Distributed Systems

CS425/ECE428

02/12/2020

Today's agenda

- Finally wrap-up global snapshots
  - Chapter 14.5
- Multicast
  - Chapter 15.4

Recap: Global snapshot

- State of each process (and each channel) in the system at a given instant of time.
- Useful to capture a global snapshot of the system:
  - Checkpointing, distributed debugging, deadlock detection, garbage collection, etc.
- Difficult to capture global state at same instant of time.
- Capture consistent global state.
  - If captured state includes an event **e**, it includes all other events that *happened before* **e**.
- Chandy-Lamport algorithm captures consistent global state.

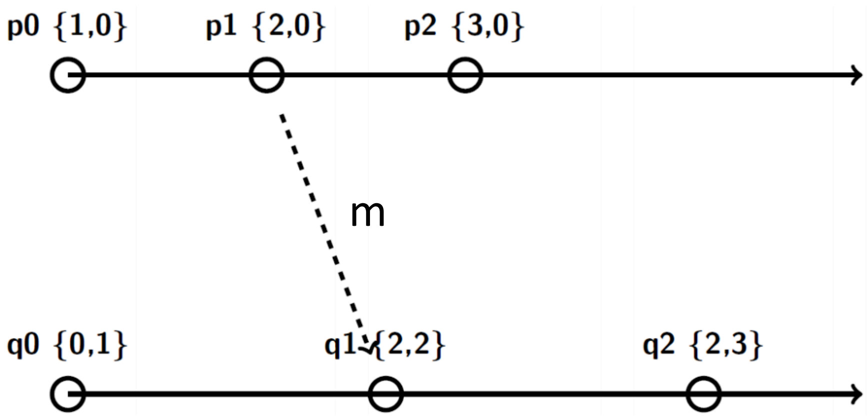
Chandy-Lamport Algorithm: Usefulness

- Consistent global snapshots are useful for detecting global system properties:
  - Safety
  - Liveness

More notations and definitions

- Run
  - a total ordering of events that is consistent with the event ordering at each process.
- Linearization
  - a run consistent with happens-before ($\rightarrow$) relation.
- Linearizations pass through consistent global states.
- A global state $\mathbf{S_k}$ is reachable from global state $\mathbf{S_i}$, if there is a linearization that passes through $\mathbf{S_i}$ and then through $\mathbf{S_k}$.
- The distributed system evolves as a series of transitions between global states S_0 , S_1 , ….

State Transitions: Example



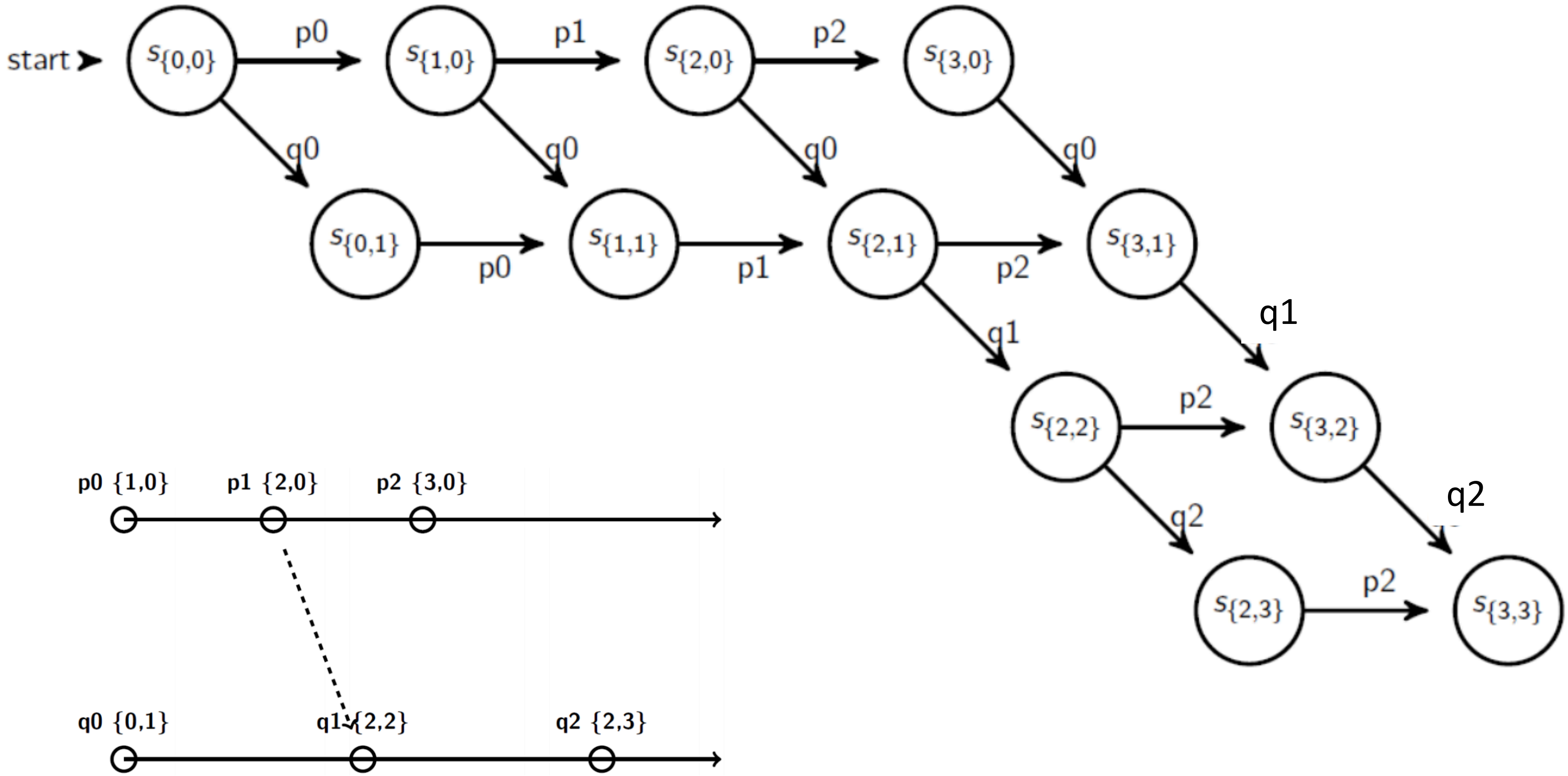
- Causal order:
  - p0 → p1 → p2
  - q0 → q1 → q2
  - p0 → p1 → q1 → q2
- Concurrent:
  - p0 || q0
  - p1 || q0
  - p2 || q0, p2 || q1, p2 || q2

Many linearizations:

- < p0, p1, p2, q0, q1, q2>
- < p0, q0, p1, q1, p2, q2>
- <q0, p0, p1, q1, p2, q2 >
- <q0, p0, p1, p2, q1,q2 >
- ……

State Transitions: Example

Execution Lattice. Each path is a linear execution of events.



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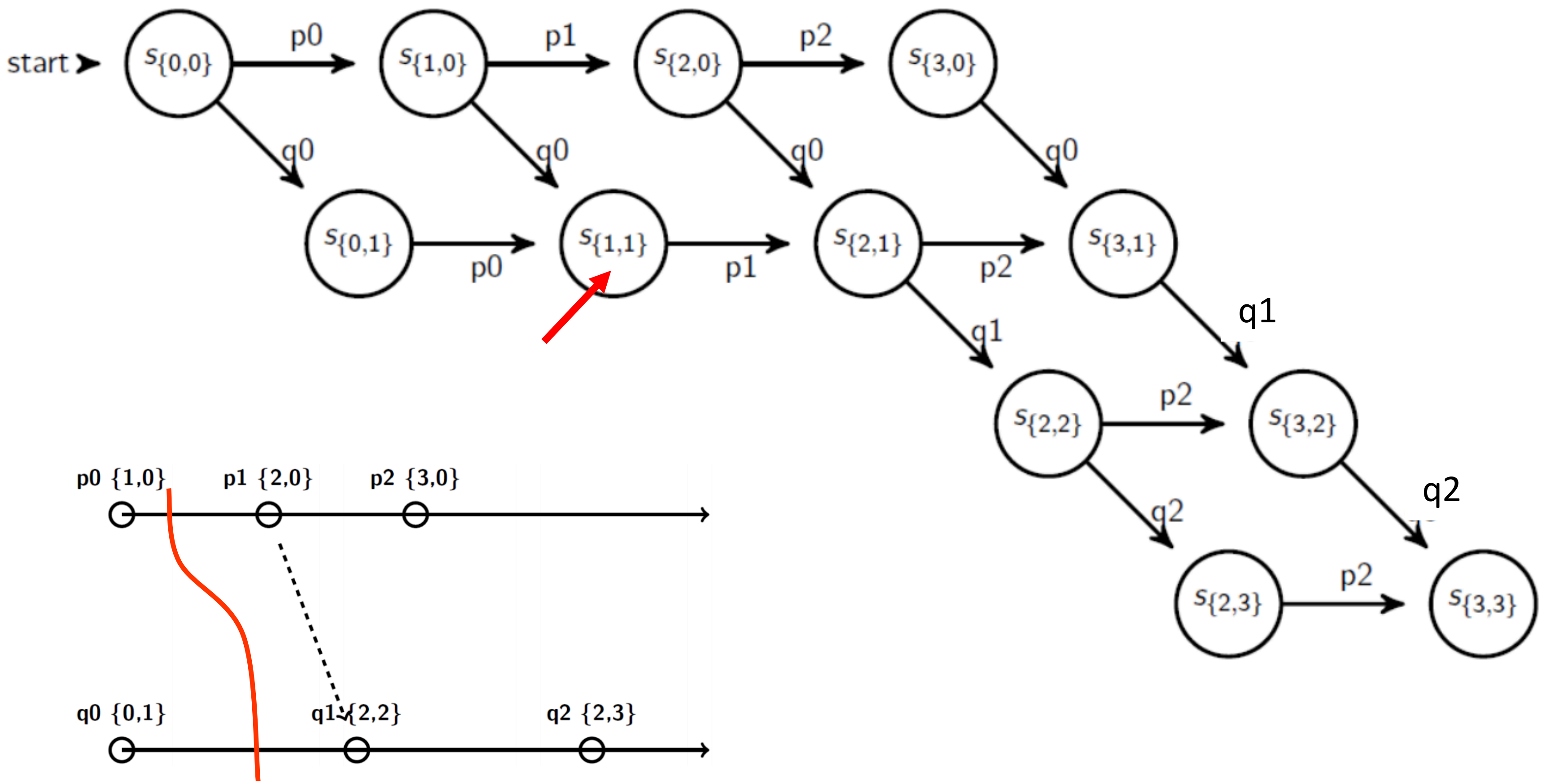

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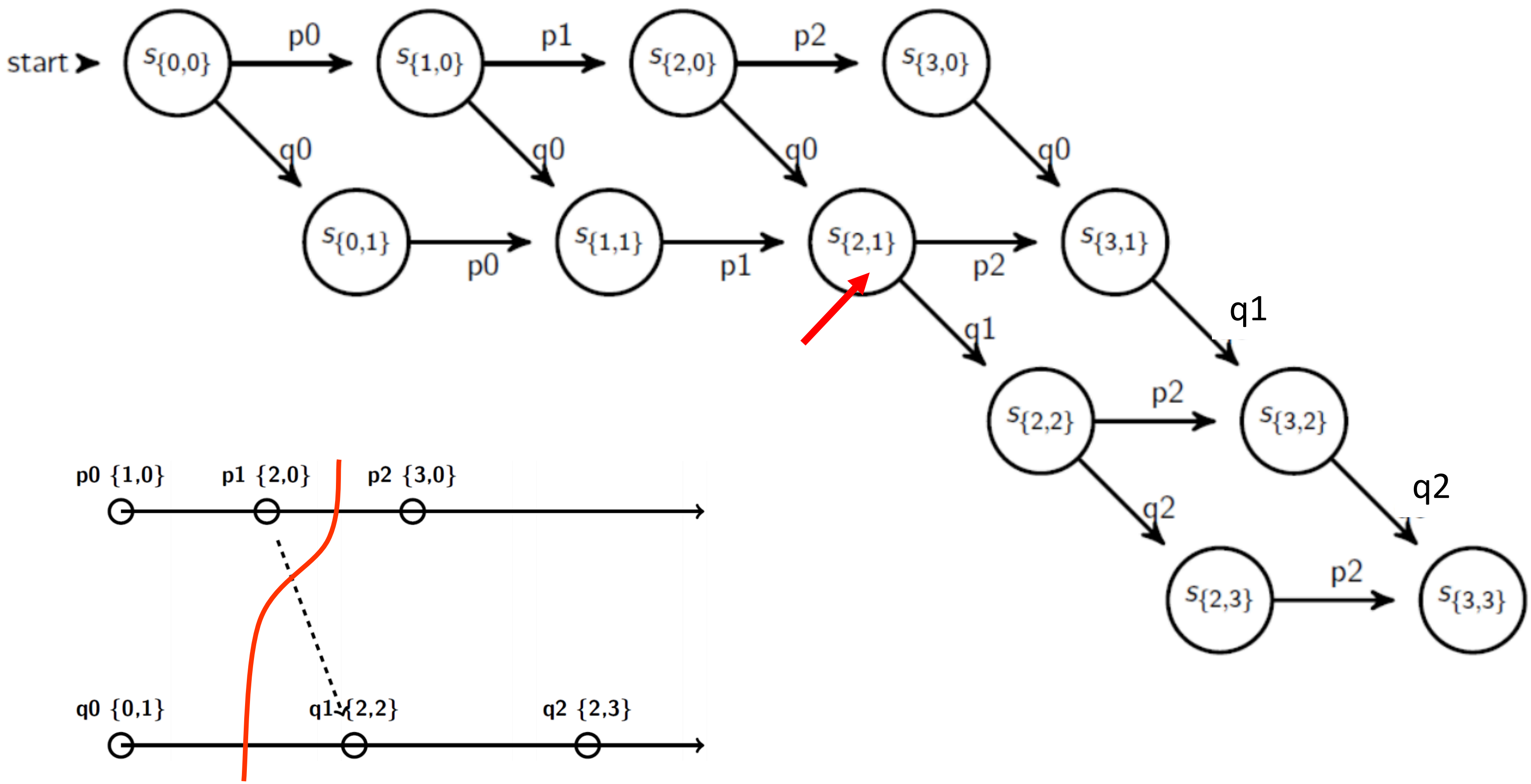

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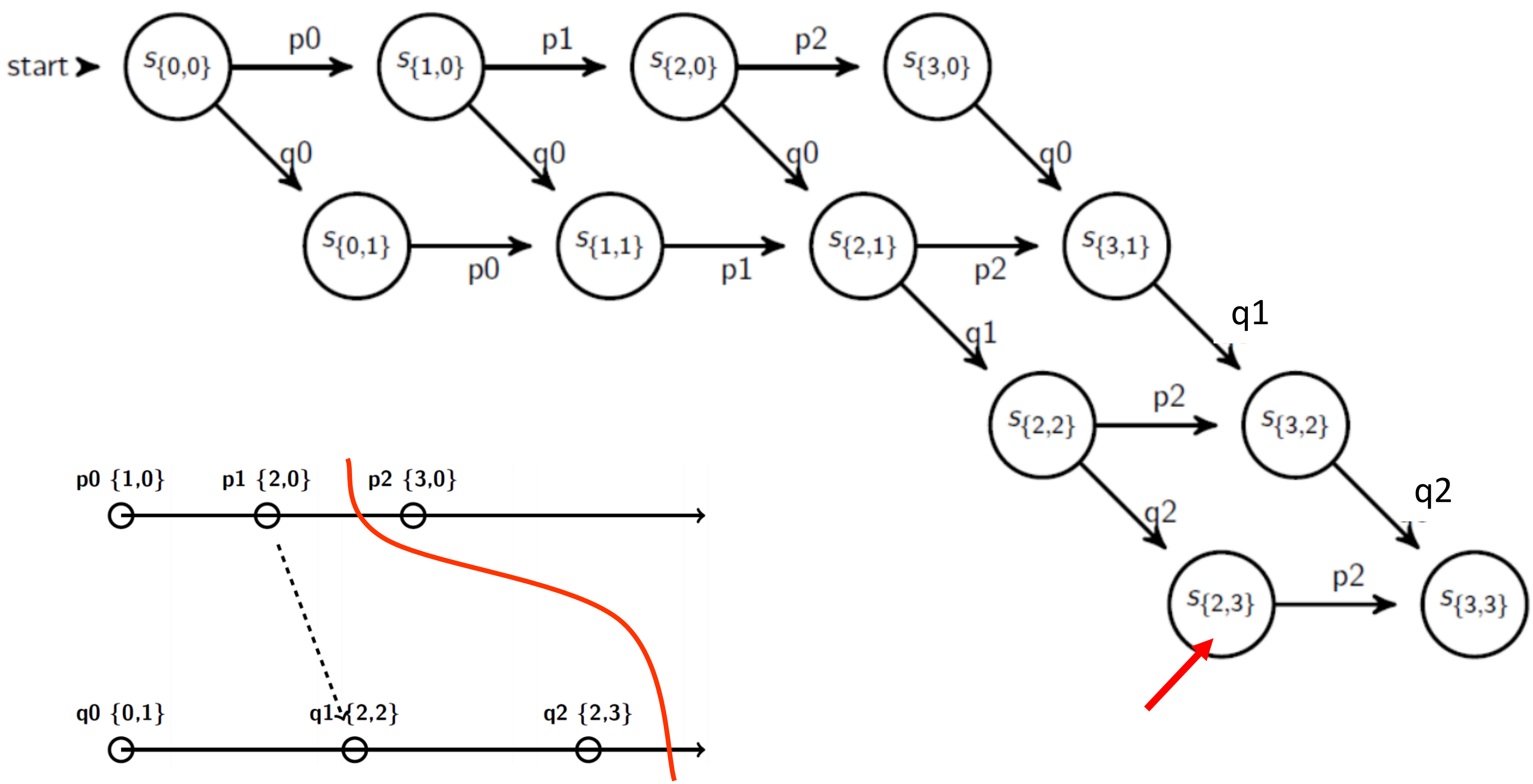
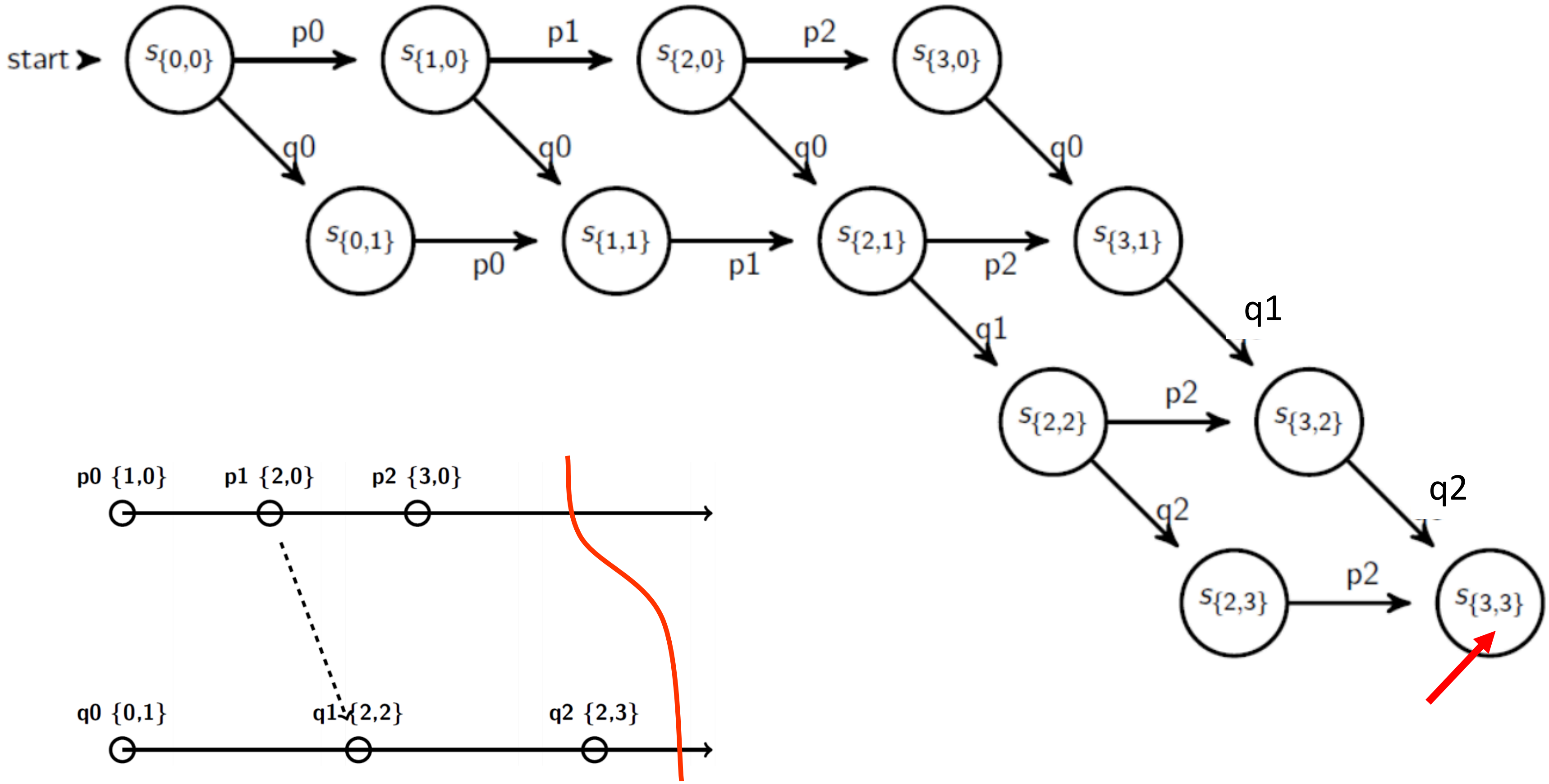


State Transitions: Example



Global State Predicates

- A global-state-predicate is a property that is *true* or *false* for a global state.
  - Is there a deadlock?
  - Has the distributed algorithm terminated?
- Two ways of reasoning about predicates (or system properties) as global state gets transformed by events.
  - Liveness
  - Safety

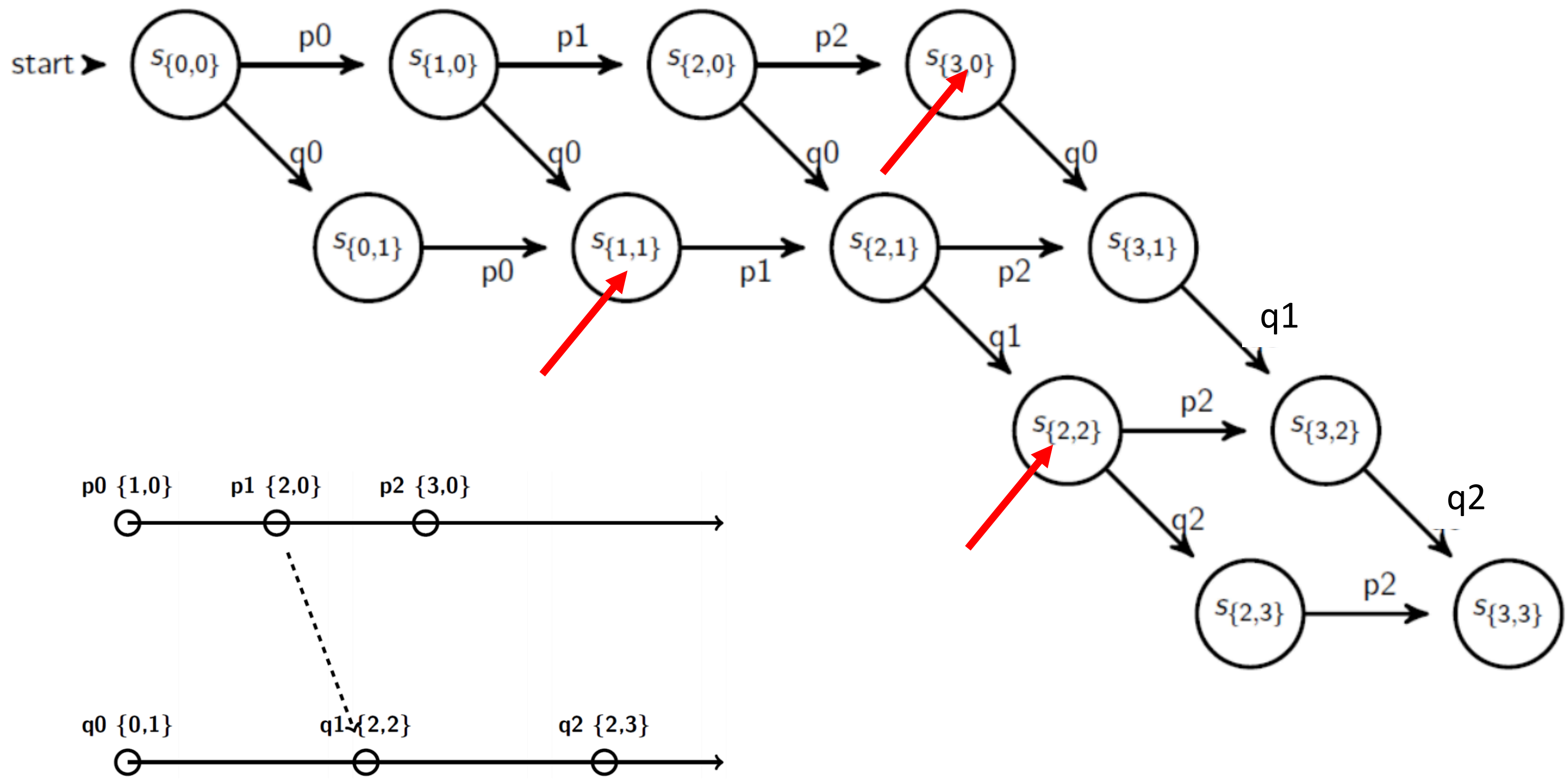
Liveness

- **Liveness = guarantee that something good will happen, eventually**
- **Examples:**
  - Guarantee that a distributed computation will terminate.
  - "Completeness" in failure detectors.
  - All processes eventually decide on a value.
- A global state S_0 satisfies a **liveness** property P iff:
  - $liveness(P(S_0)) \equiv \forall L \in$ linearizations from S_0, L passes through a S_L & $P(S_L)$ = true
  - For any linearization starting from S_0, P is true for some state S_L reachable from S_0.

Liveness Example

If predicate is true only in the marked states, does it satisfy liveness?

No



Liveness Example

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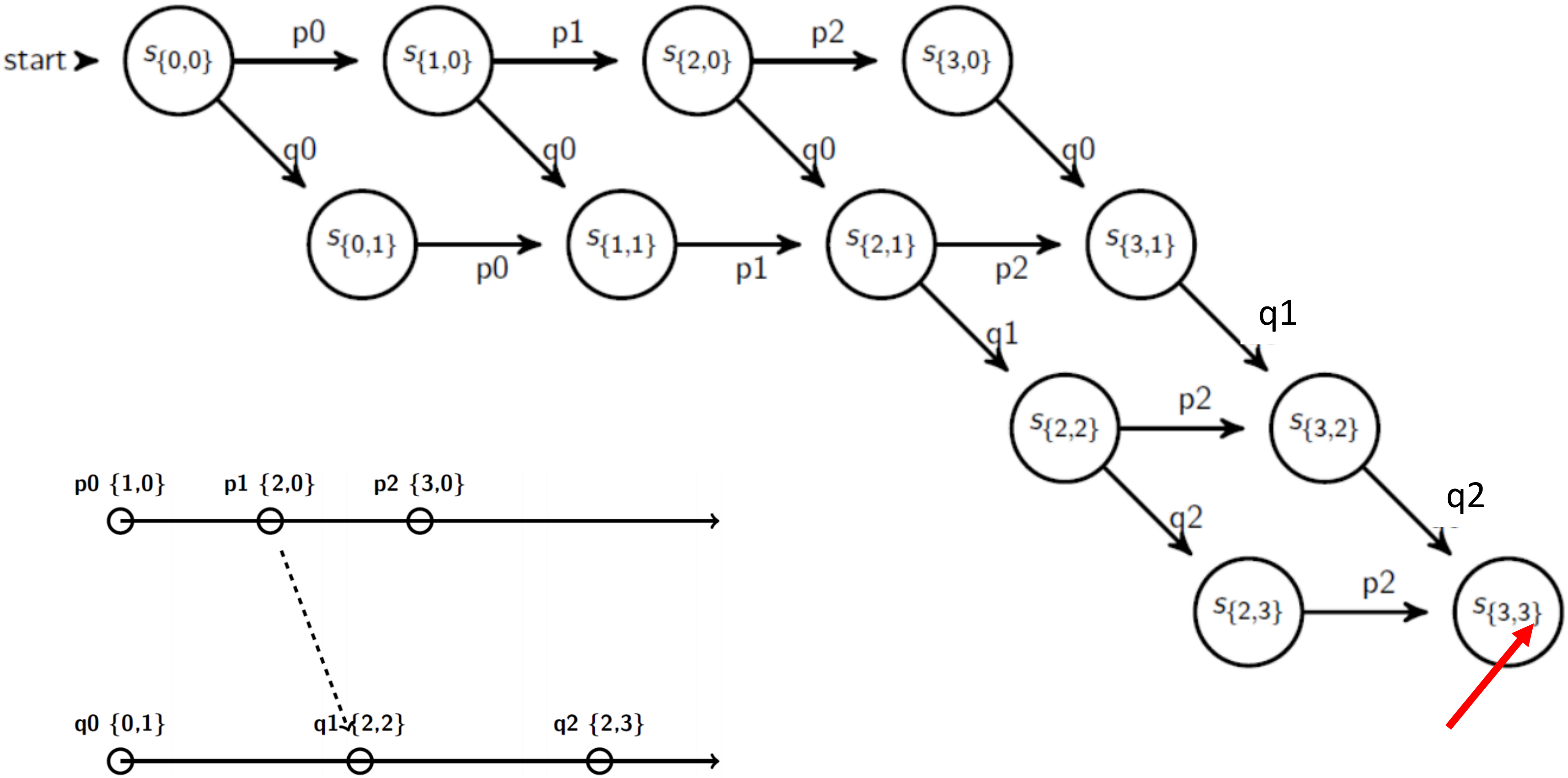

Safety

- **Safety = guarantee that something bad will never happen.**
- **Examples:**
  - There is no deadlock in a distributed transaction system.
  - "Accuracy" in failure detectors.
  - No two processes decide on different values.
- A global state S_0 satisfies a **safety** property P iff:
  - $safety(P(S_0)) \equiv \forall S$ reachable from S_0, $P(S) = true$.
  - For all states S reachable from S_0, P(S) is true.

Safety Example

If predicate is true only in the marked states, does it satisfy safety?

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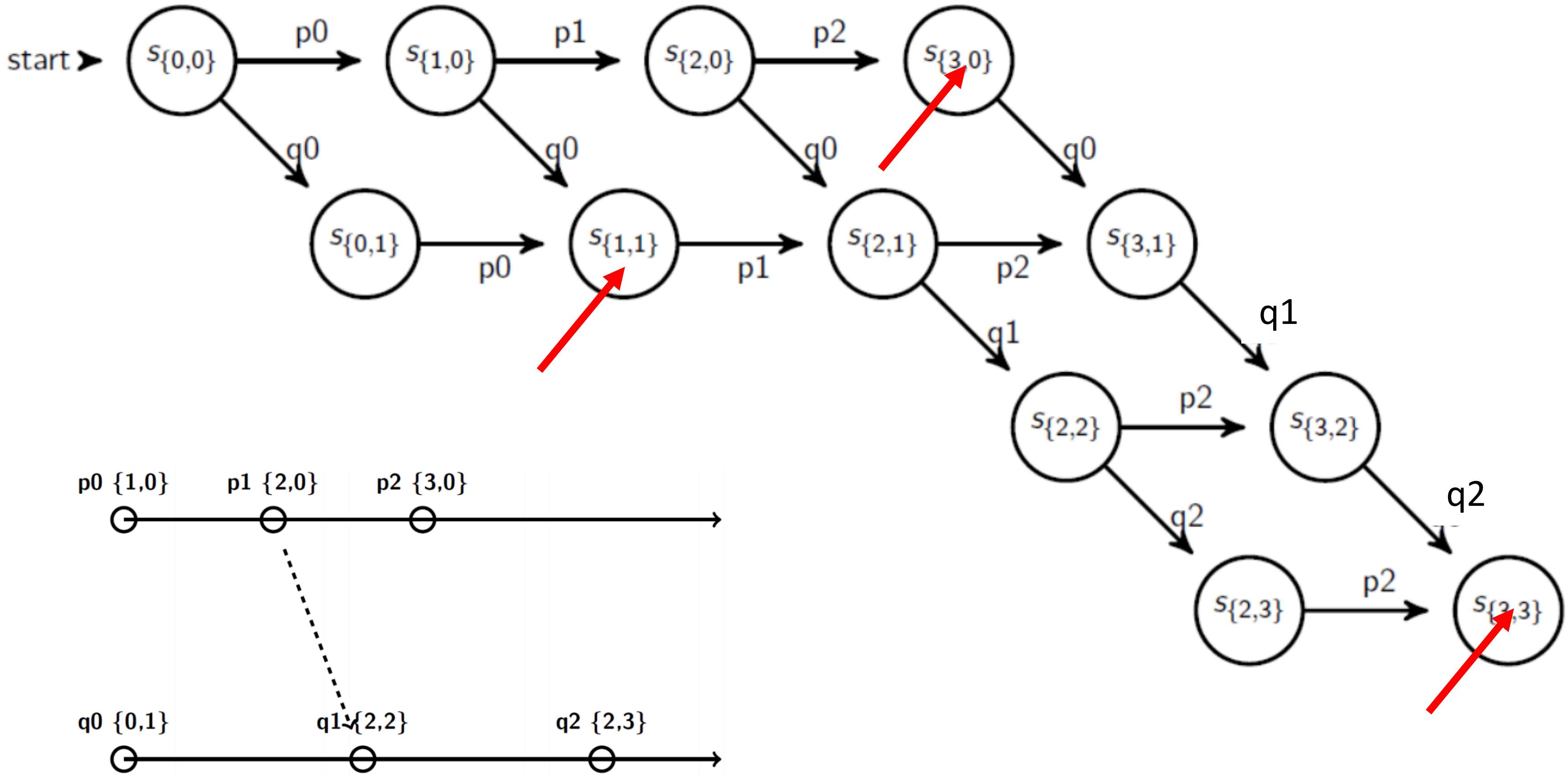
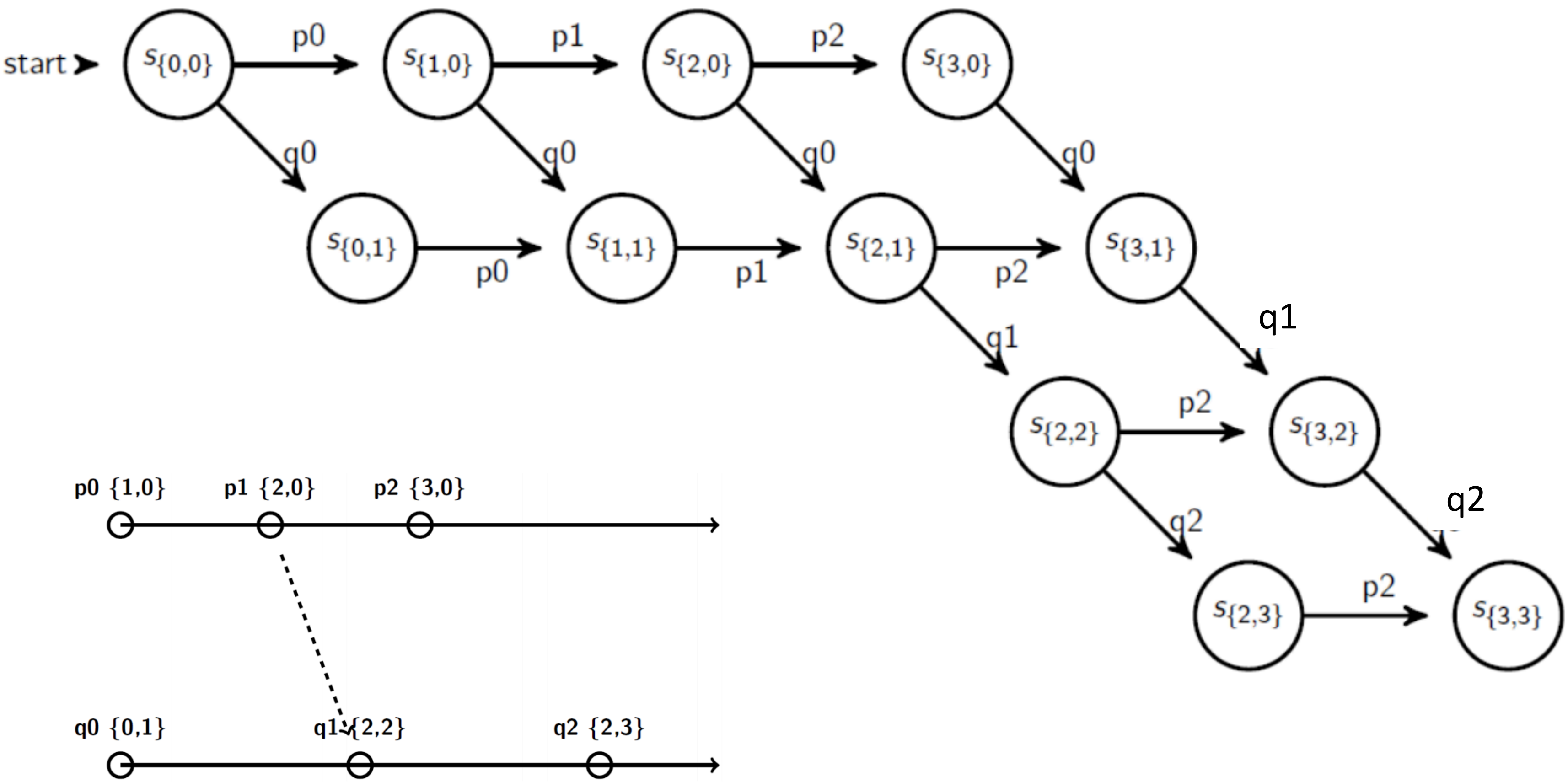


Safety Example

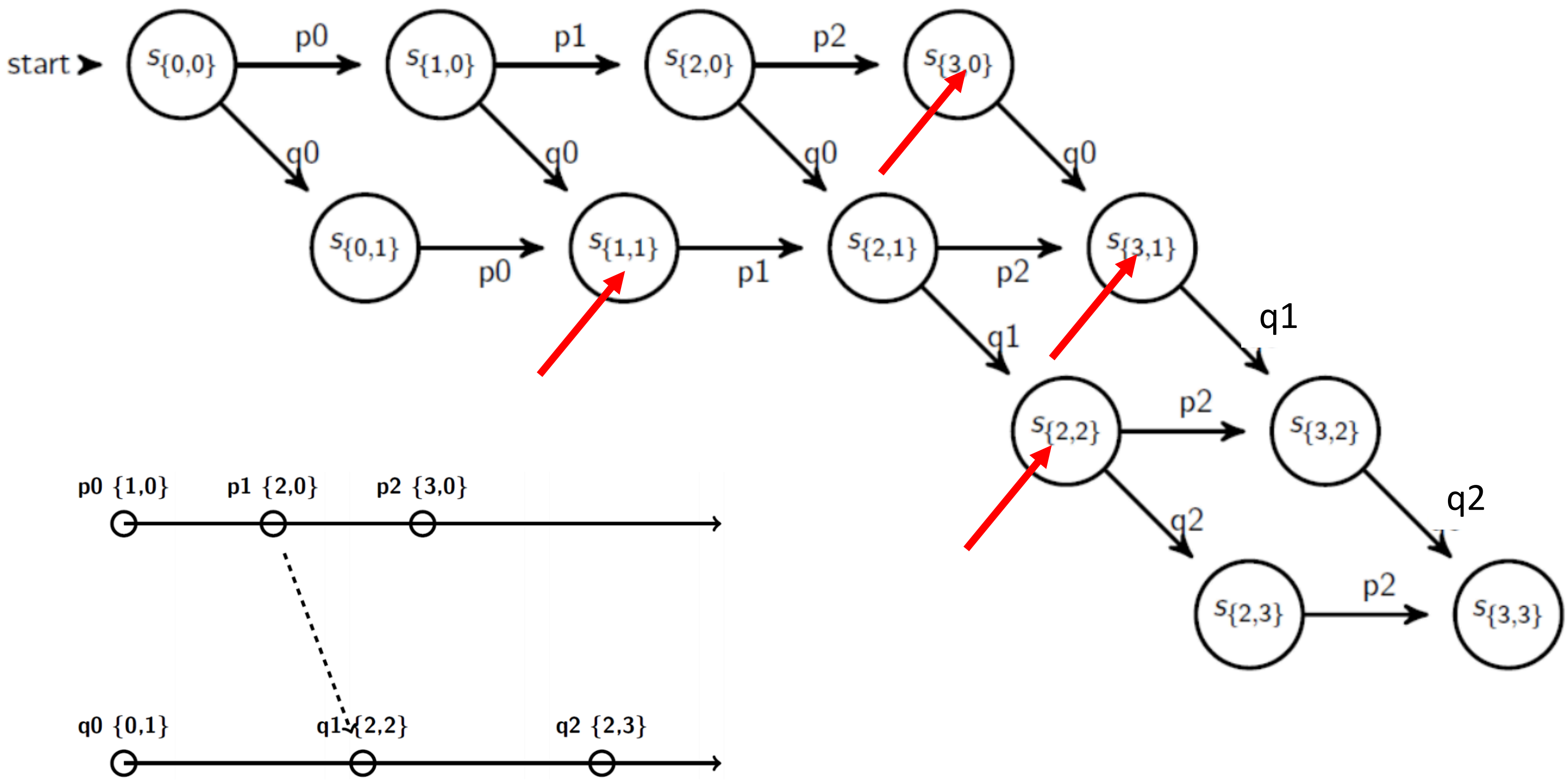
If predicate is true only in the **unmarked** states, does it satisfy safety?

Yes



Liveness Example

Technically satisfies liveness, but difficult to capture or reason about.



Stable Global Predicates

- Stable = once true, stays true forever afterwards

Stable Global Predicates

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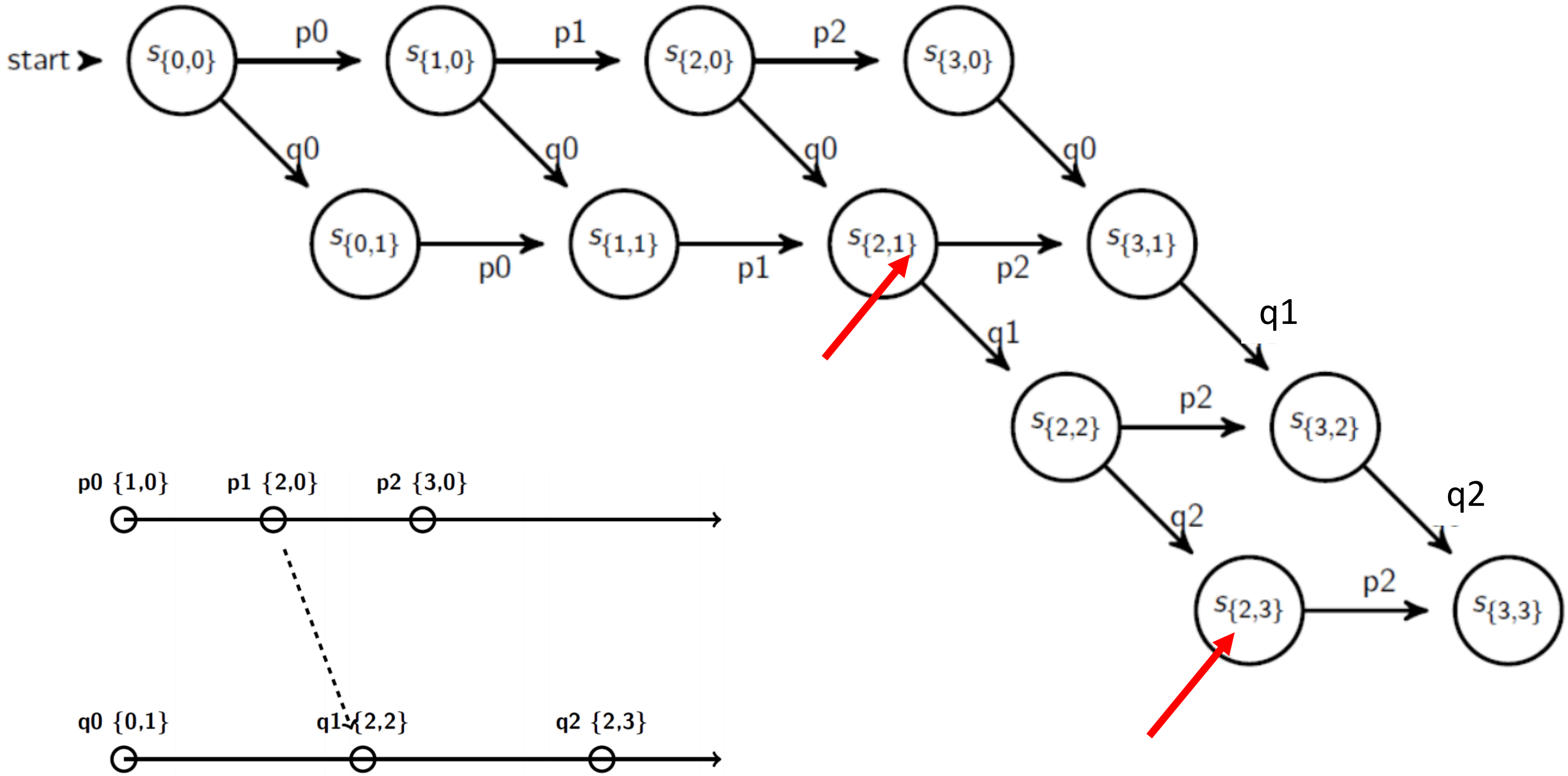
No



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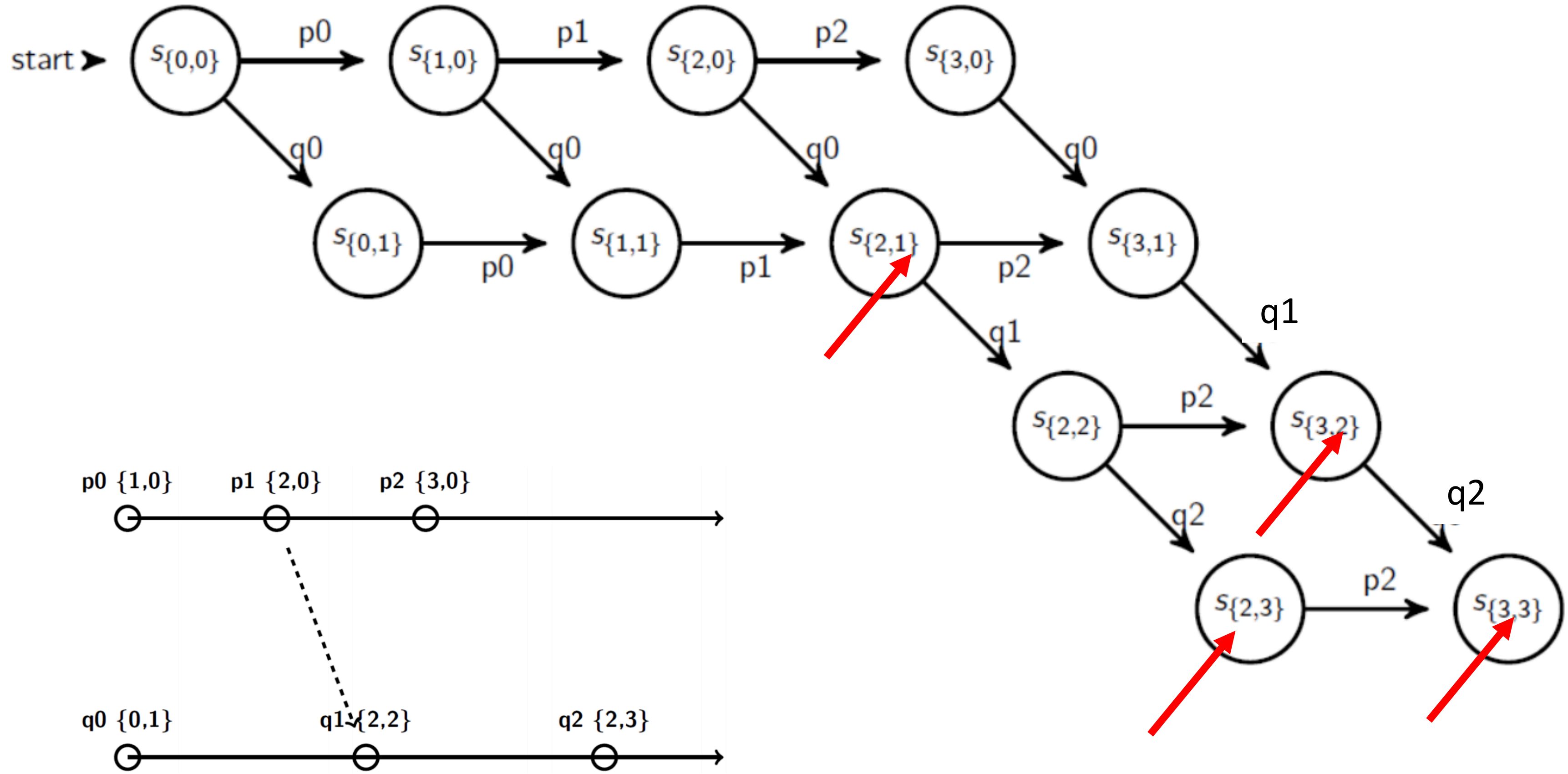

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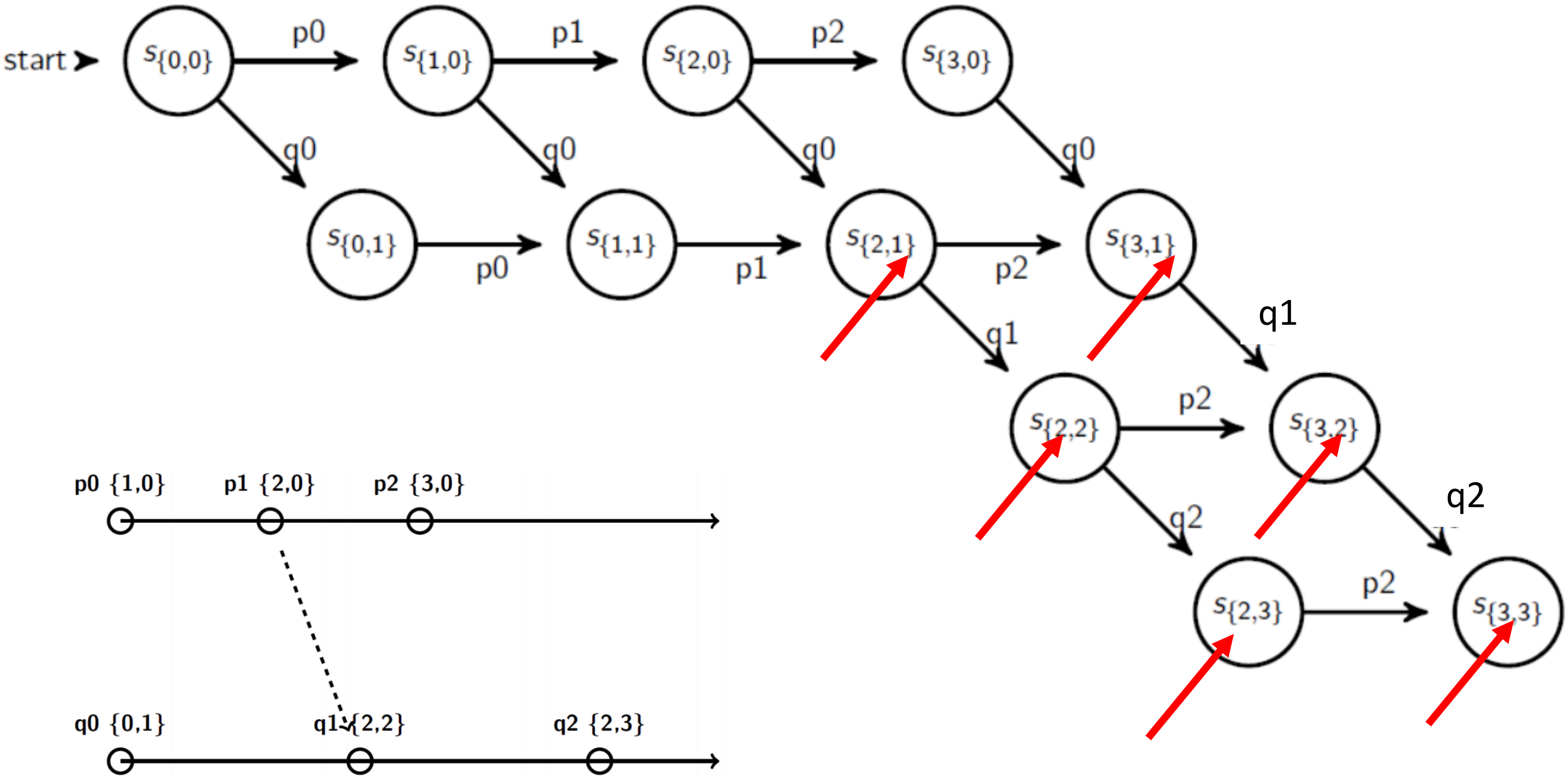


Stable Global Predicates

- Stable = once true, stays true forever afterwards
- Stable liveness examples
  - Computation has terminated.
- Stable non-safety examples
  - There is a deadlock.
  - An object is orphaned (no pointers point to it).
- *All stable global properties can be detected using the Chandy-Lamport algorithm.*

Global Snapshot Summary

- The ability to calculate global snapshots in a distributed system is very important.
- But don't want to interrupt running distributed application.
- Chandy-Lamport algorithm calculates global snapshot.
- Obeys causality (creates a consistent cut).
- Can be used to detect stable global properties.
- Safety vs. Liveness.

Today's agenda

- Wrap-up global states and snapshots
  - Chapter 14.5
- Multicast
  - Chapter 15.4

Communication modes

- **Unicast**
  - Messages are sent from exactly one process to one process.
- **Broadcast**
  - Messages are sent from exactly one process to all processes on the network.
- **Multicast**
  - Messages broadcast within a group of processes.
  - A multicast message is sent from any one process to the group of processes on the network.

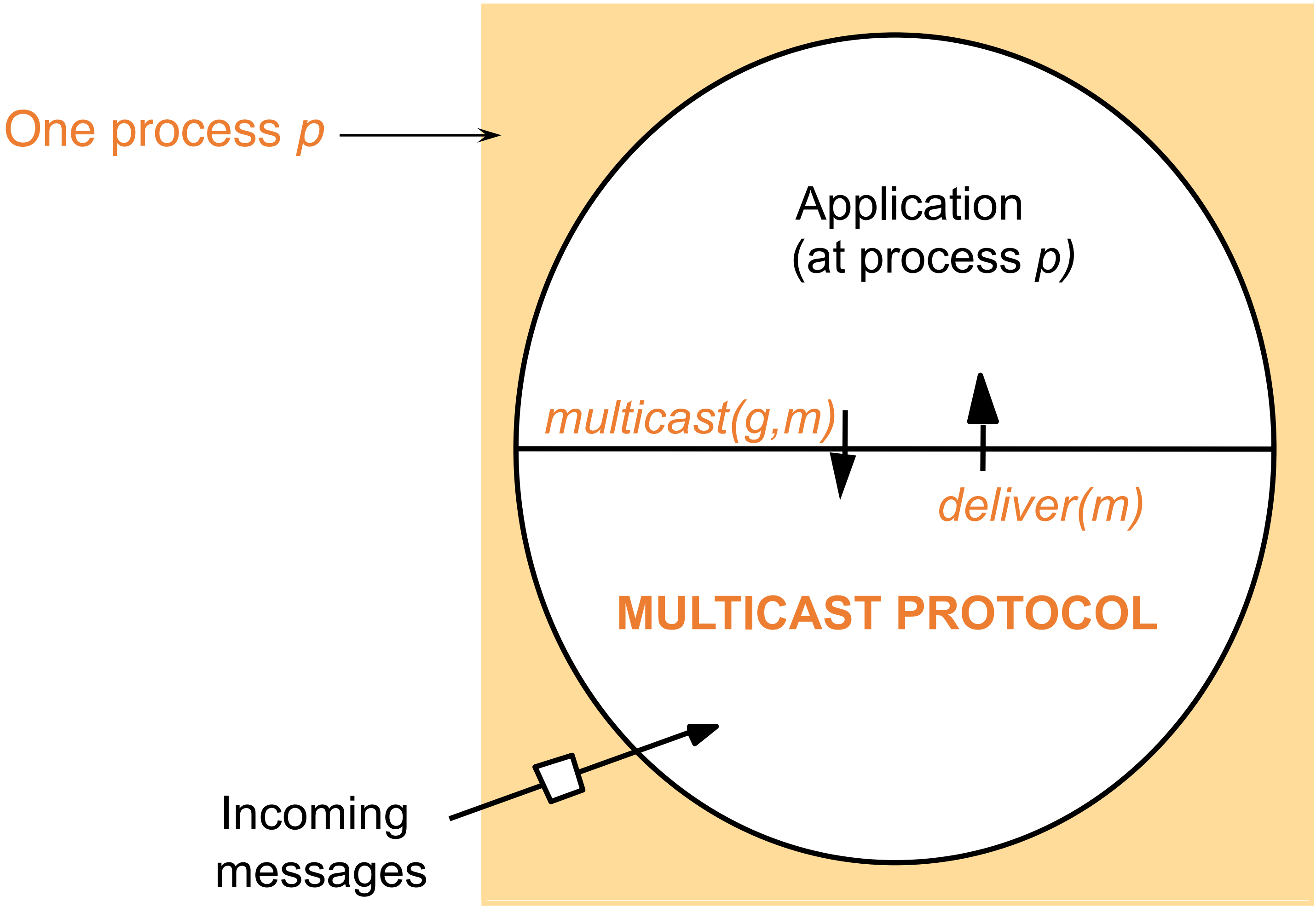
Where is multicast used?

- Distributed storage
  - Write to an object are multicast across replica servers.
  - Membership information (e.g., heartbeats) is multicast across all servers in cluster.
- Online scoreboards (ESPN, French Open, FIFA World Cup)
  - Multicast to group of clients interested in the scores.
- Stock Exchanges
  - Group is the set of broker computers.
- ……

Communication modes

- **Unicast**
  - Messages are sent from exactly one process to one process.
    - *Best effort:* if a message is delivered it would be intact; no reliability guarantees.
    - *Reliable:* guarantees delivery of messages.
    - *In order:* messages will be delivered in the same order that they are sent.
- **Broadcast**
  - Messages are sent from exactly one process to all processes on the network.
- **Multicast**
  - Messages broadcast within a group of processes.
  - A multicast message is sent from any one process to the group of processes on the network.
  - *How do we define (and achieve) reliable or ordered multicast?*

What we are designing in this class?



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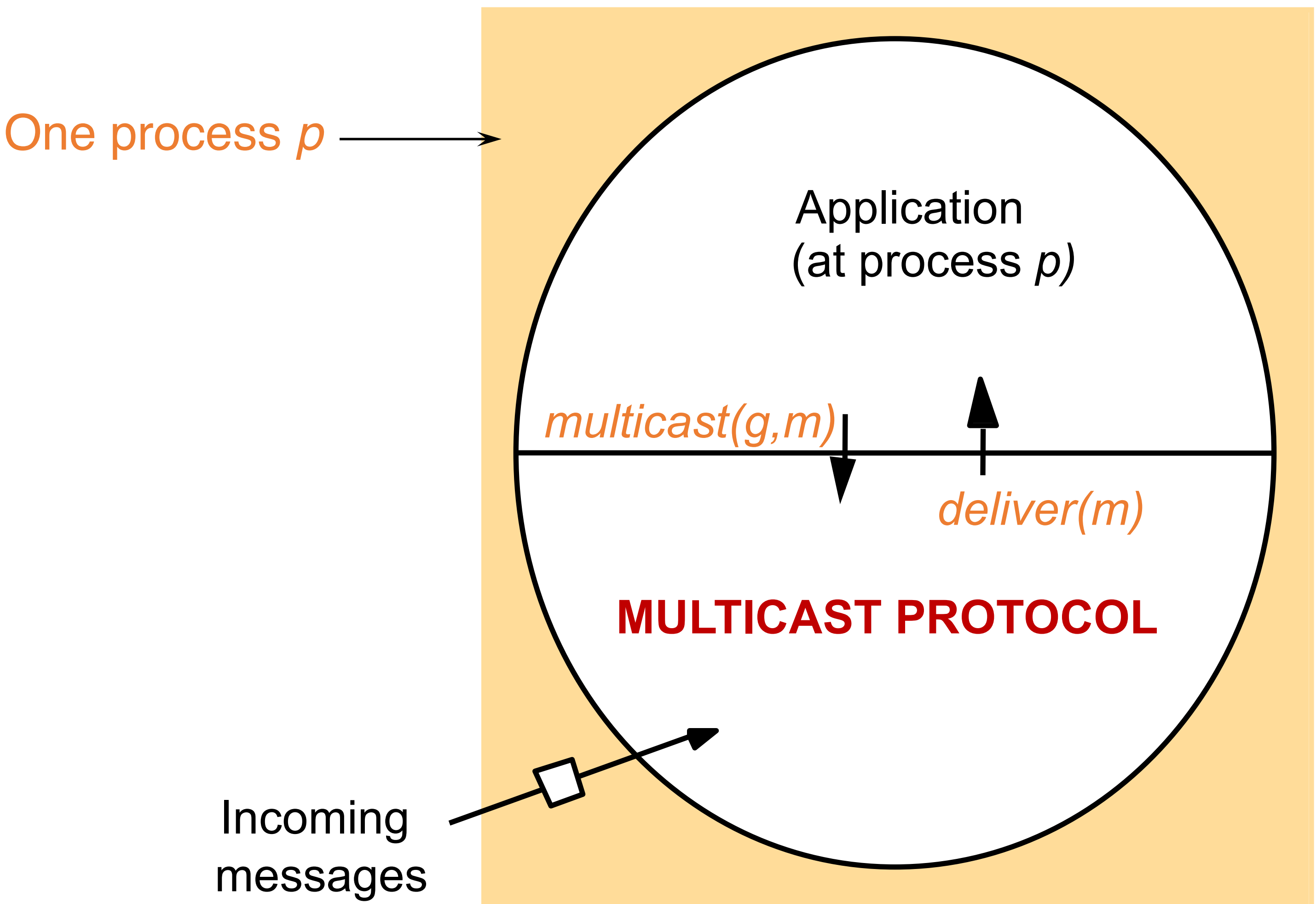


Basic Multicast (B-Multicast)

- Straightforward way to implement B-multicast:
  - use a reliable one-to-one send (unicast) operation:

    B-multicast(group g, message m):

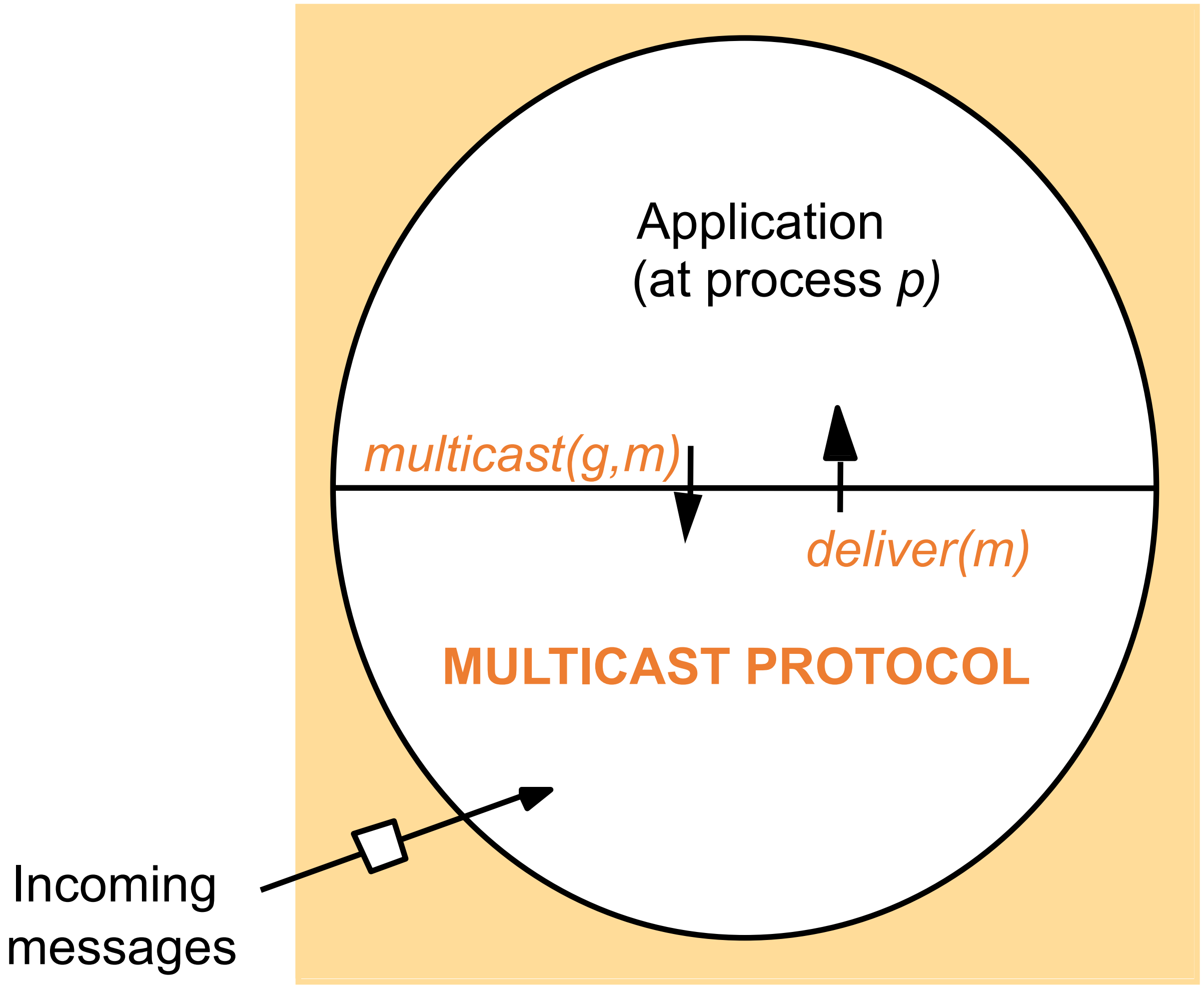
    for each process p in g, send (p,m).

    receive(m): B-deliver(m) at p.
- Guarantees: message is eventually delivered to the group if:
  - Processes are non-faulty.
  - The unicast "send" is reliable.
  - *Sender does not crash.*
- *Can we provide reliable delivery even after sender crashes?*

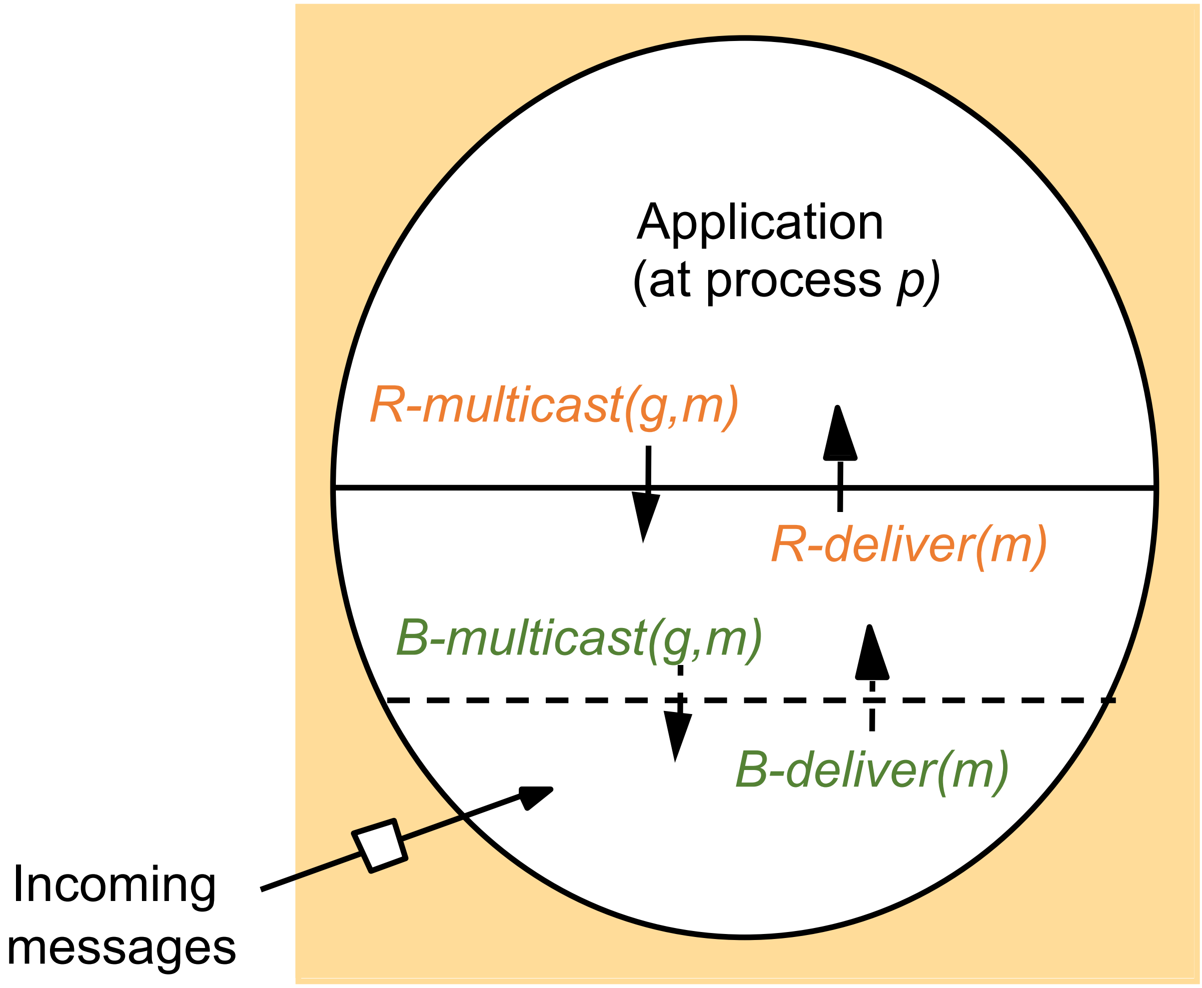
Reliable Multicast (R-Multicast)

- **Integrity**: A *correct* (i.e., non-faulty) process *p* delivers a message *m* at most once.
  - *Assumption: no process sends **exactly** the same message twice*
- **Validity**: If a *correct* process multicasts (sends) message *m*, then it will eventually deliver *m* itself.
  - *Liveness for the sender.*
- **Agreement**: If a *correct* process delivers message *m*, then all the other *correct* processes in group(*m*) will eventually deliver *m*.
  - *All or nothing.*
- Validity and agreement together ensure overall liveness: if some correct process multicasts a message *m*, then, all correct processes deliver *m* too.

Implementing R-Multicast



Implementing R-Multicast



Implementing R-Multicast

On initialization

    Received := {};

For process p to R-multicast message m to group g

    B-multicast(g,m); ($p \in g$ is included as destination)

On B-deliver(m) at process q with g = group(m)

    if ($m \notin$ Received):

        Received := Received $\cup$ {m};

        if ($q \neq p$): B-multicast(g,m);

        R-deliver(m)

Reliable Multicast (R-Multicast)

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Ordered Multicast

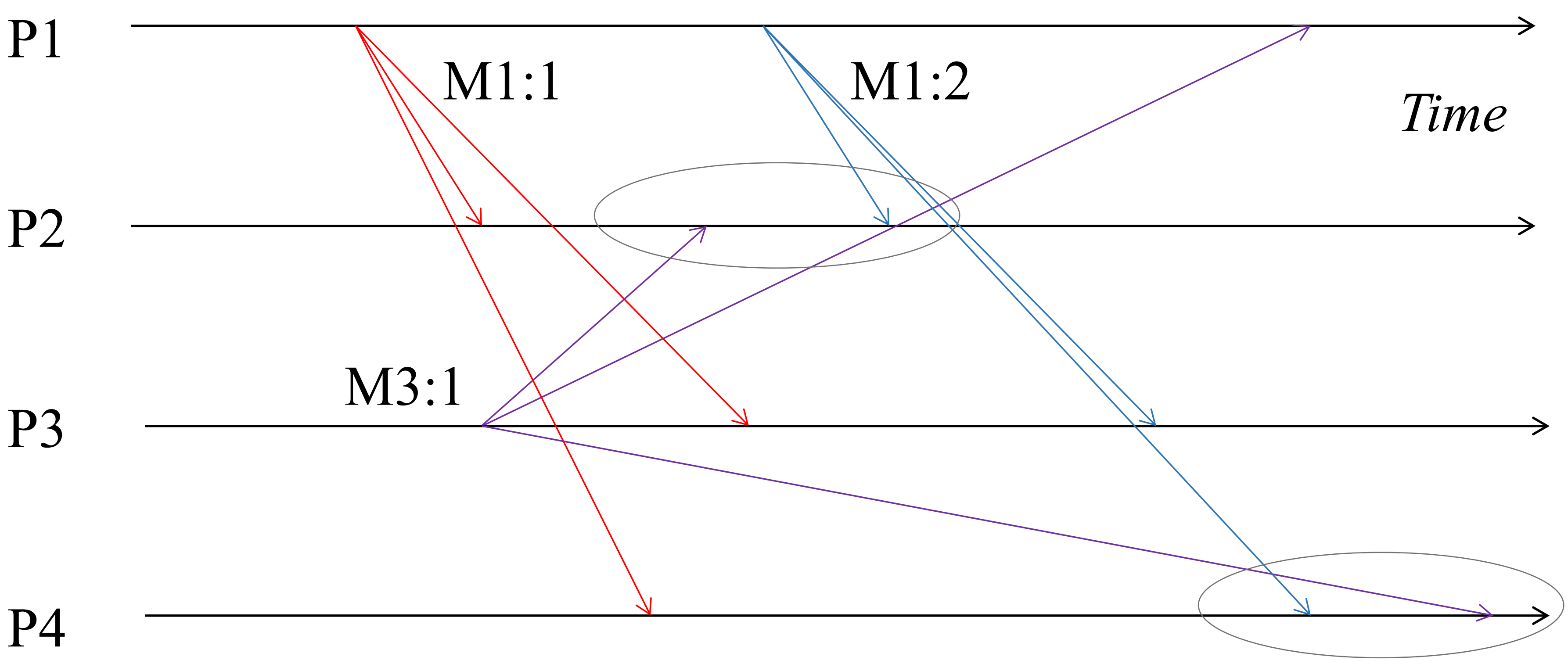
- Three popular flavors implemented by several multicast protocols:
  1. FIFO ordering
  2. Causal ordering
  3. Total ordering

1. FIFO Order

- Multicasts from each sender are delivered in the order they are sent, at all receivers.
- Don't care about multicasts from different senders.

- More formally
    - *If a correct process issues multicast(g,m) and then multicast(g,m'), then every correct process that delivers m' will have already delivered m.*

FIFO Order: Example



M1:1 and M1:2 should be delivered in that order at each receiver.

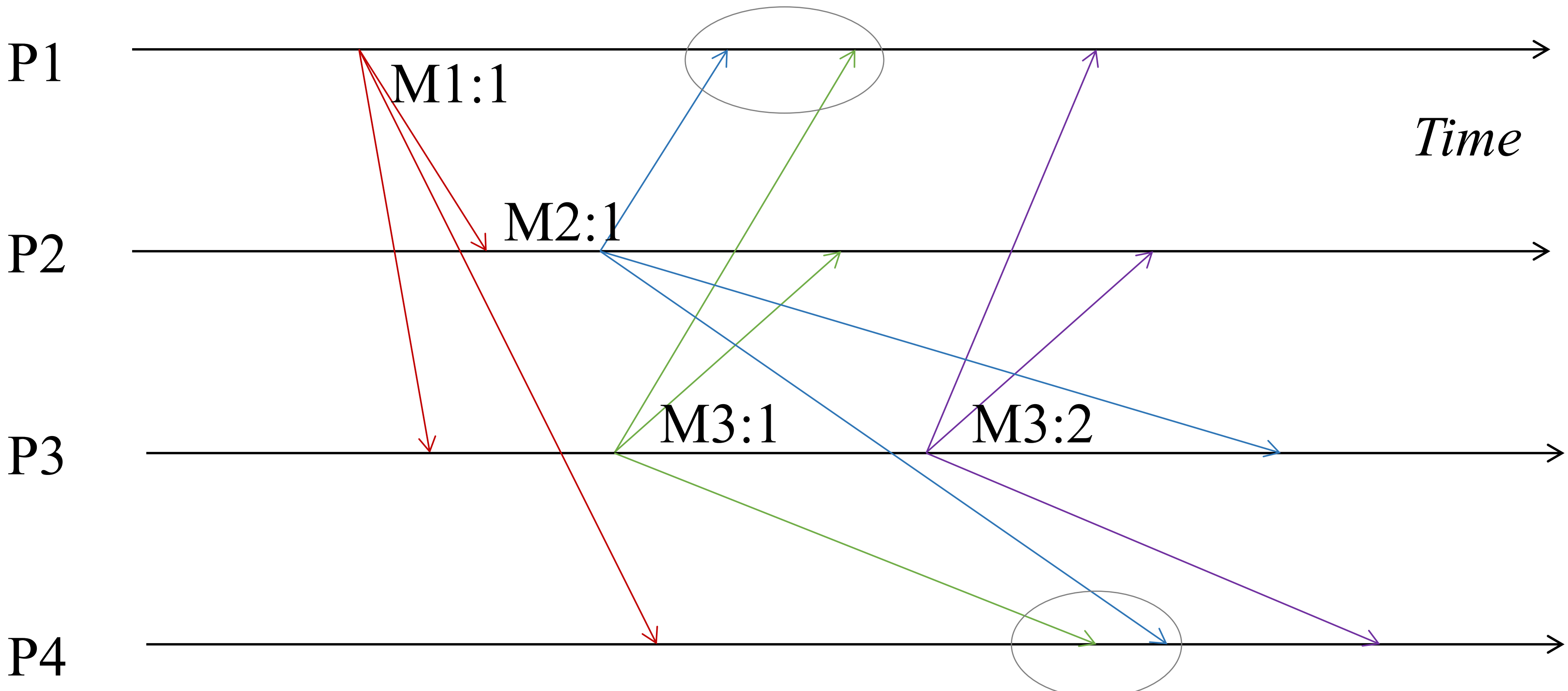
Order of delivery of M3:1 and M1:2 could be different at different receivers.

2. Causal Order

- Multicasts whose send events are causally related, must be delivered in the same causality-obeying order at all receivers.

- More formally
  - *If multicast(g,m) → multicast(g,m') then any correct process that delivers m' will have already delivered m.*
  - *(→ is Lamport's happens-before)*
  - (→ counts messages **delivered** to the application, rather than all network messages)

Causal Order: Example



M3:1 → M3:2, M1:1 → M3:1, M1:1 → M2:1, and so should be delivered in that order at each receiver.

M3:1 and M2:1 are concurrent and thus ok to be delivered in different orders at different receivers.

Causal vs FIFO

- Causal Ordering => FIFO Ordering

- Why?
  - If two multicasts M and M' are sent by the same process P, and M was sent before M', then M → M'.
  - Then a multicast protocol that implements causal ordering will obey FIFO ordering since M → M'.

- Reverse is not true! FIFO ordering does not imply causal ordering.

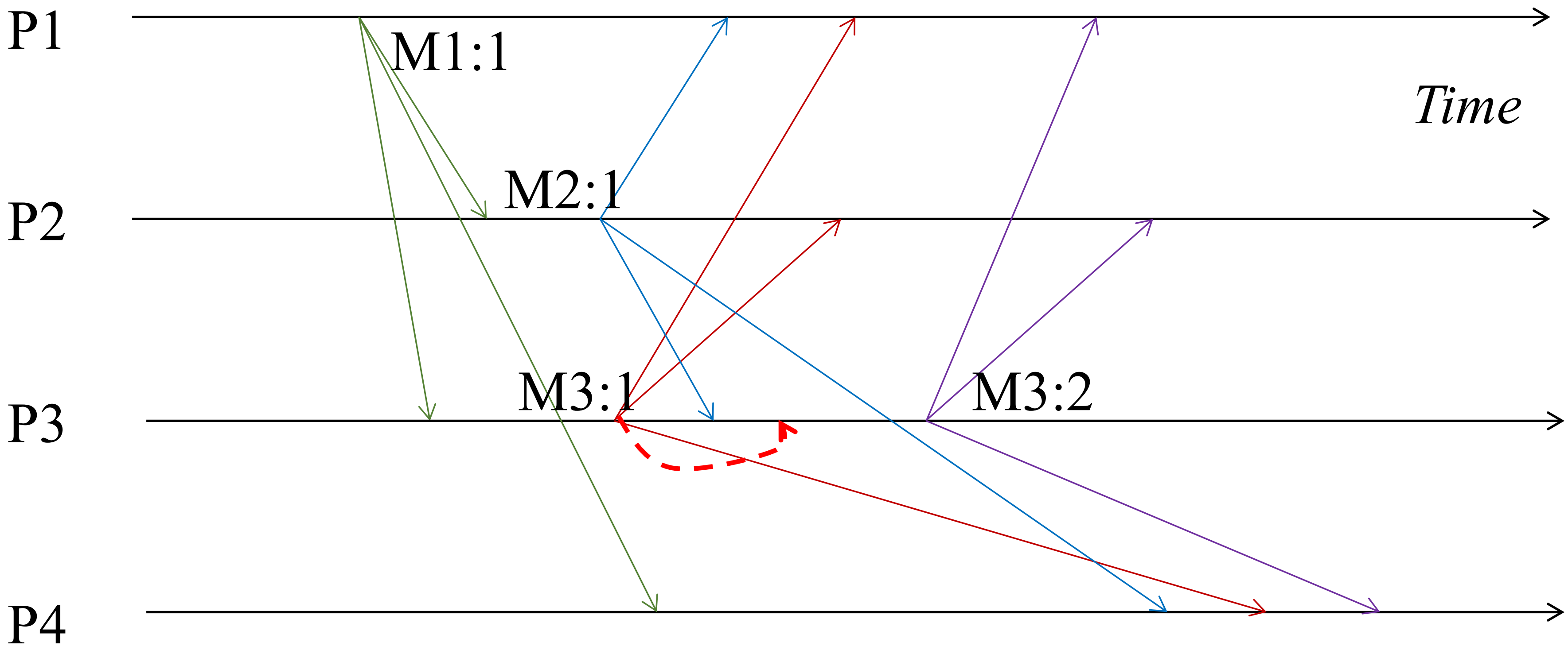
Where is causal ordering useful?

- Group = set of your friends on a social network.
- A friend sees your message *m*, and she posts a response (comment) *m'* to it.
  - If friends receive *m'* before *m*, it wouldn't make sense
  - But if two friends post messages m'' and n'' concurrently, then they can be seen in any order at receivers.
- A variety of systems implement causal ordering:
  - social networks, bulletin boards, comments on websites, etc.

3. Total Order

- Ensures all processes deliver all multicasts in the same order.
- Unlike FIFO and causal, this does not pay attention to order of multicast sending.
- Formally
  - If a correct process delivers message *m* before *m'* (independent of the senders), then any other correct process that delivers *m'* will have already delivered *m*.

Total Order: Example



The order of receipt of multicasts is the same at all processes.
M1:1, then M2:1, then M3:1, then M3:2
May need to delay delivery of some messages.

Causal vs Total

- Total ordering does not imply causal ordering.
- Causal ordering does not imply total ordering.

Hybrid variants

- Since FIFO/Causal are orthogonal to Total, can have hybrid ordering protocols too.
  - FIFO-total hybrid protocol satisfies both FIFO and total orders.
  - Causal-total hybrid protocol satisfies both Causal and total orders.

Ordered Multicast

- **FIFO ordering:** If a correct process issues multicast(*g*,*m*) and then multicast(*g*,*m'*), then every correct process that delivers *m'* will have already delivered m.
- **Causal ordering:** If multicast(*g*,*m*) → multicast(*g*,*m'*) then any correct process that delivers *m'* will have already delivered *m*.
  - Note that → counts messages **delivered** to the application, rather than all network messages.
- **Total ordering**: If a correct process delivers message *m* before *m'* (independent of the senders), then any other correct process that delivers *m'* will have already delivered *m*.

Next Question

How do we implement ordered multicast?