Theoretical Foundations of Distributed Operating Systems

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Outline

Two Important Characteristics

- Absence of Global Clock
  - there is no common notion of time
- Absence of Shared Memory
  - no process has up-to-date knowledge about the system

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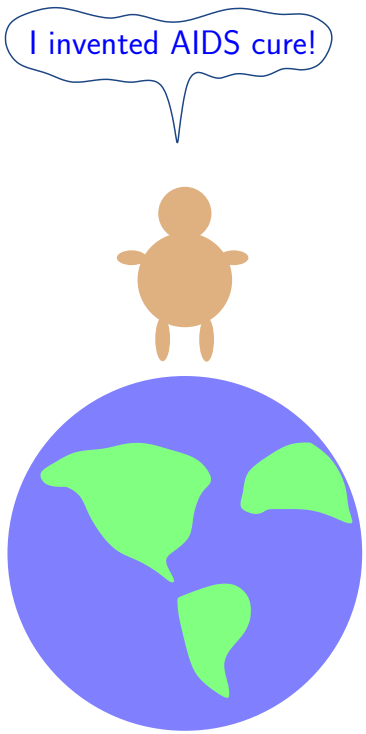
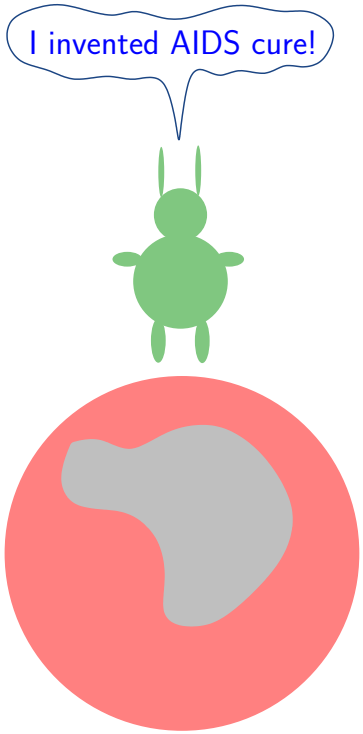


Earth



Mars

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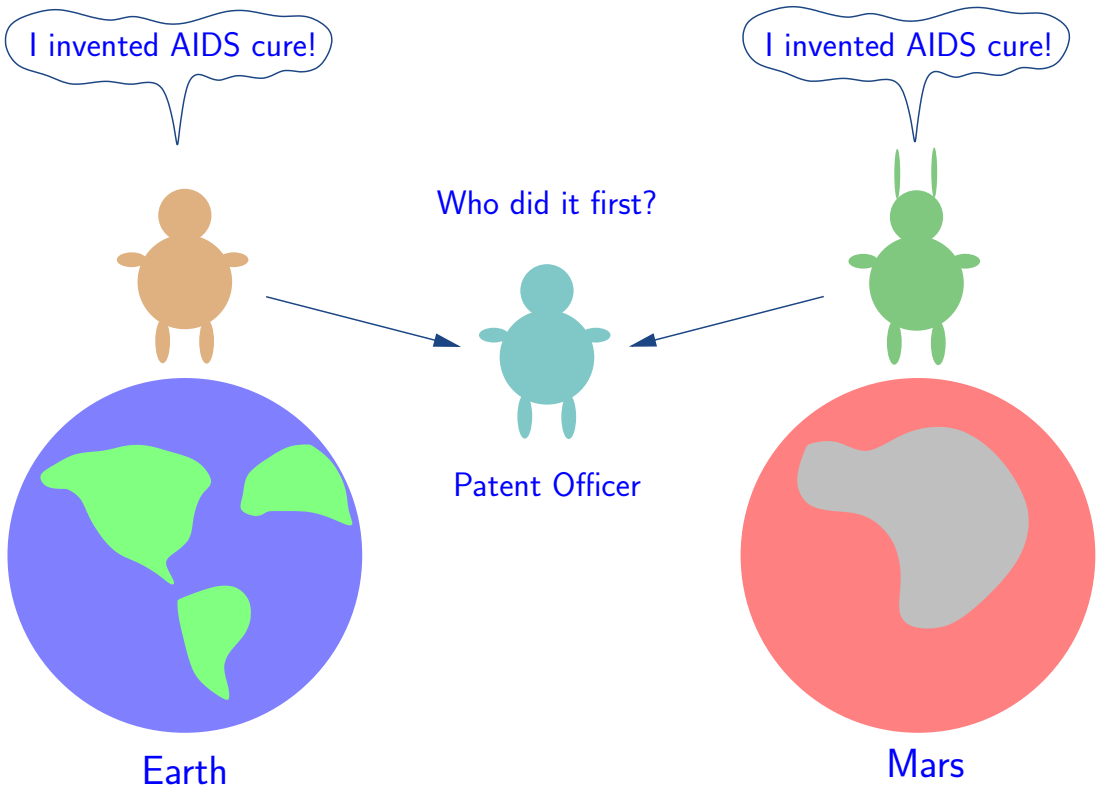

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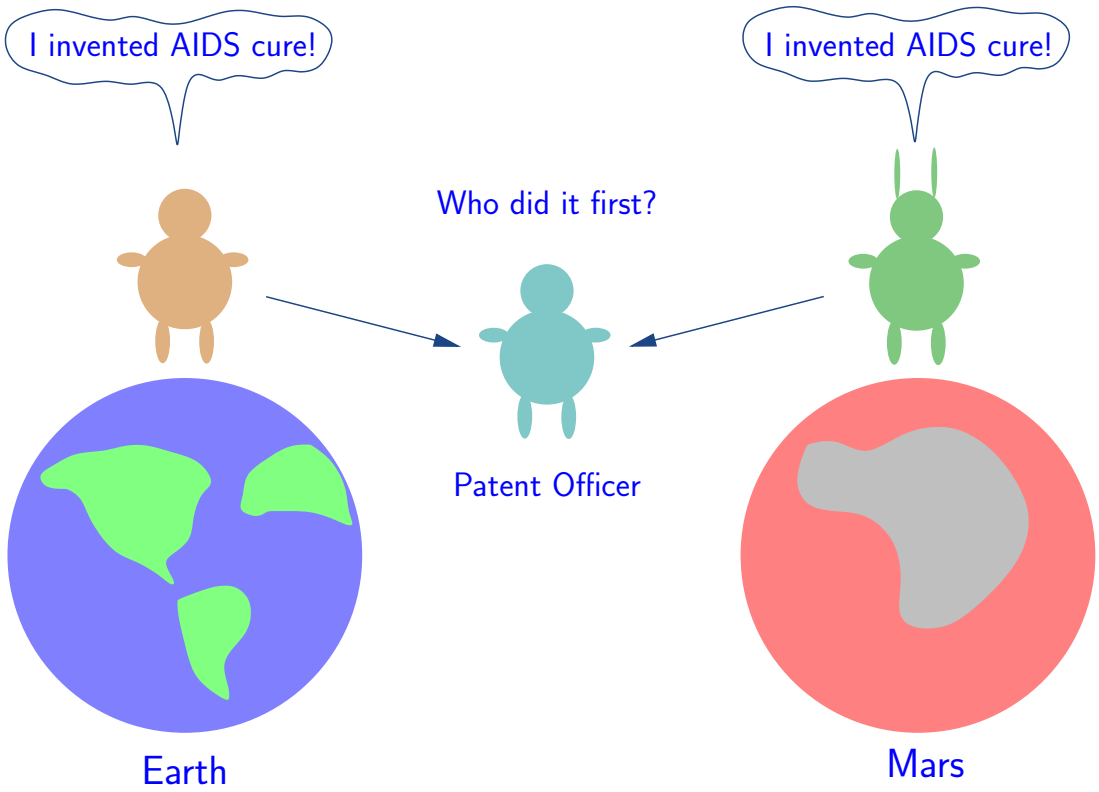

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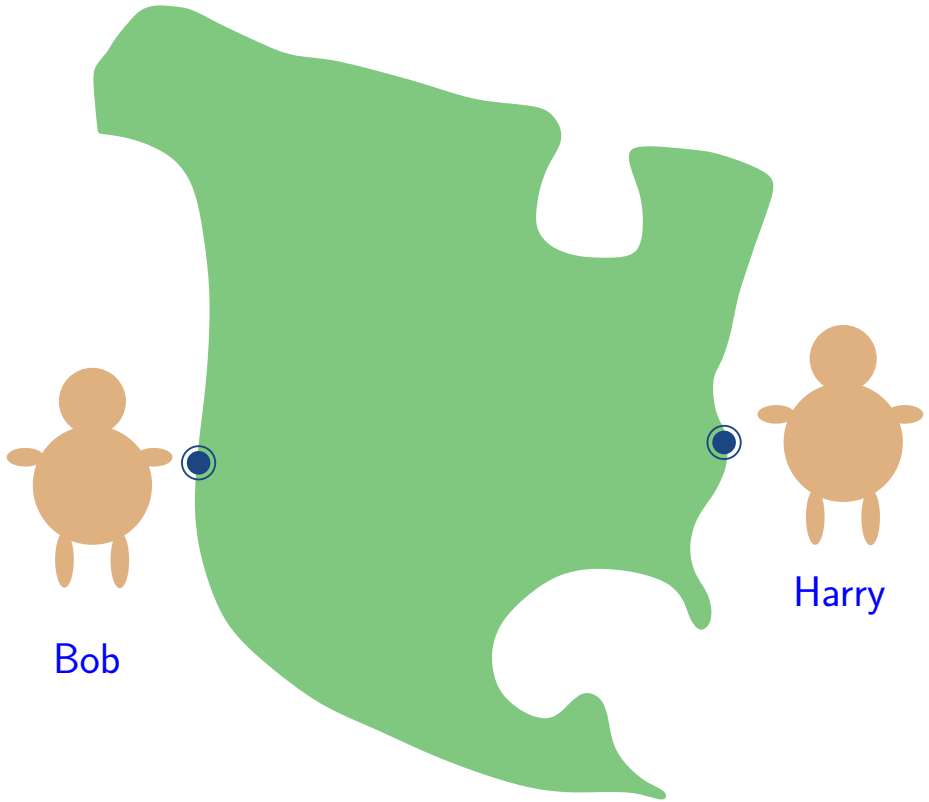

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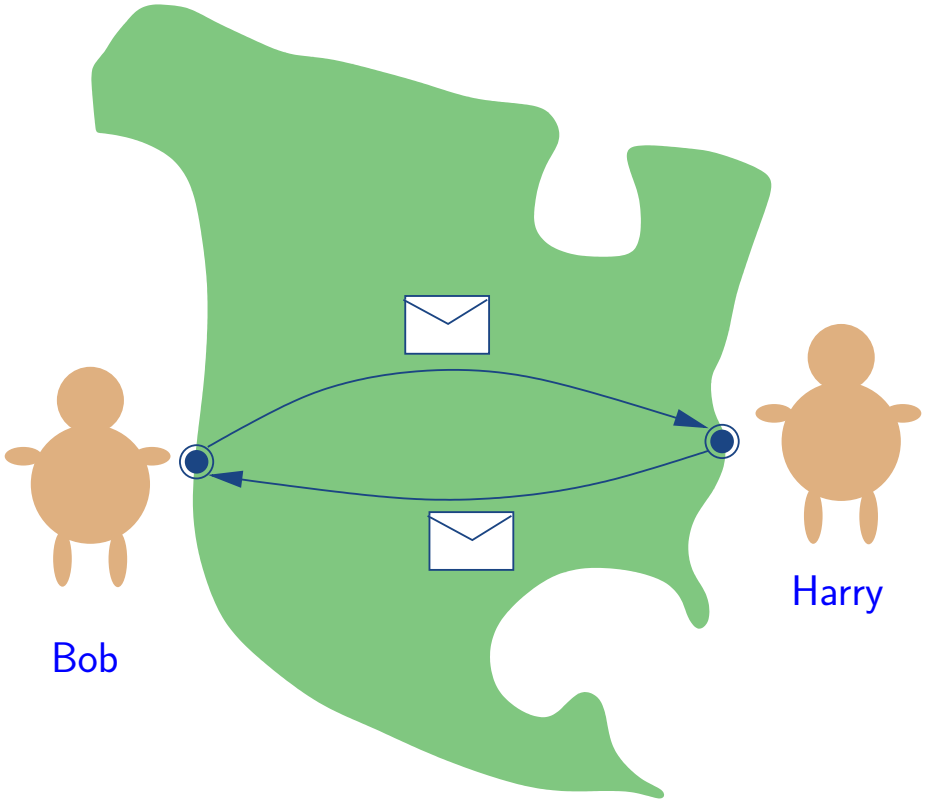

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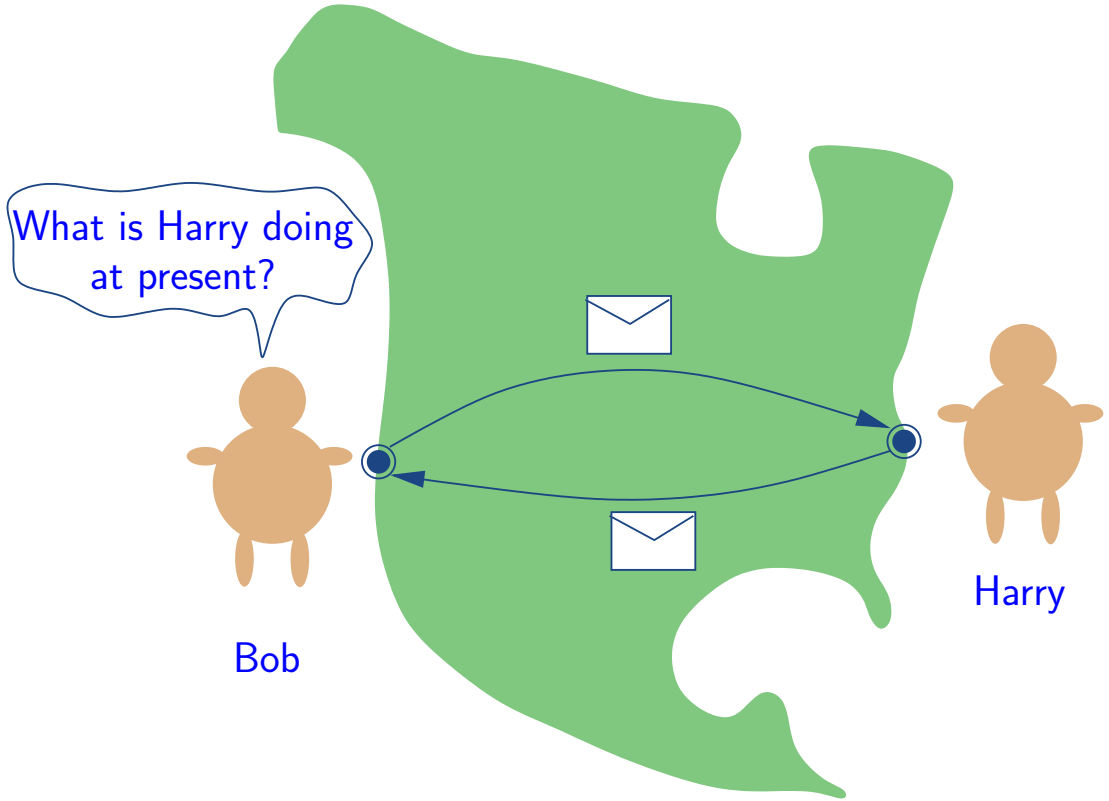

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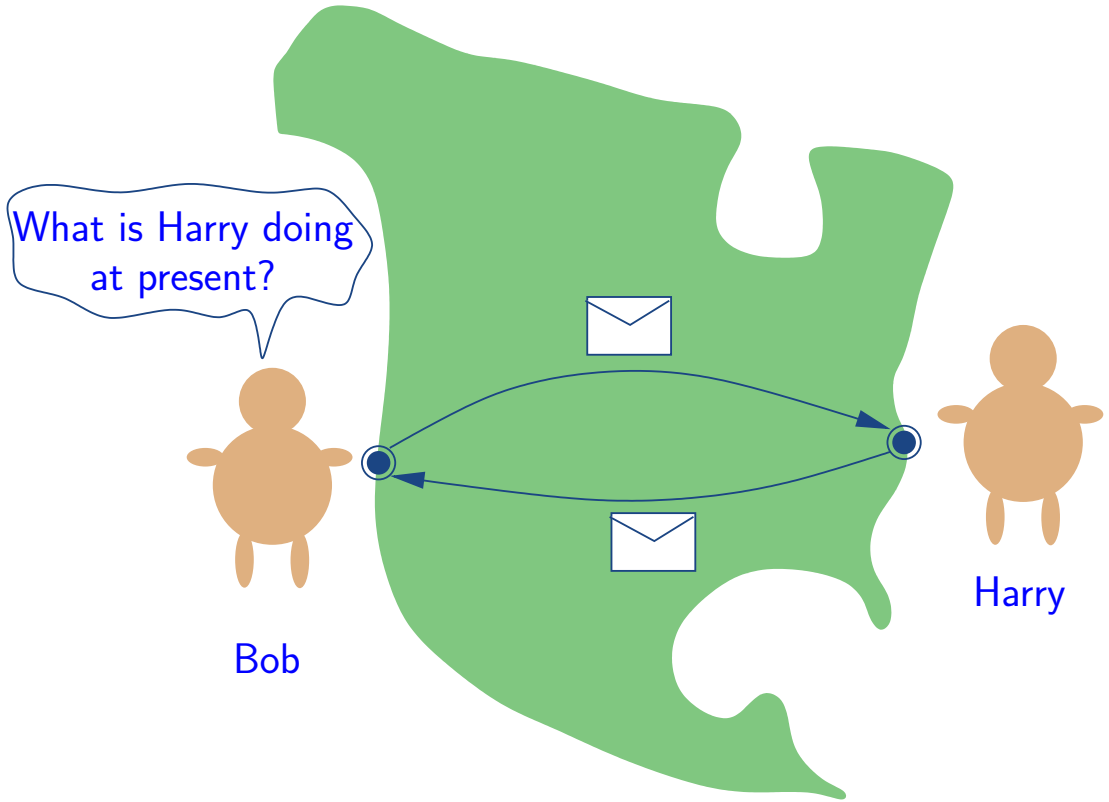

Problem: How do we obtain a coherent view of the system?

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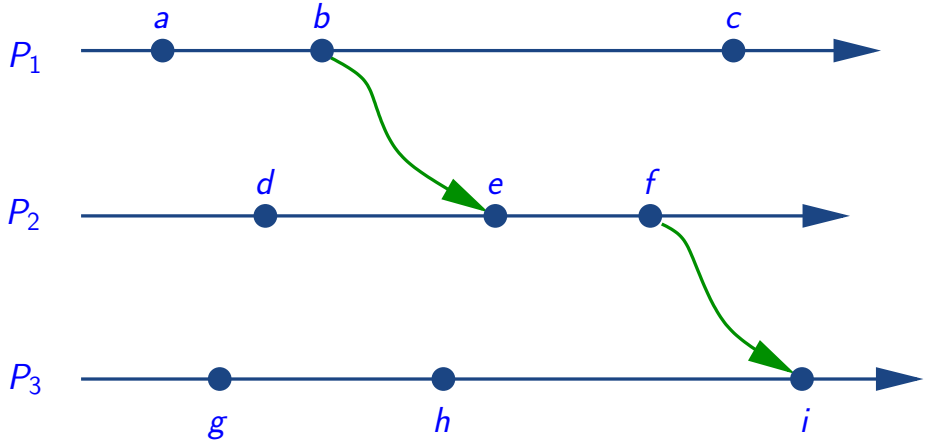

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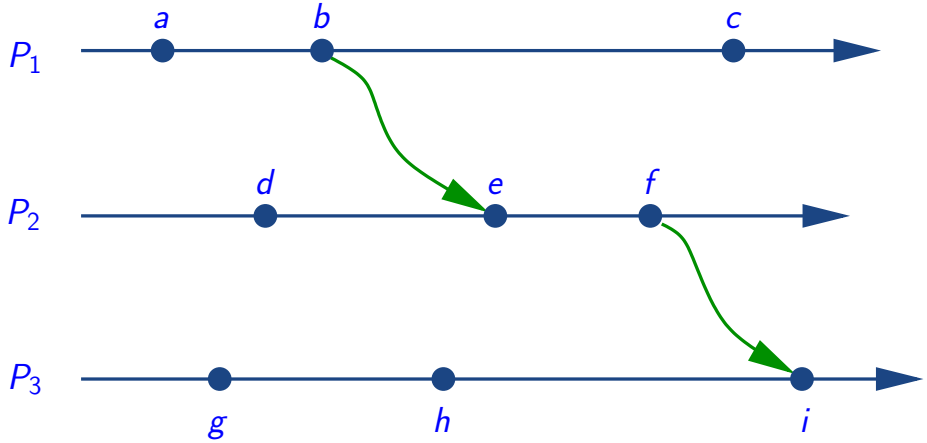

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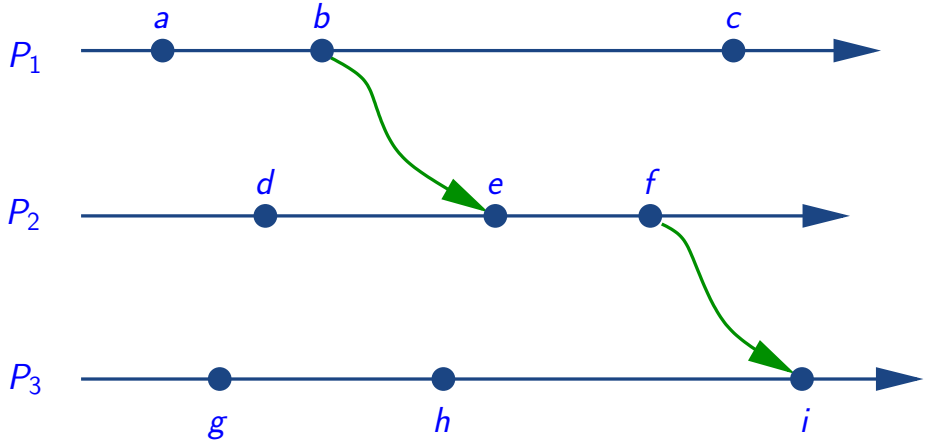

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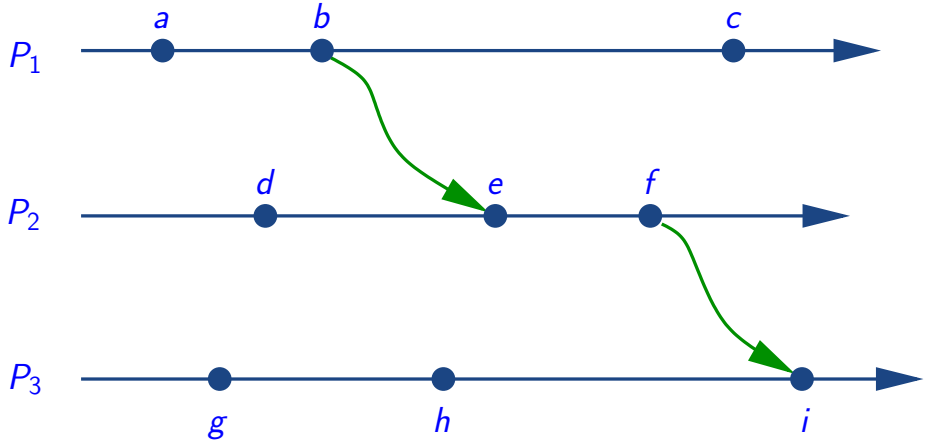

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  - Examples: $a \| d$, $d \| h$, $c \| e$
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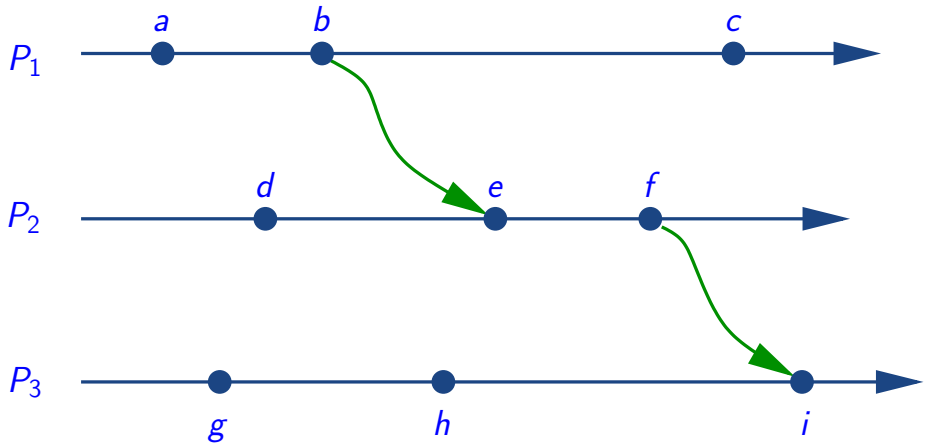

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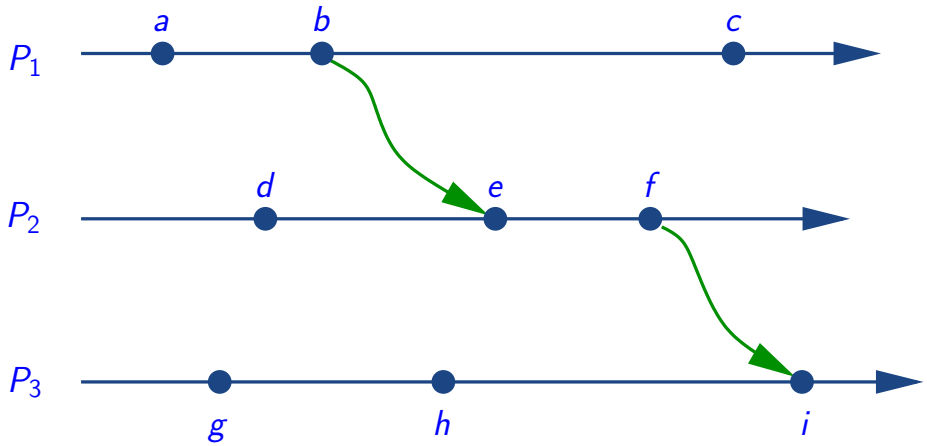

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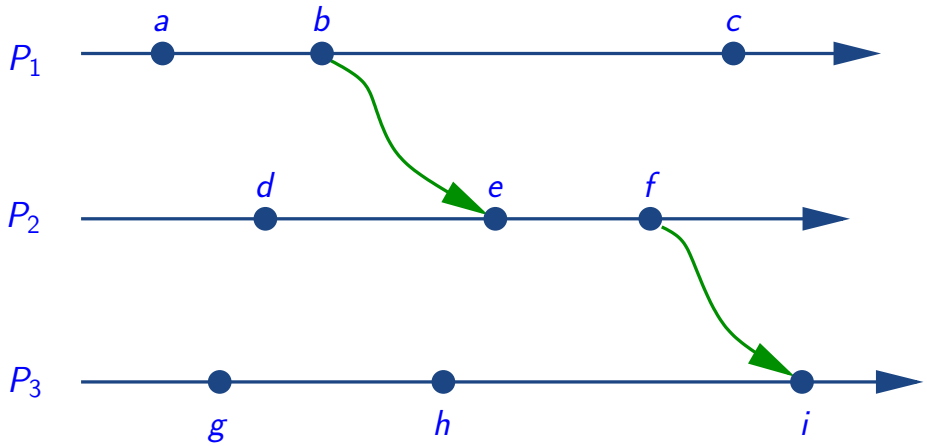

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Different Kinds of Clocks

- Logical Clocks
  - used to totally order all events
- Vector Clocks
  - used to track happened-before relation
- Matrix Clocks
  - used to track what other processes know about other processes
- Direct Dependency Clocks
  - used to track direct causal dependencies

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Logical Clock

- Implements the notion of virtual time
- Can be used to totally order all events
- Assigns timestamp to each event in a way that is consistent with the happened-before relation:

$$e \rightarrow f \implies C(e) < C(f)$$

$C(e)$: timestamp for event e
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Implementing Logical Clock

- Each process has a local scalar clock, initialized to zero
  - C_i denotes the local clock of process P_i
- Action depends on the type of the event
- Protocol for process P_i:
  - On executing an interval event:
    $C_i := C_i + 1$
  - On sending a message m:
    $C_i := C_i + 1$
    piggyback C_i on m
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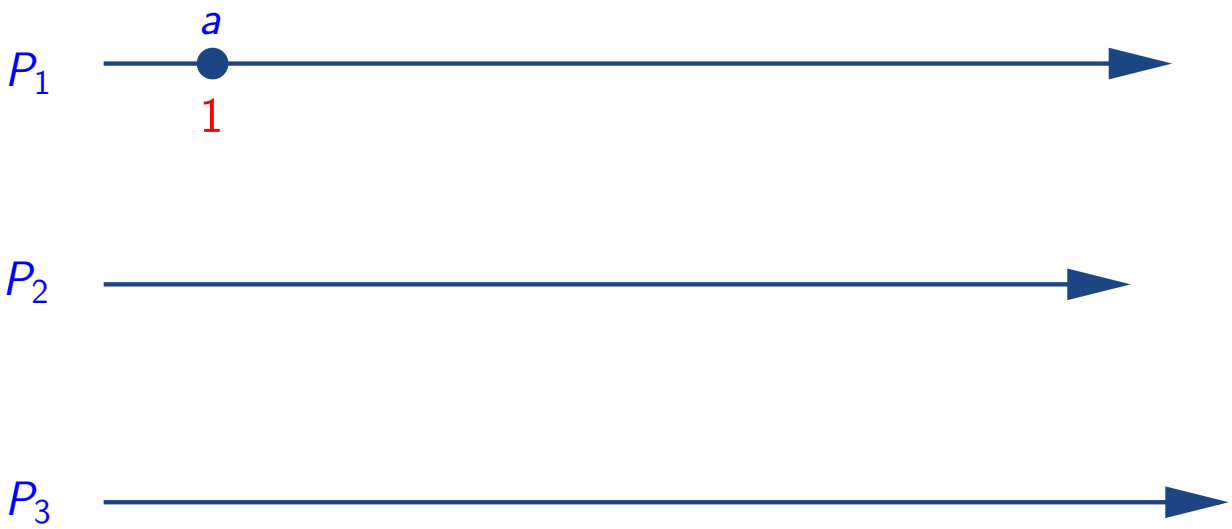
Implementing Logical Clock: An Illustration



a: internal event $\qquad C(a) = 1$

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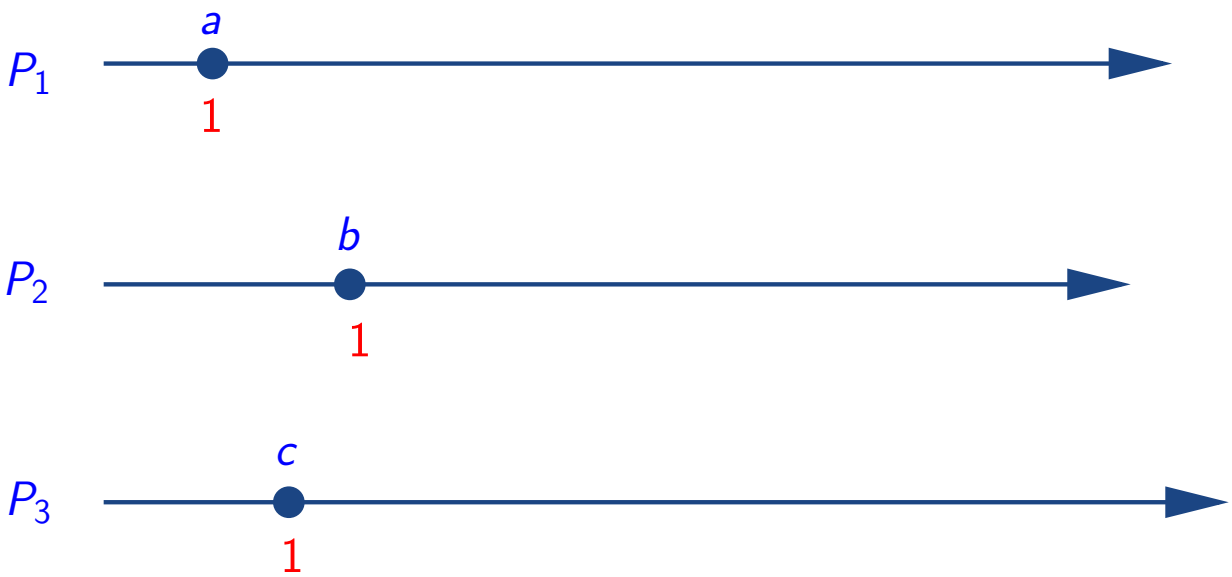

b and c: internal events $\quad C(b) = 1$ and $C(c) = 1$

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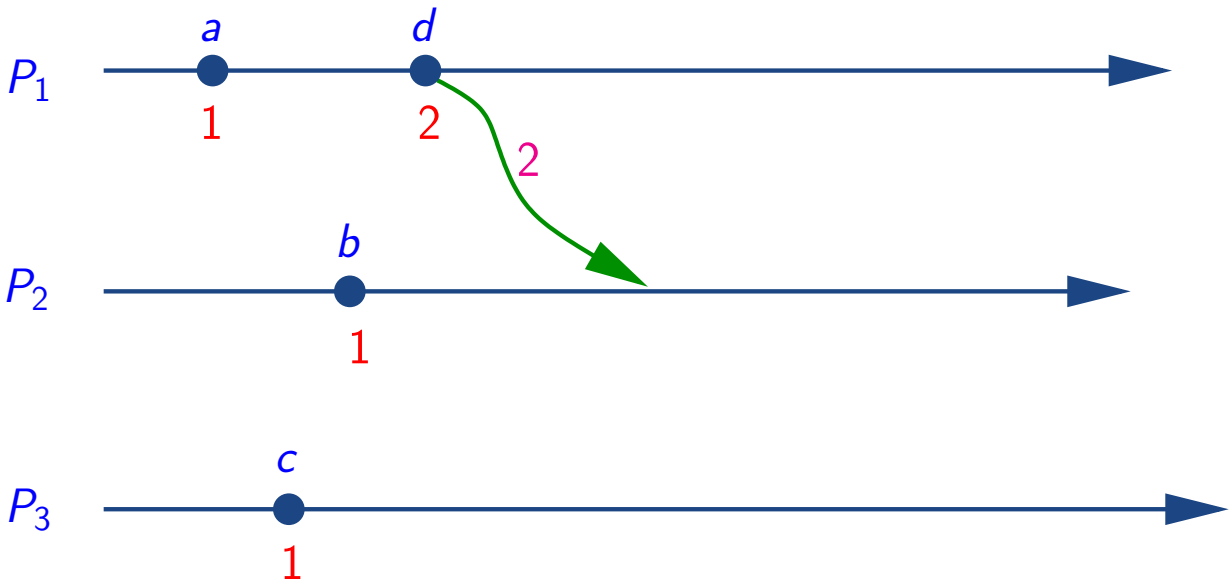

d: send event $\qquad C(d) = 2$

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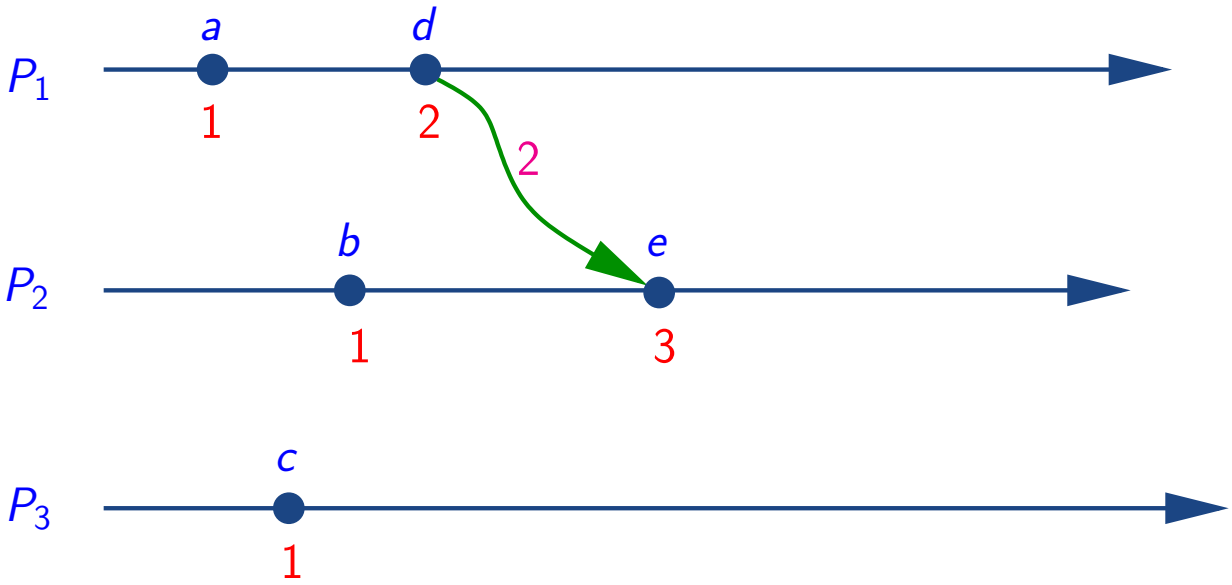

e: receive event $\qquad C(e) = 3$

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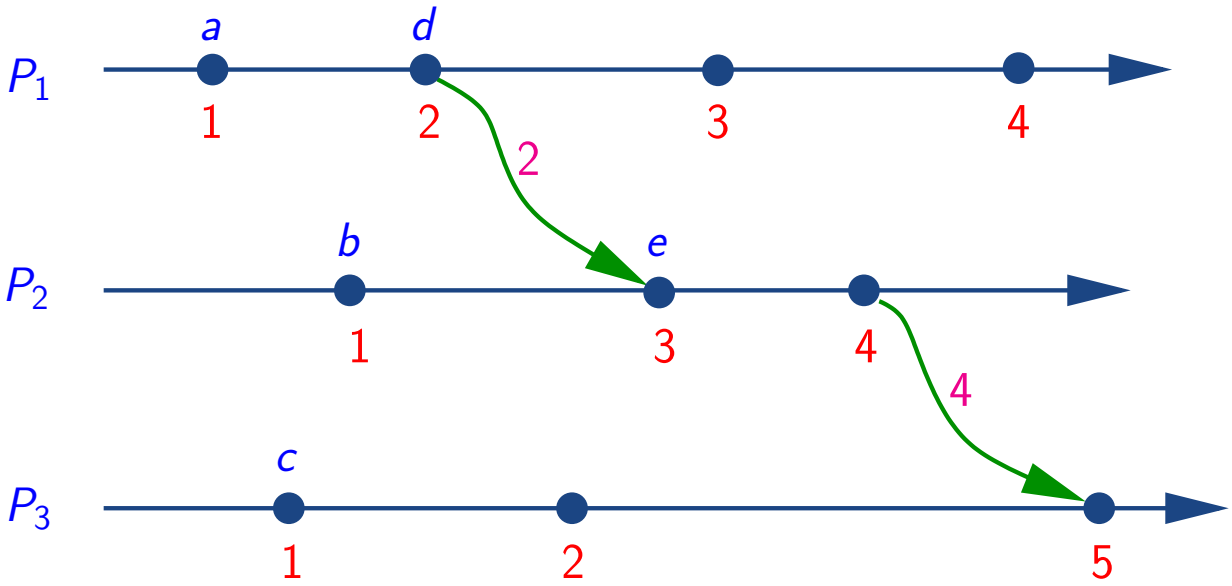

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- Vectors are compared component-wise:
  - Equality:
$$V = V' \quad \text{iff} \quad \langle \forall i : V[i] = V'[i] \rangle$$
  - Less Than:
$$V < V' \quad \text{iff} \quad \langle \forall i : V[i] \leq V'[i] \rangle \wedge \langle \exists i : V[i] < V'[i] \rangle$$
- Example:
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$$\begin{bmatrix} 1 \\ 2 \\ 0 \end{bmatrix} < \begin{bmatrix} 2 \\ 3 \\ 1 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 2 \\ 1 \\ 1 \end{bmatrix} < \begin{bmatrix} 2 \\ 3 \\ 4 \end{bmatrix} \quad \text{but} \quad \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \not< \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix}$$

Implementing Vector Clock

- Each process has a local vector clock
  - C_i denotes the local clock of process P_i
- Action depends on the type of the event
- Protocol for process P_i:
  - On executing an interval event:
    $C_i[i] := C_i[i] + 1$
  - On sending a message m:
    $C_i[i] := C_i[i] + 1$
    piggyback C_i on m
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    let t_m be the timestamp piggybacked on m
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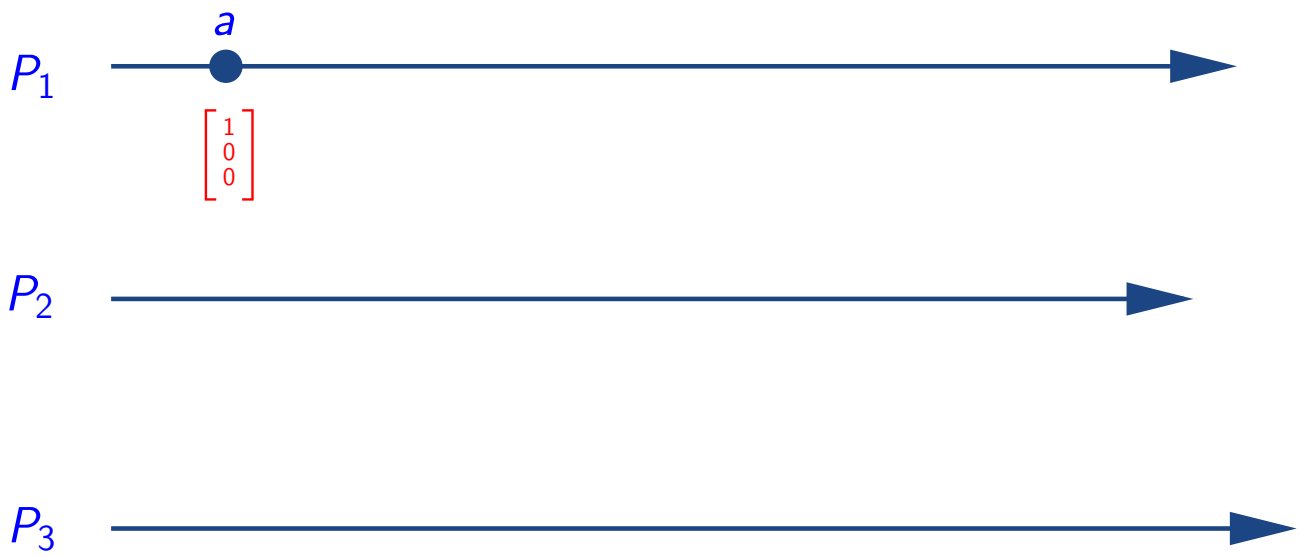

a: internal event $\qquad C(a) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$

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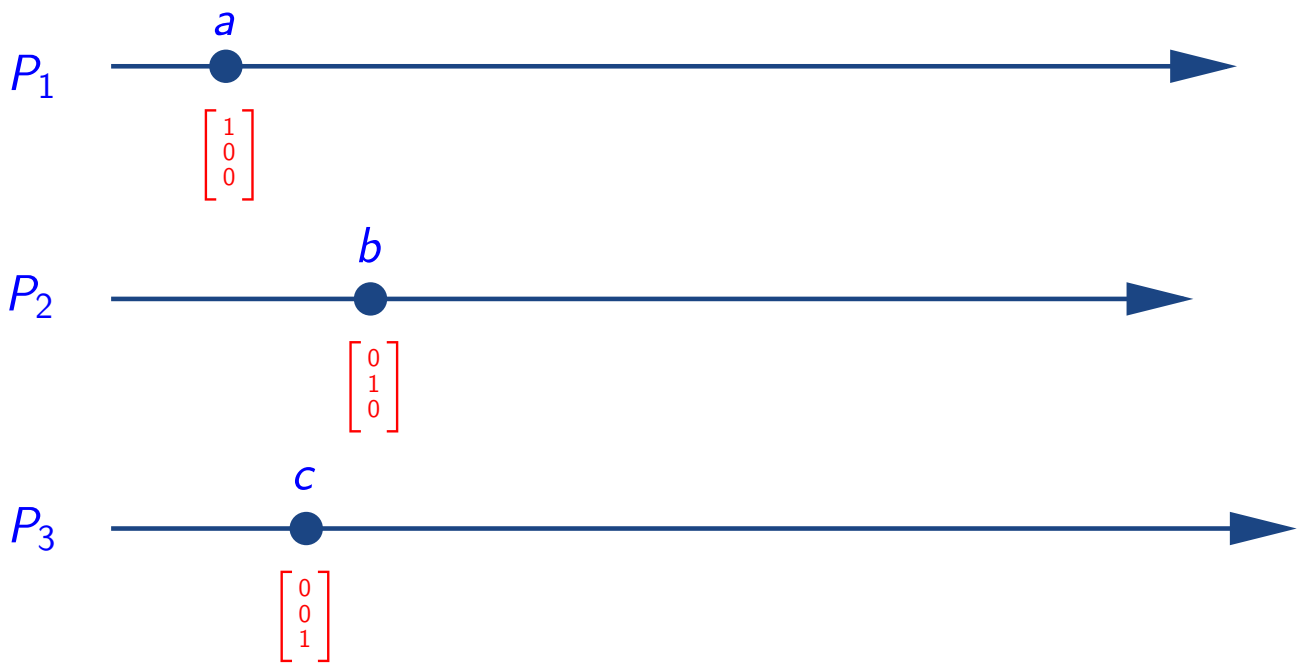

b and c: internal events $\quad C(b) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ and $C(c) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

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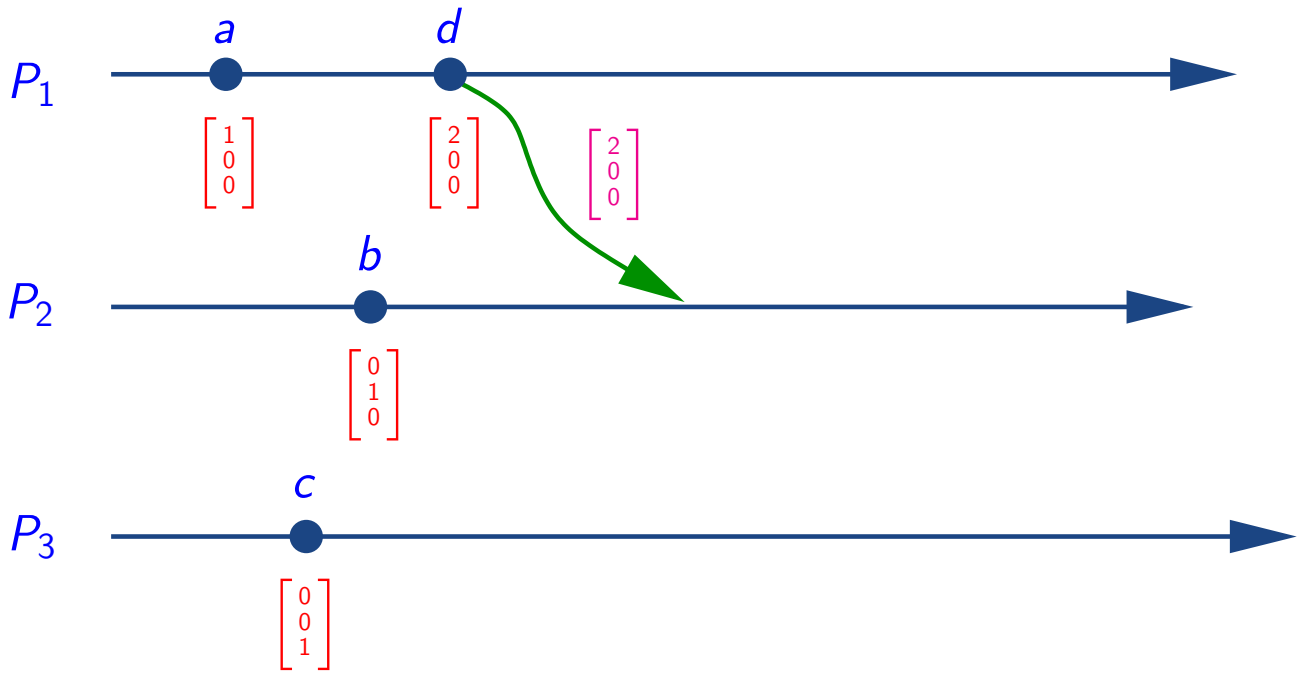

d: send event $\qquad C(d) = \begin{bmatrix}2\\0\\0\end{bmatrix}$

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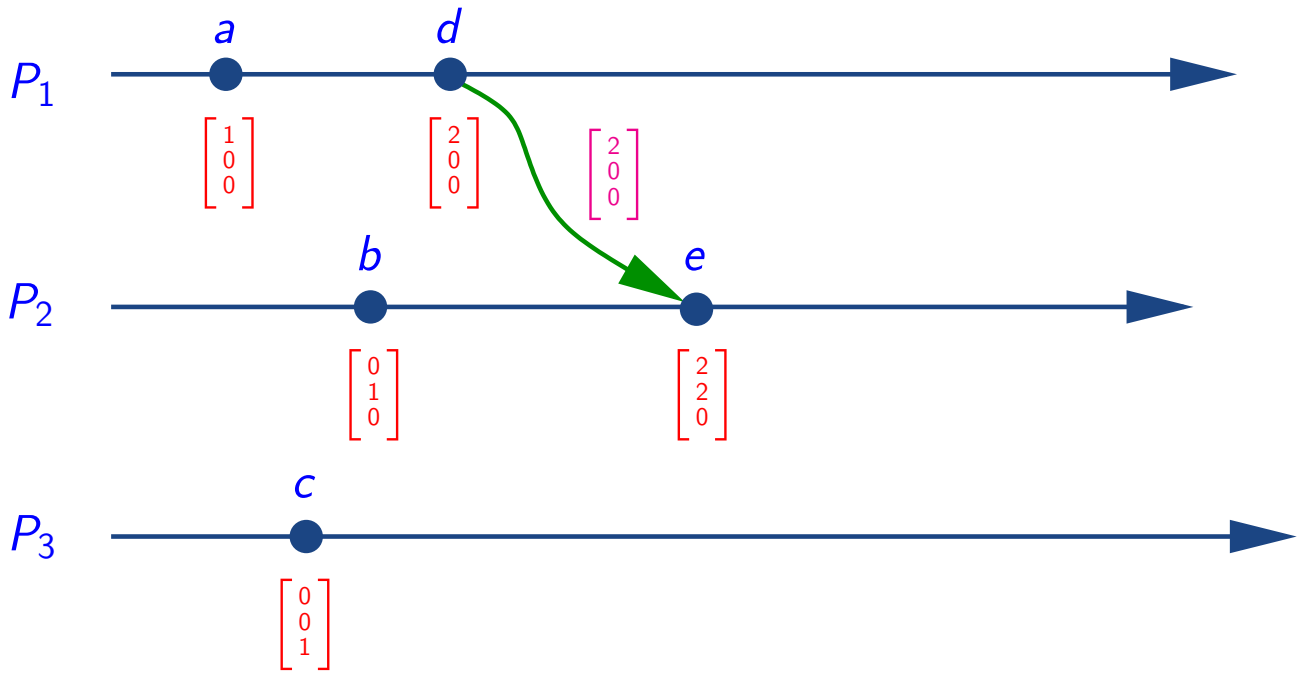

e: receive event $\qquad C(e) = \begin{bmatrix}2\\2\\0\end{bmatrix}$

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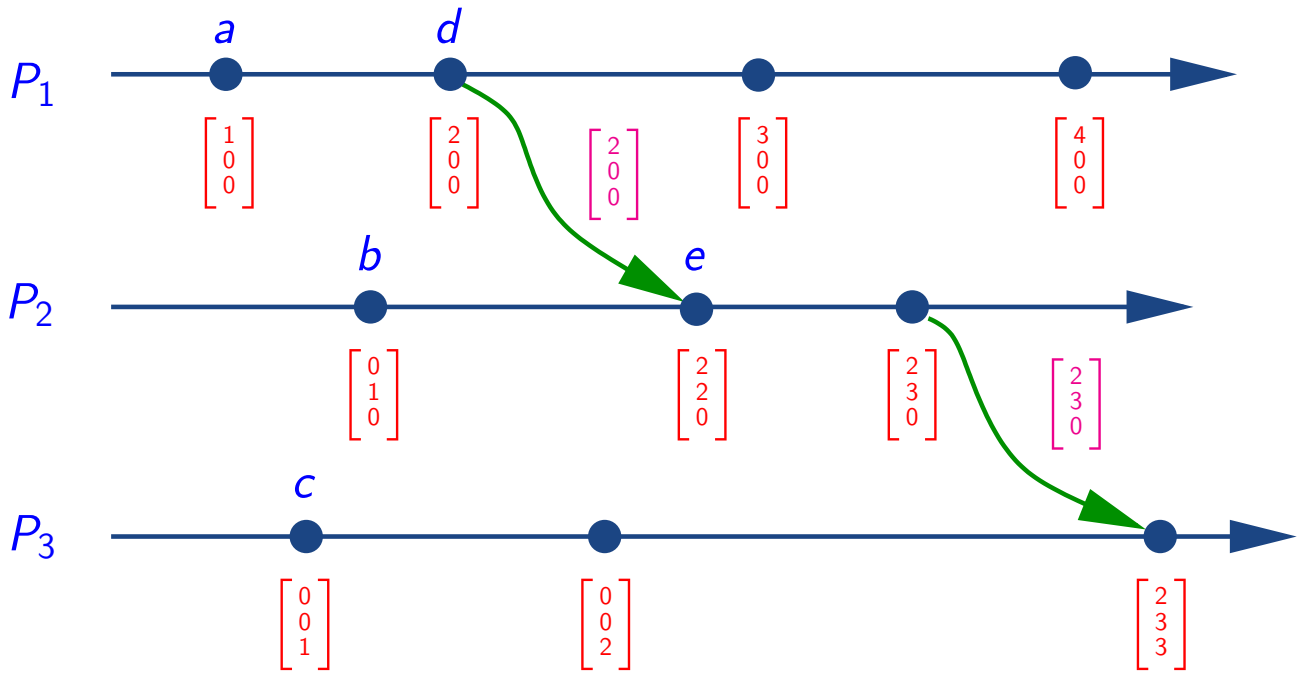

Properties of Vector Clock

- How many comparisons are needed to determine whether an event e happened-before another event f?
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  - Can we do better?
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Outline

Ordering of Messages

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- Example:
  - m_2 cannot be interpreted until m_1 has been received
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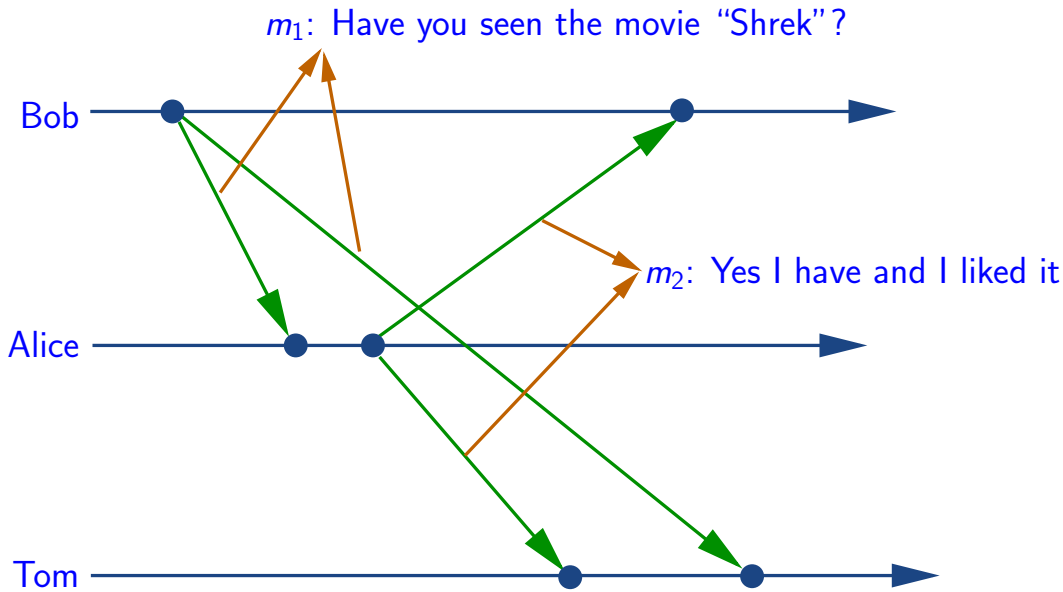

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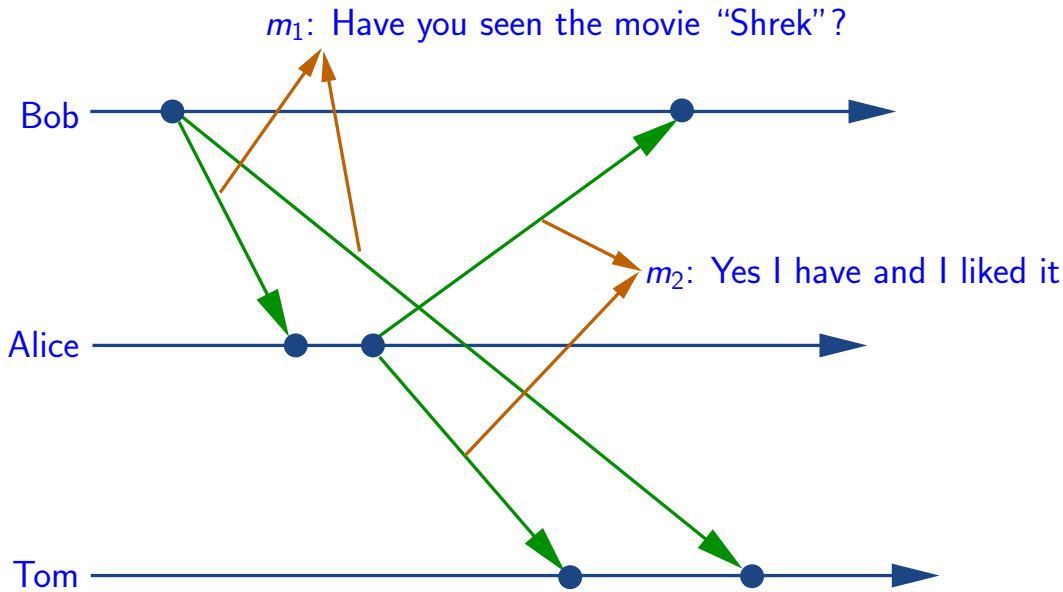

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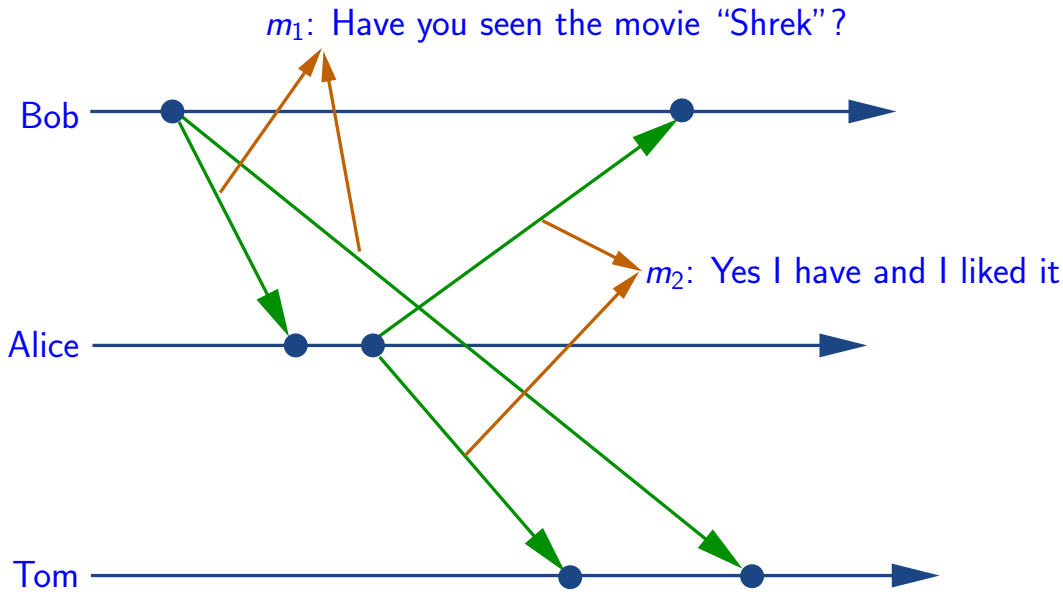

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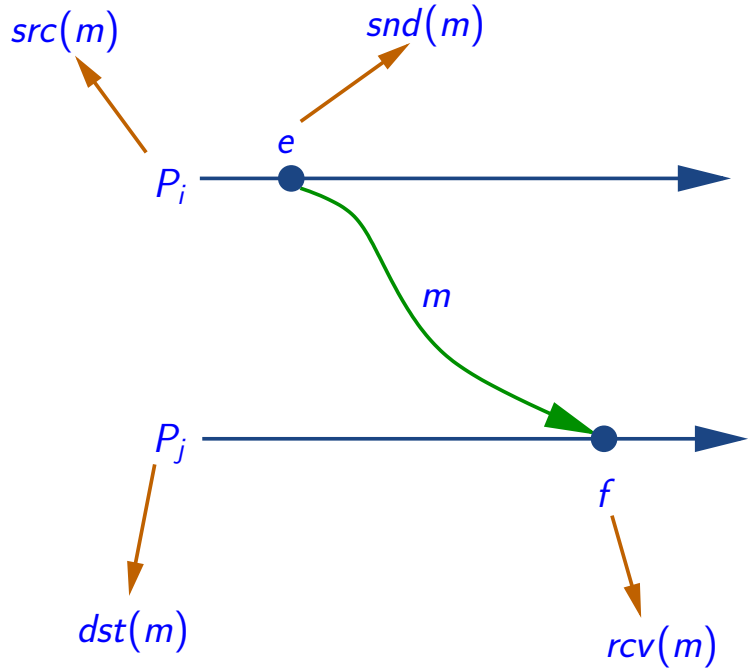
Useful Notations

- For a message m:
  - $src(m)$: source process of m
  - $dst(m)$: destination process of m
  - $snd(m)$: send event of m
  - $rcv(m)$: receive event of m



Causal Delivery of Messages

- A message w causally precedes a message m if $snd(w) \rightarrow snd(m)$
- An execution of a distributed system is said to be causally ordered if the following holds for every message m:

  every message that *causally precedes* m and is *destined for the same process* as m is *delivered before* m

  Mathematically, for every message w:

$$(snd(w) \rightarrow snd(m)) \wedge (dst(w) = dst(m)) \Longrightarrow rcv(w) \rightarrow rcv(m)$$

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A Causally Ordered Delivery Protocol

- Proposed by Birman, Schiper and Stephenson (BSS)
- Assumption:
  - communication is broadcast based: a process sends a message to every other process
- Each process maintains a vector with one entry for each process:
  - let V_i denote the vector for process P_i
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The BSS Protocol

- Protocol for process P_i:
  - On broadcasting a message m:

    piggyback V_i on m
    $V_i[i] := V_i[i] + 1$

  - On arrival of a message m from process P_j:

    let V_m be the vector piggybacked on m
    deliver m once $V_i \geq V_m$

  - On delivery of a message m sent by process P_j:

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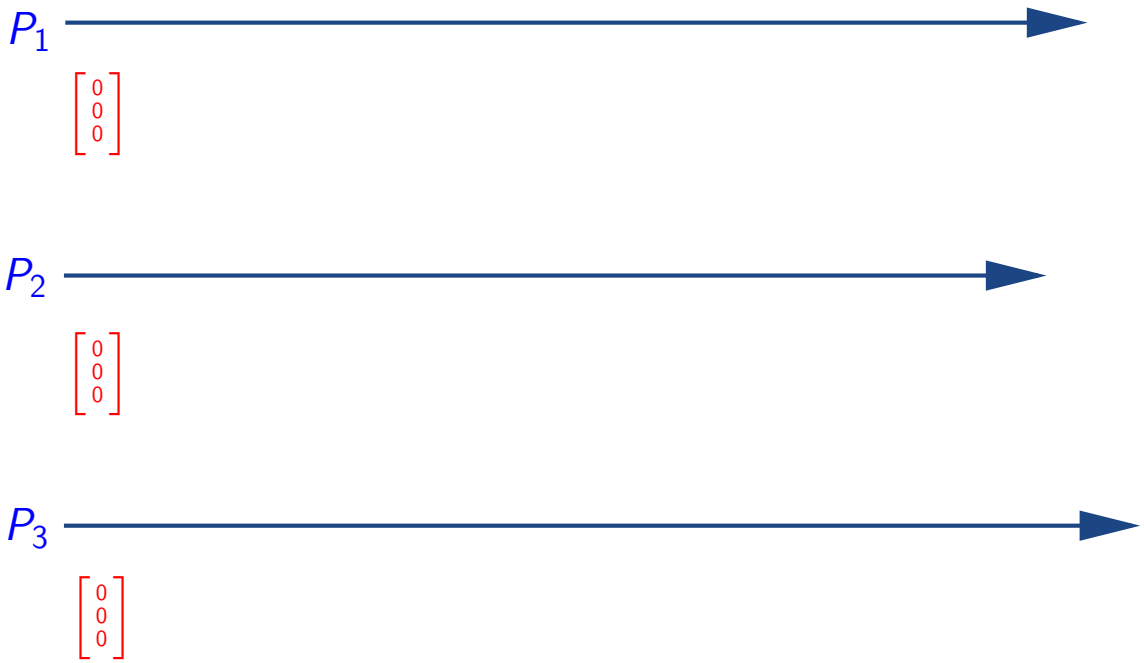

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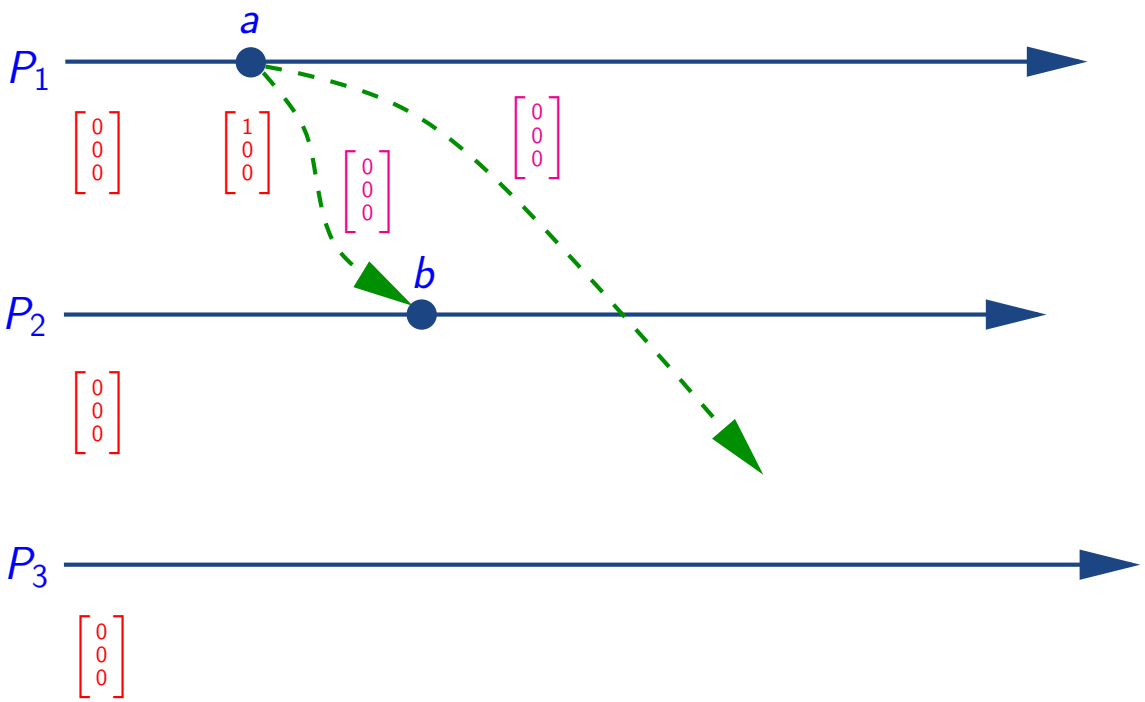

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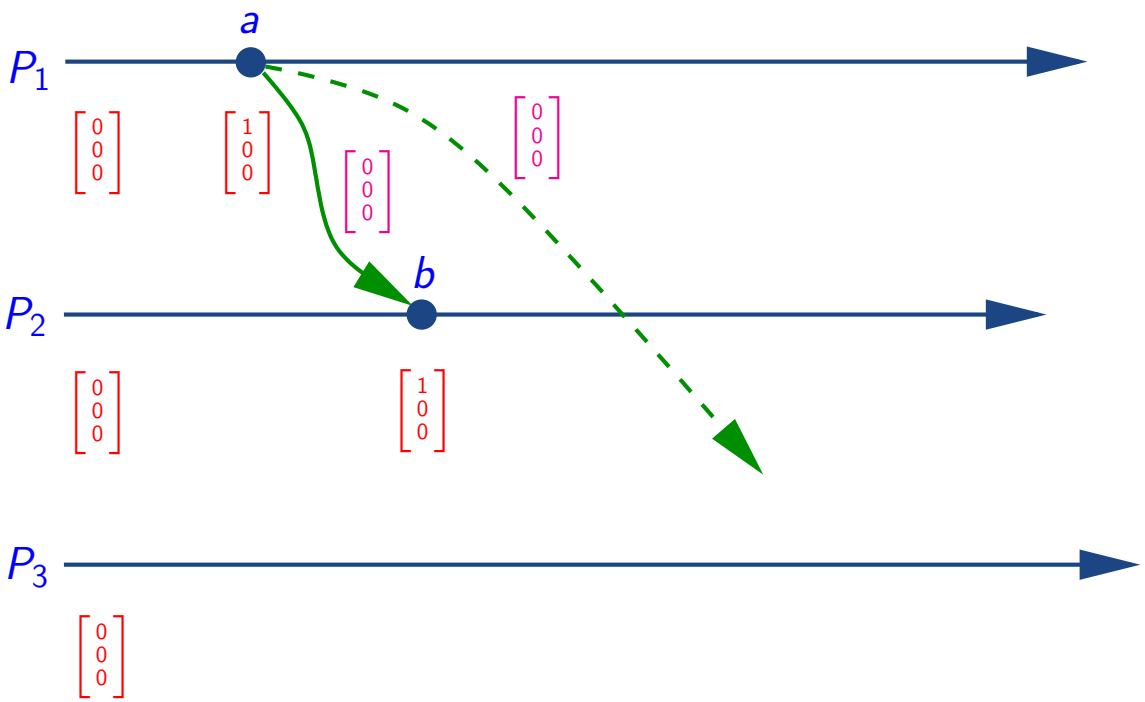

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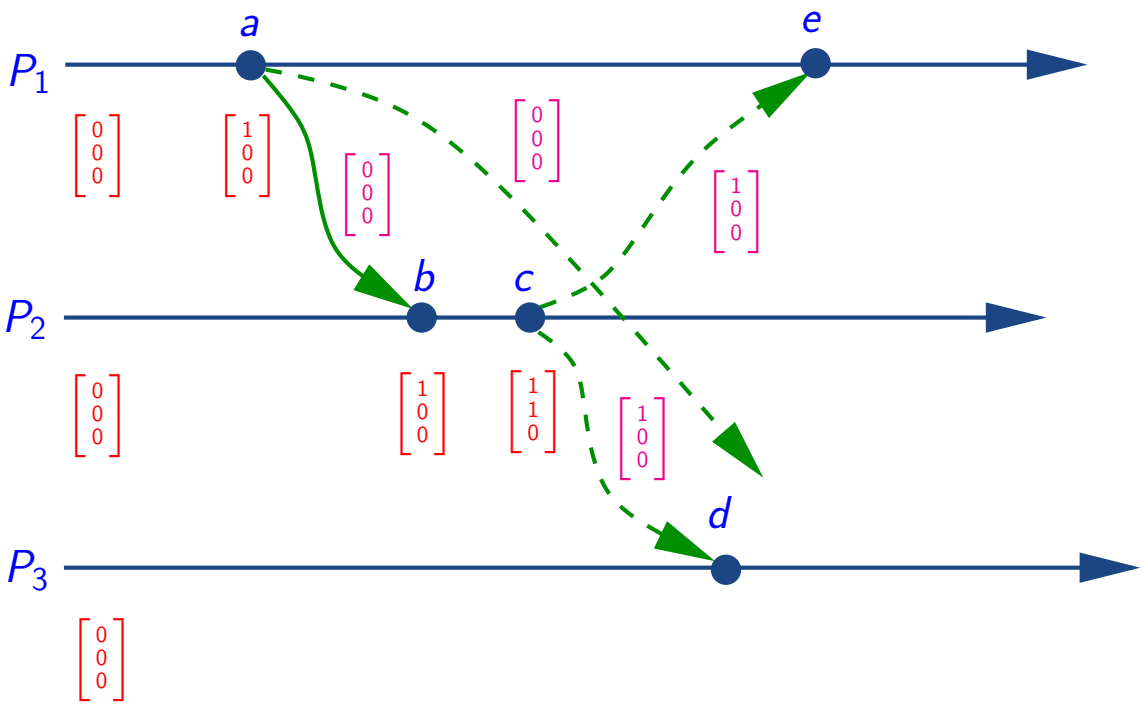

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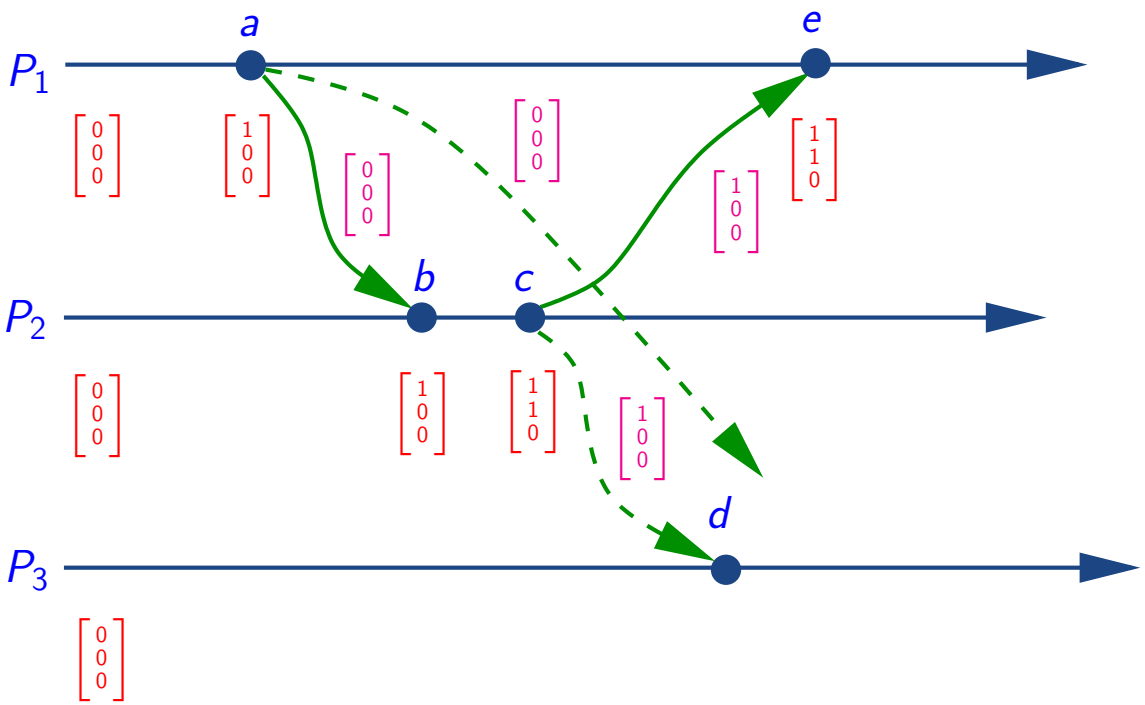

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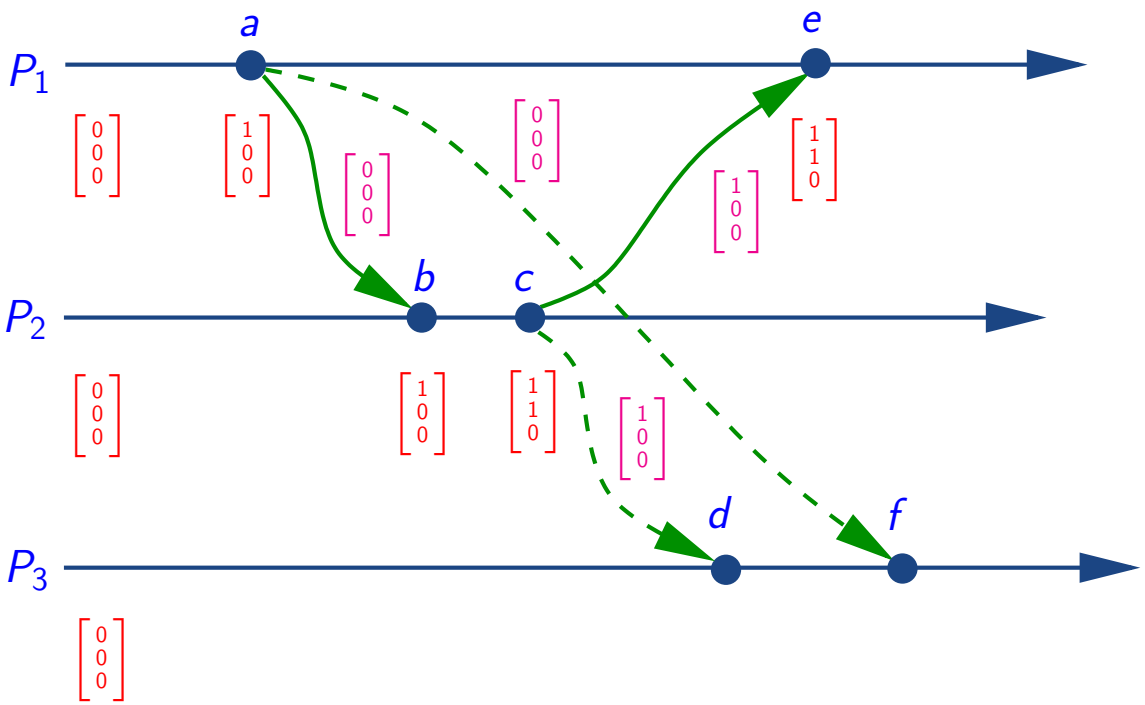

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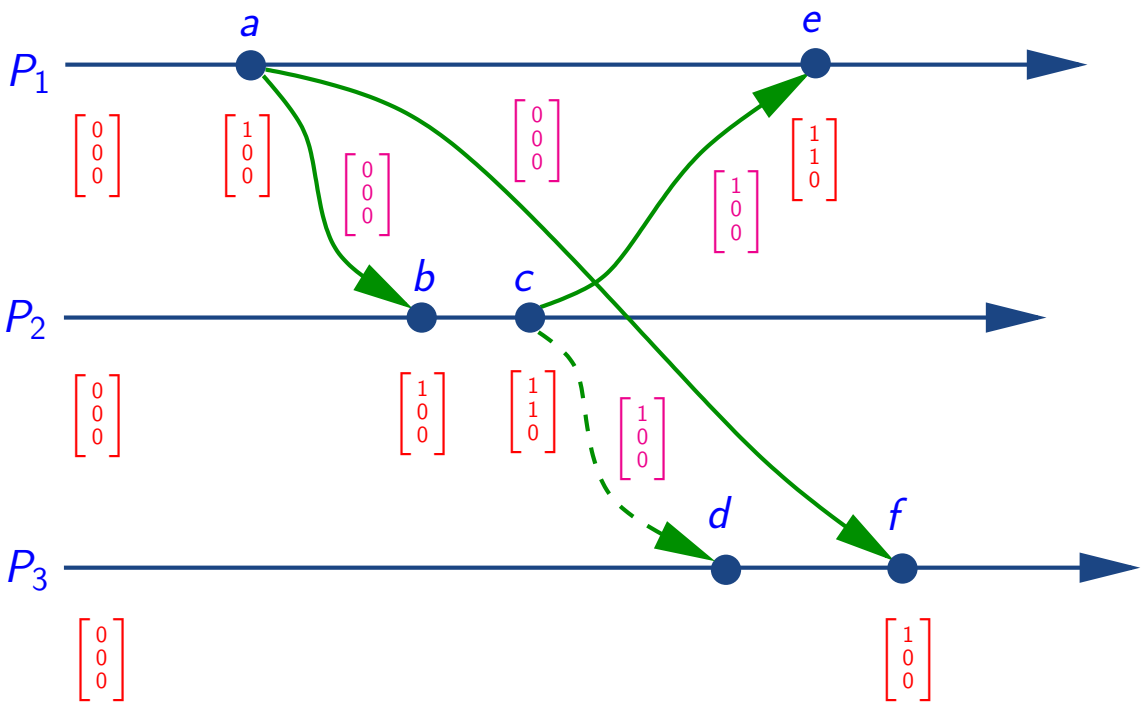

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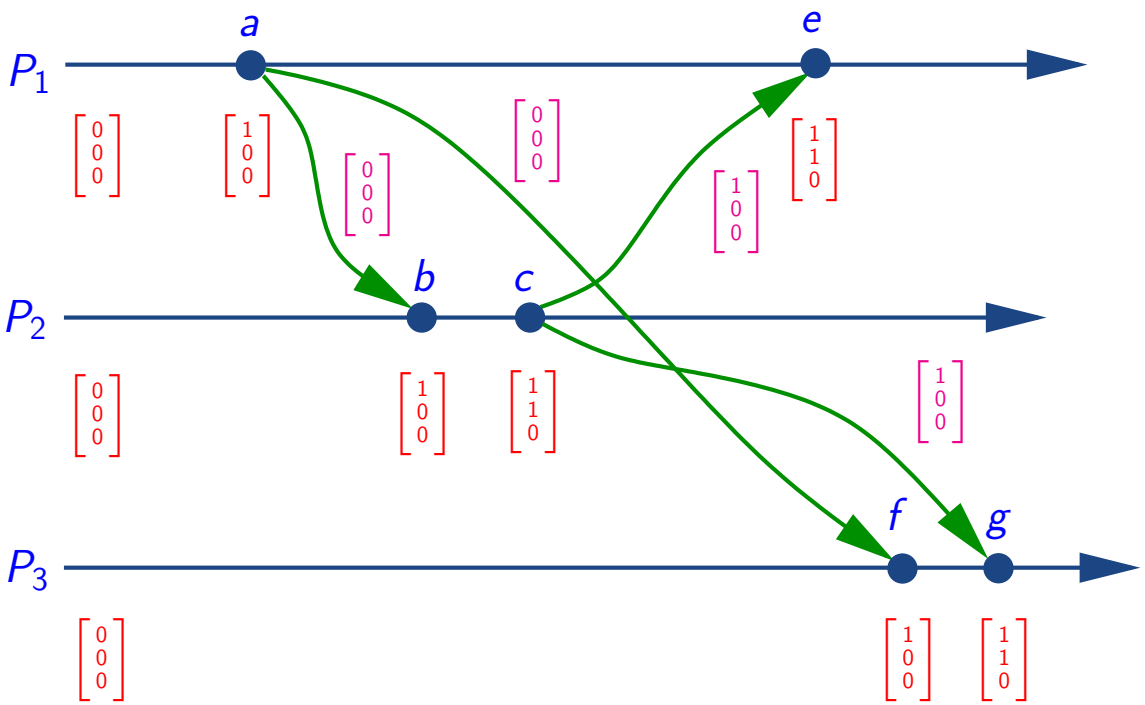

Another Causally Ordered Delivery Protocol

- Proposed by Raynal, Schiper and Toueg (RST)
- Assumption:
  - communication is unicast based: a process sends a message to only one other process
- Each process P_i maintains a matrix M_i of size $N \times N$
  - N is the number of processes in the system
- The entry (j, k) in the matrix M_i captures the following knowledge:
  - Suppose $M_i[j, k] = x$
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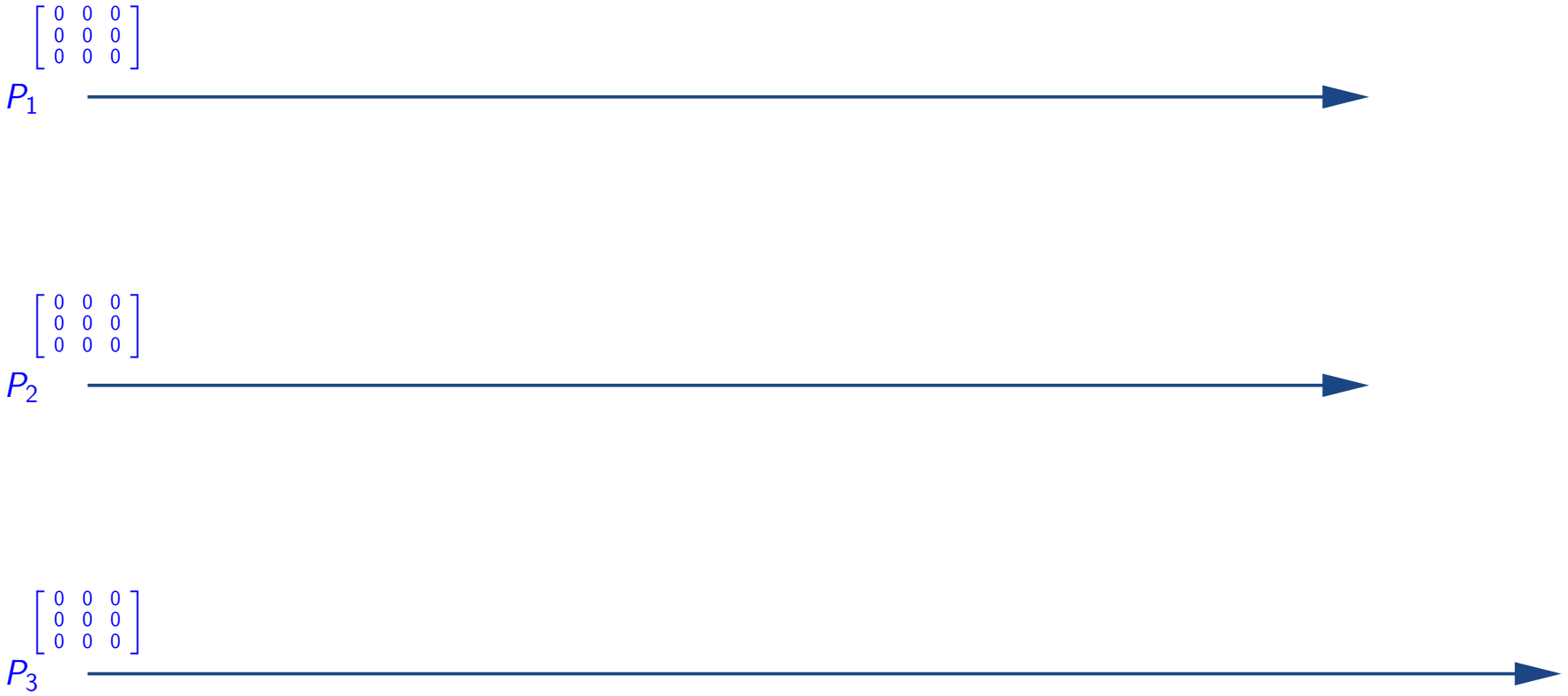
    merge M_i and M_m
    $\forall x, y : M_i[x, y] := \max(M_i[x, y], M_m[x, y])$
    increment $M_i[j, i]$ by 1

The RST Protocol: An Illustration



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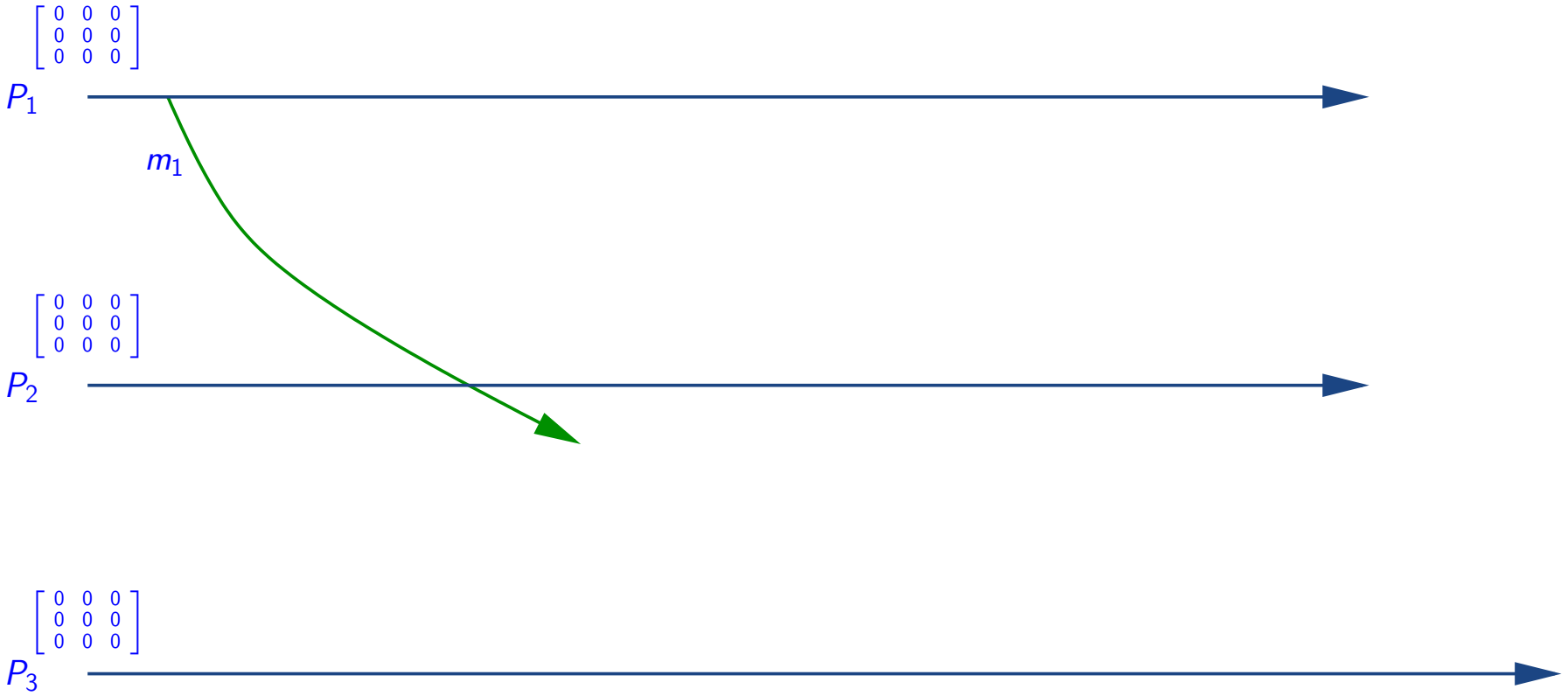

P_1 sends m_1 to P_3

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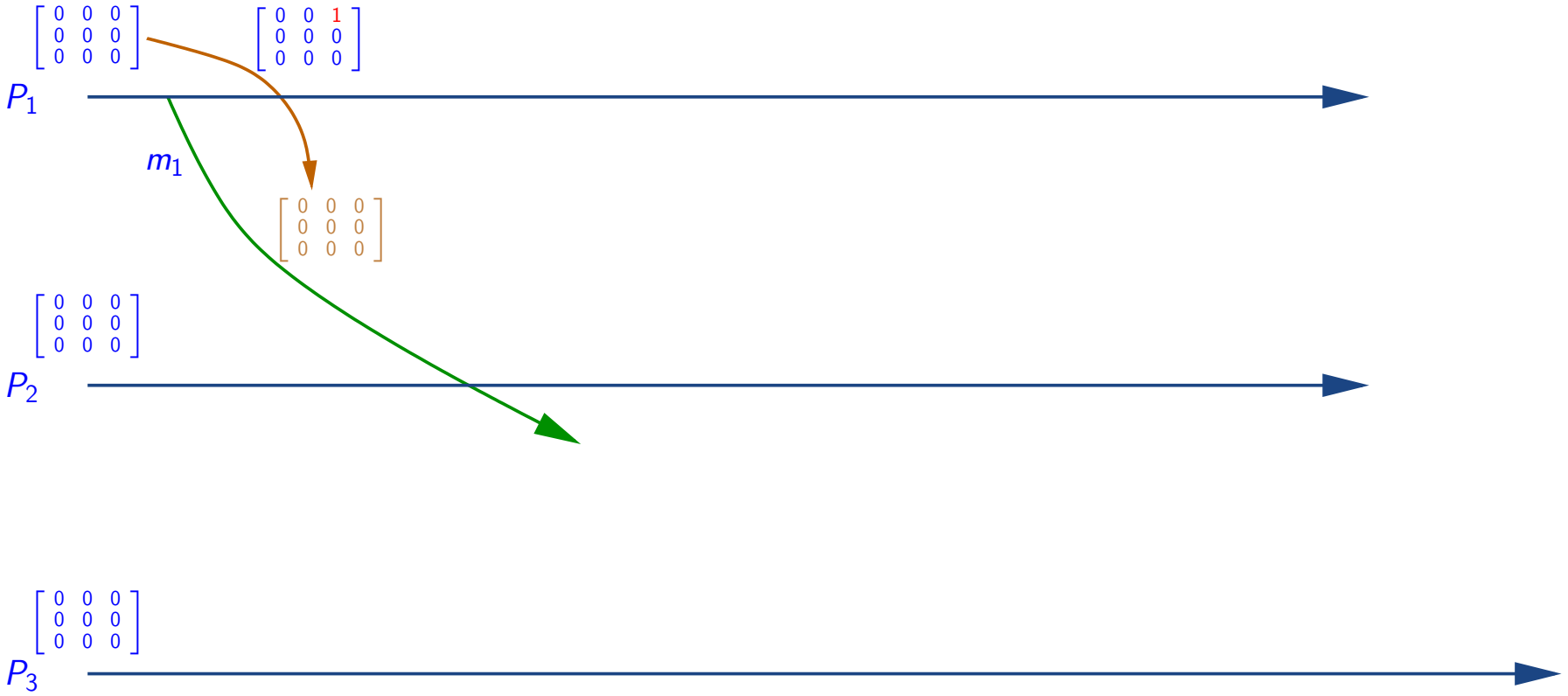

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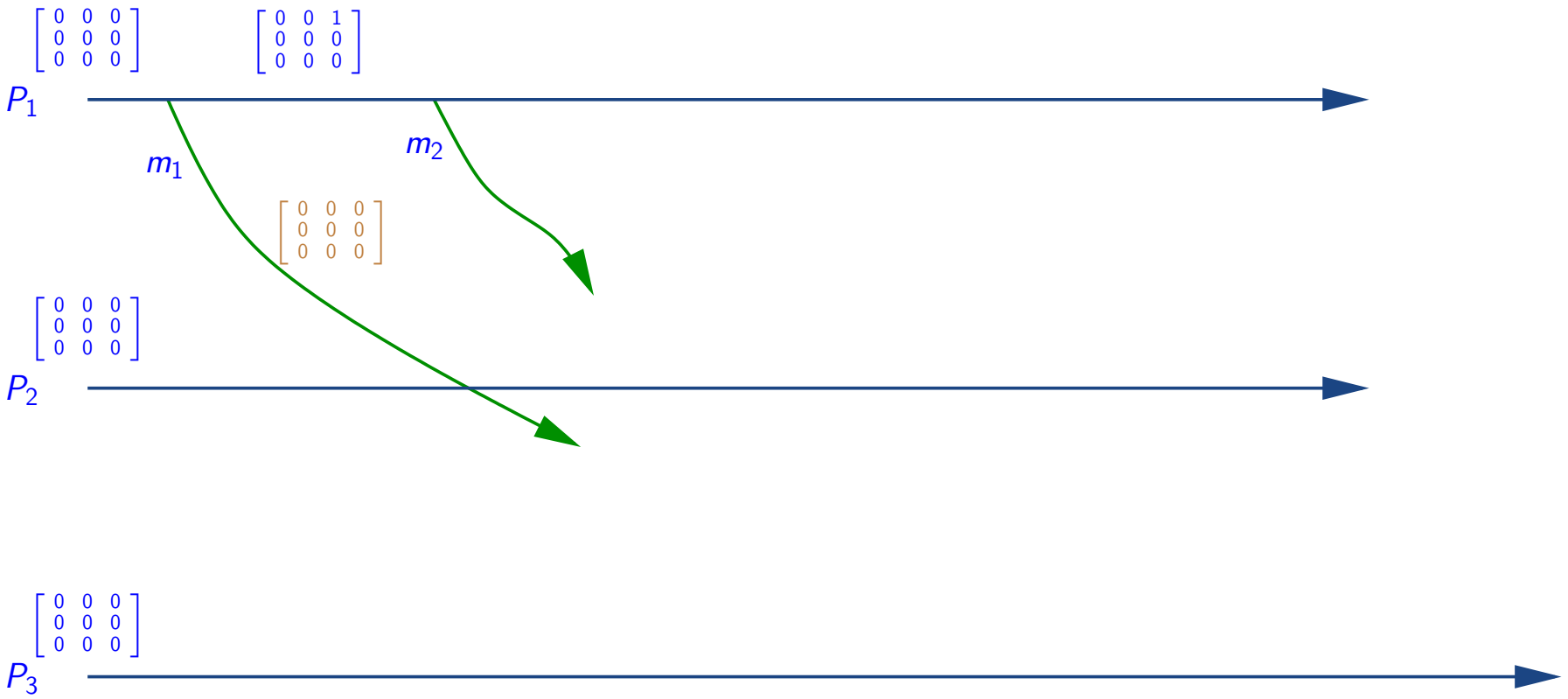

P_1 sends m_2 to P_2

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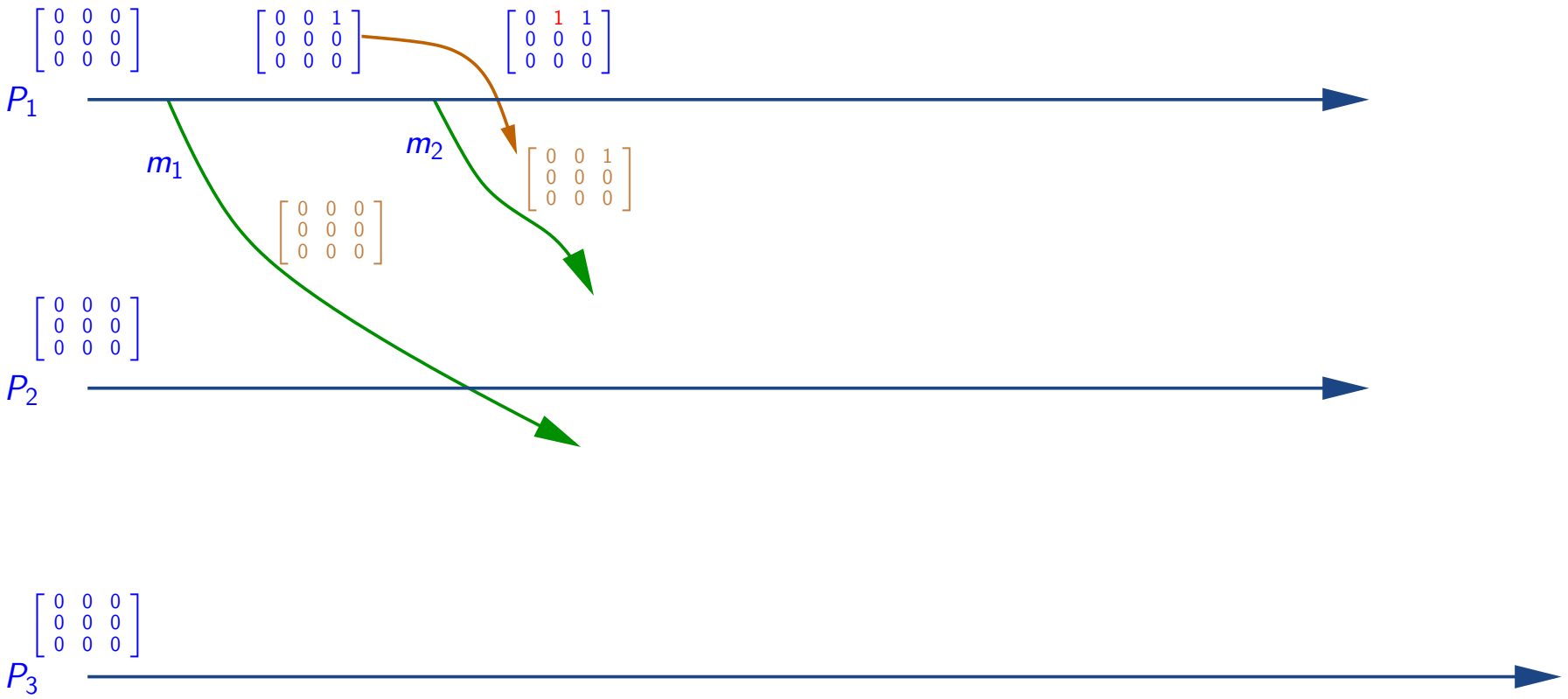

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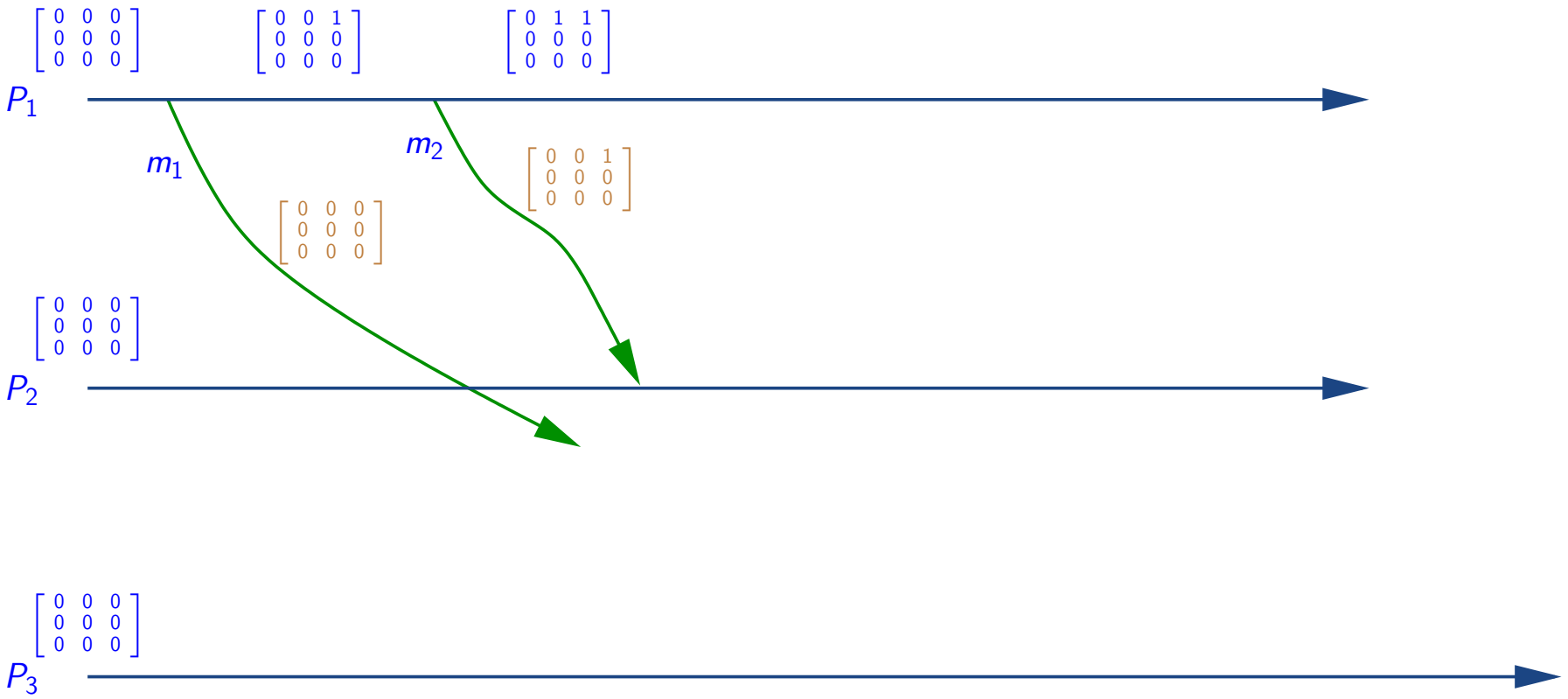

m_2 arrives at P_2

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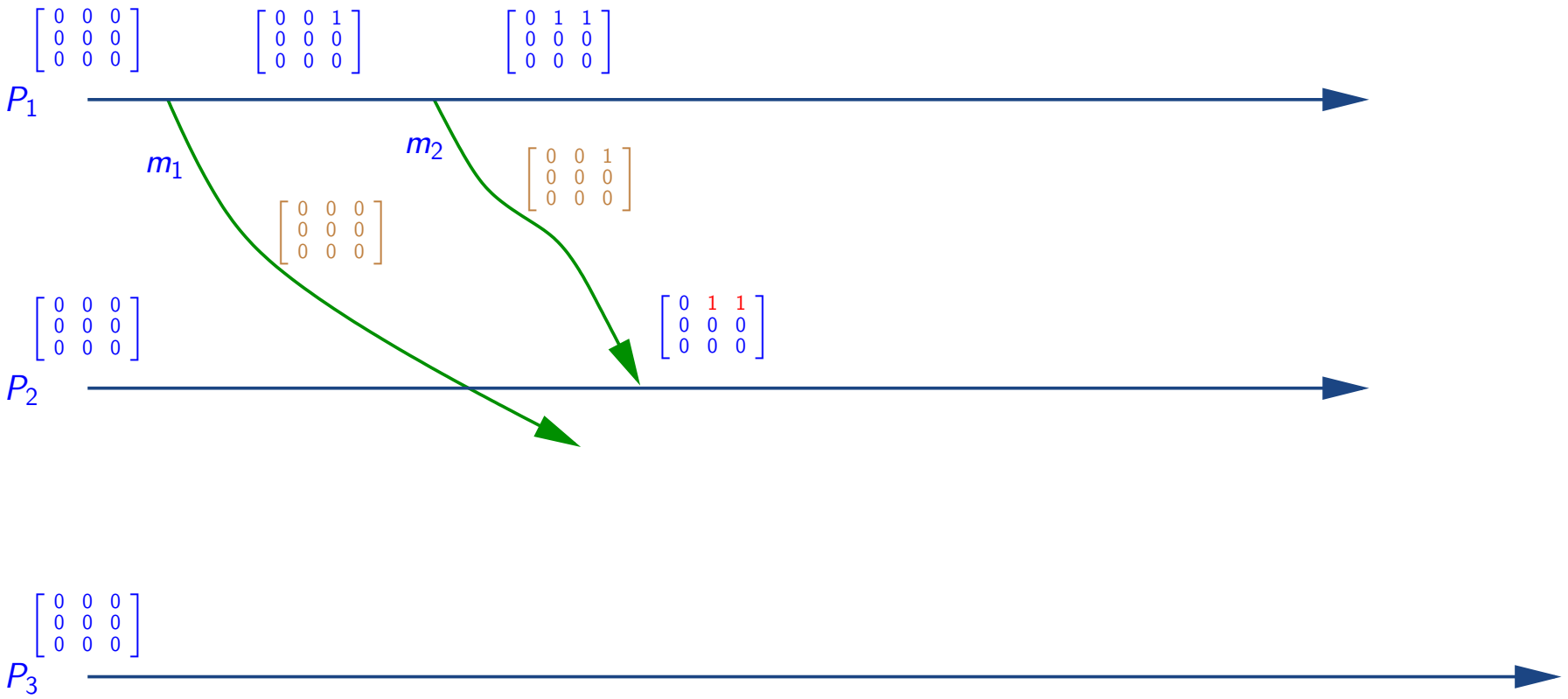

P_2 delivers m_2

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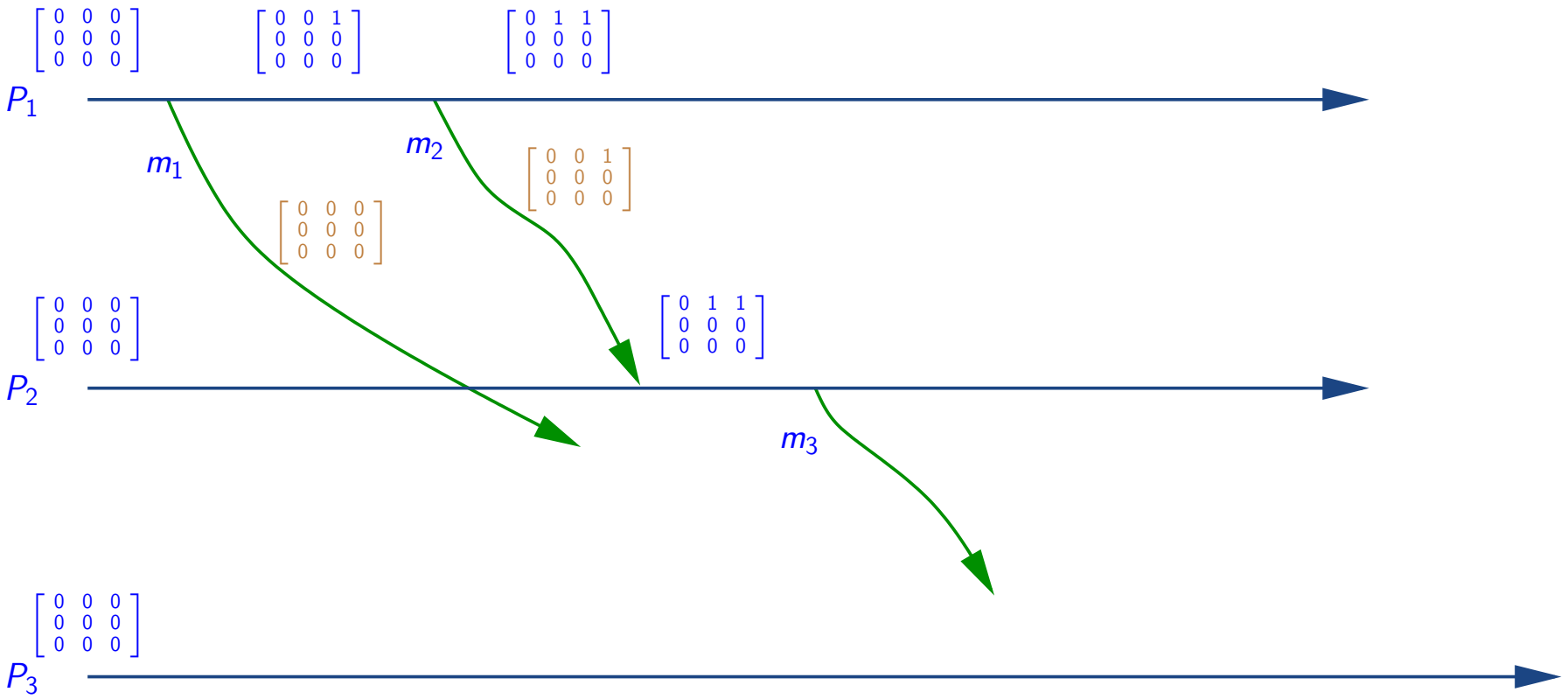

P_2 sends m_3 to P_3

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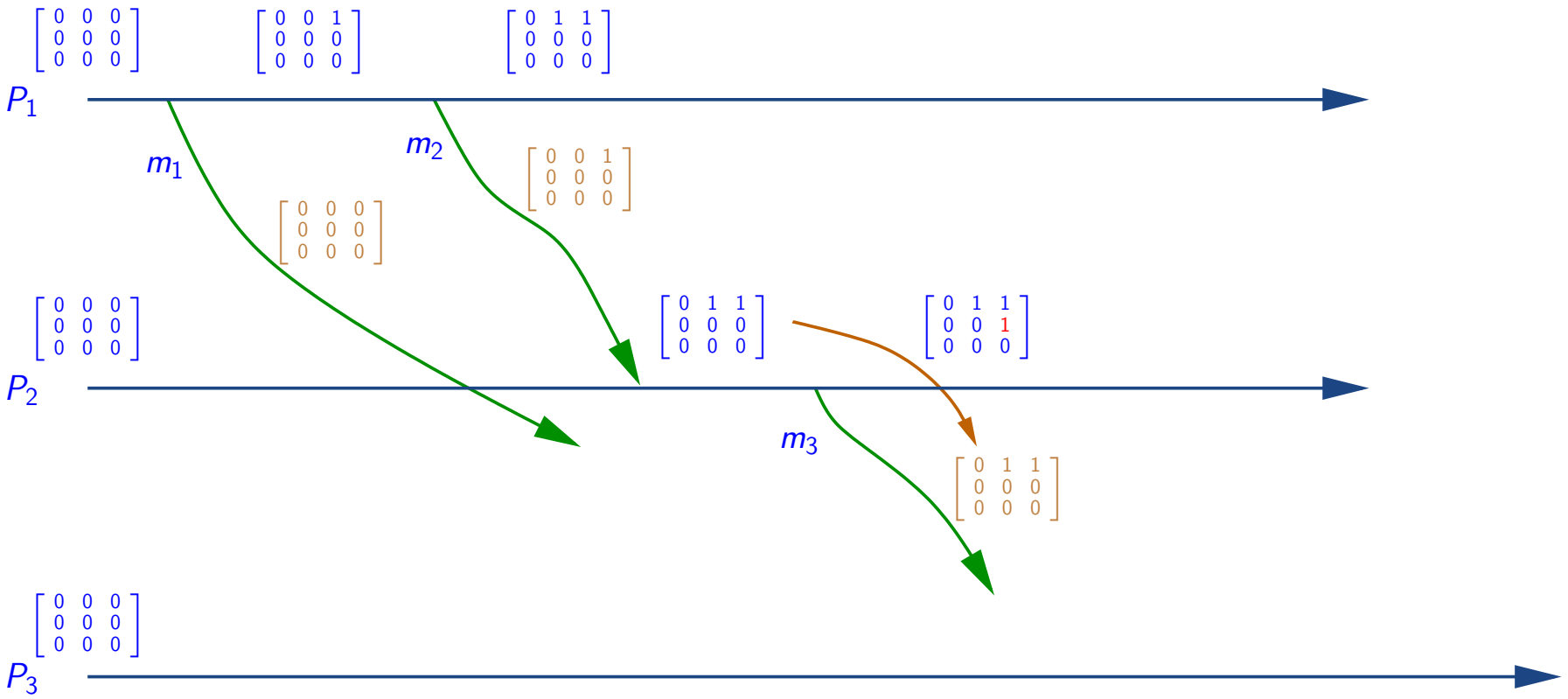

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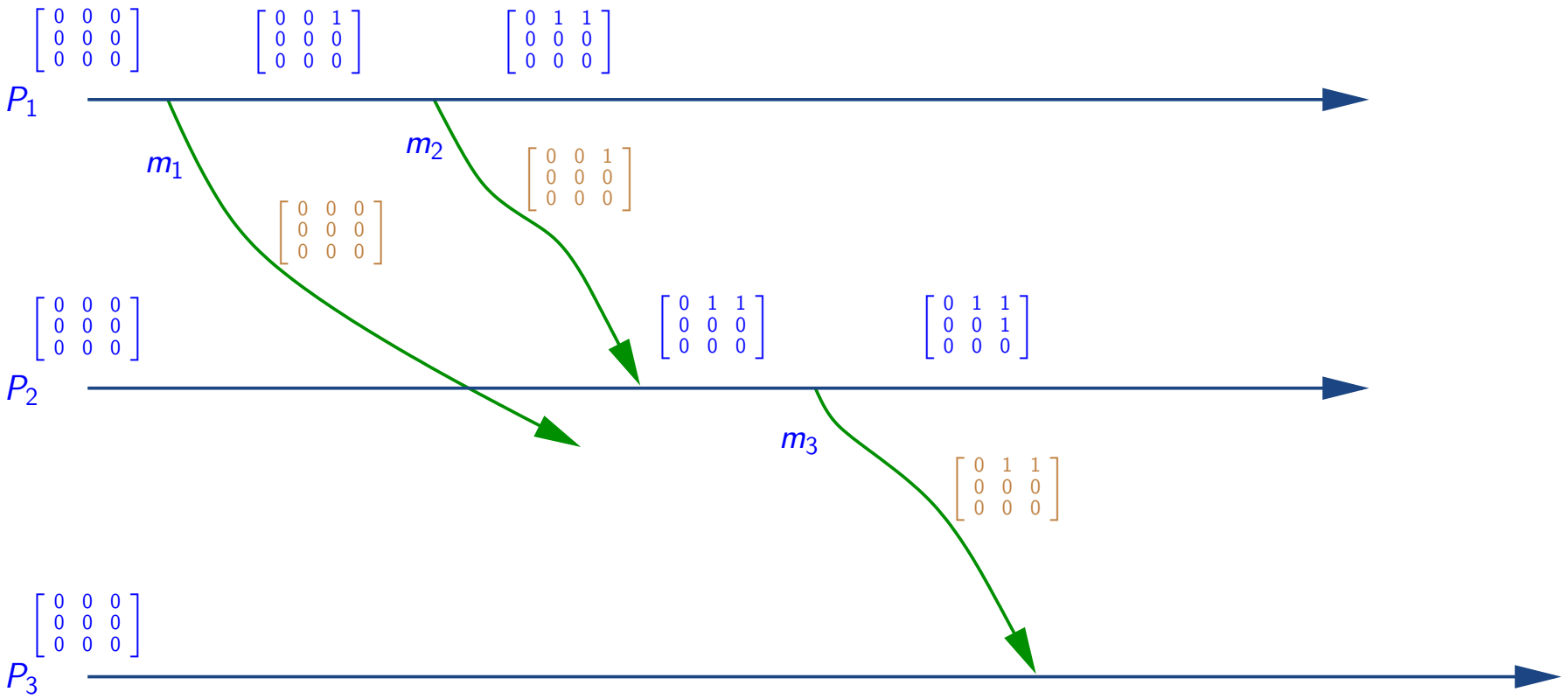

m_3 arrives at P_3 and is buffered

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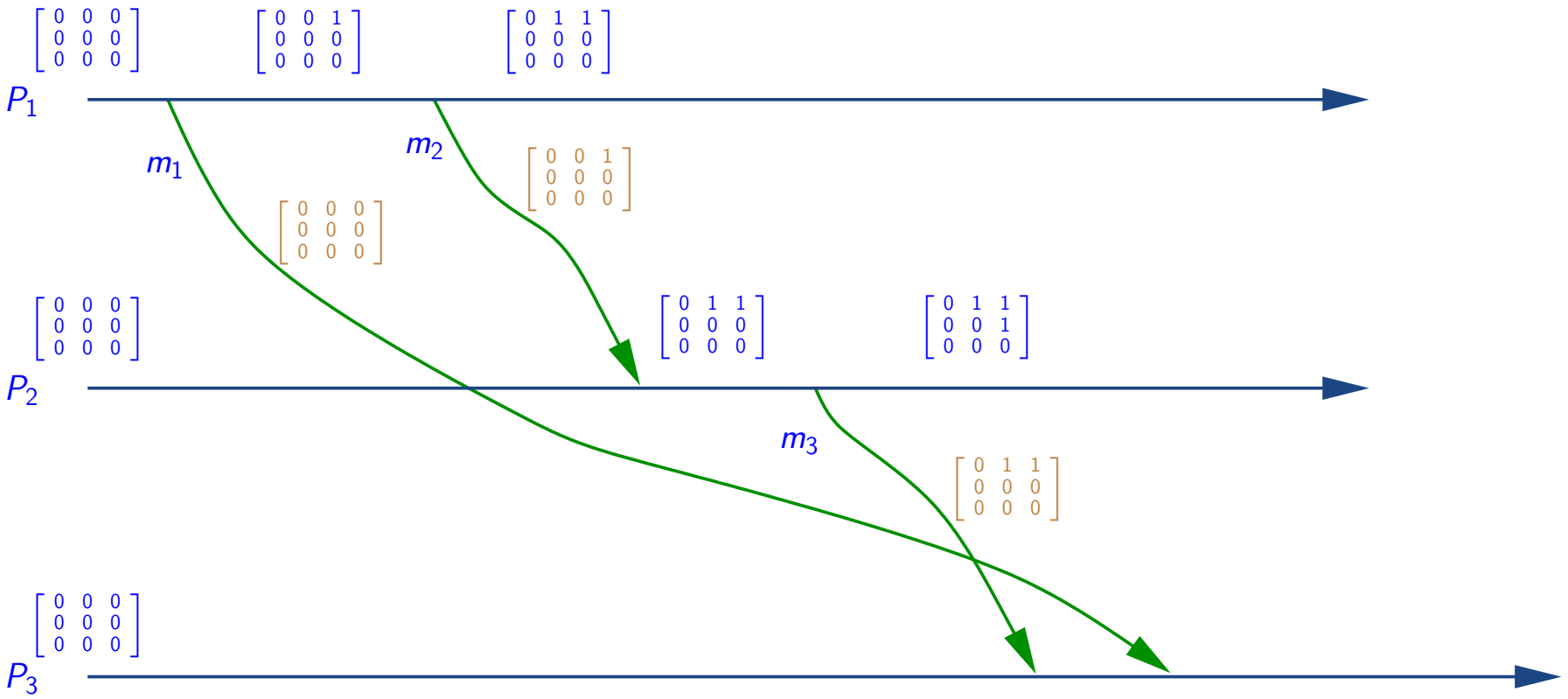

m_1 arrives at P_3

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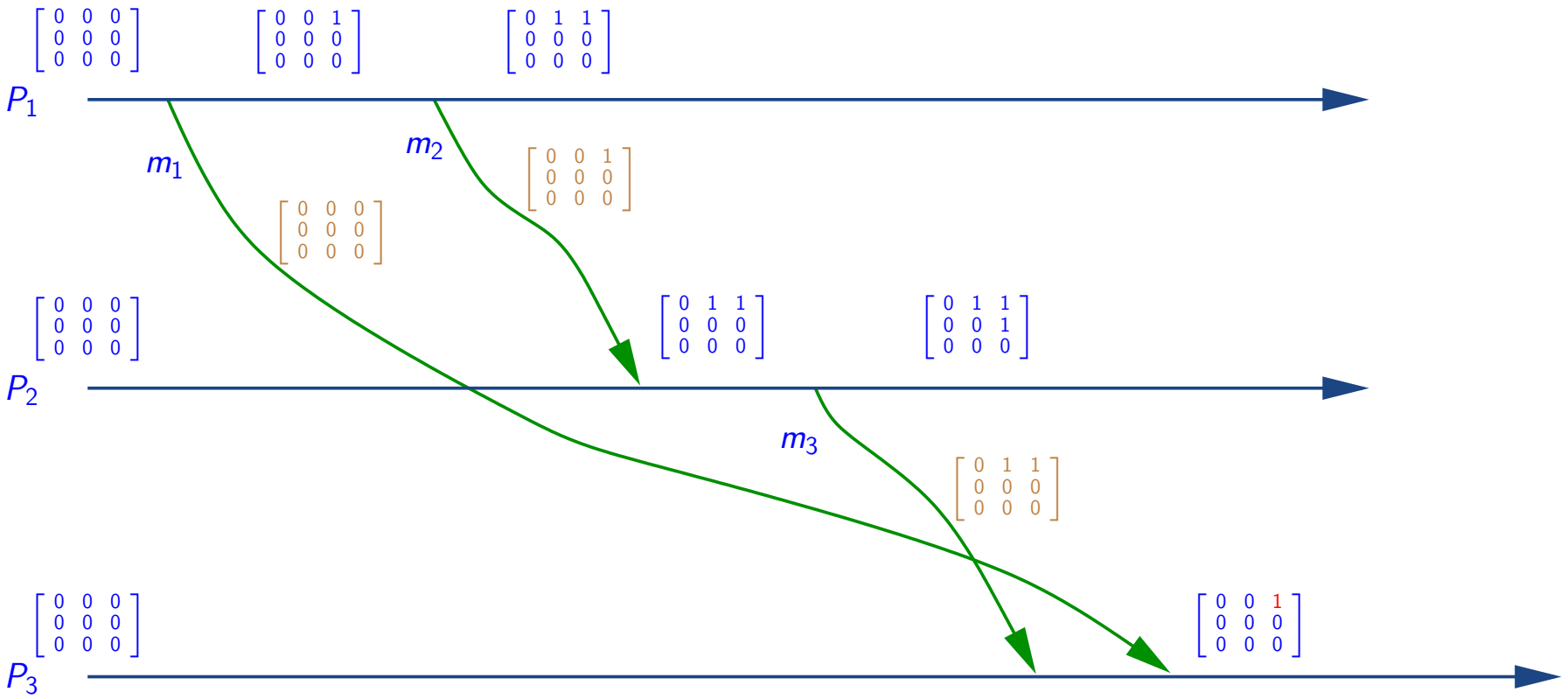

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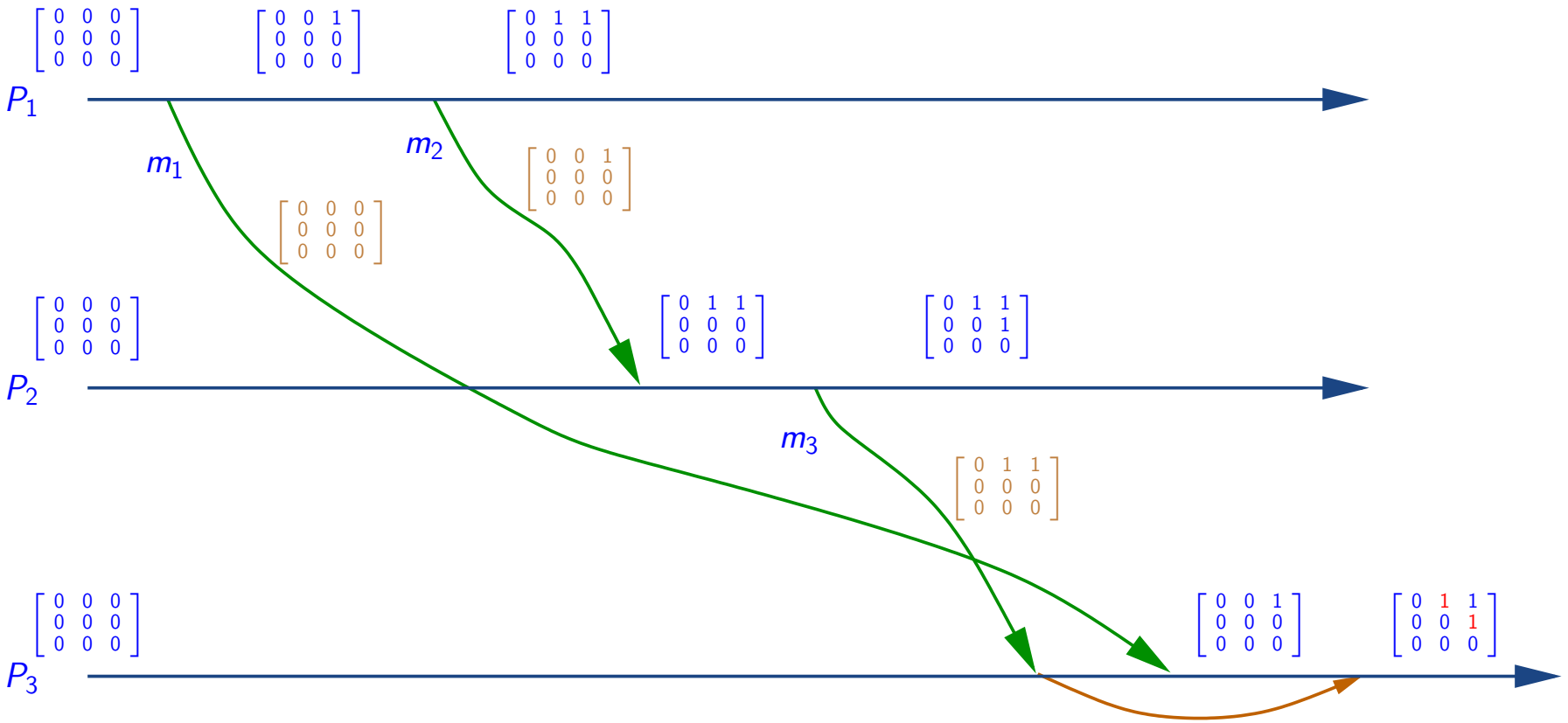

P_3 delivers m_2

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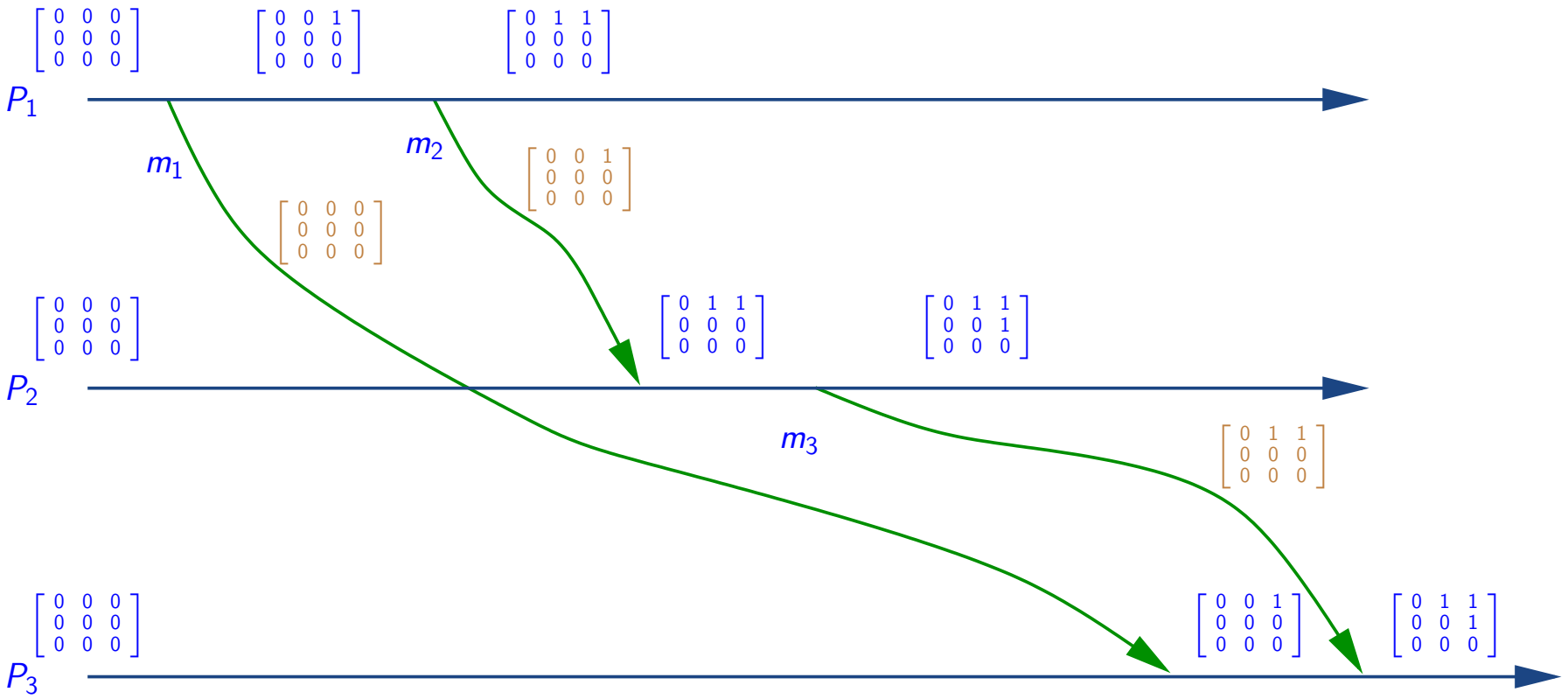

Outline

State of a Distributed System

- State of a distributed system is a collection of states of all its processes and channels:
  - a process state is given by the values of all variables on the process
  - a channel state is given by the set of messages in transit in the channel
    - can be determined by examining states of the two processes it connects
- State of a process is called local state or local snapshot
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Events and Local States

- A process changes its state by executing an event
- Example:
  - Process P_1 changes its state from $x = 0$ to $x = 2$ on executing event e
  - Process P_2 changes its state from $x = 2$ to $y = 3$ on executing event f

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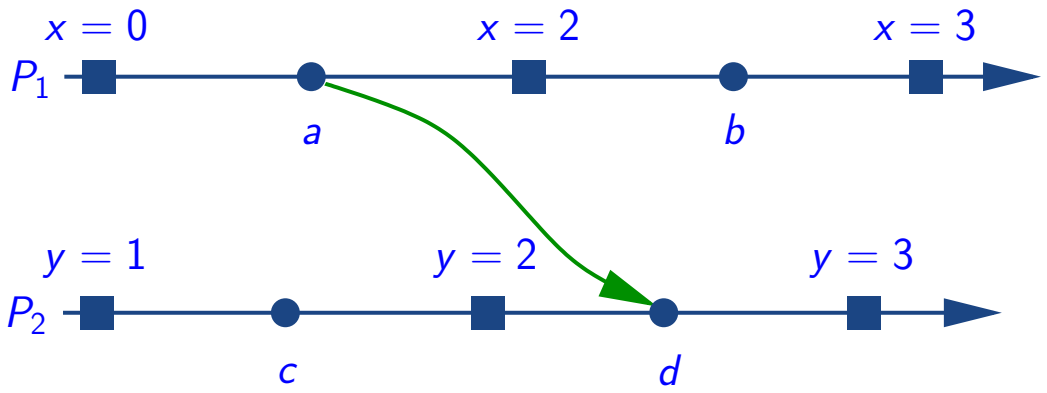

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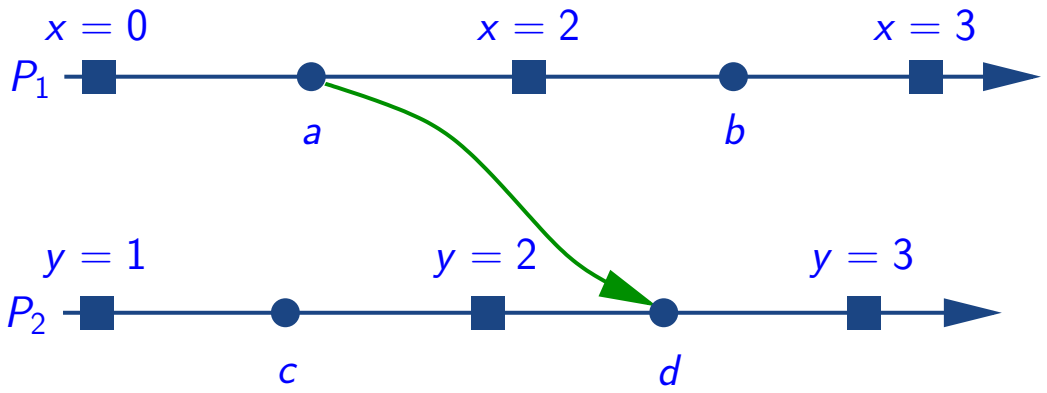

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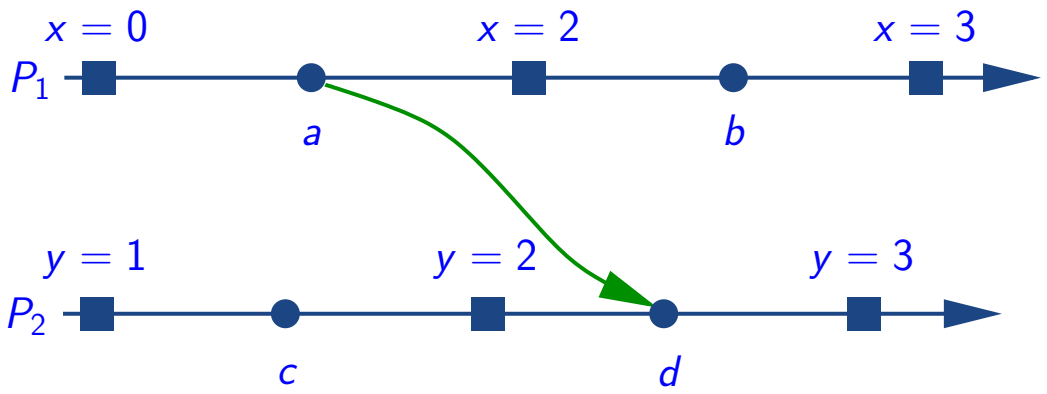

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When is a Global State Meaningful?

- Example:

  - Is it possible for x to be 0 and y to be 3 at the same time?
  - Does $\{p, u\}$ form a meaningful global state?

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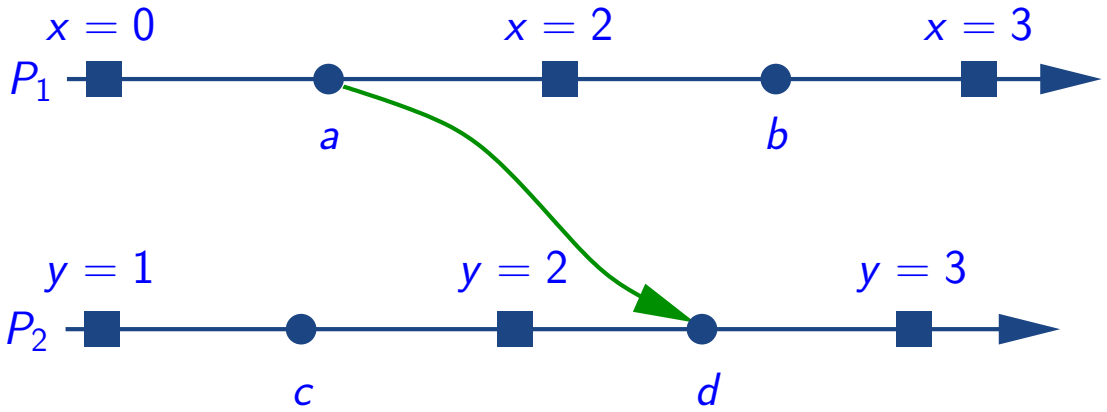

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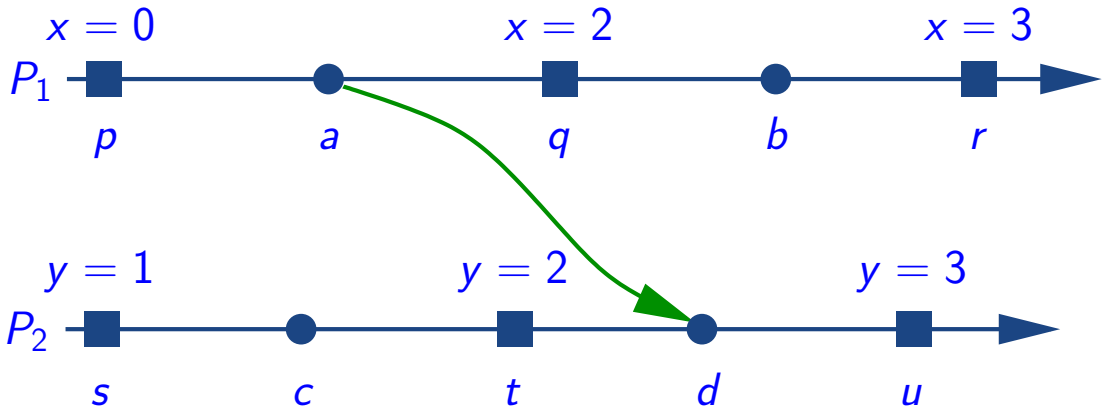

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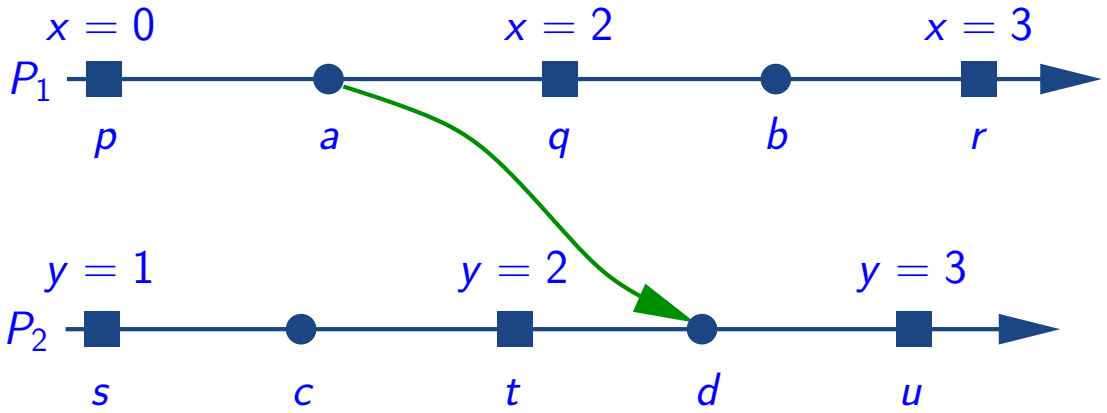

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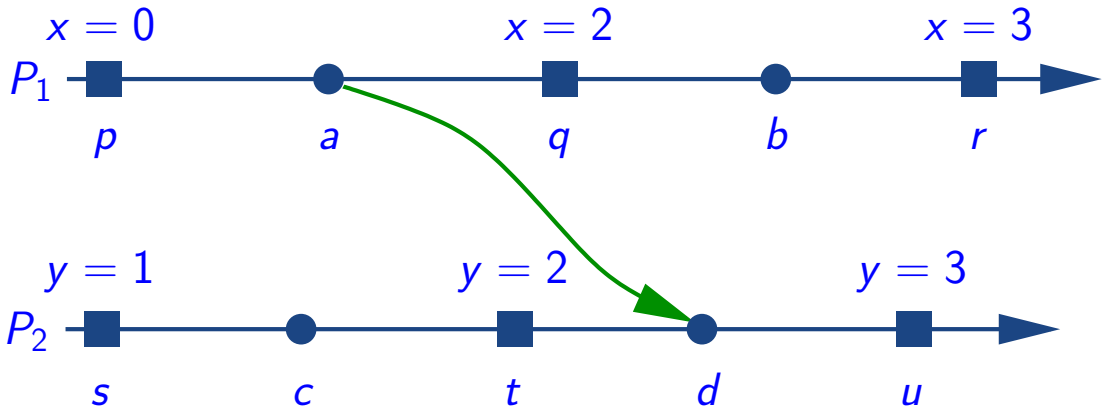

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Revisiting Happened-Before Relation

- Earlier, happened-before relation was defined on events
- The relation can be extended to local states as follows:
  - let s be a local state of process P_i
  - let t be a local state of process P_j
  - $s \rightarrow t$ if there exist events e and f such that:
    1. P_i executed e after s,
    2. P_j executed f before t, and
    3. $e \rightarrow f$
- If $s \rightarrow t$, then s and t cannot co-exist at the same time
  Also, s must occur before t
- If $s \parallel t$, then s and t can co-exist simultaneously

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- Proposed by Chandy and Lamport (CL)
- Assumptions and Features:
  - channels satisfy first-in-first-out (FIFO) property
  - channels are not required to be bidirectional
  - communication topology may not be fully connected
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- *Initially:* all processes are colored blue
- *Eventually:* all processes become red
- On changing color from blue to red:

  record local snapshot
  send a marker message along all outgoing channels

- On receiving marker message along incoming channel C:

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- Global Snapshot: local snapshots of processes *just after they turn red*
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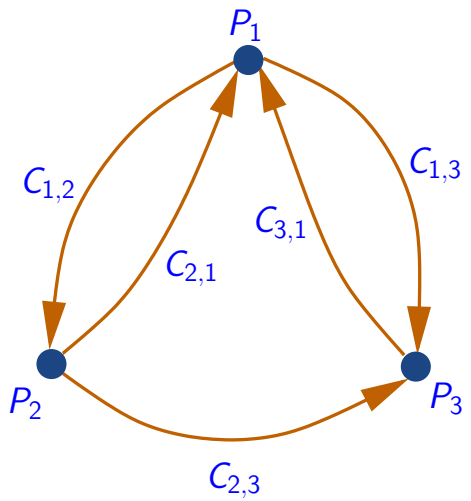
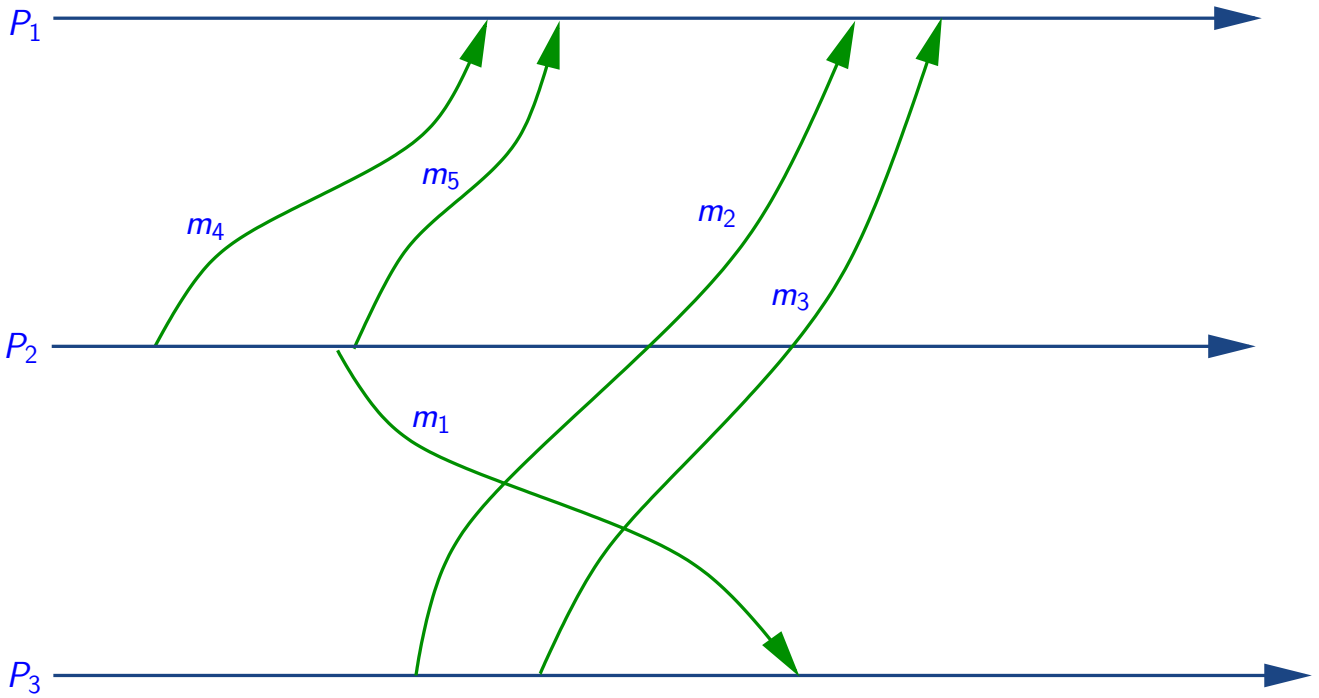
The CL Protocol: An Illustration

- Three processes: P_1, P_2 and P_3
- Five channels: $C_{1,2}$, $C_{1,3}$, $C_{2,1}$, $C_{2,3}$ and $C_{3,1}$

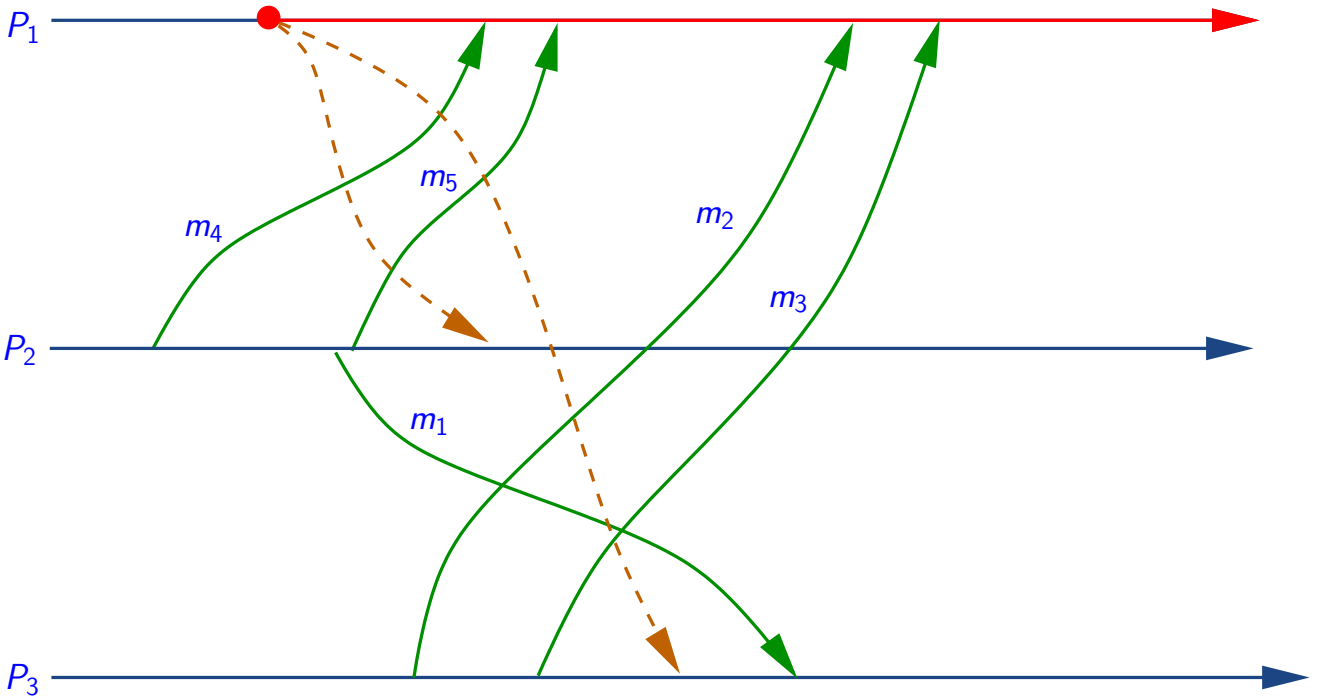


The CL Protocol: An Illustration (Continued)



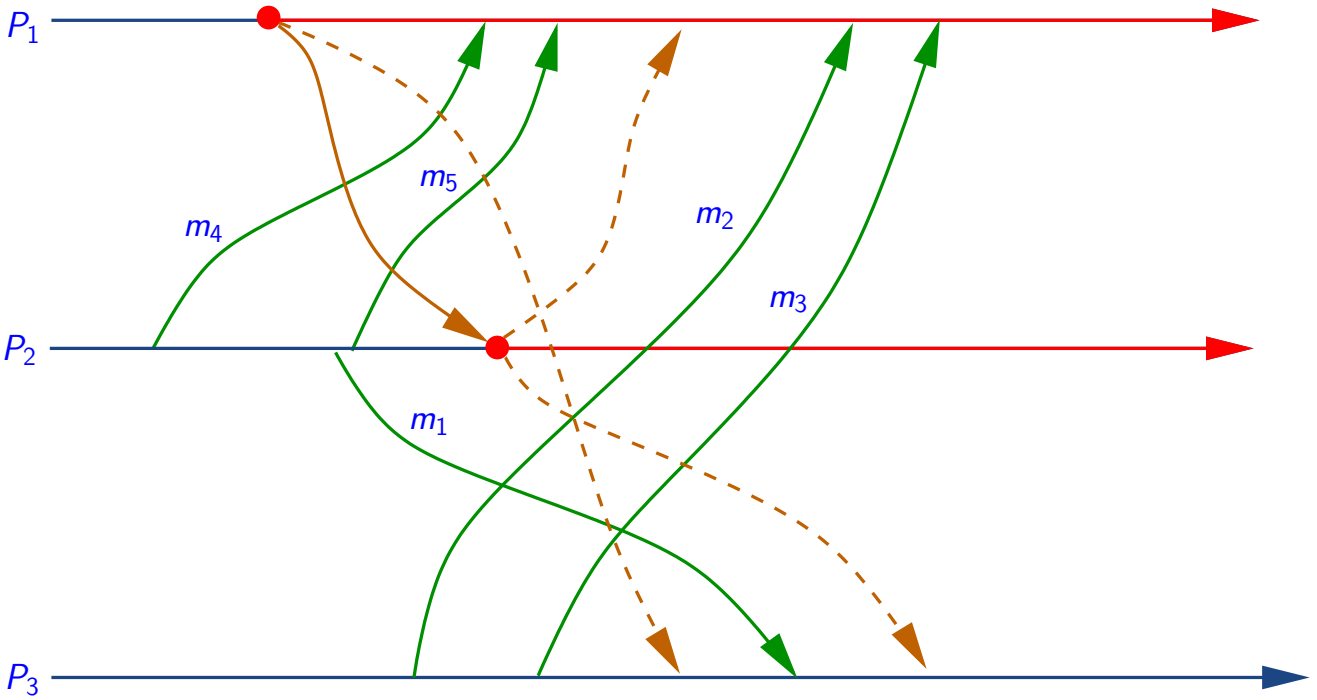
1. All processes are blue

The CL Protocol: An Illustration (Continued)



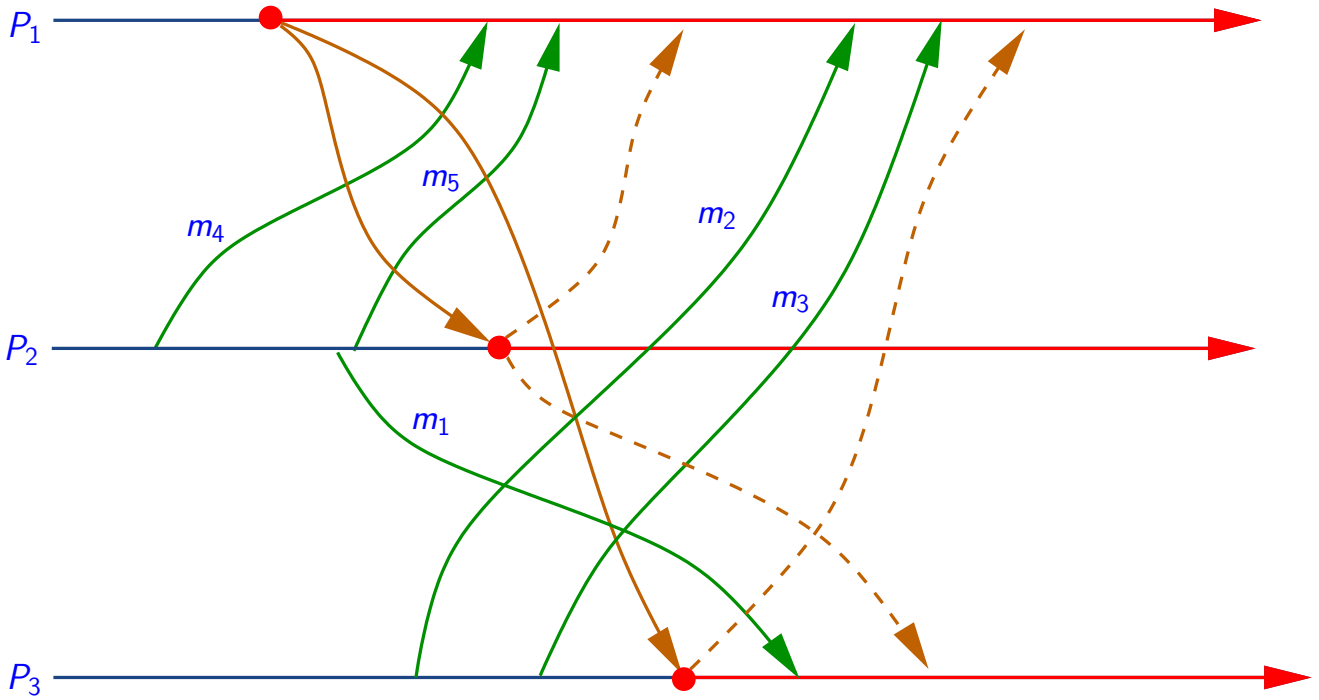
1. P_1 turns red
2. P_1 sends a marker message along $C_{1,2}$ and $C_{1,3}$

The CL Protocol: An Illustration (Continued)



1. P_2 receives the marker message along $C_{1,2}$ and turns red
2. P_2 sends a marker message along $C_{2,1}$ and $C_{2,3}$
3. P_2 records the state of $C_{1,2}$ as $\emptyset$

The CL Protocol: An Illustration (Continued)



1. P_3 receives the marker message along $C_{1,3}$ and turns red
2. P_3 sends a marker message along $C_{3,1}$
3. P_3 records the state of $C_{1,3}$ as $\emptyset$

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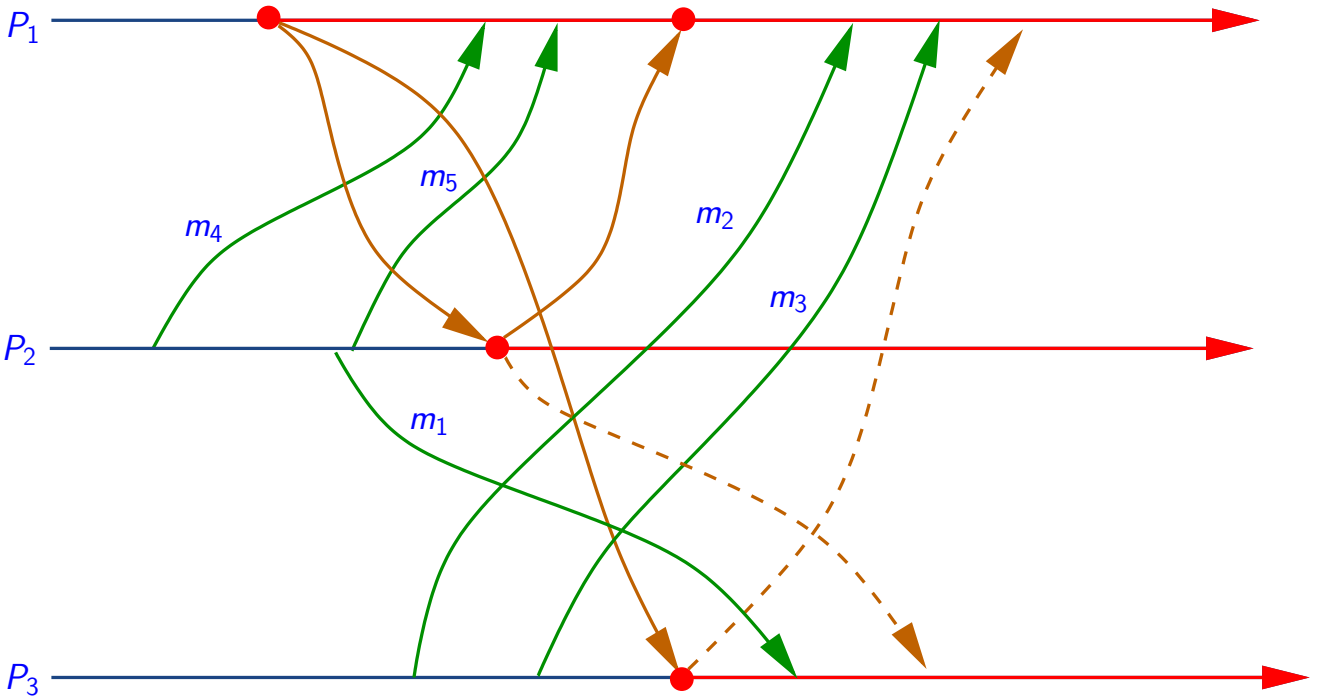

1. P_1 receives the marker message along $C_{2,1}$
2. P_1 records the state of $C_{2,1}$ as $\{m_4, m_5\}$

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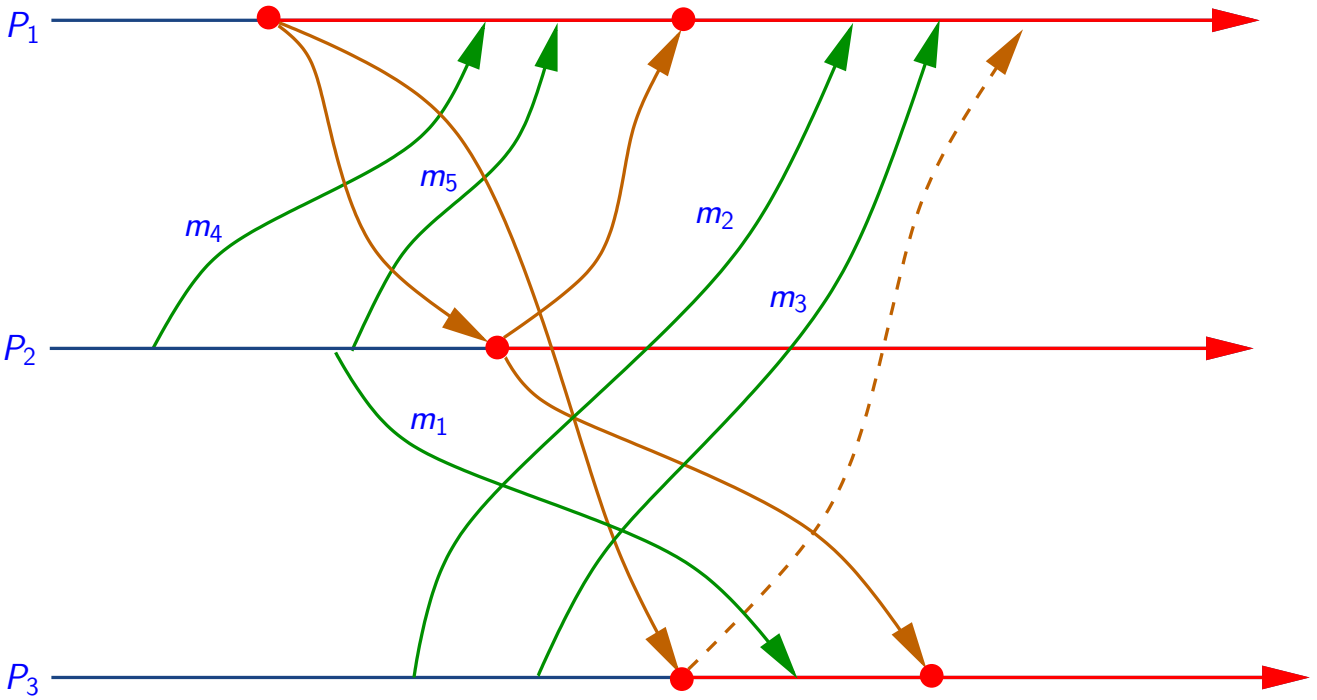
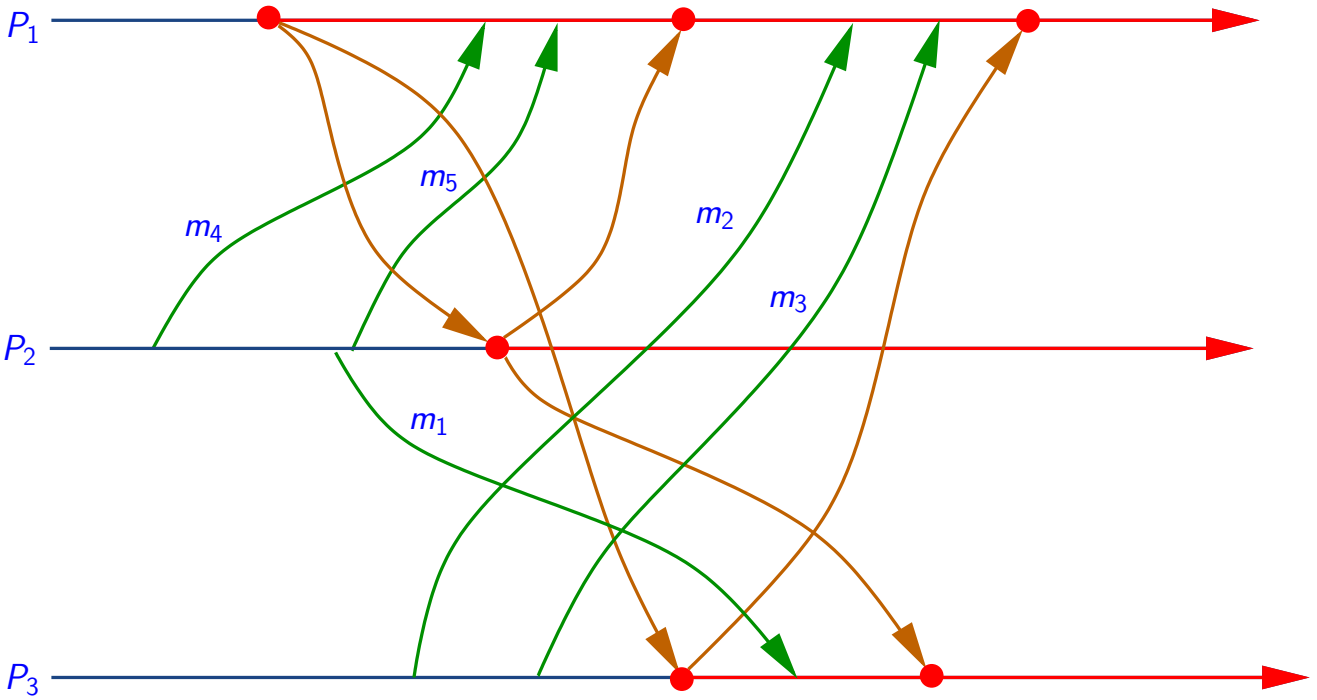


1. P_3 receives the marker message along $C_{2,3}$
2. P_3 records the state of $C_{2,3}$ as $\{m_1\}$

The CL Protocol: An Illustration (Continued)



1. P_1 receives the marker message along $C_{3,1}$
2. P_1 records the state of $C_{3,1}$ as $\{m_2, m_3\}$

Outline

A Subclass of Distributed Computation

- Many distributed computations obey the following paradigm:
  - A process is either in active state or passive state
  - A process can send an application message *only when it is active*
  - An active process can become passive at any time
  - A passive process, on receiving an application message, becomes active
- Intuitively:
  - If a process is active, then it is doing some work
  - If process is passive, then it is idle
  - An active process uses an application message to send a part of its work to another process

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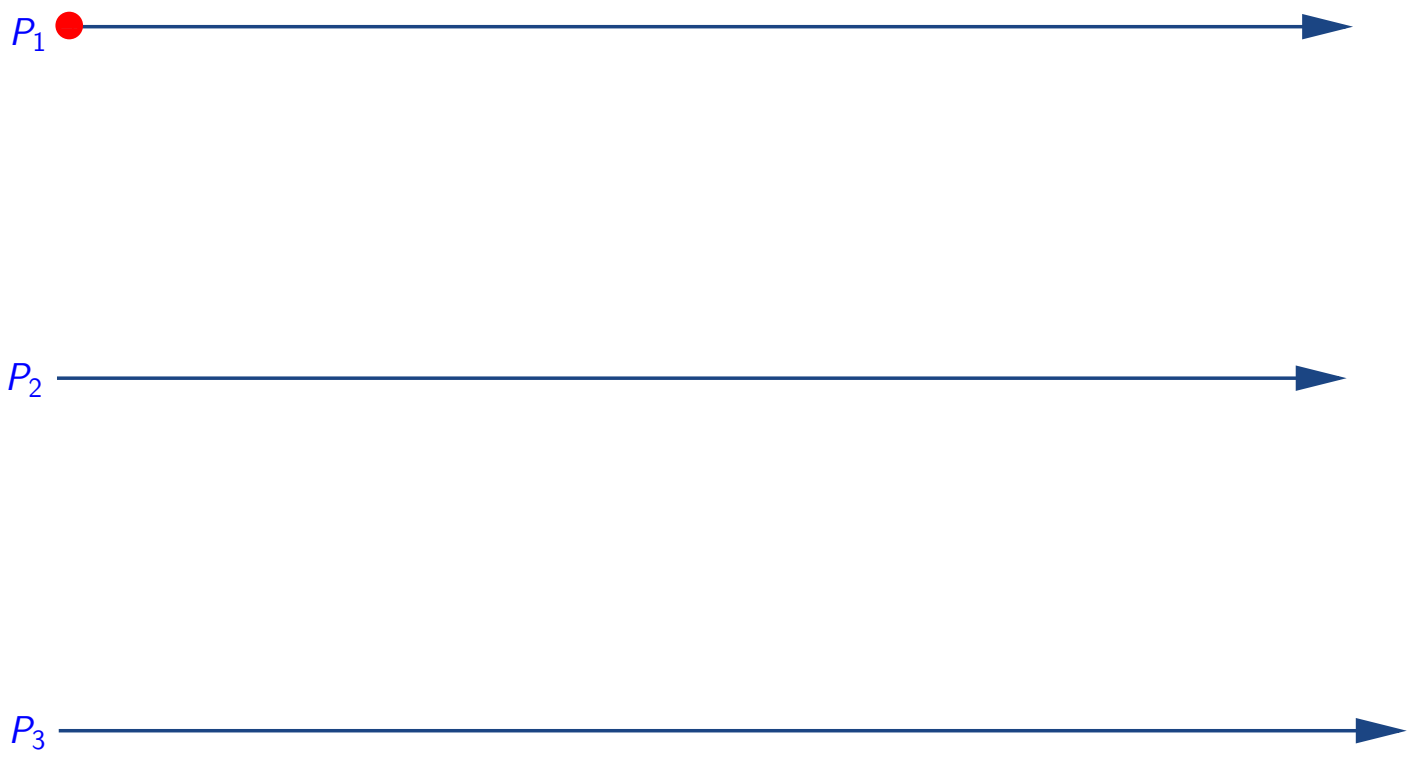

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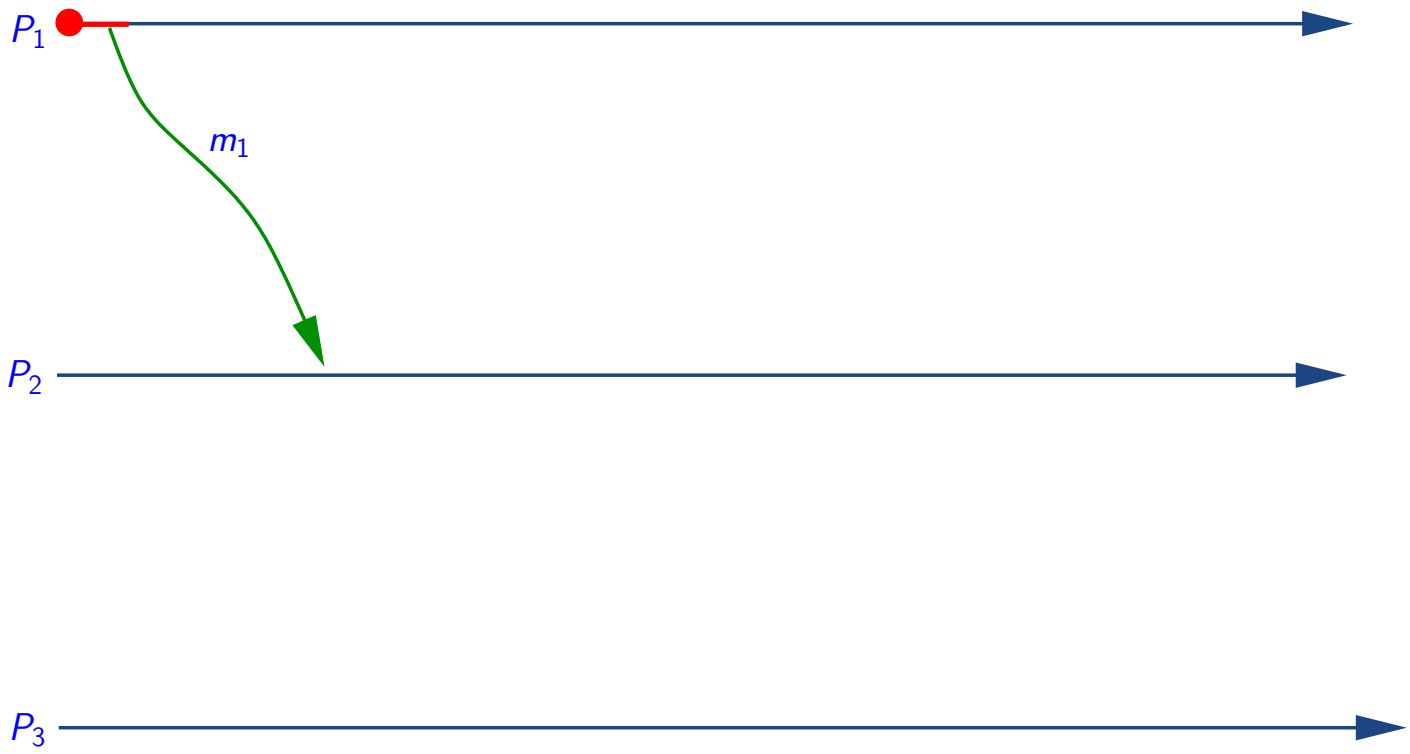

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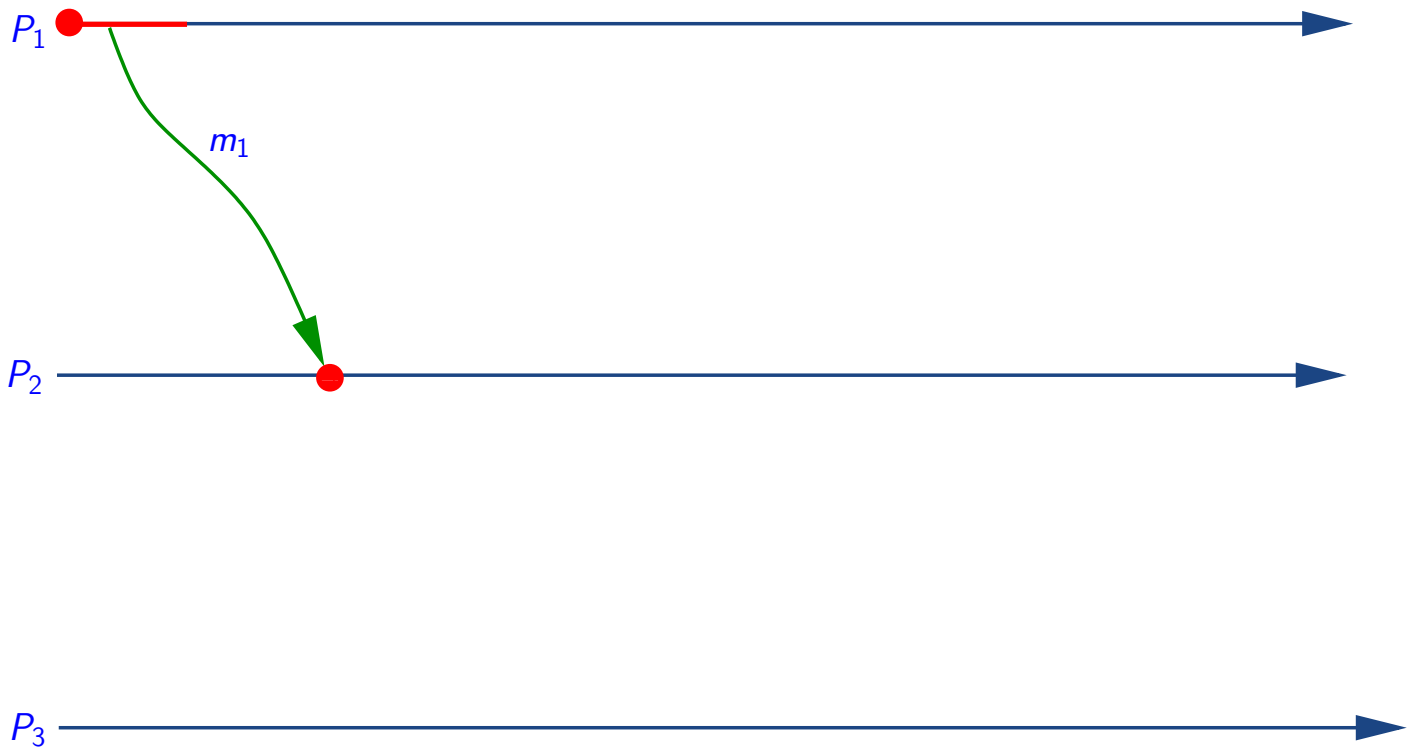

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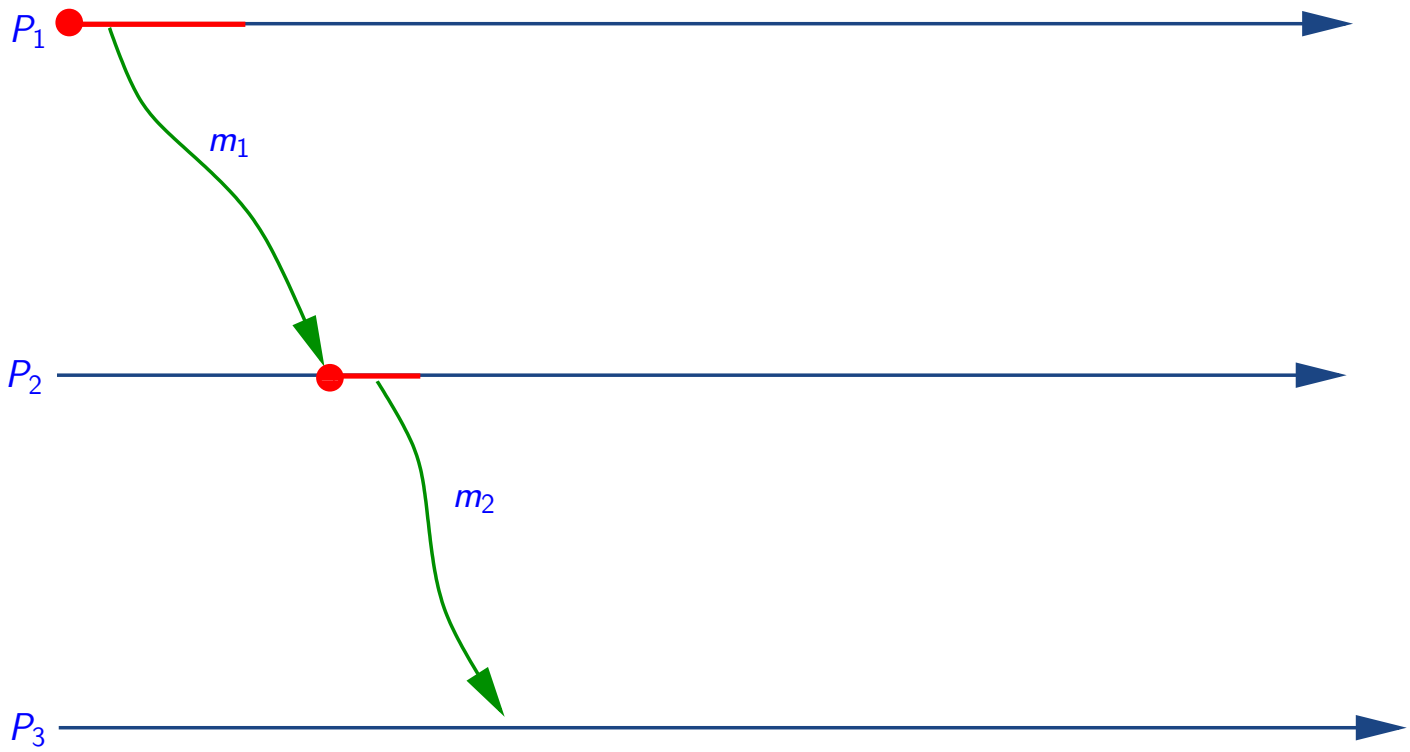

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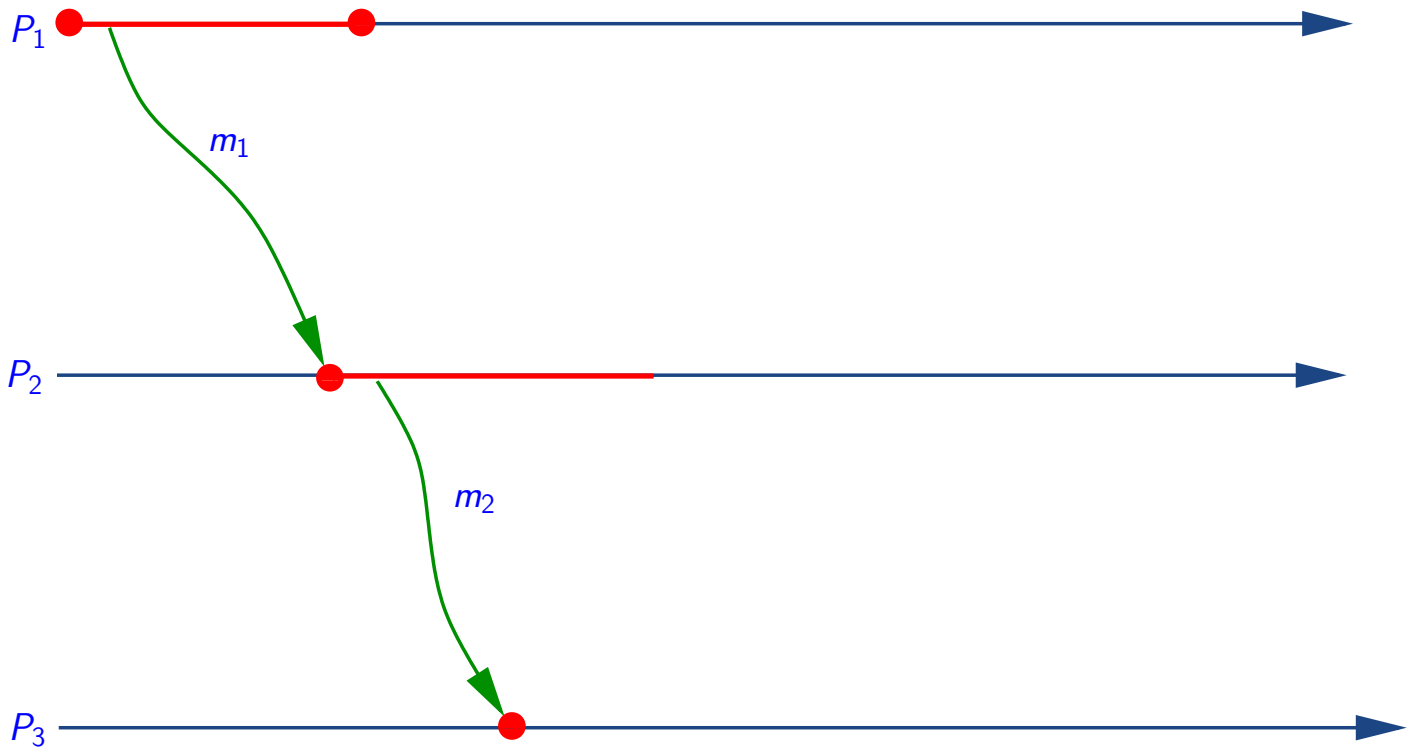

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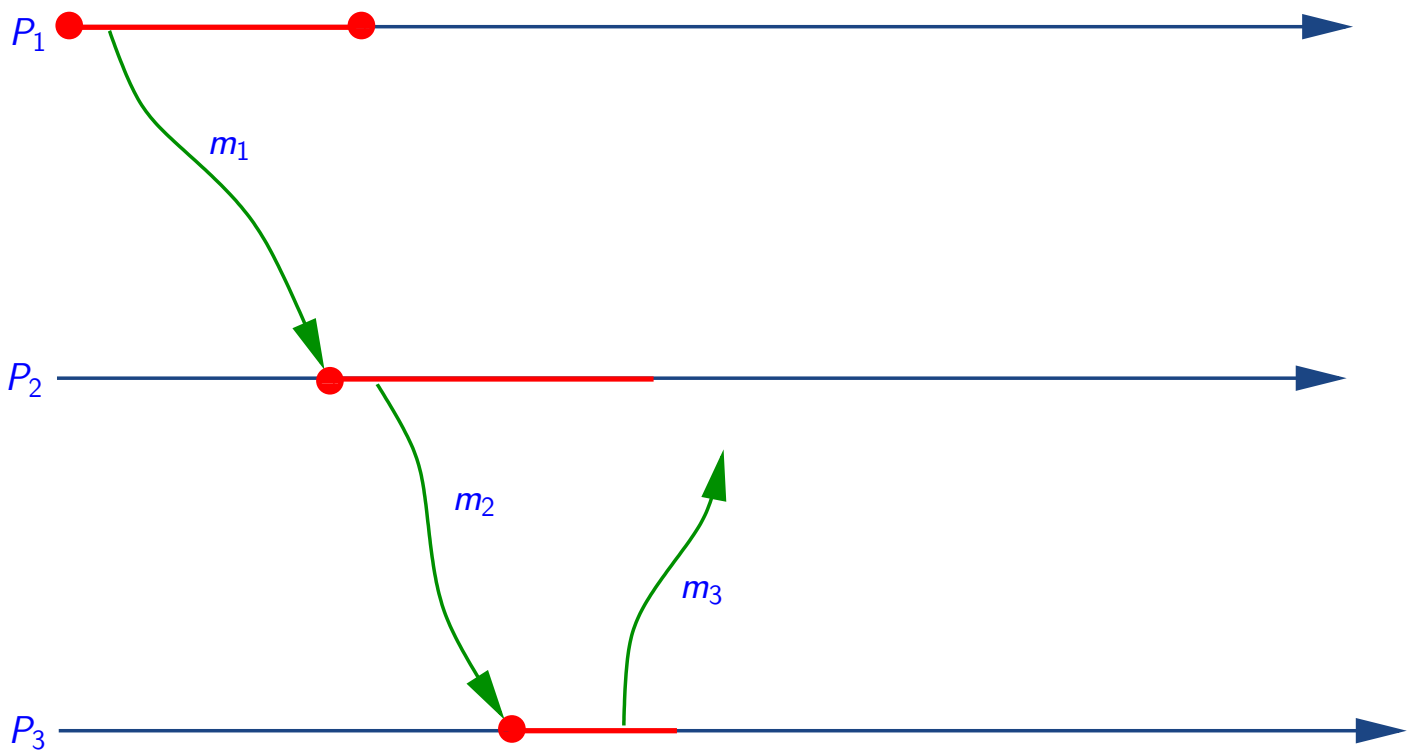

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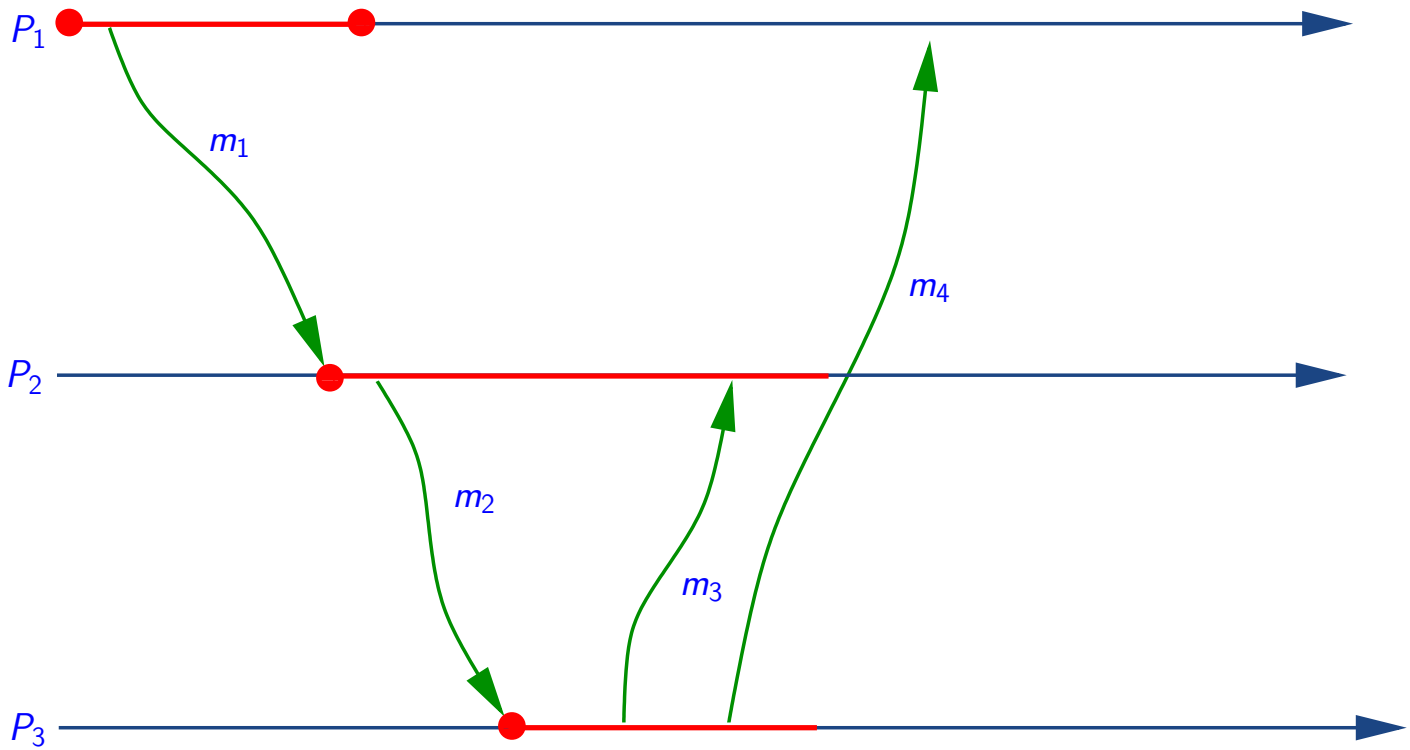

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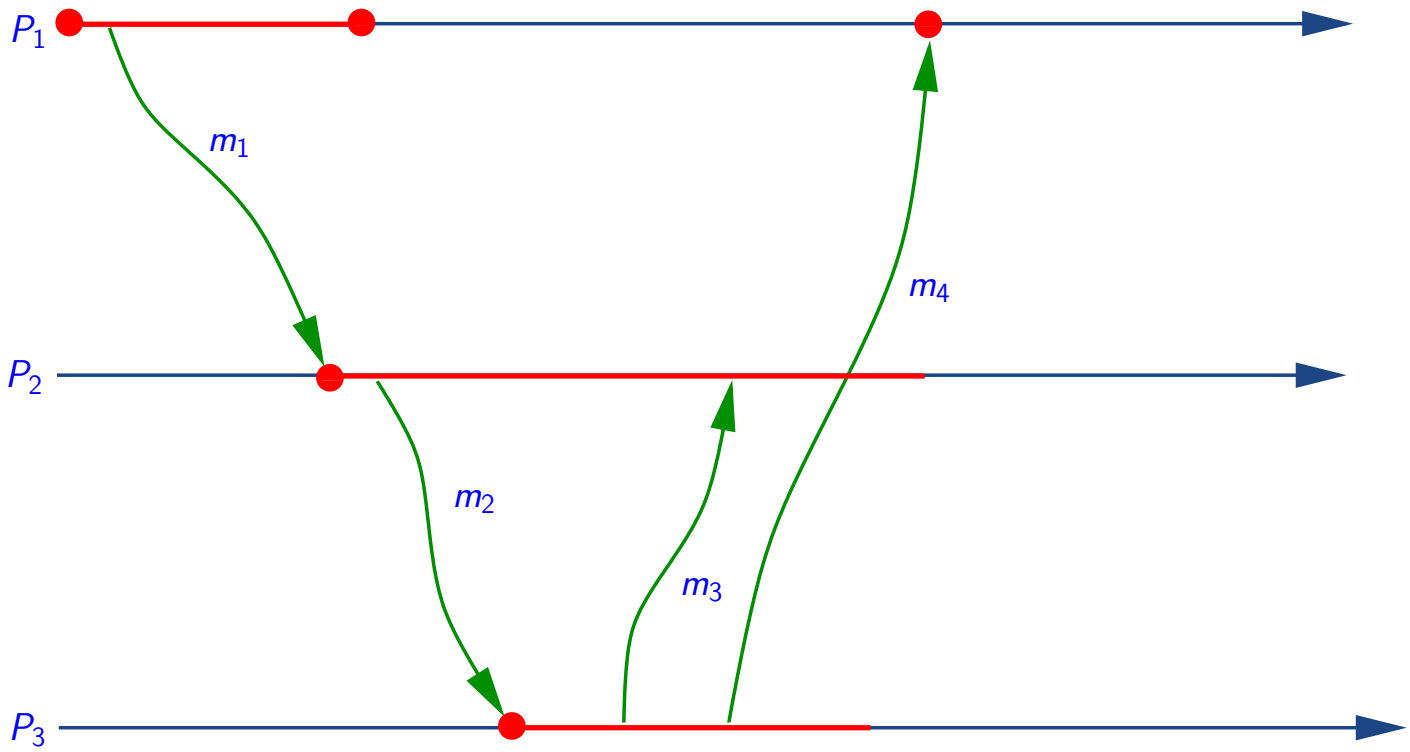

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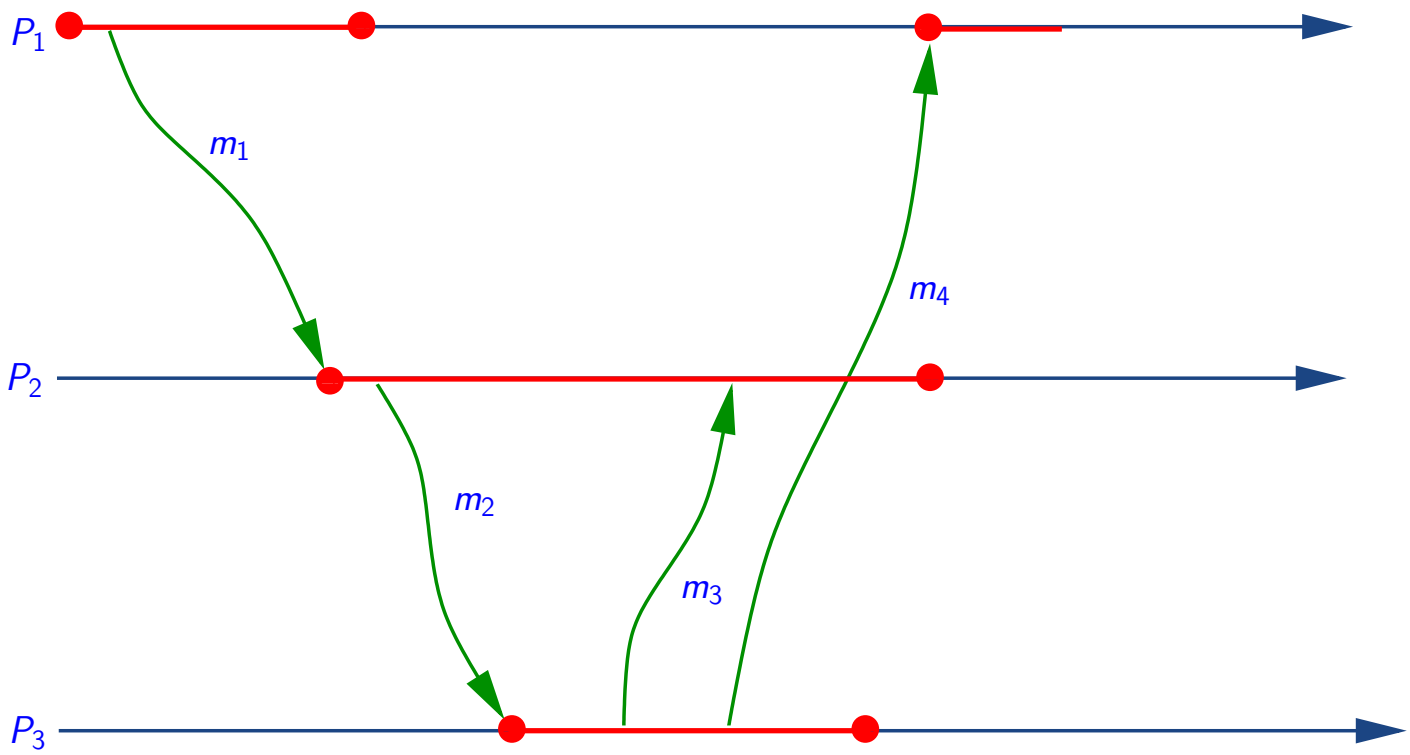

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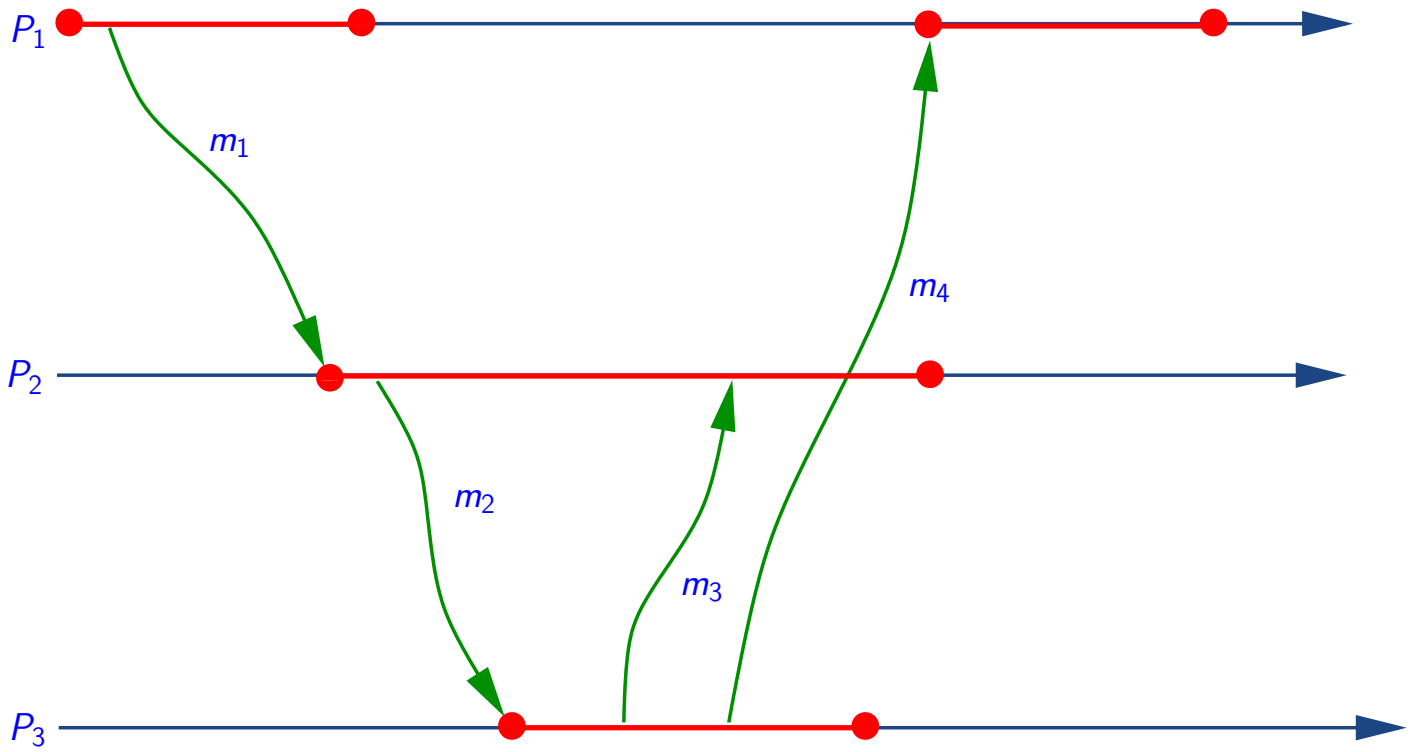

Termination Detection

- To detect if the computation has finished doing all the work
  - all processes have become passive, and
  - all channels have become empty
- Different types of computations:
  - diffusing: only one process is active in the beginning
  - non-diffusing: any subset of processes can be active in the beginning
    - no process knows which processes are active and which processes are passive

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Huang's Protocol

- *Assumption:* computation is diffusing
  - the initially active process is called the coordinator
    - coordinator is responsible for detecting termination
- *Initially:*
  - coordinator has a weight of 1
  - all other processes have a weight of 0
- *Invariants:*
  - total amount of weight in the system is 1
  - a non-coordinator process has a non-zero weight *if and only if* it is active
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Huang's Protocol (Continued)

- Actions:
  - On sending an application message:
    - send half of the weight along with the message
  - On receiving an application message:
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  - On becoming passive:
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- Coordinator announces termination once:
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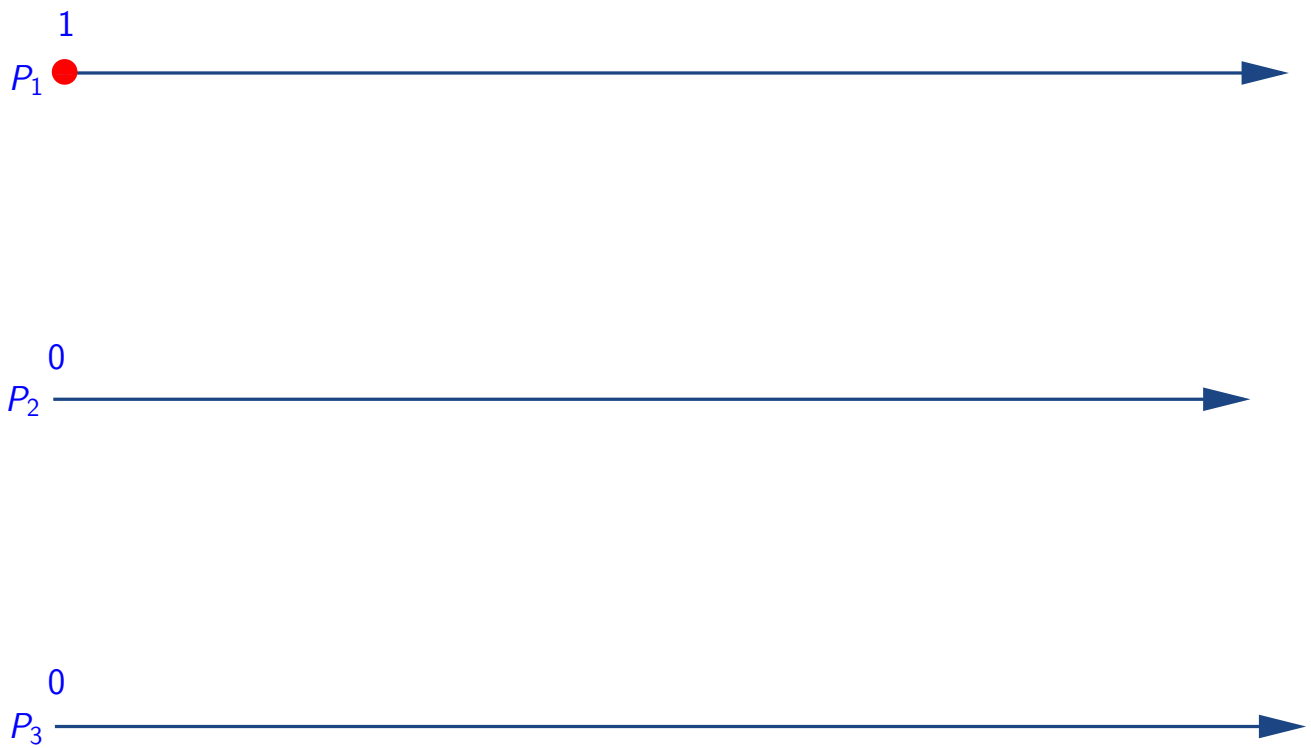

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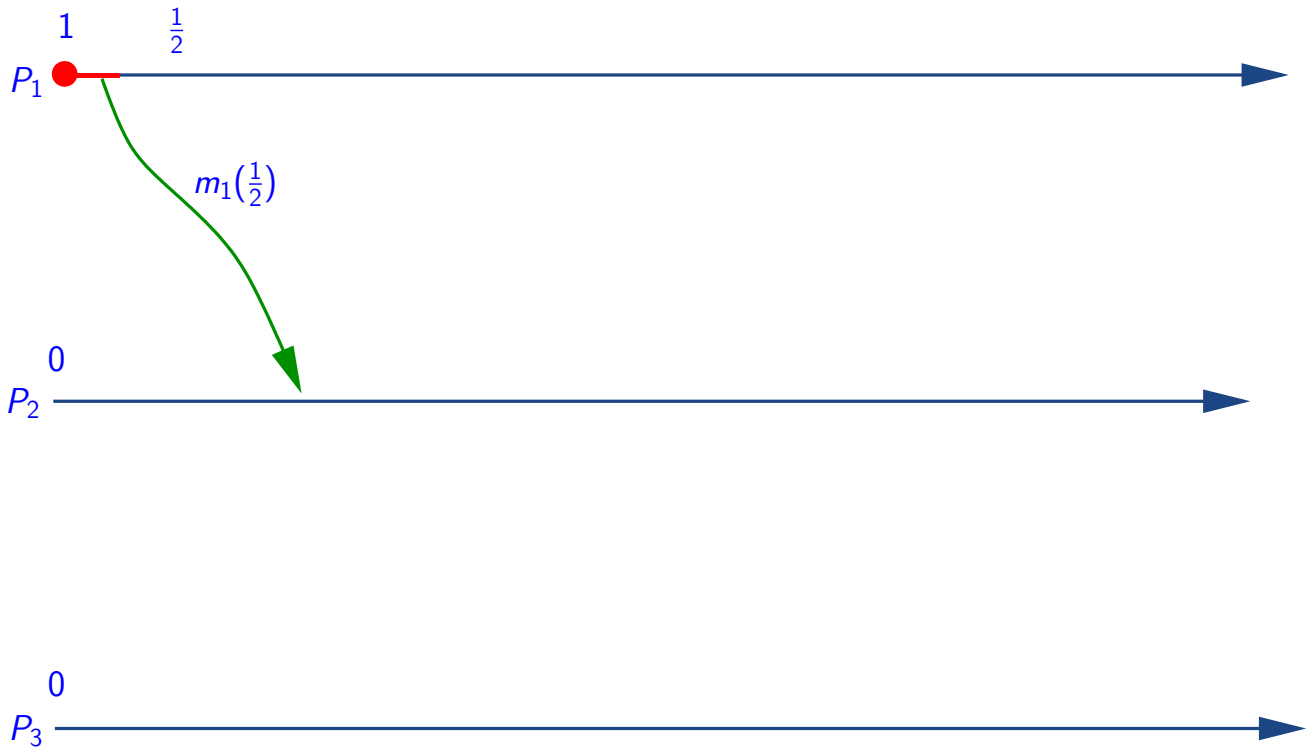

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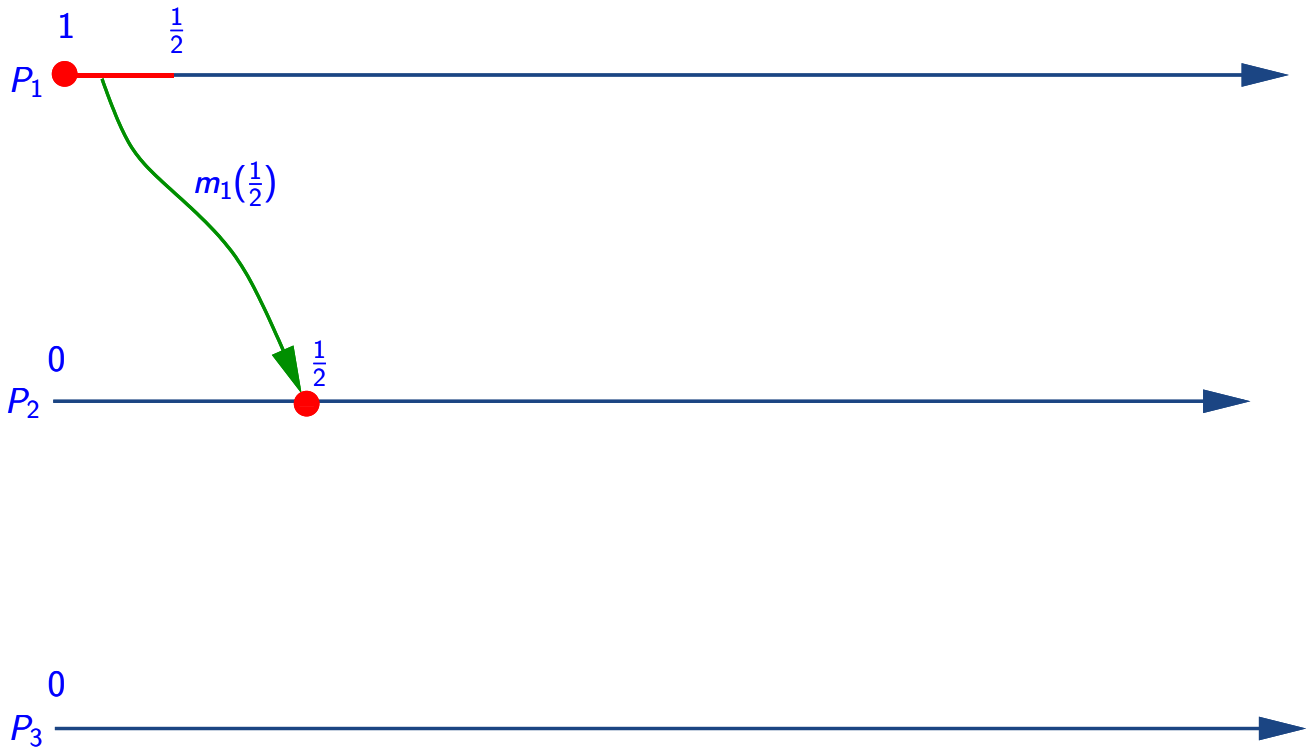

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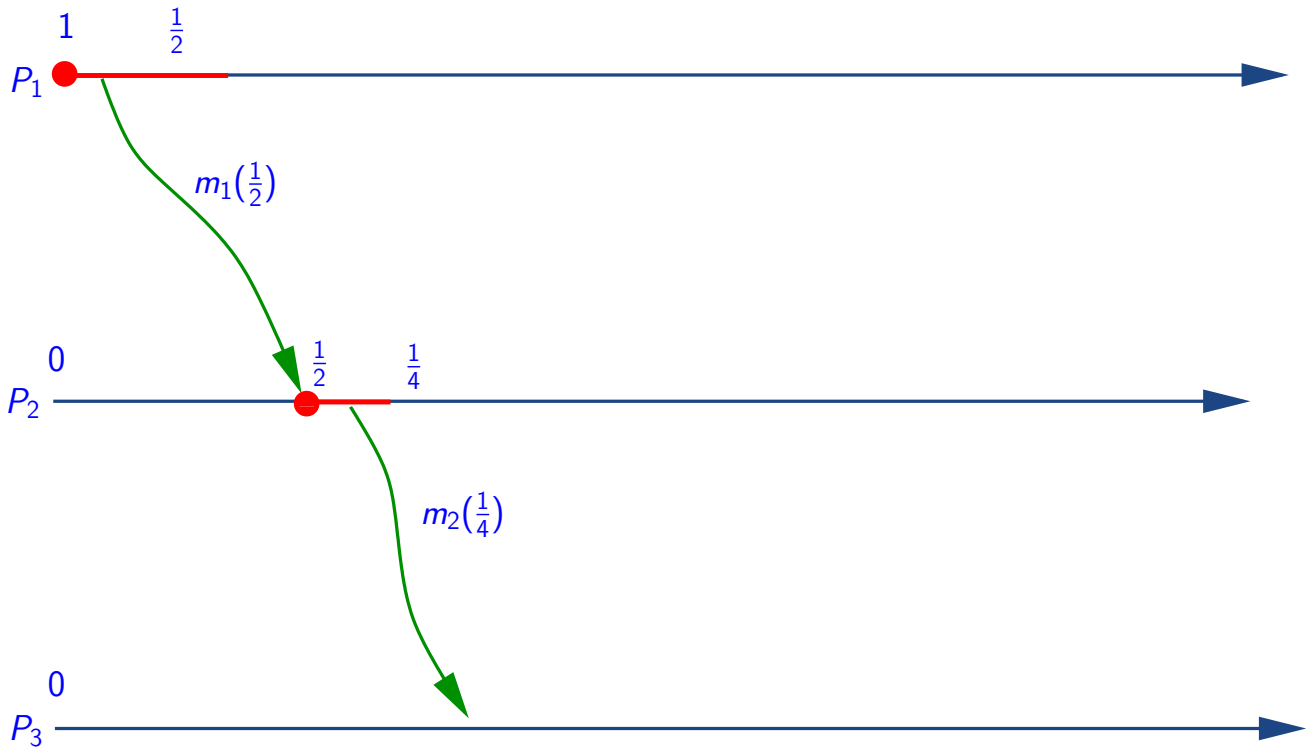

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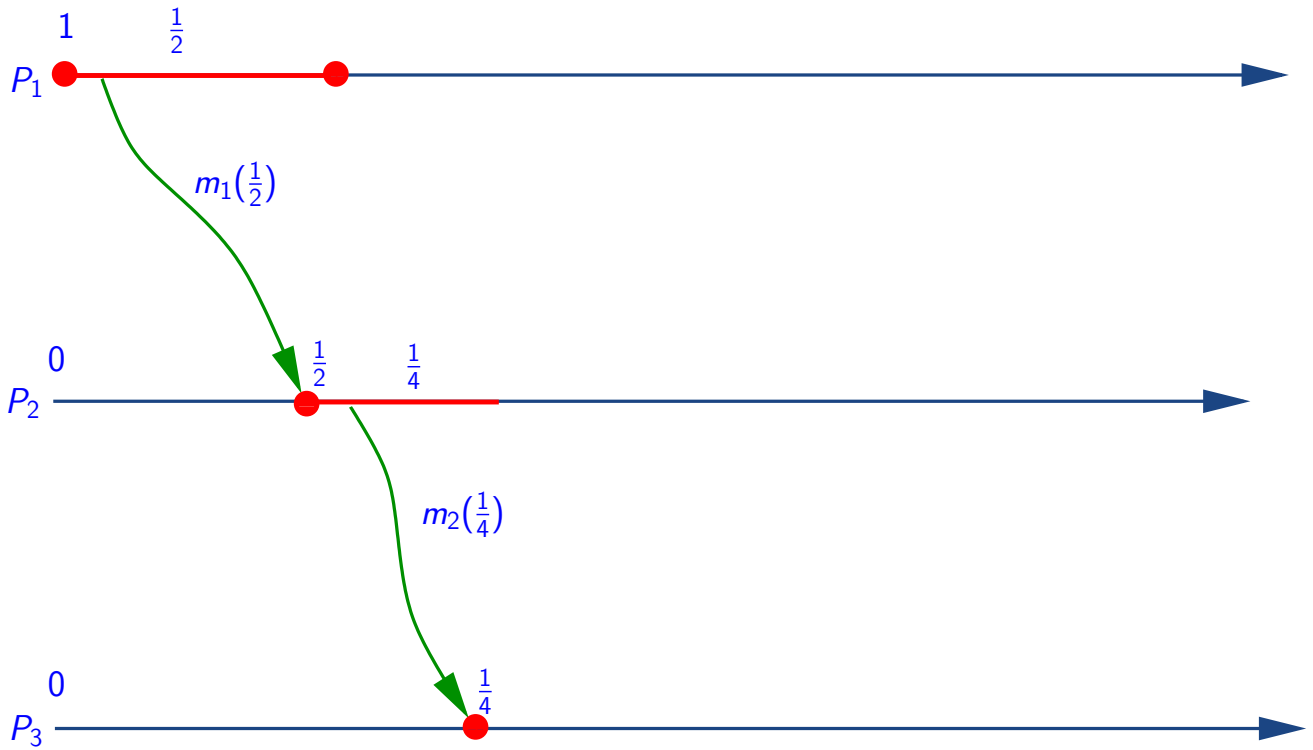

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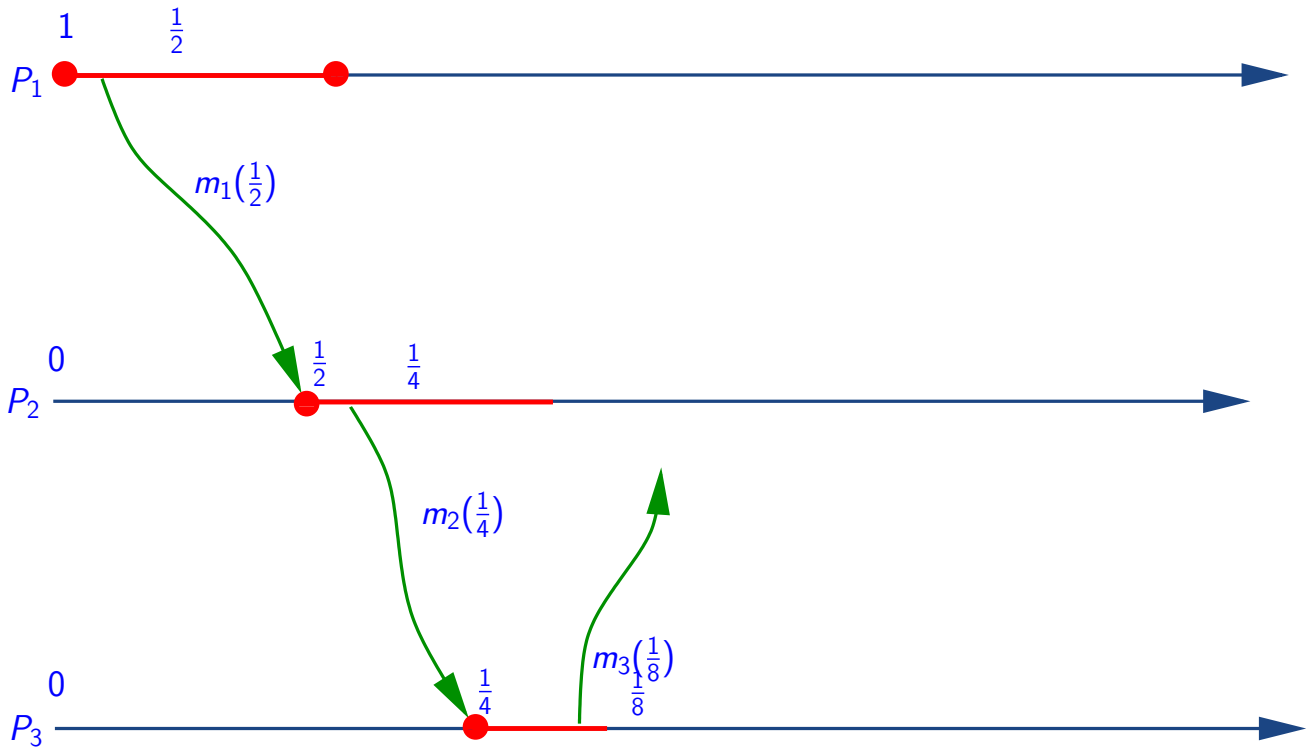

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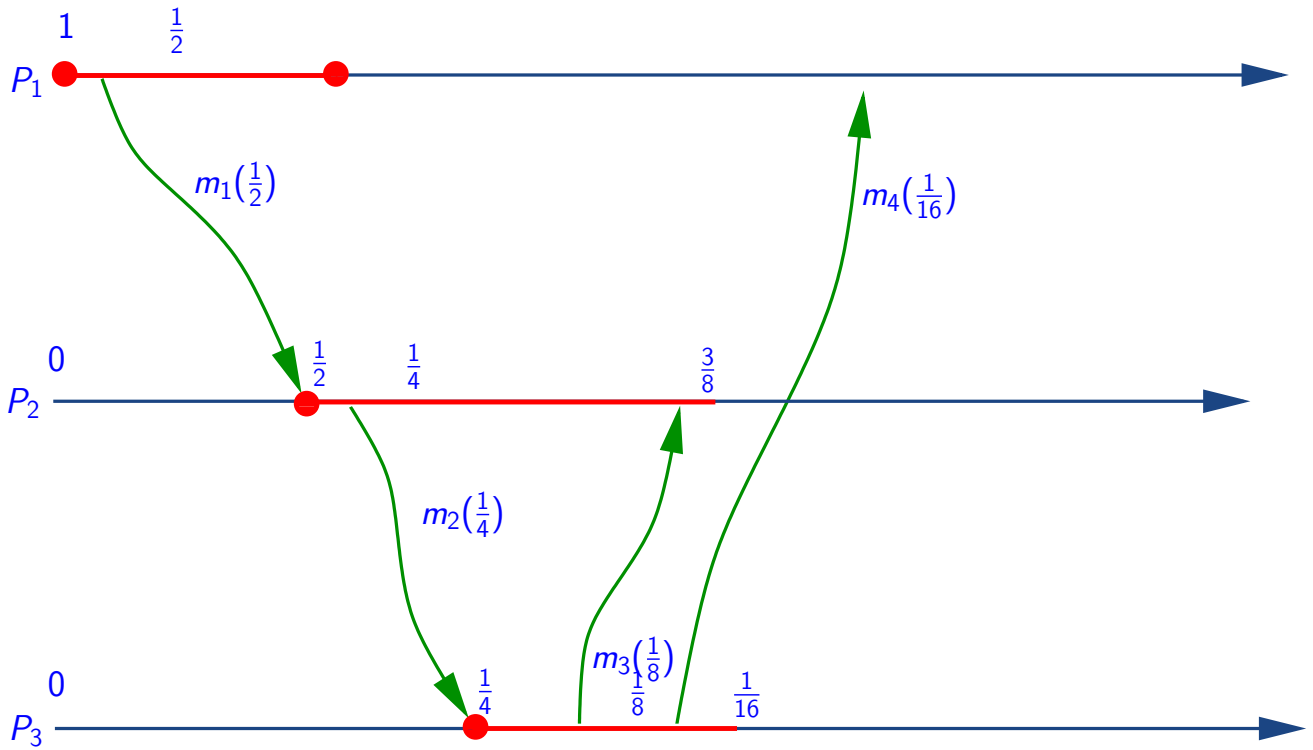

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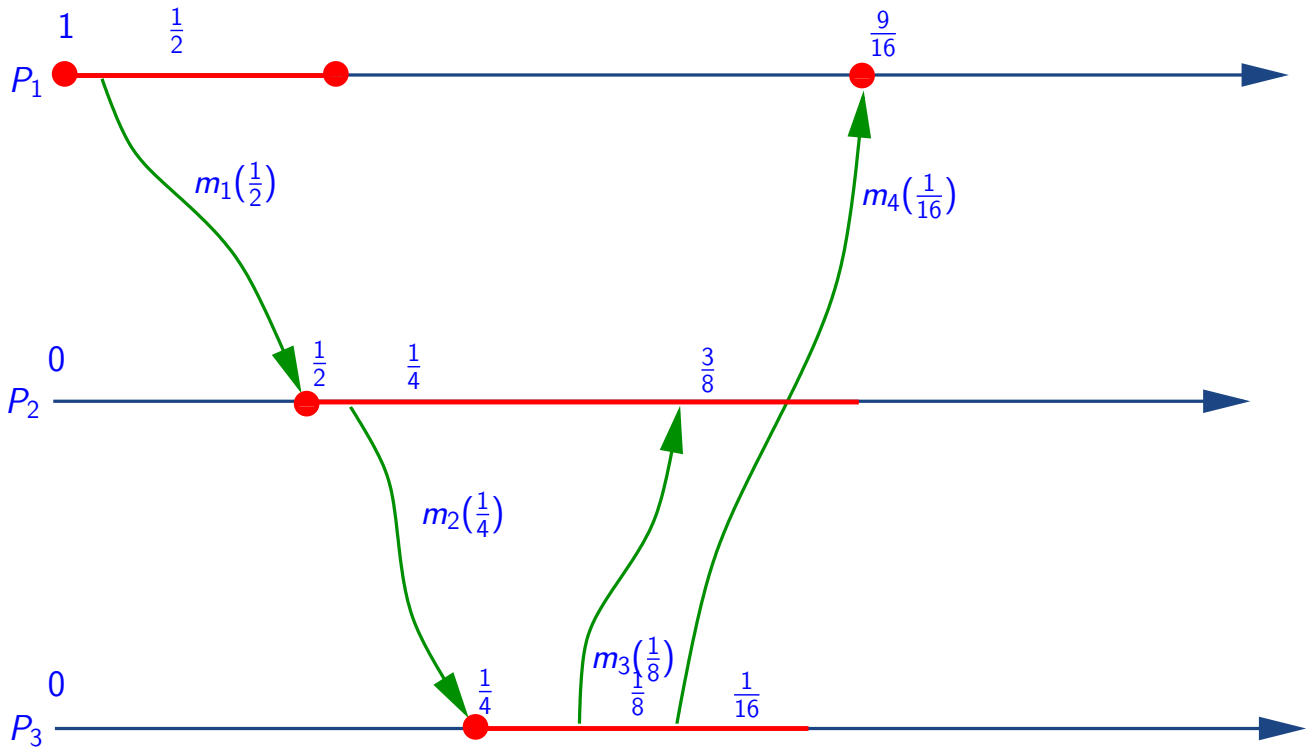

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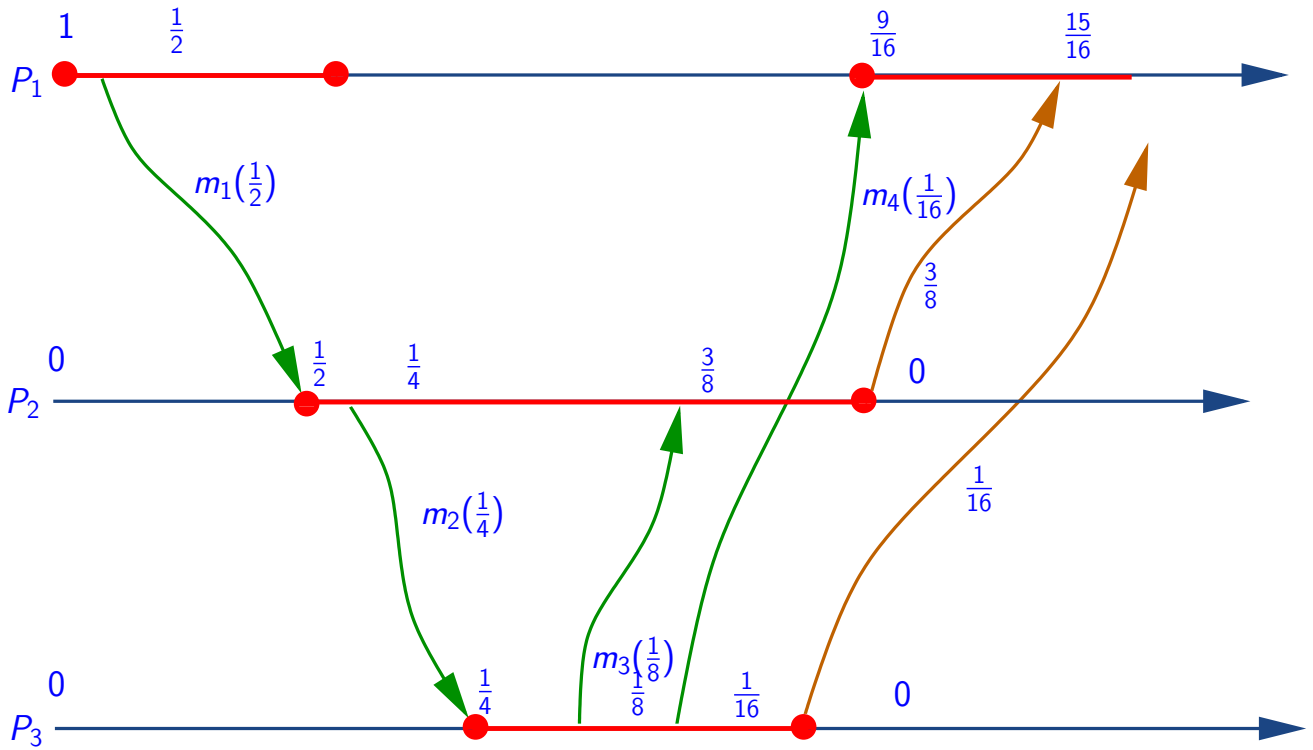

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