416 Distributed Systems

Time in distributed systems

Feb 8, 2022

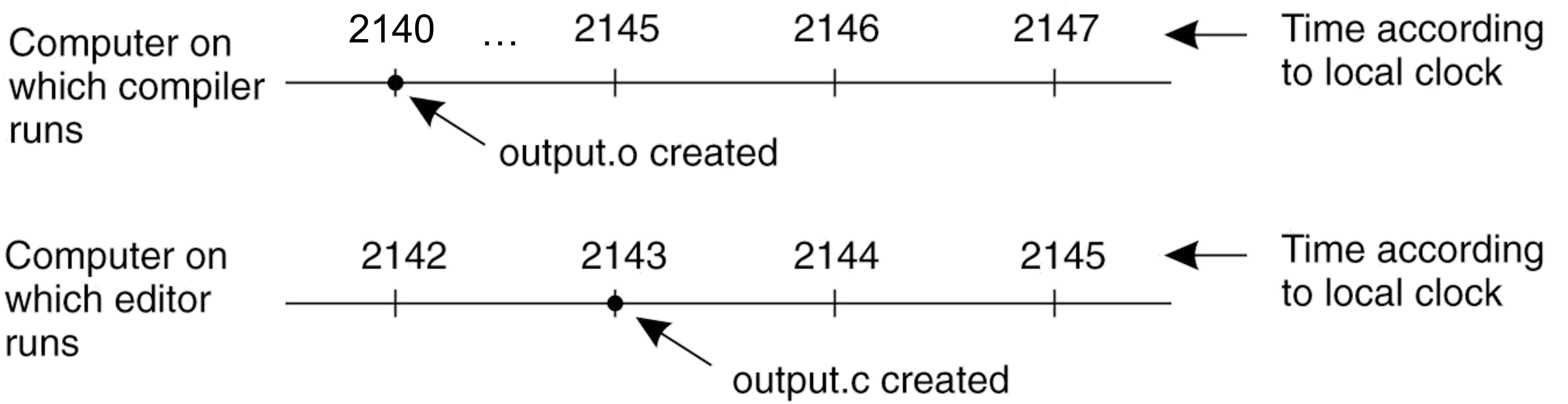
Today's Lecture

- Need for time synchronization
- Time synchronization techniques
- Logical clocks
  - Lamport Clocks
  - Vector Clocks

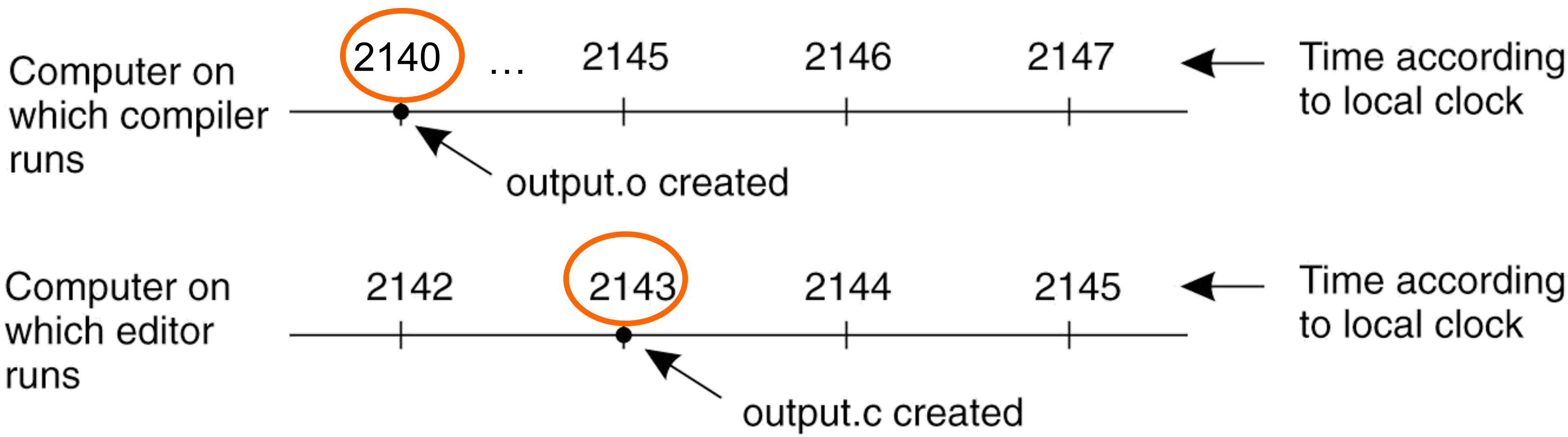
Why Global Timing?

- Suppose there were a globally consistent time standard
- Would be handy
  - Who got last seat on airplane?
  - Who submitted final auction bid before deadline?
  - Did defense move before snap? (warning: football reference)
  - In A2:
    - Did *GameComplete@client1* happen before or after *ServerFailed@server2*?

Impact of Clock Synchronization

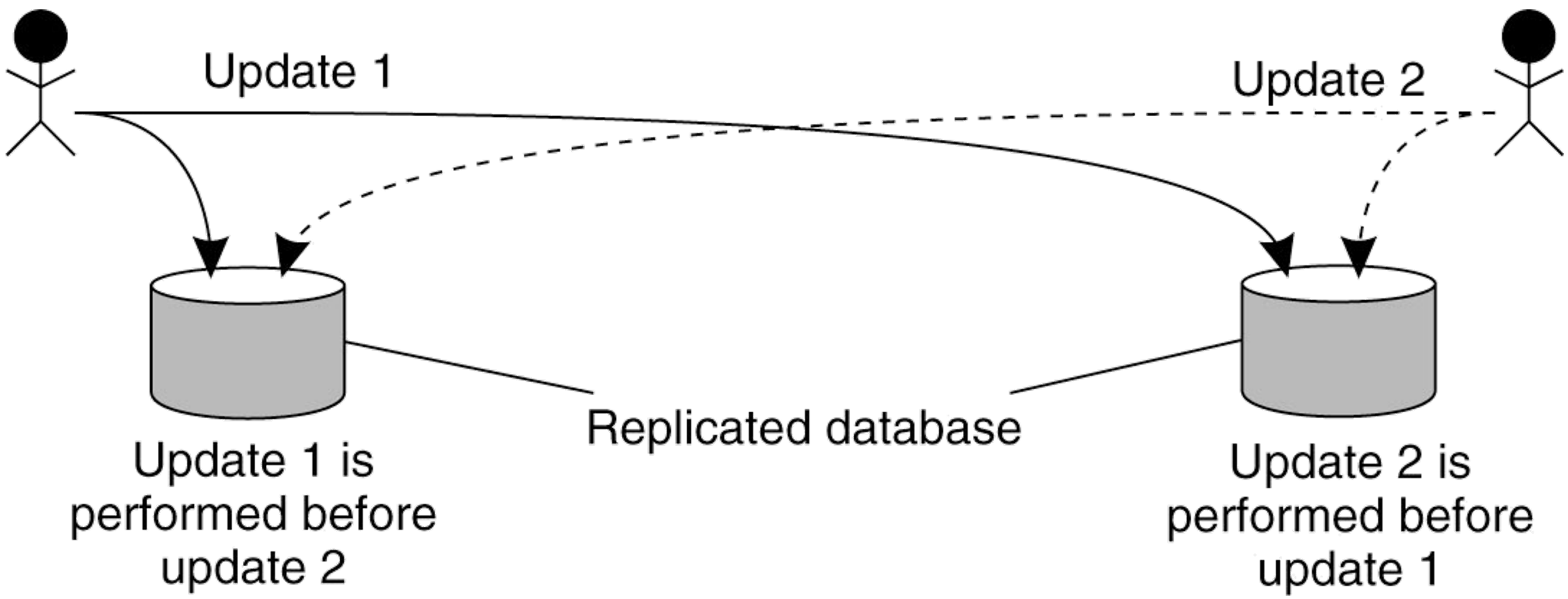


Impact of Clock Synchronization



- When each machine has its own clock, an event that occurred after another event may nevertheless be assigned an earlier time.

Replicated Database Update



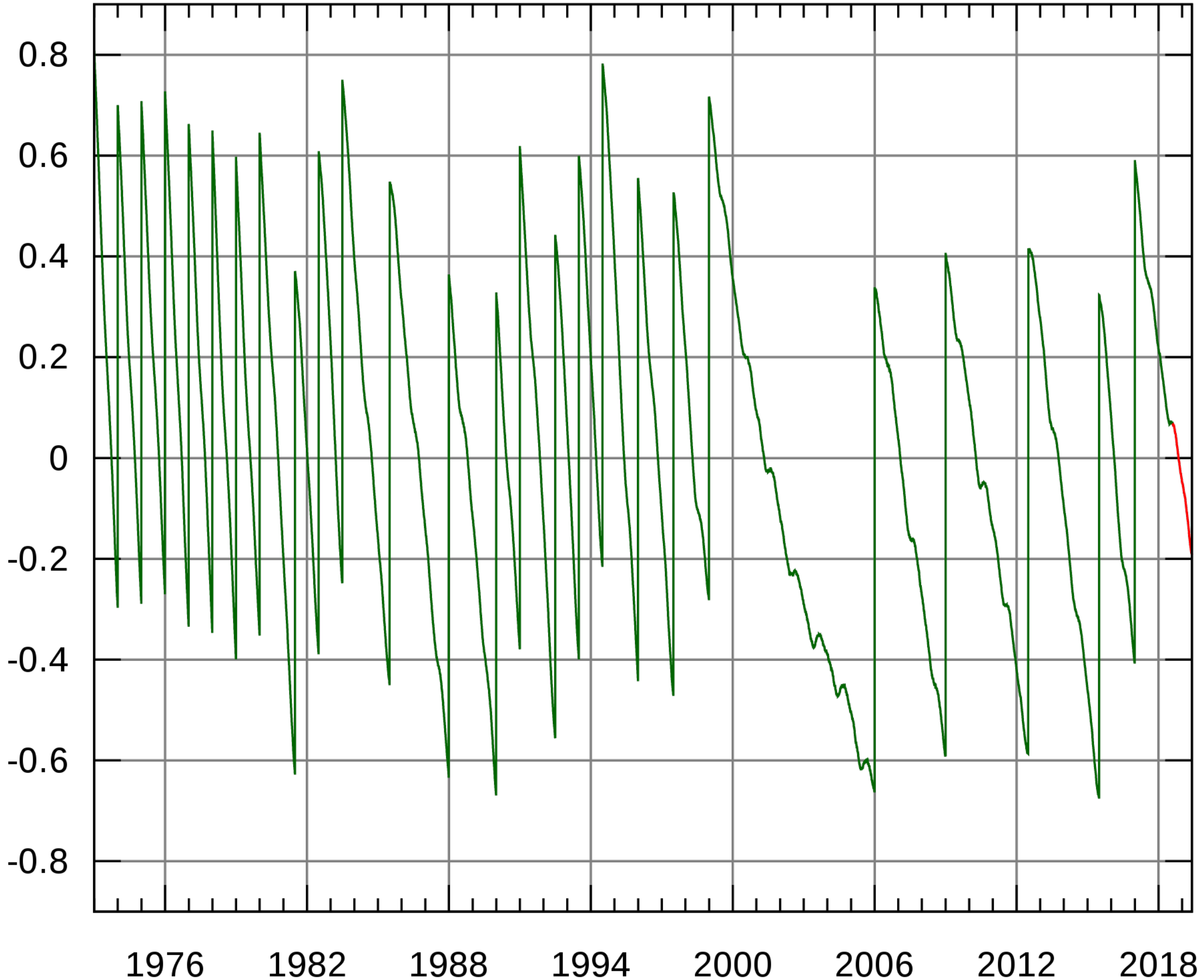
- Updating a replicated database and leaving it in an inconsistent state

Time Standards

- UT1 (universal time)
  - Based on astronomical observations
  - ~ "Greenwich Mean Time" (GMT)
- TAI (international atomic time)
  - Started Jan 1, 1958
  - Each second is 9,192,631,770 cycles of radiation emitted by Cesium atom
  - Has diverged from UT1 due to slowing of earth's rotation
- UTC (coordinated universal time)
  - TAI + leap seconds to be within 0.9s of UT1
  - Currently ~37s

Comparing Time Standards

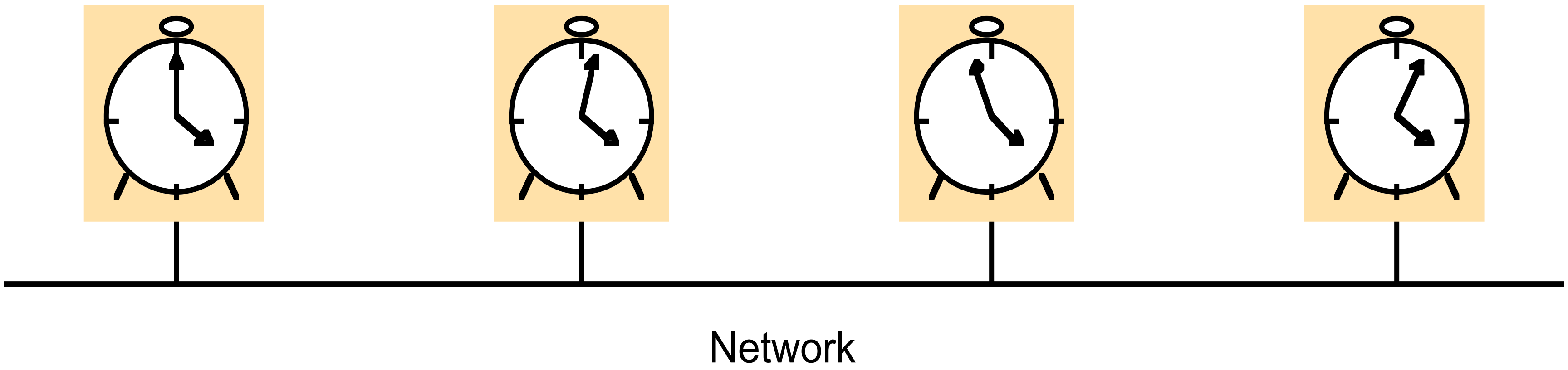
UT1 – UTC



Coordinated Universal Time (UTC)

- Is broadcast from radio stations on land and satellite (e.g., GPS)
- Computers with receivers can synchronize their clocks with these timing signals
- Signals from land-based stations are accurate to about 0.1-10 millisecond
- Signals from GPS are accurate to about 1 microsecond
  - Why can't we use GPS receivers on all our computers?

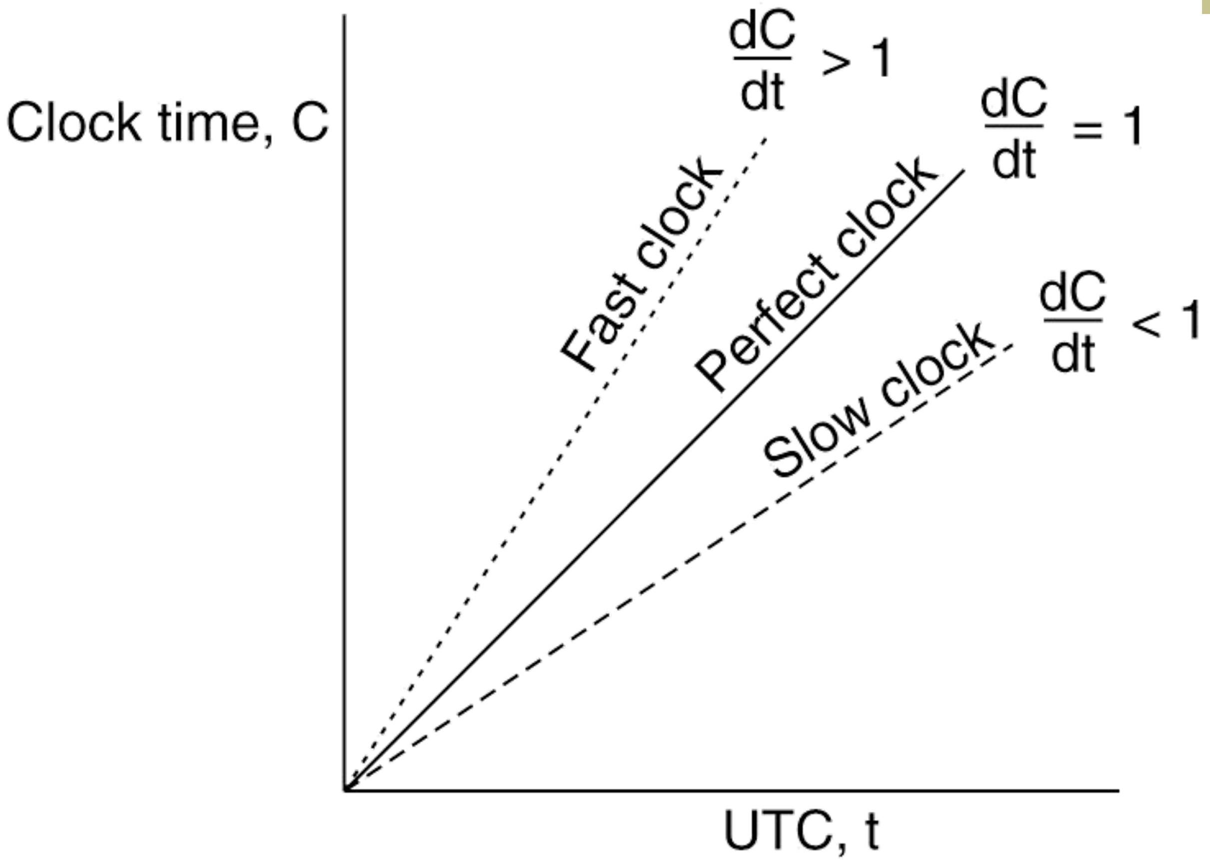
Clocks in a Distributed System



- Computer clocks are not generally in perfect agreement
  - **Skew**: the difference between the times on two clocks (at any instant)

- Computer clocks are subject to clock drift (they count time at different rates; consider batteries)
  - **Clock drift rate**: the difference per unit of time from some ideal reference clock
  - Ordinary quartz clocks drift by about 1 sec in 11-12 days. (10^{-6} secs/sec).
  - High precision quartz clocks drift rate is about 10^{-7} or 10^{-8} secs/sec

Clock drift visualized



- The relation between clock time and UTC when clocks tick at different rates.

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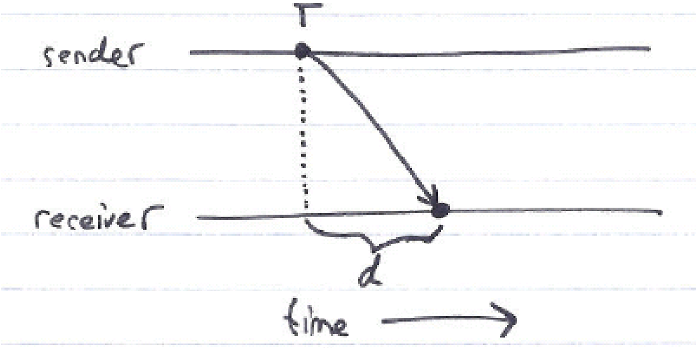
- Vector Clocks

Perfect networks

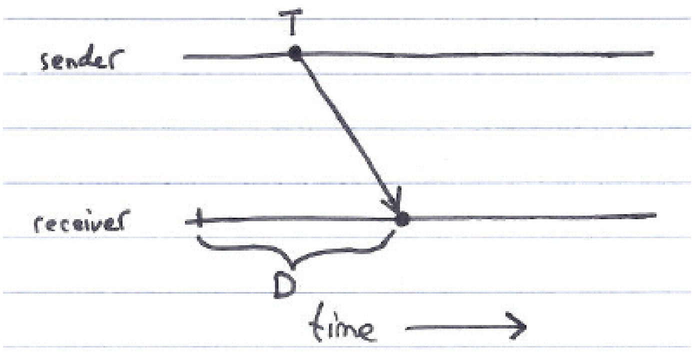
- Messages always arrive, with propagation delay exactly *d*



- Sender sends time *T* in a message
- Receiver sets clock to *T+d*
    - Synchronization is exact

Synchronous networks

- Messages always arrive, with propagation delay *at most* *D*



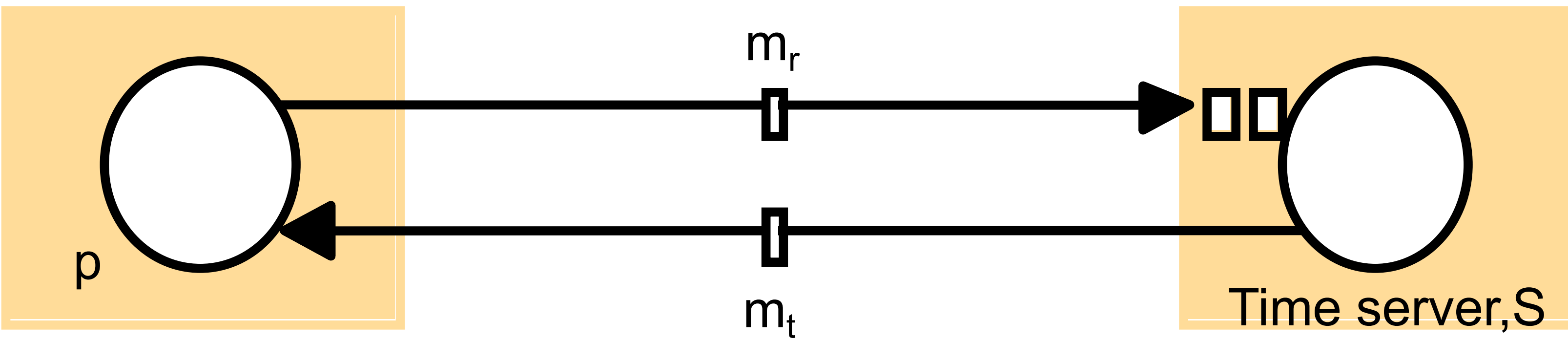
- Sender sends time *T* in a message
- Receiver sets clock to *T* + *D/2*
  - Synchronization error is at most *D/2*

Synchronization in the real world

- Real networks are asynchronous
  - Message delays are arbitrary
- Real networks are unreliable
  - Messages don’t always arrive

Cristian's Time Sync ('89)

- A time server *S* receives signals from a UTC source
  - Process *p* requests time in m_r and receives *t* in m_t from *S*
  - *p* sets its clock to $t + T_{round\text{-}trip}/2$
  - Accuracy $\pm\ (T_{round\text{-}trip}/2 - min)$:
    - Where *min* is minimum one-way transmission delay
    - because the earliest time *S* puts *t* in message m_t is *min* after *p* sent m_r.
    - the latest time was *min* before m_t arrived at *p*
    - the time by *S*'s clock when m_t arrives is in the range $[t+min,\ t + T_{round\text{-}trip} - min]$



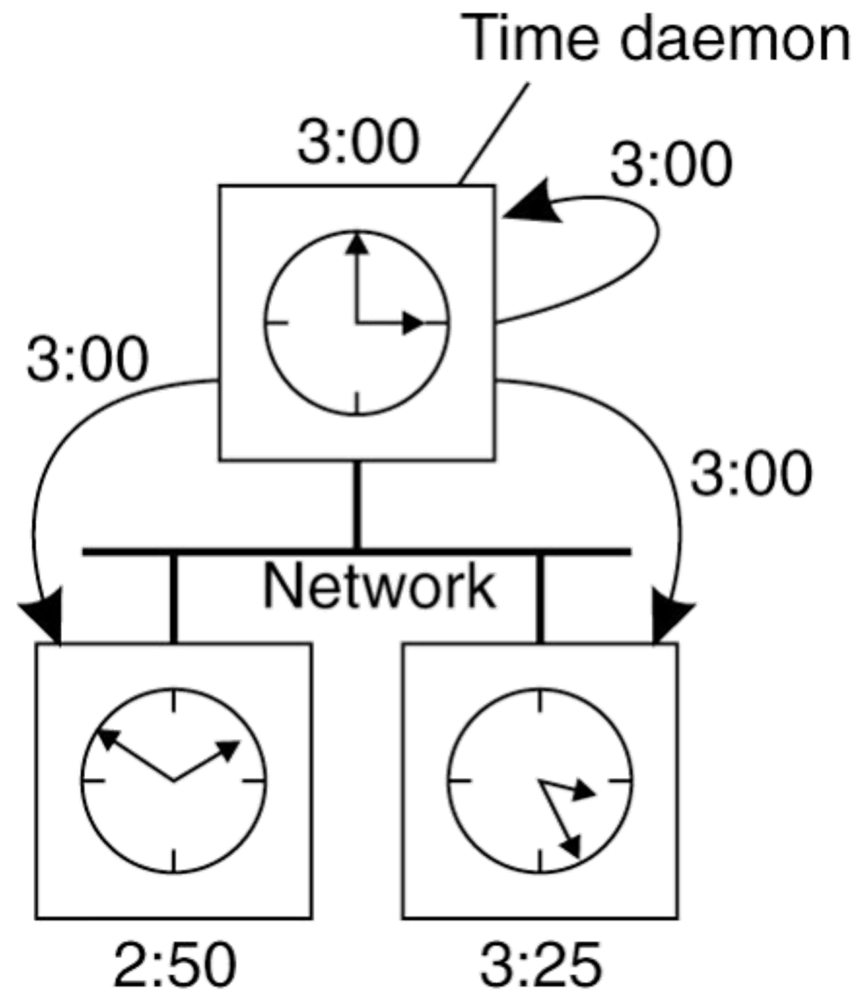
T_{round} is the round trip time recorded by *p*
min is an estimated minimum one way delay

Berkeley algorithm

- Cristian's algorithm -
  - a single time server might fail, so they suggest the use of a group of synchronized servers
  - it does not deal with faulty servers
- Berkeley algorithm (also 1989)
  - An algorithm for *internal* synchronization of a group of computers
  - A *coordinator* polls to collect clock values from the others (*replicas*)
  - The coordinator uses round trip times to estimate the replicas' clock values (only coordinator computes RTT)
  - It takes an average (eliminating any above average round trip time or with faulty clocks)
  - It sends the required adjustment to the replicas (better than sending the time which depends on the round trip time)
  - Failures
    - If coordinator fails, can elect a new coordinator to take over (not in bounded time)

The Berkeley Algorithm (1)

- The time daemon asks all the other machines for their clock values.

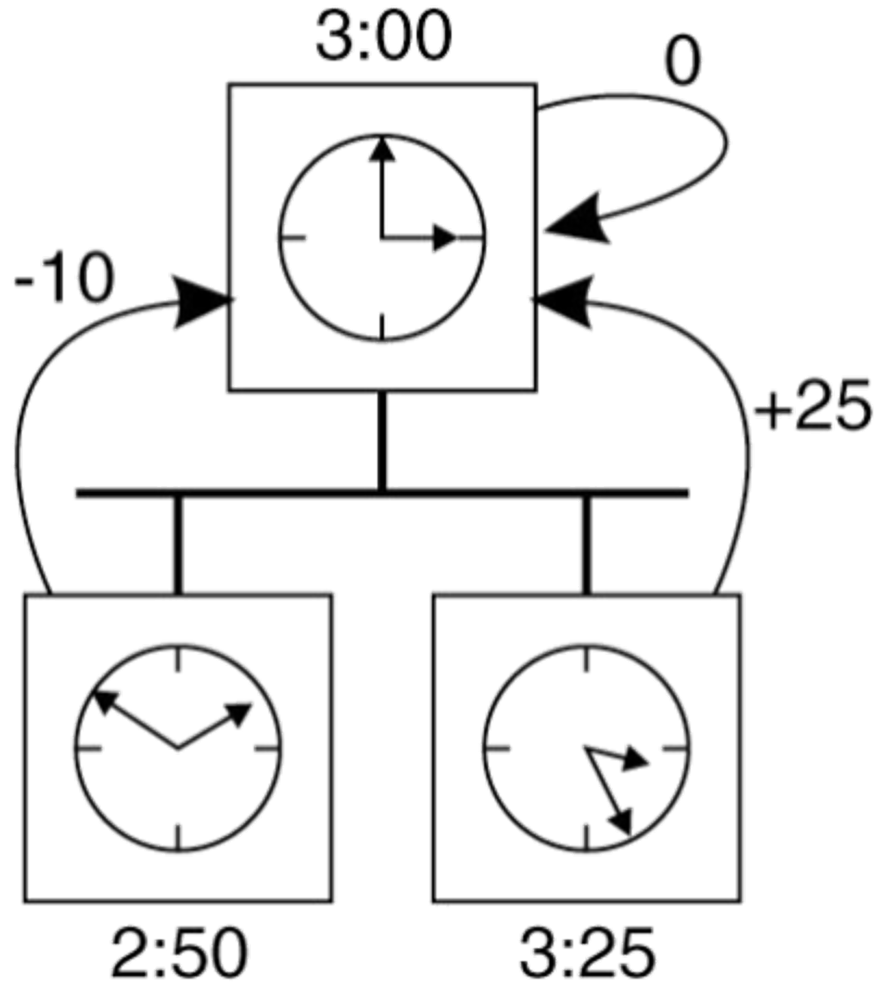


The Berkeley Algorithm (2)

- The machines answer.

Compute avg:
+15 / 3 = +5

Adjustment:
0 → +5 = +5
-10 → +5 = +15
+25 → +5 = -20



The Berkeley Algorithm (3)

- The time daemon tells everyone how to adjust their clock.

Compute avg:
+15 / 3 = +5

Adjustment:
0 → +5 = +5
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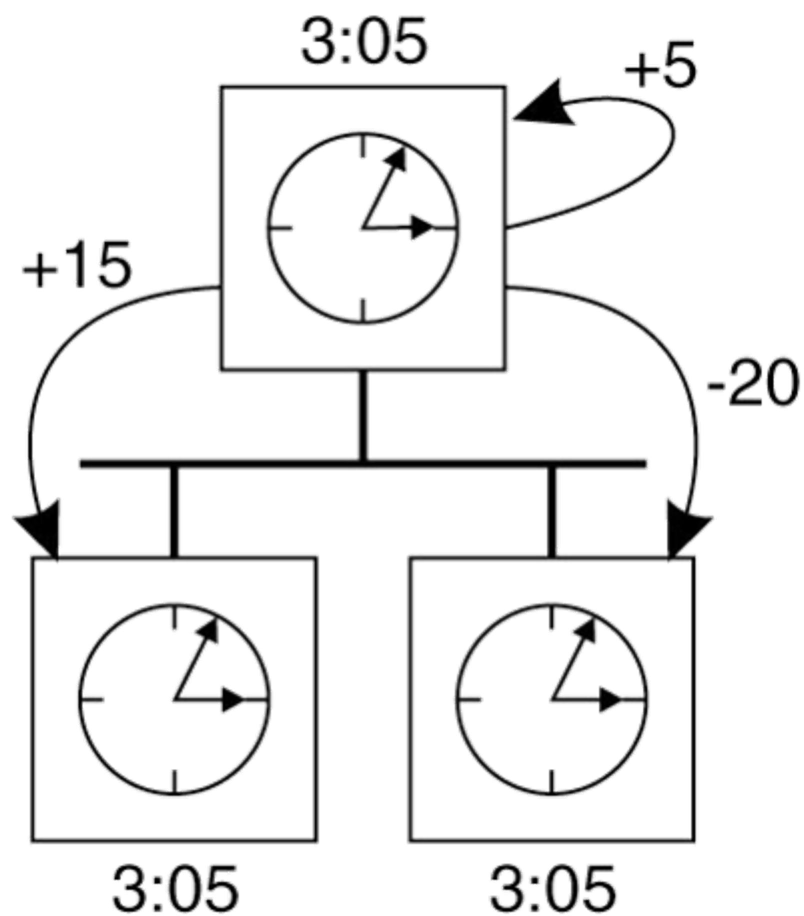


Network Time Protocol (NTP)

(invented by David Mills, 1981)

- A time service for the Internet - synchronizes clients to

Reliability from redundant paths, scalable, authenticates time sour…

Primary servers are connected to UTC

Secondary servers are synchronized to primary servers

Synchronization subnet - lowest level servers in users' computers

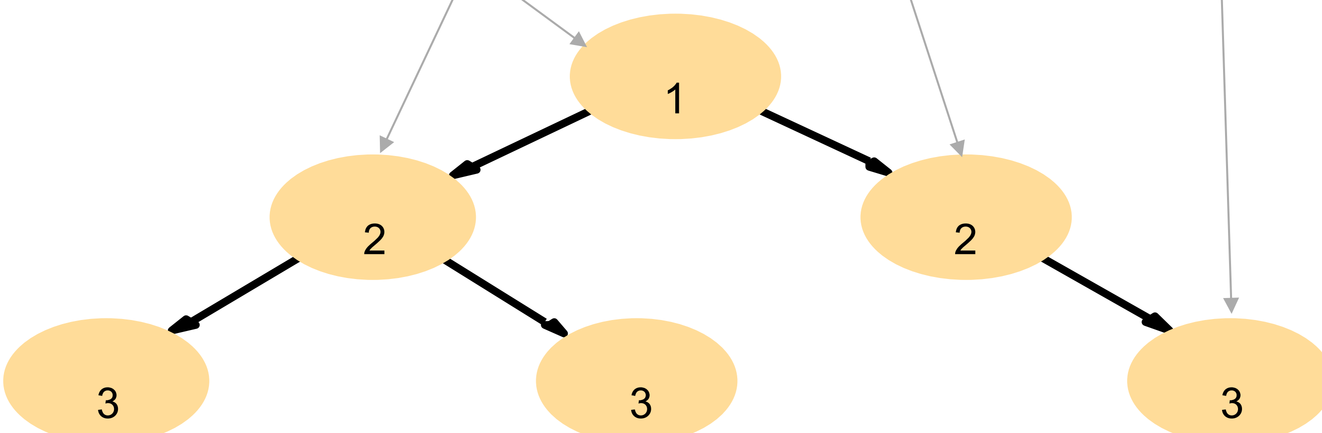


Figure 10.3

The Network Time Protocol (NTP)

- Uses UDP (minimal overhead/OS stack latency)
- Uses a hierarchy of time servers
  - Class 1 servers have highly-accurate clocks
    - connected directly to atomic clocks, etc.
  - Class 2 servers get time from only Class 1 and Class 2 servers
  - Class 3 servers get time from any server (usually 3)
- Synchronization similar to Cristian's alg.
  - Modified to use multiple one-way messages instead of immediate round-trip
- Accuracy: Local ~1ms, Global ~10ms

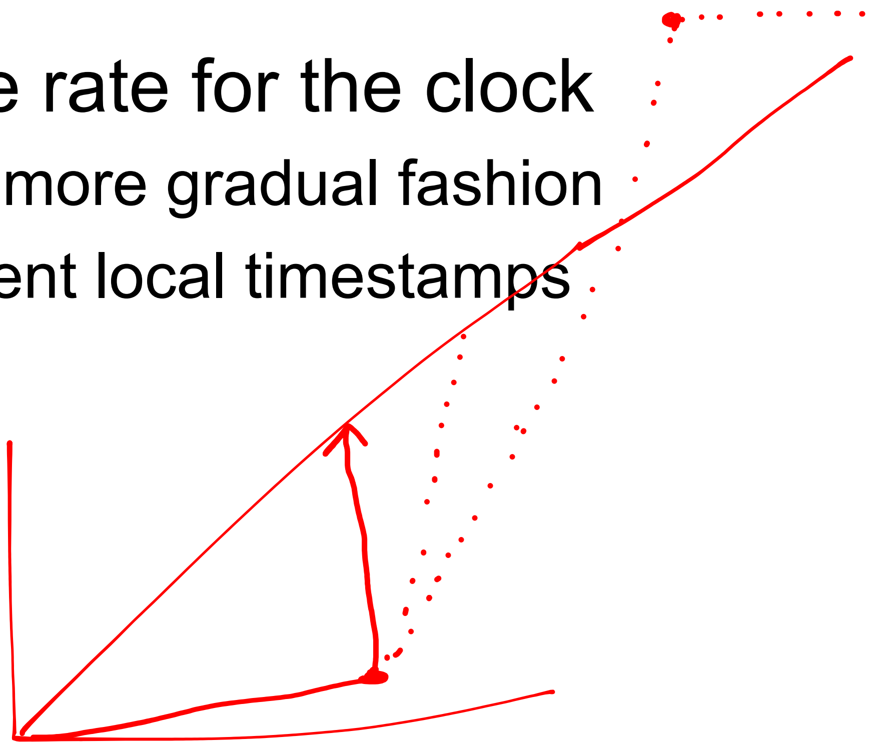
How To Change Time

- Can’t just change time
  - Why not?

How To Change Time

- Can't just change time
  - Why not?

- Change the update rate for the clock
  - Changes time in a more gradual fashion
  - Prevents inconsistent local timestamps



Important Lessons

- Clocks on different systems will always behave differently
  - Skew and drift between clocks

- Time disagreement between machines can result in undesirable behavior

- Clock synchronization
  - Rely on a time-stamped network messages
  - Estimate delay for message transmission
  - Can synchronize to UTC or to local source
  - Clocks never exactly synchronized

- Often inadequate for distributed systems
  - might need totally-ordered events
  - might need millionth-of-a-second precision

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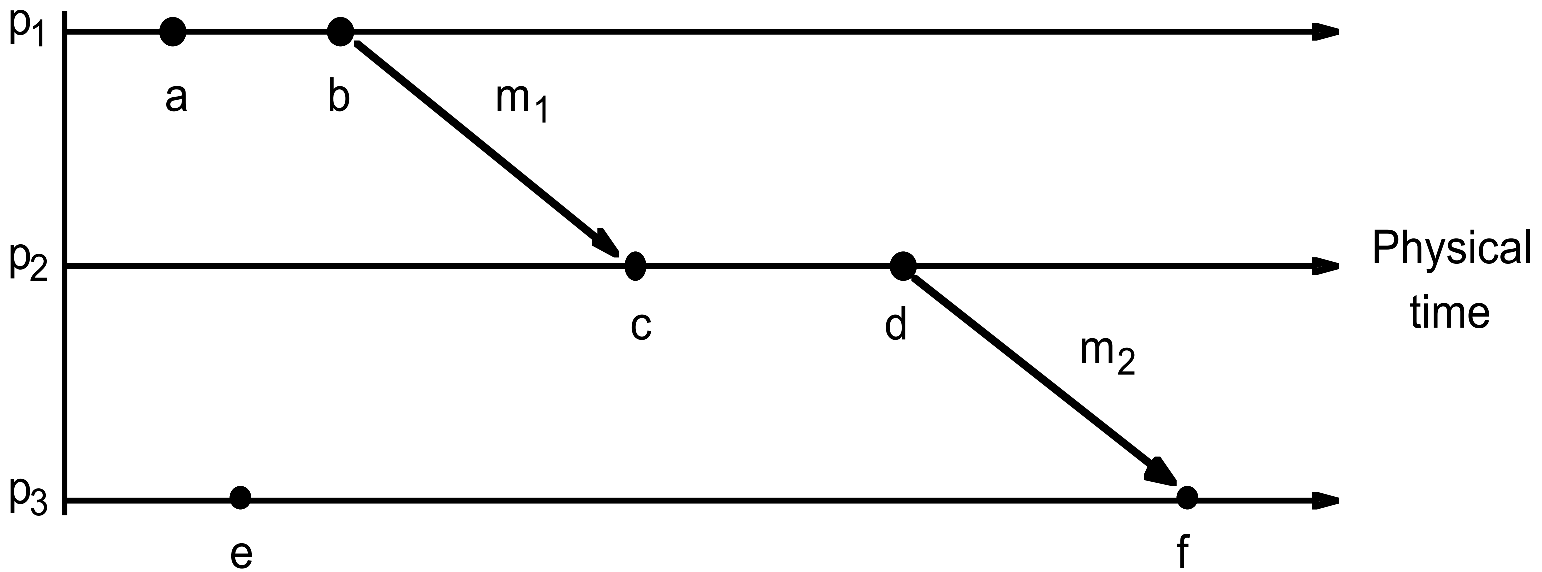
- Lamport Clocks
- Vector Clocks

Logical time

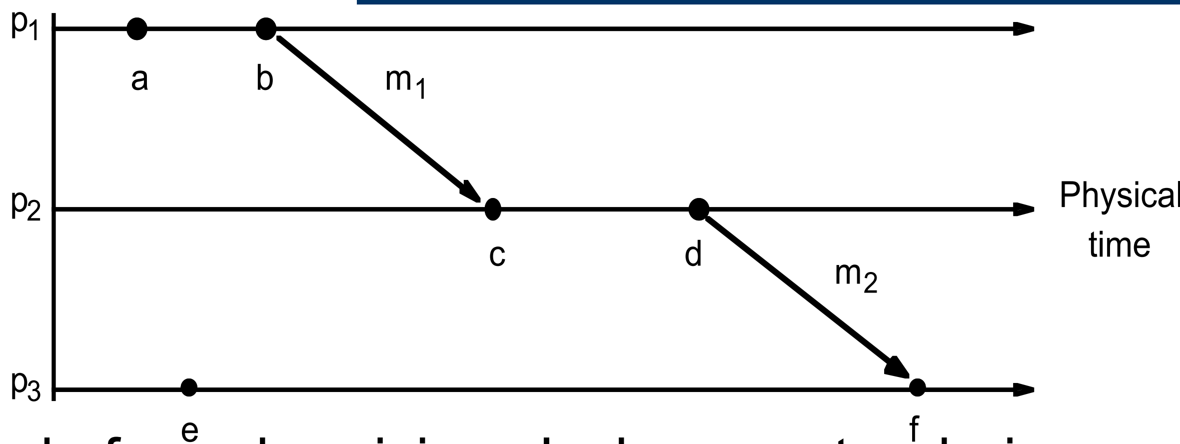
- Capture just the “happens before” relationship between events
  - Discard the infinitesimal granularity of time
  - Corresponds roughly to causality

Logical time and logical clocks (Lamport 1978)

- Events at three processes



Logical time and logical clocks (Lamport 1978)

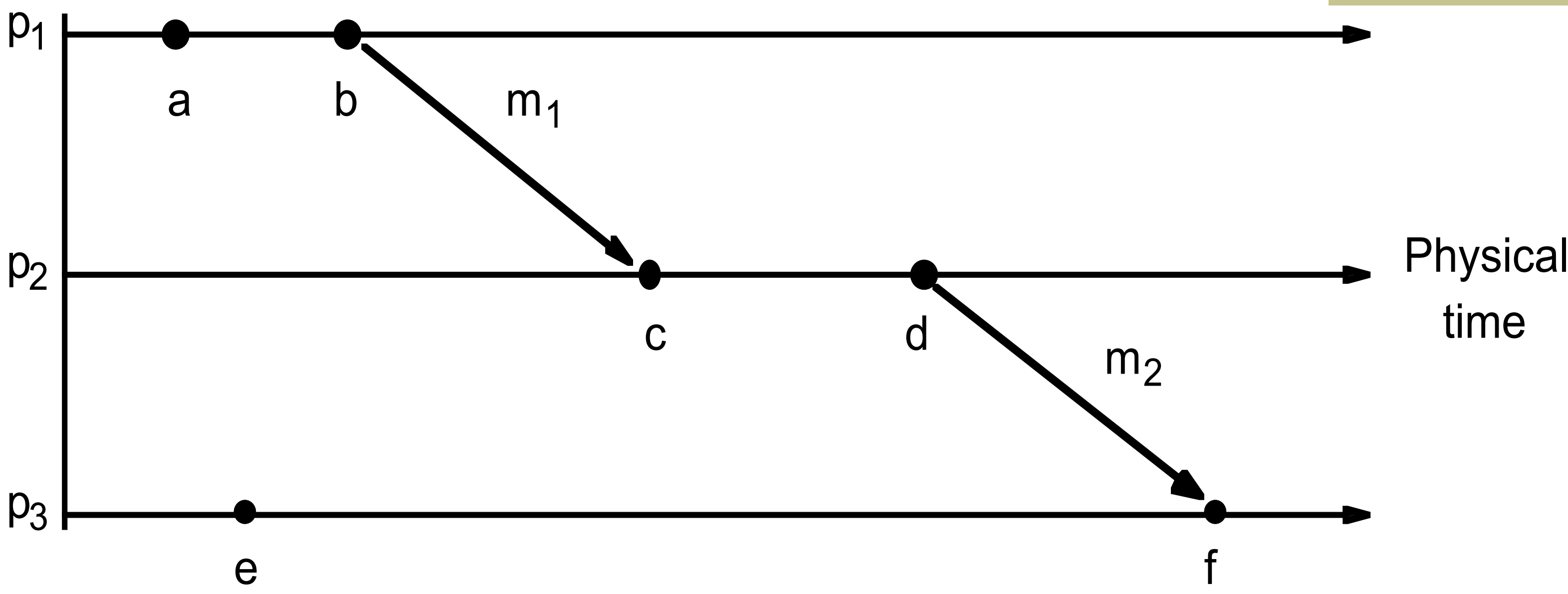


- Instead of synchronizing clocks, event ordering can be used

  1. If two events occurred at the same process p_i (i = 1, 2, … N) then they occurred in the order observed by p_i, that is the definition of: $\rightarrow_i$
  2. When a message, m is sent between two processes, send(m) ‘happens before’ receive(m)
  3. The ‘happened before’ relation is transitive

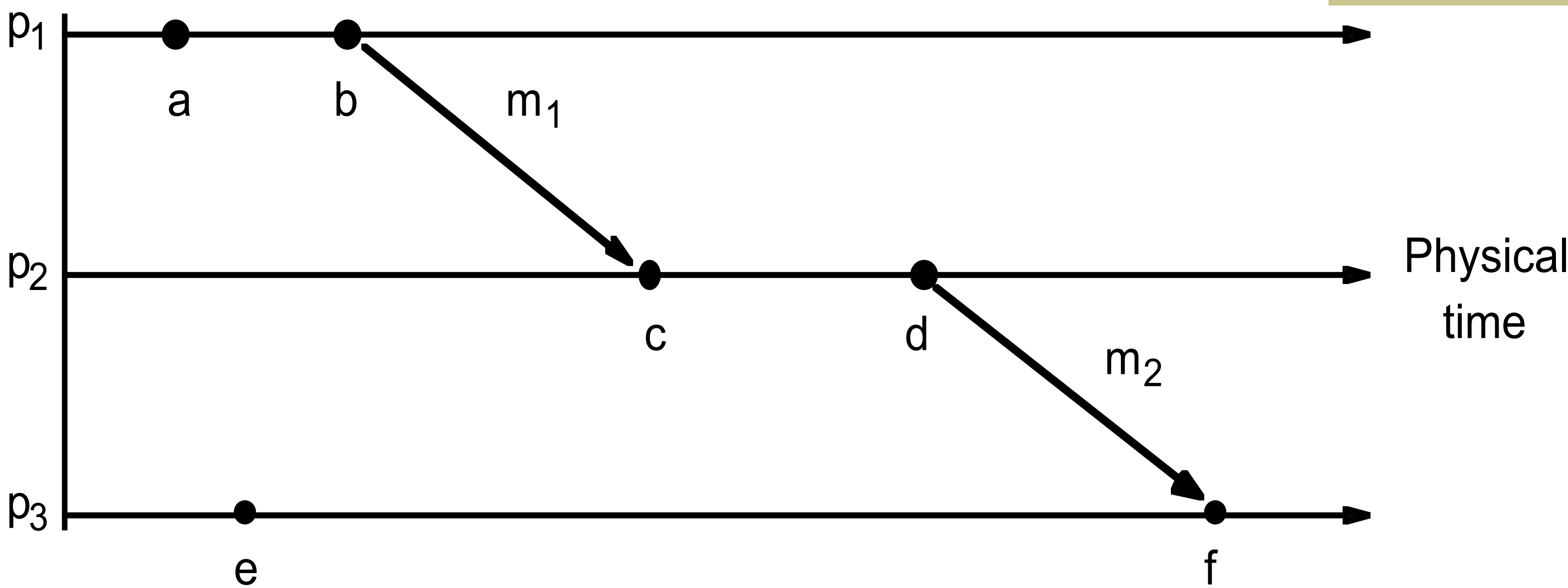
- The happened before relation (→) is necessary for causal ordering

Logical time and logical clocks (Lamport 1978)



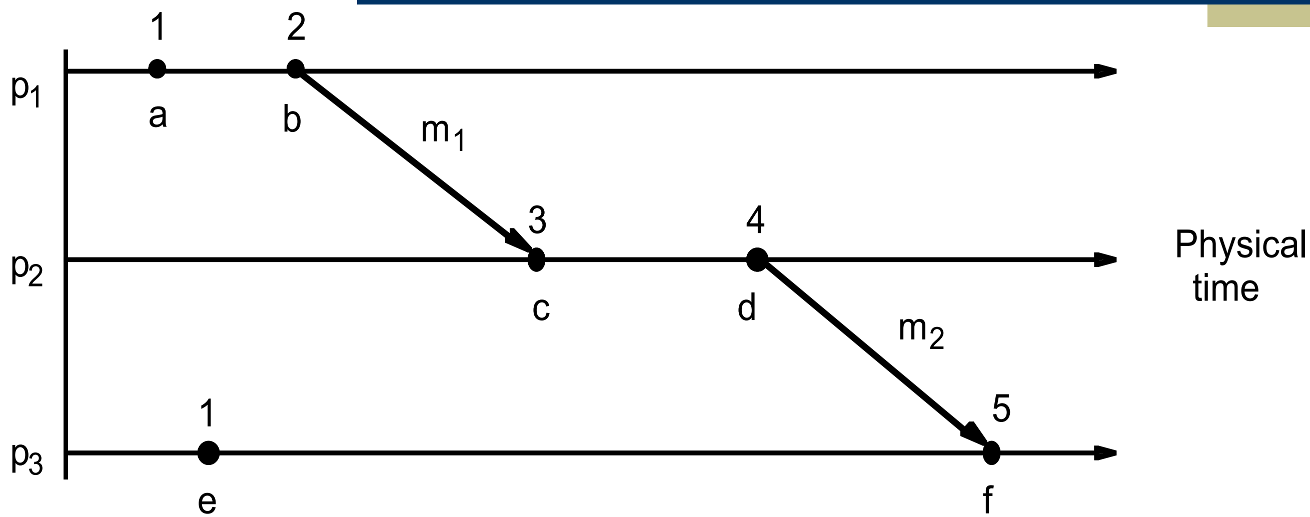
- $a \rightarrow b$ (at p_1) $c \rightarrow d$ (at p_2)
- $b \rightarrow c$ because of m_1
- also $d \rightarrow f$ because of m_2

Logical time and logical clocks (Lamport 1978)



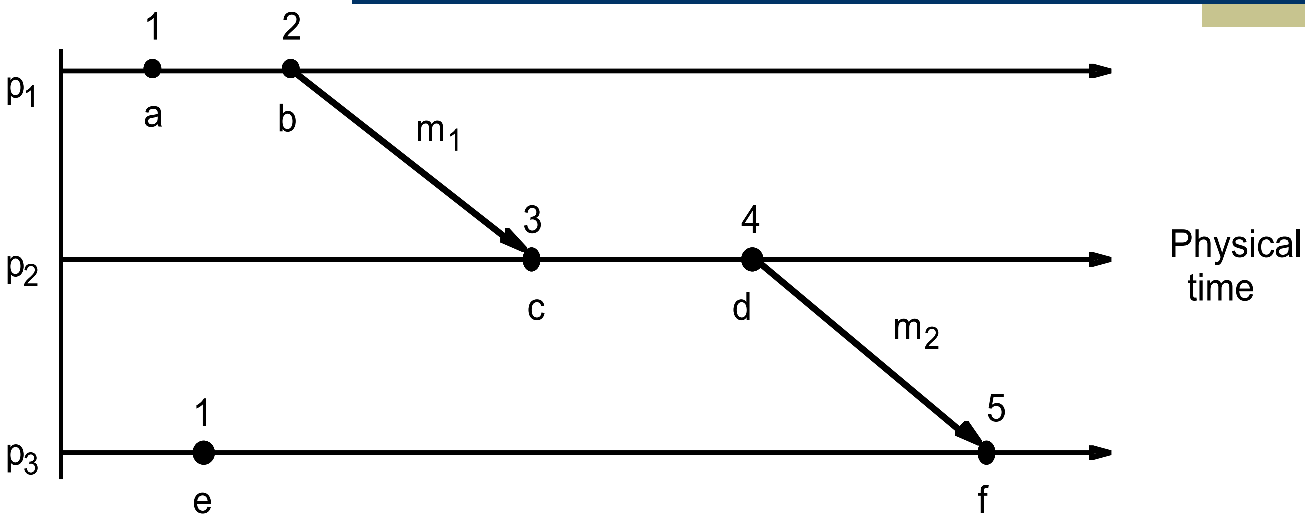
- Not all events are related by $\rightarrow$
- Consider *a* and *e* (different processes and no chain of messages to relate them)
  - they are not related by $\rightarrow$; they are said to be concurrent
  - written as *a* || *e*

Lamport Clock (1)



- A logical clock is a monotonically increasing software counter
  - It need *not* relate to a physical clock.
- Each process p_i has a logical clock, L_i which can be used to apply logical timestamps to events
  - Rule 0: initially all clocks are set to 0
  - Rule 1: L_i is incremented by 1 before each event at process p_i
  - Rule 2:
    - (a) when process p_i sends message *m*, it piggybacks $t = L_i$
    - (b) when p_j receives *(m,t)* it sets $L_j := max(L_j, t)$ and applies rule 1 before timestamping the event *receive* (*m)*

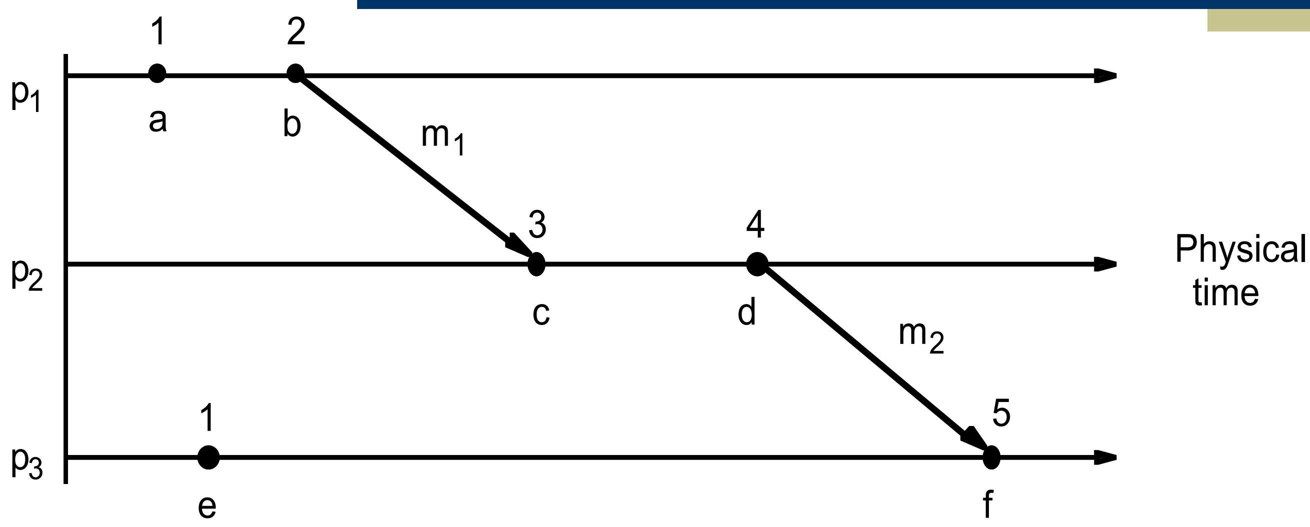
Lamport Clock (1)



- each of p_1, p_2, p_3 has its logical clock initialised to zero,
- the clock values are those immediately after the event.
- e.g. 1 for a, 2 for b.

- for m_1, 2 is piggybacked and c gets max(0,2)+1 = 3

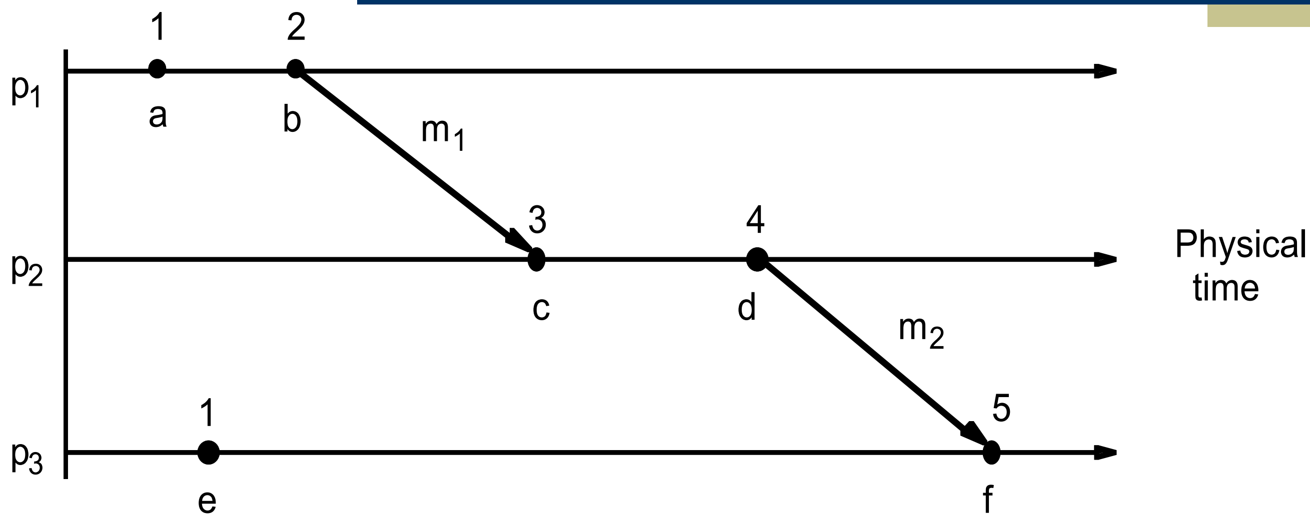
Lamport Clock (1)



- $e \rightarrow e'$ (e happened before e') implies $L(e)<L(e')$
  (where L(e) is Lamport clock value of event e)

- **The converse is not true**, that is $L(e)<L(e')$ does not imply $e \rightarrow e'$. What's an example of this above?

Lamport Clock (1)



- $e \rightarrow e'$ (e happened before e') implies $L(e)<L(e')$

- The converse is not true, that is $L(e)<L(e')$ does not imply $e \rightarrow e'$
  - e.g. $L(b) > L(e)$ but $b \parallel e$

Lamport logical clocks

- Lamport clock *L* orders events consistent with logical "happens before" ordering
  - If e → e', then $L(e) < L(e')$
- But not the converse
  - $L(e) < L(e')$ does not imply $e \rightarrow e'$

- Similar rules for concurrency
  - $L(e) = L(e')$ implies $e \| e'$ (for distinct e, e')
  - $e \| e'$ does not imply $L(e) = L(e')$
  - i.e., Lamport clocks arbitrarily order some concurrent events

Total-order Lamport clocks

- Many systems require a total-ordering of events, not a partial-ordering
- Use Lamport's algorithm, but break ties using the process ID; one example scheme:
  - $L(e) = M * L_i(e) + i$
    - M = maximum number of processes
    - i = process ID

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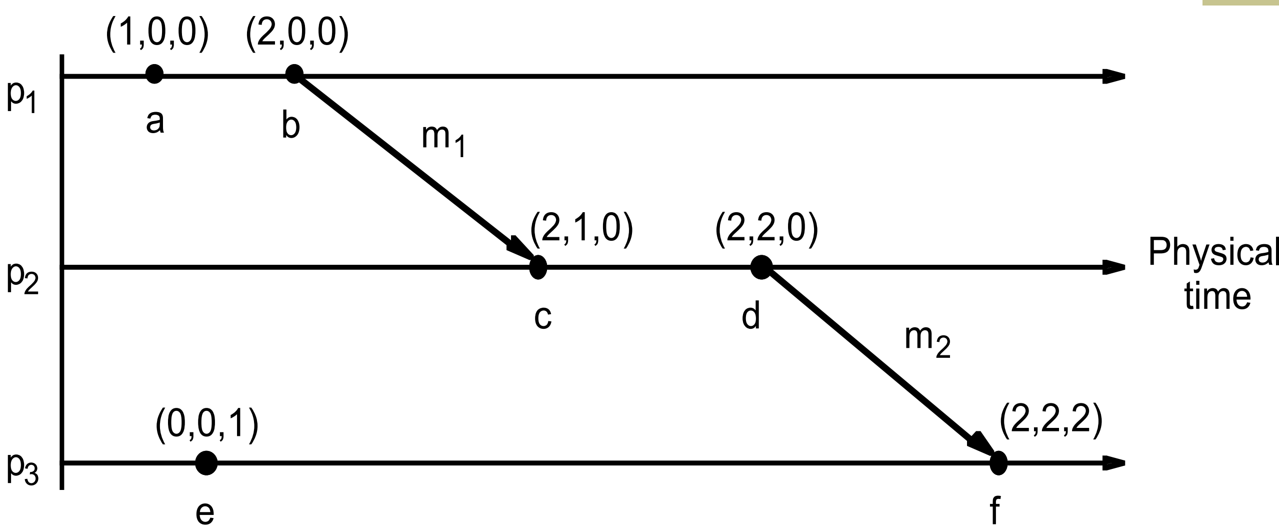
Vector Clocks

- Vector clocks overcome the shortcoming of Lamport logical clocks
  - $L(e) < L(e')$ does not imply *e* happened before *e'*
- Goal
  - Want ordering that matches happened before
  - $V(e) < V(e')$ if and only if $e \rightarrow e'$
- Method
  - Label each event by vector $V(e)$ $[c_1, c_2 \ldots, c_n]$
    - c_i = # events in process i that precede e

Vector Clock Algorithm

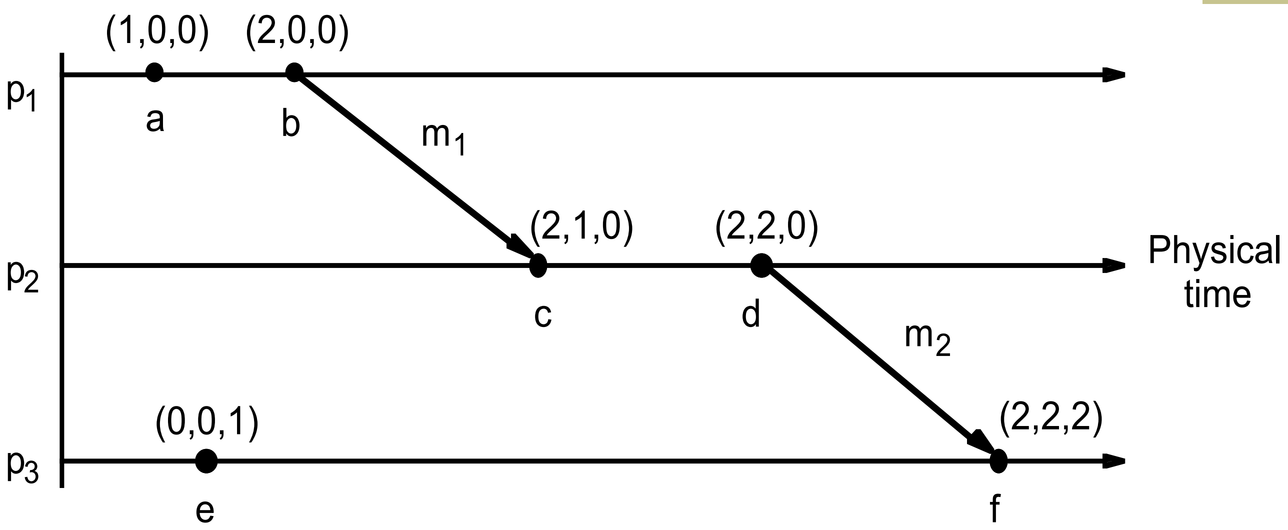
- Initially, all vectors [0,0,…,0]
- For event on process i, increment own c_i
- Label message sent with local vector
- When process j receives message with vector $[d_1, d_2, \ldots, d_n]$:
  - Set each local vector entry k to $\max(c_k, d_k)$
  - Increment value of c_j

Vector Clocks



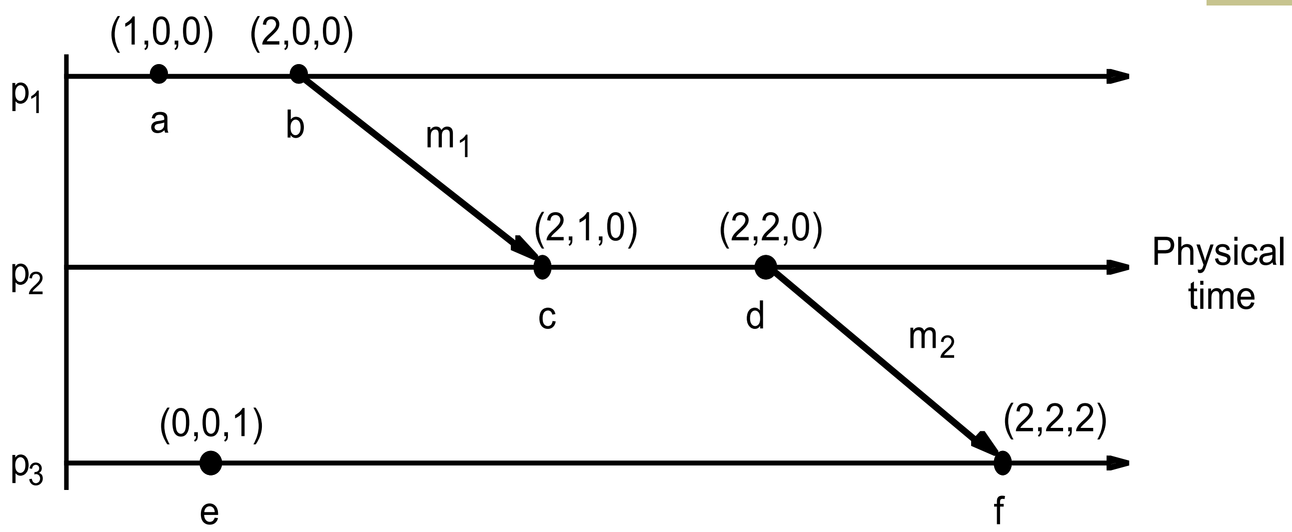
- At p_1
  - *a occurs at* (1,0,0); *b* occurs at (2,0,0)
  - piggyback (2,0,0) on m_1
- At p_2 on receipt of m_1 use *max* ((0,0,0), (2,0,0)) = (2, 0, 0) and add 1 to own element = (2,1,0)
- Meaning of =, <=, max etc for vector timestamps
  - compare elements pairwise

Vector Clocks



- Note that e → e' implies V(e)<V(e'). The converse is also true
- Can you see a pair of concurrent events; Can you infer they are concurrent from their vectors clocks?

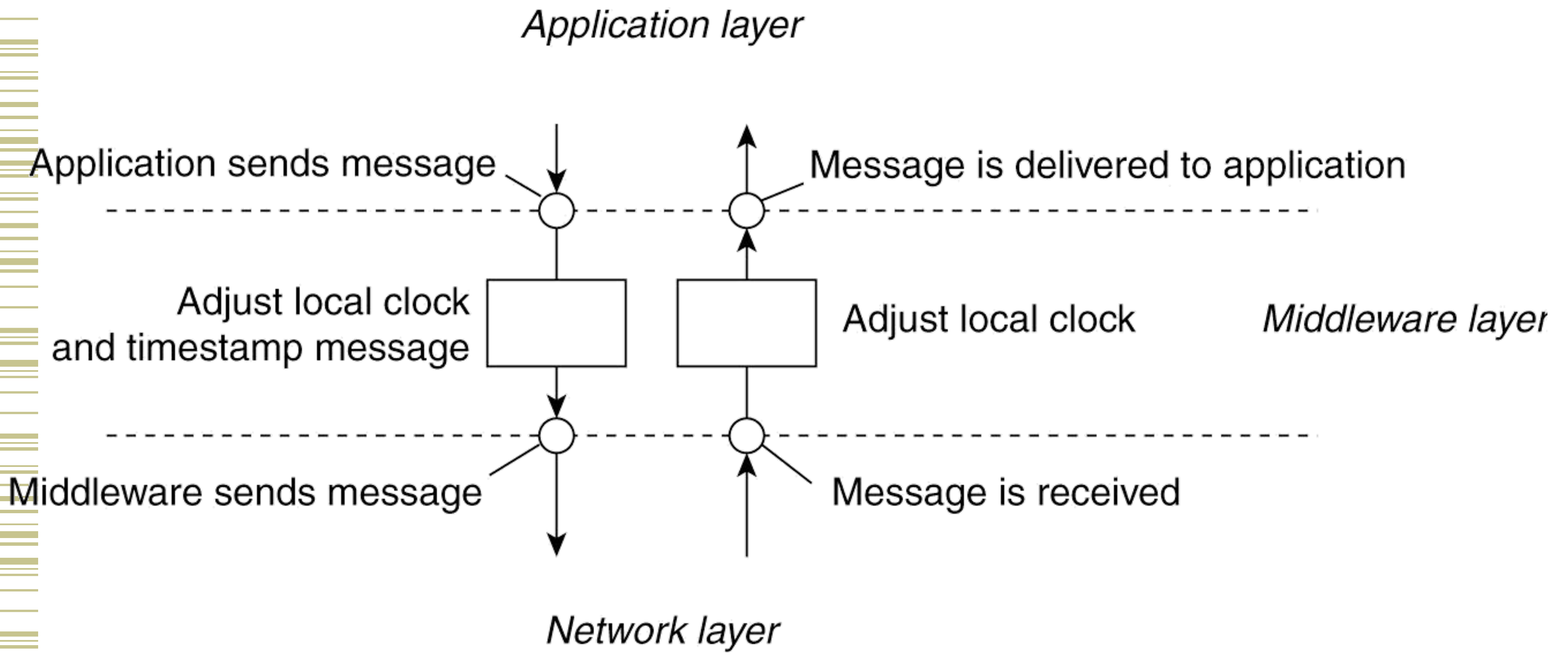
Vector Clocks



- Note that e → e’ implies V(e)<V(e’). The converse is also true
- Can you see a pair of concurrent events?
  - *c* || *e* (concurrent) because neither *V*(c) <= *V*(*e*) nor *V*(*e*) <= *V*(*c*)

Implementing logical clocks

- Positioning of logical timestamping in distributed systems.



Distributed time

- Premise
  - The notion of time is well-defined (and measurable) at each single location
  - But the relationship between time at different locations is unclear
    - Can minimize discrepancies, but never eliminate them
- Reality
  - Stationary GPS receivers can get global time with < 1μs error
  - Few systems designed to use this; logical clocks key mechanism for ordering
    - Recent exception: (Spanner system from Google)

Important Points

- Physical Clocks
  - Can keep closely synchronized, but never perfect
- Logical Clocks
  - Encode happens before relationship (necessary for causality)
  - Lamport clocks provide only one-way encoding
  - Vector clocks precedence necessary for causality (but *not sufficient*: could have been caused by some event along the path, not all events)