Logical Clocks

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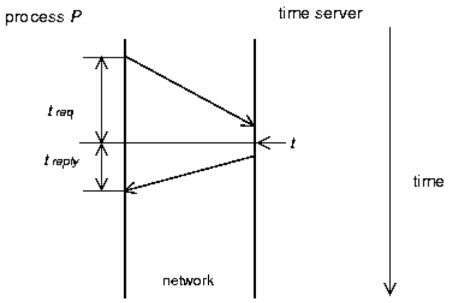
Clock Synchronization

- Time is unambiguous in centralized systems
    - System clock keeps time, all entities use this for time
- Distributed systems: each node has own system clock
    - Two clocks could differ at a given point in time (skew)
    - Clocks that agree at time t might disagree later (drift)
- Makes it harder to reason about events on different systems
- Some examples:
    - Makefile: edit on one system, compile on another system
    - Kerberos leases: valid only for a certain period of time
    - Using timestamps to serialize transactions

Pair-wise synchronization: Cristian's Algorithm

- Synchronize machines to a *time server* with a UTC receiver (some trusted physical clock)
- Machine P requests time from server (every once in a while)
  - 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

Logical Clocks

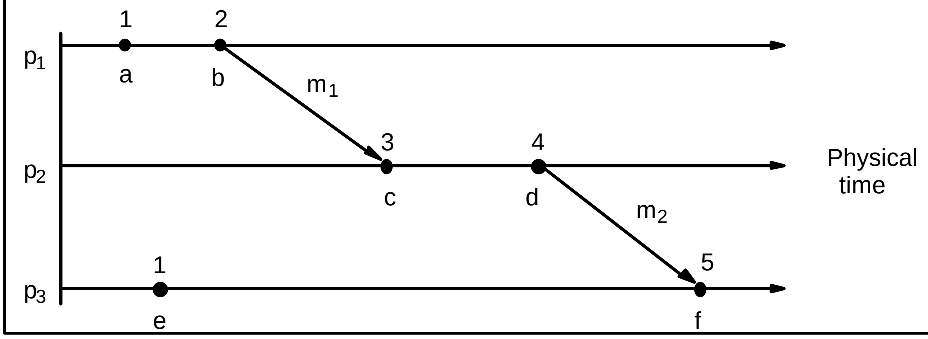
- For many problems, internal consistency of clocks is important
  - Absolute time is less important
  - Use *logical* clocks
- Key idea:
  - Clock synchronization need not be absolute
  - If two machines do not interact, no need to synchronize them
  - More importantly, processes need to agree on the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

Logical Ordering of Events

- Two kinds of ordering:
  - If a process p1 does operation o1 followed by operation o2, then we would like to say o1 occurred before o2
  - If a message is sent/received:
    - Process p1 sends message m (let this be operation o1)
    - Process p2 receives the message m (let this be operation o2)
    - Then o1 occurred before o2
  - Relations are transitive:
    - If o1 occurred before o2 and o2 occurred before o3, then o1 occurred before o3

Logical clocks

- Each process maintains a local counter
- Counter is incremented for every local event (including send events)
- Counter value is sent along with every message
- When message is received:
    - Take max of local counter and message's counter → new local counter
    - Increment local counter by one



Analysis of logical clocks

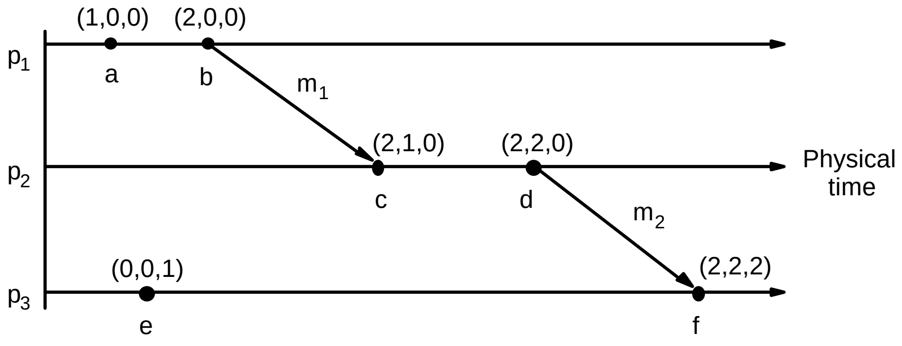
- If event e1 happened before e2:
  LC(e1) < LC(e2)

- Are we done? Are logical clocks sufficient to reason about distributed systems?

Vector Clocks

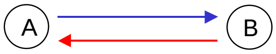
- Each process i maintains a vector V_i
  - $V_i[i]$: number of events that have occurred at i
  - $V_i[j]$: number of events i knows have occurred at process j
- Update vector clocks as follows
  - Local event: increment $V_i[\mathbf{I}]$
  - Send a message :piggyback entire vector V
  - Receipt of 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 $V_j[i] = V_j[i]+1$
- Convince yourself that if V(A)<V(B), then A precedes B

Vector Clocks Example

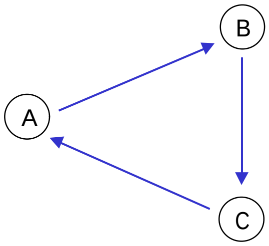


Motivating Example for Reasoning about Global State

- Assume that we have processes interacting in a client-server mode



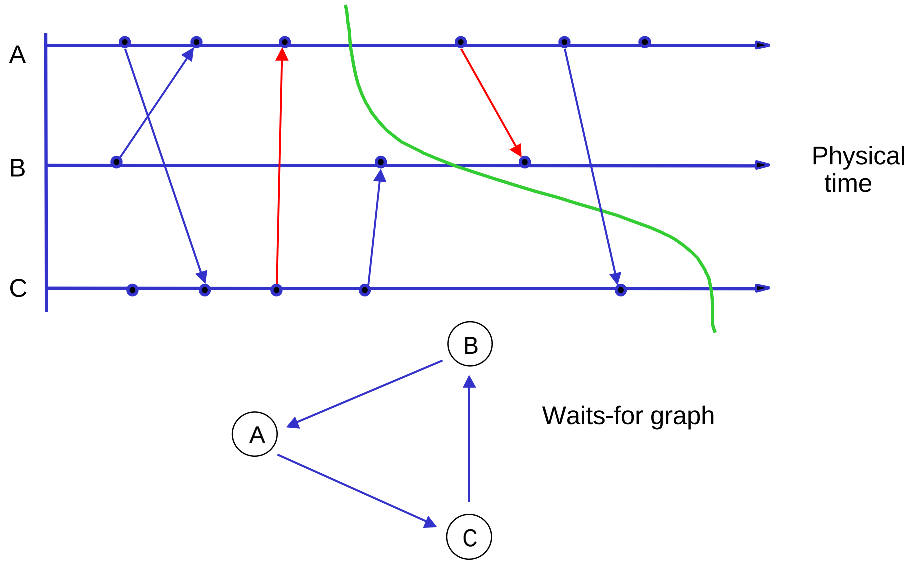
- Client makes request to server
  - Waits for response
  - While waiting for response, client simply blocks; does not satisfy requests from other nodes



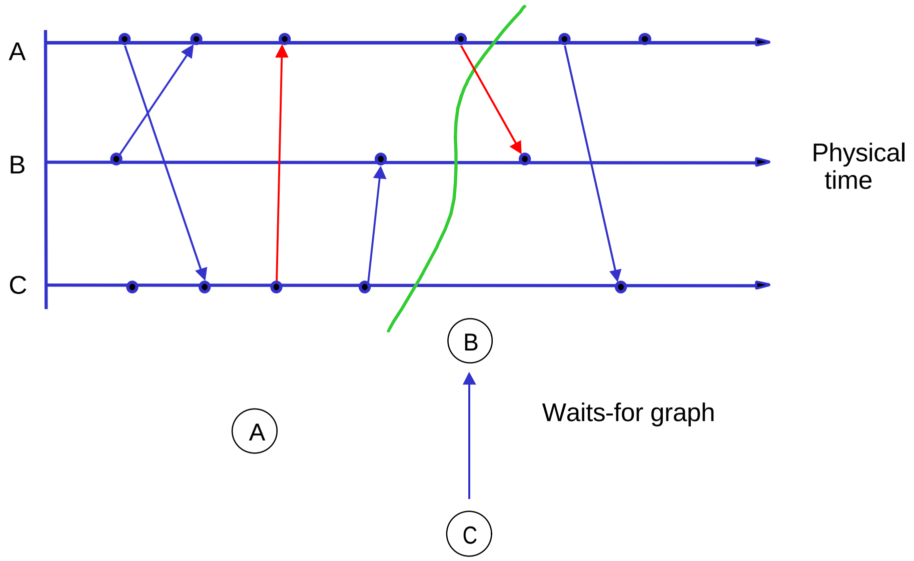
Deadlock Detection

- Assume that you have a centralized server
- It queries each node
  - Each node responds with a list of requests that are pending (requests for which a response has not been sent)
- Centralized server can then build a “waits-for” graph:
  - Cycle in graph implies deadlock

Possible Execution

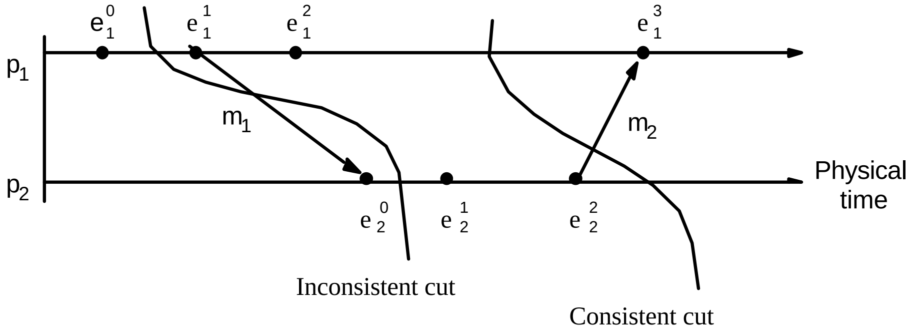


Different Observation



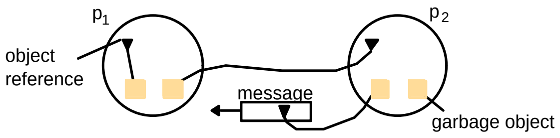
Consistent & Inconsistent Cuts

- A cut is inconsistent if:
  - You include an event e2 in p2
  - Event e1 of p1 influences e2
  - But e1 is not included

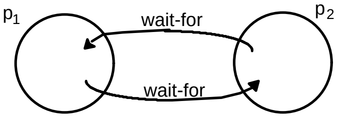


Other Applications

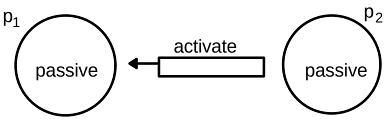
a. Garbage collection



b. Deadlock



c. Termination



Snapshot

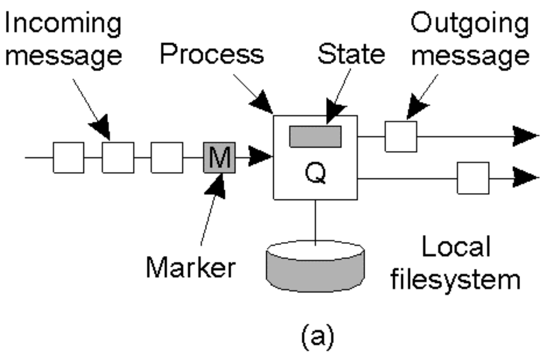
- Develop a simple synchronous protocol
- Refine protocol as we relax assumptions
- Initial assumptions:
  - Real time clock known to all processes
  - Message delays are bounded

- Algorithm: (assume that all messages are timestamped)
  - Process P_0 selects “t_{ss}”
  - P_0 sends “take a snapshot at t_{ss}” to all processes
  - When clock of P_i reads t_{ss} then it:
    - Records its local state (σ_i)
    - Sends an empty message along all its outgoing channels
    - Starts recording messages on each of incoming channels
    - Stops recording a channel when it receives first message with timestamp greater than or equal to t_{ss}

Snapshot (2nd attempt)

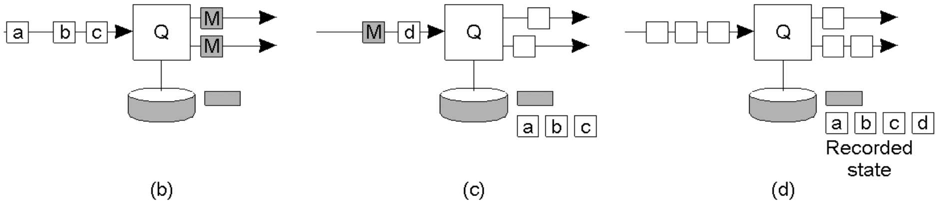
- Operate with logical clocks
- Algorithm:
  - P_0 sends “take a snapshot”
  - When P_i receives “take a snapshot” for the first time from P_j :
    - Records its local state (σ_i)
    - Sends “take a snapshot” along all its outgoing channels
    - Sets channel from P_j to be empty
    - Starts recording messages on each of incoming channels
  - When P_i receives “take a snapshot” beyond the first time from P_k
    - Stops recording channel from P_k
  - When P_i has received “take a snapshot” on all channels, it sends collected state to P_o and stops

Snapshot Algorithm Example



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

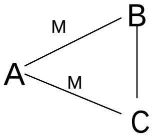
Snapshot Algorithm Example



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

Distributed Snapshot

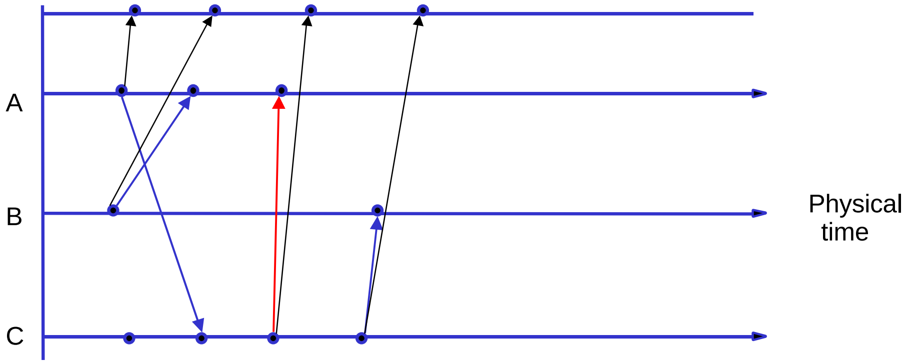
- A process finishes when
  - It receives a marker on each incoming channel and processes them all
  - State: local state plus state of all channels
  - Send state to initiator, initiator analyzes state



- 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)

A Different Approach

- Monitor process does not query explicitly
- It just passively collects information
- Uses it to build an "observation"

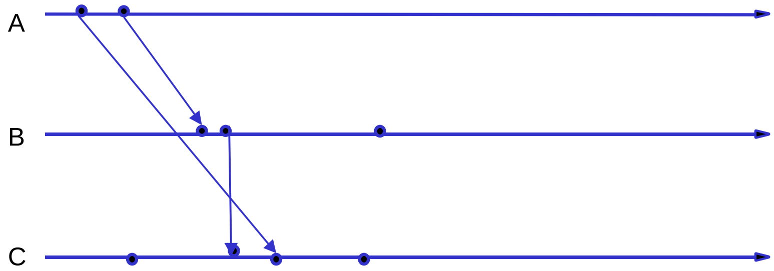


Delivery of messages to monitor

- What properties do we need to satisfy in delivering messages to the monitor?

Causal Delivery

- A message cannot be delayed to appear after a later message

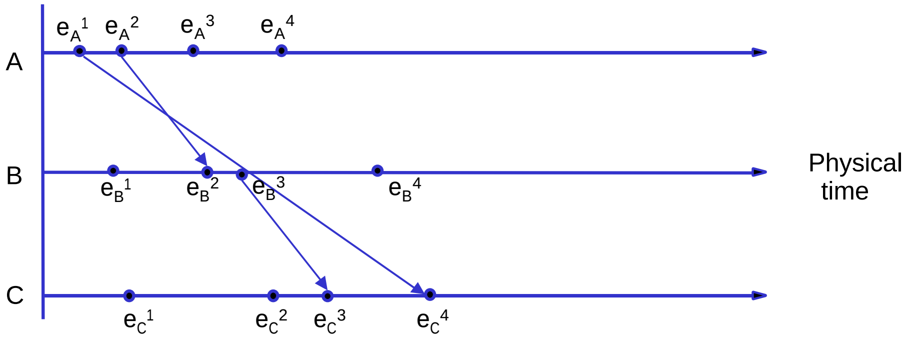


Summary so far…

- Interested in “global predicate detection”
    - Whether the state of a distributed application matches some predicated (deadlocks, termination, distributed garbage collection, etc.)
- Two approaches:
    - A centralized process sends messages to capture the current state of all processes
        - Centralized process needs to observe a “consistent cut”
        - Snapshot protocol finds a consistent cut
            - Intuition: rely on FIFO property of channels; propagate markers along channels and save state as marker messages reach processes
    - Each process continually sends messages to centralized process when “interesting” events happen
        - Centralized process builds global state – can compute all possible global states that may or may not occur in the system

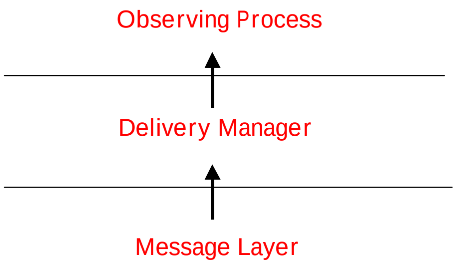
Delivery of events to centralized process

- Requirements:
    - FIFO: messages from same processor is delivered in order
        - e_A^1 should be reported before e_A^2
    - Causal properties are preserved; consistent observations are made
        - e_A^1 should be reported before e_C^4



How to deliver messages?

- Each event notification is tagged with logical clock value
- Messages are “delivered” to observing process in a manner that satisfies above properties
- Delivery manager delivers messages in increasing order of logical clock values
  - Ties are broken based on processor ids


Observing Process

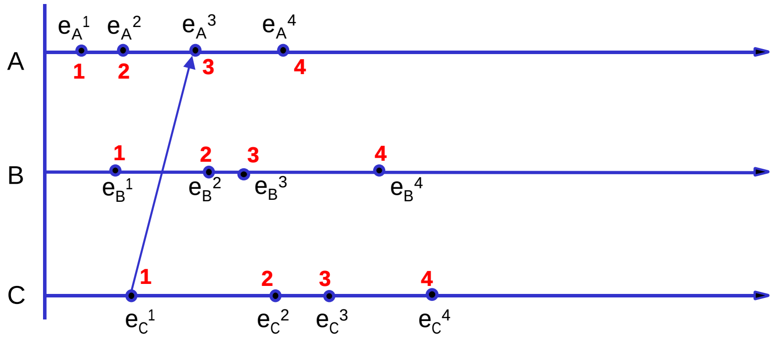
Delivery Manager

Message Layer

Gap Detection

- Consider the following state:
  - Observing processor has received the following event notifications:

    e_A^1 e_A^2 e_B^1 e_A^3 e_B^2
  - Notification of e_C^1 has been delayed
  - Gap detection problem: given two events e1 and e2, detect whether or not there is another event e3 that occurs in the middle



Gap detection using logical clocks

- Wait for a while until there is at least one undelivered observation from each process
- Deliver the event with the lowest logical clock value

- Has liveness issues:
  - Requires processors to continually send observations to observing processor

- Is there a better solution? Is there some way of deciding whether or not to delay delivery as soon as a message is received?

Global Predicate Evaluation

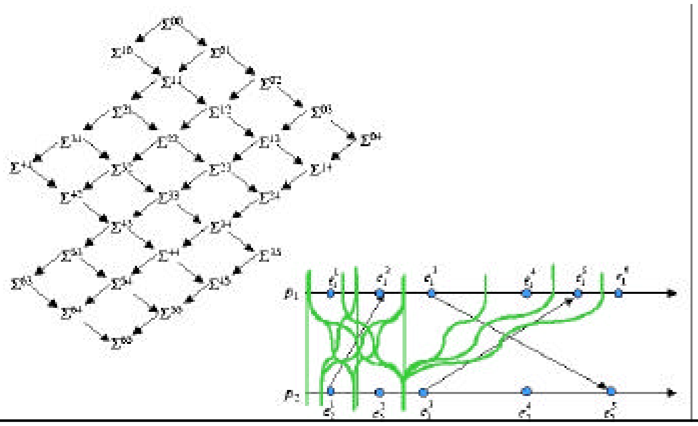
- Two methods:
  - Distributed snapshot initiated at arbitrary times
  - Centralized observations made using reports of all events

- Global predicates that can be evaluated using either method:
  - Deadlock detection
  - Termination detection
  - Garbage collection

- When would you use distributed snapshots and when would you use centralized observations?

Formalisms

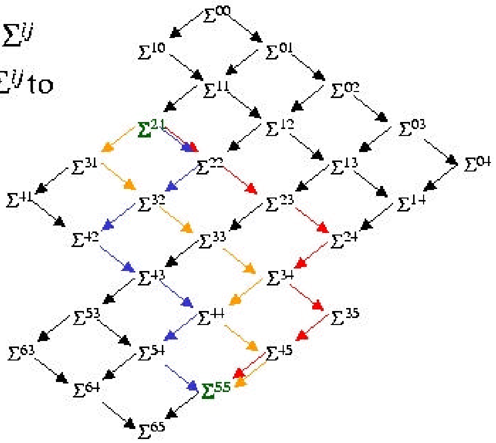
- Denote global states by ∑
- For example, assume two processes
    - Σ^{ij} would refer to process 1 at state i and process 2 at state j
- Define a lattice of valid global states



Reachability

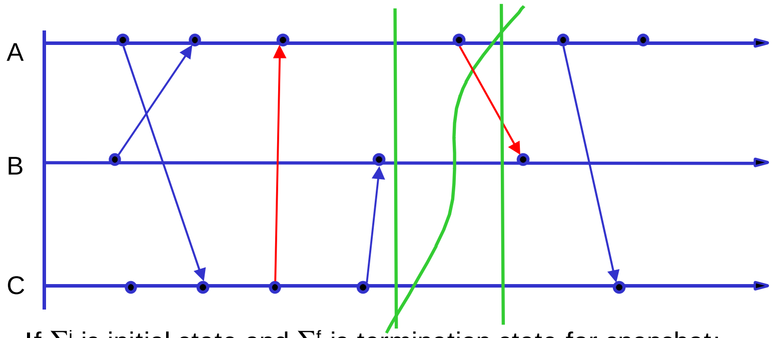
We say that
Σ^{kl} is reachable from Σ^{ij}
if there is a path from Σ^{ij} to
Σ^{kl} in the lattice.

$\boxed{\Sigma^{ij} \leadsto \Sigma^{kl}}$



Why do we care about Σ?

- Deadlock is a stable property
  - Deadlock now implies deadlock in the future



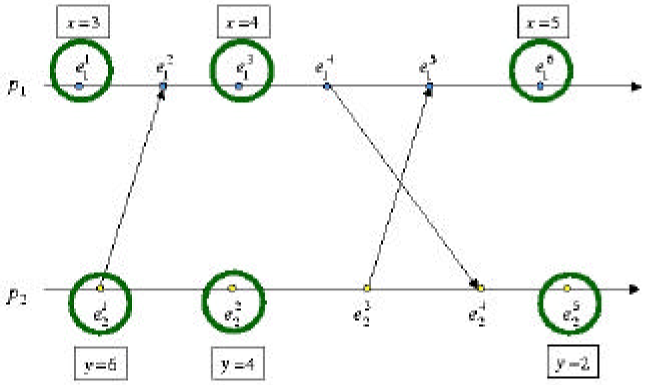
- If Σ^i is initial state and Σ^f is termination state for snapshot:

$$\Sigma^i \sim \Sigma^s \sim \Sigma^f$$

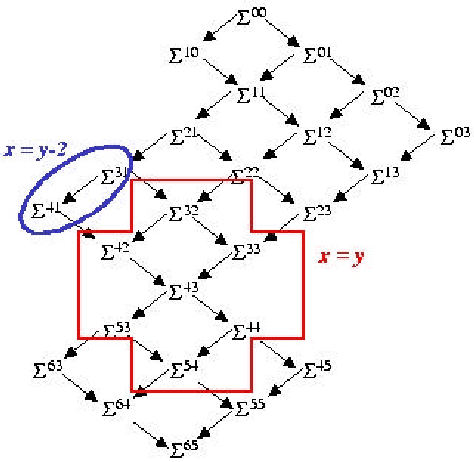
- Deadlock in Σ^s implies deadlock in Σ^f
- No deadlock in Σ^s implies no deadlock in Σ^i

Global Predicate Detection

- What if we want to detect non-stable predicates?
- Say we want to evaluate predicate at Σ^{ij}
  - Cannot use snapshots
  - Example: detect if “x == y” or “x == y – 2”



The Lattice



- In Σ^{31} or Σ^{41}, the predicate (x == y – 2) is detected

  (Notice that it might be detected, but might never have occurred.)

- We know that (x == y) has occurred, but it may not be detected if tested before Σ^{32} or after Σ^{54}

- Not enough to look at one state: look at all observations instead

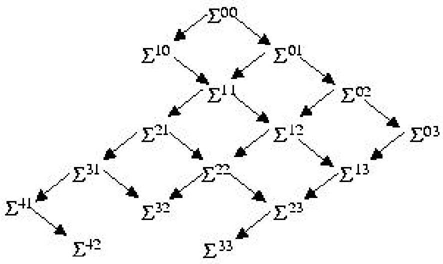
Possibly and Definitely

- Possibly: There exists a consistent observation O of the computation such that the predicate holds in a global state of O

- Definitely: For every consistent observation O of the computation, there exists a global state of O in which the predicate holds

Computing Possibly and Definitely

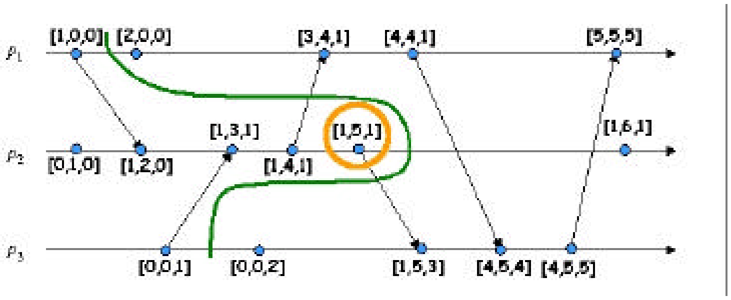
- Scan lattice level after level
- To compute Possibly(Φ):
  - If Φ holds in one global state, th declare Possibly(Φ) to be true
- To compute Definitely(Φ):
  - Given a level, only expand those nodes that correspond to states which !Φ holds
  - If no such state, announce Definitely(Φ)



Building the lattice

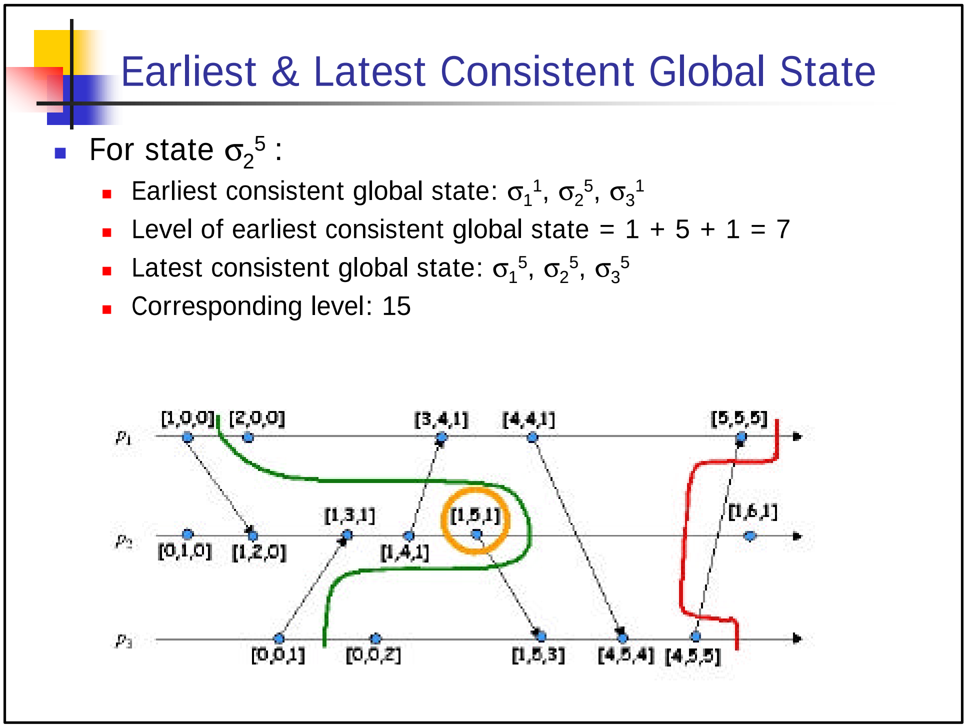
- P0 collects local state from each process
- For each process, keep a sequence Q of local states in FIFO order
- Construct global states as combination of all possible local states
- When is it safe to “drop” a local state?
- How to build level i+1 of lattice given level i?

Earliest Consistent Global State



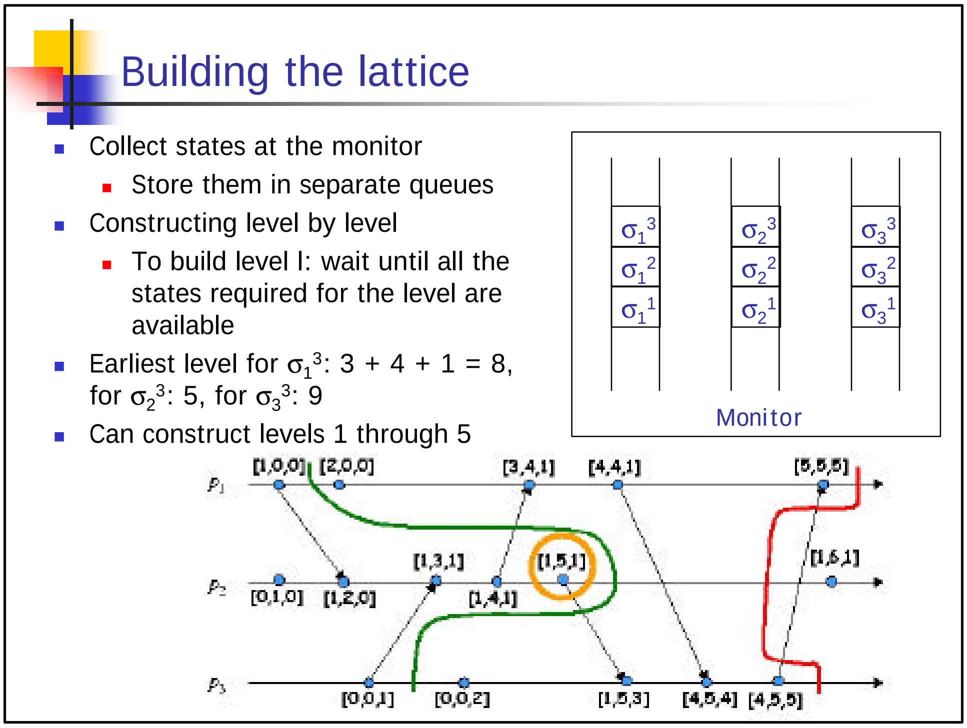
Notation and Terminology

- $\Sigma^{i1\ i2\ i3\ldots in}$ represents the global state after i_1 operations by processor 1, i_2 operations by processor 2, etc.
- Level of $\Sigma^{i1\ i2\ i3\ldots in}$ is $i_1 + i_2 + \ldots + i_n$
- σ_i^j represents state of processor i after j operations
- Earliest consistent global state: $\Sigma_{min}(\sigma_i^j)$, latest consistent global state: $\Sigma_{max}(\sigma_i^j)$



Earliest & Latest Consistent Global State

- For state σ_2^5 :
  - Earliest consistent global state: $\sigma_1^1, \sigma_2^5, \sigma_3^1$
  - Level of earliest consistent global state = 1 + 5 + 1 = 7
  - Latest consistent global state: $\sigma_1^5, \sigma_2^5, \sigma_3^5$
  - Corresponding level: 15



Building the lattice

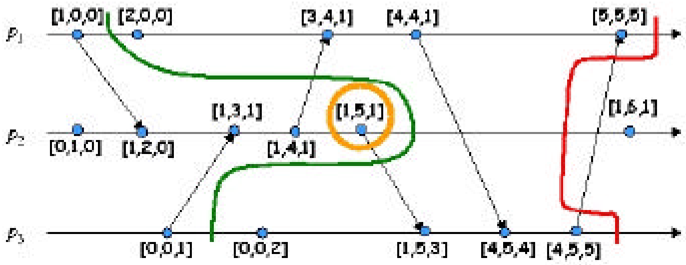
- Collect states at the monitor
  - Store them in separate queues
- Constructing level by level
  - To build level l: wait until all the states required for the level are available
- Earliest level for σ_1^3: 3 + 4 + 1 = 8, for σ_2^3: 5, for σ_3^3: 9
- Can construct levels 1 through 5

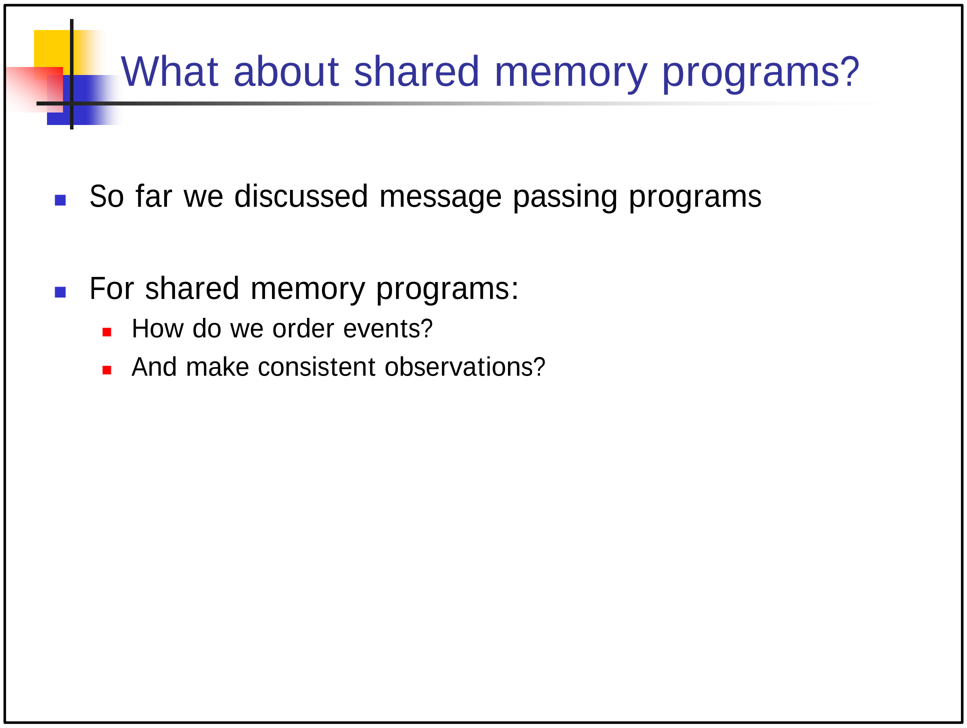
Building the lattice (contd.)

- Once monitor decides to build level L+1:
  - It takes all the consistent global states of level L
  - Extends them by one extra step for some processor
  - For example: $\Sigma^{i1\ i2\ i3 \ldots in}$ is a level L global state (stored in the lattice), then construct $\Sigma^{i1+1\ i2\ i3 \ldots in}$, $\Sigma^{i1\ i2+1\ i3 \ldots in}$, … , $\Sigma^{i1\ i2\ i3 \ldots in+1}$
  - Some of these are inconsistent states: can be detected by looking at the vector clock values of local states
  - Discard these spurious global states

Building the lattice (contd.)

- Once the monitor has finished building level L, it can discard some of the local states from its queue
- Consider σ_2^5: latest consistent global state it belongs to is $\sigma_1^5\ \sigma_2^5\ \sigma_3^5$
- Corresponding level = 15
- Discard σ_2^5 after computing level 15





What about shared memory programs?

- So far we discussed message passing programs
- For shared memory programs:
  - How do we order events?
  - And make consistent observations?