Loosely Time-Triggered Architectures: Improvements and Comparisons

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Timothy Bourke

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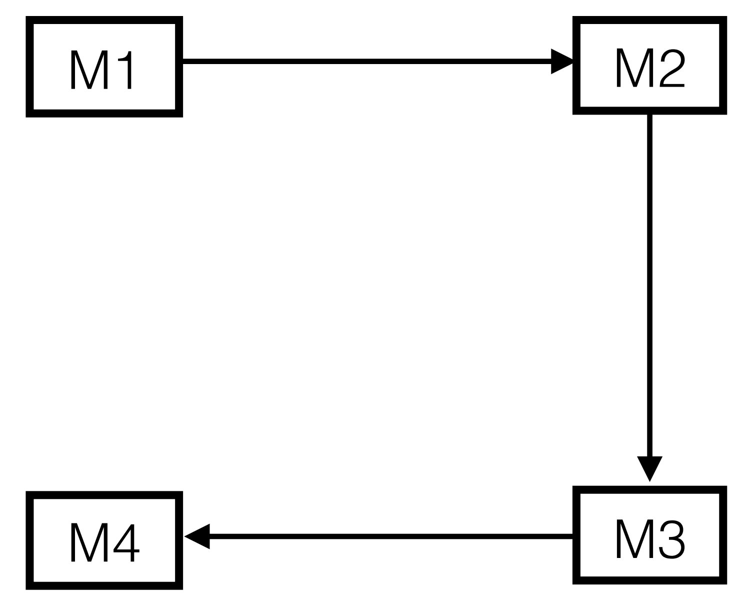
Synchronous Applications…

Composition of Communicating Mealy Machines

- Each machine is characterized by
  - an initial state S_{init}
  - a transition function $F \;:\; \mathcal{S} \times \mathcal{V}^I \rightarrow \mathcal{S} \times \mathcal{V}^O$
- Machines communicate through unit delays.



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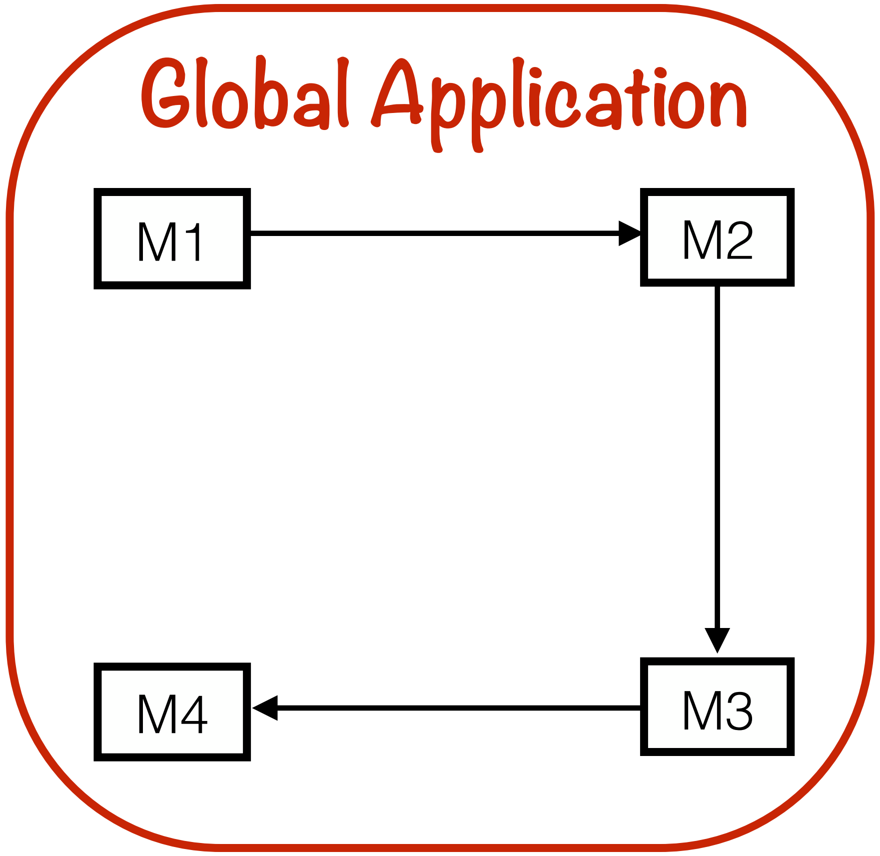

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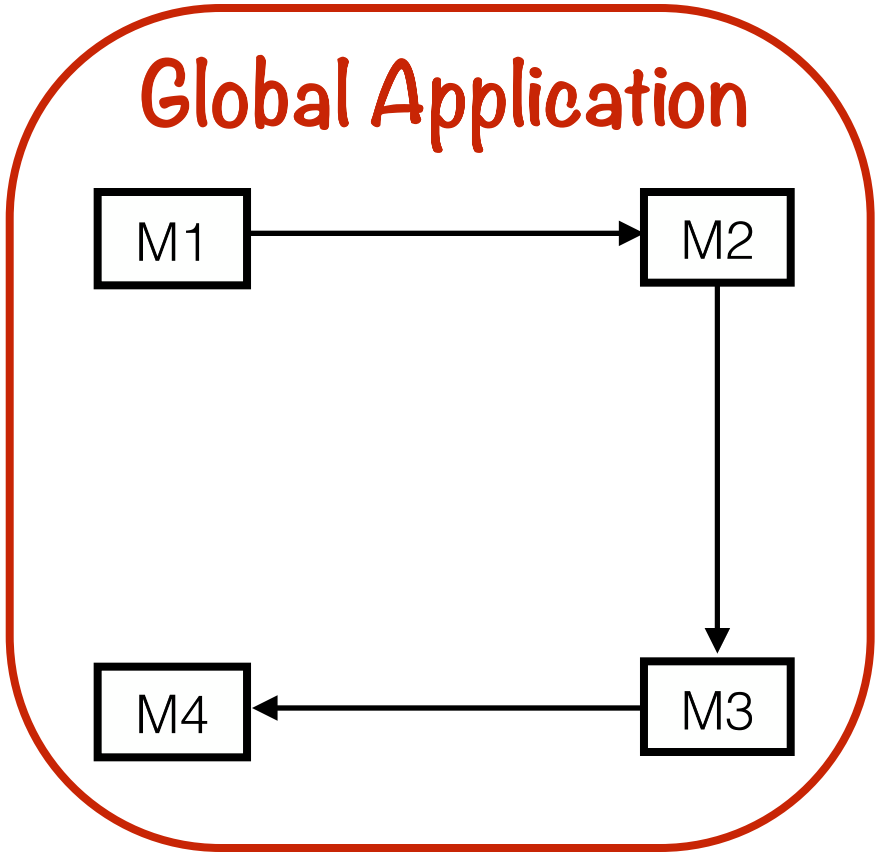

Composition forms a global synchronous application.
Semantics: Sequence of values on each variable

...on Quasi-Periodic Architecture

- A set of "quasi-periodic" processes with local clocks and nominal period T^n (jitter ε)

$$0 < T_{\min} \leq T^n \leq T_{\max} \quad \text{or}$$

$$T^n - \varepsilon \leq \kappa_i - \kappa_{i-1} \leq T^n + \varepsilon$$

$(\kappa_i)_{i \in \mathbb{N}}$ clock activations

- Buffered communication without message inversion or loss

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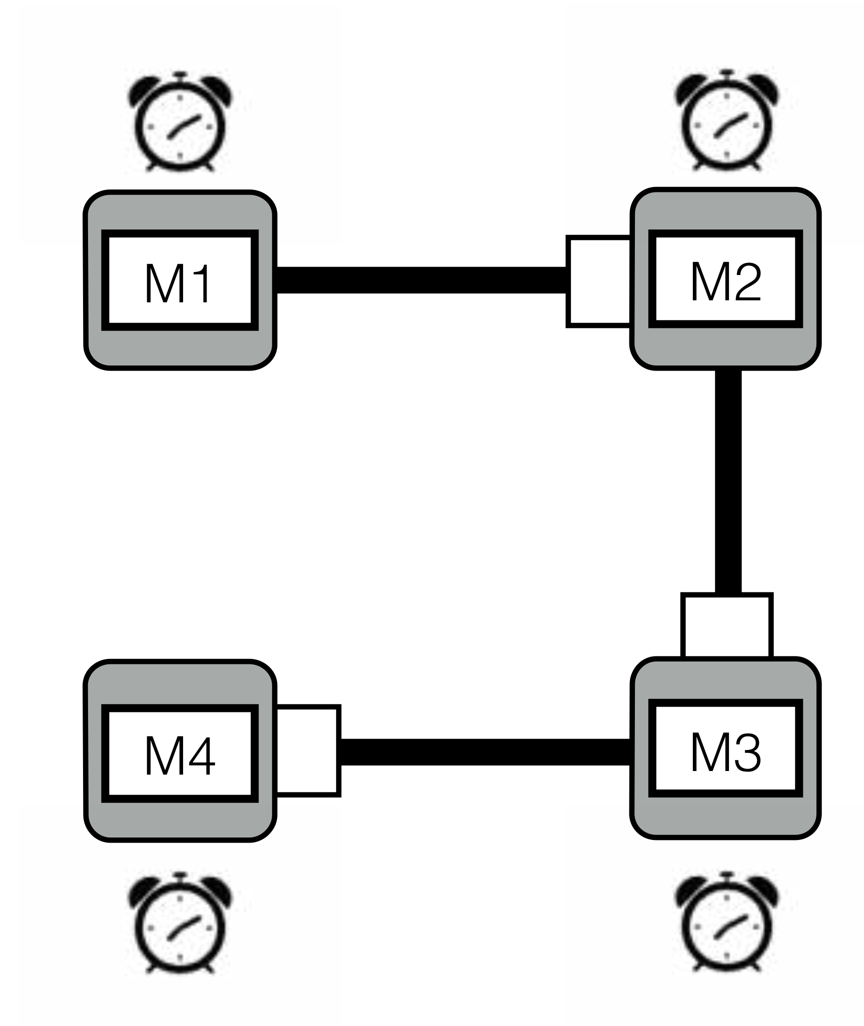

"Cooking Book" [Caspi 2000]

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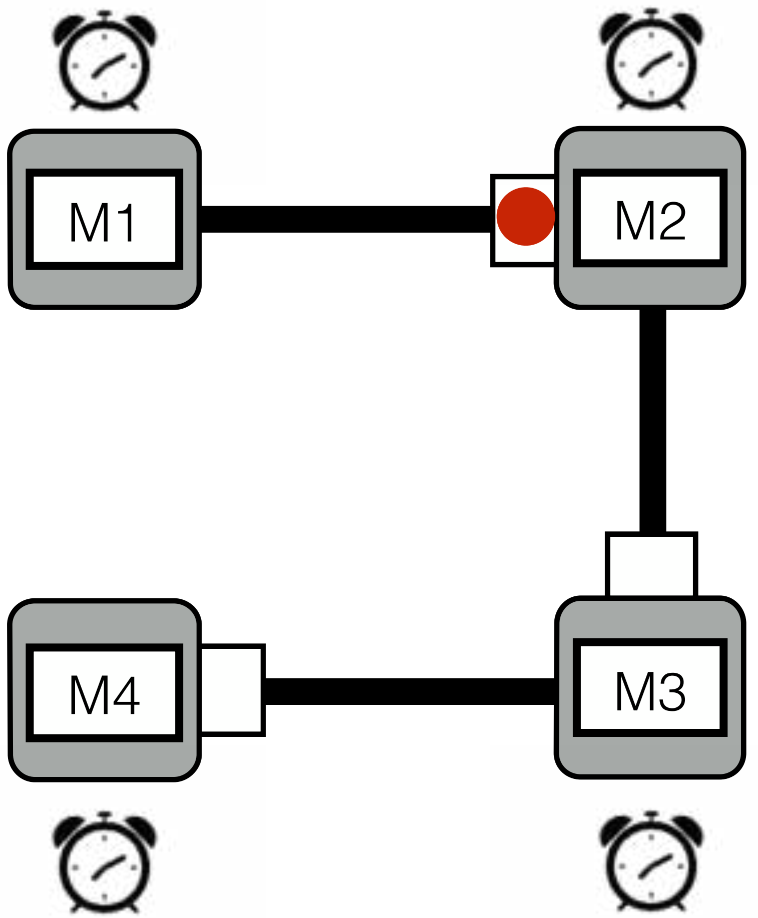

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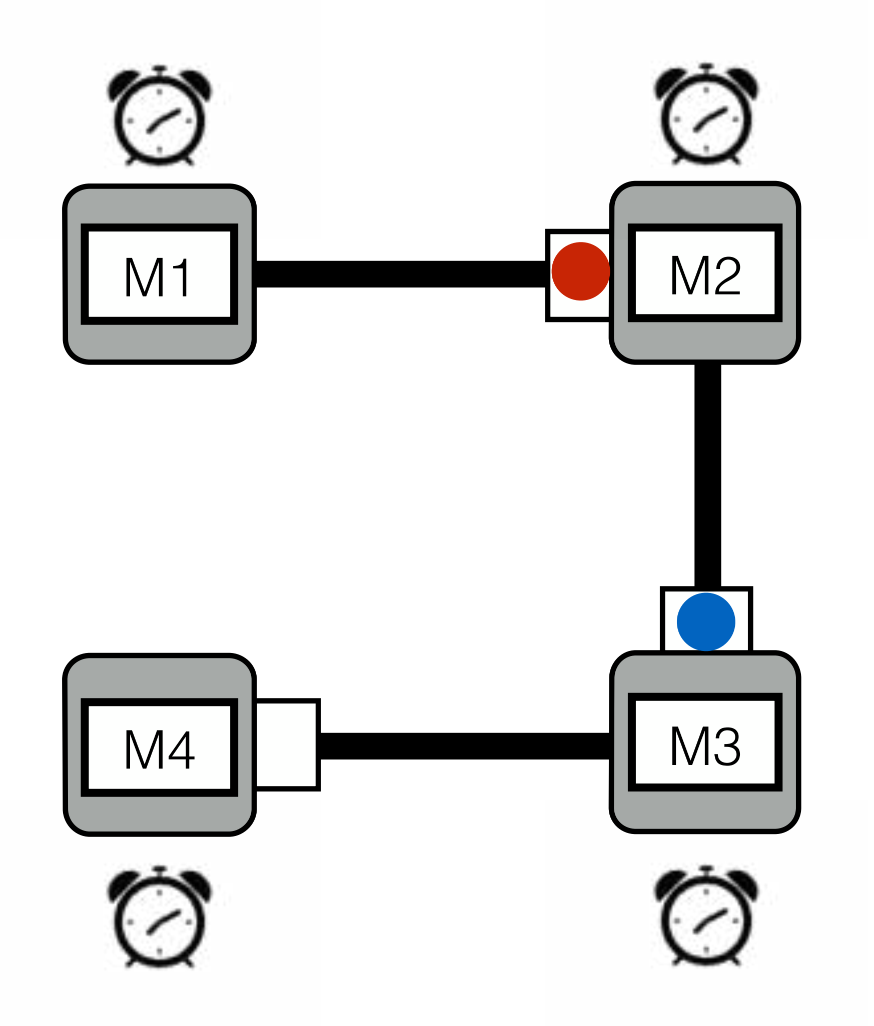

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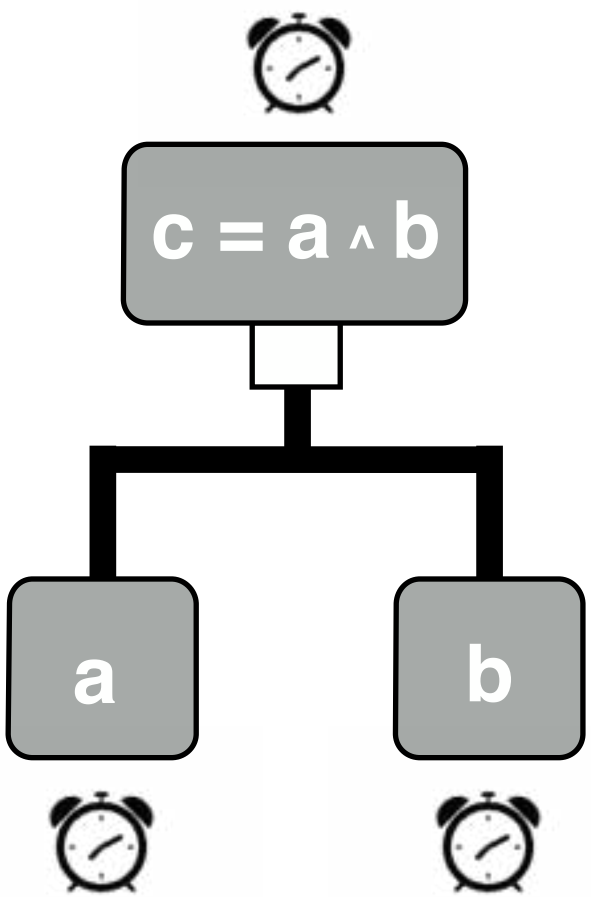
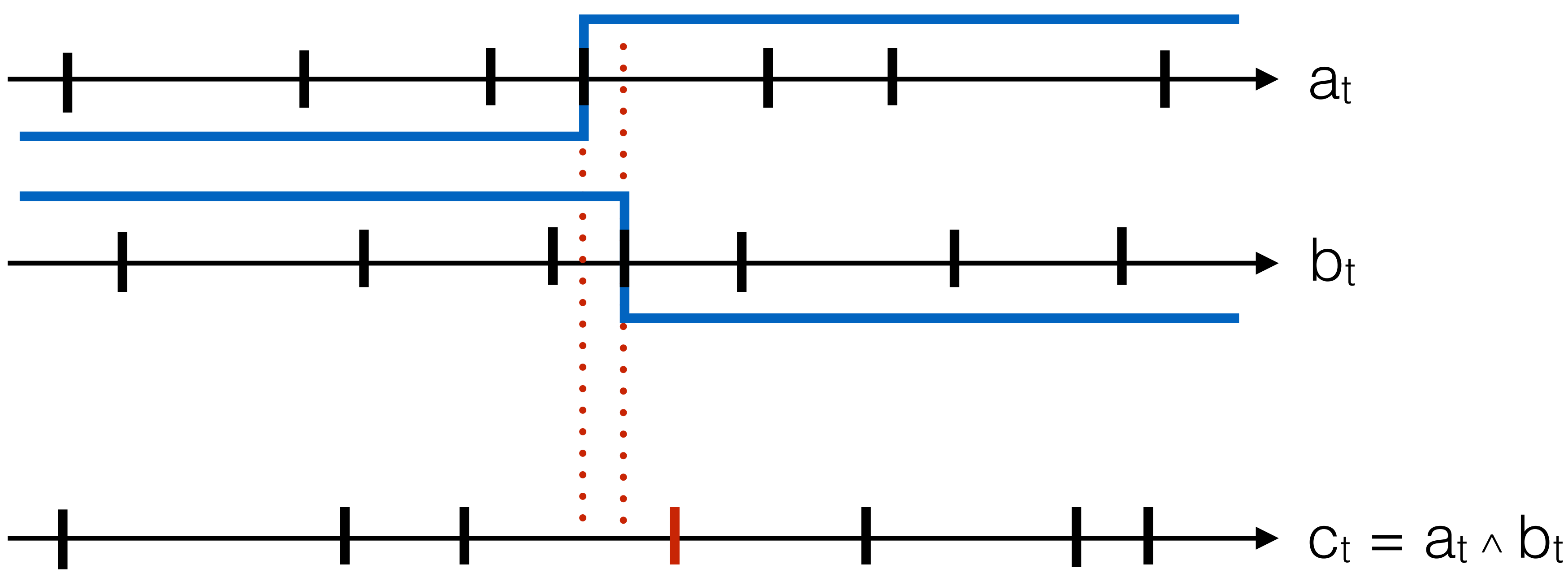
Sampling Artifacts

- **Overwriting:** Loss of values
- **Oversampling:** Duplication of values
- **Combination of signals**





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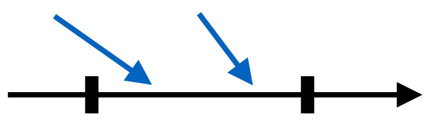

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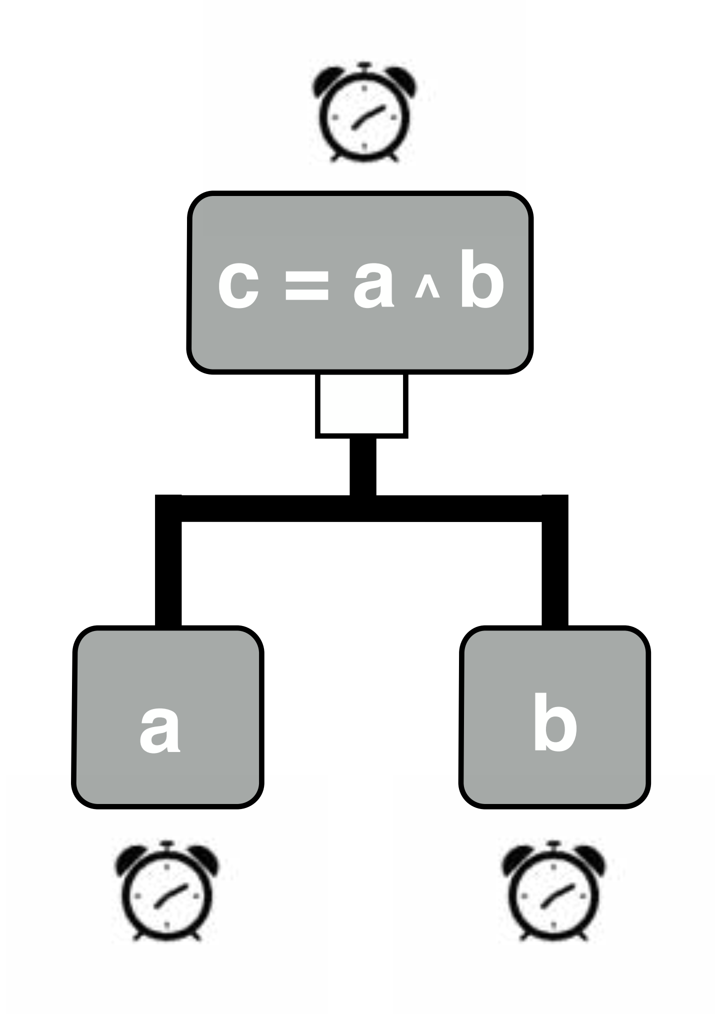

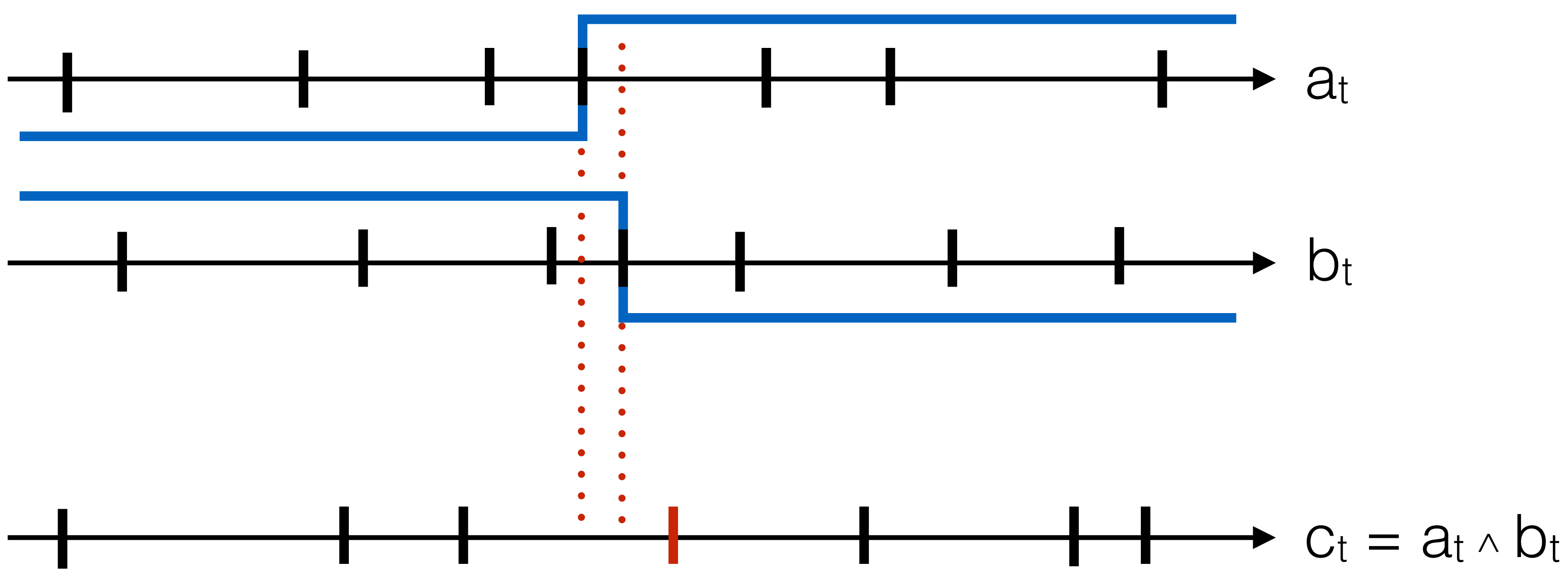

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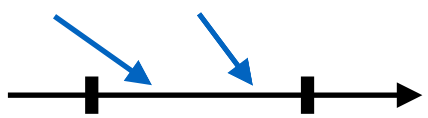

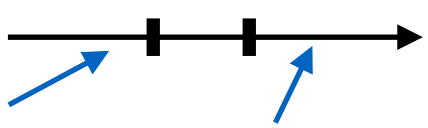

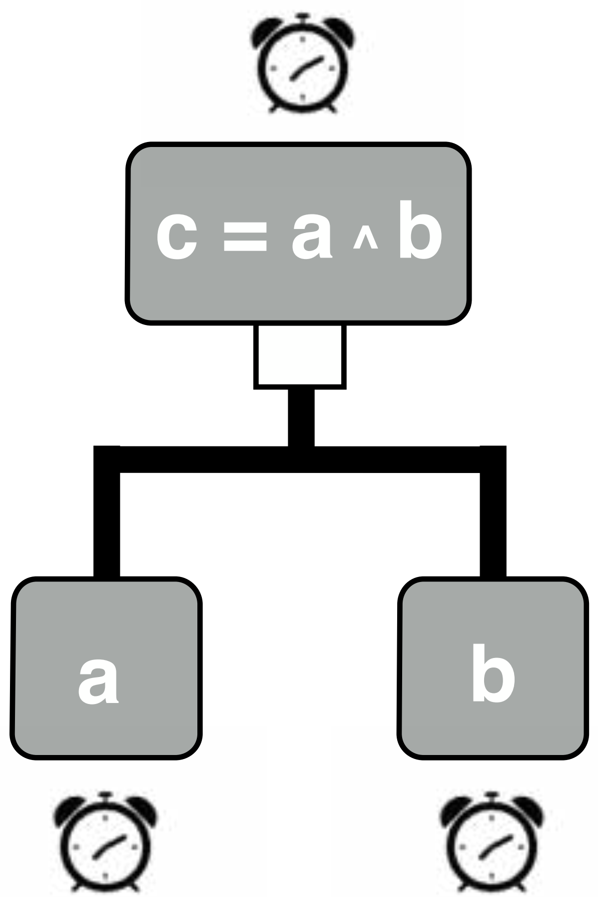

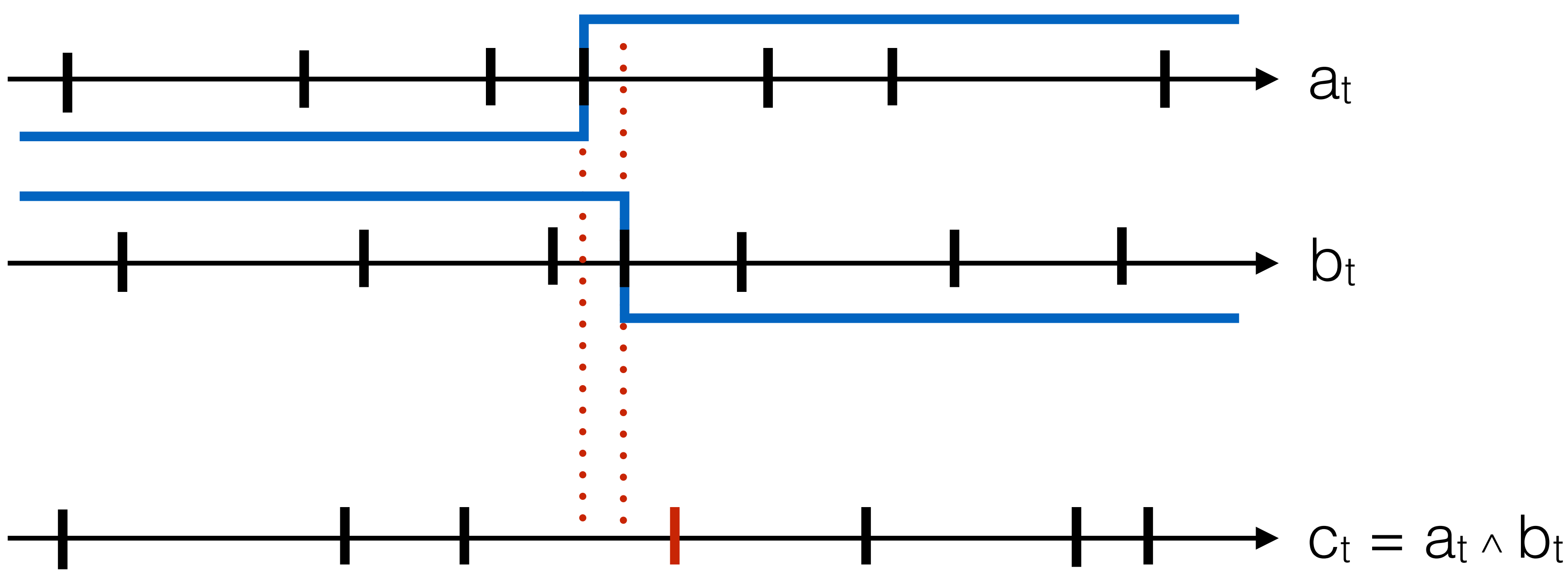

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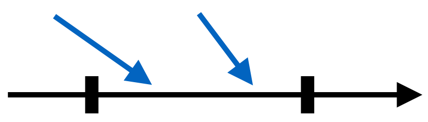

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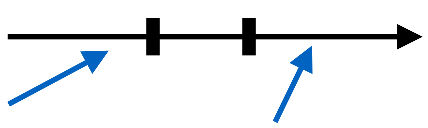

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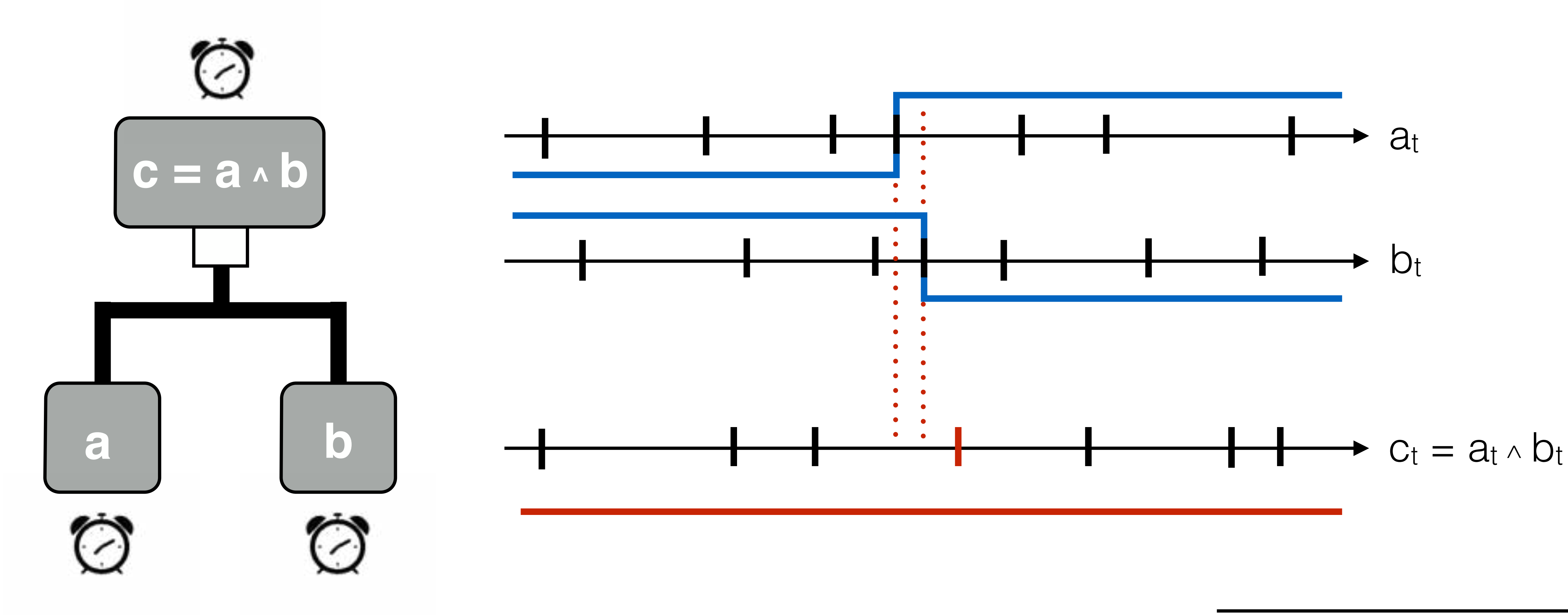

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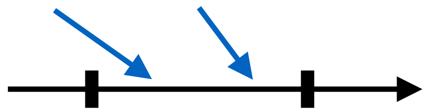

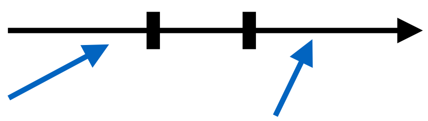

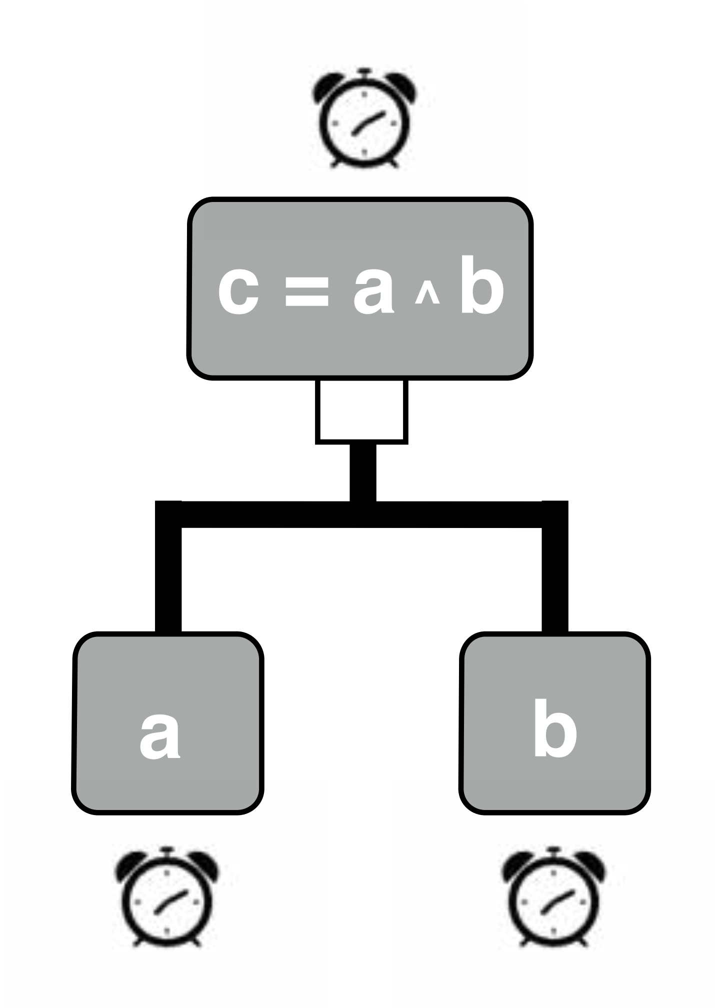

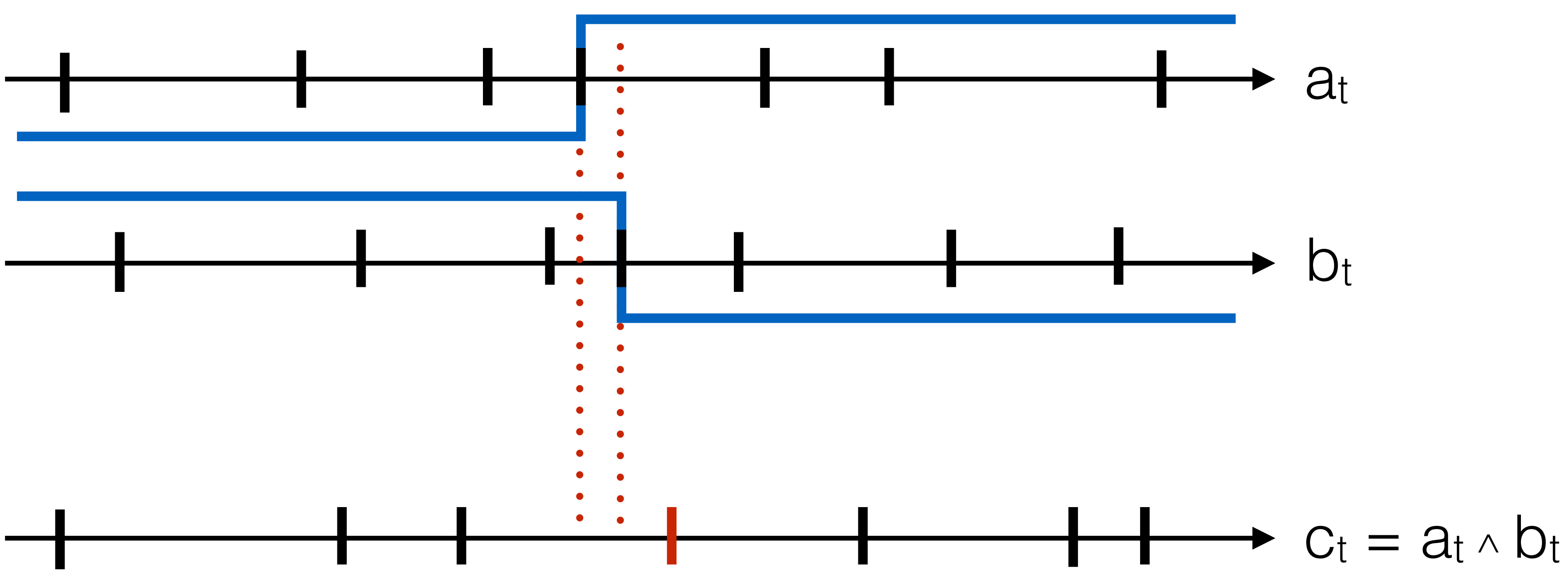

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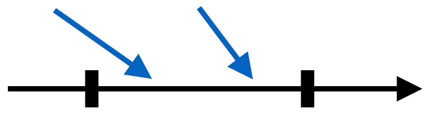

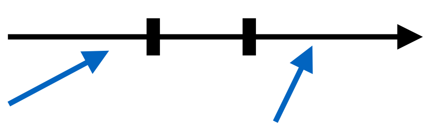

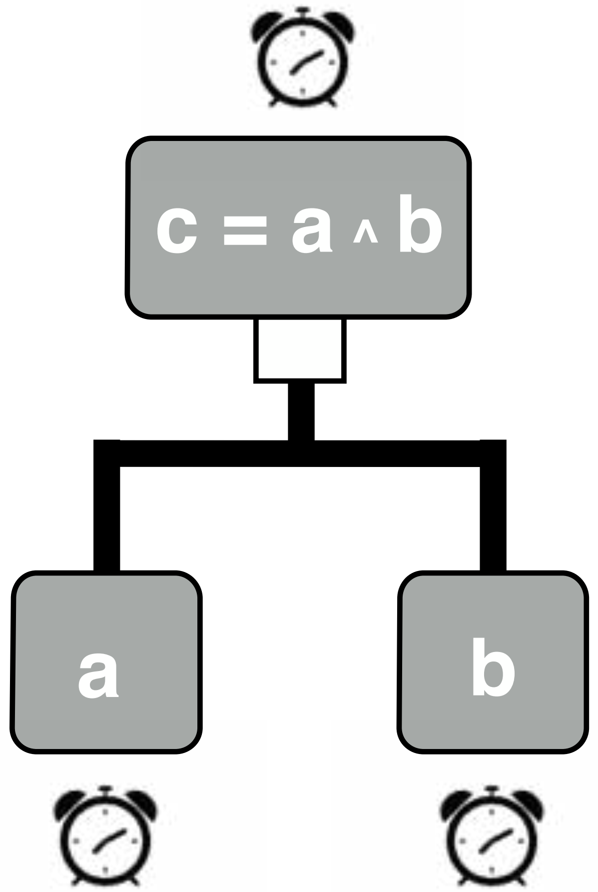

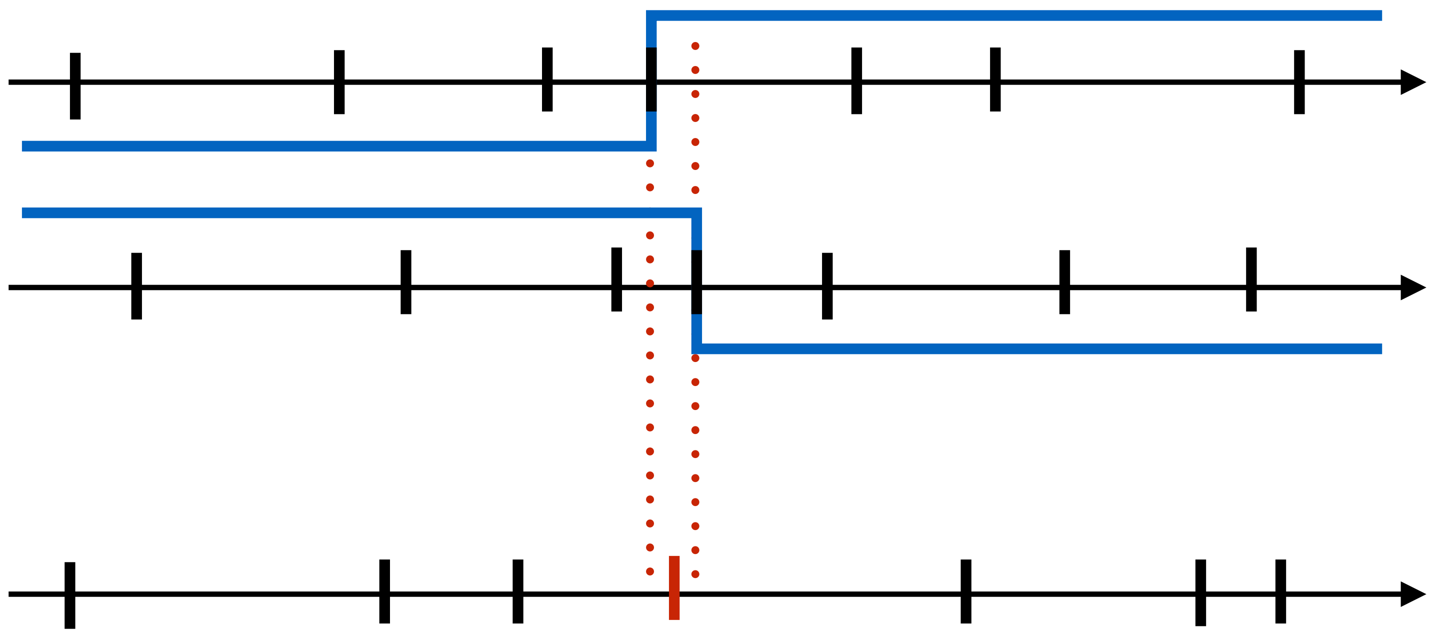

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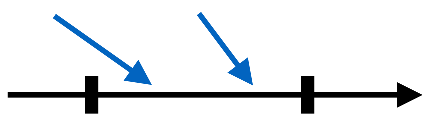

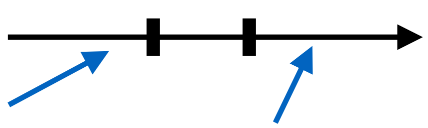

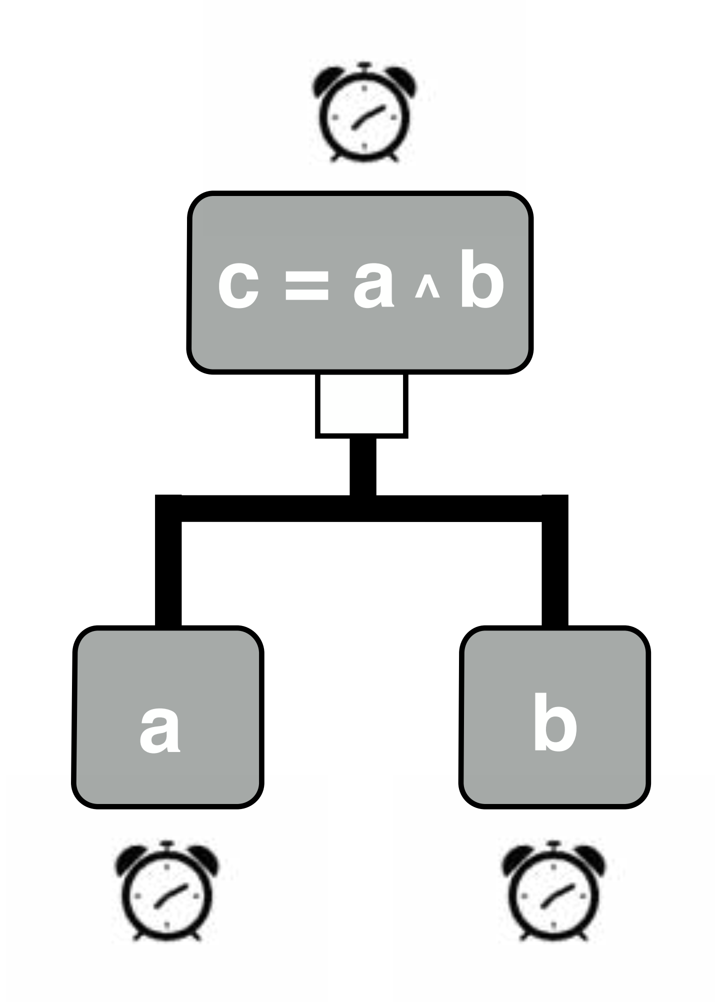

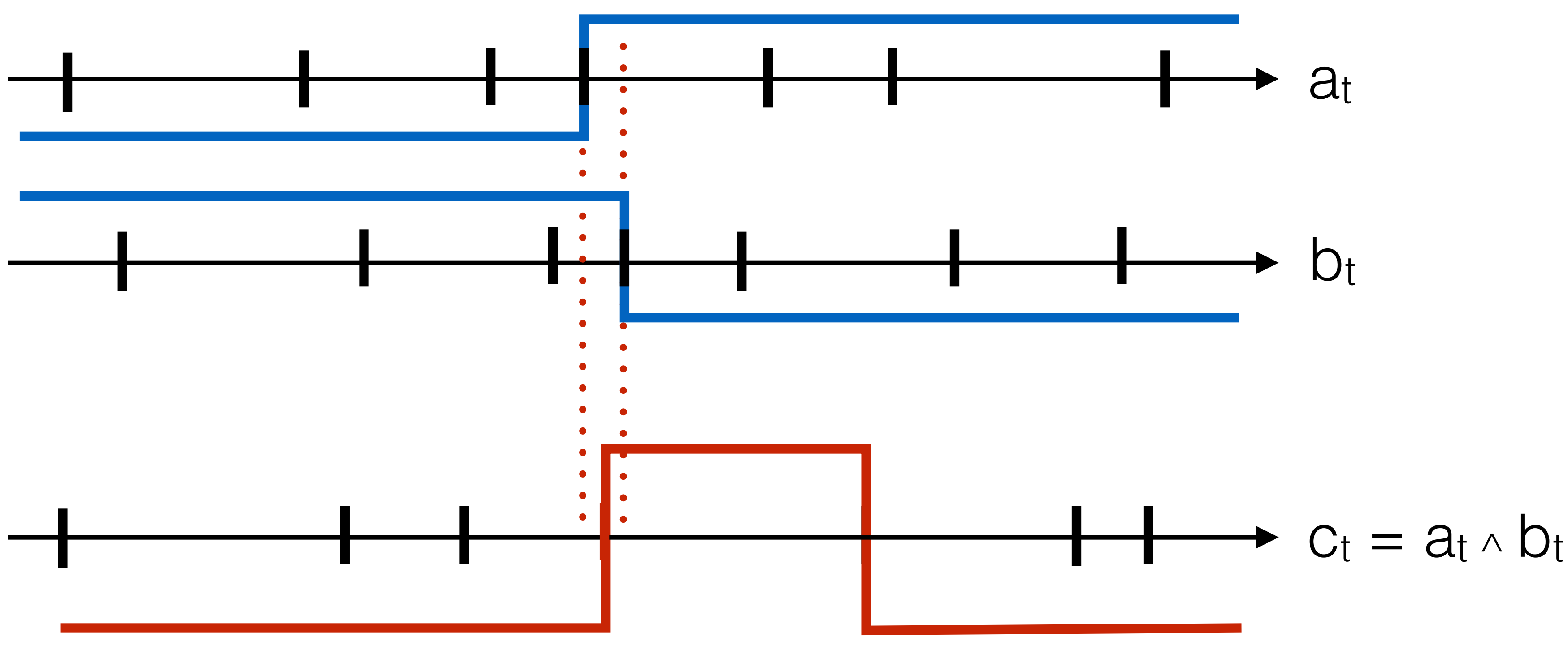

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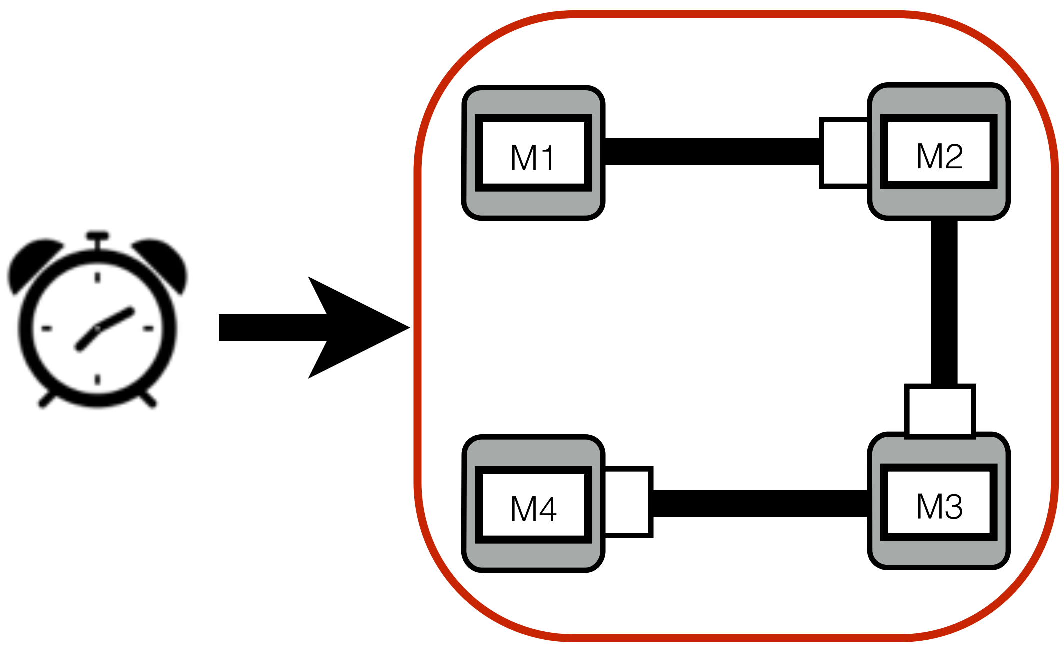
Clock synchronization

e.g. TTA [Kopetz, Bauer 2003]



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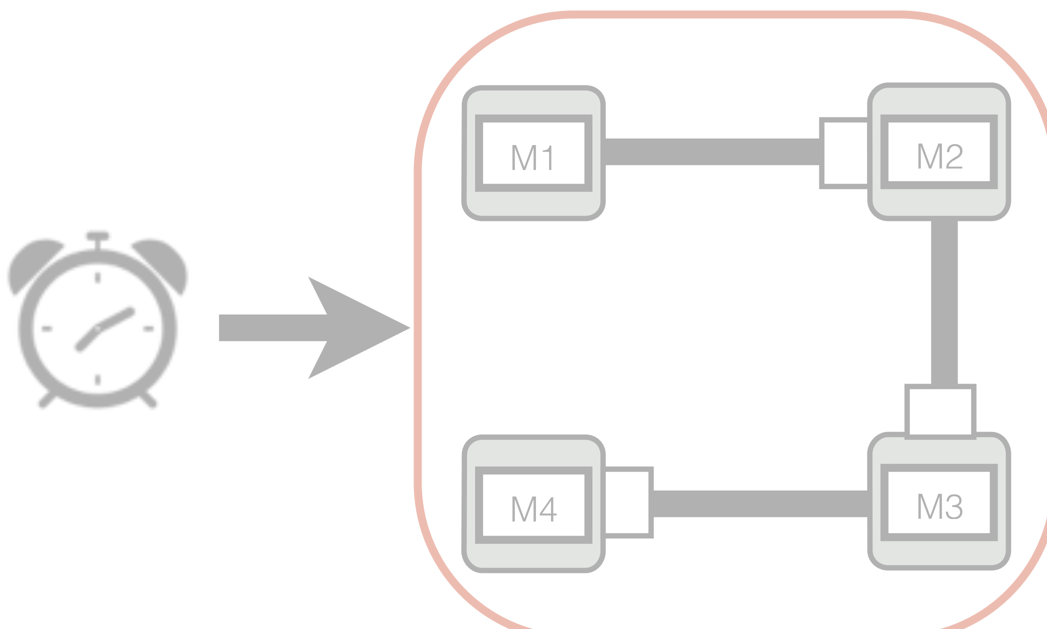

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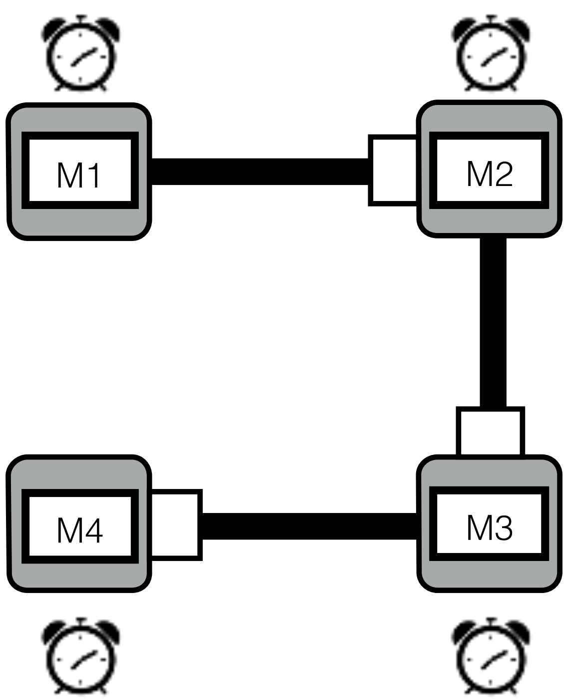
Unsynchronized nodes + Middleware = LTTA

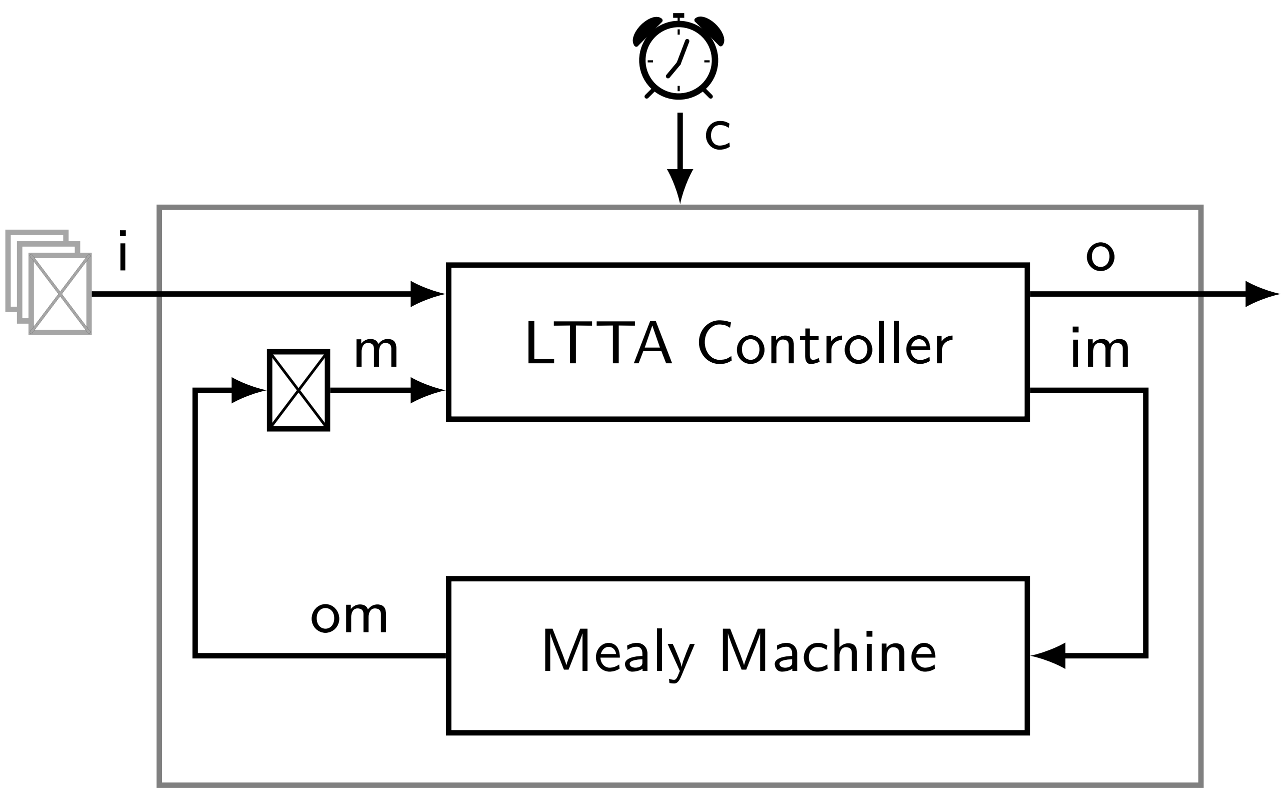


Are they a good idea?

A Synchronous Framework

Everything can be expressed as a **Zélus** program

- discrete control (application and controllers)
- continuous time (architecture)



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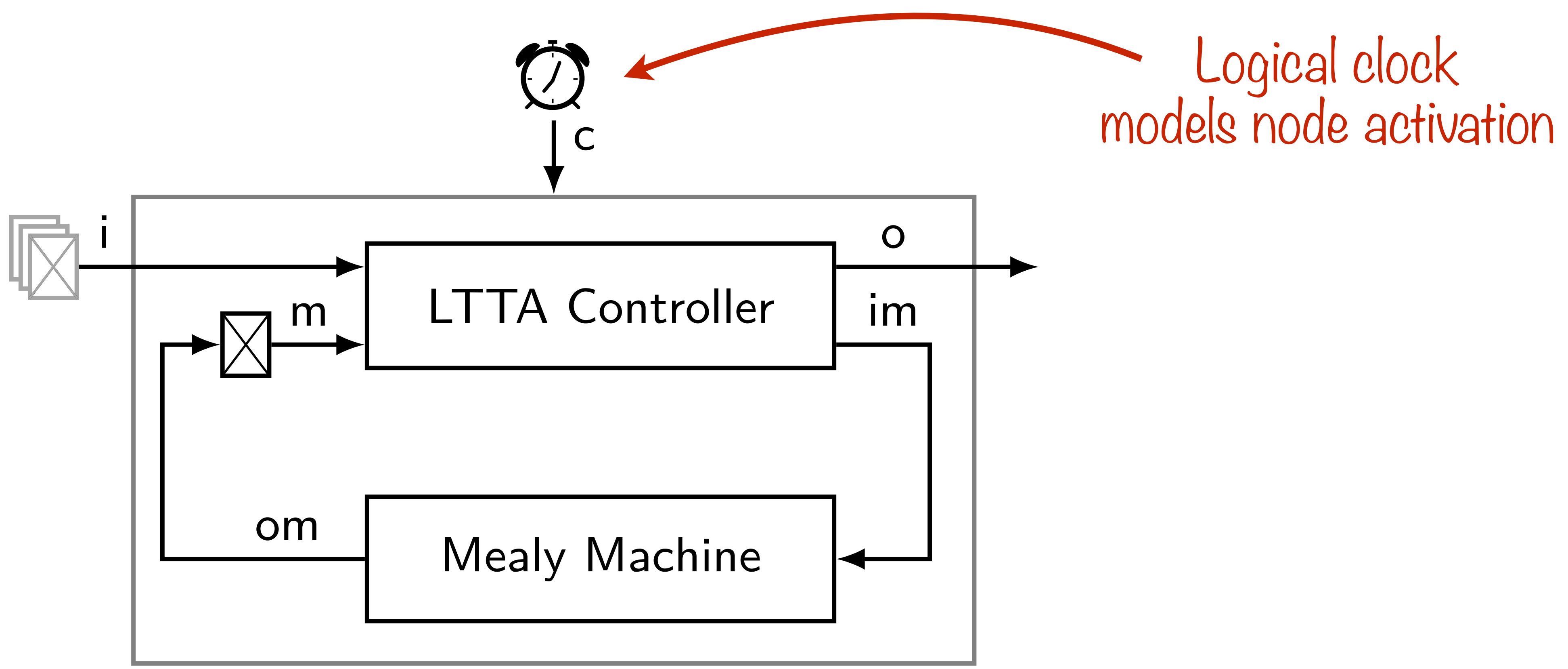

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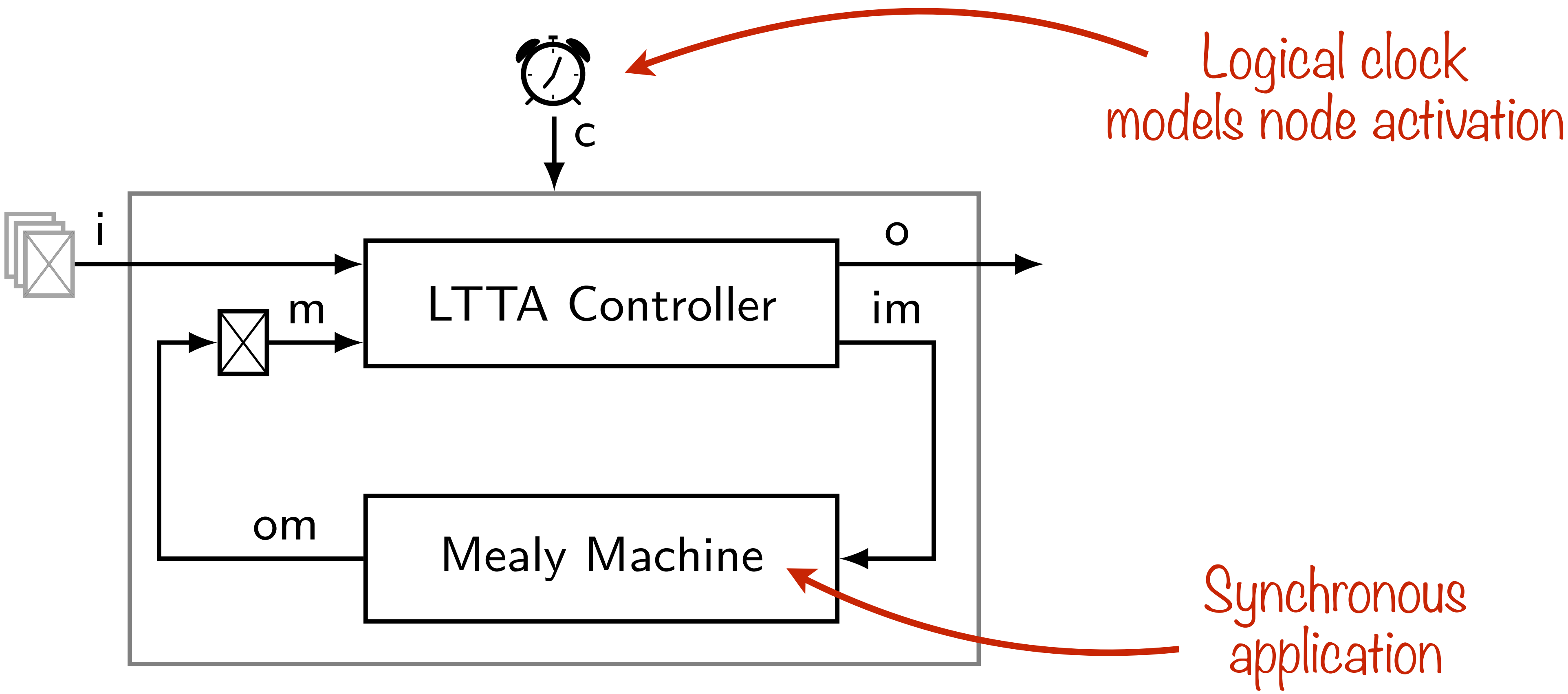

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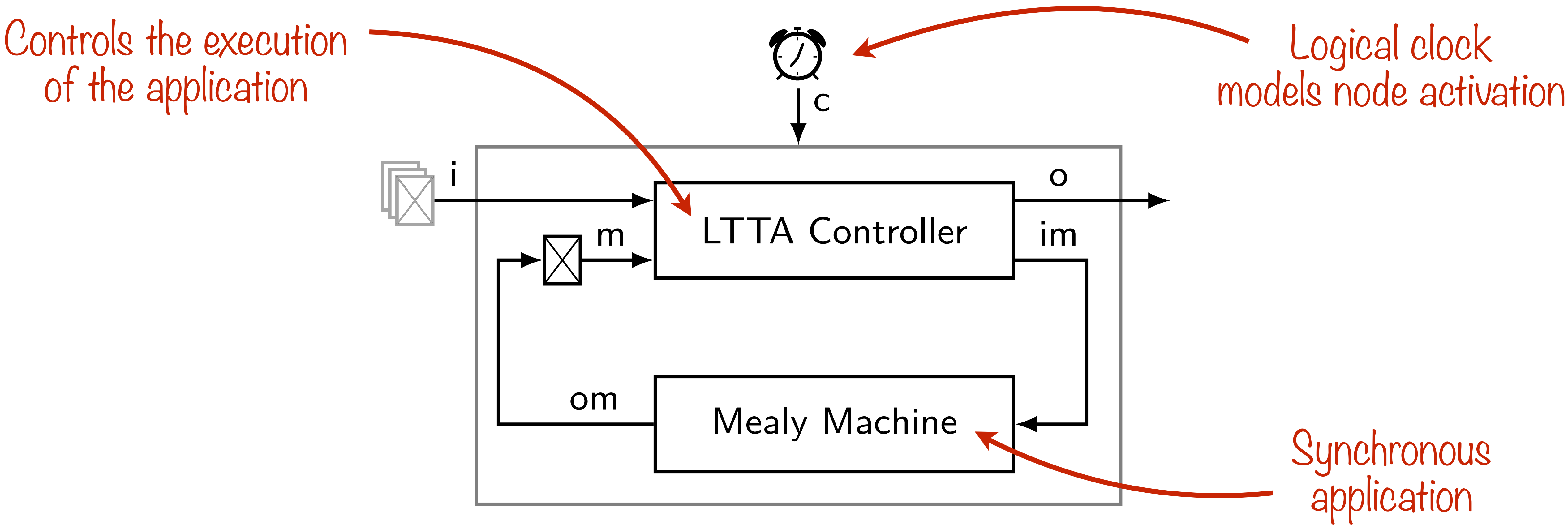

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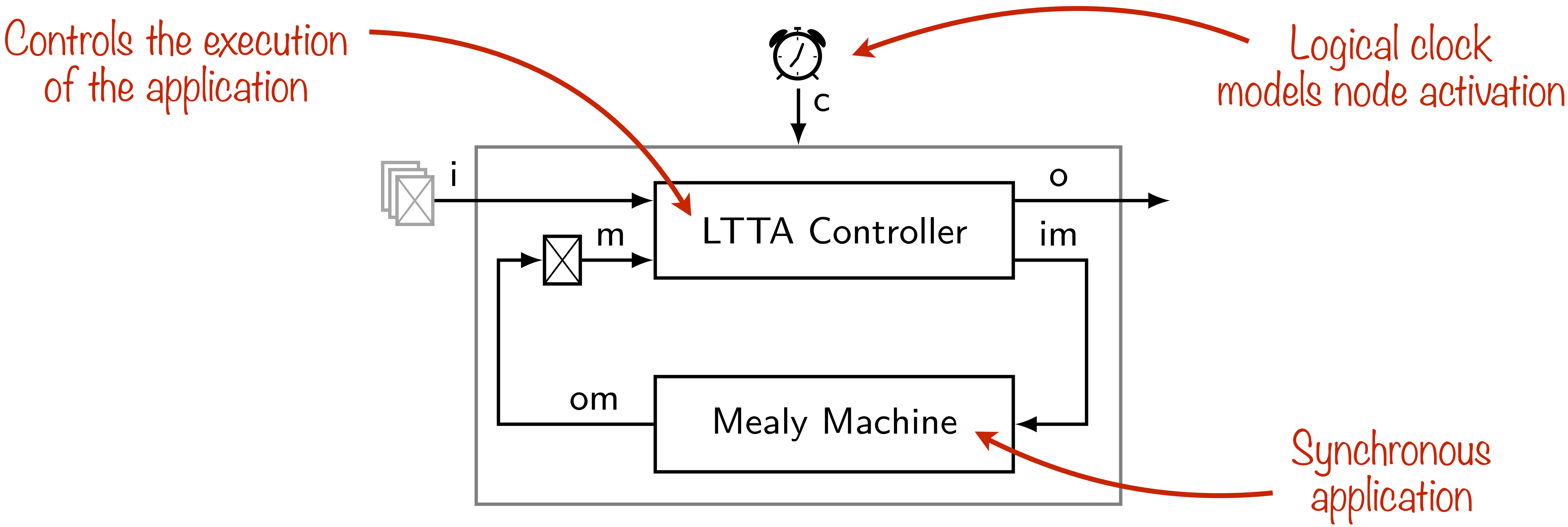

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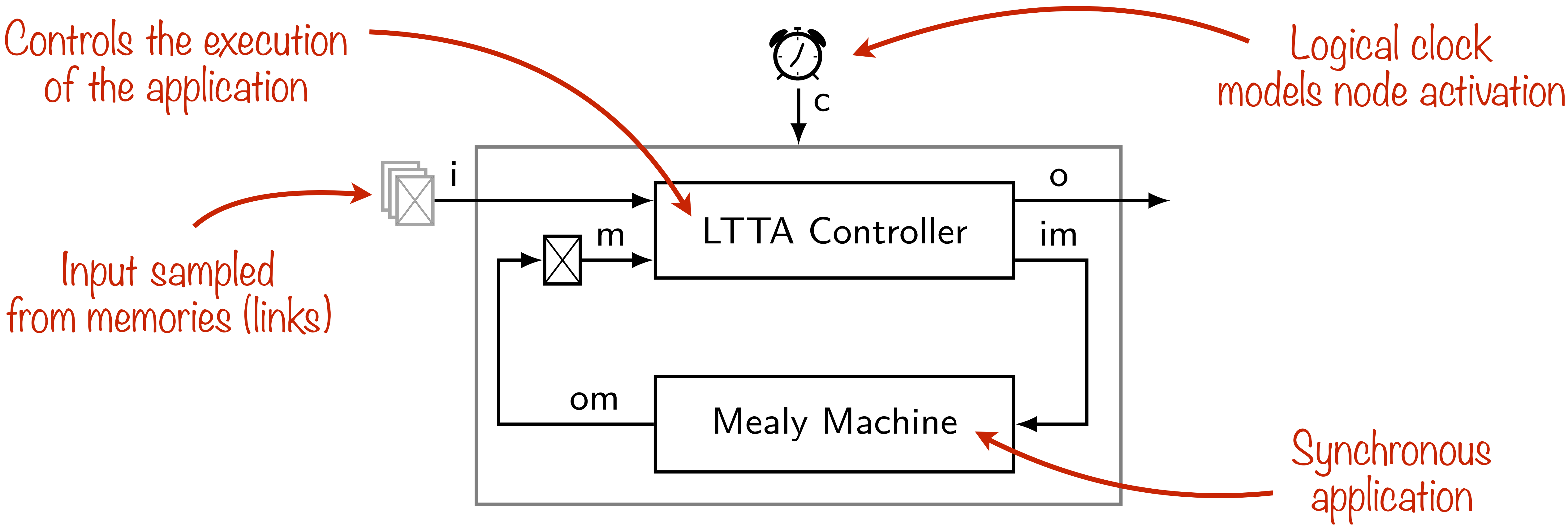

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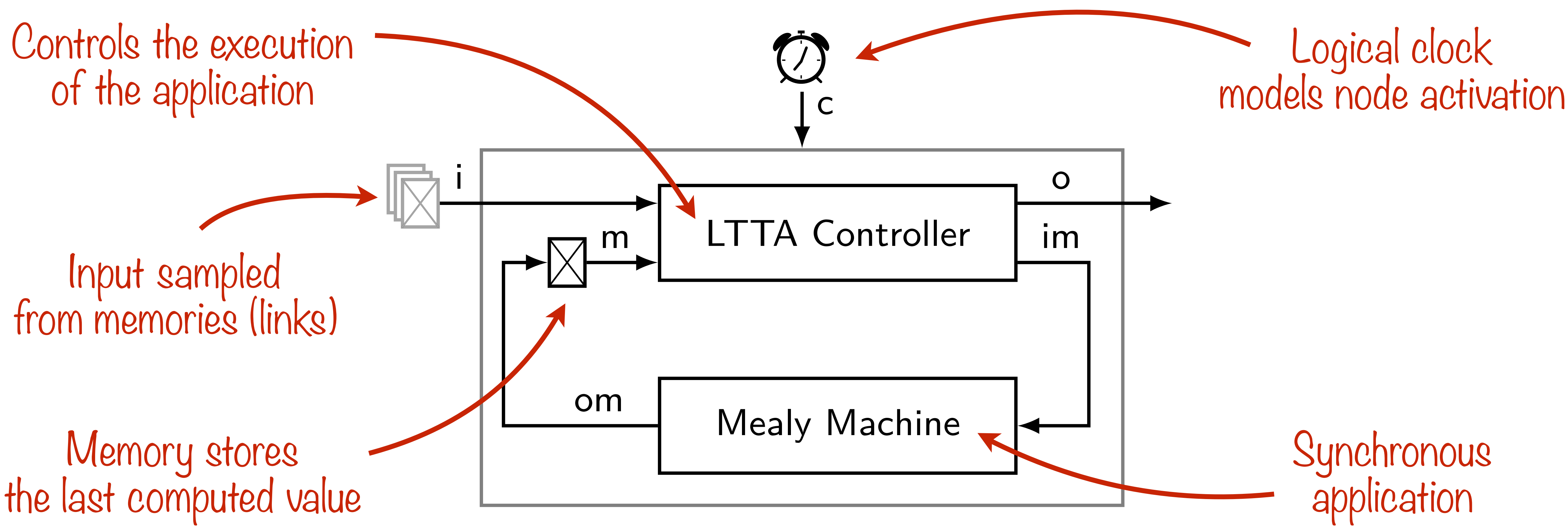

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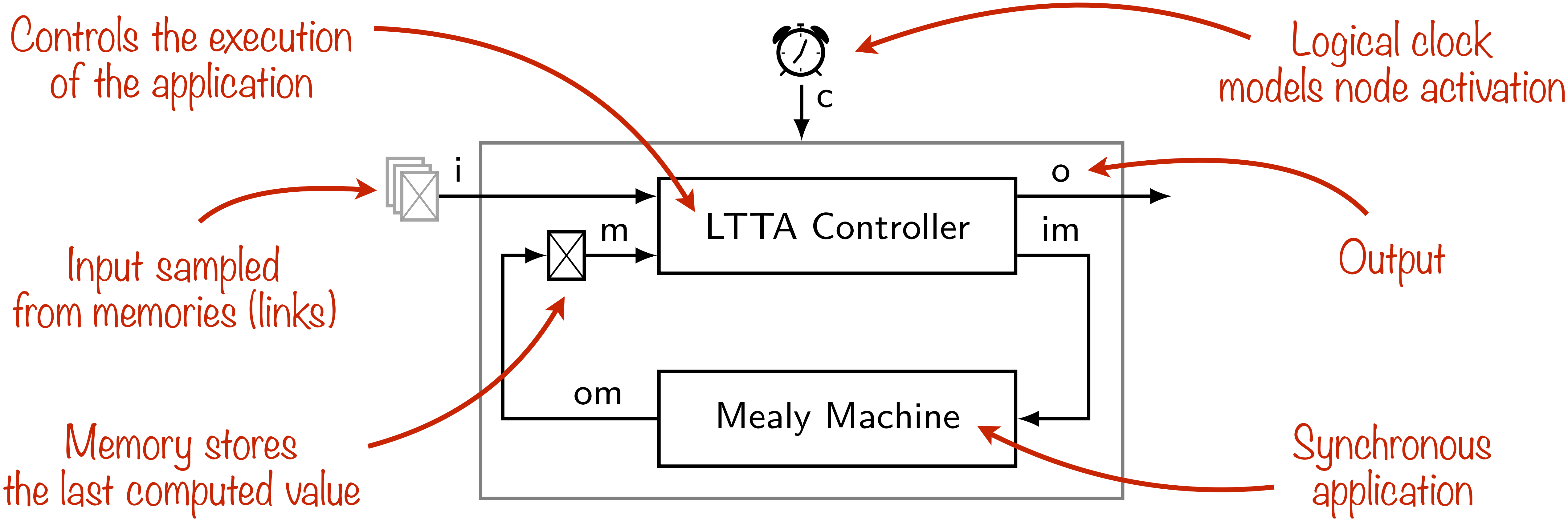

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- A producer waits for **acknowledgements** from its consumers before sending a new value.
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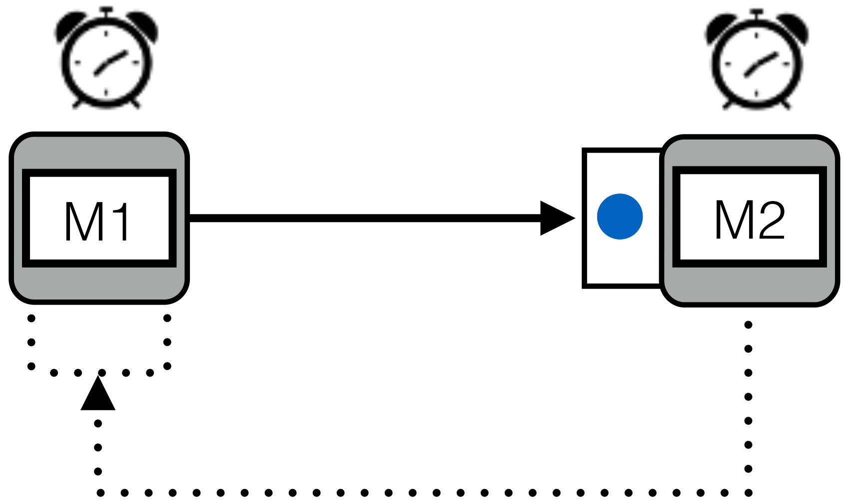

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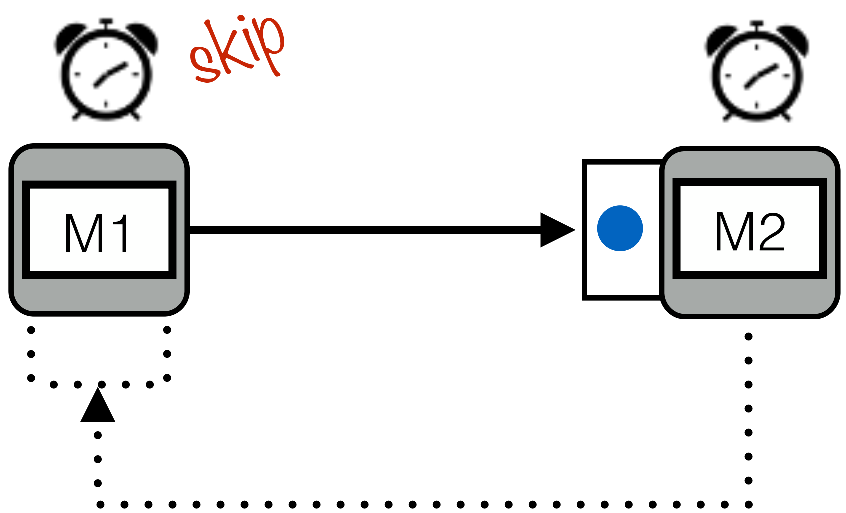

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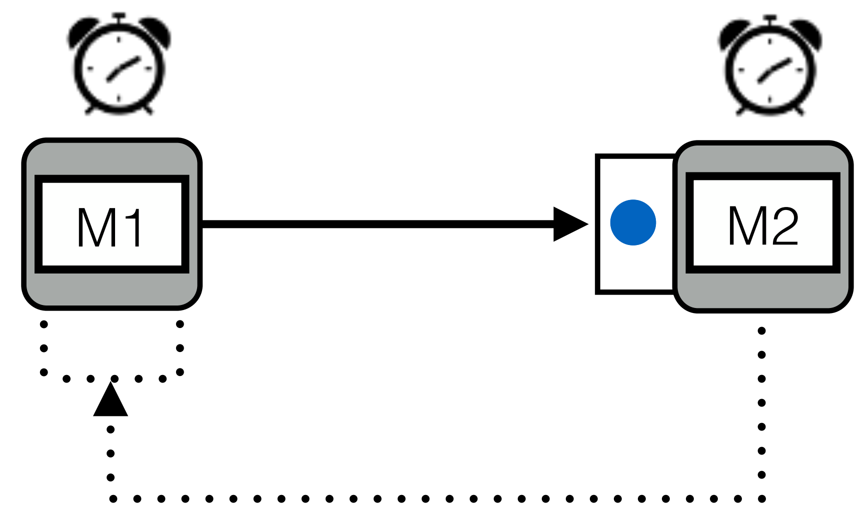

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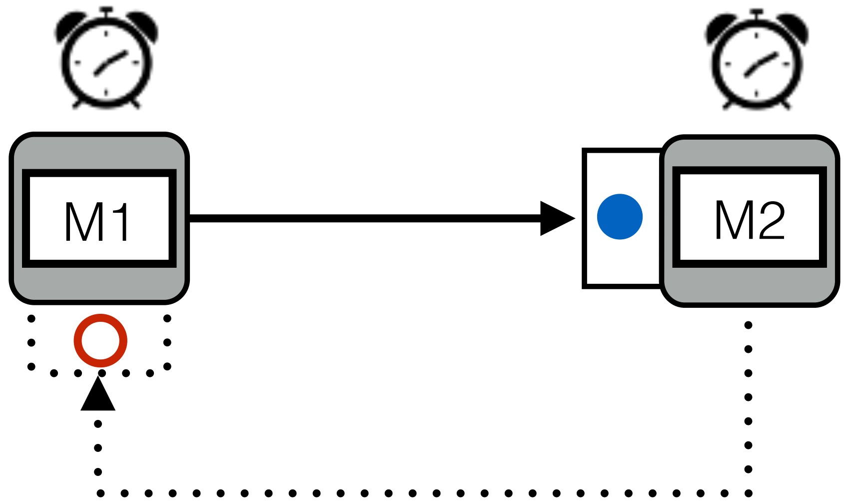

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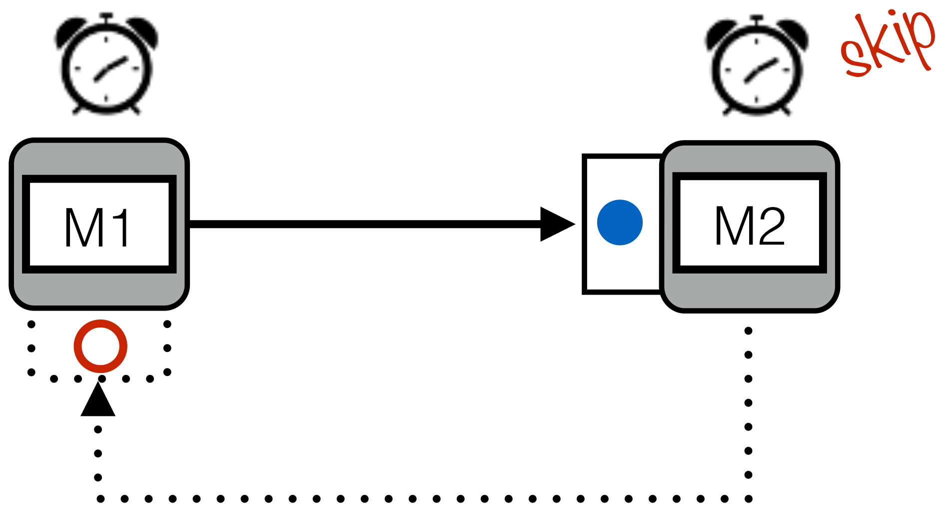

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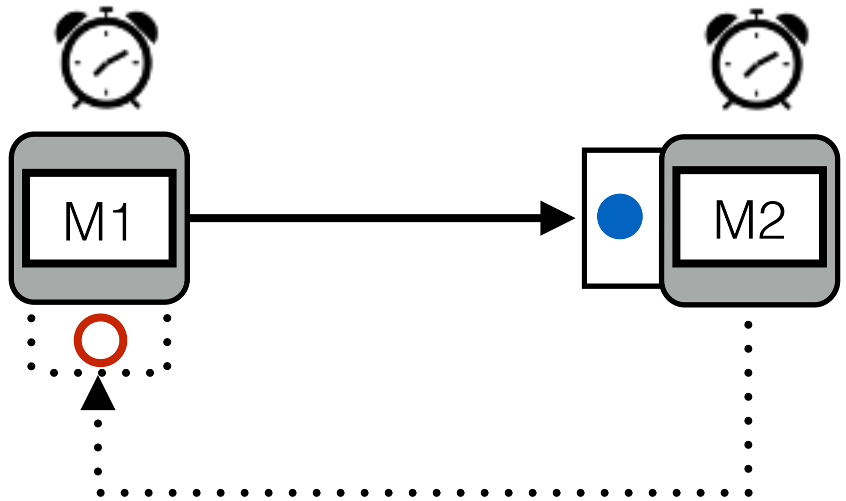

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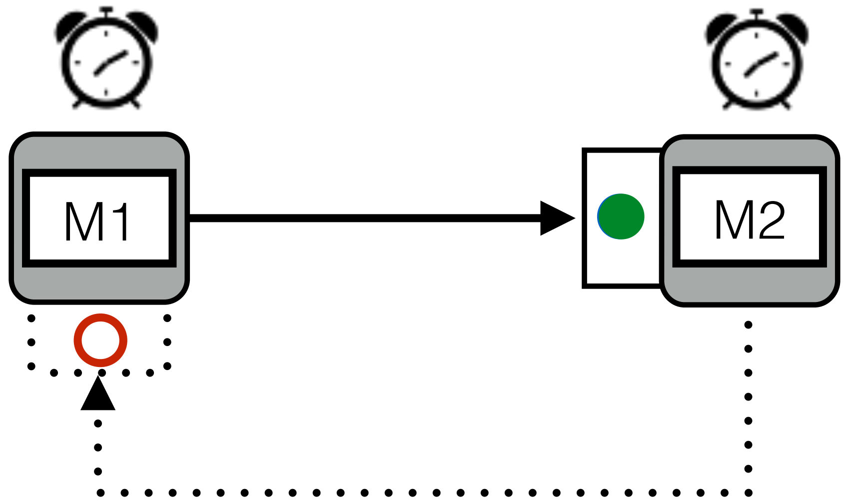

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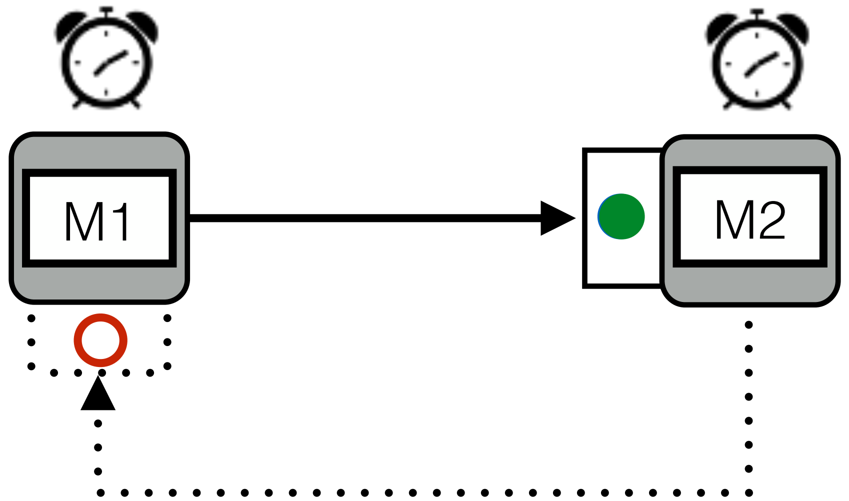

Flexibility: there is no assumption on the architecture.
Robustness: if a node crashes the entire network is stuck.

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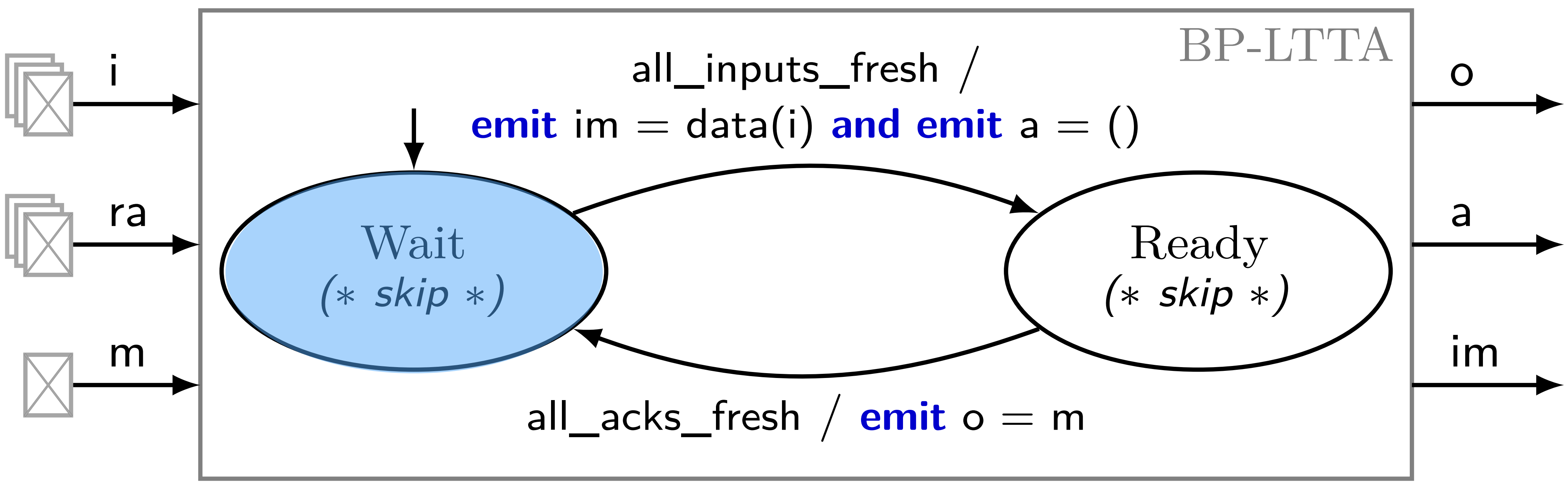

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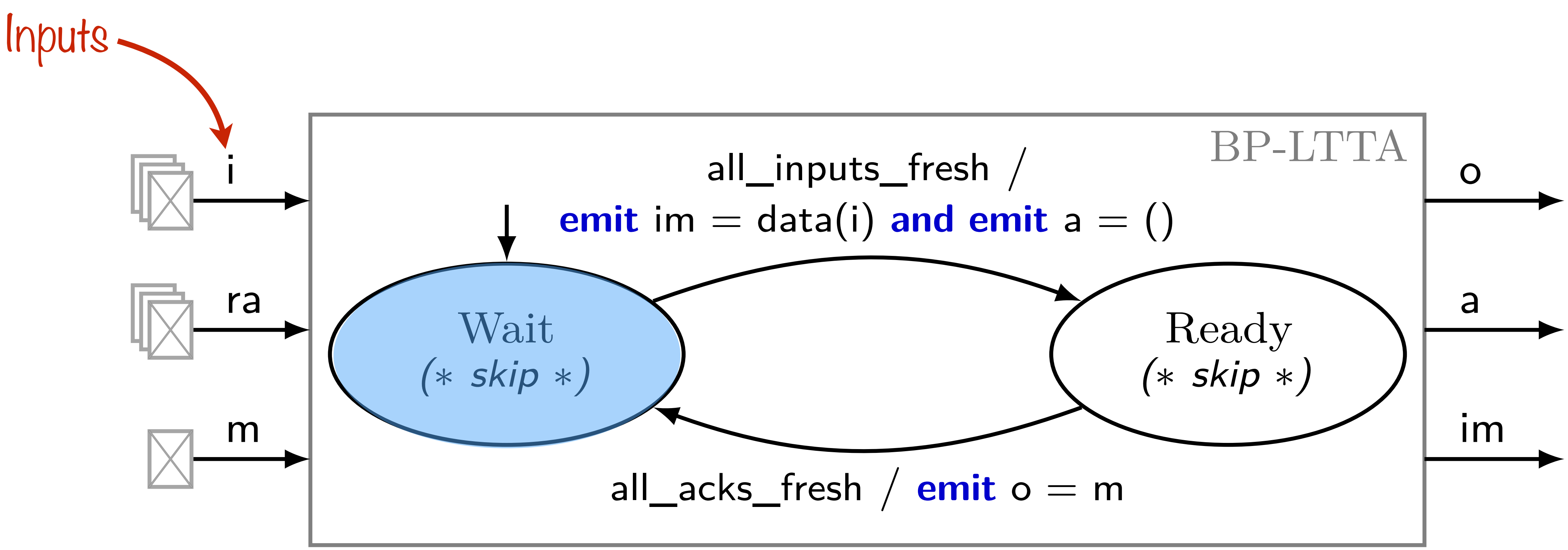

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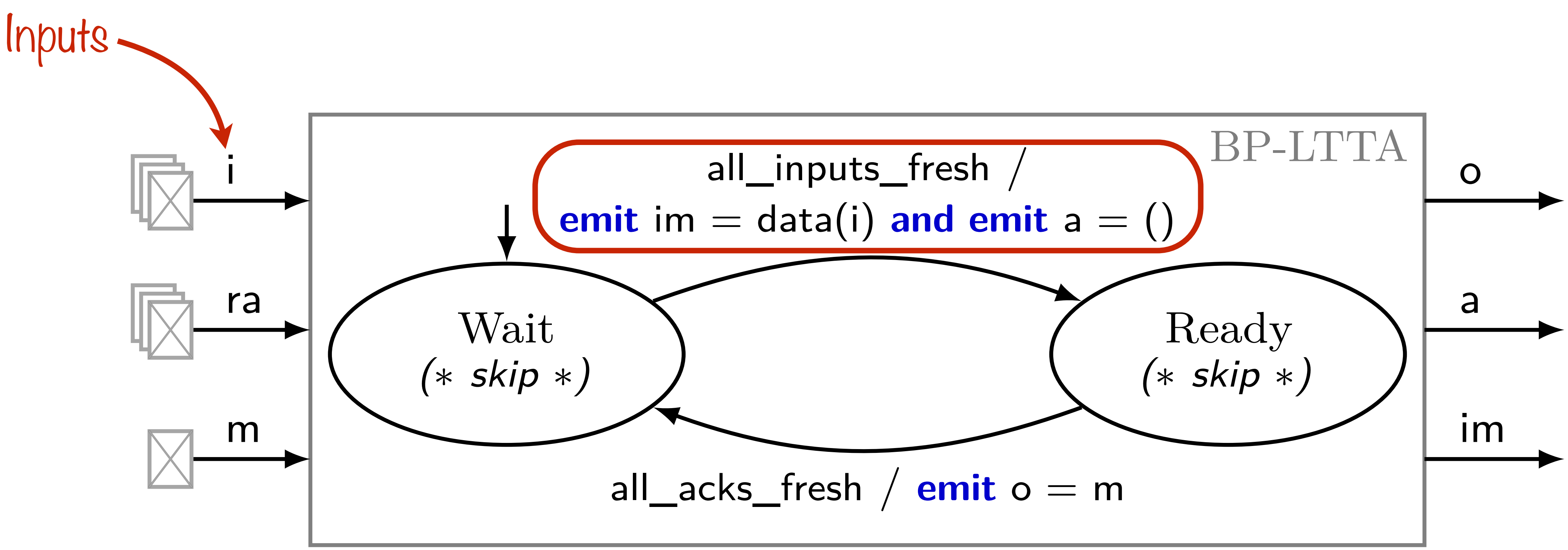

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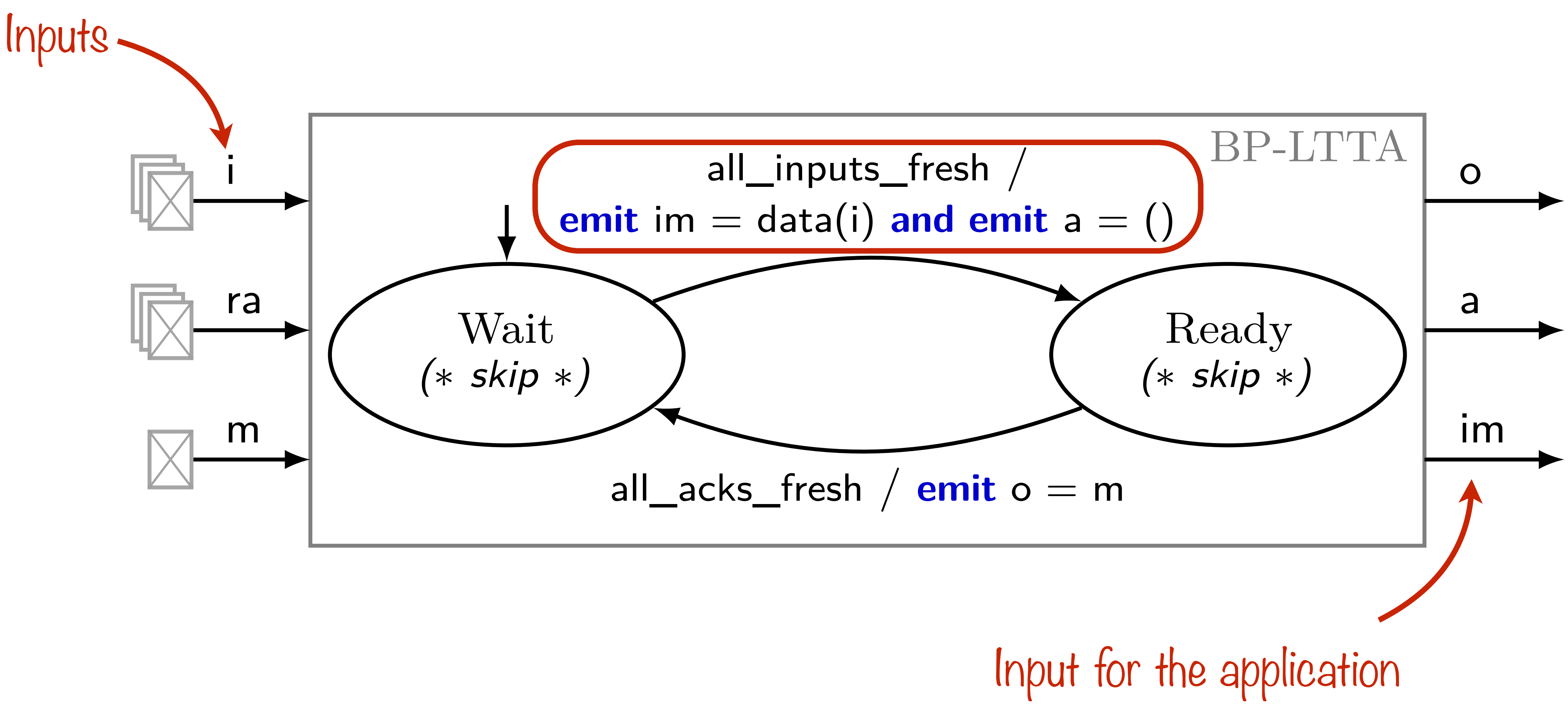

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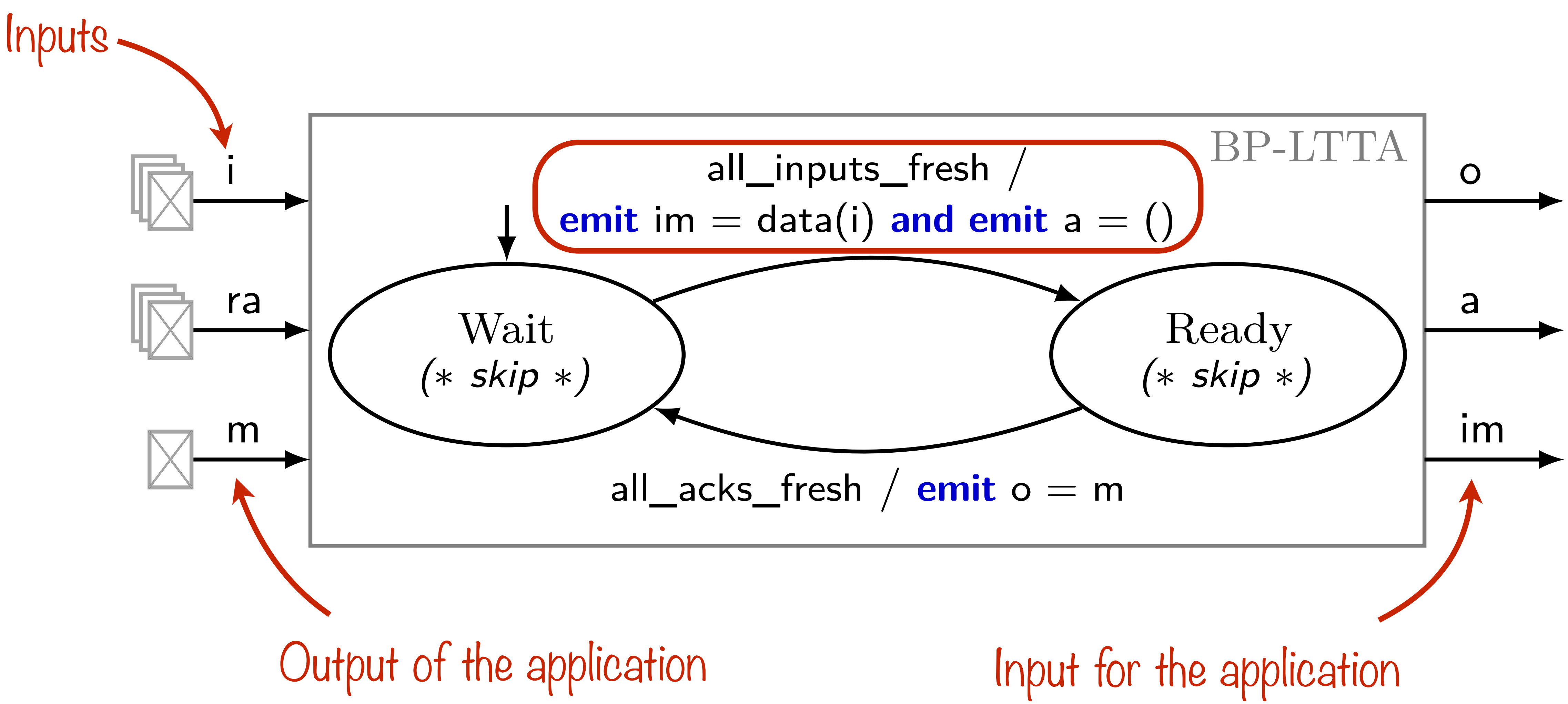

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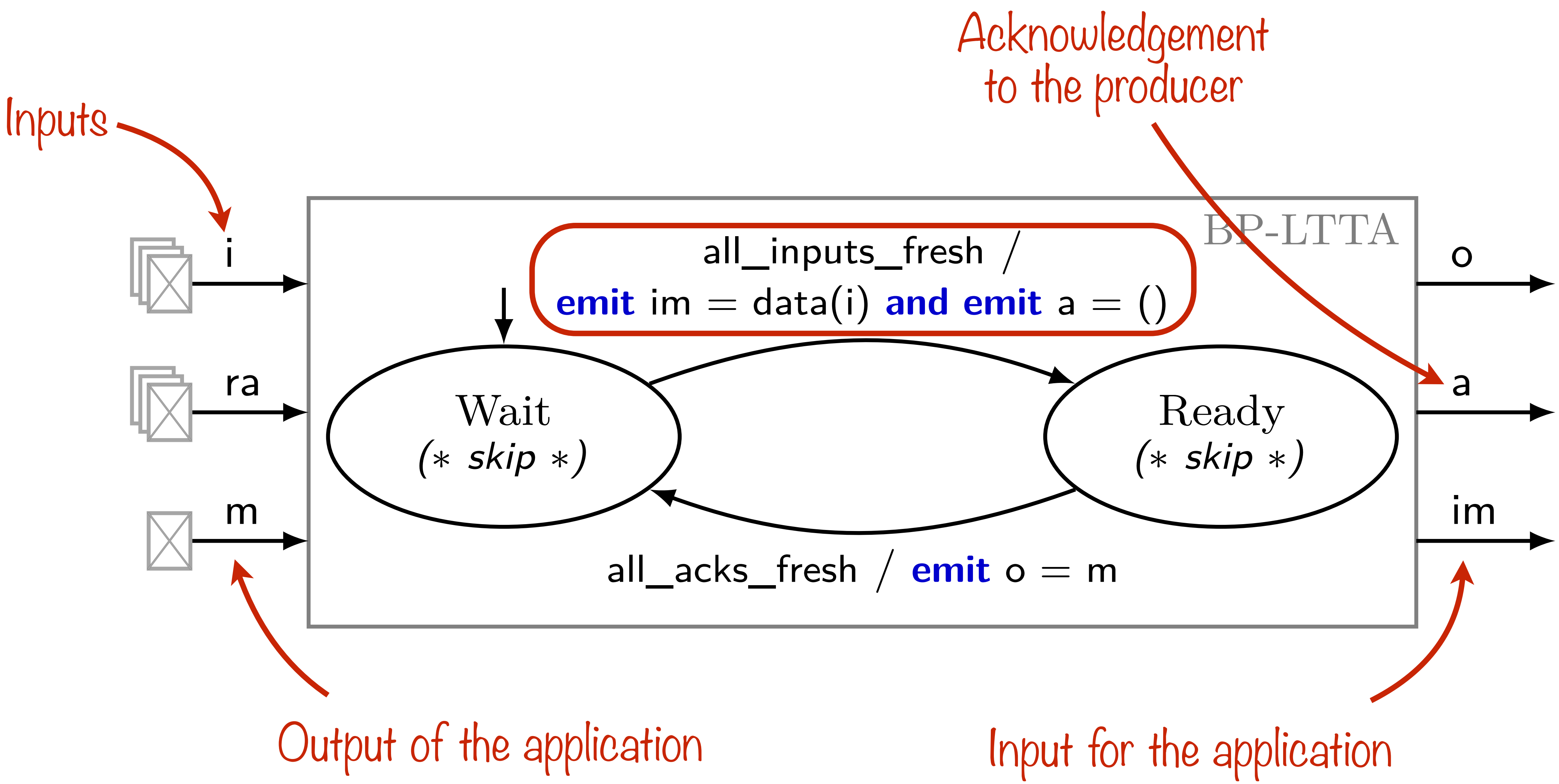

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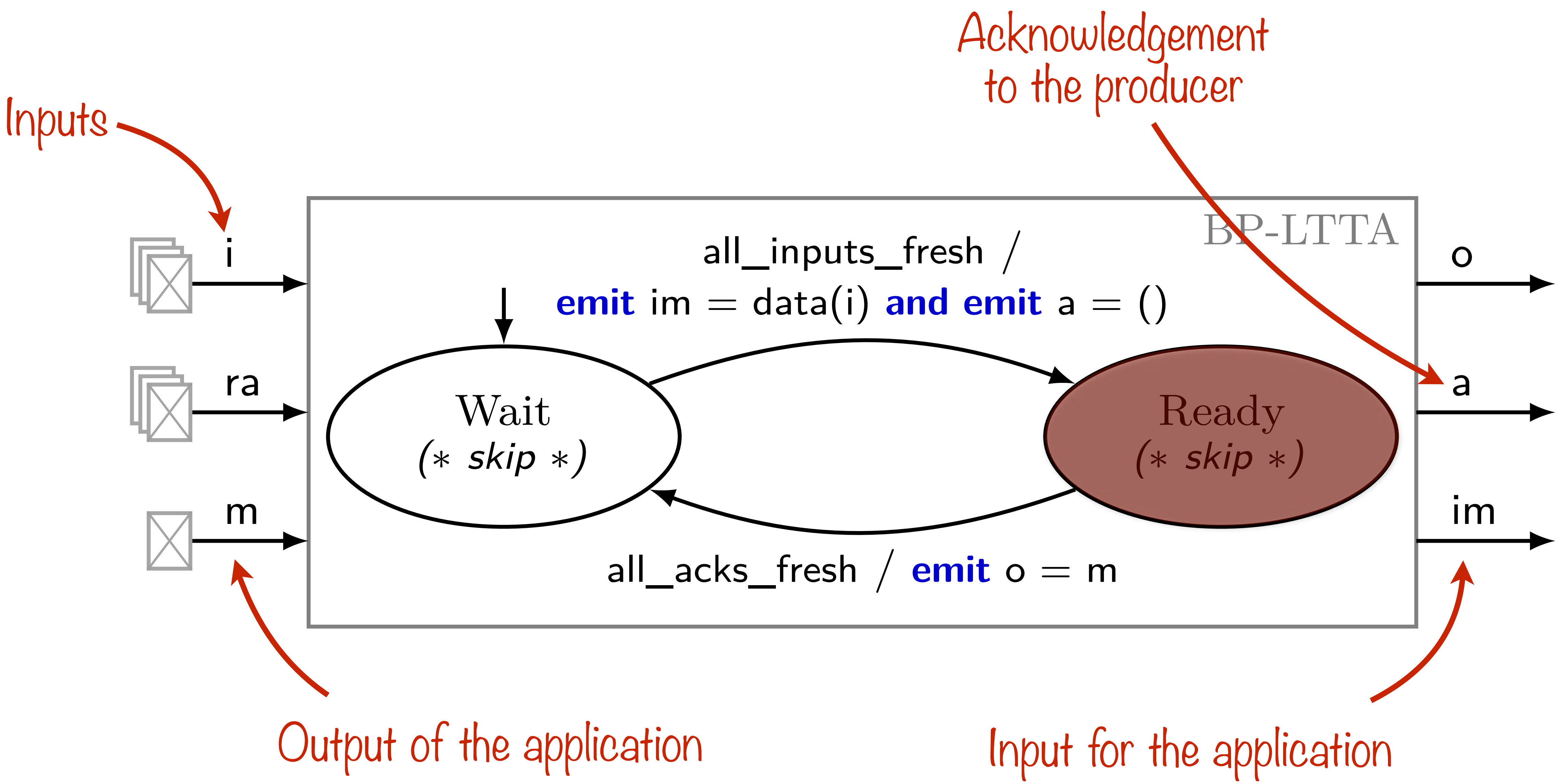

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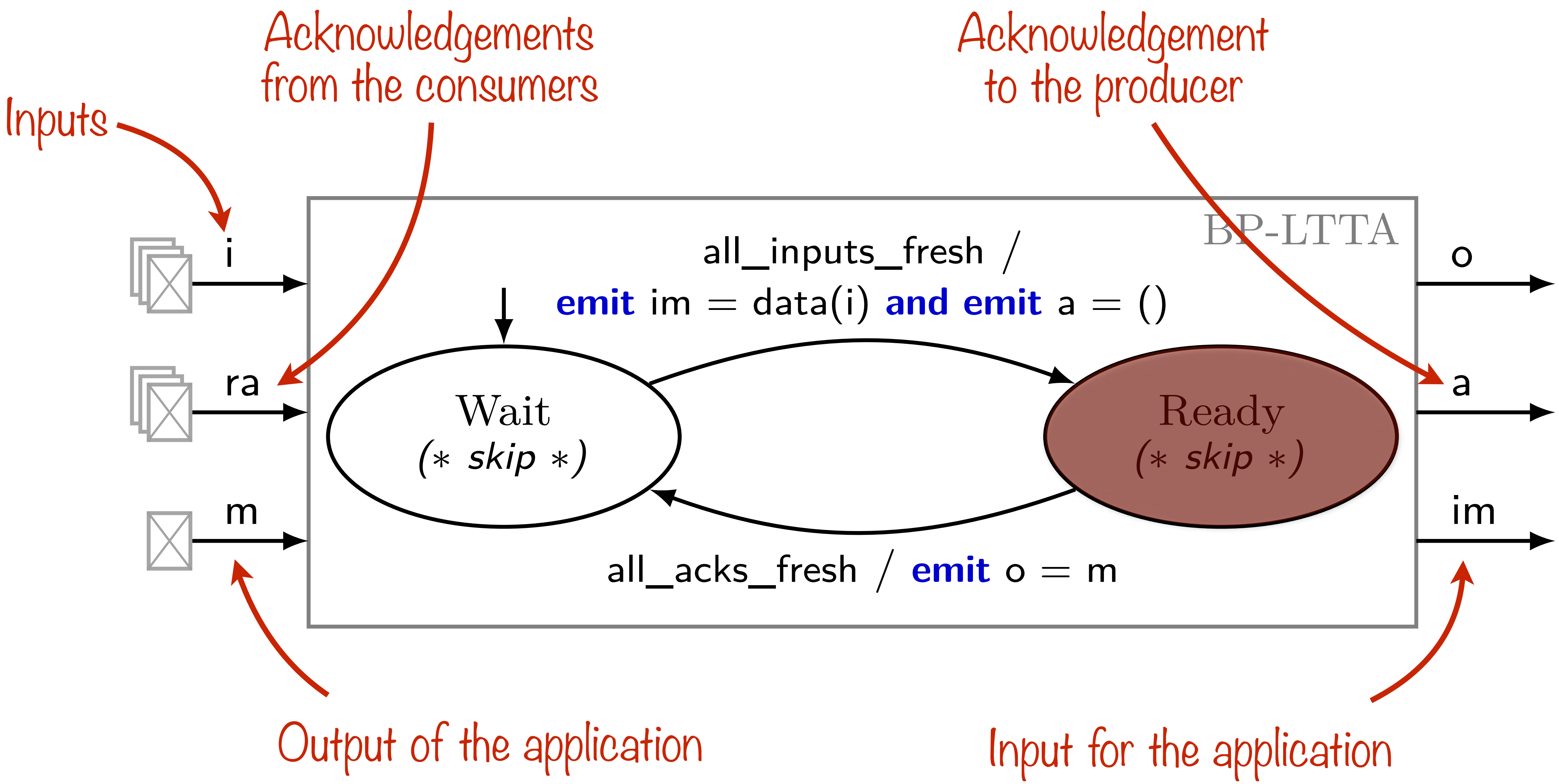

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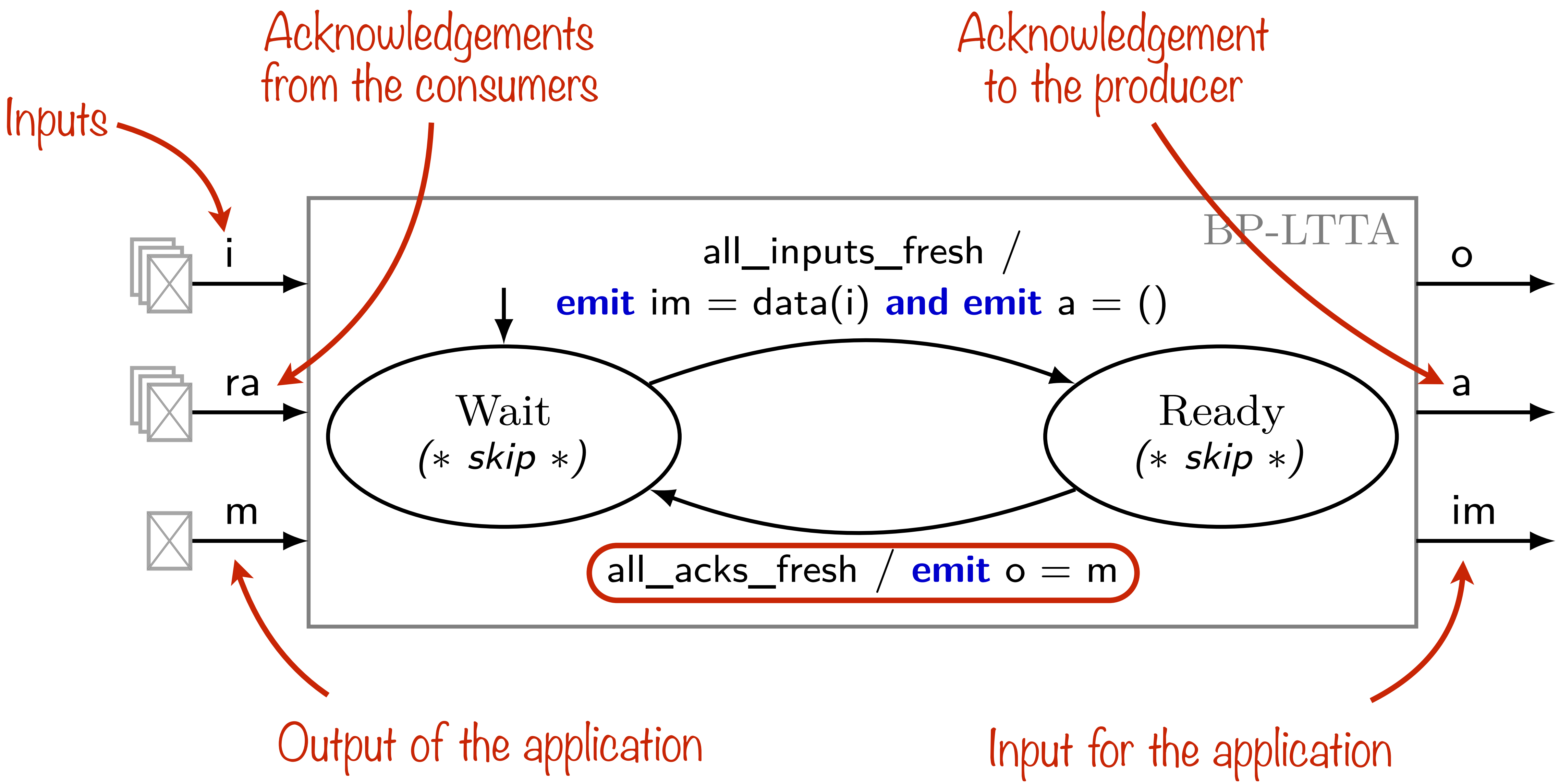

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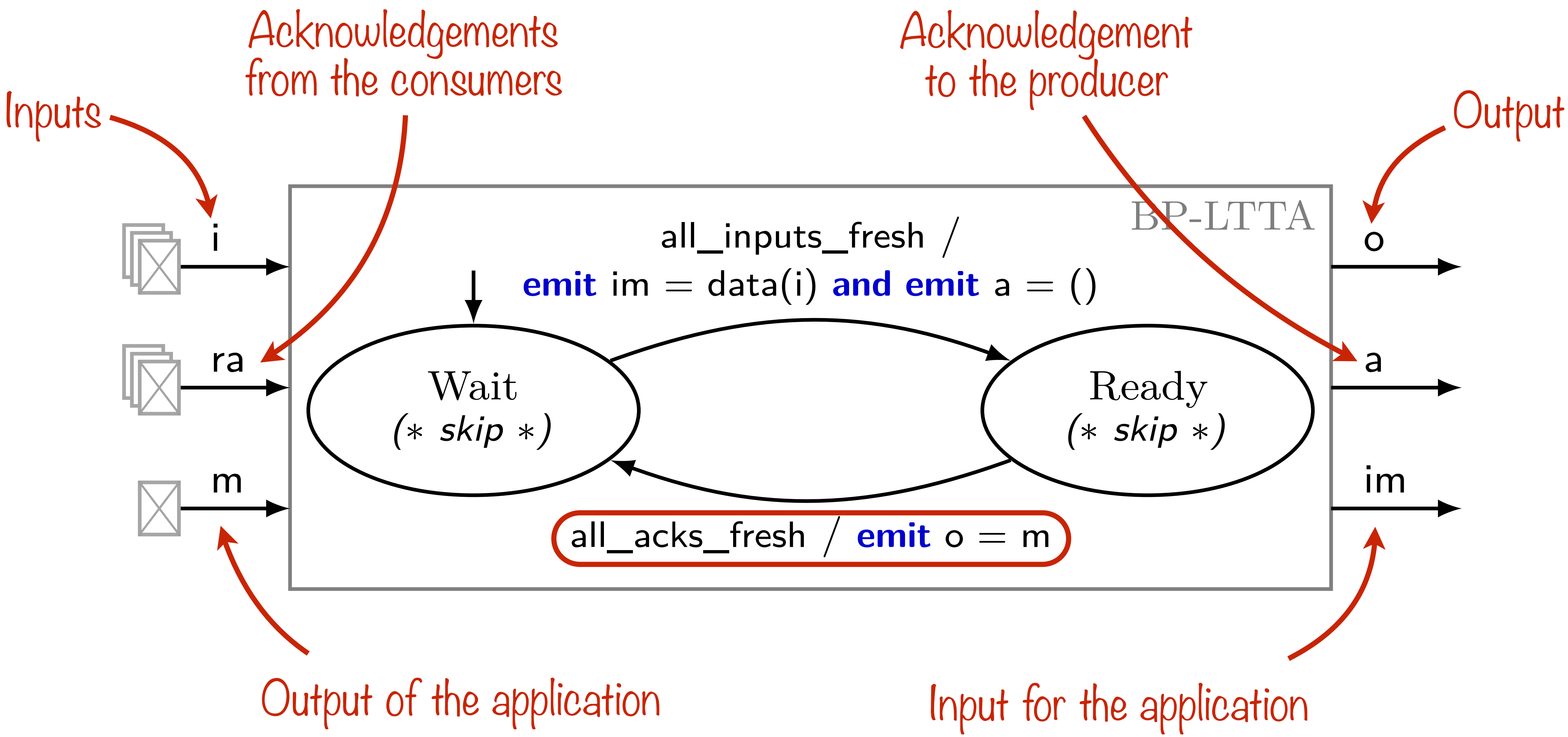

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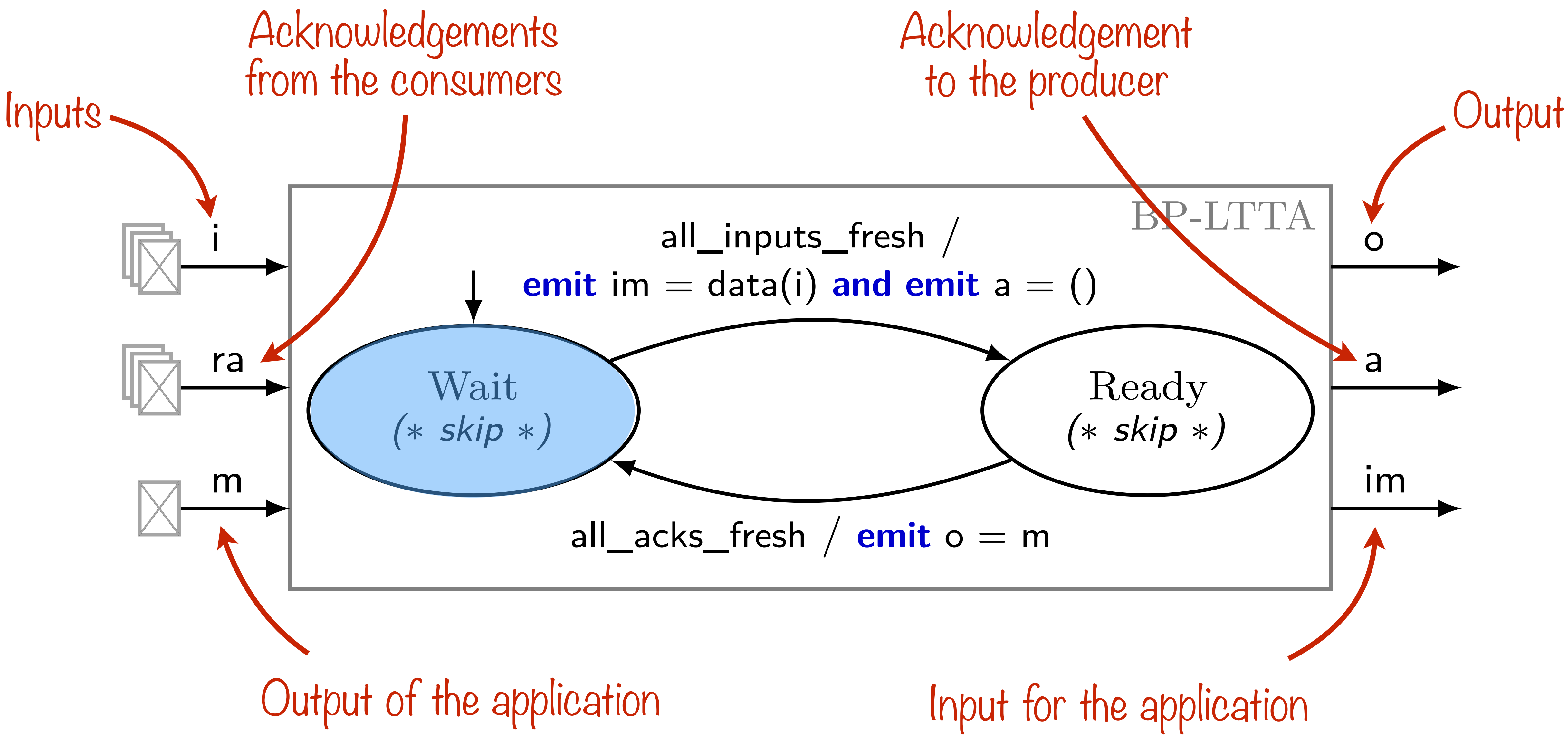

Controller **waits** for new inputs and **delays** publications

Time-Based LTTA

Why another protocol?

Back-pressure multiplies the number of messages and memories, and **blocks if a node crashes**

We can take advantage of the **quasi-periodic** nature of the architecture to replace acknowledgment by **waiting**.

At some point, a node can be sure that:

- the last sent data has been read
- a fresh value is available in the memory

[Caspi & Benveniste 2008]

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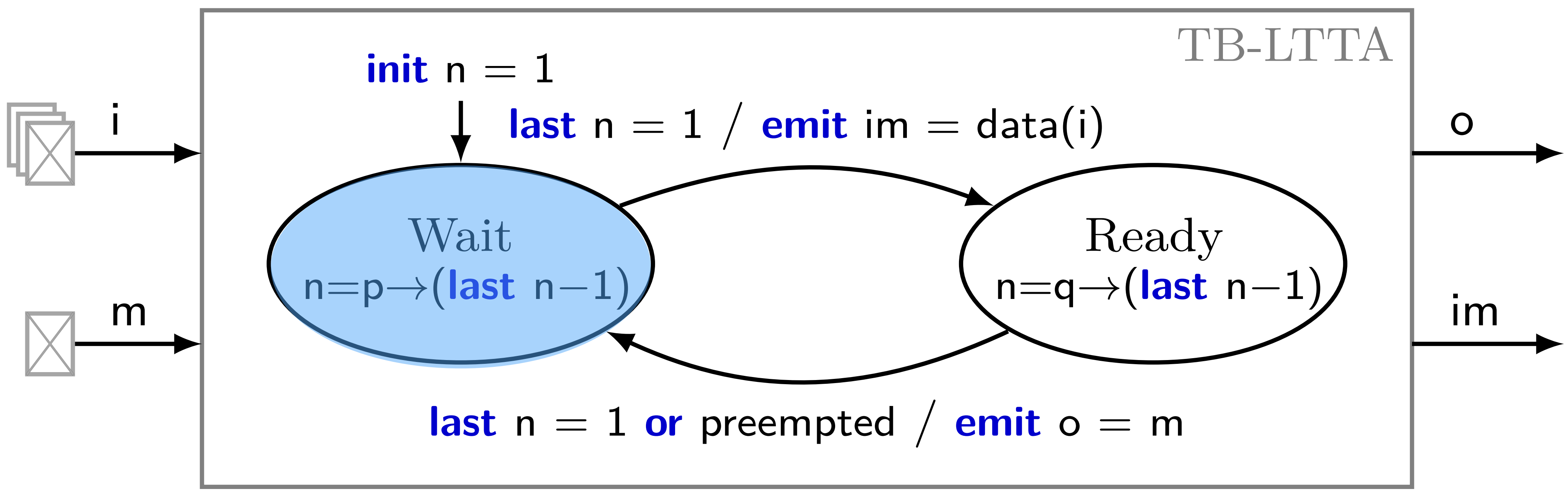
Flexibility: it requires architecture characteristics.
Robustness: controllers can run in a degraded mode.

[Caspi & Benveniste 2008]

Time-Based LTTA

Wait: await the publication of the slowest node.
Ready: resynchronize with the fastest node.



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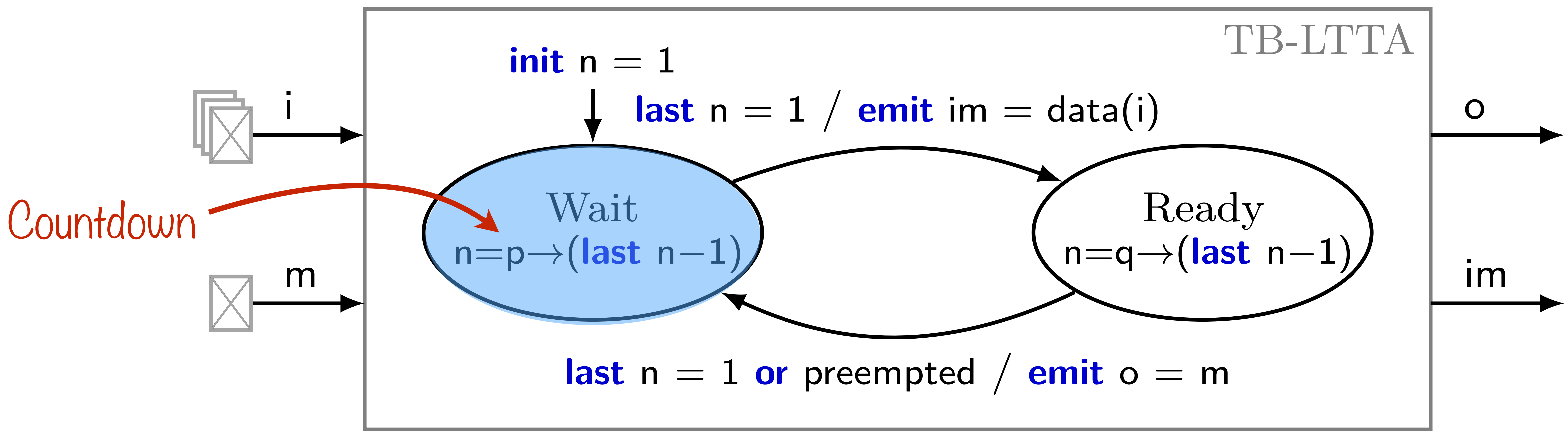

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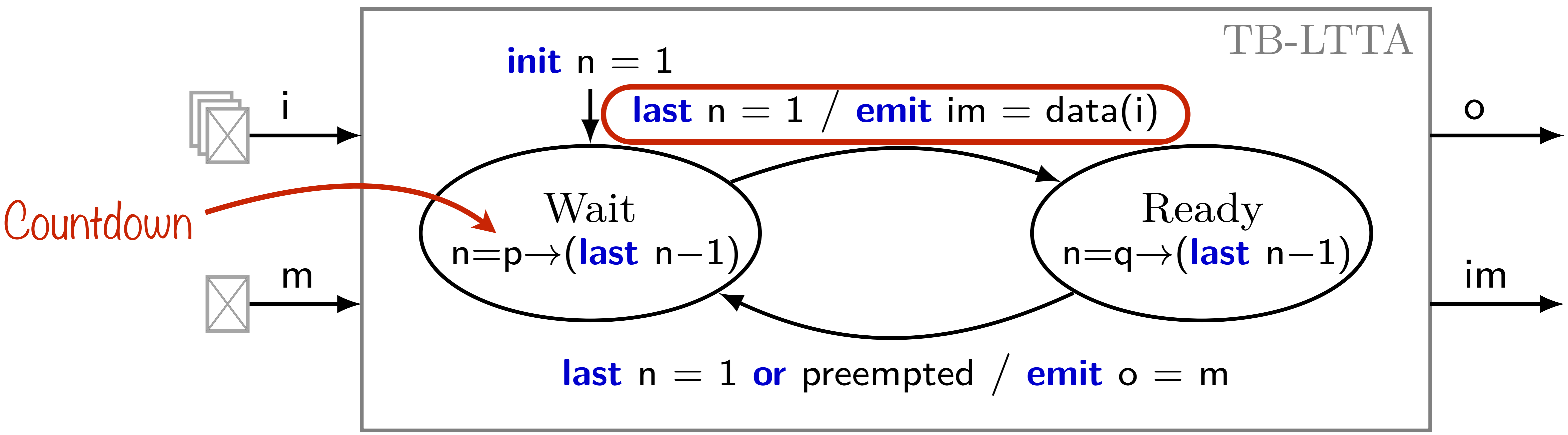

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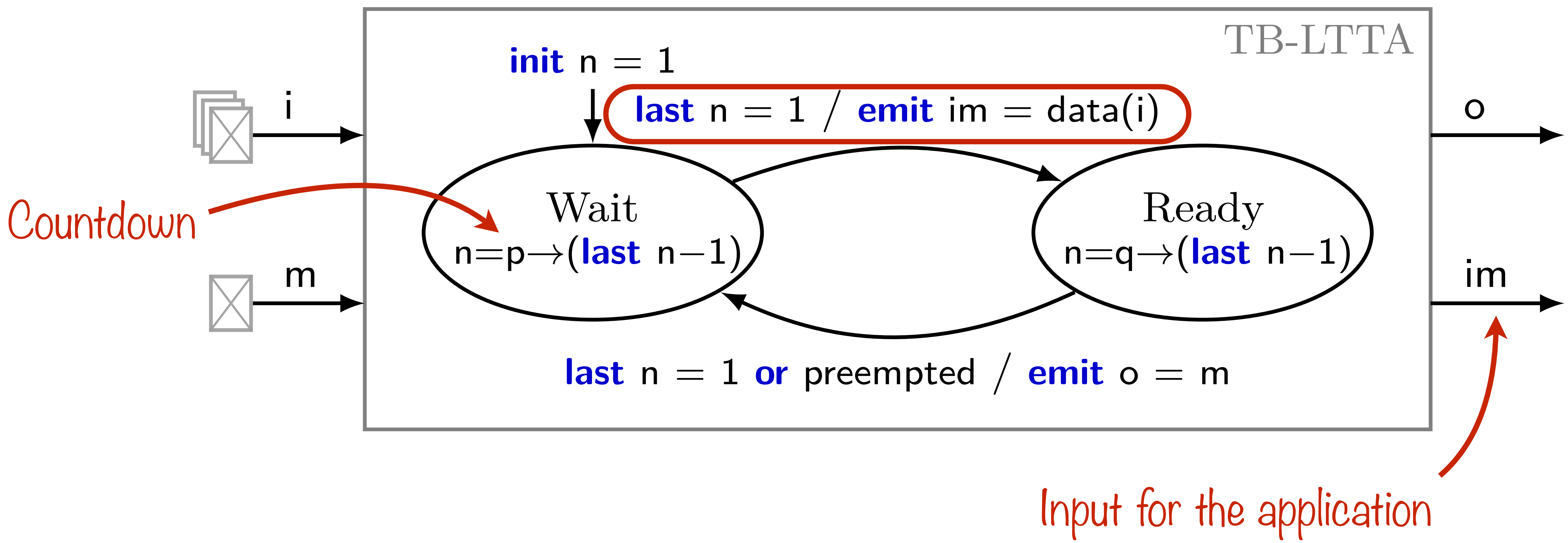

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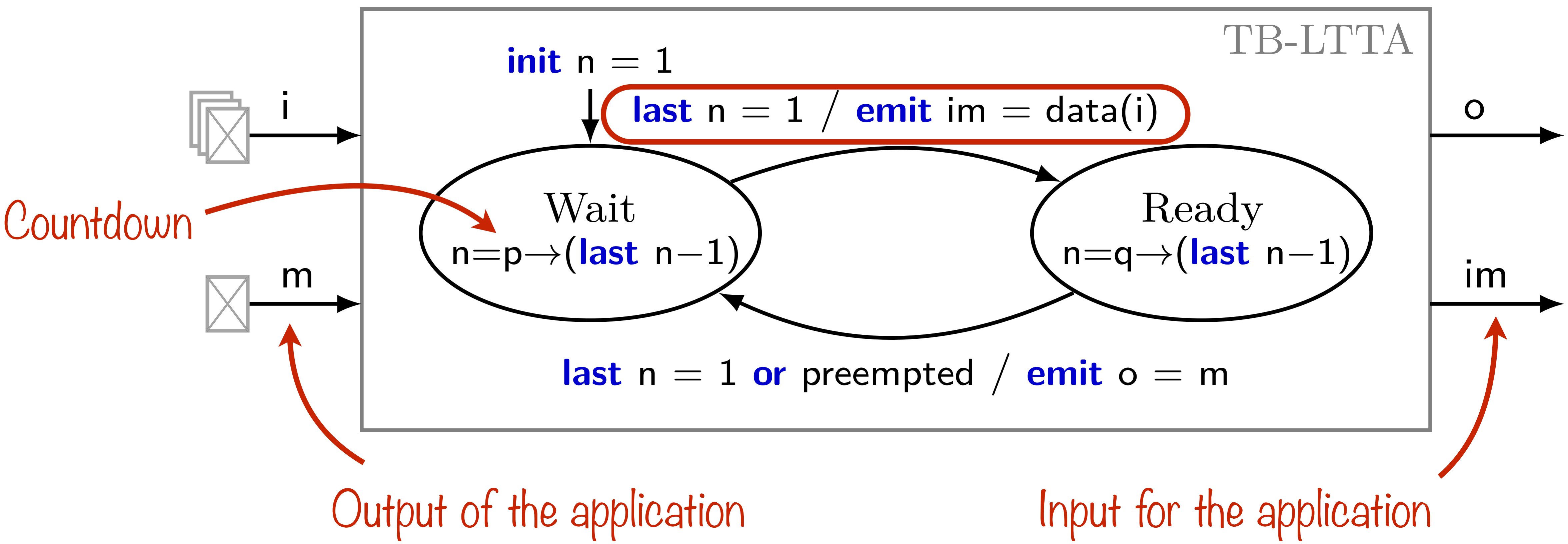

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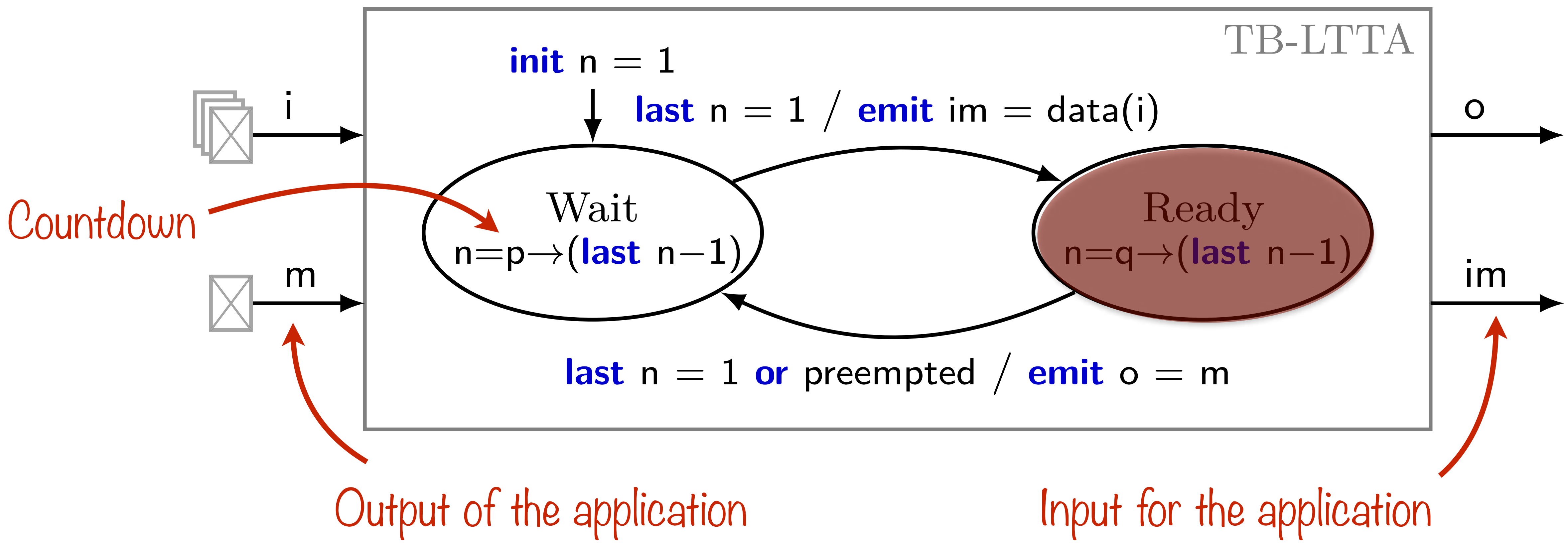

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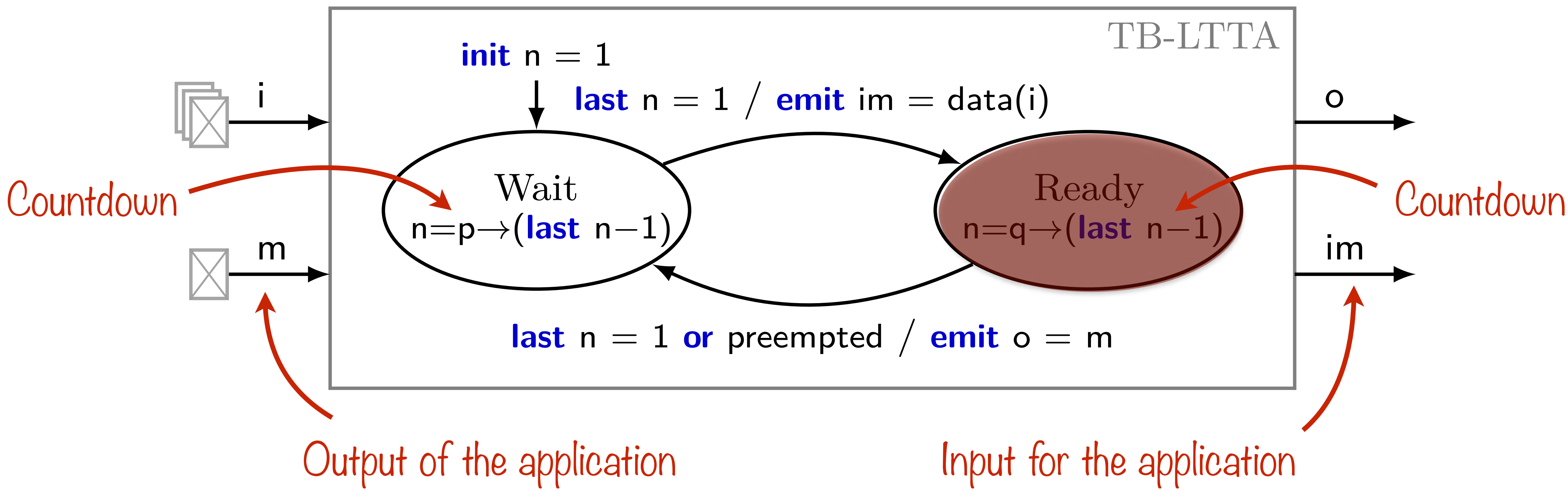

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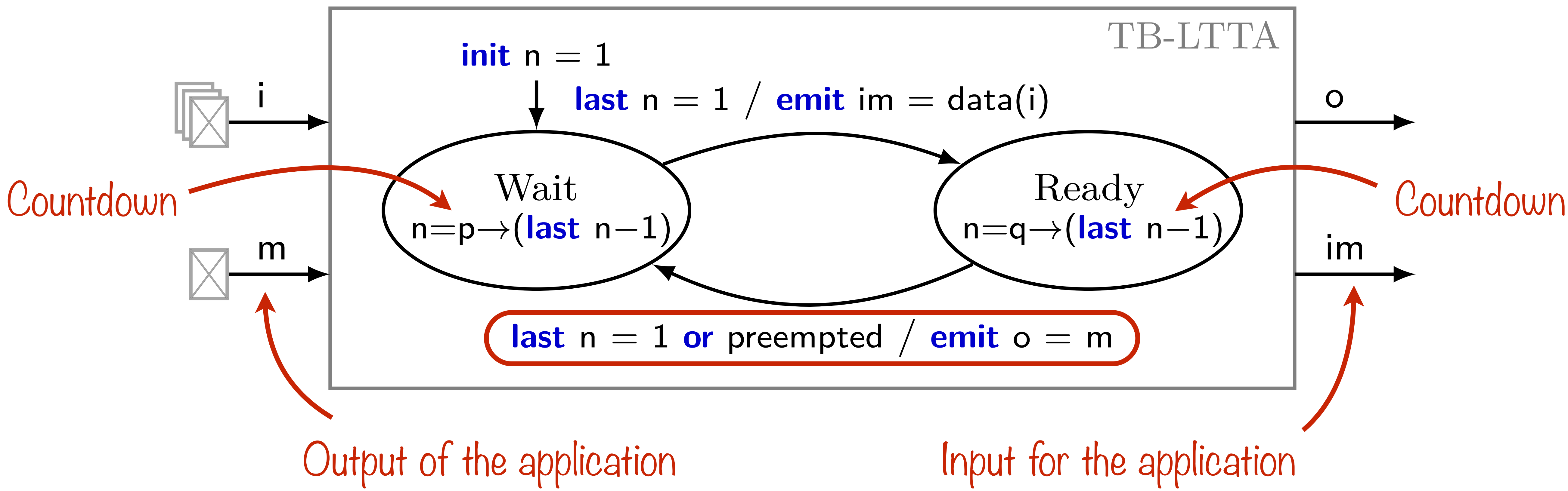

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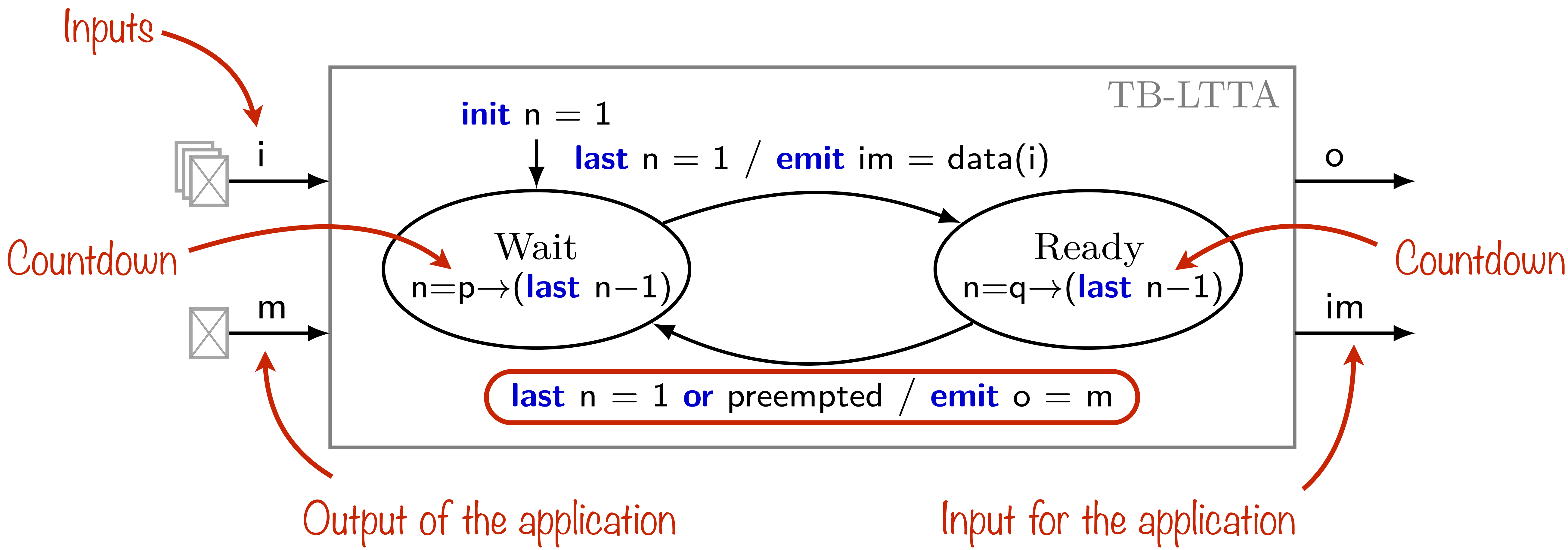

Preemption: when a publication is detected, the consumers have finished executing

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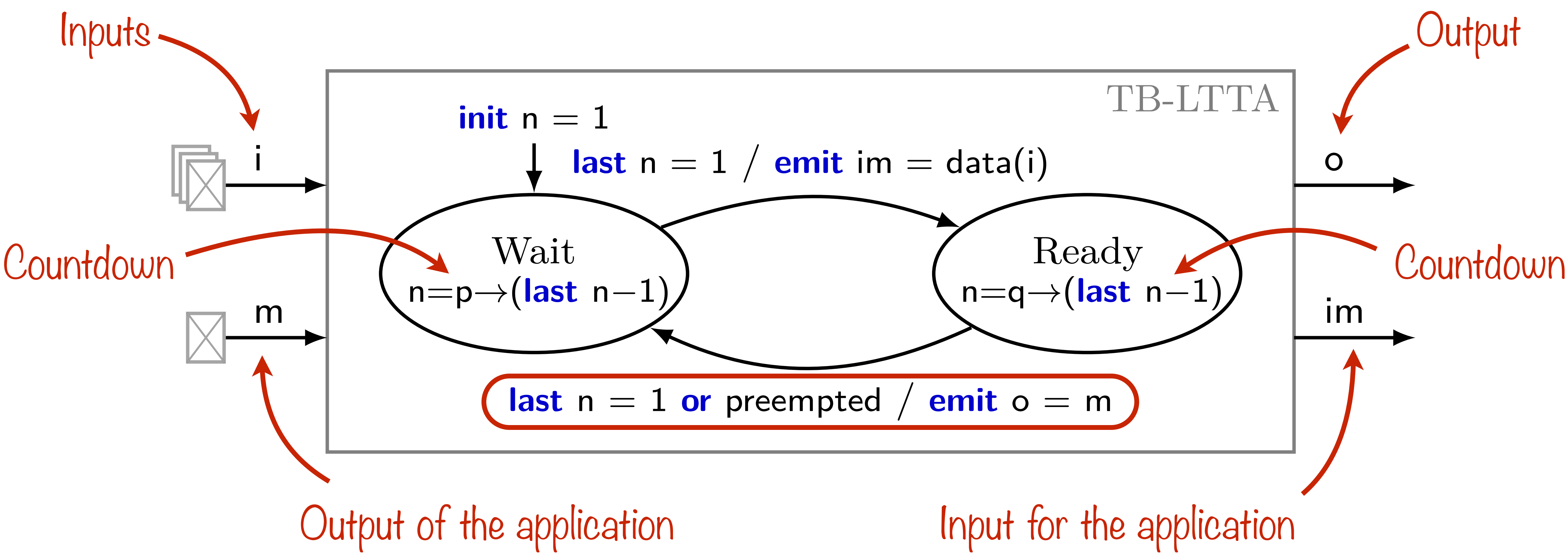

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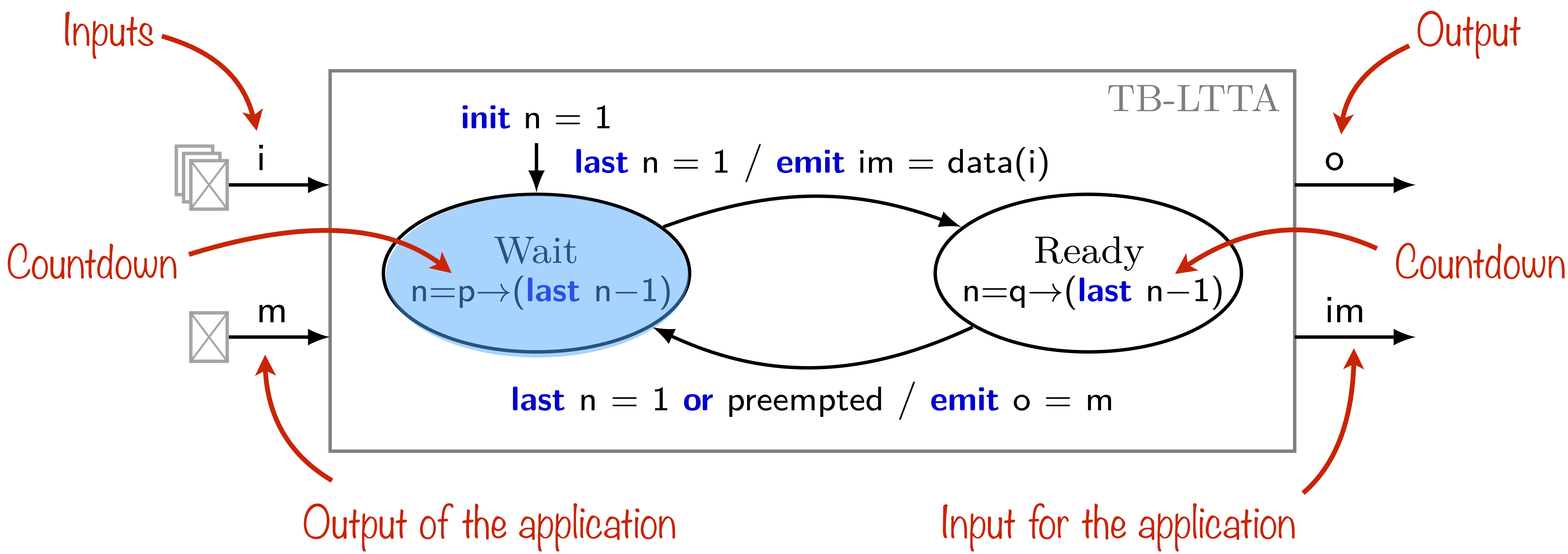

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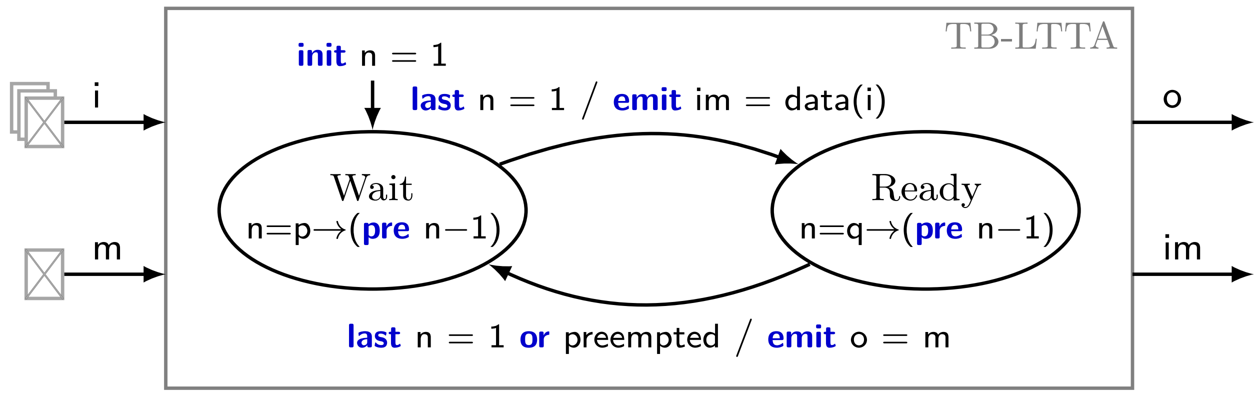
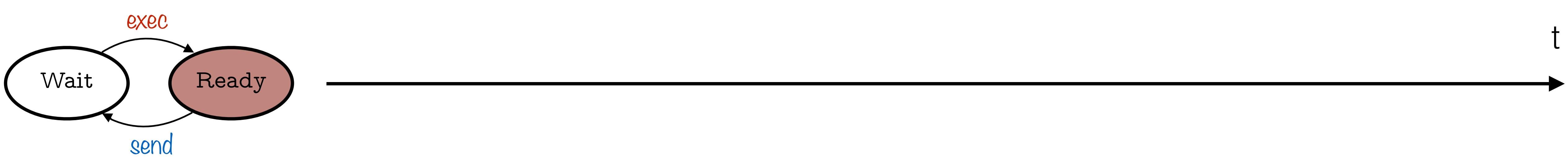
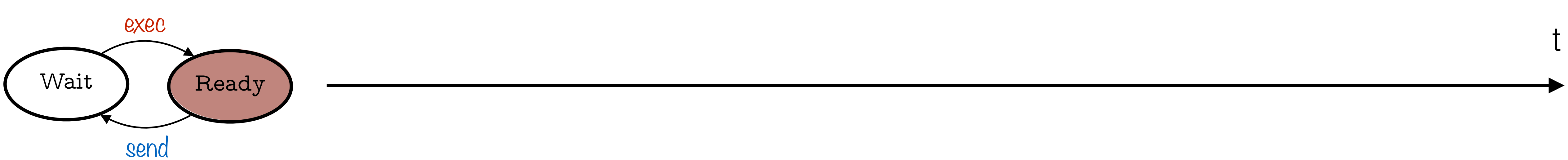
Time-Based LTTA

Simulation p=3 q=2

- Send
- Exec







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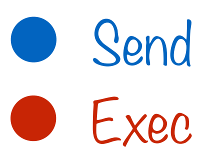

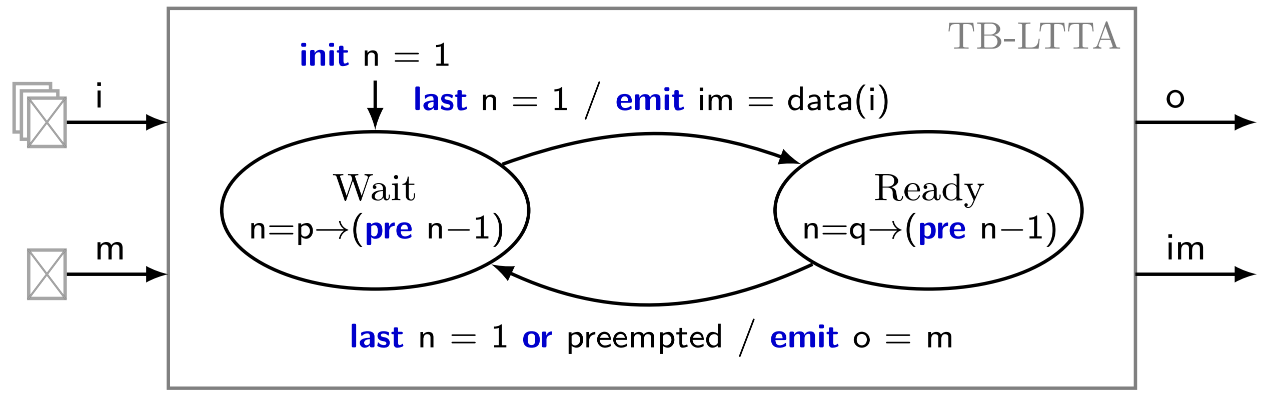

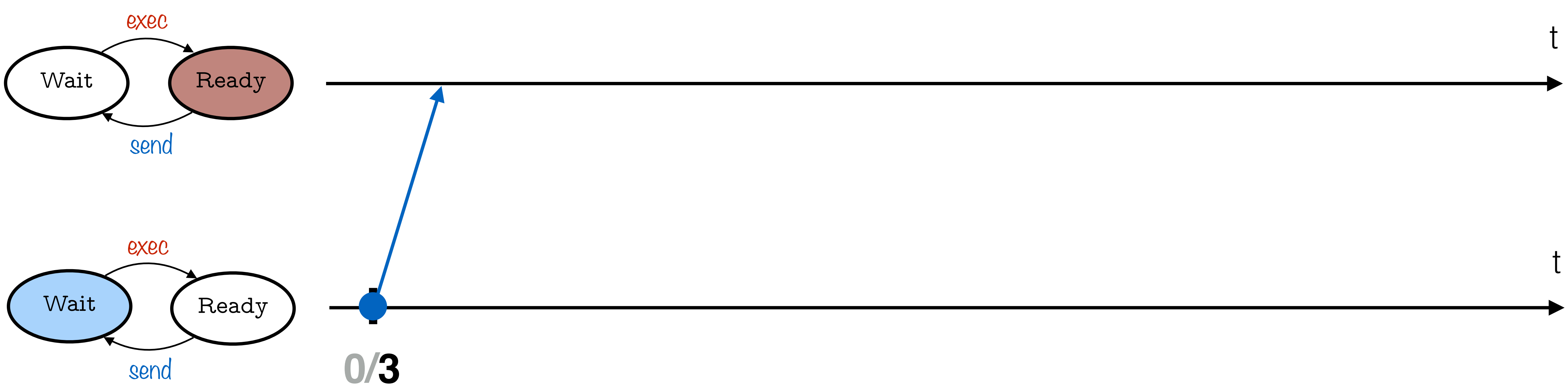

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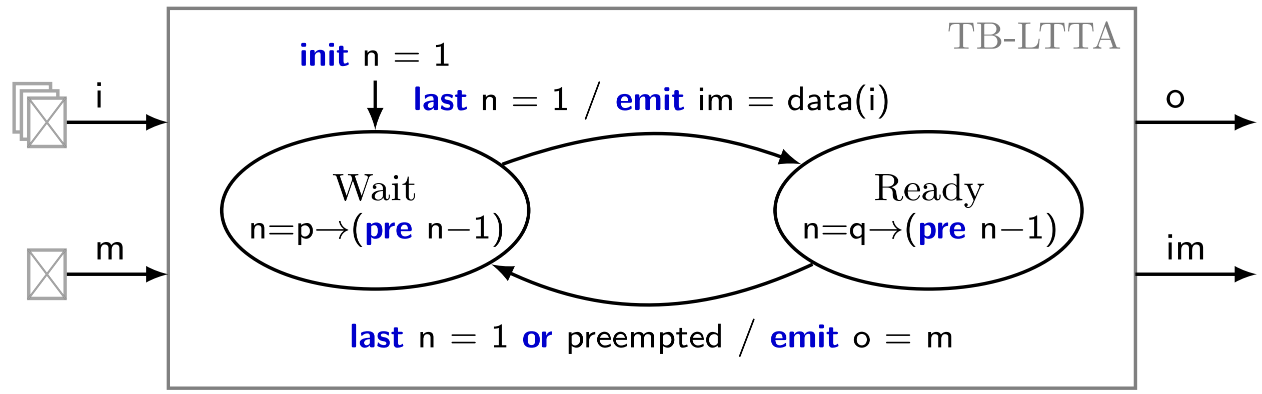

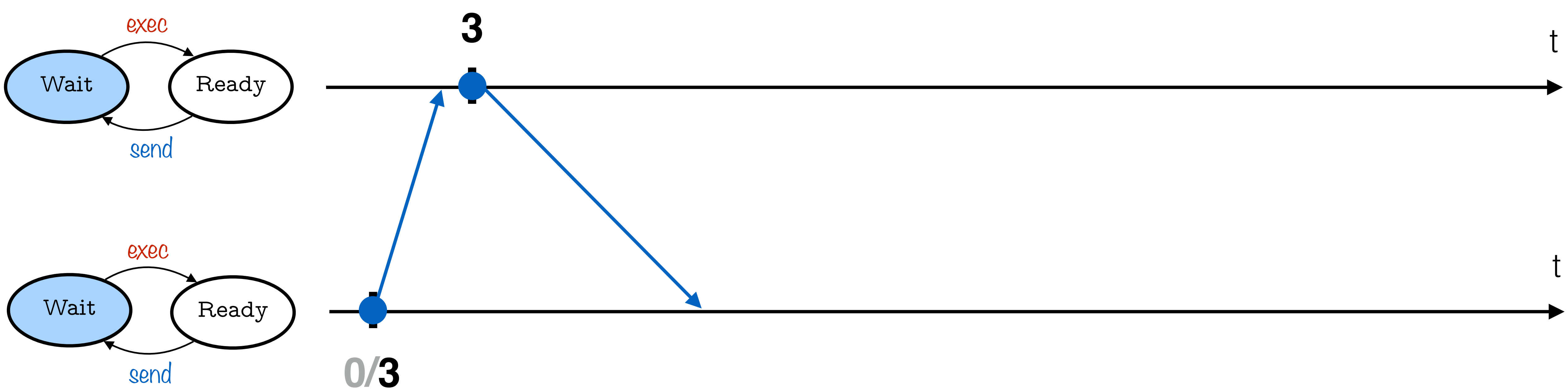

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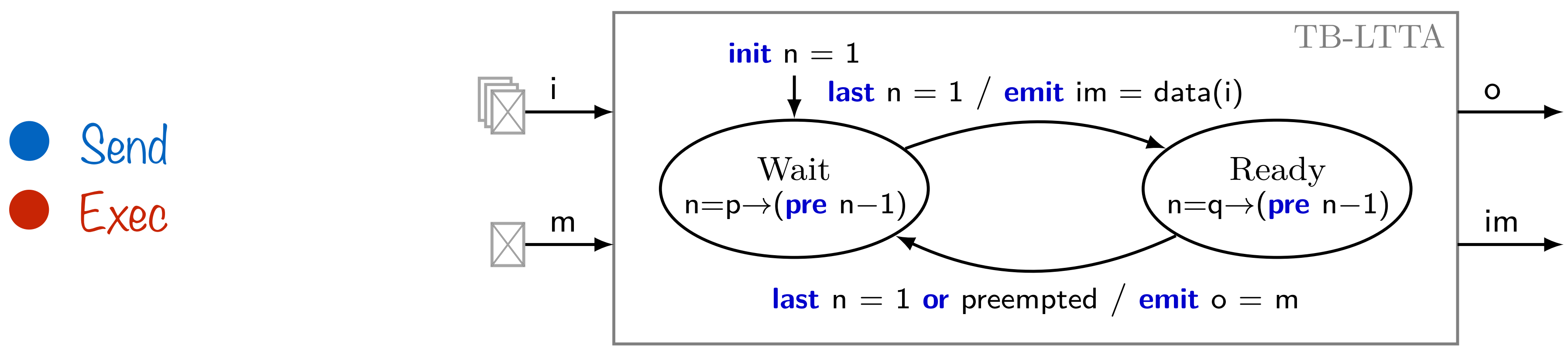

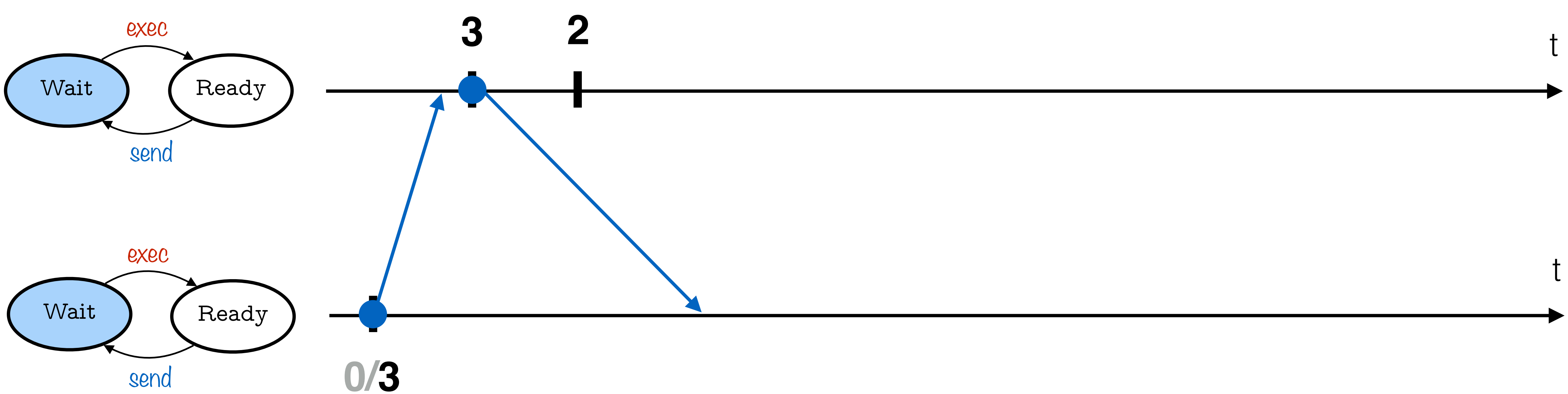

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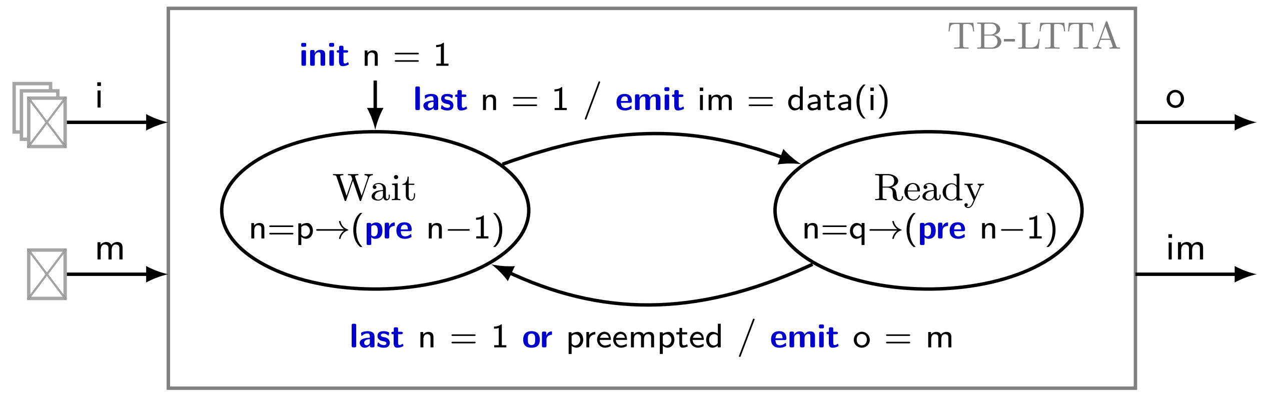

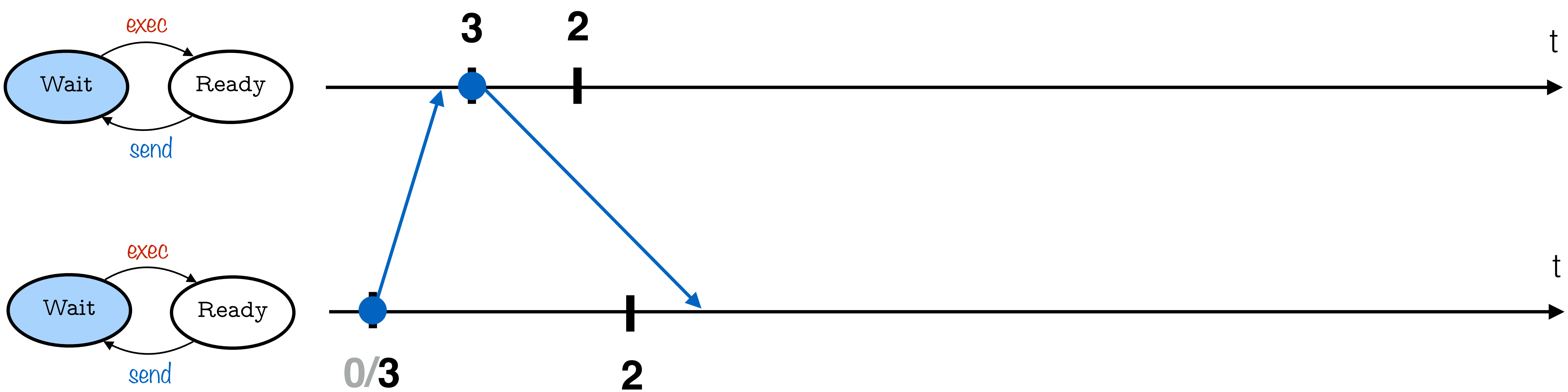

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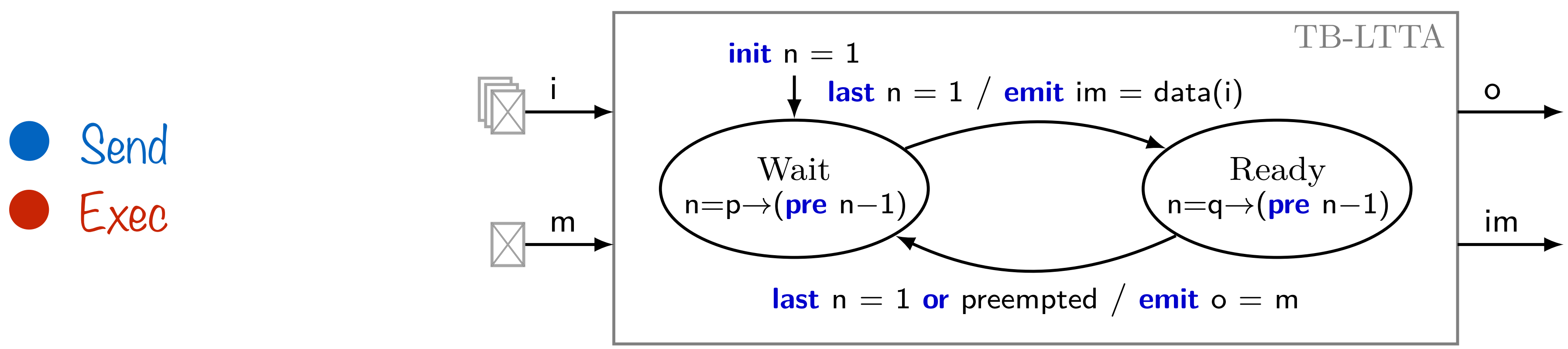

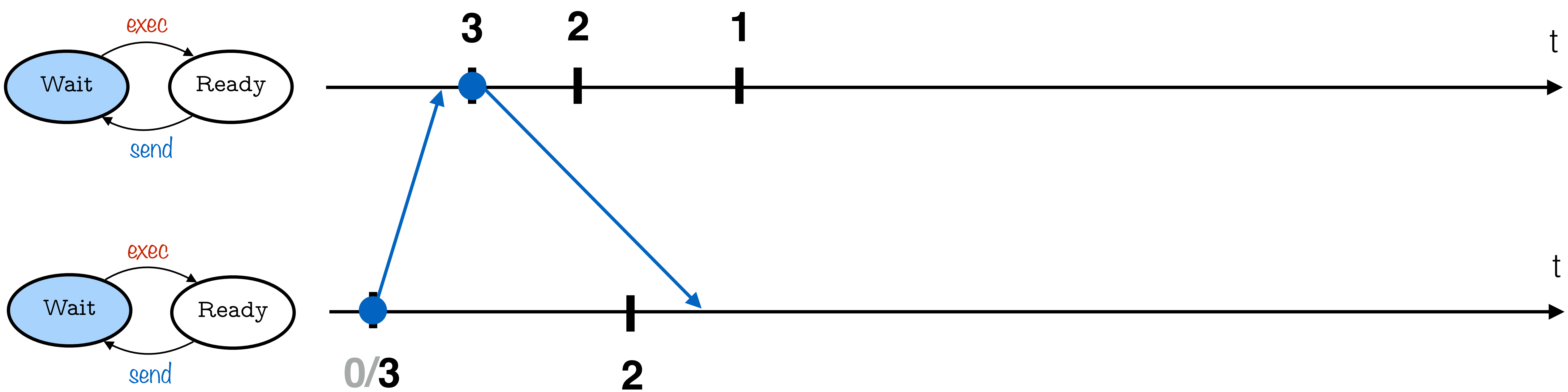

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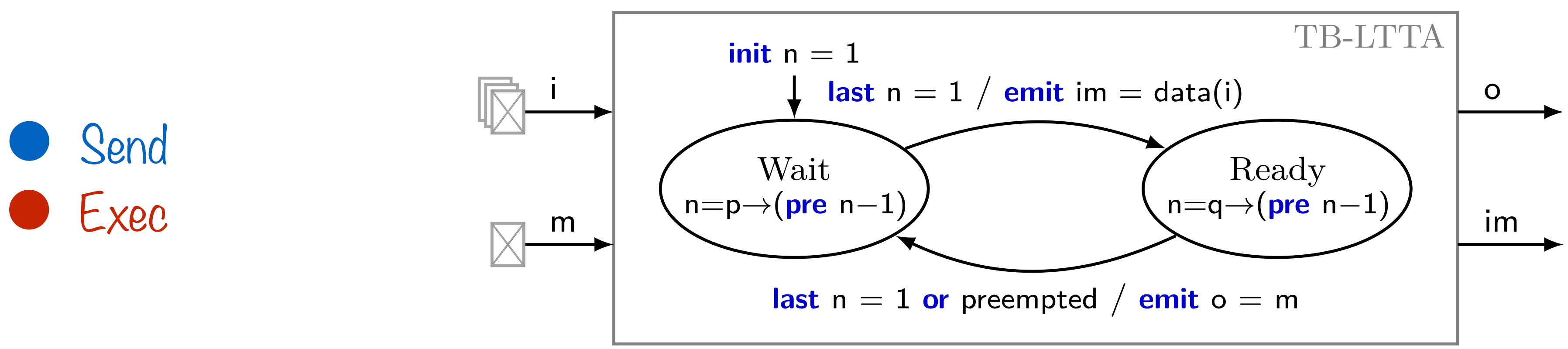

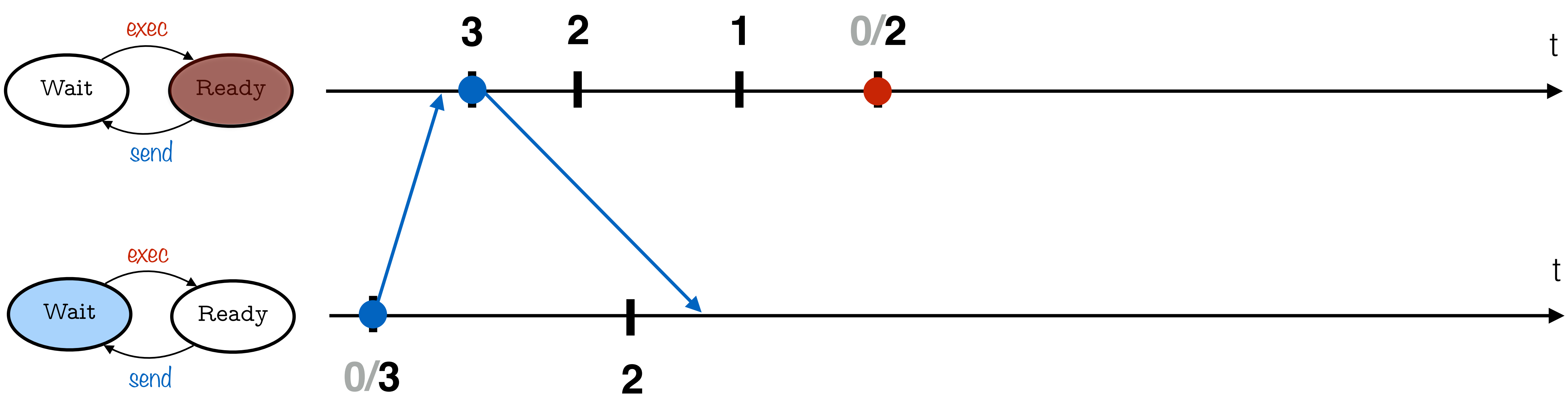

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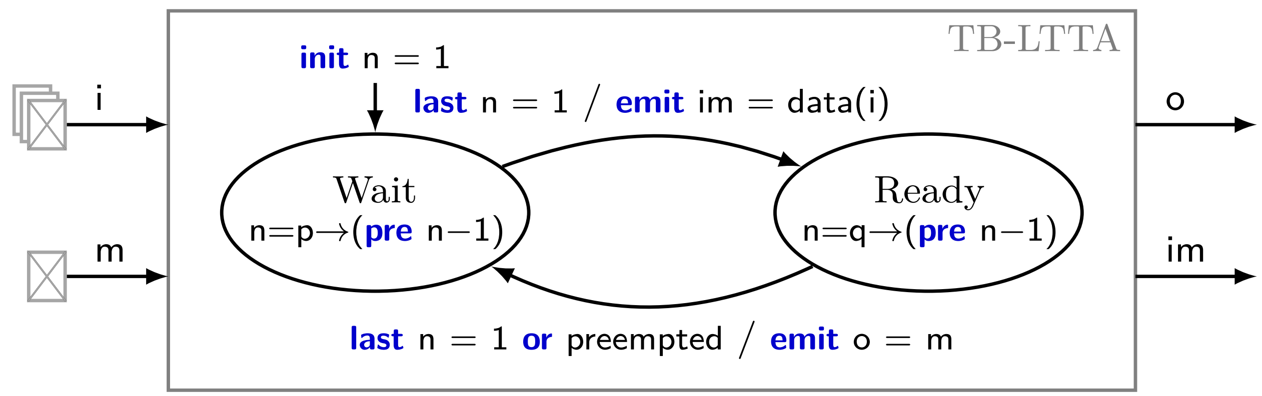

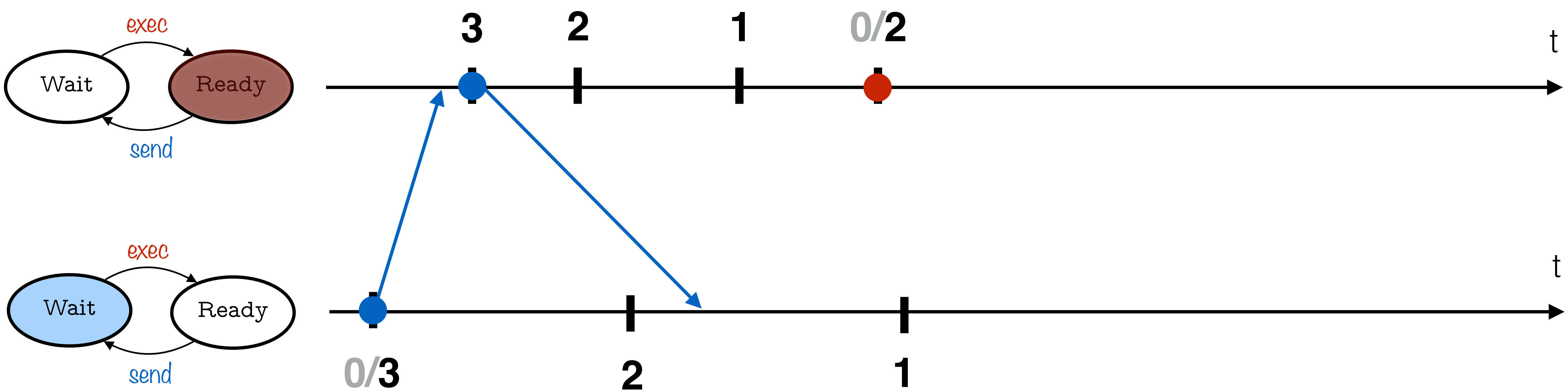

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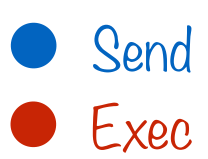

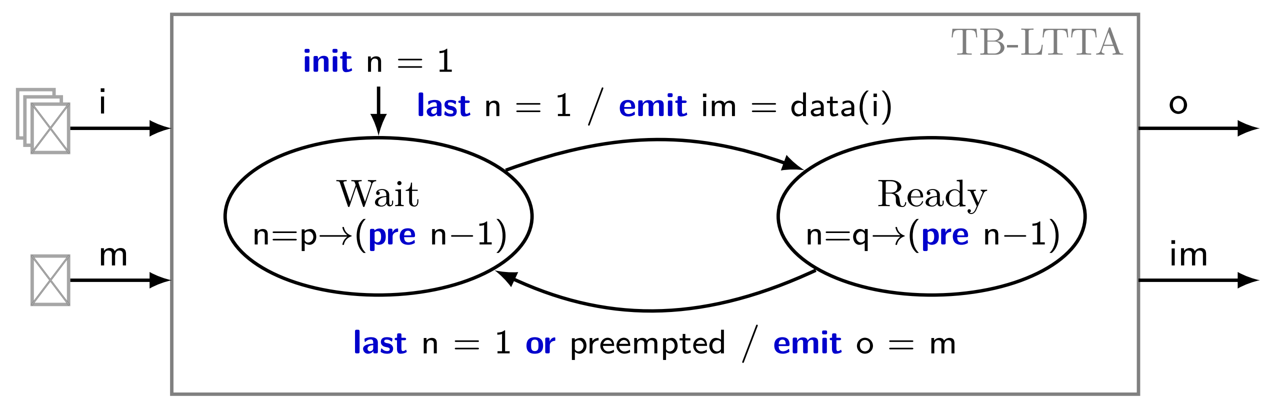

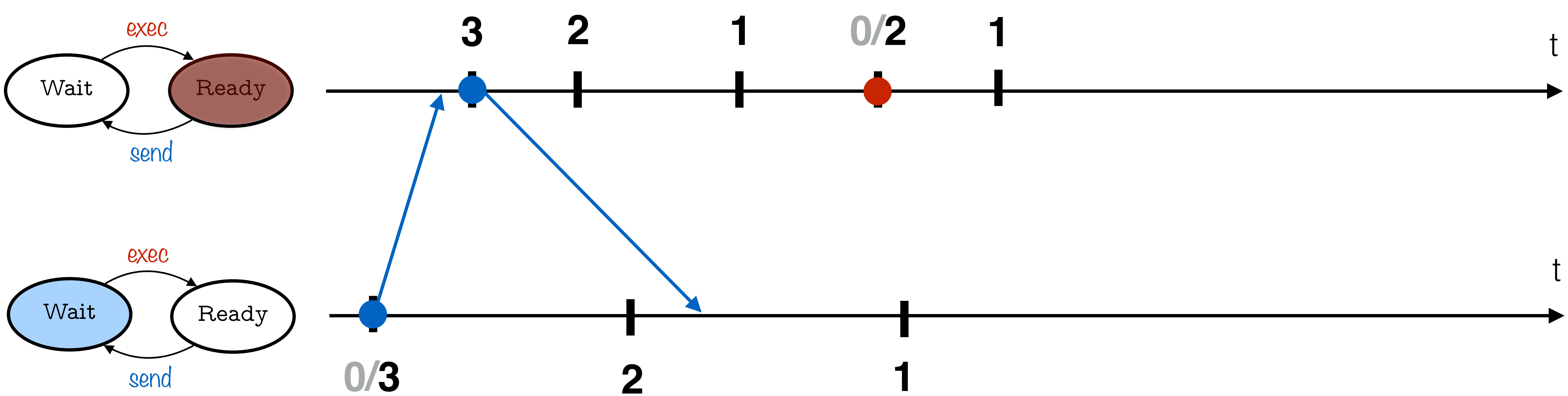

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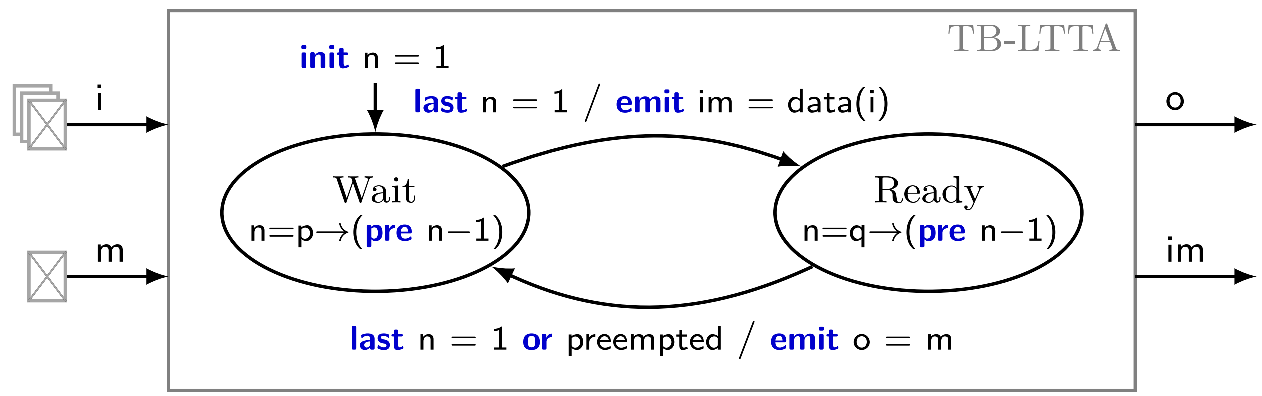

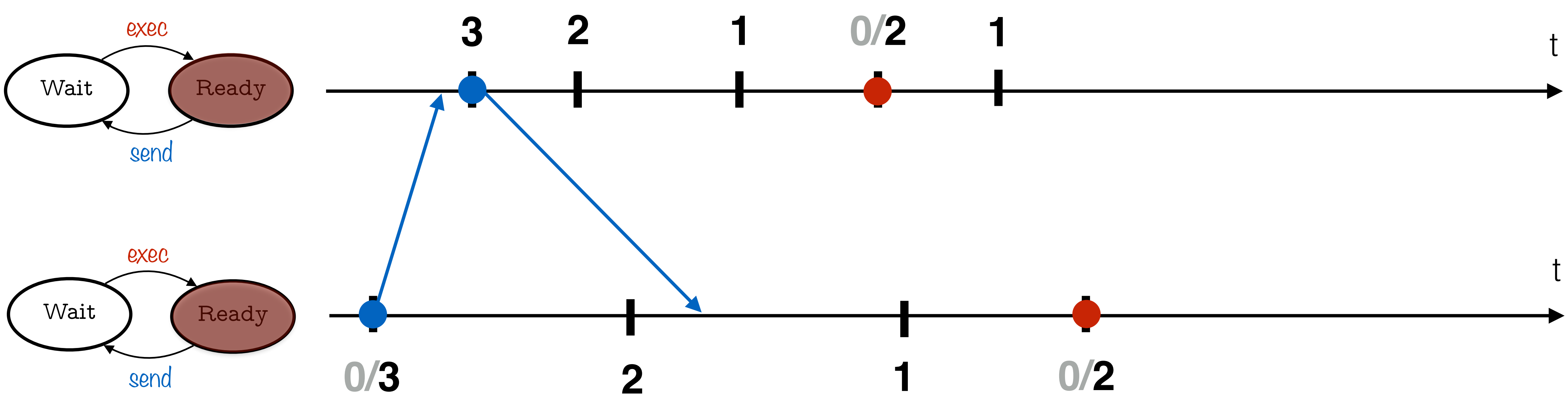

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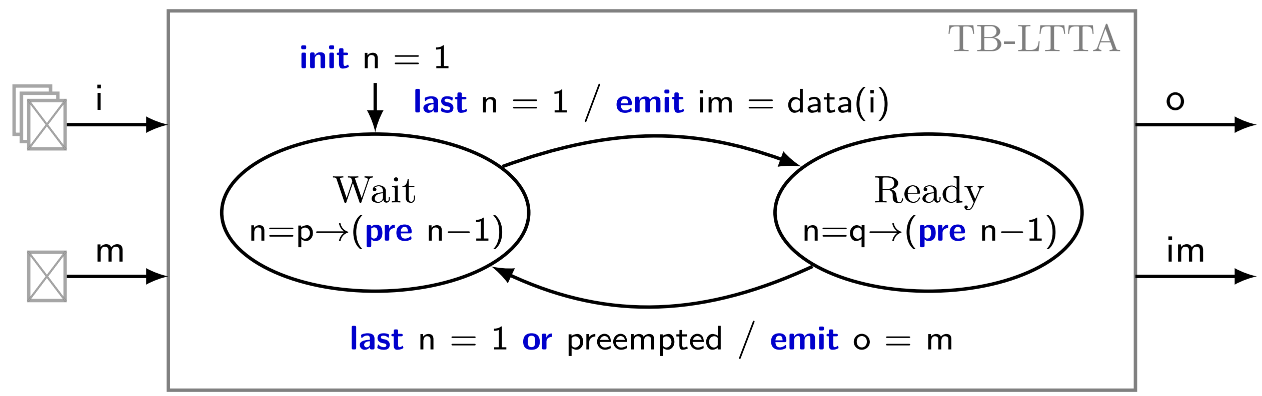

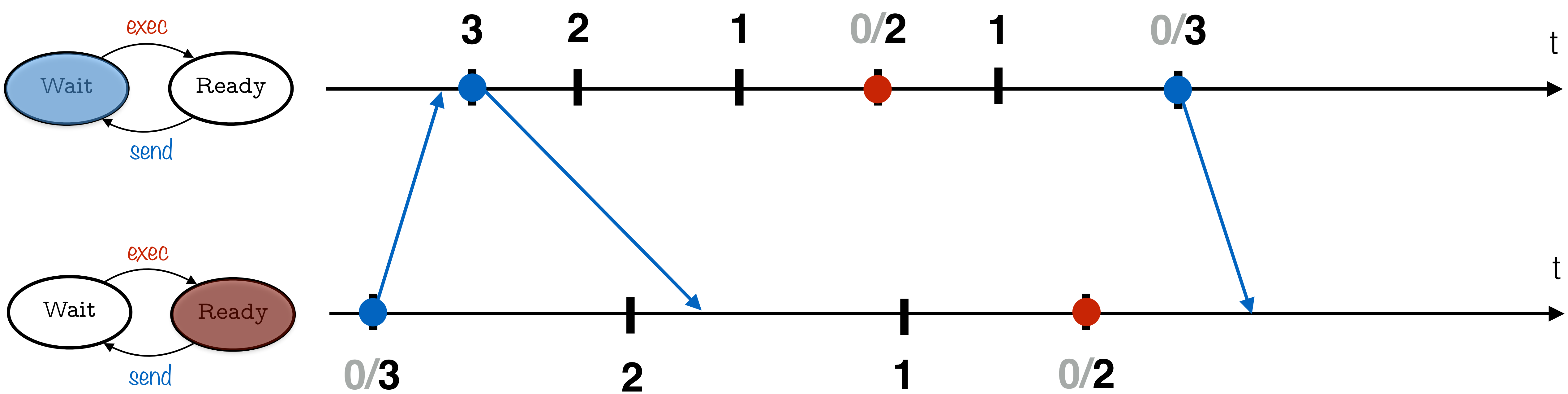

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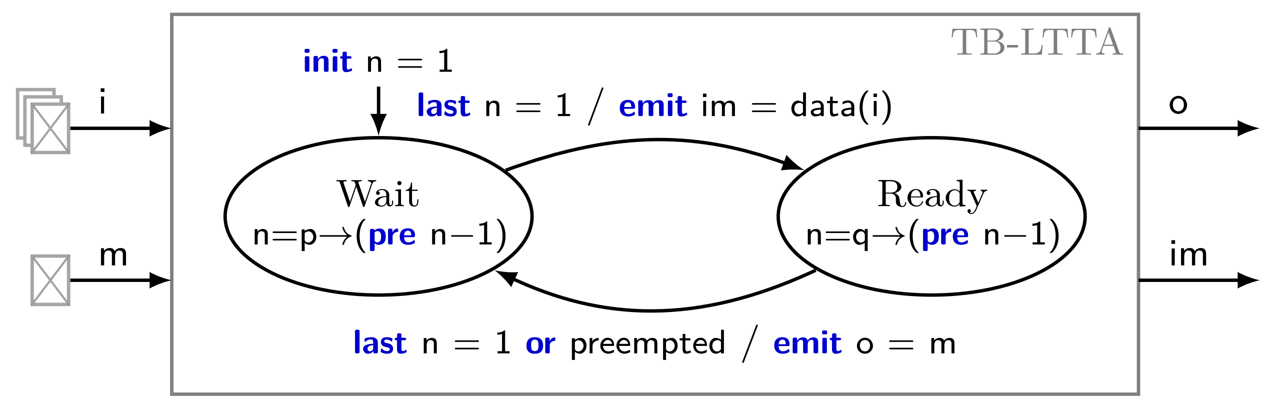

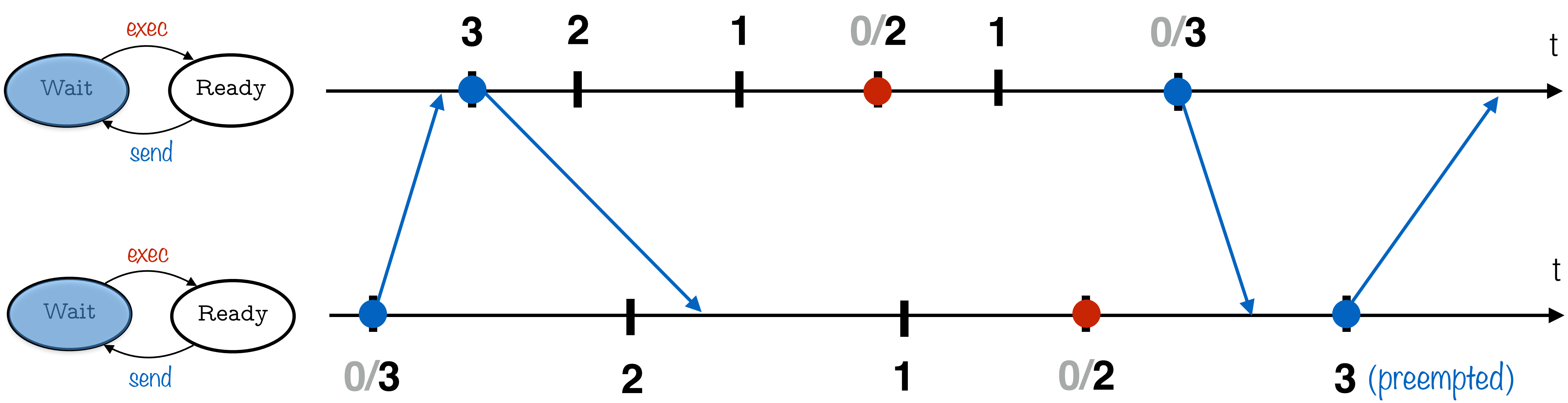

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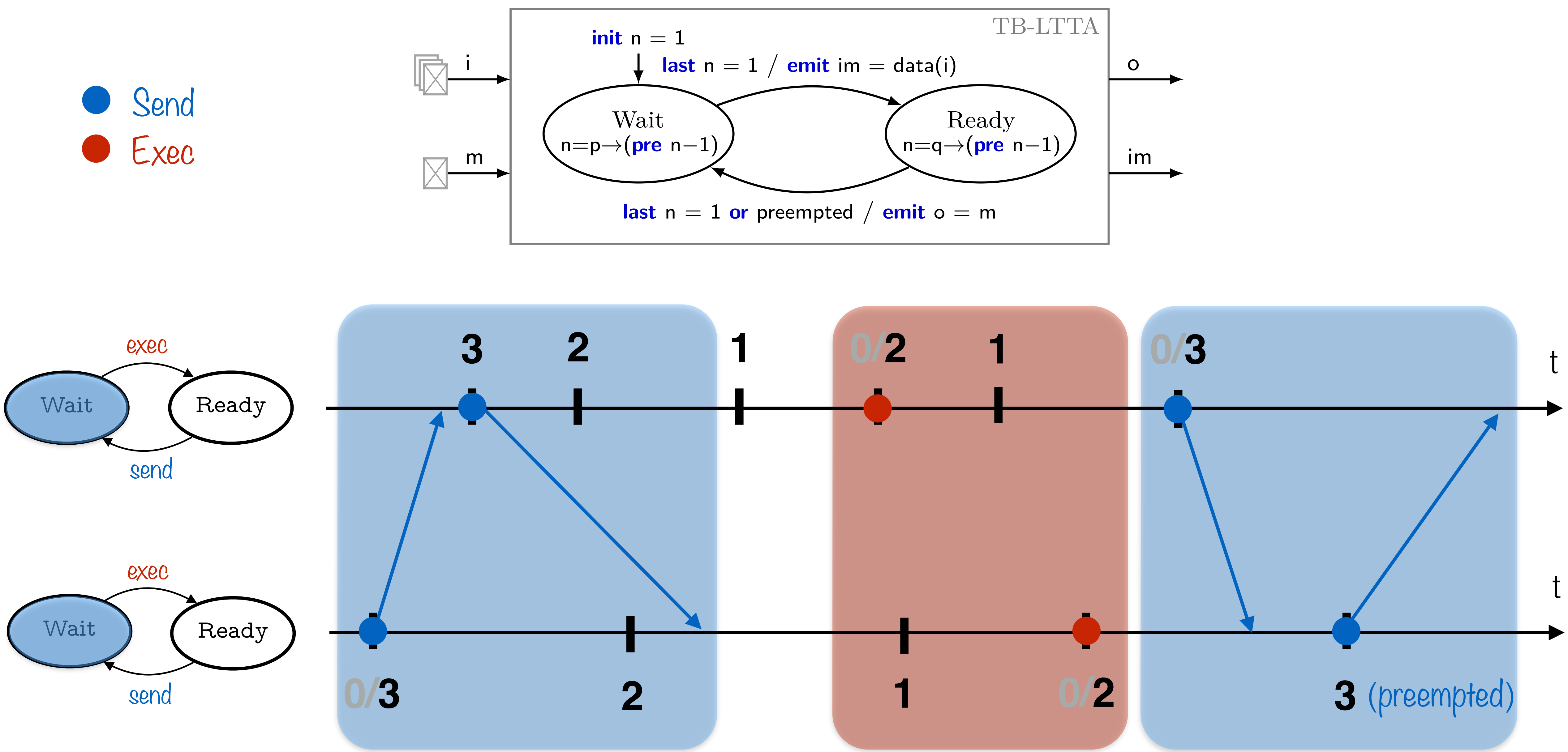


Nodes alternate between **send** and **exec** phases

Time-Based LTTA

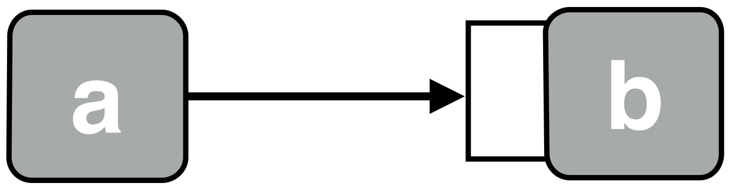
Theorem 1:
The composition of the controller and the application is always well-defined (no causality cycle).

Theorem 2:
The following constraints on the initial counter values ensure the preservation of the semantics

$$
\begin{aligned}
p &> \frac{2\tau_{max} + T_{max}}{T_{min}} \\
q &> \frac{\tau_{max} - \tau_{min} + (p+1)T_{max}}{T_{min}} - p
\end{aligned}
$$

Theorem 3:
The worst case throughput is given by $1/\lambda_{\text{TB}} = (p+q)T_{\max}$

Preservation of the Semantics



$$p > \frac{2\tau_{max} + T_{max}}{T_{min}}$$

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Property 1: $S^a_{k-1} \prec E^b_k$

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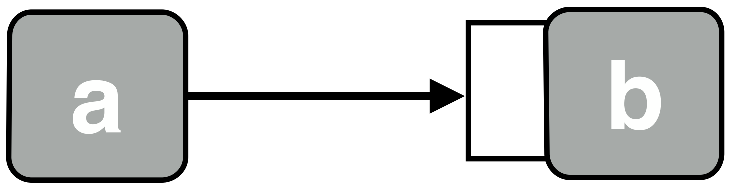

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S^b_{k-1}

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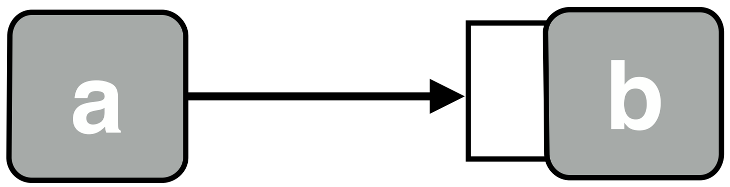

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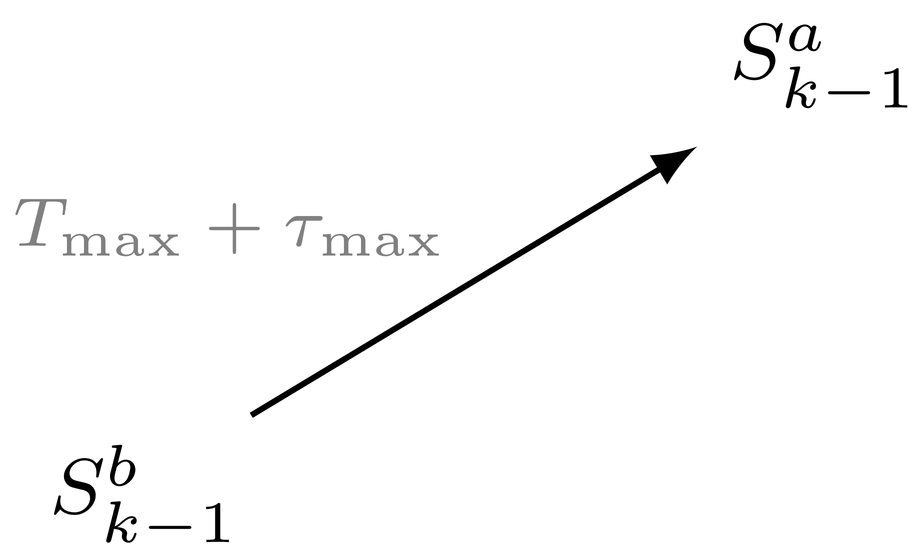

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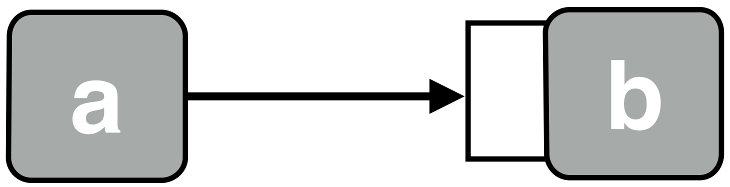

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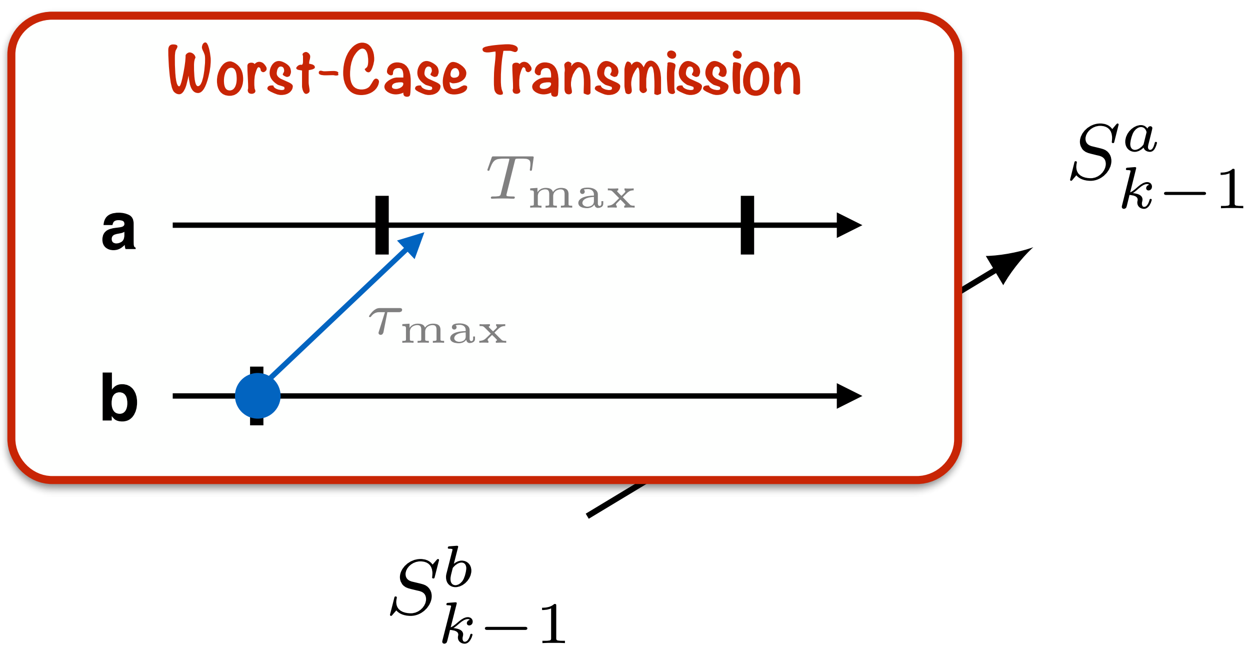

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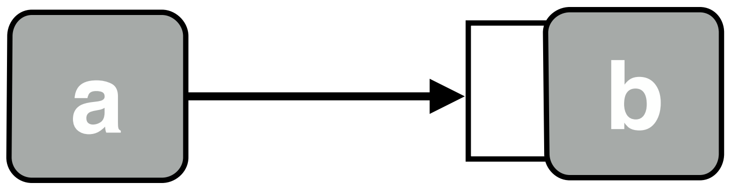

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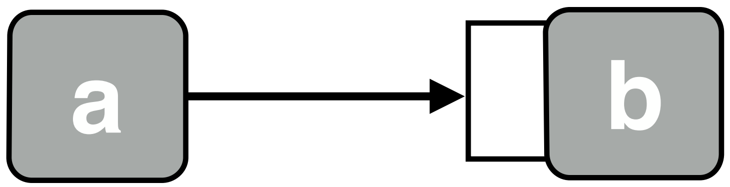
$$S^b_{k-1} \xrightarrow{T_{\max} + \tau_{\max}} S^a_{k-1}$$

Preservation of the Semantics



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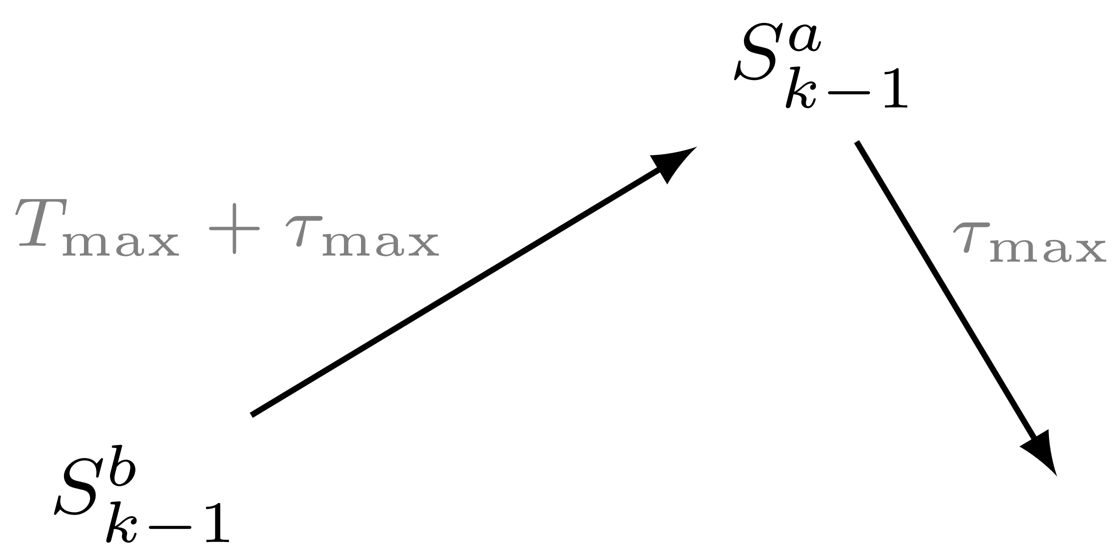

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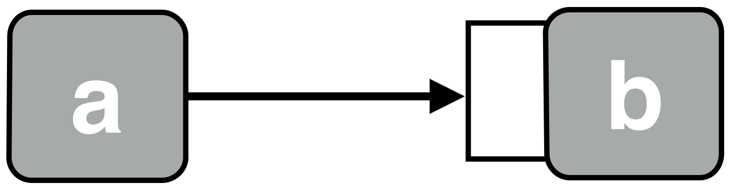

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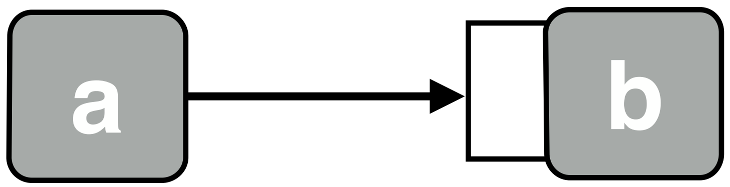
$$\begin{tikzcd}
 & S^a_{k-1} \arrow[dr, "\tau_{\max}"] & \\
S^b_{k-1} \arrow[ur, "T_{\max} + \tau_{\max}"] \arrow[rr, "pT_{\min}"'] & & E^b_k
\end{tikzcd}$$

Preservation of the Semantics



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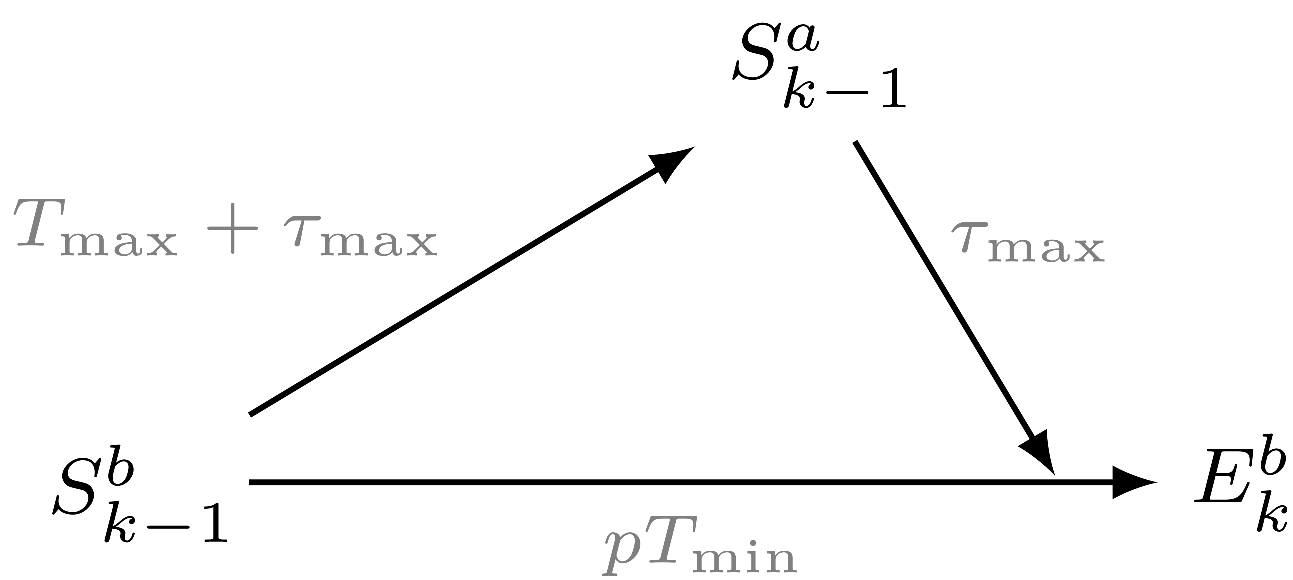

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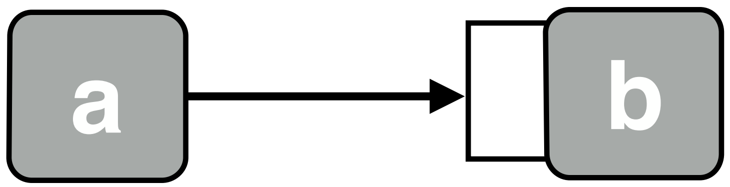

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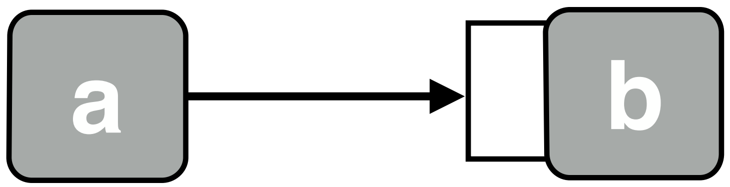
Property 2: $E^b_k \prec S^a_k$

Preservation of the Semantics



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$$q > \frac{\tau_{max} - \tau_{min} + (p+1)T_{max}}{T_{min}} - p$$

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S^a_{k-1}

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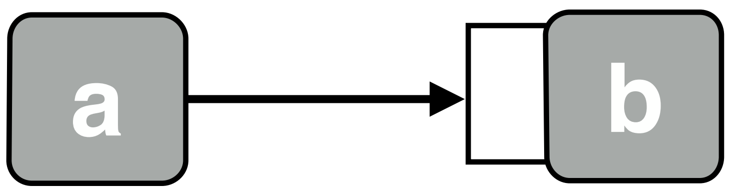

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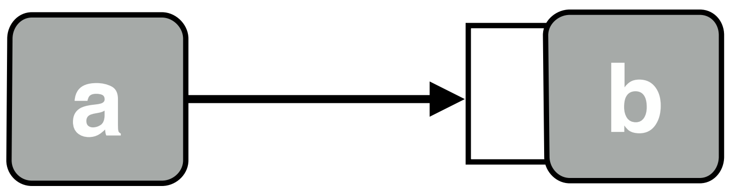

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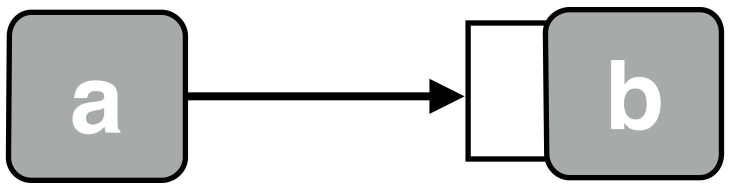

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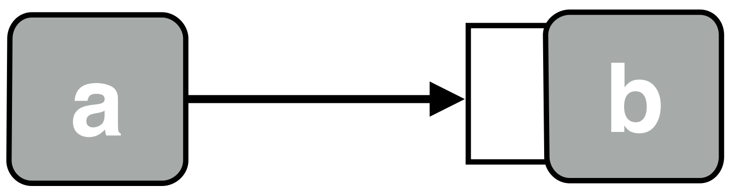
$$\begin{tikzcd} S^a_{k-1} \arrow[r, "pT_{\min}"] & E^a_k \arrow[r, "qT_{\min}"] & S^a_k \arrow[dr, "\tau_{\min}"] & \\ & & & {} \end{tikzcd}$$

Preservation of the Semantics



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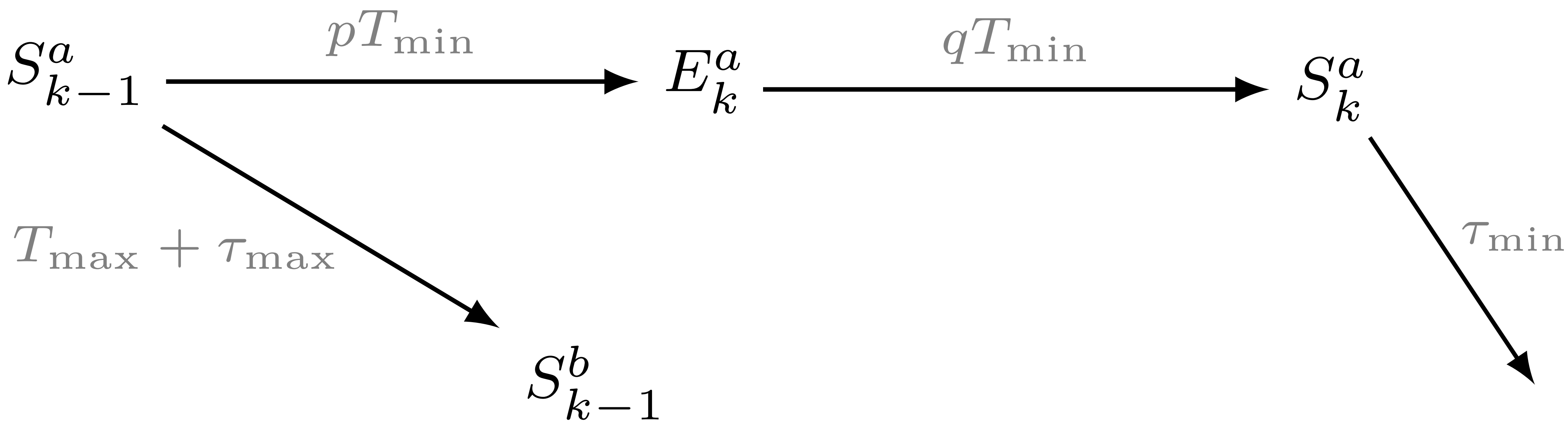

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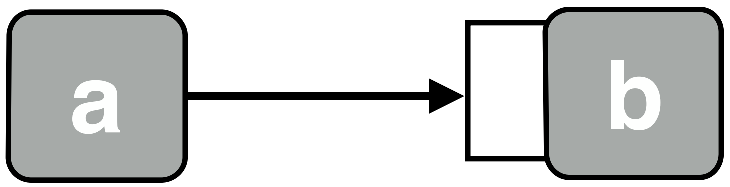

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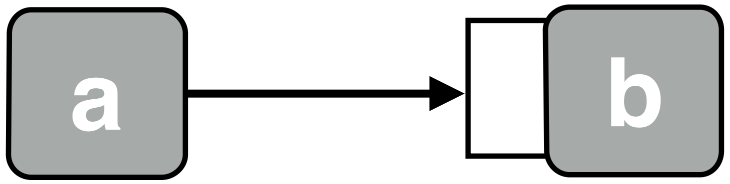
Preservation of the Semantics



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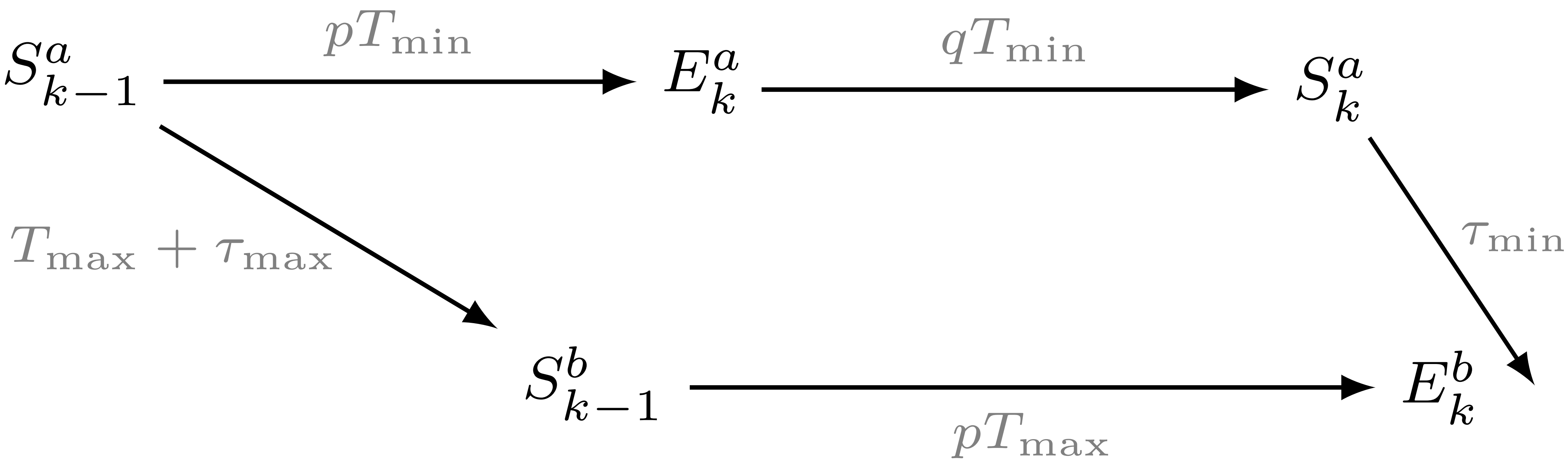
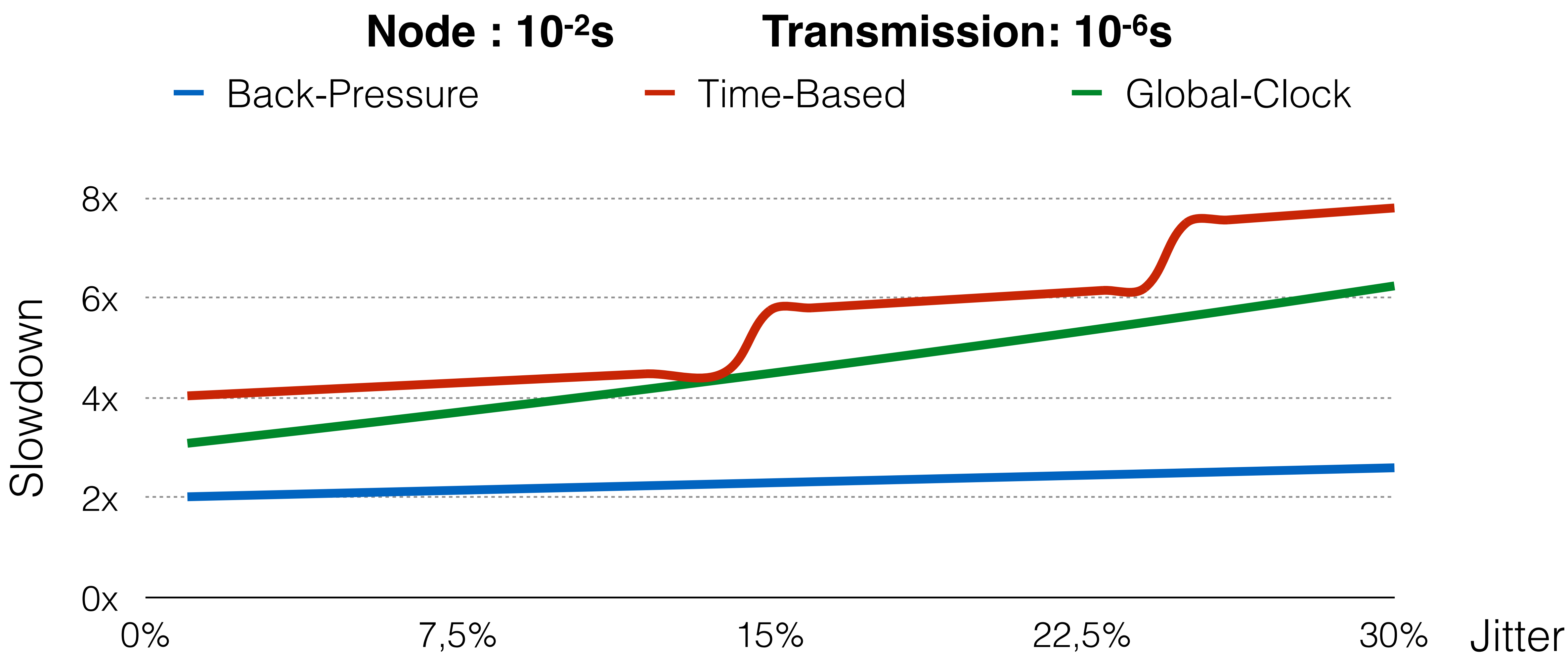


What about Clock Synchronization?

Worst-Case Evaluation

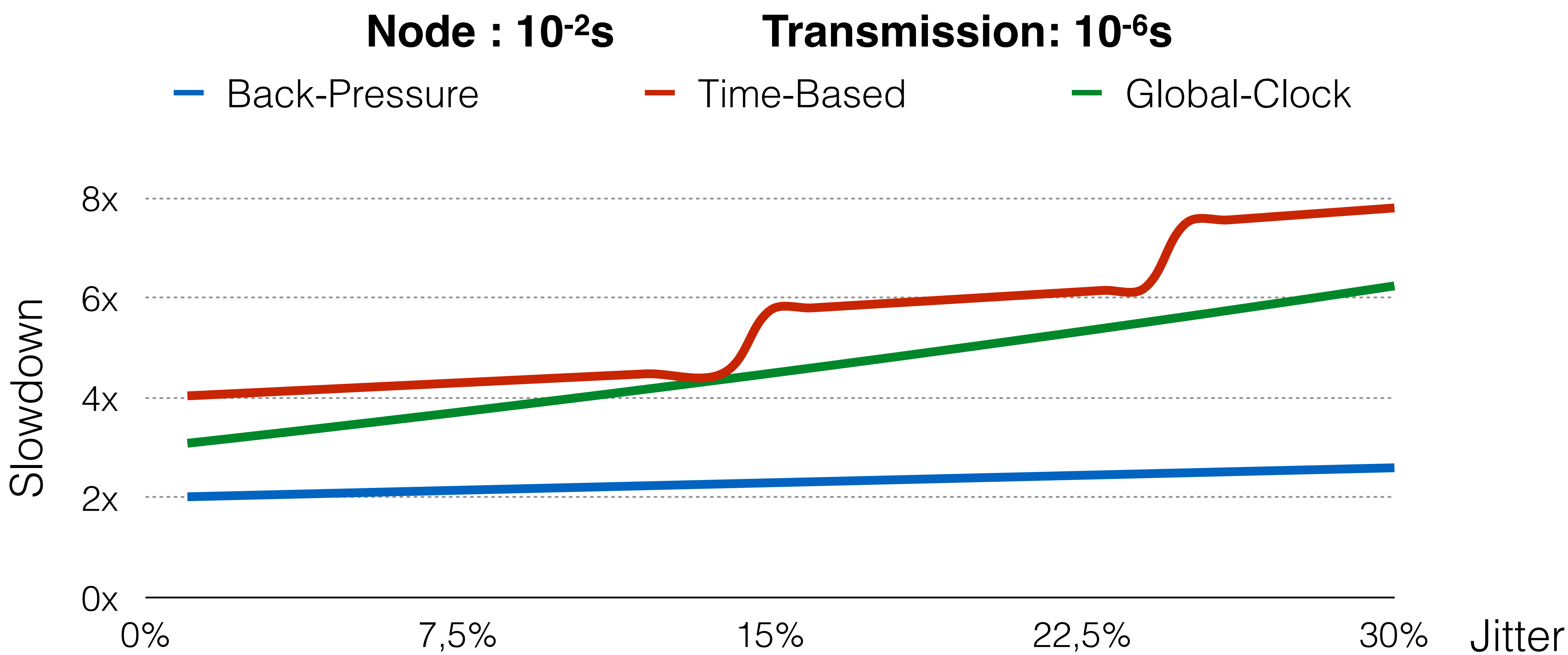
Analytical comparison with synchronous execution*



*The smaller, the better

Worst-Case Evaluation

Analytical comparison with synchronous execution*



However:

- Global-Clock is as efficient as possible
- LTTA are **simpler** protocols (two control states)
- Time-Based is the **least intrusive**

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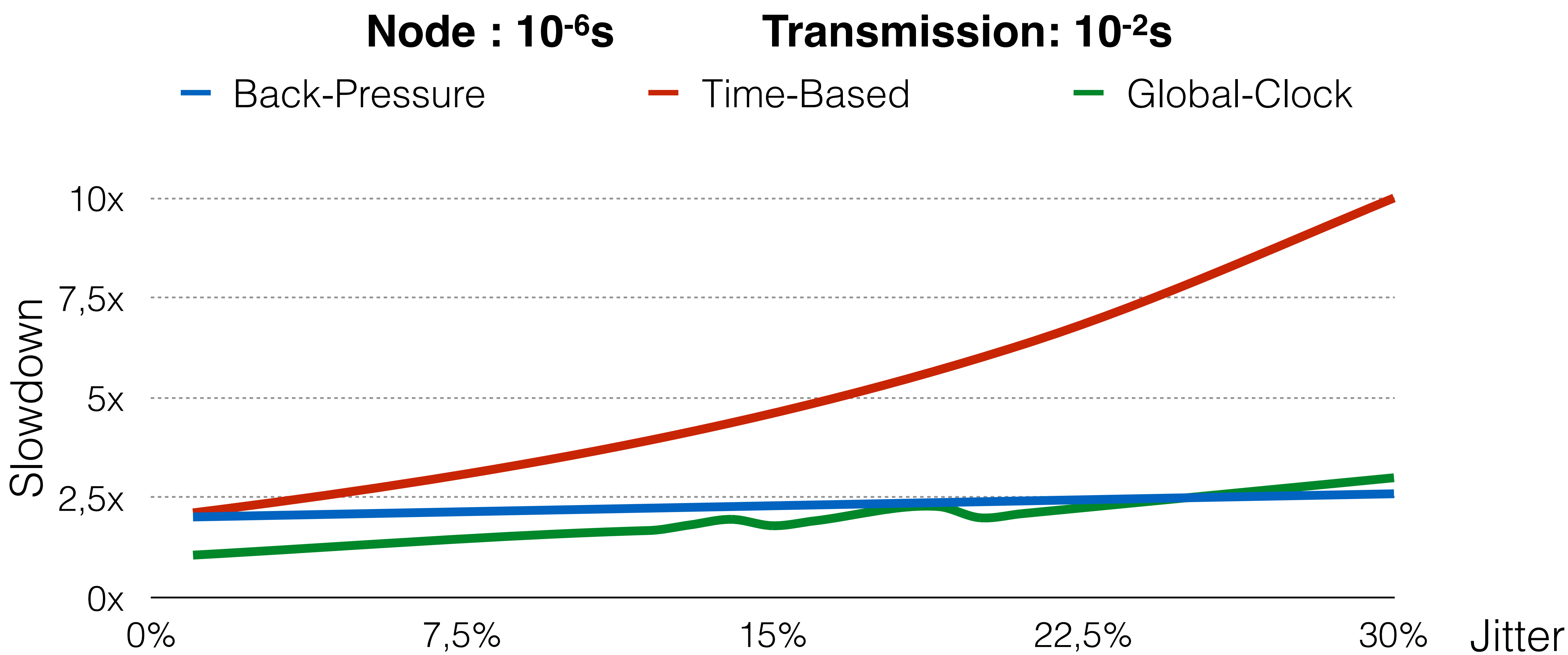

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Contributions

- Clarification of the assumptions on the synchronous application

- A unifying synchronous framework for LTTAs
  that gives executable code for simulation

- Simplification of the Time-Based protocol
  - Relaxing broadcast communication
  - No more global synchronization

- Theoretical comparison with clock synchronization deployed on the same architecture

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  Erratum

- Theoretical comparison with clock synchronization deployed on the same architecture