Distributed Systems

CS425/ECE428

Feb 3 2022

Instructor: Radhika Mittal

Logistics Related

- MP0 deadline extended by one day due to VM cluster service disruptions.
    - New due date: Friday, Feb 4^{th}, 11:59pm.

Today's agenda

- **Global State**
  - Chapter 14.5
  - Goal: reason about how to capture the state across all processes of a distributed system without requiring time synchronization.

Recap: How to capture global state?

- State of each process (and each channel) in the system *at a given instant of time.*
  - Difficult to capture -- requires precisely synchronized time.

- Relax the problem: find a consistent global state.
  - For a system with n processes $<p_1, p_2, p_3, \ldots., p_n>$, capture the state of the system after the c_i th event at process p_i.
    - State corresponding to the cut defined by frontier events $\{e_i^{c_i}$, for $i = 1,2, \ldots n\}$.
  - We want the state to be consistent.
    - Must correspond to a consistent cut.
      - If an event e belongs to the cut, all events that "happened before" e must also belong to the cut.

Chandy-Lamport Algorithm Intuition

- First, initiator p_i:
  - records its own state.
  - creates a special **marker** message.
  - sends the **marker** to all other process.
  - start recording messages received on other channels.
    - until a marker is received on a channel.
- When a process receives a **marker**.
  - If marker is received for the first time.
    - records its own state.
    - sends marker on all other channels.
    - start recording messages received on other channels.
      - until a marker is received on a channel.

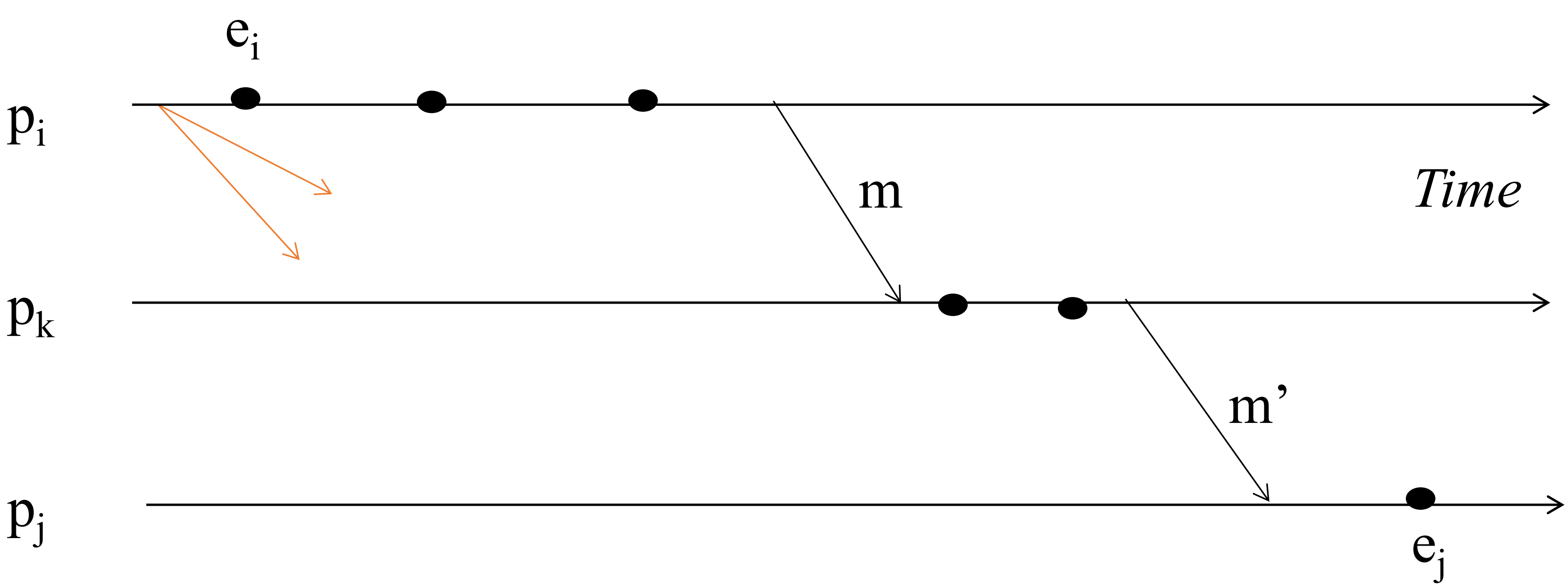
Chandy-Lamport Algorithm: Properties

- Any run of the Chandy-Lamport Global Snapshot algorithm creates a consistent cut.
- Let $\mathbf{e}_i$ and $\mathbf{e}_j$ be events occurring at $\mathbf{p}_i$ and $\mathbf{p}_j$, respectively such that
  - $\mathbf{e}_i \rightarrow \mathbf{e}_j$ ($\mathbf{e}_i$ happens before $\mathbf{e}_j$)
- The snapshot algorithm ensures that

  if $\mathbf{e}_j$ is in the cut then $\mathbf{e}_i$ is also in the cut.
- That is: if $\mathbf{e}_j \rightarrow$ < $\mathbf{p}_j$ records its state>, then it must be true that $\mathbf{e}_i \rightarrow$ <$\mathbf{p}_i$ records its state>.

Chandy-Lamport Algorithm: Properties

- Given $\mathbf{e_i} \rightarrow \mathbf{e_j}$. If $\mathbf{e_j} \rightarrow$ < $\mathbf{p_j}$ records its state>, then it must be true that $\mathbf{e_i} \rightarrow$ <$\mathbf{p_i}$ records its state>.
- By contradiction, *suppose* $\mathbf{e_j} \rightarrow$ *< p_j records its state>, and <p_i records its state>* $\rightarrow \mathbf{e_i}$.



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- Given **e_i** → **e_j**. If **e_j** → < **p_j** records its state>, then it must be true that **e_i** → <**p_i** records its state>.
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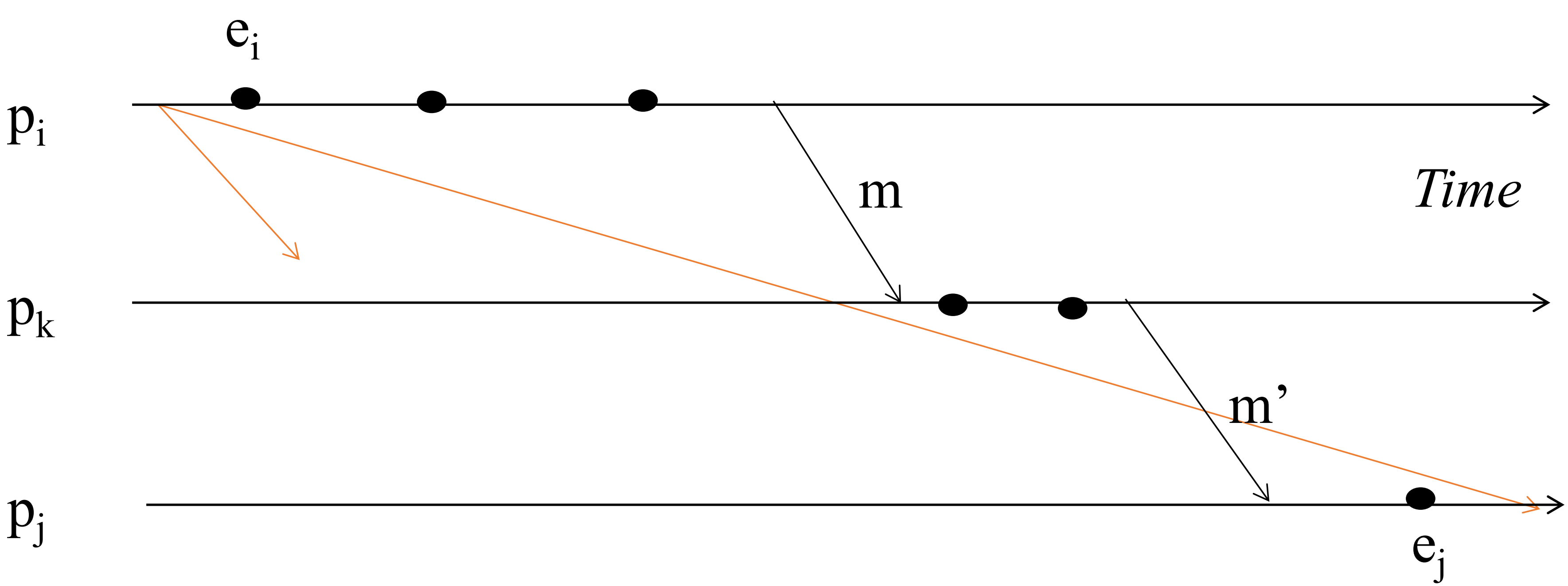

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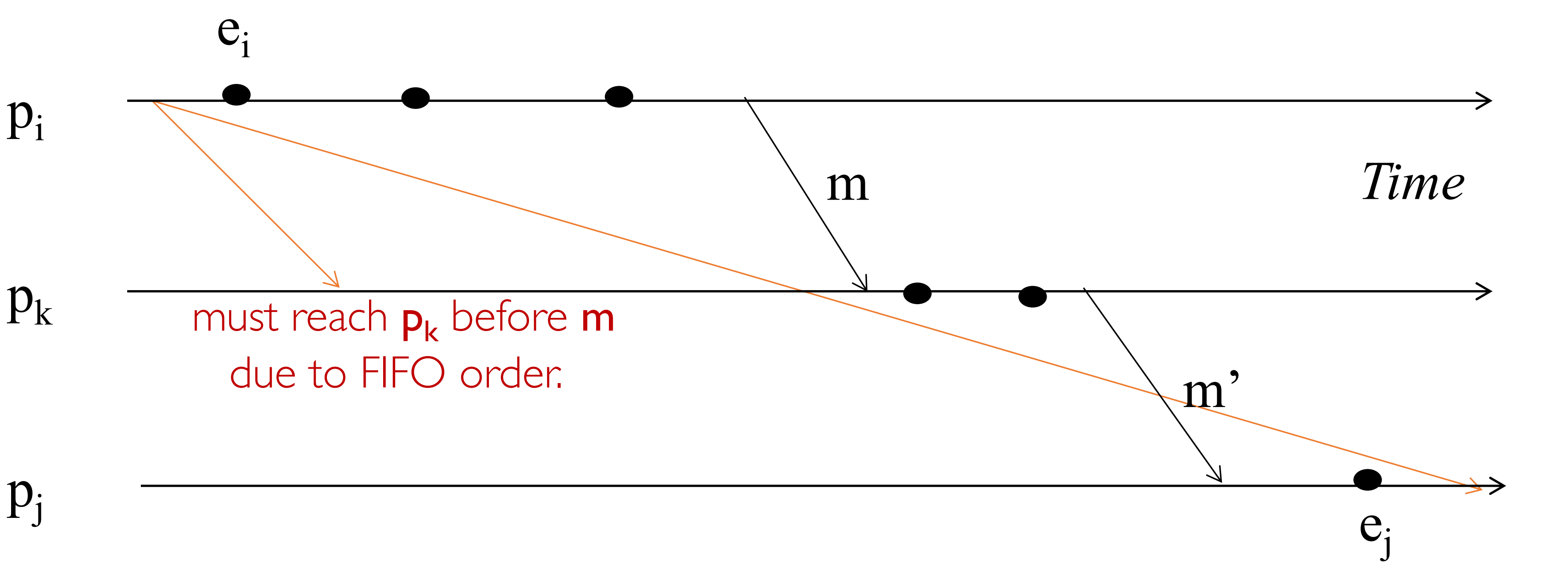

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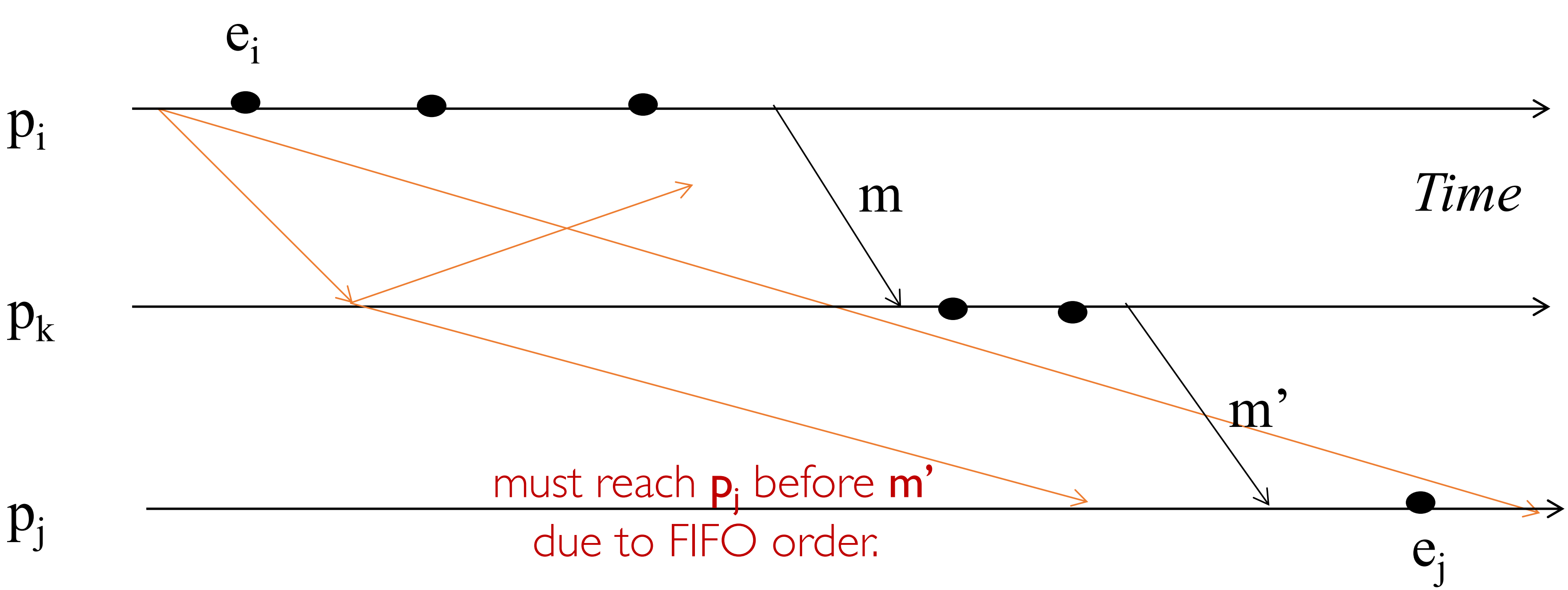

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- By contradiction, *suppose* $\mathbf{e}_j \rightarrow$ *< $\mathbf{p}_j$ records its state>, and <$\mathbf{p}_i$ records its state>* $\rightarrow \mathbf{e}_i$.
- Consider the path of app messages (through other processes) that go from $\mathbf{e}_i$ to $\mathbf{e}_j$.
- Due to FIFO ordering, markers on each link in above path will precede regular app messages.
- Thus, since <$\mathbf{p}_i$ records its state> $\rightarrow \mathbf{e}_i$, it must be true that $\mathbf{p}_j$ received a marker before $\mathbf{e}_j$.
- Thus $\mathbf{e}_j$ is not in the cut => contradiction.

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.

Chandy-Lamport Algorithm: Usefulness

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

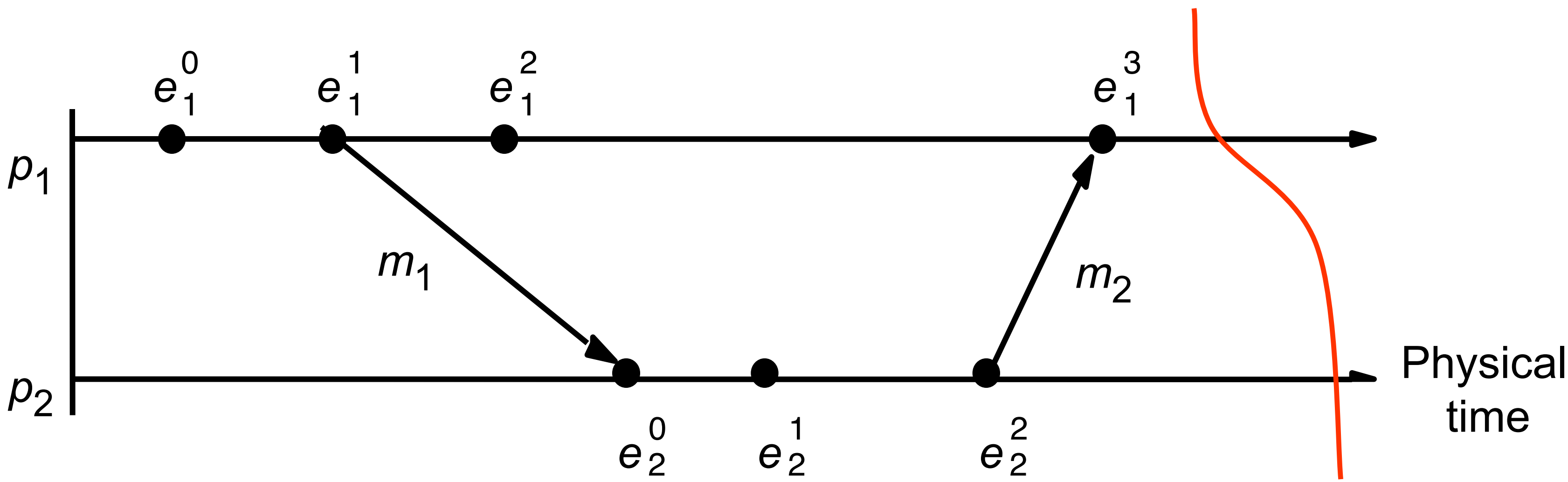
More notations and definitions

- **history(p_i)** = $h_i = \langle e_i^0, e_i^1, \ldots \rangle$
- **global history**: $H = \cup_i (h_i)$

- A **run** is a total ordering of events in H that is consistent with each **h_i**'s ordering.

- A **linearization** is a run consistent with happens-before ($\rightarrow$) relation in H.

Example



Order at p_1: < $e_1^0, e_1^1, e_1^2, e_1^3$ > Order at p_2: < e_2^0, e_2^1, e_2^2 >

Causal order across p_1 and p_2: < $e_1^0, e_1^1, e_2^0, e_2^1, e_2^2, e_1^3$ >

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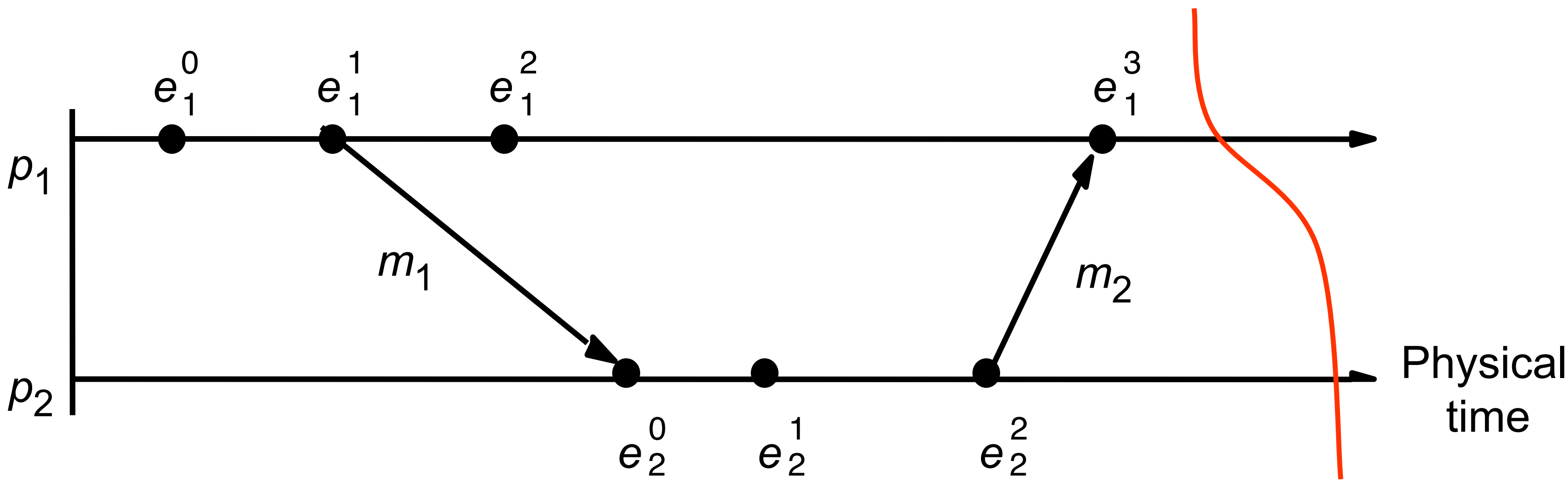

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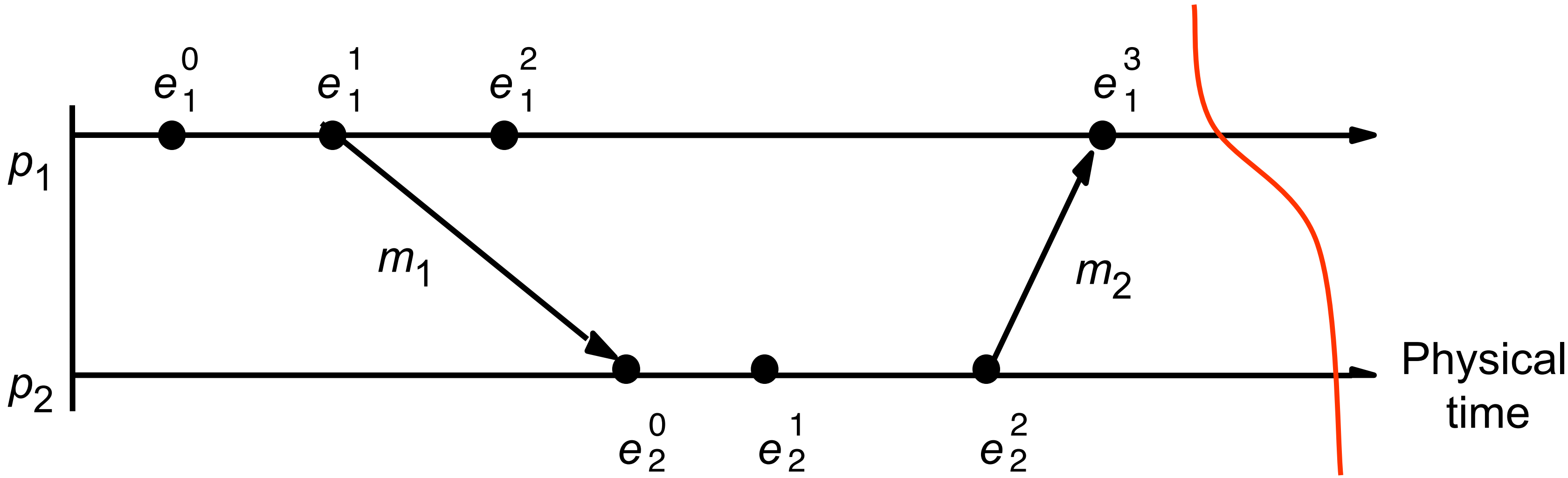

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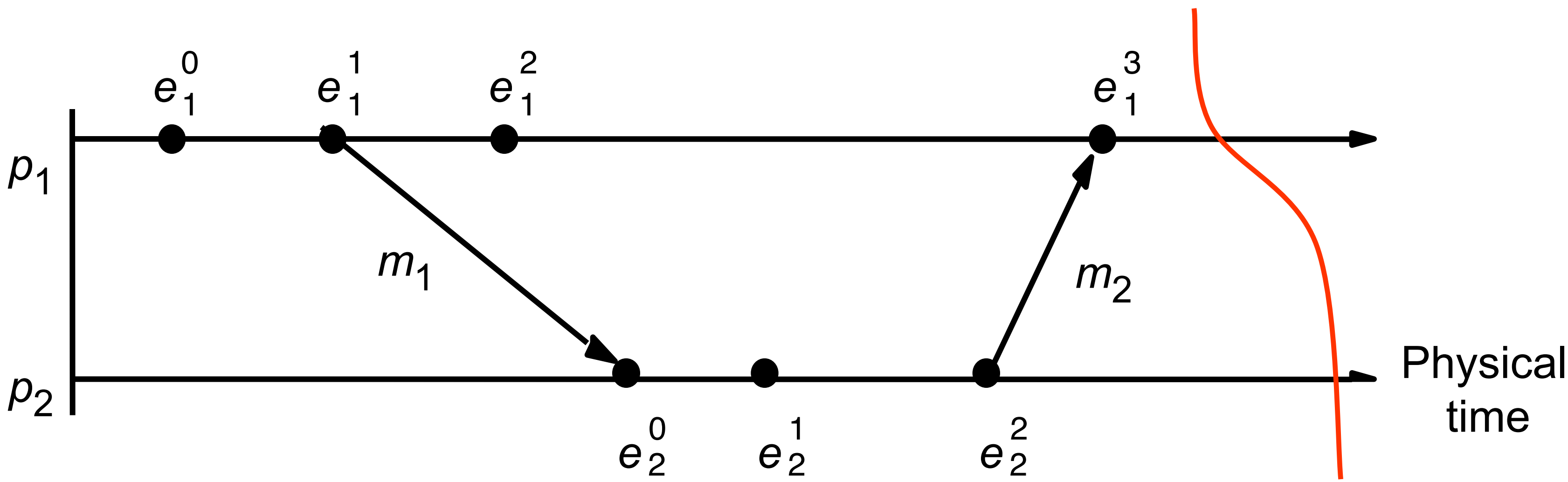

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$< e_1^0, e_1^1, e_2^0, e_2^1, e_1^2, e_2^2, e_1^3 >$: Linearization

$< e_1^0, e_2^1, e_2^0, e_1^1, e_1^2, e_2^2, e_1^3 >$: Not even a run

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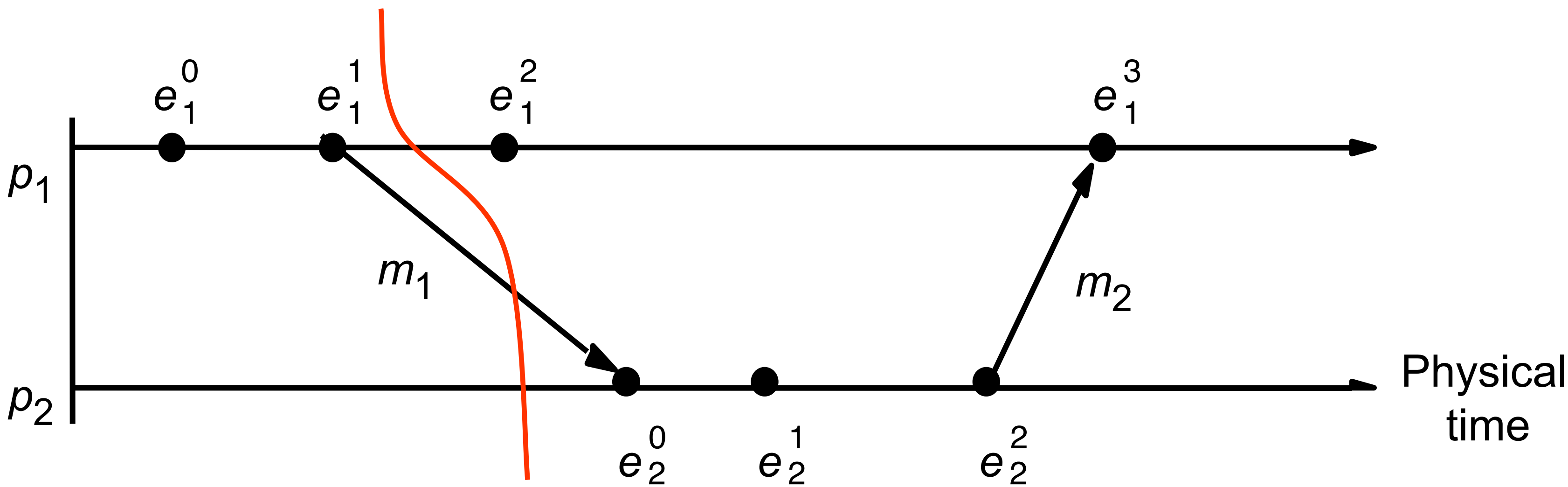

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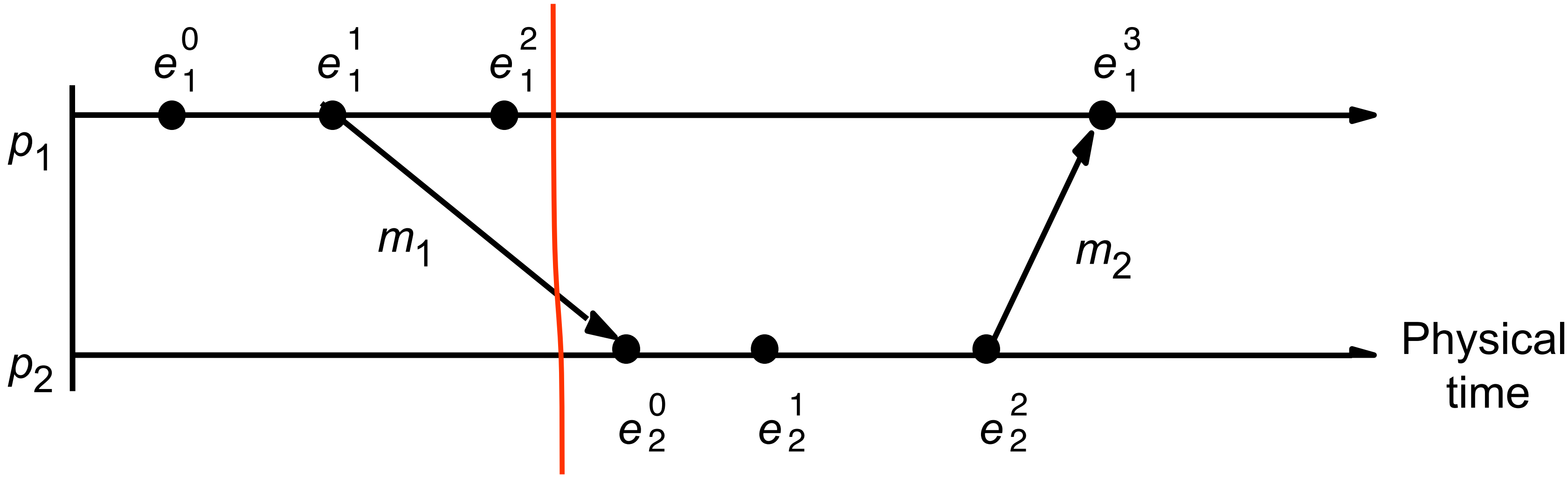

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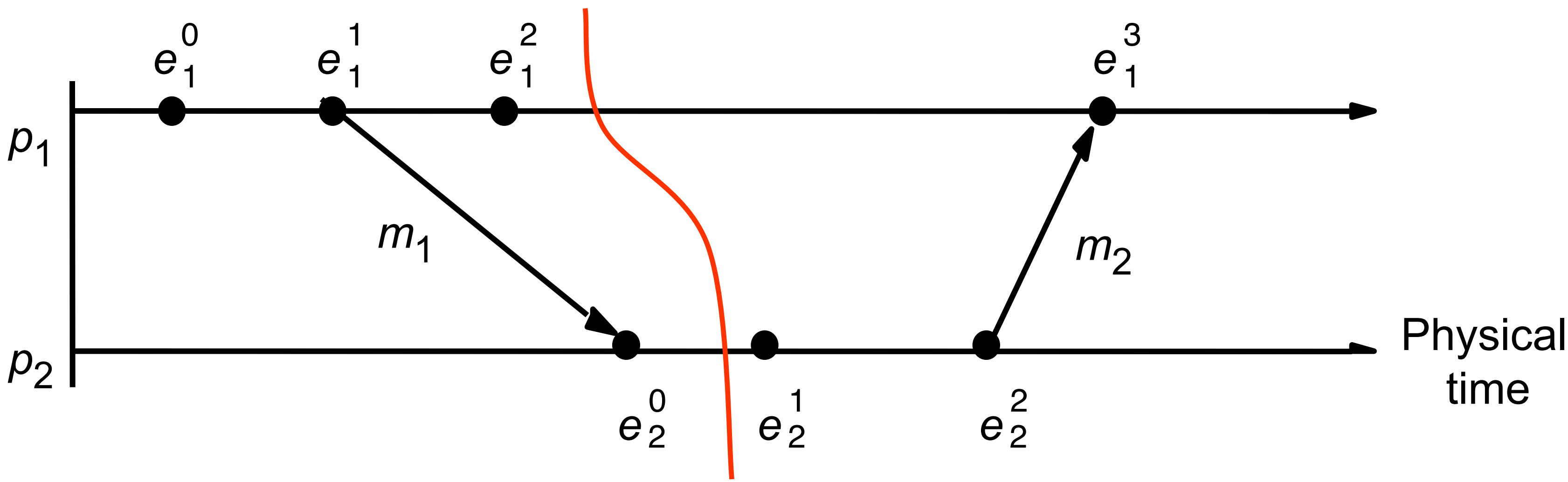

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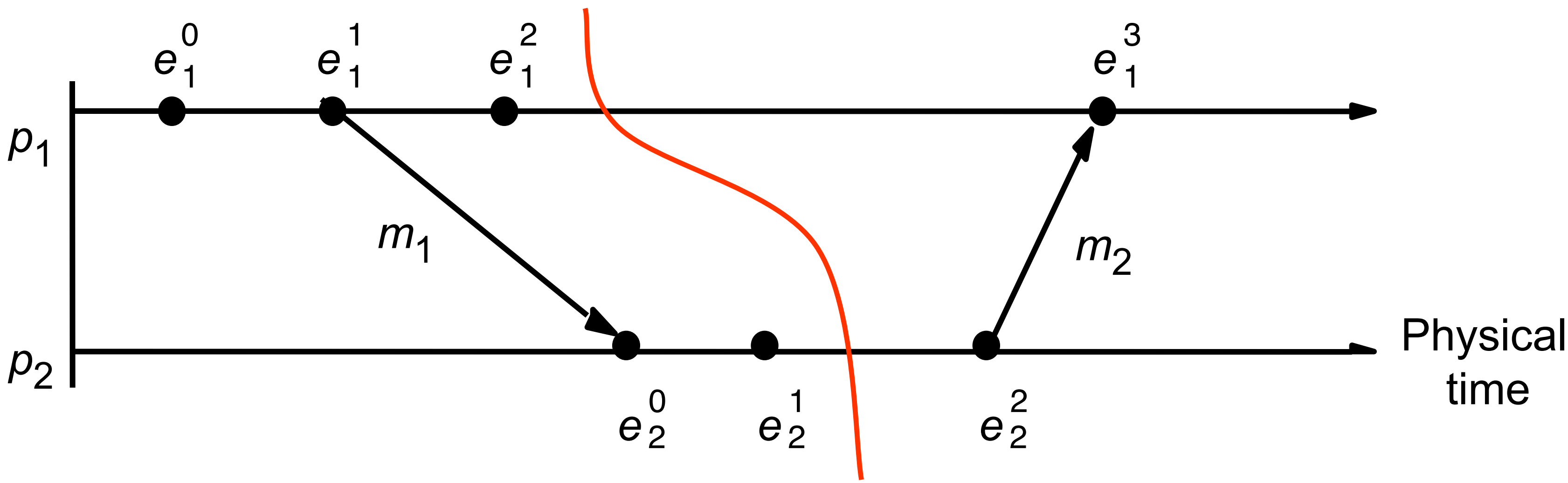

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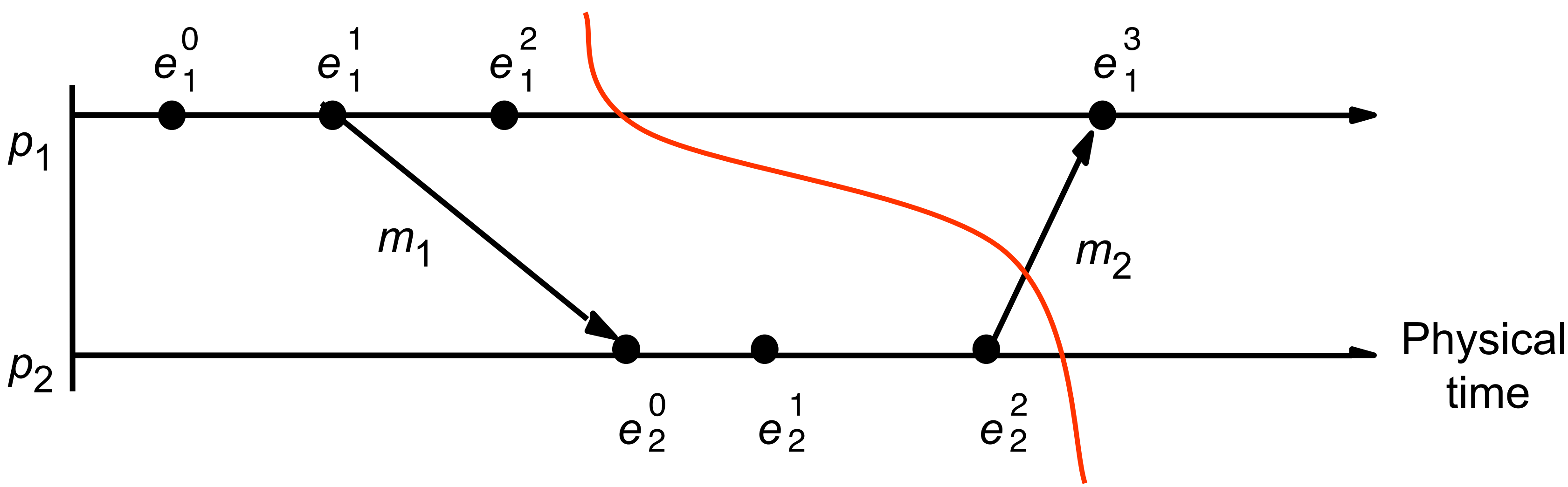

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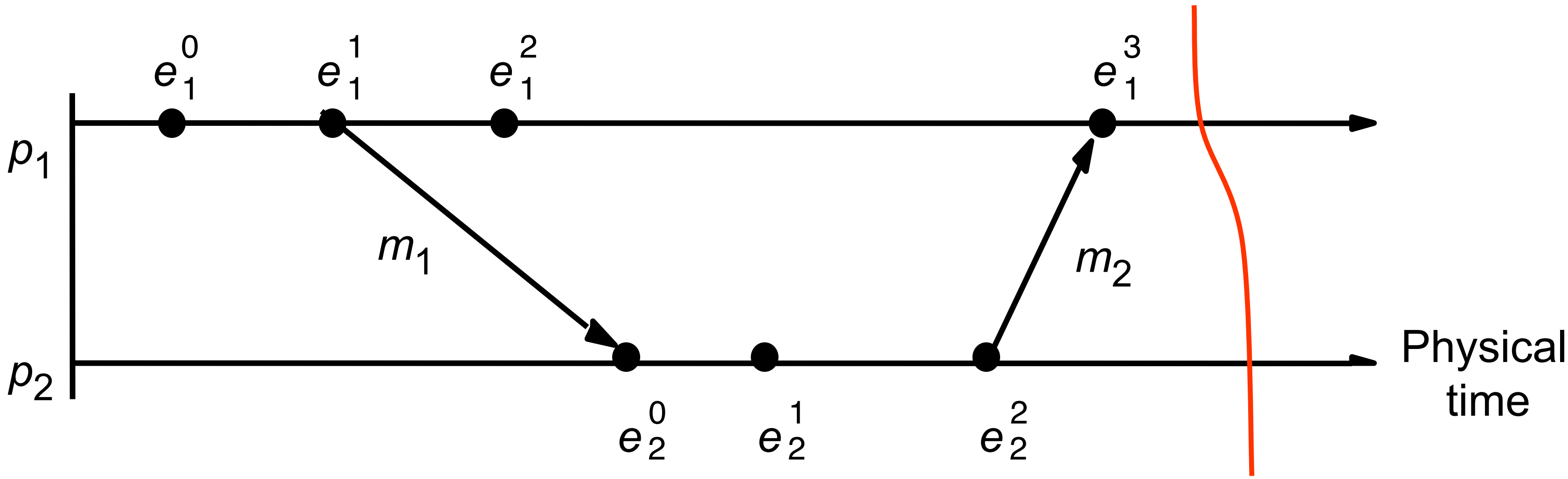

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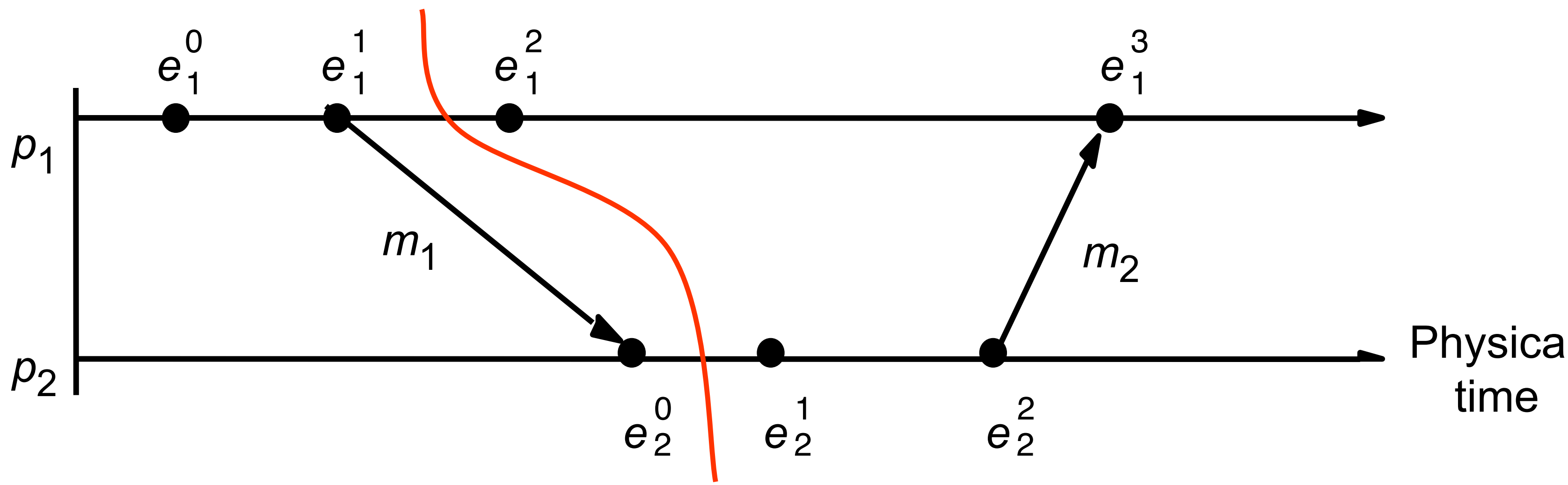

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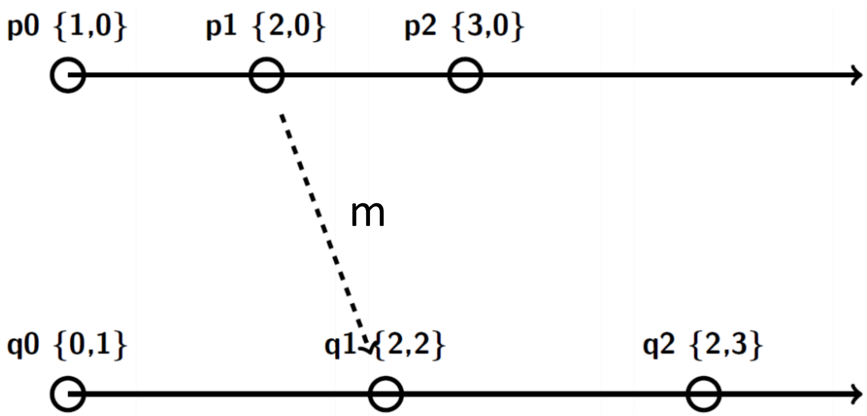
More notations and definitions

- 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



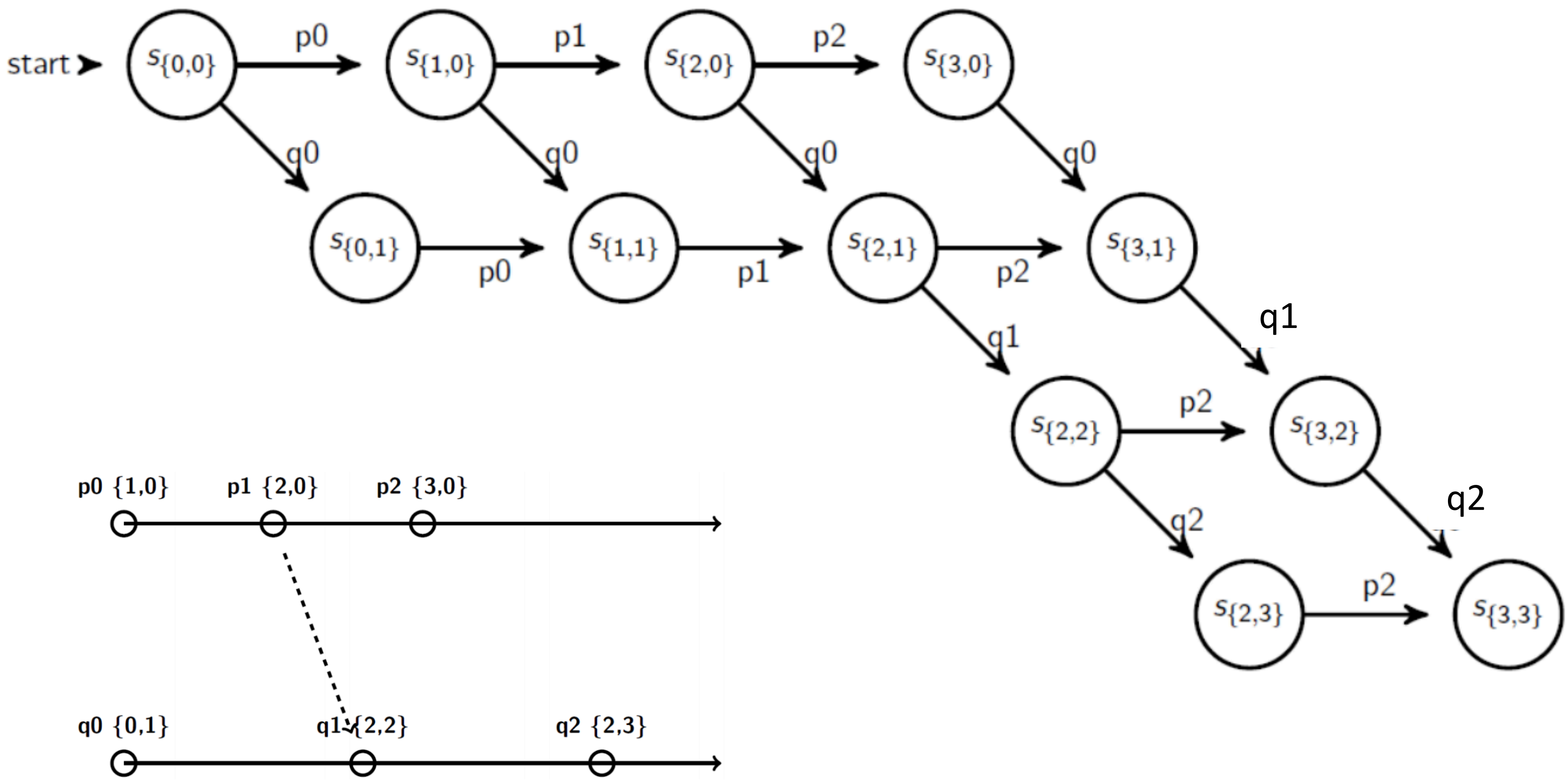
- Causal order:
  - p0 → p1 → p2
  - q0 → q1 → q2
  - p0 → p1 → q1 → q2
- Concurrent:
  - p0 || q0
  - p1 || q0
  - p2 || q0, p2 || q1, p2 || q2

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 represents a linearization.



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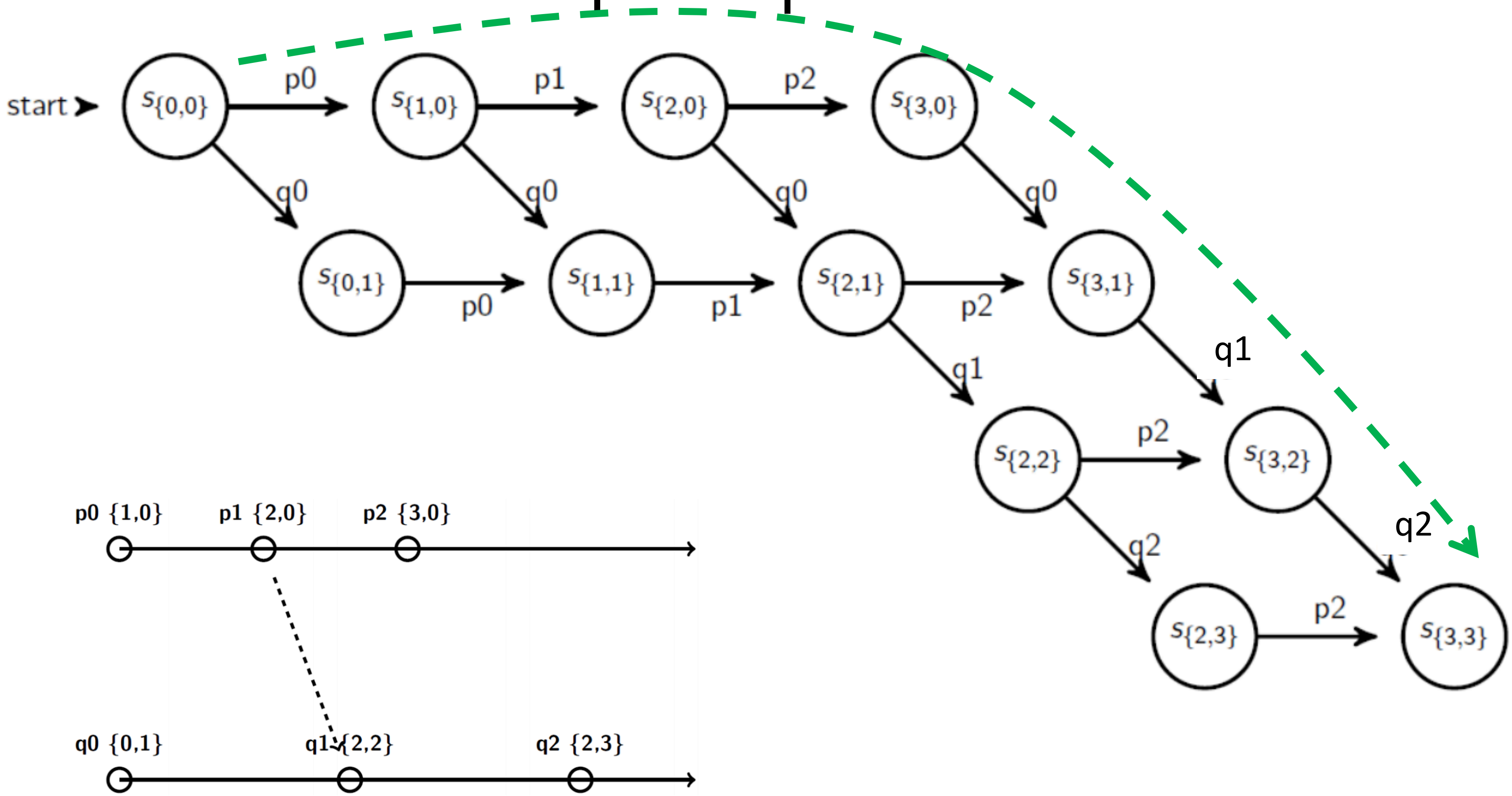

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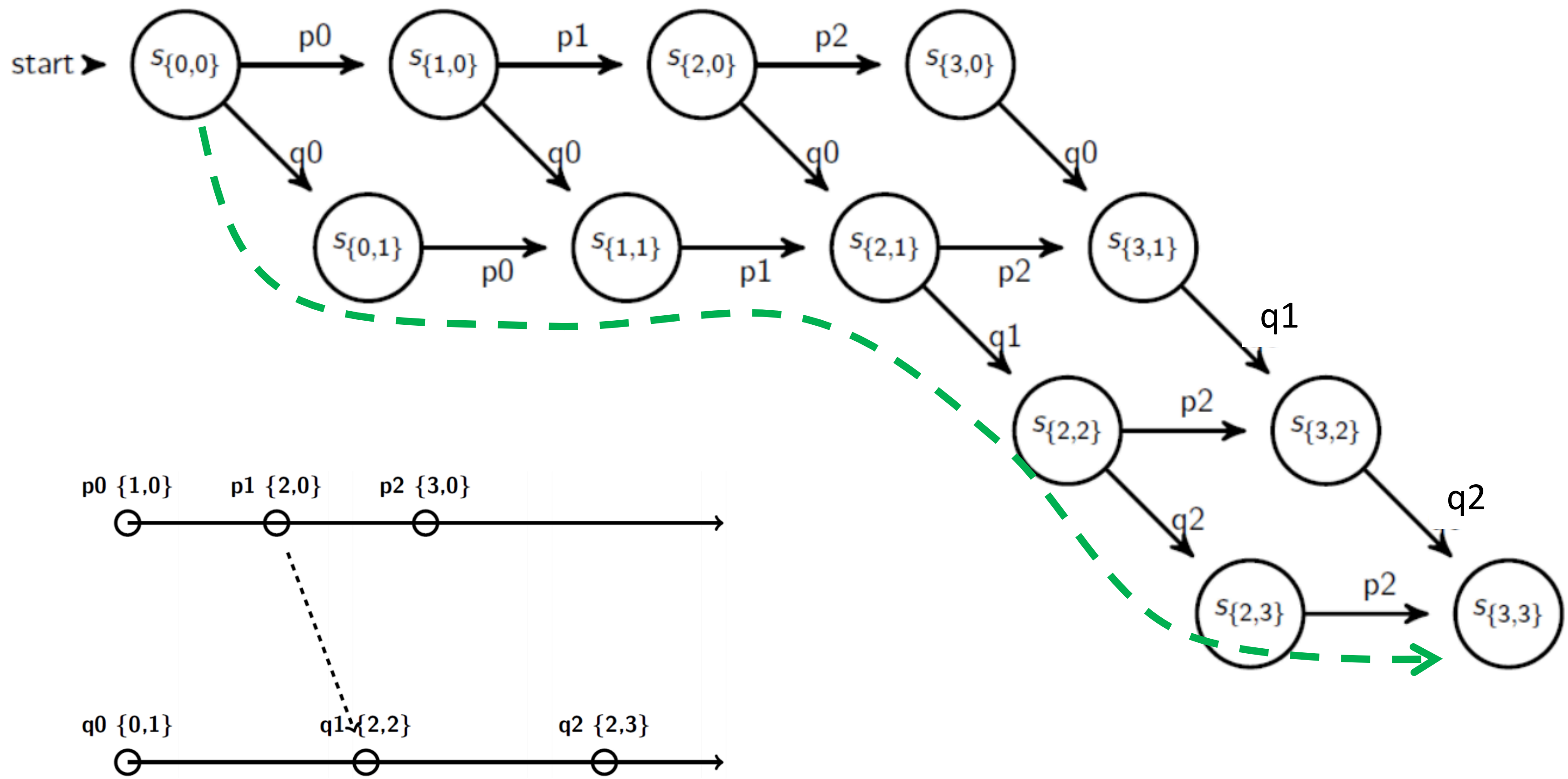

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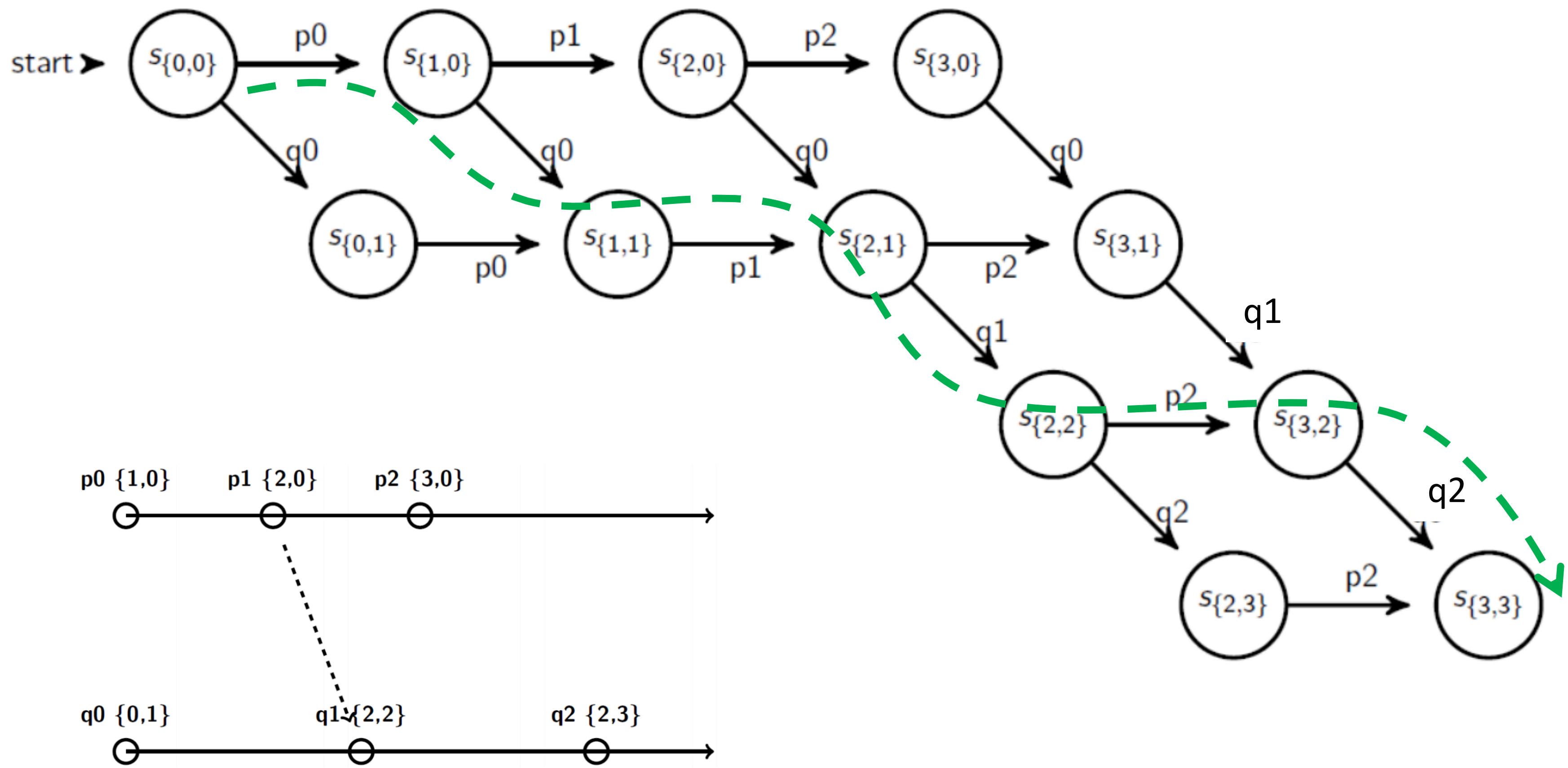

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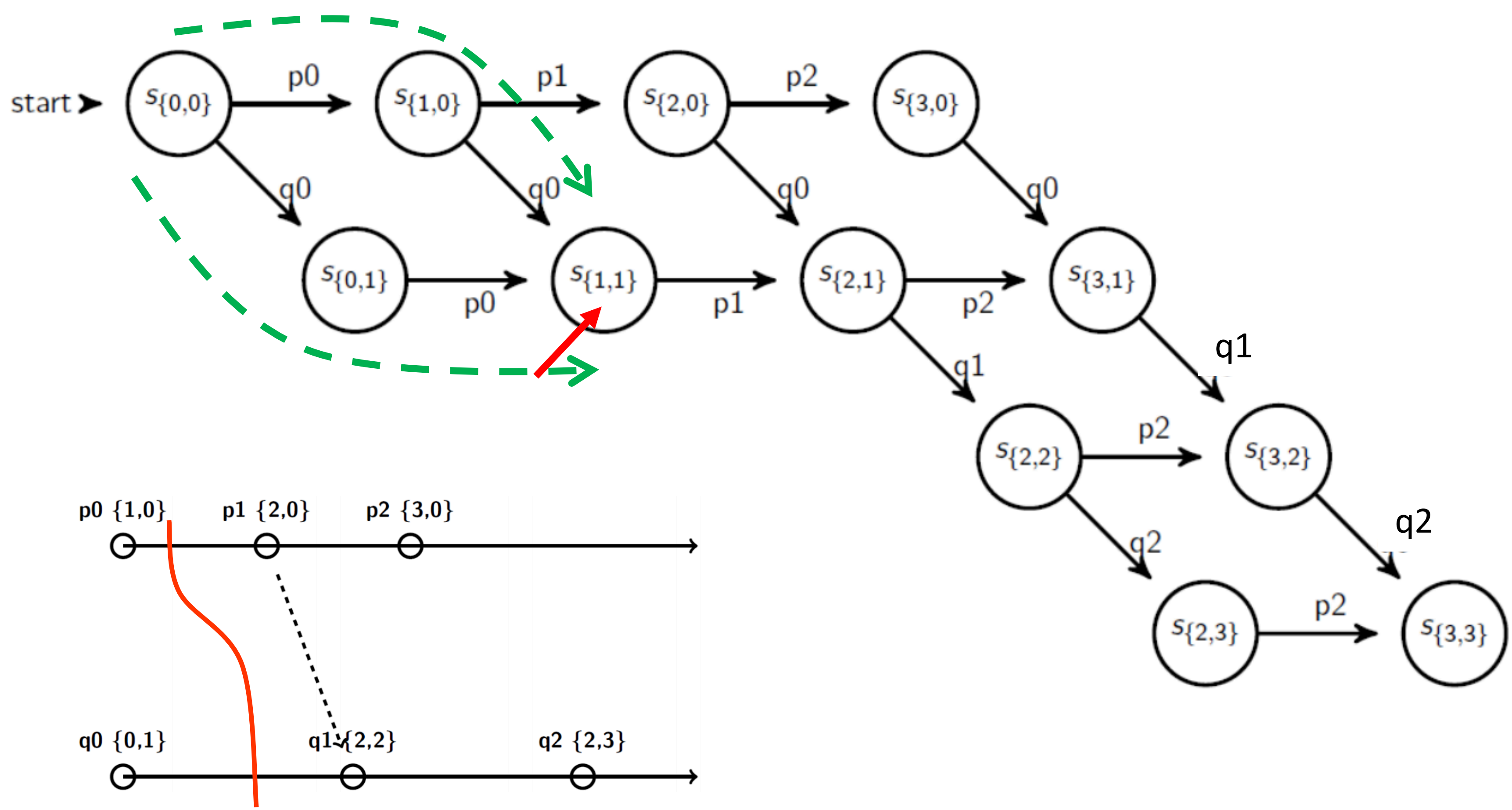

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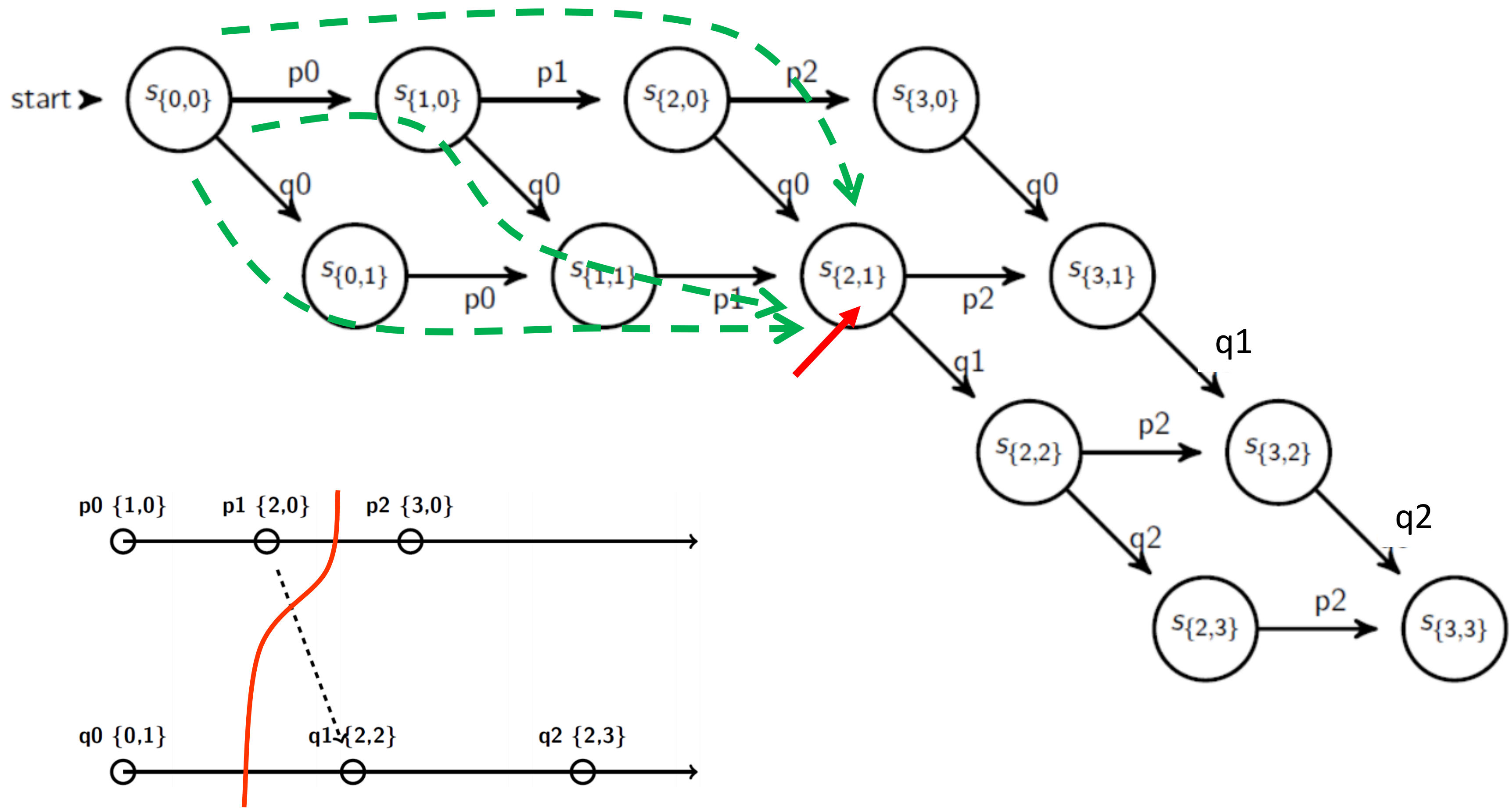

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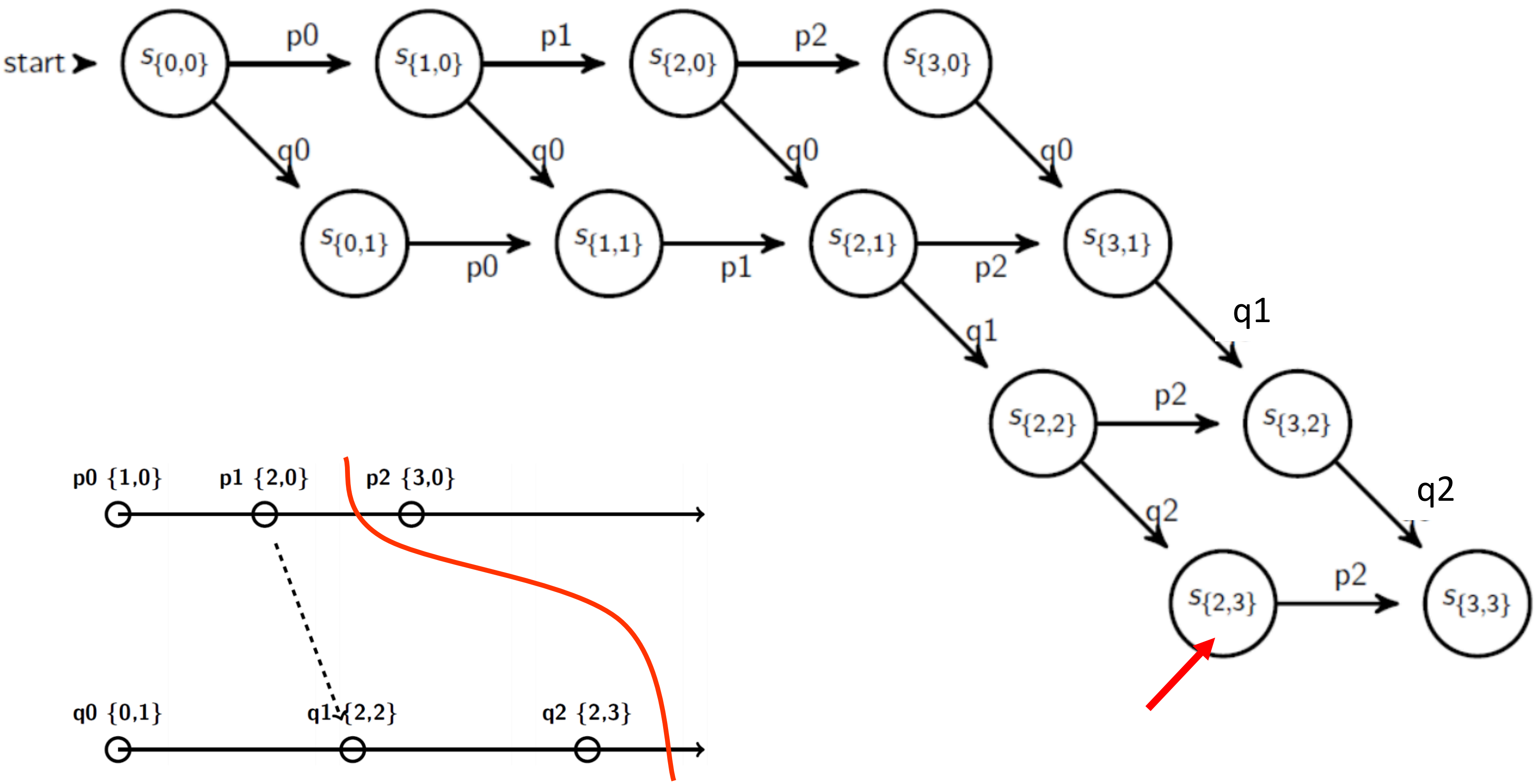

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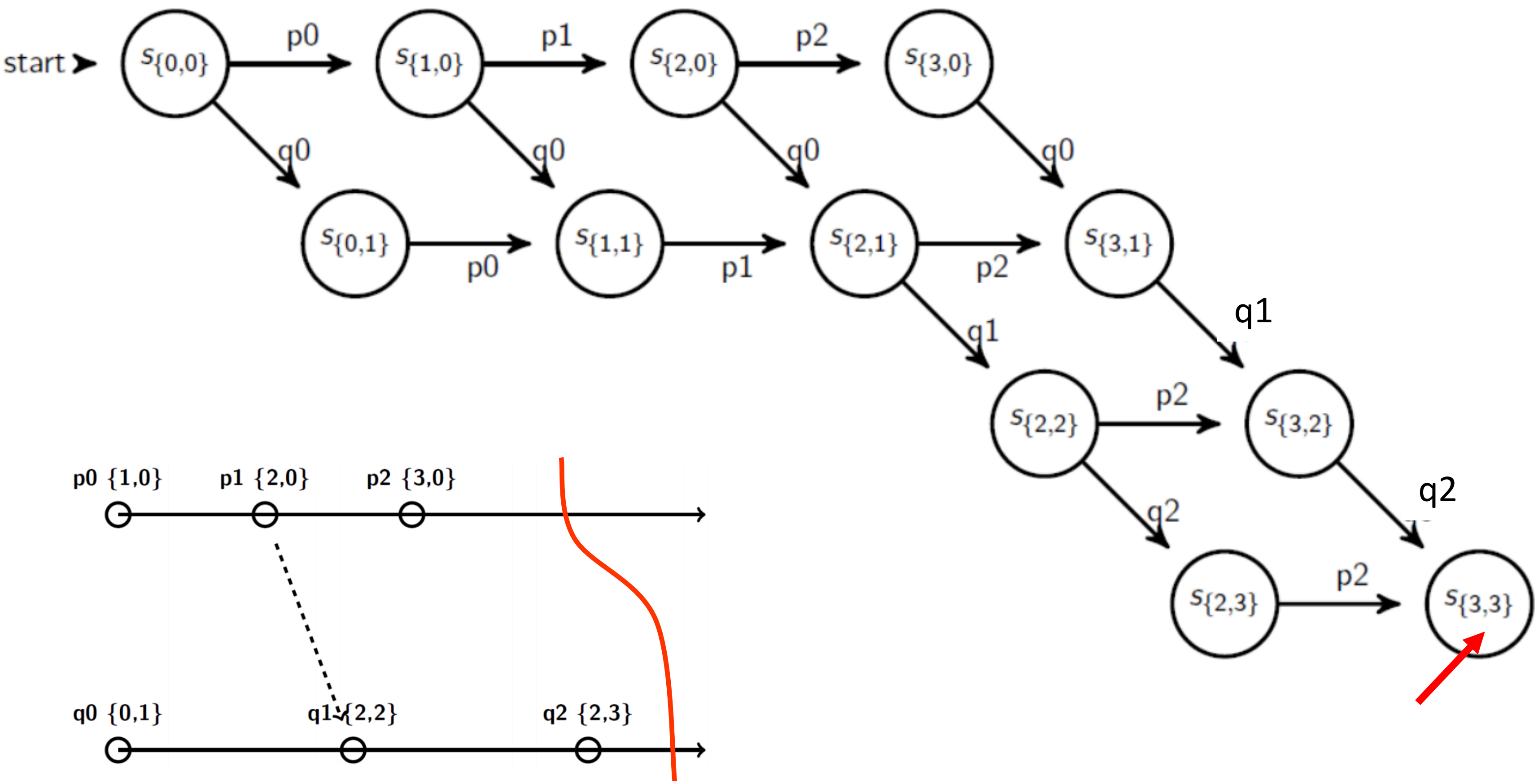

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Global State Predicates

- 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

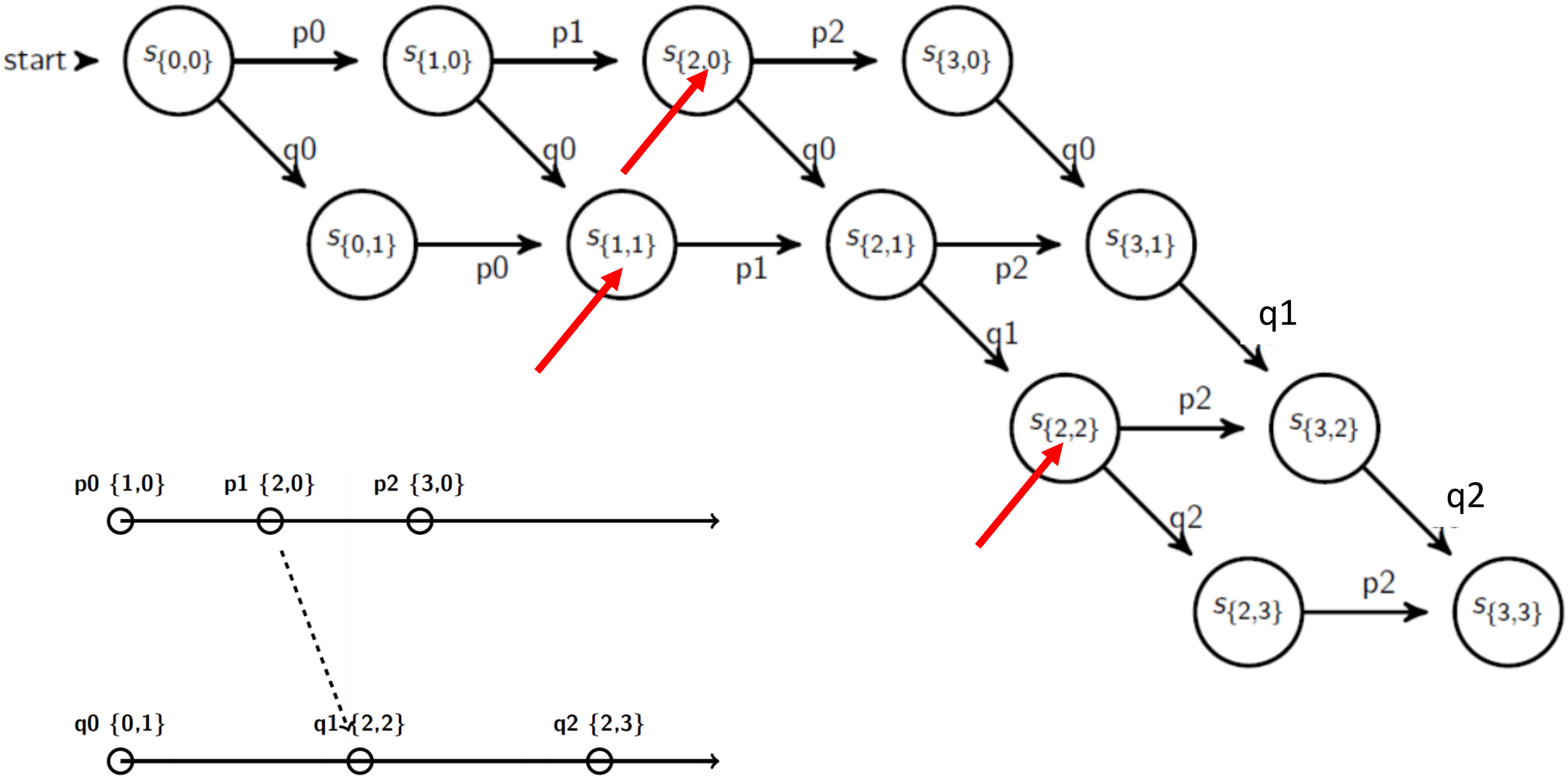
- **Liveness = guarantee that something good will happen, eventually**

- **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:
  - liveness(P(S_0)) $\equiv$ $\forall L \in$ linearizations from S_0, L passes through a S_L & P(S_L) = true
  - For all linearizations 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?
Yes



Liveness Example

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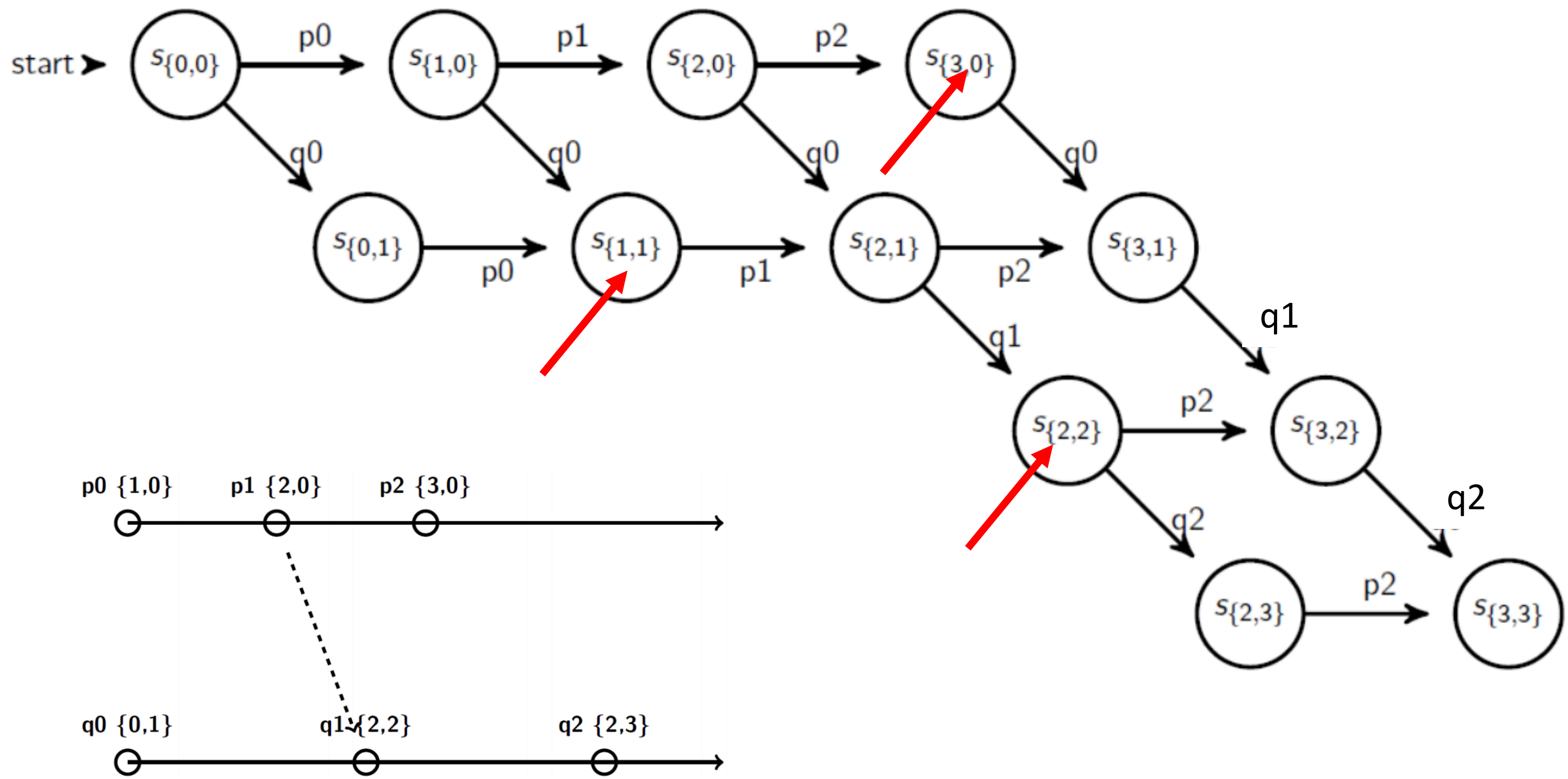
No



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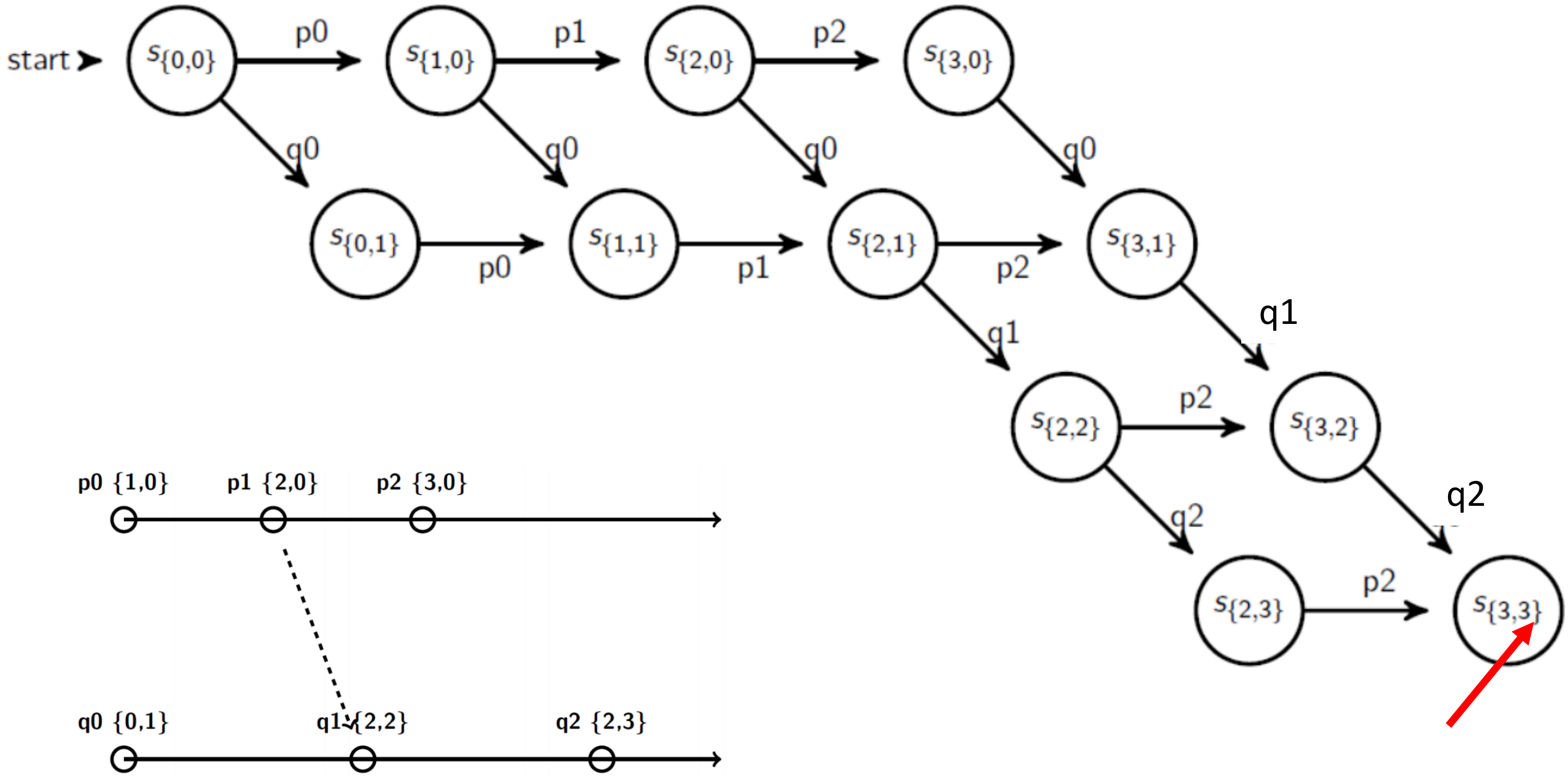

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Safety

- **Safety = guarantee that something bad will never happen.**
- **Examples:**
  - There is no deadlock in a distributed transaction system.
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  - No two processes decide on different values.
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  - $\text{safety}(P(S_0)) \equiv \forall S$ reachable from S_0, $P(S) = \text{true}$.
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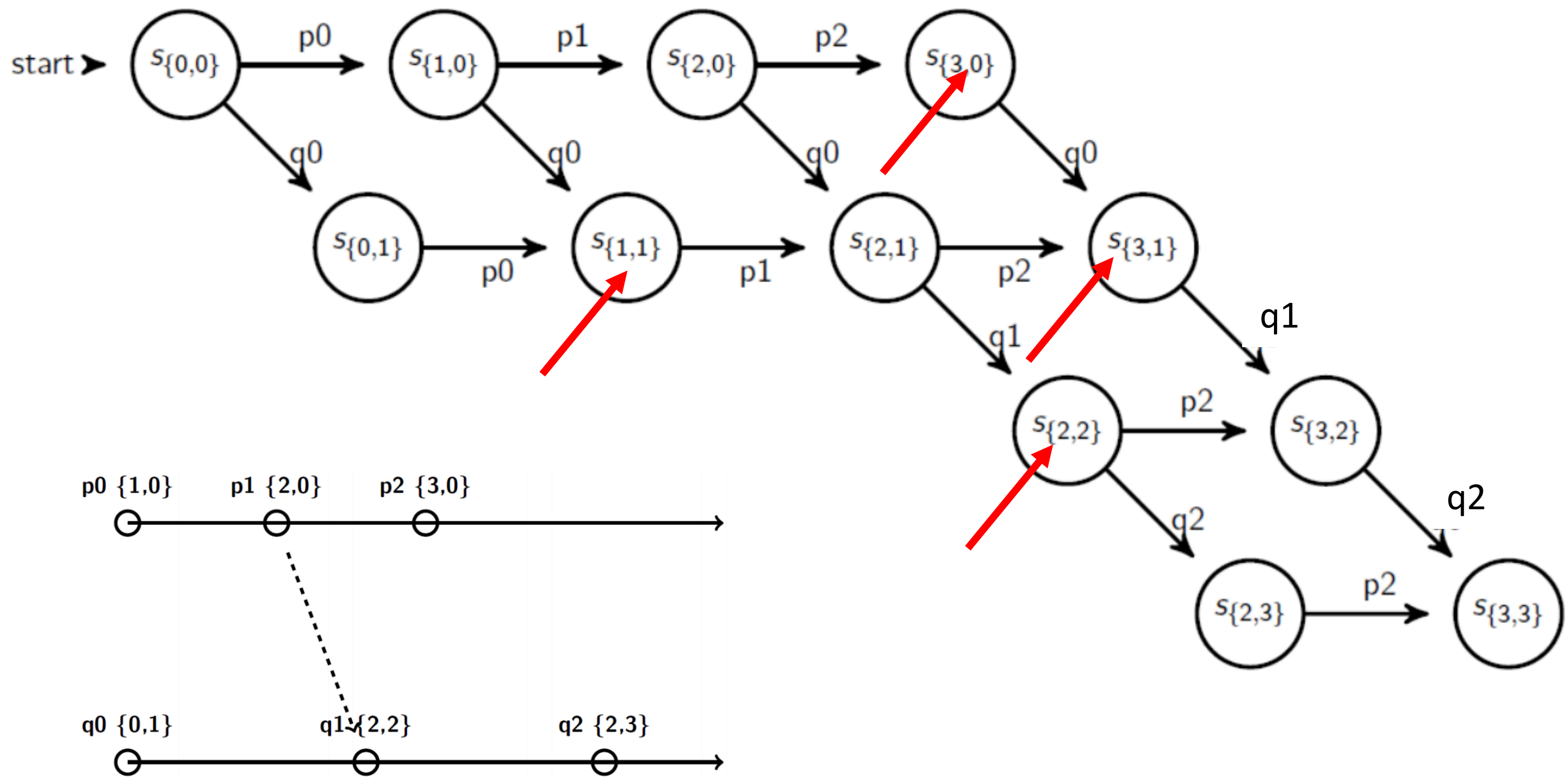
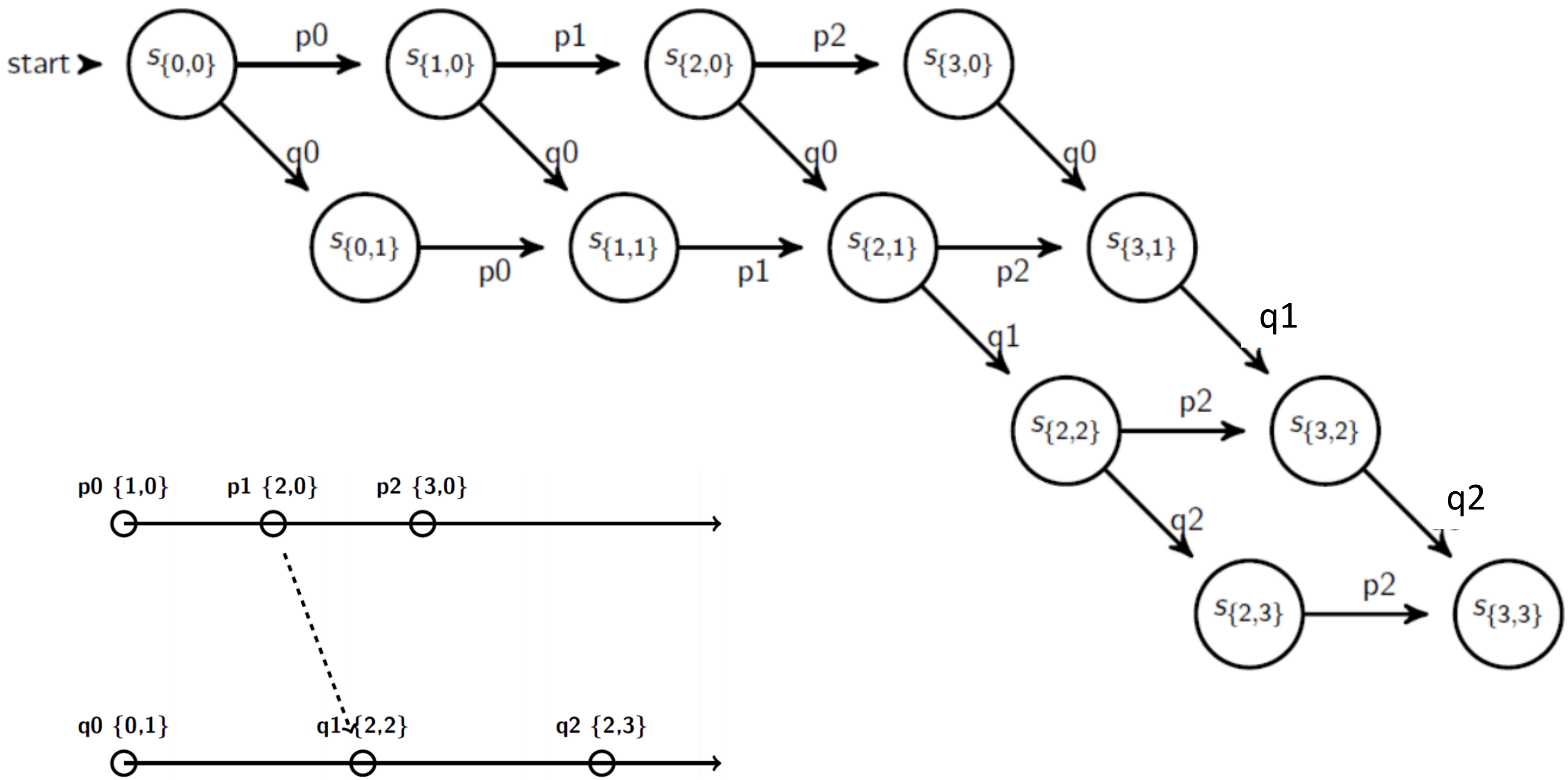


Safety Example

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

Yes



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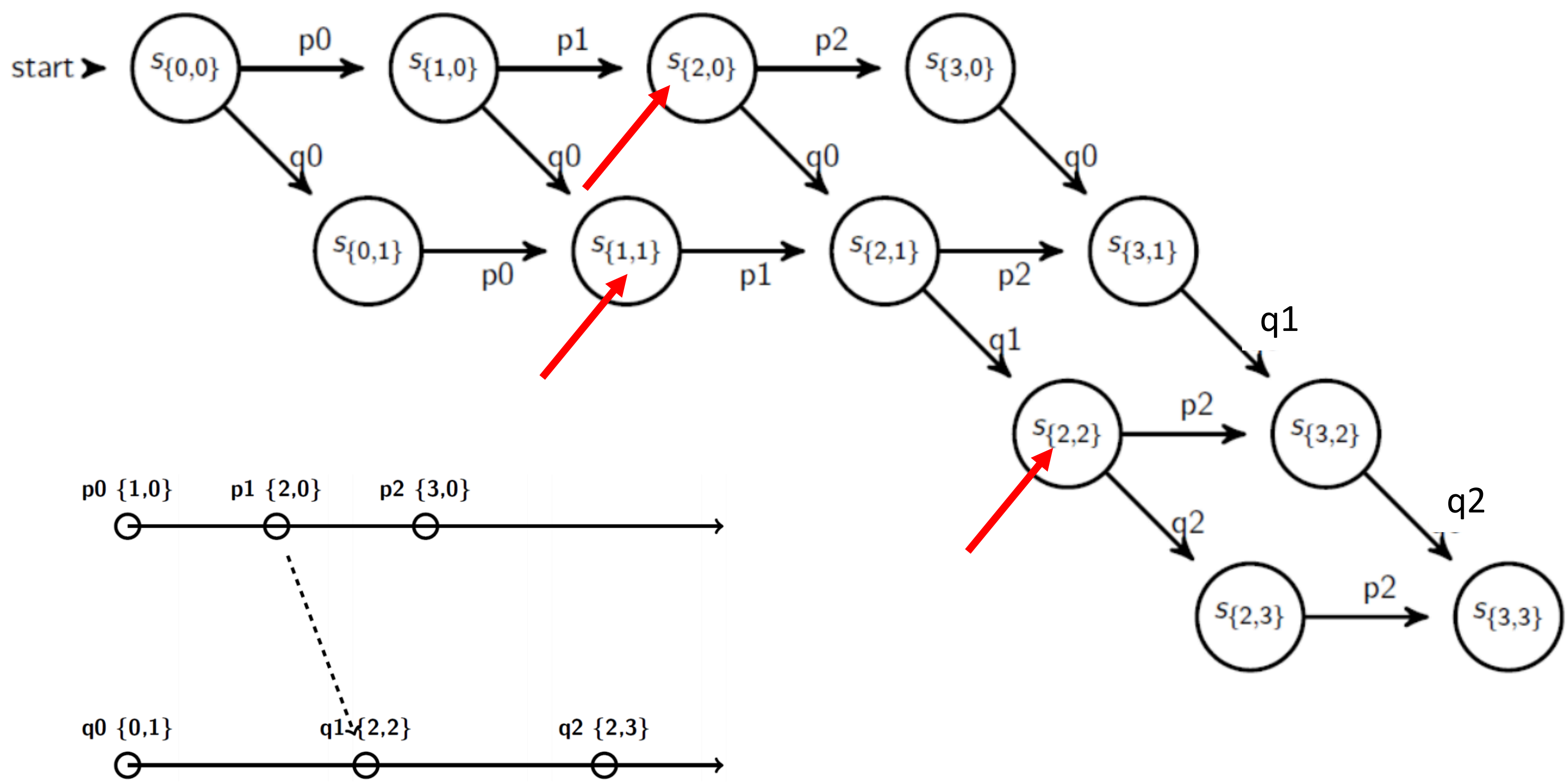
  - $\text{safety}(P(S_0)) \equiv \forall S$ reachable from S_0, $P(S) = \text{true}$.
  - For all states S reachable from S_0, P(S) is true.

Liveness Example

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



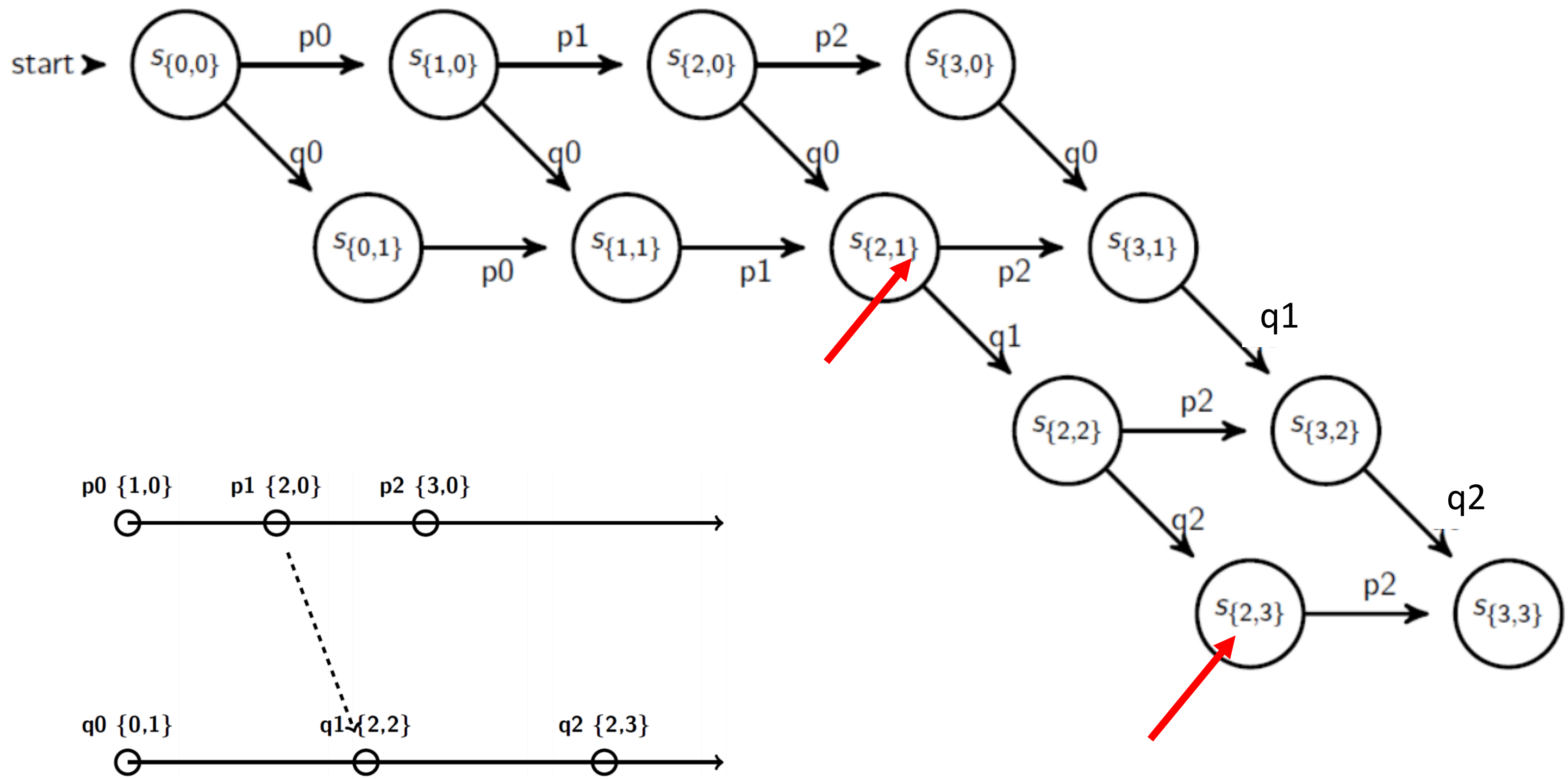
Stable Global Predicates

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

Stable Global Predicates

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

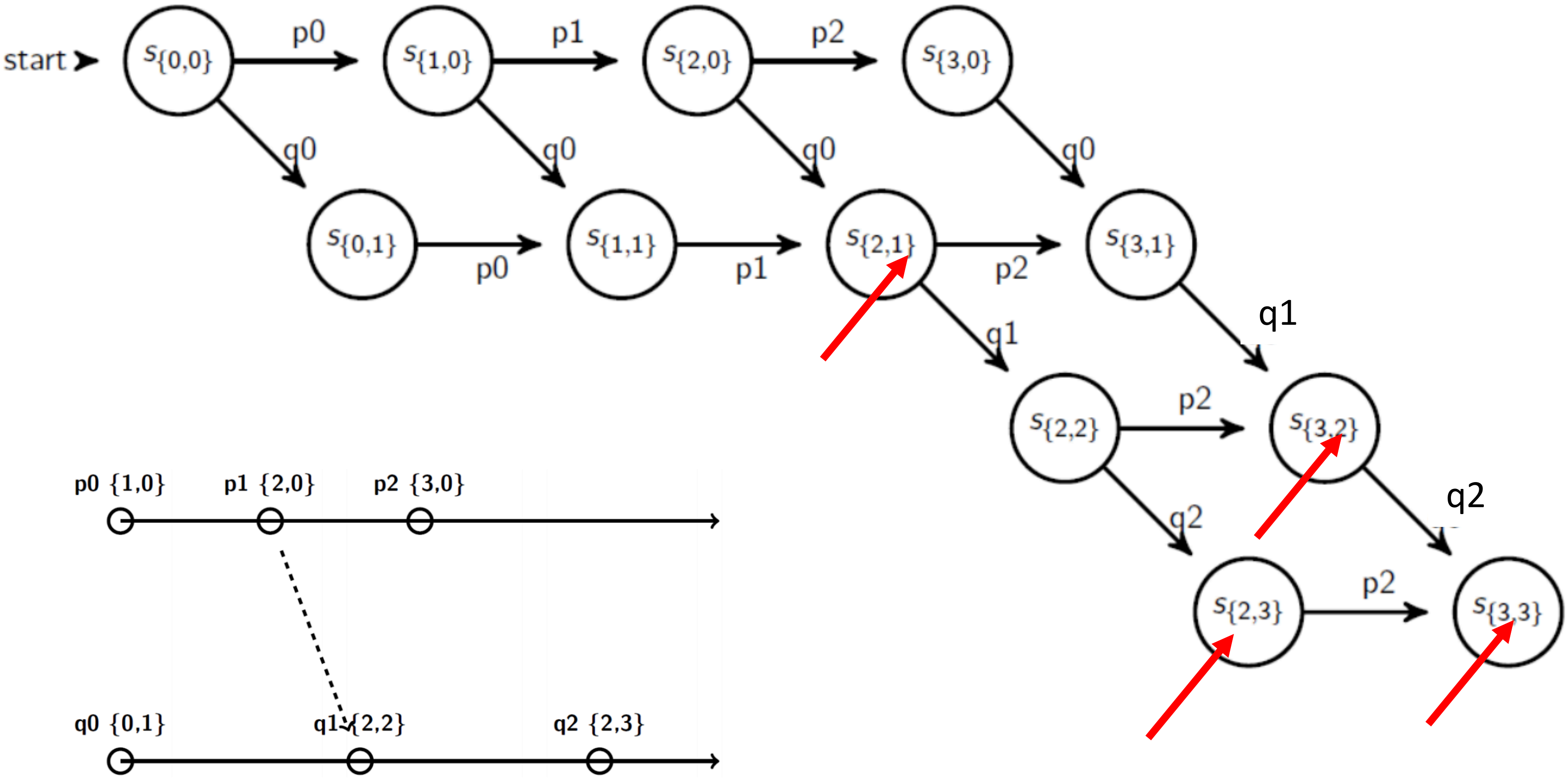
No



Stable Global Predicates

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

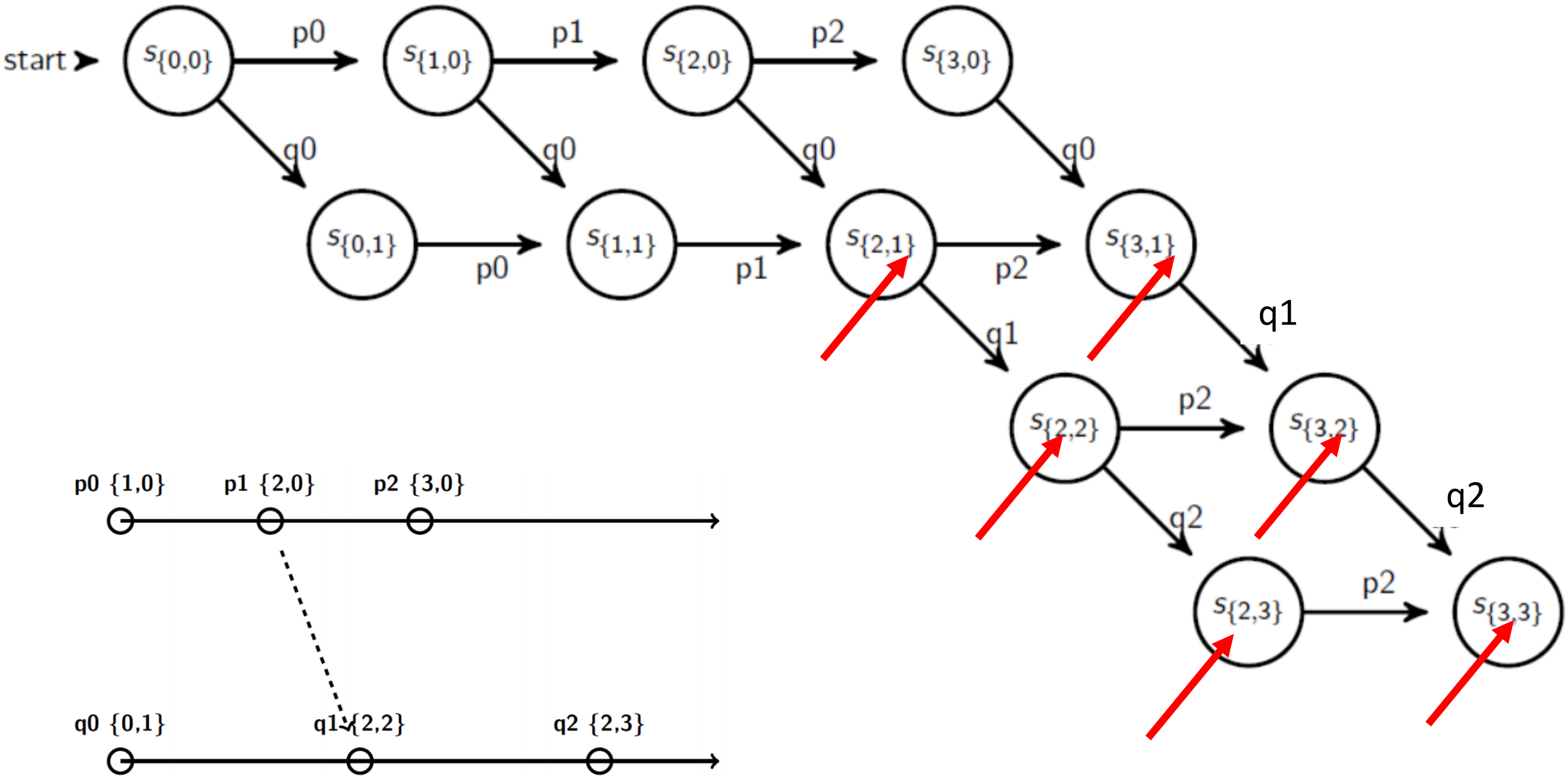
No



Stable Global Predicates

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

Yes



Stable Global Predicates

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