Virtual time & Global states

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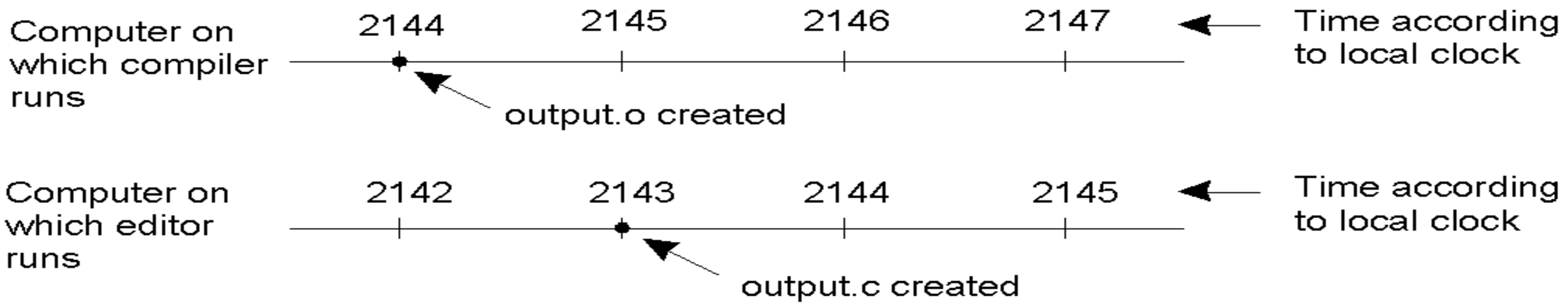
Contents

- Time ordering and clock synchronization
- Virtual time (logical clock)
- Distributed snapshot (global state)
- Consistent/Inconsistent global state
- Rollback Recovery
- Debugging & Race messages

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

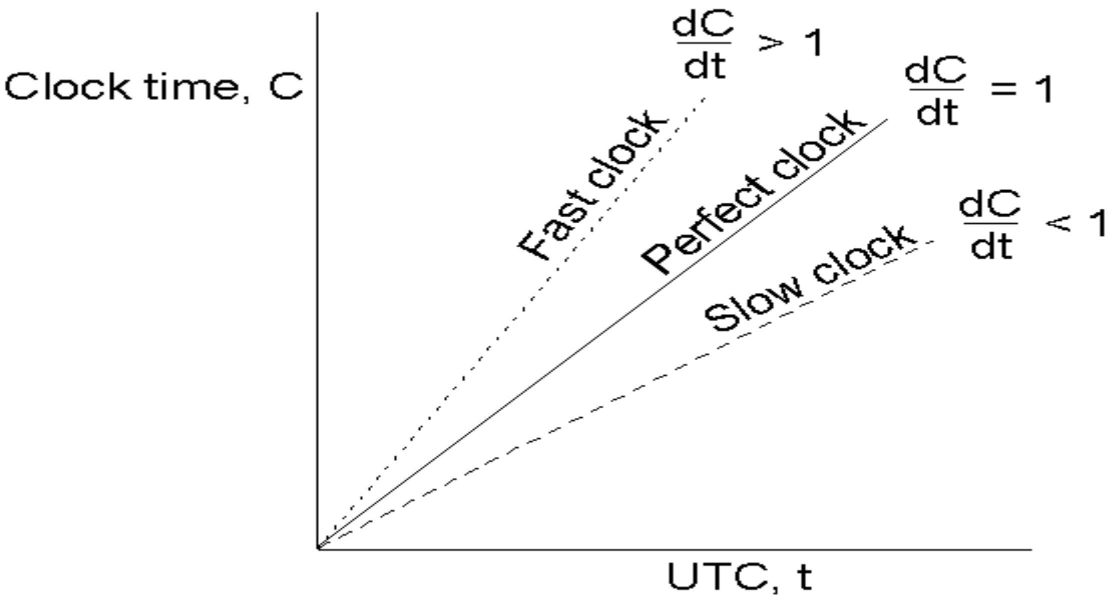


Physical clocks: a primer

- Accurate clocks are atomic oscillators
  - 1s ~ 9,192,631,770 transitions of the cesium 133 atom
- Most clocks are less accurate (e.g., mechanical watches)
  - Computers use crystal-based blocks (one part in million)
  - Results in *clock drift*
- How do you tell time?
  - Use astronomical metrics (solar day)
- Universal coordinated 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
- Need to synchronize machines with a master or with one another

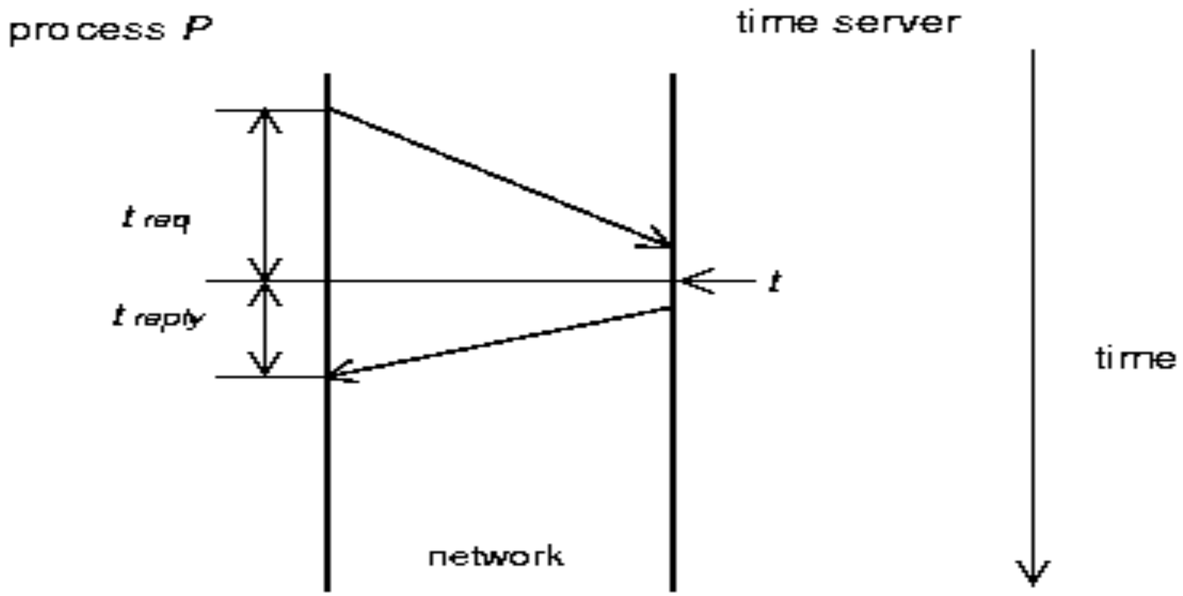
Clock synchronization

- Each clock has a maximum drift rate r
    - $1-r \le dC/dt \le 1+r$
  - Two clocks may drift by $2r*D_t$ in time D_t
  - To limit drift to d ➔ resynchronize every $d/2r$ seconds



Cristian's algorithm

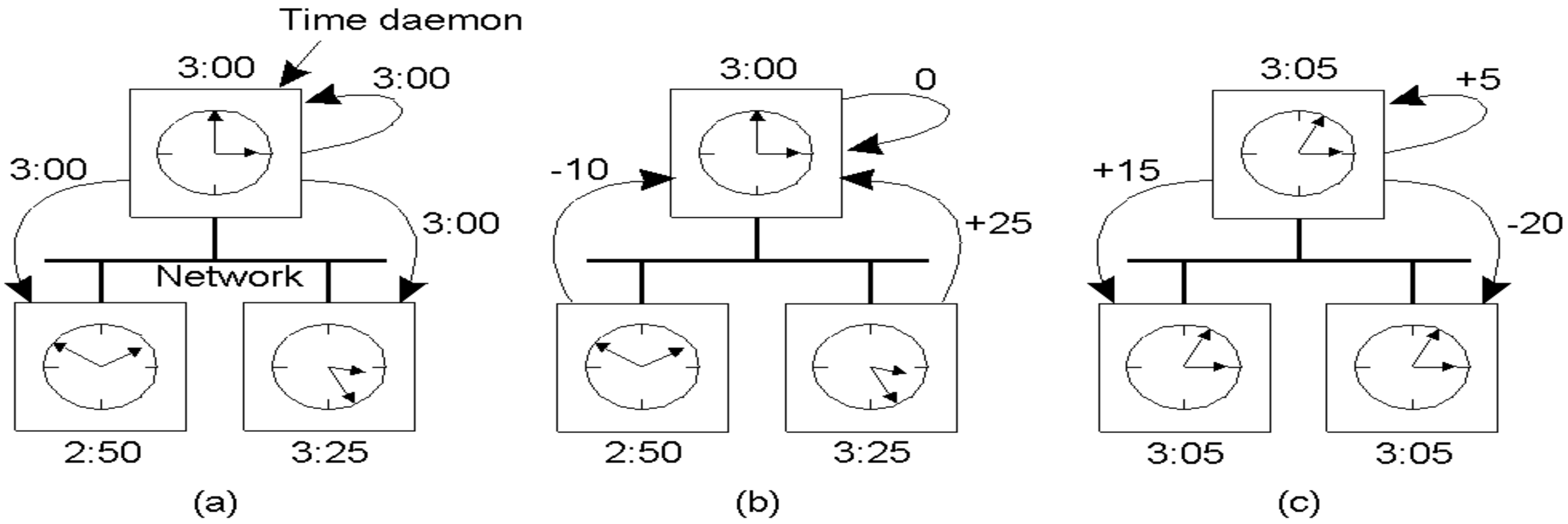
- Synchronize machines to a *time server* with a UTC receiver
- Machine P requests time from server every `d/2r` seconds
  - Receives time t from server, P sets clock to $t+t_{reply}$ where t_{reply} is the time to send reply to P
  - Use $(t_{req}+t_{reply})/2$ as an estimate of t_{reply}
  - Improve 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 algorithm
  - 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 resynchronization 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)
    - Uses advanced techniques for accuracies of 1-50 ms

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
  - Cannot order events on different machines using local times
- Key idea [Leslie Lamport]
  - Processes exchange messages
  - Message must be sent before received
  - Send/receive used to order events (and synchronize clocks)

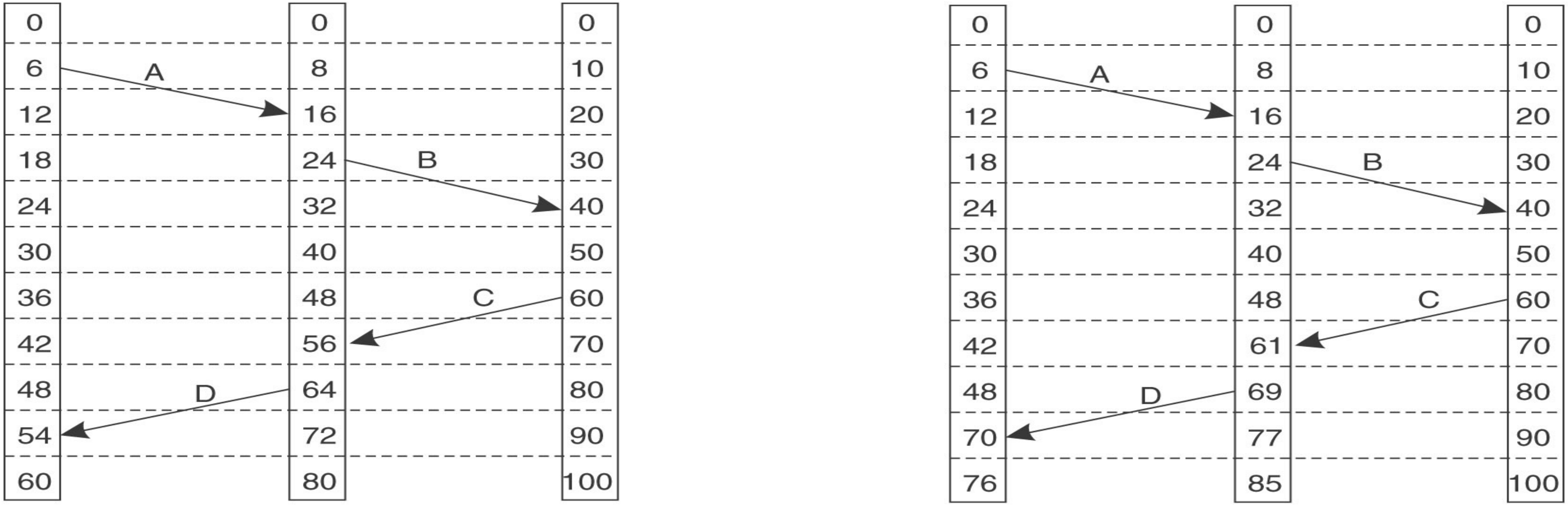
Happened-Before relation

- 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: $(A \rightarrow B) \cap (B \rightarrow C) \Rightarrow A \rightarrow C$
- 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 $C(A)$ $<, =$ 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



(a) (b)

More Canonical problems

- Causality
    - Vector timestamps

- Global state and termination detection

- Election algorithms

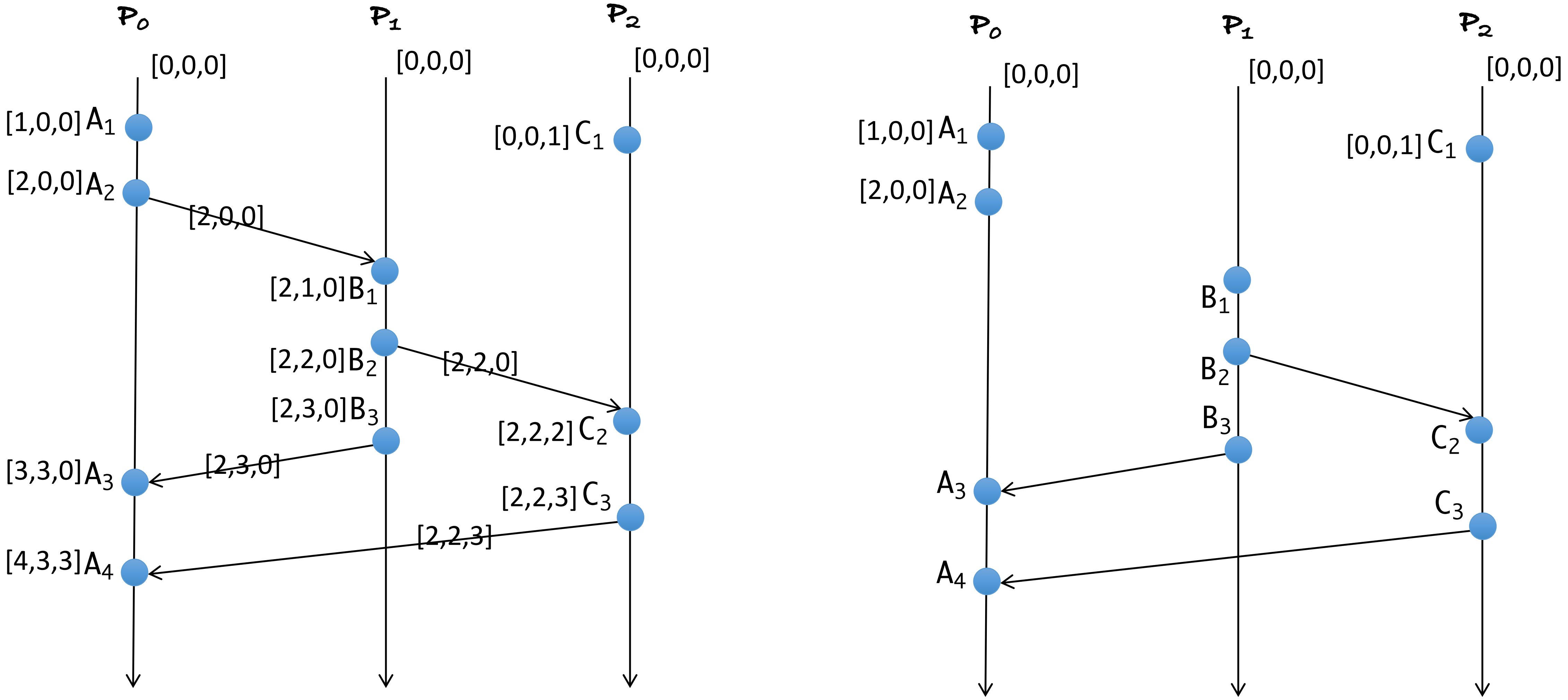
Causality

- 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*
  - 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 process i
  - $V_i[j]$: number of events occurred at process j that process i knows
- Update vector clocks as follows
  - Local event: increment $V_i[i]$
  - Send a message: piggyback entire vector V
  - Receipt of a message:
    - ✧ $V_j[j] = V_j[j]+1$
    - ✧ Receiver is told about how many events the sender knows occurred at another process k

      $V_j[k] = \max(V_j[k], V_i[k])$
- *Homework:* convince yourself that if $V(A) < V(B)$, then A causally precedes B

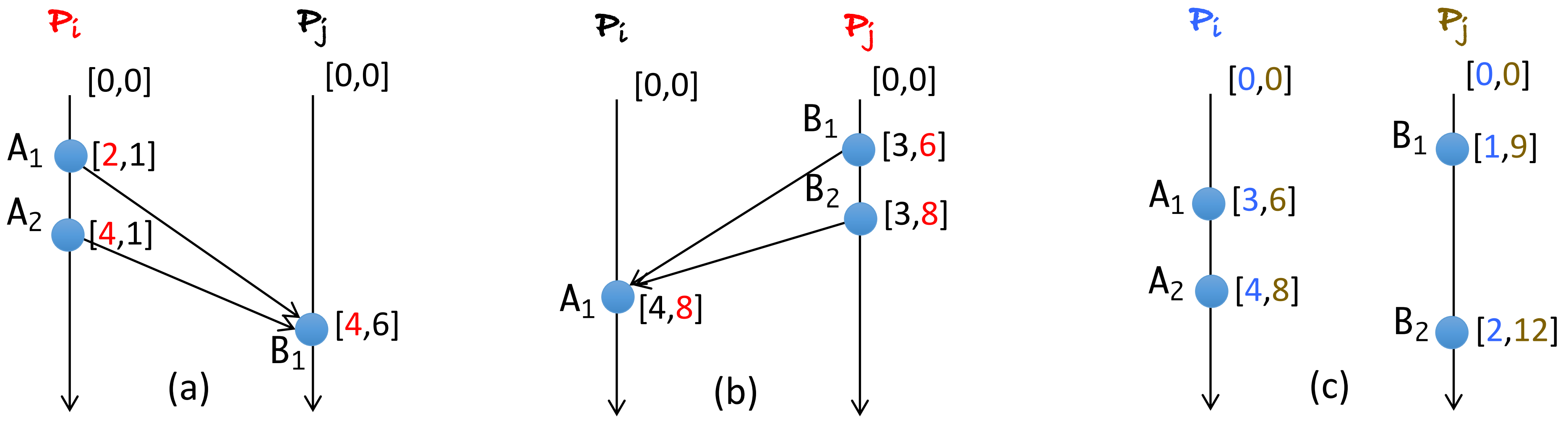


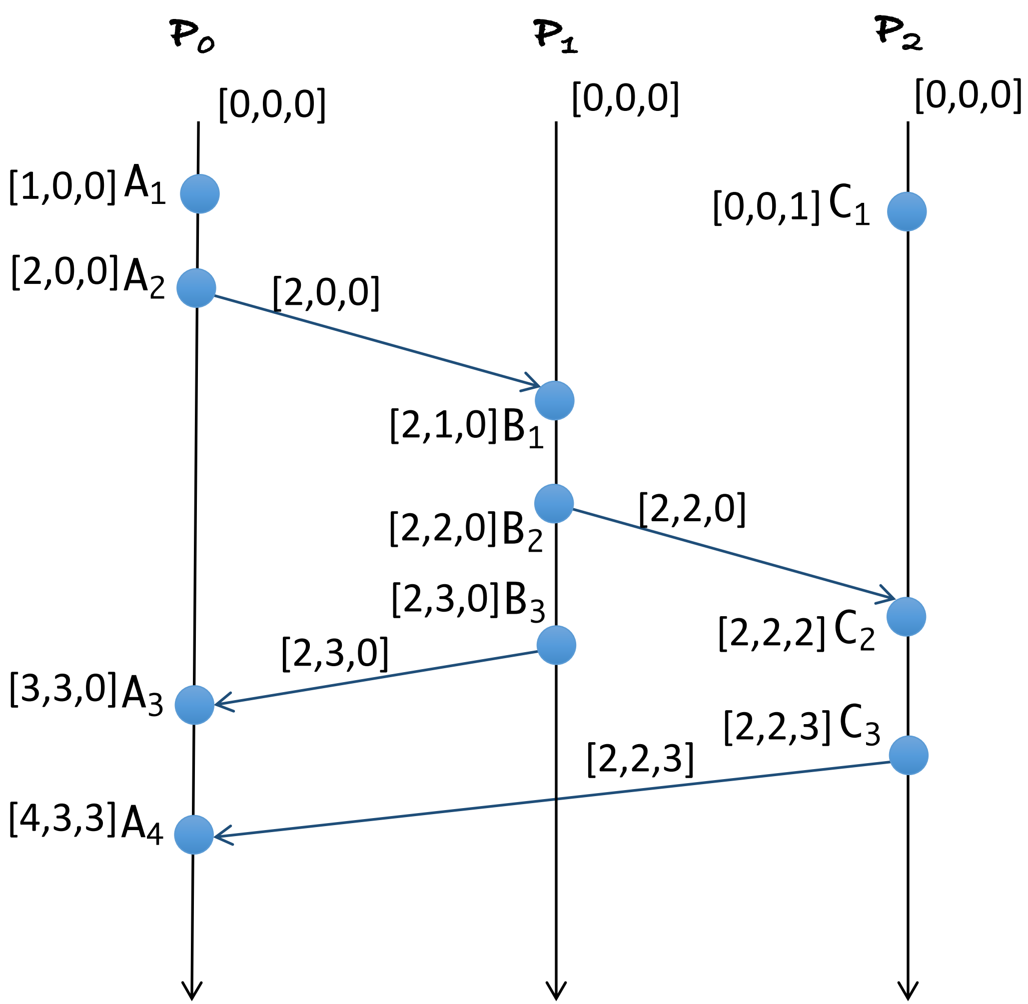
P0
P1
P2
[0,0,0]
[0,0,0]
[0,0,0]
[1,0,0] A1
[0,0,1] C1
[2,0,0] A2
[2,0,0]
[2,1,0] B1
[2,2,0] B2
[2,2,0]
[2,3,0] B3
[2,2,2] C2
[3,3,0] A3
[2,3,0]
[2,2,3] C3
[2,2,3]
[4,3,3] A4
P0
P1
P2
[0,0,0]
[0,0,0]
[0,0,0]
[1,0,0] A1
[0,0,1] C1
[2,0,0] A2
B1
B2
B3
C2
A3
C3
A4

Vector Clocks: Happened–Before

Event A in process i has the vector V_A and event B in process j has the vector V_B:

- $A \rightarrow B \Leftrightarrow V_B[i] \geq V_A[i]$
- $B \rightarrow A \Leftrightarrow V_A[j] \geq V_B[j]$
- $A \parallel B \Leftrightarrow \neg(A \rightarrow B) \wedge \neg(B \rightarrow A)$
  $\Leftrightarrow (V_B[i] < V_A[i]) \wedge (V_A[j] < V_B[j])$





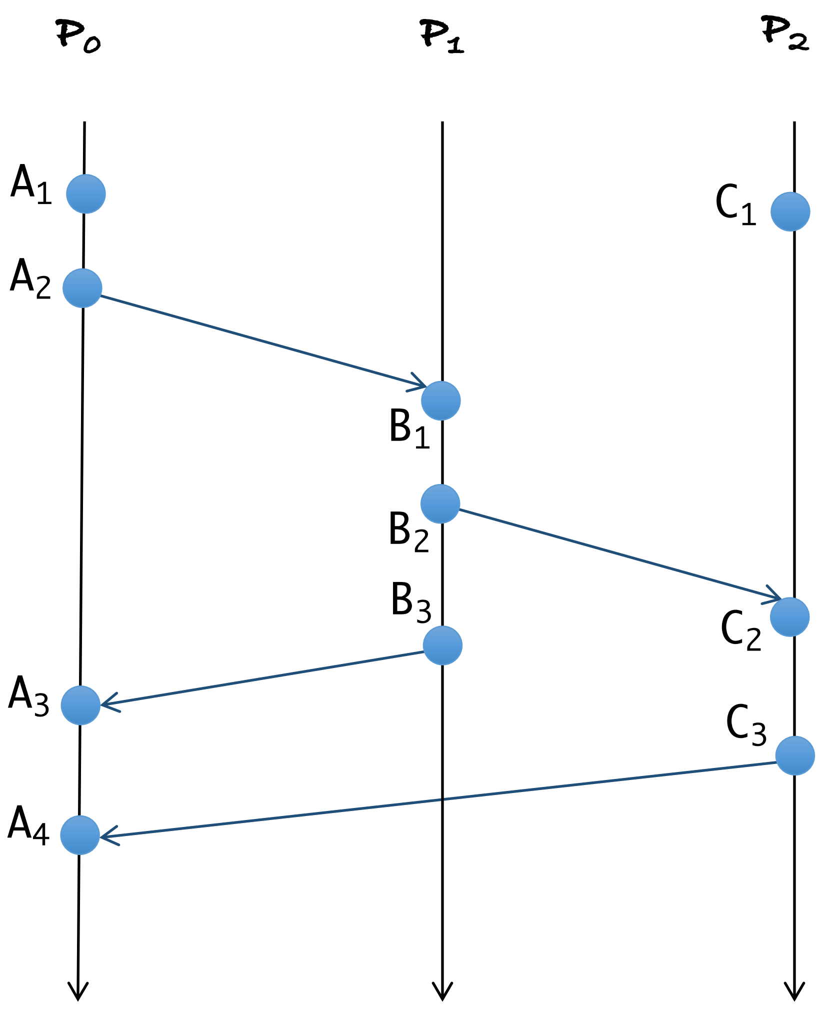
$A_1 \rightarrow A_2,\ A_2 \rightarrow A_3,\ A_3 \rightarrow A_4$
$B_1 \rightarrow B_2,\ B_2 \rightarrow B_3$
$C_1 \rightarrow C_2,\ C_2 \rightarrow C_3$

$A_2 \rightarrow B_1,\ B_2 \rightarrow C_2$
$B_3 \rightarrow A_3,\ C_3 \rightarrow A_4$

$A_1 \rightarrow B_1,\ A_2 \rightarrow B_2,\ B_1 \rightarrow C_2,\ B_2 \rightarrow A_3$
$B_2 \rightarrow C_3,\ C_2 \rightarrow A_4,\ B_3 \rightarrow A_4$

$A_1 \rightarrow B_2,\ A_1 \rightarrow C_2,\ A_1 \rightarrow C_3,\ A_1 \rightarrow B_3$
$B_1 \rightarrow C_3,\ B_1 \rightarrow A_4,\ B_3 \rightarrow A_4$
$C_1 \rightarrow A_4,\ \ldots$

$A_1 \parallel C_1,\ A_2 \parallel C_1,\ A_3 \parallel C_1$
$B_1 \parallel C_1,\ B_2 \parallel C_1,\ B_3 \parallel C_1$
$B_3 \parallel C_2,\ A_3 \parallel C_2,\ \ldots$



Did you see their relations?

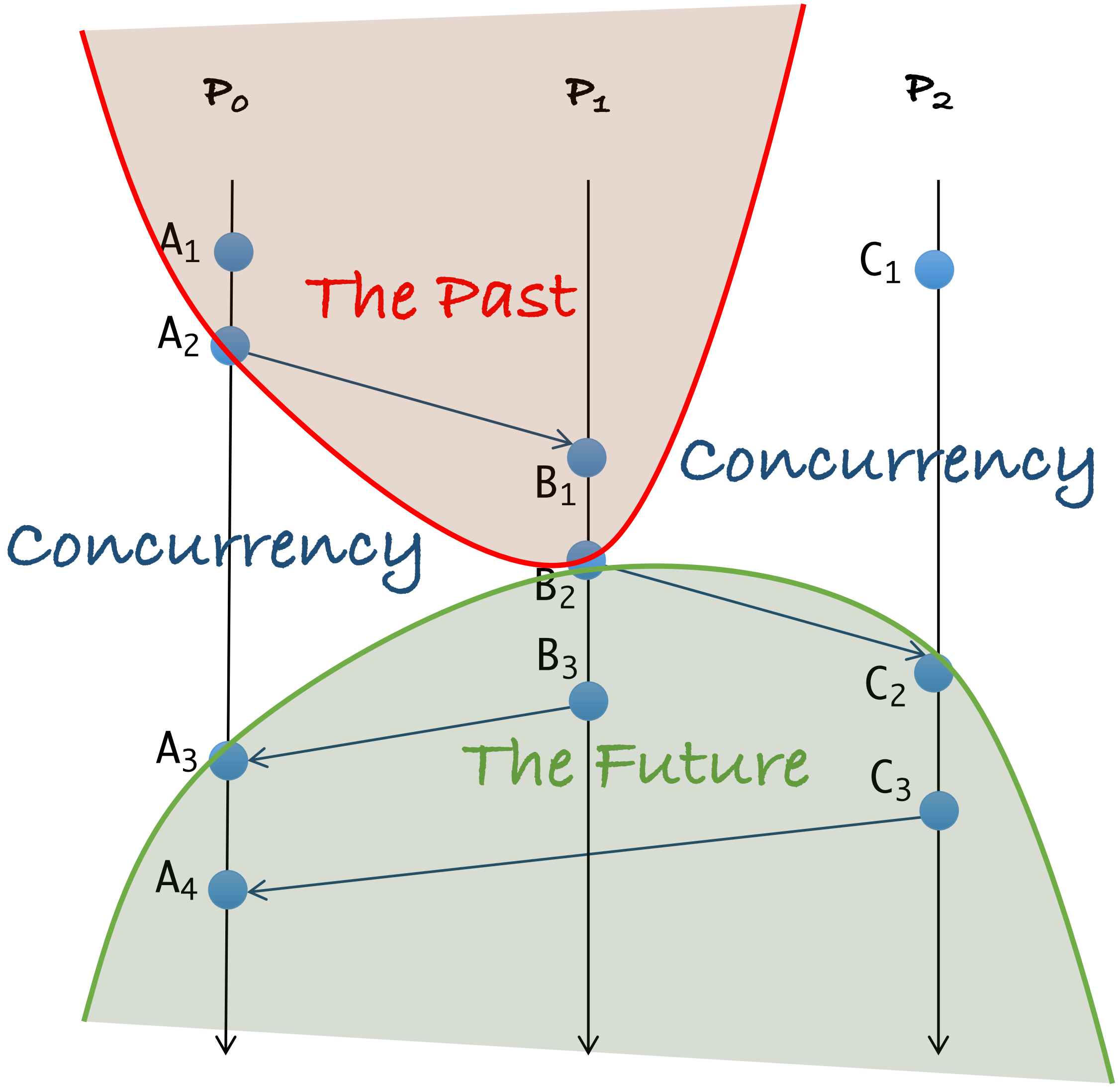
$A_1 \rightarrow A_2$, $A_2 \rightarrow A_3$, $A_3 \rightarrow A_4$
$B_1 \rightarrow B_2$, $B_2 \rightarrow B_3$
$C_1 \rightarrow C_2$, $C_2 \rightarrow C_3$

$A_2 \rightarrow B_1$, $B_2 \rightarrow C_2$
$B_3 \rightarrow A_3$, $C_3 \rightarrow A_4$

$A_1 \rightarrow B_1$, $A_2 \rightarrow B_2$, $B_1 \rightarrow C_2$, $B_2 \rightarrow A_3$
$B_2 \rightarrow C_3$, $C_2 \rightarrow A_4$, $B_3 \rightarrow A_4$

$A_1 \rightarrow B_2$, $A_1 \rightarrow C_2$, $A_1 \rightarrow C_3$, $A_1 \rightarrow B_3$
$B_1 \rightarrow C_3$, $B_1 \rightarrow A_4$, $B_3 \rightarrow A_4$
$C_1 \rightarrow A_4$

$A_1 \parallel C_1$, $A_2 \parallel C_1$, $A_3 \parallel C_1$
$B_1 \parallel C_1$, $B_2 \parallel C_1$, $B_3 \parallel C_1$
$B_3 \parallel C_2$, $A_3 \parallel C_2$, . . .



Did you see their relations?

$A_1 \rightarrow A_2$, $A_2 \rightarrow A_3$, $A_3 \rightarrow A_4$
$B_1 \rightarrow B_2$, $B_2 \rightarrow B_3$
$C_1 \rightarrow C_2$, $C_2 \rightarrow C_3$

$A_2 \rightarrow B_1$, $B_2 \rightarrow C_2$
$B_3 \rightarrow A_3$, $C_3 \rightarrow A_4$

$A_1 \rightarrow B_1$, $A_2 \rightarrow B_2$, $B_1 \rightarrow C_2$, $B_2 \rightarrow A_3$
$B_2 \rightarrow C_3$, $C_2 \rightarrow A_4$, $B_3 \rightarrow A_4$

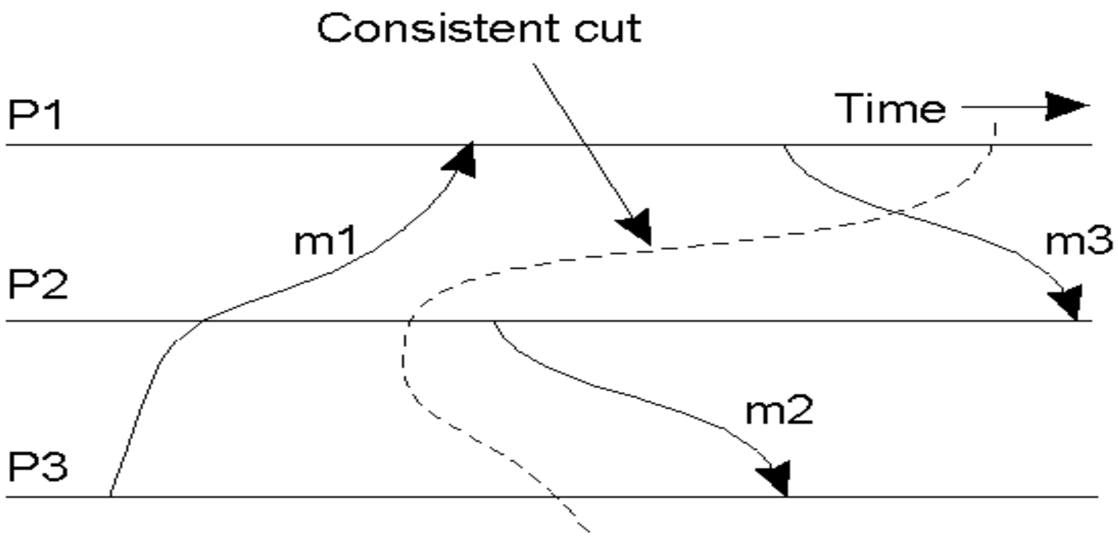
$A_1 \rightarrow B_2$, $A_1 \rightarrow C_2$, $A_1 \rightarrow C_3$, $A_1 \rightarrow B_3$
$B_1 \rightarrow C_3$, $B_1 \rightarrow A_4$, $B_3 \rightarrow A_4$
$C_1 \rightarrow A_4$

$A_1 \parallel C_1$, $A_2 \parallel C_1$, $A_3 \parallel C_1$
$B_1 \parallel C_1$, $B_2 \parallel C_1$, $B_3 \parallel C_1$
$B_3 \parallel C_2$, $A_3 \parallel C_2$, ...

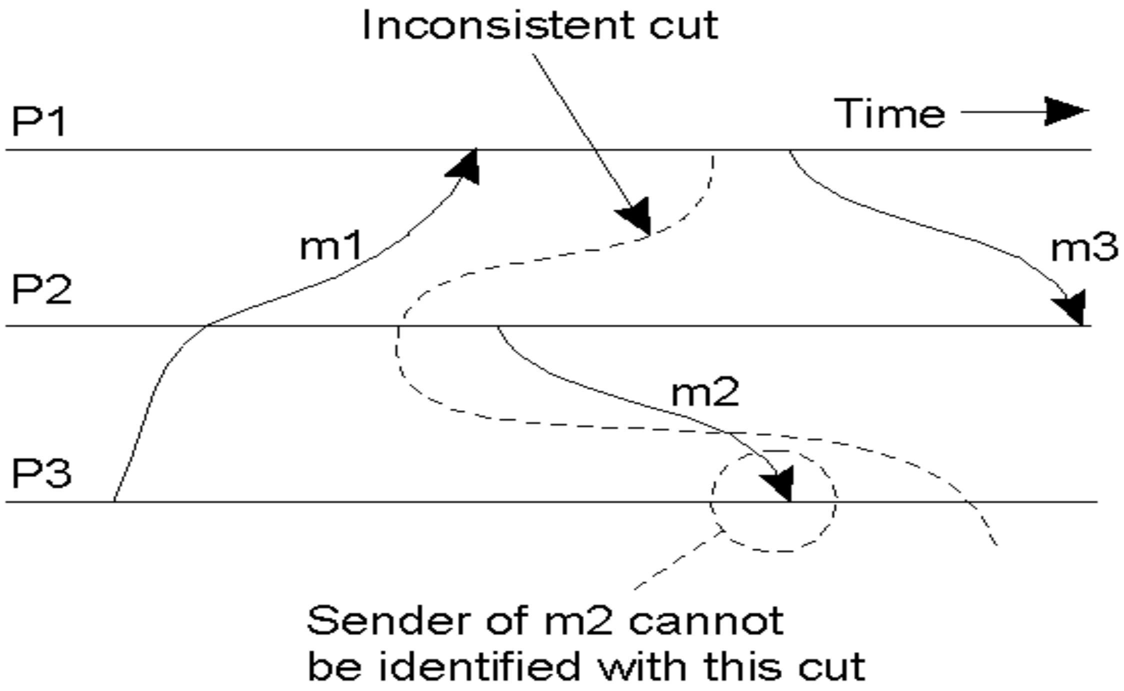
Global State

- 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

Consistent/Inconsistent cuts



(a) A consistent cut



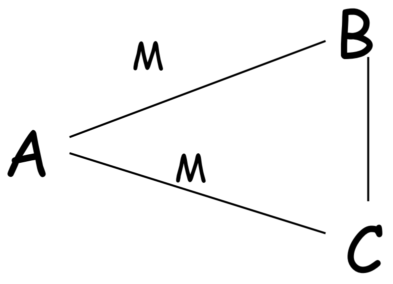
(b) An inconsistent cut

Distributed snapshot algorithm

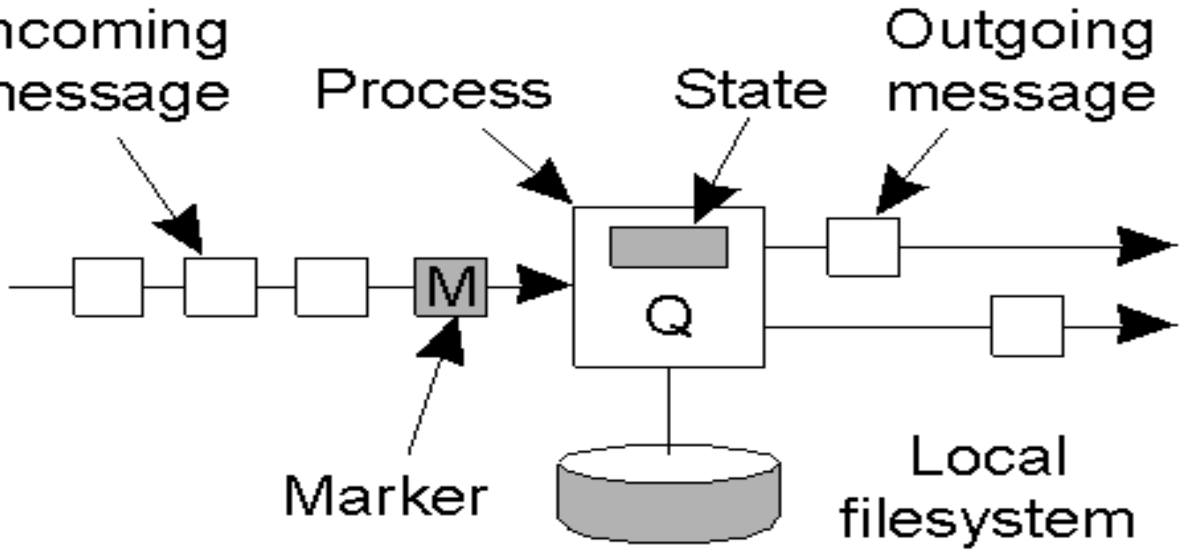
- Assume each process communicates with another process using unidirectional point-to-point channels (e.g, TCP connections)
- Any process can initiate the algorithm
  - Checkpoint local state
  - Send marker on every outgoing channel
- On receiving a marker
  - Checkpoint state if first marker and send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

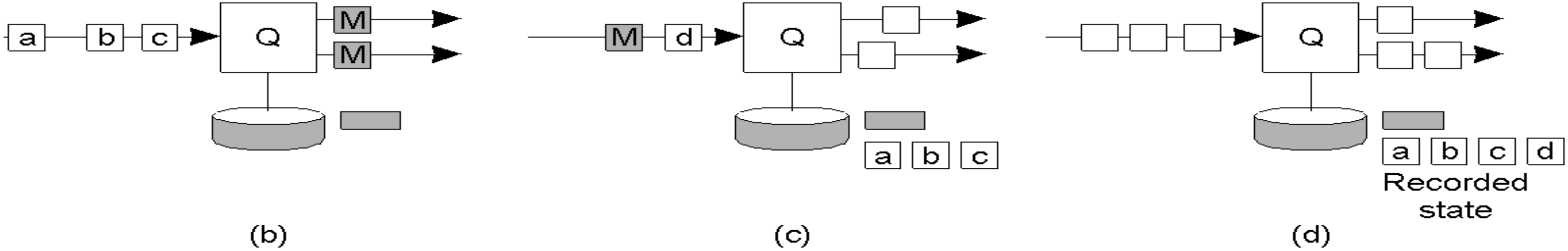


Snapshot algorithm example (1)



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

Snapshot algorithm example (2)



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

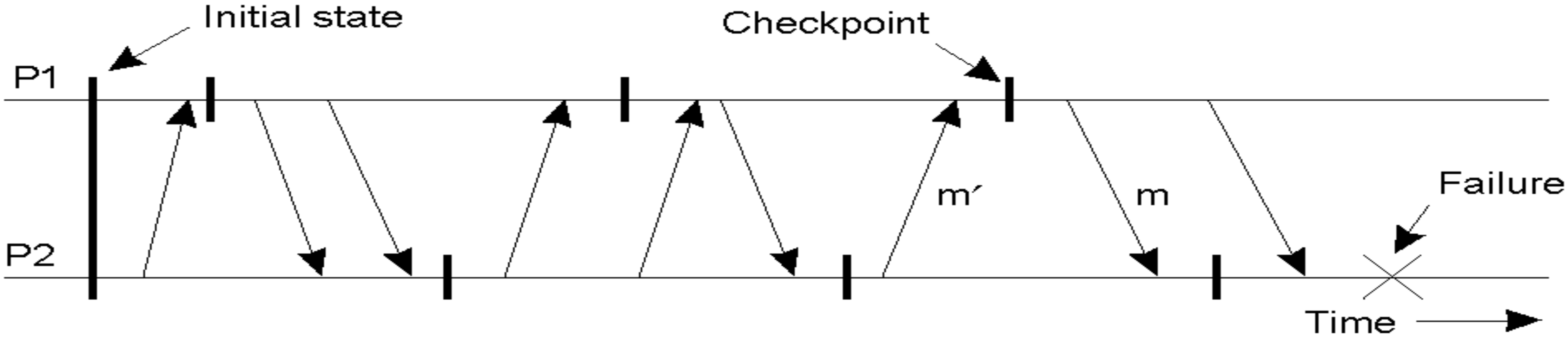
(c) Q records all incoming messages

(d) Q receives a marker from its incoming channel and finishes recording the state of the incoming channel

Recovery

- Techniques thus far allow failure handling
- Recovery: operations that must be performed after a failure to recover to a correct state
- Techniques:
  - Checkpointing:
    - ✧Periodically checkpoint state
    - ✧Upon a crash roll back to a previous checkpoint with *a consistent state*

Independent checkpointing



- Each processes periodically checkpoints independently of other processes
- Upon a failure, work backwards to locate a consistent cut
- Problem: if most recent checkpoints form inconsistenct cut, will need to keep rolling back until a consistent cut is found
- Cascading rollbacks can lead to a domino effect.

Coordinated checkpointing

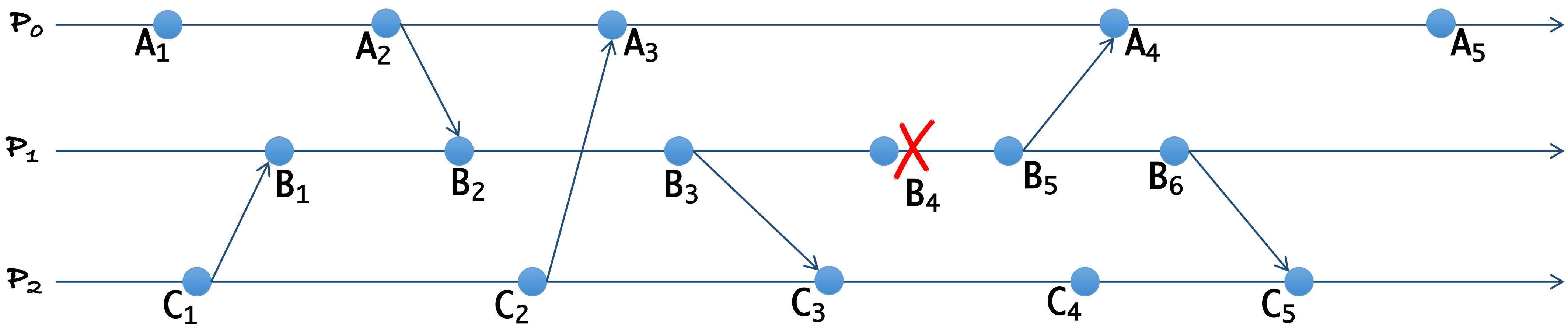
- Take a distributed snapshot
- Upon a failure, roll back to the latest snapshot
  - o All process restart from the latest snapshot

Message logging

- Checkpointing is expensive
  - All processes restart from previous consistent cut
  - Taking a snapshot is expensive
  - Infrequent snapshots => all computations after previous snapshot will need to be redone [wasteful]
- Combine checkpointing (expensive) with message logging (cheap)
  - Take infrequent checkpoints
  - Log all messages between checkpoints to local stable storage
  - To recover: simply replay messages from previous checkpoint
    - ✧Avoids recomputations from previous checkpoint

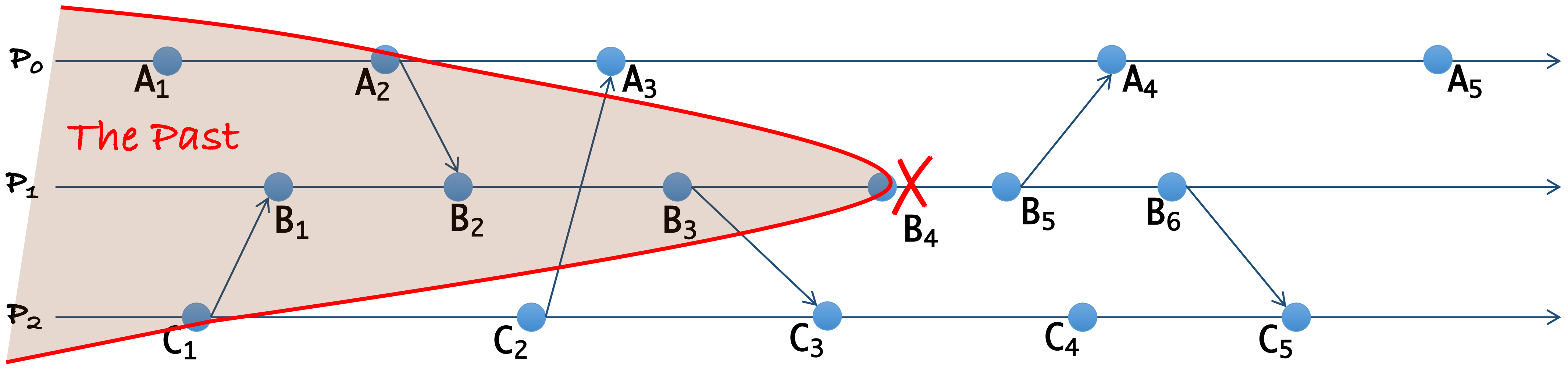
Debugging

Debugging



- Error is detected at B_4
- Where is the root of error?
  - P_1: Somewhere before B_4
  - P_2, P_3?

Debugging

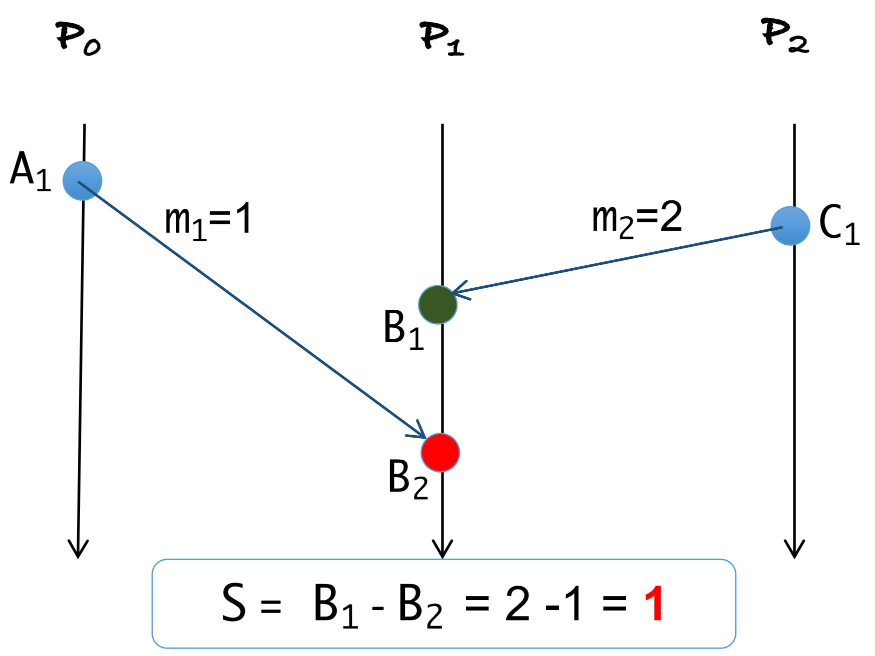


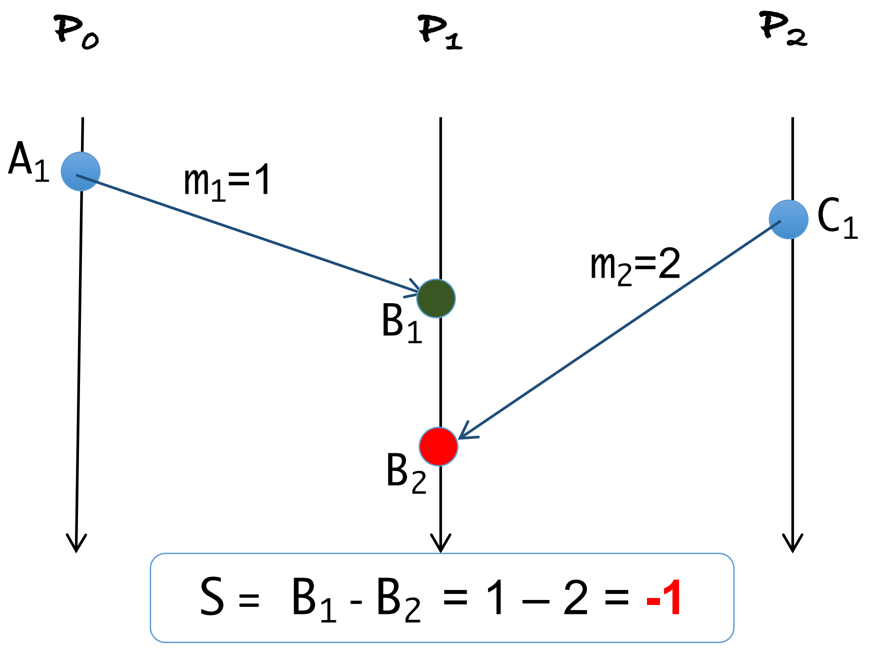
- Error is detected at B_4
- Where is the root of error?
  - P_1: Somewhere before B_4
  - P_0, P_2?

- Event E → B_4, then actions at E may lead to the error at B_4
- Debugging area = Past(B_4)

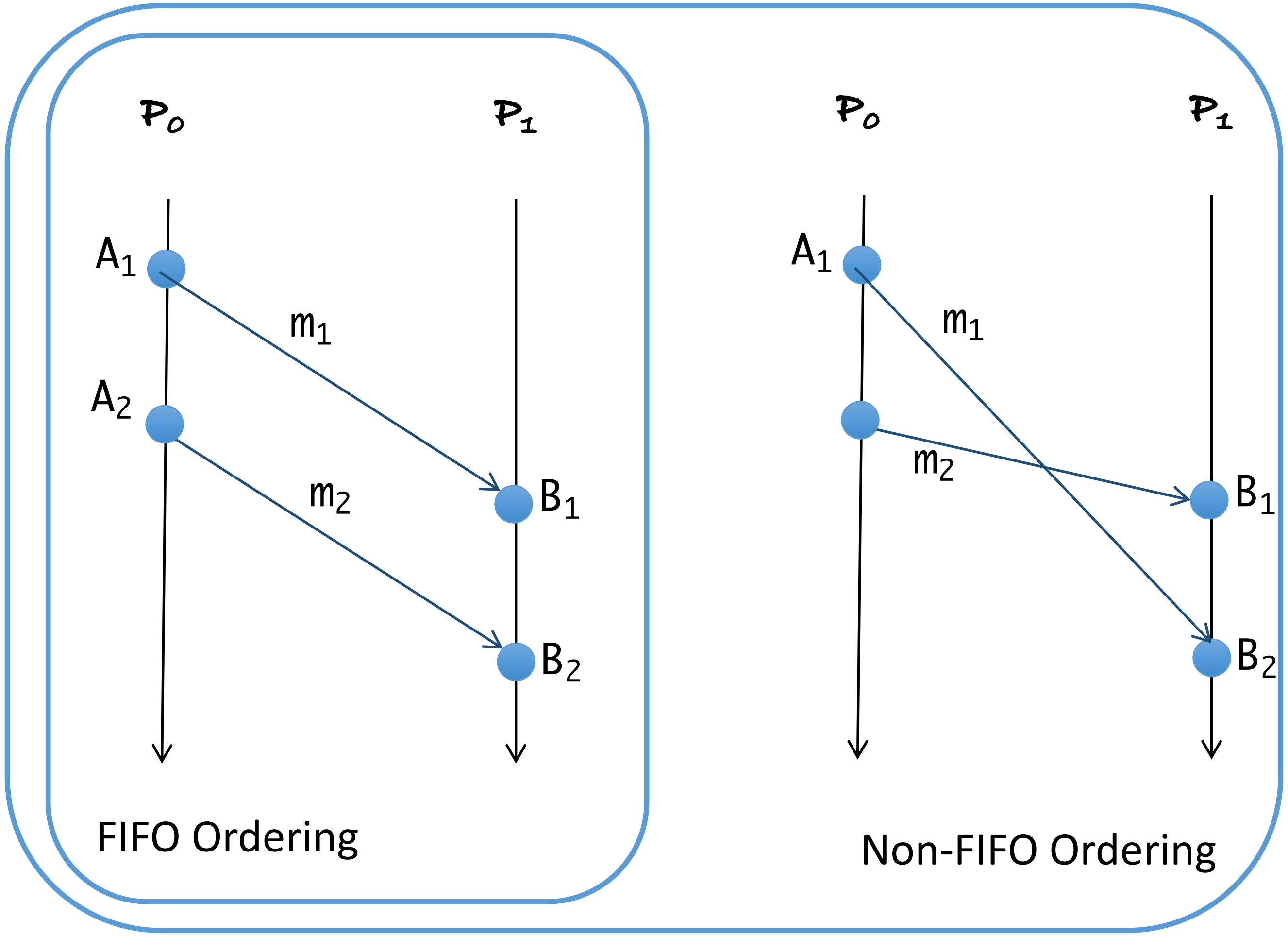
Race messages

Race messages





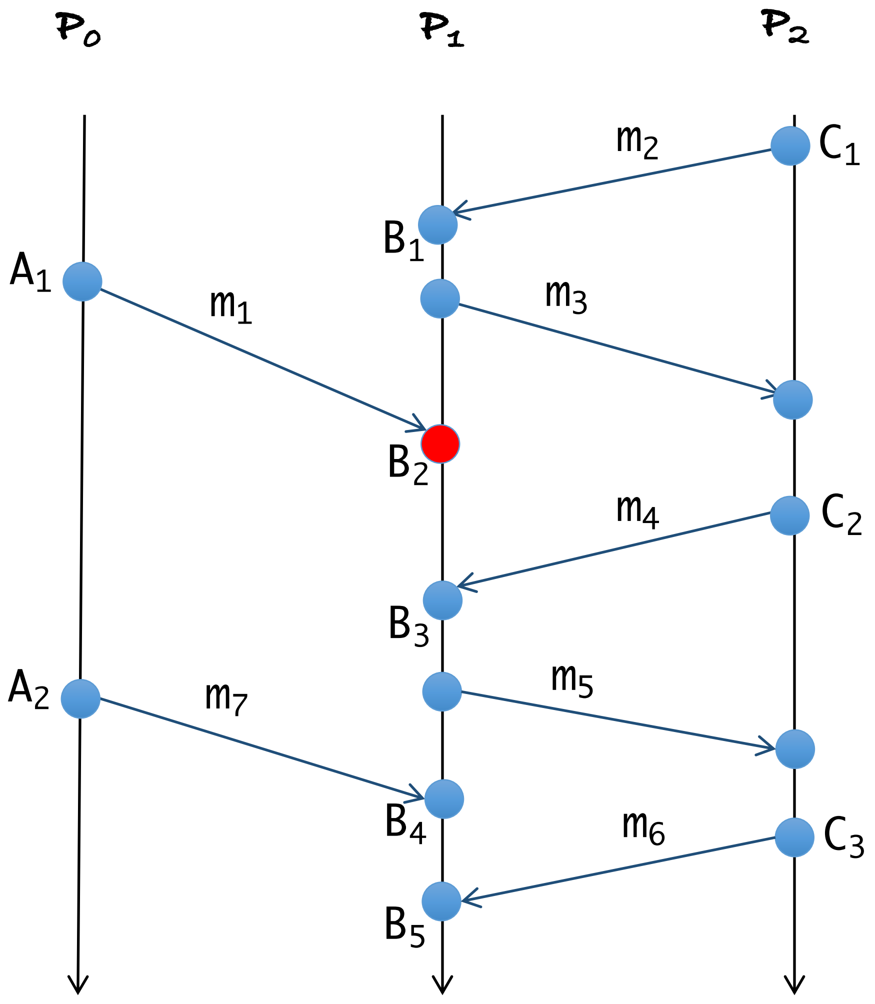
Non-determinism of parallel/distributed progam



- FIFO ordering per process

  $(\text{Send}\ (m_1) \rightarrow \text{Send}\ (m_2)) \Rightarrow (\text{Receive}\ (m_1) \rightarrow \text{Receive}\ (m_2))$

Race messages



- Receive from any source

FIFO ordering per process

- ($B_2 \parallel C_2$) $\Rightarrow$ m_4 may be received at B_2
- The opposite is wrong?
  - ($A_1 \rightarrow B_3$) but m_1 may be received at B_3
- Finding all race messages at a receive event is a problem