Counter Machines & Distributed Automata

A Story about Exchanging Space and Time

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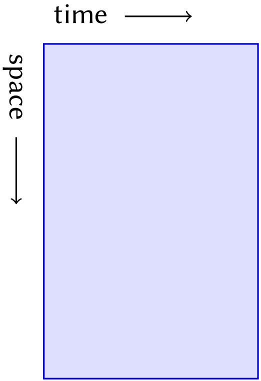
A space-time duality

Image credit: NASA/ESA/CXC/SSC/STScI

A space-time duality

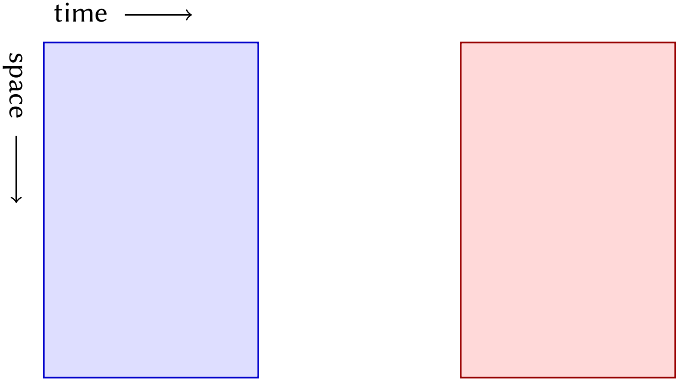
A space-time duality



time ⟶

space ⟶

A space-time duality



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space

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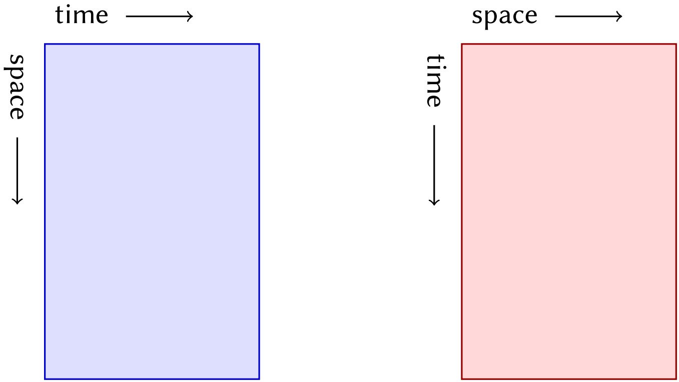

time ⟶

space ⟶

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time ⟶

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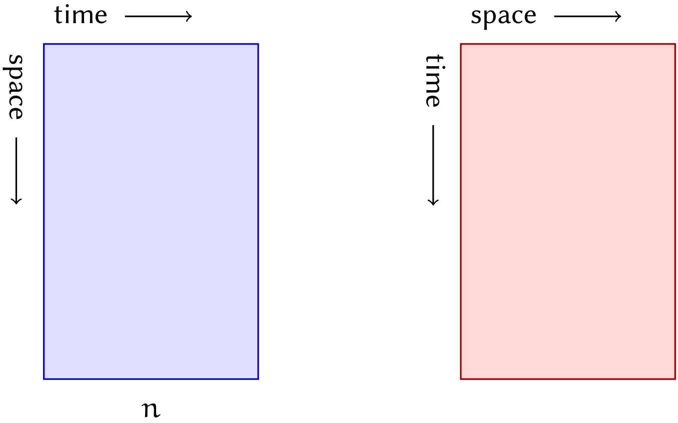

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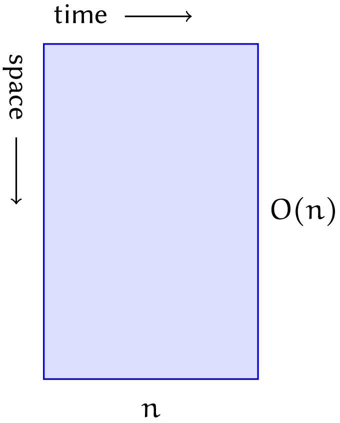

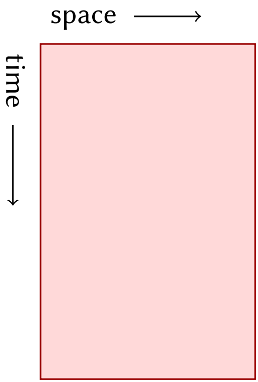

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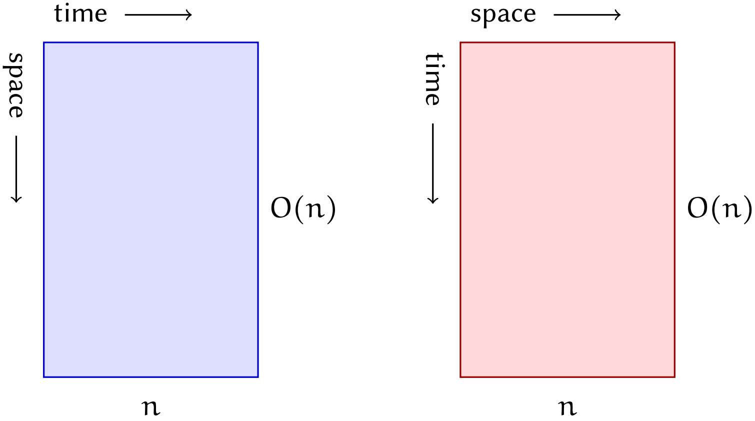

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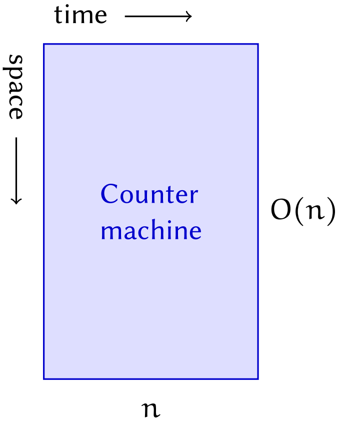

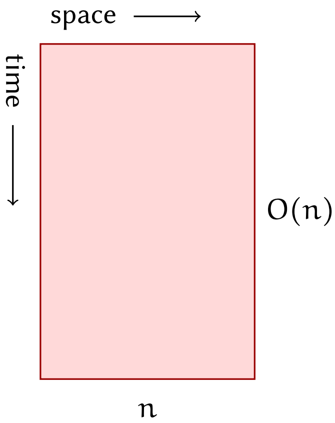

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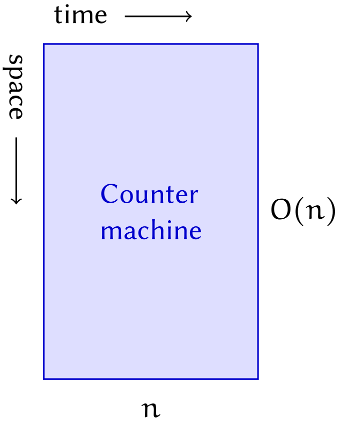

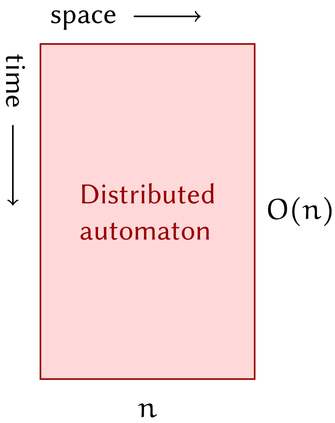

Counter machines

Counter machines

a	b	a	c	a	c

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$w \in \{a, b, c\}^+$ s.t.

$\forall$ prefix u of w

$|u|_a \geq |u|_b \geq |u|_c$

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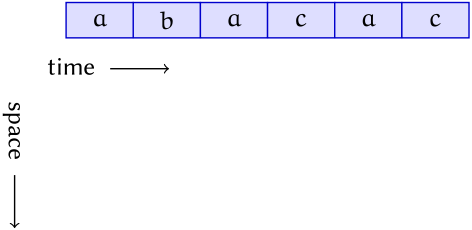

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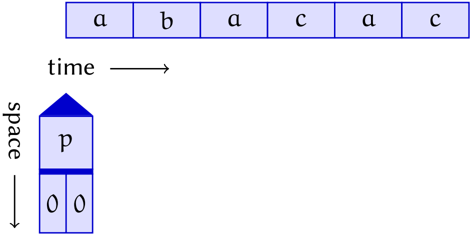

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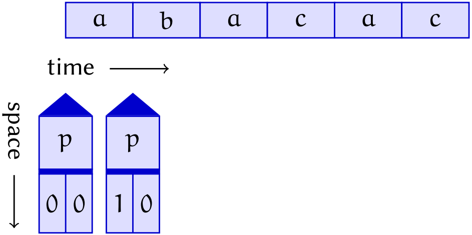

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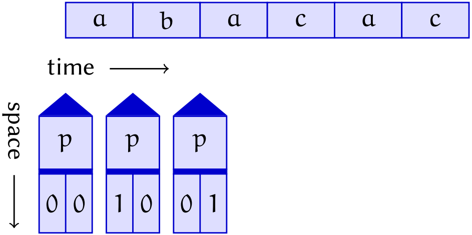

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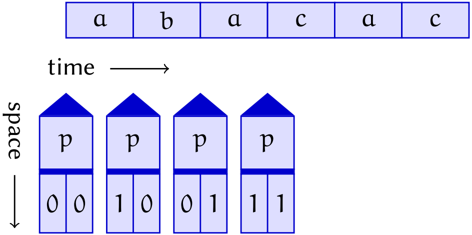

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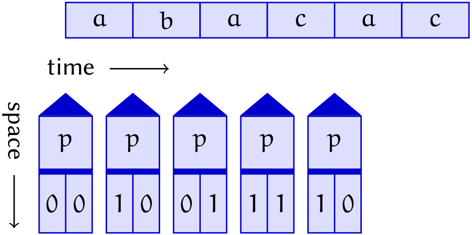

a b a c a c

time ⟶

space ⟶

p 0 0

p 1 0

p 0 1

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p 1 0

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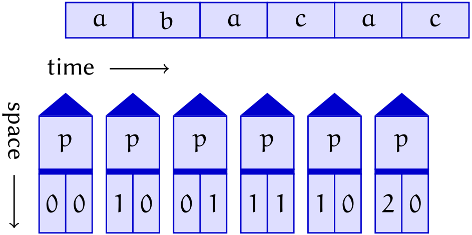

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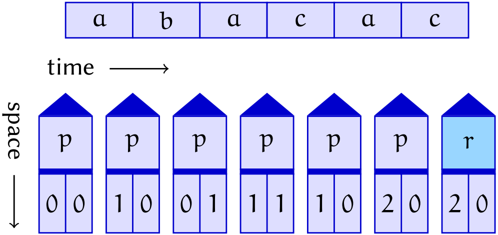

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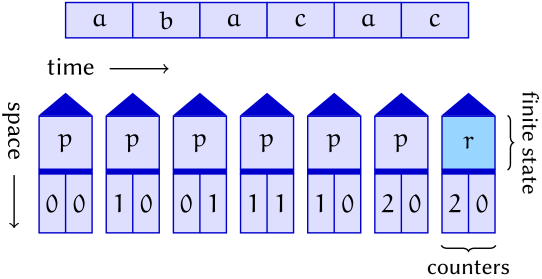

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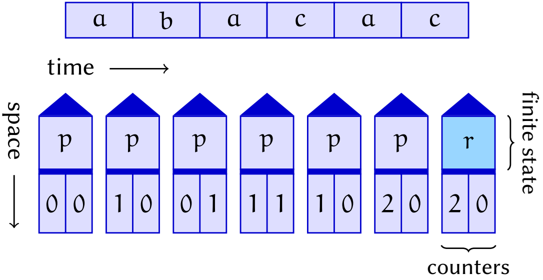

- One-way, deterministic, no ε-transitions.

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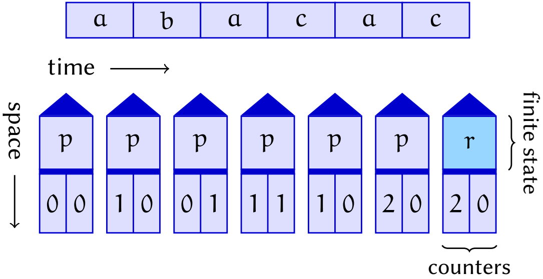

- One-way, deterministic, no ε-transitions.
- Multiple counters $x, y, \ldots$ with values in $\mathbb{Z}$.

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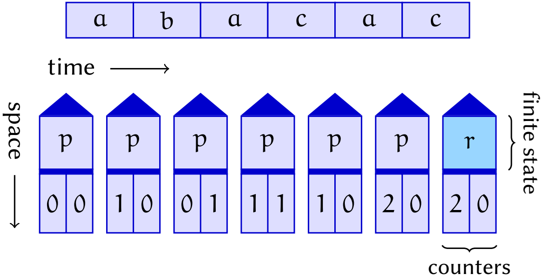

- One-way, deterministic, no ε-transitions.
- Multiple counters $x, y, \ldots$ with values in $\mathbb{Z}$.
- Counter values known up to some threshold.

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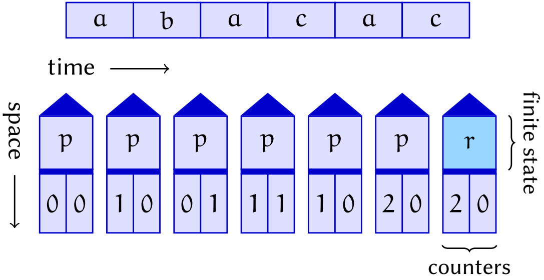

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- Counter updates of the form $x \coloneqq y_1 + \cdots + y_n + c$.

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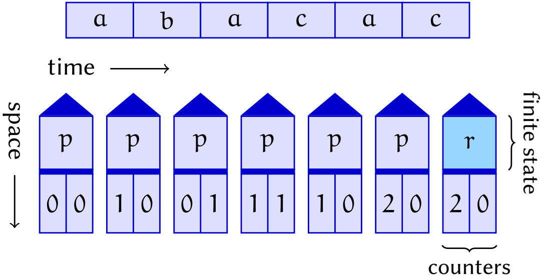

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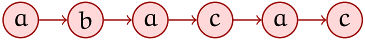
- Counter updates of the form $\underbrace{x \coloneqq y_1 + \cdots + y_n + c}_{\text{allows copy and sum}}$.

Distributed automata

Distributed automata



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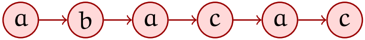
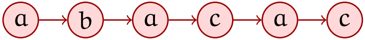


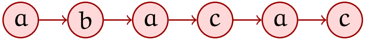
- Finite-state machine on each node.

Distributed automata



- Finite-state machine on each node.
- Synchronous transitions of the form $\delta\colon \underbrace{Q}_{\text{left}} \times \underbrace{Q}_{\text{self}} \to Q$.

Distributed automata



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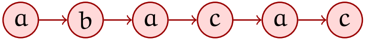

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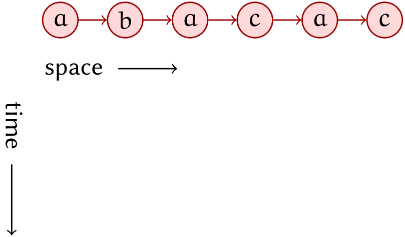

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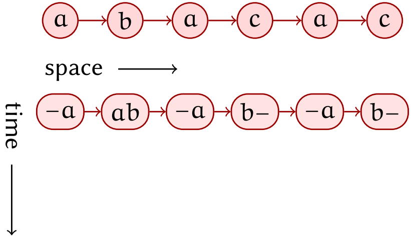

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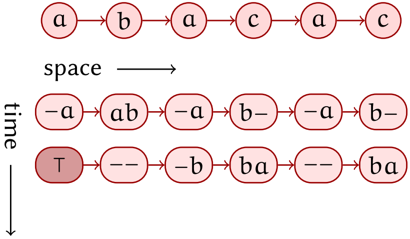

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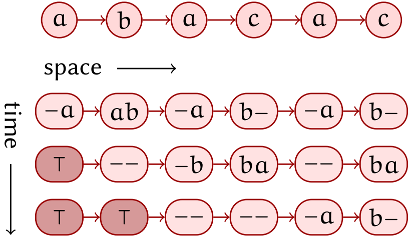

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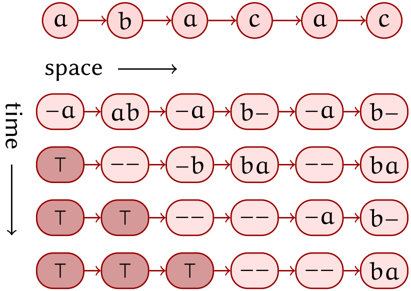

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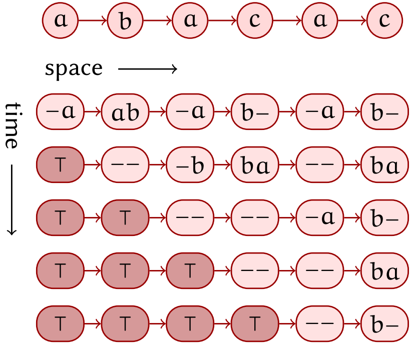

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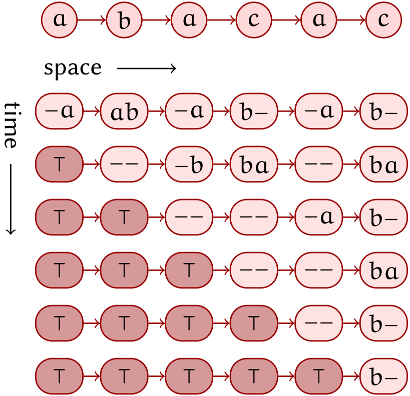

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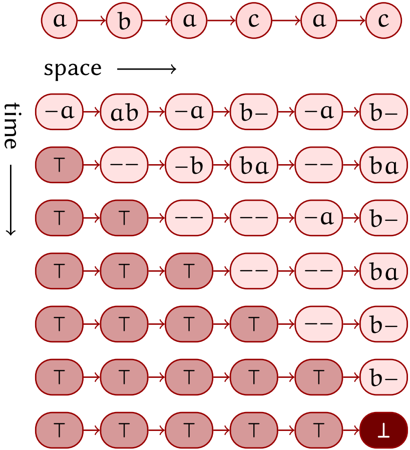

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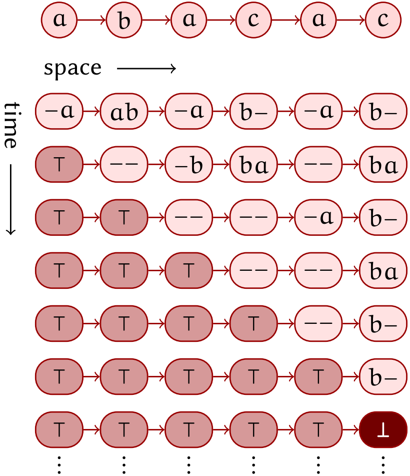

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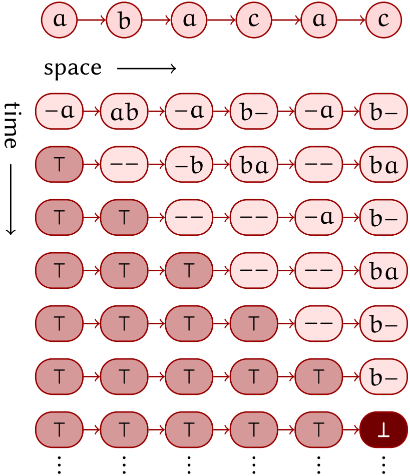

The same as (reversed, one-dimensional) one-way cellular automata.

Our translations

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Copyless
counter machines

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Counters can be summed up but not copied.

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LINEAR SPACE

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LINEAR SPACE

Quasi-acyclic
distributed automata

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Quasi-acyclic
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The state diagram has no directed cycles except for self-loops.

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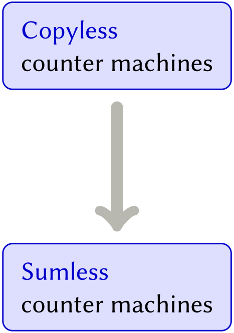

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LINEAR SPACE

Quasi-acyclic distributed automata

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LINEAR TIME

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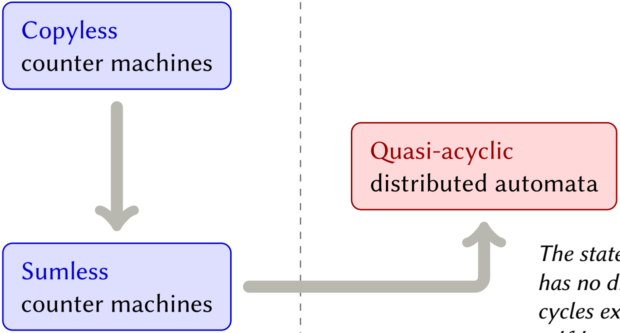

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LINEAR SPACE

LINEAR TIME

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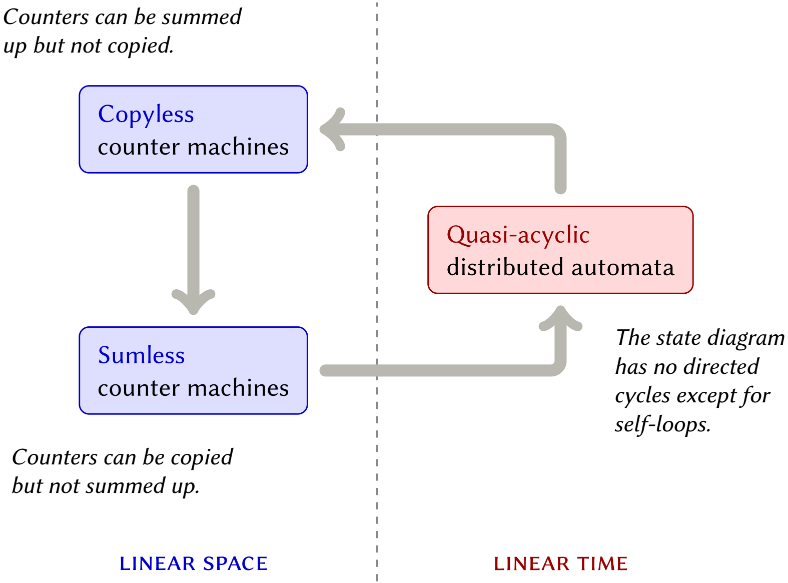

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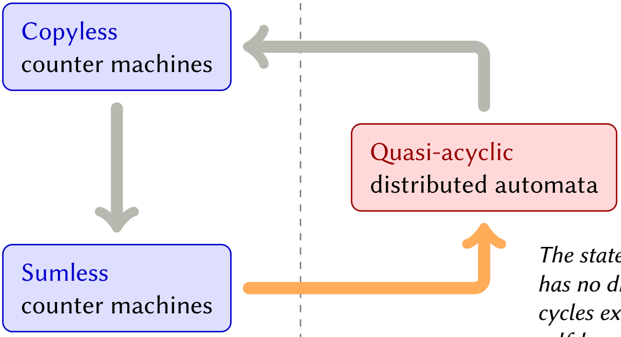

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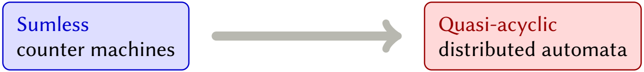
LINEAR SPACE

LINEAR TIME

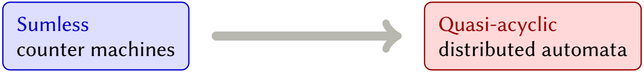
Using time as space



Sumless
counter machines

Quasi-acyclic
distributed automata

Using time as space

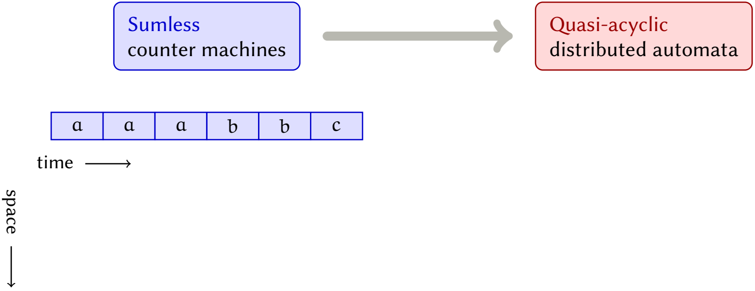


Sumless
counter machines

Quasi-acyclic
distributed automata

a	a	a	b	b	c

Using time as space



Sumless counter machines

Quasi-acyclic distributed automata

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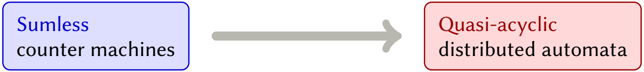
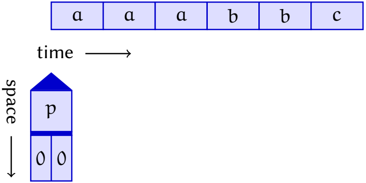
Using time as space



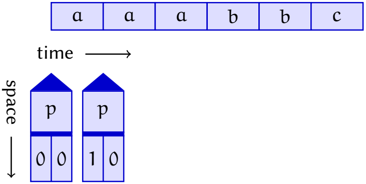
Sumless counter machines

Quasi-acyclic distributed automata



Using time as space

Sumless counter machines → Quasi-acyclic distributed automata



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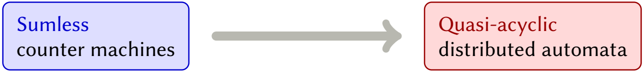
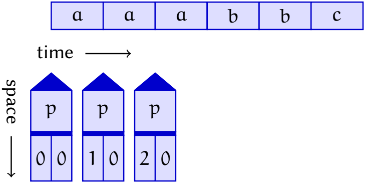


Sumless counter machines

Quasi-acyclic distributed automata



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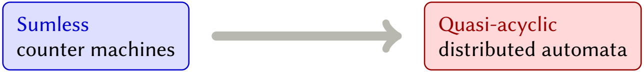
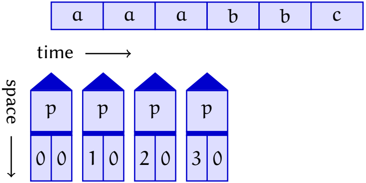


Sumless
counter machines

Quasi-acyclic
distributed automata

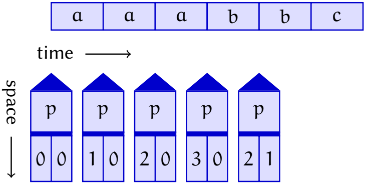


Using time as space

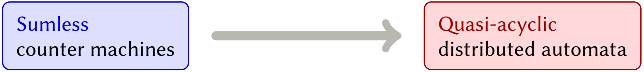
Sumless
counter machines

→

Quasi-acyclic
distributed automata

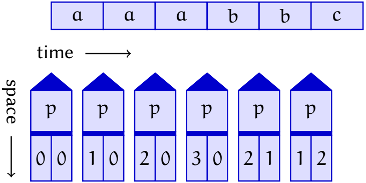


Using time as space



Sumless counter machines

Quasi-acyclic distributed automata



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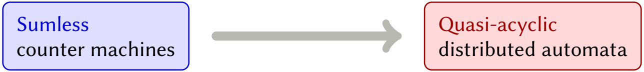
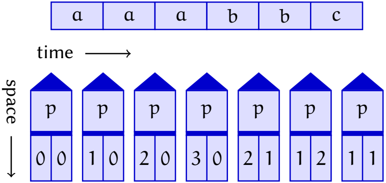


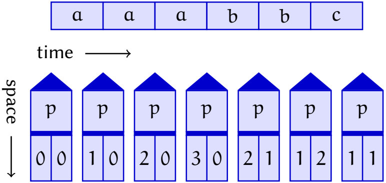
Sumless counter machines

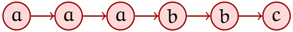
Quasi-acyclic distributed automata



Using time as space

Sumless counter machines → Quasi-acyclic distributed automata





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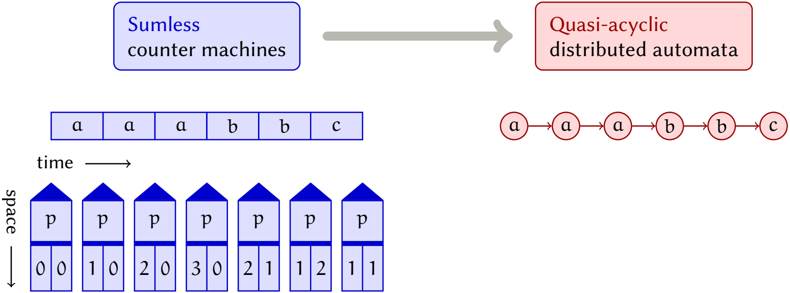

Sumless counter machines

Quasi-acyclic distributed automata

Without loss of generality:

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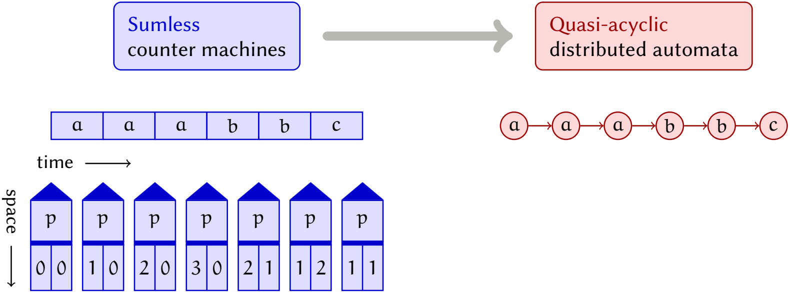

Sumless counter machines

Quasi-acyclic distributed automata

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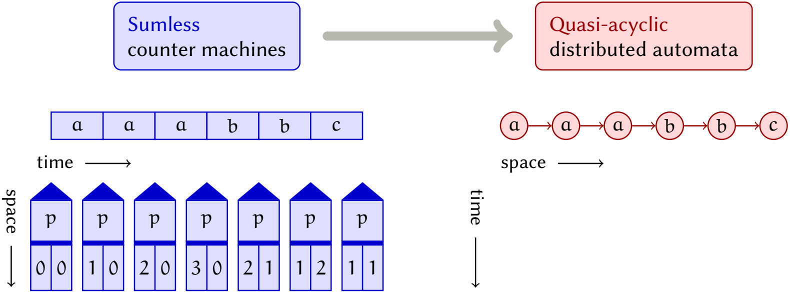

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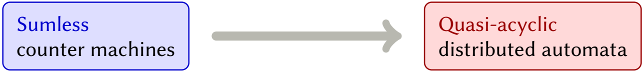

Sumless
counter machines

Quasi-acyclic
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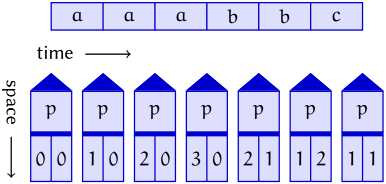

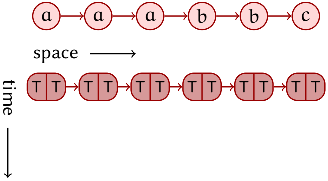

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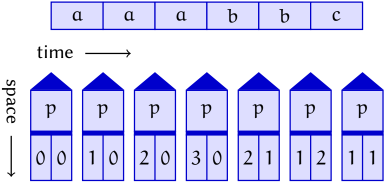
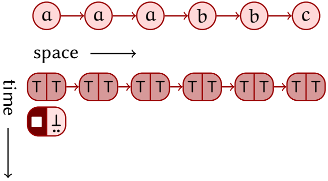
Sumless counter machines → Quasi-acyclic distributed automata





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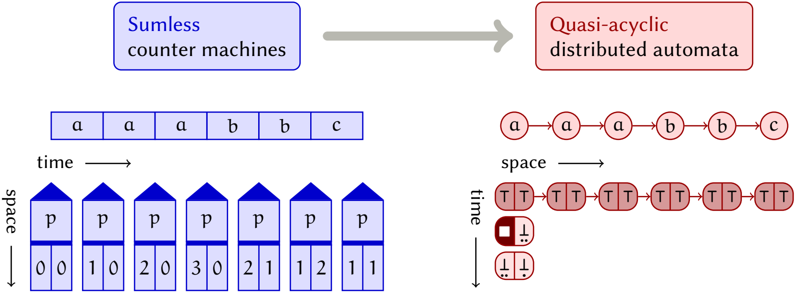

Sumless counter machines → Quasi-acyclic distributed automata

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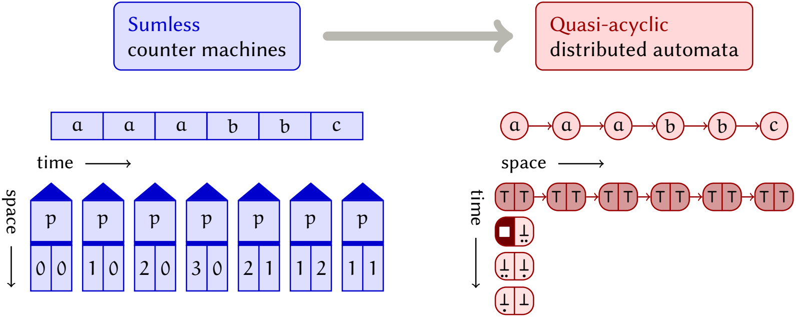

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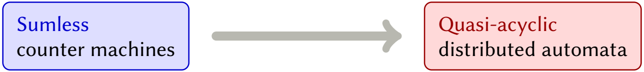
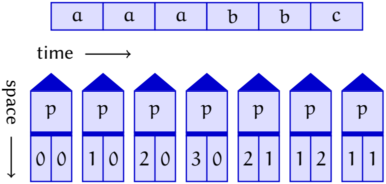
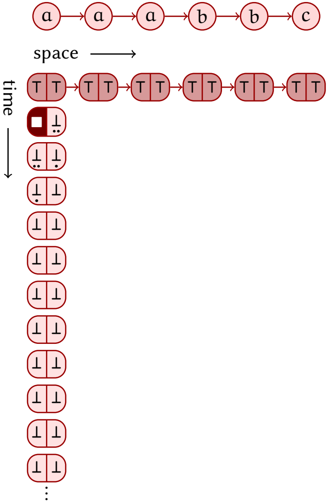


Sumless counter machines

Quasi-acyclic distributed automata





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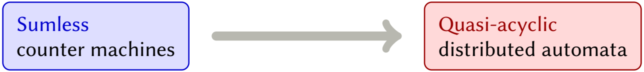
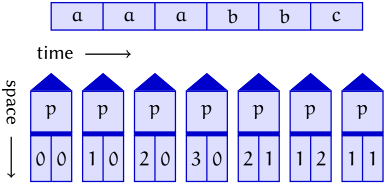
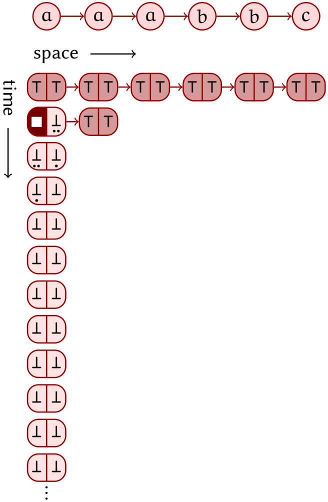

Sumless counter machines

Quasi-acyclic distributed automata





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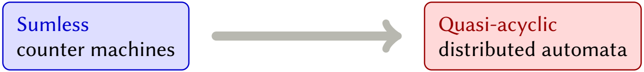
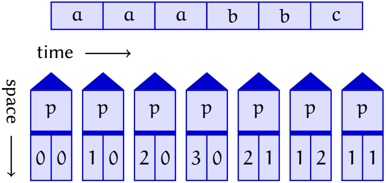
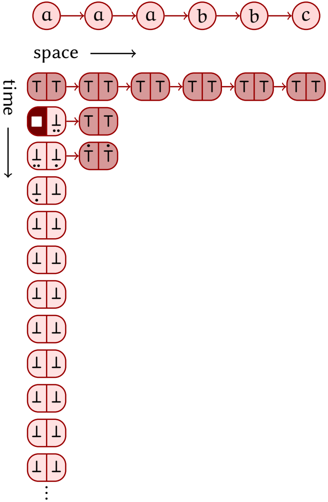


Sumless counter machines

Quasi-acyclic distributed automata





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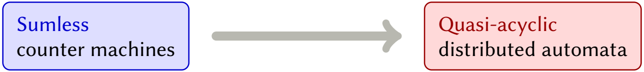
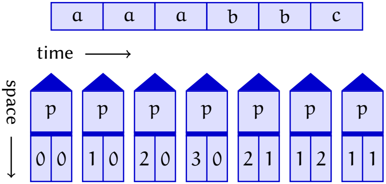
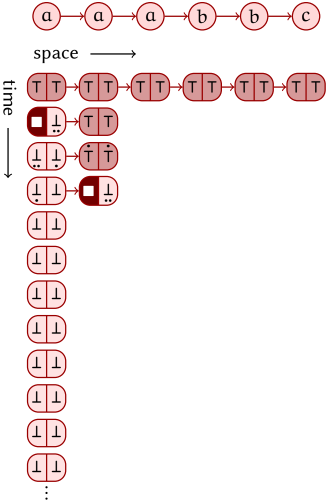


Sumless counter machines

Quasi-acyclic distributed automata





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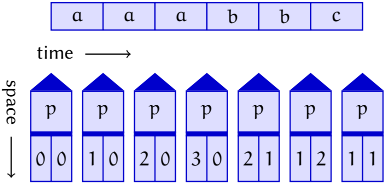
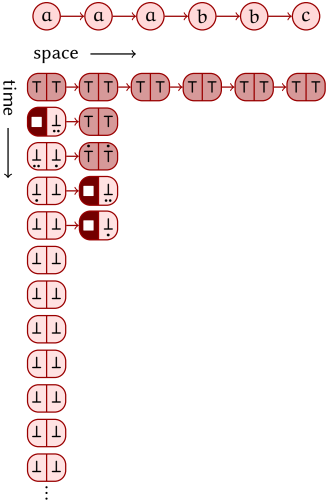
Using time as space

Sumless counter machines

Quasi-acyclic distributed automata





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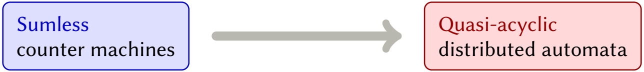

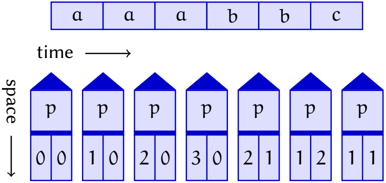

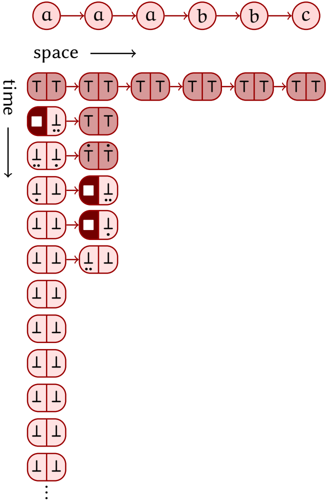

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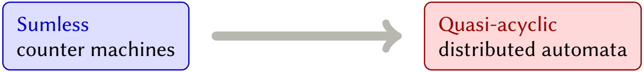
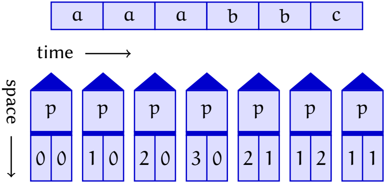
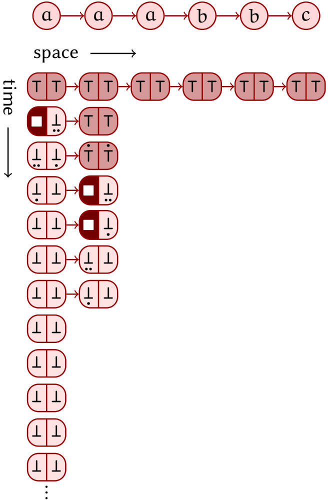


Sumless counter machines

Quasi-acyclic distributed automata





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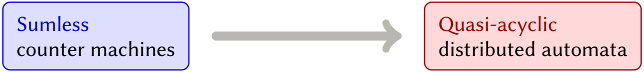
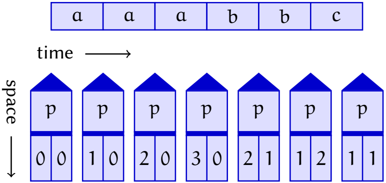
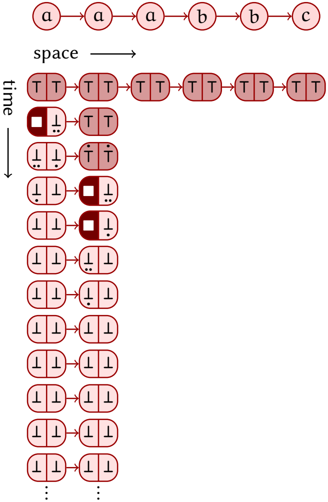


Sumless counter machines

Quasi-acyclic distributed automata





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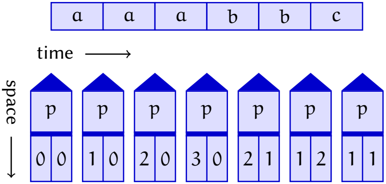
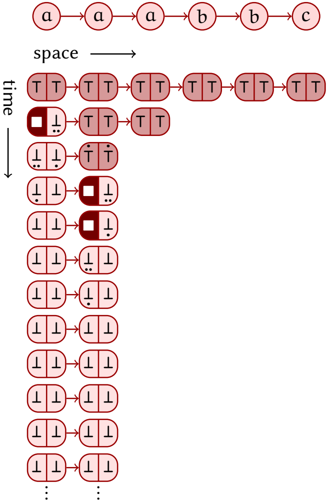
Using time as space

Sumless counter machines → Quasi-acyclic distributed automata





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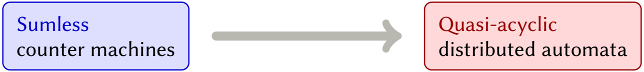

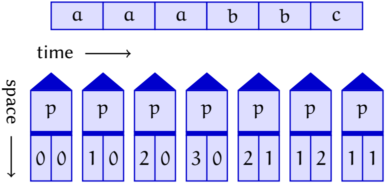

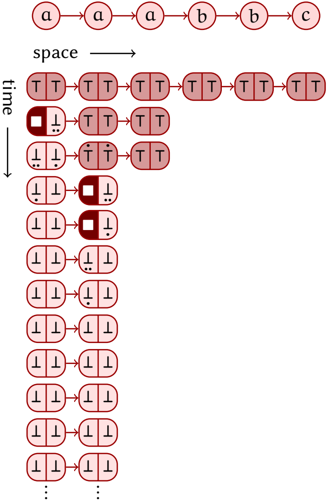

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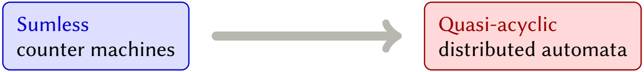

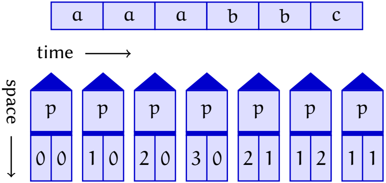

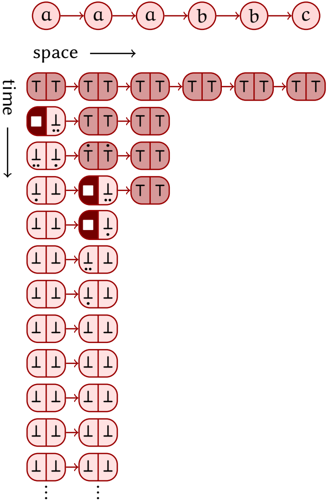

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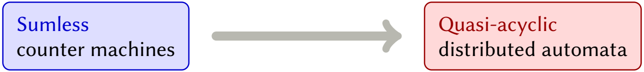

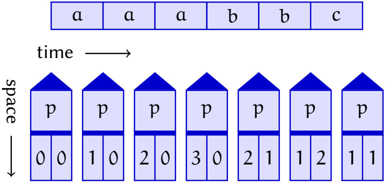

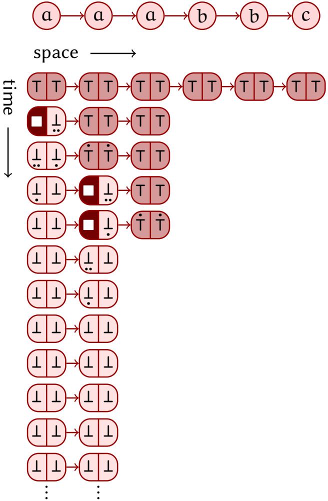

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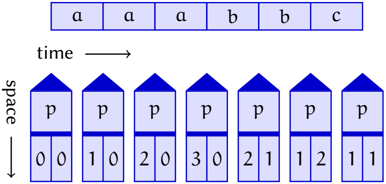
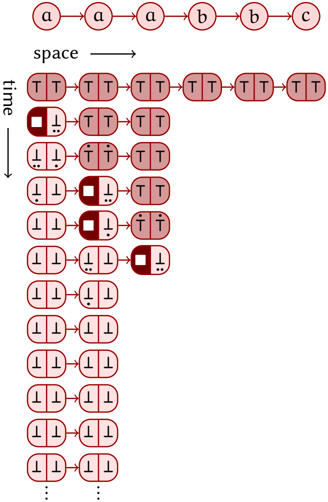
Using time as space

Sumless counter machines

Quasi-acyclic distributed automata





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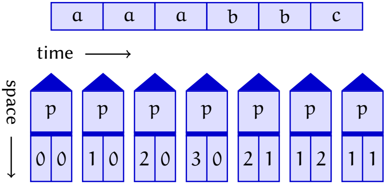
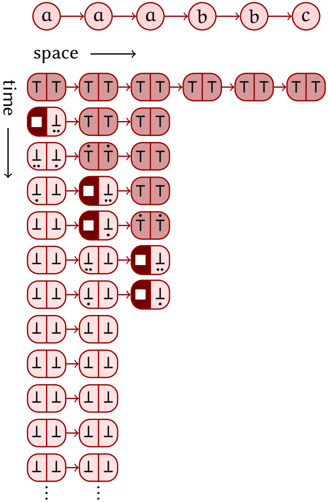
Sumless counter machines → Quasi-acyclic distributed automata





Without loss of generality:

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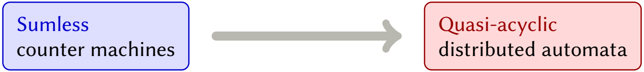
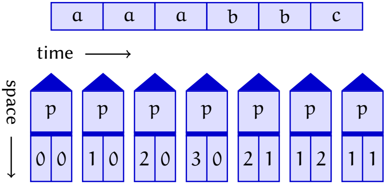
- Counters can only be tested for 0, incremented by $-1, 0, 1$, and copied.

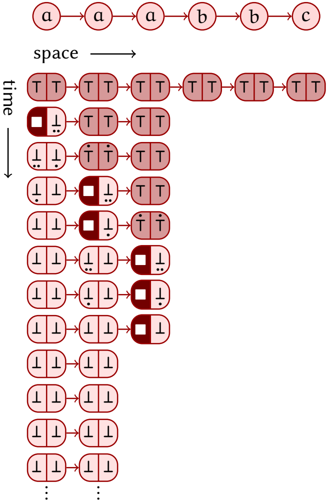
Using time as space



Sumless counter machines

Quasi-acyclic distributed automata





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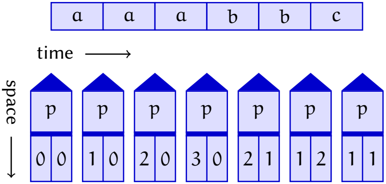
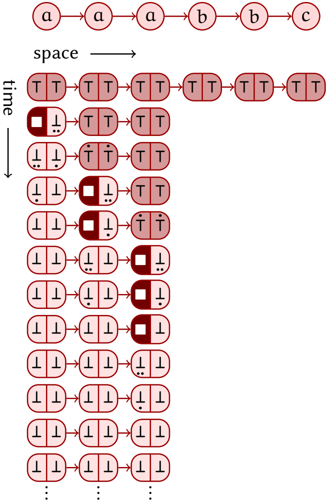
Using time as space

Sumless counter machines

Quasi-acyclic distributed automata





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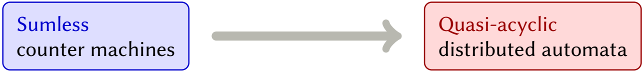
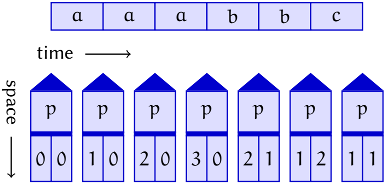
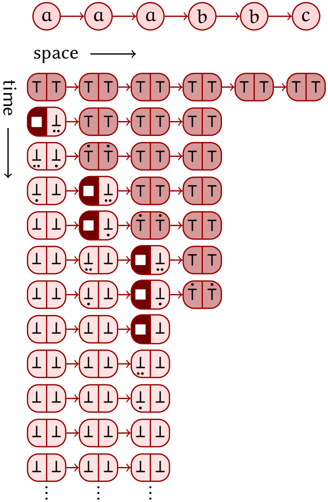


Sumless counter machines

Quasi-acyclic distributed automata





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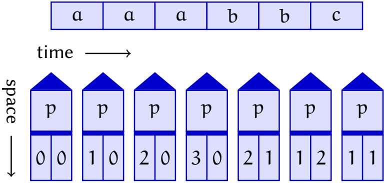
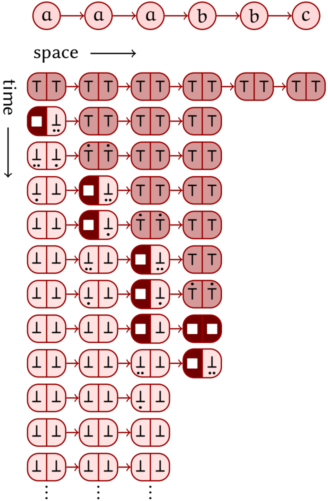
Using time as space

Sumless counter machines → Quasi-acyclic distributed automata





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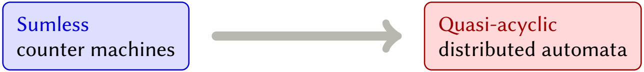

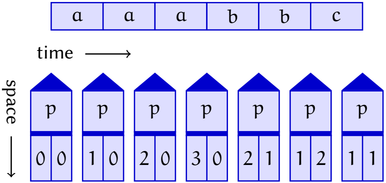

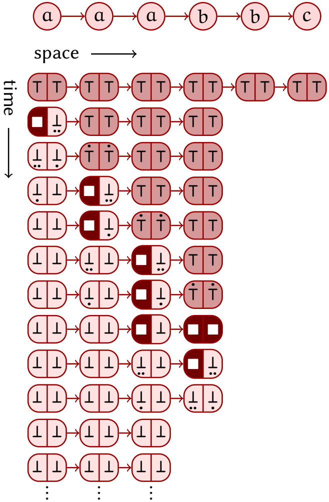

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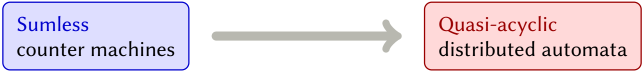
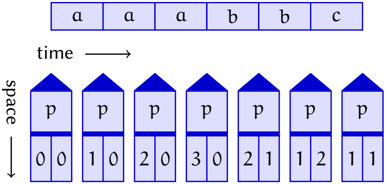
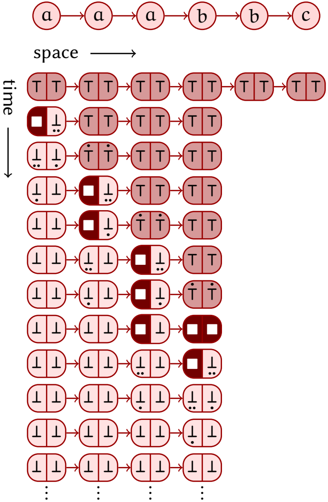


Sumless counter machines

Quasi-acyclic distributed automata





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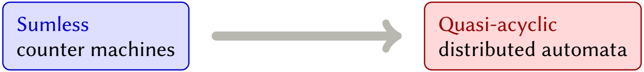
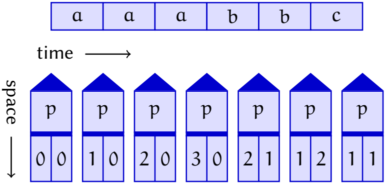
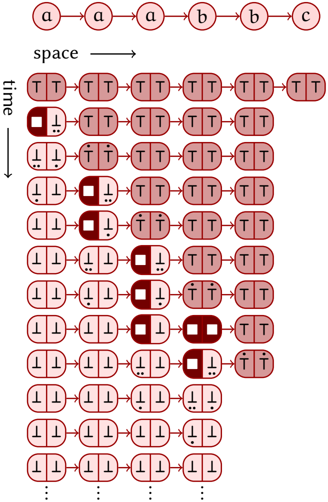

Sumless counter machines

Quasi-acyclic distributed automata





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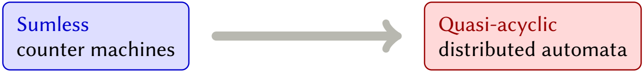
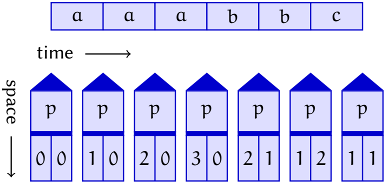
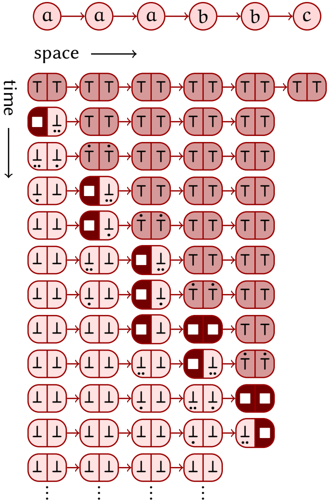


Sumless counter machines

Quasi-acyclic distributed automata





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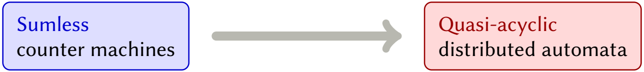
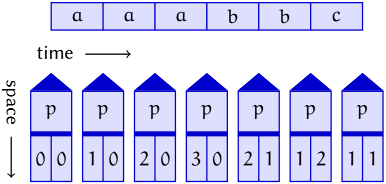
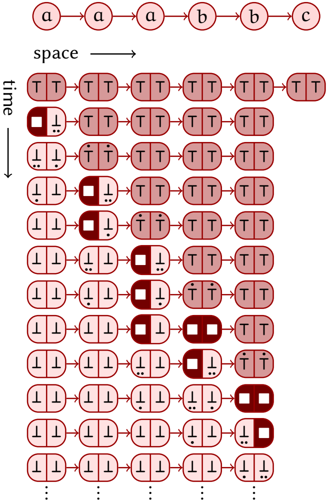


Sumless counter machines

Quasi-acyclic distributed automata





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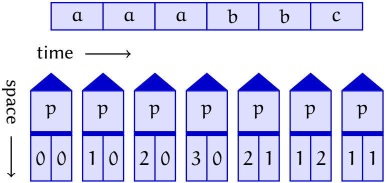
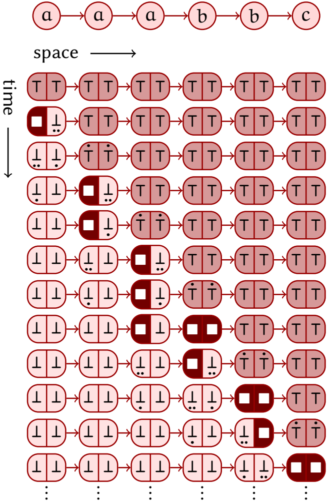
Using time as space

Sumless counter machines

Quasi-acyclic distributed automata





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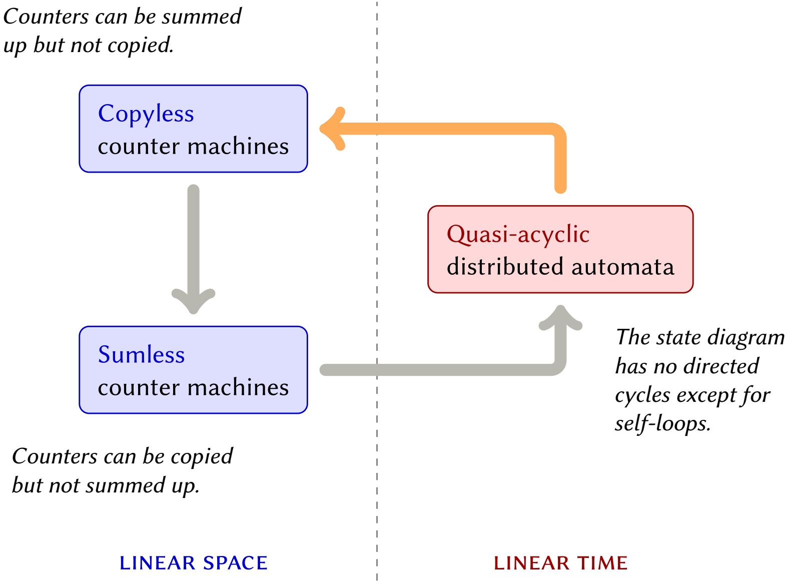
Our translations



Counters can be summed up but not copied.

Copyless counter machines

Sumless counter machines

Counters can be copied but not summed up.

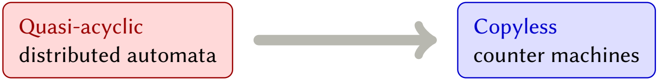
Quasi-acyclic distributed automata

The state diagram has no directed cycles except for self-loops.

LINEAR SPACE

LINEAR TIME

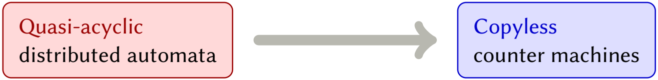
Using space as time



Quasi-acyclic
distributed automata

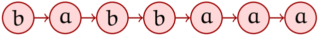
Copyless
counter machines

Using space as time

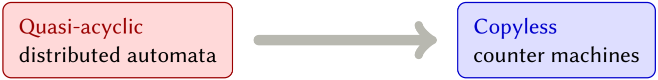


Quasi-acyclic distributed automata

Copyless counter machines

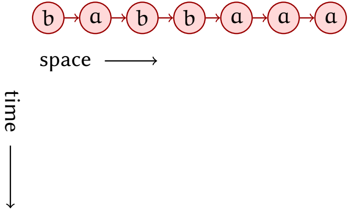


Using space as time



Quasi-acyclic distributed automata

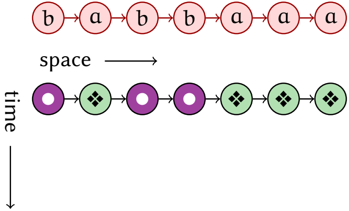
Copyless counter machines



Using space as time

Quasi-acyclic distributed automata

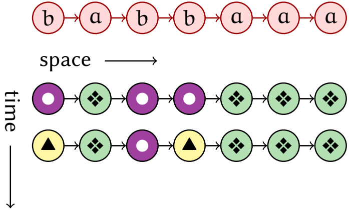
Copyless counter machines



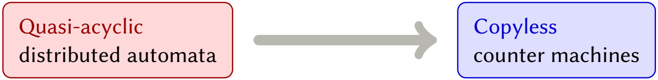
Using space as time

Quasi-acyclic distributed automata

Copyless counter machines

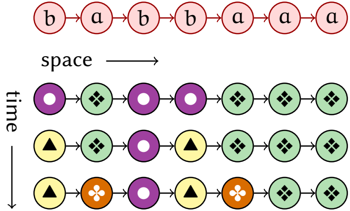


Using space as time



Quasi-acyclic distributed automata

Copyless counter machines



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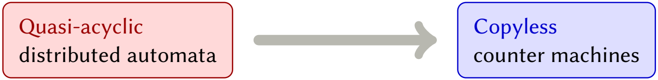
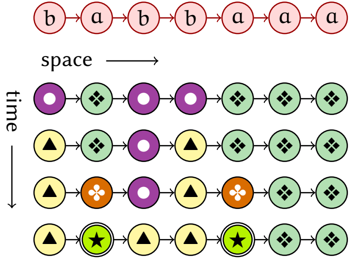


Quasi-acyclic distributed automata

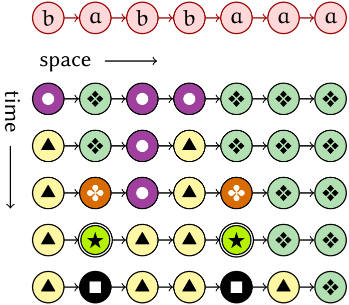
Copyless counter machines



Using space as time

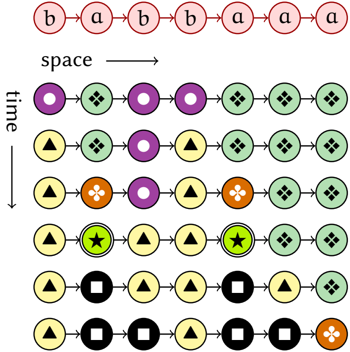
Quasi-acyclic distributed automata

Copyless counter machines

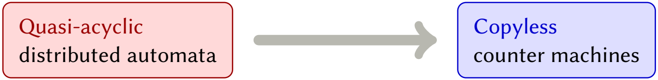


Using space as time

Quasi-acyclic distributed automata → Copyless counter machines

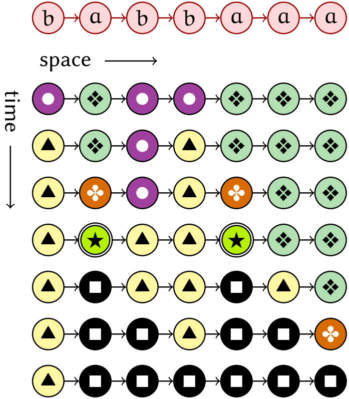


Using space as time



Quasi-acyclic distributed automata

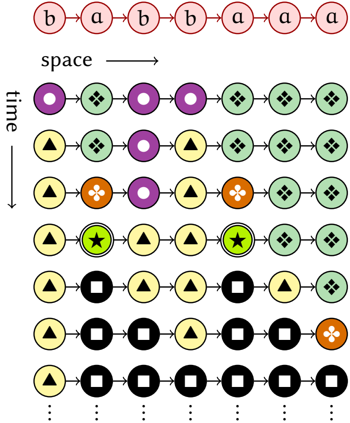
Copyless counter machines



Using space as time

Quasi-acyclic distributed automata

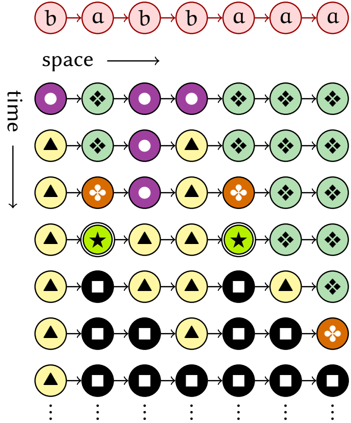
Copyless counter machines



Using space as time

Quasi-acyclic distributed automata

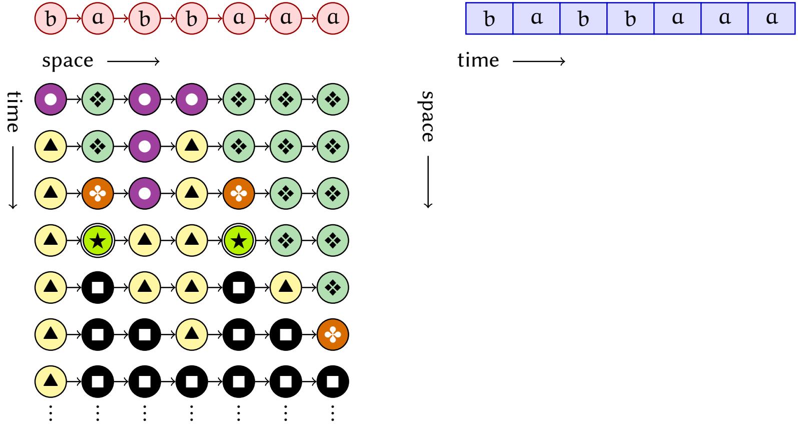
Copyless counter machines



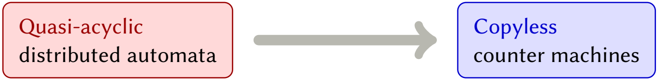
b	a	b	b	a	a	a

Using space as time

Quasi-acyclic distributed automata → Copyless counter machines

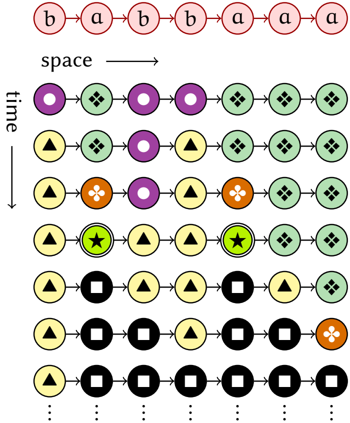


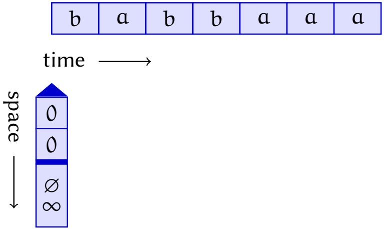
Using space as time



Quasi-acyclic distributed automata

Copyless counter machines



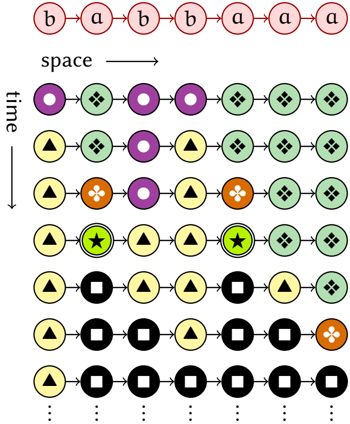


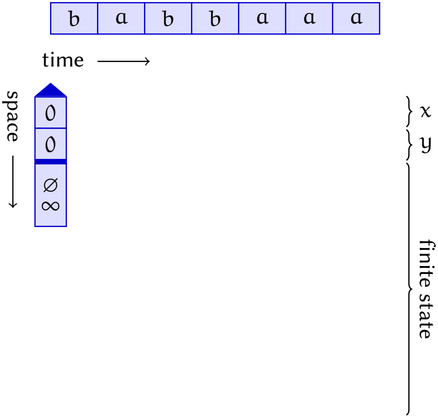
Using space as time

Quasi-acyclic
distributed automata

→

Copyless
counter machines





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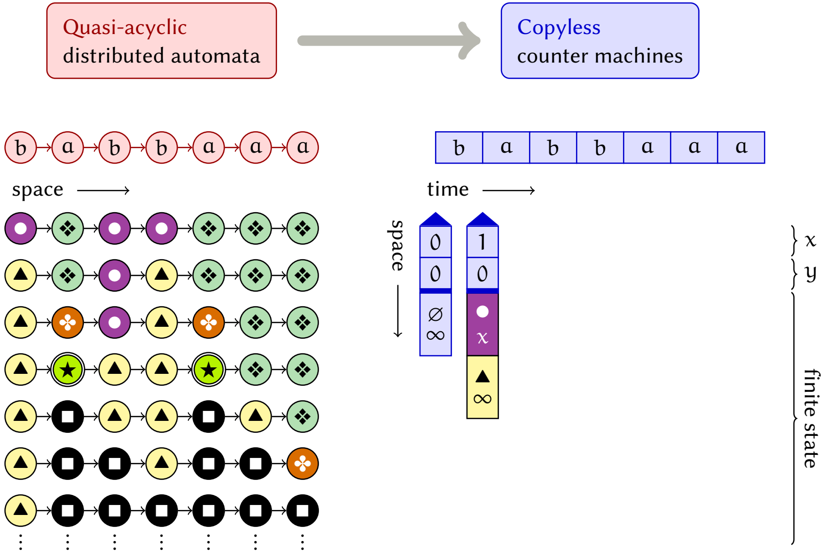
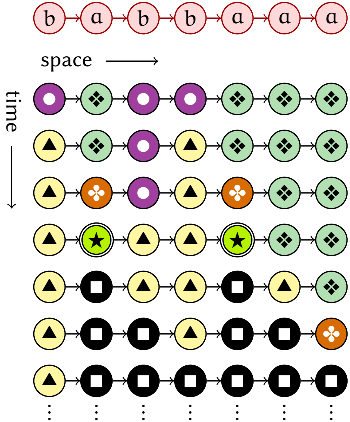
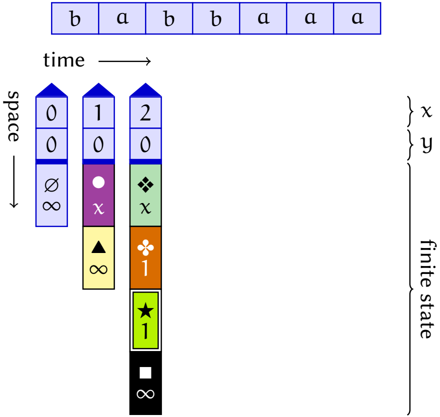


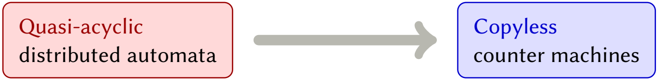
Using space as time

Quasi-acyclic distributed automata → Copyless counter machines

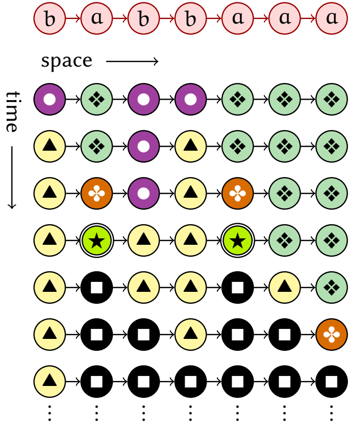


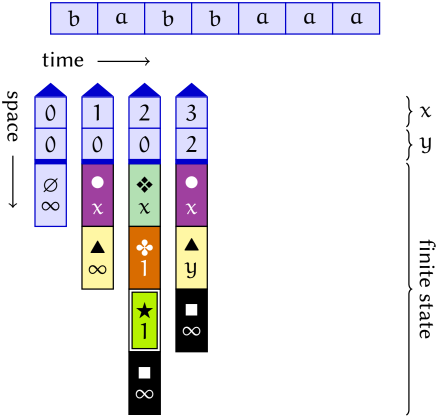


Using space as time


Quasi-acyclic distributed automata

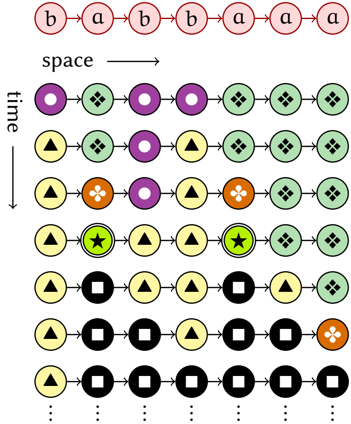
Copyless counter machines

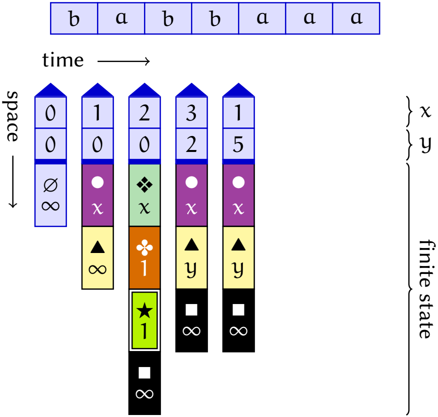




Using space as time

Quasi-acyclic distributed automata → Copyless counter machines

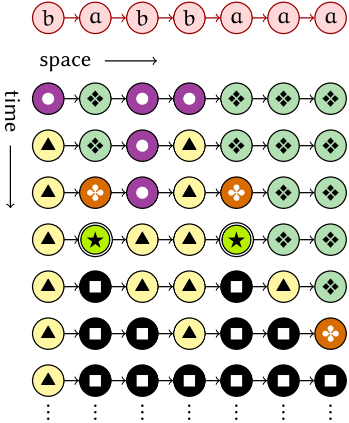


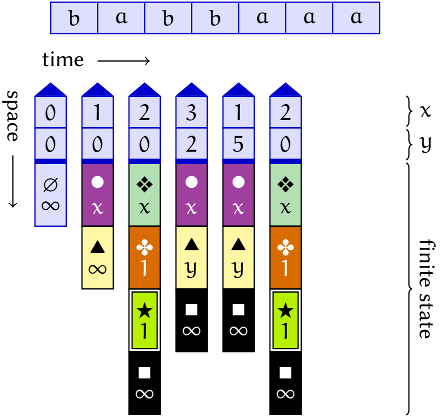


Using space as time

Quasi-acyclic distributed automata

Copyless counter machines

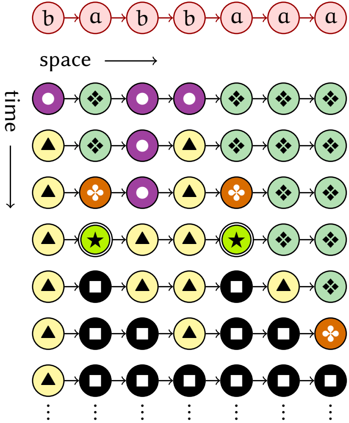


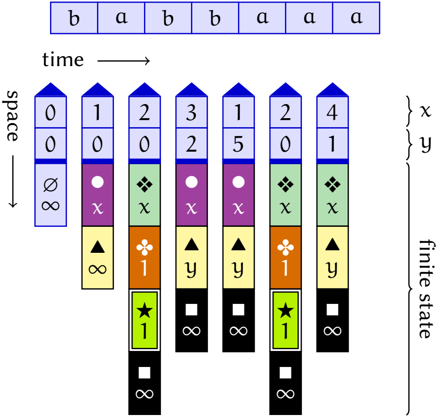


Using space as time

Quasi-acyclic distributed automata

Copyless counter machines

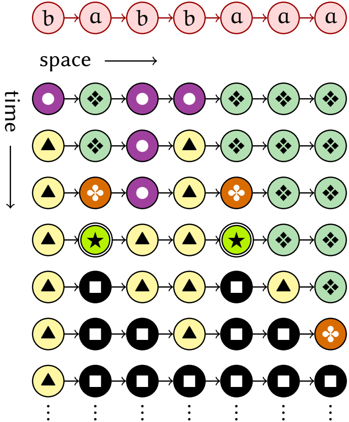


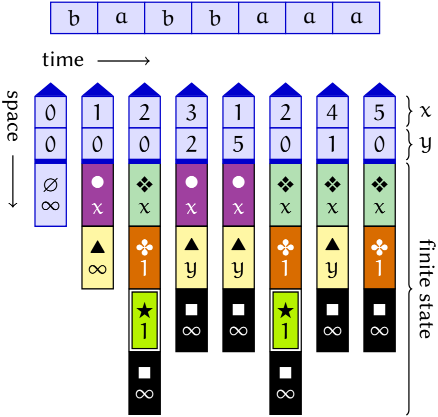


Using space as time

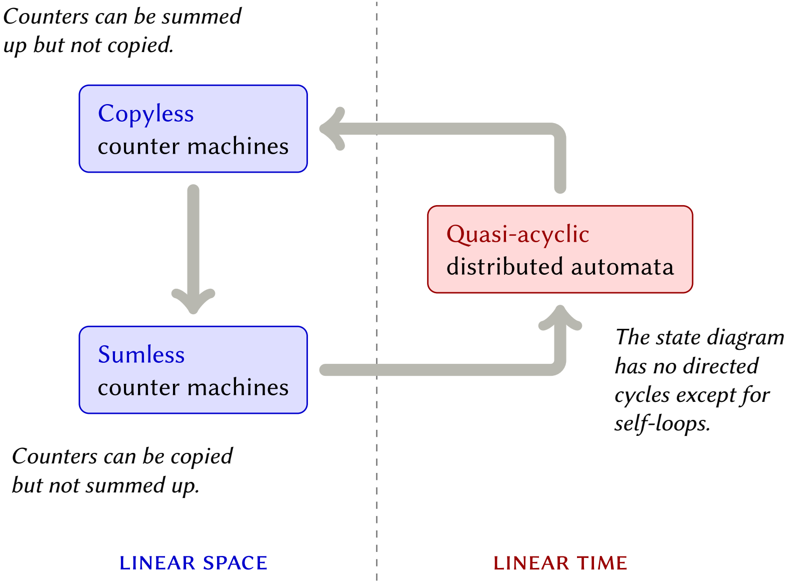
Quasi-acyclic distributed automata

Copyless counter machines





Our translations



Counters can be summed up but not copied.

Copyless counter machines

Sumless counter machines

Counters can be copied but not summed up.

Quasi-acyclic distributed automata

The state diagram has no directed cycles except for self-loops.

LINEAR SPACE

LINEAR TIME

Possible future work

Possible future work

RESTRICTION:

- Counter machines that are both copyless and sumless.

Possible future work

RESTRICTION:

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Thanks!