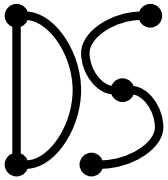


Research Group
Distributed Systems

Distributed Systems

Clocks & Time II

Olaf Landsiedel

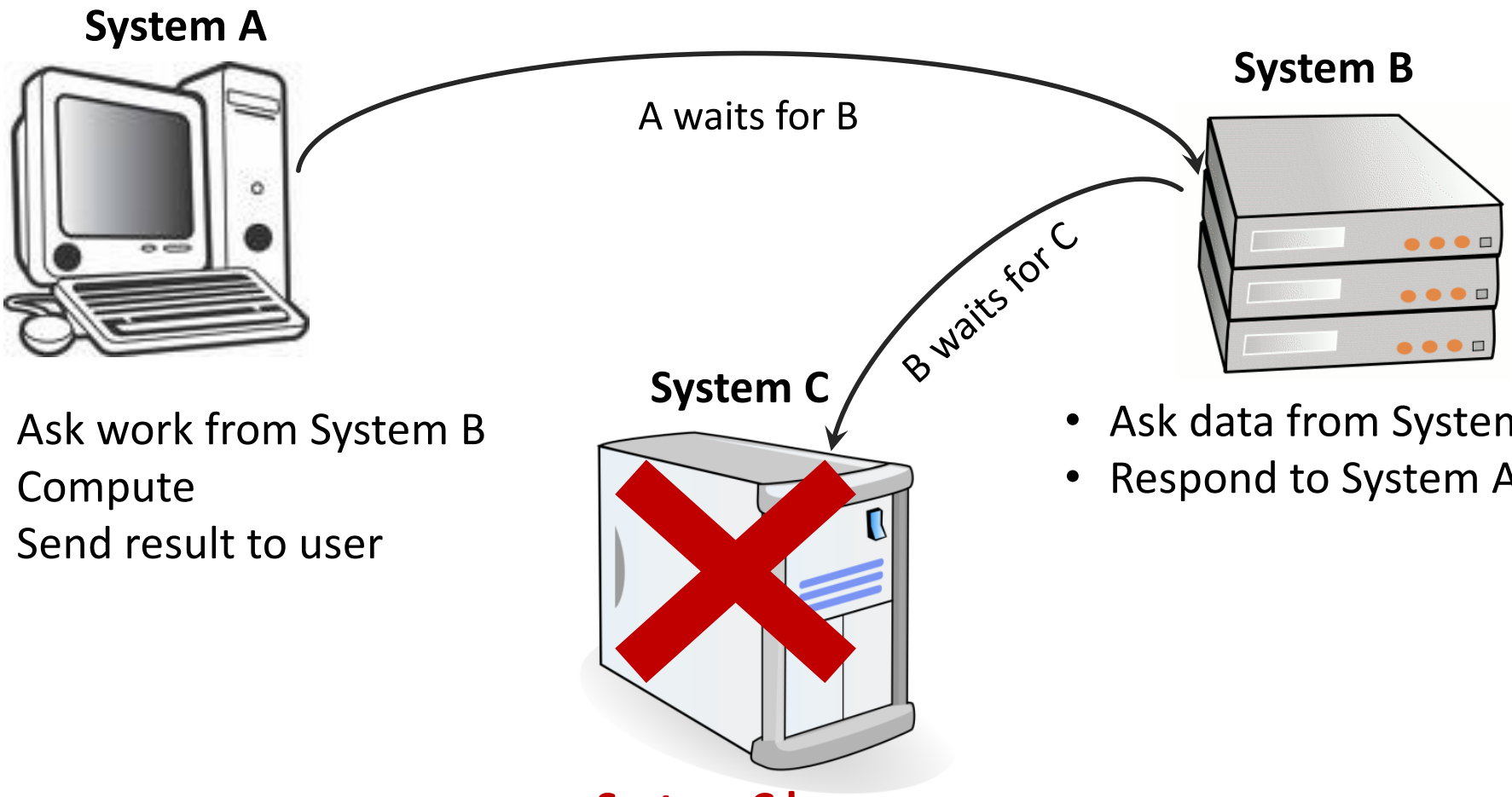
Last Time

- Topic: Clocks and Time I
  - Physical Clocks
  - Main lessons learned from last time?

Asynchronous Distributed System?

- Define:
  - Asynchronous Distributed System
  - > no notion of a global clock

A Distributed Computation With Data Dependencies



- Ask work from System B
- Compute
- Send result to user

- Ask data from System C
- Respond to System A

Detecting and Fixing the Problem

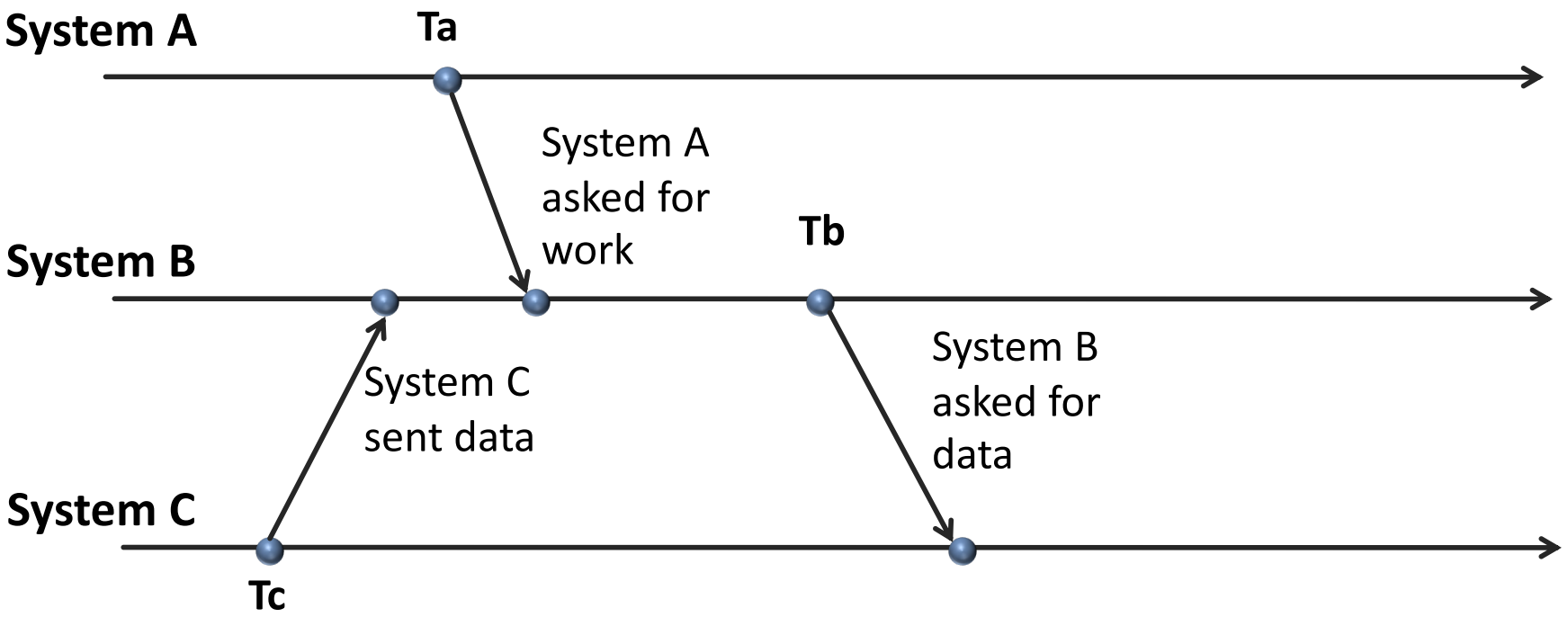
- User gets no response from System A
- How do we detect that System C is causing the problem?
- Easy to detect if we get a snapshot of a global state
- Constructing global state in an asynchronous distributed system is a difficult problem

A Naïve Approach

- Each system records each event it performed and its timestamp
- Suppose events in the this system happened in this real order:
  - **Time Tc0:** System C sent data to System B (before C stopped responding)
  - **Time Ta0:** System A asked for work from System B
  - **Time Tb0:** System B asked for data from System C

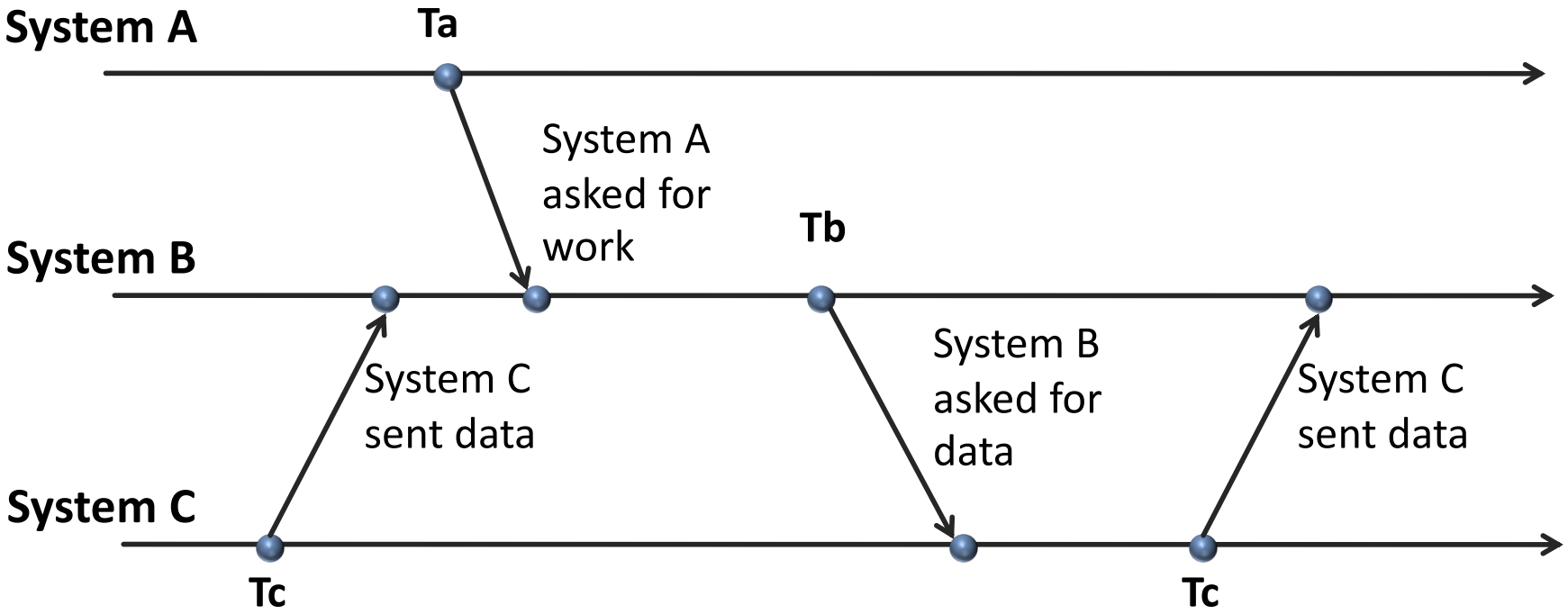
A Naïve Approach (cont)

- Ideally, we will construct real order of events from local timestamps and detect this dependency chain:



A Naïve Approach (cont)

- But in reality, we do not know if Tc occurred before Ta and Tb, because in an asynchronous distributed system clocks are not synchronized!



This Lecture's Topic

- We will learn how to solve this problem in an asynchronous distributed system
- Our goal is to construct a consistent global state in presence of unsynchronized local clocks
- We will begin by creating a formal model for
  - Distributed computation
  - Event precedence in a distributed computation
- We will use a event precedence model to define consistent global state
- Then we will learn to construct consistent global states

Model of a Distributed Computation

- Collection of processes $p_0, \ldots, p_n$
- Processes communicate by sending messages
- Event ***send(m)*** enqueues message m on the sending end
- Event ***receive(m)*** dequeues message m on the receiving end
- Events $e_i^0, e_i^1, \ldots, e_i^n$ are steps of a distributed computation at process p_i
- $h_i = e_i^0, e_i^1, \ldots, e_i^n$ is a local history of p_i

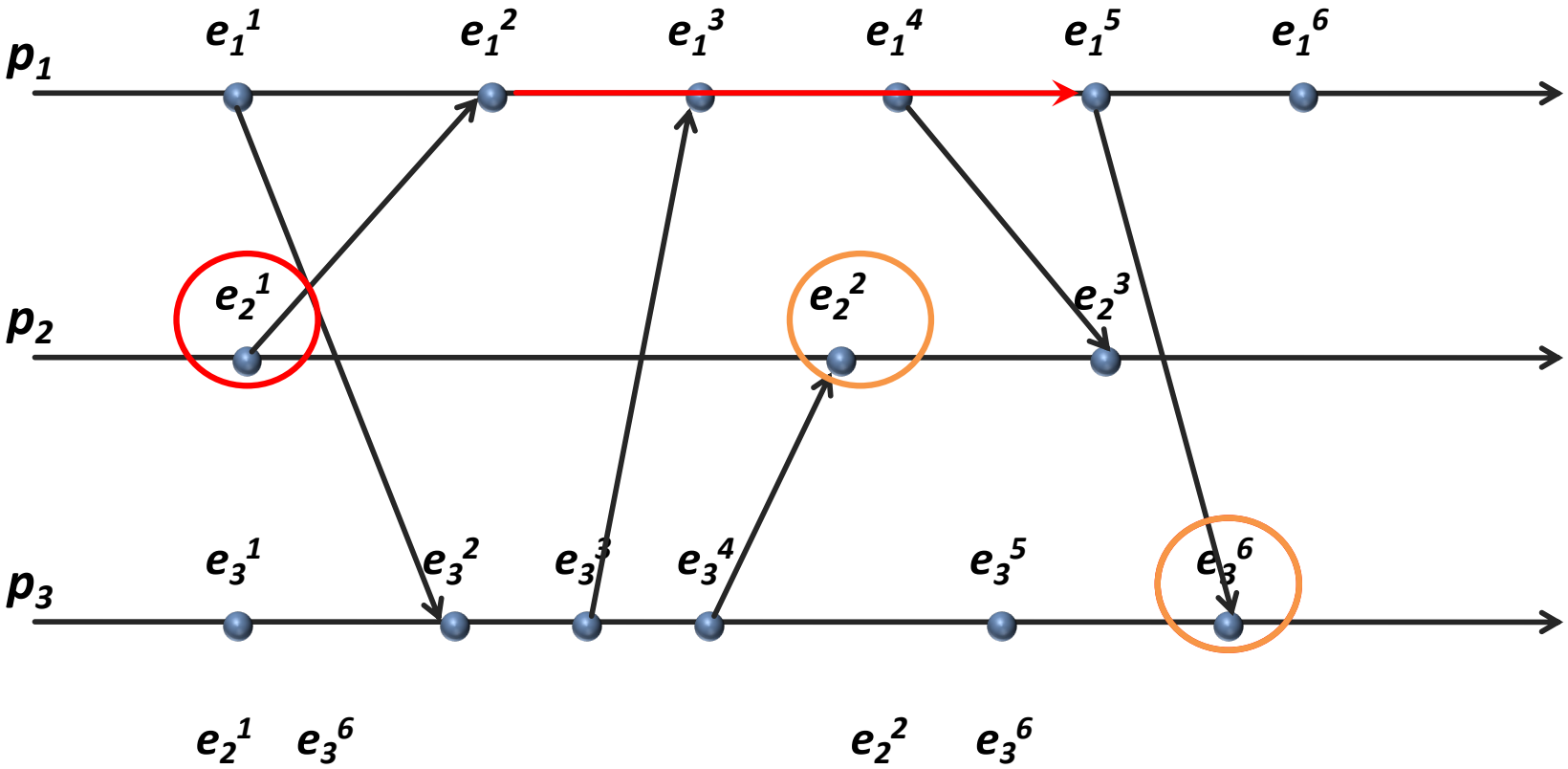
Events and Causal Precedence

- In an asynchronous distributed system there is no notion of global clock
- Events cannot be ordered according to some real order
- We can only talk about ***causal event ordering***, that is if one event affects the outcome of another event
- For example events ***send(m)*** and ***receive(m)*** are in causal order, because ***receive(m)*** could not have occurred before ***send(m)***

Formal Rules for Ordering of Events

- If local events precede one another, then they also precede one another in the global ordering:
  - On node i: If $e_i^k, e_i^m \in h_i$ and $k < m$, then $e_i^k \rightarrow e_i^m$
- Sending a message always precedes receipt of that message:
  - If $e_i = send(m)$ and $e_j = receive(m)$, then $e_i \rightarrow e_j$
- Event ordering is transitive:
  - If $e \rightarrow e'$ and $e' \rightarrow e''$, then $e \rightarrow e''$

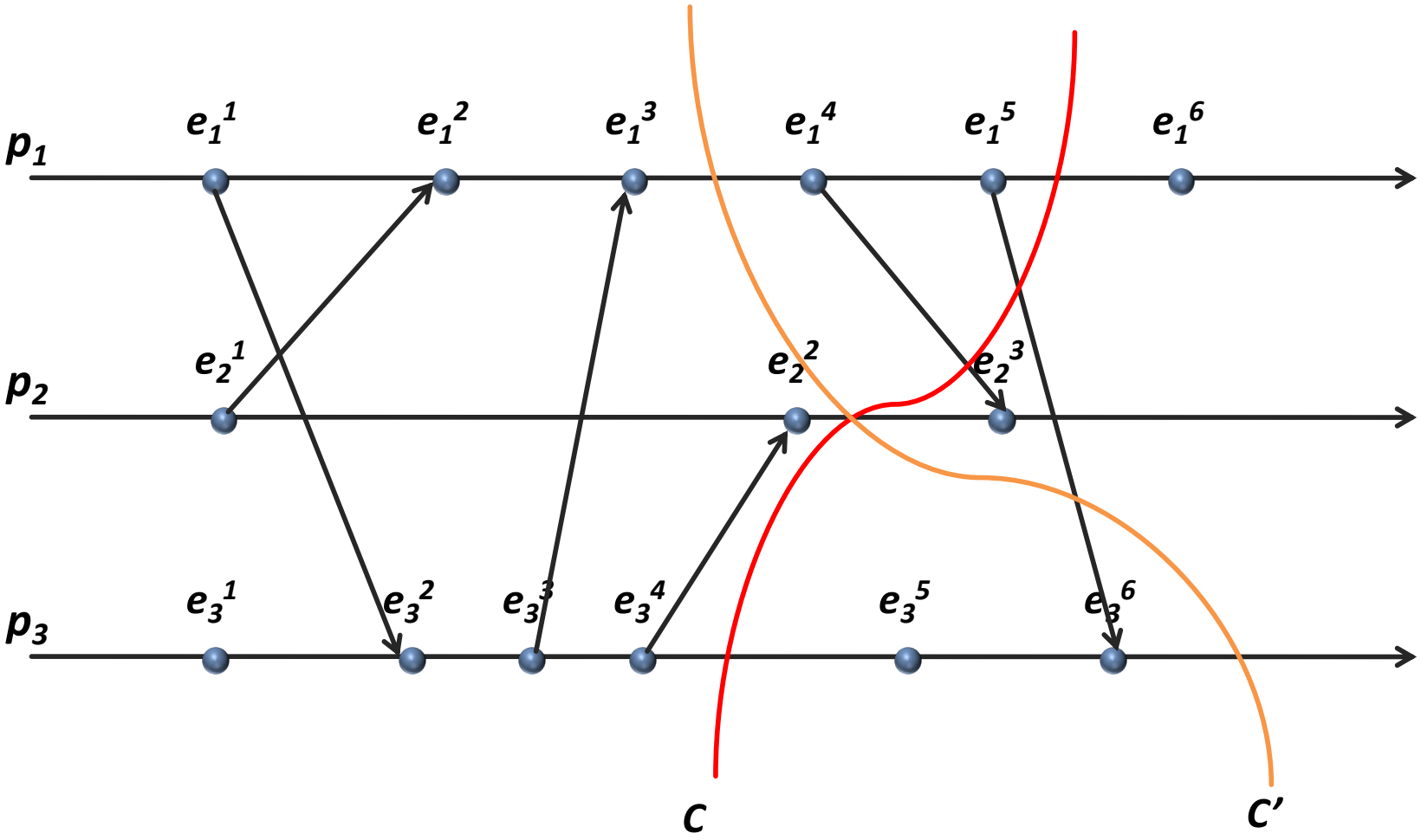
Space-time Diagram of a Distributed Computation



Cuts of a Distributed Computation

- Suppose there is an ***external monitor*** process
- External monitor constructs a global state:
  - Asks processes to send it local history
- Global state constructed from these local histories is a ***cut of a distributed computation***

Example Cuts

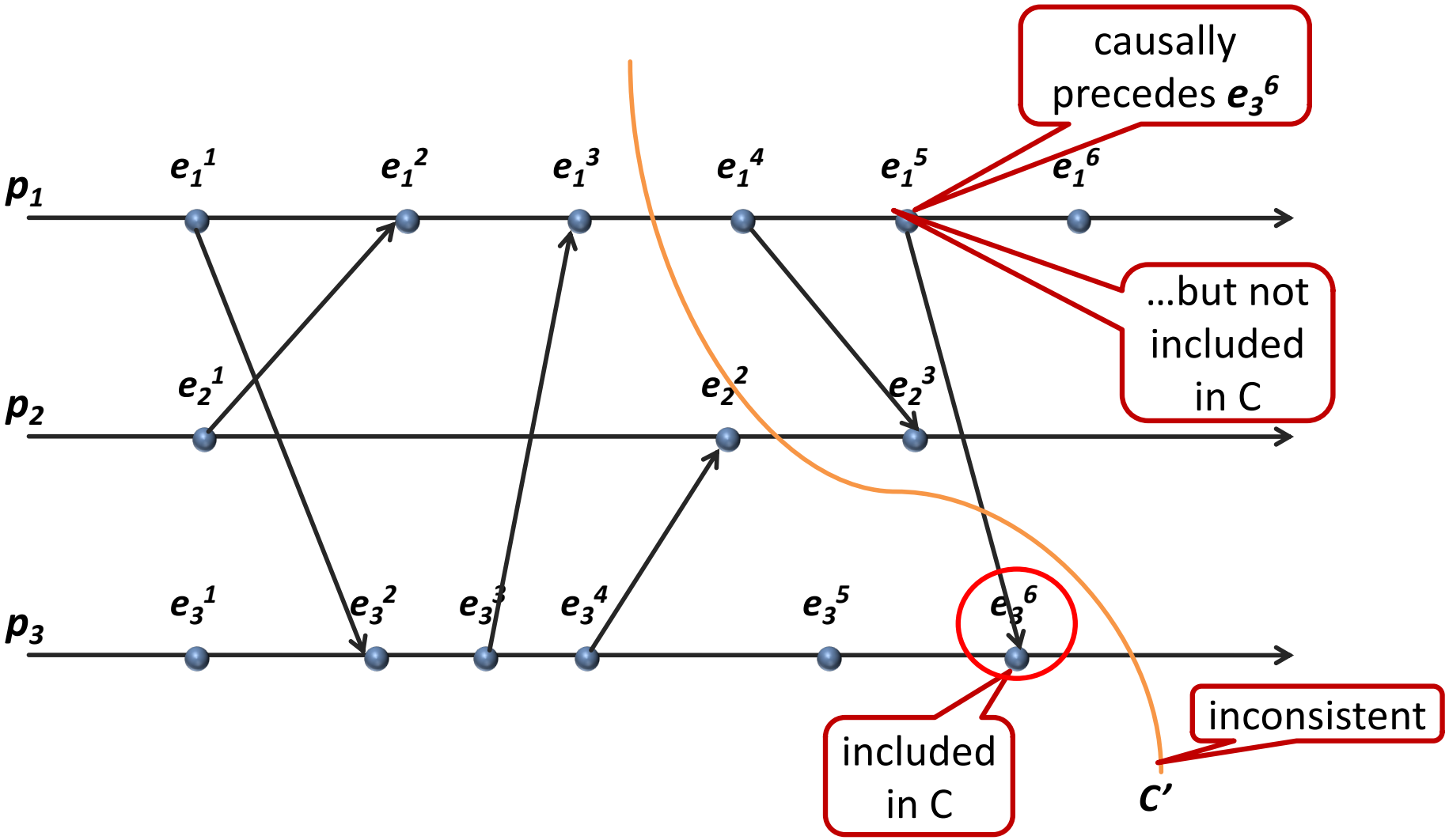


Consistent vs. Inconsistent Cuts

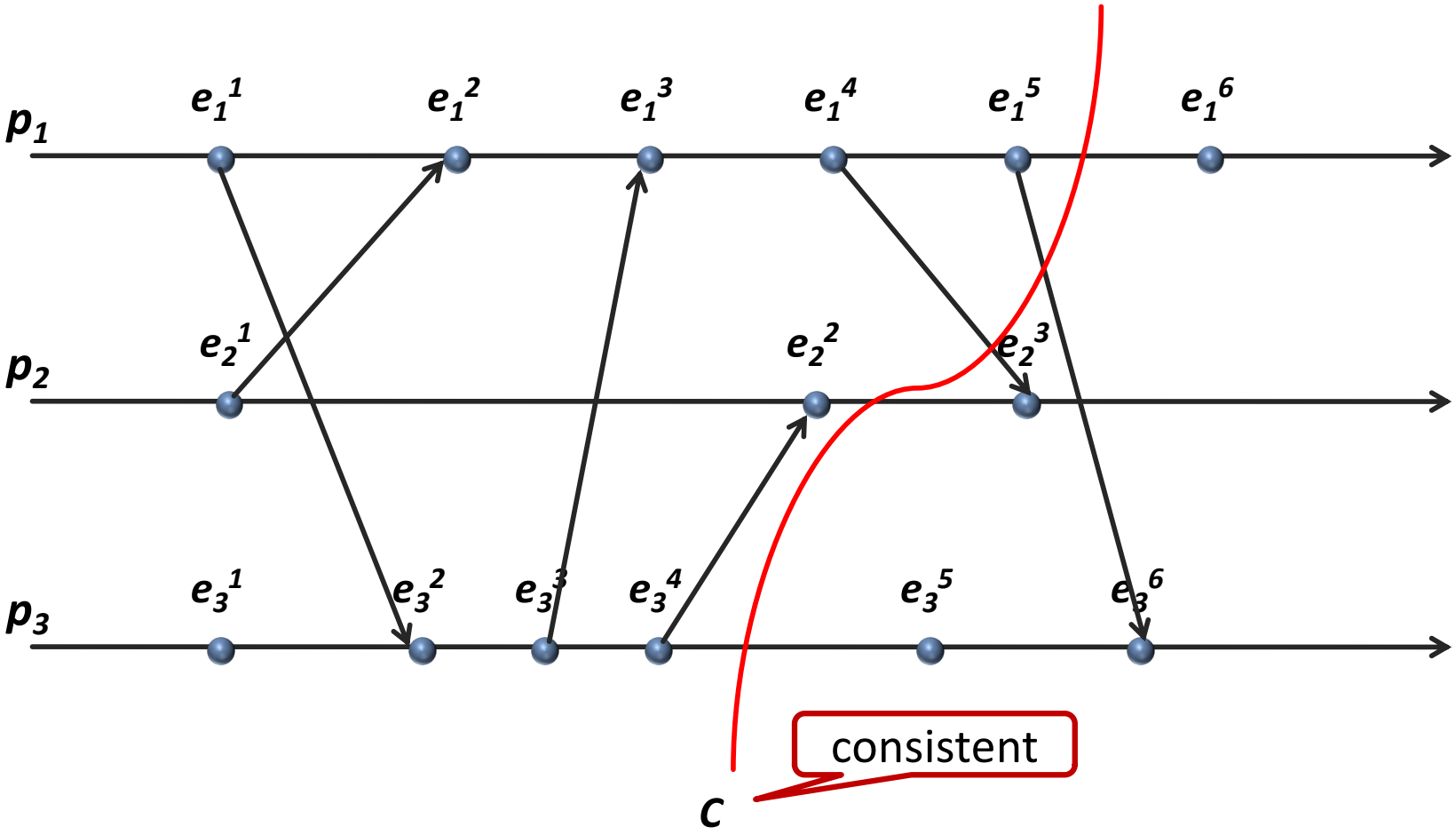
- A cut is consistent if for any event *e* included in the cut, any event *e'* that causally precedes *e* is also included in that cut
- For cut *C:*

$$(e \in C) \wedge (e' \rightarrow e) \Rightarrow e' \in C$$

Are These Cuts Consistent?



Are These Cuts Consistent?

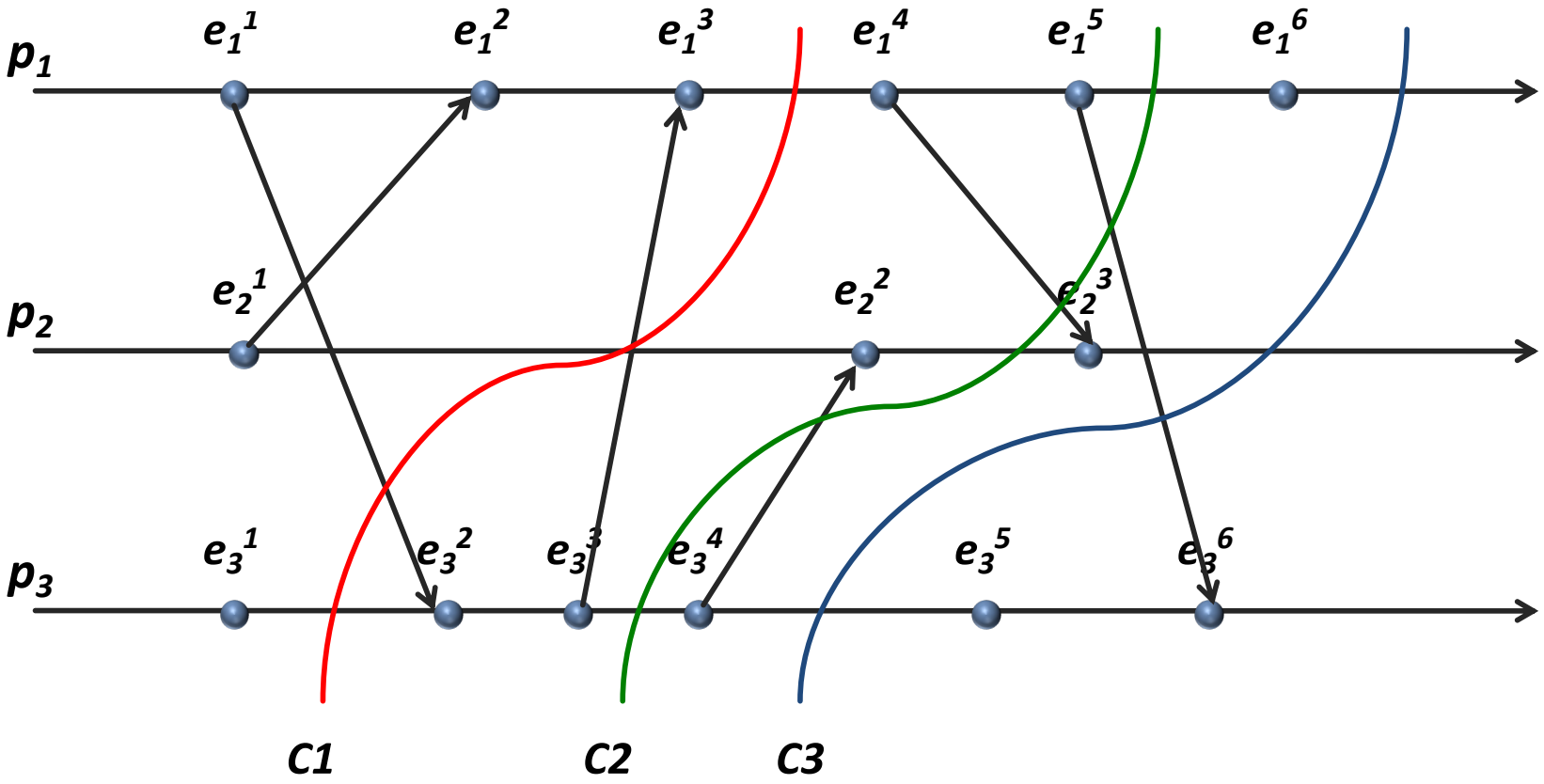


Questions

- Is event ordering transitive?
  - $e \rightarrow e'$ *and* $e' \rightarrow e''$, *then* $e \rightarrow e''$
- When is a cut consistent?
  - $(e \in C) \wedge (e' \rightarrow e) \Rightarrow e' \in C$

Are These Cuts Consistent?

olafland.polldaddy.com/s/cuts



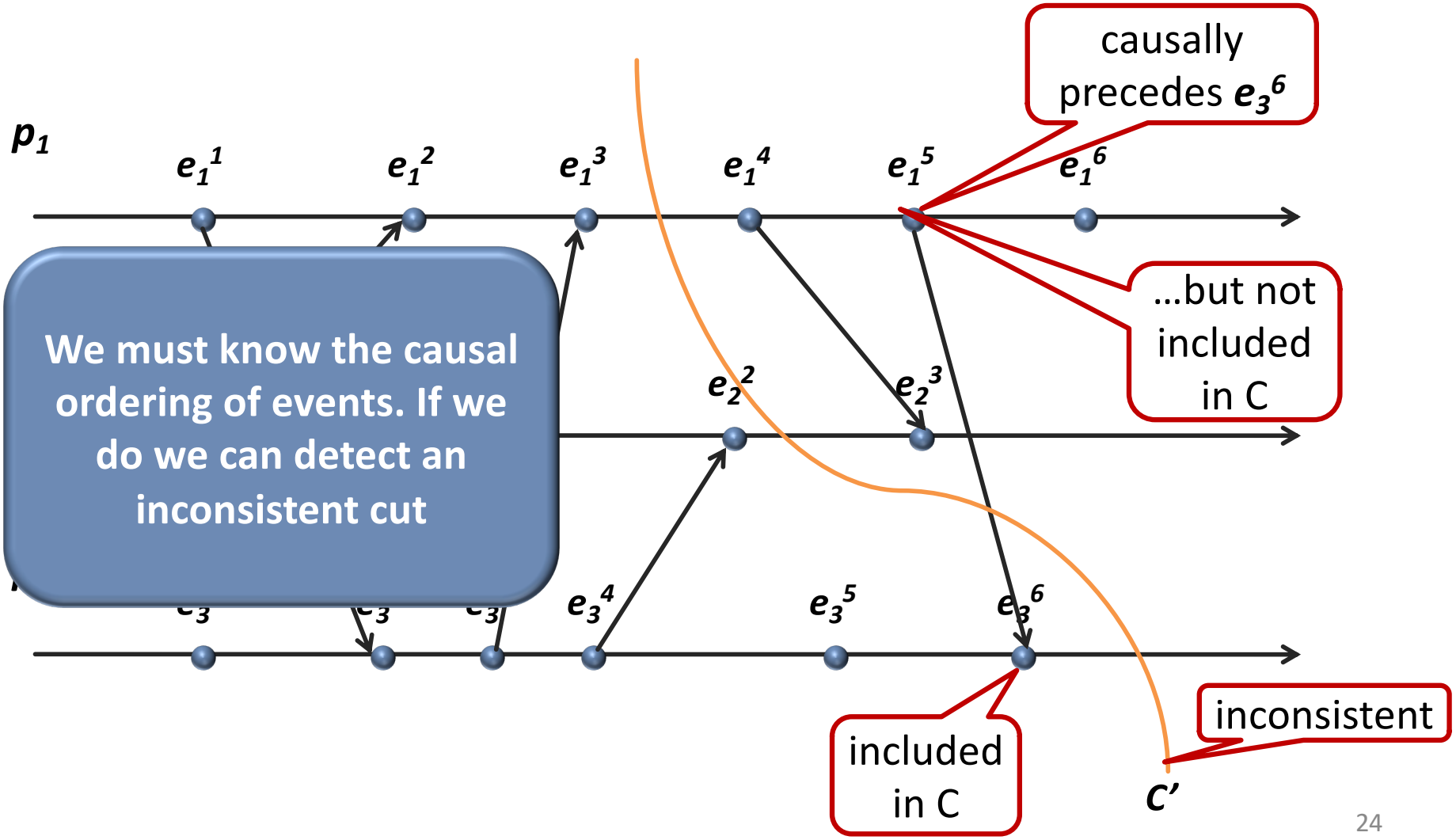
Cuts and Global State

- Recall that our goal is to construct a consistent global state
- We'd like to get a snapshot of a distributed system as would have been observed by a perfect observer
- ***A consistent cut corresponds to a consistent global state***
- What's next: we will learn how to construct consistent cuts in the absence of synchronized clocks
- Consistent global states can be constructed via:
  - Active monitoring
  - Passive monitoring

Passive vs. Active Monitoring

- **Common settings**
  - There is a process p_0 external to the distributed computation
  - There are processes p_i $(1 \leq i \leq n)$, part of the computation
- **Passive monitoring:**
  - Each process p_i sends to p_0 a timestamp of each event it executes
- **Active monitoring:**
  - When p_0 desires to find out the state of the system it asks all processes p_i to send its state

What Do We Need to Know to Construct a Consistent Cut?



Constructing a Consistent Cut

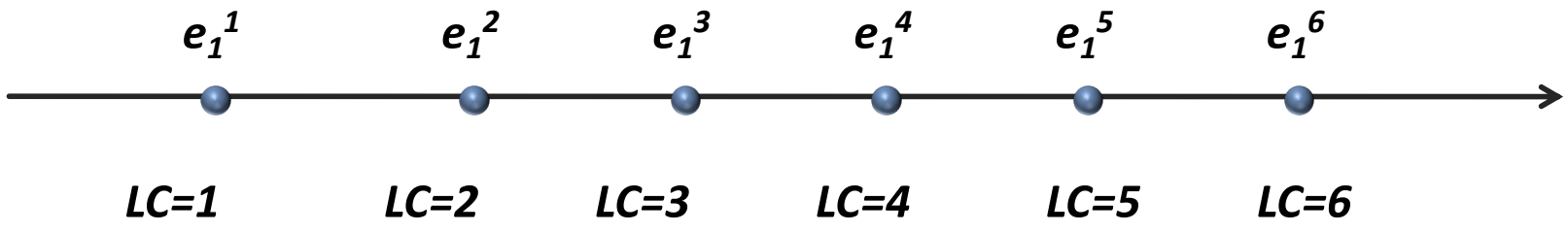
- We must know the causal ordering of events
- If there was a global clock, we would detect this as follows:
- ***RC(e)*** – timestamp of event e given by a global clock
- Clock condition:

  $$e' \rightarrow e \Rightarrow RC(e') < RC(e)$$

- **What to do if there is no global clock?**
- We will use **logical clocks** and **vector clocks**

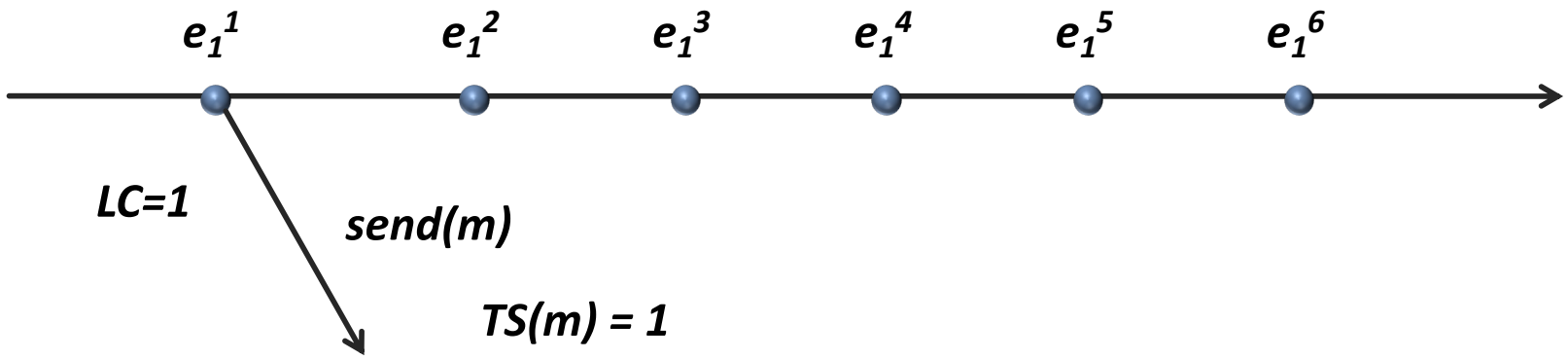
Logical Clocks

- Each process maintains a local value of a logical clock ***LC***
- Logical clock of process *p* counts **how many events in a distributed computation causally preceded the current event at *p*** (including the current event).
- $LC(e_i)$ – the logical clock value at process p_i at event e_i
- Suppose we had a distributed system with only a single process



Logical Clocks (cont.)

- In a system with more than one process logical clocks are updated as follows:
- Each message m that is sent contains a timestamp TS(m)
- TS(m) is the logical clock value associated with sending event at the sending process



Logical Clocks (cont)

- When the receiving process receives message m, it updates its logical clock to:

$$max\{LC, TS(m)\} + 1$$

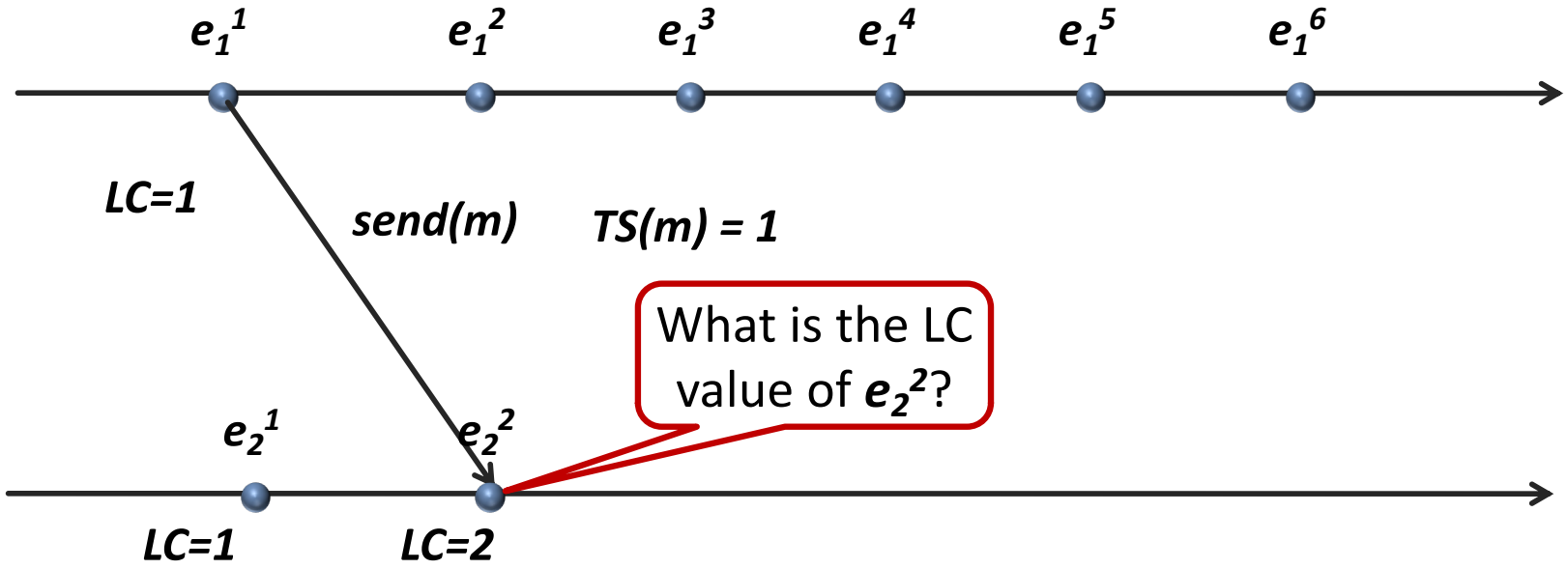
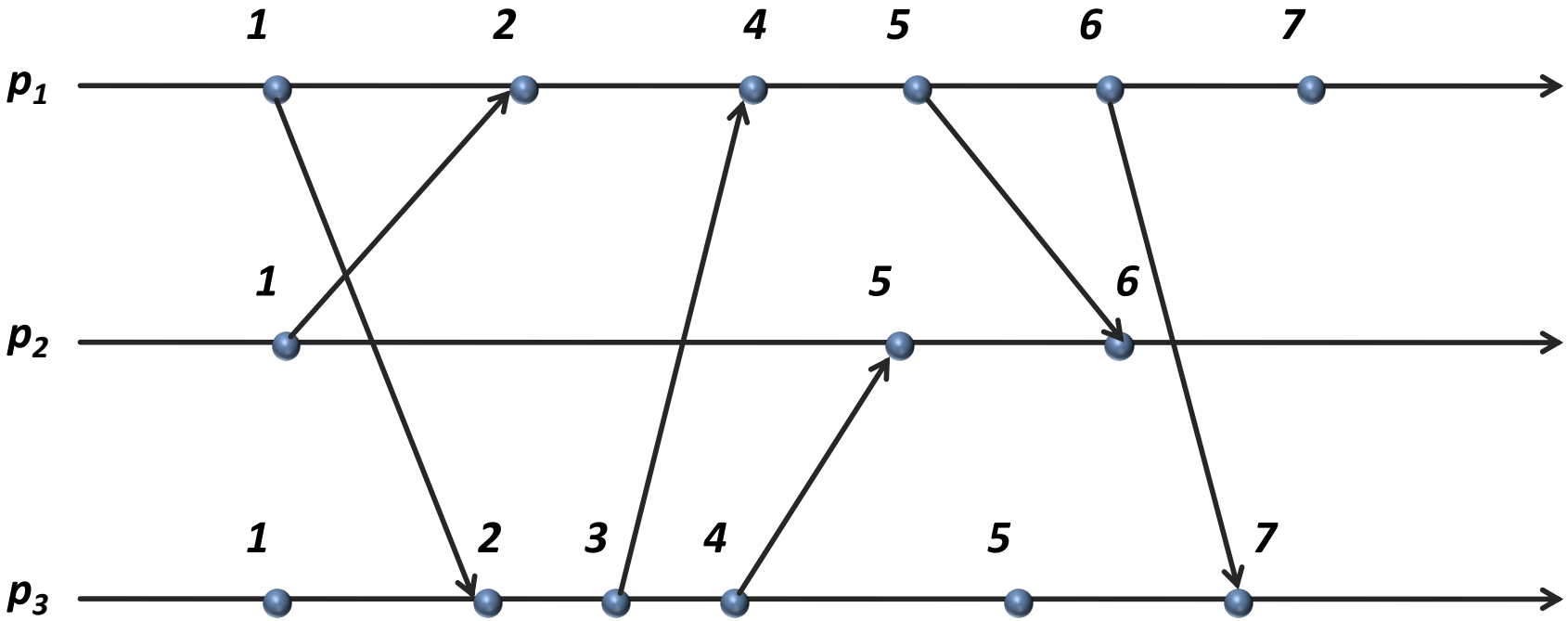


Illustration of a Logical Clock



Questions

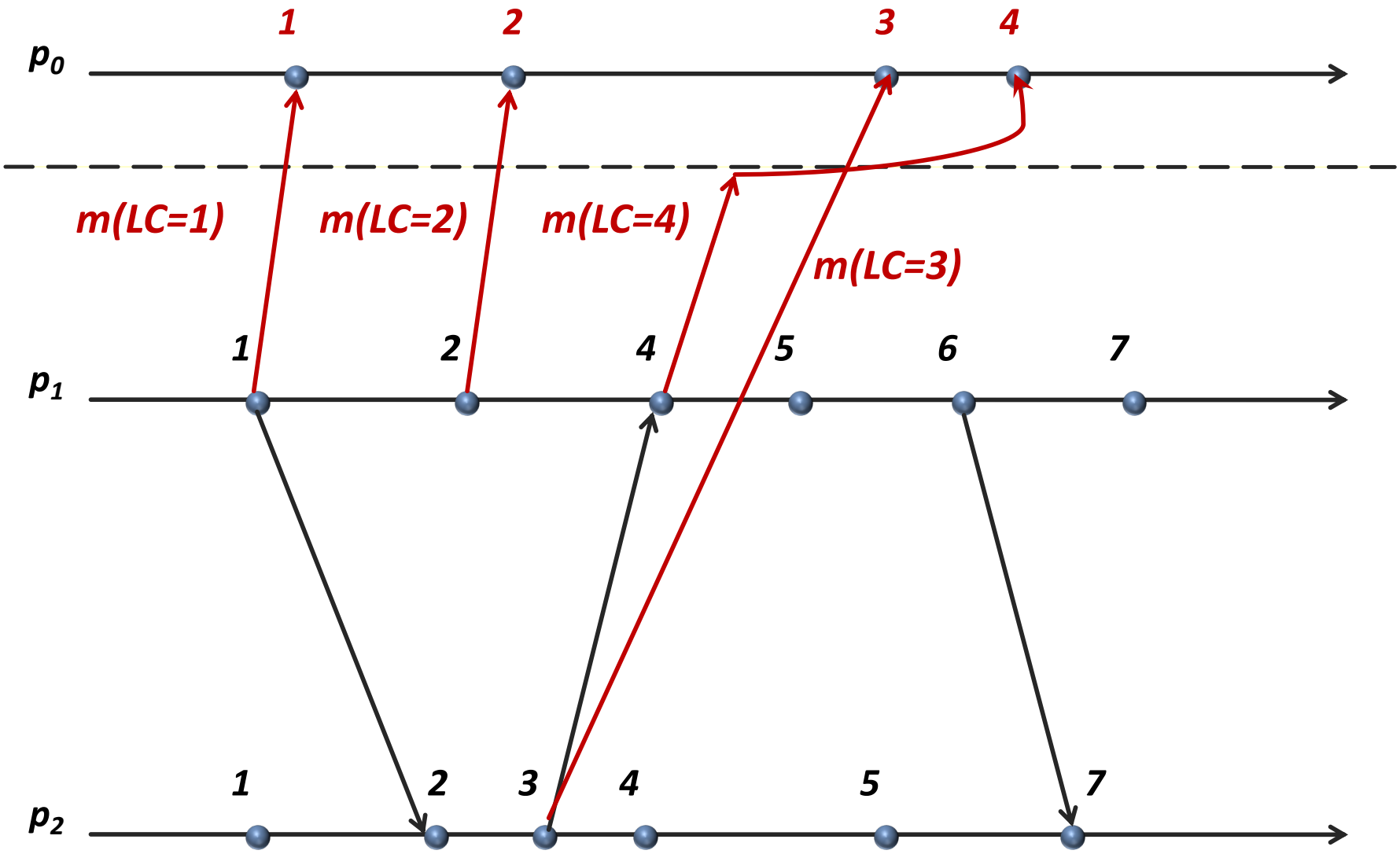
- Logical clock: when a node receives a msg?
  - Max of local and received value, inc. by one
- 2 nodes, by which value can their logical clocks differ the most?
  - Arbitrary large

Causal Delivery with Logical Clocks

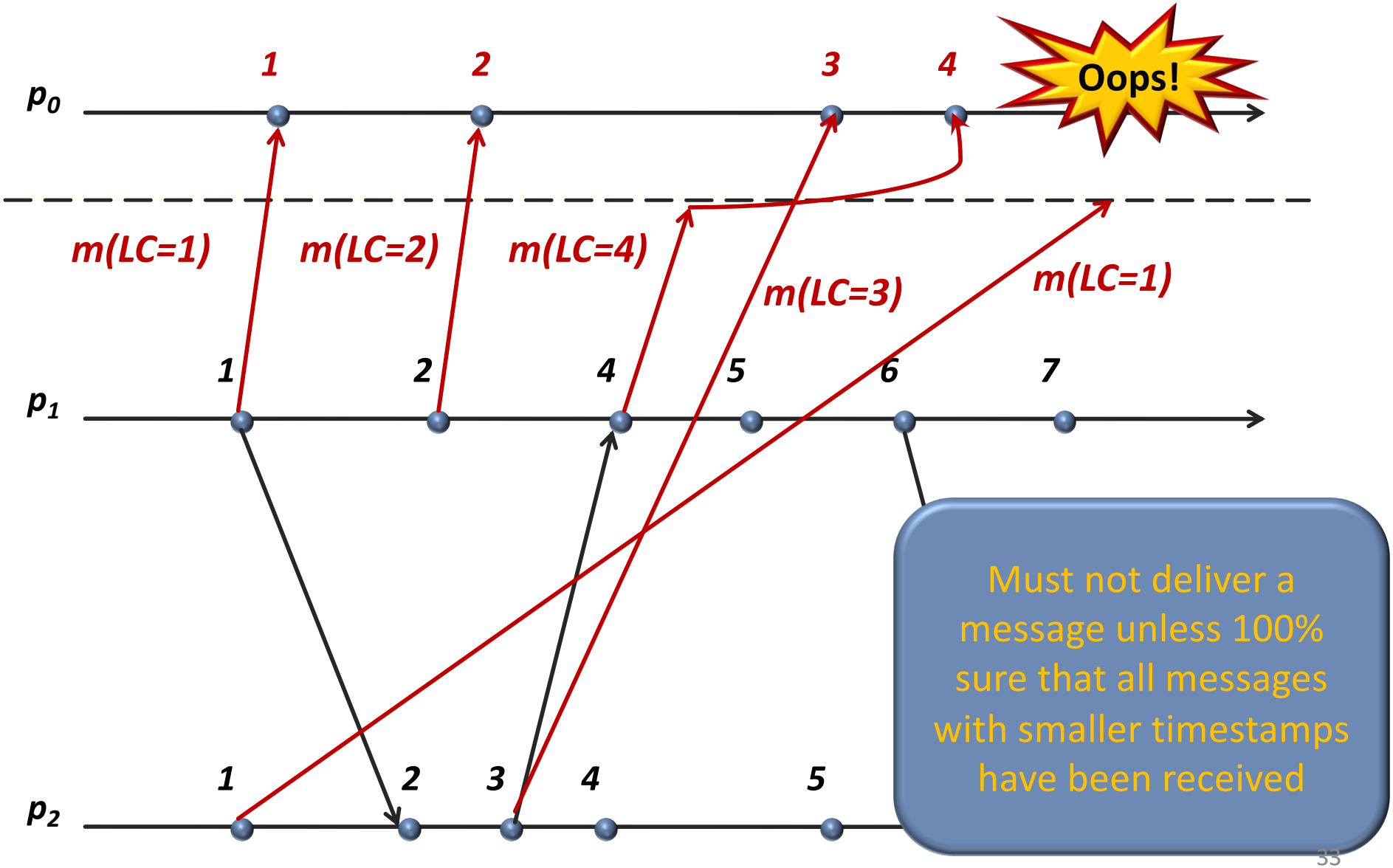
- We have a external monitor process p_0
- Each process p_i sends an ***event notification*** message m to p_0 after each event e_i
- To let p_0 construct a correct causal ordering of events, we define the following delivery rule for event notification messages:

Causal delivery rule: Event notification messages are delivered to p_0 in the increasing logical clock timestamp order

Causal Delivery Rule



Gap Detection Rule



Rules to Achieve Causal Delivery

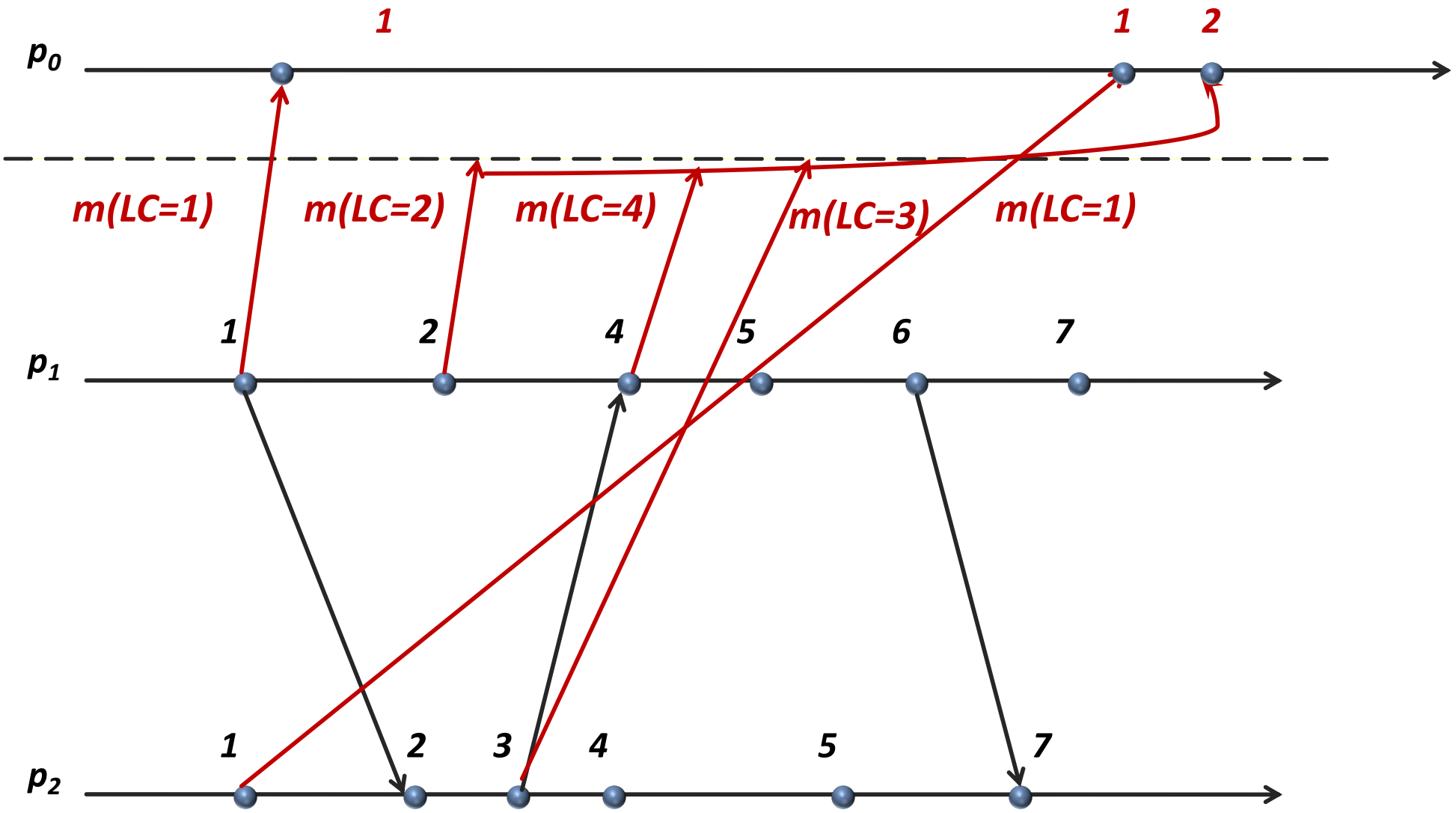
- **Rule #1:**

  Do not deliver event notification message from a process p_i unless all messages with smaller timestamps have been delivered (FIFO delivery)

- **Rule #2:**

  Do not deliver to p_0 event notification message with a timestamp TS(m) unless p_0 received messages with timestamps one smaller, equal or greater than TS(m) from all other processes

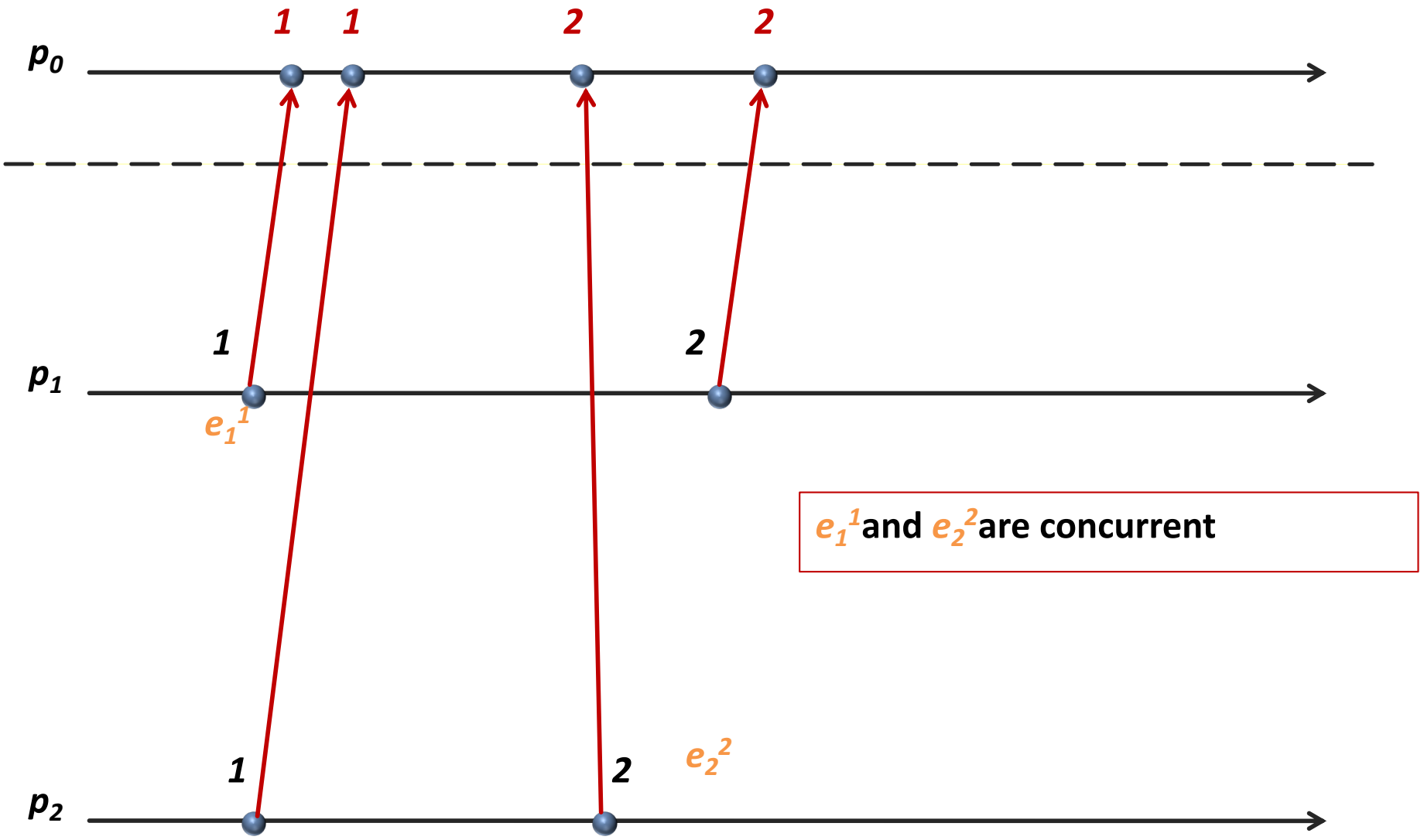
Causal Delivery Rules



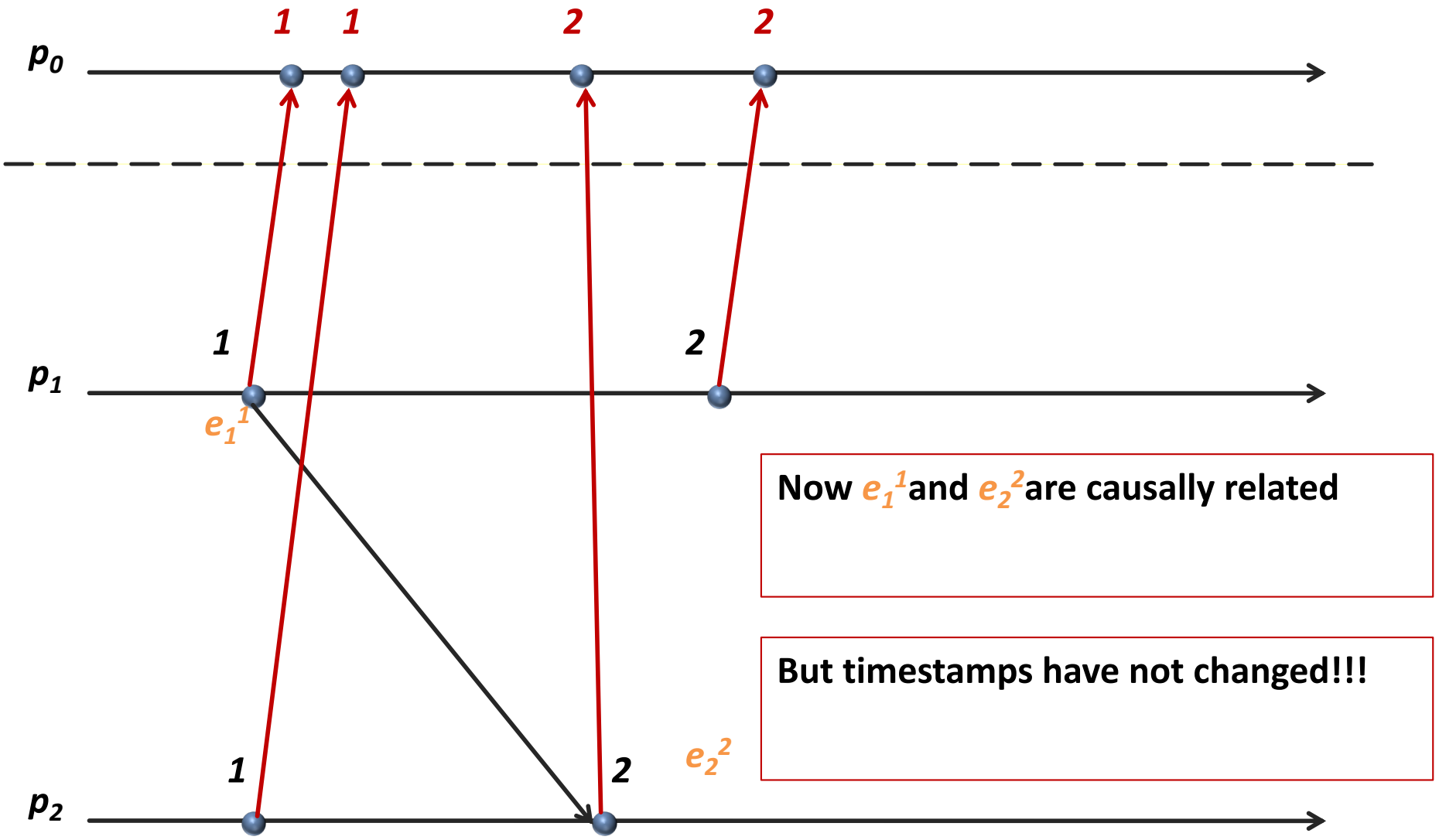
Causal Precedence Relation

- Detecting causal precedence relationship with logical clocks requires sending more than just timestamps!

Causal Precedence or Concurrency?



Causal Precedence or Concurrency?



Causal Precedence Relation

- Using just timestamps from logical clocks does not help us detect whether two events are causally related or concurrent
- We could fix this by including a local history in the event notification message
- Not a good idea: messages will become large
- A better idea: **vector clocks**

Introduction to Vector Clocks

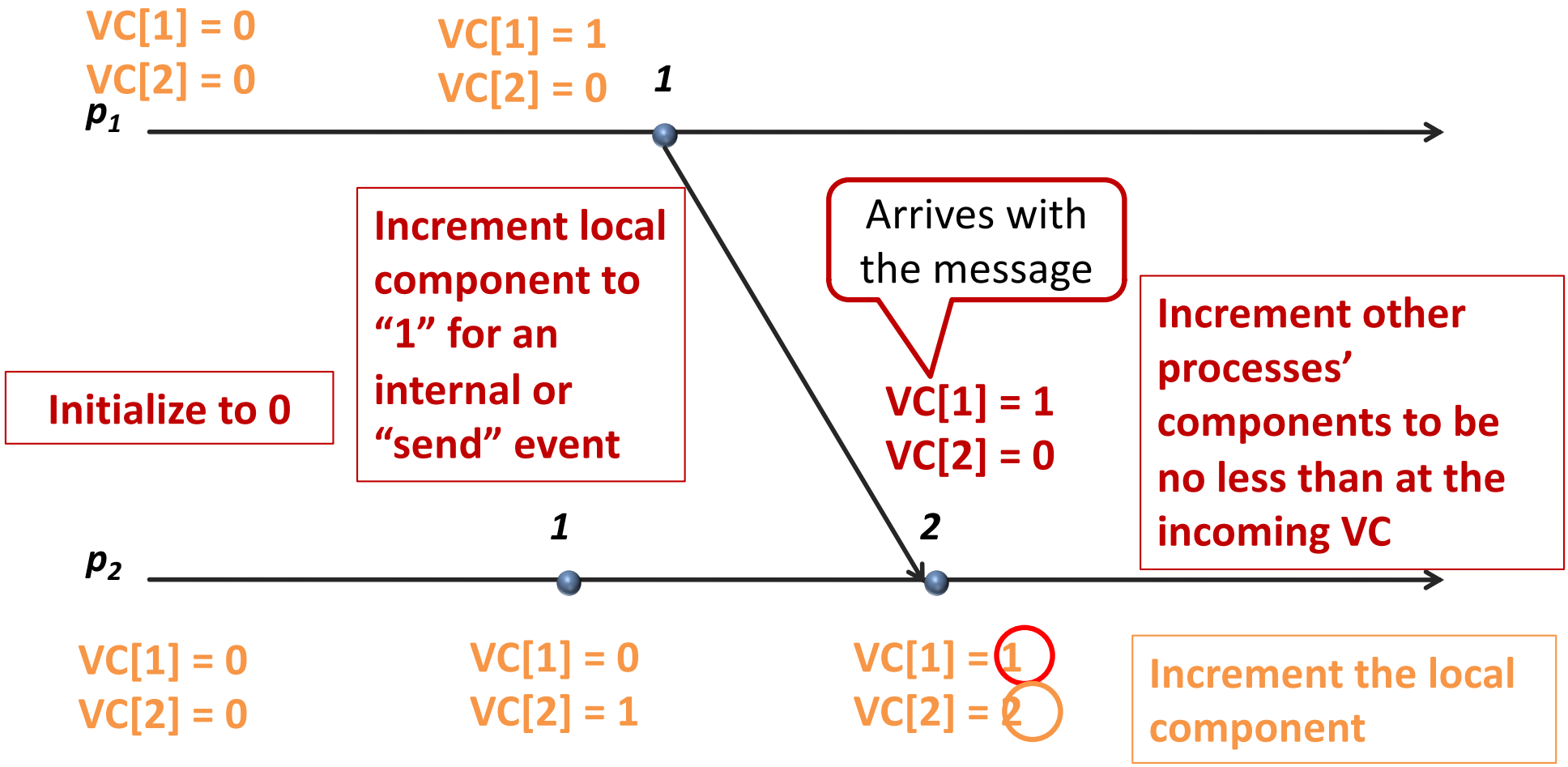
- The clock of each process is represented by a vector
- The vector dimension is the number of processes in the system
- Each entry of a vector clock corresponds to a process
- Suppose there are three processes: p_1, p_2, and p_3
- Then the vector clock at each process will look like this:

  VC[1] – entry for process p_1

  VC[2] – entry for process p_2

  VC[3] – entry for process p_3

Using Vector Clocks



The Meaning of Vector Clocks

- An entry of a vector clock for process p_i is **the number of events at p_i**

  VC[1] = 3 – number of events at p_1

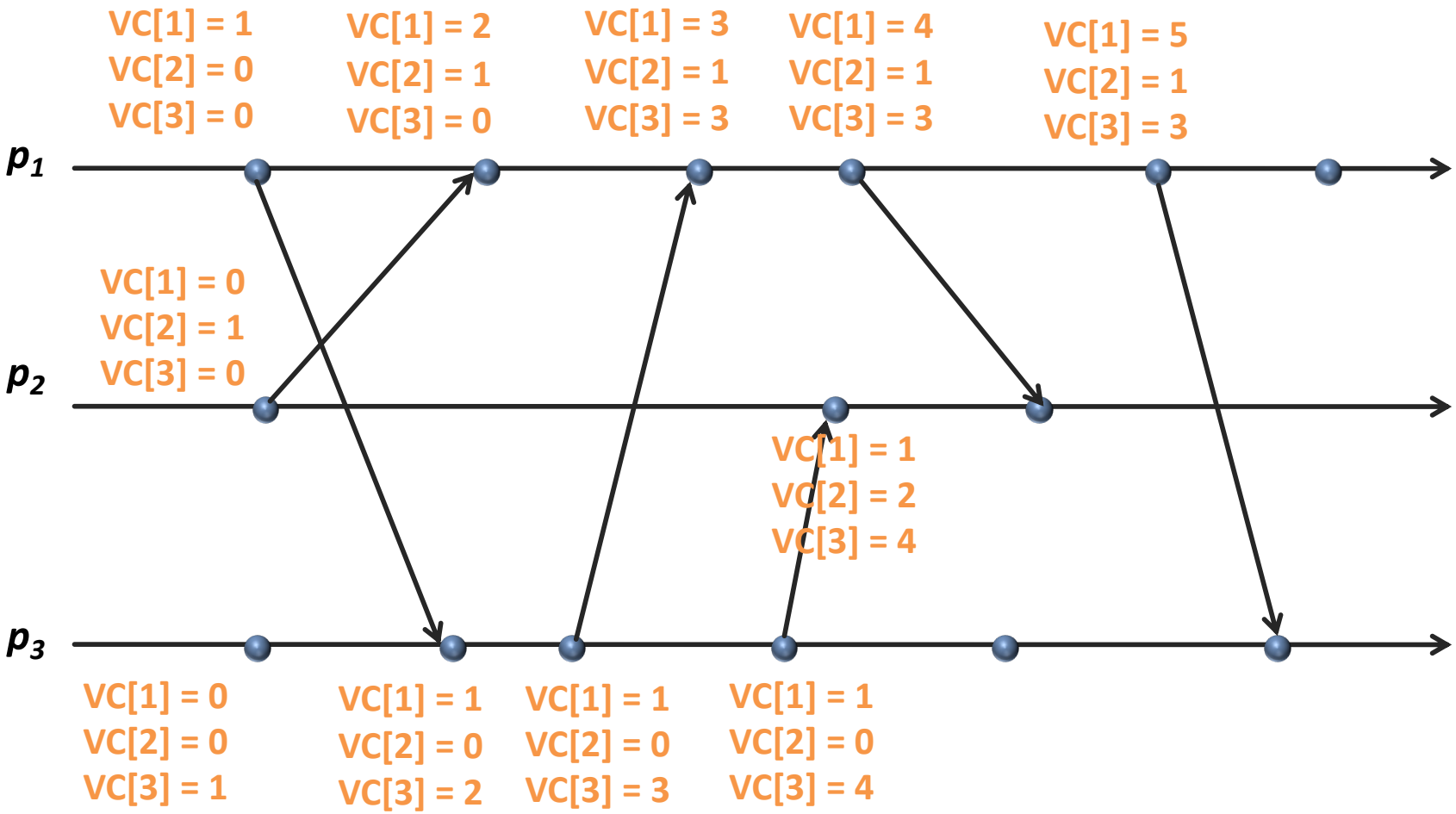
  VC[2] = 0 – number of events at p_2

  VC[3] = 1 – number of events at p_3
- p_1 knows for sure how many events it executed
- But how can it be sure about p_2 and p_3? It can't!
- So p_1**'s** entries for p_2 and p_3 are...
  what p_1 **thinks** about p_2 and p_3

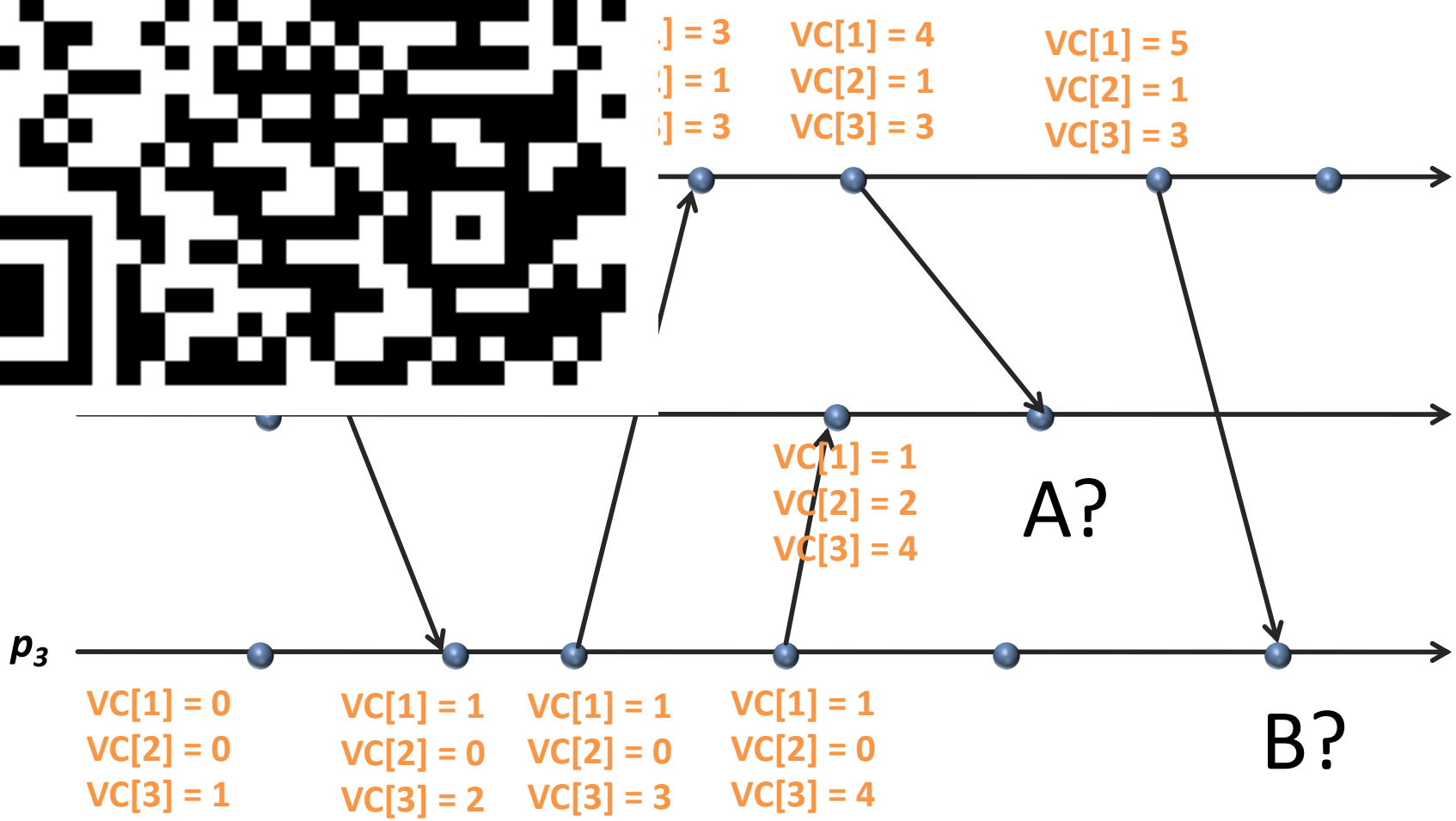
Meaning of Vector Clocks (cont)

- p_1 thinks incorrectly about other processes if p_1 does not communicate with other processes
- Once p_1 exchanges messages with other processes, it updates its information about other processes using vector clock timestamps received from other processes

Another Vector Clock Example



tor Clock Example



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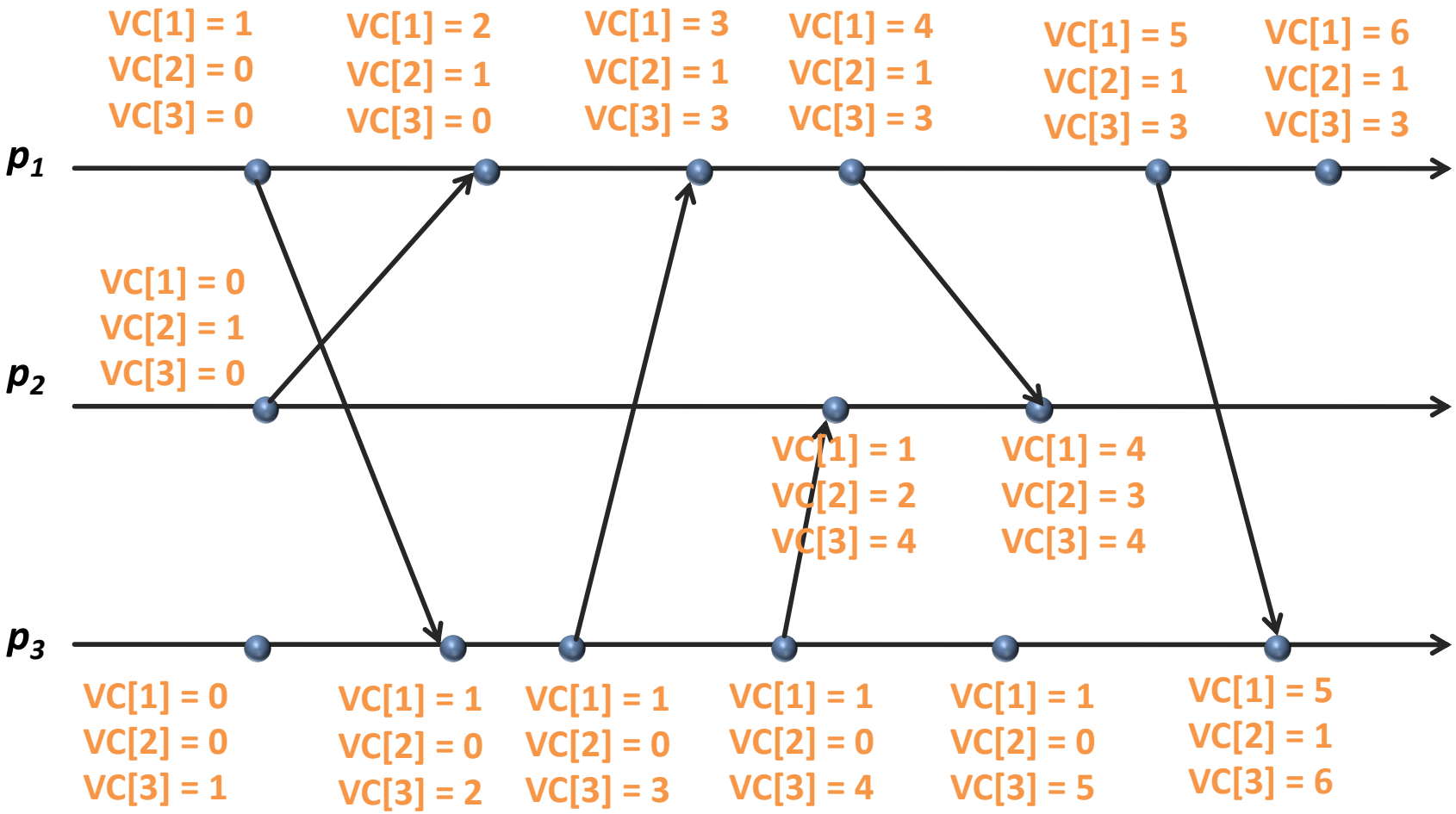
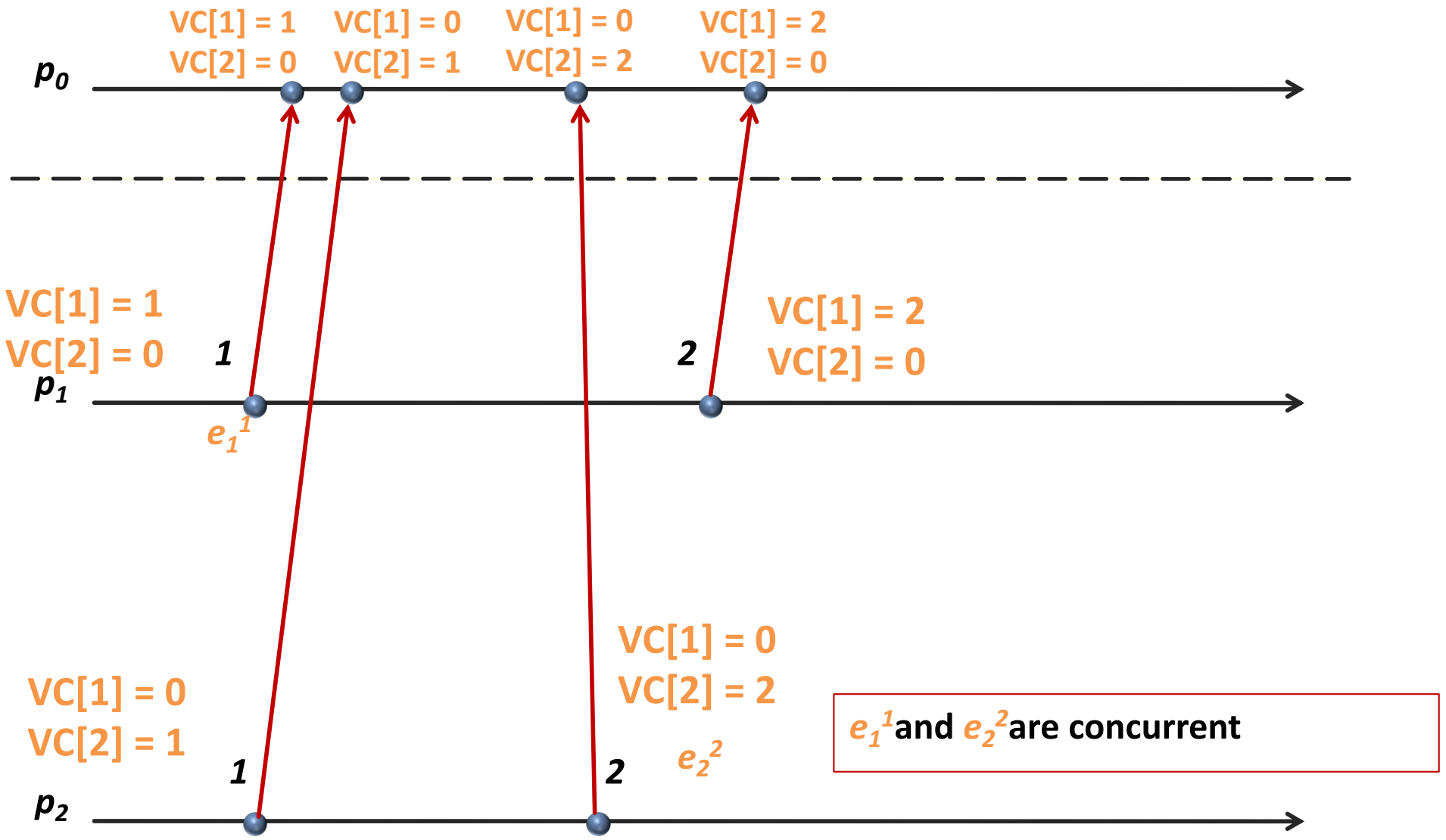
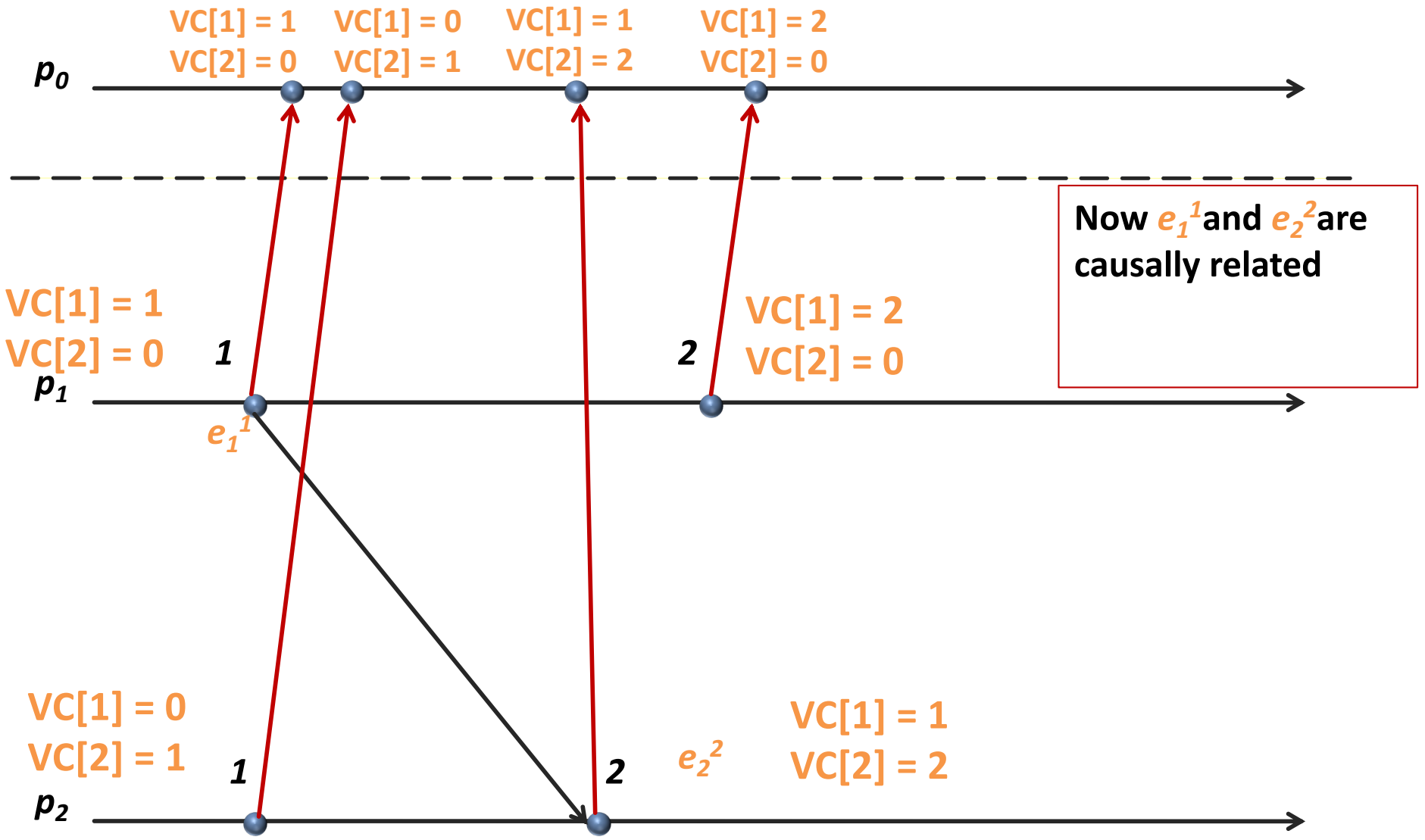
Another Vector Clock Example



Causal Precedence or Concurrency?



Causal Precedence or Concurrency?



Vector Clocks Detect Causal Precedence

- Let us look at timestamps received by observer p_0:
- **In case when events were concurrent:**
  - From p1: VC[1] = 2, VC[2] = 0
  - From p2: VC[1] = 0, VC[2] = 2
- **In case when events were causally related:**
  - From p1: VC[1] = 2, VC[2] = 0
  - From p2: VC[1] = 1, VC[2] = 2

Now the timestamps help detect causal precedence

Use Vector Clocks to Construct Consistent Cuts

- A consistent cut is a cut that does not include ***pairwise inconsistent events***
- So the first step is to understand pairwise inconsistency

Informal Definition of Pairwise Inconsistency

- Look at vector timestamps of two events: e_i at p_i and e_j at p_j
- If at event e_i process p_i thinks that process p_j executed more events than process p_j thinks it has executed at event e_j, the events are pairwise inconsistent

Example:

timestamp at p_3

VC[1] = 5
VC[2] = 1
VC[3] = 6

p_3 thinks that p_1 has executed 5 events

timestamp at p_1

VC[1] = 4
VC[2] = 1
VC[3] = 3

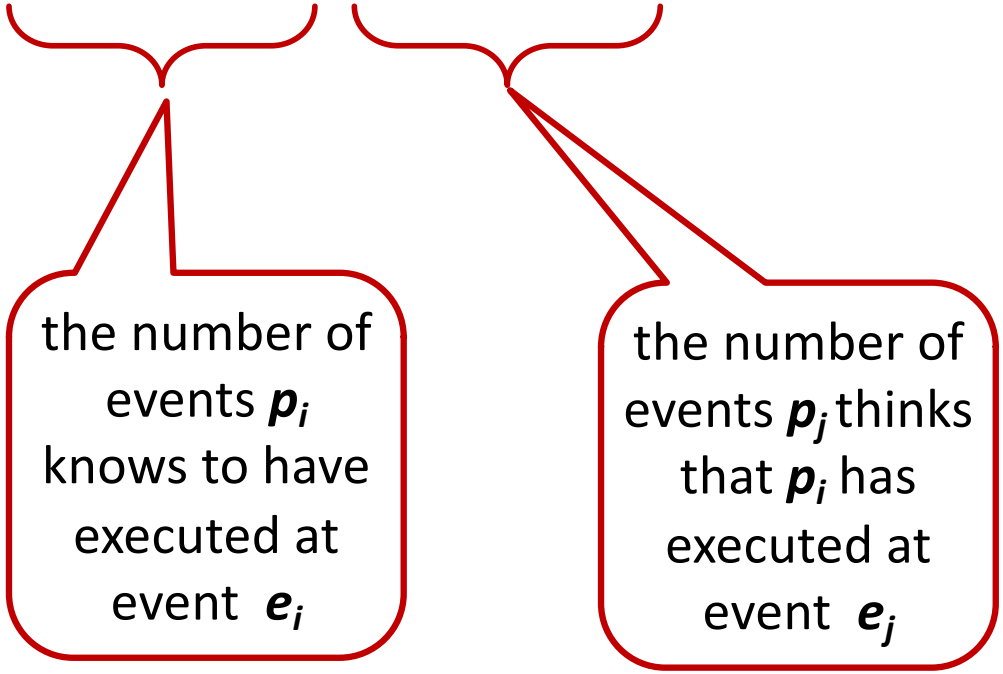
p_1 has executed 4 events!

  - The events are pairwise inconsistent
  - Process p_1 must know better about what it's doing than process p_3 could ever know.

Formal Definition of Pairwise Inconsistency

- Two events e_i and e_j, are pairwise inconsistent if:

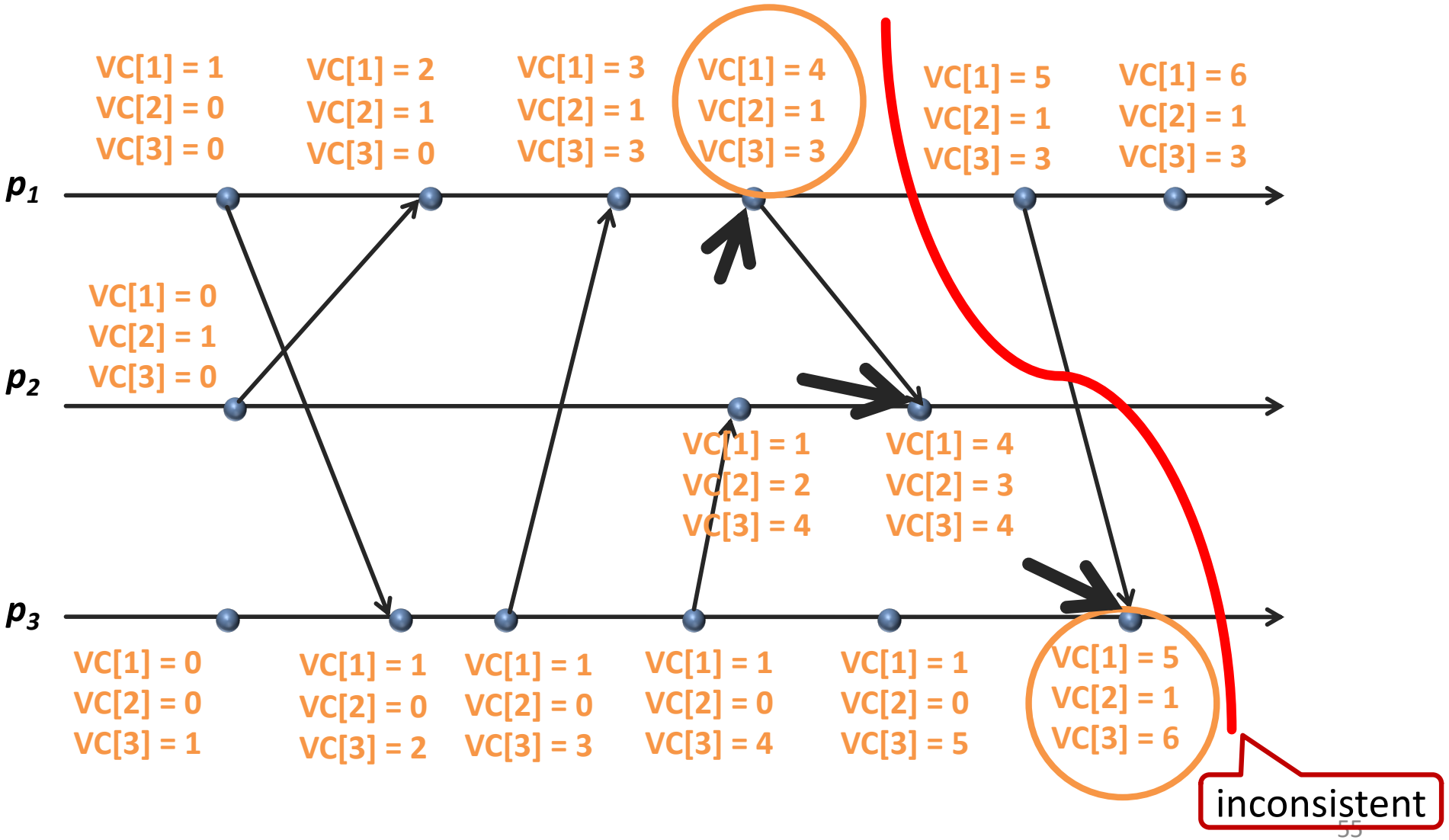
$$(VC(e_i)[i] < VC(e_j)[i]) \wedge (VC(e_j)[j] < VC(e_i)[j])$$



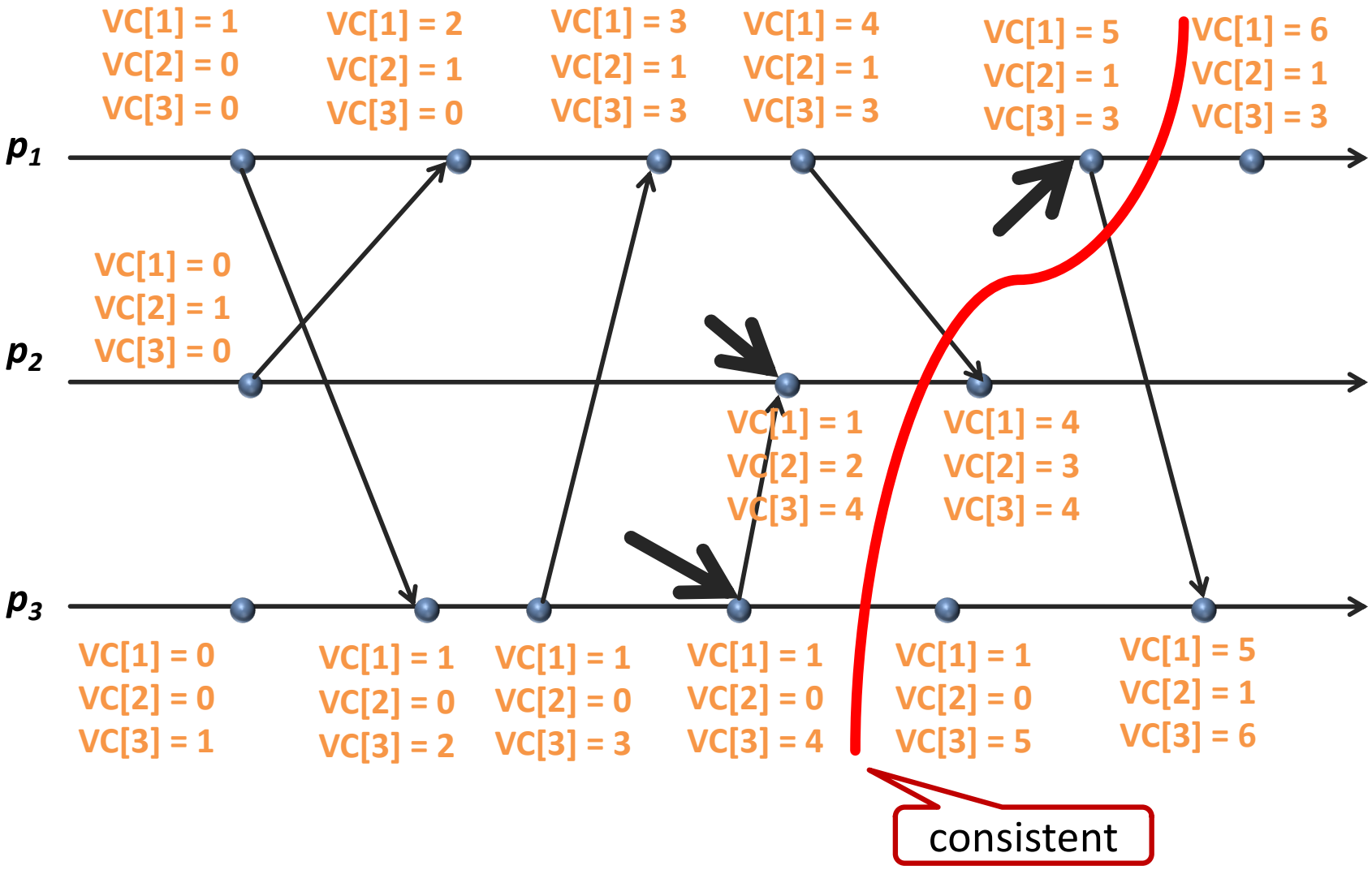
Cut Consistency

- Among all events in the frontier of the cut, check each pair of events for pairwise inconsistency
- If at least two events are pairwise inconsistent, then the cut is inconsistent

Is this Cut Consistent?



And What About This One?



Active Monitoring

- Recall: we used vector clocks so we can construct consistent global states (or cuts) from processes' local histories via passive monitoring
- Remember, there is another type of monitoring – **active monitoring**
  - Active monitoring is also referred to as constructing a ***distributed snapshot***

Distributed Snapshot Protocol (Chandy and Lamport)

- Monitor p_0 sends "take snapshot" message to all processes p_i
- If p_i receives such "take snapshot" message for the first time, it:
  - Records its state
  - Stops doing any activity related to the distributed computation
  - Relays the "take snapshot" message on all of its outgoing channels
  - Starts recording a state of its incoming channels – records all messages that have been delivered after the receipt of the first "take snapshot" message

Distributed Snapshot Protocol (Chandy and Lamport)(cont.)

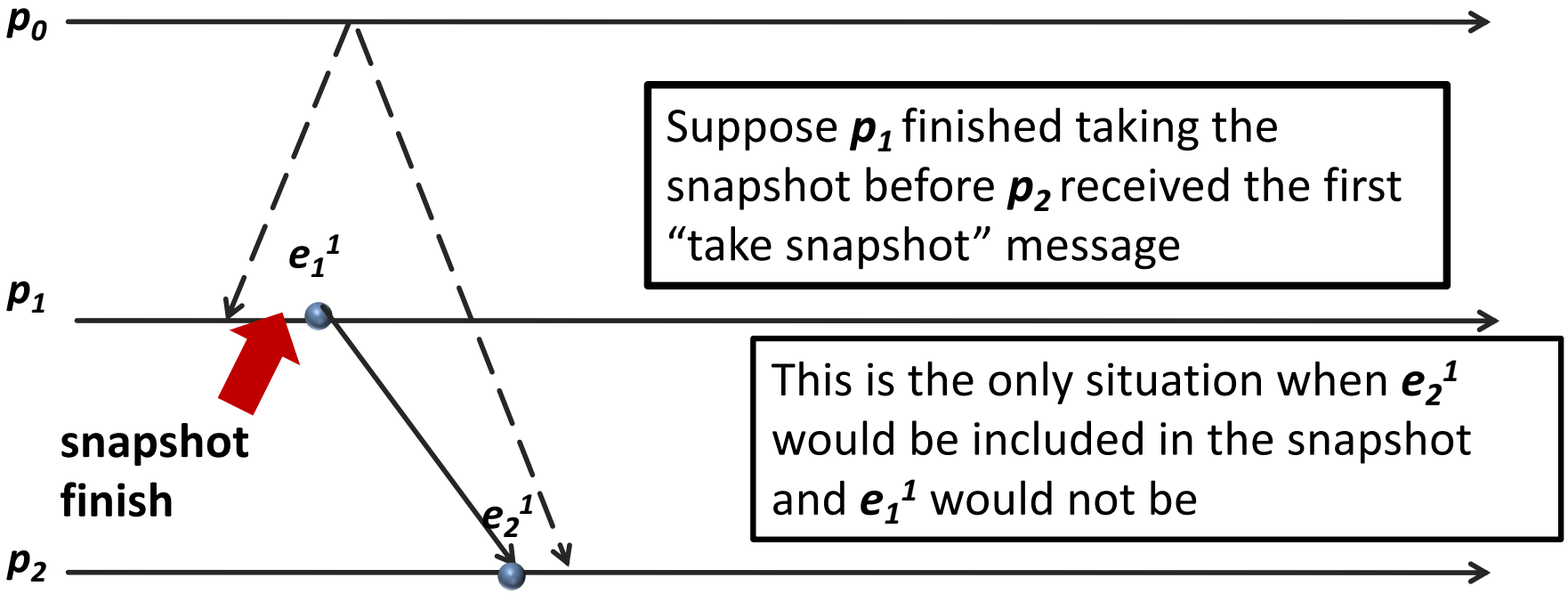
- When p_i receives a "take snapshot" message from process p_j, it stops recording the state of the channel between itself and p_j
- When p_i received "take snapshot" message from all processes and from p_o, it stops recording the snapshot and sends it to p_o

Properties of Chandy-Lamport Protocol

- Let's see why this protocol constructs only consistent snapshots, provided that FIFO channels are used
- Recall the key property of a consistent snapshot (i.e., consistent cut):
  - If event $(e \rightarrow e'')$ and e'' is included in the snapshot, then e must also be included in that snapshot
- Let's see why this property holds if we use the Chandy-Lamport distributed snapshot protocol

Properties of Chandy-Lamport Protocol

Can it happen that e_2^1 is included in the snapshot and e_1^1 is not?



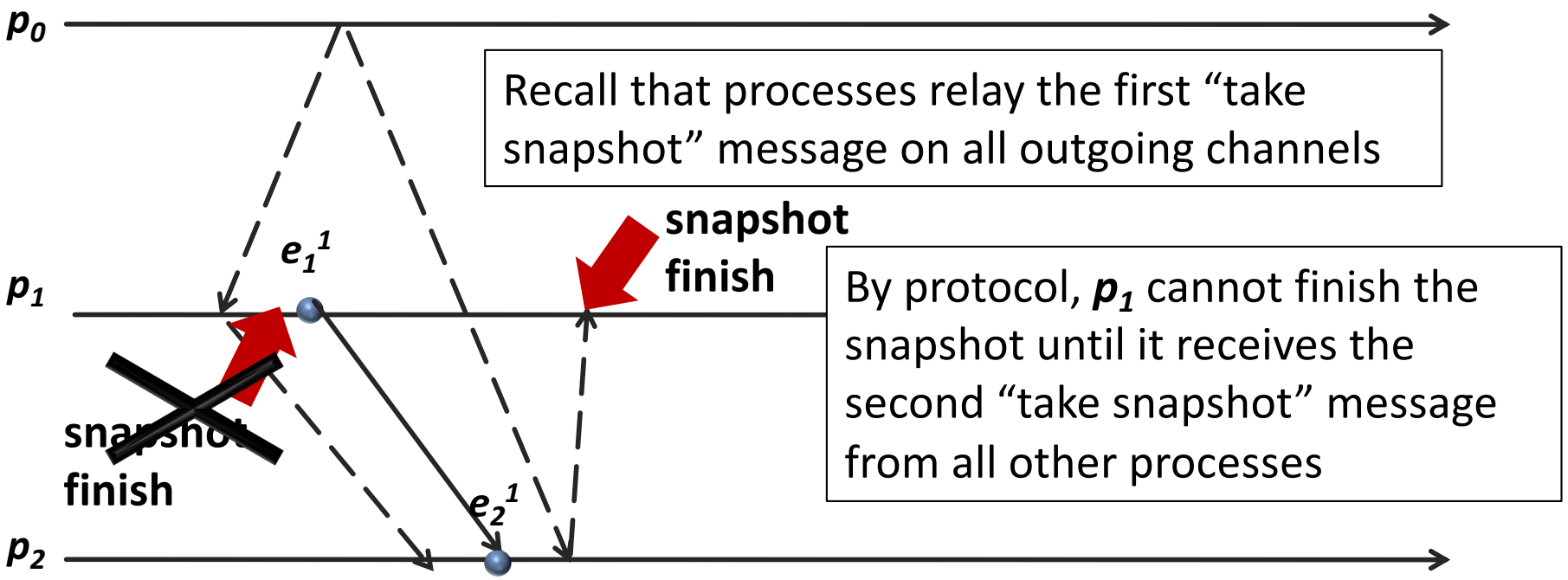
Suppose p_1 finished taking the snapshot before p_2 received the first "take snapshot" message

This is the only situation when e_2^1 would be included in the snapshot and e_1^1 would not be

"take snapshot" message

Let's see why this won't happen

Chandy-Lamport Protocol: Example 1



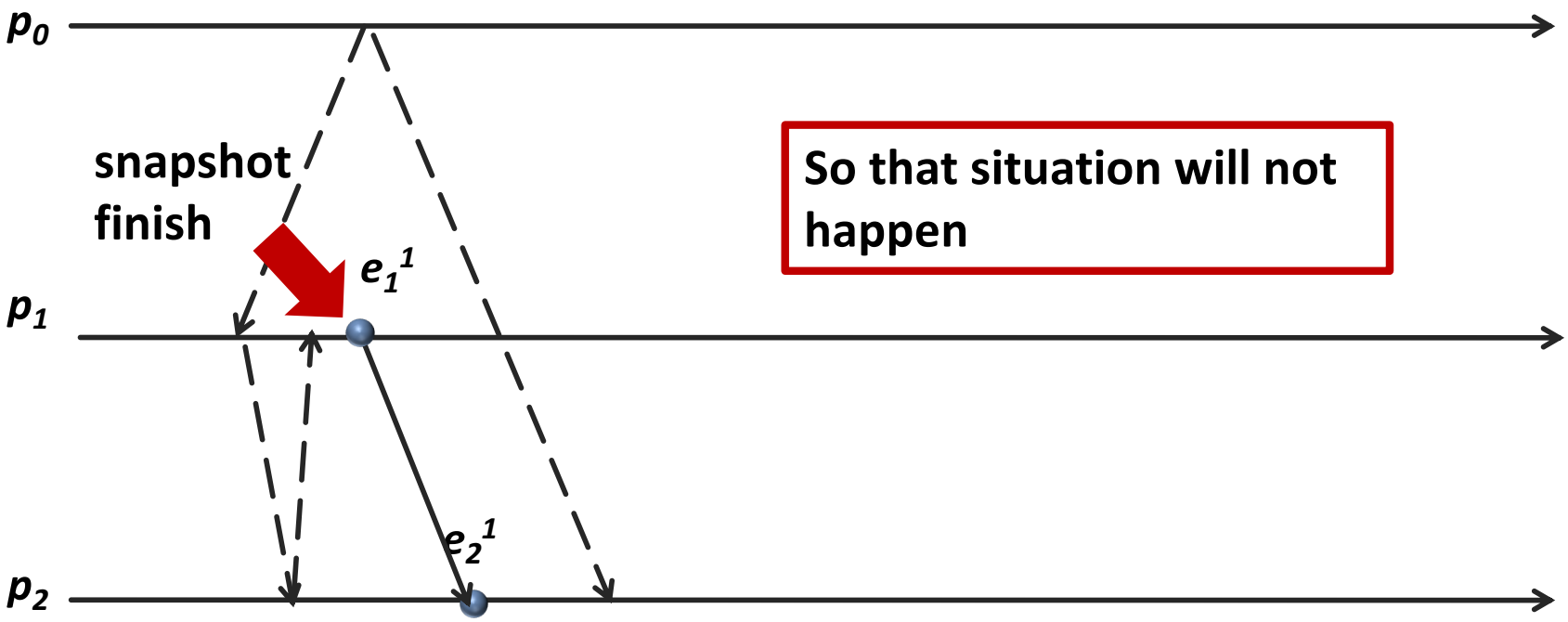
Recall that processes relay the first "take snapshot" message on all outgoing channels

By protocol, p_1 cannot finish the snapshot until it receives the second "take snapshot" message from all other processes

So p_1 cannot send e_1^1 and finish taking the snapshot before p_2 received the first "take snapshot" message.

So that situation will not happen

Chandy-Lamport Protocol: Example 2



So that situation will not happen

But p_2 must **stop recording events** from p_1 after it receives the "take snapshot" message from p_1.

Questions

- Active monitoring vs. passive monitoring?
  - Active monitoring: query the system
- Goal of Chandy and Lamport protocol?
  - Global snapshot

Summary

- Constructing a consistent global state is difficult in absence of global clocks
- Consistent global states can be constructed using
  - Active monitoring (distributed snapshots)
  - Passive monitoring (local event histories with vector clock timestamps)

Questions?

In part, inspired from / based on slides from

– Alexandra Fedorova