Distributed Systems

CS425/ECE428

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Acknowledgements for some of materials: Indy Gupta and Nikita Borisov

Logistics

- MP0 is due today at 11:59pm.
- AI policy:
  - Same as web search. Can't use AI in any way that trivializes the assignment (e.g. auto-generating significant piece code/solution).
  - Ok to use it for boiler-plate code (create TCP sockets, create a Go channel, etc).
- HW1 Q1 clarification: please see Campuswire post #75. Homework PDF on the course website has been updated too.
- Reminder to share your name when you speak up in class.

Today's agenda

- Global State (contd.)
  - Chapter 14.5
- Multicast
  - Chapter 15.4

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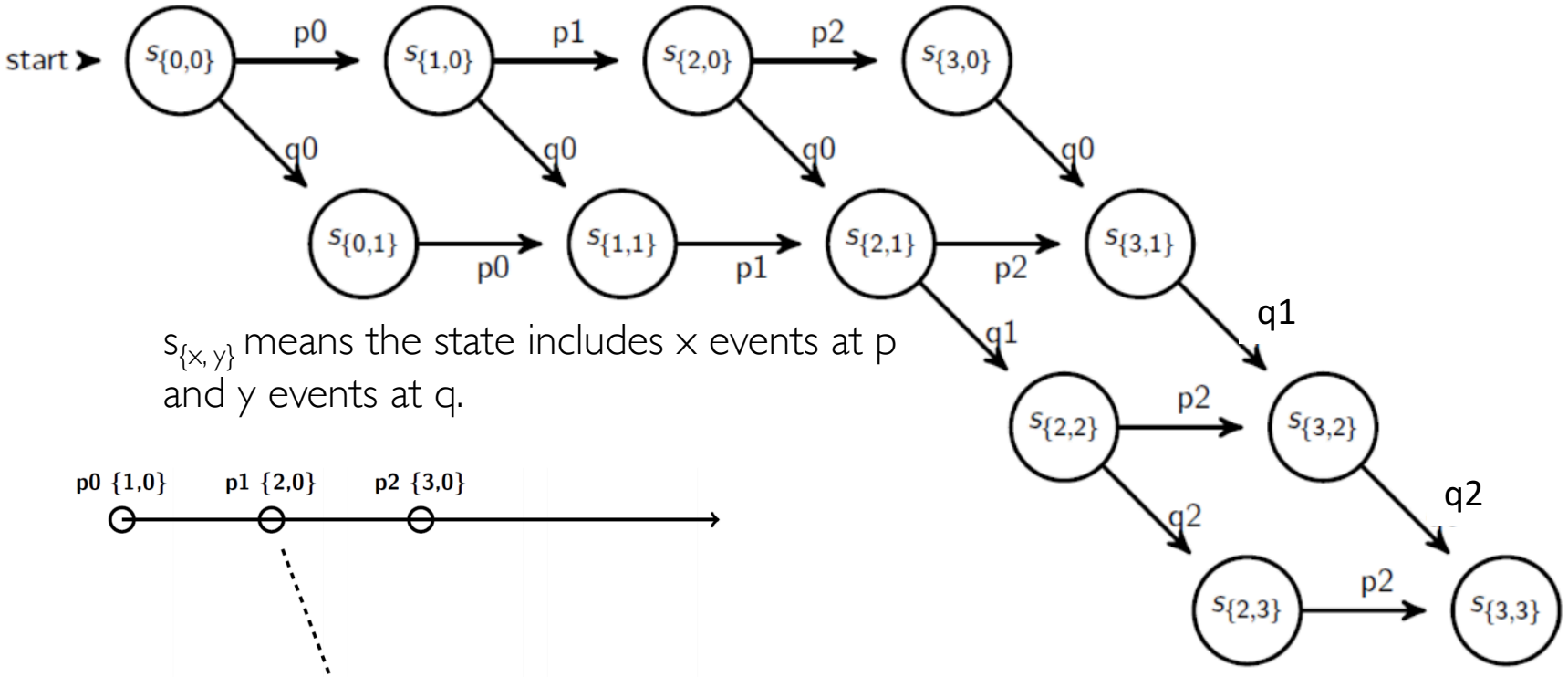
More notations and definitions

- A run is a total ordering of events in H that is consistent with each $\mathbf{h_i}$'s ordering.
- A linearization is a run consistent with happens-before ($\rightarrow$) relation in H.
- 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

Execution Lattice. Each path represents a linearization.



$s_{\{x,y\}}$ means the state includes x events at p and y events at q.

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

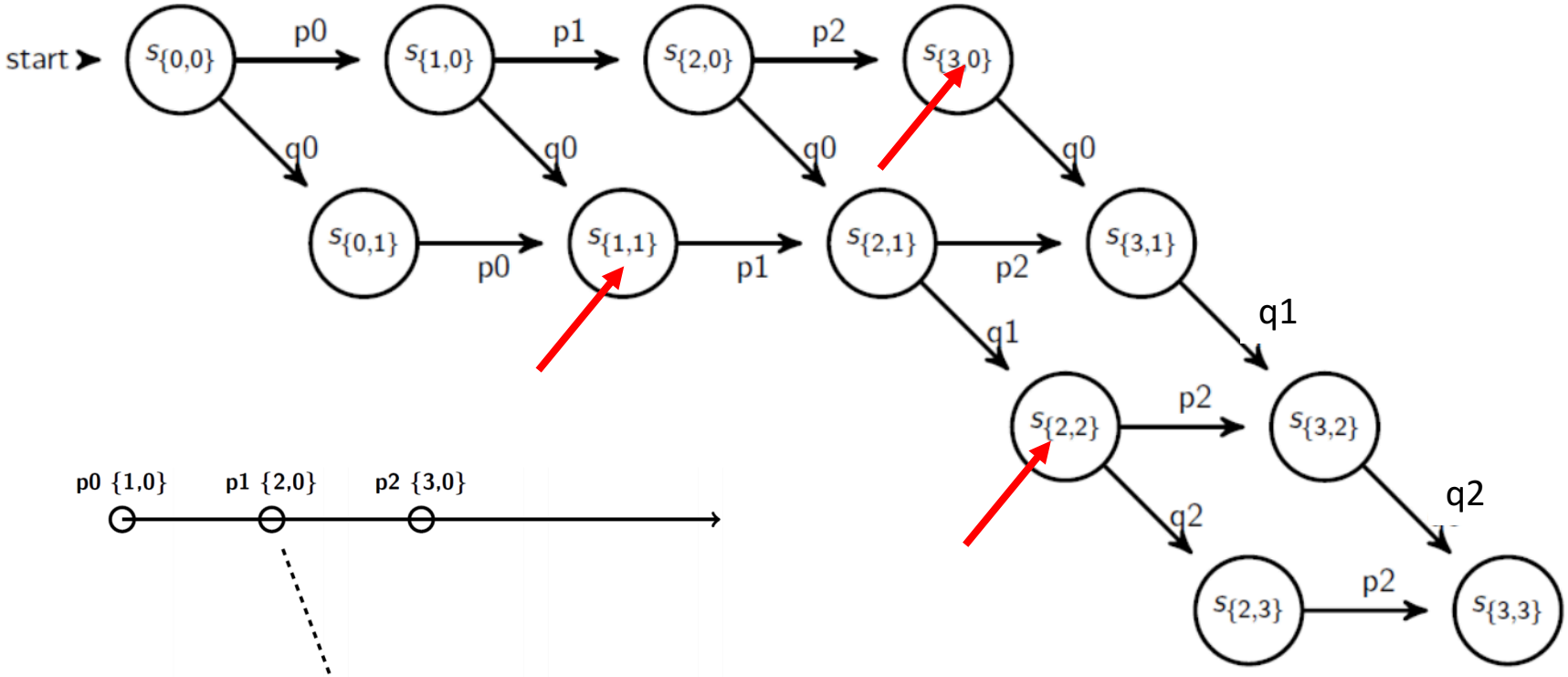
- Examples:
  - A distributed computation will terminate.
  - "Completeness" in failure detectors: the failure will be detected.
  - All processes will eventually decide on a value.

- A global state S_0 satisfies a **liveness** property P iff:
  - For all linearizations starting from S_0, P is true for some state S_L reachable from S_0.
  - liveness($P(S_0)$) ≡ $\forall L \in$ linearizations from S_0, L passes through a S_L & $P(S_L)$ = true

Liveness Example

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

No



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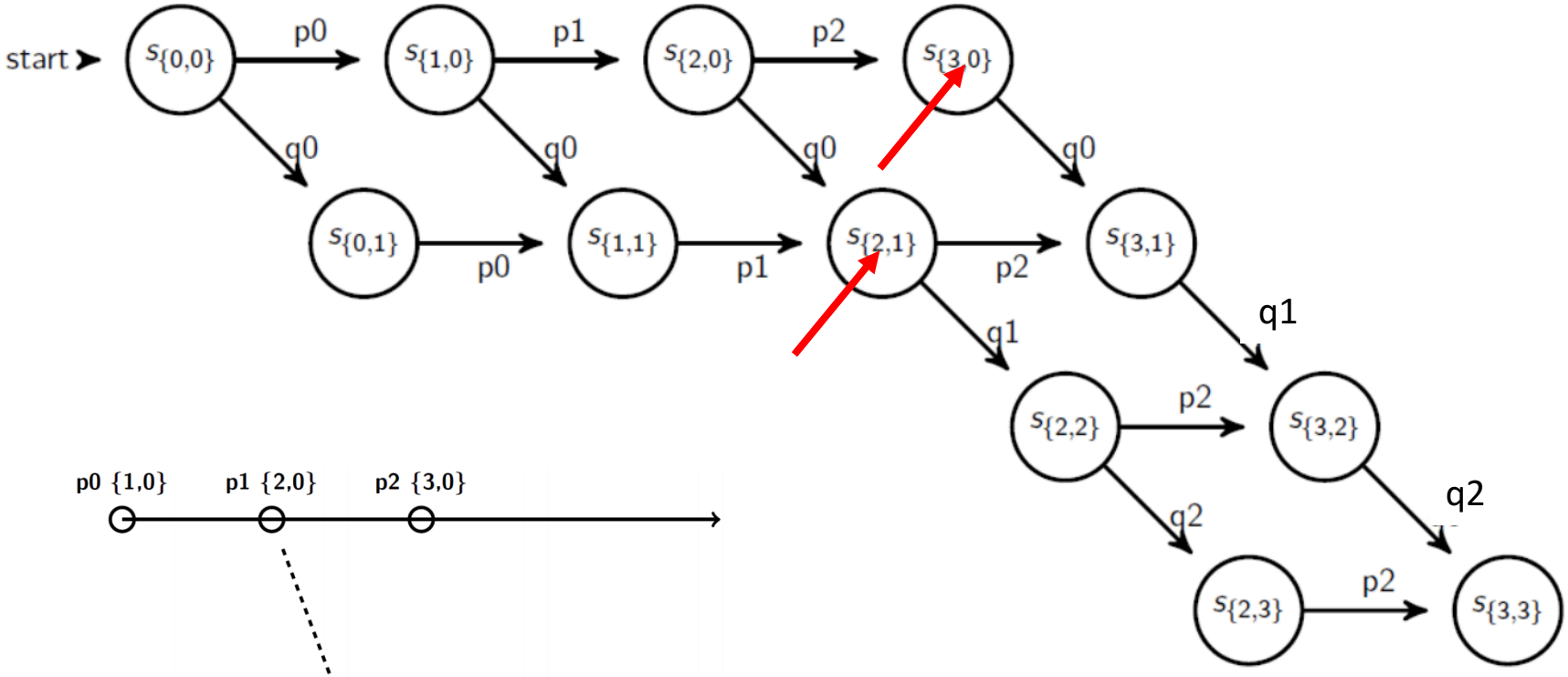

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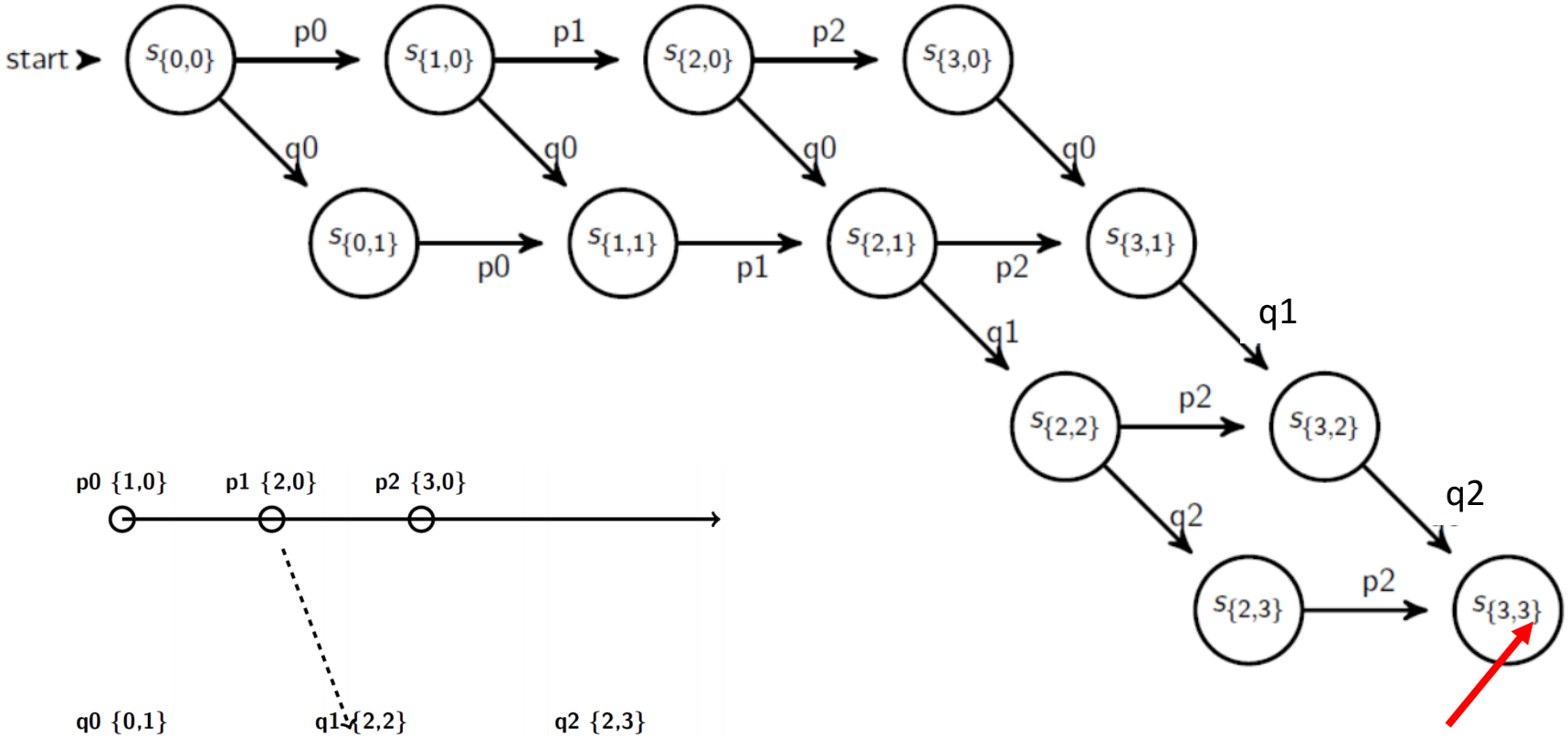

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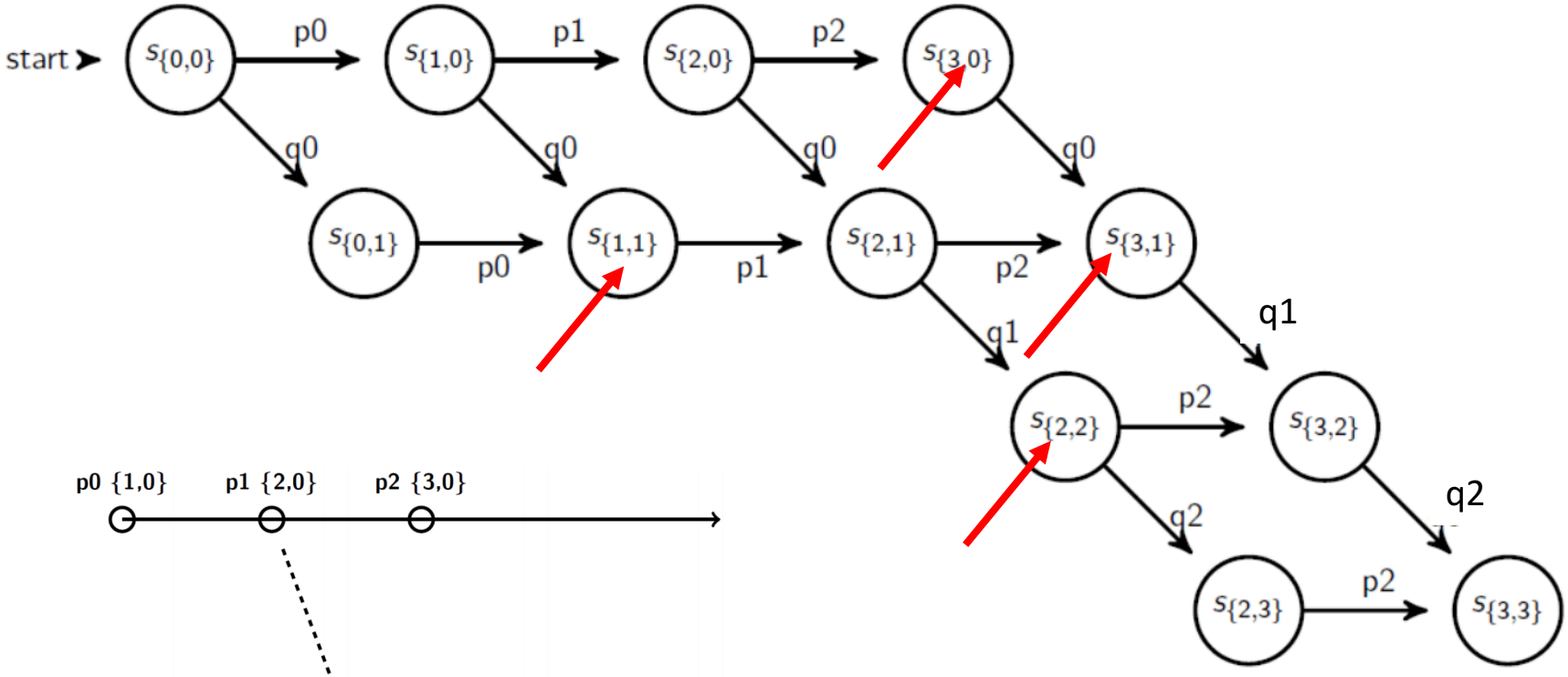
Safety

- Safety = guarantee that something bad will never happen.
- Examples:
  - There is no deadlock in a distributed transaction system.
  - "Accuracy" in failure detectors: an alive process is not detected as failed.
  - No two processes decide on different values.
- A global state S_0 satisfies a **safety** property P iff:
  - For all states S reachable from S_0, P(S) is true.
  - safety($P(S_0)$) ≡ $\forall$S reachable from S_0, P(S) = true.

Safety Example

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

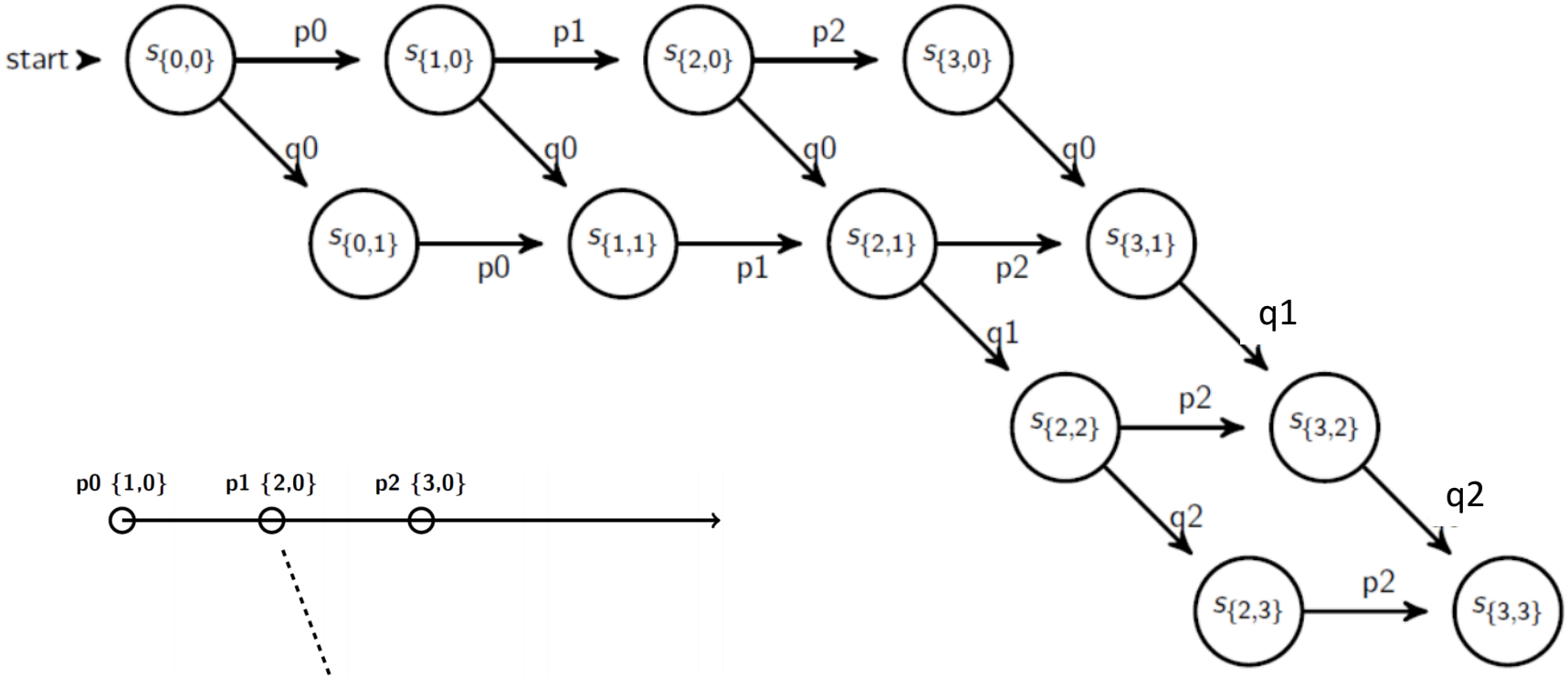
No



Safety Example

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

Yes



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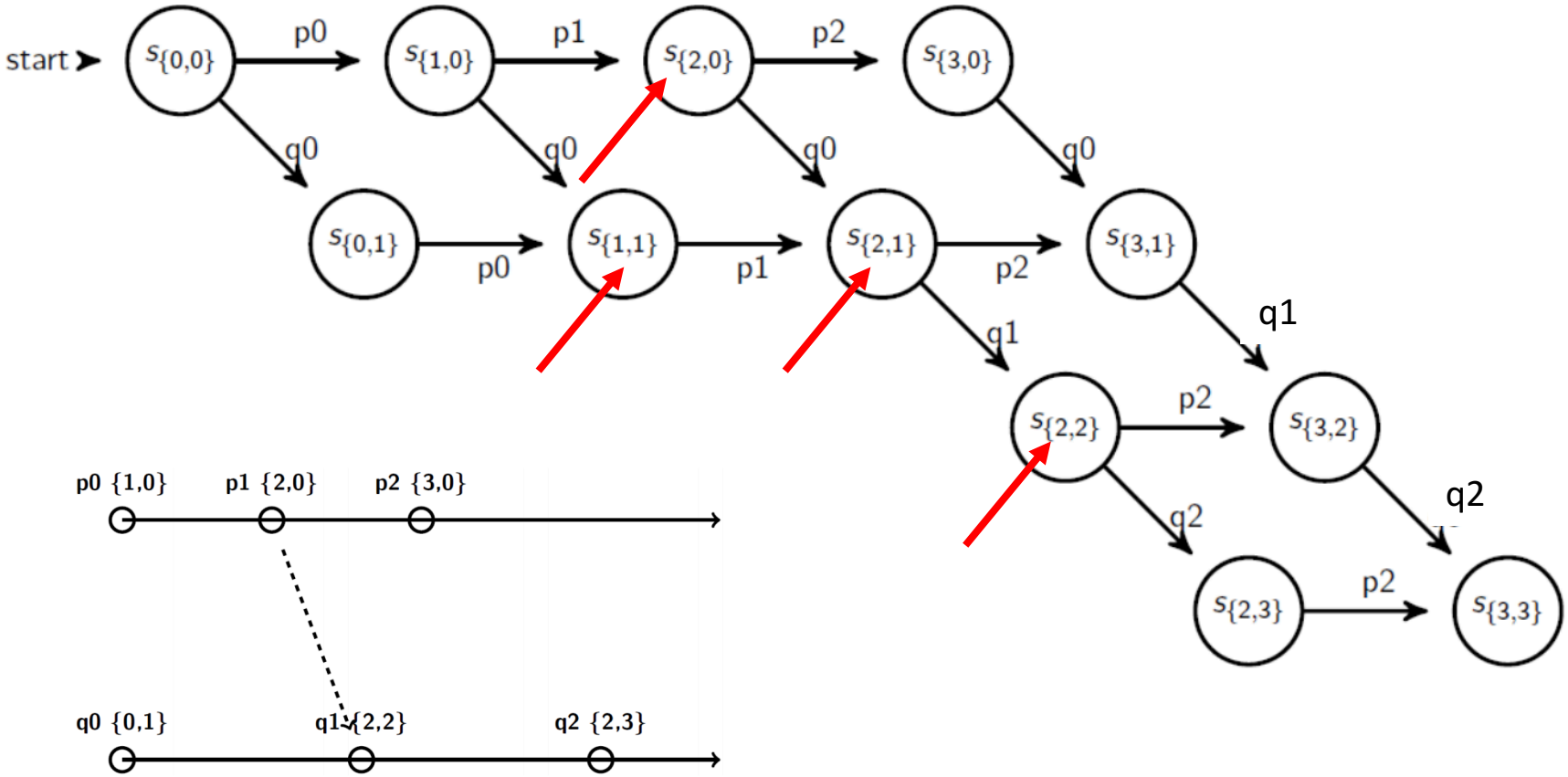
Liveness Example

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



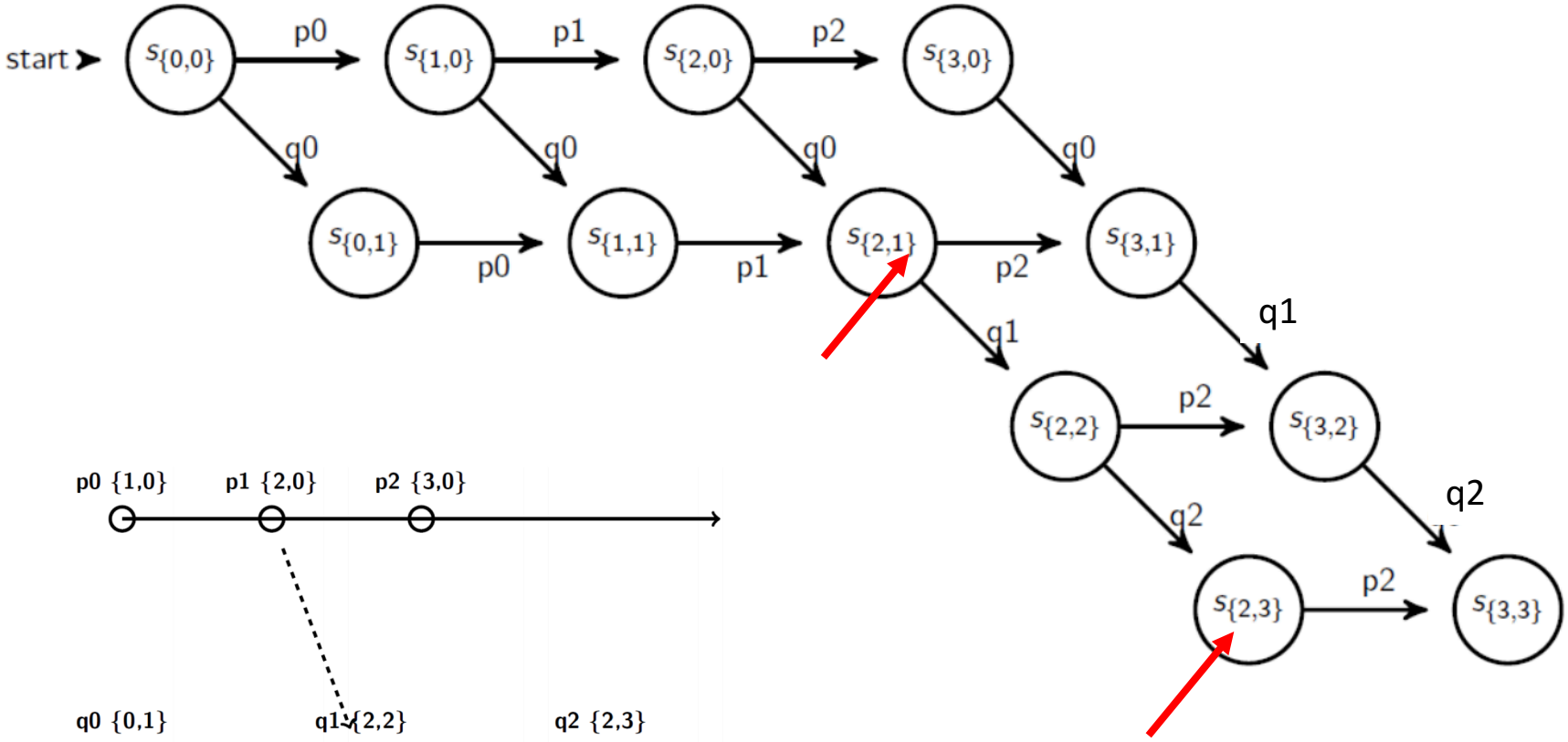
Stable Global Predicates

- once true, stays true forever afterwards (for stable liveness)

Stable Global Predicates

If predicate is true only in the marked states, is it true in a stable way?

No



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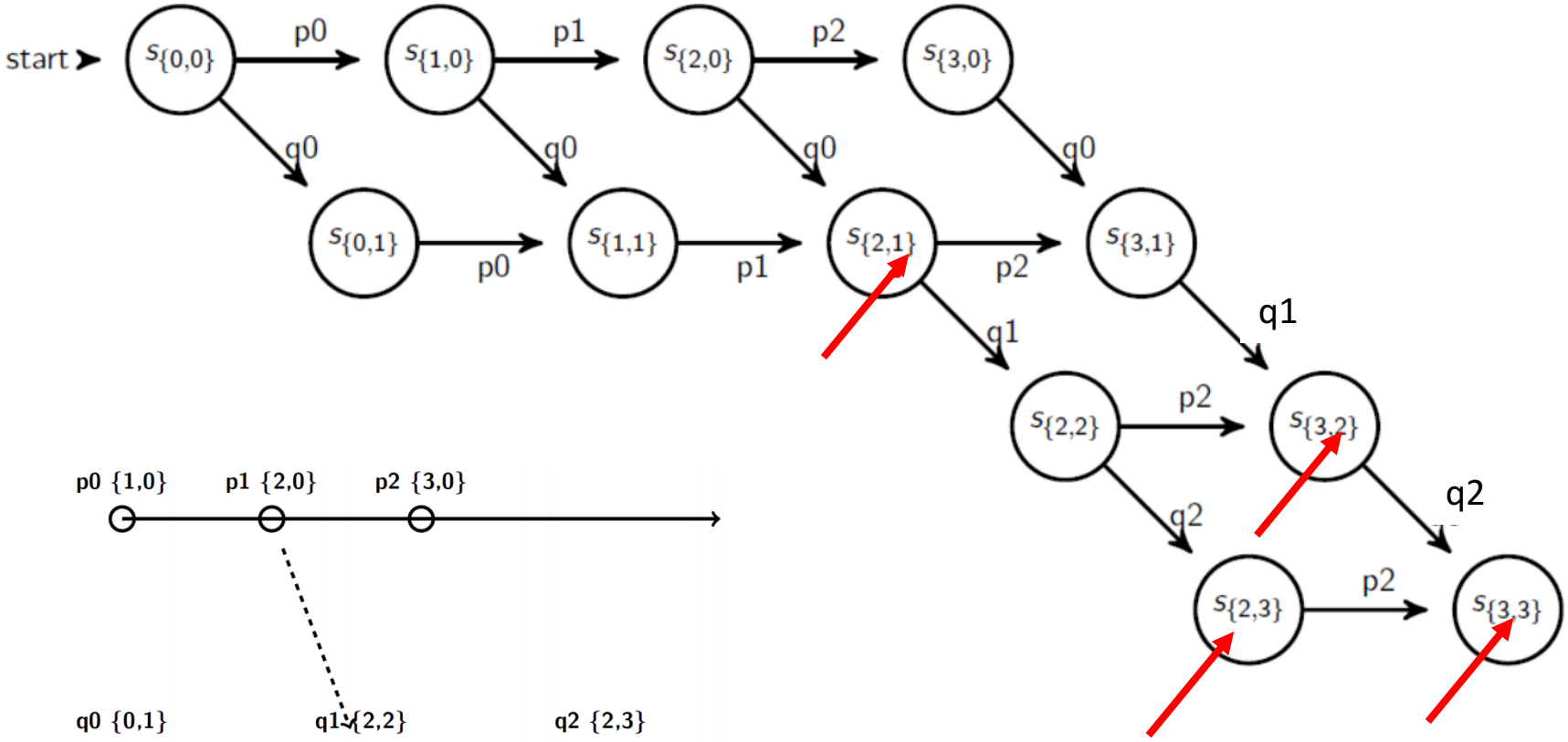

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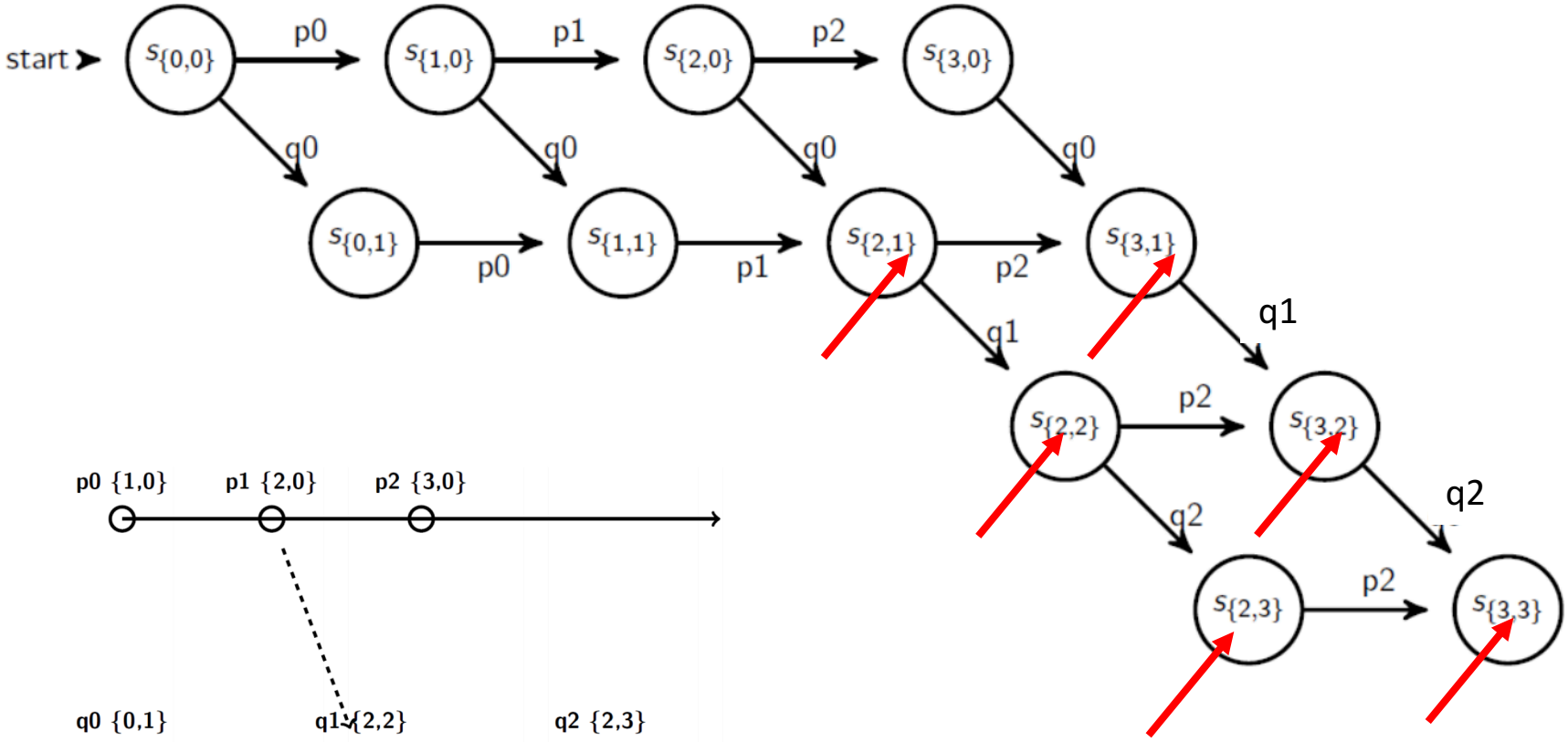


Stable Global Predicates

- once true for a state S, stays true for all states reachable from S (for stable liveness)
- once false for a state S, stays false for all states reachable from S (for stable non-safety)
- Stable liveness examples (once true, always true)
  - Computation has terminated.
- Stable non-safety examples (once false, always false)
  - There is no deadlock.
  - An object is not orphaned.
- *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 global properties.
- Safety vs. Liveness.

Today's agenda

- Global State (contd.)
  - Chapter 14.5

- **Multicast**
  - Chapter 15.4
  - **Goal:** reason about desirable properties for message delivery among a group of processes.

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 a group of processes on the network.

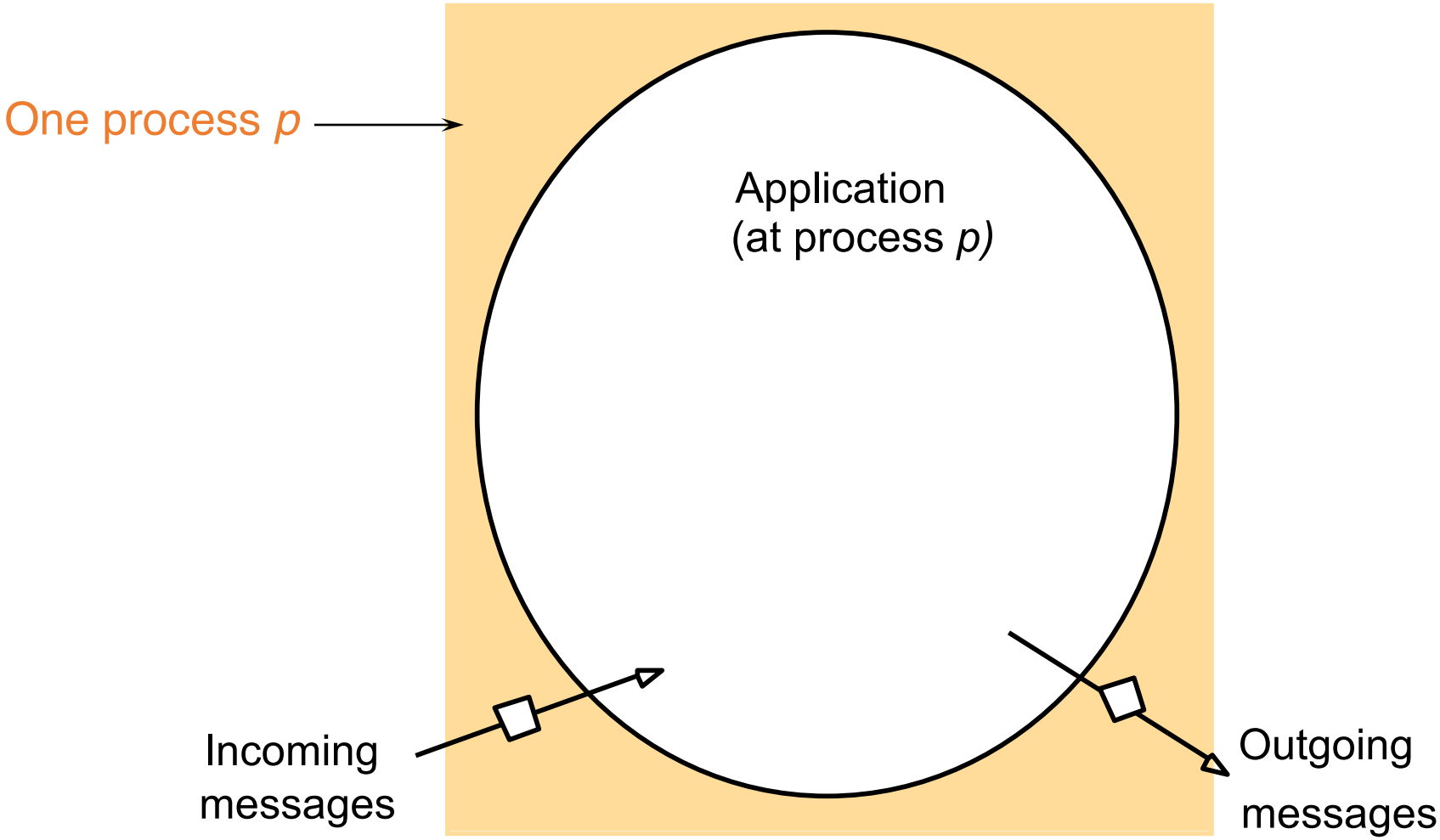
Where is multicast used?

- 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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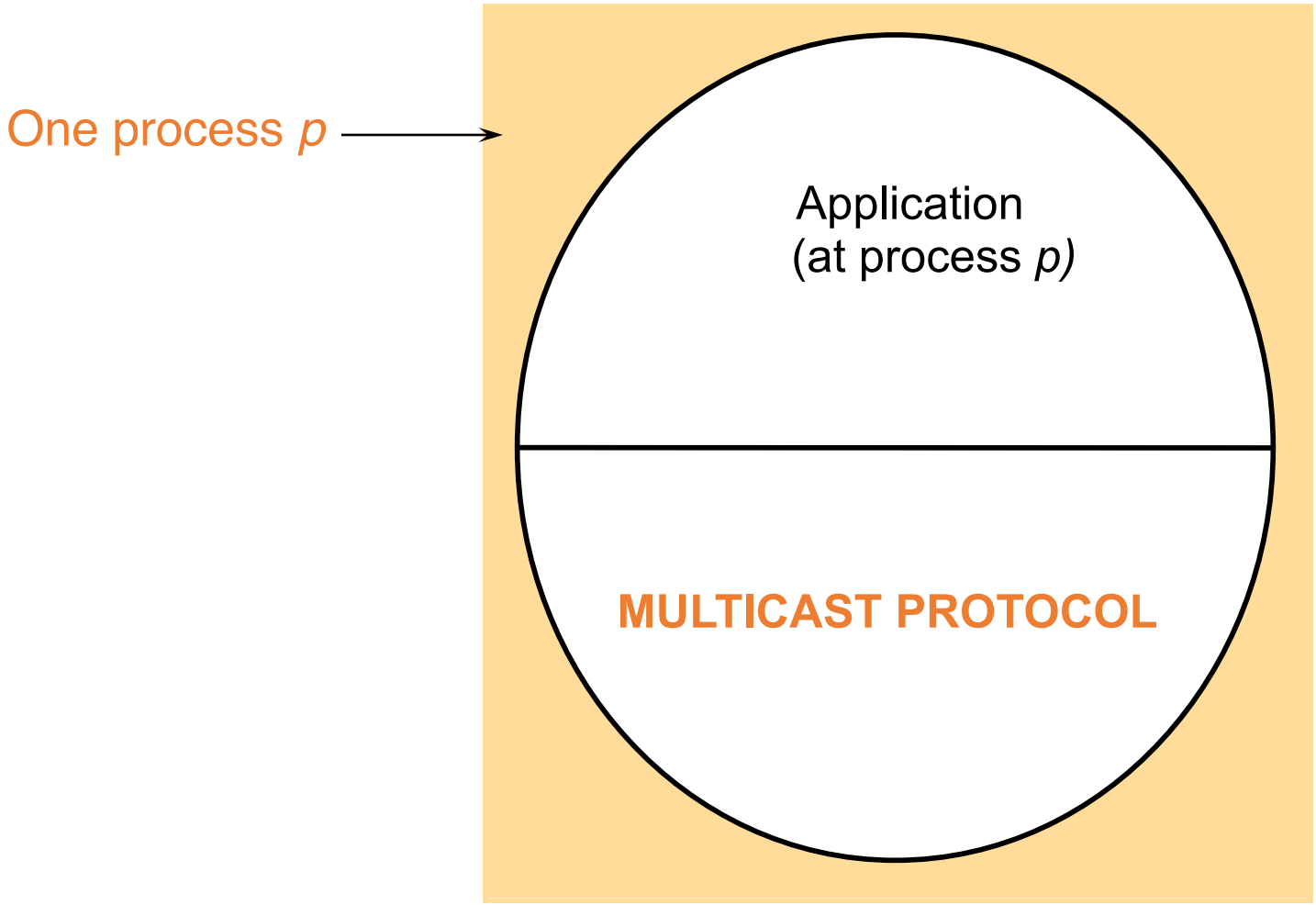

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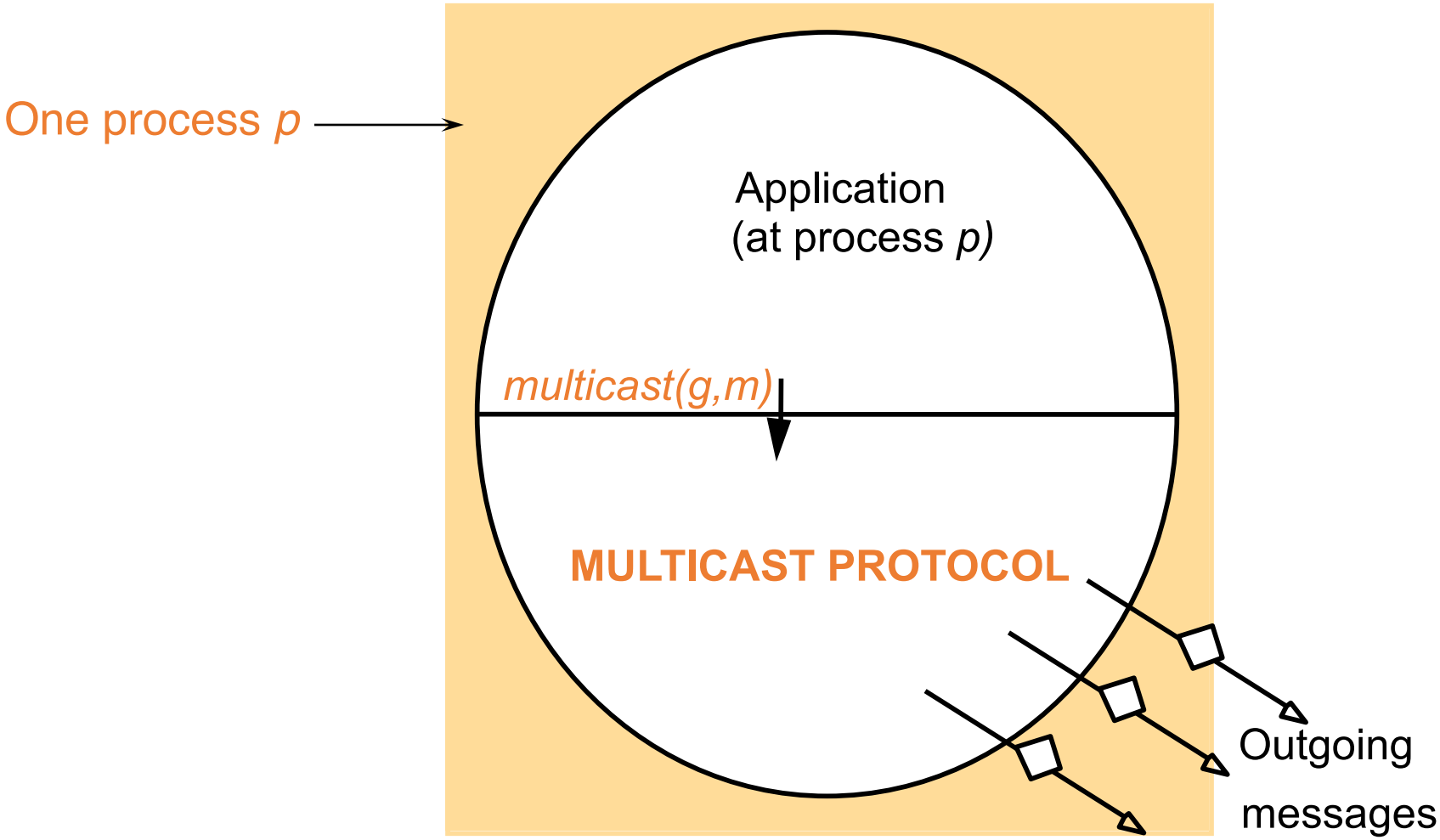

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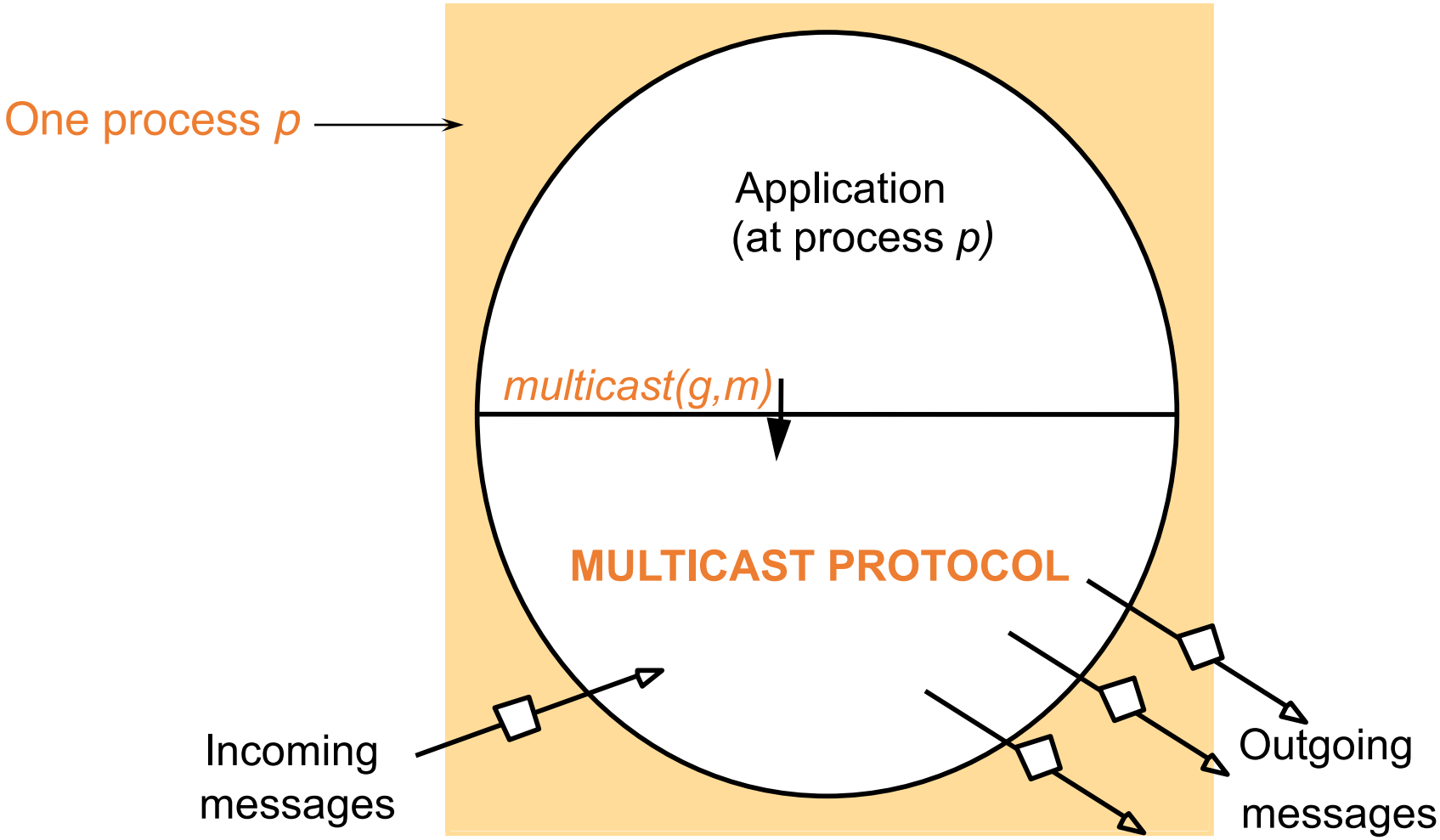

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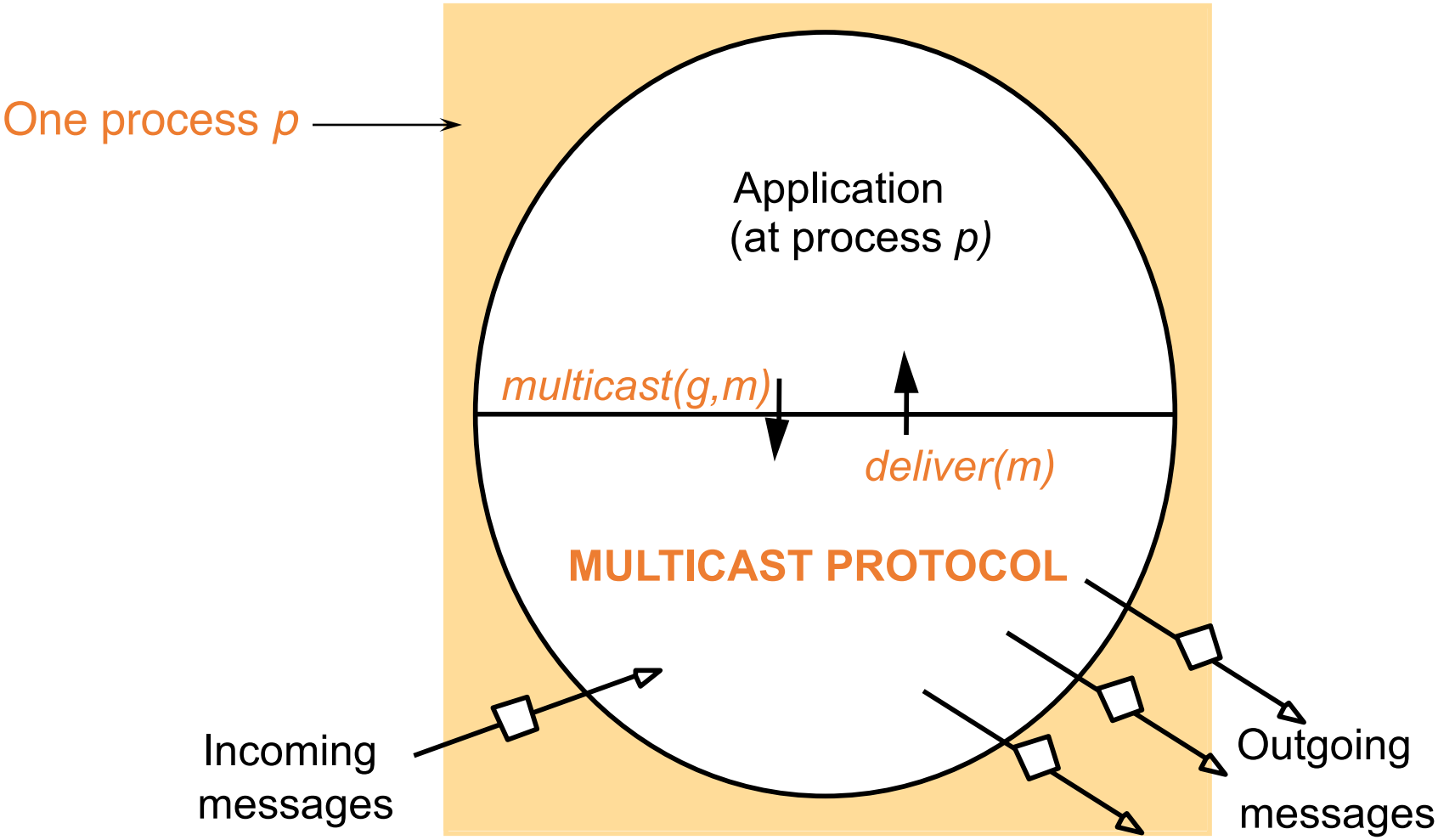

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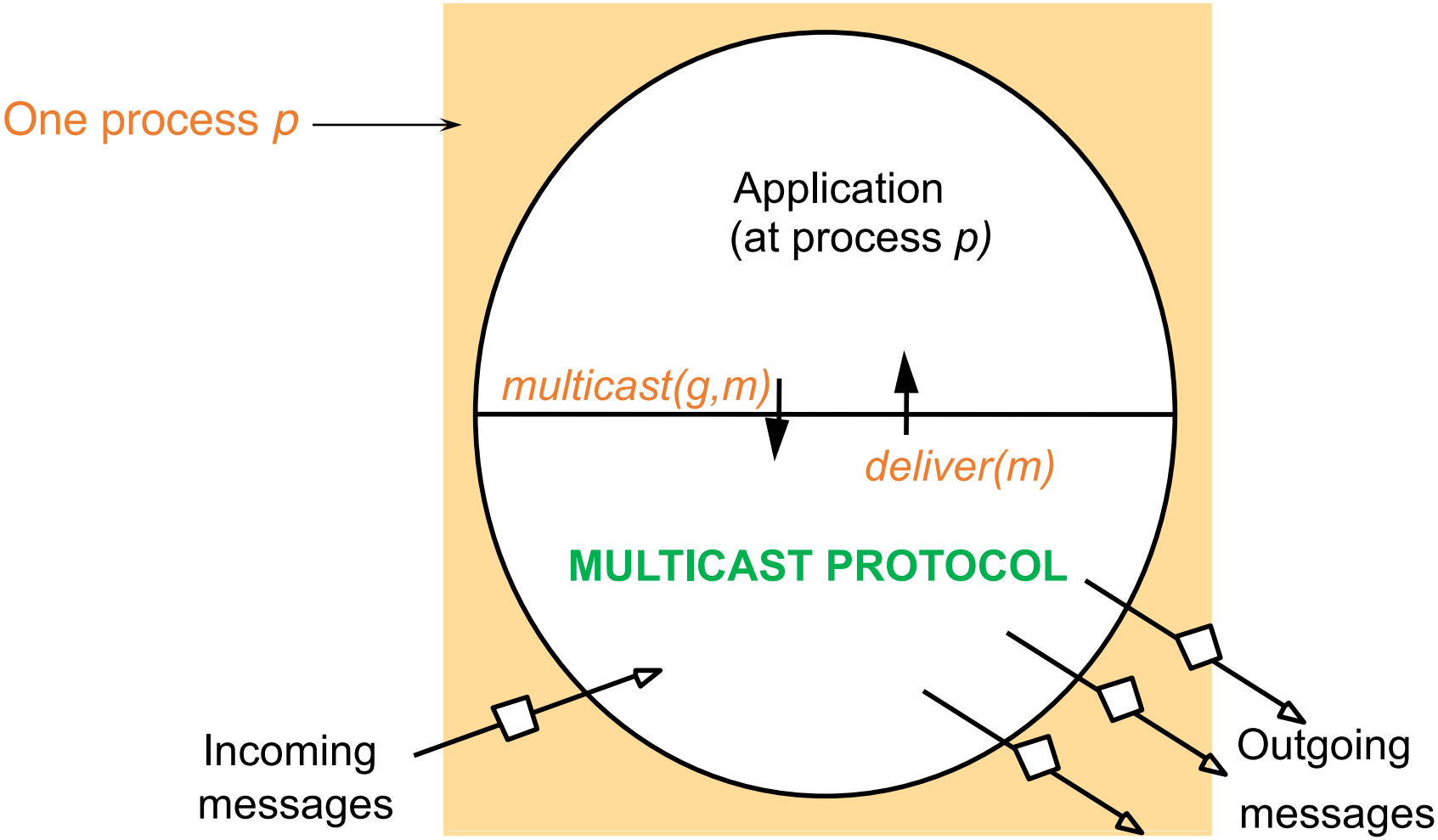

'g' is a multicast group that also includes the process 'p'.

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?*
  - *What does this mean?*

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* to 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.

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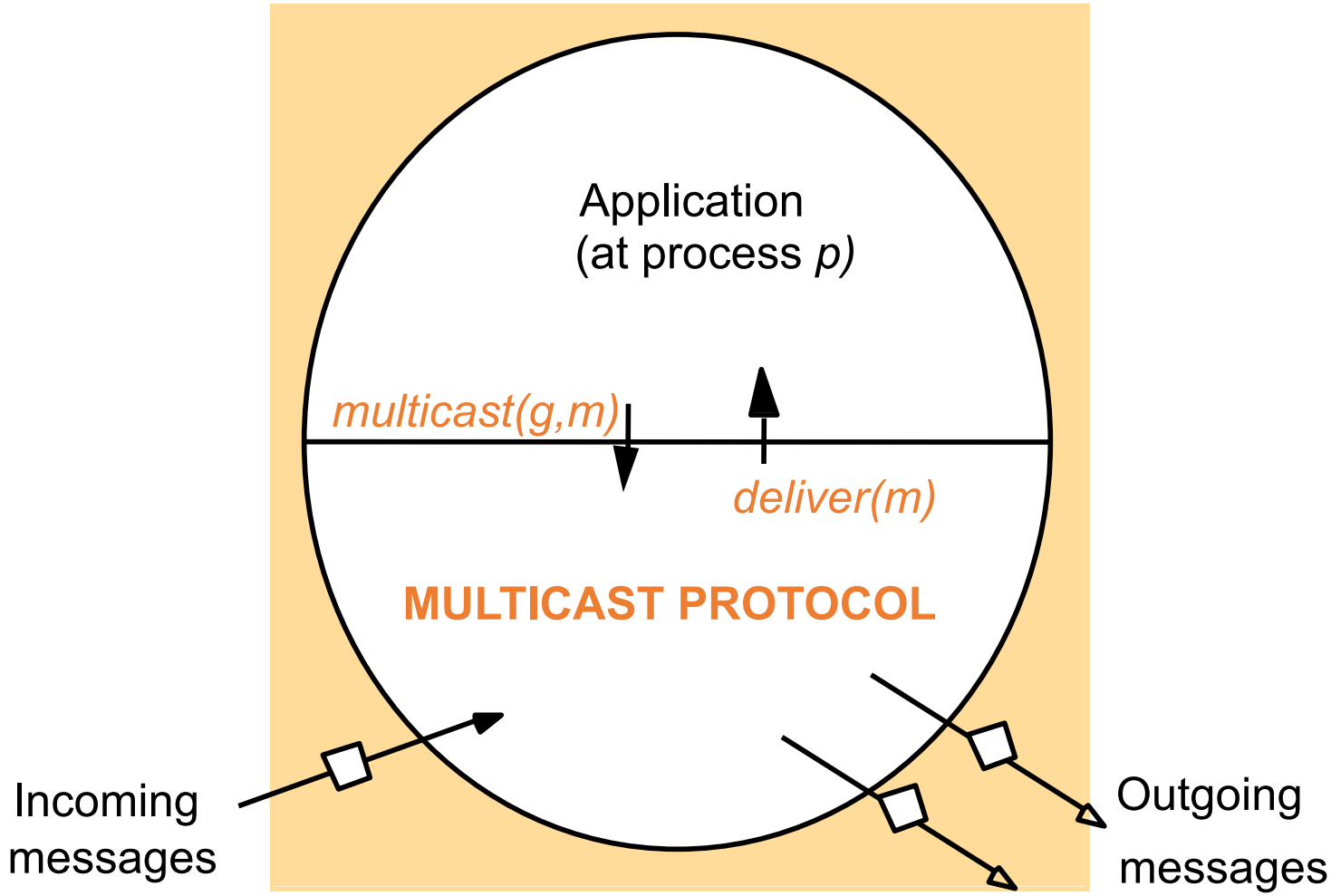
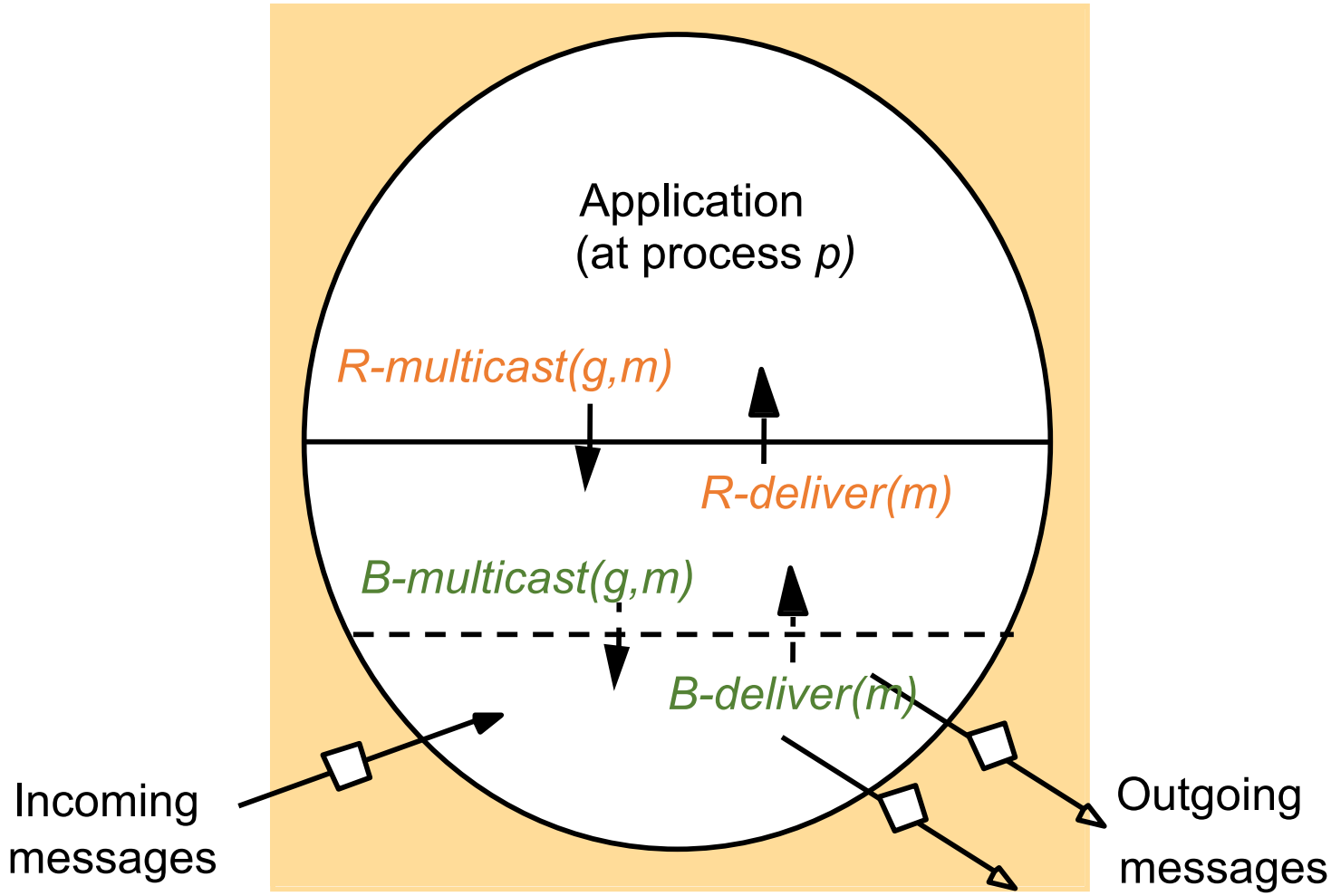
What happens if a process initiates B-multicasts of a message but fails after unicasting to a subset of processes in the group?

Agreement is violated! R-multicast not satisfied.

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 ∈ g is included as destination)

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

    if (m ∉ Received):

        Received := Received ∪ {m};

        if (q ≠ p): B-multicast(g,m);

        R-deliver(m)

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Ordered Multicast

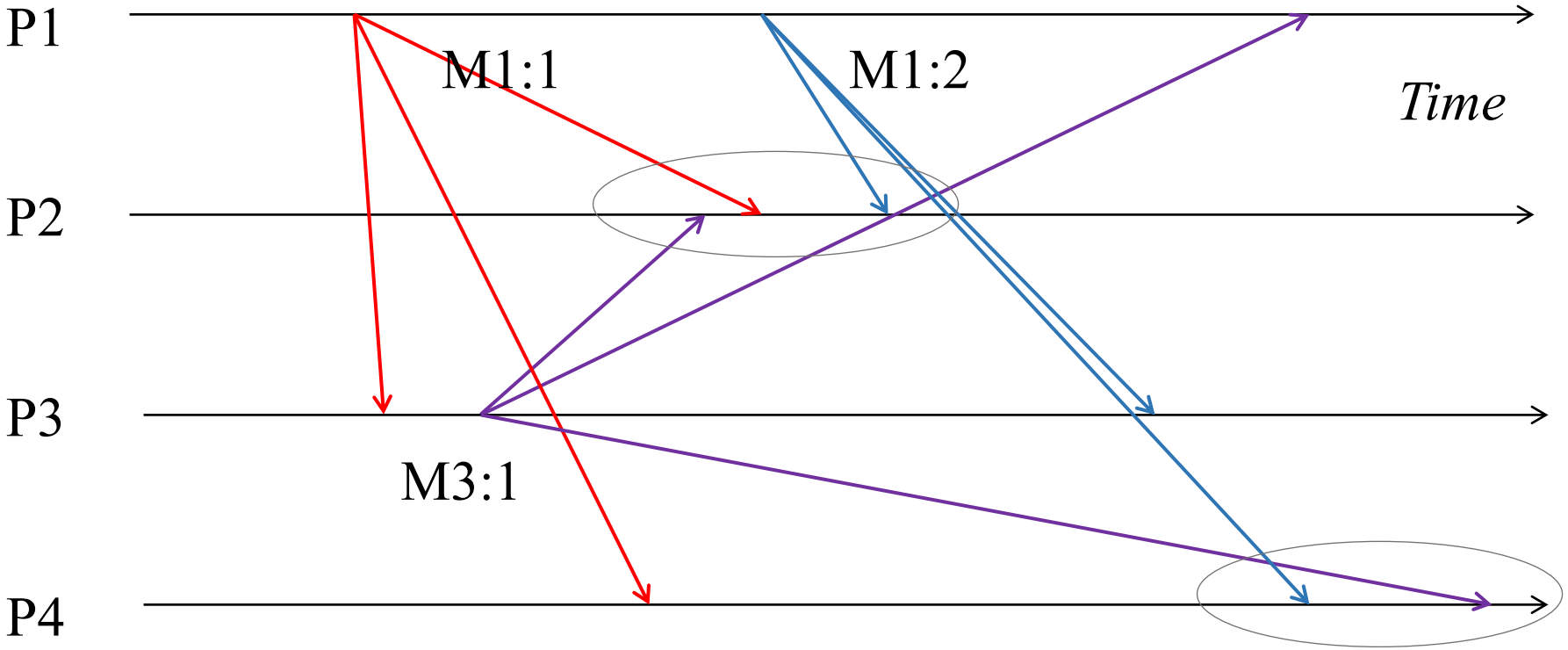
- Three popular flavors implemented by several multicast protocols:
  1. FIFO ordering
  2. Causal ordering
  3. Total ordering

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*
  - → is induced only by multicast messages in group g, and when they are **delivered** to the application, rather than all network messages.

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.

HB Relationship for Causal Ordering

- HB rules in causal ordered multicast:
  - If ∃ p_i , **e** $\rightarrow_i$ **e'** then **e** → **e'**.
    - If ∃ p_i , multicast(*g*,*m*) $\rightarrow_i$ multicast(*g*,*m'*), then multicast(*g*,*m*) → multicast(*g*,*m'*)
    - If ∃ p_i , delivery(*m*) $\rightarrow_i$ multicast(*g*,*m'*), then delivery(*m*) → multicast(*g*,*m'*)
    - …
  - For any message m, **send(m) → receive(m)**

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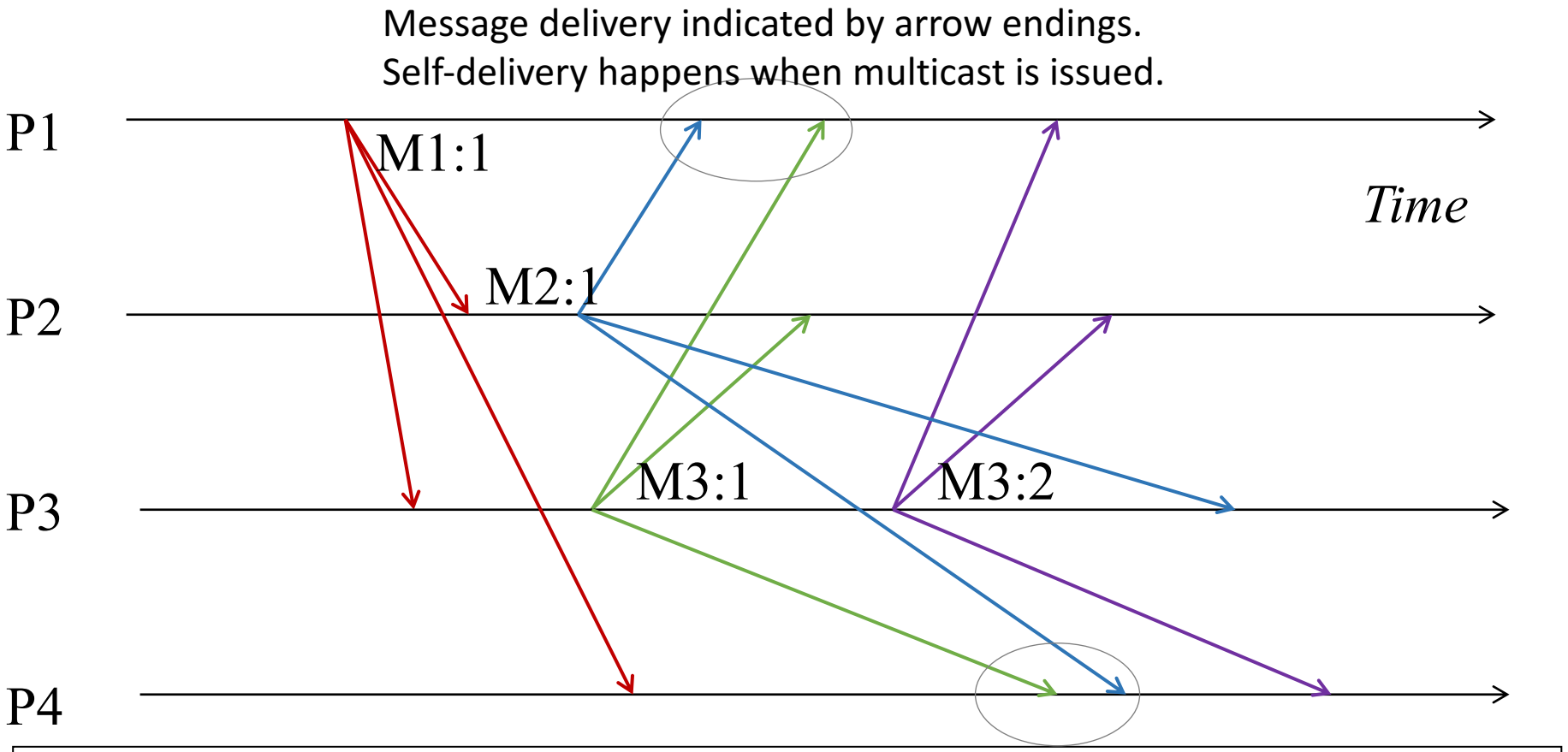
    - If ∃ p_i , delivery(*m*) $\rightarrow_i$ multicast(*g*,*m'*), then delivery(*m*) $\rightarrow$ multicast(*g*,*m'*)
    - …
  - ~~For any message m, **send(m) → receive(m)**~~
    - For any *multicast* message m, **multicast(*g*,*m*) → delivery(m)**
  - If **e** → **e'** and **e'** → **e"** then **e** → **e"**
    - multicast(*g*,*m*) at p_i → delivery(m) at p_j
    - delivery(*m*) at p_j → multicast(*g*,*m'*) at p_j
    - multicast(*g*,*m*) at p_i → multicast(*g*,*m'*) at p_j
- *Application can only see when messages are "multicast" by the application and "delivered" to the application, and not when they are sent or received by the protocol.*

Causal Order: Example



M3:1 → M3:2, M1:1 → M2:1, M1:1 → M3:1 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 any (and even different) orders at different receivers.

Ordered Multicast

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  1. FIFO ordering
  2. Causal ordering
     - More examples in next class.
  3. Total ordering
     - Next class