Logical Clocks

- For many problems, internal consistency of clocks is important
  - Absolute time is less important
  - Use *logical* clocks
- Key idea:
  - Clock synchronization need not be absolute
  - If two machines do not interact, no need to synchronize them
  - More importantly, processes need to agree on the *order* in which events occur rather than the *time* at which they occurred

Event Ordering

- *Problem:* define a total ordering of all events that occur in a system
- Events in a single processor machine are totally ordered
- In a distributed system:
  - No global clock, local clocks may be unsynchronized
  - Can not order events on different machines using local times
- Key idea [Lamport]
  - Processes exchange messages
  - Message must be sent before received
  - Send/receive used to order events (and synchronize clocks)

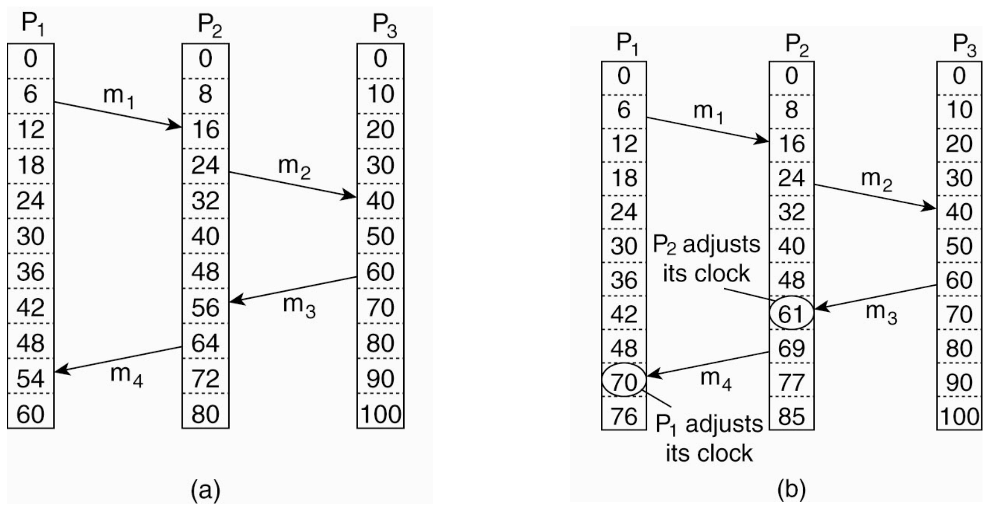
Happened Before Relation

- If *A* and *B* are events in the same process and *A* executed before *B*, then *A* -> *B*
- If A represents sending of a message and B is the receipt of this message, then A -> B
- Relation is transitive:
  - A -> B and B -> C => A -> C
- Relation is undefined across processes that do not exchange messages
  - Partial ordering on events

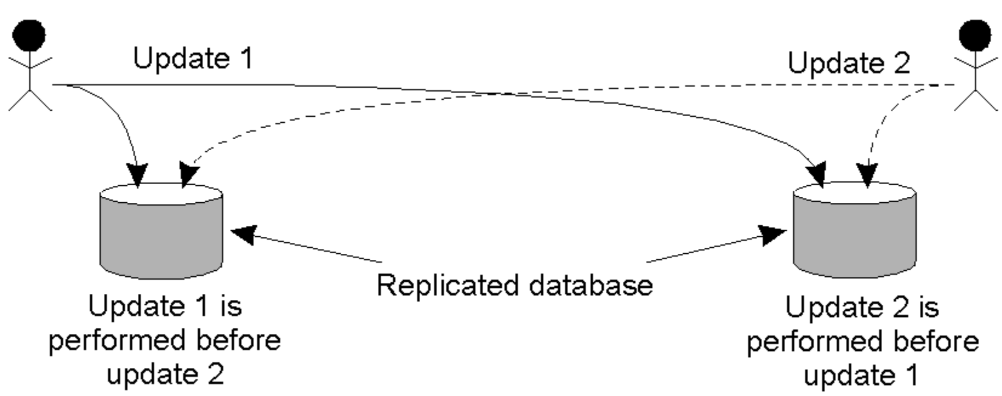
Event Ordering Using *HB*

- Goal: define the notion of time of an event such that
  - If A-> B then C(A) < C(B)
  - If A and B are concurrent, then C(A) <, = or > C(B)
- Solution:
  - Each processor maintains a logical clock LC_i
  - Whenever an event occurs locally at I, $LC_i = LC_i+1$
  - When *i* sends message to *j,* piggyback Lc_i
  - When *j* receives message from *i*
    - If $LC_j < LC_i$ then $LC_j = LC_i +1$ else do nothing
  - Claim: this algorithm meets the above goals

Lamport's Logical Clocks



Example: Totally-Ordered Multicasting



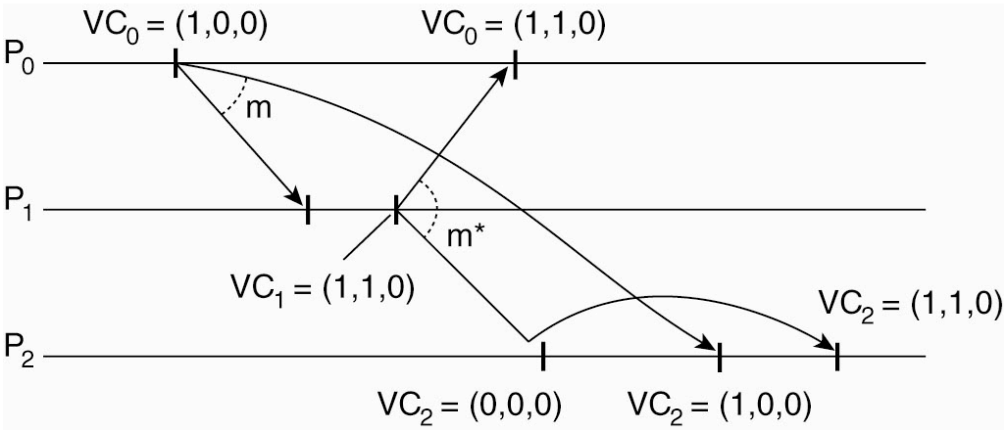
Causality

- Lamport's logical clocks
  - If $A \text{ -> } B$ then $C(A) < C(B)$
  - Reverse is not true!!
    - Nothing can be said about events by comparing time-stamps!
    - If $C(A) < C(B)$, then ??
- Need to maintain *causality*
  - If a -> b then a is casually related to b
  - *Causal delivery*:If send(m) -> send(n) => deliver(m) -> deliver(n)
  - Capture causal relationships between groups of processes
  - Need a time-stamping mechanism such that:
    - If $T(A) < T(B)$ then A should have causally preceded B

Vector Clocks

- Each process *i* maintains a vector V_i
  - $V_i[i]$: number of events that have occurred at i
  - $V_i[j]$: number of events I knows have occurred at process j
- Update vector clocks as follows
  - Local event: increment $V_i[I]$
  - Send a message :piggyback entire vector V
  - Receipt of a message: $V_j[k] = \max(V_j[k], V_i[k])$
    - Receiver is told about how many events the sender knows occurred at another process *k*
    - Also $V_j[i] = V_j[i]+1$
- *Exercise:* prove that if $V(A)<V(B)$, then A causally precedes B and the other way around.

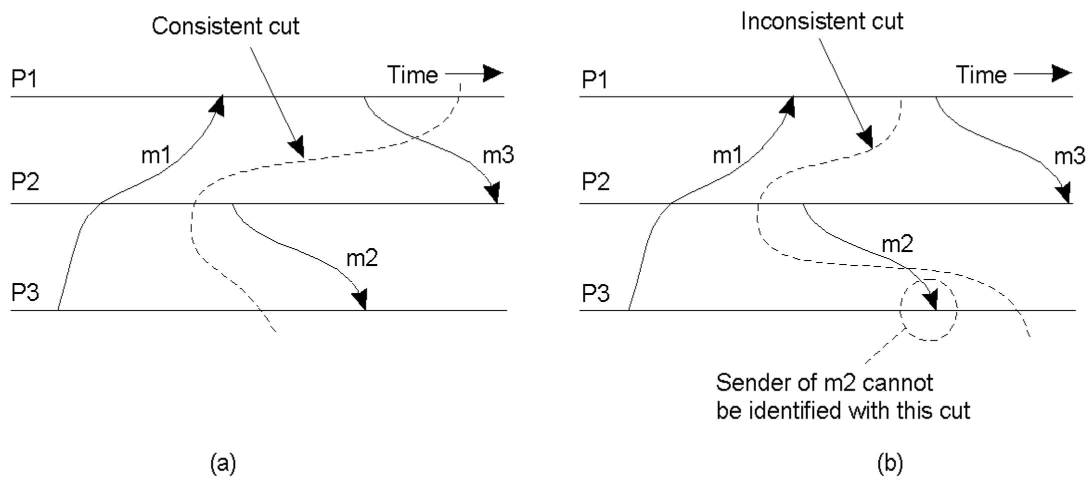
Enforcing Causal Communication

- 

Global State

- Global state of a distributed system
  - Local state of each process
  - Messages sent but not received (state of the queues)
- Many applications need to know the state of the system
  - Failure recovery, distributed deadlock detection
- Problem: how can you figure out the state of a distributed system?
  - Each process is independent
  - No global clock or synchronization
- Distributed snapshot: a consistent global state

Global State (1)



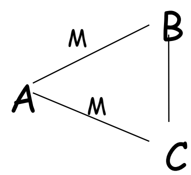
a) A consistent cut
b) An inconsistent cut

Distributed Snapshot Algorithm

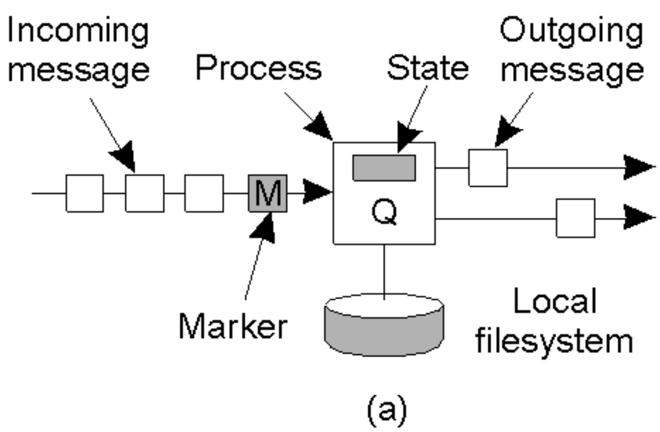
- Assume each process communicates with another process using unidirectional point-to-point channels (e.g, TCP connections)
- Any process can initiate the algorithm
  - Checkpoint local state
  - Send marker on every outgoing channel
- On receiving a marker
  - Checkpoint state if first marker and send marker on outgoing channels, save messages on all other channels until:
  - Subsequent marker on a channel: stop saving state for that channel

Distributed Snapshot

- A process finishes when
  - It receives a marker on each incoming channel and processes them all
  - State: local state plus state of all channels
  - Send state to initiator
- Any process can initiate snapshot
  - Multiple snapshots may be in progress
    - Each is separate, and each is distinguished by tagging the marker with the initiator ID (and sequence number)

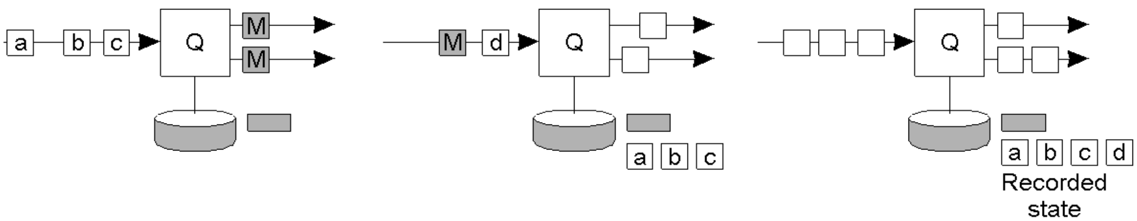


Snapshot Algorithm Example



a) Organization of a process and channels for a distributed snapshot

Snapshot Algorithm Example



(b) (c) (d)

b) Process Q receives a marker for the first time and records its local state

c) Q records all incoming message

d) *Q* receives a marker for its incoming channel and finishes recording the state of the incoming channel