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 $A \rightarrow B$

• If $A$ represents sending of a message and $B$ is the receipt of this message, then $A \rightarrow B$

• Relation is transitive:
  – $A \rightarrow B$ and $B \rightarrow C$  $\Rightarrow$ $A \rightarrow C$

• 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 $A \rightarrow B$ then $C(A) < C(B)$
  – If $A$ and $B$ are concurrent, then $C(A) \leqslant = \geqslant C(B)$

• 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 $A \rightarrow B$ 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 $a \rightarrow b$ then $a$ is casually related to $b$
  – Causal delivery: If $send(m) \rightarrow send(n) => deliver(m) \rightarrow deliver(n)$
  – 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

• Figure 6-13. 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