Logical Clocks and Casual Ordering

CS60002: Distributed Systems

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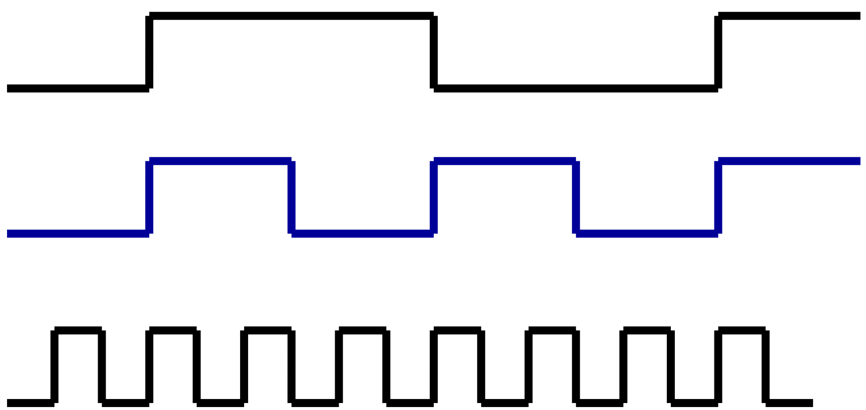
Why do we need global clocks?

- For causally ordering events in a distributed system
  - Example:
    - Transaction T transfers Rs 10,000 from S1 to S2
    - Consider the situation when:
      - State of S1 is recorded after the deduction and state of S2 is recorded before the addition
      - State of S1 is recorded before the deduction and state of S2 is recorded after the addition
- Should not be confused with the clock-synchronization problem



What data is being transmitted? 0101?

Yes, if this is the clock

If this is the clock, then 01110001

The receiver needs to know the clock of the sender

Ordering of Events

Lamport's *Happened Before* relationship:

For two events a and b, a → b if

- *a and b are events in the same process and a occurred before b, or*
- *a is a send event of a message m and b is the corresponding receive event at the destination process, or*
- *a → c and c → b for some event c*

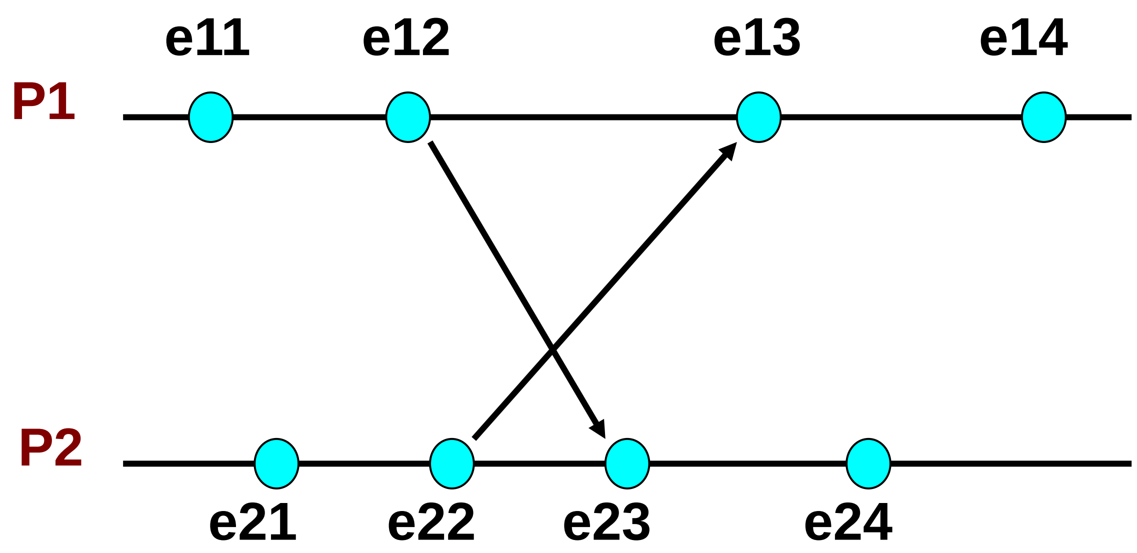
Causally Related versus Concurrent

Causally related events:

- Event a causally affects event b if $a \rightarrow b$

Concurrent events:

- Two distinct events a and b are said to be concurrent (denoted by a||b) if $a \not\rightarrow b$ and $b \not\rightarrow a$



A space-time diagram

e11 and e21 are concurrent

e14 and e23 are concurrent

e22 causally affects e14

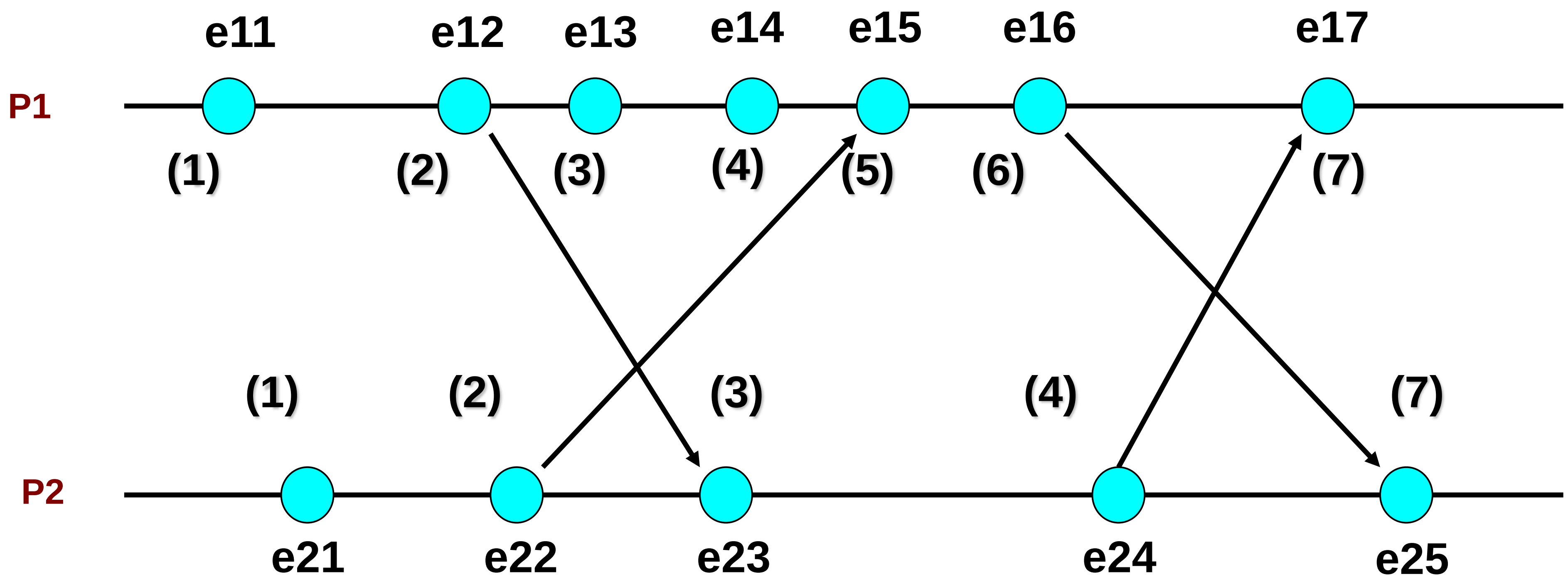
Lamport's Logical Clock

Each process i keeps a clock C_i

- Each event a in i is time-stamped $C_i(a)$, the value of C_i when a occurred
- C_i is incremented by 1 for each event in i
- In addition, if a is a send of message m from process i to j, then on receive of m,

$$C_j = \max (C_j, C_i(a)+1)$$

How Lamport's clocks advance



Points to note

- if a $\rightarrow$ b, then C(a) < C(b)
- $\rightarrow$ is a partial order
- Total ordering possible by arbitrarily ordering concurrent events by process numbers

Limitation of Lamport's Clock

$a \rightarrow b$ implies $C(a) < C(b)$

BUT

$C(a) < C(b)$ doesn't imply $a \rightarrow b$!!

So not a true clock !!

Solution: *Vector Clocks*

Each process P_i has a clock C_i, which is a vector of size n

The clock C_i assigns a vector $C_i(a)$ to any event *a* at P_i

Update rules:

- $C_i[i]$++ for every event at process I
- If a is send of message m from i to j with vector timestamp t_m, then on receipt of m:

$$C_j[k] = \max(C_j[k], t_m[k]) \text{ for all } k$$

Partial Order between Timestamps

For events a and b with vector timestamps t^a and t^b,

- **Equal:** $t^a = t^b$ iff $\forall i, t^a[i] = t^b[i]$
- **Not Equal:** $t^a \neq t^b$ iff $\exists i, t^a[i] \neq t^b[i]$
- **Less or equal:** $t^a \leq t^b$ iff $\forall i, t^a[i] \leq t^b[i]$
- **Not less or equal:** $t^a \nleq t^b$ iff $\exists i, t^a[i] > t^b[i]$
- **Less than:** $t^a < t^b$ iff $(t^a \leq t^b \text{ and } t^a \neq t^b)$
- **Not less than:** $t^a \nless t^b$ iff $\neg(t^a \leq t^b \text{ and } t^a \neq t^b)$
- **Concurrent:** $t^a \,||\, t^b$ iff $(t^a < t^b \text{ and } t^b < t^a)$

Causal Ordering

- $a \longrightarrow b$ iff $t_a < t_b$
- Events a and b are causally related iff $t_a < t_b$ or $t_b < t_a$, else they are concurrent
- Note that this is still not a total order

Use of Vector Clocks in Causal Ordering of Messages

- If send(m1) $\rightarrow$ send(m2), then every recipient of both message m1 and m2 must "deliver" m1 before m2.
  - "deliver" – when the message is actually given to the application for processing

Birman-Schiper-Stephenson Protocol

- To broadcast m from process i, increment $C_i(i)$, and timestamp m with $VT_m = C_i[i]$

- When $j \neq i$ receives m, j delays delivery of m until
  - $C_j[i] = VT_m[i] - 1$ and
  - $C_j[k] \geq VT_m[k]$ for all $k \neq i$
  - Delayed messages are queued in j sorted by vector time. Concurrent messages are sorted by receive time.

- When m is delivered at j, C_j is updated according to vector clock rule.

Problem of Vector Clock

- Message size increases since each message needs to be tagged with the vector
- Size can be reduced in some cases by only sending values that have changed

Global State Recording

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Global State Collection

- **Applications:**
  - Checking "stable" properties, checkpoint & recovery

- **Issues:**
  - Need to capture both node and channel states
  - system cannot be stopped
  - no global clock

Notations

Some notations:

- LS_i: Local state of process I
- send(m_{ij}) : Send event of message m_{ij} from process i to process j
- rec(m_{ij}) : Similar, receive instead of send
- time(x) : Time at which state x was recorded
- time (send(m)) : Time at which send(m) occurred

Definitions

- $send(m_{ij}) \in LS_i$ iff $time(send(m_{ij})) < time(LS_i)$

- $rec(m_{ij}) \in LS_j$ iff $time(rec(m_{ij})) < time(LS_j)$

- $transit(LS_i, LS_j)$

  $= \{ m_{ij} \mid send(m_{ij}) \in LS_i \text{ and } rec(m_{ij}) \notin LS_j \}$

- $inconsistent(LS_i, LS_j)$

  $= \{ m_{ij} \mid send(m_{ij}) \notin LS_i \text{ and } rec(m_{ij}) \in LS_j \}$

Definitions

- Global state: collection of local states

  GS = {LS1, LS2,…, LSn}

- GS is consistent iff

  for all i, j, $1 \leq i, j \leq n$,

  inconsistent(LSi, LSj) = Φ

- GS is transitless iff

  for all i, j, $1 \leq i, j \leq n$,

  transit(LSi, LSj) = Φ

- GS is strongly consistent if it is consistent and transitless.

Chandy-Lamport's Algorithm

- Uses special marker messages.

- One process acts as initiator, starts the state collection by following the marker sending rule below.

- Marker sending rule for process P:
  - P records its state and
  - For each outgoing channel C from P on which a marker has not been sent already, P sends a marker along C before any further message is sent on C

Chandy Lamport's Algorithm contd..

- **When Q receives a marker along a channel C:**
  - If Q has not recorded its state then Q records the state of C as empty; Q then follows the marker sending rule
  - If Q has already recorded its state, it records the state of C as the sequence of messages received along C after Q's state was recorded and before Q received the marker along C

Notable Points

- Markers sent on a channel distinguish messages sent on the channel before the sender recorded its states and the messages sent after the sender recorded its state

- The state collected may not be any state that actually happened in reality, rather a state that “could have” happened

- Requires FIFO channels

- Message complexity O(|E|), where E = no. of links

Termination Detection

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Termination Detection

- **Model**
  - processes can be active or idle
  - only active processes send messages
  - idle process can become active on receiving a computation message
  - active process can become idle at any time
  - Termination: all processes are idle and no computation message are in transit

  - Can use global snapshot to detect termination also

Huang's Algorithm

- One controlling agent, has weight 1 initially
- All other processes are idle initially and has weight 0
- Computation starts when controlling agent sends a computation message to a process
- An idle process becomes active on receiving a computation message
- B(DW) – computation message with weight DW. Can be sent only by the controlling agent or an active process
- C(DW) – control message with weight DW, sent by active processes to controlling agent when they are about to become idle

Weight Distribution and Recovery

- Let current weight at process = W
- Send of B(DW):
  - Find W1, W2 such that W1 > 0, W2 > 0, W1 + W2 = W
  - Set W = W1 and send B(W2)
- Receive of B(DW):
  - W = W + DW;
  - if idle, become active
- Send of C(DW):
  - send C(W) to controlling agent
  - Become idle
- Receive of C(DW):
  - W = W + DW
  - if W = 1, declare “termination”