# Causality

- Lamport's logical clocks
  - If *A -> 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

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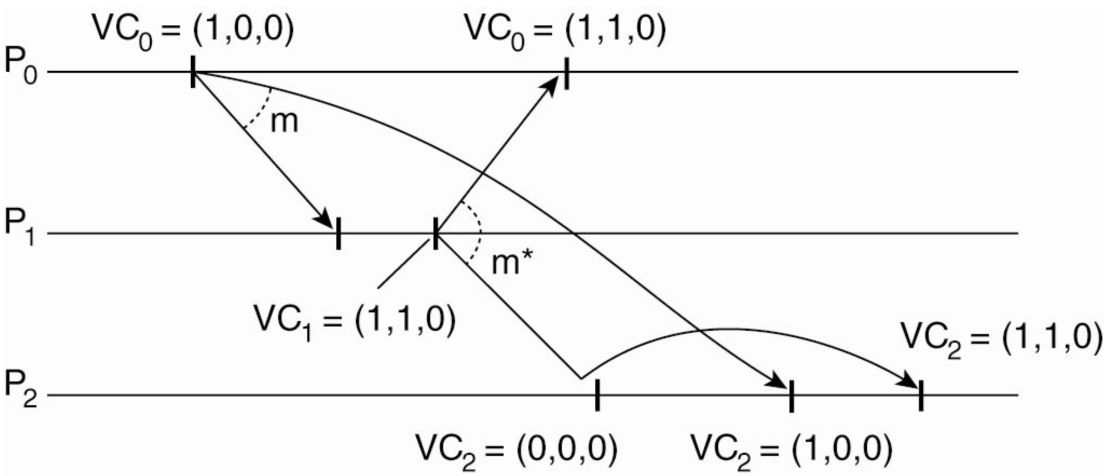
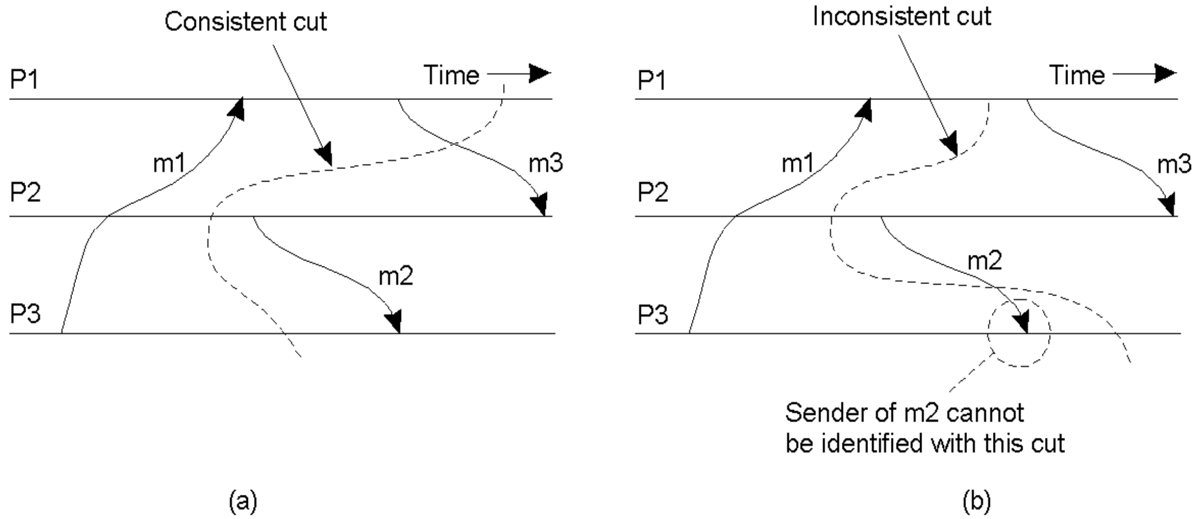





# Global State

- 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

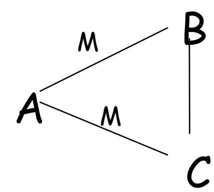


# Distributed Snapshot Algorithm

- 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

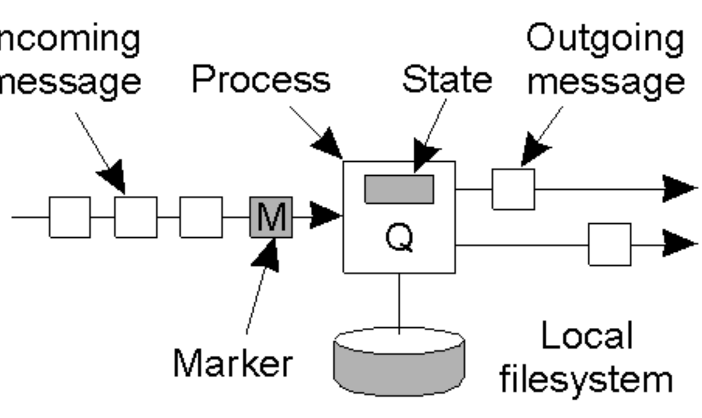
# Distributed Snapshot

- 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)





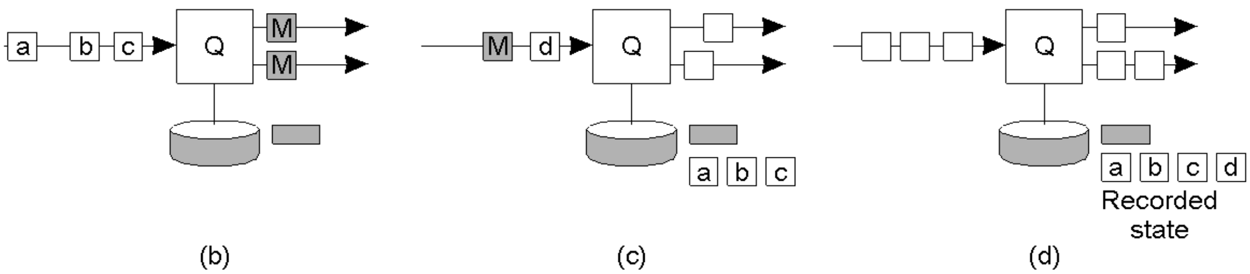

# Snapshot Algorithm Example




(a)

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

# Snapshot Algorithm Example




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



# Termination Detection

- Detecting the end of a distributed computation
- Notation: let sender be *predecessor*, receiver be *successor*
- Two types of markers: Done and Continue
- After finishing its part of the snapshot, process *Q* sends a Done or a Continue to its predecessor
- Send a Done only when
  - All of *Q*'s successors send a Done
  - *Q* has not received any message since it check-pointed its local state and received a marker on all incoming channels
  - Else send a Continue
- Computation has terminated if the initiator receives Done messages from everyone