CS 138: Ordering and Global State

Administrivia

- HW2 is out today, due on the 15th (1 week)
- Review session will be on Monday, March 21st, 5:30pm
- Midterm will be on Tuesday, March 22nd, with material up to Raft (next two classes)

Global State

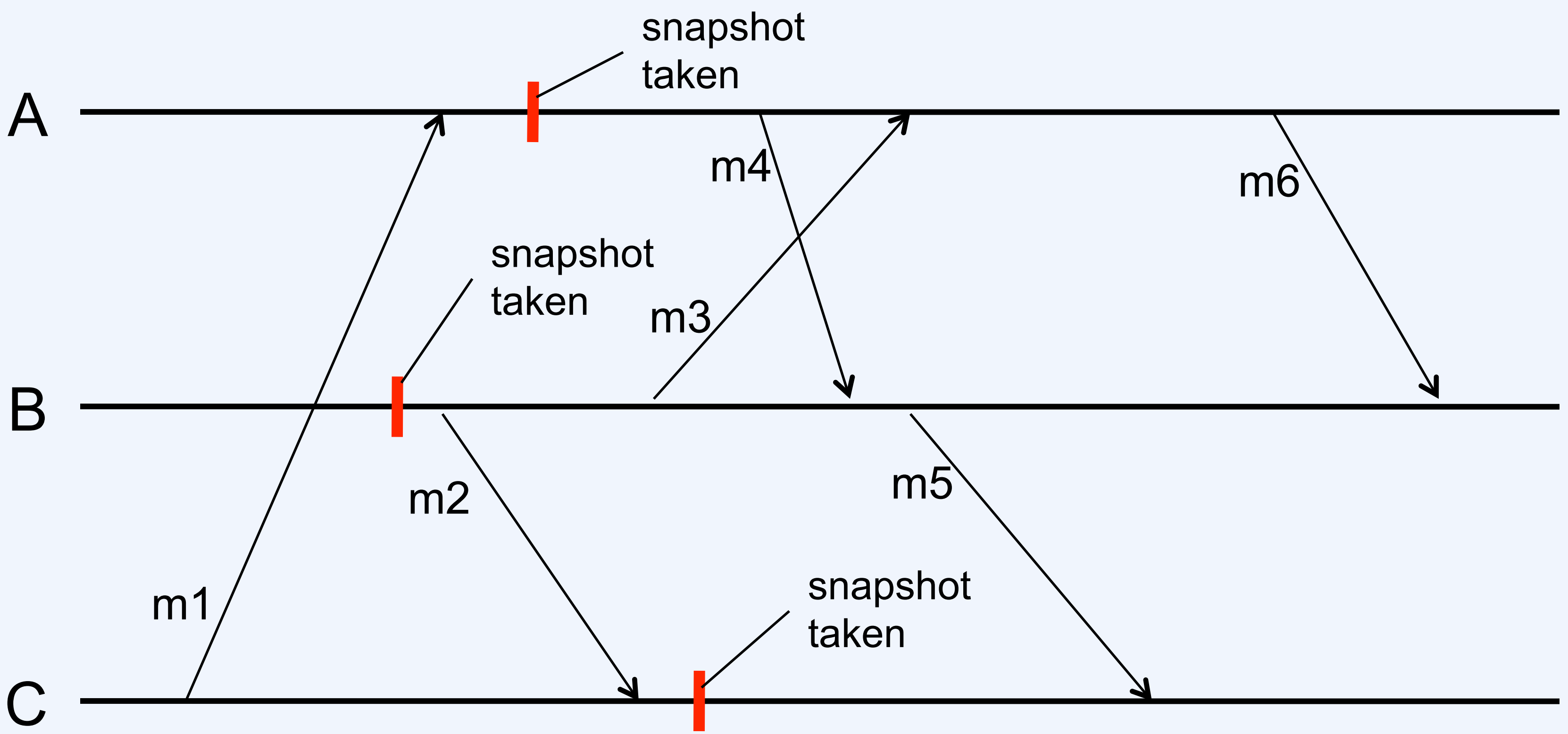
Failure Happens

- What to do about it?
  - you of course have everything backed up
  - so, restore the backups

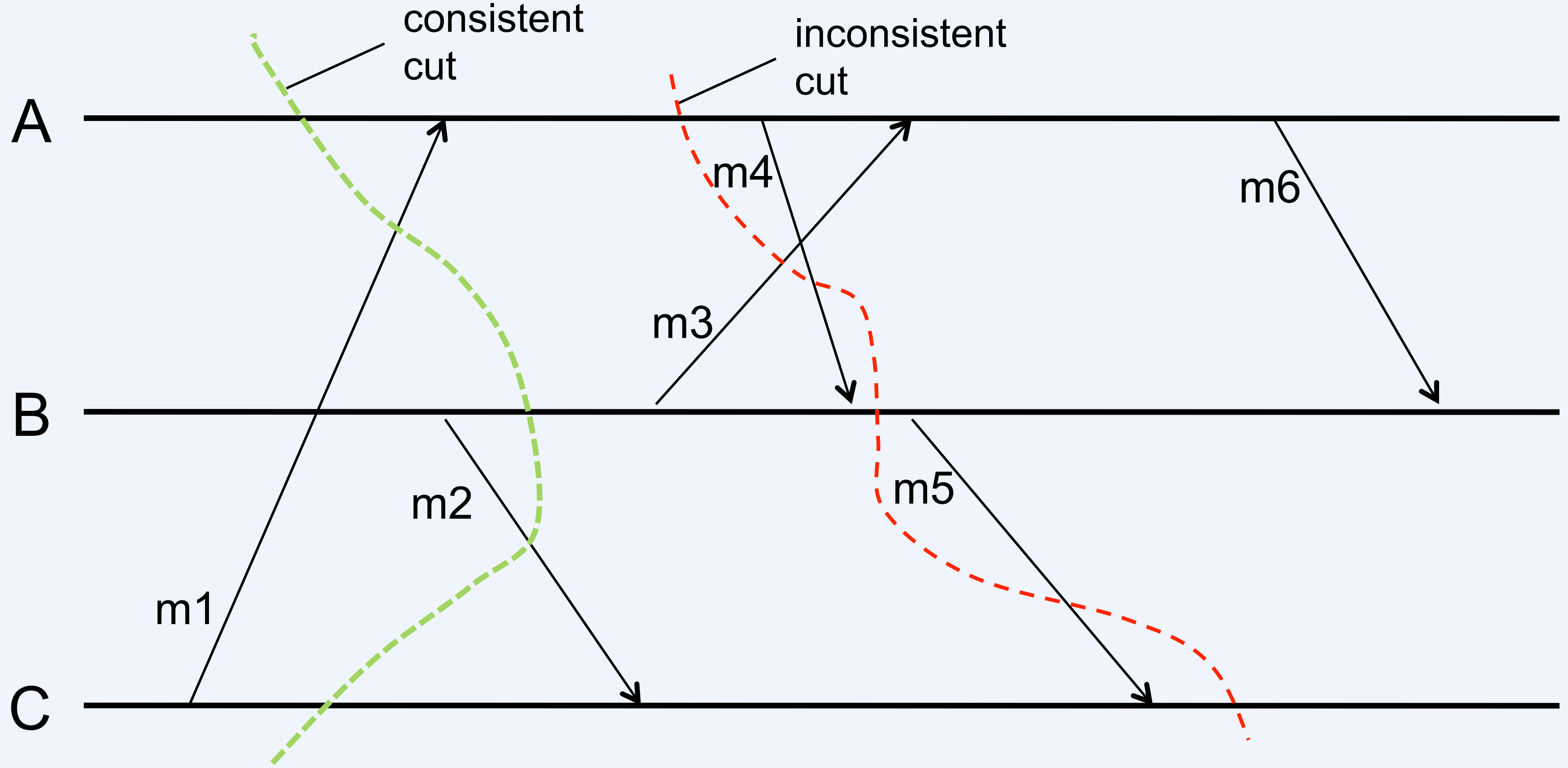
Global State

- Your system consists of 100 nodes
  - each produces a snapshot of itself periodically
  - does some collection of these snapshots constitute a meaningful notion of “global state”?

Distributed Snapshots (1)



Distributed Snapshots (2)

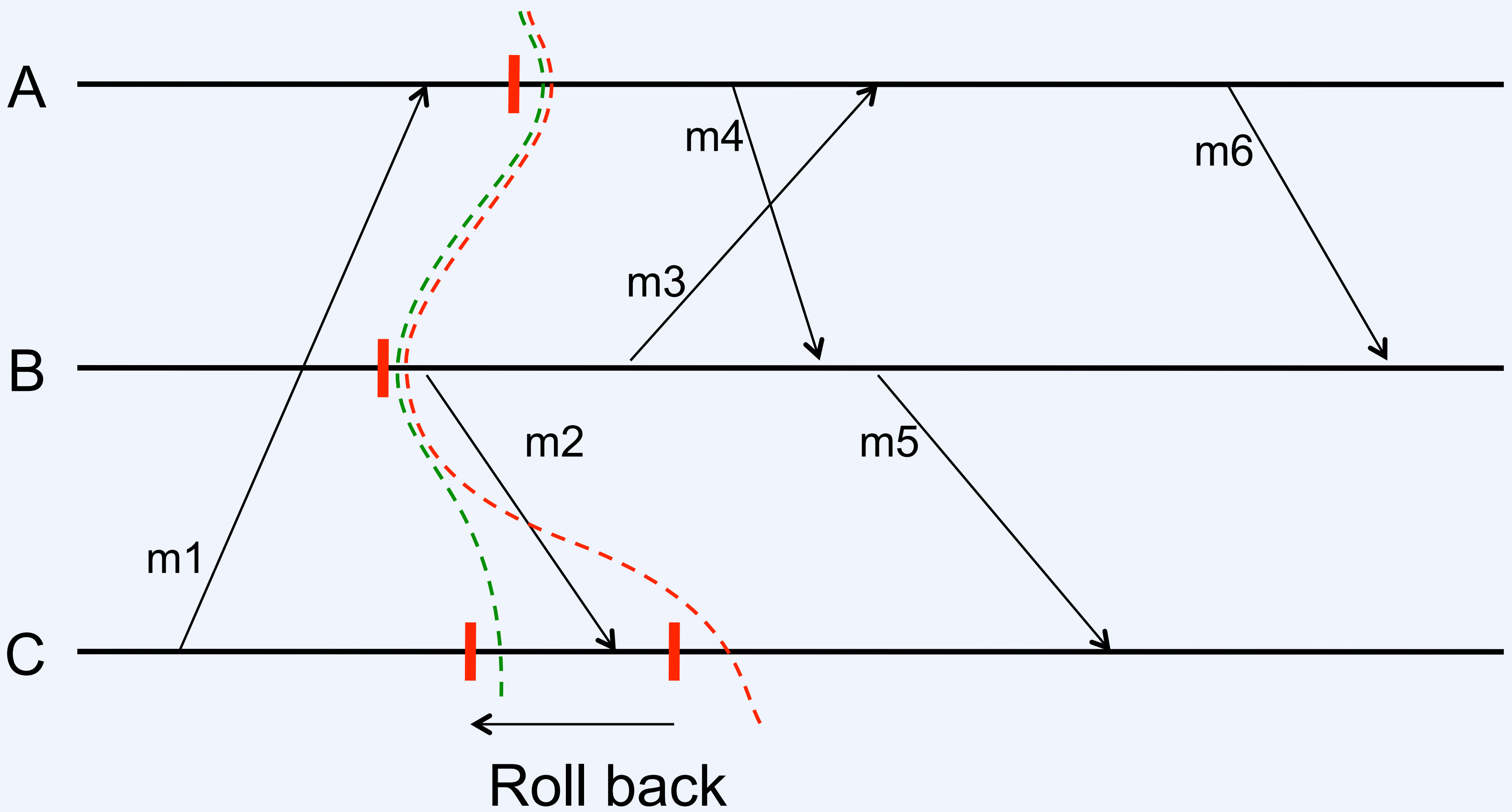


A cut is a **consistent cut** if, for each event *e* it contains, it also contains all events that happened before *e*

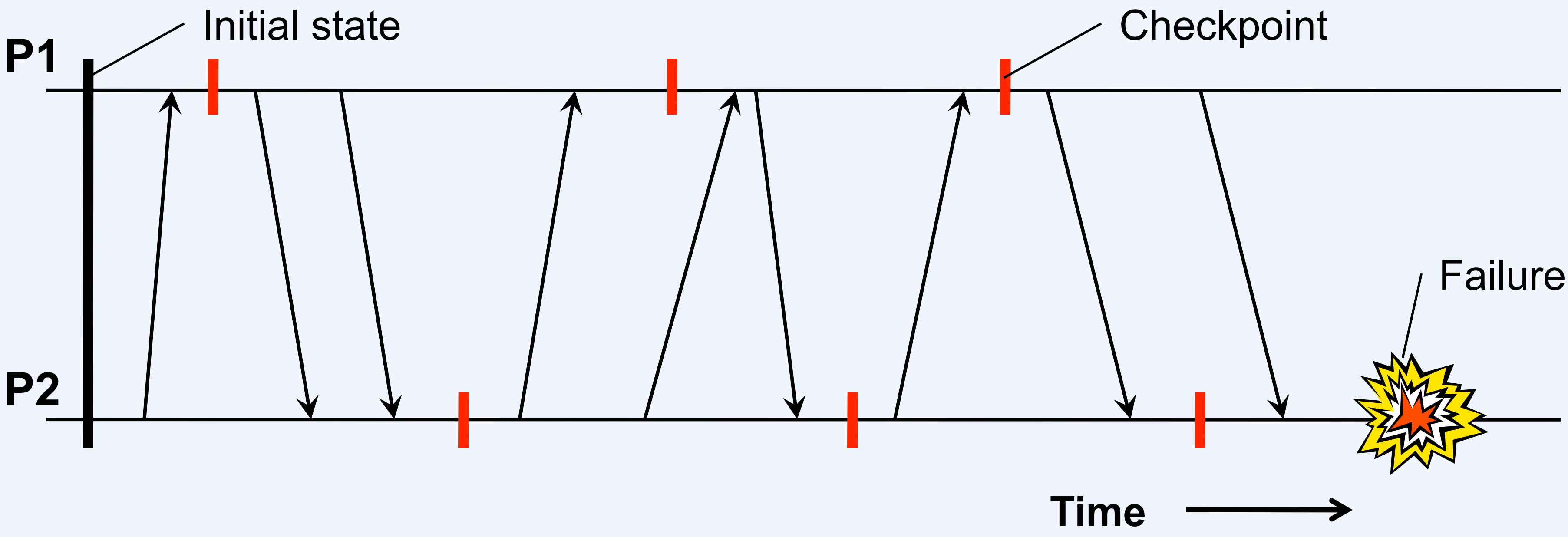
Checkpointing

- Produce a distributed snapshot
  - how?
- Independent checkpointing
  - each process checkpoints itself periodically when convenient
  - to produce distributed snapshot
    - start with most recent checkpoints
    - roll back until consistent global checkpoint is achieved

Independent Checkpoining



Domino Effect



Coping

- Take independent, periodic checkpoints, plus a few more

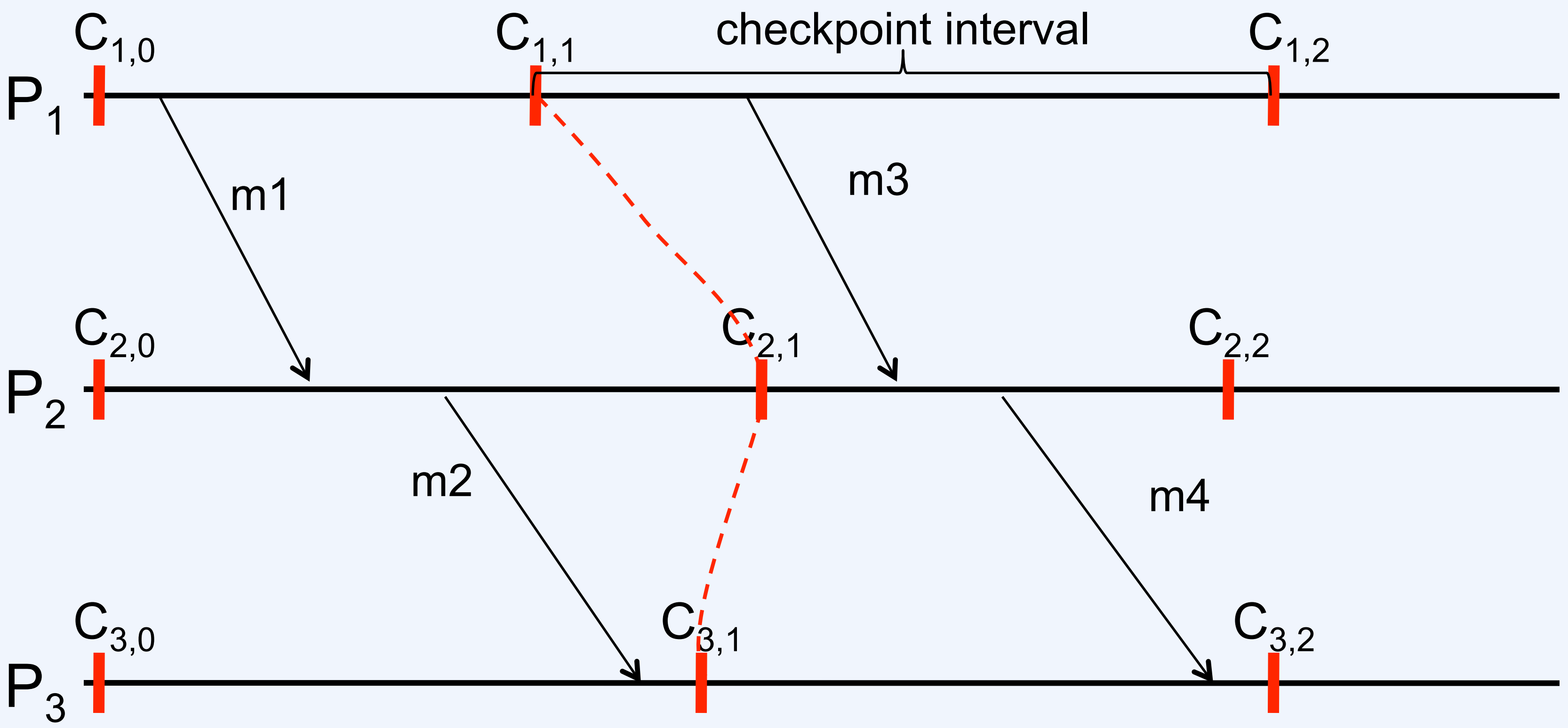
  or

- Produce a global snapshot on demand

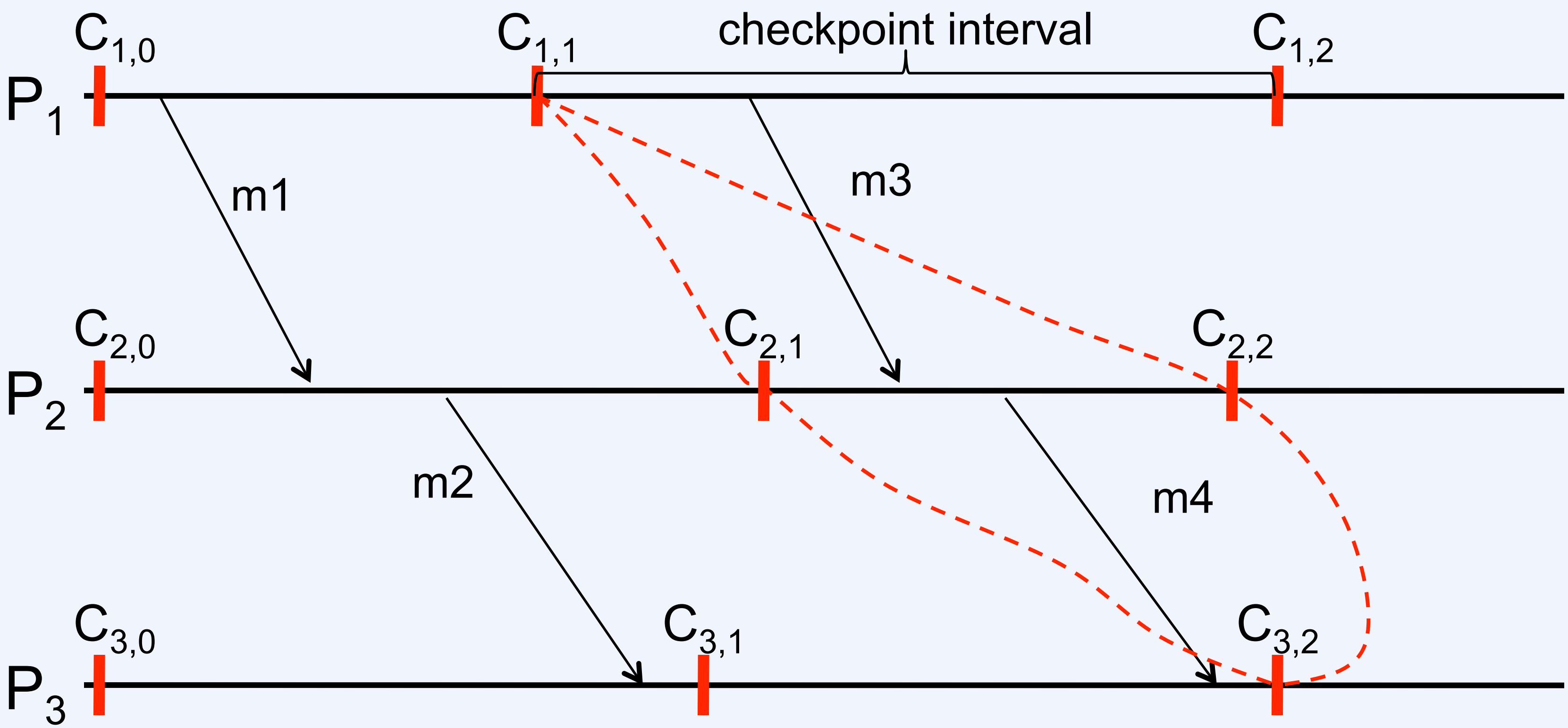
Independent Checkpoints

- Goal
  - all checkpoints are “useful”
    - no need to roll back
- What are the conditions for checkpoints to for a consistent cut?

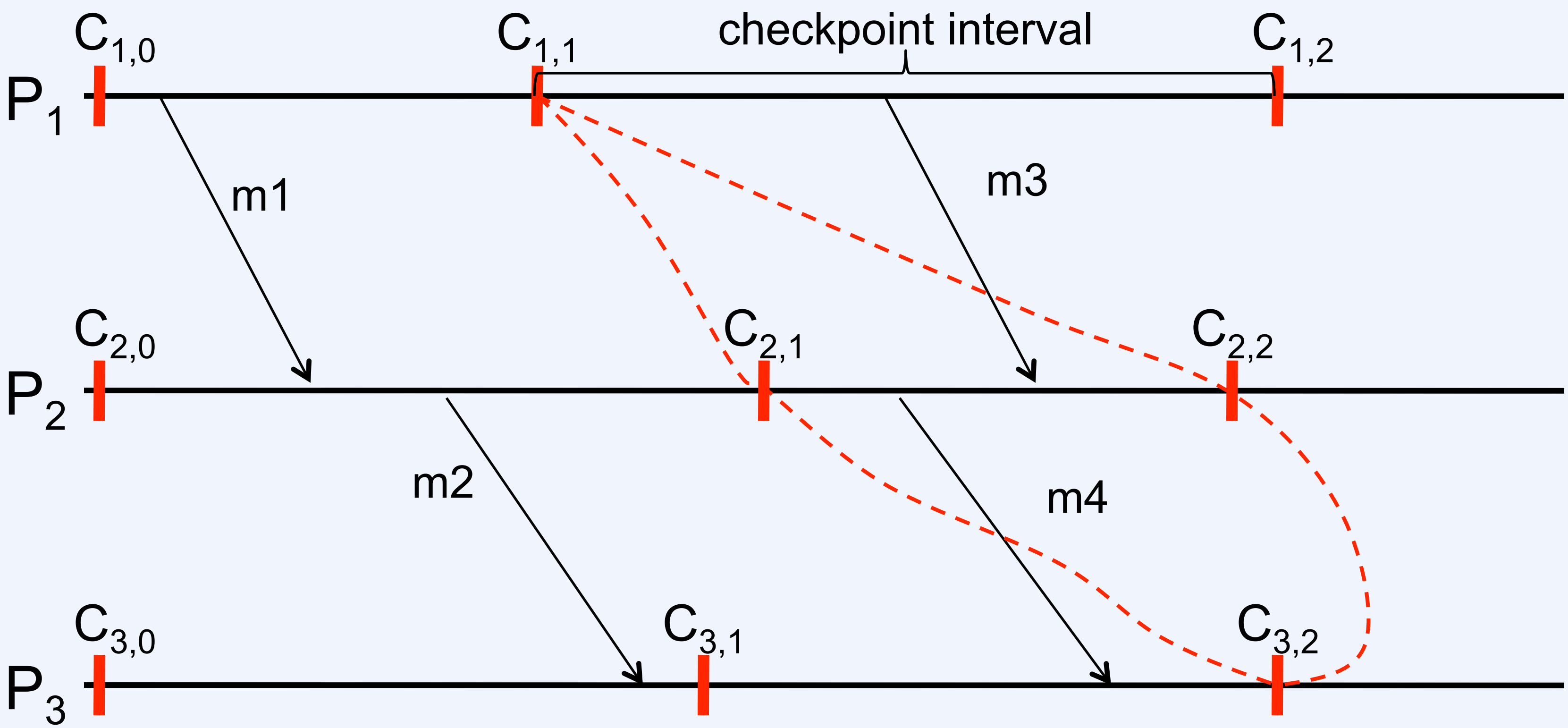
Causal Paths



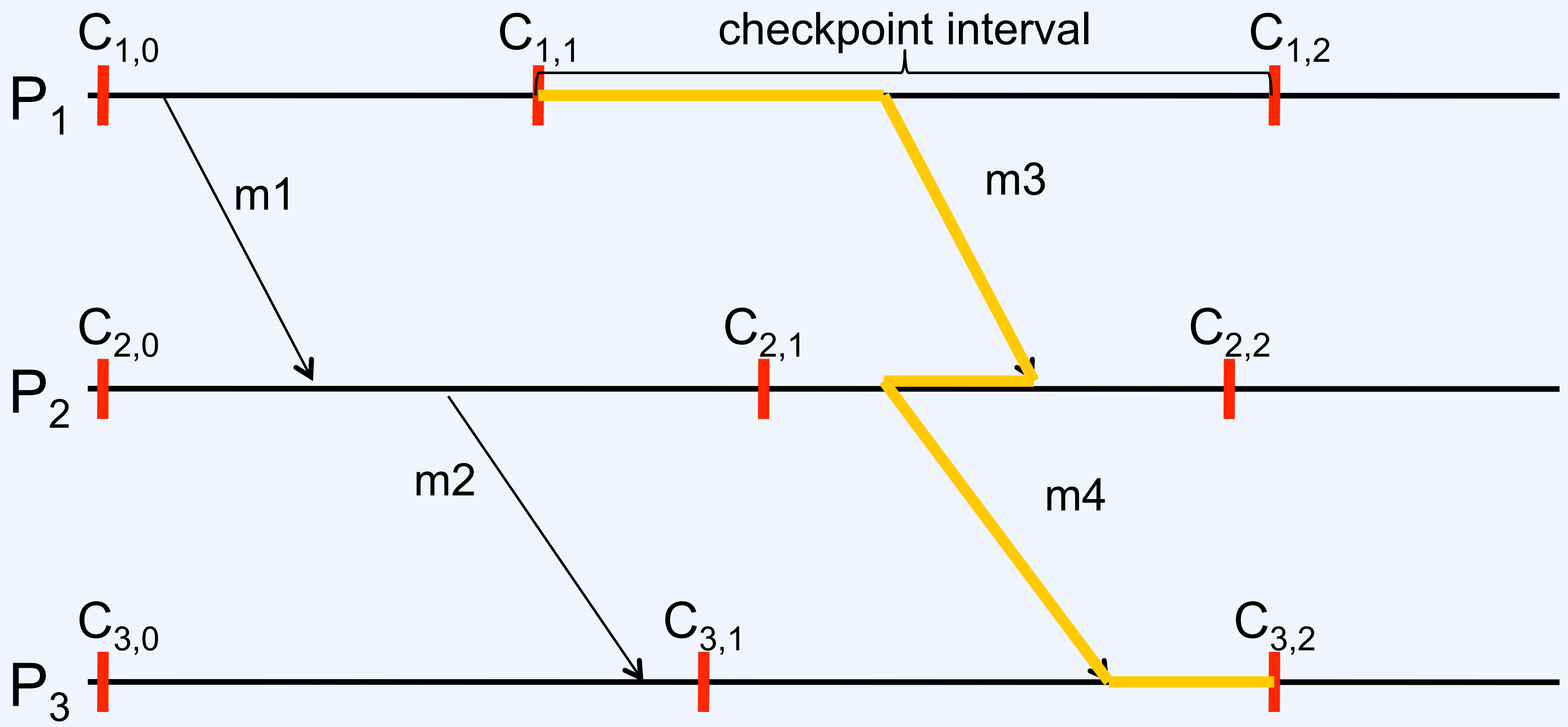
Causal Paths



Non-Causal Paths



Zigzag Paths



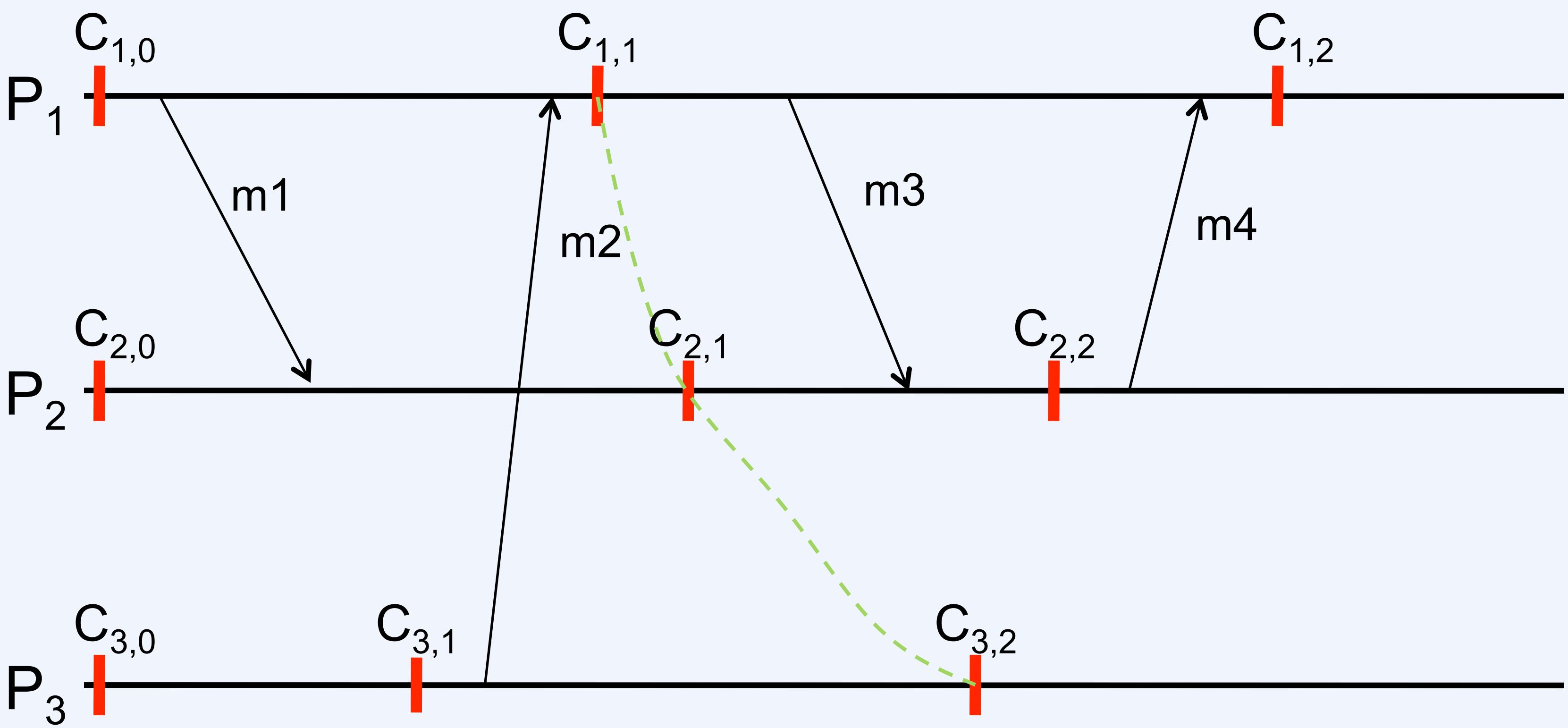
Zigzag Path Definition

- A zigzag path exists from $C_{p,i}$ to $C_{q,k}$ iff there are messages m_1, m_2, … m_n such that
  - m_1 is sent by process p after $C_{p,i}$
  - if m_h ($1 \le h \le n$) is received by process r, then m_{h+1} is sent by r in the same or a later checkpoint interval (although m_{h+1} may be sent before or after m_h is received), and
  - m_n is received by process q before $C_{q,k}$

Theorem

- **A set of checkpoints S, each from a different process, can belong to the same consistent global snapshot iff no checkpoint in S has a zigzag path to any other checkpoint (including itself) in S**

Zigzag Cycles



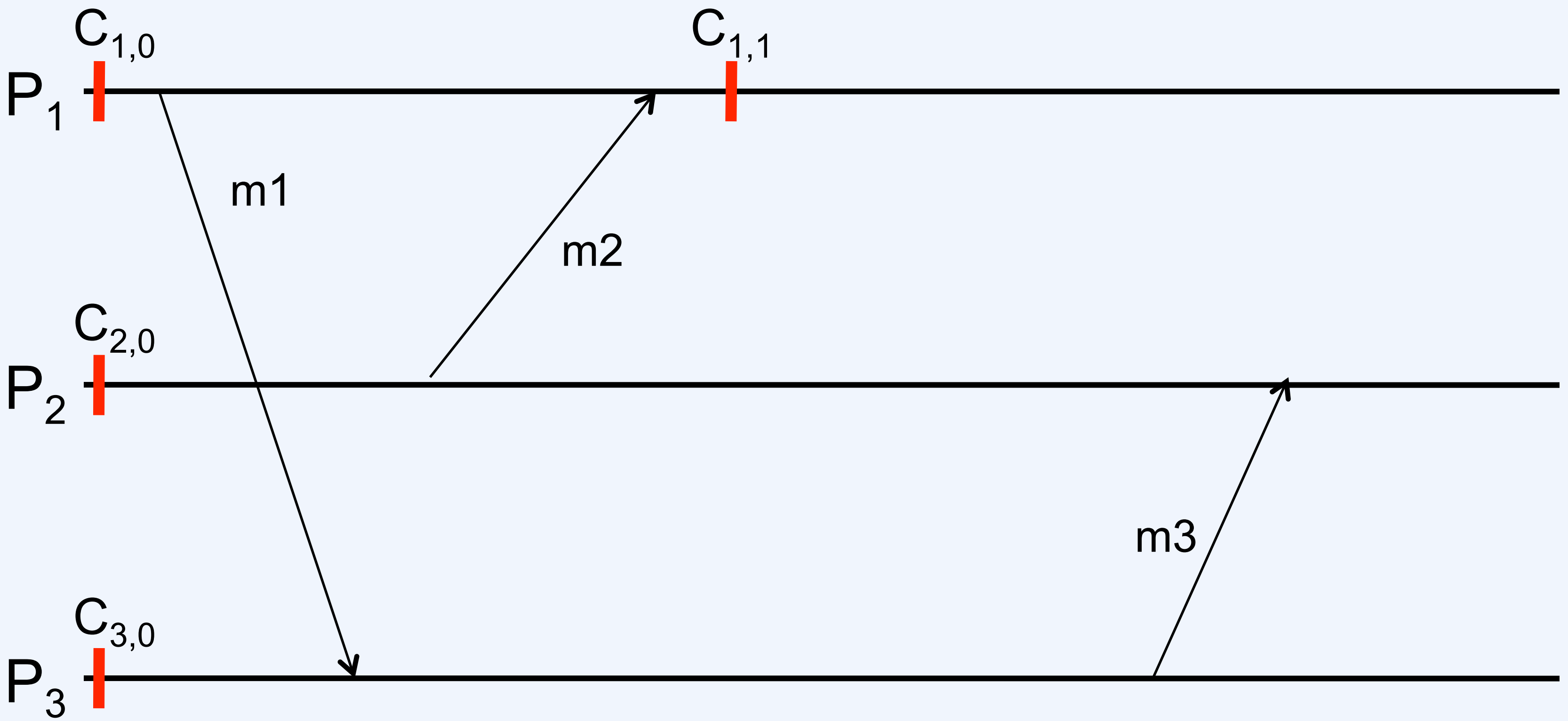
Corollary

- **A checkpoint is *useful* if it potentially belongs to some consistent global checkpoint**
- **Corollary: A checkpoint is useful iff it is part of no zigzag cycle**

Adaptive Checkpointing

- On receipt of a message, receiver checks if message completes a zigzag cycle
  - if so, a new checkpoint is taken before the message is processed
  - thus, no cycle

However …



Coping …

- On receipt of message, check for a causal path to a checkpoint preceding the send
  - the path plus the just-received message form a zigzag cycle
- Doesn’t catch all zigzag cycles
  - testing shows it catches most of them

Finding Causal Paths

- Use vector clocks
  - components are counts of checkpoints in each process
  - details may be an exercise …

Producing a Consistent Global Snapshot on Demand

- Process A wants all other processes to send it snapshots that together form a consistent cut (and thus a global snapshot)
- Can this be done?

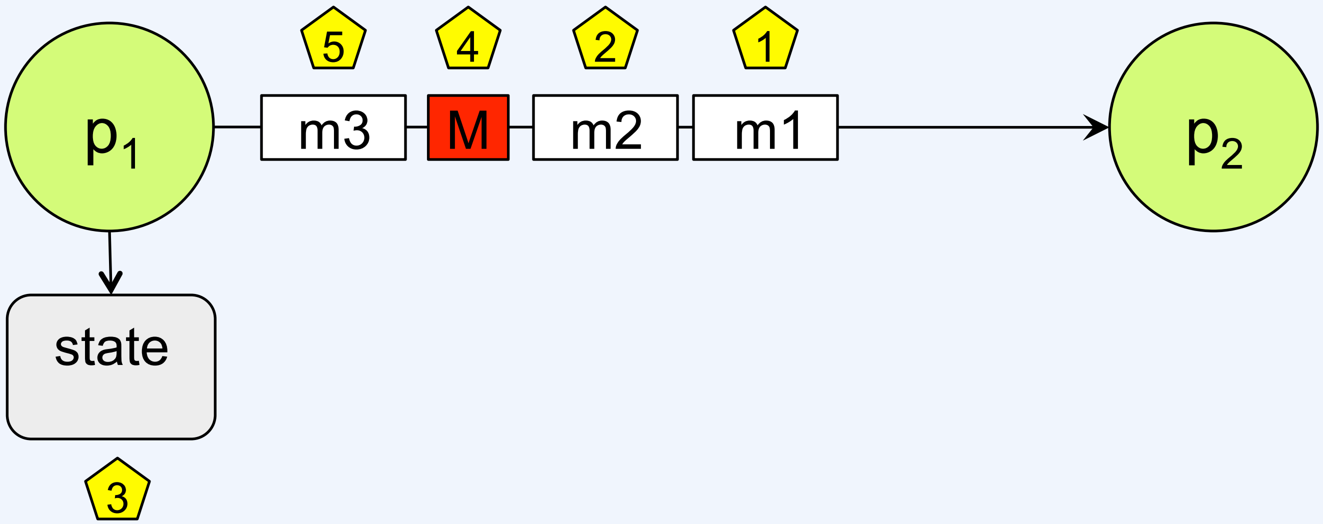
Distributed Snapshot Algorithm

- Chandy & Lamport, 1985
  - algorithm to select a *consistent cut*
  - any process may initiate a snapshot at any time
  - processes can continue normal execution
    - send and receive messages
  - assumes:
    - no failures of processes & channels
    - strong connectivity
      - at least one path between each process pair
    - unidirectional, FIFO channels
    - reliable delivery of messages

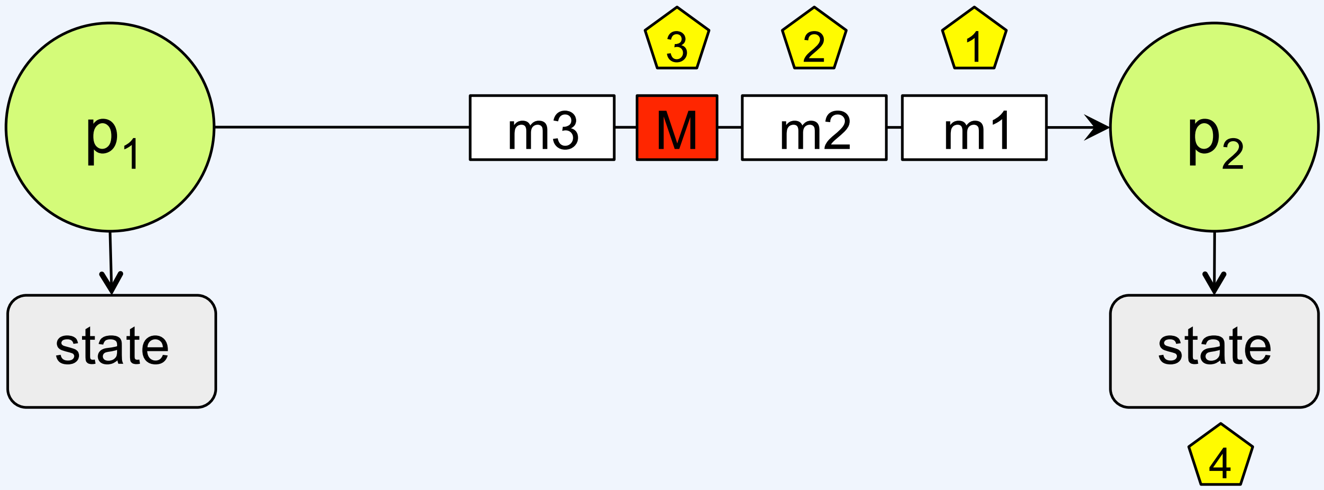
Approach

- Snapshot consists of saved states of all nodes along with messages in transit
- For each pair of directly connected nodes A and B
  - must record messages sent before A saved its state but received after B saved its state
  - nodes send out special *marker* messages immediately after saving their states

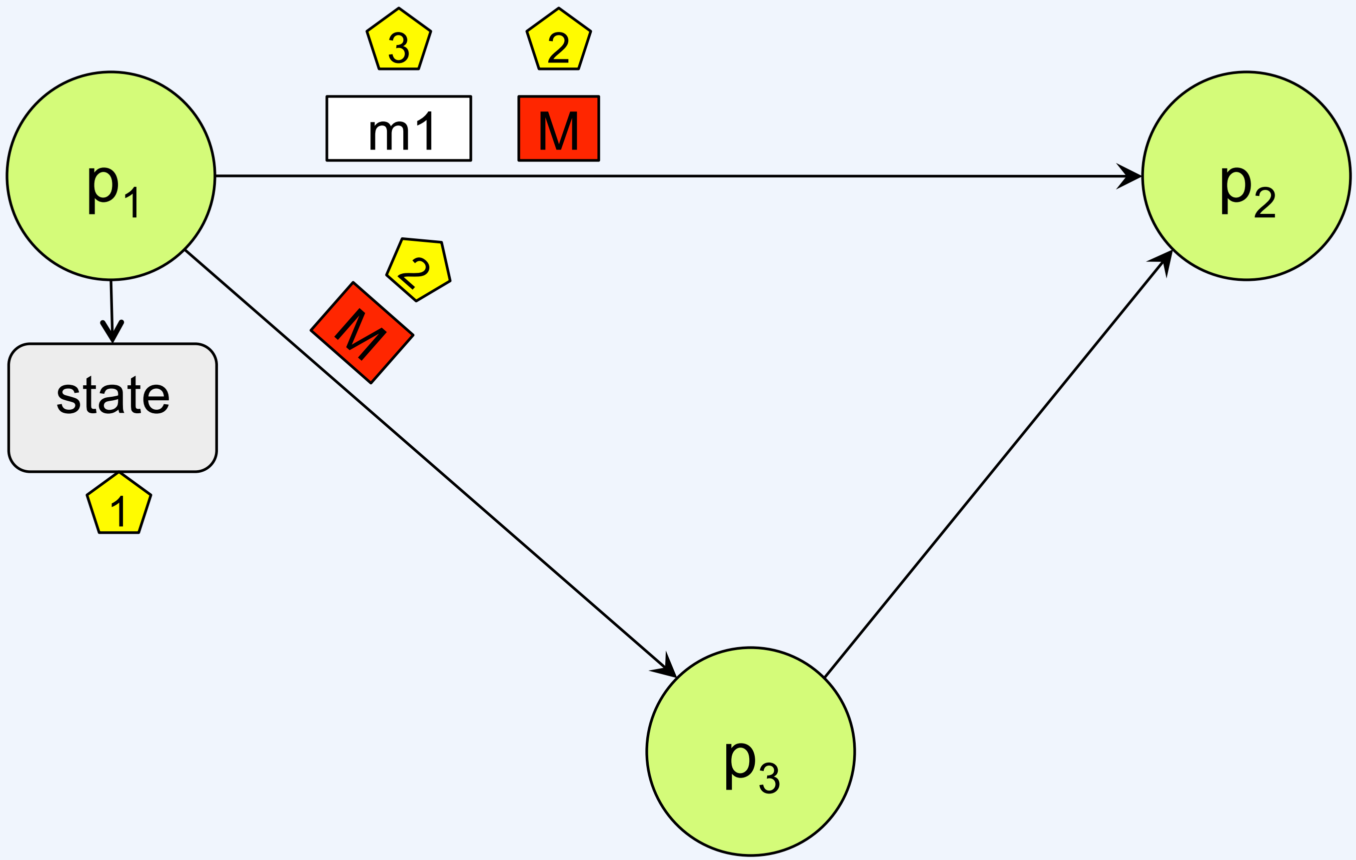
Example: Sending



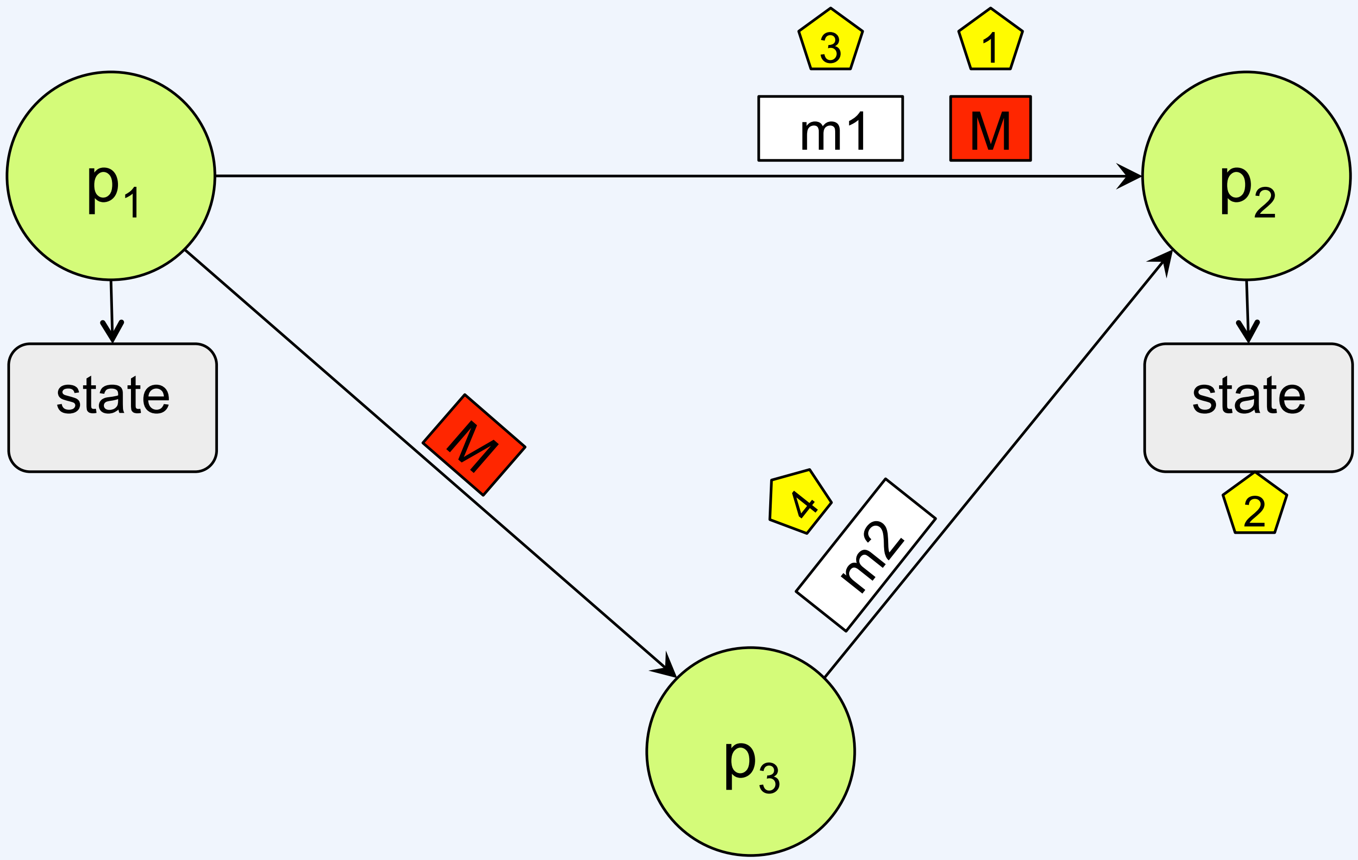
Example: Receiving



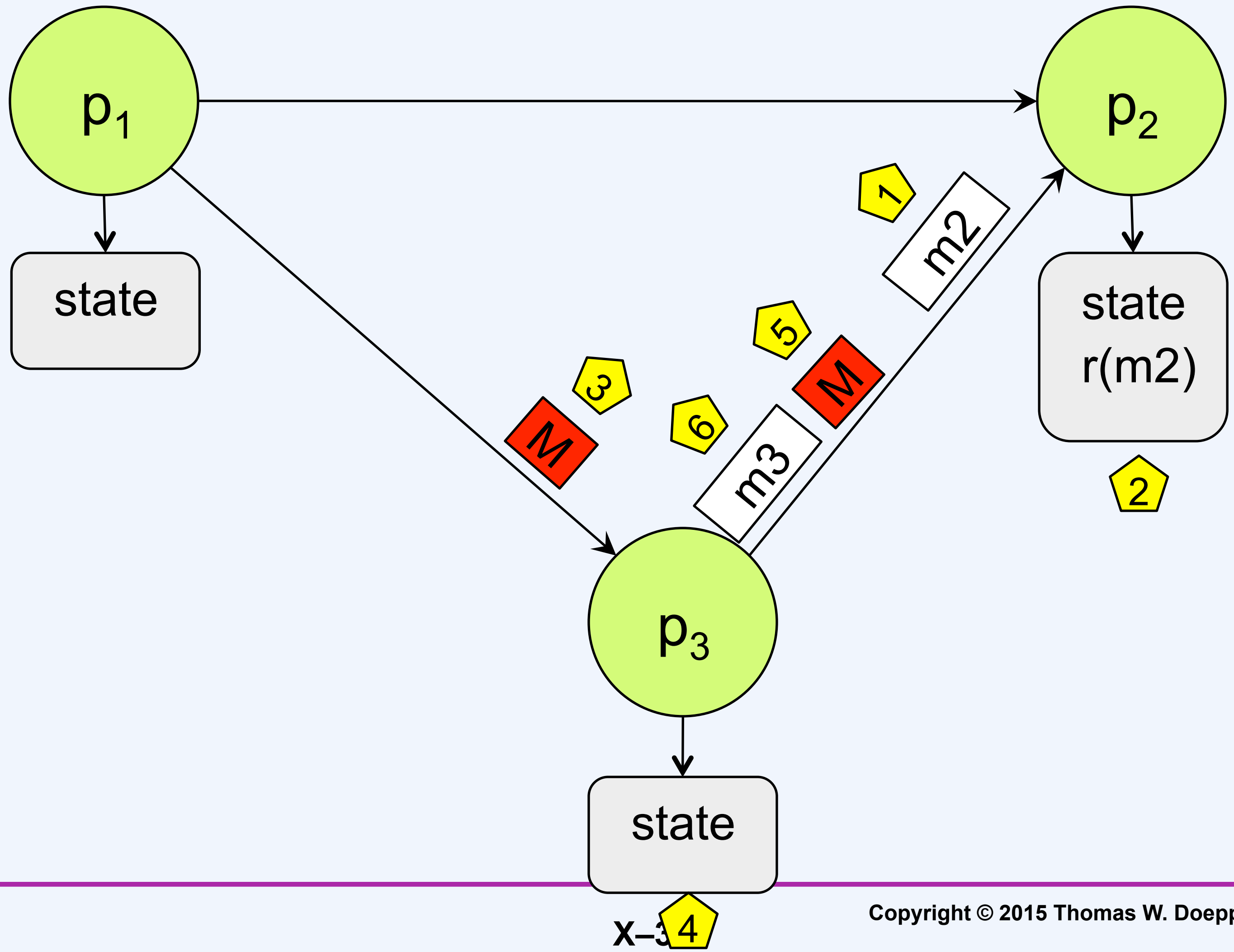
Another Example: part 1



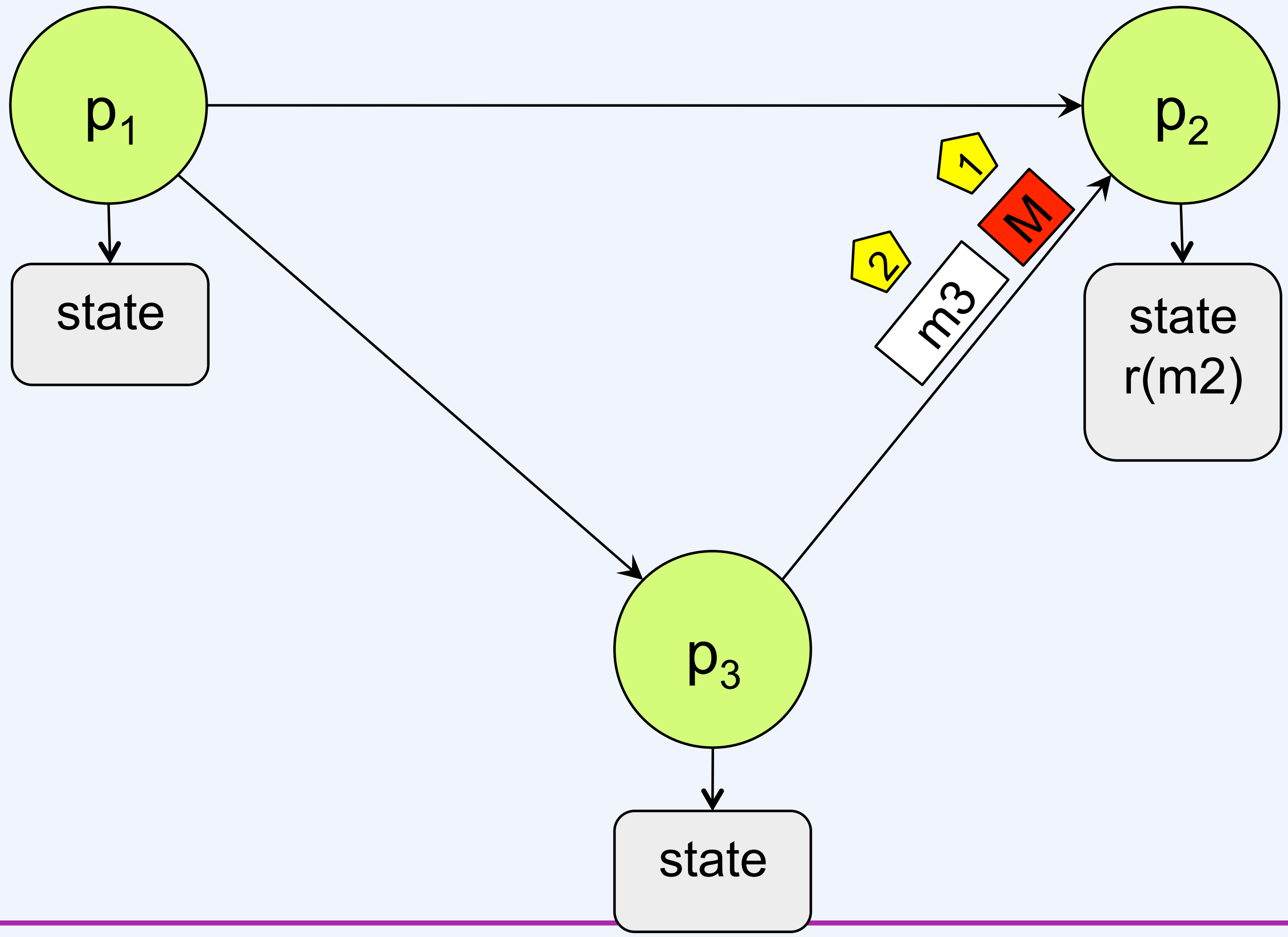
Another Example: part 2



Another Example: part 3



Another Example: part 4



Snapshot Rules

- ***Marker receiving rule for process p_i***

  On p_i's receipt of a *marker* message over channel *c*:

  if (p_i has not yet recorded its state)

  it records its state

  it records the state of *c* as the empty sequence

  it turns on recording of messages arriving over other channels

  else

  p_i records the state of *c* as the set of messages it has received over *c* since it saved its state and before it received the marker over c

- ***Marker sending rule for process p_i***

  After p_i has recorded its state, for each outgoing channel *c*:

  p_i sends one marker message over *c* (before it sends any other messages over *c*)

Termination

- Process P has completed its part of the algorithm when it has processed markers on all input channels
- It sends its saved local state and channel histories to the initiator
  - the intent is that collection of local states form consistent cut
    - channel histories are the messages in transit at time of cut

Analysis

- Does it find a consistent cut?
  - if so, then for any P_a and P_b, if m is a message sent from P_a to P_b, then if recv(m) is in the cut, so is send(m)
    - i.e., if recv(m) occurred before P_b recorded its state, then send(m) occurred before P_a recorded its state
  - stronger statement: if for any P_a and P_b, if e_a and e_b are events in P_a and P_b, such that e_a happens before e_b ($e_a \rightarrow e_b$), then if e_b is in the cut, so is e_a
    - i.e., if e_b occurred before P_b recorded its state, then e_a occurred before P_a recorded its state

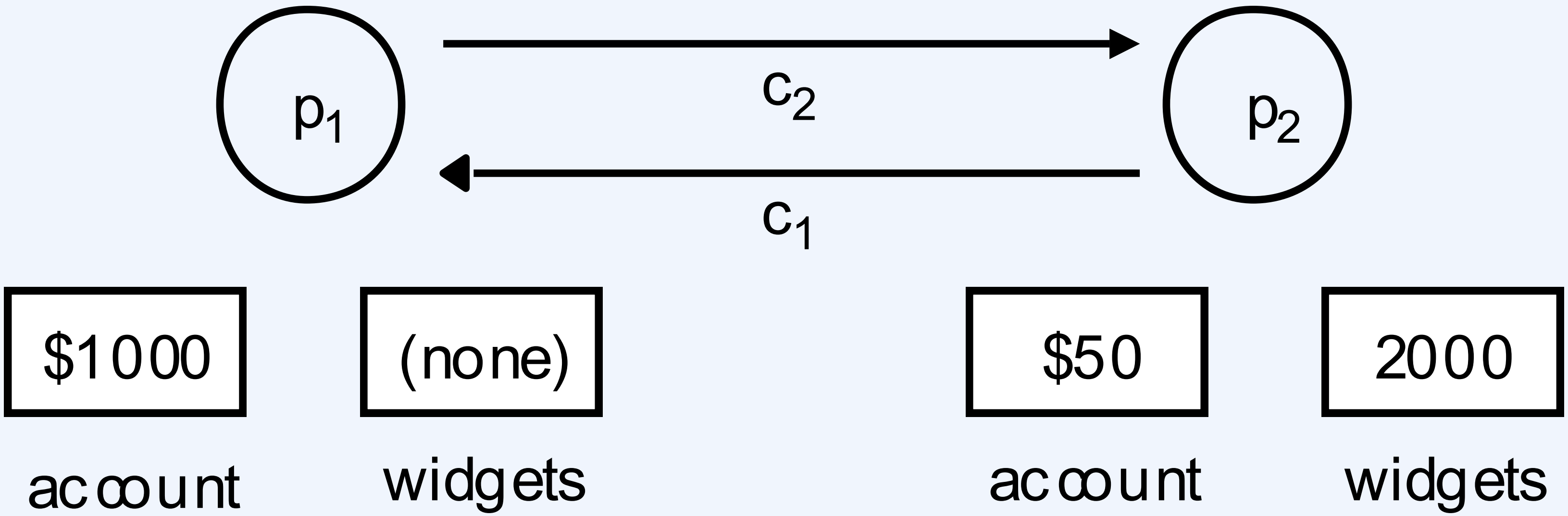
Proof

- Assume no: P_a recorded its state before e_a occurred (e_b is in the cut, but e_a is not)
  - since $e_a \rightarrow e_b$, there was some sequence of messages m_1, m_2, … , m_h that brought on $e_a \rightarrow e_b$
  - since P_a recorded its state before e_a occurred, it sent marker messages out on all its outgoing channels before transmitting m_1
  - since the channels are FIFO, a marker reached P_b before m_h
  - but then P_b would have recorded its state before e_a
  - but then e_b would not have been in the cut
    - contradiction

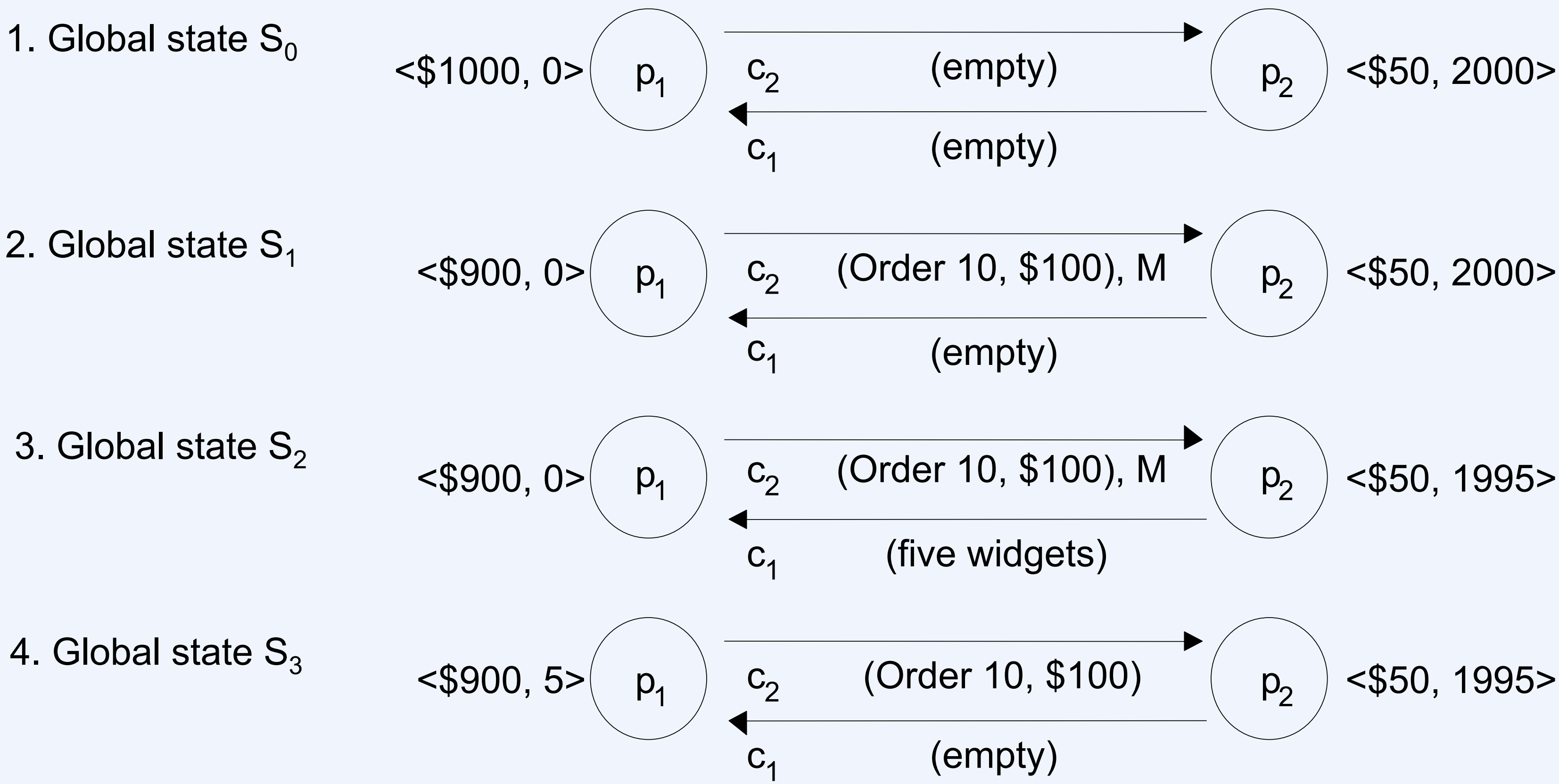
More Analysis

- Snapshot taken isn't necessarily a state that actually happened!
  – but it could have happened …
- If distributed system deadlocks, no distributed snapshot

Example (part 1)

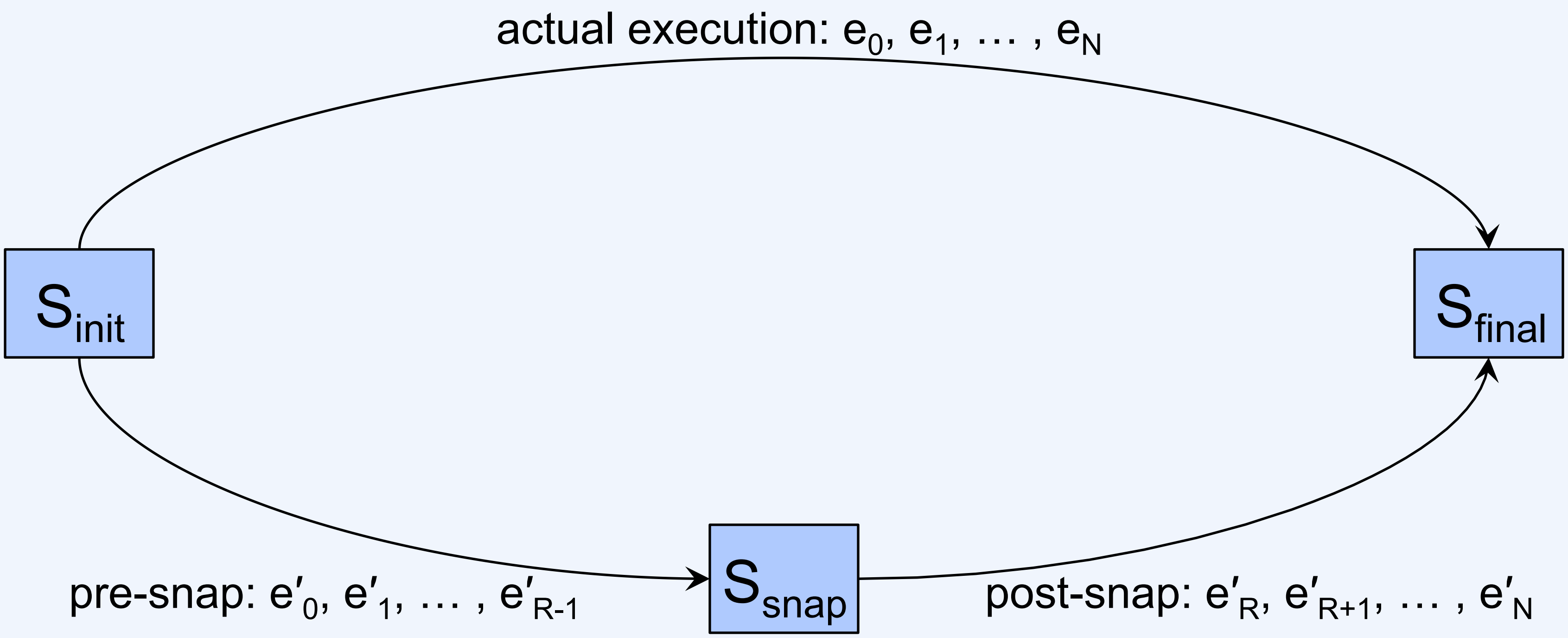


Example (part 2)



(M = marker message)

Reachability

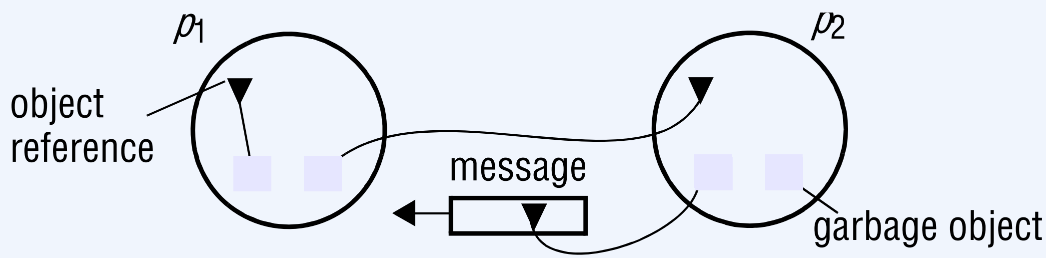


Global Properties

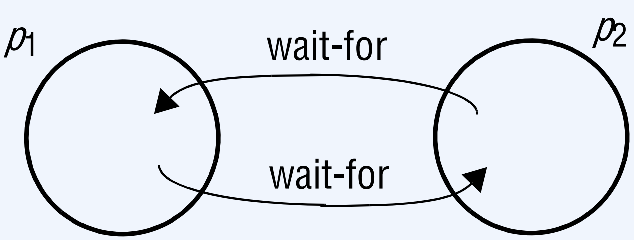
- Safety
  - bad things will not happen
  - e.g., mutual exclusion is a safety property
- Liveness
  - good things will happen
  - e.g., termination is a liveness property
- Stable properties
  - once true — always true
- Transient properties
  - once true — who knows?

Stable Global Properties

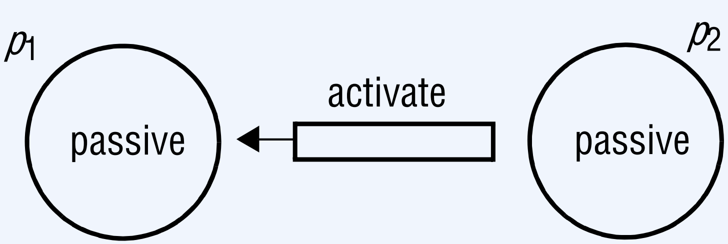
(a) Garbage collection



(b) Deadlock



(c) Termination



Transient Properties

- Distributed debugging
  - assert($\forall a \neq b$ ($|x_a - y_b| < 10$))
    - x_a and y_a reside in process a

How To …

- State collection
  - each process sends snapshots to central server
  - contain vector timestamps
- Central server checks for transient property ϕ
  - looks at global states that could have resulted from initial state, given vector timestamps
- *possibly* ϕ
  - if ϕ holds in at least one of them
- *definitely* ϕ
  - for all possible (causally consistent) orderings, ϕ holds at some point