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TDT 4225 Very Large, Distributed Data Volumes

Chapter 14
Time and global states

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Part 1: Time

- Why is time important?
- Physical time
  - Skew, drift, UTC
  - External and internal synchronization
  - NTP: Network Time Protocol
- Logical time
  - Definitions
  - Logical clocks
  - Vector clocks

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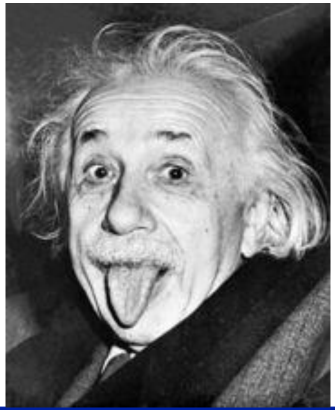
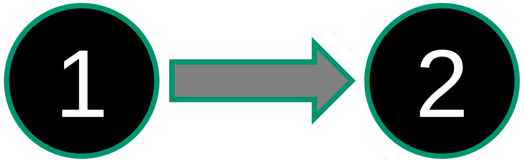
Why is time important?

- Time is used «everywhere»
  - When did something happen?
  - What happened first and what happened later?
  - Bank transactions, e-mail, ...
- Trivial for a single computer
- More difficult in a distributed system
  - Communication takes time
  - What is the time?
    - No universally correct time



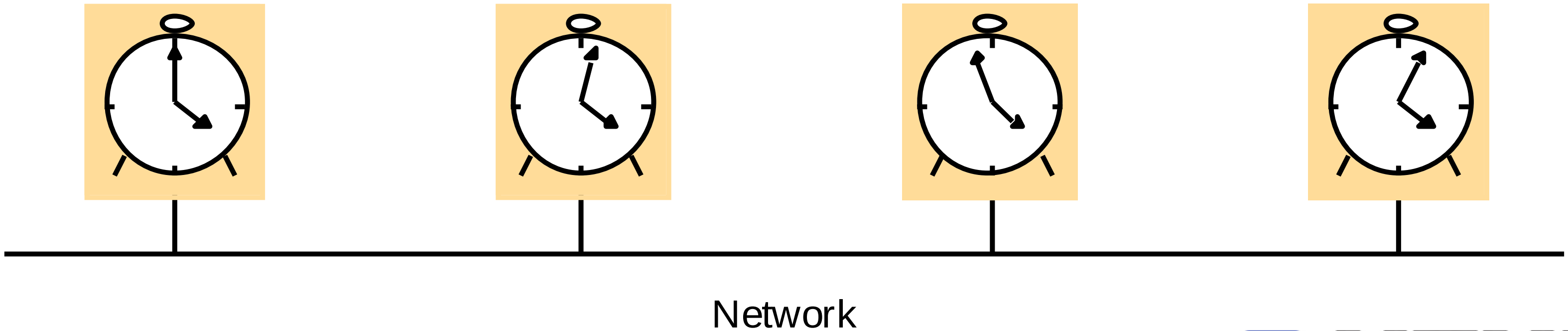
Physical and logical time

- Physical time
  - Timestamp of event
  - Can derive order of events
  - Requires synchronized clocks
- Logical time
  - Order of events
  - Focused on cause and effect
  - Typically a counter incremented for each event



Physical time

- Demand for physical time
- Ordering of events based on timestamp
- Can we trust clocks?
  - «Skew» - difference between clocks at a point in time
  - «Drift» – skew changes over time



UTC – Coordinated Universal Time

- Highly accurate international time standard
- Based on atomic clocks
- An extra second is sometimes inserted
  due to Earth's rotation slowing down (leap seconds)
- Time zones are relative to UTC
  - We are at UTC+1 (UTC+2 in the summer)
- Transmitted using
  - Ground based stations (~1 ms accuracy)
  - Satellites GPS (~1 µs accuracy)

Physical clock synchronization

- External synchronization
  - Clocks synchronized against an external time source
  - Christian's algorithm
- Internal synchronization
  - Synchronization of clocks internally in a distributed system
  - Not necessarily the «correct» time
  - The Berkeley algorithm
- Basic problem: Communication takes time

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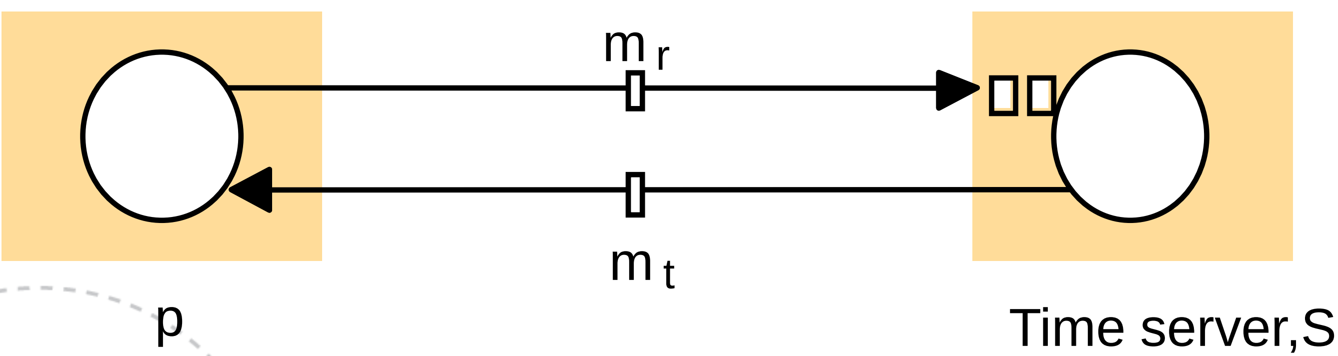
Christian's algorithm

External time server, S (UTC)

1. p sends message m_r to S
2. S replies with its time t in message m_t
3. When p receives m_t, it sets its clock to t + half of the time passed since m_r was sent



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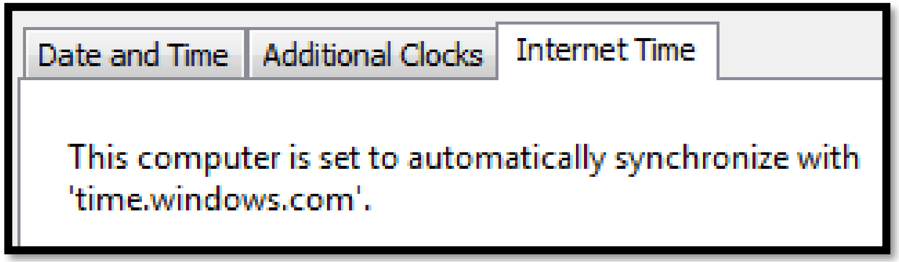
The Berkeley algorithm

One node selected as *master*

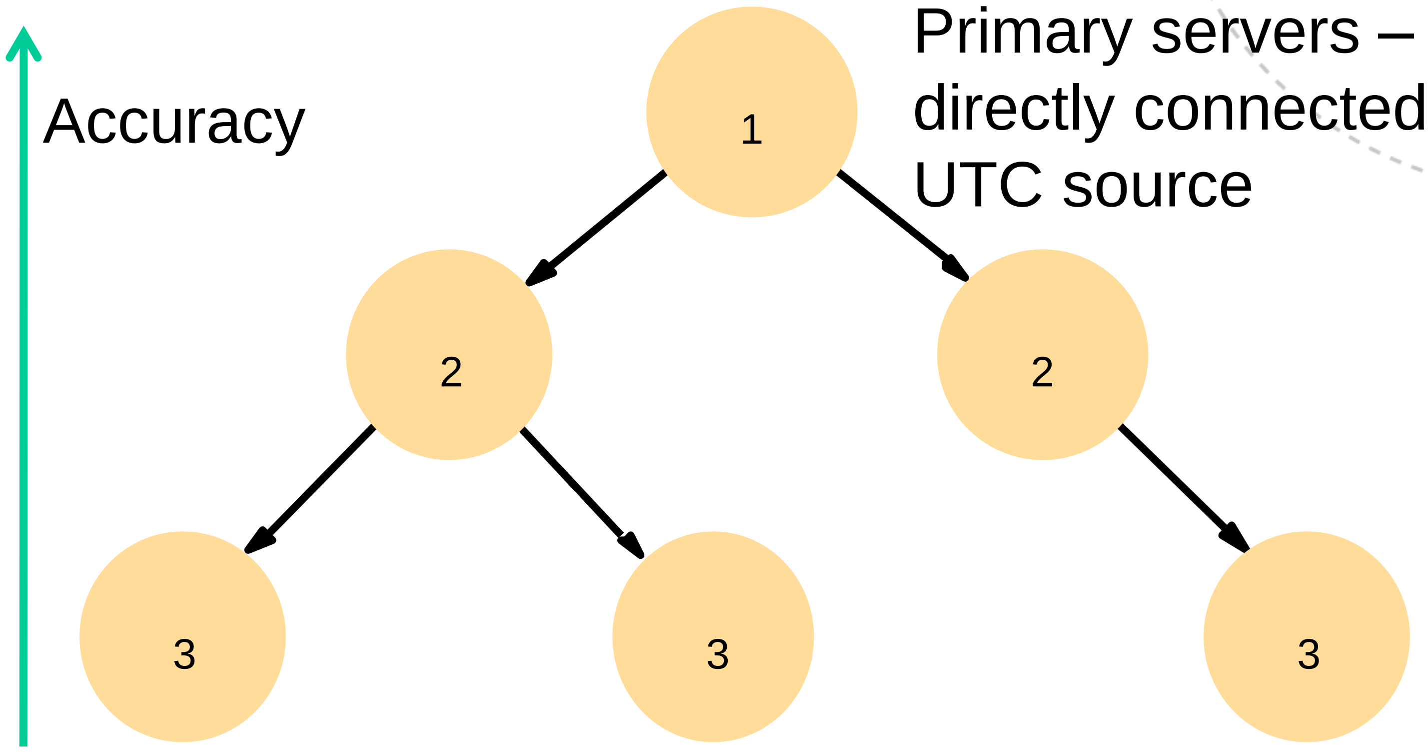
1. The master polls all other nodes *(slaves)*
2. Slaves reply with their local time
3. Master calculates average time
   - Message latency considered
   - Ignores outliers
4. Master sends individual differences to each slave (why differences?)

NTP: Network Time Protocol

- Protocol for synchronizing clocks connected to the Internet
- Uses UTC
- Focus on:
  - Scalability – hierarch of servers
  - Correctness – handle clock drift
  - Reliability – dynamic reconfiguration
  - Security – authentication etc.



NTP: Server hierarchy (logical)



Primary servers – directly connected to a UTC source

Leaf nodes – end user machines
Does not have to be stratum 3

NTP: Synchronization

Three synchronization modes:

1. Multicast (LAN)
   - Assumes fixed message latency
   - Periodic multicast (not on demand)
2. Procedure-call (e.g. Christian's algorithm)
3. Symmetric mode (high accuracy)
   - Servers communicate in pairs
   - One server can be in multiple pairs
   - Estimates *offset* and *delay*

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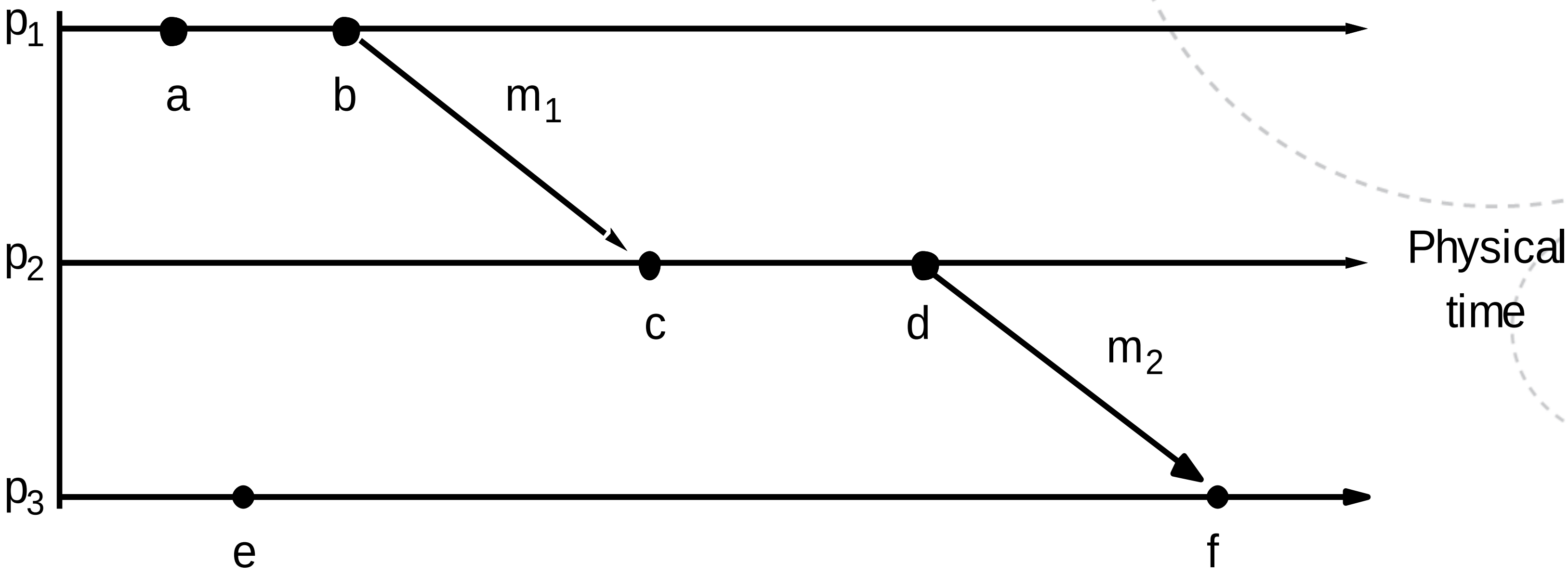
Logical time

- If we only need to order events, physical time is overkill
- Also, perfect synchronization of physical clocks is impossible!
- Local time – focus on event order
  - Two local events happened in the order observed by the process executing them
  - A message must be sent before it can be received
  - I.e. cause → effect

Definitions

- Collection of processes p_i, $i = 1, 2, \ldots N$
- Every process p_i has a state s_i
  - E.g. the values of all variables
- Processes communicate using messages
- Events
  - State change
  - Sending or receiving a message

Happened-before (→)



- Local events: a→b; c→d; e→f
- Messages: b→c; d→f
- Derived: a→c; a→f; b→d
- Concurrent: a || e; b || e; c || e; d || e

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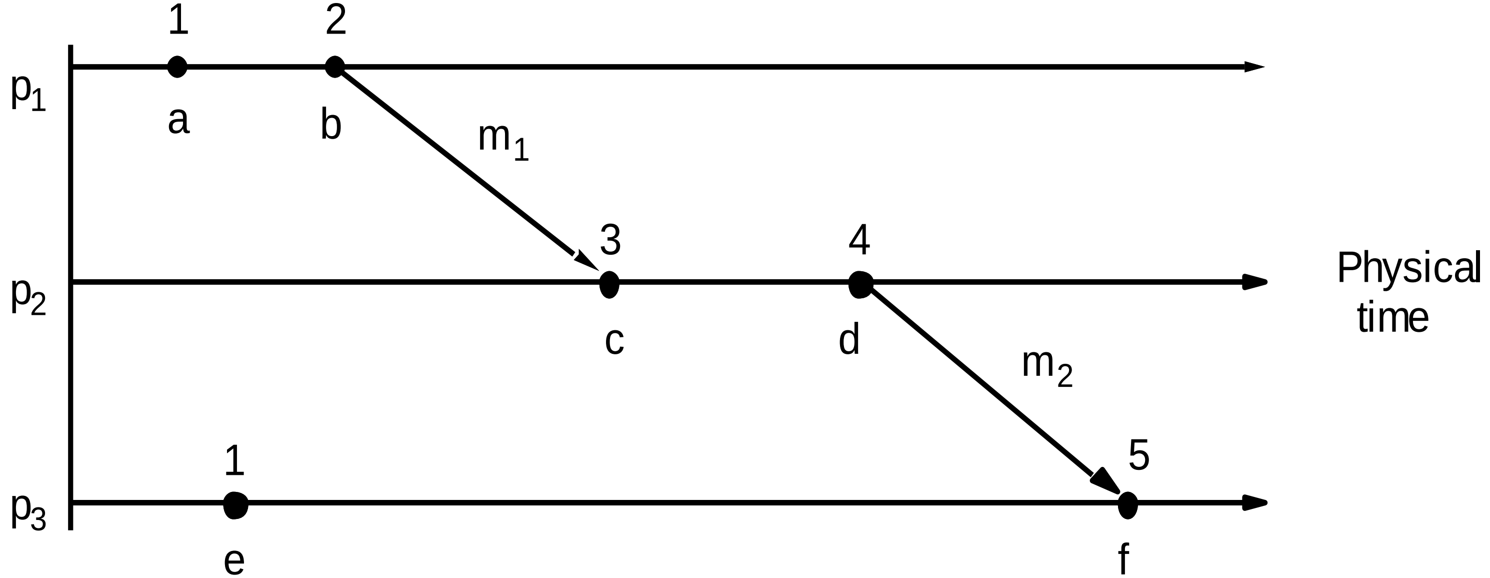
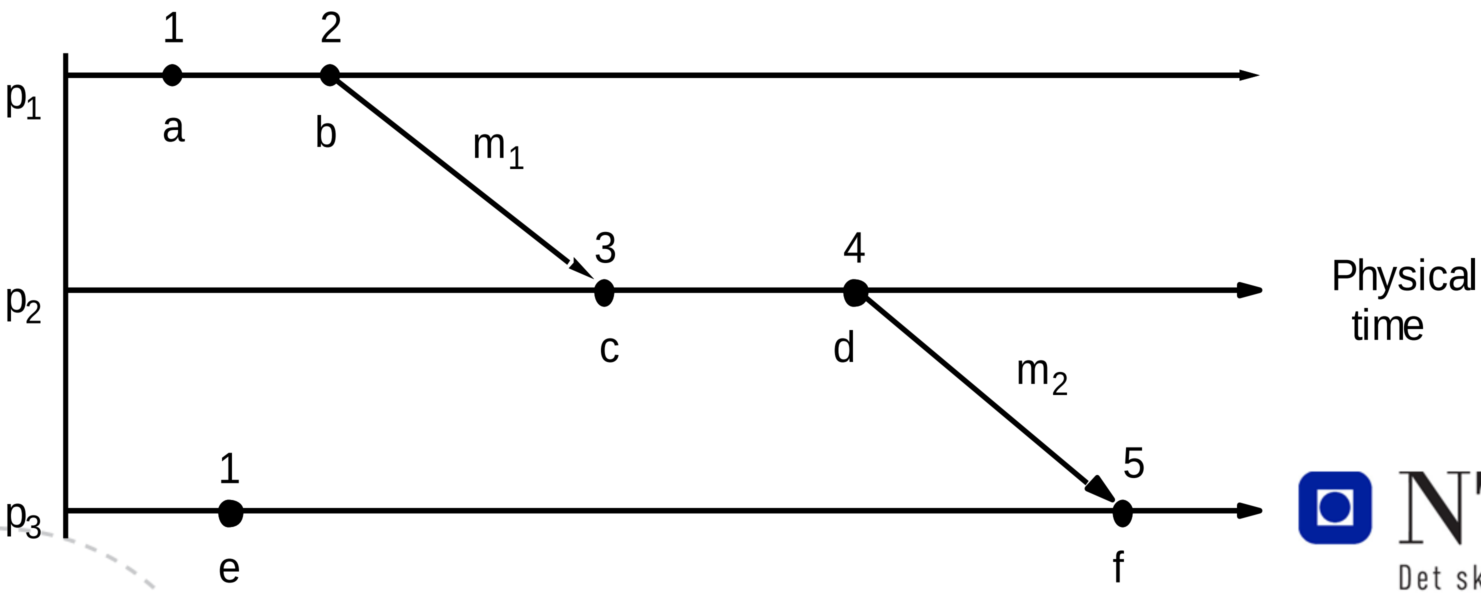
Logical clocks (Lamport) (1/2)

- Every process has a logical clock (counter) L_i
- Before every event: $L_i = L_i + 1$
- Attach clock value to every message, $t = L_i$
- When receiving, $L_j = \max(L_j\ , t) + 1$

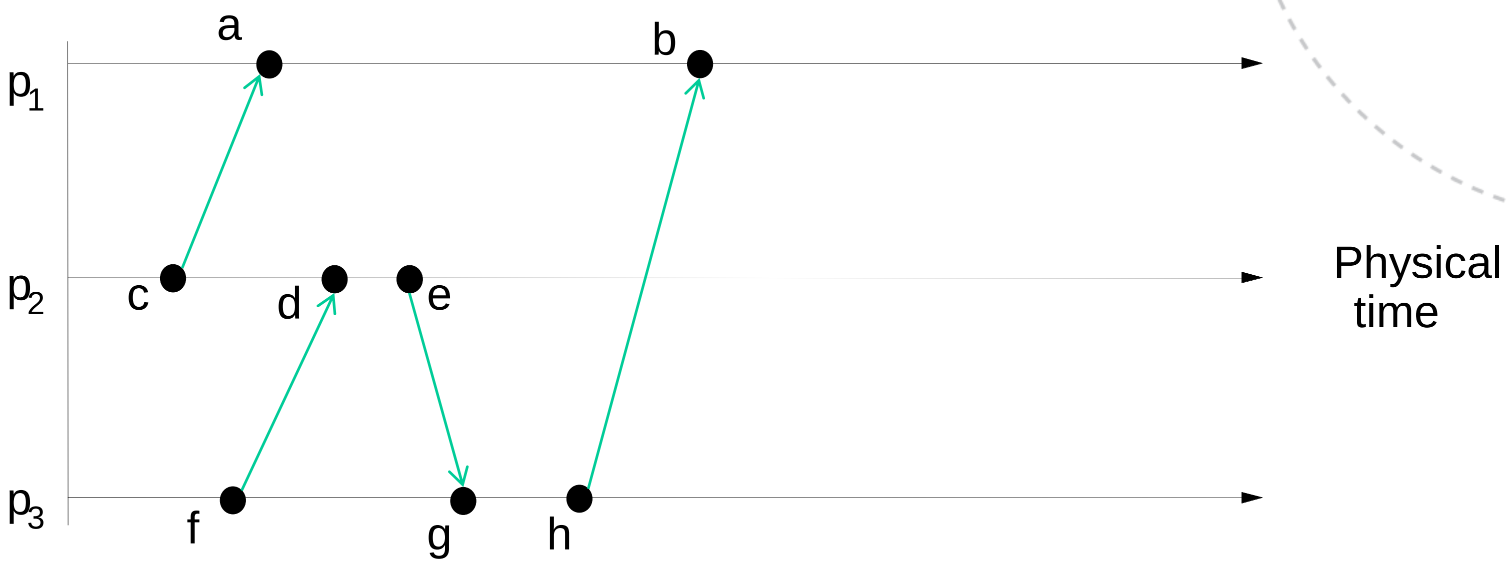


Logical clocks(Lamport) (2/2)

- If e→e' then L(e) < L(e')
- But the reverse is not true!
  - L(e) < L(b) without e→b
  - But L(e') > L(e) ➔ (not e'→e)



Try yourselves!



- What are the logical clock values?
- Is d $\rightarrow$ g?
- Is a $\rightarrow$ g?

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Vector clocks (1/3)

- Logical clocks only get you so far
- To figure out more about event order, we need to store/transfer more info
- Vector clock, given N processes
  - Every process has a vector of N elements
  - Contains the number of events from each process that the given process can have been affected by

Vector clocks (2/3)

Definitions:

- V_i – vector at process *i*
- Initially all vector elements = 0
- Before each event at p_i :
  $V_i[i] = V_i[i] + 1$
- p_i attaches $t = V_i$ to all messages
- When p_i receives a message,
  $V_i[j] = \max(V_i[j], t[j])$, for $j = 1, 2...N$

  (Also $V_i[i] = V_i[i] + 1$)

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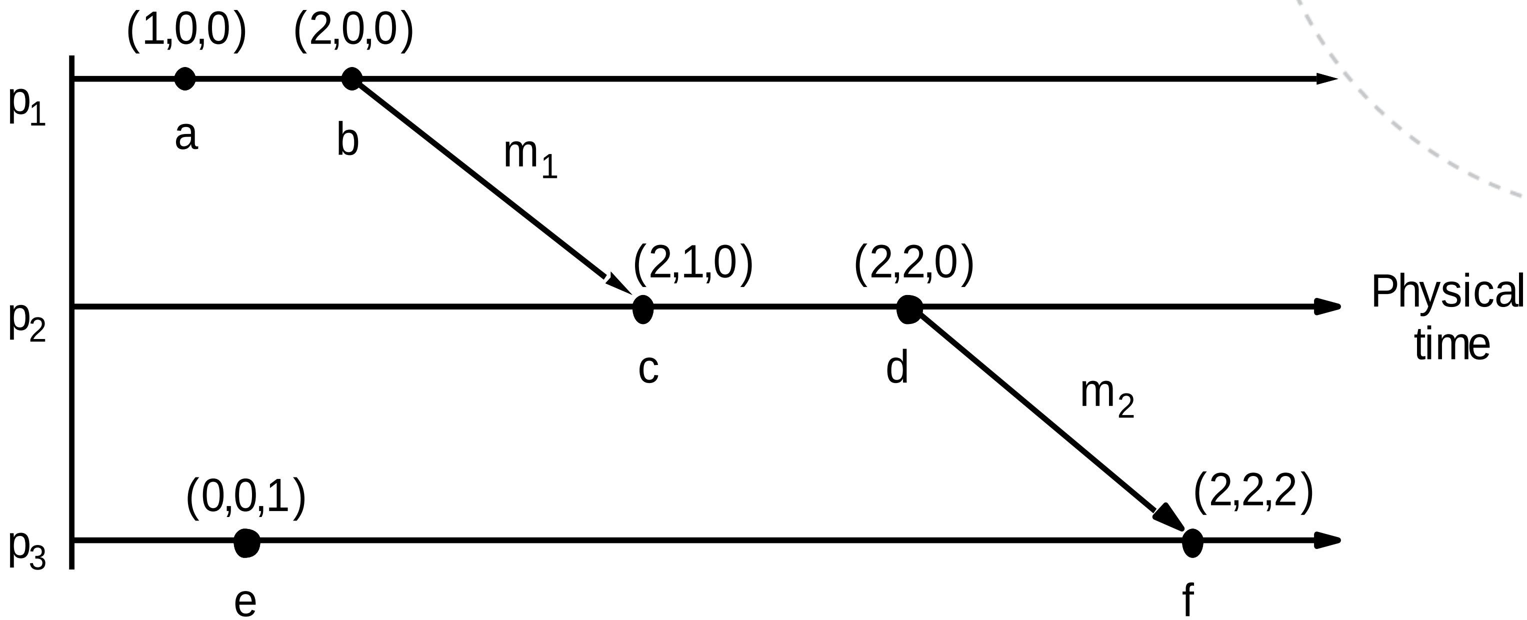
Vector clocks (3/3)



- If e→e' then V(e) < V(e') As before
- If V(e) < V(e') then e→e' **New!**
  - V < V' iff V ≤ V' and V ≠ V'
  - ≤ and = must hold for all pairs of vector elements

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Part 2: Global states

- What and why?
  - Distributed garbage collection
  - Distributed deadlock detection
  - Distributed debugging
- How?
  - Cuts and globally consistent states

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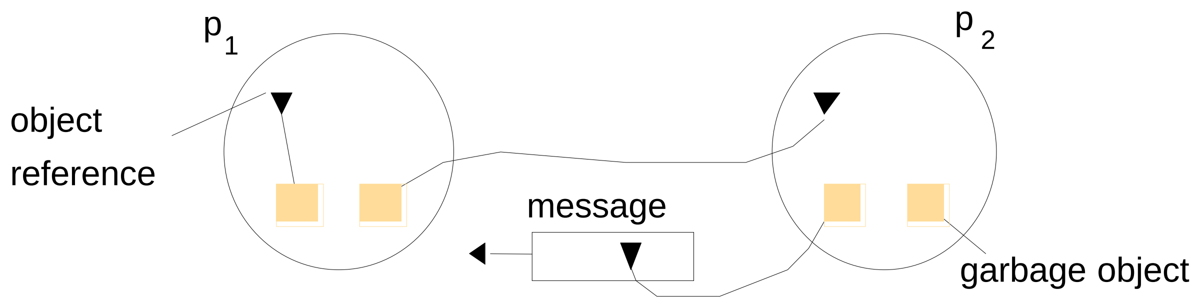
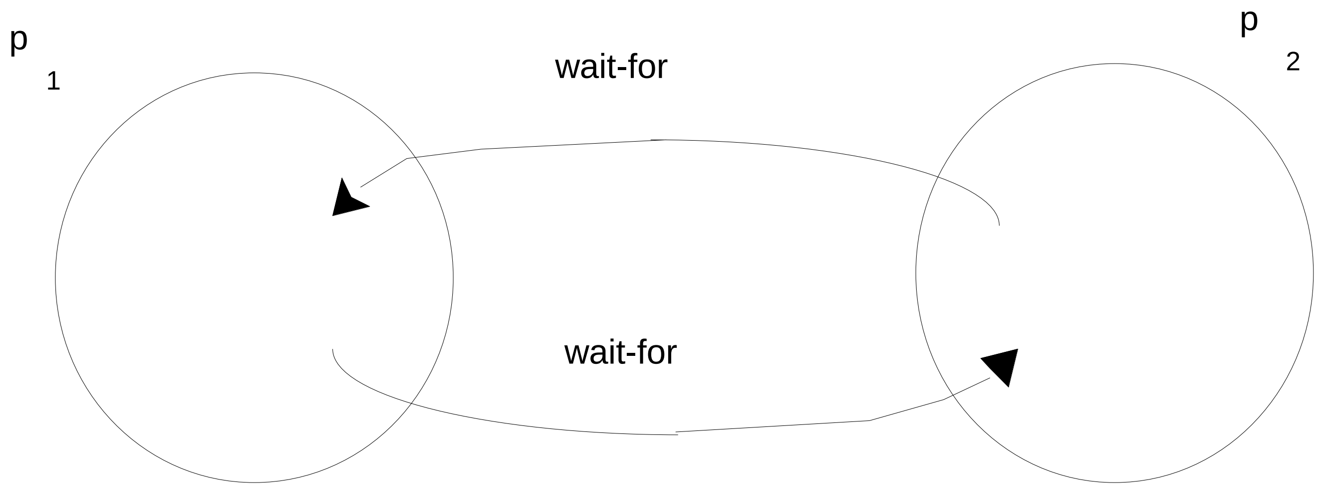
Distributed garbage collection

- Garbage: Objects without active references
- References can be:
  - Local
  - At other processes/nodes (new)
  - In messages (new)
- Need global state (including messages in transit)



Distributed deadlock detection

- Distributed waits-for cycle
- Need global state to detect this

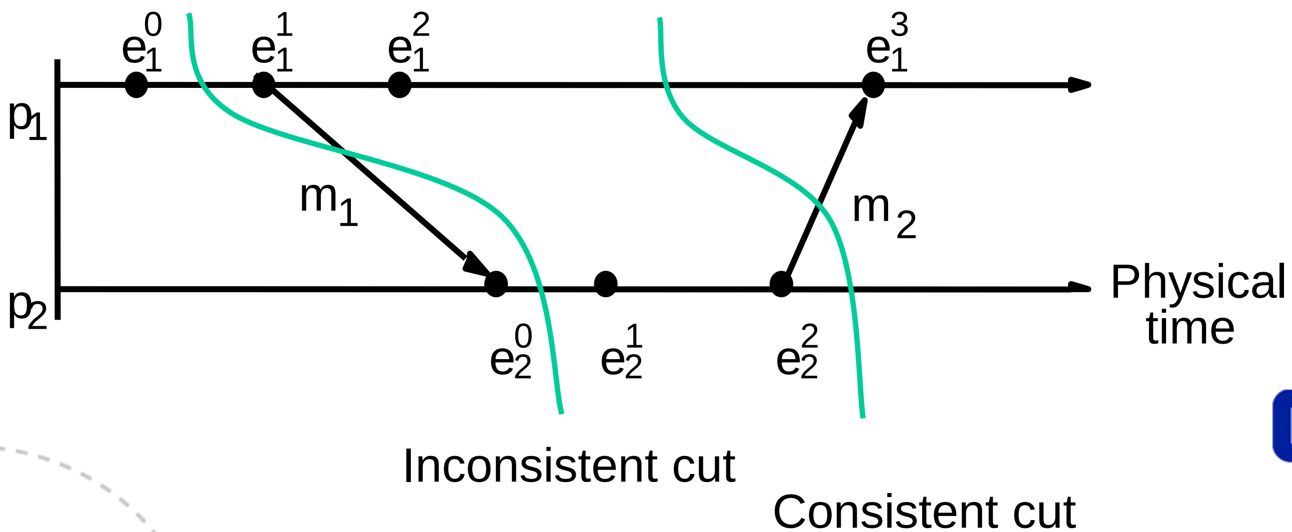


Distributed debugging

- How did variables change at runtime?
  - Example: Has | x_1 - x_2 | ever been > 50?
- Variables can be located at different processes/nodes
- Problem: Global consistent view of variable values

Cuts (1/2)

- Local history: Events at one process
- Global history: Union of all local histories
- Cut: Subset of global history (local prefix)
- What is the problem?
  - How to find consistent cuts without global time?



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Cuts (2/2)

- A cut C is consistent if
  - For all events $e \in C$, $f \rightarrow e \Rightarrow f \in C$
  - Inconsistent: The system could never have been in this state
  - Consistent ➔ Global consistent state
- Run
  - Global history where the order satisfies all local histories
- Consistent run / linearization
  - All global states passed through are consistent
- Reachable
  - S' is reachable from S if there is a consistent run between them

Distributed debugging

- After the fact: Was a condition true during execution?
- All participants send information about state changes to an external observer
- Global state predicate ϕ
  - Possibly ϕ
    - At least one consistent run passes through a global consistent state where ϕ = true
  - Definitely ϕ
    - All consistent runs pass through a global consistent state where ϕ = true

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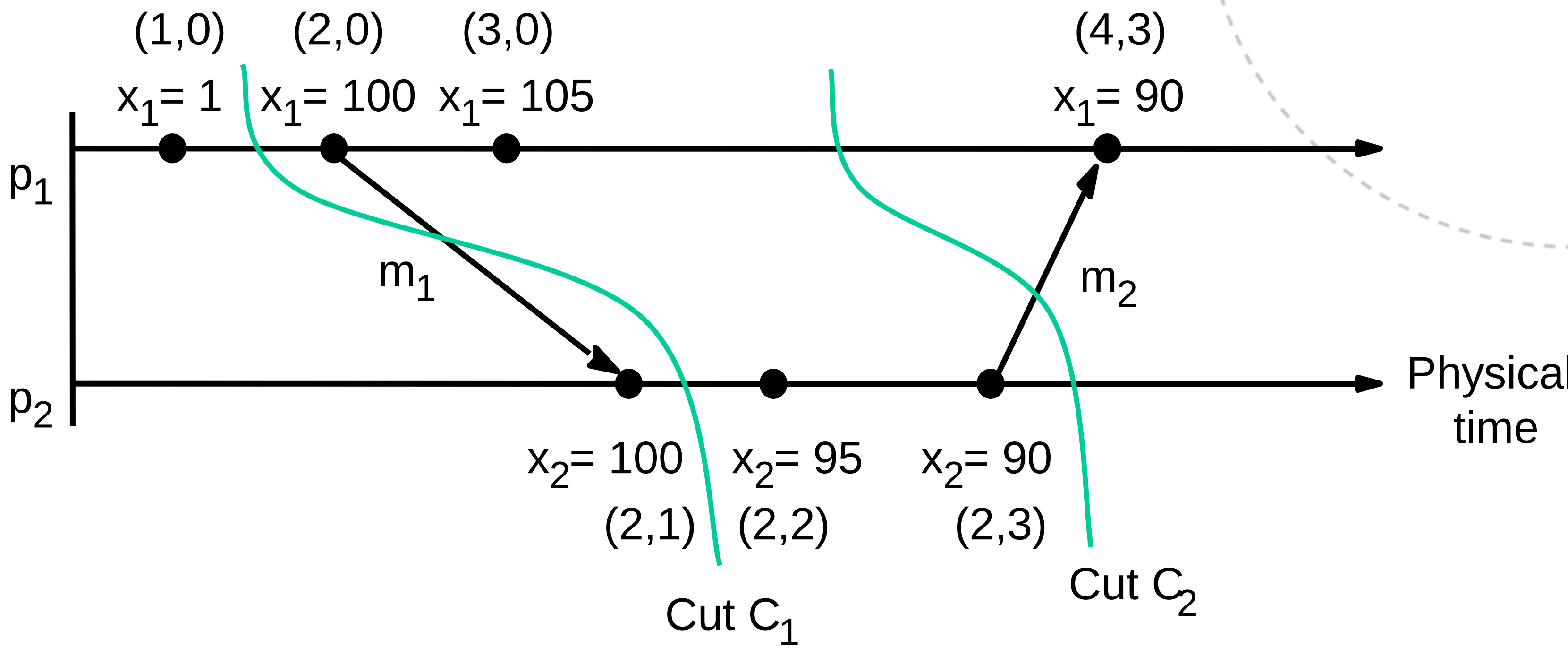
Observing global state



- The observer is notified about all state changes
- Uses vector clocks to find global consistent states
- Has | x_1 - x_2 | ever been > 50?

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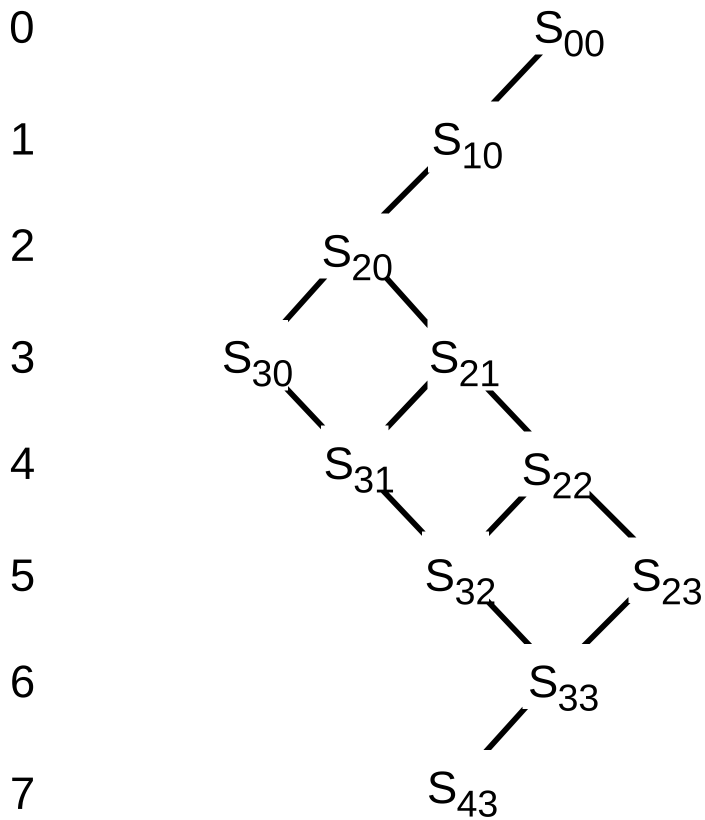
Alternative consistent runs



Sij = global state after *i* events at process 1 and *j* events at process 2

Possibly ϕ Passes S where ϕ = true
Definitely ϕ Can't avoid S where ϕ = true