A Synchronous View of Loosely Time-Triggered Architectures

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Séminaire 68NQRT'15

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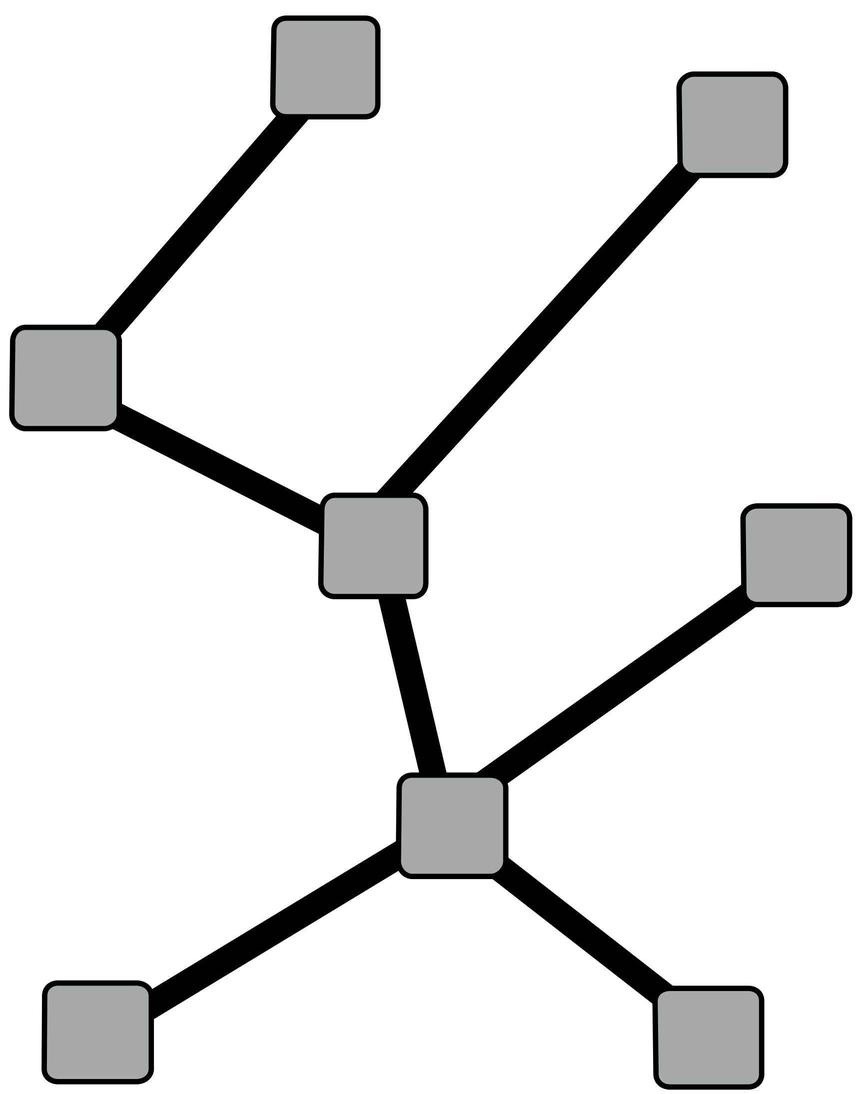
Overview



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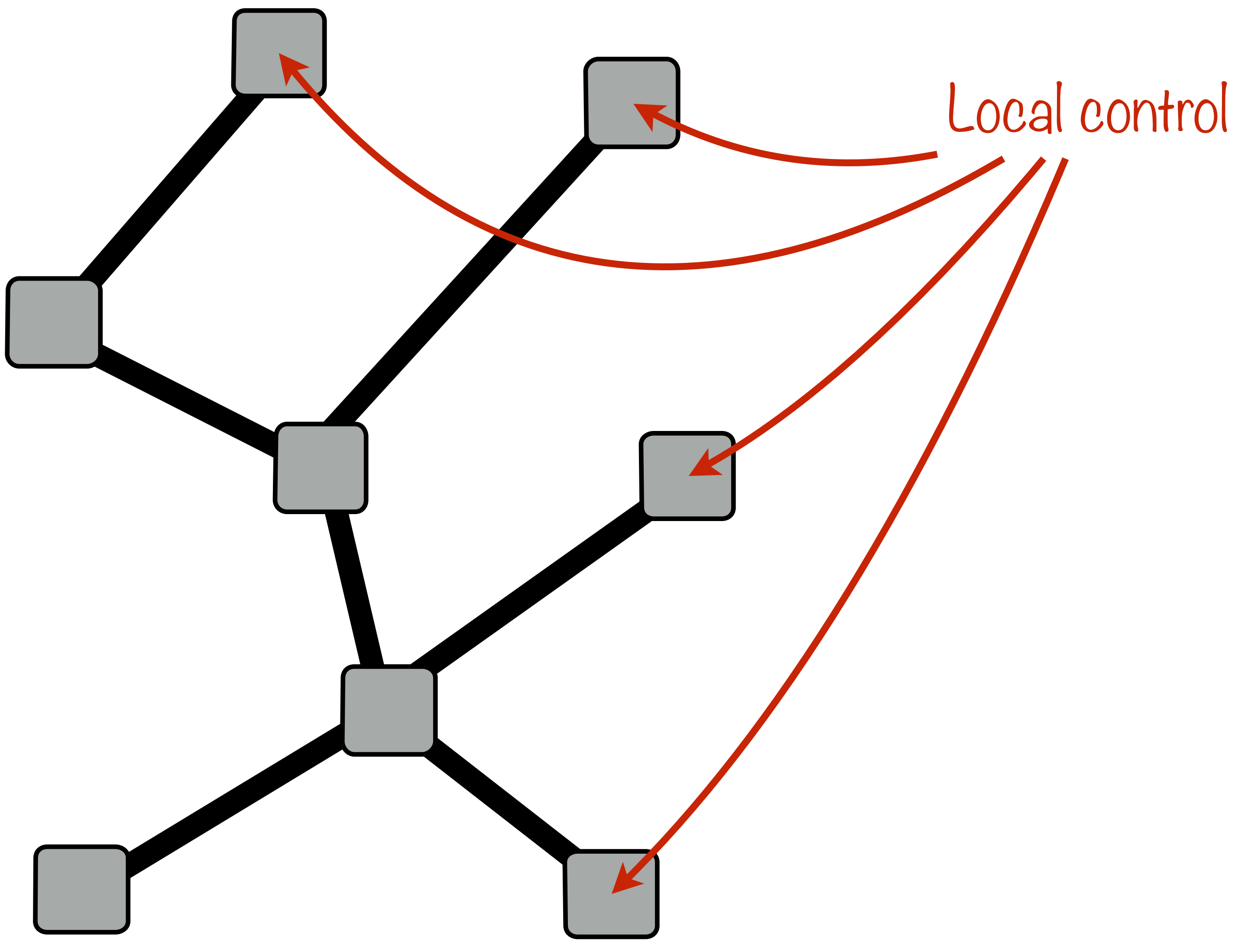

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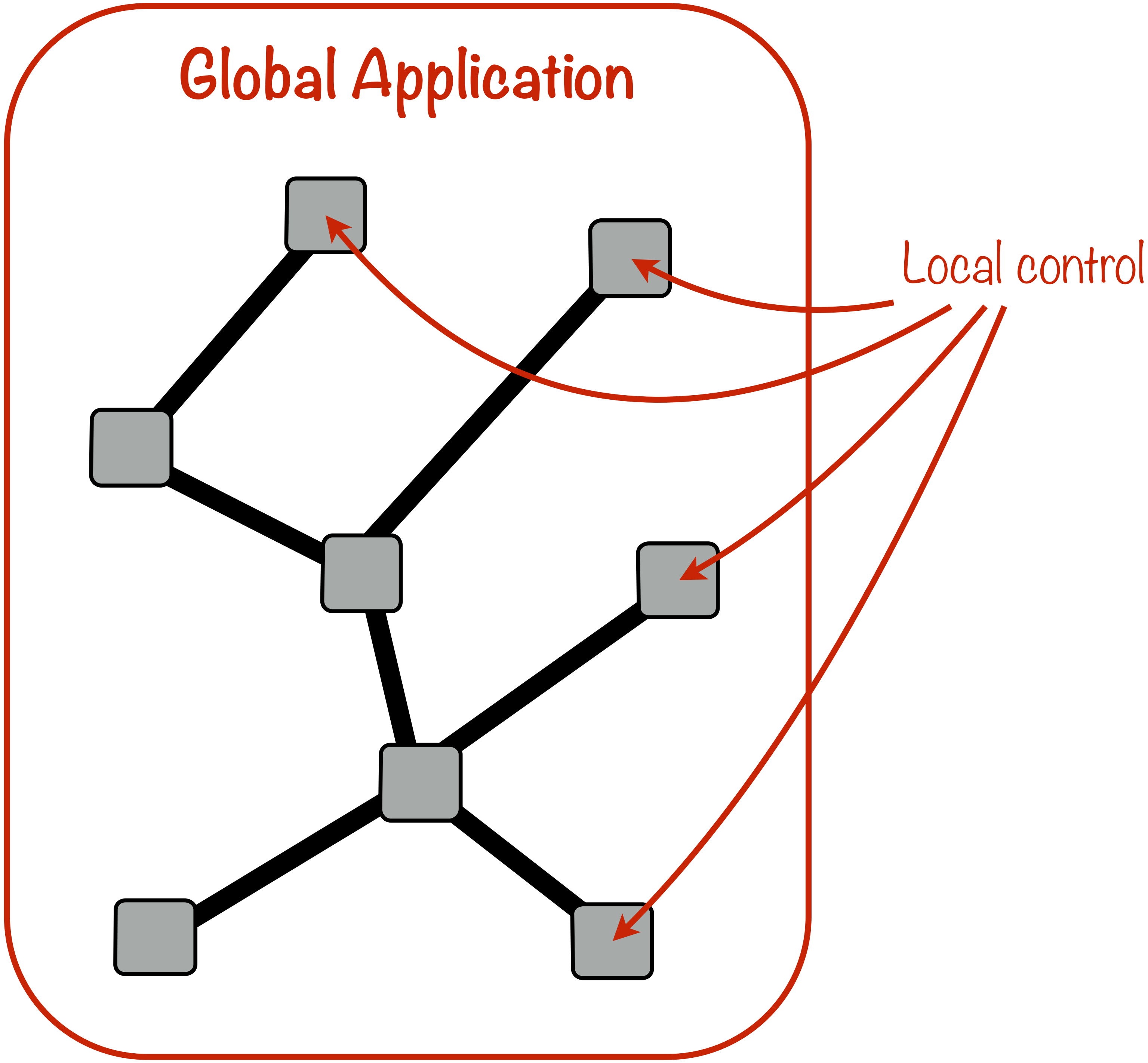

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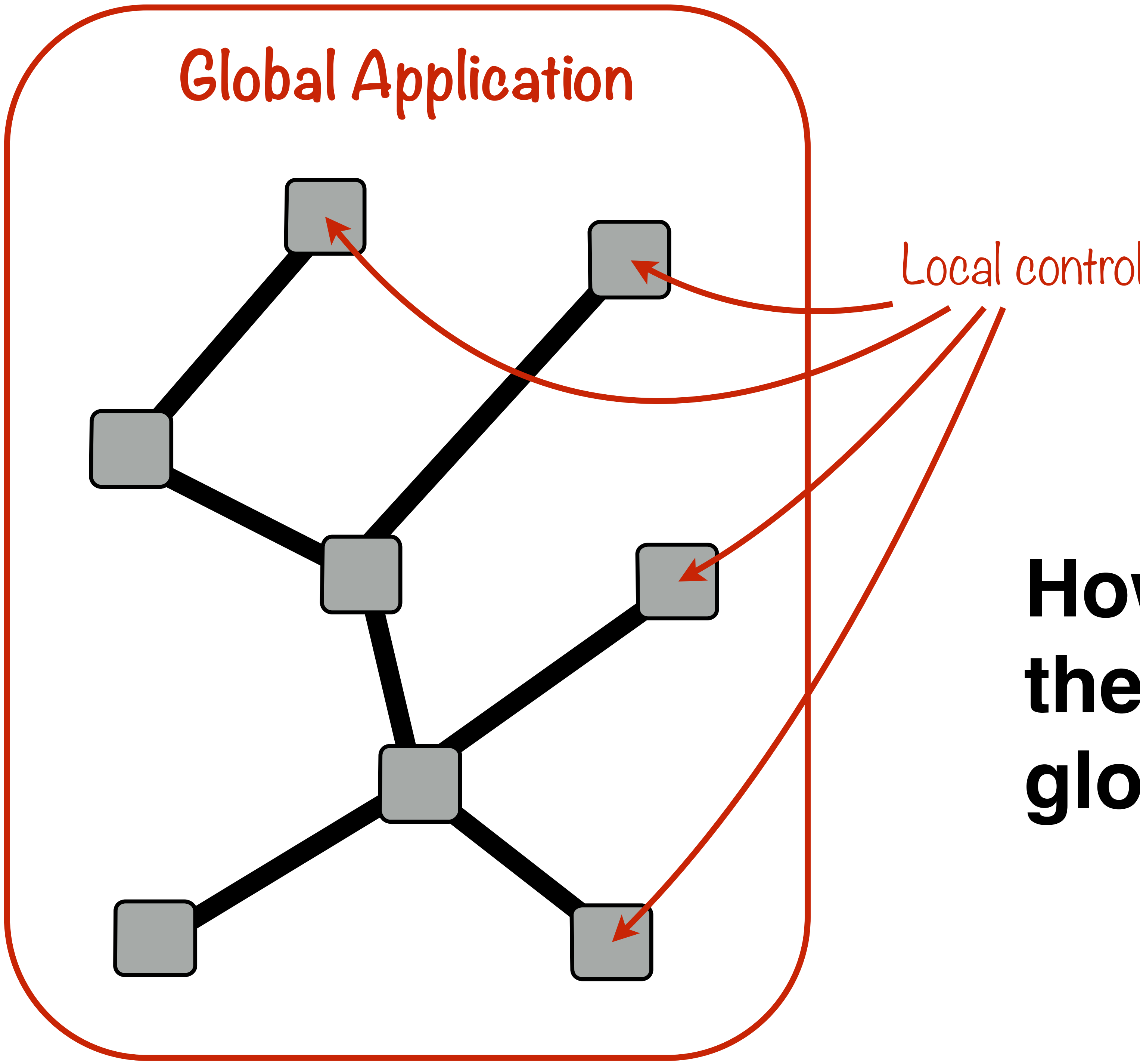
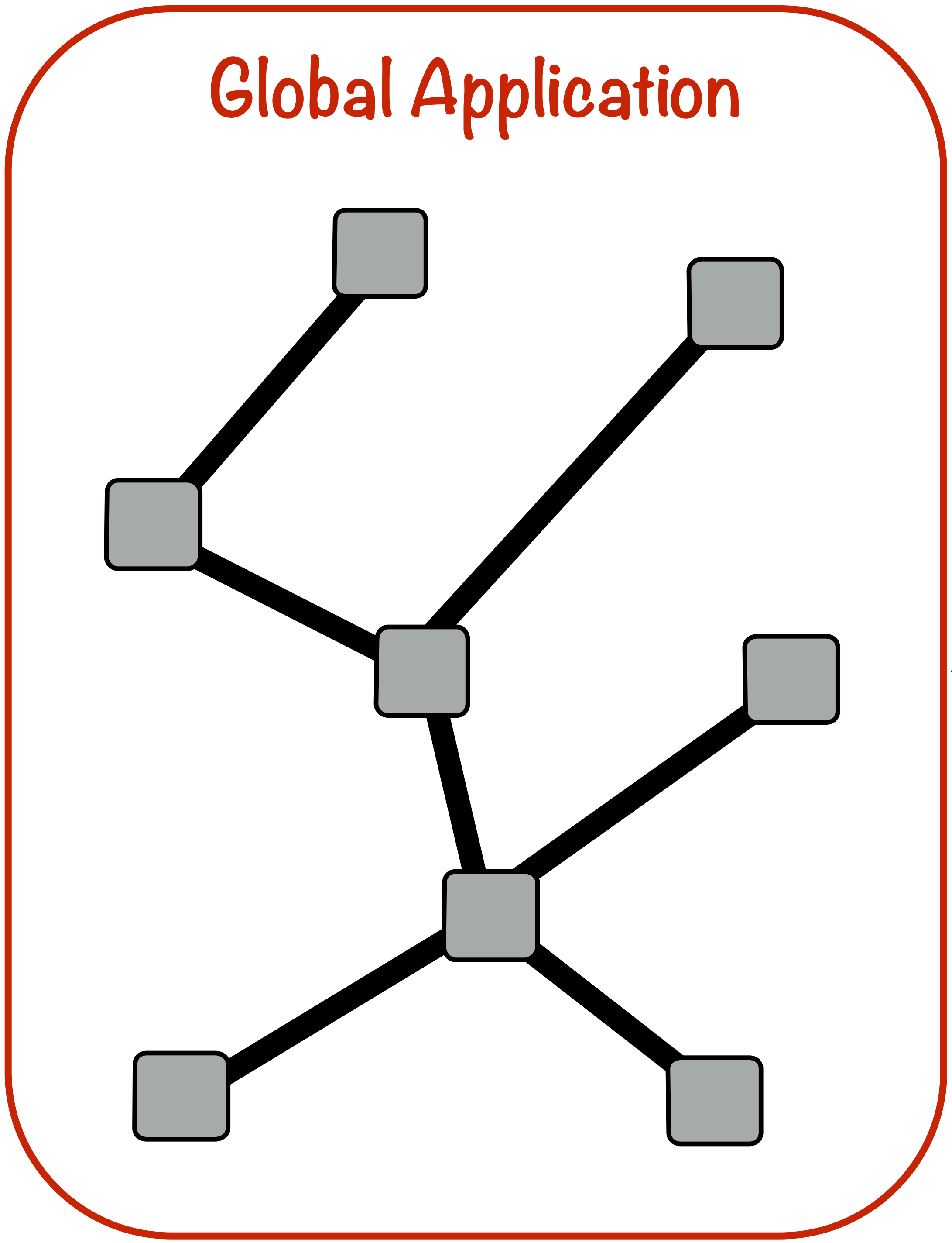


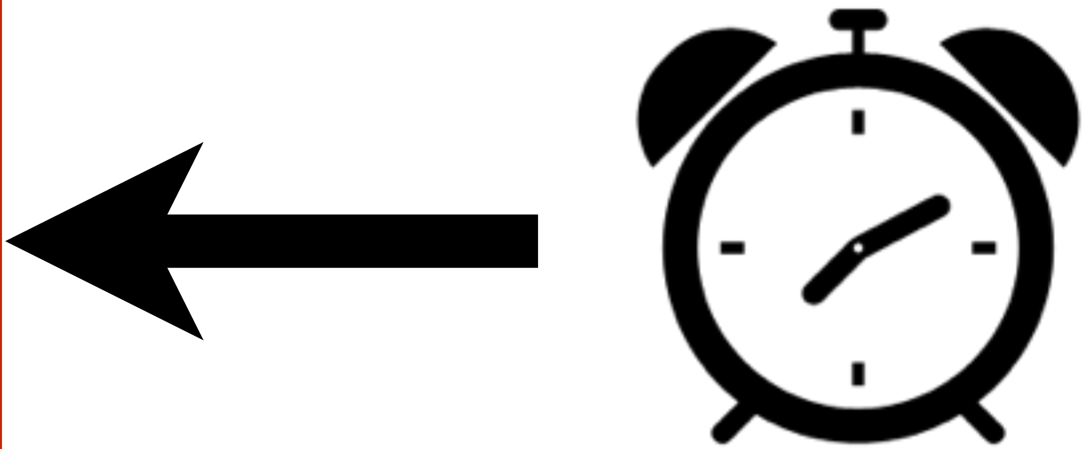
How to preserve the semantics of the global application?

Overview



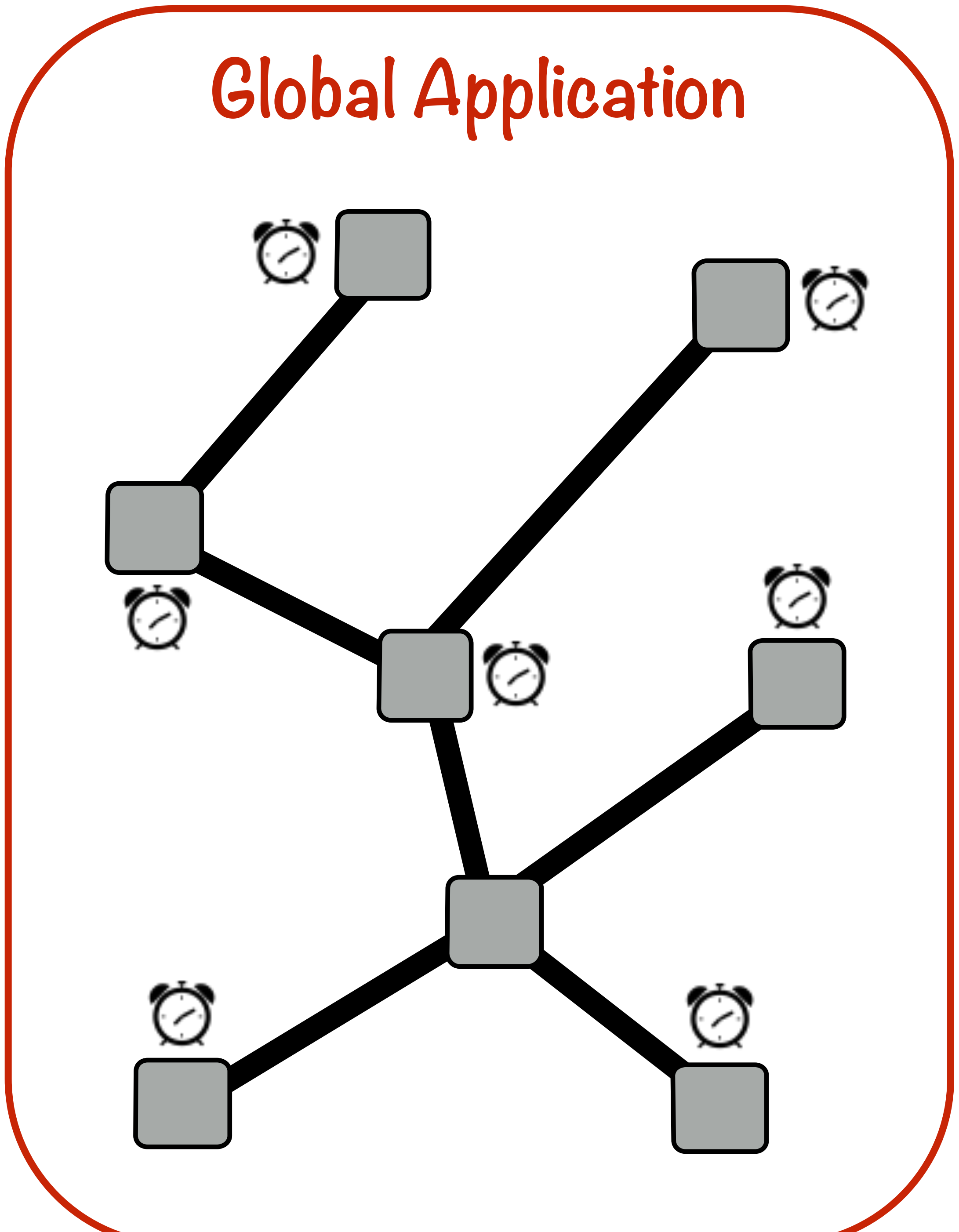
Clock synchronization

eg. TTA [Kopetz, Bauer 2003]



Introduces control dependencies between nodes.

Overview



Unsynchronized nodes + Middleware = LTTA

[Tripakis et al. 2008]
[Caspi, Benveniste 2008]

Less constraining protocols.
Limited control dependencies.

Outline

1. What is an LTTA?
    1. Quasi-Periodic Architecture
    2. Synchronous Applications

2. General Framework

3. The two protocols
    1. Back-Pressure LTTA
    2. Time-Based LTTA

4. What About Clock Synchronisation?

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Quasi-Periodic Architecture

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

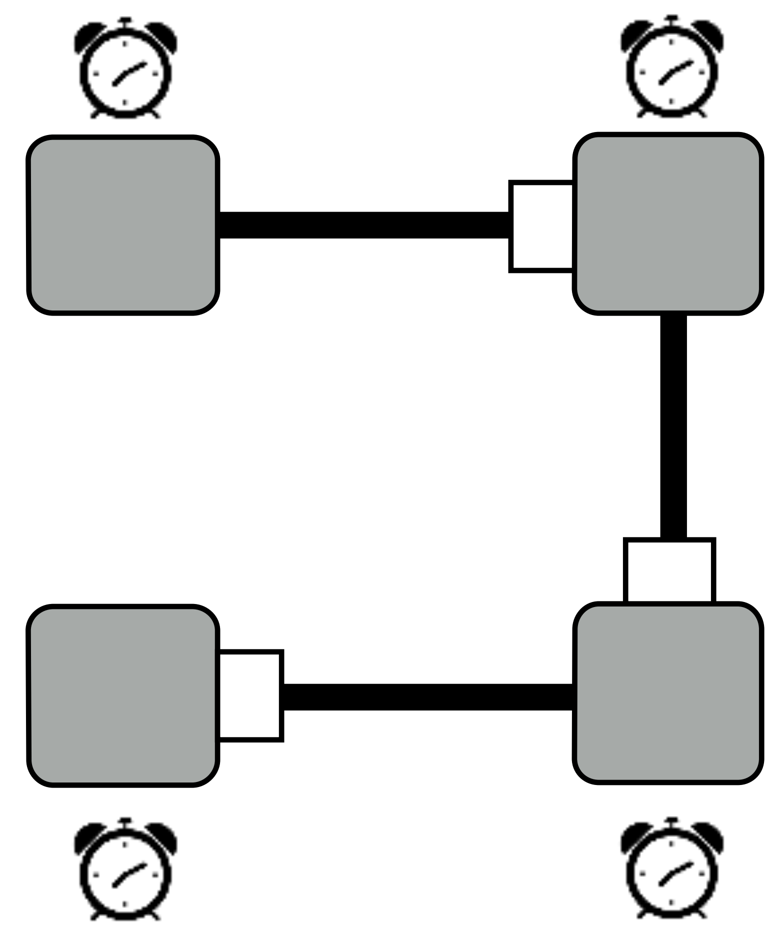
$$0 < T_{\min} \leq T^n \leq T_{\max} \quad \text{or}$$
$$T^n - \varepsilon \leq \kappa_i - \kappa_{i-1} \leq T^n + \varepsilon$$

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

- Buffered communication without message inversion or loss

- Bounded communication delay

$$\tau_{\min} \leq \tau \leq \tau_{\max}$$



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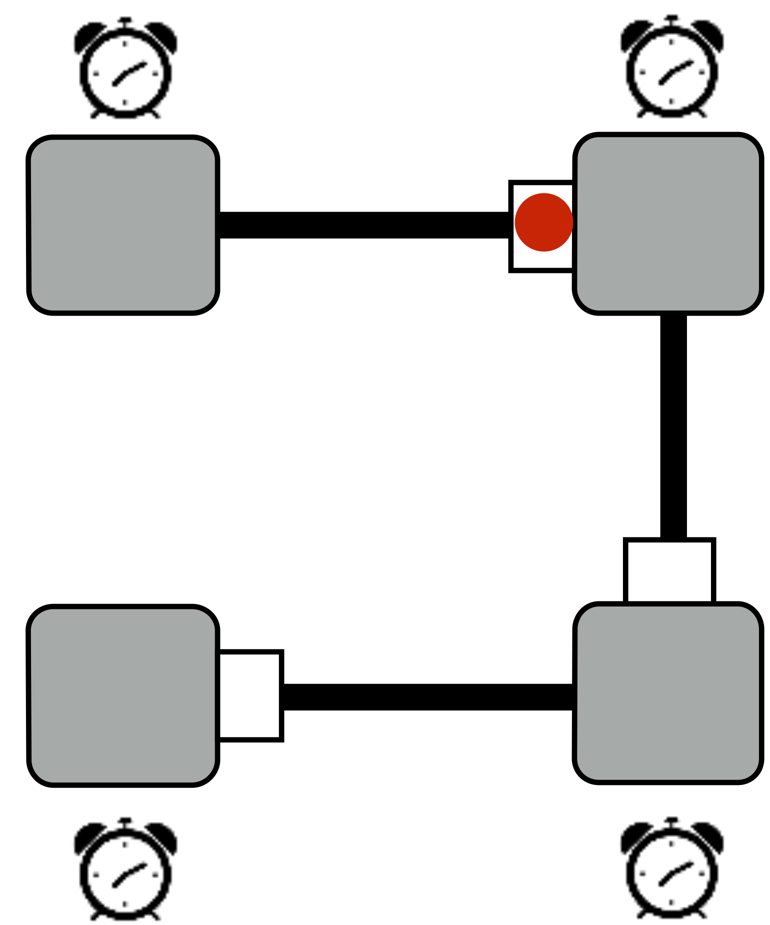

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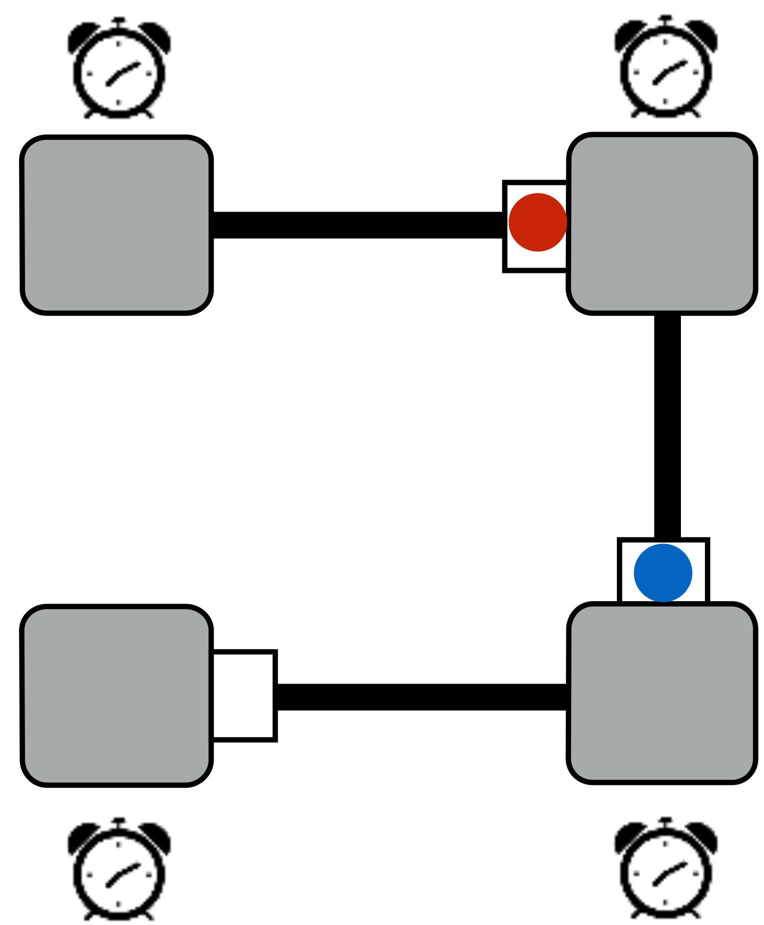
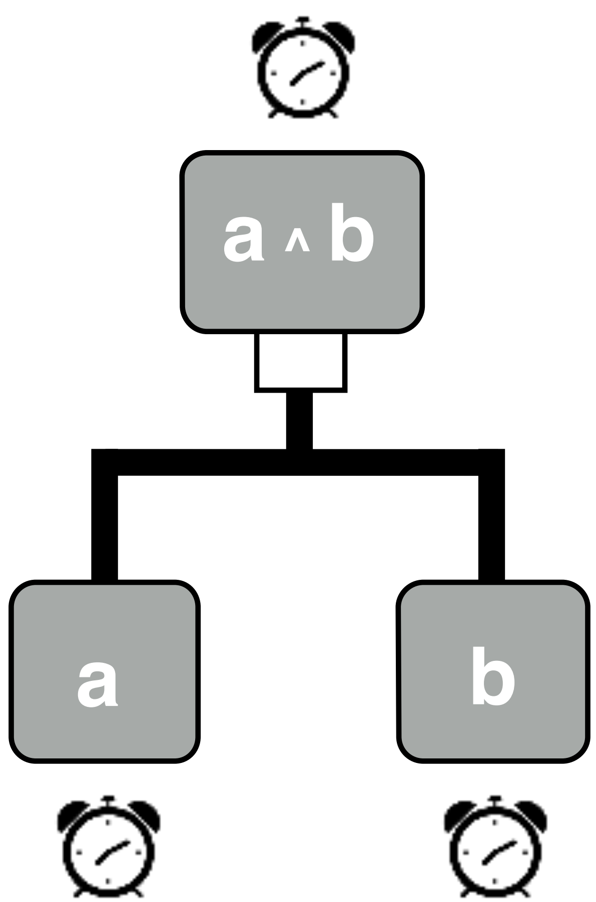
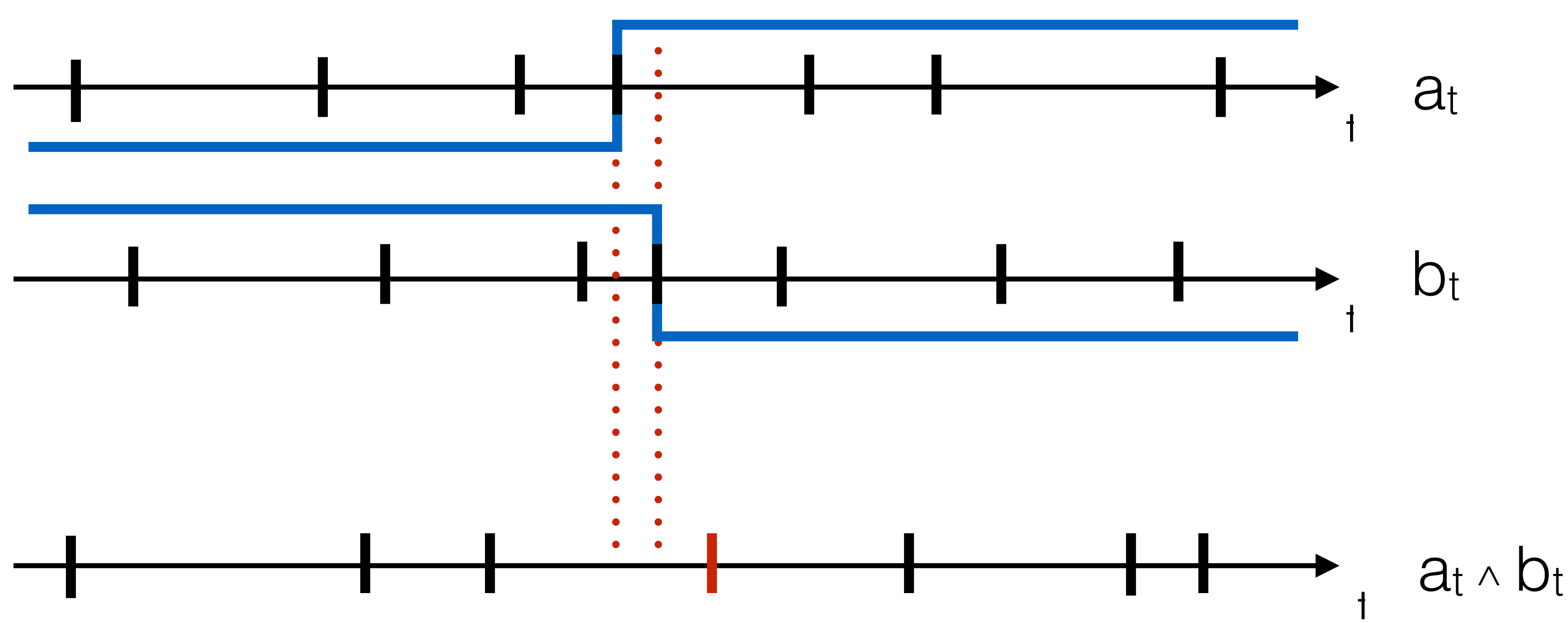


Problems

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





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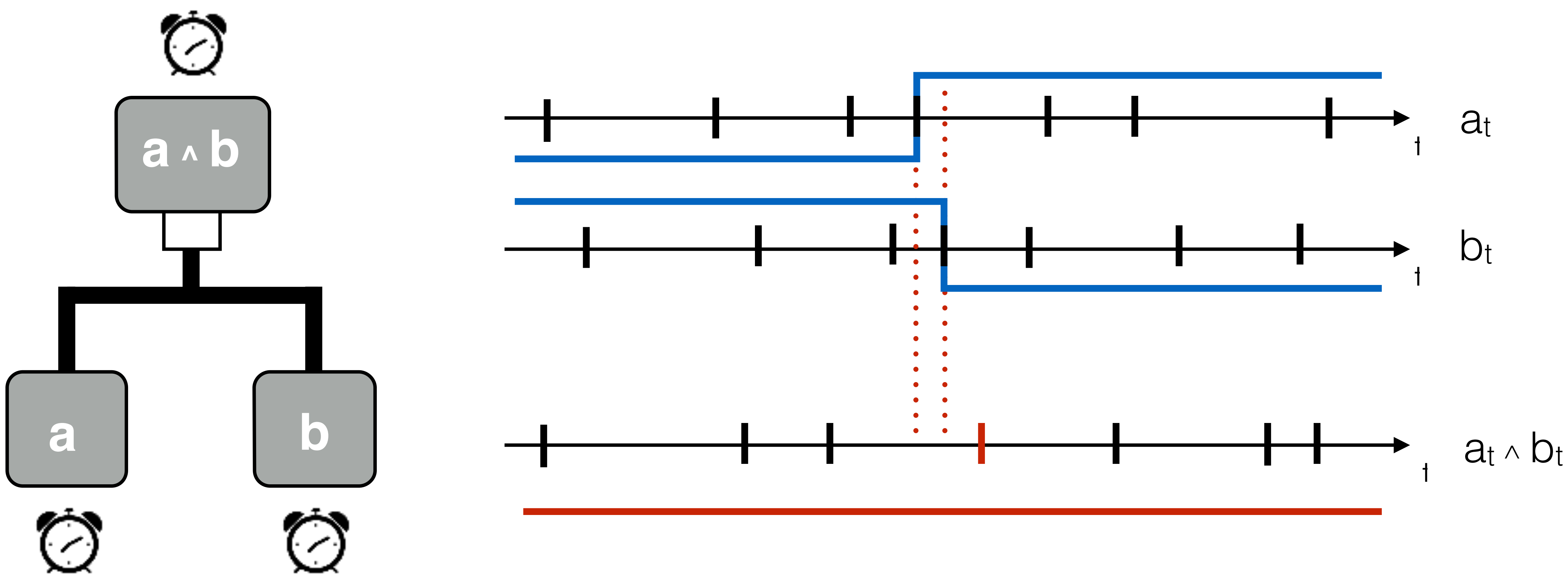

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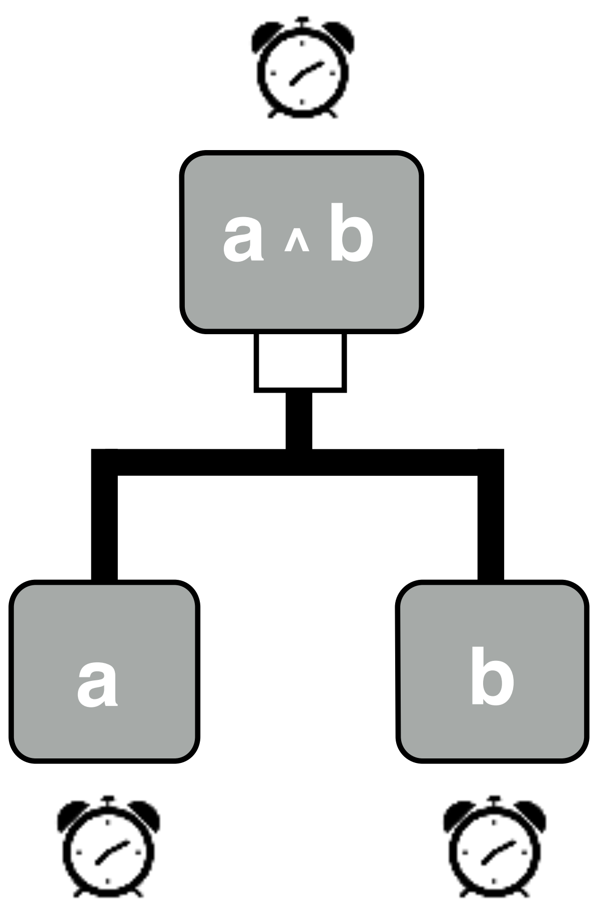

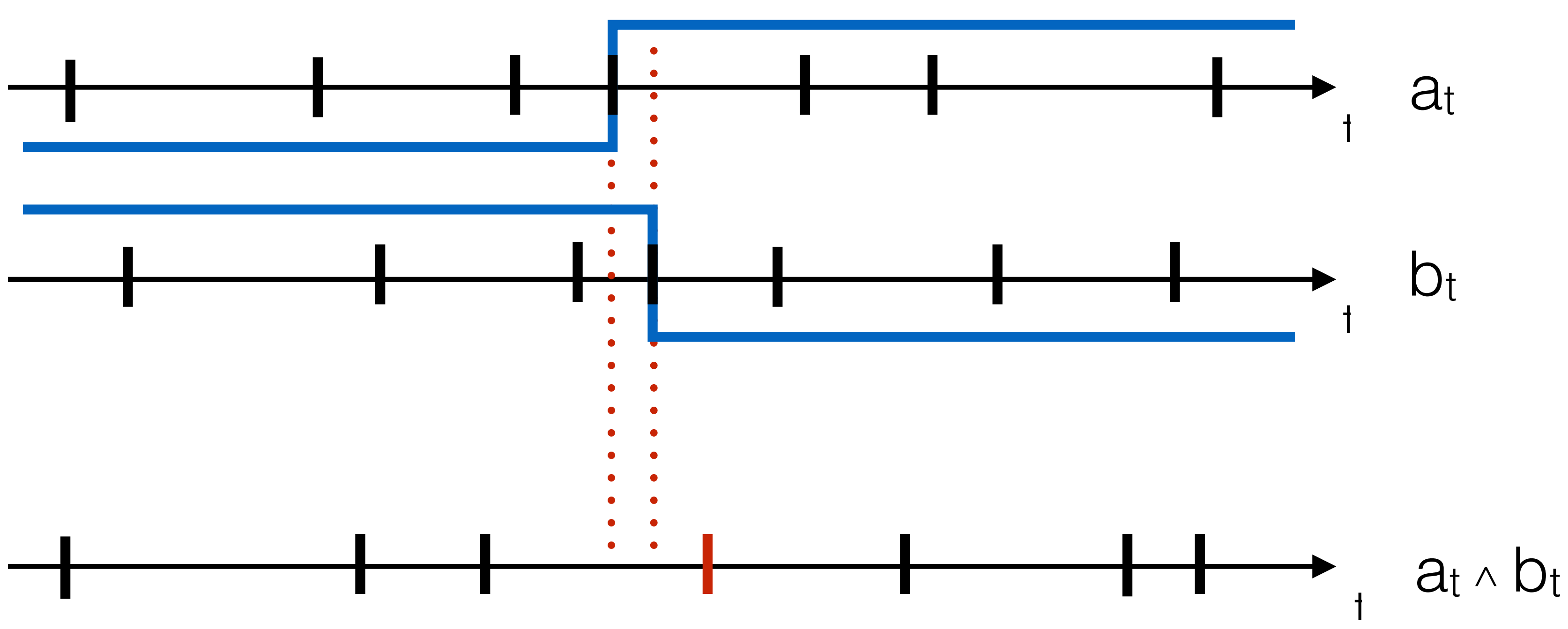

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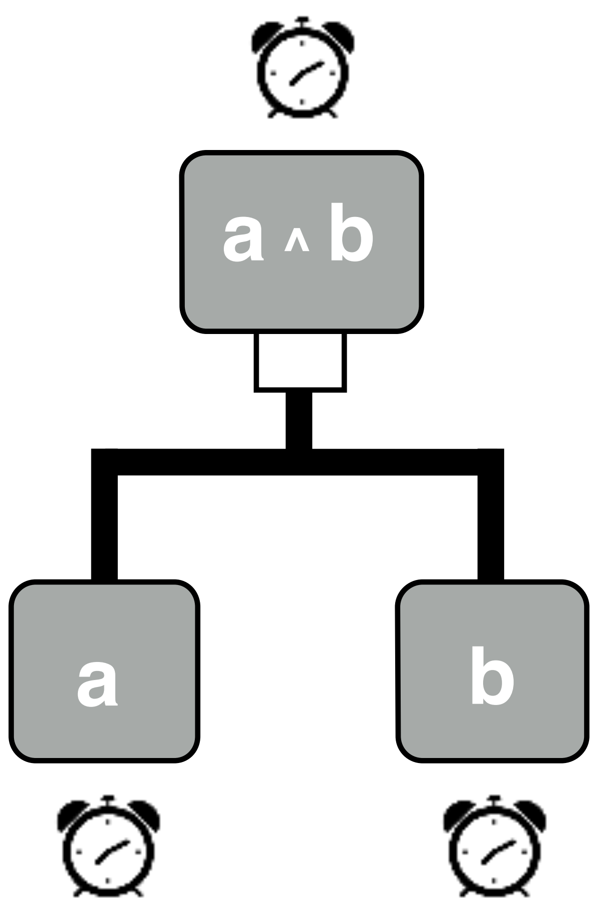

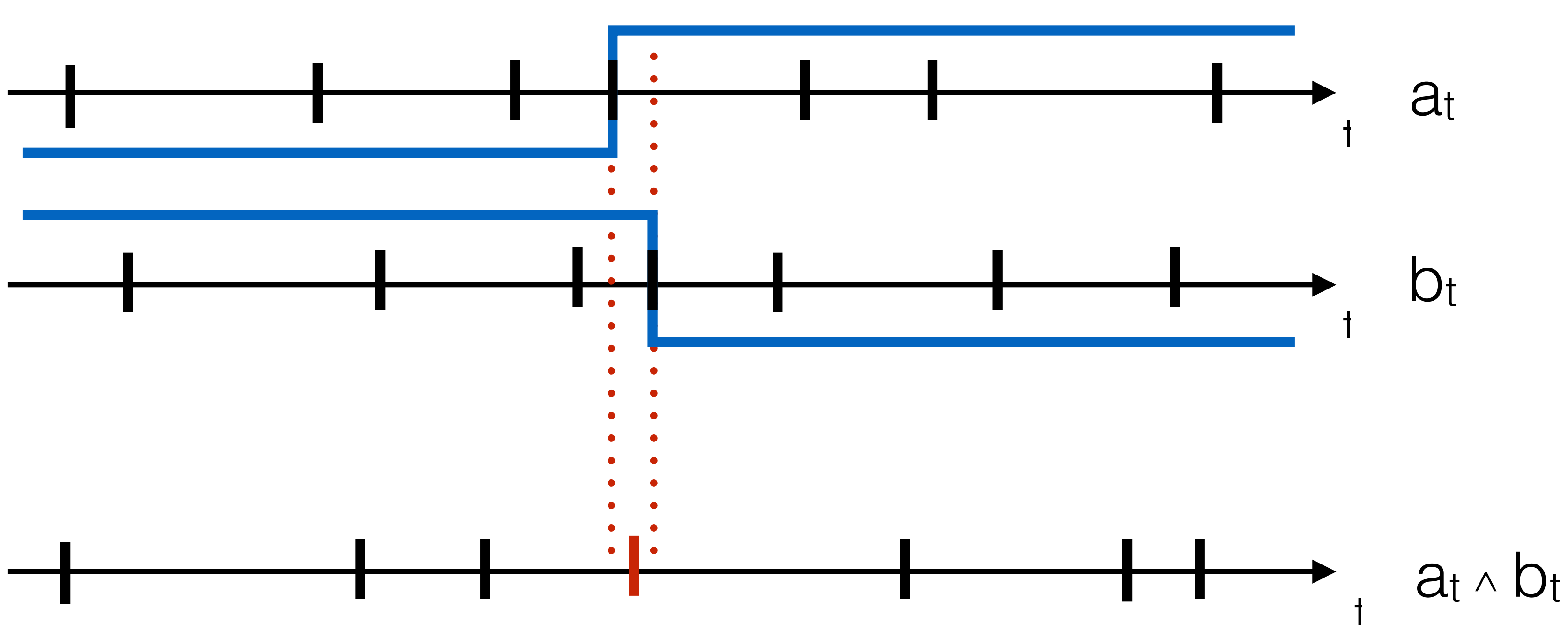

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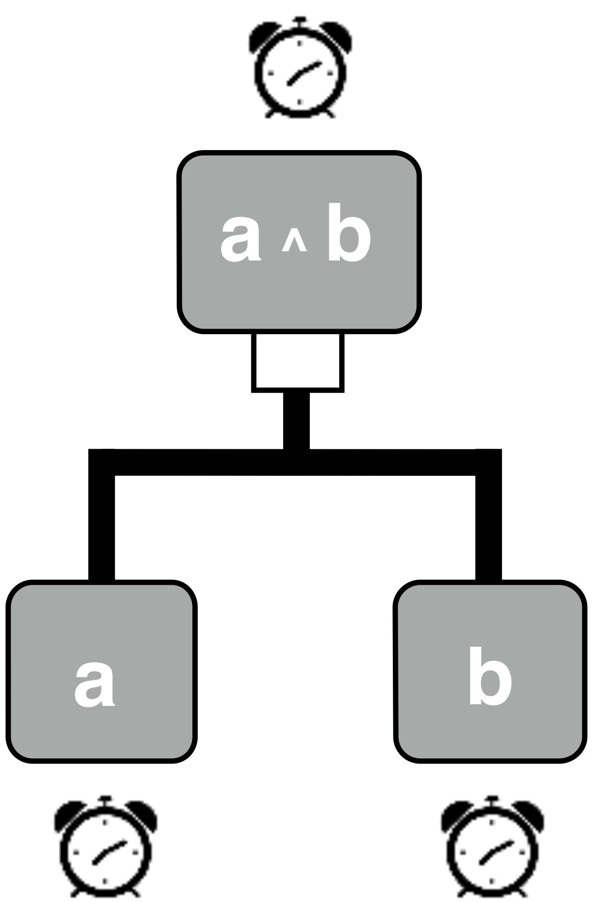
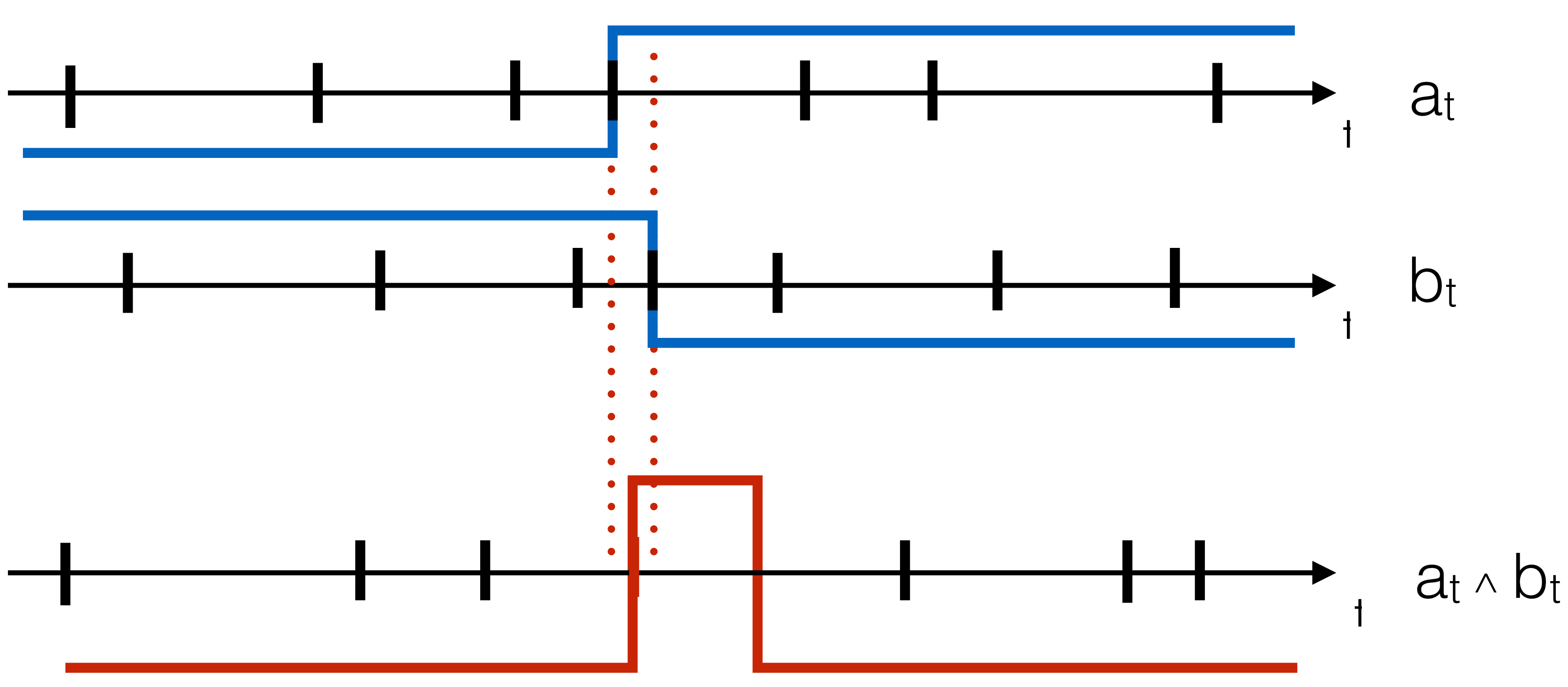




Synchronous Applications

Network of Communicating Mealy Machines

- Initial state S_{init}, Inputs I, Output O
- Transition function $F \;:\; \mathcal{S} \times \mathcal{V}^I \to \mathcal{S} \times \mathcal{V}^O$

Semantics

Synchronous $\quad [\![m]\!]^S \;:\; (\mathcal{V}^{n_i})^\infty \to (\mathcal{V}^{n_o})^\infty$

Kahn $\quad [\![m]\!]^K \;:\; (\mathcal{V}^\infty)^{n_i} \to (\mathcal{V}^\infty)^{n_o}$

Synchronous Applications

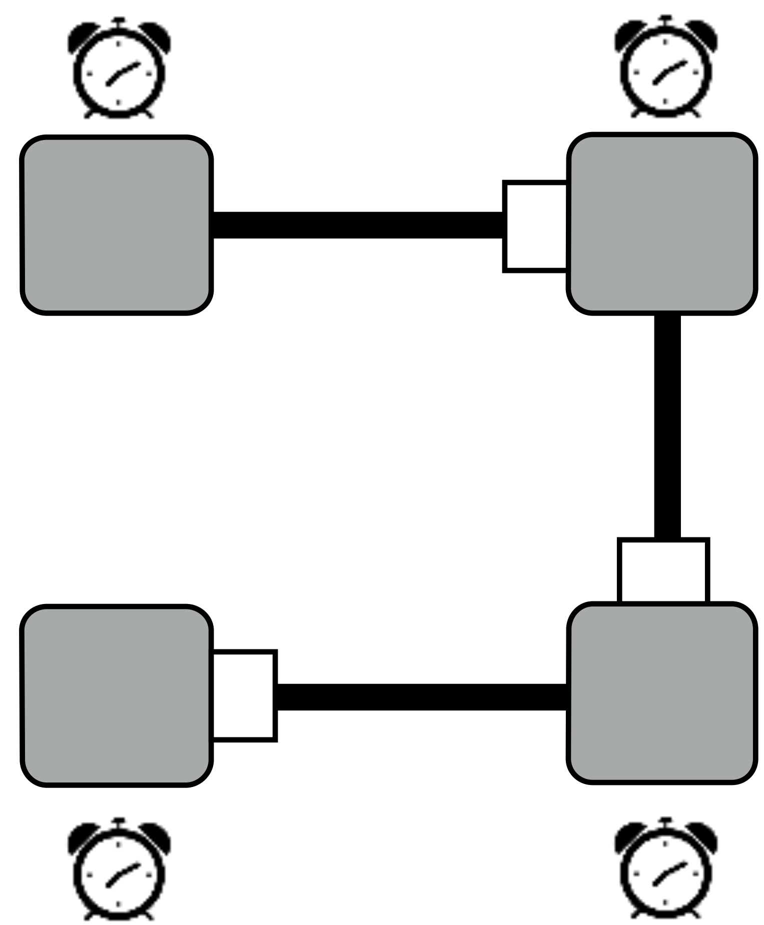
Network of Communicating Mealy Machines

- **‘Moore-style’ Composition:** machines communicate through a unit delay
- **No instantaneous dependency** between nodes (avoid ‘microschedule’ and ‘causality’ issues)
- A composition is also a Mealy machine

Basically, classic synchronous programs ‘mono-clock’.

What are LTTAs?

- **Base:** A quasi-periodic architecture
- **Goal:** Safely deploy a synchronous application
- **Idea:** Add a layer of middleware



Different Approaches

- **Discrete abstractions,** e.g., quasi-synchrony [Caspi 2000]
  - Allows verifications
  - State explosion, incomplete model

- **Petri nets,** [Benveniste et al. 2010]
  - Unify LTTA protocols
  - Complex model, no implementation

- **Zélus:**
  - A single language for discrete- and real-time,
  - Implementation, simulation using numerical solvers
  - But no verification at this point

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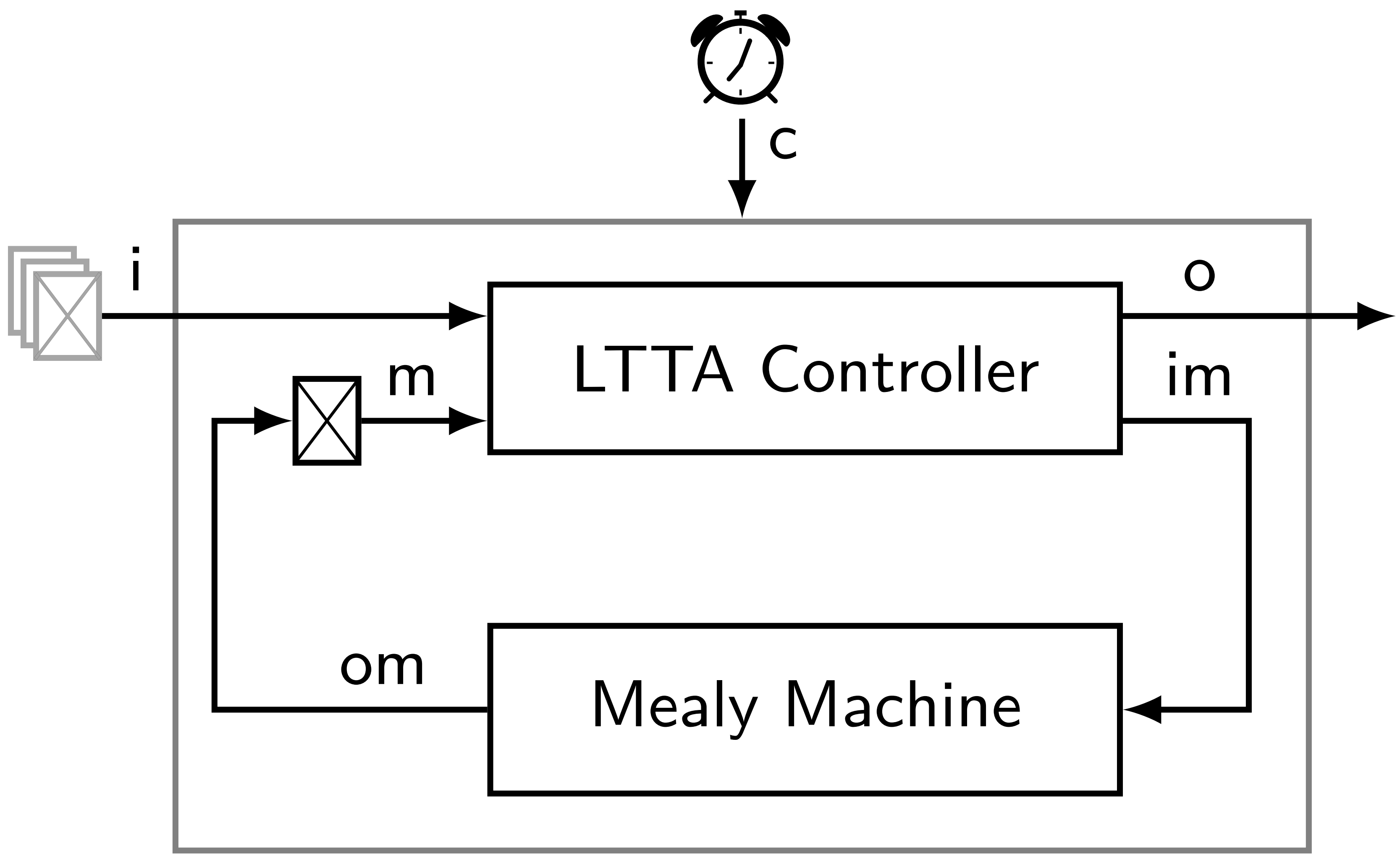
General Framework

Modelling nodes



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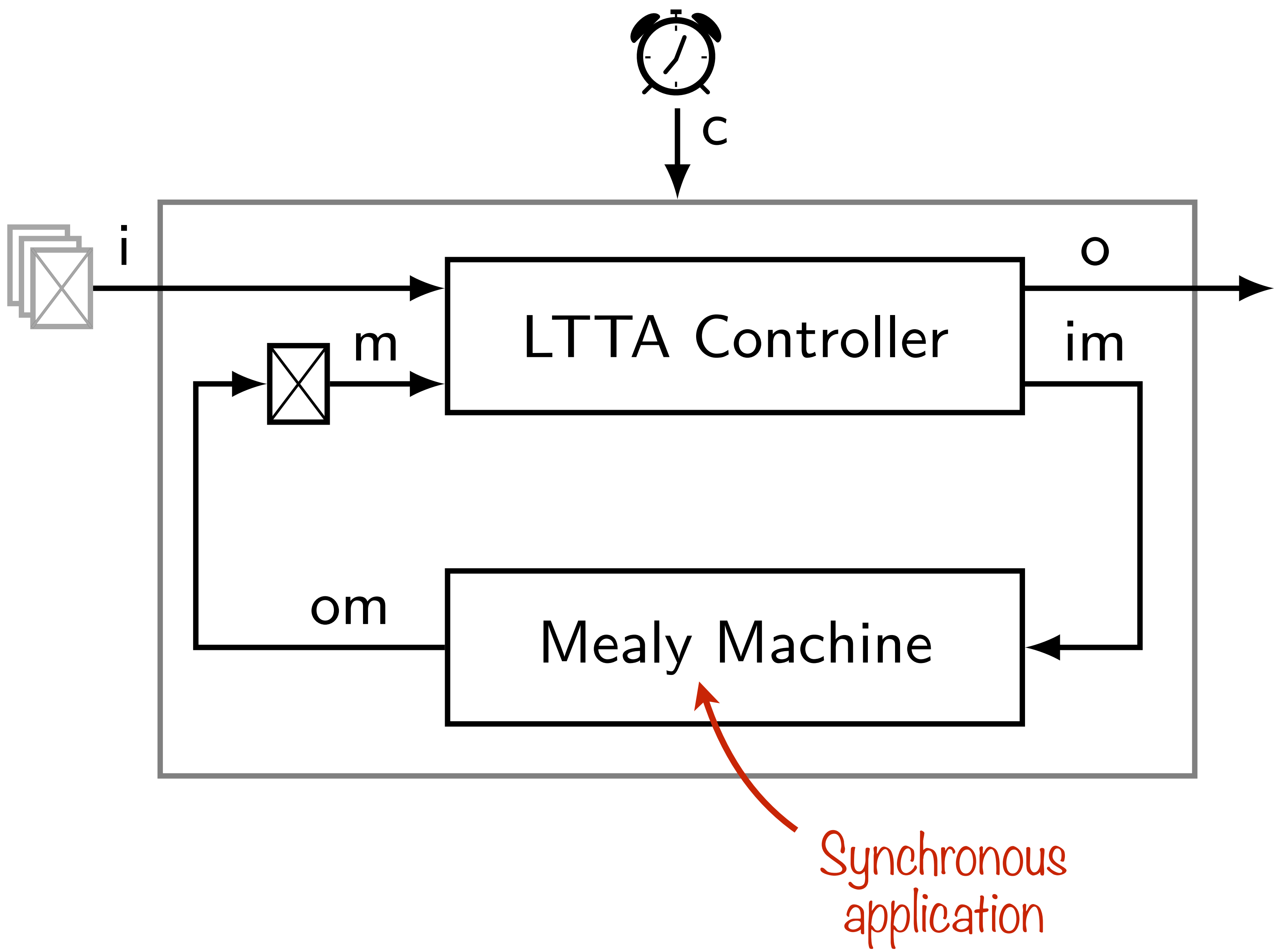

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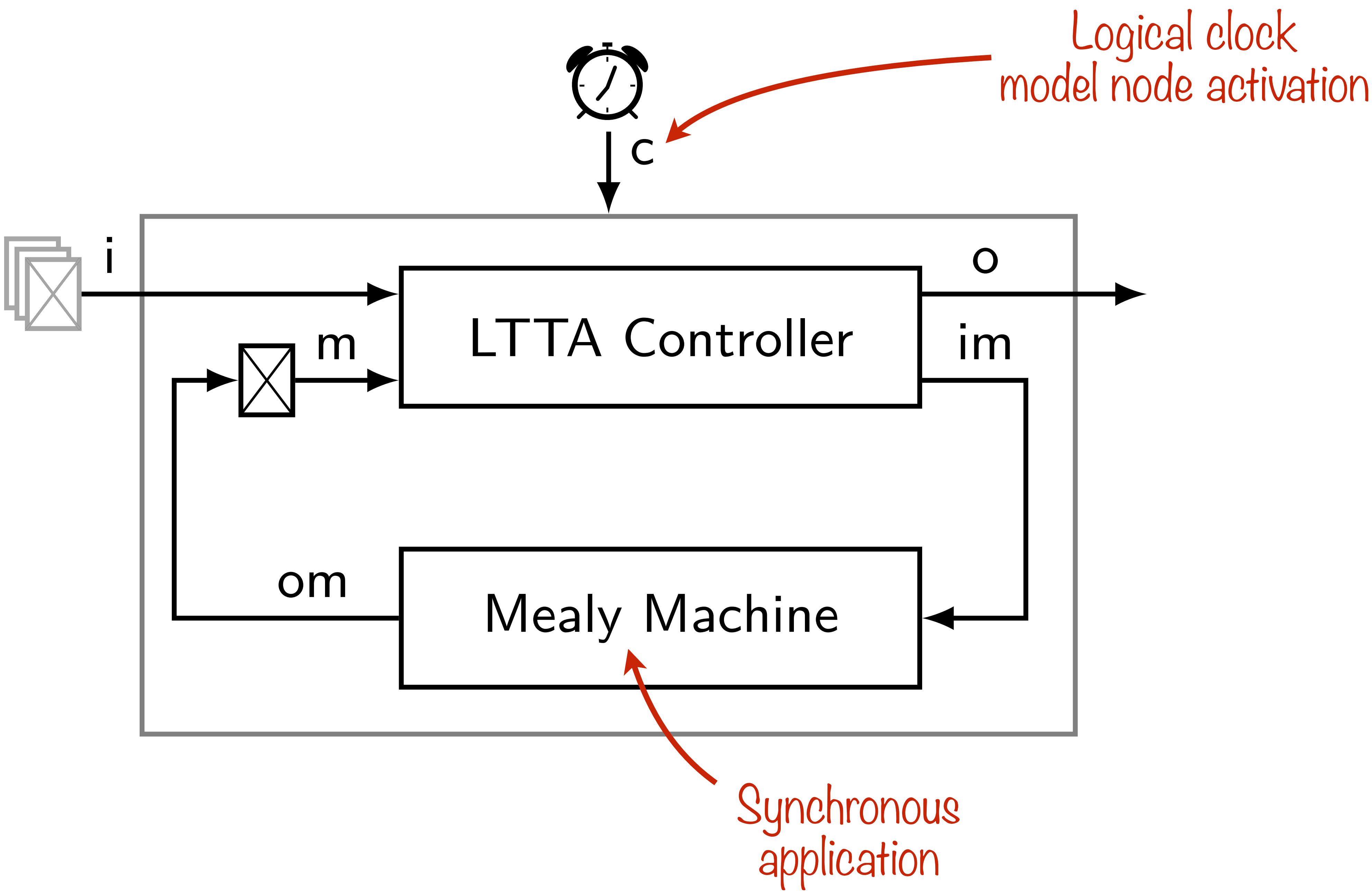

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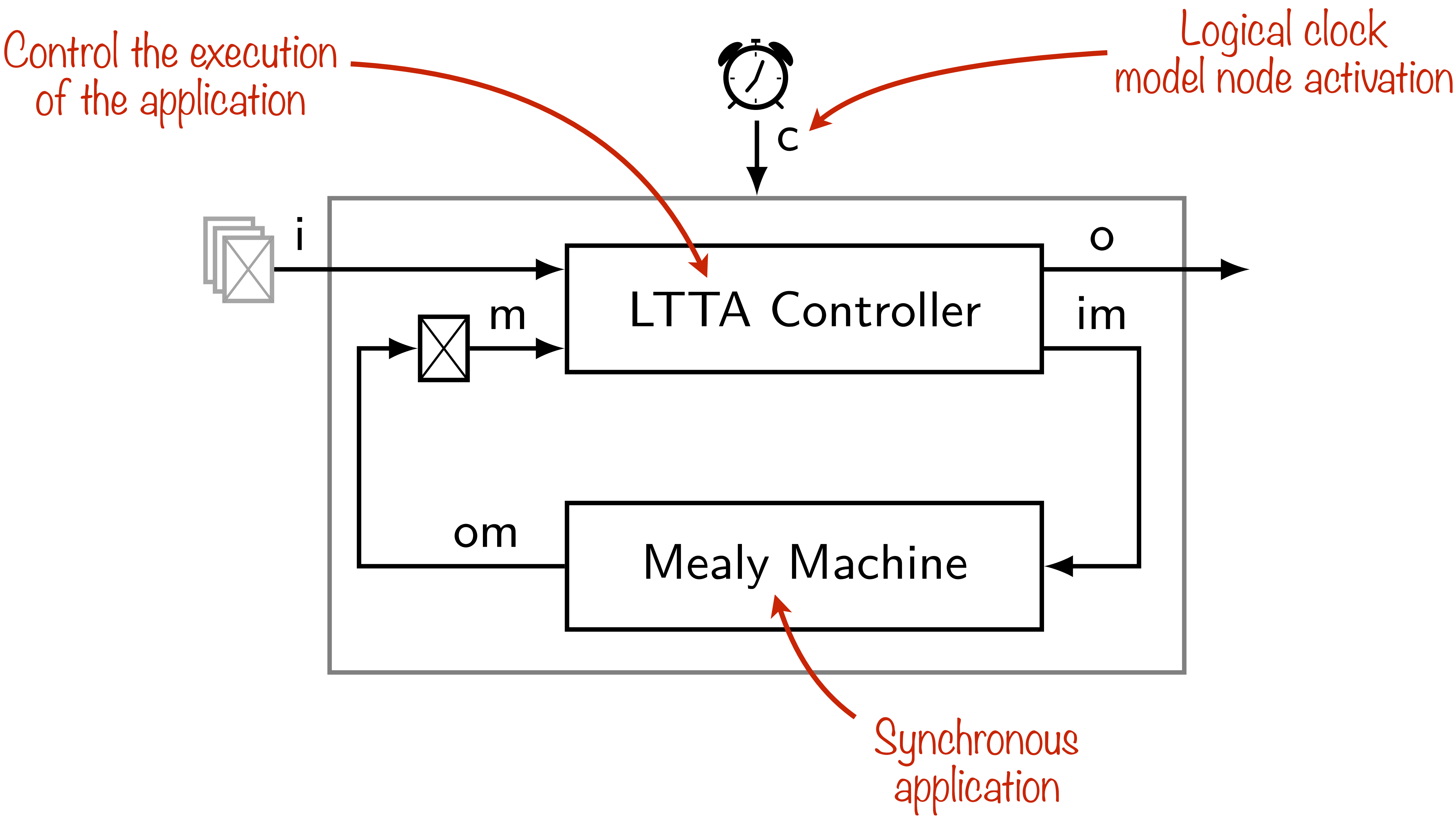

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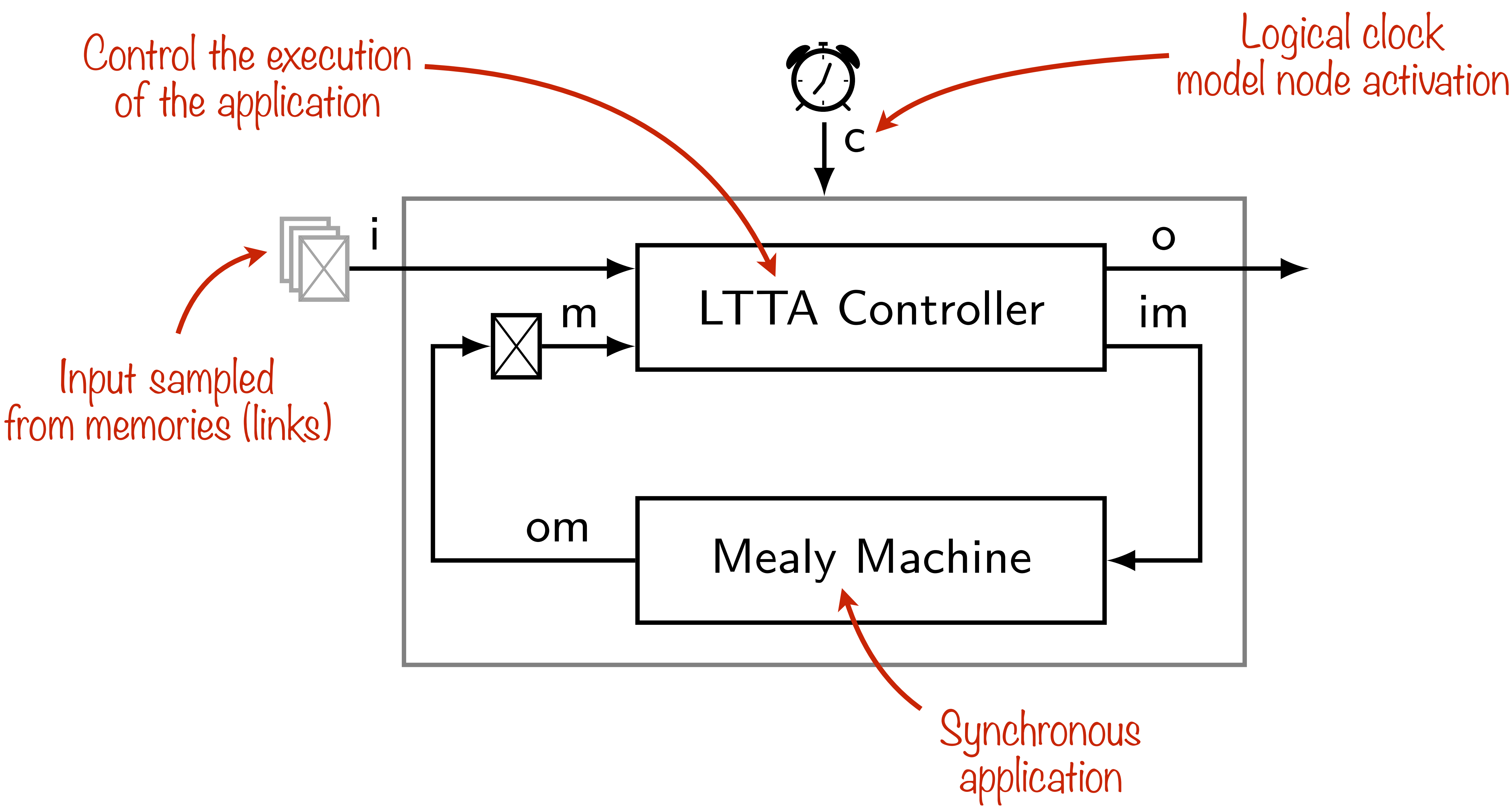

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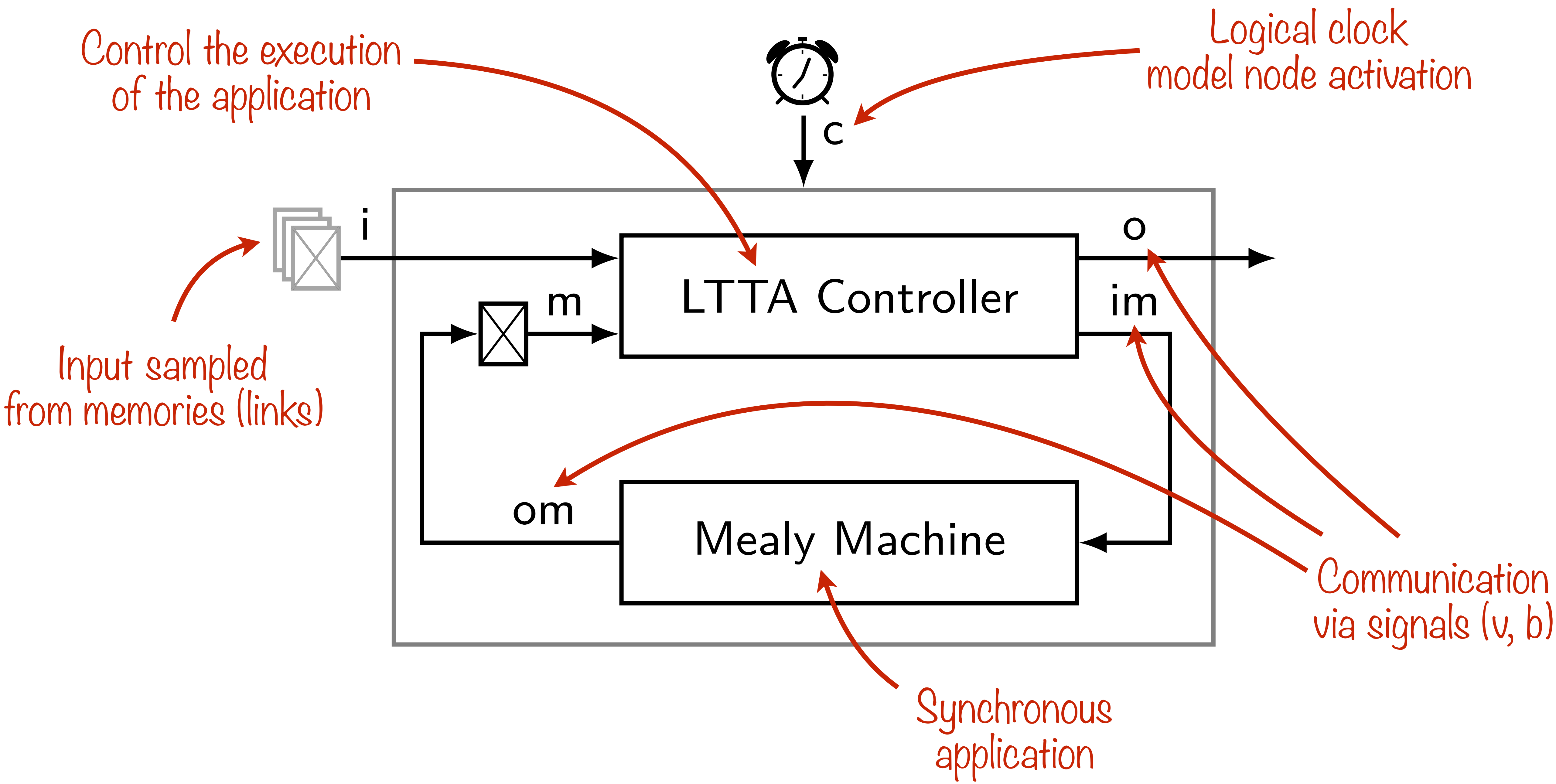

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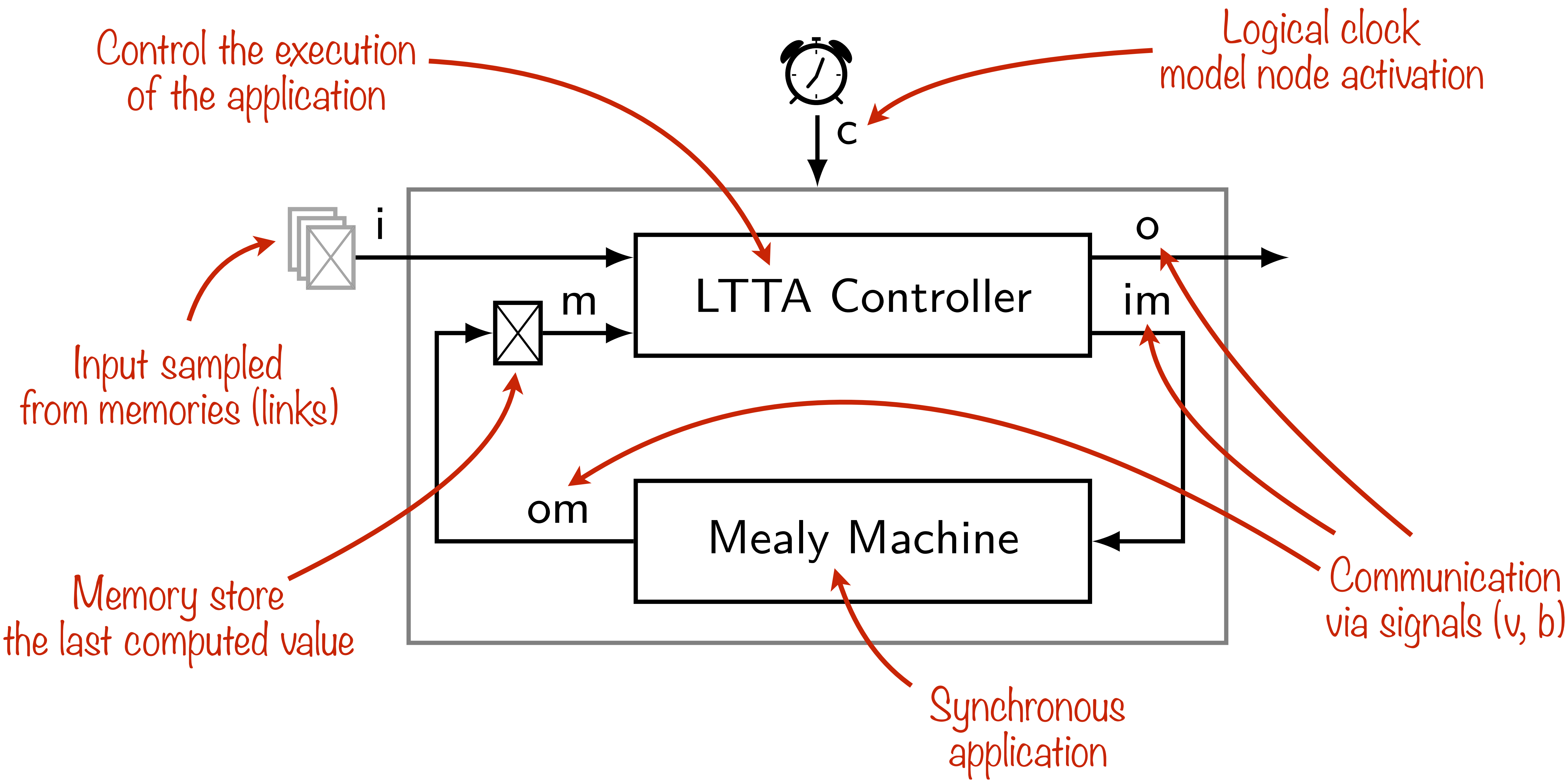

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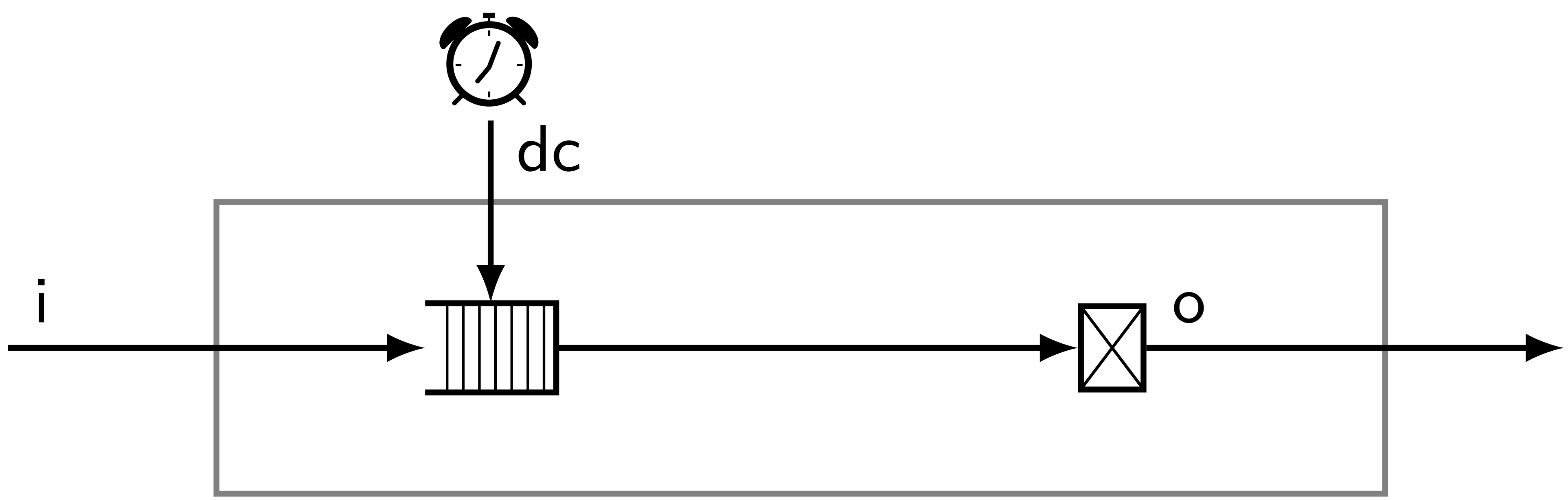
Modelling Links



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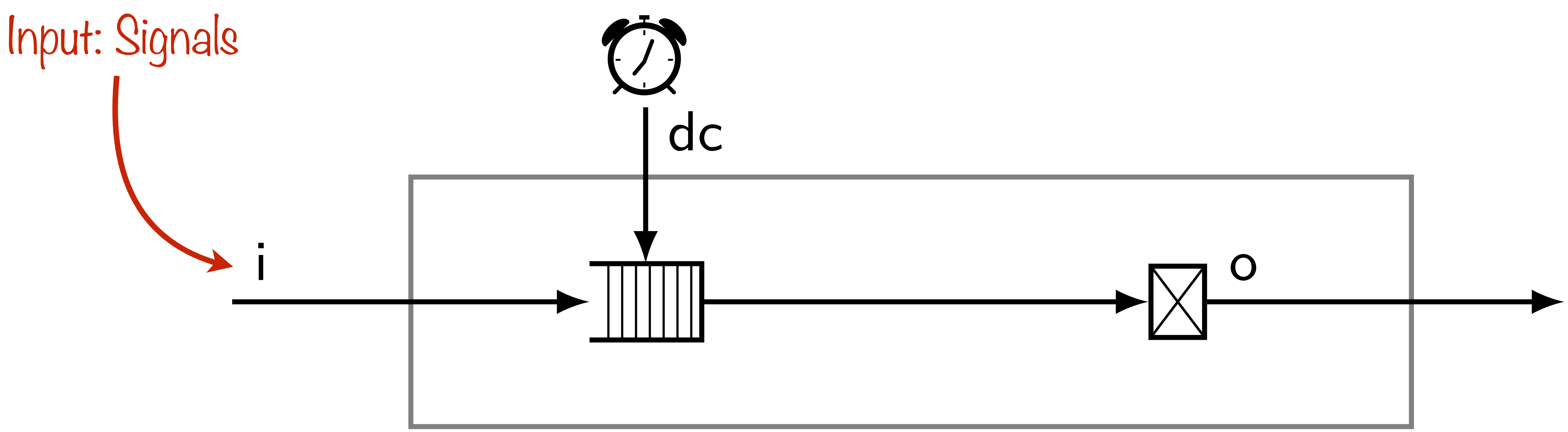

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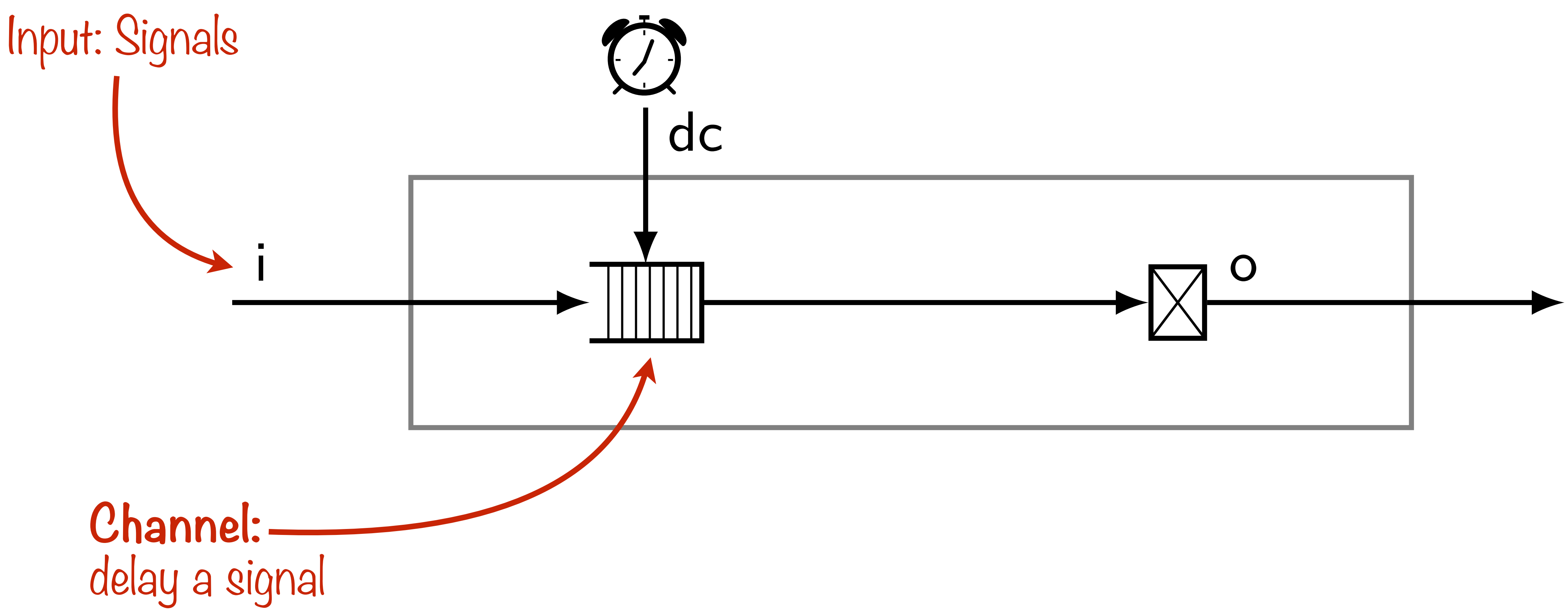

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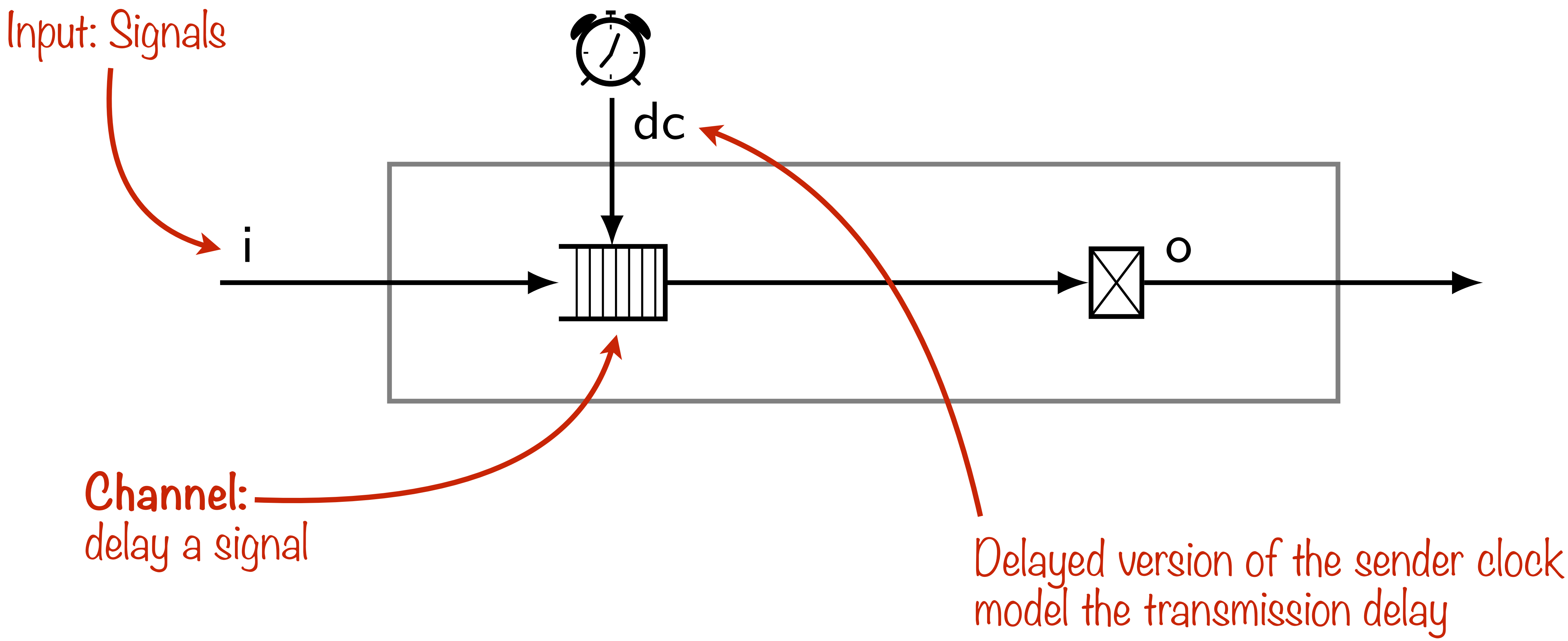

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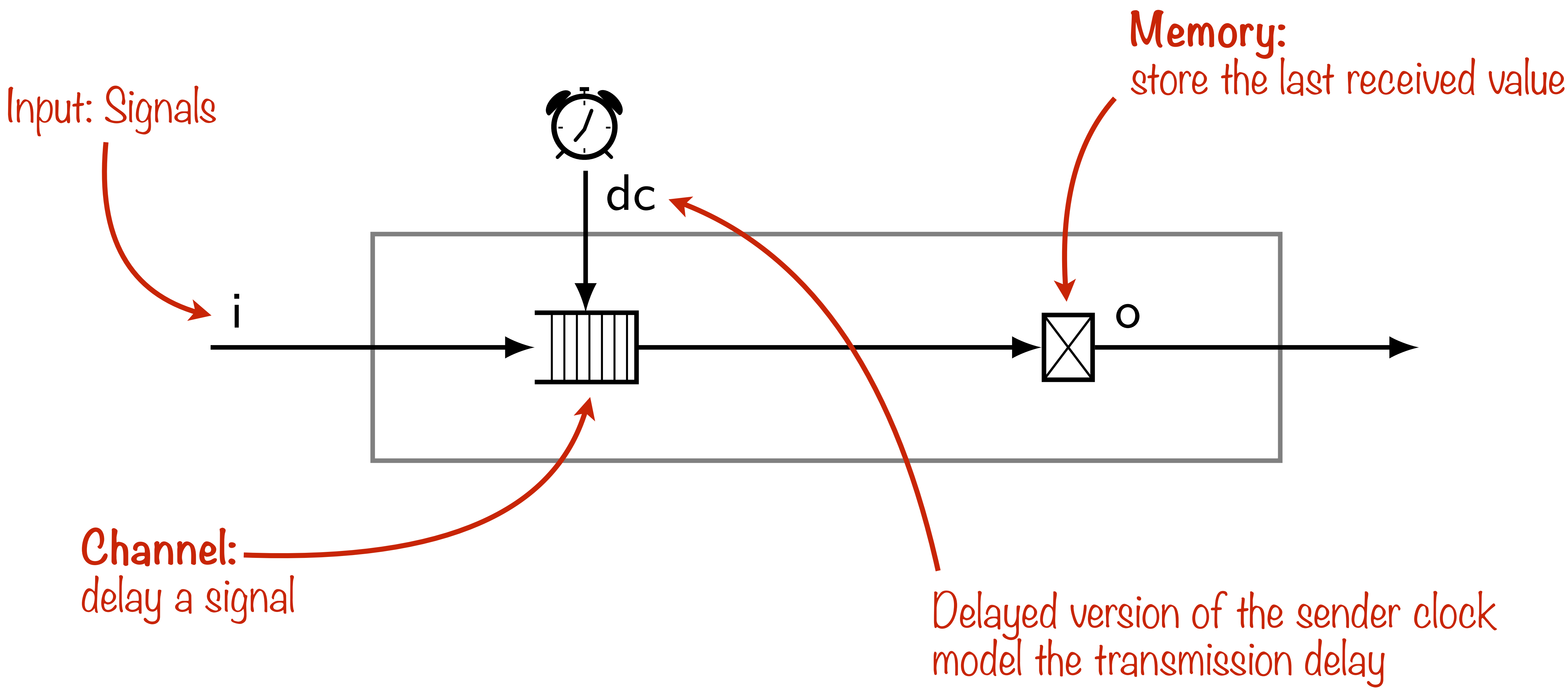
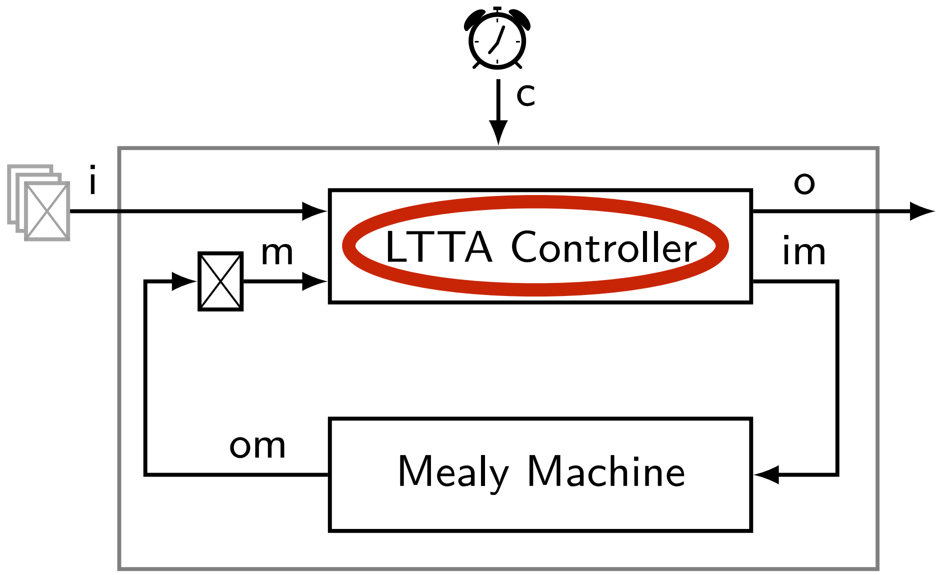


What's next?

Design controllers that ensure a synchronous execution of embedded machines

- **Back-Pressure LTTA**
  [Tripakis et al. 2008]

- **Time-Based LTTA**
  [Caspi, Benveniste 2008]



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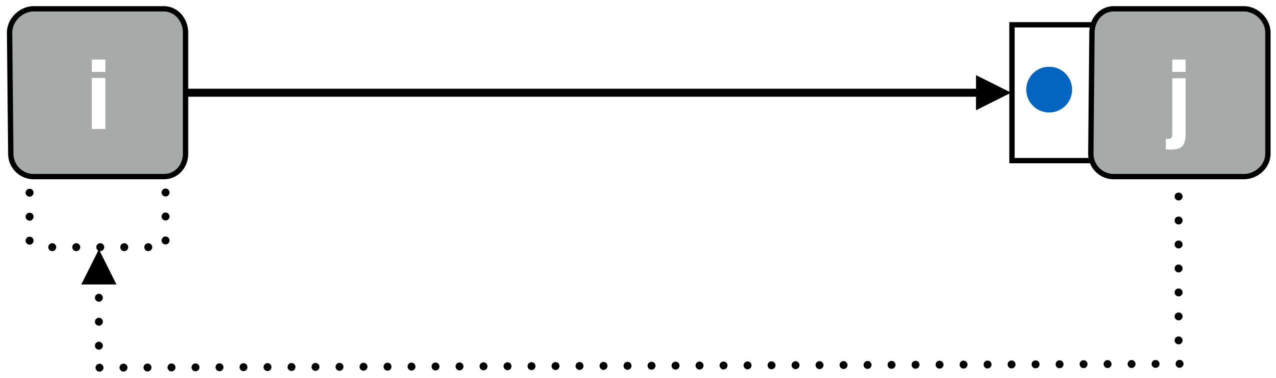
Back-Pressure Kahn Network

Buffer of Size 1



- Reading from a buffer is acknowledged to the writer
- Nodes alternate between **exec** and **send**

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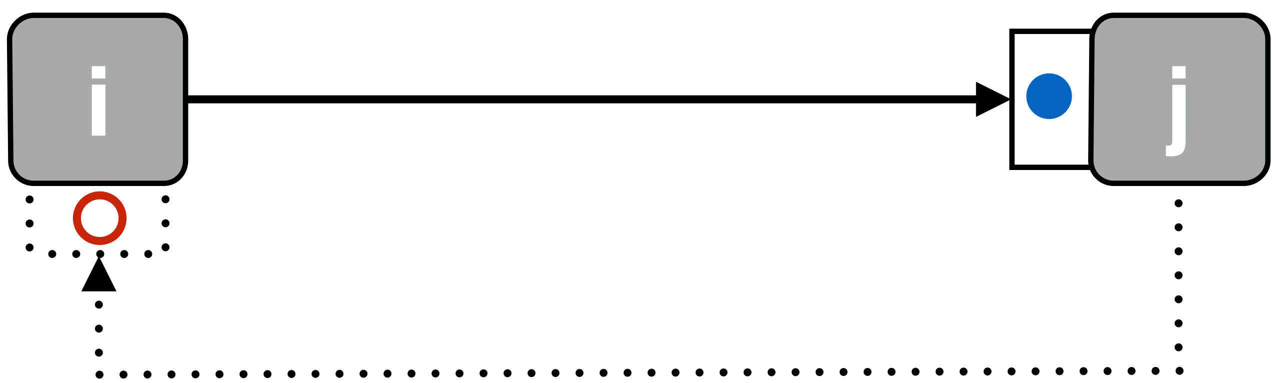

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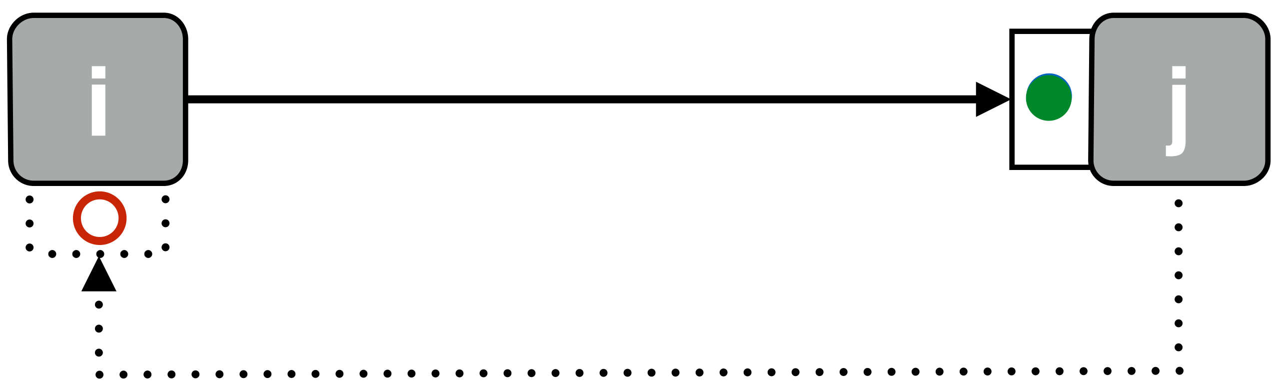

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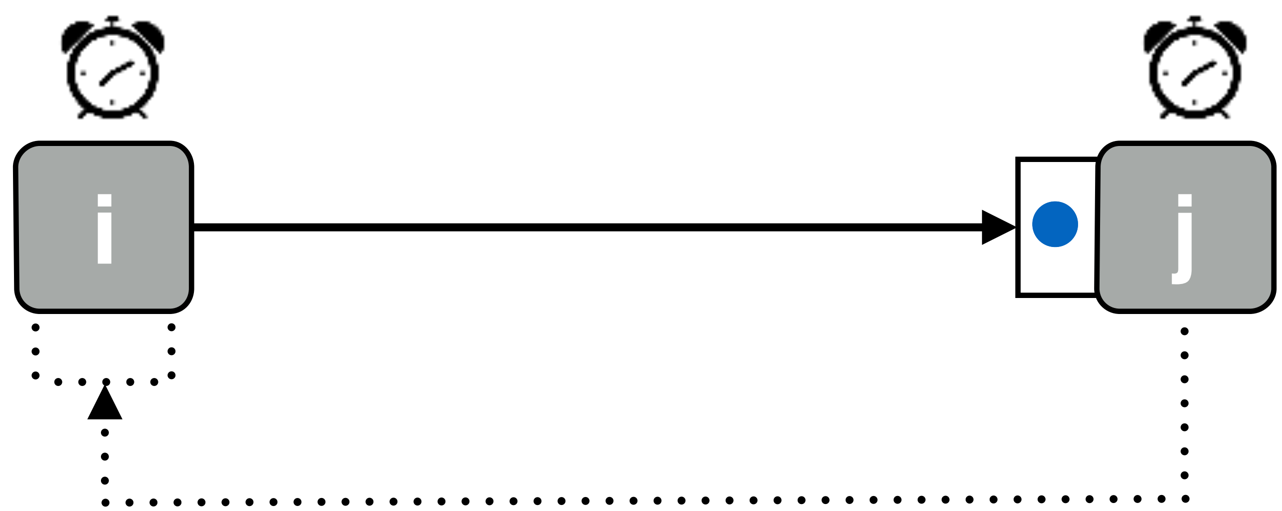

- **Difference:** nodes are triggered by their local clock
- **Idea:** adding skipping mechanism

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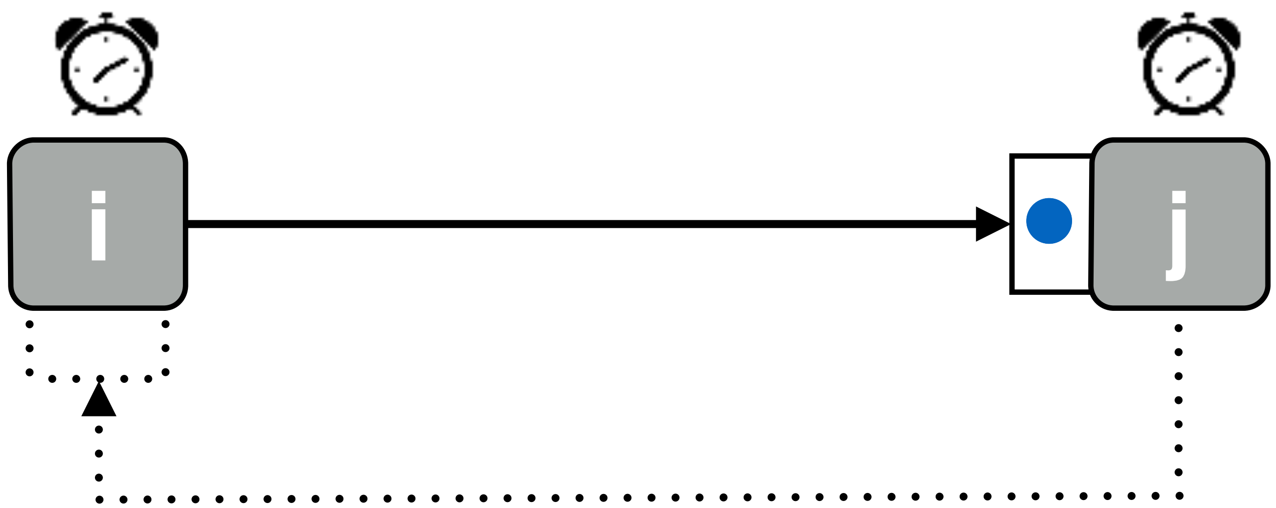

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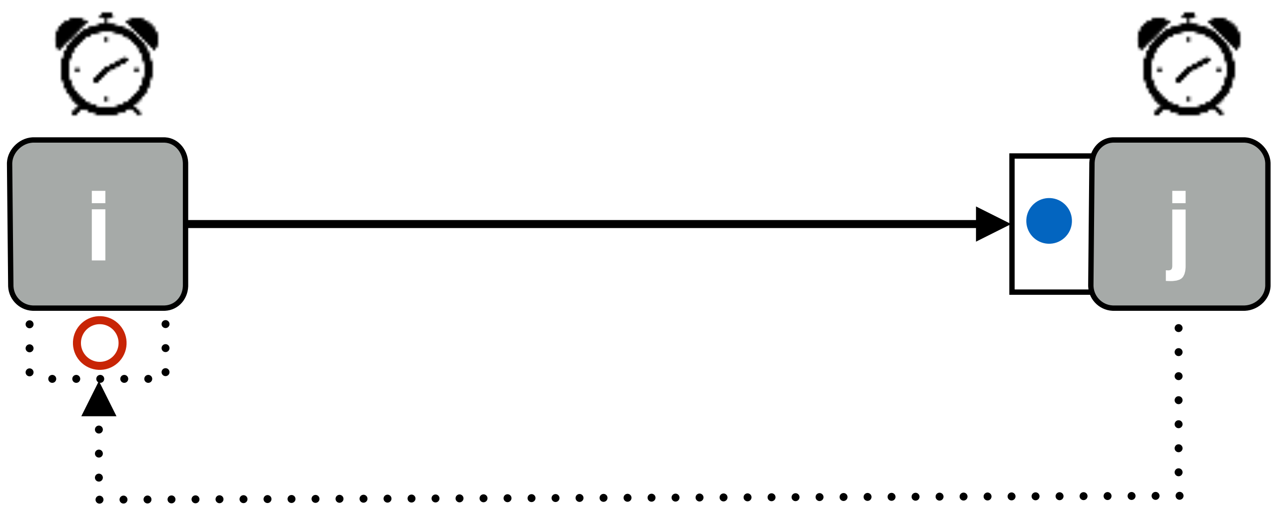

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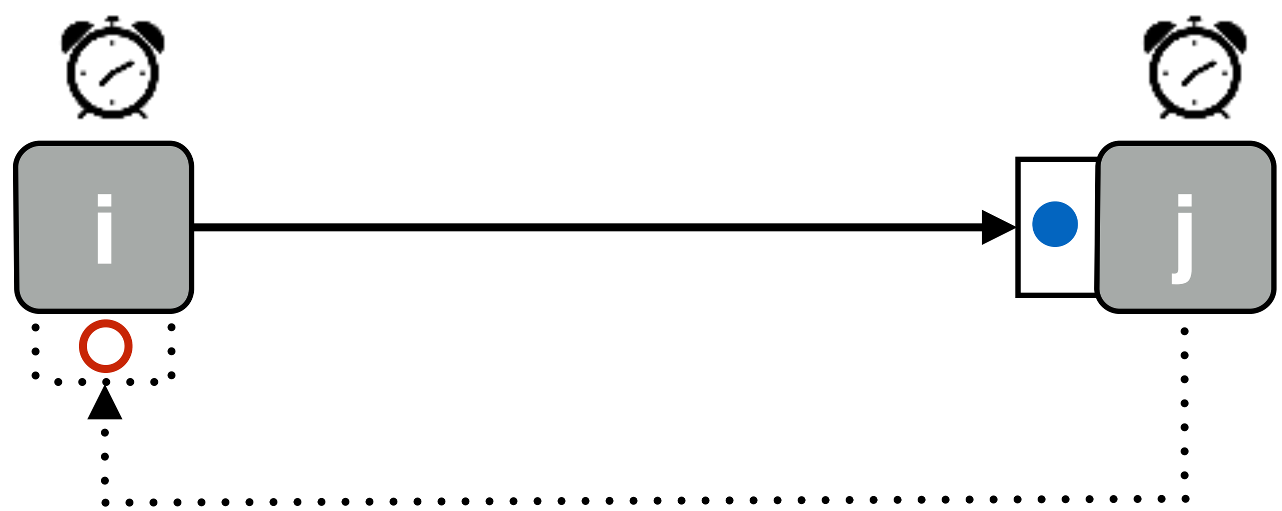

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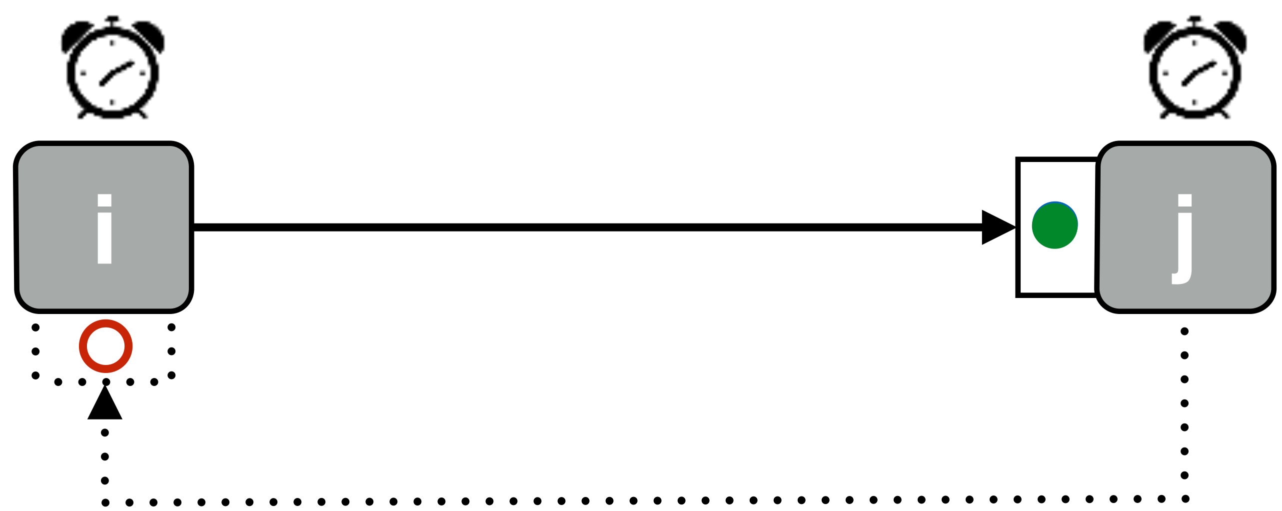

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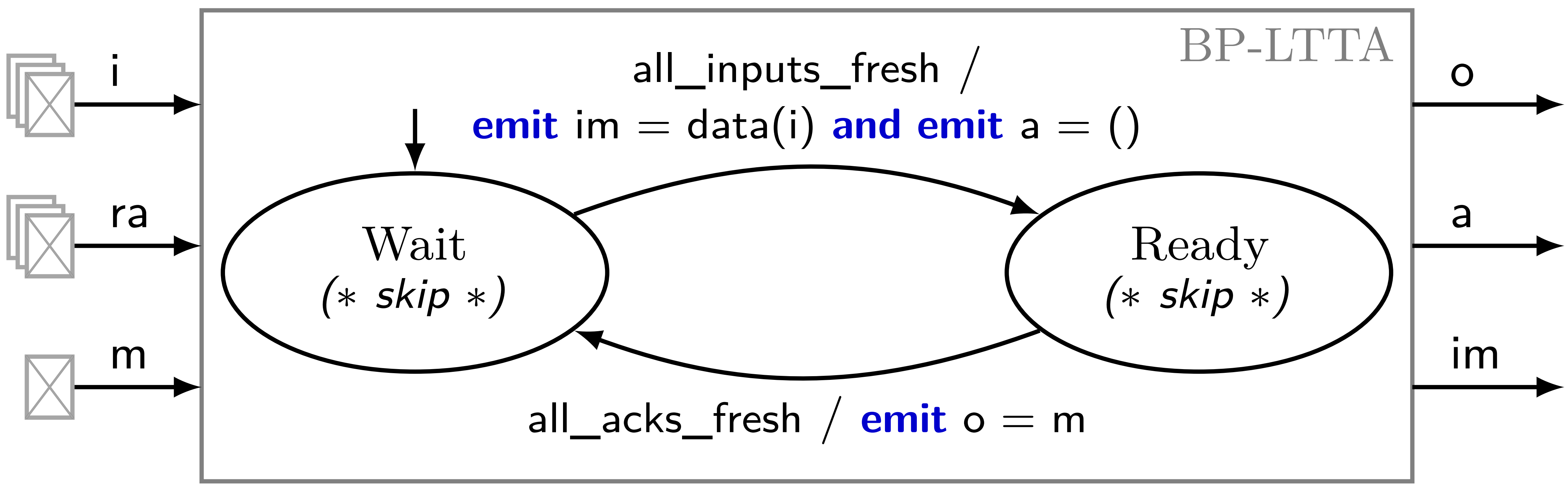


Back-Pressure LTTA

- **Theorem 1:**
  Composition of the controller and the embedded machine is always well-defined (no cycle)

- **Theorem 2:**
  Back-pressure LTTA preserves the Kahn semantics of the embedded application
  (forget the skips)

- **Theorem 3:**
  The worst case throughput is: $1/\lambda_{\mathrm{BP}} = 2(T_{\max} + \tau_{\max})$

Time-Based LTTA

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

- **Idea:** Replace back-pressure by waiting, using timing characteristics of the architecture

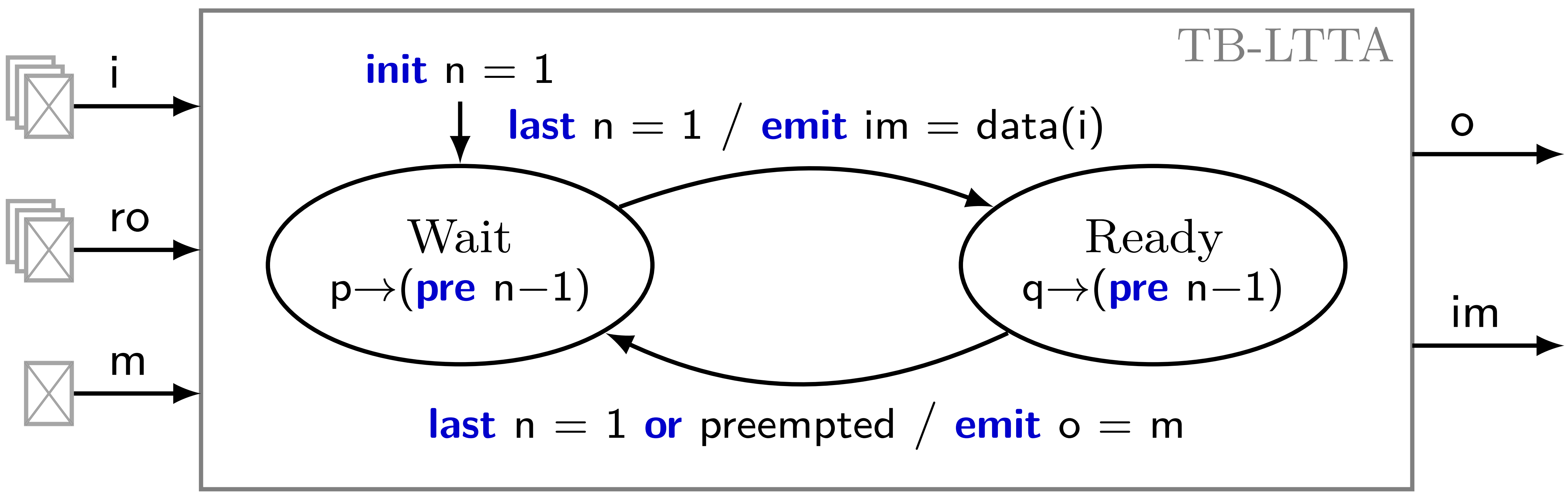
- **First solution:** [Caspi, Benveniste 2008]
Slow down the nodes to mimic a synchronous architecture, global synchronisation

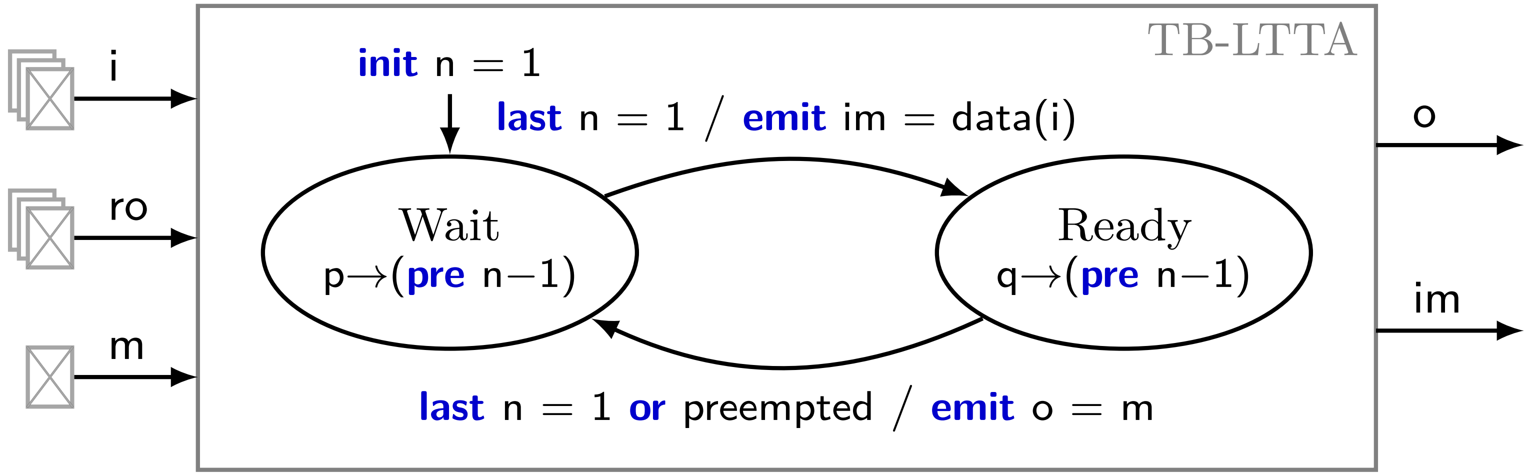
- **Our proposal:** Relax broadcast assumption,
localise synchronisations

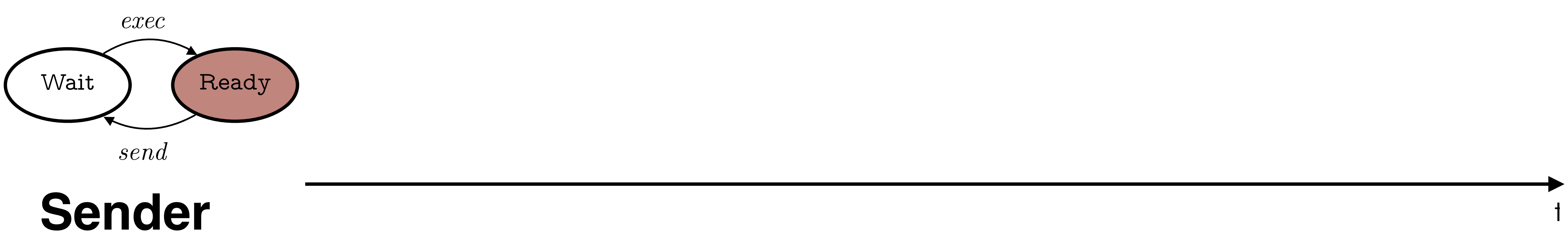
Time-Based LTTA

- Nodes alternate between **exec** and **send**
- Sender sees publication of all receivers
- **Idea:** At some point, a node can be sure that:
  - the last sent data has been read
  - a fresh value is available in the memory

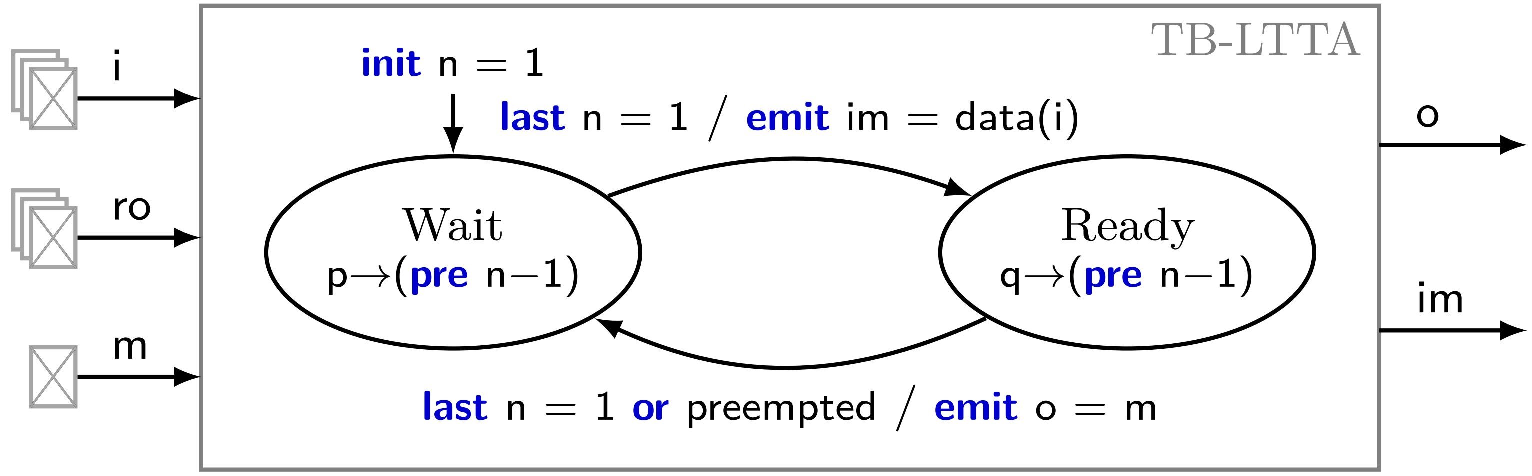
Time-Based LTTA

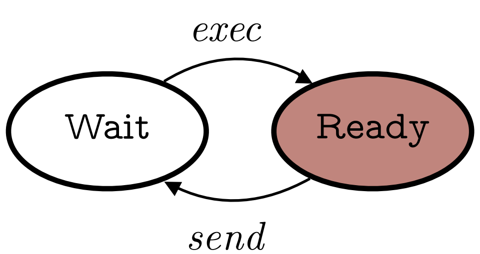



TB-LTTA
i
ro
m
init n = 1
last n = 1 / emit im = data(i)
Wait
p→(pre n−1)
Ready
q→(pre n−1)
last n = 1 or preempted / emit o = m
o
im

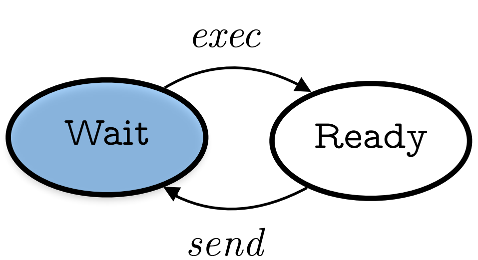

exec
Wait
Ready
send
Sender
t


exec
Wait
Ready
send
Receiver
t

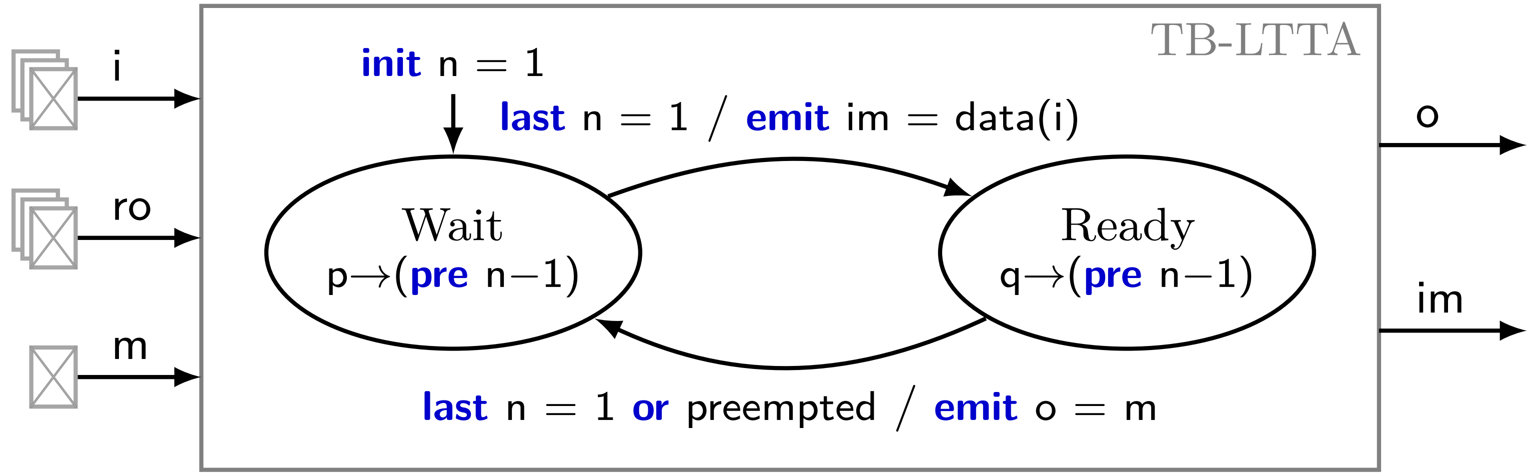




Sender



Receiver



Sender

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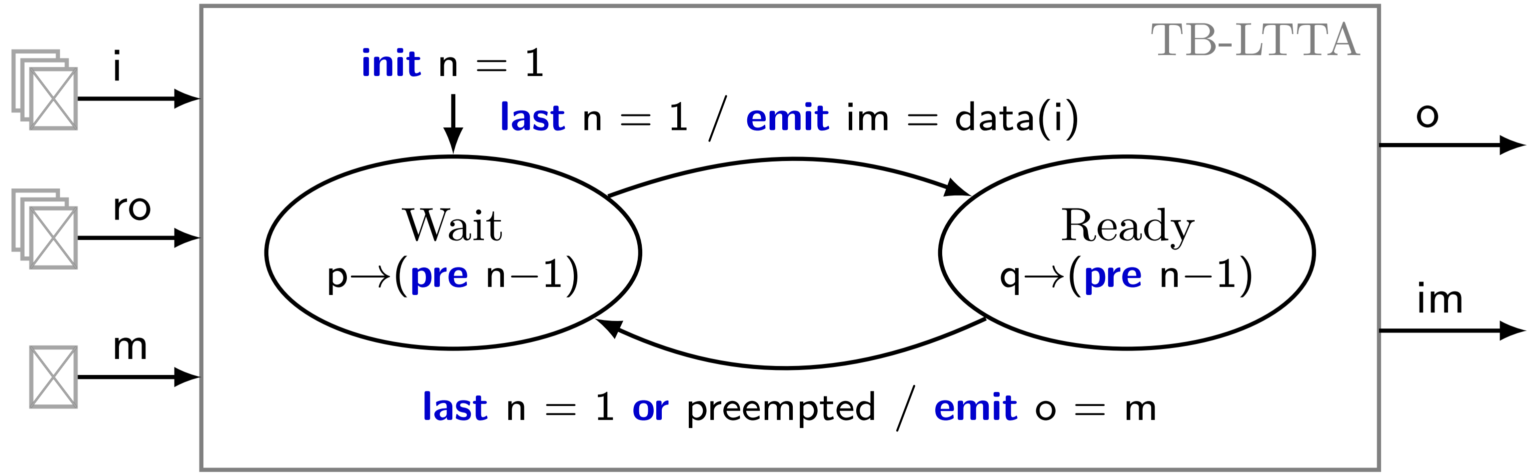

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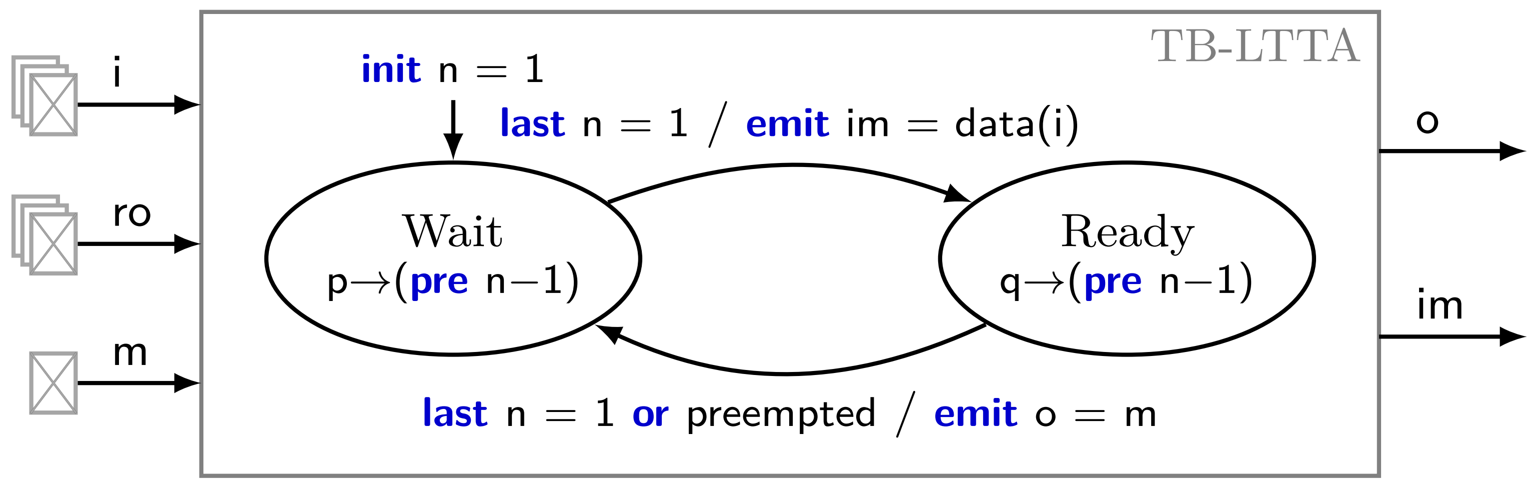

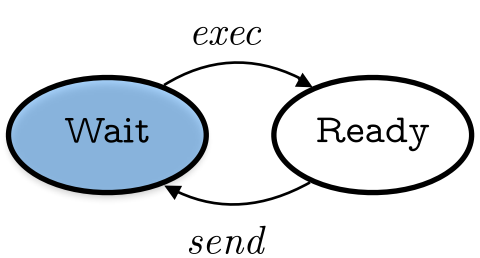

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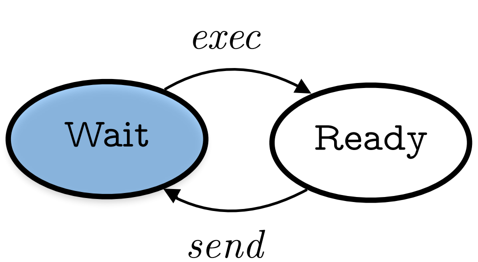

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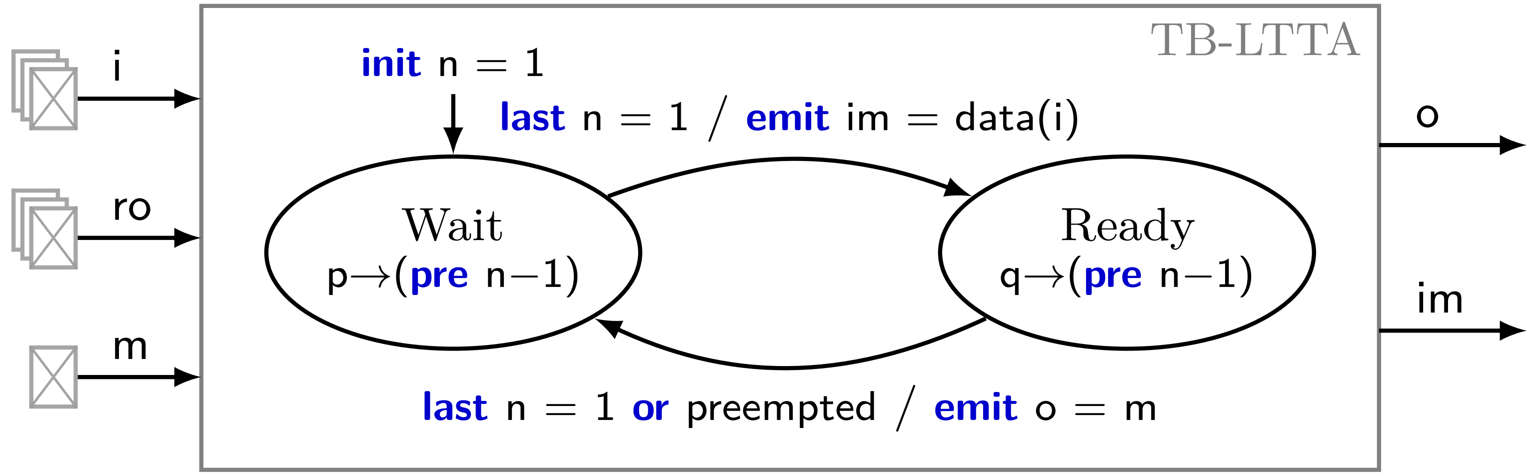
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i
ro
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last n = 1 / emit im = data(i)
Wait
p→(pre n−1)
Ready
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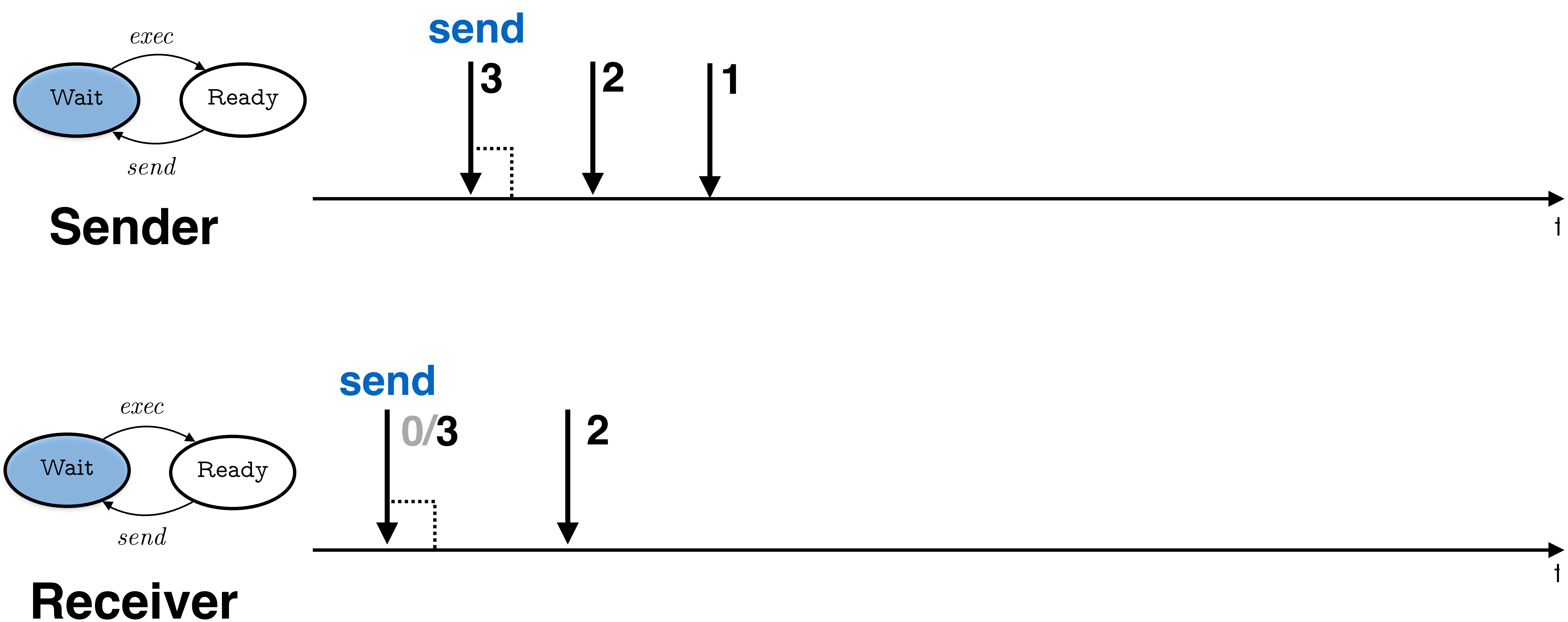
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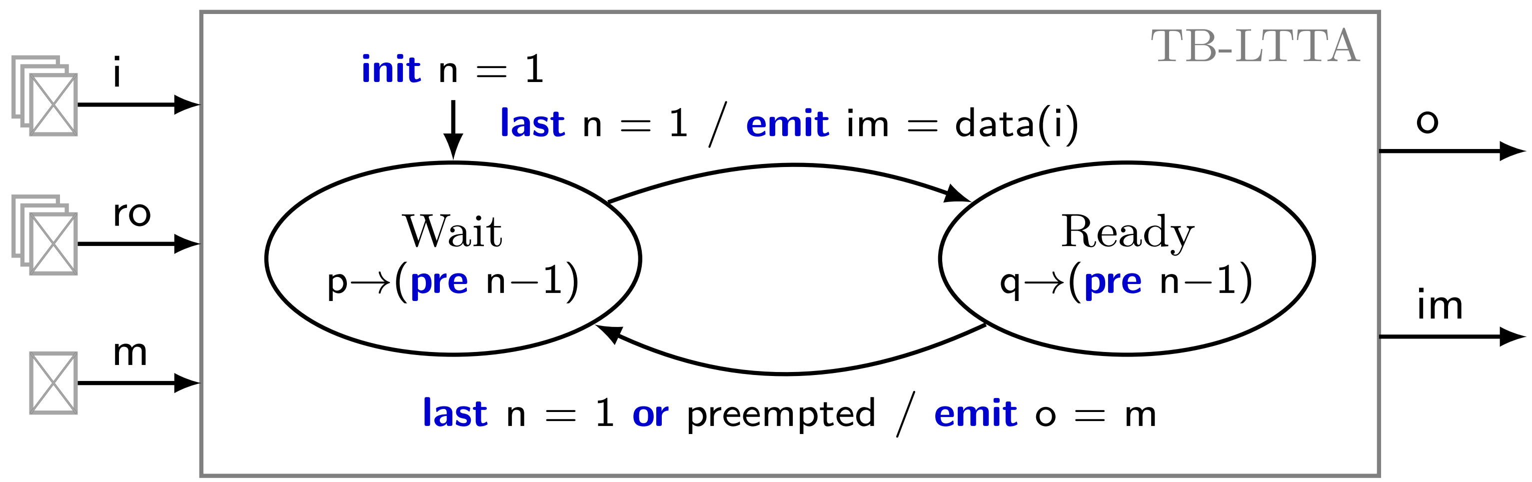
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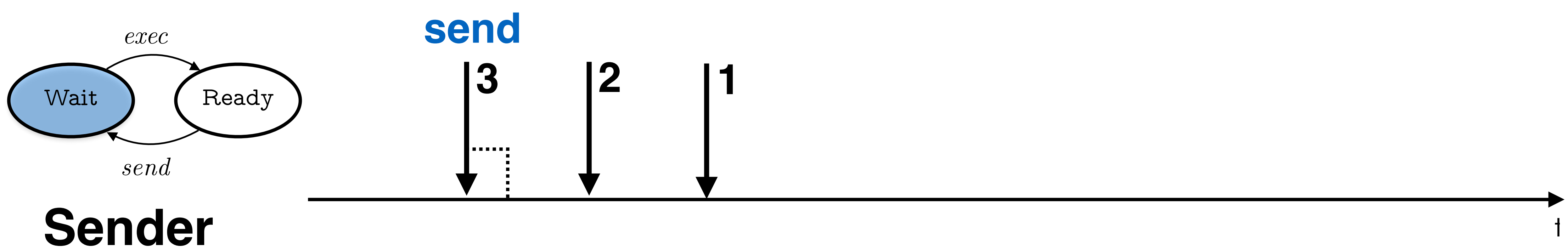
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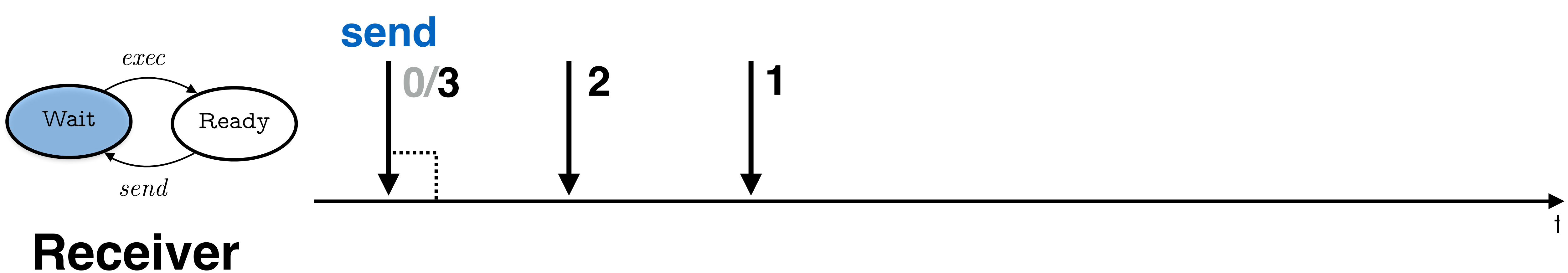
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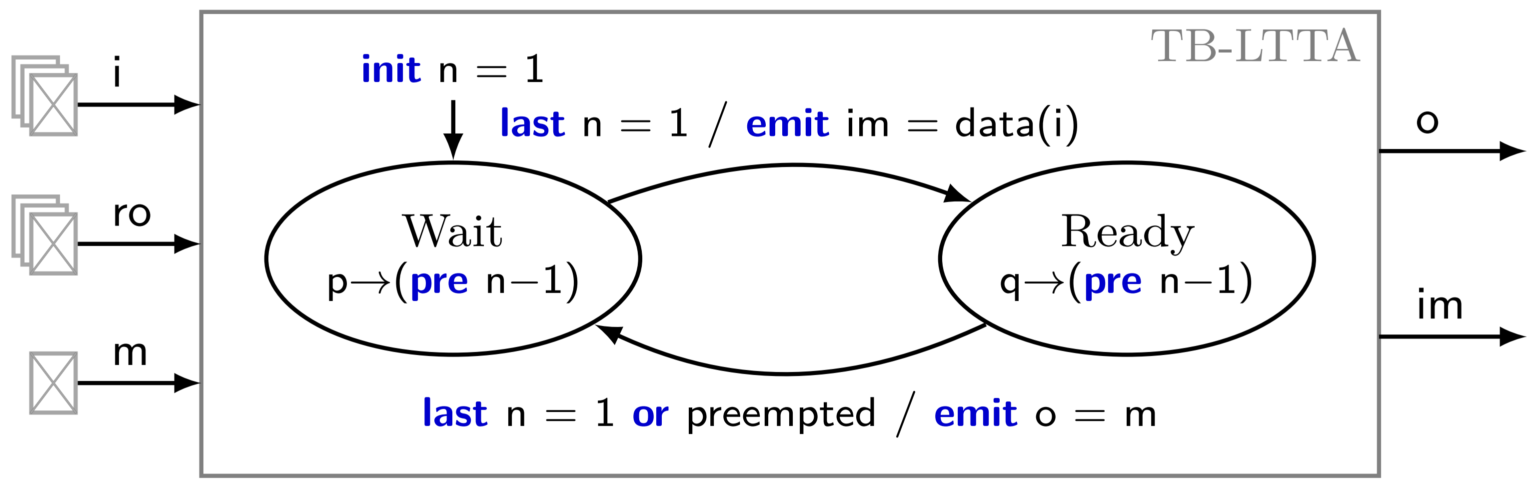
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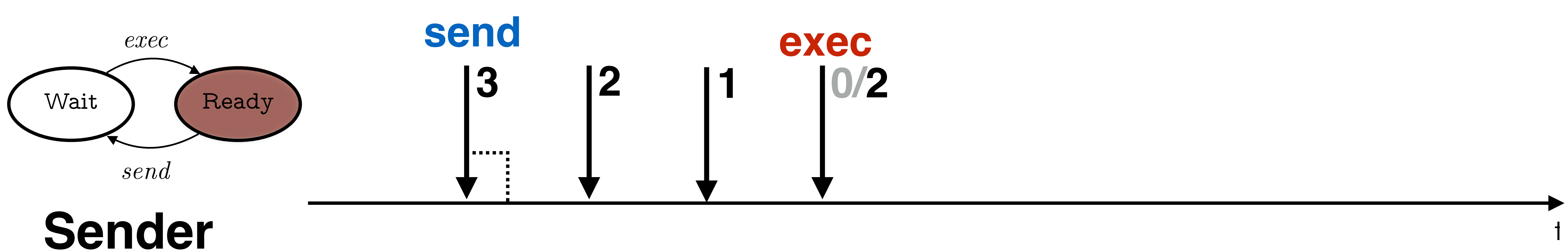
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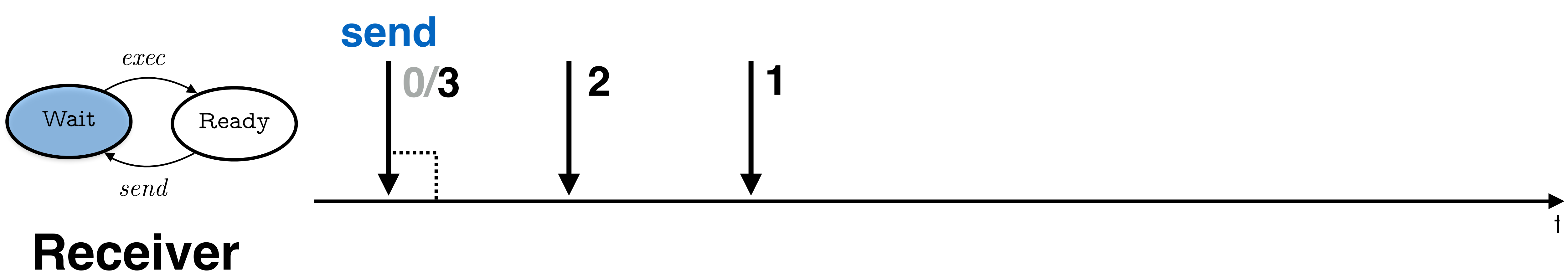
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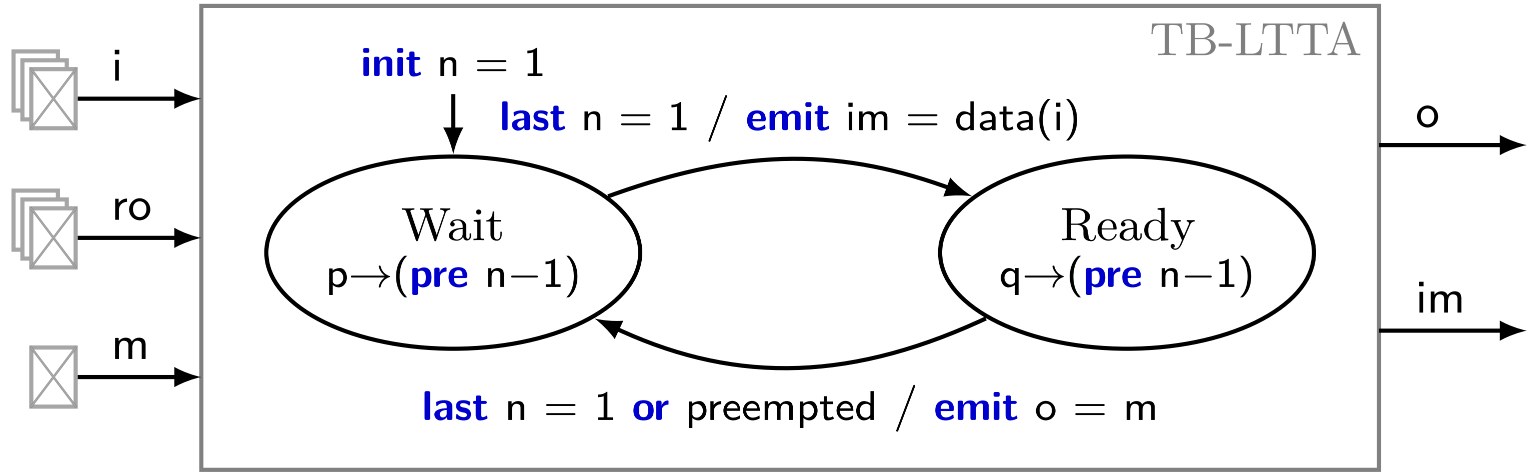
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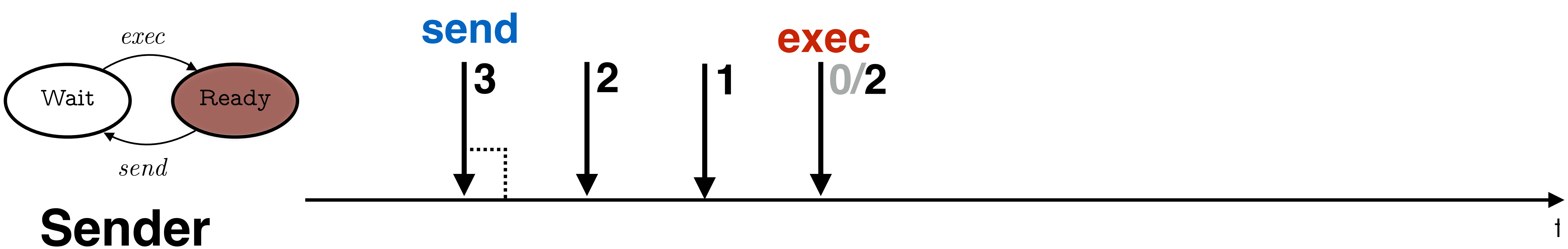
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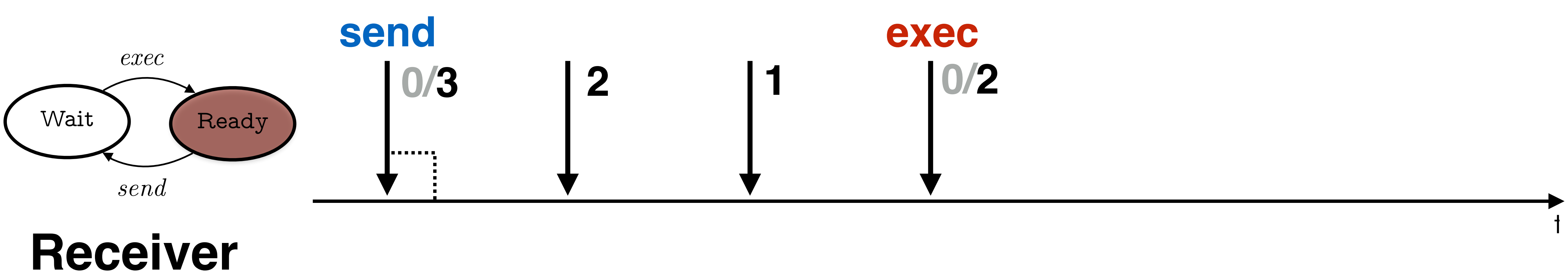
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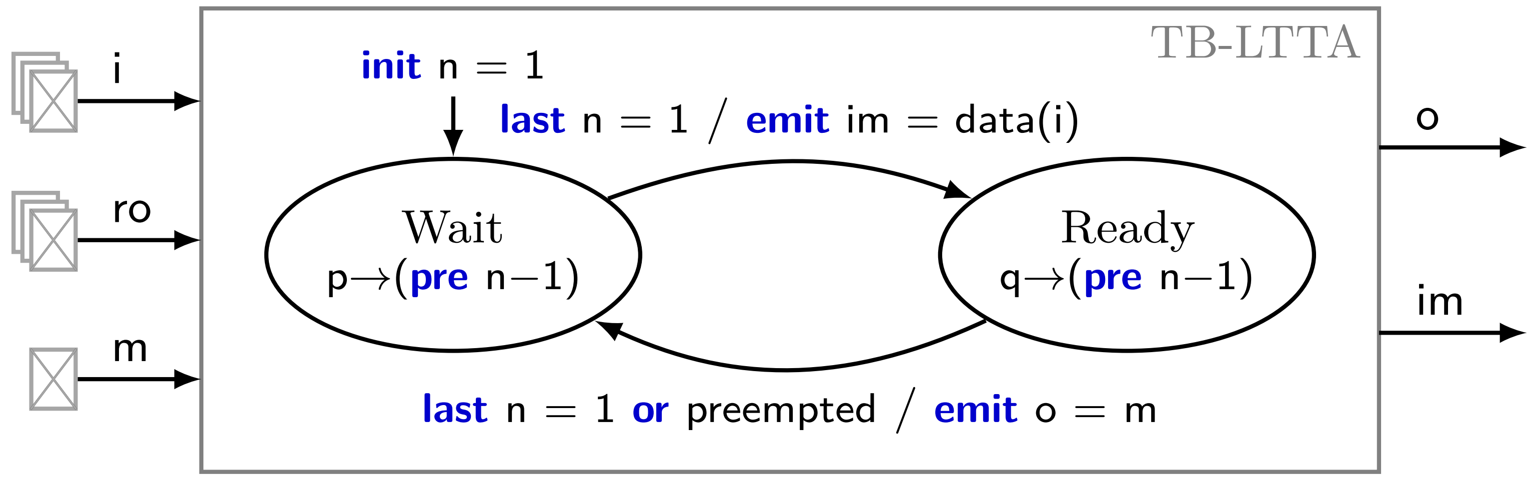

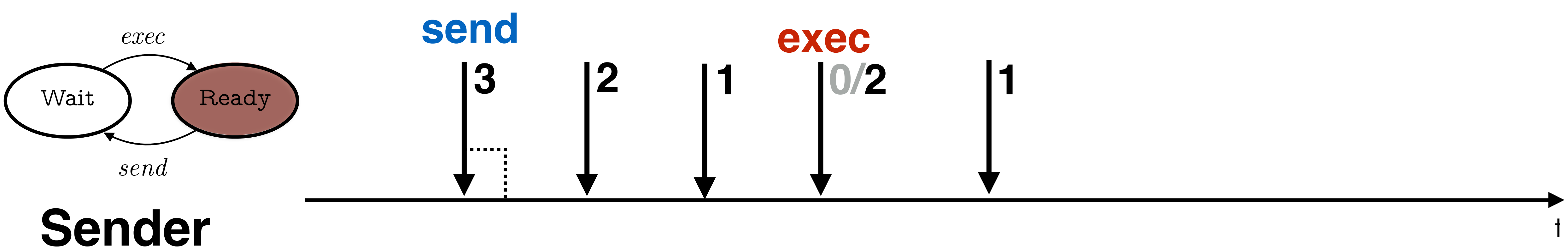

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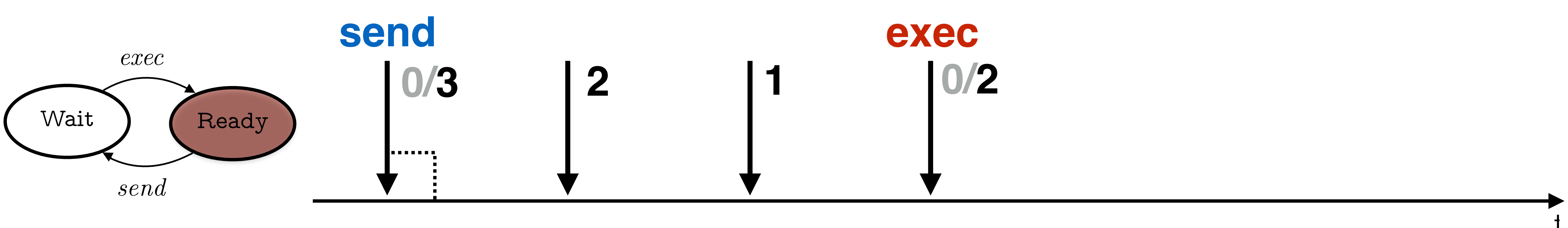

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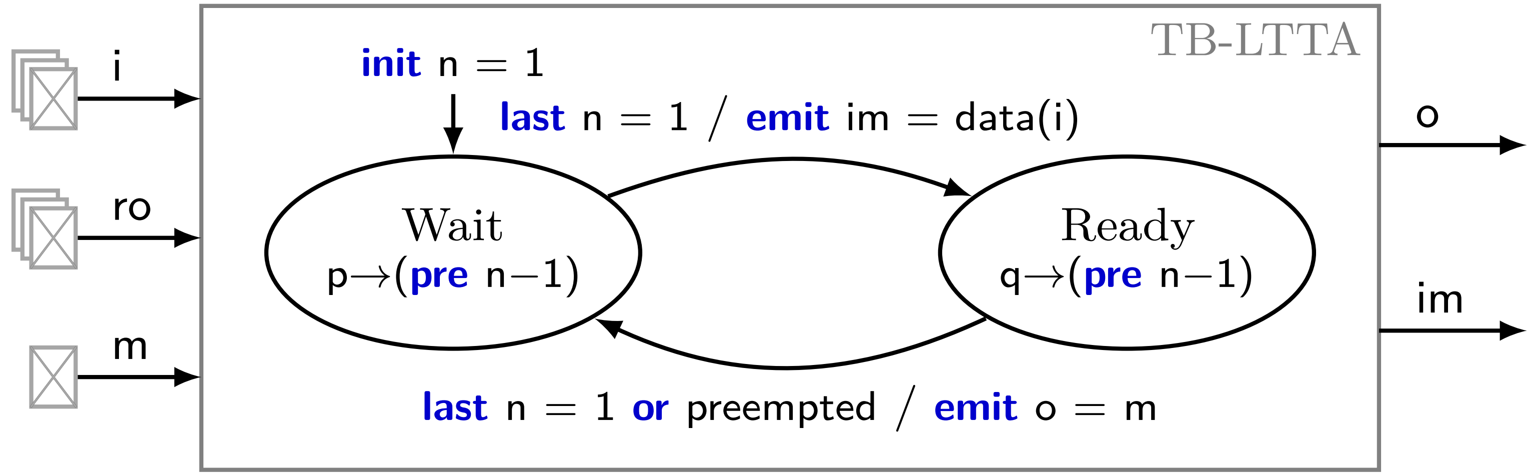

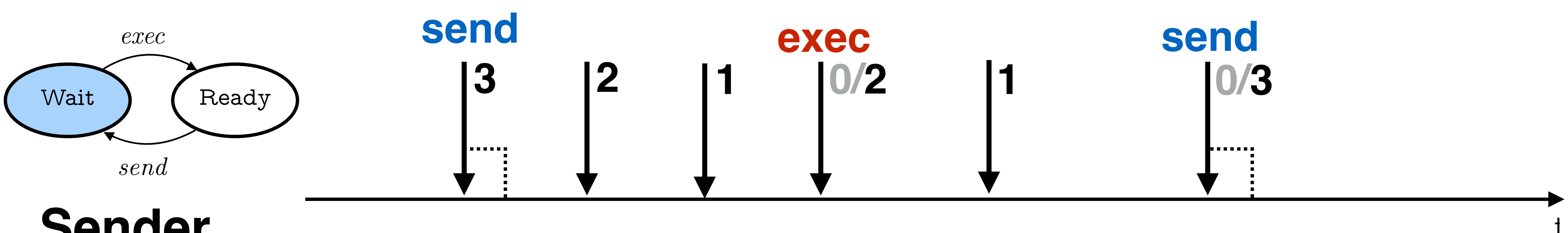

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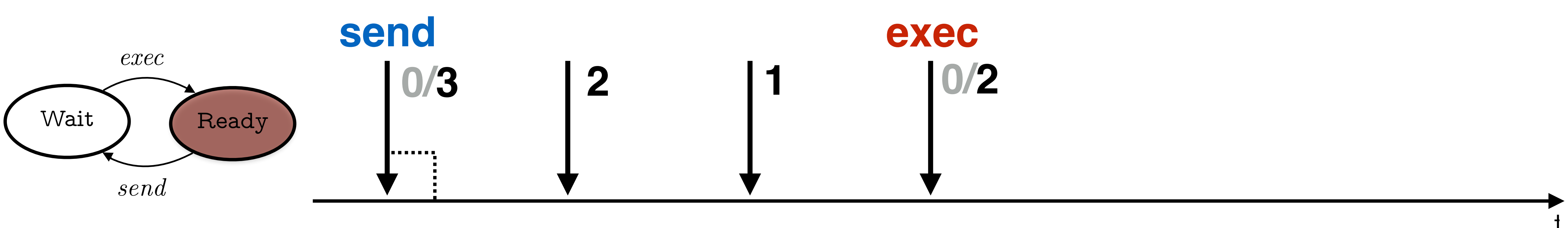

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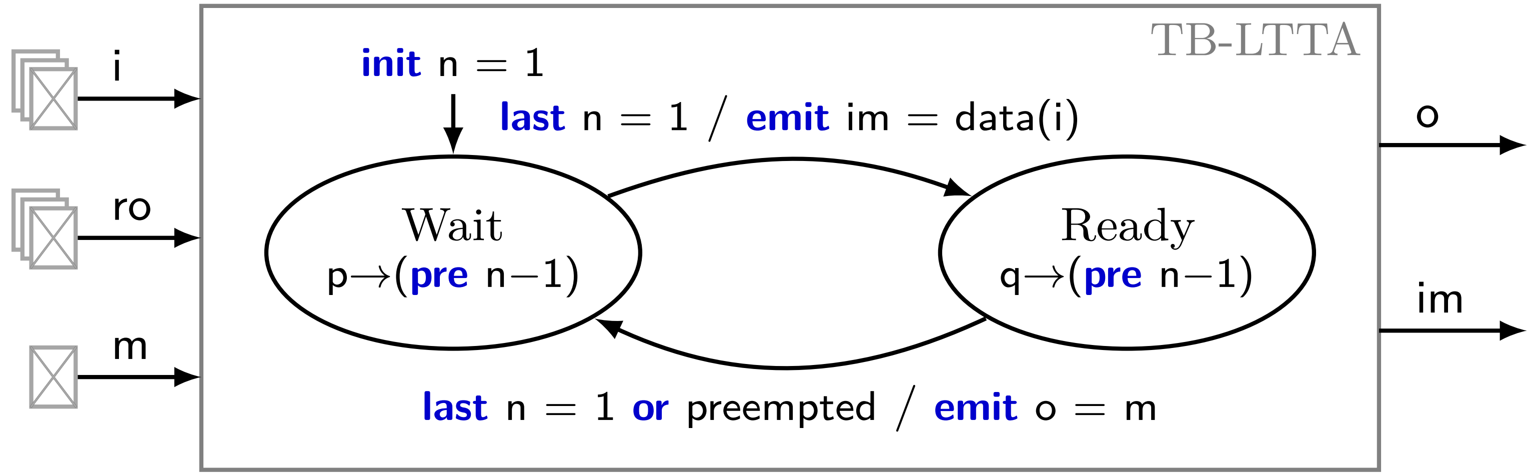

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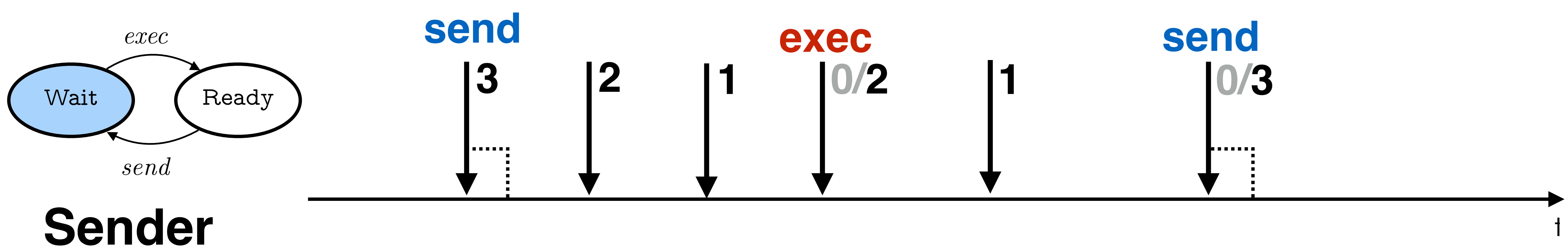

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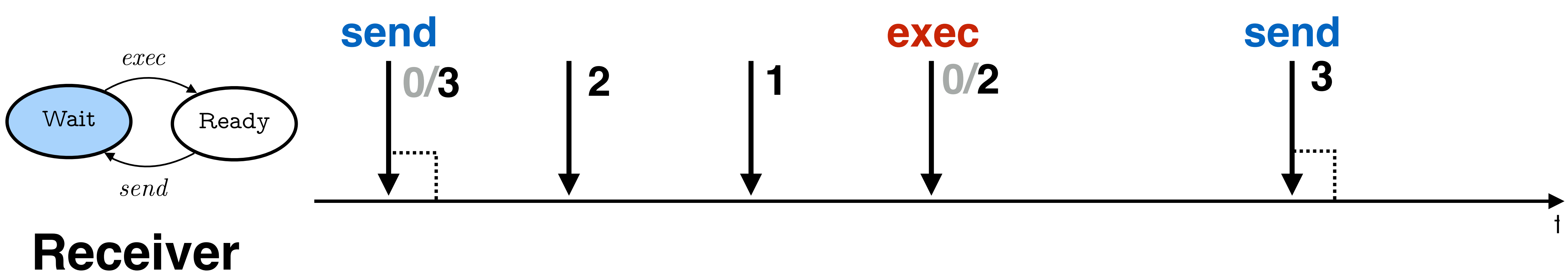

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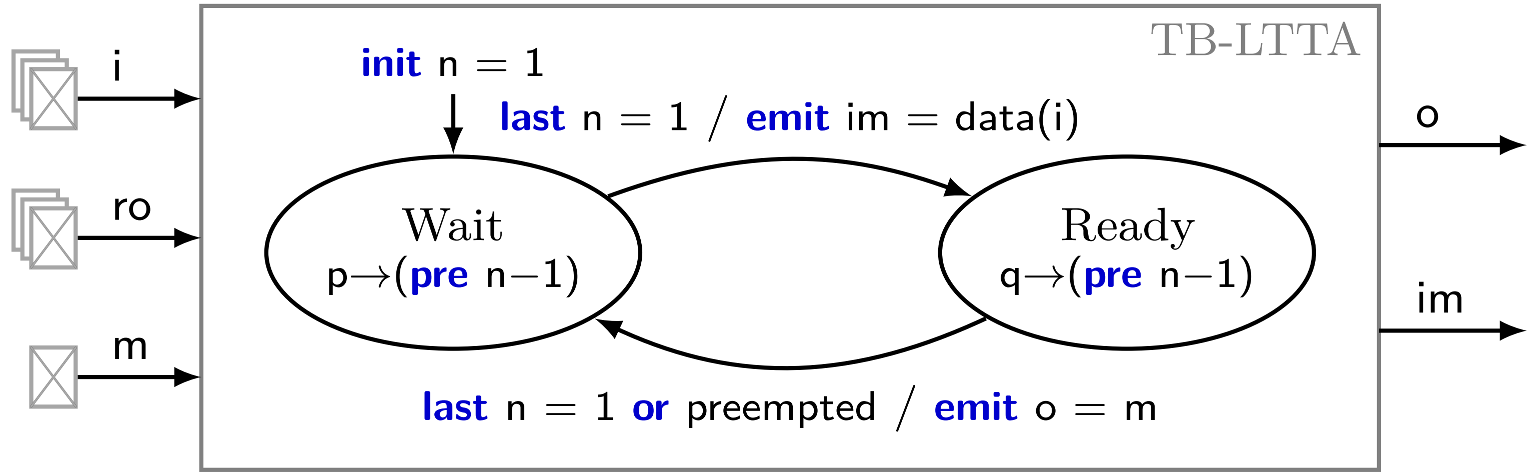

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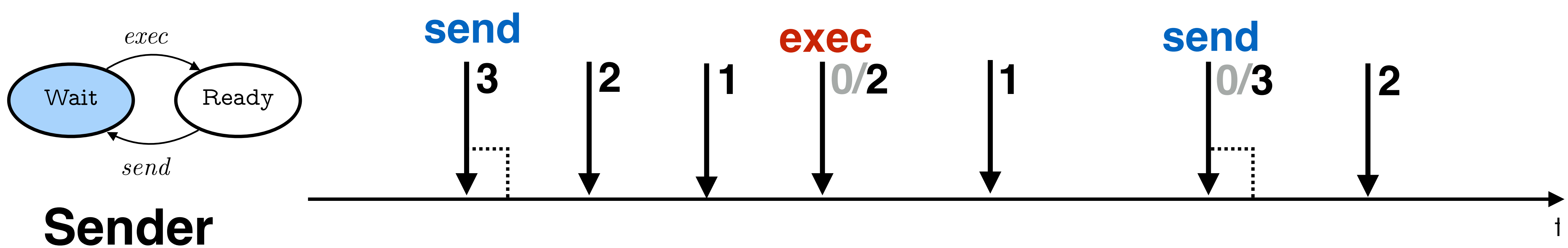

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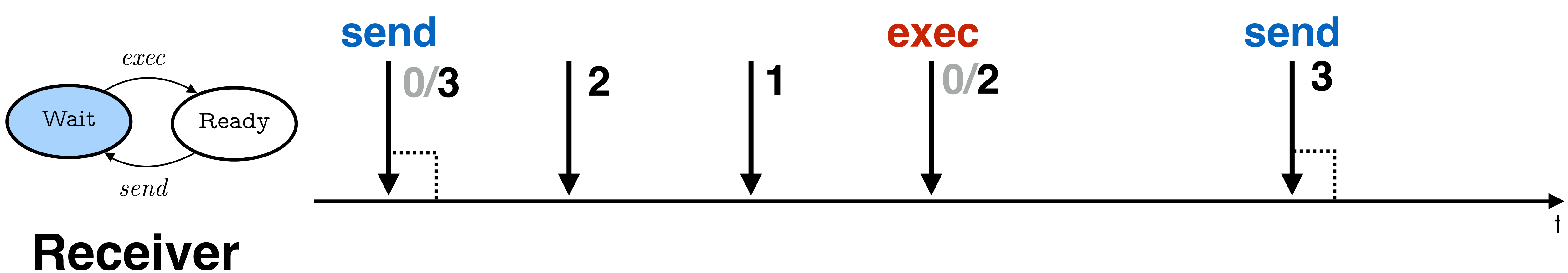

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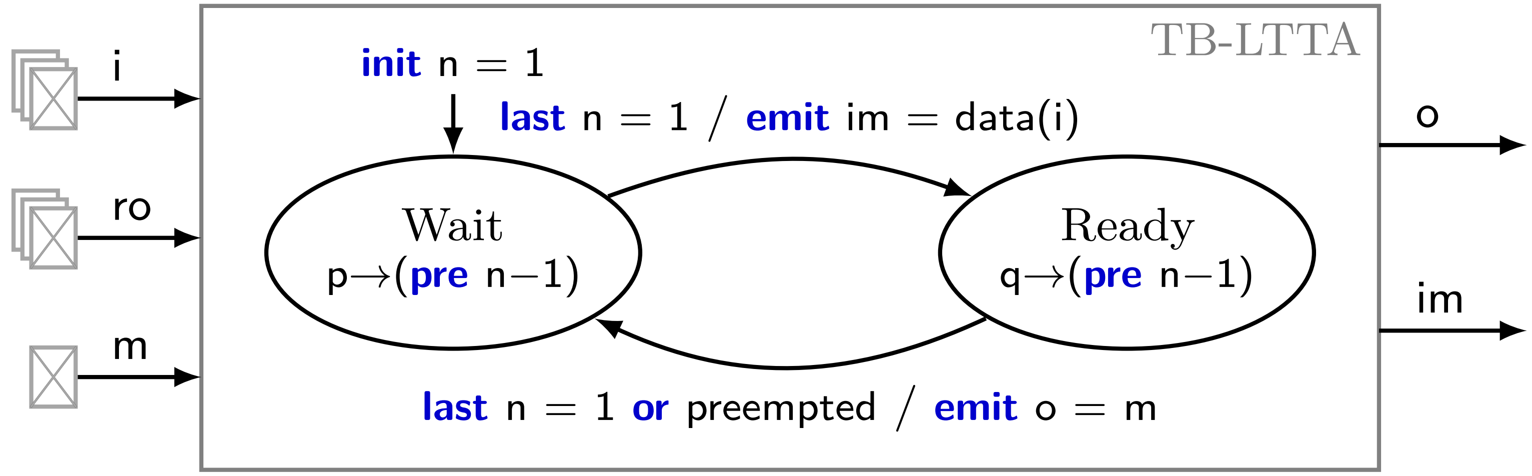
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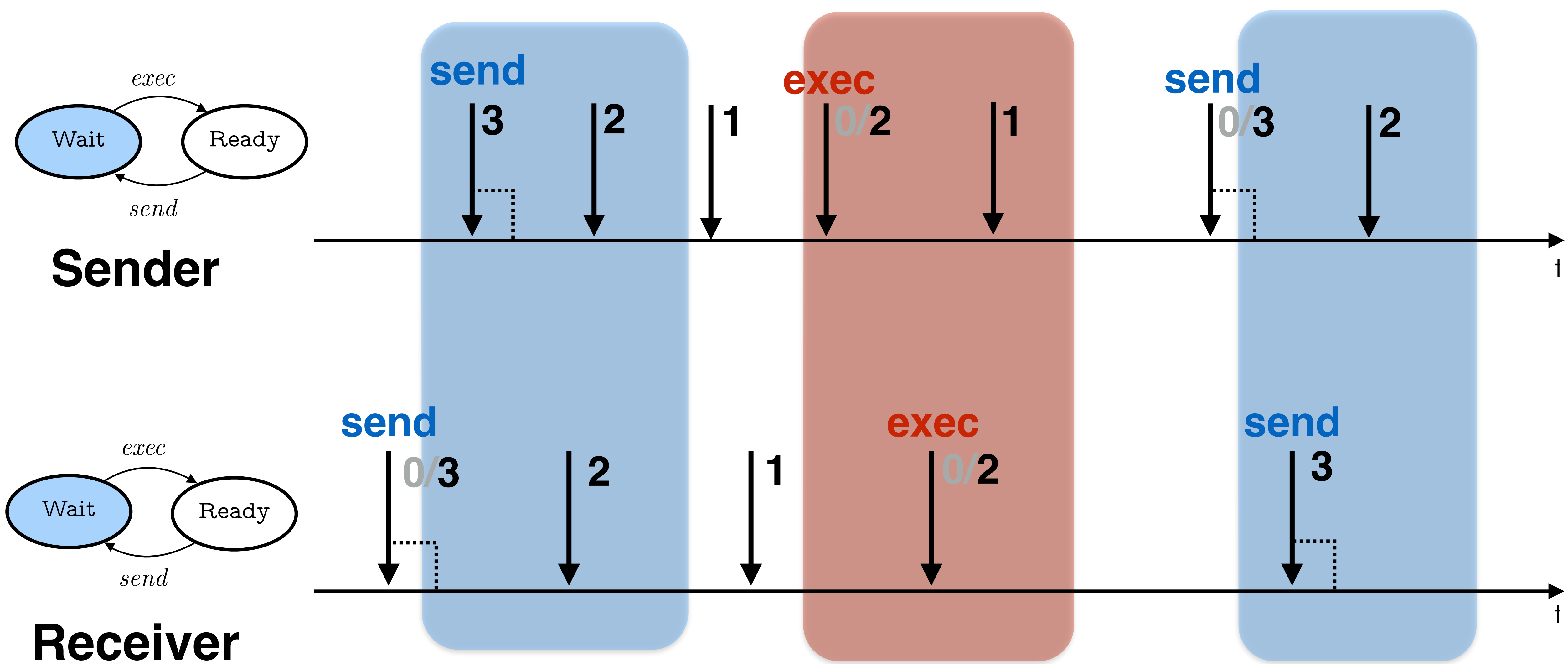
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Time-Based LTTA

- **Theorem 1:**
  Composition of the controller and the embedded machine is always well-defined (no cycle)

- **Theorem 2:**
  Time-based LTTA preserves the Kahn semantics of the embedded application

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

The Time-Based Protocol

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

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

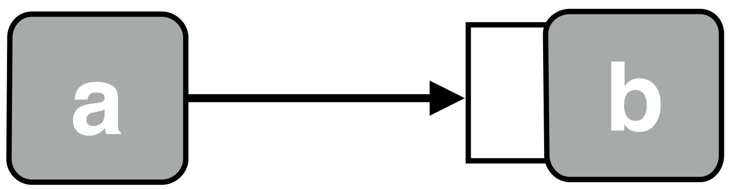
The Time-Based Protocol

Proof sketch

- Worst case reasoning
- Tuning constants p and q (counter initial values)
- Ensure that the receiver always reads the proper data

$\square$

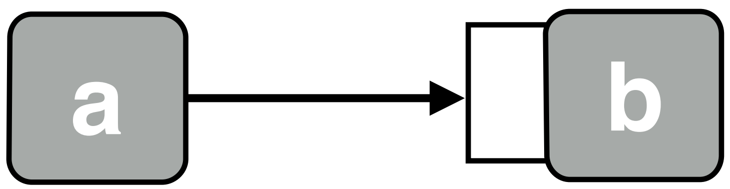
The Time-Based Protocol



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

Property 1: $W^{a}_{k-1} \prec E^{b}_{k}$

The Time-Based Protocol



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

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

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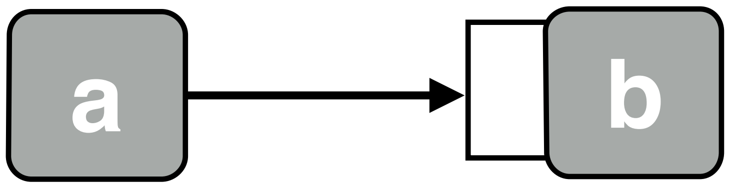
W^b_{k-1}

The Time-Based Protocol



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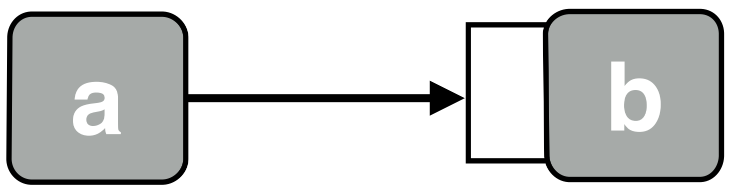
\end{aligned}
$$

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

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

The Time-Based Protocol



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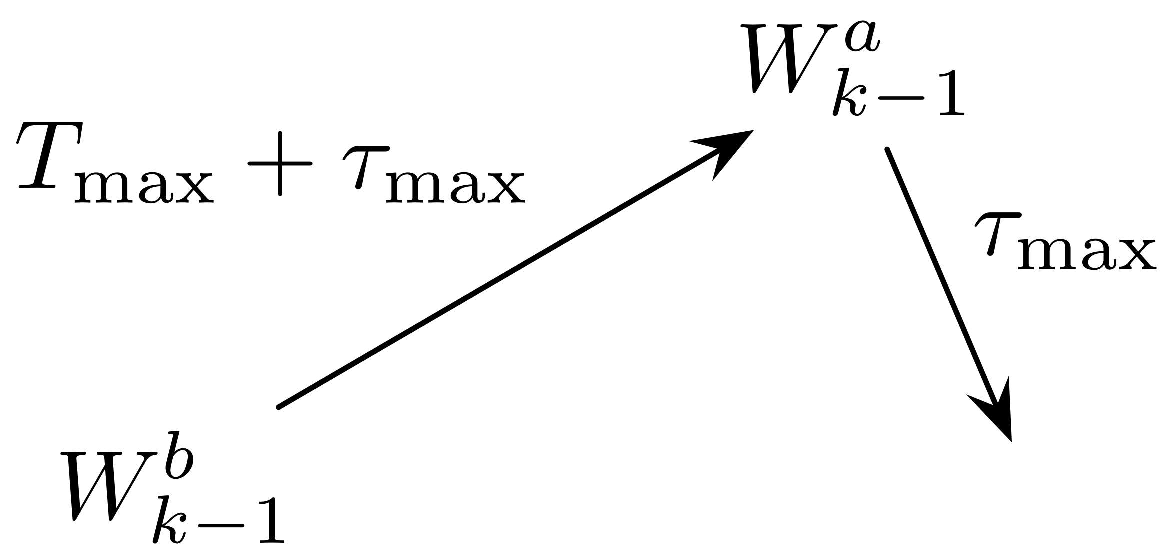

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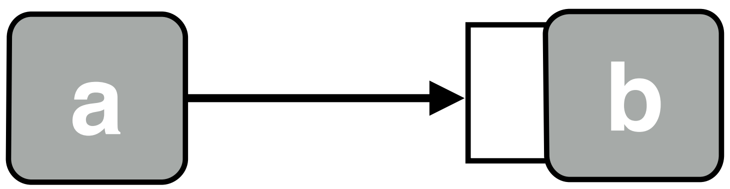

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p &> \frac{2\tau_{\max}}{T_{\min}} + \frac{T_{\max}}{T_{\min}} \\
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\end{aligned}
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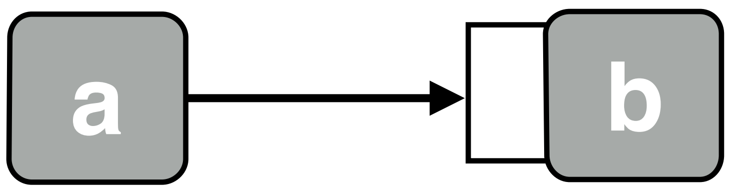
$$
\begin{tikzcd}
 & W^a_{k-1} \arrow[dr, "\tau_{\max}"] & \\
W^b_{k-1} \arrow[ur, "T_{\max} + \tau_{\max}"] \arrow[rr, "pT_{\min}"'] & & E^b_k
\end{tikzcd}
$$

The Time-Based Protocol



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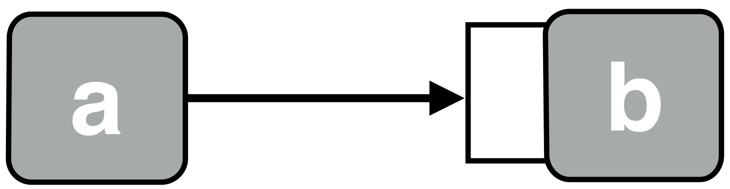

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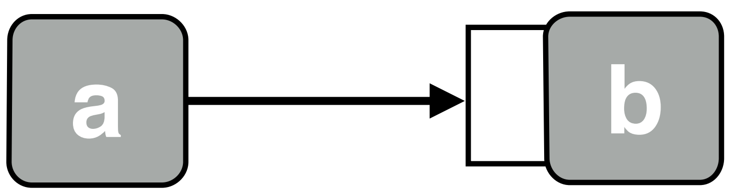
W^a_{k-1}

The Time-Based Protocol



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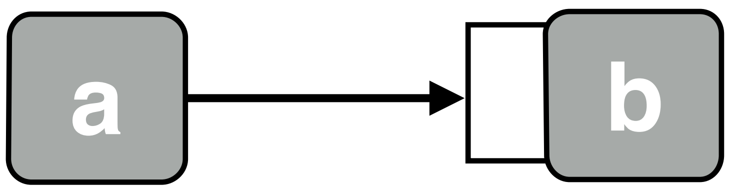

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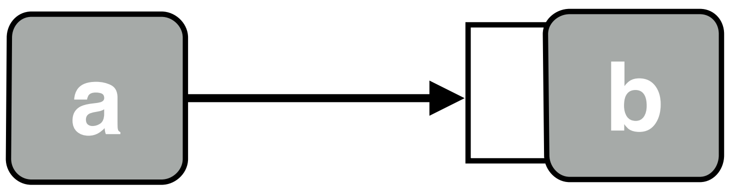
The Time-Based Protocol



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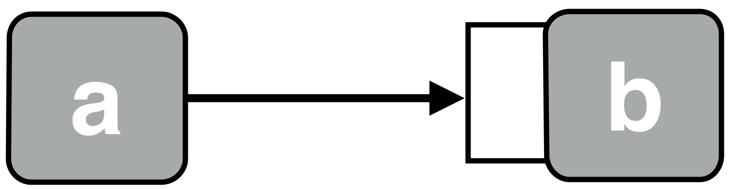
$$

The Time-Based Protocol



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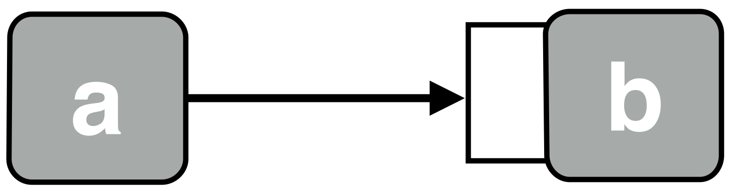
The Time-Based Protocol



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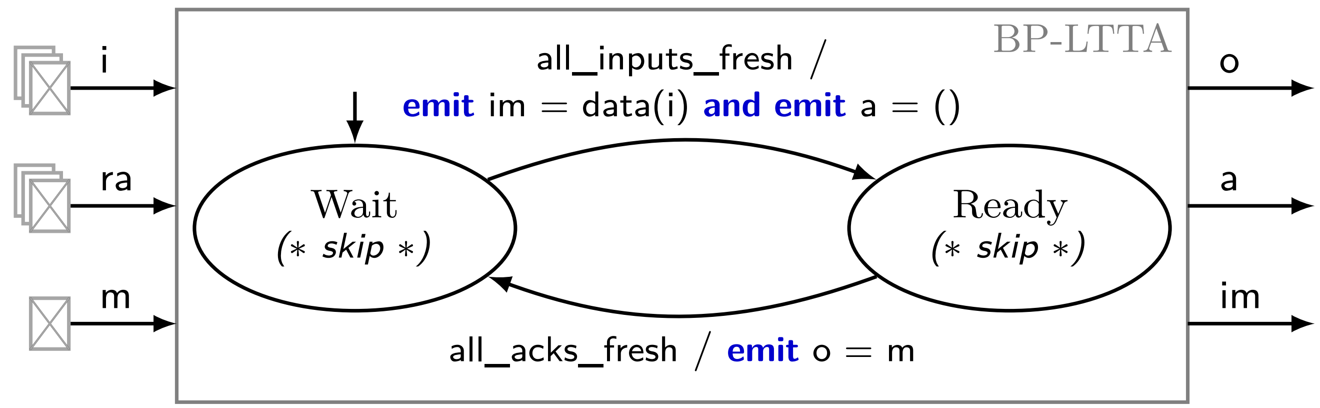
& W^b_{k-1} \arrow[rr, "pT_{\max}"'] & & E^b_k
\end{tikzcd}
$$

The Time-Based Protocol

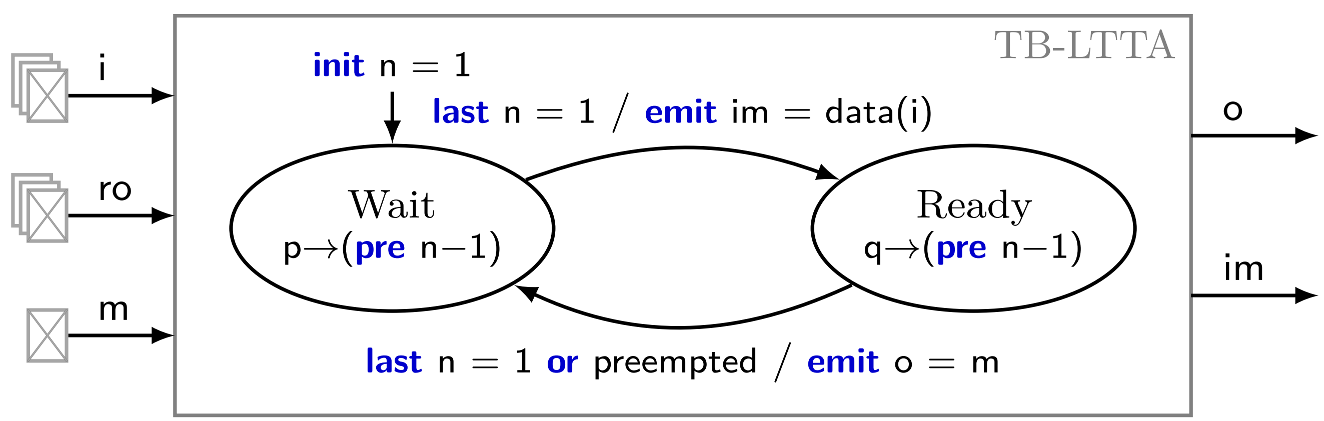
Corollary: The protocol ensures alternation between **exec** and **send** phases for each pair of communicating nodes

Broadcast communication: ensure clean alternation throughout the entire architecture (idem for back-pressure LTTA)

Comparison



Back-pressure



Time-based

Comparison

	Time-Based	Back-Pressure
Flexibility	Require architecture specifications	Very flexible
Robustness	Can run in a degraded mode	Stuck if a node crash
Fault Tolerance	Can be programmed in the application	Implemented in the Middleware
Communication	Any	Any
Pipelining	Limited	Optimal

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Outline

1. What is an LTTA?
   1. Quasi-Periodic Architecture
   2. Synchronous Applications

2. General Framework

3. The two protocols
   1. Back-Pressure LTTA
   2. Time-Based LTTA

4. **What About Clock Synchronisation?**

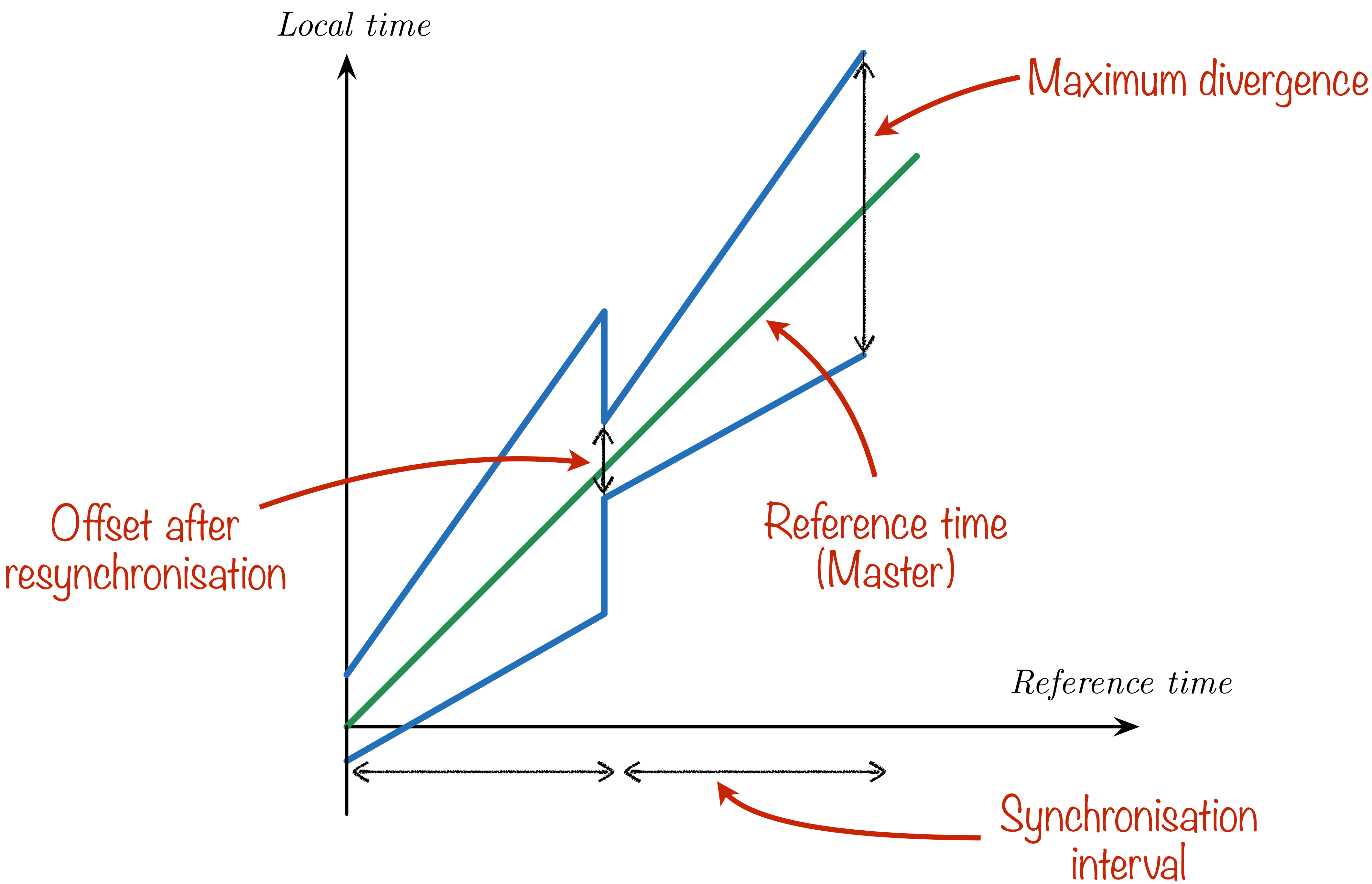
Global Clock Protocol

Central Master Synchronisation

- **Goal:** Implement clock synchronisation on a quasi-periodic architecture
- We use the most efficient protocol for comparison purposes
- One node is used as a time reference for all other nodes: the **central master clock**

Global Clock Protocol

The Big Picture



Global Clock Protocol

Central Master Synchronisation

Synchronisation interval	R
Offset after resynchronisation	$\Phi = \tau_{\max} + T_{\max} - \tau_{\min}$
Drift rate	$\rho = \frac{T_{\max}}{T_n} - 1 = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}}$
Maximum divergence	$\Gamma = 2\rho R$
Precision	$\Pi = \Phi + \Gamma$

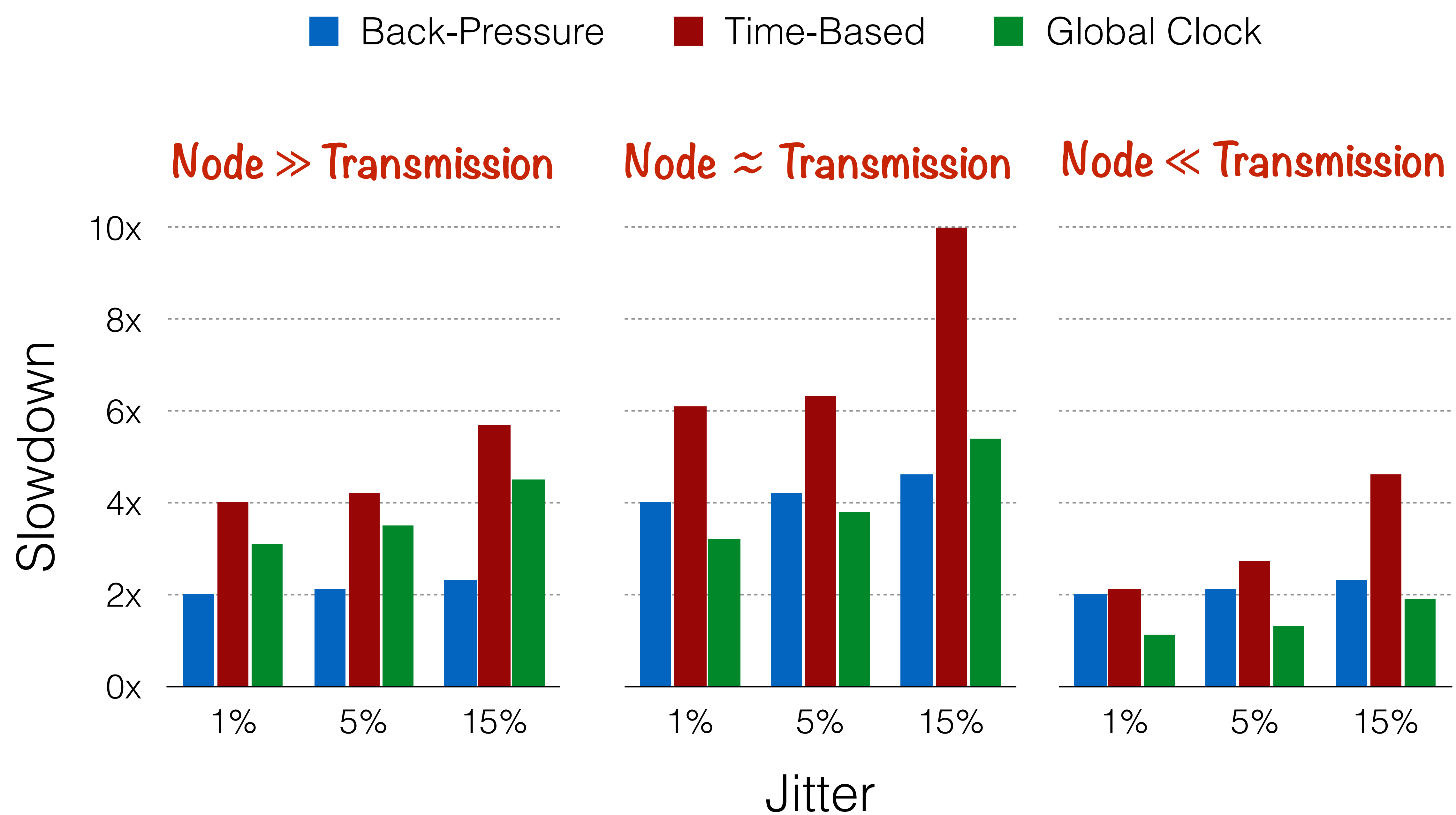
Global Clock Protocol

Lock-Step Execution

- Given the precision of the synchronisation one can build a global notion of time or **macroticks**
- Activating nodes on each macrotick imposes a synchronous execution.
- But we need to wait for the transmission delay between execution steps.

Comparative Evaluation

Compared to synchronous execution*



* The smaller, the better.

Conclusion

- Our new model simplifies and clarifies those of previous papers
- A new proposition for the time-based protocol that does not require broadcast communication and does allow pipelining
- Model and Simulation of the protocols in Zélus
  Discrete model + link with continuous time
- Comparison with clock synchronisation deployed on the same architecture