Distributed Systems
CS 380D

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Types of knowledge

- Common knowledge:
  - known by everyone in group
  - each node **can** assume others know this
- Distributed knowledge:
  - known by some members of group
  - a node **cannot** assume others know this
- Simultaneous actions requires common knowledge

Common Knowledge

- Impossible to obtain if communication is over unreliable channels
- Demonstrated in the Coordinated Attack Problem
- Internal Common Knowledge:
  - assume something is common knowledge
  - hope no node encounters state that disproves assumption

Muddy Children Puzzle

- n children play, k get muddy
- Each can observe all others, don't know their own state
- Dad says "at least one of you is muddy"
- Dad asks each of them: "do you know if you are muddy"?
- claim: After k-1 rounds, all children will answer yes

Muddy Children Puzzle

- Children get information from:
  - Observation of other children
  - Hearing what other children say
  - Inferences based on previous rounds
- Common knowledge: father says at start “at least one of you is muddy”

Proof by induction

- k = 1:
  - Muddy child observes all others are clean
  - But father said someone is muddy
  - Hence child realizes they are muddy, answers yes
  - Once other children hear muddy child answer yes, they also answer yes
- k = 2:
  - Each muddy child observes one other muddy child
  - in first round, k = 1, all answer no as they are unsure of their own state
  - Muddy child realizes they are muddy, since other muddy child answered no in first round (hence other child must see someone muddy)
  - In second round, all answer "yes"

Proof by induction

- k = 3
  - Say muddy children are a, b, c
  - if a is clean, b and c would have answered yes in second round
  - Hence a is not clean; b and c do similar reasoning
  - All answer yes on third round

Does father need to provide common knowledge?

- One might think no: for k > 1, seems like children get the information from direct observation
  - However, it is not common knowledge
  - For k = 2, muddy child a observes muddy child b. But does not know if b observes a, and therefore knows k >= 1

Does father need to provide common knowledge?

- Showing it does not work for k = 2:
  - Muddy children are A and B
  - In first round, even if A had seen all clean kids, they would have still answered “no” (because they do not know k >= 1)
  - In second round, A and B realizing they are muddy depends on muddy child saying yes in round 1
  - A saying “no” in round 1 does not provide B with any information
  - B still thinks k = 1 or k = 2

Does father need to provide common knowledge?

- Valid sequence if $k = 1$ from B's viewpoint:
  - A is only muddy child
  - A does not realize $k >= 1$, cannot decide between $k = 0$ and $k = 1$
  - A says "no" in first round
- B still cannot decide between $k = 1$ or $k = 2$ (both can happen with prior seq)

Common knowledge

- k >= 1 is distributed knowledge, not common knowledge
- This case clearly shows the difference between the two

Hierarchy of States of Knowledge

- Agent's knowledge depends on:
  - Starting knowledge
  - Observed history since start
- If agent i knows P then $K_i(P)$
- Agents know only true things

Hierarchy of States of Knowledge

- D(G, P) = group G has distributed knowledge of P (union of knowledge of G members = P)
- S(G, P) = someone in G knows P
- E(G, P) = everyone in G knows P
- E(G, K, P) = E(E(E.. E(G,P))))) k times
- E(E(G,P)) = everyone in G knows that everyone in G knows P
- Common knowledge: E(G, K, P) for all K >= 1

Muddy Children Puzzle

- m = "at least one child is muddy"
- Without father speaking,
  - E(G, K–1, m) = true
  - E(G, K+1, m) = false

Muddy Children Puzzle

- E(G, m) = true
- In k = 2,
  - E(G, 1, m) = true, everyone knows m
  - E(G, 2, m) = false, everyone does not know everyone knows m
  - Specifically, with muddy children A and B, A does not know B knows K >= 1
- Fathers statement makes E(G, 2, m) = true

Knowledge in distributed systems

- Communication in a distributed systems seeks to move up the hierarchy of knowledge:
  - changing S(G, P) = E(G, P) = C(G, P)
- Fact discovery:
  - Changing D to S to E to C
  - Example: finding deadlock in a set of distributed locks
- Fact publication:
  - Changing S to C
  - Example: new protocol for communication

Common Knowledge

- How does one establish it?
  - By being part of a community
    - Membership procedure imparts common knowledge
    - Example: community of licensed drivers knows what signs mean
  - By being co-present at knowledge creation
    - Example: children being in same room as father when he makes announcement

Coordinated Attack Problem

- General A sends time in message to General B
- A will not attack without ack from B
- B sends ack to A
- But B will not attack without ack from A
- A sends Ack(Ack(A)) to B
- A will not attack without ack of this message
- And so it goes.. A and B cannot agree with finite messages
- Can use induction to prove no set of K messages is enough

Coordinated Attack Problem

- Generals A and B need common knowledge of the attack time
- After A sends the first message to B, E(G) = true, but E(E(G)) is not
- After A sends the ack to B's ack, E(E(G)) = true, but E(3, G) = false
- Coordinated attack requires C(G) = E(k, G) = true for any k

Jan 28

More on Common Knowledge

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Knowledge in Processors

- Ground facts are facts about the state of the system: represents the raw state without semantics
- At each point in the protocol, a processor has a view
- A processor knows all the facts that follow from its view at a given point

View-based interpretation

- Every node has a view based on its history
- Every view is associated with a set of facts both directly known and inferred

Coordinated Attack Problem

- Even with guaranteed delivery, if messages can be delayed an unbounded amount of time, attack cannot be coordinated
- Why? No guarantee that other party seems message before attack time

Coordinated Attack Problem

- What if the delay in delivery time was bounded to "e"?
- Still not possible to coordinate attack
- Lets say Y receives a message from X at time TD
- Y knows X will not assume Y has seen it until e time has passed (TS + e)
- But TS could also be TD, message could be delivered instantly
- Y has to wait until TD + e to be sure that X knows Y has received the message
- So in total, 2e time units has to pass until it is common knowledge among X and Y that X sent a message to Y
- With each round, the time units keep increasing: k*e for K rounds
- Since common knowledge requires arbitrary K to hold, it follows that an infinite amount of time has to pass

Attaining common knowledge

- Common knowledge is attainable if multiple nodes in the system can **simultaneously** converge on a single option (among many options)
- When one node believes M, all nodes must simultaneously believe M if M is common knowledge
- The histories of all nodes must simultaneously change to reflect M

Common Knowledge in Practice

- Common knowledge needed for simultaneous coordination in a distributed system
- For other types of coordination, weaker states of knowledge is enough
- E-common knowledge: when every agent knows M within time units E
- E-common knowledge achieved through **synchronous broadcast**: all agents guaranteed to receive it within E time units

Stable properties

- E-common knowledge is useful as it allows us to identify stable properties
- A stable property S is a property of the system such that once S becomes true, it is always true
- For example, once the system is deadlocked, it is always deadlock pending some external action

Eventual Common Knowledge

- What to do for async broadcast?
- Eventual common knowledge (M): Every node knows every other node knows M or will know M in the future
- Useful in real-world scenarios: for example, in Byzantine agreement, once a value is agreed upon by one processor, all other processors decided on this value eventually

Jan 30
Consistent Global States of Distributed Systems: Fundamental Concepts and Mechanisms

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Global State of a distributed system

- Union of local state of nodes
- No way to get instantaneous snapshot of all nodes
- Only way to get local state of a node is by sending it a message
- How to find a meaningful global state of the system?

Why is this hard?

- Messages could be dropped or delayed
- Computed Global state may be:
  - Obsolete: state changed since we have checked
  - Incomplete: state of some nodes may be missing
  - Inconsistent: imagine a token is sent from A to B. Computed Global state may show token in both A and B

Computing Global State

- What if we simply used a lot of messages to nodes to compute global state?
- Would help with ensuring global state is complete or current (not obsolete), but will not help with ensuring global state is consistent
- Consistency cannot be achieved by throwing more messages at the problem

Global Predicate Evaluation (GPE)

- We construct a predicate based on the global state
- We want to evaluate whether this global predicate is true or false
- Examples: the system is deadlocked, a majority of nodes are alive and responsive

Modeling the system

- N sequential processes p1.. pn
- Each pair of processes has a channel
- Channels are reliable but may deliver messages out of order
- Why do we model system as async?
  - Physical delays are bounded
  - Software creates unbounded delays

Distributed Computation

- Activity distributed among N processes
- Each process sees three kinds of events:
  - Events local to that process
  - Send message to process pi
  - Receive message from process pj
- All events are recorded in the local history of the process
- Global history is union of histories of all participating processes

Global History

- Global history does not order all events
- An event A is only ordered with respect to event B if A happening affects B in some way
- Events are ordered using “happens-before” relationships

Lamport Clocks

- Notation: $e(i, k)$ = kth event in process i
- $e(i, j) < e(i, k)$ if $j < k$
- if $e(i, j) = send(m)$, and $e(k, l) = receive(m)$
  - then $e(i, j) < e(k, l)$
- if $e(i, j) < e(k, l)$ and $e(k, l) < e(m, n)$
  - then $e(i, j) < e(m, n)$
- All other events are considered concurrent
  - consider $e(i,j)$ and $e(k,l)$ concurrent
  - $e(i, j) < e(k,l)$ is false
  - $e(k, l) < e(i,j)$ is also false

Distributed Computation

- Formally, a distributed computation is a partially ordered set (poset) defined by the pair (H, ->)
- Not all events are ordered
- Events inside each process are totally ordered
- Events across processes are partially ordered

Cuts

- A cut of a distributed computation is a subset C of its global history H and contains an initial prefix of each of the local histories
- A cut can be defined by tuple (c1, c2, ..cN)
  - Process pi's last event in the cut is ci
  - P1's last event in the cut is c1
- Frontier of the cut: the set of events e(i, ci) for i=1..n (the last events included in the cut for each process)

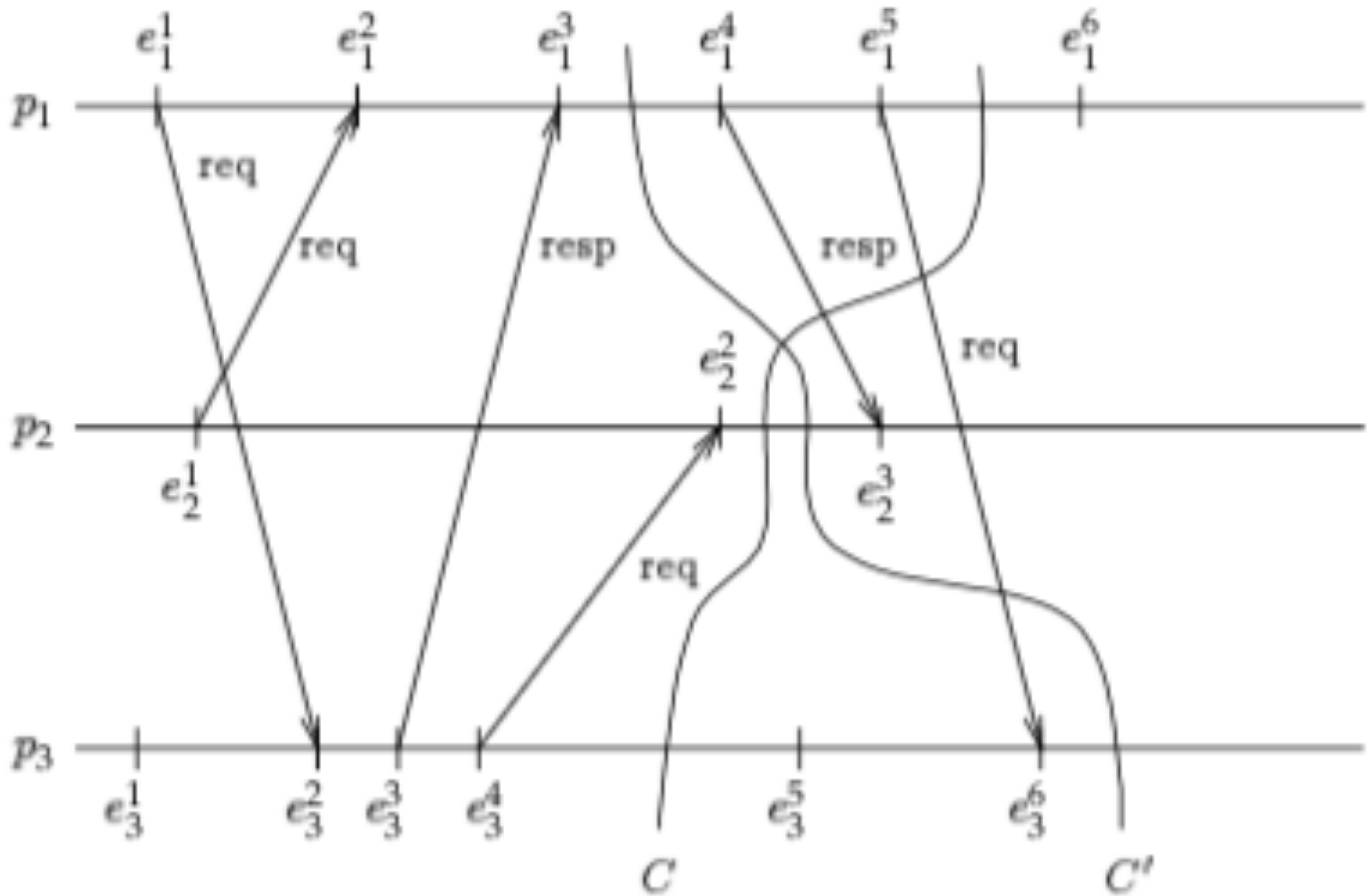

Figure 2. Cuts of a Distributed Computation

Runs

- A run of a distributed computation is total ordering R that includes all of the events in the global history and that is consistent with each local history.
- For process Pi, the events of Pi occur in the same order in R as in the history of Pi
- There are many possible runs for a single distributed computation with history H

Inconsistent Cuts

- Not all cuts are consistent
- If a cut includes receipt of a message but not the sending of the message, it is inconsistent
- More precisely, if $e(i, j) < e(k, l)$ and $e(k, l)$ is in the cut, then $e(i,j)$ must also be in the cut
- Global properties must be checked using consistent cuts (which lead to consistent global states)
- Using inconsistent cuts may lead to determination of "ghost deadlock"

Reachable States

- A run R is said to be consistent if for all events, e1 < e2 implies that e1 appears before e2 in R
- Each (consistent) global state Si of the run is obtained from the previous state Si-1 by some process executing the single event ei
- Si-1 leads to Si
- Sj is reachable from Si, if there is a series of consistent states from Si to Sj such as Si -> Sk -> Sj

Lattice

- The set of all consistent global states of a computation along with the leads-to relation defines a lattice.
- The lattice consists of n orthogonal axes, with one axis for each process
- Each path down the lattice is one run of the distributed system

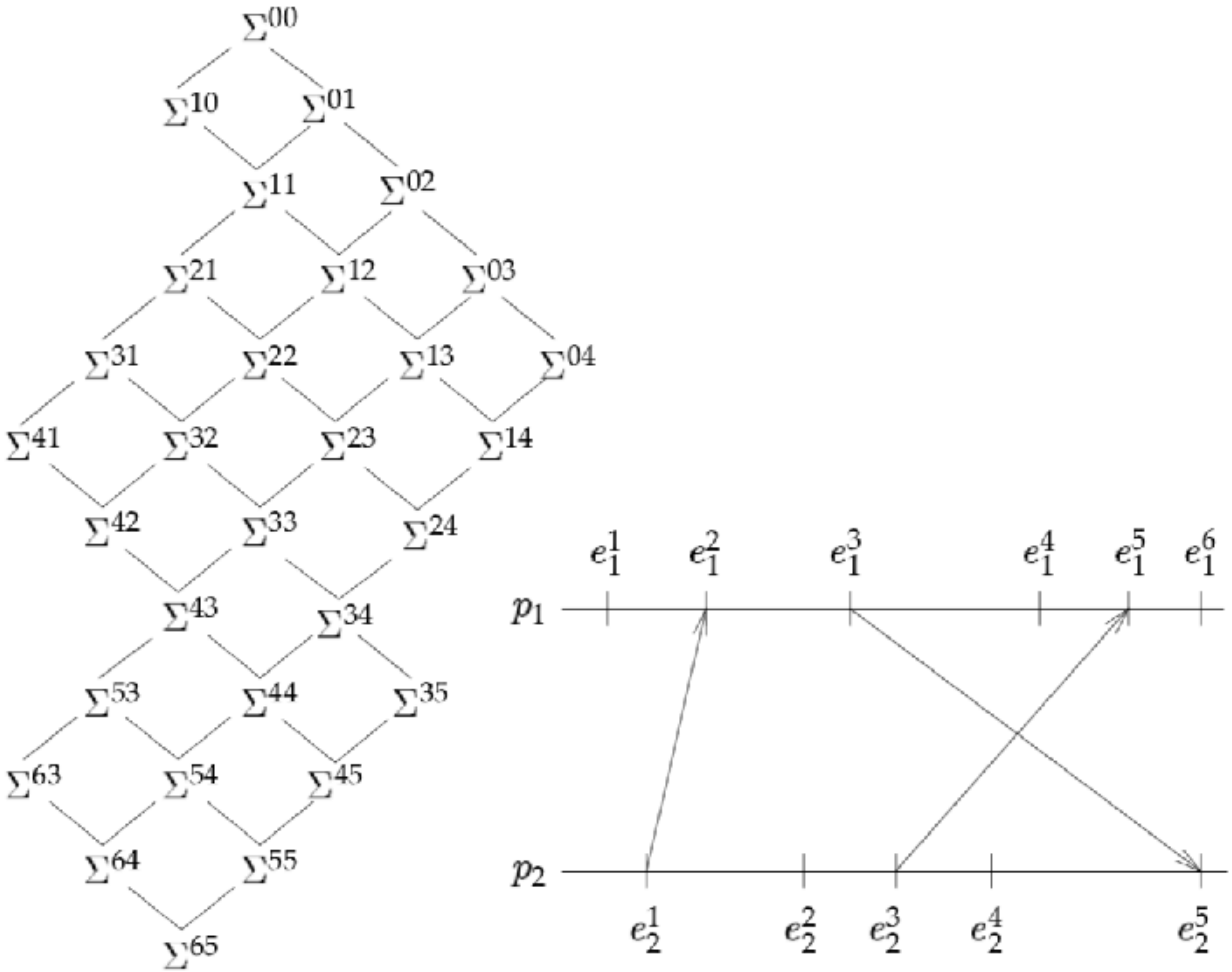

Figure 3. A Distributed Computation and the Lattice of its Global States

Observing a distributed system

- Idea 1: Active Observer
  - One monitor process sends messages to all processes
  - Constructs global state based on responses
  - Can lead to inconsistent cut

Observing a distributed system

- Idea 2: Passive Observer
  - One monitor process gets copy of all messages sent by processes
  - Different monitors observe different cuts (and hence different global states)
  - Consistent observation leads to a consistent run

Observing a distributed system

- We ensure messages from the same process are delivered in order (FIFO delivery)
    - Implemented using per-process sequence numbers
- Delivery Rule:
    - if $e1 < e2$, then $ts(e1) < ts(e2)$.
    - Deliver messages in timestamp order

Feb 4
Consistent Global States
(Part 2)

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Consistent observations

- A consistent observation is one that corresponds to a consistent run.
- It is the possibility of messages being reordered by channels that leads to undesirable observations
- We can restore order to messages between pairs of processes by defining a delivery rule for deciding when received messages are to be presented to the application process.

FIFO Delivery

- FIFO Delivery: sendi(m) -> sendi(m’) => deliveri(m) -> deliveri(m’)
- Clock Condition: e -> e’ => Timestamp(e) < timestamp(e’)
- Delivery Rule DR1: At time t, deliver all received messages with timestamps up to t - delta in increasing timestamp order

Gap Detection

- Given two events e and e′ along with their clock values LC(e) and LC(e′) where LC(e) < LC(e′) , determine whether some other event e″ exists such that LC(e) < LC(e″) < LC(e′)
- A message m received by process p is called stable if no future messages with timestamps smaller than TS(m) can be received by p.
- DR2: Deliver all received messages that are stable at p0 in increasing timestamp order.

Causal Delivery

- FIFO delivery is per-process
- Causal Delivery extends it across processes
- Causal Delivery: sendi(m) -> sendj(m') => deliveri(m) -> deliverj(m')
  - Note i and j can be different
- FIFO delivery between all pairs of processes not enough for causal delivery
- A -> B, A -> C; B->C
  - sendAB(M1) -> sendAC(M2)
  - B gets M1, sends it to C
  - C gets M2 before M1.
  - FIFO delivery is ensured, causal delivery is not.

Consistent Observations

- If the observer process uses a delivery rule that satisfies Causal Delivery, then all its observations will be consistent

- How do we build this in a practical distributed system?

Building the Observer

- Assume Observer has two parts: the Logic Controller and the Network Controller
- The Network Controller gets events sent by other nodes, decides in what order to show them to Logic Controller
    - Delivery rules are implemented here
- Logic Controller takes actions based on what it sees ("declare deadlock")

Building the Observer

- Network Controller gets two events E1 and E2
- Timestamp = TS
- TS(E1) < TS(E2)
- This doesn't mean E1 < E2
- Only this is true: E1 < E2 => TS(E1) < TS(E2)
- So we know E2 < E1 is false, E1 and E2 could still be concurrent

Strong Clock Condition

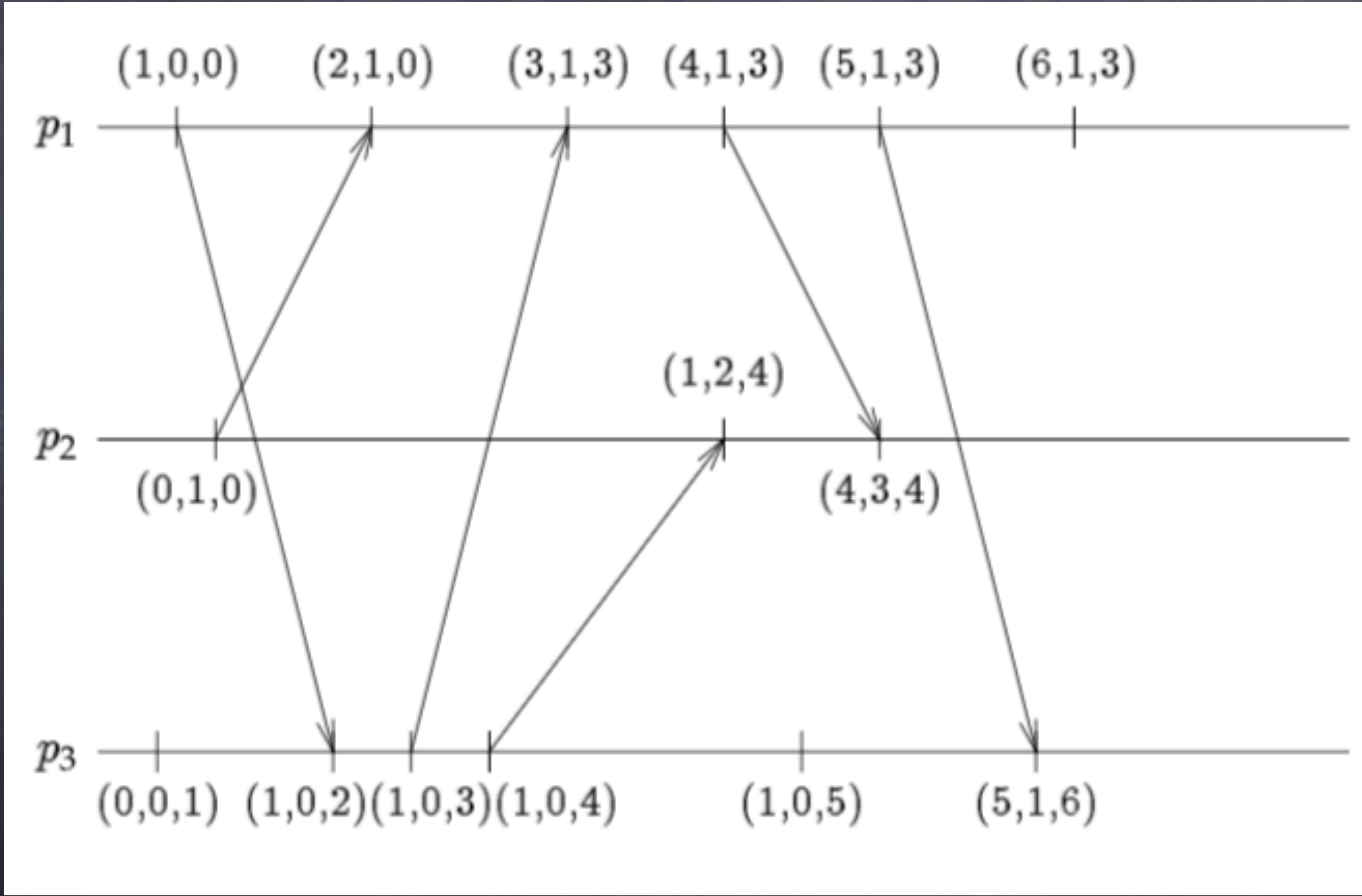
- Need stronger condition to implement Network Controller
- Strong Clock Condition:
  - $E1 < E2 \Rightarrow TS(E1) < TS(E2)$
  - $TS(E1) < TS(E2) \Rightarrow E1 < E2$

Implementing the Strong Clock Condition

- Brute force approach:
  - At each node, keep the Causal History C
  - Causal History C(e) is the set of all events e′ such that e′ < e
  - All previous local events at node are part of C(e)
  - When A sends a message to B, C(receipt of message M) = C(previous local event at B) union C(sending event at A)
  - E1 < E2 if C(E1) is a subset of C(E2)
- Problem: the set C grows too large too quickly, impractical to maintain

Vector Clocks

- Each node maintains a vector V[n] where there are n nodes
- V = 0 on initialization for all nodes
- For local event Ei at node i, update V[i] = V[i] + 1
- On receipt(M),
  - V = max(V, vector-TS(M)) for each element of V
  - V[i] +=1
- V[j] = number of events of j that casually precede this event (when this process is not j)
- V[i] = number of local events when this process is i


(1,0,0)
(2,1,0)
(3,1,3)
(4,1,3)
(5,1,3)
(6,1,3)
p1
(1,2,4)
p2
(0,1,0)
(4,3,4)
p3
(0,0,1)
(1,0,2)
(1,0,3)
(1,0,4)
(1,0,5)
(5,1,6)

Using Vector Clocks

- $V1 < V2$ if no element of V2 is bigger than its corresponding element in V1
- Strong Clock Condition: $E1 < E2 \Leftrightarrow V(E1) < V(E2)$
- V1 and V2 are concurrent if $V1[i] > V2[i]$ for some i and $V2[j] > V1[j]$ for some j

Using Vector Clocks in the Network Observer

- All events sent to observer have vector timestamps
- Network Observer obtains set of events M, then decides on order to deliver them
- A message can be delivered as soon as Network Observer determines there are no events that casually precede this message
- Consider message M from J
- M′ is last message delivered from K (K != J)
- To deliver M, NO has to determine that:
  - There is no earlier message from J that is undelivered
    - if V(M)[J] -1 message have already been delivered, there cannot be an earlier message
  - There is no undelivered message M″ such that sendK(M′) < send (M″) < sendJ(M)
    - V(M′)[K] >= V(M)[K] for all K => V(M) < V(M′)

Using Vector Clocks in the Network Observer

- Network Observer maintains array D, initialized to 0
- Deliver message M with time stamp V from J as soon as:
  - D[J] = V[J] - 1
  - D[K] >= V[K], for all K != J
- When Network Observer delivers M, D is updated by setting D[j] = V[j]

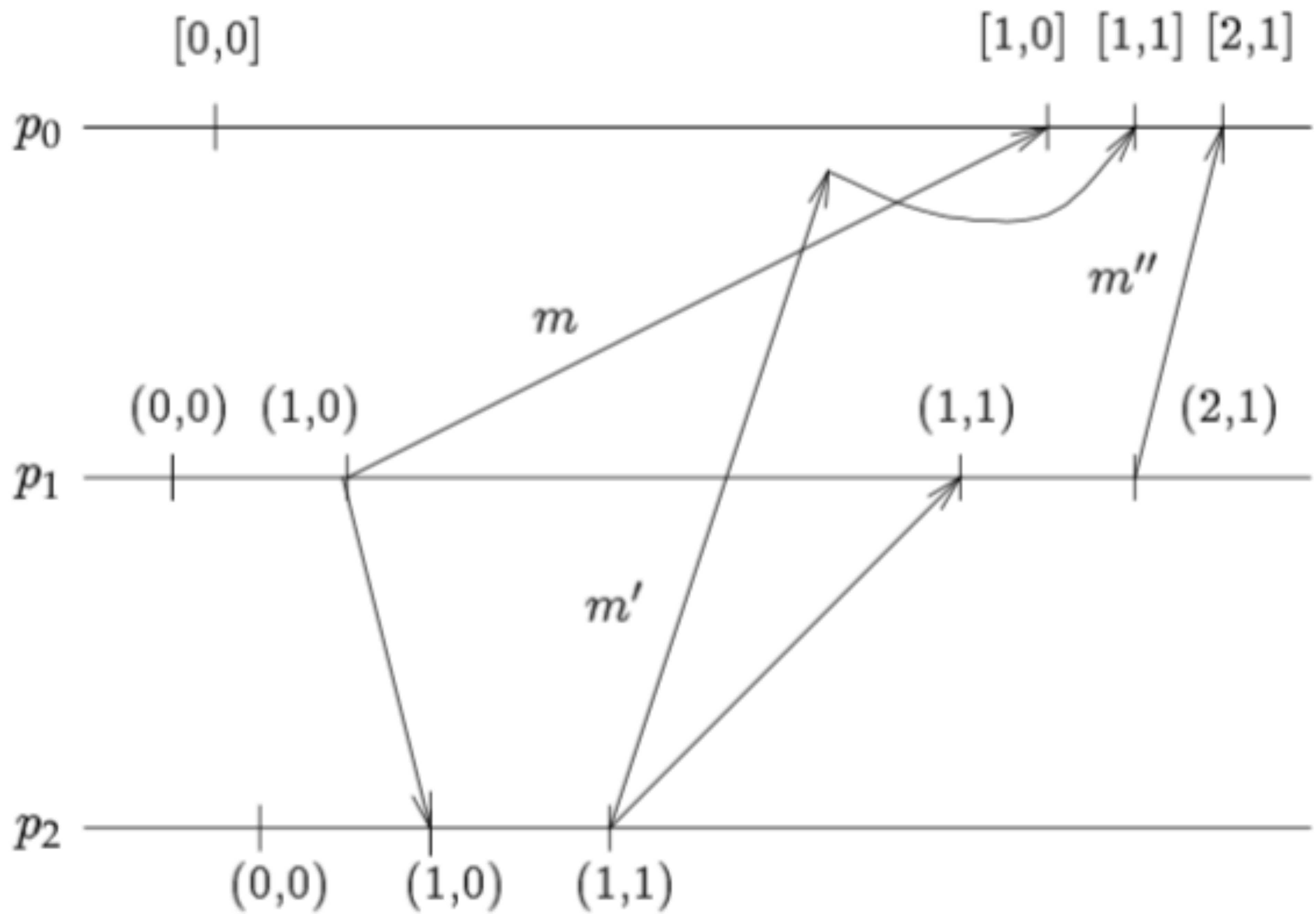


Figure 8. Causal Delivery Using Vector Clocks

Feb 6
Distributed Snapshots

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Using Vector Clocks in the Network Observer

- Network Observer maintains array D, initialized to 0
- Deliver message M with time stamp V from J as soon as:
  - D[J] = V[J] - 1
  - D[K] >= V[K], for all K != J
- When Network Observer delivers M, D is updated by setting D[j] = V[j]

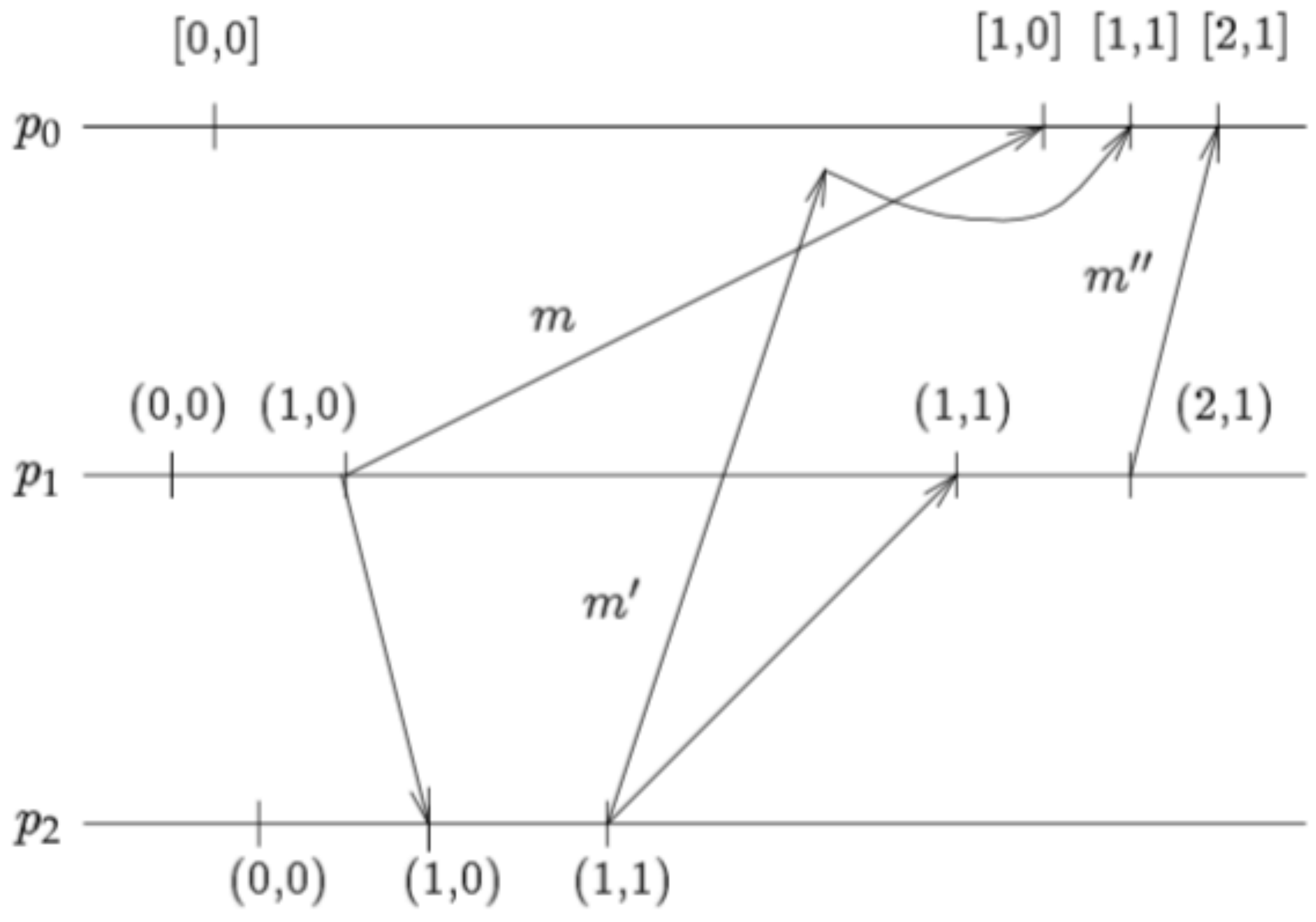

Figure 8. Causal Delivery Using Vector Clocks

State Machines

- Each process in a distributed system is modeled as a state machine
- The process is in an initial state I
- Upon getting a message M from another process, the process transitions to another state S1
- In state S1, process responds to other messages by moving to other states S2..SN
- Processes transition only on receiving messages

Distributed Snapshot Algorithm

- How to compose a global snapshot based on the snapshot of individual nodes?
- How to deal with double-counting or missing state because of messages that were in flight?

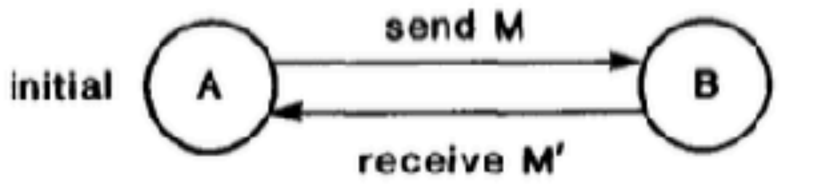

Fig. 5. State-transition diagram for process p in Example 2.2.

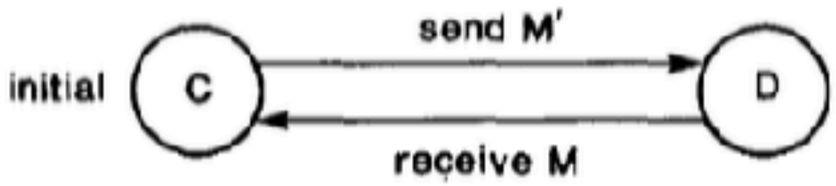

Fig. 6. State-transition diagram for process q in Example 2.2.

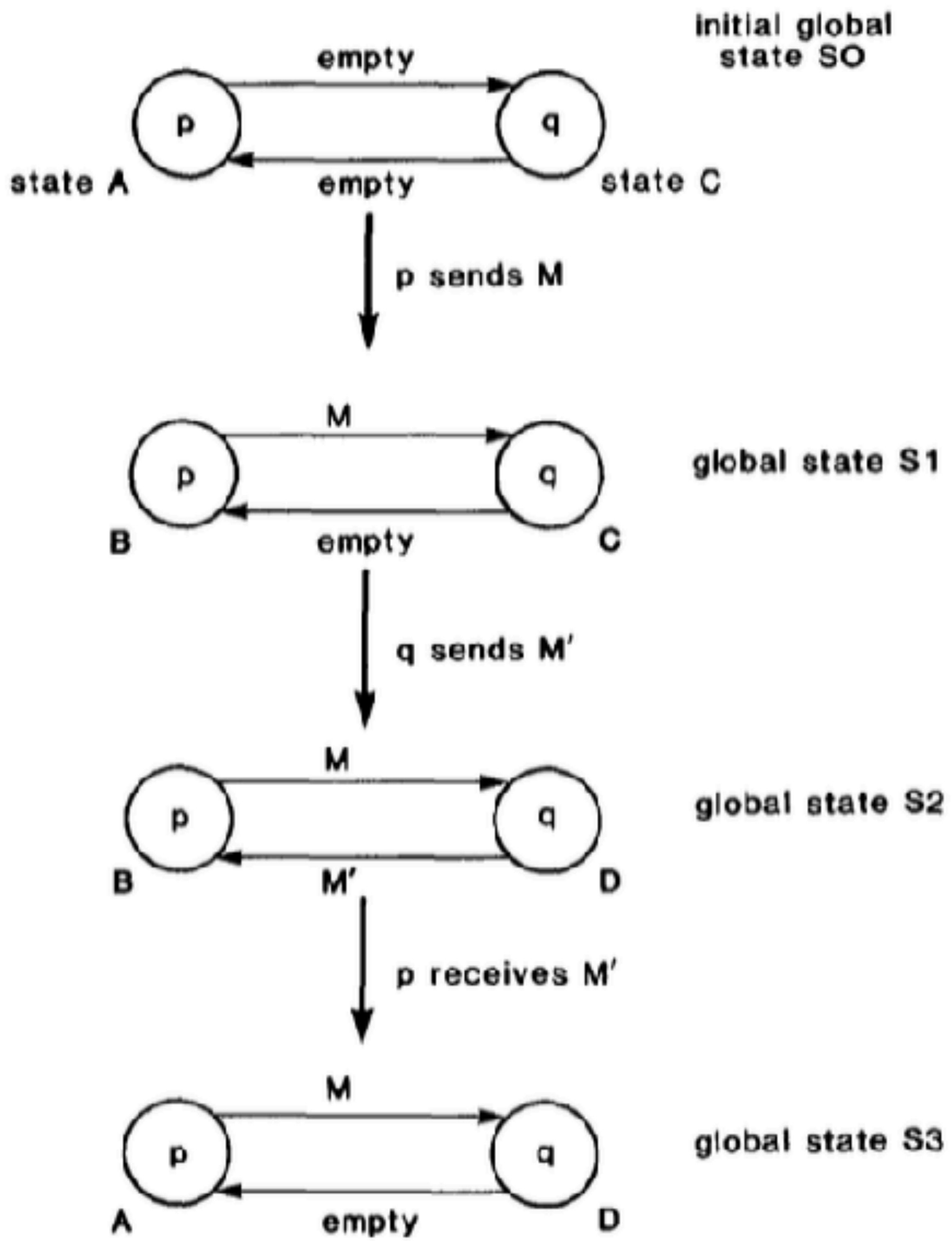

Fig. 7. A computation for Example 2.2.

Chandy Lamport Protocol

- Assumptions:
  - No message remains forever in transit
  - Messages can be delayed but not lost
  - If the graph is not strongly connected, at least one node in each component starts the process

Chandy Lamport Protocol

- Process p0 starts the protocol by sending itself a "take snapshot" message.

- Let pf be the process from which pi receives the "take snapshot" message for the first time. Upon receiving this message, pi records its local state i and relays the "take snapshot" message along all of its outgoing channels. No intervening events on behalf of the underlying computation are executed between these steps. Channel state (f,i) is set to empty and pi starts recording messages received over each of its other incoming channels.

- Let ps be the process from which pi receives the "take snapshot" message beyond the first time. Process pi stops recording messages along the channel from ps and declares channel state si as those messages that have been recorded.

Validating Predicates

- Stable predicates can be faithfully validated
- Unstable predicates are tricky:
  - Algorithm may detect state that never held in an actual run of the distributed computation
  - Predicate may have changed by the time the observer gets to know

Defining predicates

- Possibly(P): There exists a consistent observation O of the computation such that P holds in a global state of O.

- Definitely(P): For every consistent observations O of the computation, there exists a global state of O in which P holds.

Predicates

- Possibly(P) and Definitely (not P) can hold at the same time!
- How? By being true in different global states of the same run

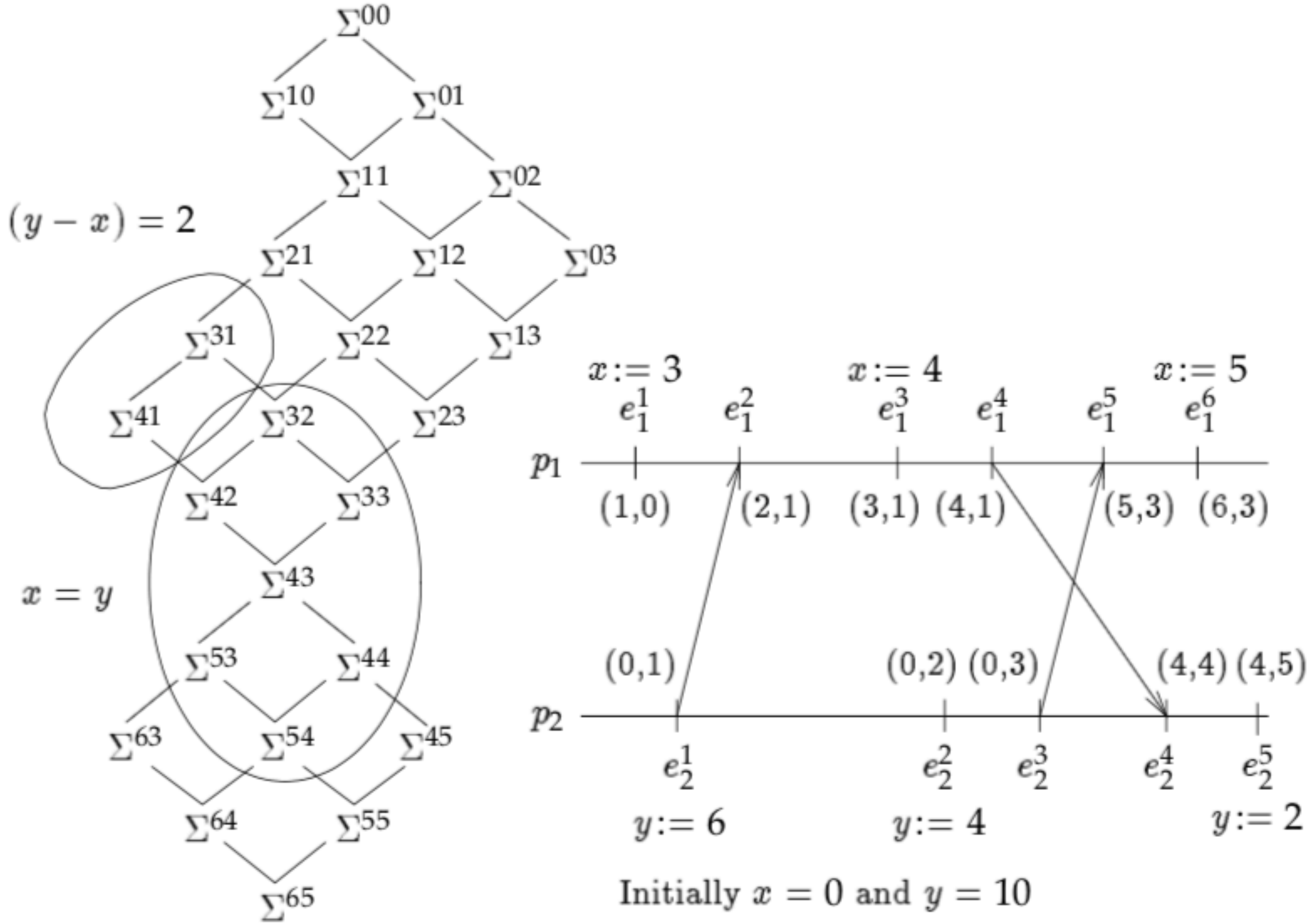

Figure 16. Global States Satisfying Predicates $(x = y)$ and $(y - x) = 2$

Feb 11
Safety and Liveness

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Safety and Liveness

- Safety: "bad things don't happen (ever)"
- Liveness: "good things happen eventually"
- We will formalize these properties to help reason about them
- We will build on the theory we have learnt so far

Property

- Property: A set of infinite sequences of program states
- A program satisfies property P if each of its histories H is a subset of P
- We will use Buchi automata to specify properties
- A buchi automaton M accepts the sequence of program states in the property it specifies

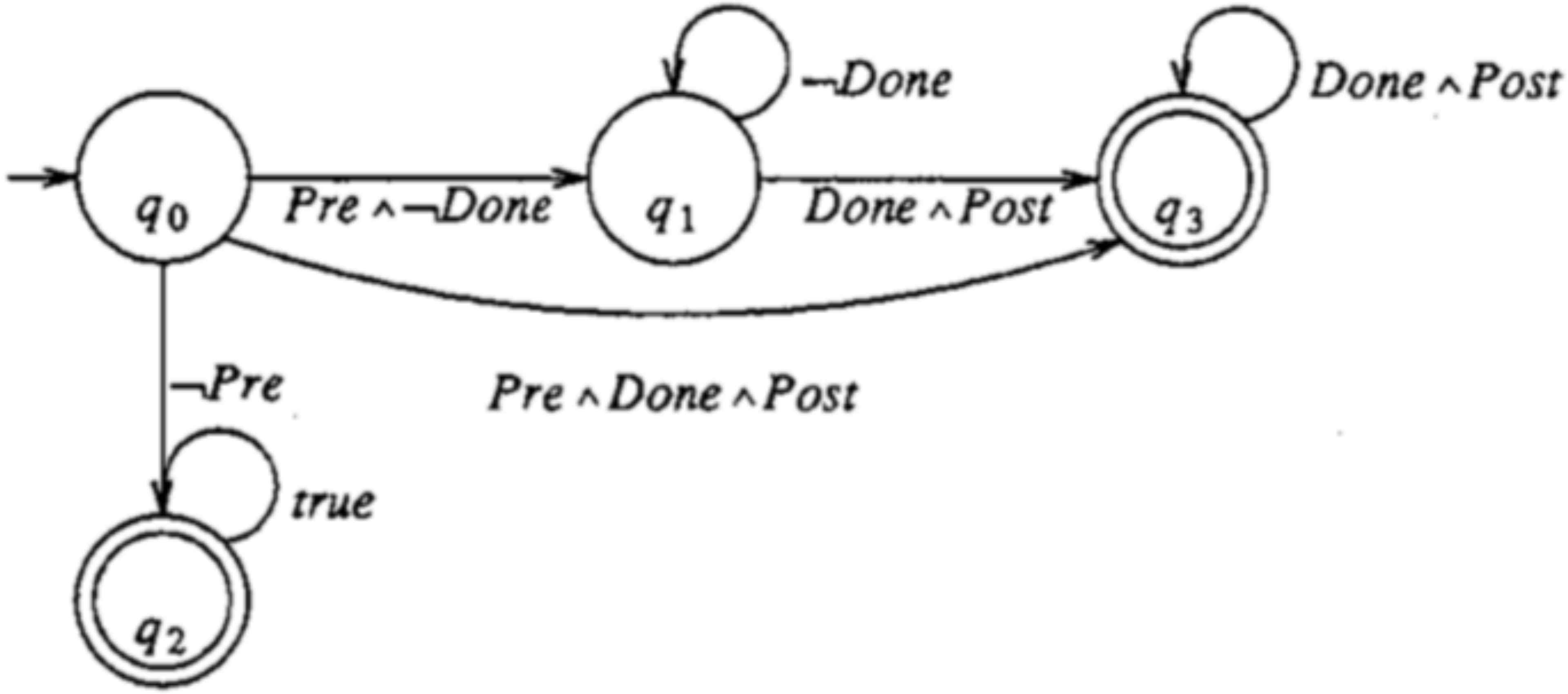
$\neg Done$
$Done \wedge Post$
q_0
$Pre \wedge \neg Done$
q_1
$Done \wedge Post$
q_3
$\neg Pre$
$Pre \wedge Done \wedge Post$
$true$
q_2

Fig. 1. m_{tc}

Buchi Automatons

- A buchi automaton contains a start state and a set of accepting states
- Arcs between states are labelled with predicates called transition predicates
- If a state does not have an arc for a given program state, we say an undefined transition occurs
- A buchi automaton is reduced if there is a path from every state to an accepting state
- Non-deterministic automatons have multiple start states or multiple transition arcs for the same input

Buchi Automatons

- Formally, a Buchi automaton m for a property of a program rc is a five-tuple (S, Q, Q-start, Q-accept, D)
- S is the set of program states of m,
  Q is the set of automaton states of m,
  D (Q, S) is the transition function of m.
-

Specifying Safety

Safety:

$$(\forall \sigma : \sigma \in S^{\omega} : \sigma \models P$$
$$\Leftrightarrow (\forall i : 0 \leq i : (\exists \beta : \beta \in S^{\omega} : \sigma[..i]\, \beta \models P))), \qquad (3.1)$$

- All runs are a subset of property P
- For a reduced Buchi automaton m, define its closure cl(m) to be the corresponding Buchi automaton in which every state has been made into an accepting state.
- The closure of m can be used to determine whether the property specified by m is a safety property.
- It rejects only by attempting an undefined transition (a "bad thing").
- If m and cl(m) accept the same language then m recognizes a safety property.

Specifying Liveness

- The thing to observe about a liveness property is that no partical execution is irremediable since if some partial execution were irremediable, then it would be a "bad thing" (and thus a safety property)
- A buchi automaton m specifies a liveness property if and only if its closure accepts every input
- For all finite inputs, there exists an infinite sequence of states that result in the property P being maintained

$$\textbf{Liveness:} (\forall \alpha : \alpha \in S^* : (\exists \beta : \beta \in S^\omega : \alpha\beta \models P)). \qquad (3.4)$$

Partioning into safety and liveness

- Given a Buchi automaton m, it is not difficult to construct Buchi automata Safe(m) and Live(m) such that Safe(m) specifies a safety property, Live(m) specifies a liveness property, and the prop- erty specified by m is the intersection of those speci- fied by Safe(m) and Live(m).
- Safe(m) = closure of m
- Live(m) = m augmented with a trap accepting state and all other state transitioning on undefined input to the trap state

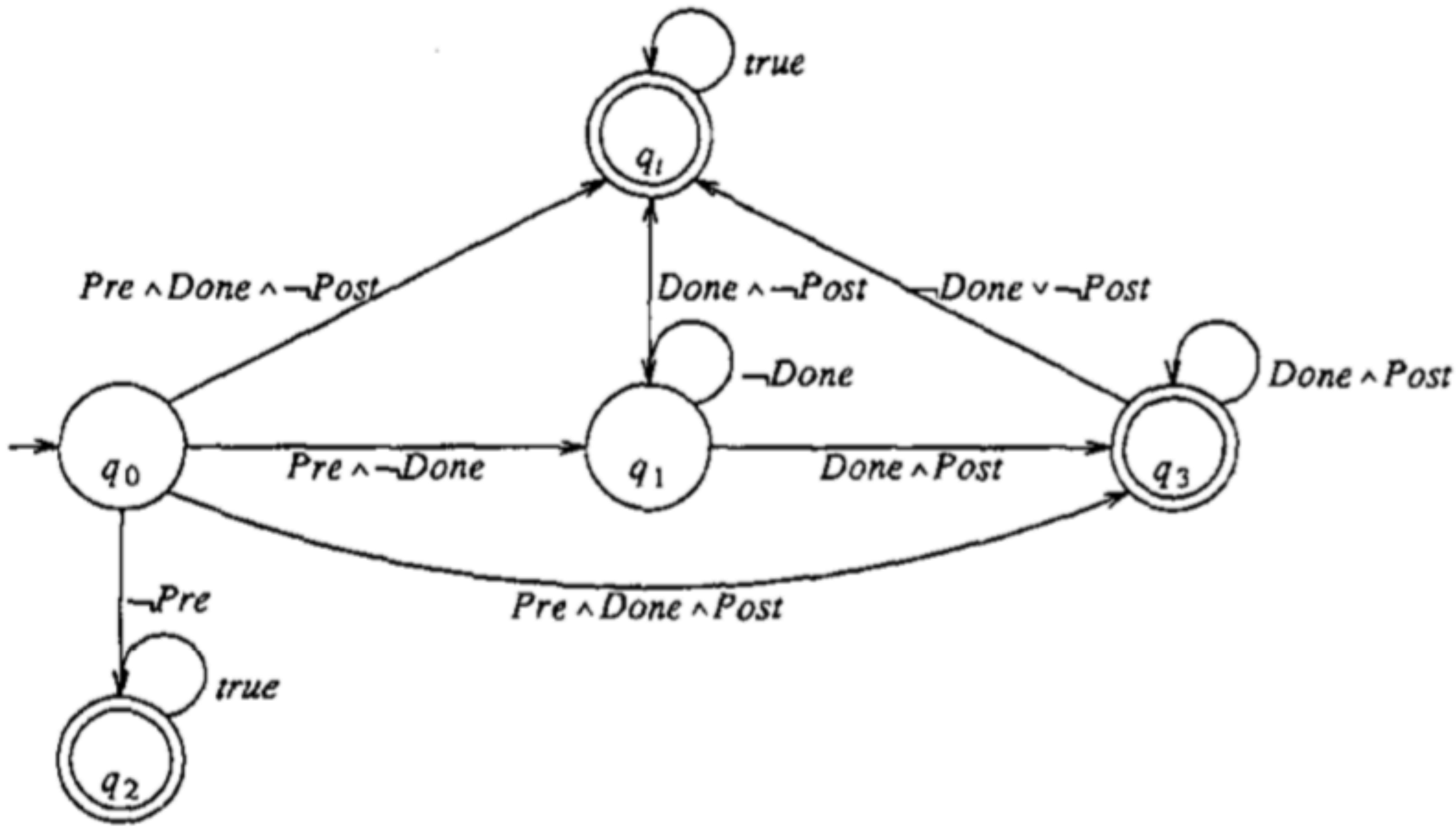

Fig. 8. *Live*(m_{tc})

Feb 13

Distributed Commit Protocols

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The problem

- We have multiple sites
- Data is divided among these sites (not replicated)
- We want to run a distributed transaction over this distributed data with ACID guarantees:
    - Atomic: all sites are updated with tx results, or none are
    - Consistent: updates are applied in a consistent fashion at all sites
    - Isolation: no tx sees partial results of other concurrent tx
    - Durability: after the tx commits, even if all sites lose power, the data is still available after reboot

Distributed Txs

- Each site has a Transaction Manager (TM)
- Txs are submitted to the TM at their local site
- Read(x) or write(x) forwarded to TM where X lives
- A Tx is Committed or Aborted — decision needs to be taken by all sites
- Incorrect if one site decides to Commit, and another site decides to Abort
- What to do if a tx site fails?

Failures in a distributed system

- A site could fail, or a link connecting sites could fail
- We assume there is a path from every site to every other site
- Failures are fail-stop
- Partial failure: some nodes are up, others are down
  - Partial failures are tricky because sites are unsure of the status of other sites (no common knowledge)
- Total failure: all nodes are down

Network Partition

- Dividing the network into two disconnected graphs, with no messages flowing from one side of the graph to the other
- Can happen due to router/link failures
- Usually temporary
- Once connection is restored, nodes can then talk to each other across the partition

Detecting Failures

- Done via time-out T
- If a node hasn't responded in time T, it is assumed to be dead
- Setting the value of T is tricky
  - If T is too high, we detect failures very late
  - If T is too low, we have false positives where we detect failures spuriously

Conditions to commit

- A Tx T can commit at Site S if:
  - T has read only committed values
  - All the values written by T are durably stored
- Each site contains a distributed coordination log where information is recorded about txs

Atomic Commitment Protocol

- AC1: All processes that reach a decision reach the same one.
- AC2: A process cannot reverse its decision after it has reached one.
- AC3: The Commit decision can only be reached if all processes voted Yes.
- AC4: If there are no failures and all processes voted Yes, then the decision will be to Commit.
- AC.5: Consider any execution containing only failures that the algorithm is designed to tolerate. At any point in this execution, if all existing failures are repaired and no new failures occur for sufficiently long, then all processes will eventually reach a decision.

Implications of the conditions

- A process can unilaterally abort the tx by voting No
- Once a process can voted Yes, it cannot later unilaterally decide No
- Uncertainty period: where a process has voted but is uncertain about the outcome (happens only when voting Yes)
- Proposition 7.1: If communication failures or total failures are possible, then every ACP may cause processes to become blocked.
- Proposition 7.2: No ACP can guarantee independent recovery of failed processes.

Two Phase Commit Protocol

- The coordinator sends a VOTE-REQ (i.e., vote request) message to all participants.
- When a participant receives a VOTE-REQ, it responds by sending to the coordinator a message containing that participant's vote: YES or NO. If the participant votes No, it decides Abort and stops.
- The coordinator collects the vote messages from all participants, If all of them were YES and the coordinator's vote is also Yes, then the coordinator decides Commit and sends COMMIT messages to all participants.
- Otherwise the coordinator decides Abort and sends ABORT messages to all participants.
- Each participant that voted Yes waits for a COMMIT or ABORT message from the coordinator. When it receives the message, it decides accordingly and stops.

Augmenting 2PC

- 2PC as outlined before satisfies AC 1-4
- Does not satisfy AC5: ".. if all existing failures are repaired and no new failures occur for sufficiently long, then all processes will eventually reach a decision."
- To handle failures, each site should durably record its vote and decision in the distributed coordination log
- Termination protocol: uncertain processes contact coordinator to learn of decision
- Cooperative Termination Protocol: uncertain processes contact each other instead of the coordinator

Feb 18
Failure Detectors

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Recap: models

- Async model: any message or event can take arbitrary time, there are no physical clocks
- Sync model: Messages get delivered within a bounded time, physical clocks can be used
- Async models are more portable, and in practice, timing assumptions in sync models are wrong at least temporarily

Consensus and Atomic Broadcast

- These are two useful primitives
- Consensus: N nodes agree on value X, in the presence of failures
- Atomic Broadcast: N nodes receive the same items in the same order, in the presence of failures
- Consensus and Atomic Broadcast are equivalent problems
- Both impossible to solve under pure asynchrony
    - We will see this result later in class

Failure Detectors

- Consensus impossible in async model because we cannot differentiate a failed node and a slow node
- Propose to solve consensus in asynchronous model by introducing unreliable failure detectors
- Model: async + crash failures + unreliable failure detectors
  - Each process p in the system maintains a list of processes suspected to be crashed

Failure Detectors

- Defined in terms of abstract properties
- Any implementation that provides those properties is then okay
  - Good engineering practice!
- Completeness: every failure is eventually detected
- Accuracy: limits false alarms
- Reducibility: D is reducible to D′ if a dist algo can transform D to D′.

W - weakest failure detectors

- Completeness: There is a time after which every process that crashes is permanently suspected by some correct process.
- Accuracy. There is a time after which some correct process is never suspected by any correct process.
- Allows a process to be wrongly identified as crashed by all processes repeatedly
- Allows a process to be added and removed again and again by other processes in their crash list

W failure detector

- Why is this useful? Guarantees safety
- A consensus system built using W gets safety, but not liveness
- No wrong values are accepted, processes don't accept different values

Failure Detector

- Every process q periodically sends a “q-is-alive” message to all
- If a process p times-out on some process q, it adds q to its list of suspects.
- If p laters gets message from q:
  - It removes q from list
  - It increases time-out value
- This does not satisfy W in async system with unbounded timeouts since correct processes be wrongly suspected forever
- However, in a sync system, this does satisfy W

Weakest failure detector - W0

- W0 satisfies the properties of W, and no other properties
- W0 is necessary and sufficient for solving consensus in async systems

The Model

- Async model, reliable communication channels
- A process fails by stopping
- Once a process fails, it does not recover
- crashed() and correct() are the set of failed and active processes
- We assume that not all processes fail at the same time
- H(p, t) = the list of processes p thinks has failed at time t

Failure Detector (FD) Properties

- Strong Completeness: every crashed process is suspected by every correct process, eventually.
- Weak completeness: every crashed process is suspected by some correct process, eventually.
- Strong Accuracy: No process is suspected before it crashes
- Weak Accuracy: Some correct process is never suspected
- If we want strong/weak accuracy to only hold at some time points, we use eventual strong/weak accuracy: after some time point t, strong accuracy holds

Eventual Strong Accuracy

- Eventual Strong Accuracy. There is a time after which correct processes are not suspected by any correct process.
- Eventual Weak Accuracy. There is a time after which some correct process is never suspected by any correct process.

FD Classes

- Perfect (P): strong completeness + strong accuracy
-

Completeness	Accuracy			
	Strong	Weak	Eventual Strong	Eventual Weak
Strong	*Perfect* $\mathcal{P}$	*Strong* $\mathcal{S}$	*Eventually Perfect* $\diamond\mathcal{P}$	*Eventually Strong* $\diamond\mathcal{S}$
Weak	$\mathcal{Q}$	*Weak* $\mathcal{W}$	$\diamond\mathcal{Q}$	*Eventually Weak* $\diamond\mathcal{W}$

FIG. 1. Eight classes of failure detectors defined in terms of accuracy and completeness.

- We can transform a failure detector with weak completeness into one that satisfies strong completeness

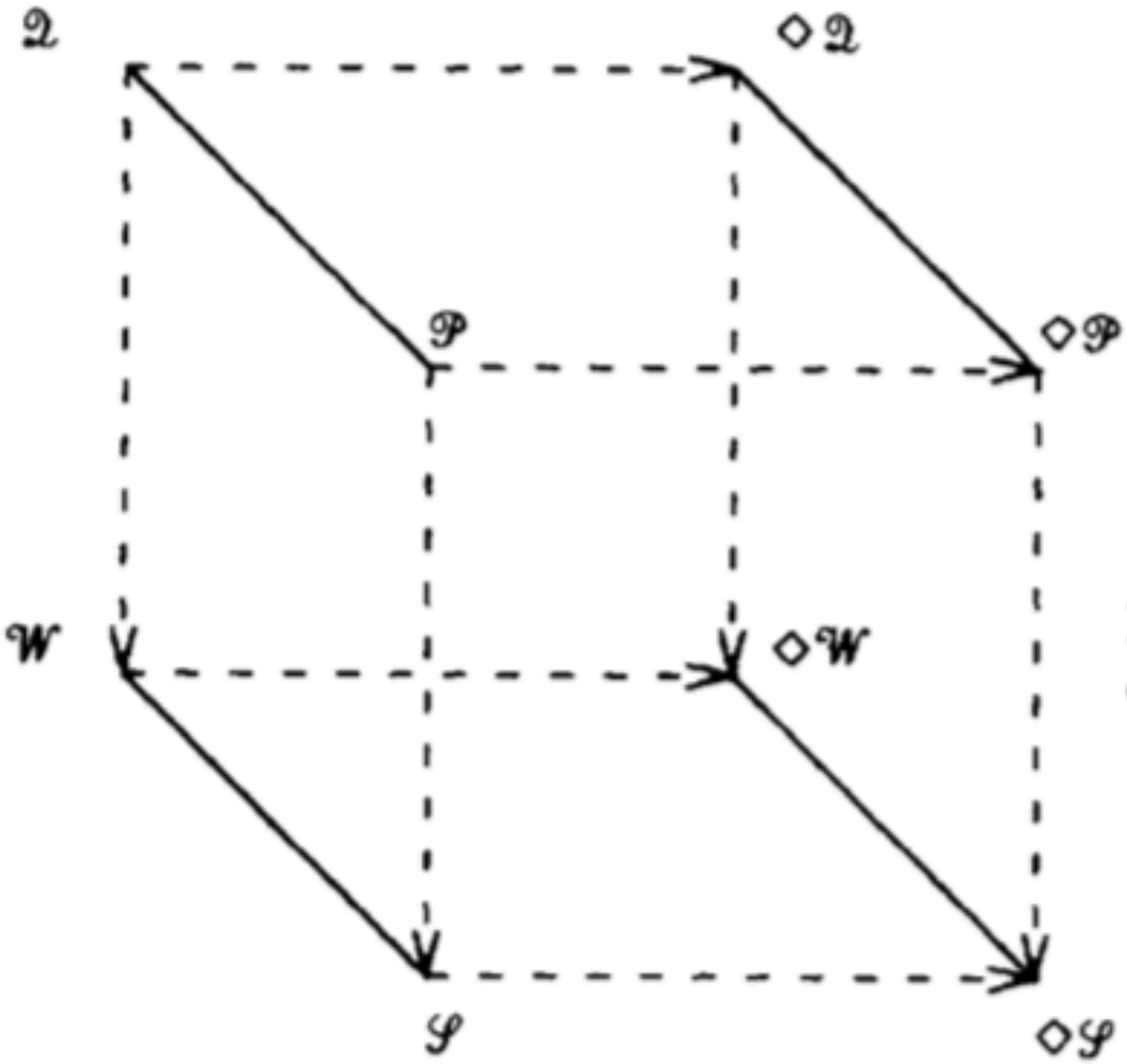

FIG. 8. Comparing the eight failure detector classes by reducibility.

C - - - -> C': C' is strictly weaker than C'

C ——— C': C is equivalent to C'

Transforming WC to SC

- WC: Some process suspects every crashed process
- SC: Every process suspects every crashed process
- Transformation algo:
  - Each process p broadcasts suspicion of crashed process q
  - On receiving a message from p about q:
    - Add q to suspects list
    - Remove p from suspects list

FD Classes

- Now we have only four classes, all with Strong C:
  - Perfect: Strong A
  - Strong: Weak A (poor naming)
  - Eventually Perfect: Eventually Strong A
  - Eventually Strong: Eventually Weak A

Reliable Broadcast

- Guarantees:
  - all correct processes deliver the same set of messages,
  - all messages broadcast by correct processes are delivered,
  - no spurious messages are ever delivered.
- Properties:
  - Validity. If a correct process R-broadcasts a message m, then it eventually R-delivers m.
  - Agreement. If a correct process R-delivers a message m, then all correct processes eventually R-deliver m.
  - Uniform integrity. For any message m, every process R-delivers m at most once, and only if m was previously R-broadcast by sender(m).

Reliable Broadcast

- R-broadcast (m):
  - Send m to all (including sender p)
- R-deliver (m):
  - If getting m for the first time:
    - If sender(m) != p then send m to all
    - Deliver(m)

Consensus

- All correct processes propose a value and must agree on a proposed value
- Termination. Every correct process eventually decides some value.
- Uniform integrity. Every process decides at most once.
- Agreement. No two correct processes decide differently.
- Uniform validity. If a process decides v, then v was proposed by some process.

Solving Consensus using Strong FD

- FD has strong completeness but weak accuracy
    - every crashed process is suspected by every correct process, eventually.
    - Some correct process is never suspected
-

Every process p executes the following:

```
procedure propose(v_p)
    V_p ← ⟨⊥, ⊥, ..., ⊥⟩                                        {p's estimate of the proposed values}
    V_p[p] ← v_p
    Δ_p ← V_p

    Phase 1: {asynchronous rounds r_p, 1 ≤ r_p ≤ n − 1}
             for r_p ← 1 to n − 1
                 send (r_p, Δ_p, p) to all
                 wait until [∀q : received (r_p, Δ_q, q) or q ∈ 𝒟_p]      {query the failure detector}
                 msgs_p[r_p] ← {(r_p, Δ_q, q) | received (r_p, Δ_q, q)}
                 Δ_p ← ⟨⊥, ⊥, ..., ⊥⟩
                 for k ← 1 to n
                     if V_p[k] = ⊥ and ∃(r_p, Δ_q, q) ∈ msgs_p[r_p] with Δ_q[k] ≠ ⊥ then
                         V_p[k] ← Δ_q[k]
                         Δ_p[k] ← Δ_q[k]

    Phase 2: send V_p to all
             wait until [∀q : received V_q or q ∈ 𝒟_p]                   {query the failure detector}
             lastmsgs_p ← {V_q | received V_q}
             for k ← 1 to n
                 if ∃V_q ∈ lastmsgs_p with V_q[k] = ⊥ then V_p[k] ← ⊥

    Phase 3: decide( first non-⊥ component of V_p)
```

FIG. 5. Solving Consensus using any $\mathcal{D} \in \mathcal{S}$.

Algo

- Phase 1:
  - processes execute n-1 async rounds
  - In each round, p broadcast their proposed values
  - In each around, p waits for all other processes not suspected to be crashed
- At the end of Phase 2, everyone agrees on a vector of proposed values
- Phase 3: decided based on first non-null component of vector

Results

- With Strong Failure Detector, we could solve consensus
    - Key is that one correct process is never suspected of being crashed
- We can also solve consensus with weaker failure detectors
    - A FD with weak completeness and eventual weak accuracy is the weakest FD that can be used
    - Weakest FD can solve consensus as long as less than half the processes are faulty

Why are failure detectors important?

- In previous algo, each process p waits for a message for all non-crashed processs
- The failure detector helps identify this set
- Without FD, process p may block forever waiting for process q
- Strong completeness of FD ensures that every crashed process is suspected eventually -> this eliminates the endless waiting