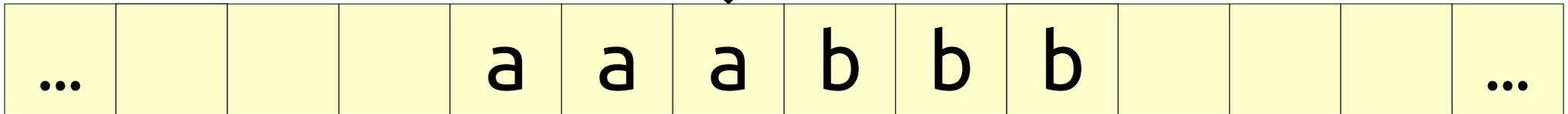
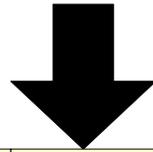
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The Idea



The Idea



Exploring This Idea

Summary for Today

- Turing machines are abstract computers that issue commands to an infinite tape subdivided into cells.
- Each step of the TM can move the tape head, change what's on the tape, or jump to a different part of the program.
- TMs can be composed together to build larger TMs out of smaller ones.

Next Time

- ***The Church-Turing Thesis***
 - How powerful are Turing machines?
- ***Decidability and Recognizability***
 - Two notions of “solving a problem.”