# Synchronization
*Physical clocks*
*Logical clocks*

# Summary so far …

A distributed system is:

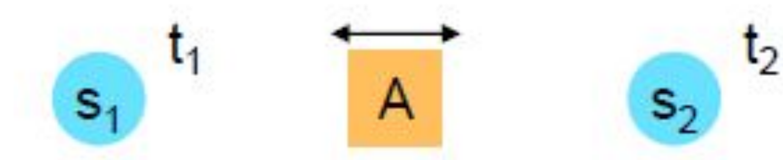
- a collection of *independent computers* that appears to its users as a *single coherent system*

Components need to:

- Communicate
  - Point to point: request-reply, RPC/RMI
  - Point to multipoint: multicast, epidemic
- Cooperate
  - Naming to enable some resource sharing
    - Naming systems for unstructured (flat) namespaces:
      - consistent hashing, DHTs
    - Naming systems for structured namespaces
  - **Event ordering**
  - **Synchronization**

# An example

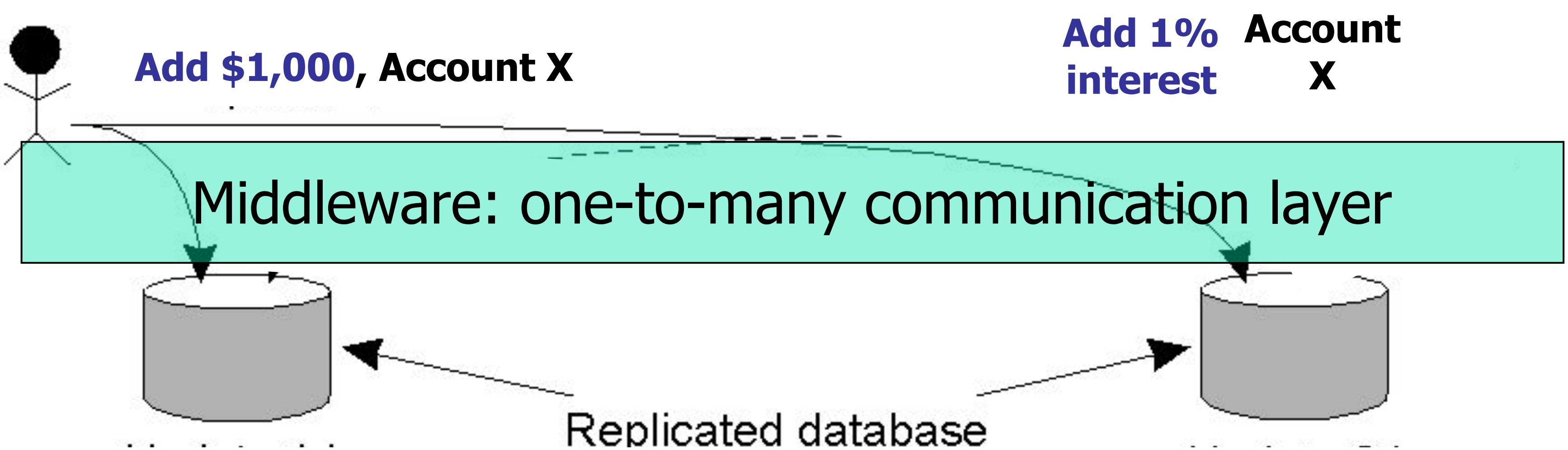
- Multiplayer game …
  - Distributed implementations generally use replicated state: each player ha its own view of the world.
  - Object ***A*** (the target) and the "world" are replicated as $S_1$ and $S_2$
- … players shoot the same target at about the same time
  - Players shot at local times $t_1$ and $t_2$ on two replicas $S_1$ and $S_2$
- Who gets the points?
  - Need to aggregate events into one consistent view.




Issues: Correctness. Overheads. Fairness.

*Room for application-specific solutions*

# Example: Replicated State Machine




*Q: Do the updates need to be executed in the same order on the two replicas?*

Issues:

- What kind of ordering: partial or total?
- Does ‘real’ (physical time) ordering matter for correctness?

# Why event ordering is more complex than in a single-box system?

- No single physical clock
  - Likely multiple physical clocks,
  - Likely out of sync and drifting
- Need to aggregate a ‘global’ view
- Failures

# What are your tools?

- Physical clocks
  - Provide [an estimate of] actual (real) time.
- 'Logical clocks'
    - Where only ordering of events matters
  - Lamport clocks
  - Vector clocks (ability to trace event dependence)

# Keeping track of time easily gets complex …

"Fifty-six standards of time are now employed by the various railroads of the country in preparing their schedules of running times"

-- New York Times, April 1883 [source]

## Other Examples?

- The October with only 20 days (in 1582)
- Leap Second

# Physical clocks (I)

- Problem: Achieve coordination on real time in a distributed system
- The standard: Coordinated Universal Time (UTC):
  - Atomic clocks: Based on the number of transitions per second of the cesium 133 atom
    - accurate but expensive
  - Leap second from time to time to compensate for days getting longer.
- UTC is broadcast through short wave radio and satellite.
  - Accuracy ± 1ms (but if weather conditions considered ±10ms)
  - Needs a receiver

## Problem:

- Suppose we have a distributed system with a UTC-receiver somewhere in it.
- How do we:
  - distribute time to each machine, and
  - maintain a bound on how much local time differs from actual tim?

Internal mechanism (the "clock") at each node

- Each machine has a *timer*
- Timer causes an *interrupt* *H* times a second
  - Interrupt handler adds 1 (a '*tick'*) to a software clock
- Software clock keeps track of the number of *ticks* since some agreed-upon time in the past.

Time is correct
Drift = 0

Clock does not deviate
Drift rate = 0

# Clock drift and drift rate

**Notation**: Value of clock on machine *p* at real time ***t*** is $C_p(t)$

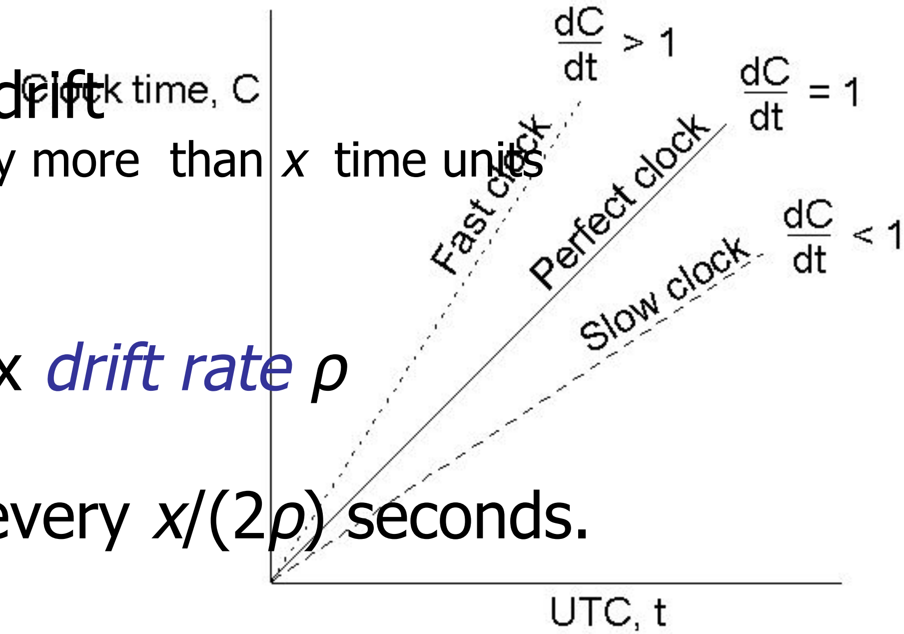
*Clock drift* **:** $|C_p(t) - t|$ ***Drift rate:*** $\frac{dC_p(t)}{dt} - 1$

**Ideally:** $C_p(t) == t$ $dC_p(t) = dt$

**Goal:** Guarantee on maximum drift
i.e., never let clocks on two nodes differ by more than *x* time units

## How?

- Manufacturer guarantees max *drift rate* $\rho$
  $1 - \rho \leq (dC/dt) \leq 1 + \rho$
- Nodes synchronizes at least every $x/(2\rho)$ seconds.

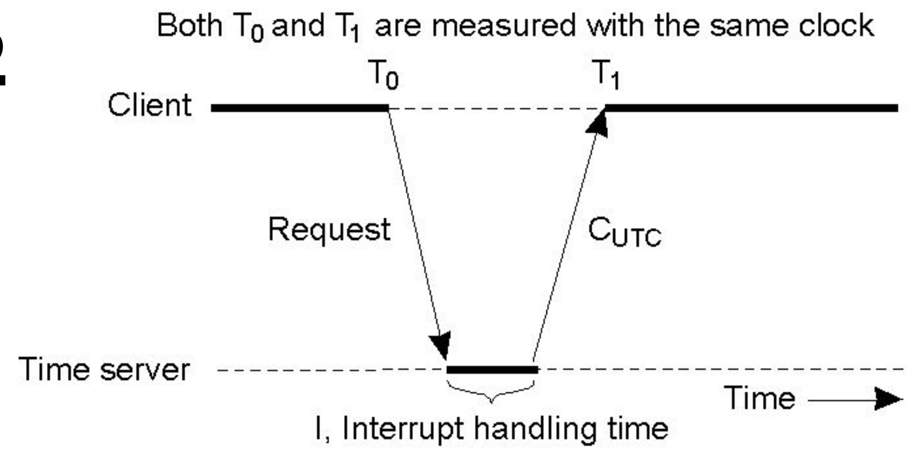


# Building a complete system …

- Every machine asks a **time server** for the accurate time at least once every $x/(2\rho)$ seconds

Client updates time to?

$$T_{new}=C_{UTC}+(T_1-T_0)/2$$




## Q: Problems?

- **Fundamental:** setting the time back is **never** allowed ☐ smooth adjustments.

# Real world: Network Time Protocol (NTP)

- Stratum 1 NTP servers – receive time from external sources (cesium clocks, GPS, radio broadcasts)
- Stratum N+1 servers synchronize with stratum N servers and between themselves
  - Self-configuring network
- Survey (fairly old: 2006)
  - > 1M NTP servers
  - 0.2% of the NTP servers >128ms offset from synchronization peer
  - Excluding these: - median: 0.7ms
    - mean: 7ms

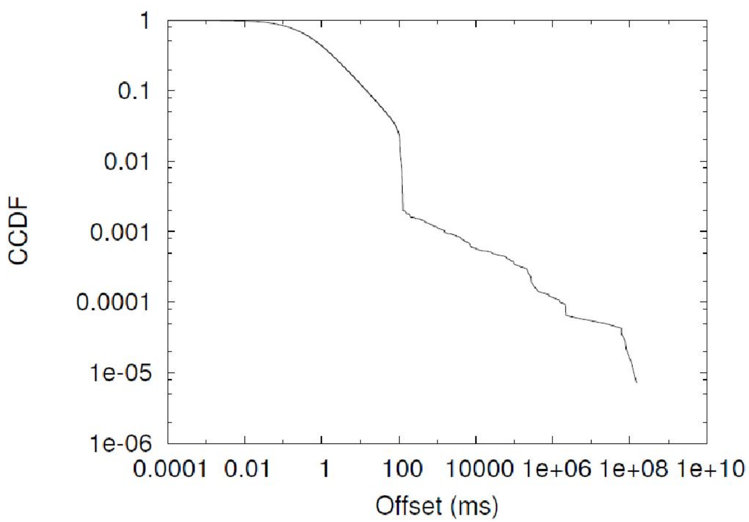



Fig. 1: CCDF of host–peer offsets

# [Summary so far] Physical clocks

- Clock drift: time difference between two clocks
- Sources of errors (drift)
  - Variability in time to propagate radio signals. (±10ms)
  - Clocks are not perfect: Drift rates
  - Network latencies are not symmetric
  - Differences in speed to process messages
- System design to limit drift
  - One node holds the 'true' time
  - Other nodes contact this node periodically and adjust their clocks
    - How often?
    - How exactly the adjustment is done?

- We've established that clocks can not be *perfectly* synchronized (and atomic clocks are costly).

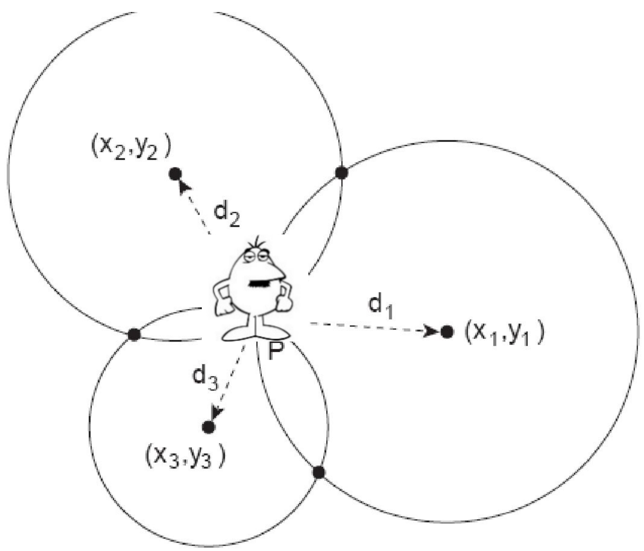
- What can one do in these conditions?
  - Get a better estimate of time by using different technology
    - e.g., use GPS to obtain time in your system
  - Expose uncertainty and design the system to take drift into account
    - Example 1: Google's Spanner
    - Example 2: Server design to provide at-most-once semantics
  - Give up physical clocks!
    - Consider only event order - Logical clocks

# GPS – Global Positioning Systems Intro

**Basic idea:** To estimate distance to a landmark (e.g., s satellite)

- Estimate signal *propagation time* between you and the landmark
- Multiply by signal speed

**Strawman:** Assume that the clocks of the satellites and receiver are accurate and perfectly synchronized:




But, in real world:

- 3D not 2D
- The receiver's clock is definitely out of sync with the satellite

- Unknowns: $x_r$, $y_r$, $z_r$ coordinates of the receiver.
- Known:
  - $x_i$, $y_i$, $z_i$ coordinates of satellite i
  - $T_i$ is the send timestamp on a message from satellite *i*
  - $\Delta I_i = (T_{now} - T_i)$ measured delay for message sent by satellite *i*
- Distance to satellite *i can be estimated:*
  - (1) Propagation time*:* $d_i = c \times \Delta I_i$
  - (2) Geometric distance:

$$d_i = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2}$$

- 3 satellites☐ 3 equations in 3 unknowns. I'M DONE!
- … BUT: I assumed receiver clock is synchronized!

*the satellite has an atomic clock anyways so Ti is correct

- Unknowns: $x_r$, $y_r$, $z_r$ coordinates of the receiver.
- Known: $X_i$, $Y_i$, $Z_i$ - coordinates of satellite i
  - $T_i$ - the send timestamp on a message from satellite *i*

$\Delta I_i = (T_{now} - T_i)$ propagation delay of message sent by satellite *i*

- Distance to satellite *i can be estimated:*
  - Propagation time: $d_i = c \times \Delta I_i$
  - Geometric distance: $$d_i = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2}$$
- So far I assumed receiver clock is synchronized*!
  - What if it needs to be adjusted? $T_{real} = T_{now} + \Delta r$
  - $\Delta I_i = (T_{now} + \Delta r) - T_i$
  - Collect one more measurement from one more satellite!

*the satellite has a atomic clock anyways so Ti is correct

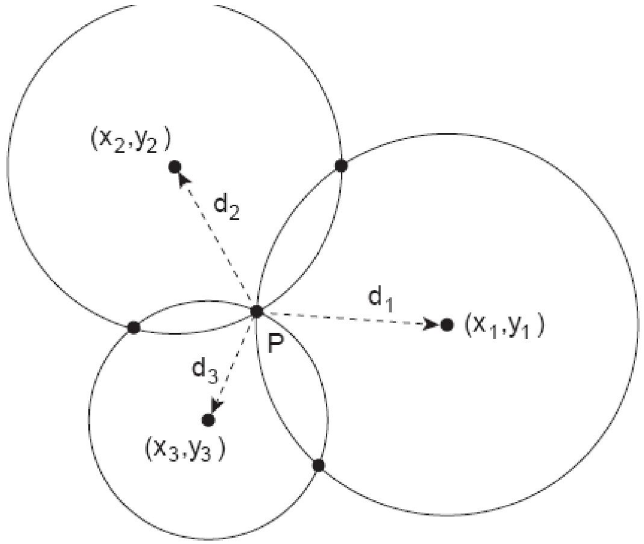
# Two takeaways

- (1) Triangulation technique
  - Can be used in other contexts: e.g., computing geographical position in wired networks
- (2) Enough information to correct the clock drift at the receiver

# Similar triangulation techniques work in other contexts: Computing geographical position in wired networks

**Observation:** a node $P$ needs at least $k + 1$ landmarks to compute its own position in a $k$-dimensional space.

Consider two-dimensional case:



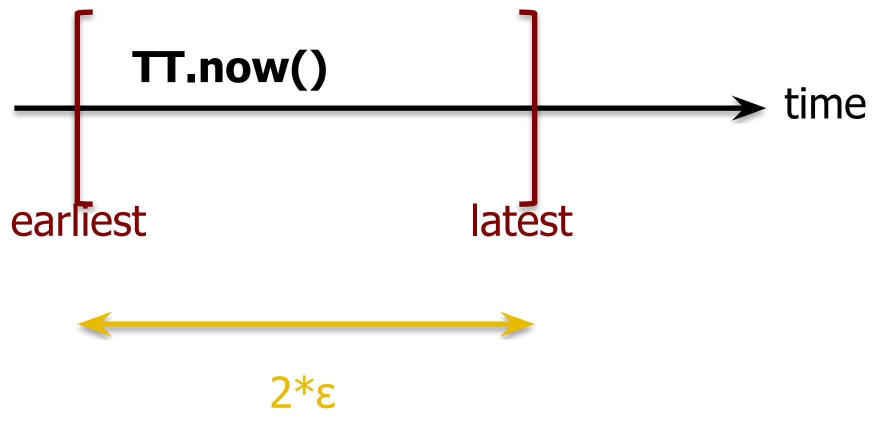

**Solution:** $P$ needs to solve three equations in two unknowns $(x_P, y_P)$

- We've established that clocks can not be *perfectly* synchronized (and atomic clocks are costly).

- What can one do in these conditions?
  - Get a better estimate of time by using new technology
    - e.g., use GPS to obtain time in your system
  - Expose uncertainty / design the system to account for drift
    - Example 1: Google's Spanner – Extended time API
    - Example 2: Server design to provide at-most-once semantics
  - Give up physical clocks!
    - Consider only event order - Logical clocks

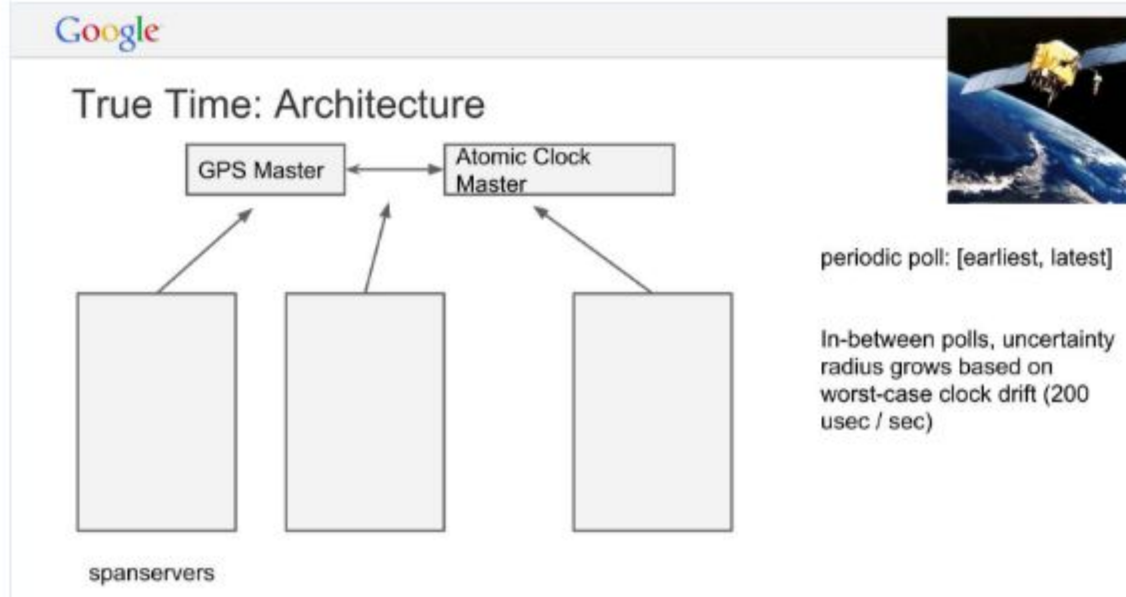
# Google's Spanner

- "Global wall-clock time" with bounded uncertainty
  - Time estimate: TT.now() ☐ [earliest, latest]
  - Guaranteed interval

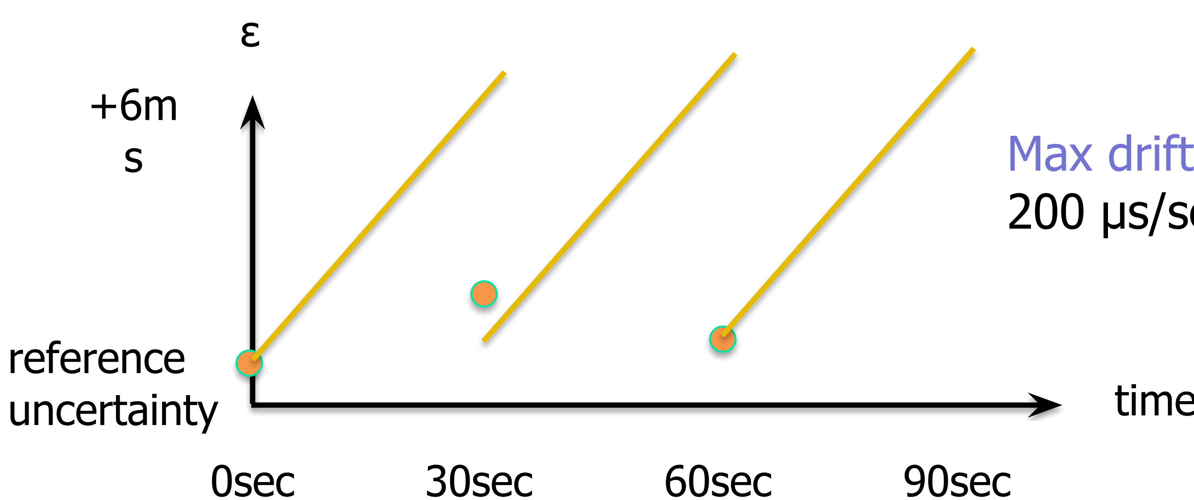



*Spanner: Google's Globally-Distributed Database - internally '11, OSDI 12, product '17*

# TrueTime implementation



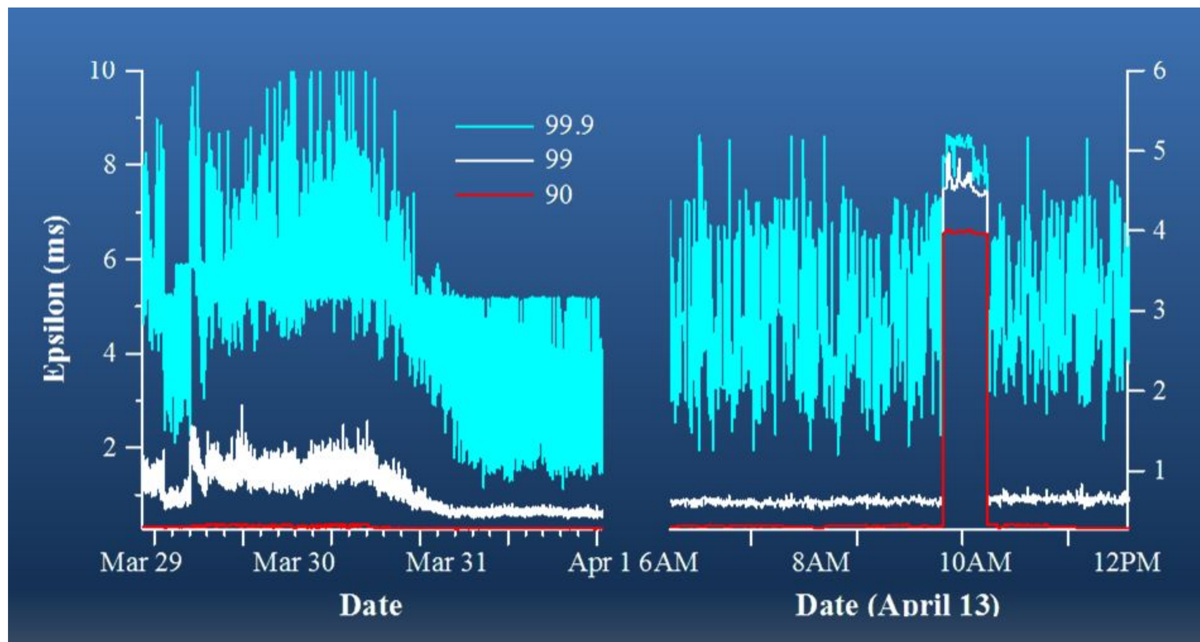

ε = reference ε +
worst-case local-clock drift




Max drift rate: 200 μs/sec □ Max drift: 6ms (for a 30s sync interval)

# Practical Experience @Google

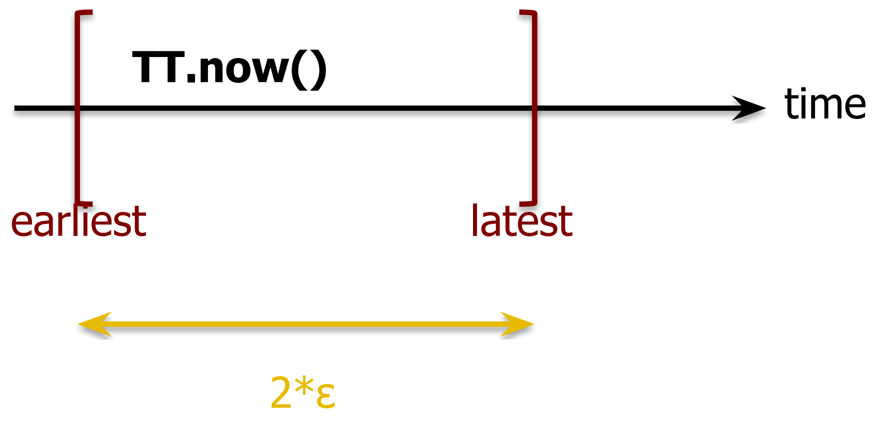
- (1) Is $\varepsilon$ truly a bound on clock uncertainty?
  - Violations of guarantees [drift rate] unlikely: Bad CPUs 6 times more likely than bad clocks (based on 1y of data)
    - "As a result, we believe that TrueTime's implementation is as trustworthy as any other piece of software upon which Spanner depends"
- (2) How bad does $\varepsilon$ get?
  - Network-induced uncertainty



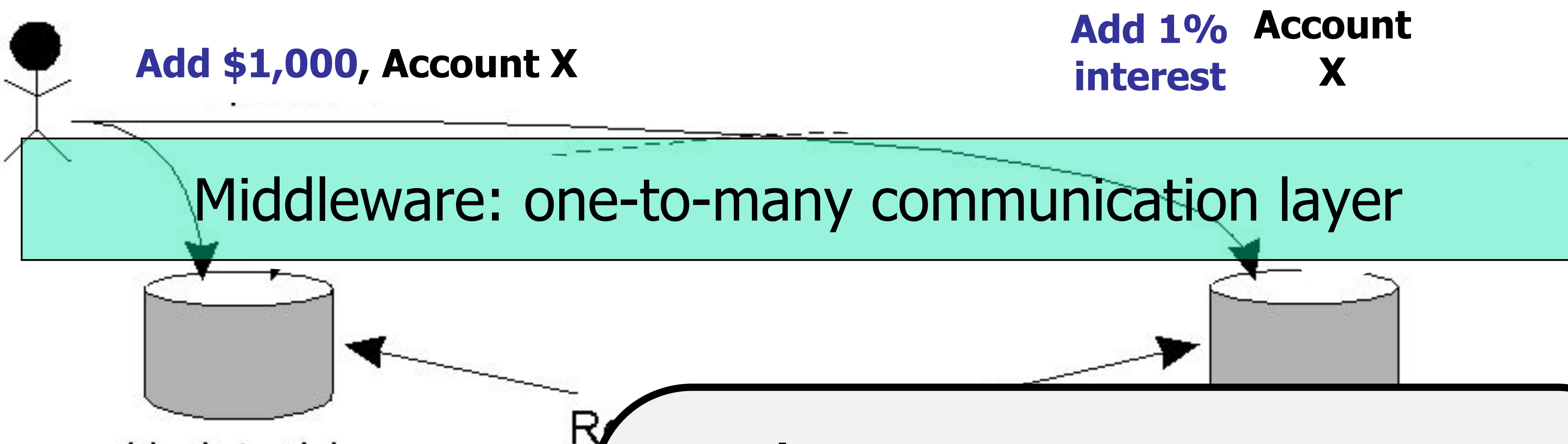

$\varepsilon$ sampled at timeslave daemons immediately after polling the time masters

# Recap: expose uncertainty of time estimates

- "Global wall-clock time" with bounded uncertainty
  - Time estimate
  - Guaranteed interval



# How would Spanner/TrueTime help here ….




Goal (for next few slides):

aggregate data from transaction initiators to construct a correct ordering of events

[NB: This is a over-simplified view of spanner]

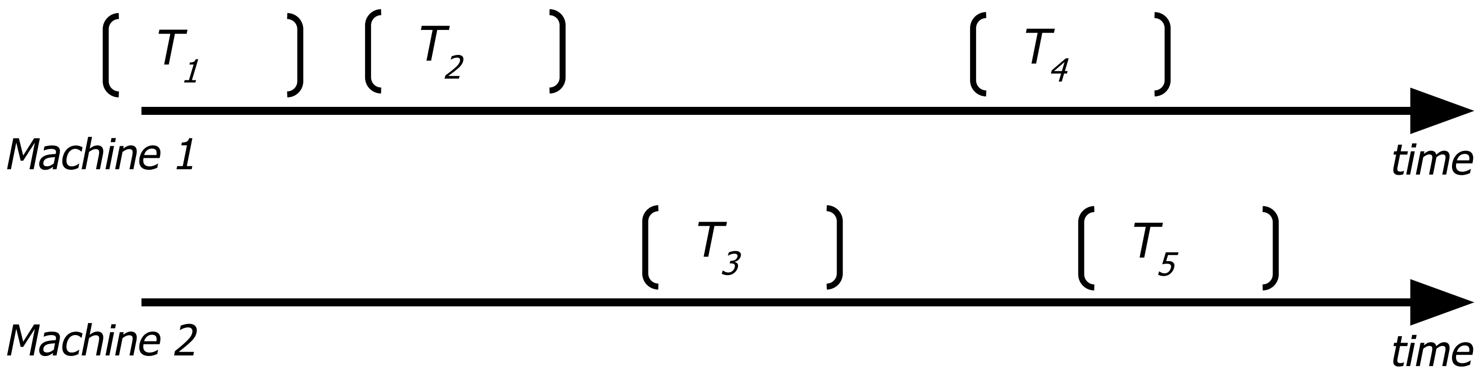
*Q: Do the updates*

*same order on the t*

Issues:

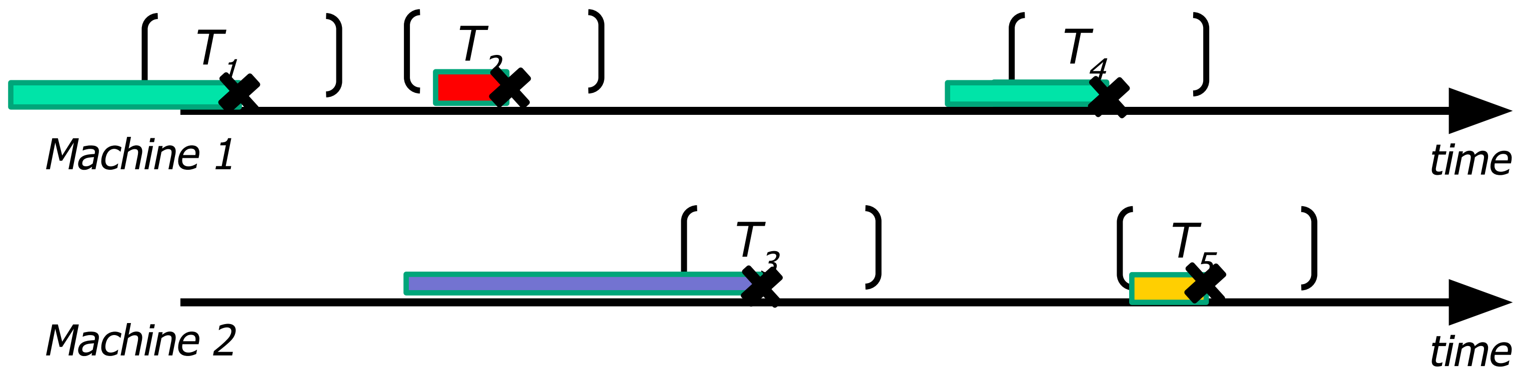
- What kind of ordering
- Does 'real' (physical time) ordering matter for correctness?

# Ok – so how does this help with event ordering?



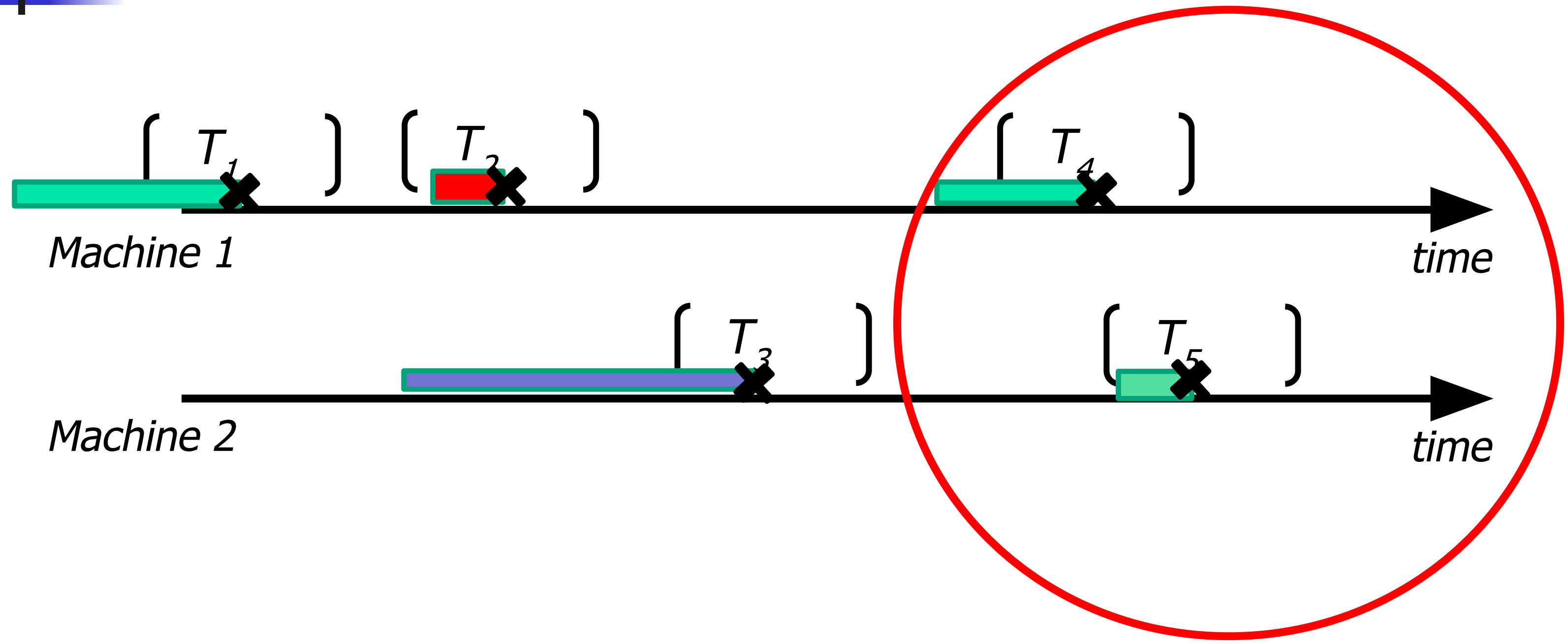

- Events get timestamped (with uncertainty intervals)
- Use the timestamps to recreate a global view for the order in which events occurred.
  - Order unambiguous as long as the uncertainty intervals do not overlap

# Ordering transactions



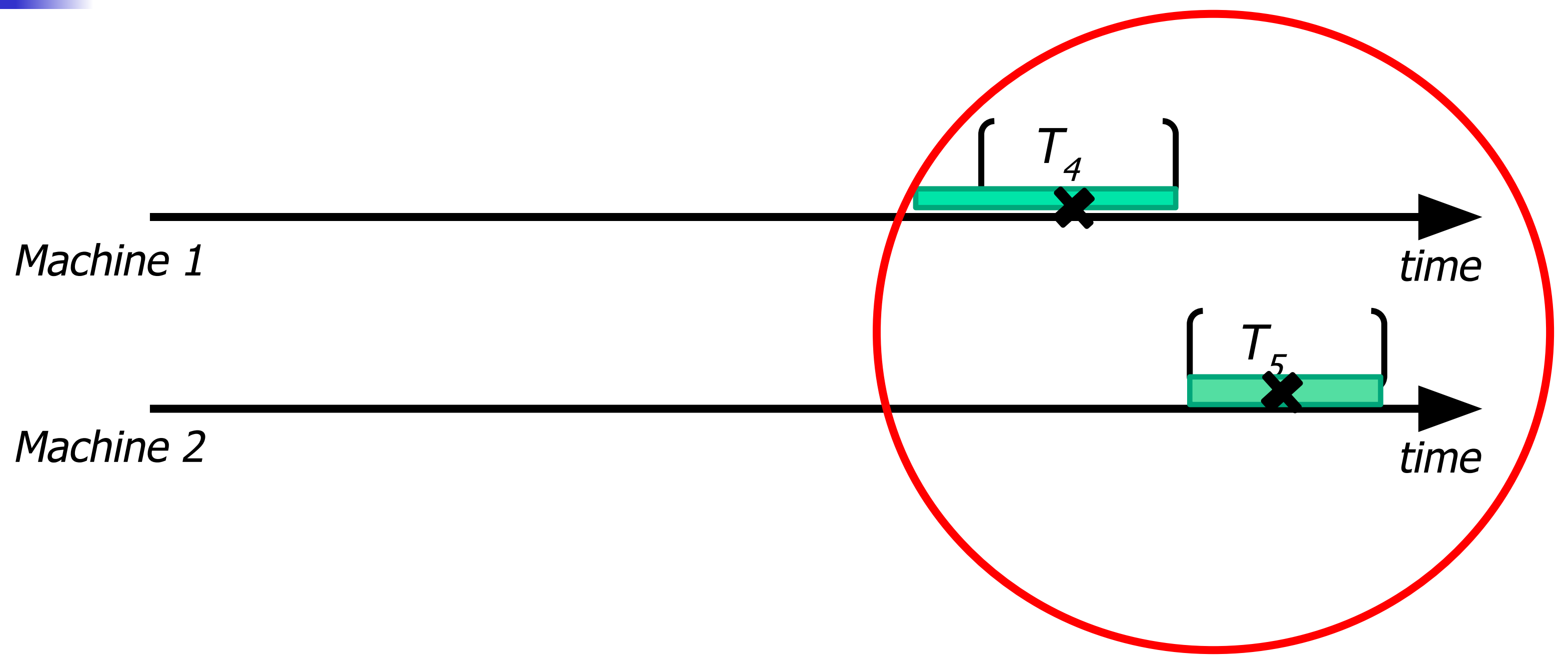

- Assume that $T_x$ are transaction timestamps.
  - Timestamps taken at commit time
- Goal is to recreate the global transaction order
  - If two transactions are not conflicting: order does not matter
  - Else: need to get the order right

# Ordering transactions




- Assume that $T_x$ are transaction commit timestamps.
- Goal is to recreate the global transaction order
  - If two transactions are not conflicting: order does not matter
  - Else:  need to get the order right

# Spanner solution




- Move timestamp within the transaction
  - So that full uncertainty interval is within the transaction
- If needed (i.e., transaction is too short) extend the transaction
  - i.e., delay releasing the resources
- This way conflicting transactions have timestamps that can be ordered without uncertainty

- We’ve established that clocks can not be *perfectly* synchronized (and atomic clocks are costly).

- What can one do in these conditions?
  - Get a better estimate of time
    - e.g., use GPS to extract time in your system /
  - Expose uncertainty and design the system to take drift into account
    - Example 1: Google’s Spanner – Extended time API
    - Example 2: Server design to provide at-most-once semantics
  - Give up physical clocks!
    - Consider only event order - Logical clocks

# Efficient <u>at-most-once</u> message delivery

Goal : Server has to identify previously served requests to implement at-most-once semantics

[Old] Assumptions:

- Message propagation time bounded
- Physical clocks not used
  - (so no need to make assumptions about drift rates)
- Client may resend messages for up to *MaxLifeTime*

Issues

- 1: For how long to maintain 'transaction' data?
- 2: How to deal with server failures?
  - (minimize the state that is persistently stored, when to restart)

# Issue1: For how long to maintain transaction data at server?

- Server's goals:
  - 1. Identify message duplicates – at-most-once delivery
  - 2. While trying to avoid storing too much state

- Context:
  - No bound on message propagation time
  - Any two clocks in the system differ by at most *MaxClockDrift*
  - Client may resend messages for up to *MaxLifeTime*

- Mechanism idea: Server discards messages that have been generated too far in the past.
  - Client protocol: client sends transactionID and physical timestamp
  - Server computes: $G = T_{now} - MaxLifeTime - MaxClockDrift$
    - … and maintains transaction data only for the interval $[G..T_{now}]$
  - Discards messages with $msg_{timestamp}$ older than $G$
  - Ignores (or delays) messages that arrive in future: $msg_{timestamp} > T_{current}$

# Efficient at-most-once message delivery

Design goal : Server has to identify previously served requests to implement at-most-once semantics

[New] Assumptions:

- No bound on message propagation time
- There is a bound on clock drift
  - any two clocks in the system differ by at most *MaxClockDrift*
- Client may resend messages for up to *MaxLifeTime*
  - *after that reports error (timeout) to the application*

Issues

- 1: For how long to maintain 'transaction' data?
- 2: How to deal with server failures? What to persist across server failures? When to restart?
  - (minimize the state that is persistently stored, minimize downtime)

# Efficient at-most-once message delivery (II)

- Issue 2: What to persistently store across server failures?
  - Strawman #1: Store nothing persistently.
    - Incorrect if server reboots quickly
  - Strawman #2: Persistently store ALL transactions.
    - Costly
  - Strawman #3: Store nothing persistently, and wait *MaxLifeTime* after reboot before starting to process messages
    - Correct but lowers availability.

# Efficient at-most-once message delivery (II)

- Issue 2: What to persistently store across server failures?

- Towards a solution: need to approximate failure time
  - Write current time (*CT*) to disk every $\Delta T$
  - At recovery read it
    - Failure time is approximated as $G_{\text{failure}}$ from last saved *CT*

  - After recovery – when a new message arrives

    (let's ignore clock drift for now and assume perfect clocks)
    - Discard messages with timestamp older than $G_{failure} + \Delta T$
      - *Reason:* the server might have seen these in the past (but lost the cache)
    - Process messages with timestamp newer than $G_{failure} + \Delta T$
      - *Reason: surely not seen before failure*

[Quiz-like question: Change the formulas to consider clock drift]

# Quiz-like question

- Previous solution
  - no assumption on maximum message propagation time
  - uses physical clocks (with a bound on max clock drift)

- You can now assume an upper bound *B* on message propagation time
  - Design a solution that does not use physical clocks?

- We’ve established that clocks can not be *perfectly* synchronized (and atomic clocks are costly).

- What can I do in these conditions?
  - Get a better estimate of time by using new technology
    - GPS systems
  - Expose uncertainty / Design the system to take drift into account
    - Example: Server design to provide at-most-once semantics
  - Give up physical clocks!
    - Consider only event order - Logical clocks

# Logical clocks -- Time Revisited

- What’s important?
  - The precise time two events occurred?

OR

  - The order in which the two events occured?

## (1) Alice intends to quit her employer

- She removes her boss as a friend
- Posts *"I'll quit tomorrow! Here is the story: … "*

  (visible to friends only)

Alice expects her boss will not be able to see her post

## (2) Bob, a friend of Alice,

- Reads Alice's post
- Messages Charlie, a common friend:

  *"Wow! Alice just posted that she'll quit! Read her story!"* *

## (3) Charlie, a friend of both

- Reads Bob's message
- Goes to Alice's timeline to read the story

Charlie expects to see Alice's post

Common expectation: process events in the order they occurred

* We are in 2003, post sharing has not been invented

# Logical clocks: ROADMAP

**Define partial order for events**
"happens before" relationship "□"

What are the constraints?
What does 'ordering' mean?

**Logical clocks**

Assign timestamps to events such that:
*if a □ b then ts(a) < t(b)*

Come up with a system to 'label' events that respects these constraints

**Build systems**
E.g., totally ordered group communication

How is this used?

# What are the constraints? What does 'order' mean?

Need to introduce a notion of ordering (before we can order anything).

The **happened-before** relation (notation: "→") on a set of events in a distributed system

- if *a*, *b* are events in the same process, and *a* occurs before *b*, (in physical time) then $a \rightarrow b$
- if *a* is the event of sending a message by a process, and *b* receiving same message by another process then $a \rightarrow b$

Property: Transitive: if a☐b and b☐c then a☐ c

Two events are *concurrent* if nothing can be said about the order in which they happened (i.e. happens-before is a partial order)

# Logical clocks: ROADMAP

**Define partial order for events**

"happens before" relationship

Notation: □

What are the constraints?
What does 'ordering' mean?

**Logical clocks**

Assign <u>timestamp</u> to events such that if a □ b then ts(a) < t(b)

Come up with a system to 'label' events that respects these constraints

**Build systems**

E.g., totally ordered group communication

How may this be used?

# Logical clocks

**Objective:** Build a view on the system's behavior that is consistent with the 'happened-before' relation

Attach a timestamp *ts*(*e*) to each event *e*, such that:

- **P1:** If *a* and *b* are events in the same process, and *a* happened before in physical time *b*, then we demand that *ts*(*a*) < *ts*(*b*).
- **P2:** If *a* corresponds to sending a message, and *b* to the receipt of that message, then also *ts*(*a*) < *ts*(*b*).

- **Problem:** How to attach timestamps to all events in the system (consistent with the rules above) when there's no global clock
  - maintain a **consistent** set of logical clocks, one per process.

**Problem:** Need to attach timestamps to all events in the system

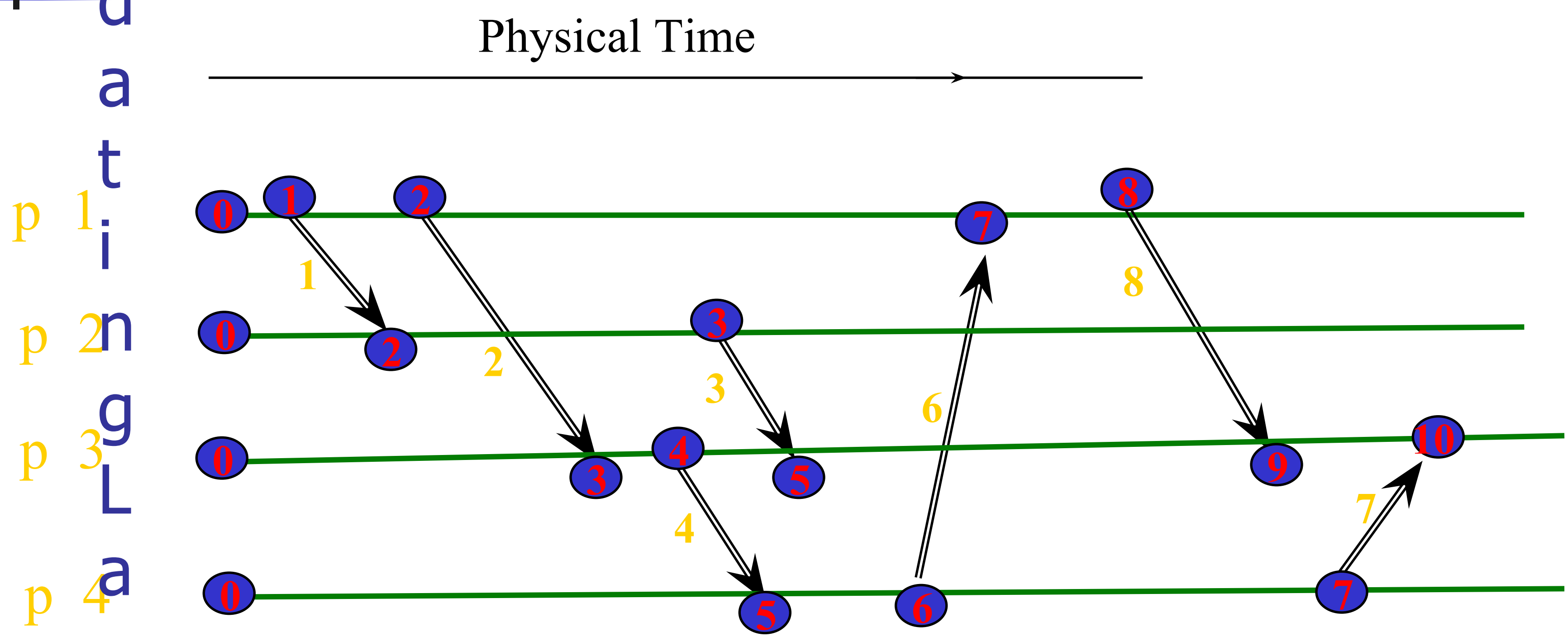
- maintain a consistent set of logical clocks, one per process.
- there's no global clock

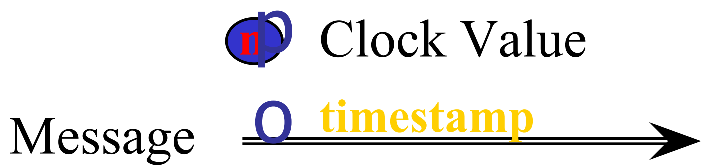
**Solution** (Lamport)**:** Each process $P_i$ maintains a **local** counter $C_i$ and adjusts it as follows:

1) For any two successive events that take place within $P_i$ the counter $c_i$ is incremented by 1.
2) Each time a message $m$ is sent by process $P_i$ the message is timestamped $ts(m) = c_i$
3) Whenever a message $m$ is received by a process $P_j$, $P_j$ adjusts its local counter $c_j$ to $\max\{C_j, ts(m)\}$; then executes step 1 before passing $m$ to the application.

- Property **P1** is satisfied by (1); Property **P2** by (2) and (3).

# Updating Lamport'




Attach a timestamp $C(e)$ to each event $e$, such that:

- **P1:** If $a$ and $b$ are events in the same process, and $a$ happened before in physical time $b$, then we demand that $C(a) < C(b)$.
- **P2:** If $a$ corresponds to sending a message $m$, and $b$ to the receipt of that message, then also $C(a) < C(b)$.

Note: C must only increase in each process

# Quiz-like question

Notation: ***timestamp(a)*** is the Lamport logical clock associated with event *a*

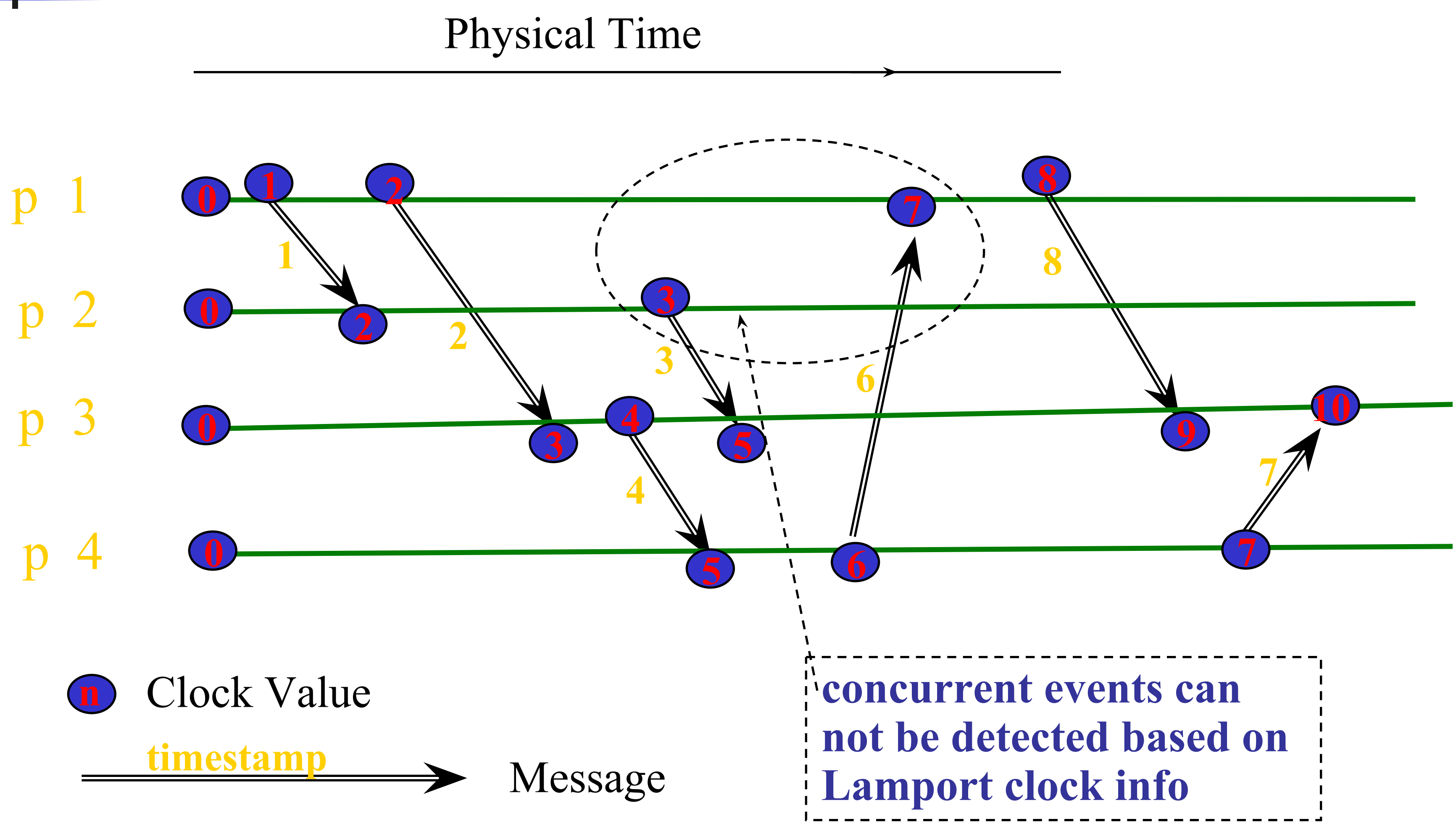
By construction if ***a* □ *b*** => ***timestamp(a) < timestamp(b)***
(if ***a*** happens before ***b***, then ***timestamp(a) < timestamp(b)***)

***Q: is the converse true?***
***That is: if timestamp(a) < timestamp(b)*** => ? ***a* □ *b***

No. If ***timestamp(a) < timestamp(b),*** it does NOT imply that ***a*** happens before ***b***

***Q: Do I know anything timestamp(a) < timestamp(b)?***
*A: Only that b□ a is FALSE (i.e.. b surely did NOT happen before a, more concrete: a and b concurrent OR a happened before b )*

# Example




Note: Lamport Timestamps: 3 < 7, but event with timestamp 3 is concurrent to event with timestamp 7, (events are not in 'happen-before' relation).

## Last Time: Logical time

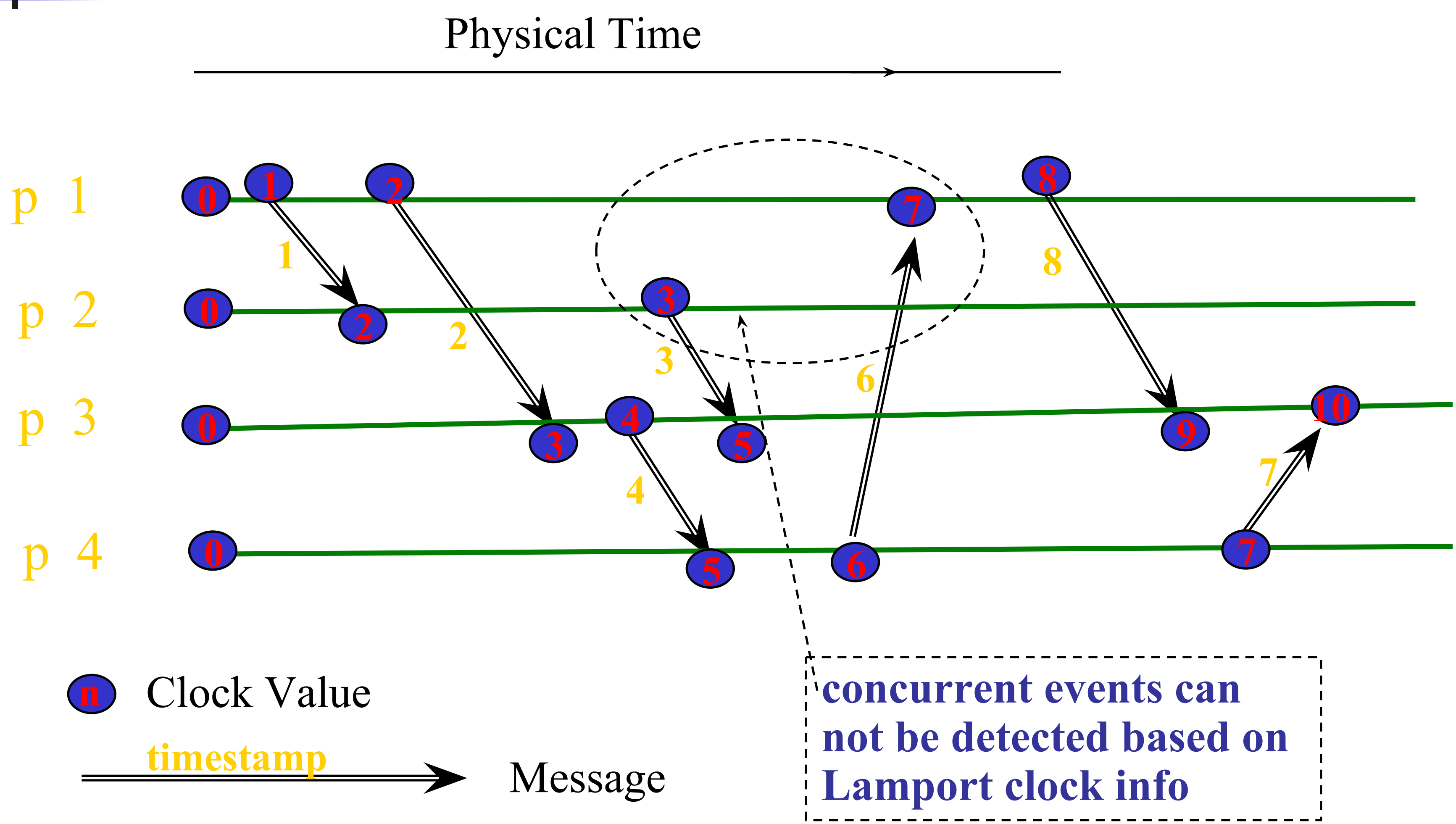
# What is that?

- Discrete assignment of sequence numbers to events, which preserves “happens-before” order

# How do Lamport clocks work?

- Processes increment their clocks upon receiving/sending new messages and based on other processes' clocks (carried with

# Example




Note: Lamport Timestamps: 3 < 7, but event with timestamp 3 is concurrent to event with timestamp 7, (events are not in 'happen-before' relation).

**Define partial order for events**

“happens before” relationship

**Logical clocks**

Assign timestamp to events such that if a □ b then ts(a) < t(b)

**Build systems**

E.g., totally ordered group communication

One example use

\big_detour{start}

# Mutual exclusion

[see separate slide set]

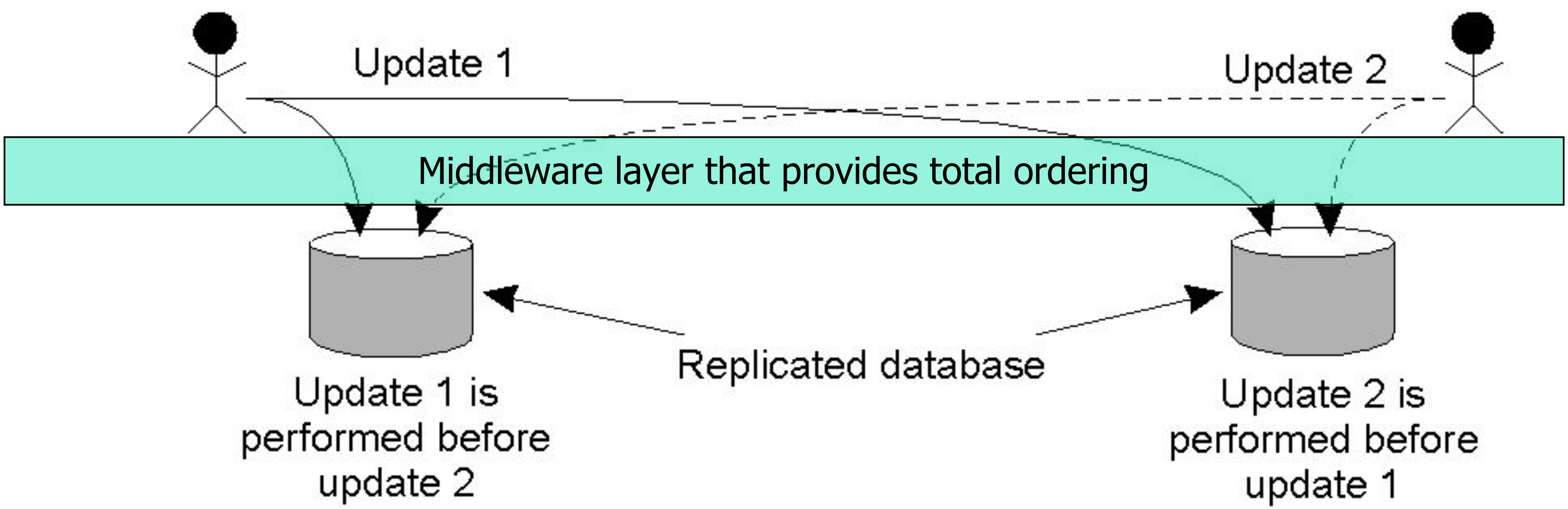
\big_detour{end}

# Example II – replicated state machine

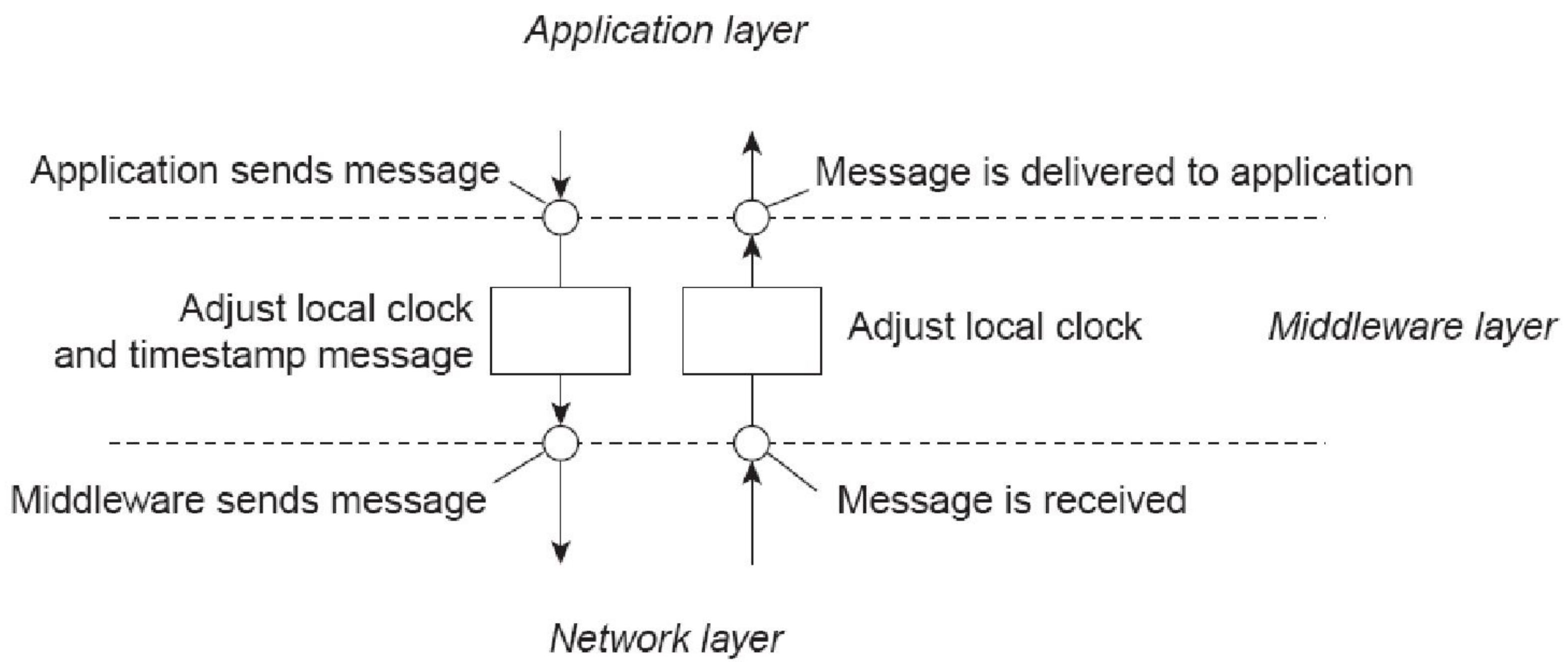
Two accounts:

- Initial state: $100 account balance
- Update 1: add $100
- Update 2: add 1% monthly interest

Updates need to be performed in the same order at the two replicas!



# Architectural view



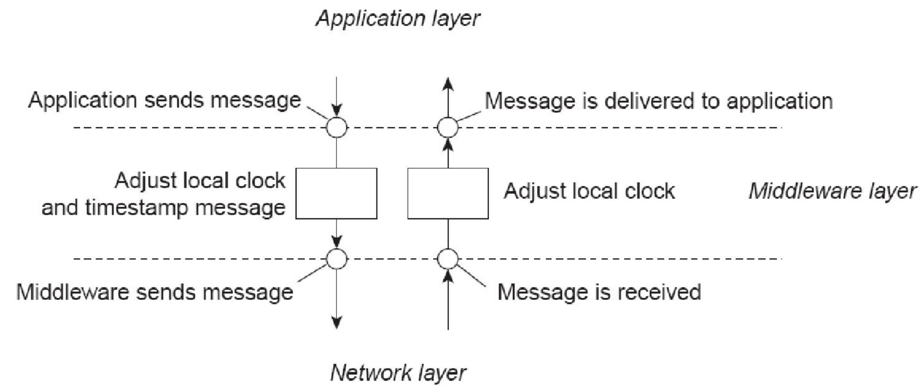

Middleware layer in charge of:

- Local management of logical clocks
  - i.e., stamping messages with (logical) clock times, updating timestamps at message receival,
- Message ordering: e.g. by delaying delivery/buffering (if needed)

# Totally ordered group communication (cont)

Setup (for simplicity)

- All members are both senders and receivers
- A one-to-many communication substrate
- FIFO / Reliable Channels
- No Side Channels




## Sketch of a solution:

- Middleware at each member maintains an ordered queue of received messages that have not yet been delivered to the application.
- **Main issue**: when to deliver to application such that, at all endpoints, messages are delivered in the same order.
- Each message is timestamped with local logical time then multicasted
  - When multicasted, also message logically sent to the sender itself
- When receiving a message, the middleware layer
  - Adds message to local queue (ordered by sending timestamp)
  - Acknowledges (using multicast) the message
  - Delivers from top of queue to application only when **all** acks for message on top have been received (or optimization: see next slide)

# Totally Ordered Multicast – Algorithm

Sending / Receiving

- Process $P_i$ sends timestamped message $msg_i$ to all others. The message itself is put in the local $queue_i$ as well
- Any incoming message $msg_i$ *received* at $P_k$ is queued in $queue_k$ according to its sent timestamp, and acknowledged to every other process.

---

Deliver to application

- $P_k$ delivers a message $msg_i$ to its application if:
  - $msg_i$ is at the head of $queue_k$ and
  - for each process $P_x$, there is an ack or a message in $queue_k$ with a larger sending timestamp.

Guarantee: all messages are delivered in the same order at all destinations

Note: We assume that communication is reliable and FIFO ordered.

# Quiz-Like Questions

- What’s the complexity of the protocol in terms of number of messages
- What happens if we drop channel reliability assumption?
  - Does the protocol still work? If it fails, explain how.
- What happens if we drop channel FIFO assumption?
  - Does the protocol still work?
  - How would you change the previous protocol to still work correctly without this assumption?
- Assume you have a bound on message propagation time in the network. Design a protocol that provides total ordering (and generates less traffic)

**Define (partial) order for events**

"happens before" relation

**Logical clocks**

Assign timestamp to events such that:

**if a □ b then ts(a) < ts(b)**

**Build systems**

E.g., totally ordered group communication

***ISSUE***

***By design*** *(with Lamport timestamps)*

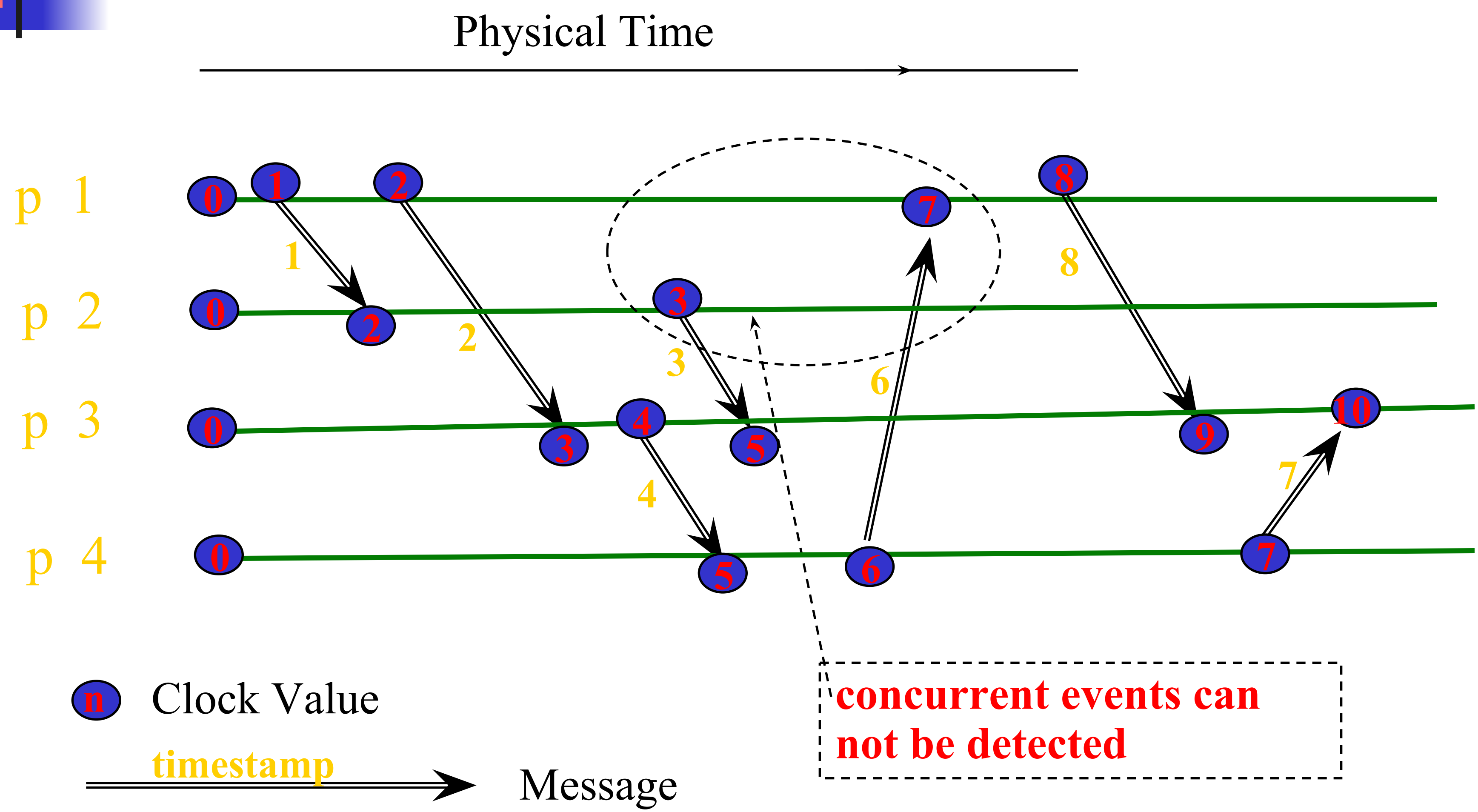
*a □ b => timestamp(a)<timestamp(b)*

***But***

If *timestamp(a)<timestamp(b)* one can not reason about relative ordering of *a* and *b*

*[the only thing you know is that b□a is FALSE]*

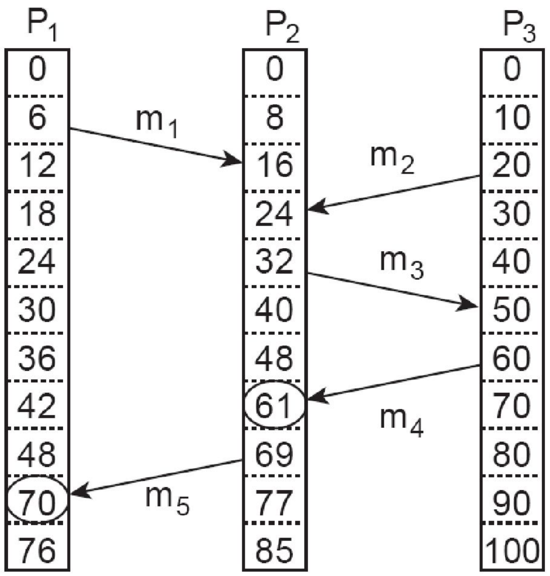
# Example




**Issue: Lamport Timestamps 3 < 7, but event with timestamp 3 is concurrent to event with timestamp 7, i.e., events are not in 'happen-before' relation.**

# Causality

- Isue: Lamport timestamps don't properly capture causality
  - Introduce more ordering than necessary




- Applications often need to reason about (i.e., order similarly) only causally related messages.
  - Example: news postings have multiple independent threads of messages.
    - What are the constraints on ordering?

- To model causality – **vector** timestamps
  - **Intuition**: each item in vector logical clock for one causality thread.

**Define partial order for events**

"happens before" relationship

**Vector clocks**

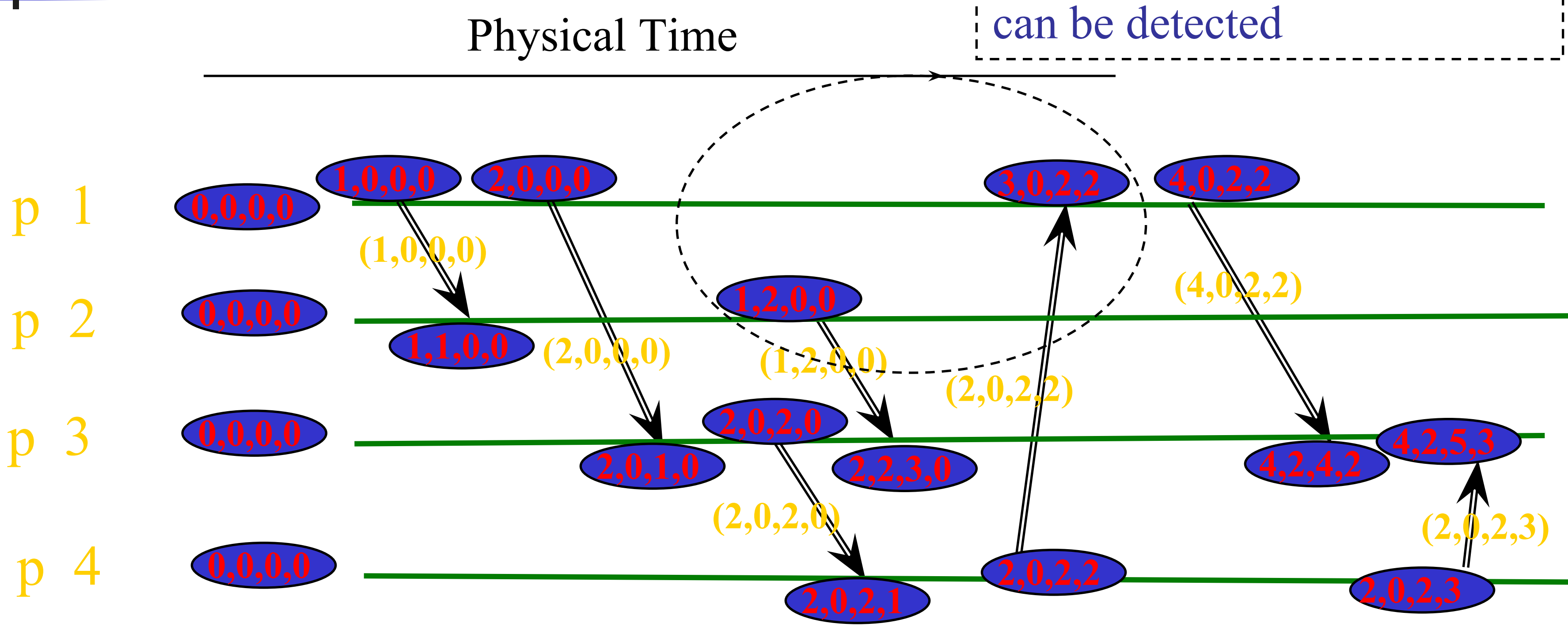
Assign timestamps to keep track of event causality

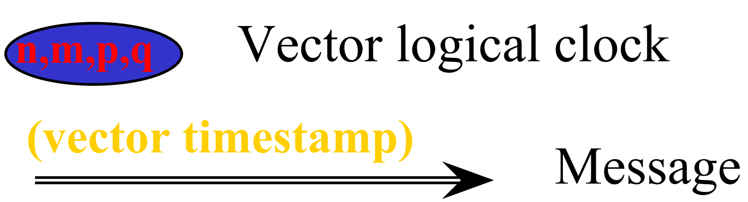
**Build systems**

E.g., **causally** ordered group communication

# Example: Vector Timestamsps

logically concurrent events can be detected



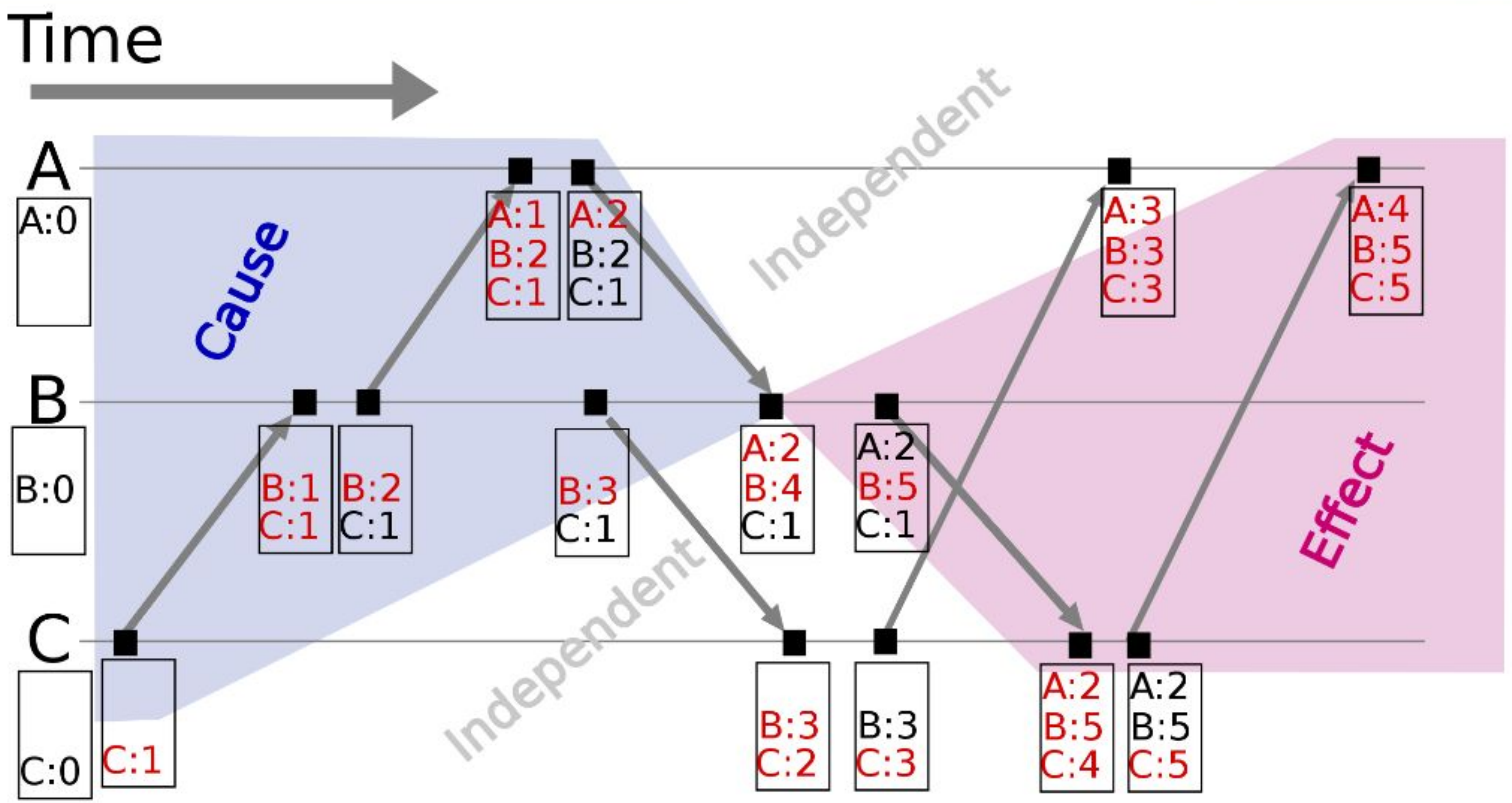




Notation

- $VT_1 < VT_2$,
  *iff* forall j ($1 \le j \le n$) such that $VT_1[j] \le VT_2[j]$
  and
  exists j ($1 \le j \le n$) such that $VT_1[j] < VT_2[j]$

- $VT_1$ is concurrent with $VT_2$
  *iff* (not $VT_1 < VT_2$ AND not $VT_2 < VT_1$)

# Vector clocks/timestamps enable reasoning about causality




Events in the blue region are the causes leading to event B4, whereas those in the red region are the effects of event B4

# Vector clocks: the formal definition

- Each process $P_i$ has an array $VC_i\,[1..n]$ of clocks (all initially at 0)
  - $VC_i\,$[j] denotes the number of events that process $P_i$ knows have taken place at process $P_j$.
- $P_i$ increments $VC_i\,$[i]: when an event occurs
  - local event, message sending, message receiving
  - timestamp of the event is vector value

- When sending
  - Messages sent by $VC_i$ includes a **vector timestamp** *vt*(*m*).
  - Result: upon arrival, recipient knows $P_i$'s timestamp.
- When $P_j$ receives a msg from $P_i$ with vector timestamp *ts*(*m*):
  - for k ≠ j: update each $VC_j\,[k]$ to $\max\{VC_j\,[k], ts(m)[k]\}$

**Note:** vector timestamps require a static notion of system membership

# Comparing vector timestamps

Notation

- $VT_1 < VT_2$,
  *iff* forall j ($1 \le j \le n$) such that $VT_1[j] \le VT_2[j]$
  and
  exists j ($1 \le j \le n$) such that $VT_1[j] < VT_2[j]$

- $VT_1$ is concurrent with $VT_2$
  *iff* (not $VT_1 < VT_2$ AND not $VT_2 < VT_1$)

# Quiz like problem

Show that:

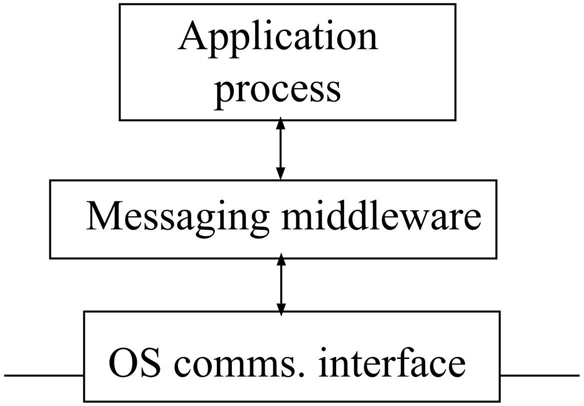
***a* □ *b*** if and only if ***vectorTS(a) < vectorTS(b)***

# Extending group communication

ASSUMPTIONS

- messages are multicast to (named) process groups
- reliable and FIFO channels
- processes don't crash
- processes behave as specified (i.e., we are not considering Byzantine behaviour)

**Architectural view**



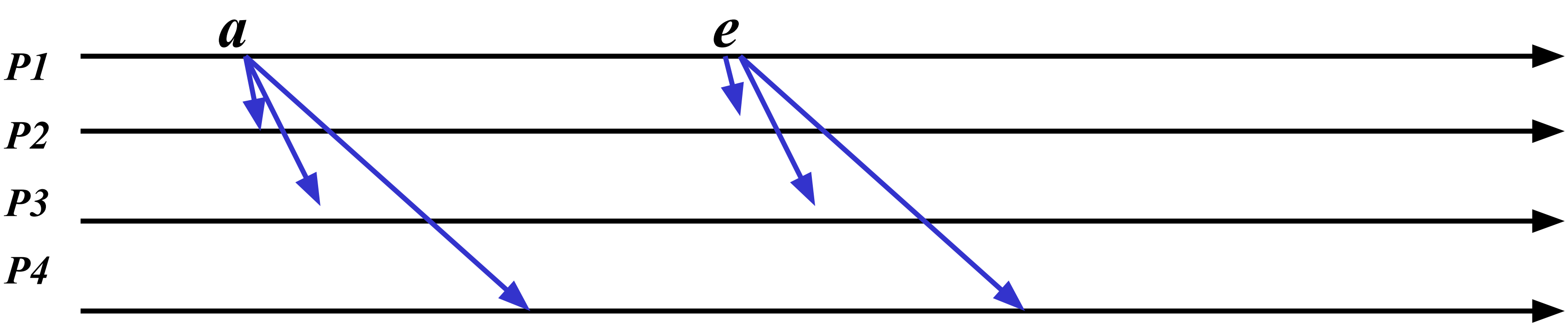

*Application:* *chooses delivery order of message service e.g.* **total order, FIFO order, causal order** *(last time we looked at 'total order')*

*Middleware: may reorder/delay message delivery to application by buffering messages to implement reordering policy*

*Basic network layer: provides reliable FIFO from each source (done at lower levels)*

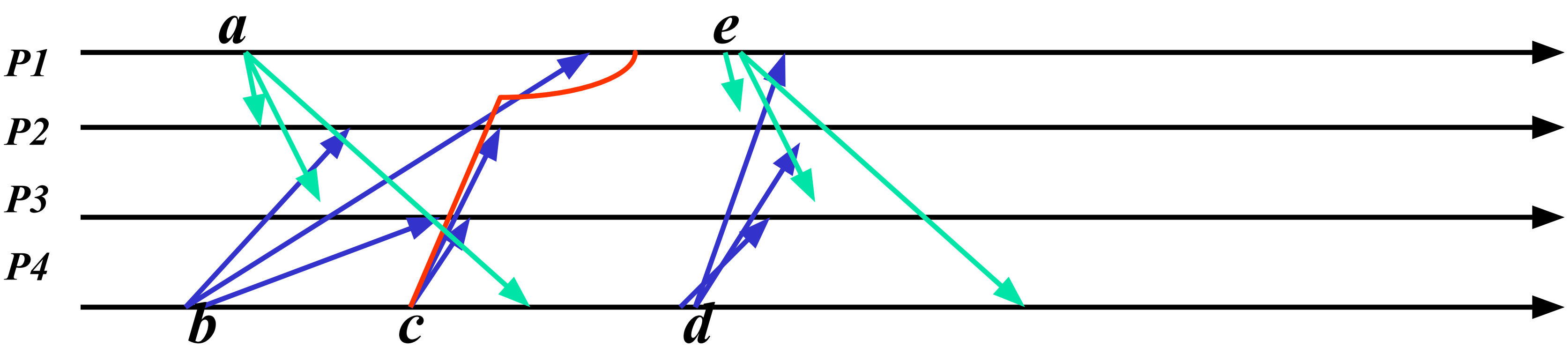
# FIFO multicast

- *FIFO* (or *sender ordered*) multicast: *Messages sent by any single sender are received in the same order*
  - Nothing guaranteed for relative ordering of messages sent by two different senders



# FIFO multicast

- *FIFO* (or *sender ordered*) multicast: *Messages sent by any single sender are received in the same order*
  - Nothing guaranteed for relative ordering of messages sent by two different senders



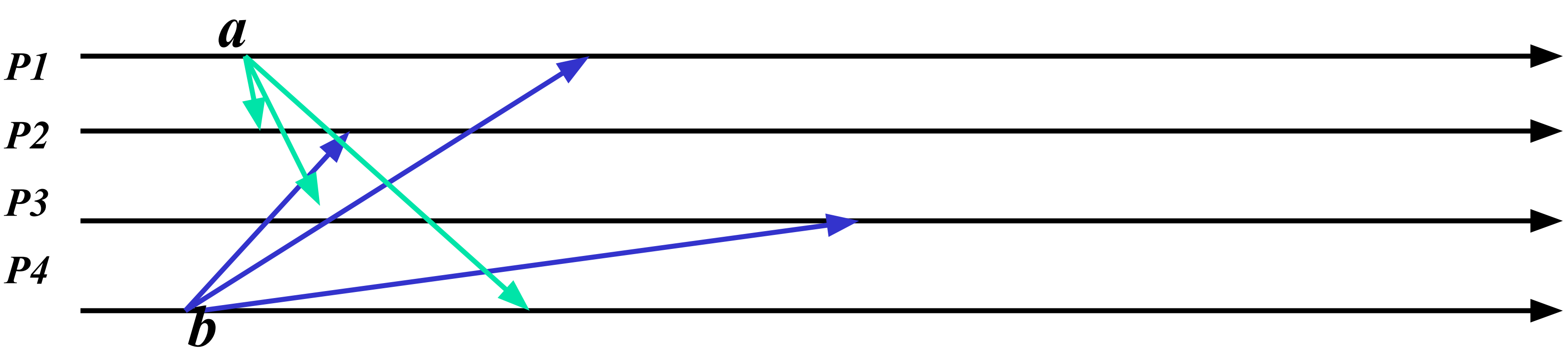

- *delivery of c to P1 is delayed until after b is delivered*
- *d and e are received in different order at P2 and P3*

# Implementing FIFO multicast

- Basic reliable (i.e., no message loss) multicast has this property
  - Without failures all we need is to run it on FIFO channels (like TCP)
  - [Later: dealing with node failures]

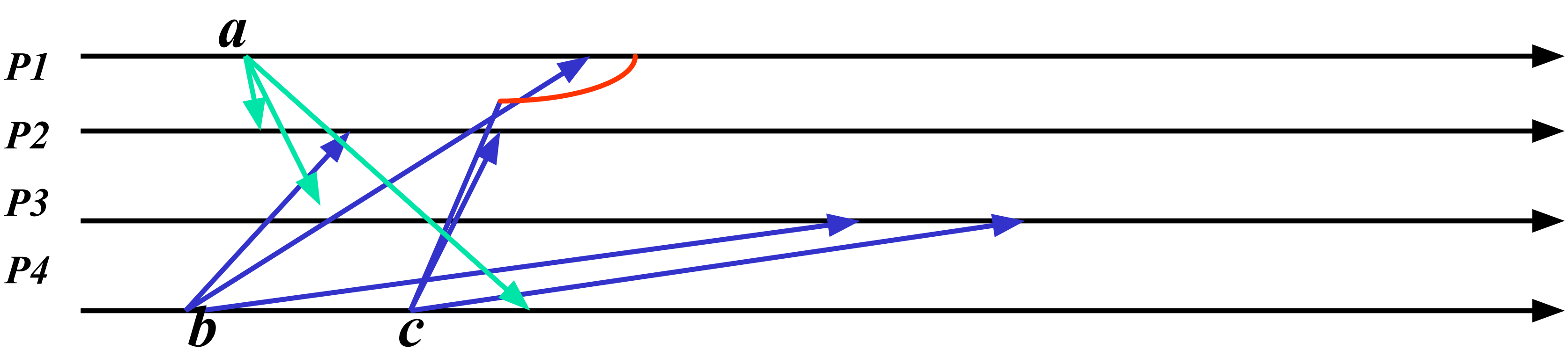
# Causal multicast

- *Causal* (or *happens-before* ordering)
- *If send(a) → send(b) (i.e., there was some causal relationship)*
  - *then deliver(a) occurs before deliver(b) at common destinations*



# Ordering properties: Causal

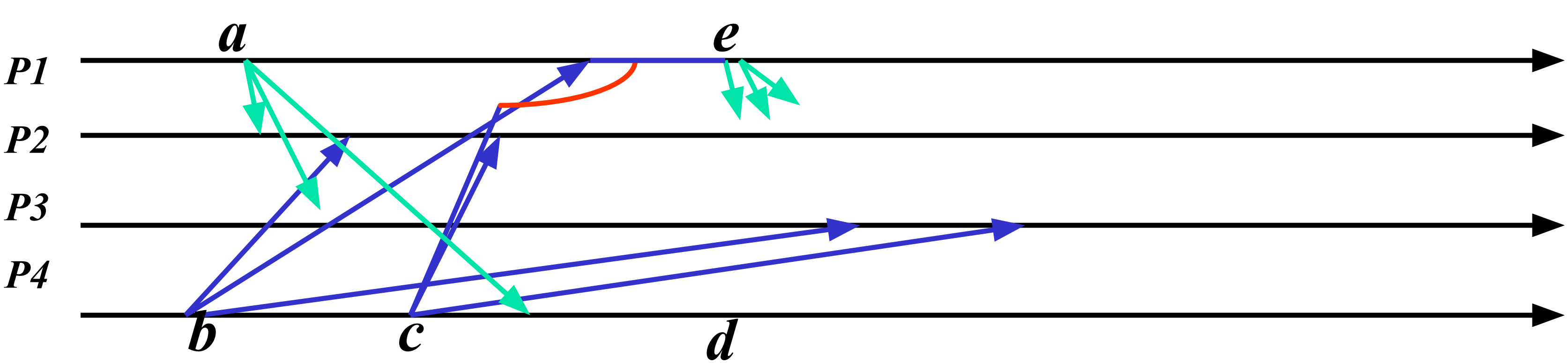
- *Causal* (or *happens-before* ordering)
- *If send(a) → send(b) (i.e., there was some causal relationship)*
  - *then deliver(a) occurs before deliver(b) at common destinations*




***delivery of c to P1 is delayed until after b is delivered***

# Ordering properties: Causal

- *Causal* (or *happens-before* ordering)
- *If send(a) → send(b) (i.e., there was some causal relationship)*
  - *then deliver(a) occurs before deliver(b) at common destinations*

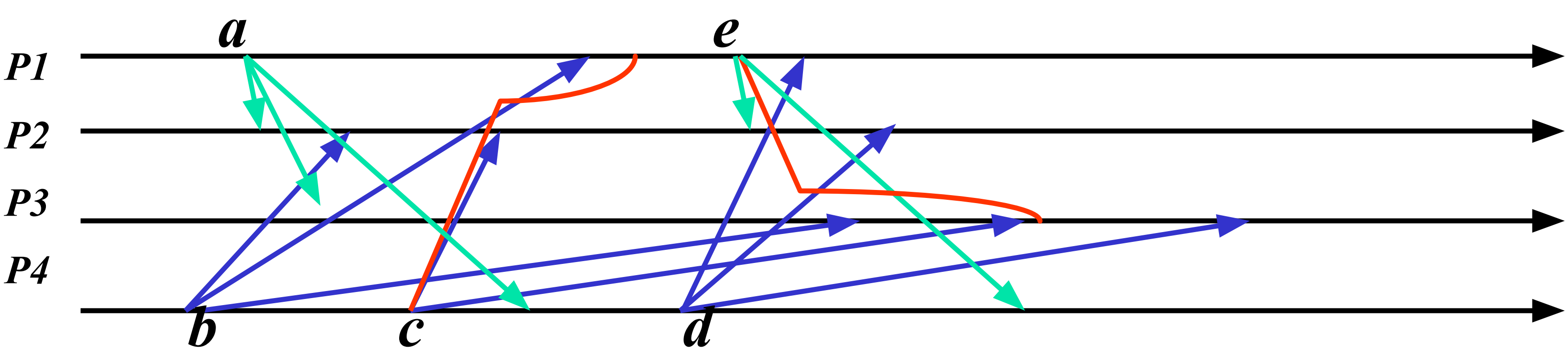



***e is sent (causally) after b and c***
***e is sent concurrently with d***

# Ordering properties: Causal

- *Causal* (or *happens-before* ordering)
- *If send(a) → send(b)*

  *(i.e., if there was some causal relationship) between a and b)*
  - *then deliver(a) occurs before deliver(b) at common destinations*



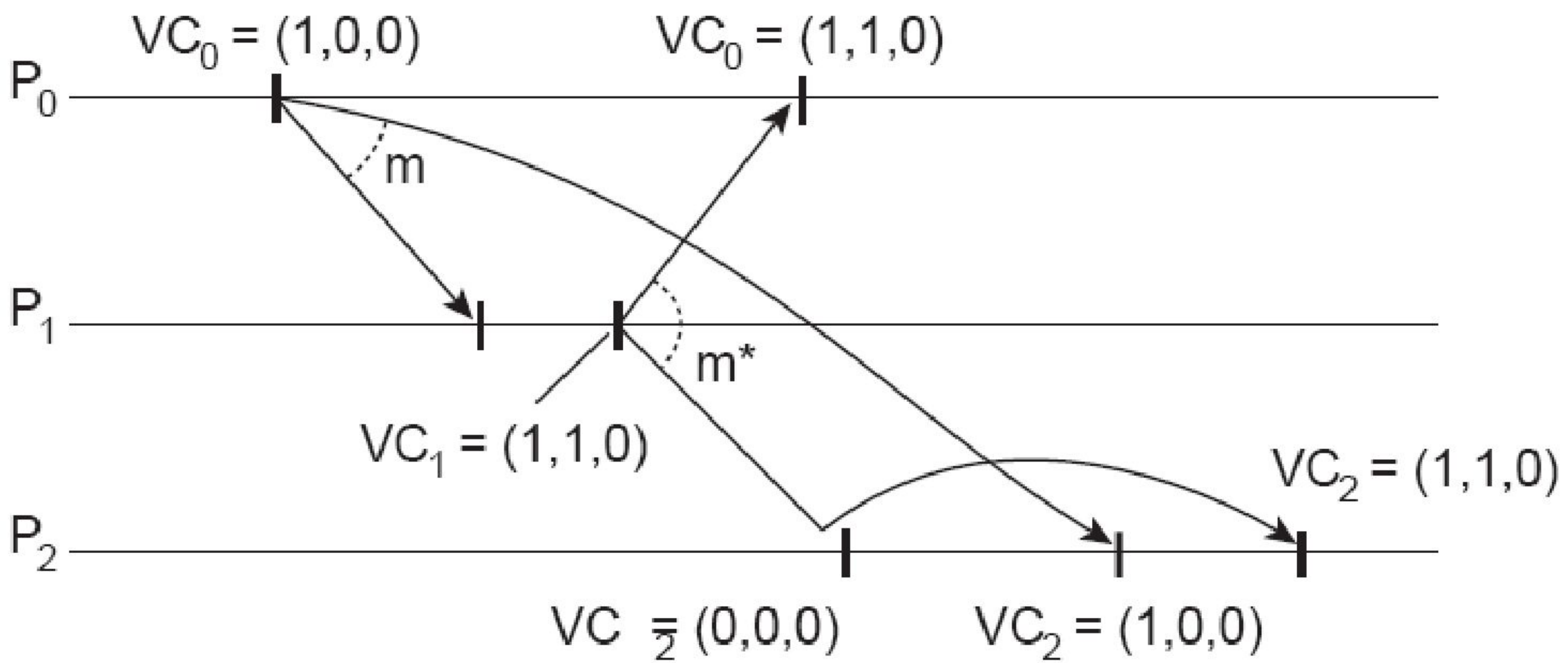

***delivery of c to P1 is delayed until after b is delivered***

***delivery of e to P3 is delayed until after b&c are delivered***

***delivery of e and d to P2 and P3 in any relative order (concurrent)***

# Implementing causally ordered multicast

[note slightly different update rule for vector clocks to enable counting the number of messages sent by each machine]




Now suppose that $P_j$ receives a message m from $P_i$ with (vector) timestamp $ts(m)$. The delivery of the message to the application layer will then be delayed until the following two conditions are met:

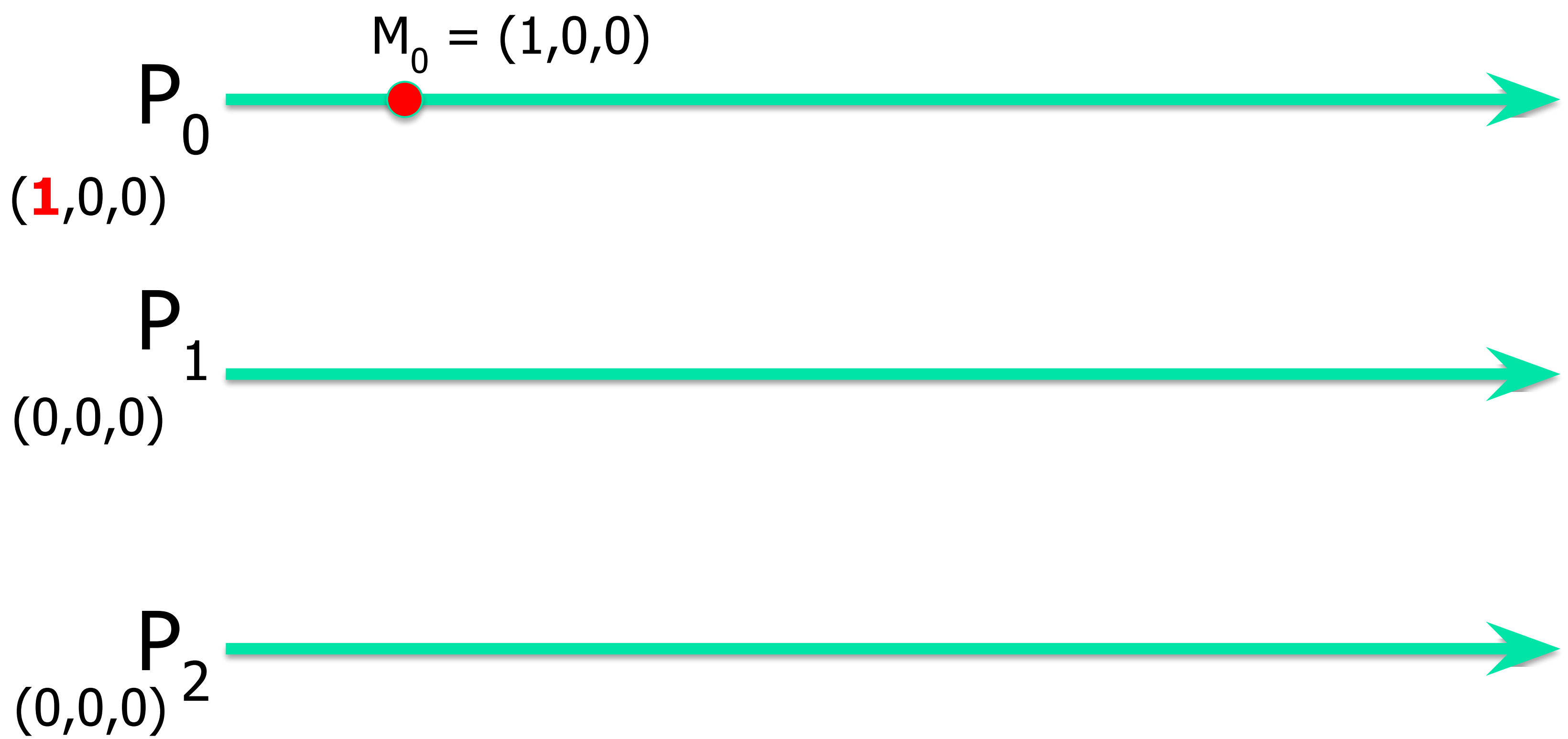
1. $ts(m)[i] = VC_j[i] + 1$
2. $ts(m)[k] \leq VC_j[k]$ for all $k \neq i$

# Implementing causally ordered multicast

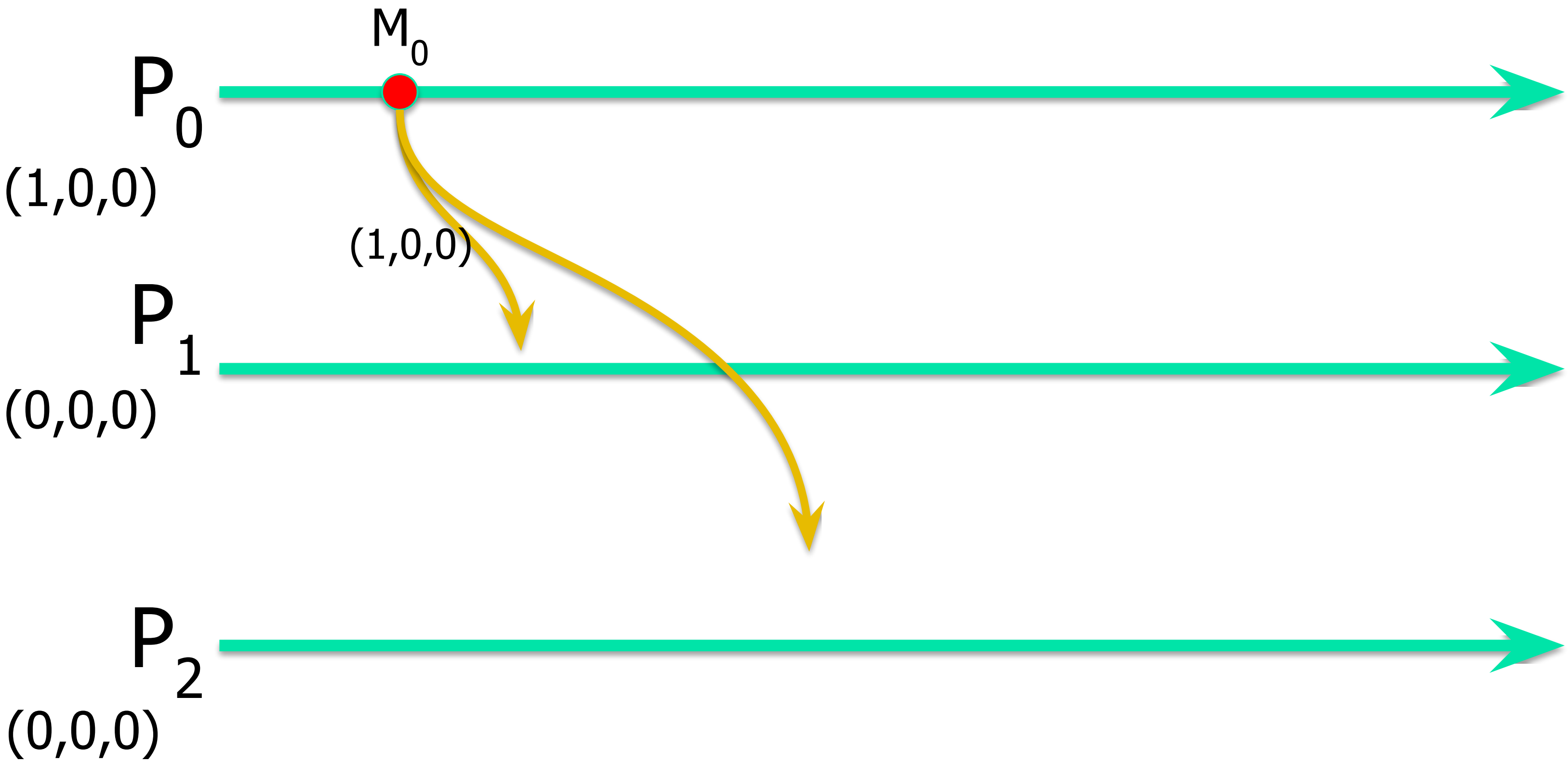

Vector clocks on each process all initialized at (0,0,0)

At process $P_i$ position $i$ will count how many messages $P_i$ has sent

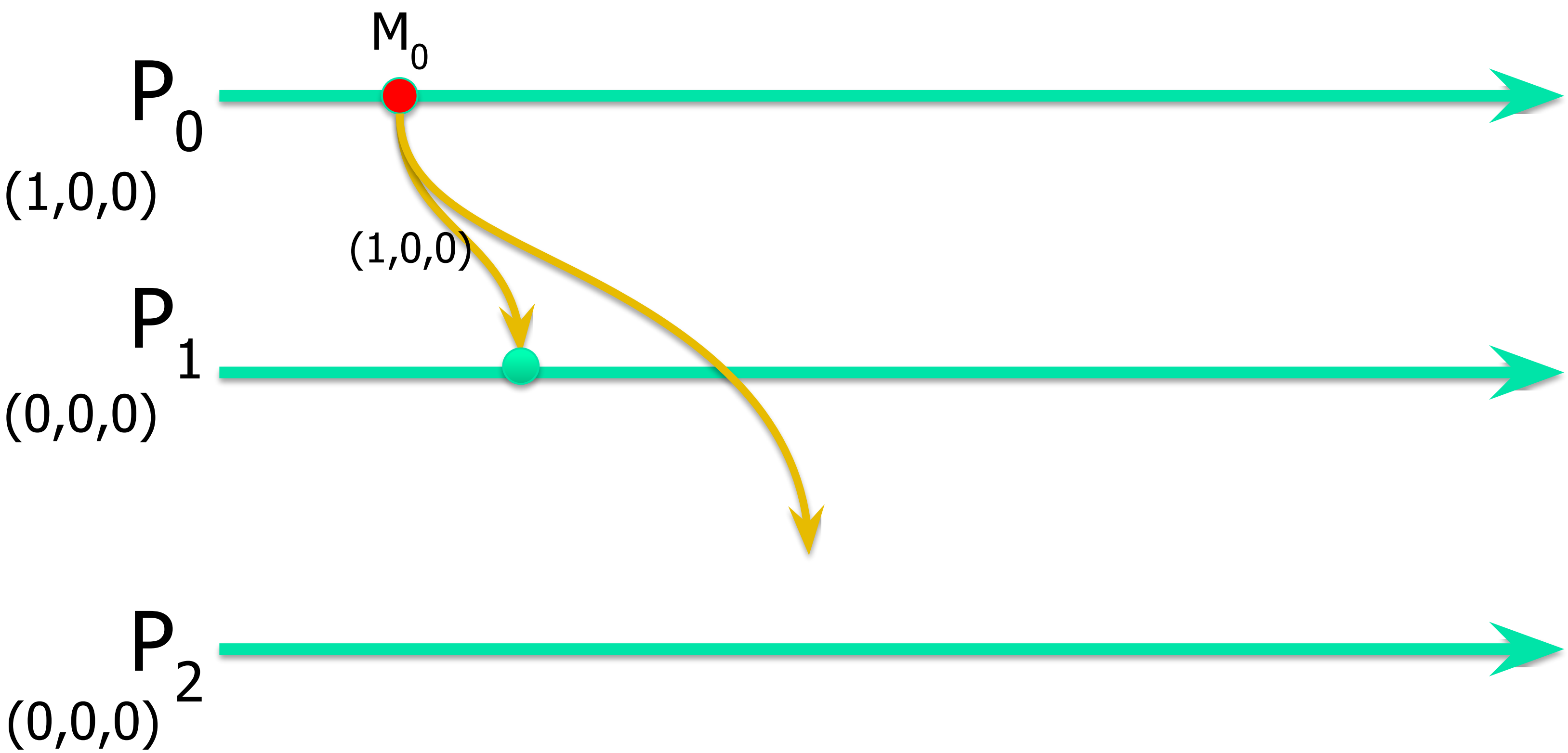
position $k \neq i$ will count how many messages $P_i$ has received from $P_k$



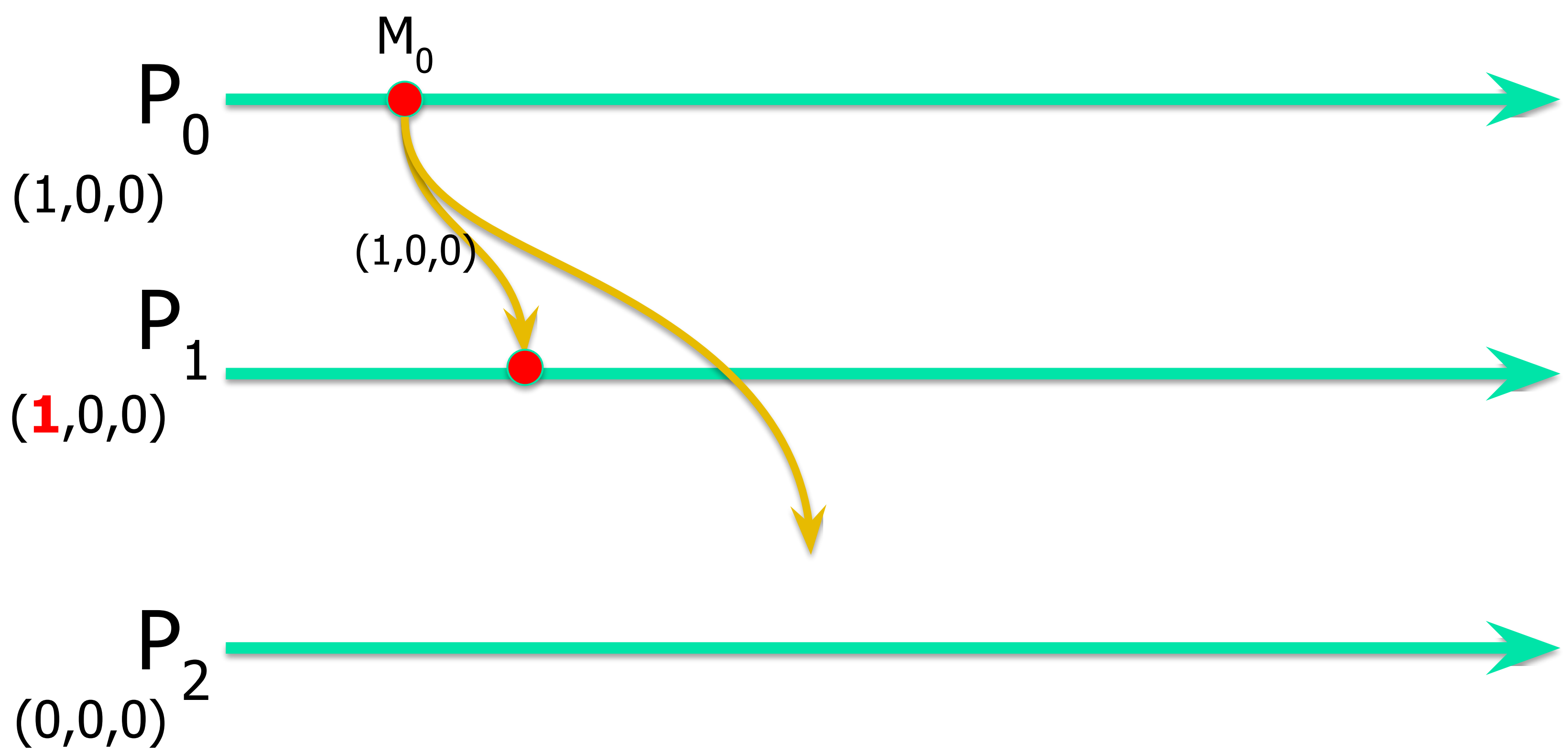

- Message Mo is initiated at Po and can be delivered to application locally.
- Vector clock at Po is updated.
- Mo is sent with its vector clock



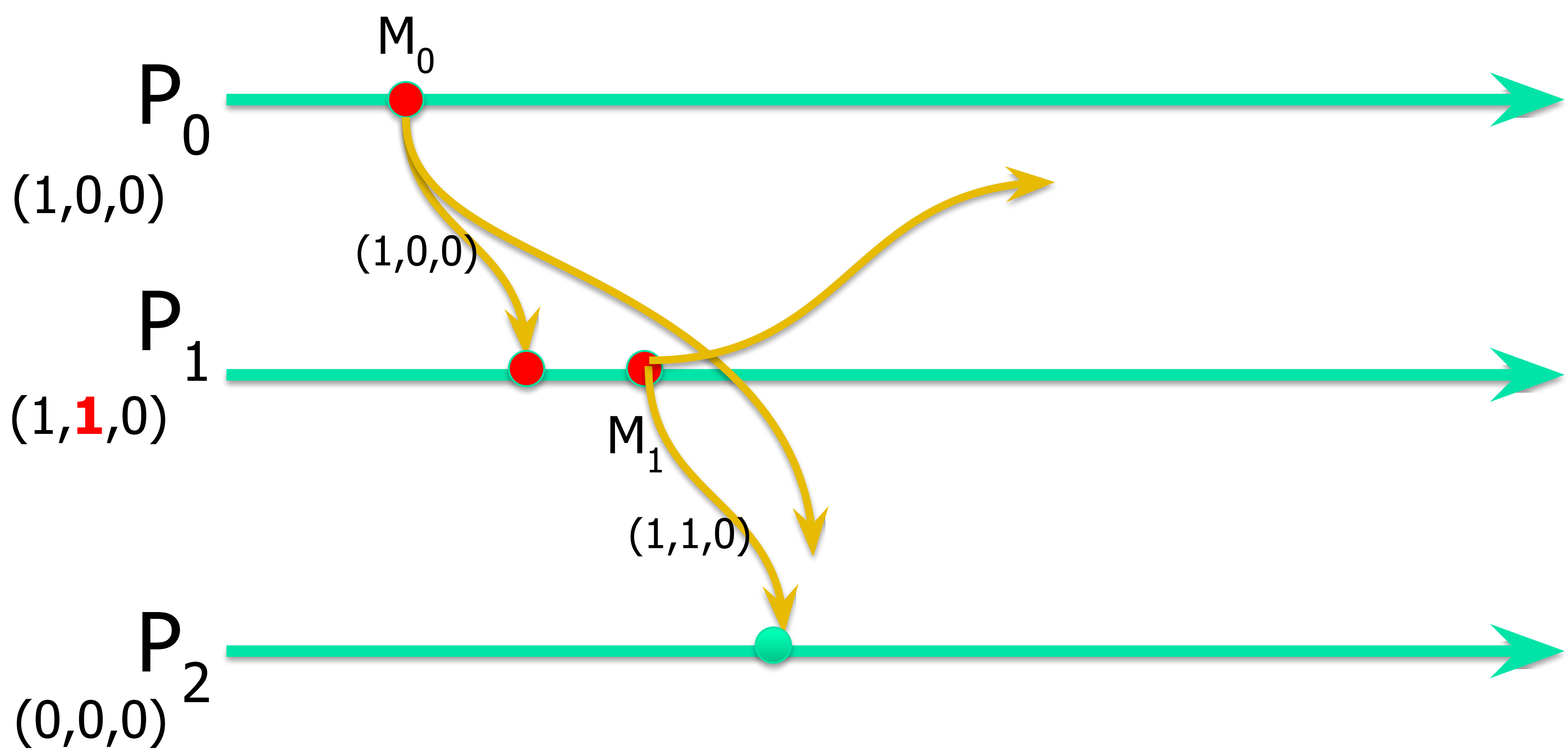

- Message Mo is initiated at Po and can be delivered to the application locally.
- Vector clock at Po is updated.
- Mo is sent with its vector clock to the other processes



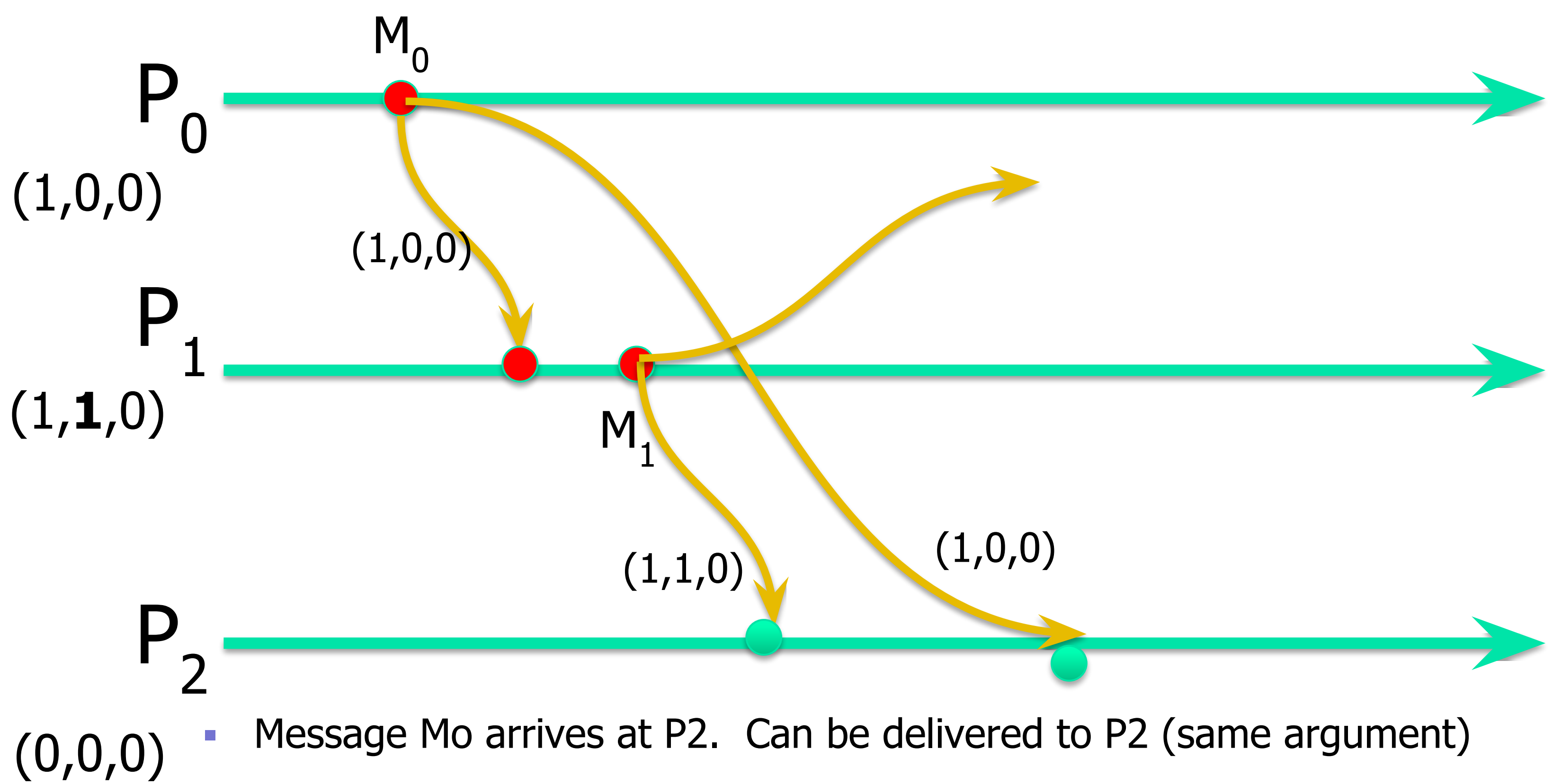

- Message Mo arrives at P1
- Message Mo can be delivered to the application at P1: the check - all messages that have potentially been received at Po before generating Mo have been seen by P1 as well



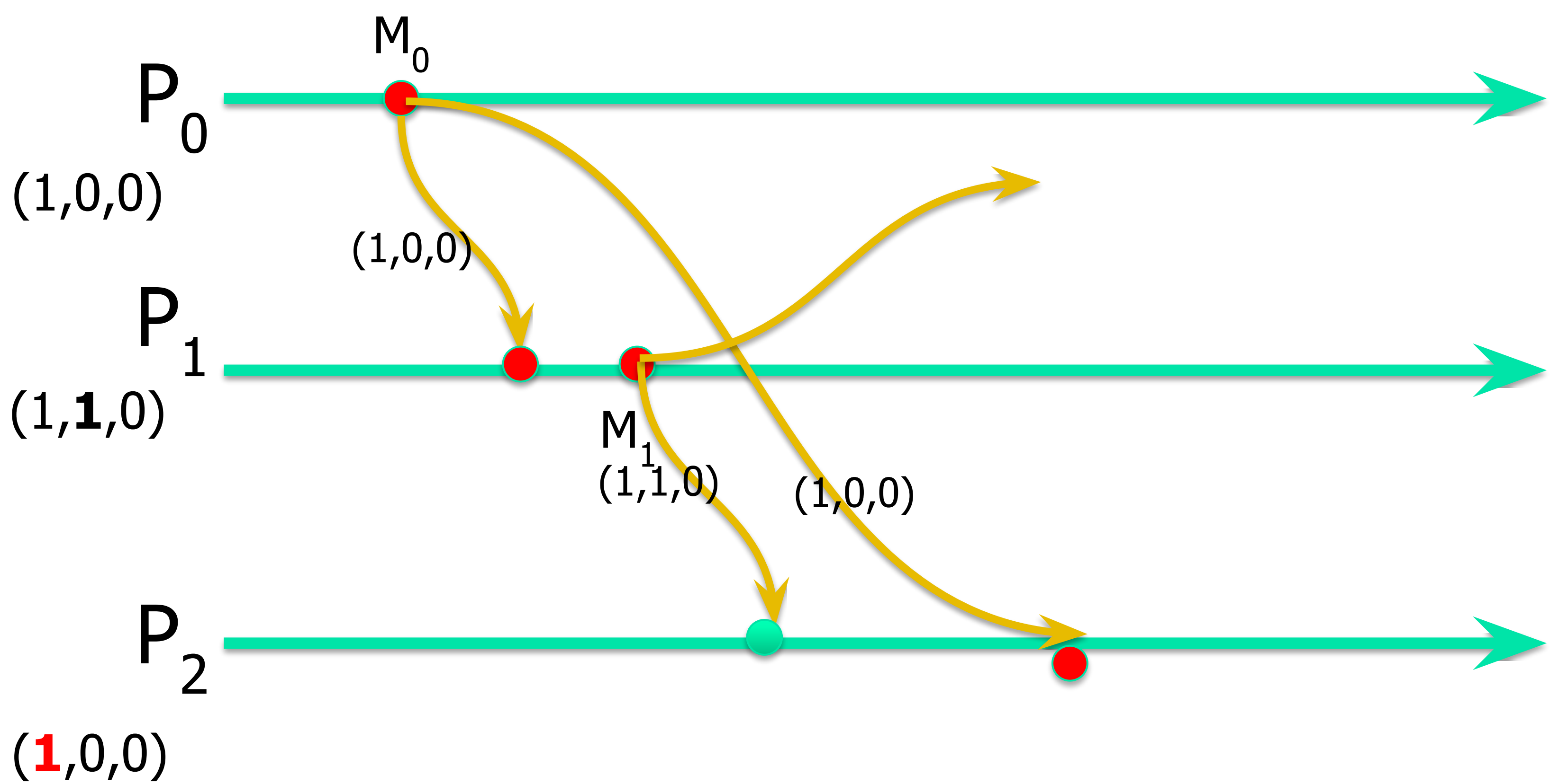

- Message Mo is delivered at P1
- P1 updates its vector clock



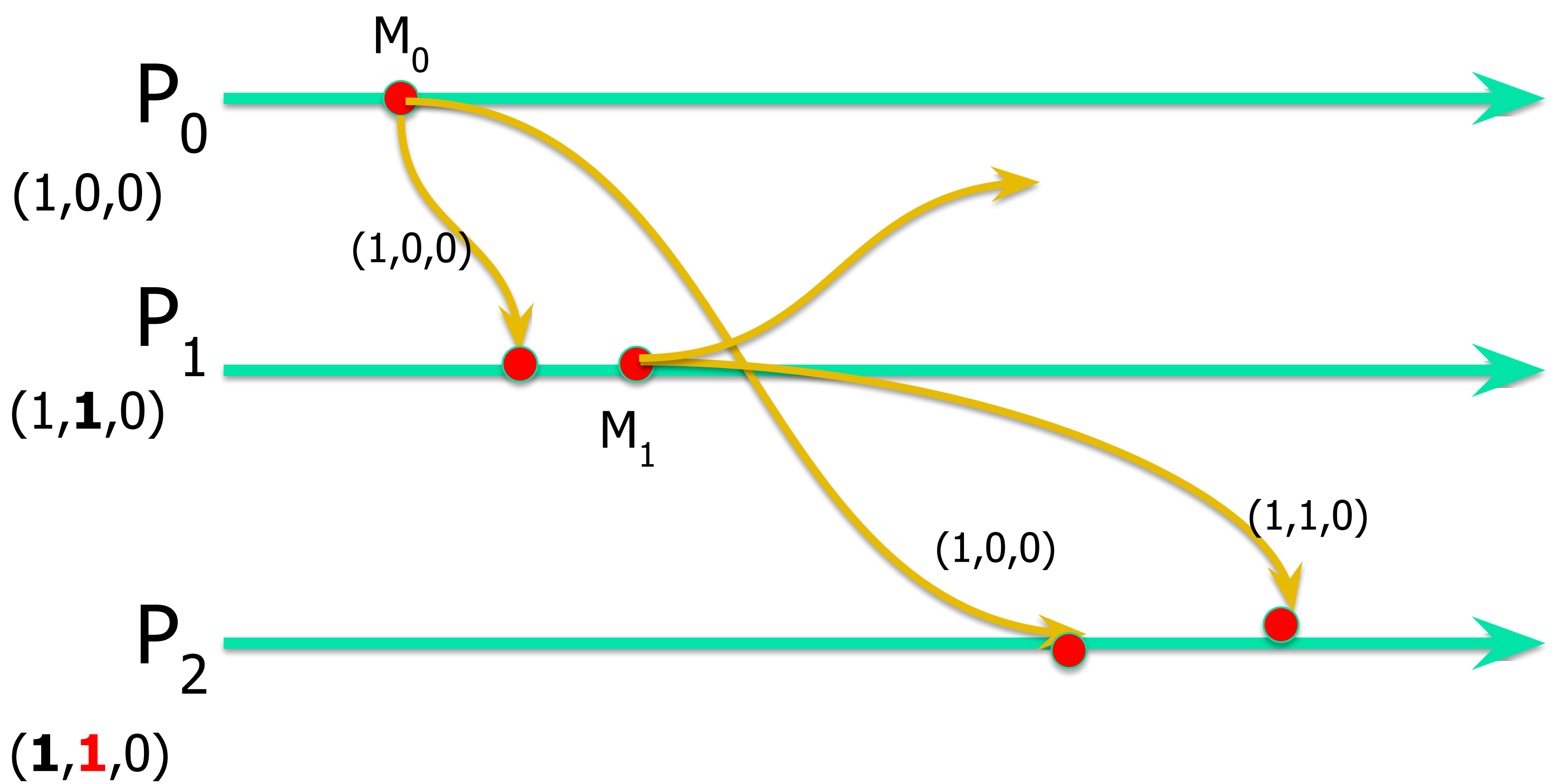

- Message M1 is created by P1. The message can be delivered to local application at P1. P1 updates its vector clock. This timestamp (1,1,0) is carried by M1.
- Message M1 arrives at P2. Can not be delivered to P2 since, M1's vector clock at position 0 implies that, when M1 was created it has one message from Po and P2 has not yet seen that message.



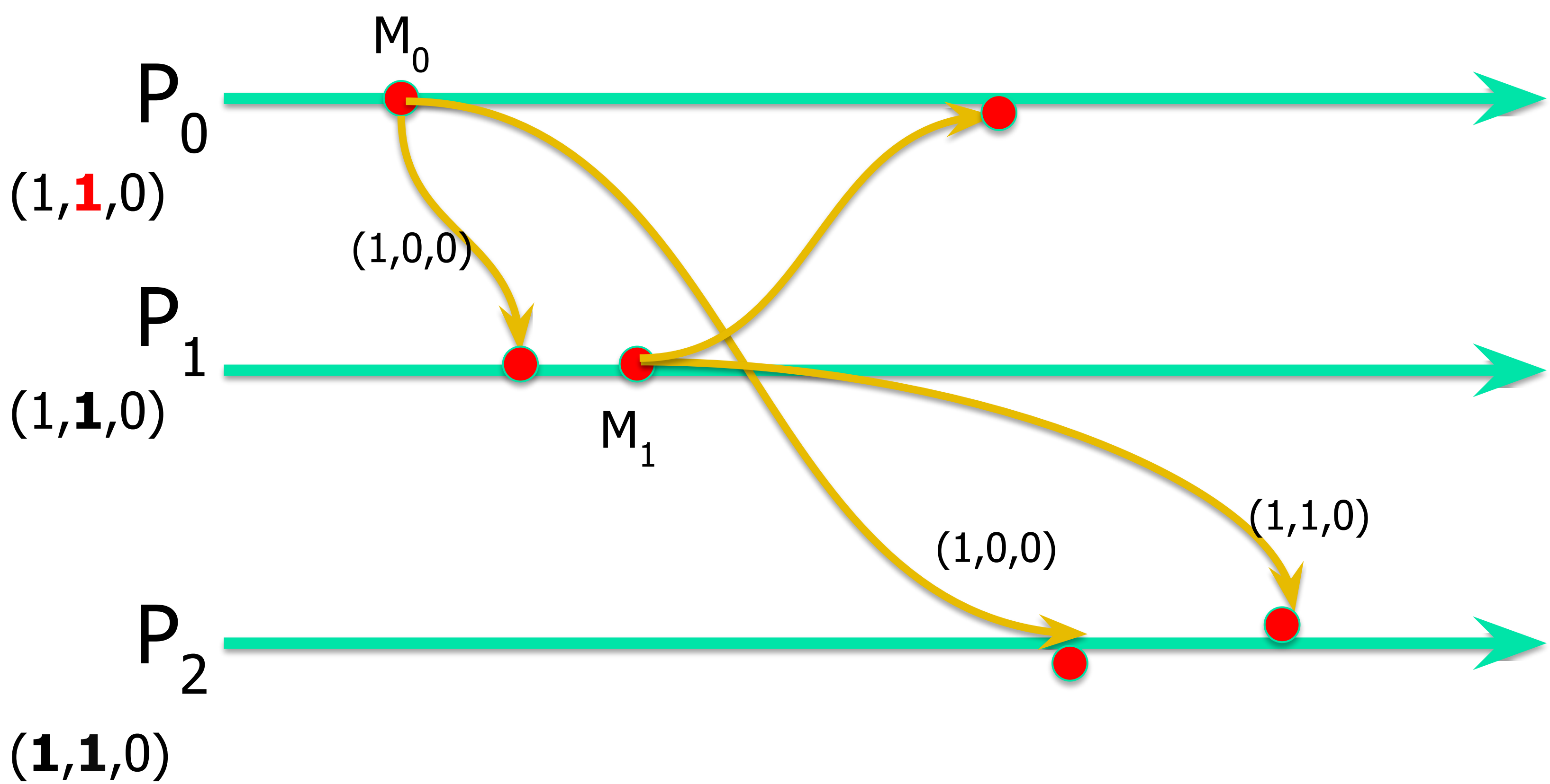

- Message Mo arrives at P2. Can be delivered to P2 (same argument)




- Message Mo is delivered to P2. P2's vector clock is updated.
- Now P2 can look at the other messages it has in its queue




- Now Mo can be delivered to application at P2. P2’s vector clock is updated.




- M1 arrives at Po and can be delivered to application. Po updates its vector clock

# Implementing causal order multicast

- Start with FIFO multicast
- Strengthen this into a causal multicast by adding vector time

- **Advantages** (compared with totally ordered multicast)
  - No additional messages needed!
    - Lower overhead
  - causal multicast (as well as FIFO multicast) are *asynchronous:*
    - Sender doesn't get blocked and can deliver a copy to itself without "stopping" to learn a safe delivery order

# Sample quiz question

**6.11** Five processes 0, 1, 2, 3, 4 in a completely connected network decide to maintain a *distributed bulletin board*. No central version of it physically exists, but every process maintains an image of it. To post a new bulletin, each process multicasts every message to the other four processes, and recipient processes willing to respond to an incoming message multicast their responses in a similar manner. To make any sense from a response, every process must *accept* every message and response in *causal order*, so a process receiving a message will postpone its *acceptance* unless it is confident that no other message causally ordered before this one will arrive in future.

To detect causality, the implementation uses *vector clocks*. Each message or response is tagged with an appropriate vector time stamp. Figure out (a) a rule for assigning these vector time stamps and (b) the corresponding algorithm using which a process will decide whether to accept a message immediately or postpone its acceptance.

# So far …

- Physical clocks
  - Two applications
    - Provide at-most-once semantics
    - Global Positioning Systems
- ‘Logical clocks’
  - Where only ordering of events matters

- Next:
  - Replication
  - One application that puts everything together