Computer Science 425
Distributed Systems

CS 425 / ECE 428

Fall 2013

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September 10, 2013

Lecture 5

Time and Synchronization

Reading: Sections 14.1-14.4

Why synchronization?

- You want to catch the 13N Silver bus at the Illini Union stop at 6.05 pm, but your watch is off by 15 minutes
  - What if your watch is Late by 15 minutes?
  - What if your watch is Fast by 15 minutes?

- Synchronization is required for
  - Correctness
  - Fairness

Why synchronization?

- **Cloud airline reservation system**
- **Server A receives a client request to purchase last ticket on flight ABC 123.**
- **Server A timestamps purchase using local clock 9h:15m:32.45s, and logs it. Replies ok to client.**
- **That was the last seat. Server A sends message to Server B saying "flight full."**
- **B enters "Flight ABC 123 full" + local clock value (which reads 9h:10m:10.11s) into its log.**
- **Server C queries A's and B's logs. Is confused that a client purchased a ticket after the flight became full.**
    - **May execute incorrect or unfair actions.**

Basics – Processes and Events

- **An Asynchronous Distributed System (DS) consists of a number of *processes.***
- **Each process has a state (values of variables).**
- **Each process takes actions to change its state, which may be an instruction or a communication action (send, receive).**
- **An event is the occurrence of an action.**
- **Each process has a local clock – events *within* a process can be assigned timestamps, and thus ordered linearly.**
- **But – in a DS, we also need to know the time order of events *across* different processes.**

☹ **Clocks across processes are not synchronized in an asynchronous DS**

(unlike in a multiprocessor/parallel system, where they are). So…

1. **Process clocks can be different**
2. **Need algorithms for either (a) time synchronization, or (b) for telling which event happened before which**

Physical Clocks & Synchronization

- **In a DS, each process has its own clock.**
- **Clock Skew versus Drift**
  - **Clock Skew = Relative Difference in clock *values* of two processes**
  - **Clock Drift = Relative Difference in clock *frequencies (rates)* of two processes**
- ***A non-zero clock drift causes skew to increase (eventually).***
- **Maximum Drift Rate (MDR) of a clock**
- **Absolute MDR is defined relative to Coordinated Universal Time (UTC). UTC is the "correct" time at any point of time.**
  - **MDR of a process depends on the environment.**
- **Max drift rate between two clocks with similar MDR is 2 * MDR**

  Max-Synch-Interval =

  (MaxAcceptableSkew—CurrentSkew) / (MDR * 2)

  (i.e., time = distance/speed)

Synchronizing Physical Clocks

- $C_i(t)$: **the reading of the software clock at process *i* when the real time is *t*.**
- **External synchronization: For a synchronization bound *D>0*, and for source S of UTC time,**

  $$|S(t) - C_i(t)| < D,$$

  for *i=1,2,...,N* and for all real times *t*.

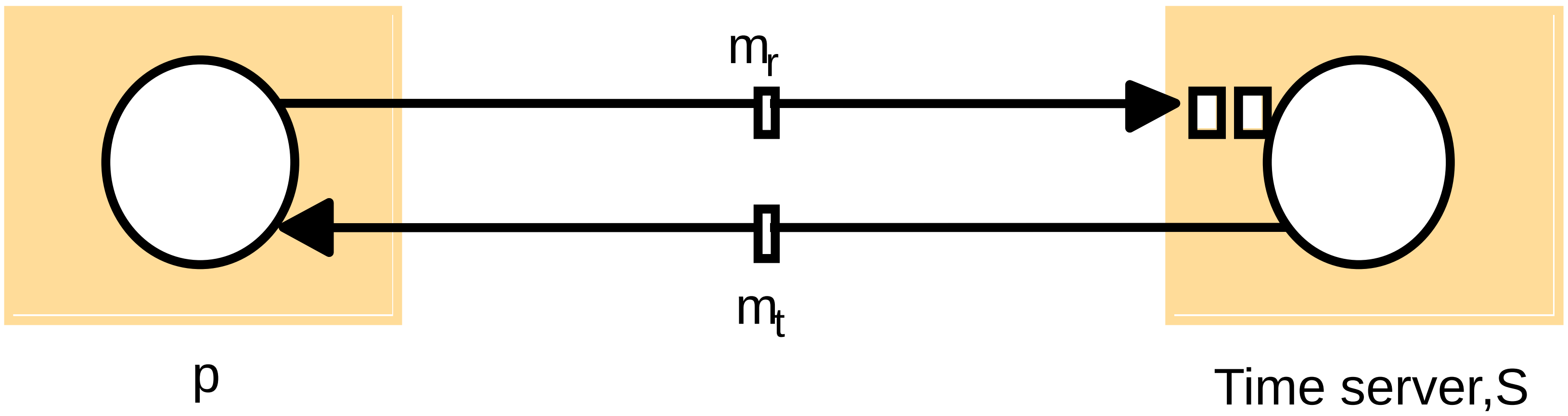
  Clocks C_i are externally accurate to within the bound *D*.
- **Internal synchronization: For a synchronization bound *D>0*,**

  $$|C_i(t) - C_j(t)| < D$$

  for *i, j=1,2,...,N* and for all real times *t*.

  Clocks C_i are internally accurate within the bound *D*.
- **External synchronization with *D* ⇒ Internal synchronization with *2D***
- **Internal synchronization with D ⇒ External synchronization with ??**

Clock Synchronization Using a Time Server



Cristian's Algorithm

- **Uses a *time server* to synchronize clocks**
- **Time server keeps the reference time (say UTC)**
- **A client asks the time server for time, the server responds with its current time *T*, and the client uses this received value to set its clock**
- **But network round-trip time introduces an error…**

Let *RTT = response-received-time – request-sent-time* (measurable at client)

Also, suppose we know: (1) the minimum value *min* of the client-server one-way transmission time [Depends on what?]

(2) and that the server timestamped the message at the *last* possible instant before sending it back

Then, the actual time could be between [T+min,T+RTT— min]

What are the two extremes?

Cristian's Algorithm (2)

- Client sets its clock to halfway between T+min and T+RTT— min i.e., at T+RTT/2
  - Expected (i.e., average) skew in client clock time will be = half of this interval = (RTT/2 – *min*)
- Can increase clock value, but should *never* decrease it – Why?
- Can adjust speed of clock too (take multiple readings) – either up or down is ok.
- For unusually long RTTs, repeat the time request
- For non-uniform RTTs, use *weighted average*

$$\text{avg-clock-error}_n = (w * \text{latest-clock-error}) + (1 - w) * \text{avg-clock-error}_{n-1}$$

Typically w=0.5

Berkeley Algorithm

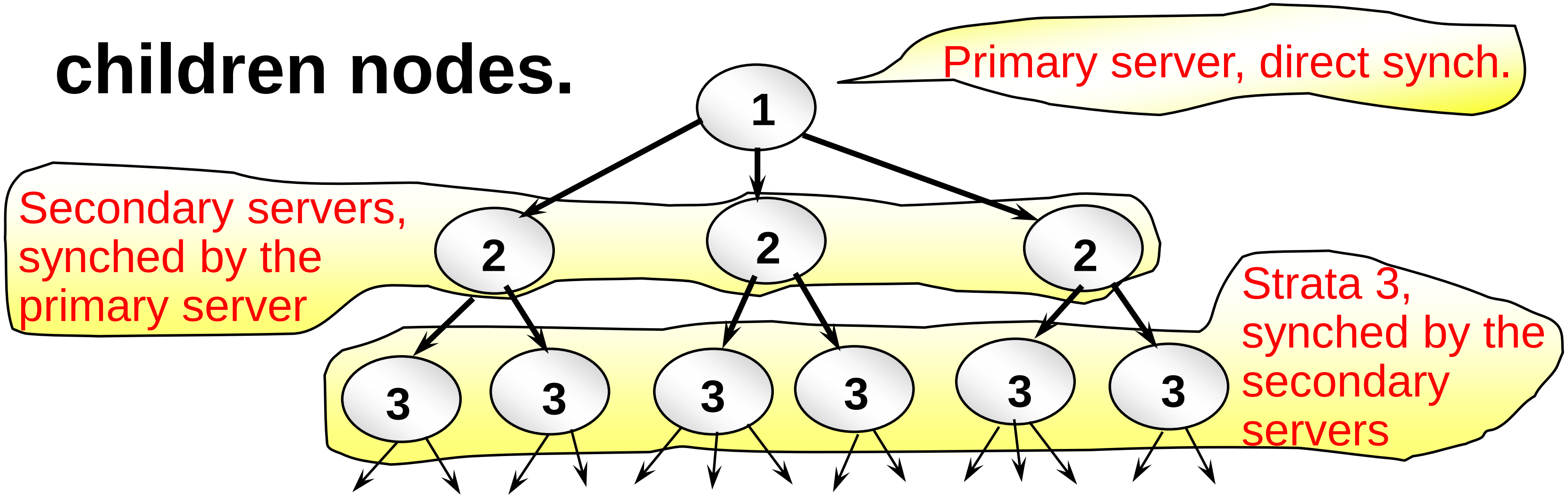
- Uses an *elected master process* to synchronize among clients, without the presence of a time server
- The *elected master* broadcasts to all machines requesting for their time, adjusts times received for RTT & latency, averages times, and tells each machine how to adjust.
- Multiple leaders may also be used.

☹ Averaging client′s clocks may cause the entire system to drift away from UTC over time (Internal Synchronization)

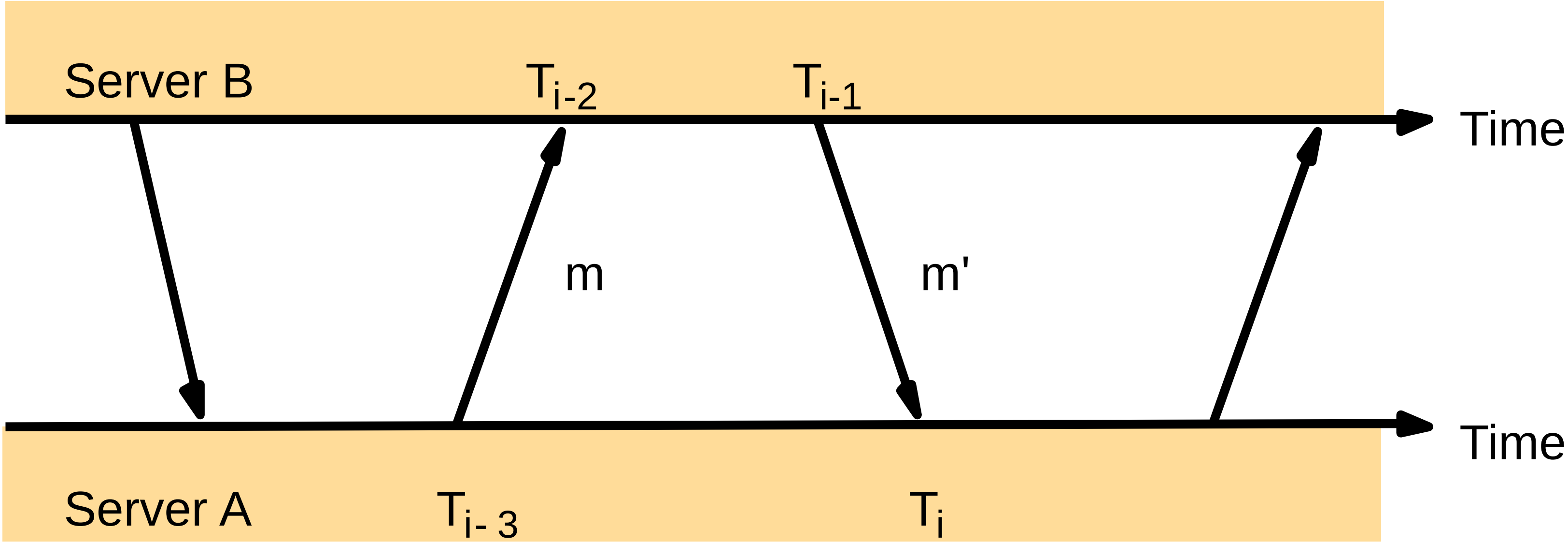
☹ Failure of the master requires some time for re-election, so drift/skew bounds cannot be guaranteed

The Network Time Protocol (NTP)

- **Uses a network of time servers to synchronize all processes on a network.**
- **Time servers are connected by a synchronization subnet tree. The root is in touch with UTC. Each node synchronizes its children nodes.**

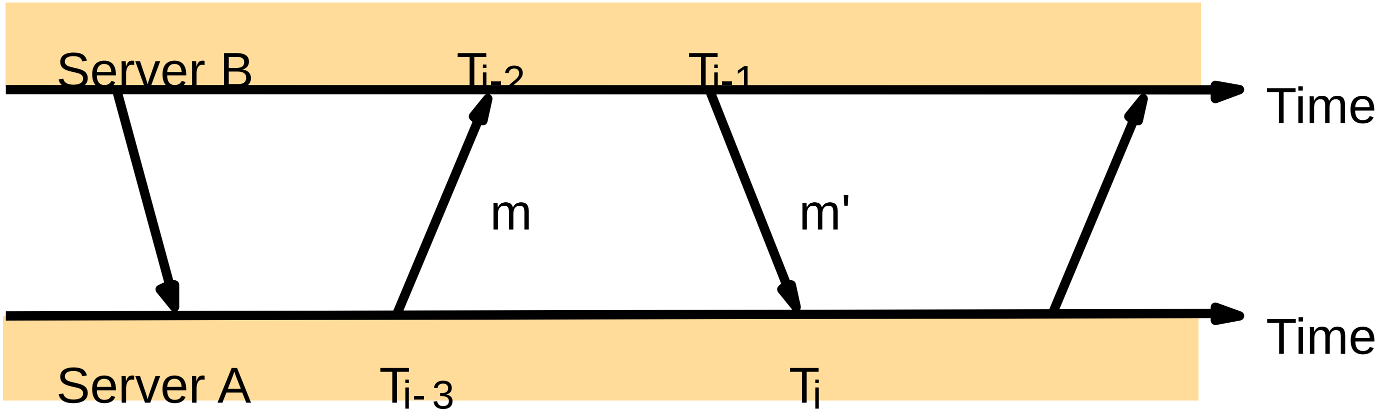


Messages Exchanged Between a Pair of NTP Peers (“Connected Servers”)



Each message bears timestamps of recent message events: the local time when the previous NTP message was sent and received, and the local time when the current message was transmitted.

Theoretical Base for NTP



- *t* and *t′:* actual transmission times for *m* and *m′(unknown)*
- *o*: true offset of clock at *B* relative to clock at *A*
- o_i: estimate of actual offset between the two clocks
- d_i: estimate of accuracy of o_i ; total transmission times for *m* and *m′*; $d_i=t+t'$

$$T_{i-2} = T_{i-3} + t + o$$

$$T_i = T_{i-1} + t' - o$$

This leads to

$$d_i = t + t' = T_{i-2} - T_{i-3} + T_i - T_{i-1}$$

$$o = o_i + (t' - t)/2, \quad \text{where}$$

$$o_i = (T_{i-2} - T_{i-3} + T_{i-1} - T_i)/2.$$

It can then be shown that

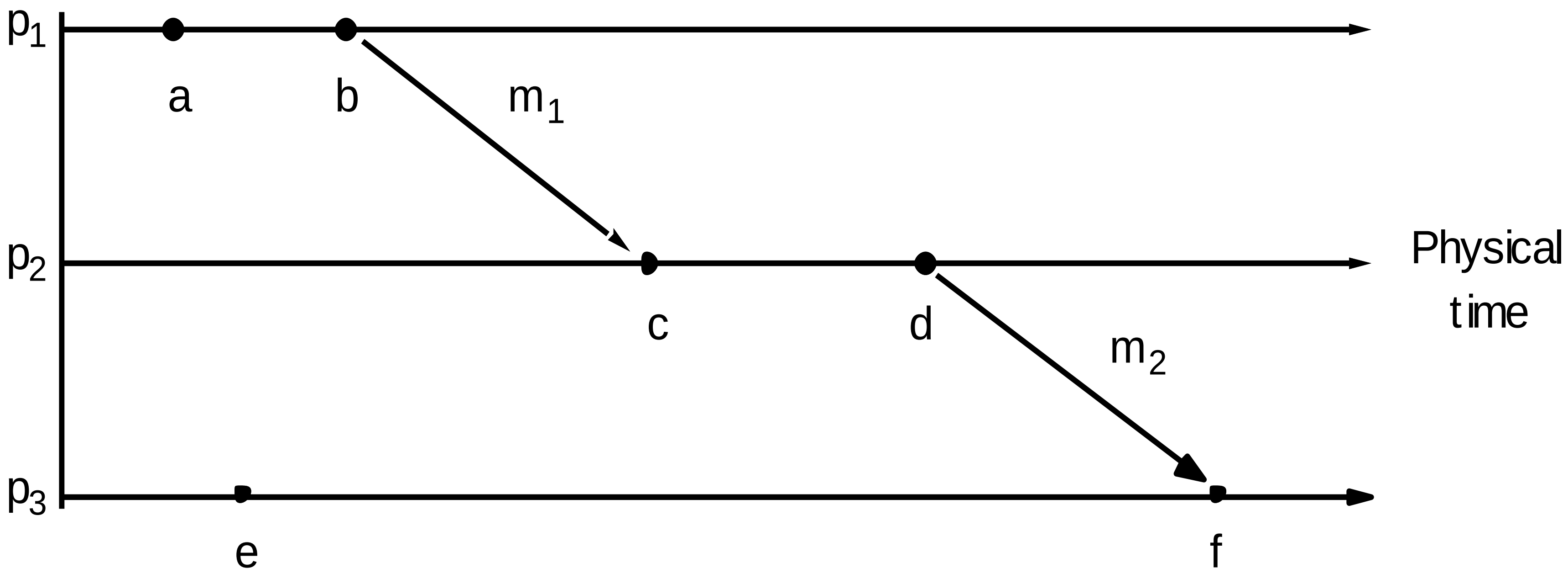
$$o_i - d_i/2 \le o \le o_i + d_i/2.$$

Logical Clocks

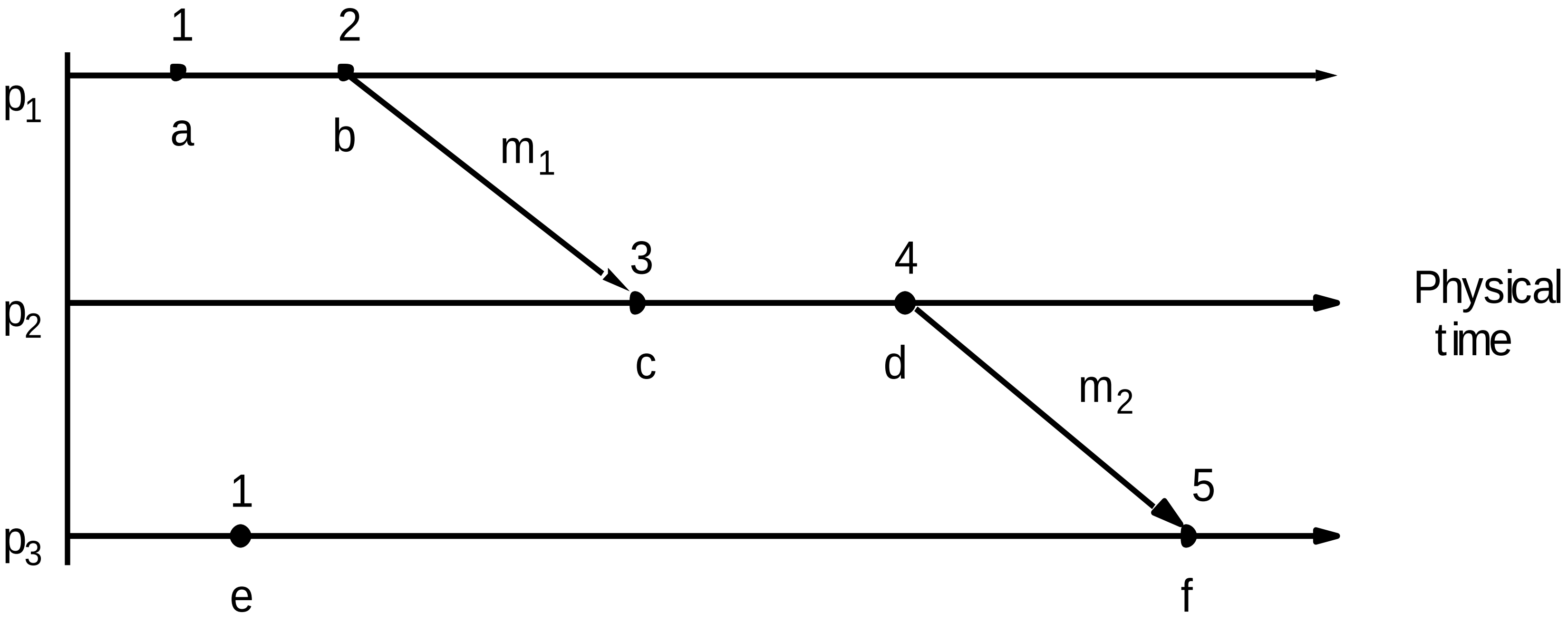
- **Is it always necessary to give *absolute* time to events?**
- **Suppose we can assign *relative* time to events, in a way that does not violate their causality**
  - **Well, that would work – we humans run our lives without looking at our watches for everything we do**
- **First proposed by Leslie *Lamport* in the 70′s**
- **Define a logical relation *Happens-Before* (→) among events:**
  1. **On the same process: $a \rightarrow b$, if $time(a) < time(b)$**
  2. **If p1 sends *m* to p2: $send(m) \rightarrow receive(m)$**
  3. **(Transitivity) If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$**
- **Lamport Algorithm assigns logical timestamps to events:**
  - ☐ **All processes use a counter (clock) with initial value of zero**
  - ☐ **A process increments its counter when a send or an instruction happens at it. The counter is assigned to the event as its timestamp.**
  - ☐ **A send (message) event carries its timestamp**
  - ☐ **For a receive (message) event the counter is updated by**

    max(local clock, message timestamp) + 1

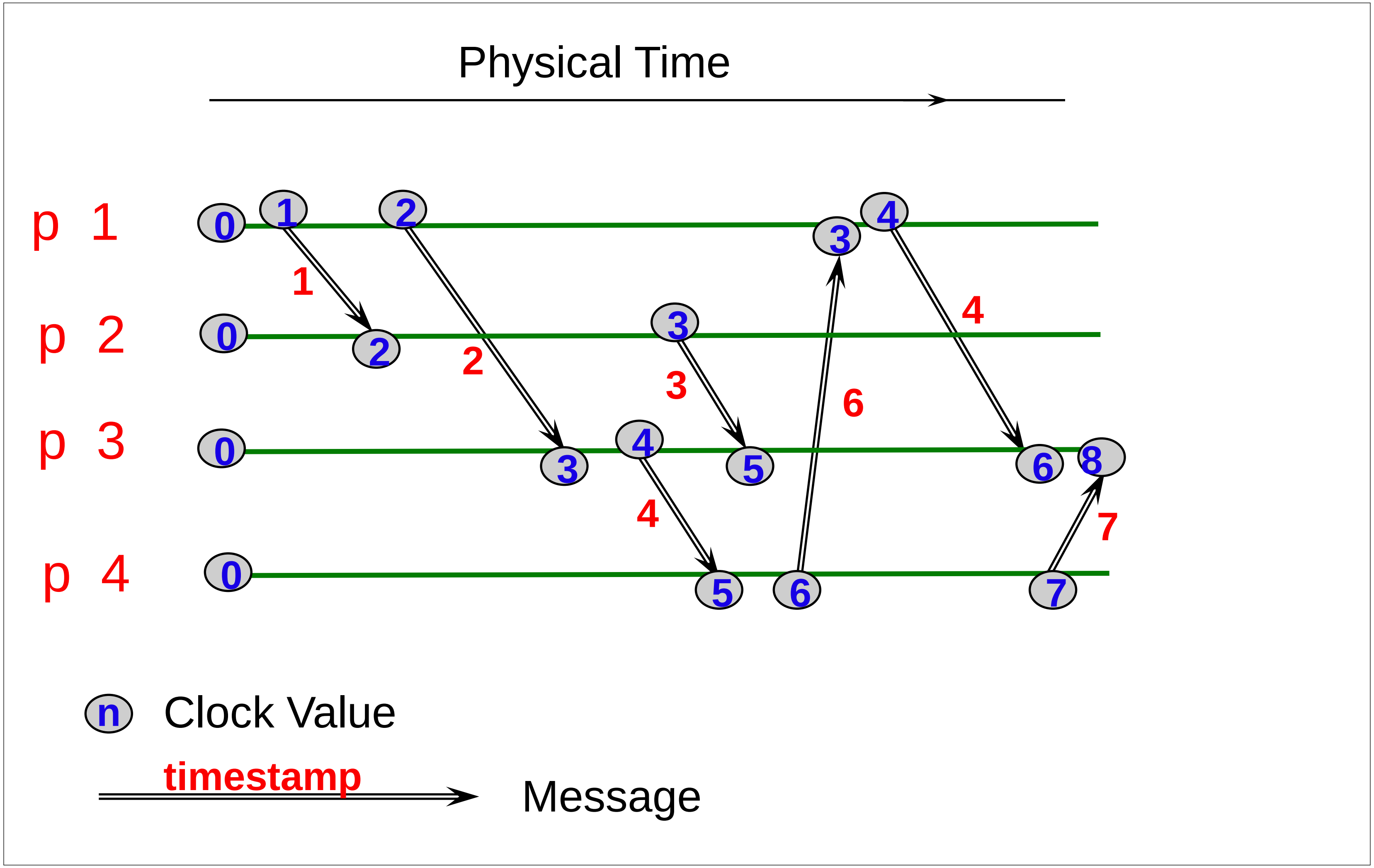
Events Occurring at Three Processes



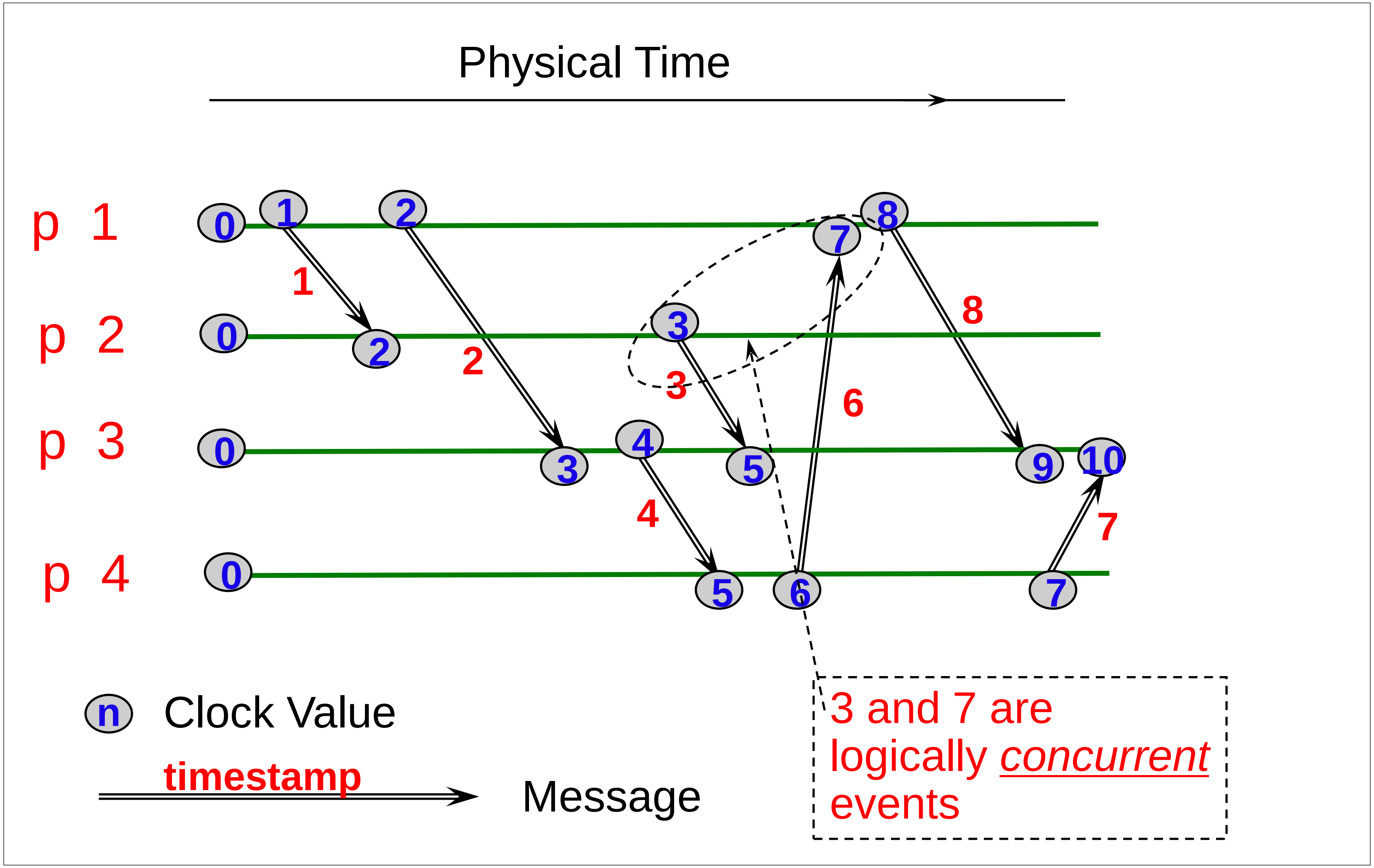
Lamport Timestamps



Find the Mistake: Lamport Logical Time



Corrected Example: Lamport Logical Time



3 and 7 are logically *concurrent* events

Vector Logical Clocks

- **With Lamport Logical Timestamp**

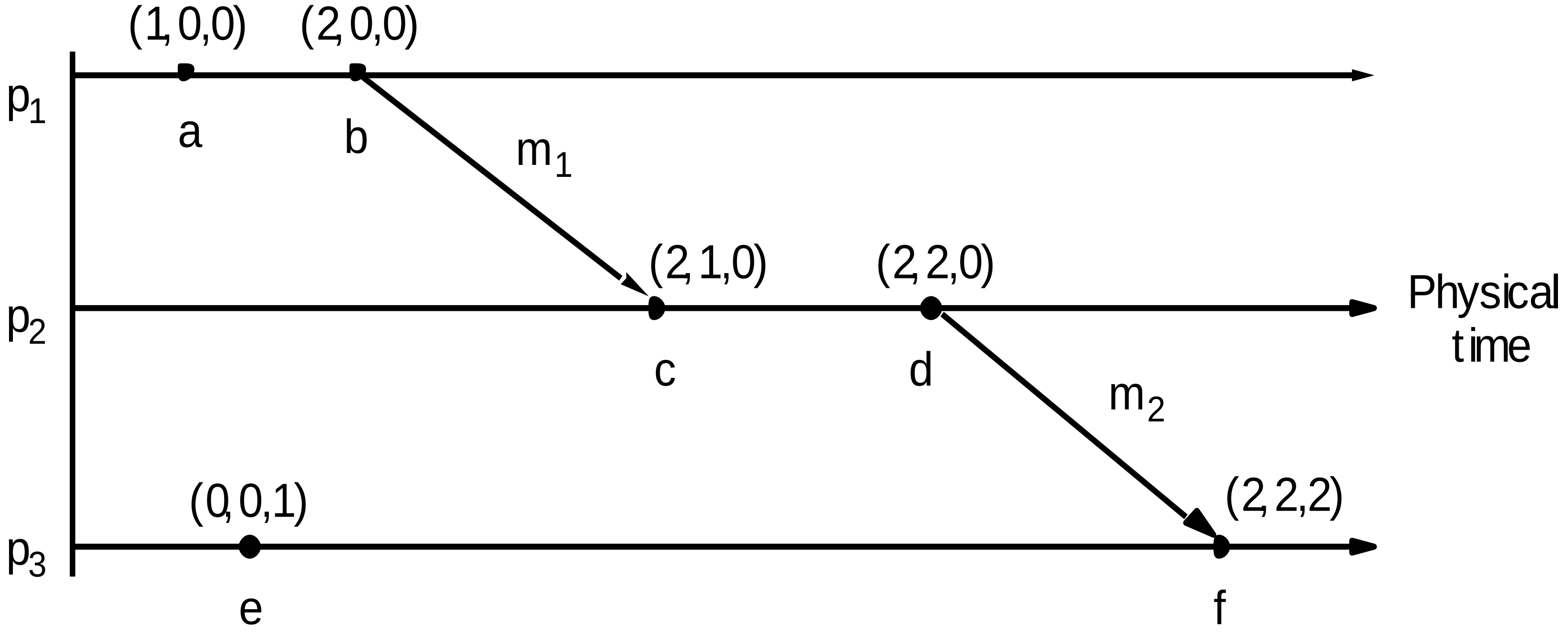
  $e \rightarrow f \Rightarrow$ timestamp(e) < timestamp (f), but

  timestamp(e) < timestamp (f) $\Rightarrow$ {$e \rightarrow f$} OR {e and f concurrent}

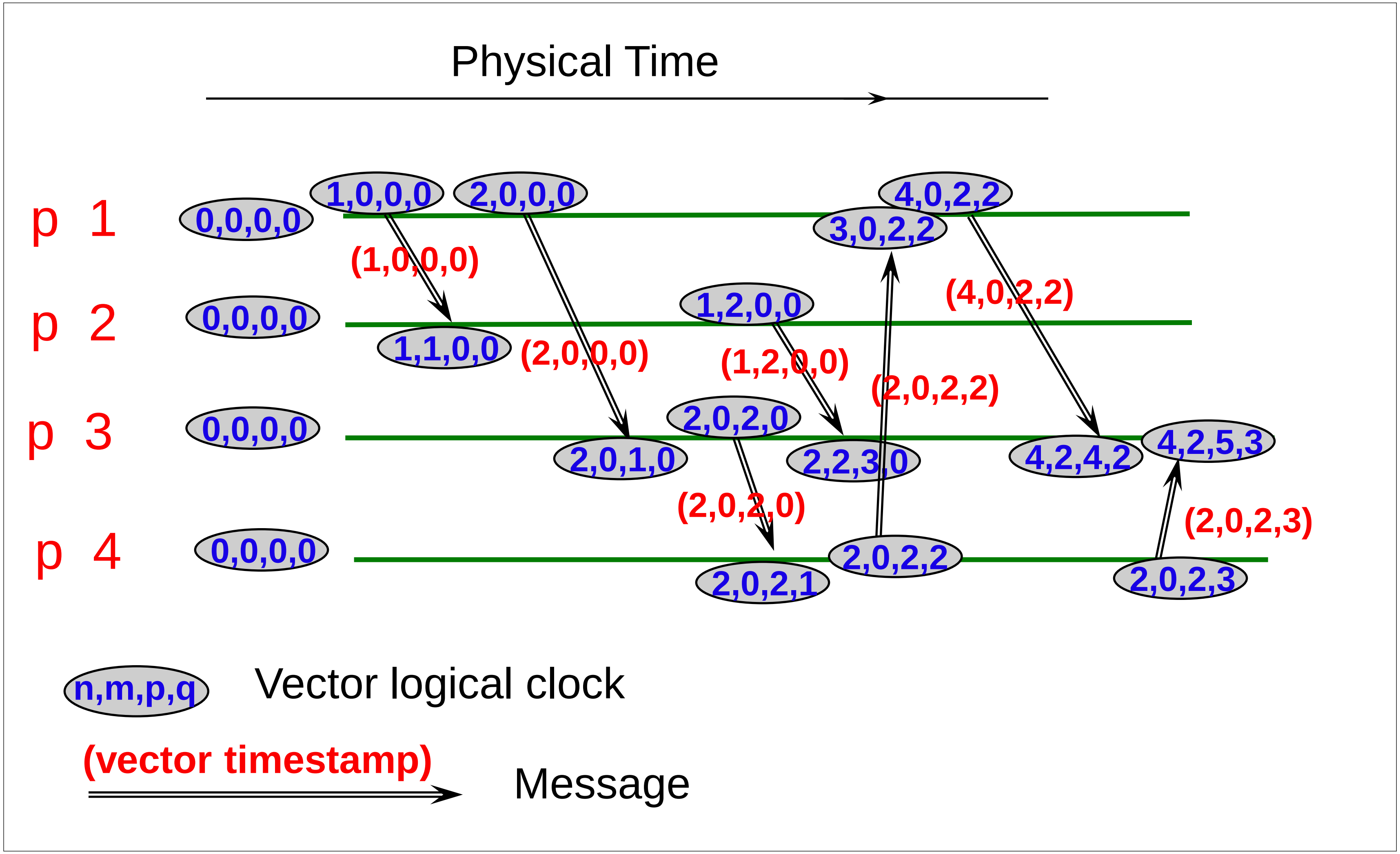
- **Vector Logical time addresses this issue:**
  - ☐ **N processes. Each uses a vector of counters (logical clocks), initially all zero. i^th element is the clock value for process i.**
  - ☐ **Each process i increments the i^th element of its vector upon an instruction or send event. Vector value is timestamp of the event.**
  - ☐ **A send(message) event carries its vector timestamp (counter vector)**
  - ☐ **For a receive(message) event,**

$$V_{receiver}[j] = \begin{cases} \mathrm{Max}(V_{receiver}[j]\,,\, V_{message}[j]), & \text{if } j \text{ is not self} \\ V_{receiver}[j] + 1 & \text{otherwise} \end{cases}$$

Vector Timestamps



Example: Vector Timestamps



Comparing Vector Timestamps

- $VT_1 = VT_2$,

  iff $VT_1[i] = VT_2[i]$, for all $i = 1, \ldots, n$
- $VT_1 \leqslant VT_2$,

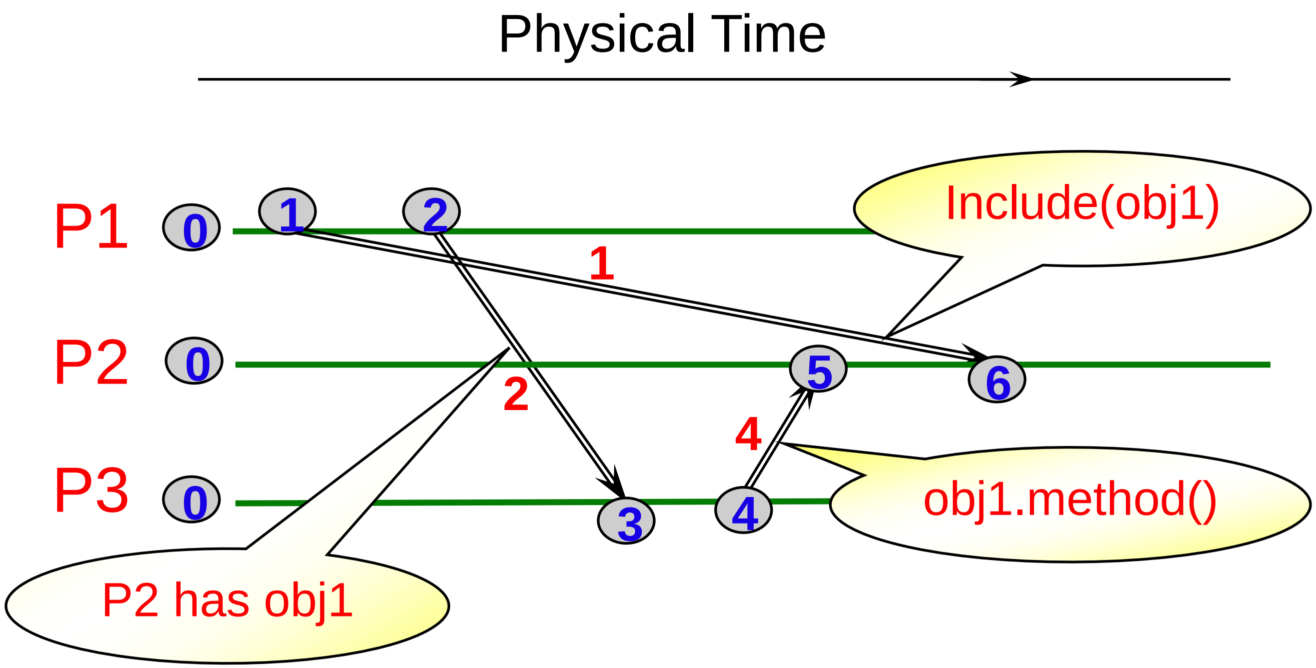
  iff $VT_1[i] \leqslant VT_2[i]$, for all $i = 1, \ldots, n$
- $VT_1 < VT_2$,

  iff $VT_1 \leqslant VT_2$ &

  $\exists j \; (1 \leqslant j \leqslant n \;\&\; VT_1[j] < VT_2[j])$
- **Then:** VT_1 is concurrent with VT_2

  iff (not $VT_1 \leqslant VT_2$ AND not $VT_2 \leqslant VT_1$)

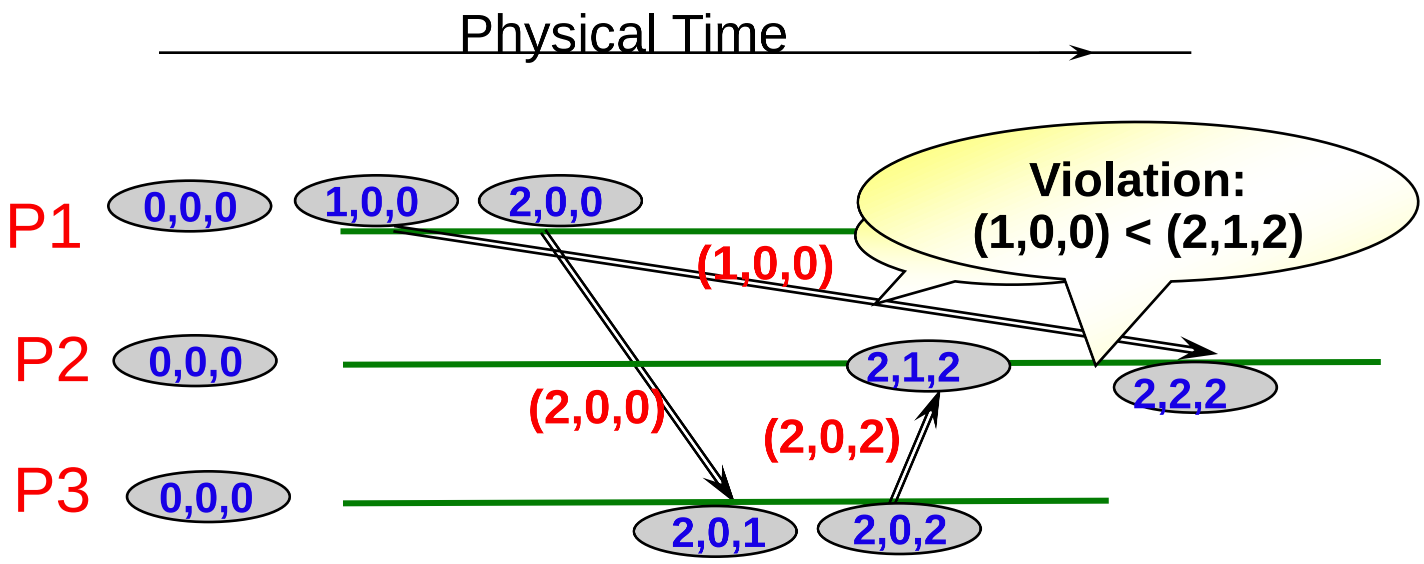
Side Issue: Causality Violation



- Causality violation occurs when order of messages causes an action based on information that another host has not yet received.

- In designing a distributed system, potential for causality violation is important to notice

Detecting Causality Violation



- **Potential causality violation can be detected by vector timestamps.**
- **If the vector timestamp of a message is less than the local vector timestamp, on arrival, there is a potential causality violation.**

Summary, Announcements

- Time synchronization important for distributed systems
  - Cristian's algorithm
  - Berkeley algorithm
  - NTP
- Relative order of events enough for practical purposes
  - Lamport's logical clocks
  - Vector clocks

- Next class: Global Snapshots. Reading: 14.5

- HW1 due next Thursday 9/19
- MP1: due this Sunday
  - By now, you should have written most of your code.