Last Class: Naming

- Naming
  - Distributed naming
  - DNS
  - LDAP

Today: Classical Problems in Distributed Systems

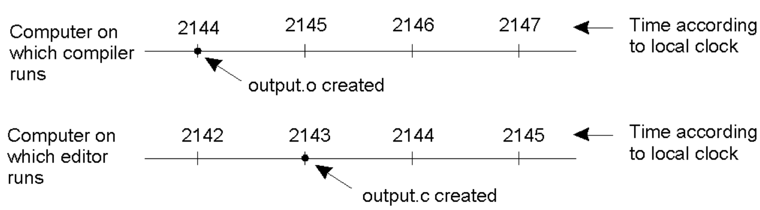
- Time ordering and clock synchronization (today)

Next few classes:

- Leader election
- Mutual exclusion
- Distributed transactions
- Deadlock detection
- CAP Theorem

Clock Synchronization

- Time in unambiguous in centralized systems
  - System clock keeps time, all entities use this for time
- Distributed systems: each node has own system clock
  - Crystal-based clocks are less accurate (1 part in million)
  - *Problem:* An event that occurred after another may be assigned an earlier time

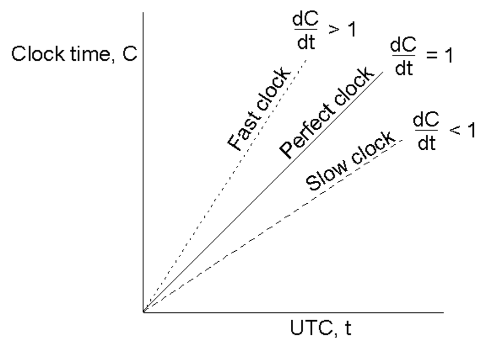


Physical Clocks: A Primer

- How do you tell time?
  - Use astronomical metrics (solar day)
- Accurate clocks are atomic oscillators (one part in 10^{13})
- Coordinated universal time *(UTC)* – international standard based on atomic time
  - Add leap seconds to be consistent with astronomical time
  - UTC broadcast on radio (satellite and earth)
  - Receivers accurate to 0.1 – 10 ms
- Most clocks are less accurate (e.g., mechanical watches)
  - Computers use crystal-based blocks (one part in million)
  - Results in *clock drift*
- Need to synchronize machines with a master or with one another

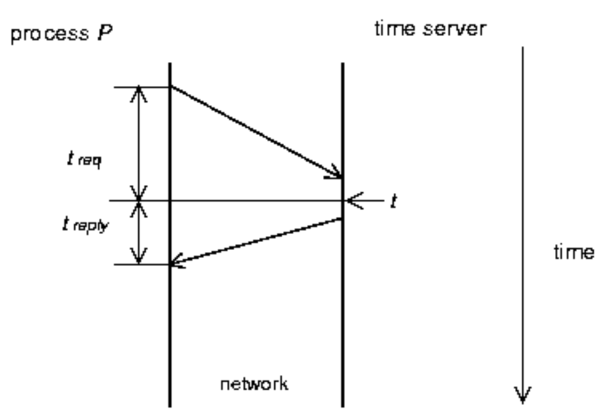
Clock Synchronization

- Each clock has a maximum drift rate ρ
    - $1-\rho \le dC/dt \le 1+\rho$
  - Two clocks may drift by $2\rho\,\Delta t$ in time Δt
  - To limit drift to δ => resynchronize every $\delta/2\rho$ seconds



Cristian's Algorithm

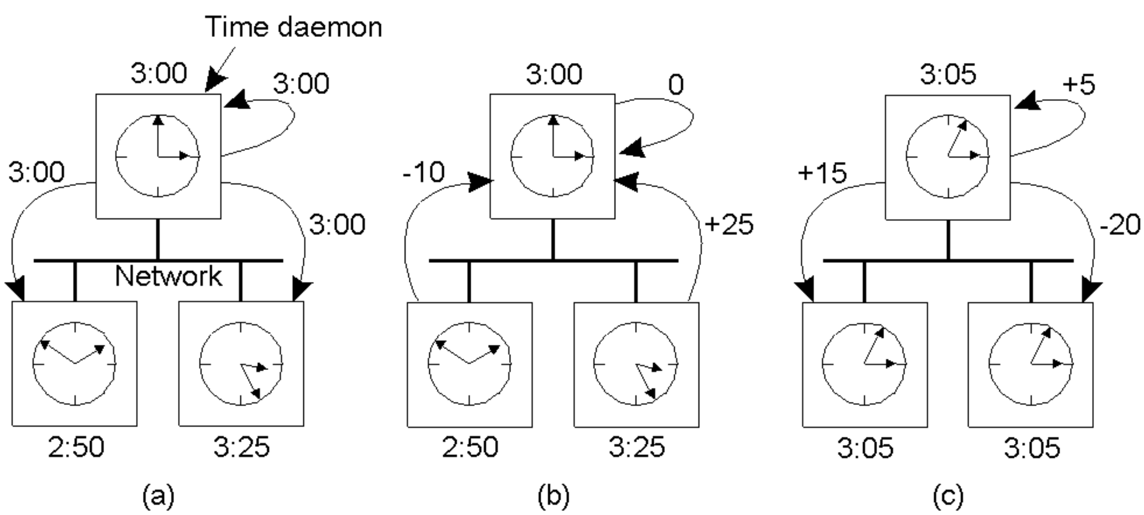
- Synchronize machines to a *time server* with a UTC receiver
- Machine P requests time from server every $\delta/2\rho$ seconds
  - Receives time t from server, P sets clock to $t+t_{reply}$ where t_{reply} is the time to send reply to P
  - Use $(t_{req}+t_{reply})/2$ as an estimate of t_{reply}
  - Improve accuracy by making a series of measurements



Berkeley Algorithm

- Used in systems without UTC receiver
  - Keep clocks synchronized with one another
  - One computer is *master*, other are *slaves*
  - Master periodically polls slaves for their times
    - Average times and return differences to slaves
    - Communication delays compensated as in Cristian's algo
  - Failure of master => election of a new master

Berkeley Algorithm

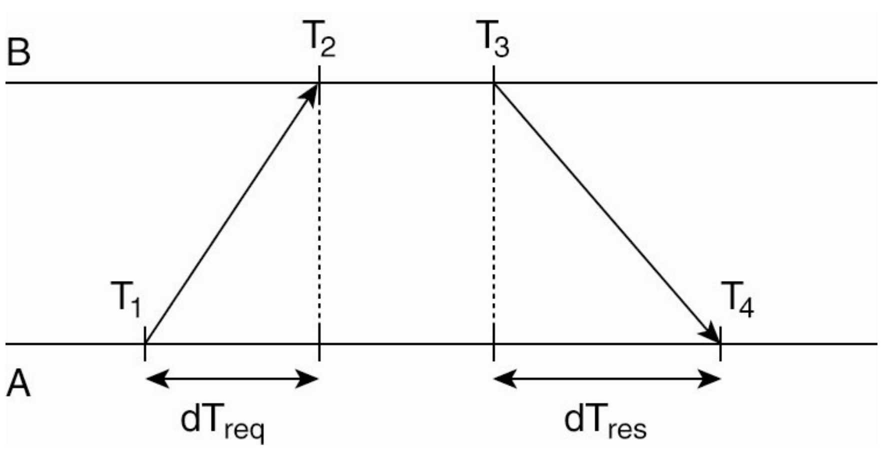


a) The time daemon asks all the other machines for their clock values
b) The machines answer
c) The time daemon tells everyone how to adjust their clock

Distributed Approaches

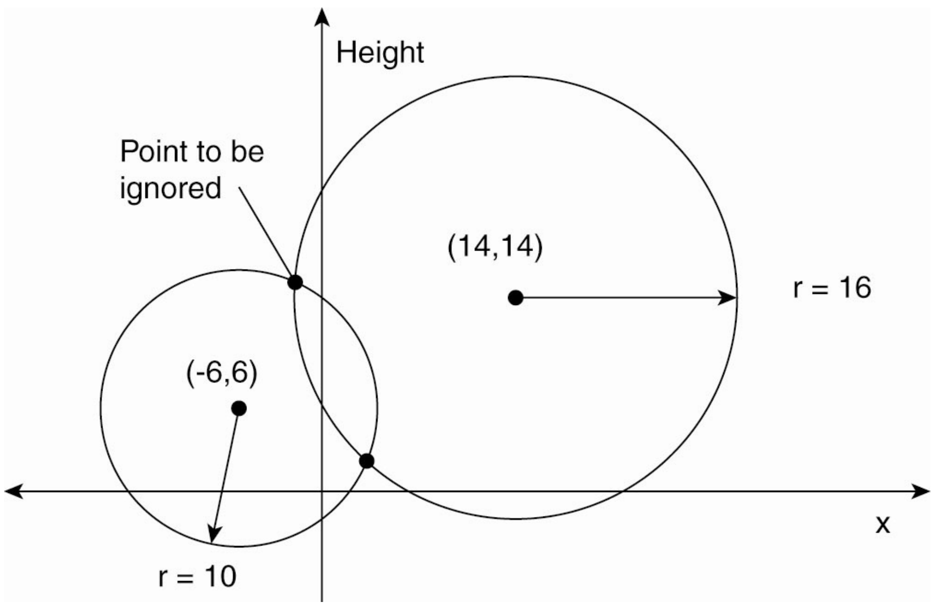
- Both approaches studied thus far are centralized
- Decentralized algorithms: use resync intervals
  – Broadcast time at the start of the interval
  – Collect all other broadcast that arrive in a period *S*
  – Use average value of all reported times
  – Can throw away few highest and lowest values
- Approaches in use today
  – *rdate*: synchronizes a machine with a specified machine
  – Network Time Protocol (NTP) - discussed in next slide
    - Uses advanced techniques for accuracies of 1-50 ms

Network Time Protocol



- Widely used standard - based on Cristian's algo
  – Uses eight pairs of delays from A to B and B to A.
- Hierarchical – uses notion of stratum
- **Clock can not go backward**

Global Positioning System



- Computing a position in a two-dimensional space.

Global Positioning System

- Real world facts that complicate GPS
- It takes a while before data on a satellite's position reaches the receiver.
- The receiver's clock is generally not in synch with that of a satellite.

GPS Basics

- D_r – deviation of receiver from actual time
- Beacon with timestamp T_i received at T_{now}
  - Delay $D_i = (T_{now} - T_i) + D_r$
  - Distance $d_i = c\,(T_{now} - T_i)$
  - Also $d_i = \text{sqrt}[\ (x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2\ ]$
- Four unknowns, need 4 satellites.
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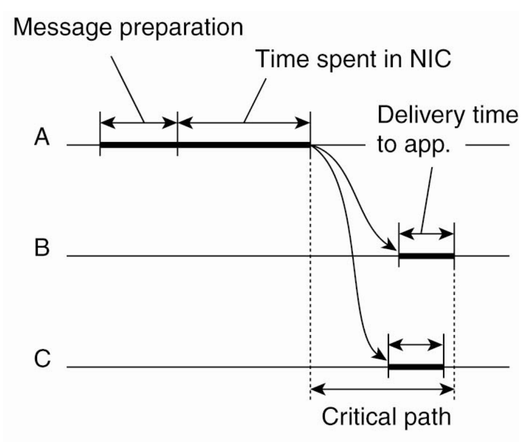
Clock Synchronization in Wireless Networks



(b)

- Reference broadcast sync (RBS): receivers synchronize with one another using RB server
  - Mutual offset = $T_{i,s} - T_{j,s}$ (can average over multiple readings)

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)

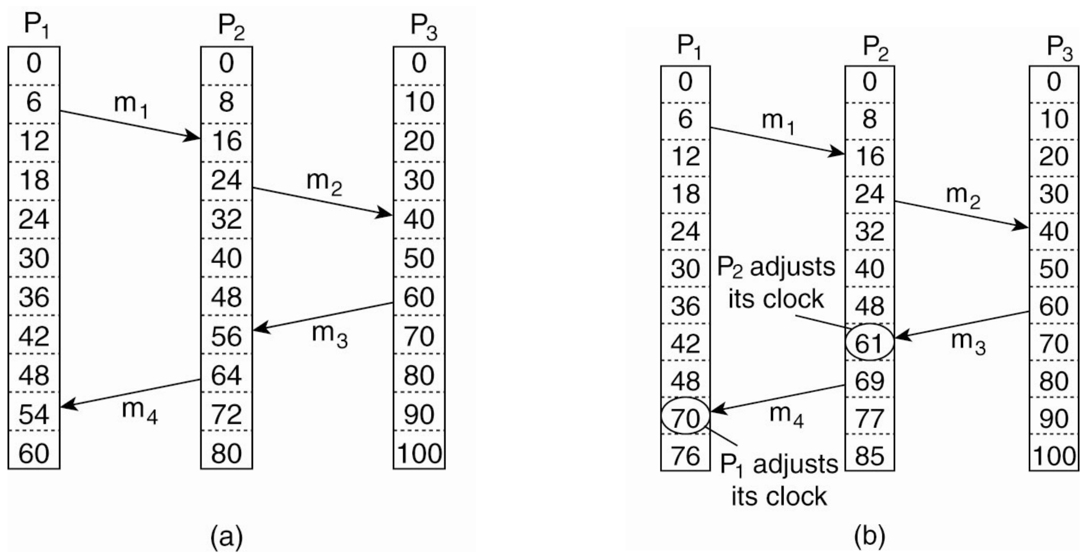
Happened Before Relation

- 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*

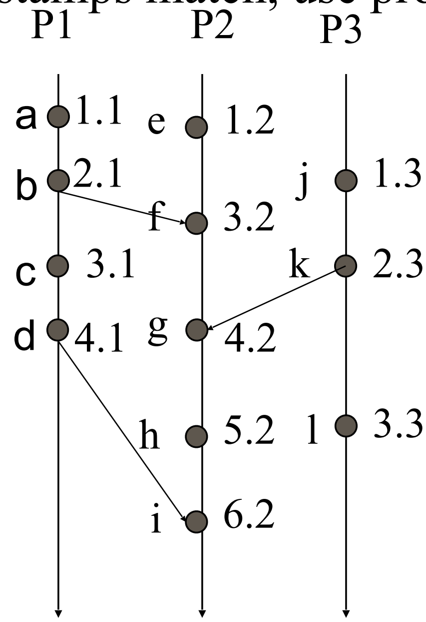
- Goal: define the notion of time of an event such that
  - If A-> B then C(A) < C(B)
  - If A and B are concurrent, then C(A) <, = or > C(B)
- Solution:
  - Each processor maintains a logical clock LC_i
  - Whenever an event occurs locally at I, $LC_i = LC_i + 1$
  - When *i* sends message to *j*, piggyback 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

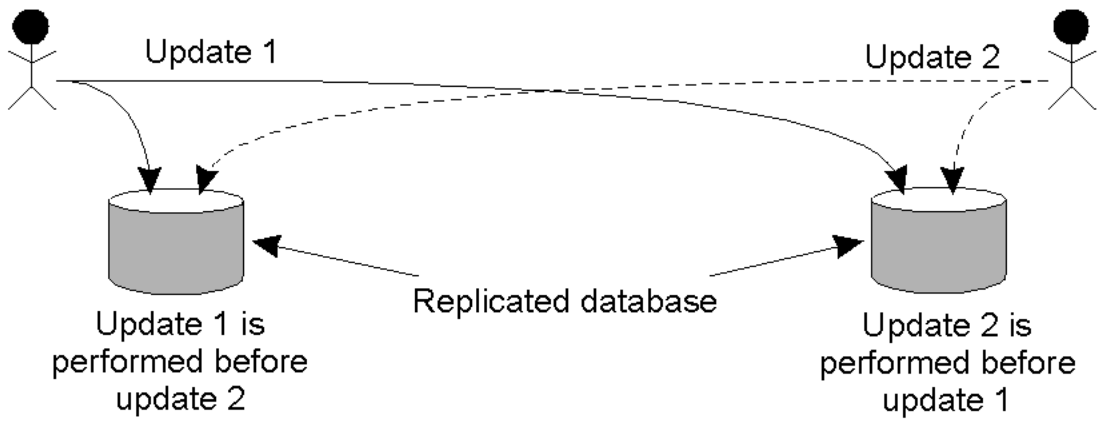


Total Order

- Create total order by attaching process number to an event. If time stamps match, use process # to order



Example: Totally-Ordered Multicasting



Algorithm

- Totally ordered multicasting for banking example
  - Update is timestamped with sender's logical time
  - Update message is multicast (including to sender)
  - When message is received
    - It is put into local queue
    - Ordered according to timestamp,
    - Multicast acknowledgement
  - Message is delivered
    - It is at the head of the queue
    - IT has been acknowledged by all processes
    - P_i sends ACK to P_j if
      - P_i has not made a request
      - P_i update has been processed and P_i's ID > P_j's Id

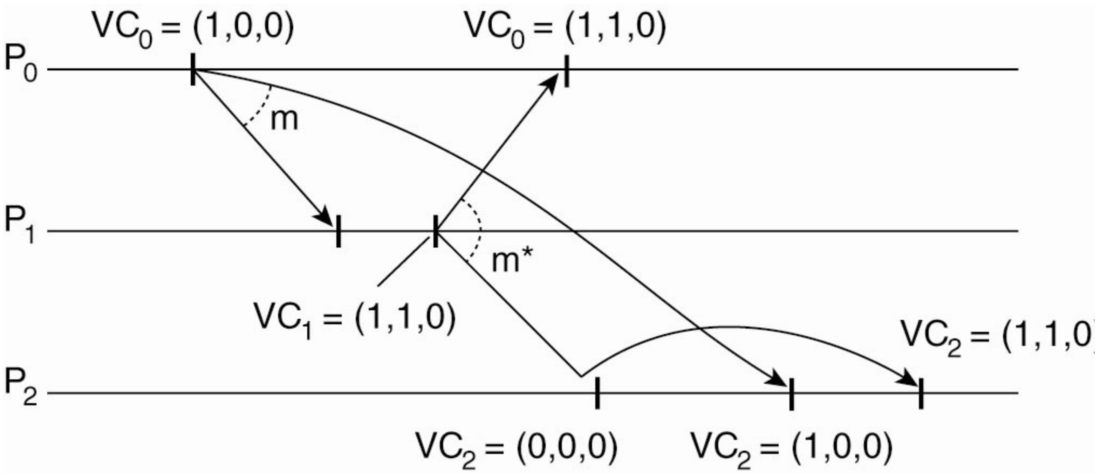
Causality

- 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.

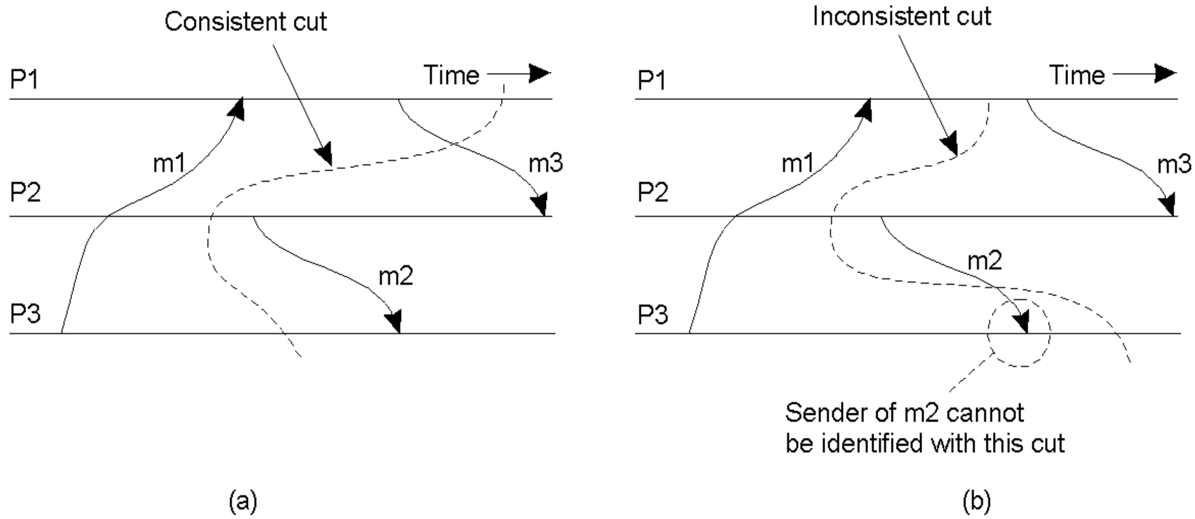
Enforcing Causal Communication

- 

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)



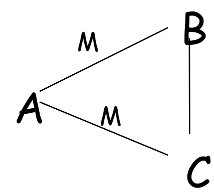
a) A consistent cut
b) An inconsistent cut

Distributed Snapshot Algorithm

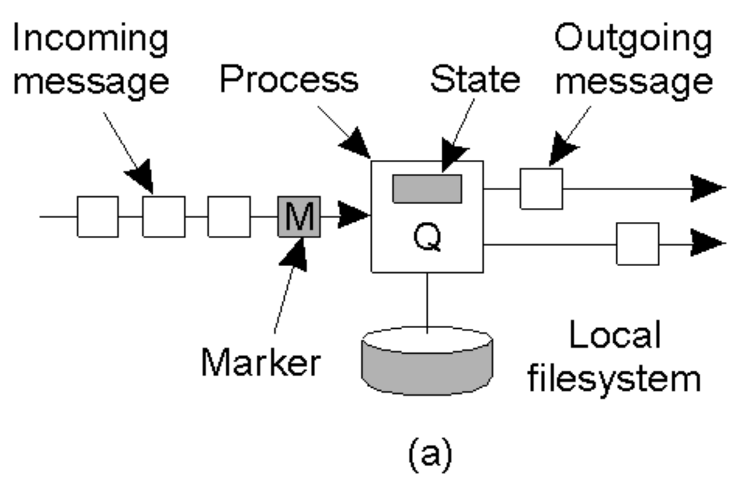
- Assume each process communicates with another process using unidirectional point-to-point channels (e.g, TCP connections)
- Any process can initiate the algorithm
  - Checkpoint local state
  - Send marker on every outgoing channel
- On receiving a marker
  - Checkpoint state if first marker and send 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)

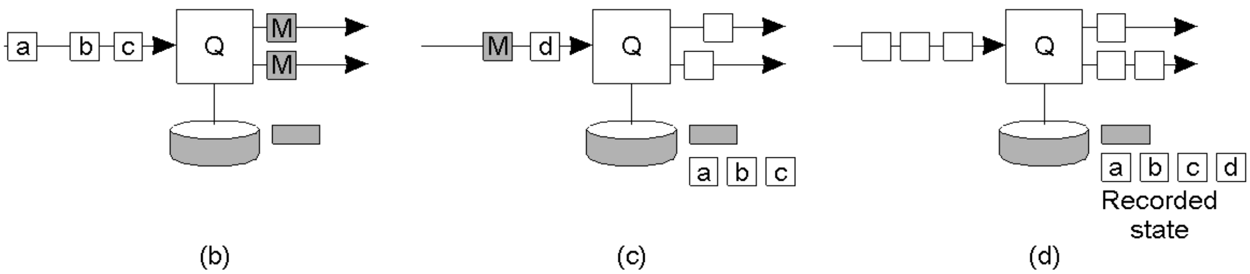


Snapshot Algorithm Example



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

Snapshot Algorithm Example



b) 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