Distributed Systems

CS425/ECE428

02/07/2020

Today’s agenda

- Wrap-up global states and snapshots
  - Chapter 14.5

- ~~Multicast~~
  - ~~Chapter 15.4~~

Recap: Timestamping events

- **Comparing timestamps across events is useful.**
  - e.g. *reconciling updates made to an object in a distributed datastore.*
  - e.g. *rollback recovery during failures.*

- **How to compare timestamps across different processes?**
  - **Physical timestamp:** requires clock synchronization.
    - e.g. Google's Spanner Distributed Database uses "TrueTime".
  - **Lamport's timestamps:** cannot fully differentiate between causal and concurrent ordering of events.
    - e.g. Oracle uses "System Change Numbers" based on Lamport's clock.
  - **Vector timestamps:** larger message sizes.
    - e.g. Amazon's DynamoDB uses vector clocks.

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* the system state.
  - Reasoning about unreferenced objects (for garbage collection).
  - Deadlock detection.
  - Distributed debugging.

Recap: Global snapshot

- State of each process (and each channel) in the system at a given instant of time.

- Difficult to capture a global snapshot of the system.
  - Requires precise clock synchronization across processes.

- *How do we capture global snapshots without precise time synchronization across processes?*
  - Relax the requirement for capturing the state of different processes and channels at the same real time instant.
  - As long as the global state is *consistent*, it is still useful.

Recap: more notations and definitions

- For a process $\mathbf{p_i}$, where events $\mathbf{e_i^0, e_i^1}$, … occur:

  history(p_i) = h_i = <$e_i^0, e_i^1, \ldots$ >

  prefix history(p_i^k) = h_i^k = <$e_i^0, e_i^1, \ldots, e_i^k$ >

  s_i^k : $\mathbf{p_i}$'s state immediately after k^{th} event.

- For a set of processes <$p_1, p_2, p_3, \ldots, p_n$>:

  global history: $H = \cup_i (h_i)$

  a **cut** $C \subseteq H = h_1^{c_1} \cup h_2^{c_2} \cup \ldots \cup h_n^{c_3}$

  the **frontier** of $C = \{e_i^{c_i}, i = 1,2, \ldots n\}$

  global state S that corresponds to cut $C = \cup_i (s_i^{c_i})$

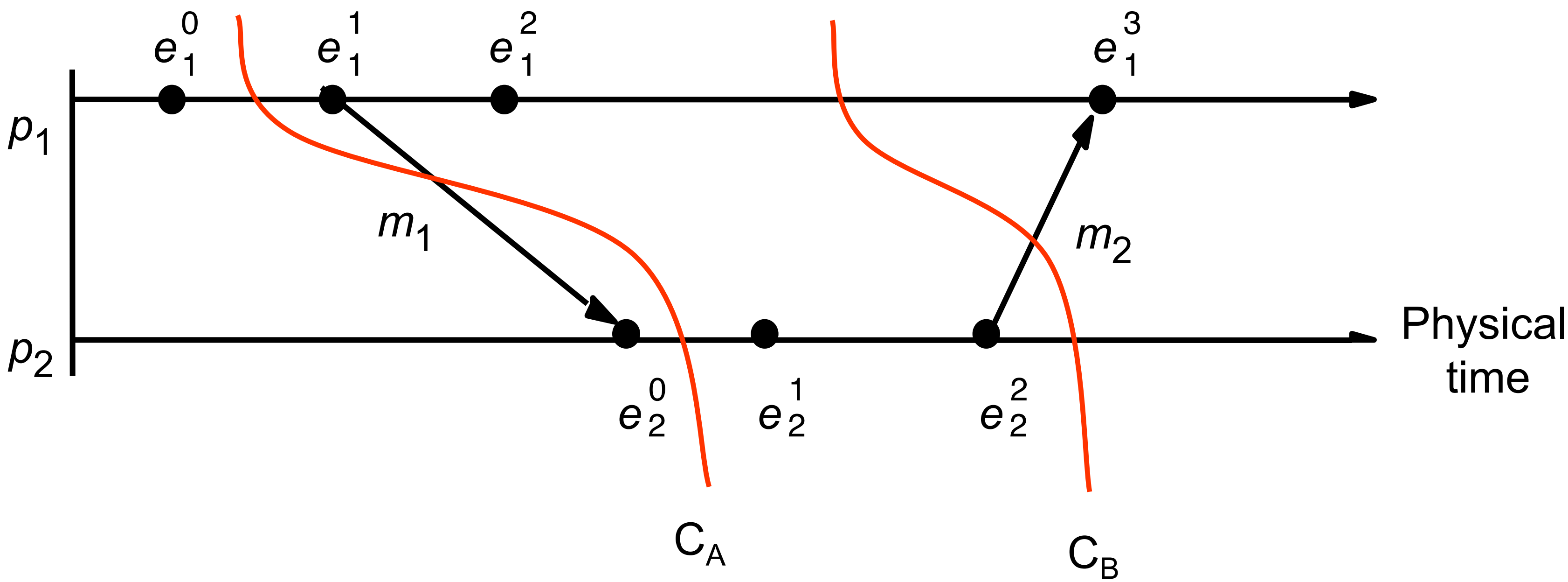
Recap: consistent cuts and snapshots

- A cut **C** is **consistent** if and only if

$$\forall \mathbf{e} \in \mathbf{C} \; (\text{if } \mathbf{f} \rightarrow \mathbf{e} \text{ then } \mathbf{f} \in \mathbf{C})$$

- A global state **S** is consistent if and only if it corresponds to a consistent cut.

Recap: Example: Cut



C_A: < e_1^0, e_2^0>
Frontier of C_A: {e_1^0, e_2^0}
Inconsistent cut.

C_B: < e_1^0, e_1^1, e_1^2, e_2^0, e_2^1 e_2^2 >
Frontier of C_B: {e_1^2, e_2^2}
Consistent cut.

Recap: Consistent cuts and snapshots

- A cut **C** is **consistent** if and only if

$$\forall \mathbf{e} \in \mathbf{C} \text{ (if } \mathbf{f} \rightarrow \mathbf{e} \text{ then } \mathbf{f} \in \mathbf{C}\text{)}$$

- A global state **S** is consistent if and only if it corresponds to a consistent cut.

- *How do we find consistent global states?*

Recap: Chandy-Lamport Algorithm

- Goal:
  - Record a global snapshot
    - Set of process state (and channel state) for a set of processes.
  - The recorded global state is consistent.
- Identifies a consistent cut.
- Records corresponding state locally at each process.

Recap: Chandy-Lamport Algorithm

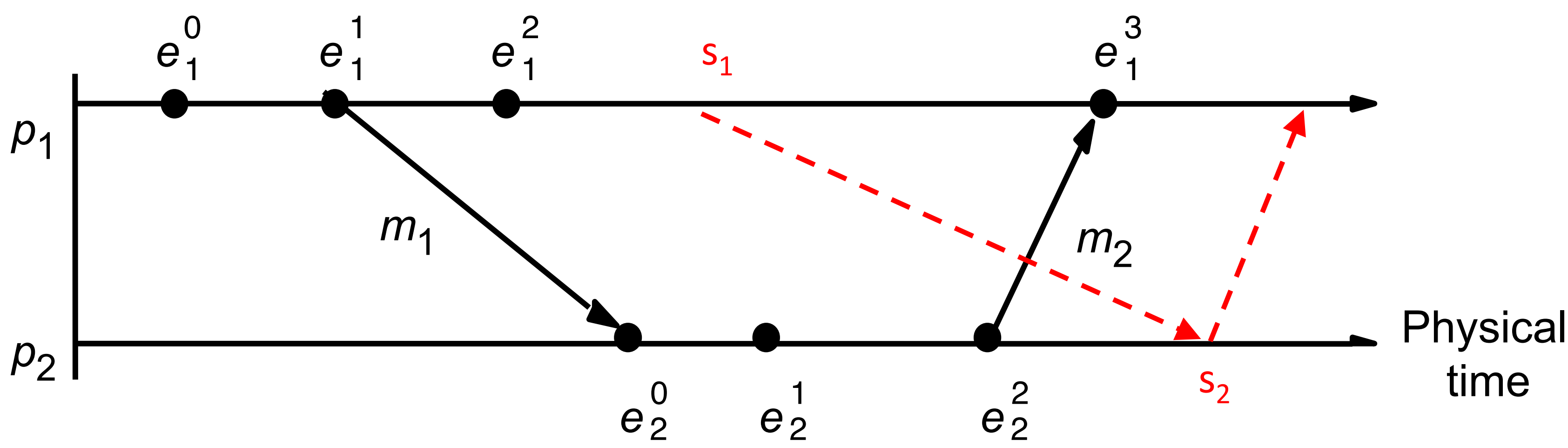
- *System model and assumptions:*
  - System of **n** processes: $<p_1, p_2, p_3, \ldots., p_n>$.
  - There are two uni-directional communication channels between each ordered process pair : p_j to p_i and p_i to p_j.
  - Communication channels are FIFO-ordered (first in first out).
  - All messages arrive intact, and are not duplicated.
  - No failures: neither channel nor processes fail.
- *Requirements:*
  - Snapshot should not interfere with normal application actions, and it should not require application to stop sending messages.
  - Any process may initiate algorithm.

Chandy-Lamport Algorithm Intuition

- First, initiator p_i:
  - records its own state.
  - creates a special **marker** message.
  - sends the **marker** to all other process.

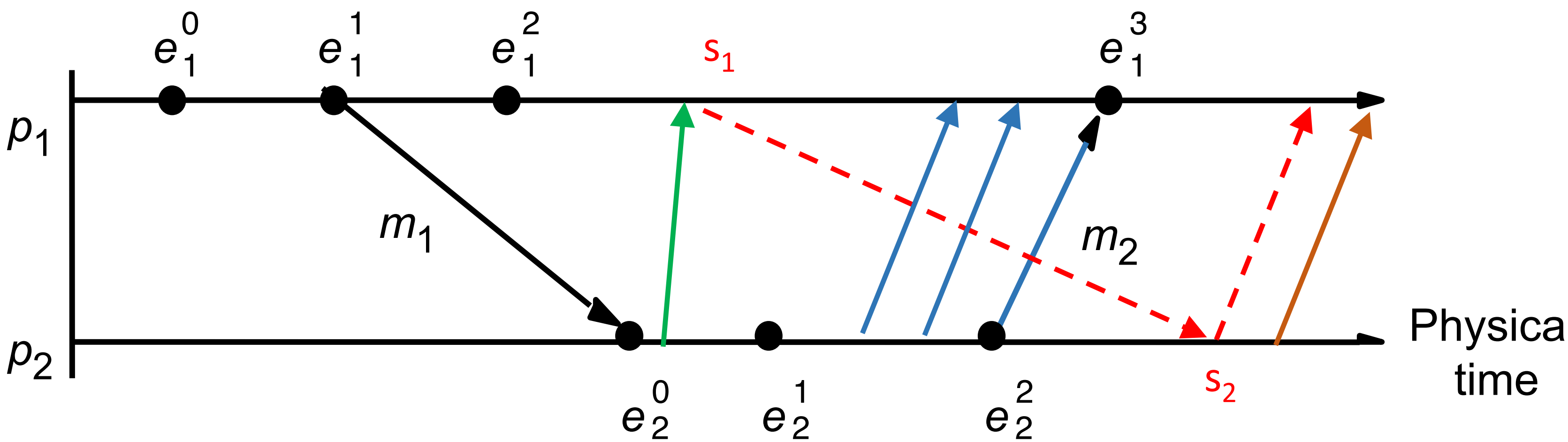
- When a process receives a **marker**.
  - records its own state.

Chandy-Lamport Algorithm Intuition



Cut frontier: $\{e_1{}^2, e_2{}^2\}$

Chandy-Lamport Algorithm Intuition



Cut frontier: $\{e_1^2, e_2^2\}$

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

- First, initiator **p_i**:
  - records its own state.
  - creates a special **marker** message.
  - for *j=1 to n* except *i*
    - **p_i** sends a **marker** message on outgoing channel **c_{ij}**
    - starts recording the incoming messages on each of the incoming channels at **p_i** : **c_{ji}** (for *j=1 to n* except *i*).

Chandy-Lamport Algorithm

Whenever a process p_i receives a **marker** message on an incoming channel c_{ki}

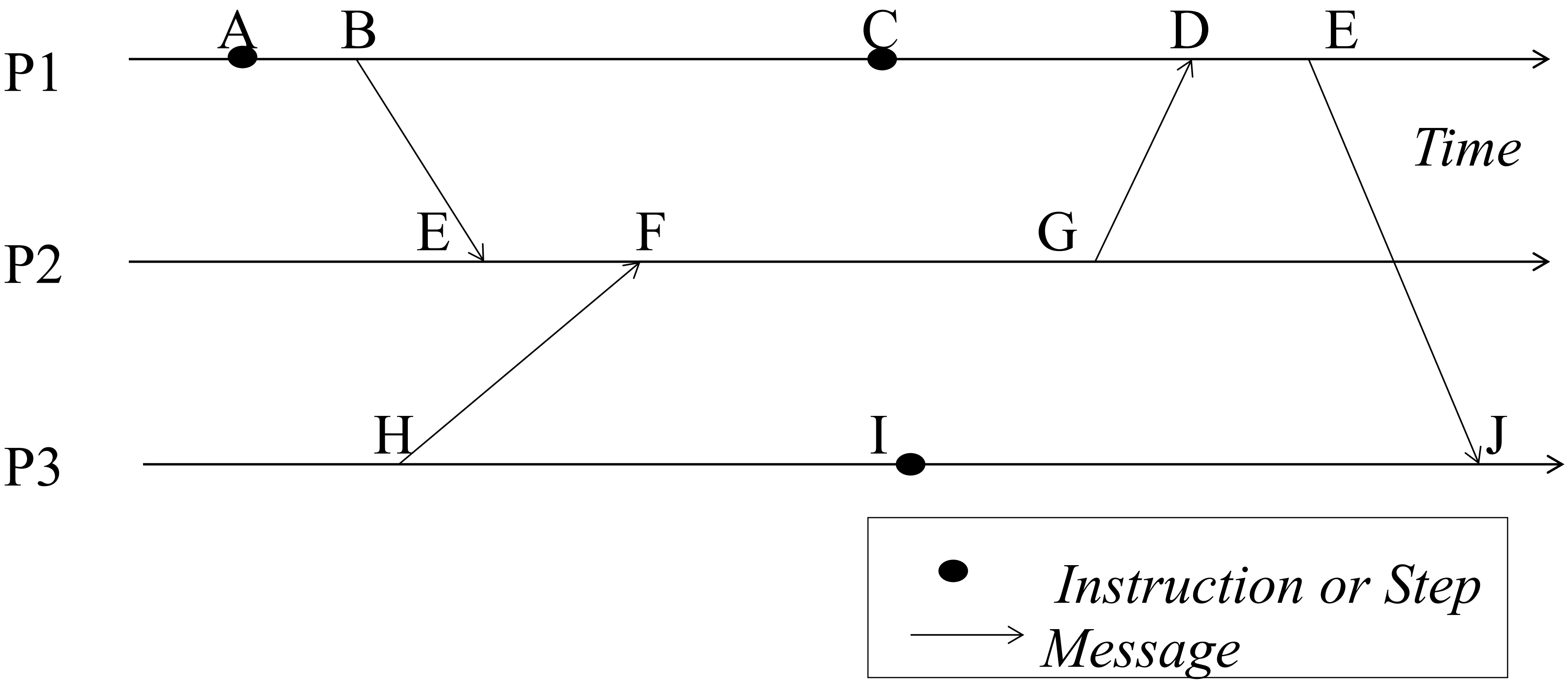
- if (this is the first **marker** p_i is seeing)
  - p_i records its own state first
  - marks the state of channel c_{ki} as "empty"
  - for j=1 to n except i
    - p_i sends out a **marker** message on outgoing channel c_{ij}
  - starts recording the incoming messages on each of the incoming channels at p_i : c_{ji} (for *j=1 to n* except *i and k*).
- else // already seen a **marker** message
  - mark the state of channel c_{ki} as all the messages that have arrived on it since recording was turned on for c_{ki}

Chandy-Lamport Algorithm

The algorithm terminates when

- All processes have received a **marker**
  - To record their own state
- All processes have received a **marker** on all the (n-1) incoming channels
  - To record the state of all channels

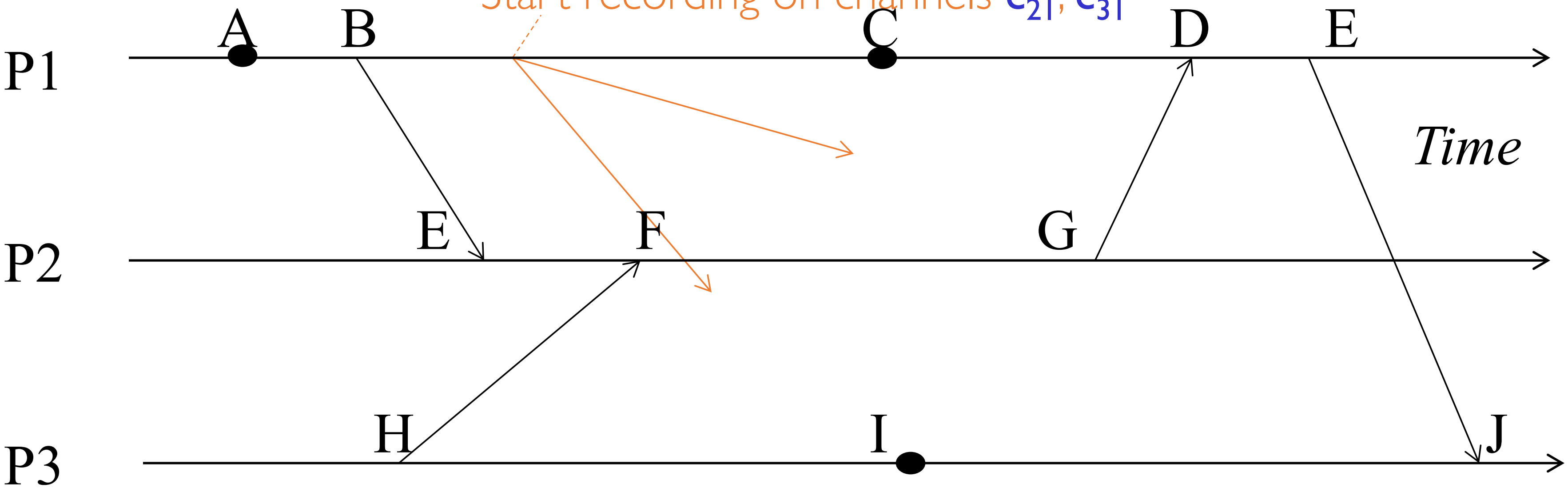
Example



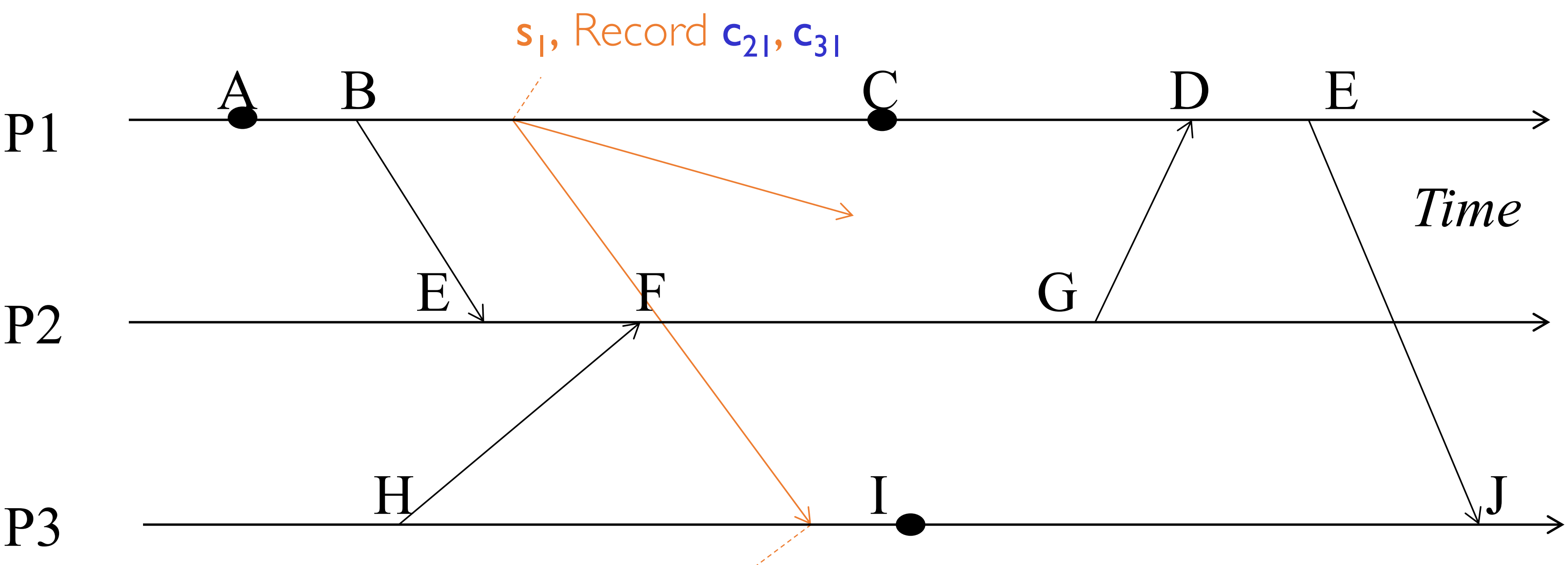
Example

p_1 is initiator:

- Record local state s_1,
- Send out markers
- Start recording on channels c_{21}, c_{31}

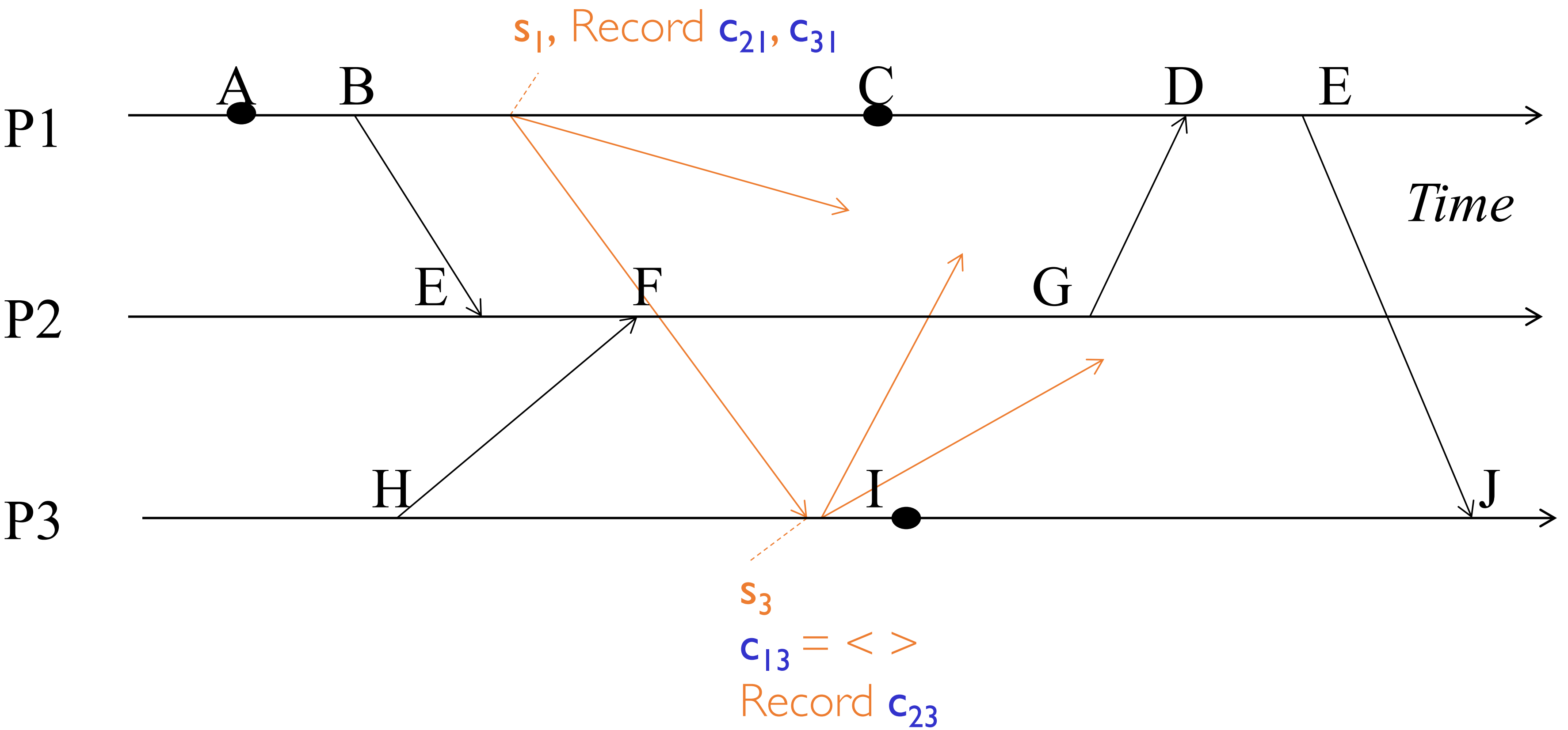


Example

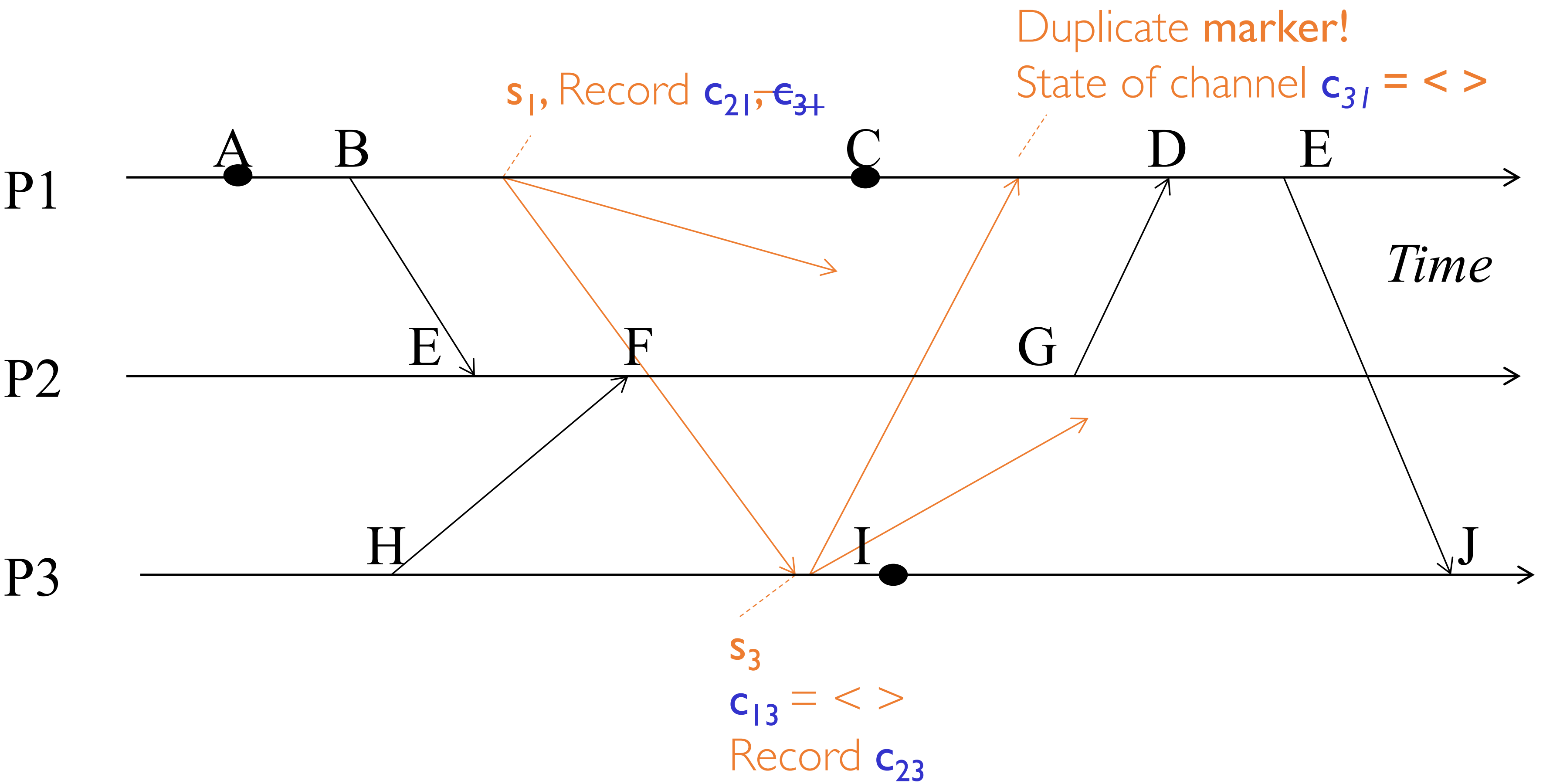


- First **marker**!
- Record own state as s_3
- Mark c_{13} state as empty
- Start recording on other incoming c_{23}
- Send out markers

Example

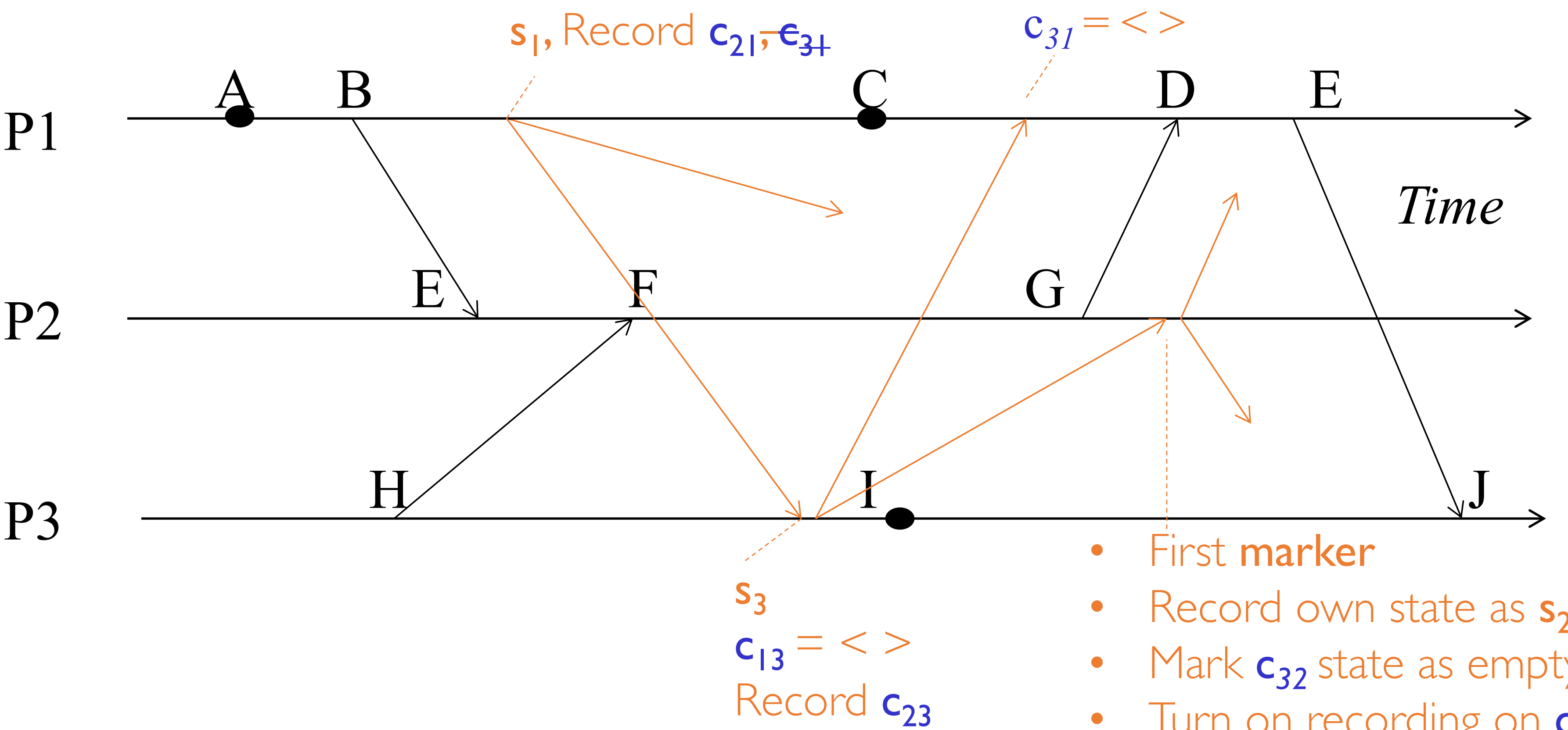


Example



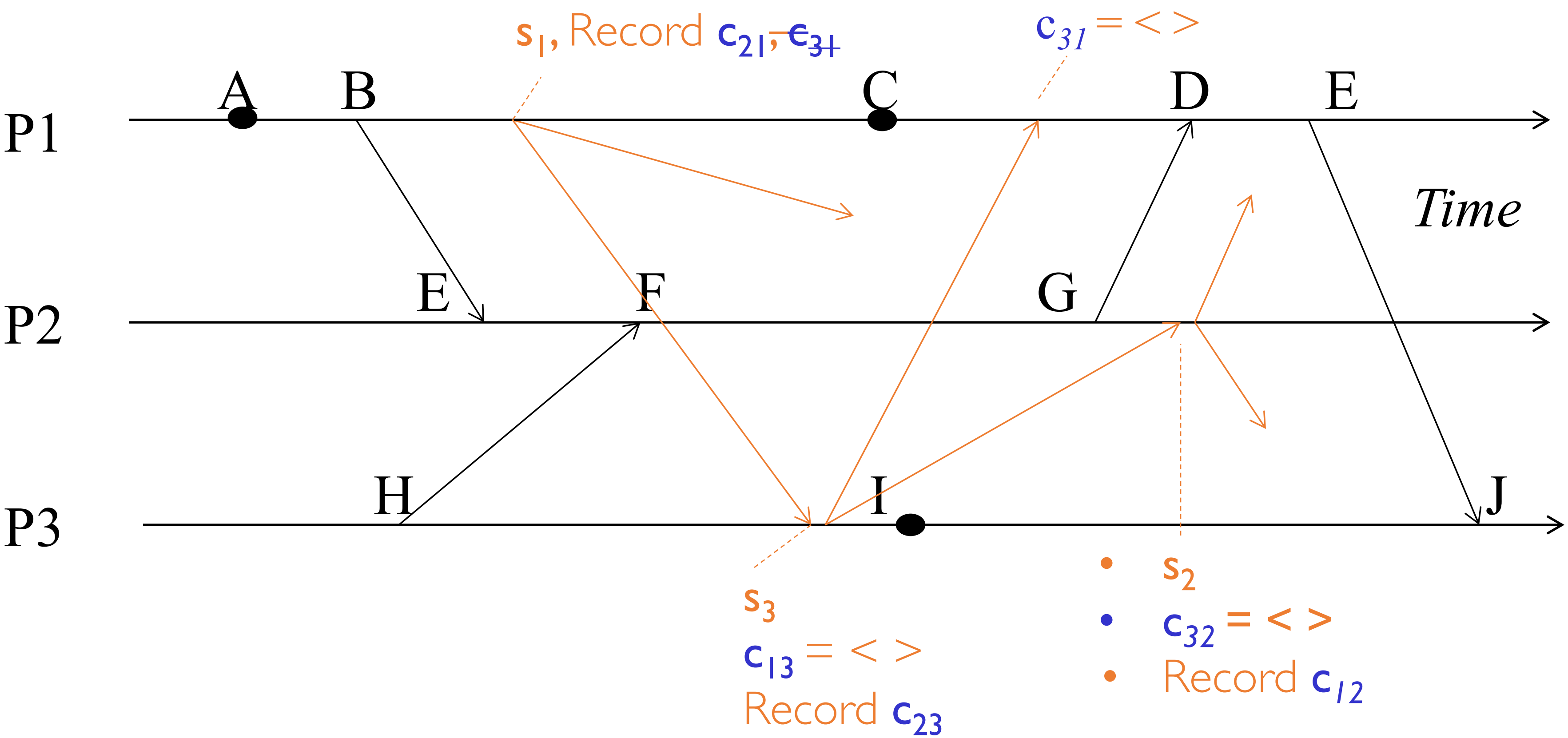
Duplicate **marker!**
State of channel c_{31} = < >
s_1, Record c_{21}, ~~c_{31}~~
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
s_3
c_{13} = < >
Record c_{23}

Example



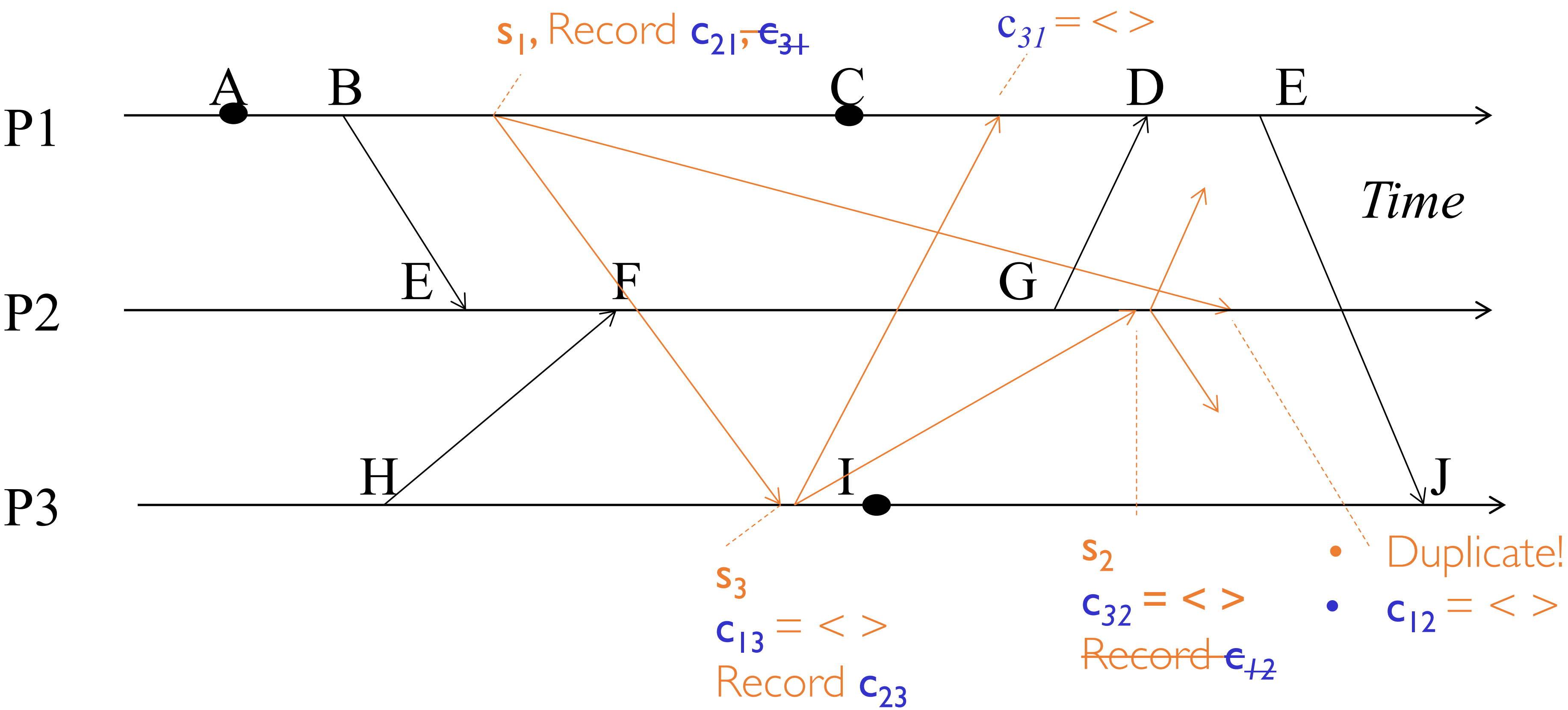
- First **marker**
- Record own state as $\mathbf{s_2}$
- Mark $\mathbf{c_{32}}$ state as empty
- Turn on recording on $\mathbf{c_{12}}$
- Send out **markers**

Example



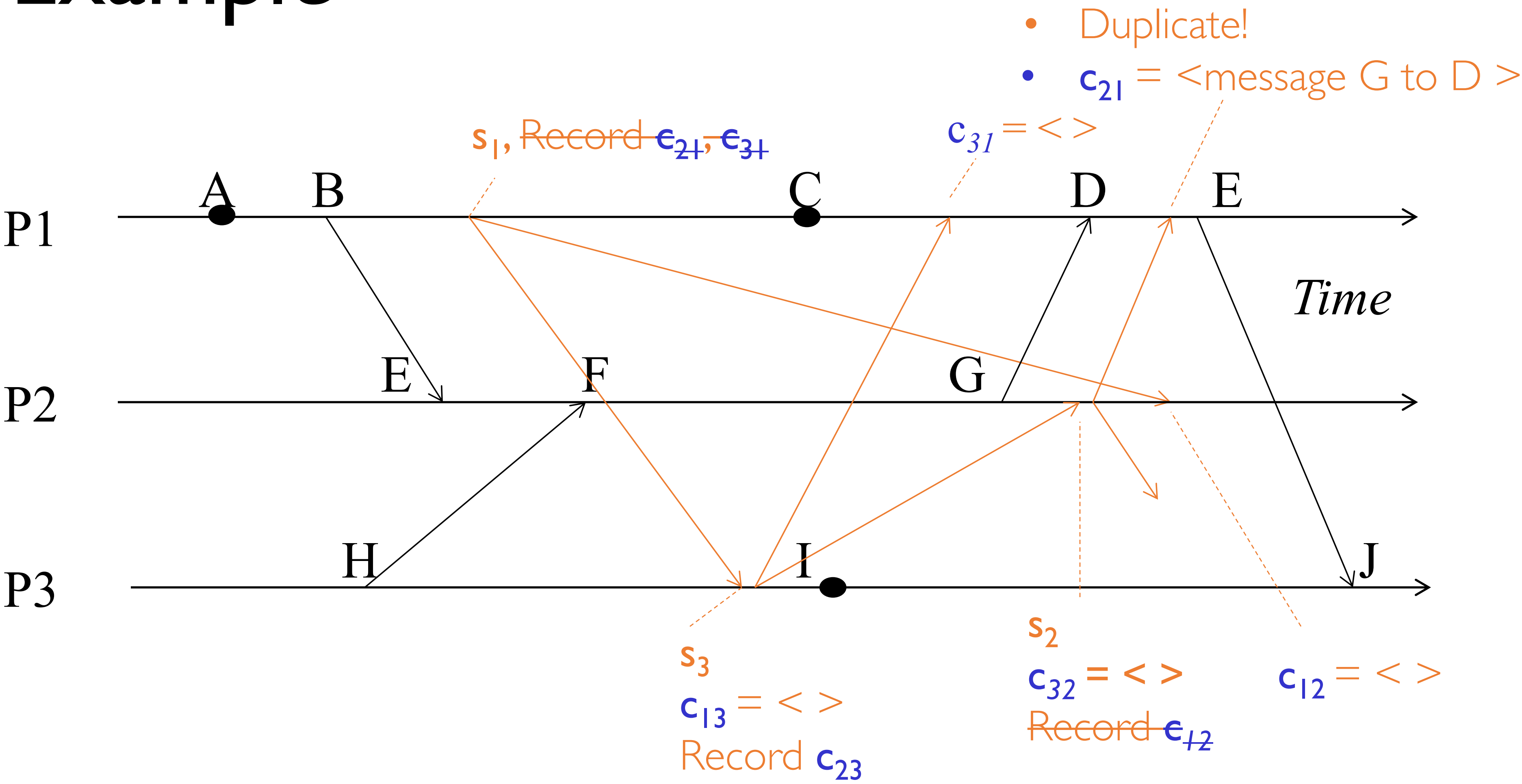
s1, Record c21, c31
c31 = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
s3
c13 = < >
Record c23
s2
c32 = < >
Record c12

Example



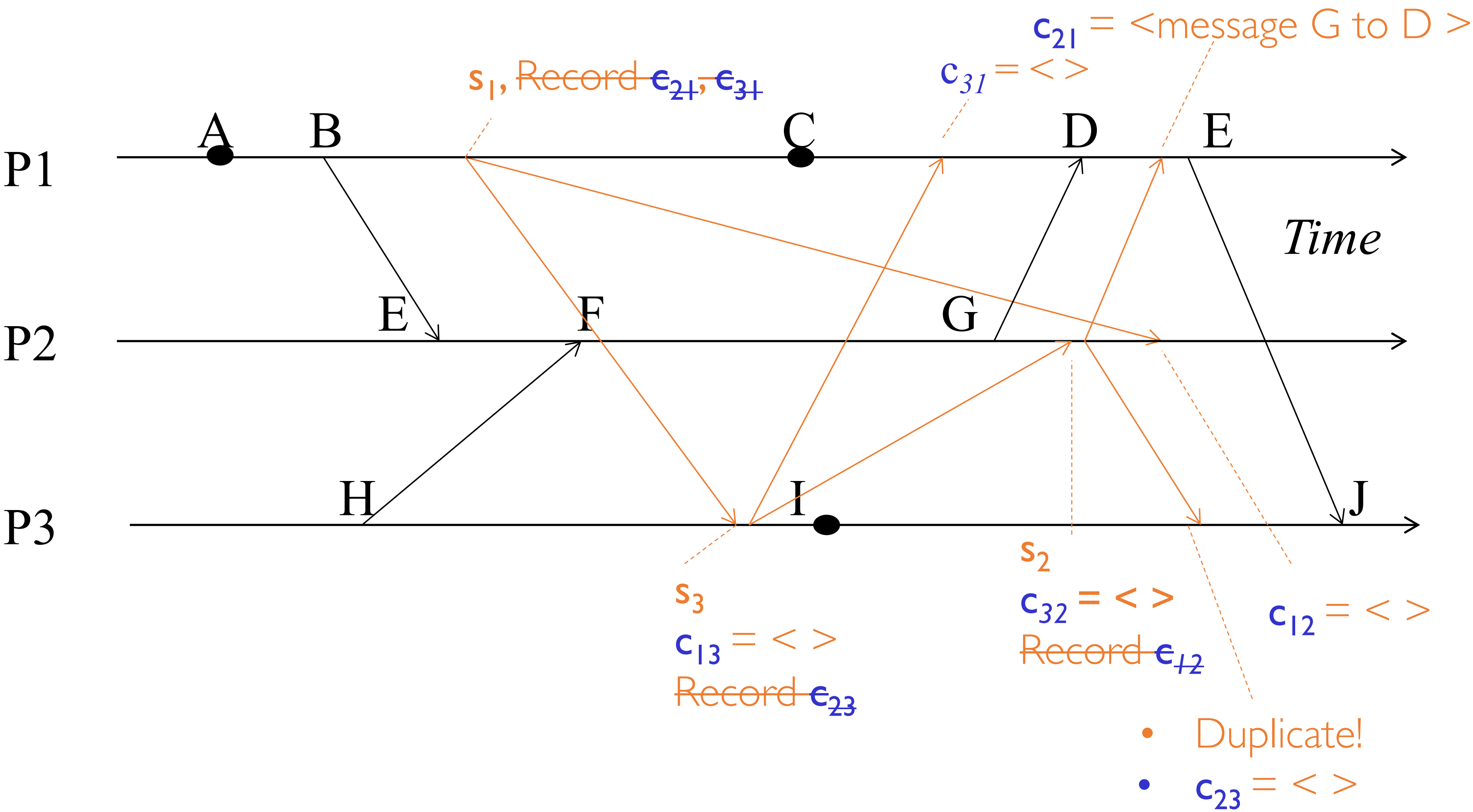
s1, Record c21, c31
c31 = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
s3
c13 = < >
Record c23
s2
c32 = < >
Record c12
Duplicate!
c12 = < >

Example



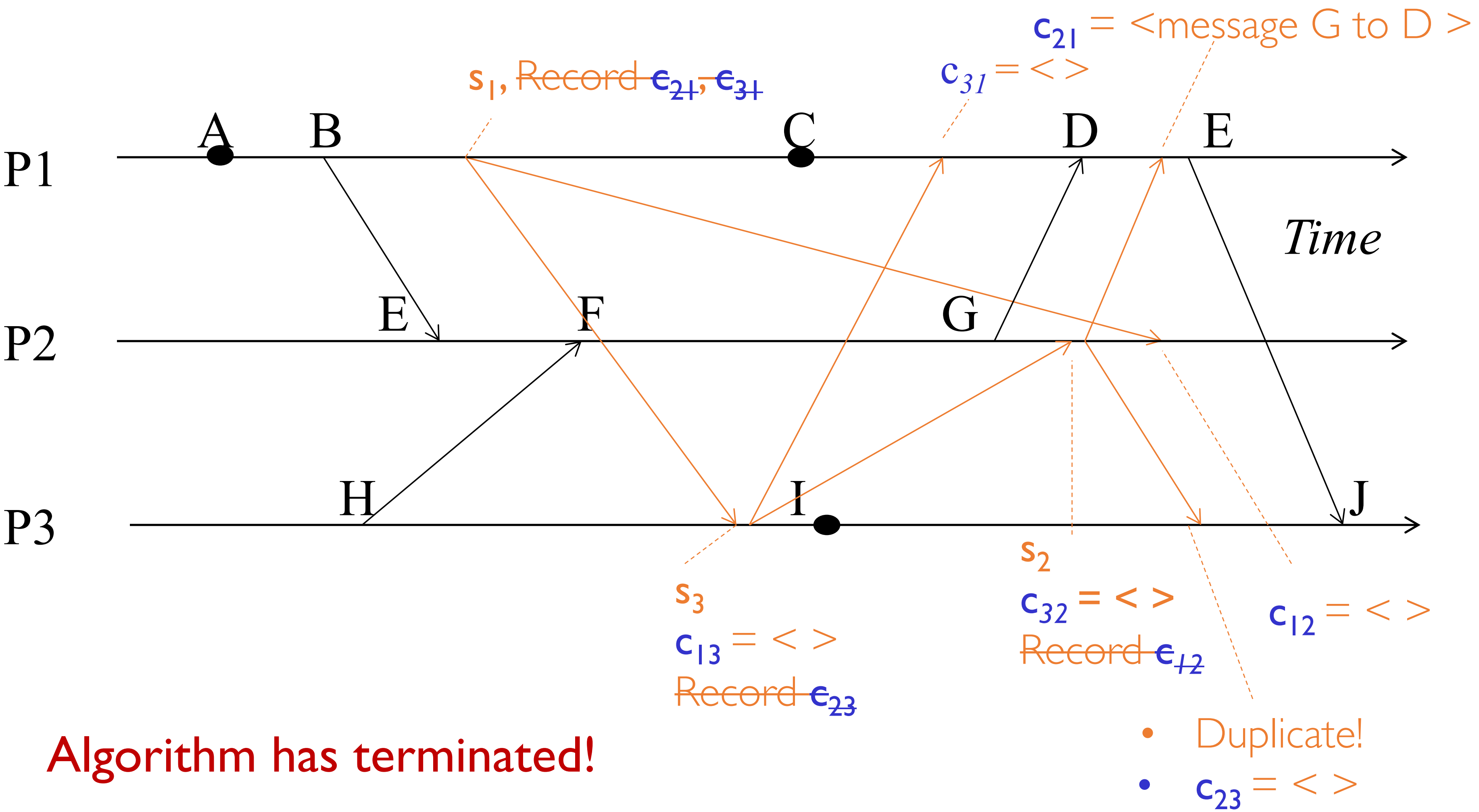
Duplicate!
c_{21} = <message G to D >
s_1, ~~Record c_{21}, c_{31}~~
c_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
s_3
c_{13} = < >
Record c_{23}
s_2
c_{32} = < >
~~Record c_{12}~~
c_{12} = < >

Example



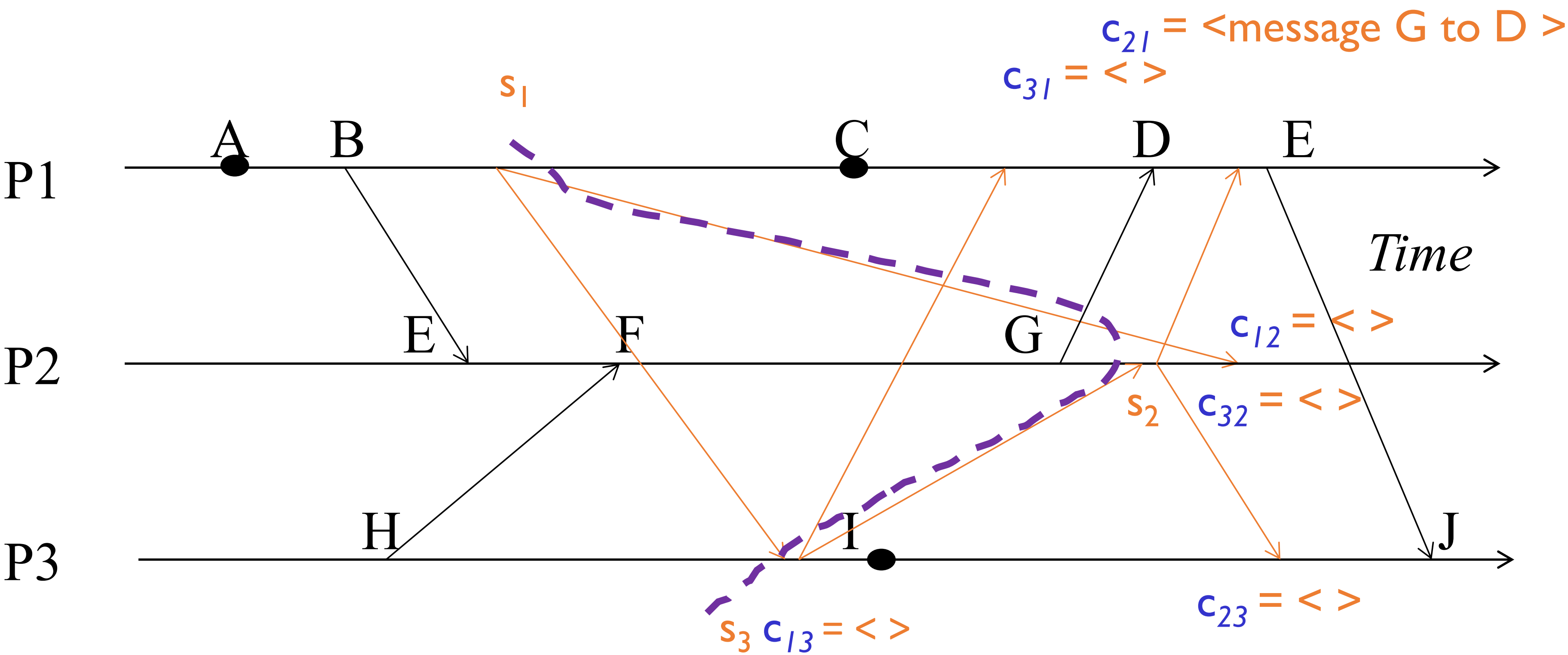
c_{21} = <message G to D >
s_1, Record c_{21}, c_{31}
c_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
s_3
c_{13} = < >
Record c_{23}
s_2
c_{32} = < >
Record c_{12}
c_{12} = < >
• Duplicate!
• c_{23} = < >

Example



Algorithm has terminated!

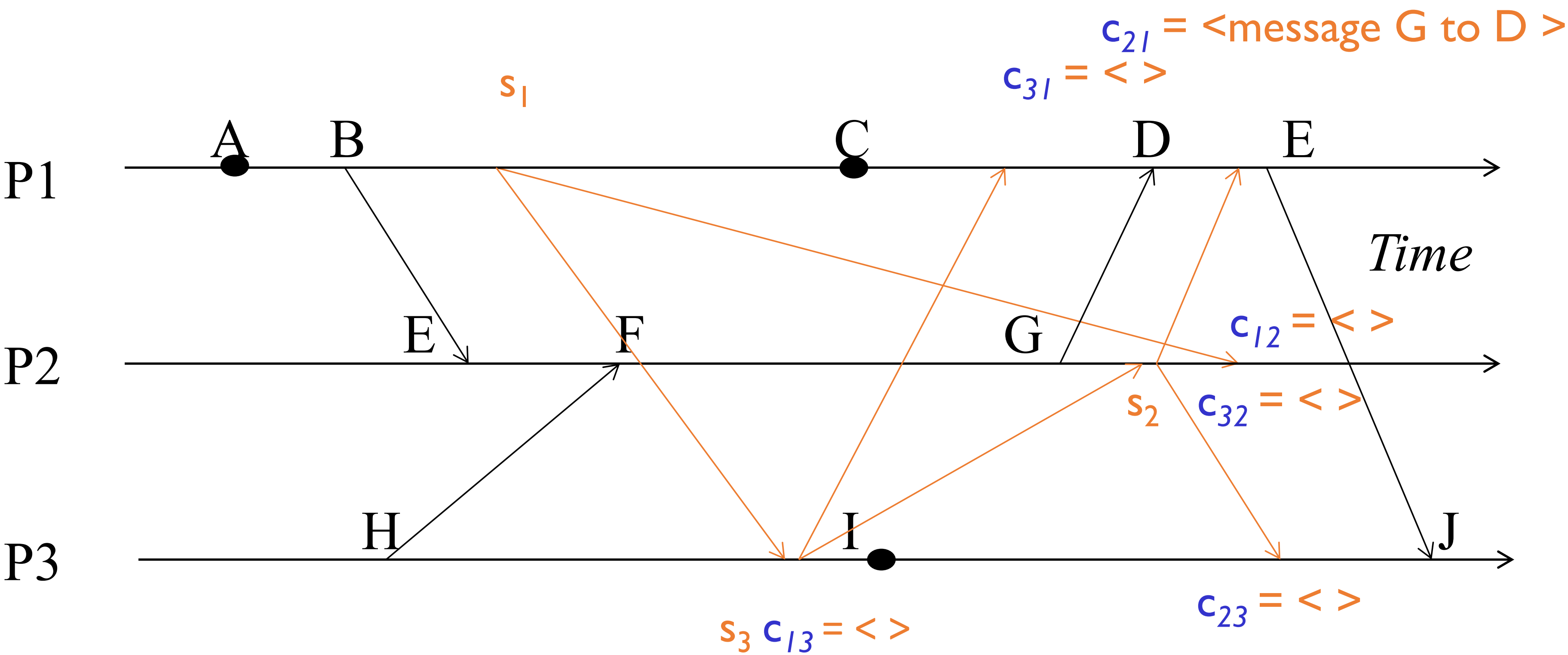
Example



Frontier for the resulting cut:
{B, G, H}

Channel state for the cut:
Only c_{21} has a pending message.

Example



Global snapshots pieces can be collected at a central location.

Chandy-Lamport Algorithm: Properties

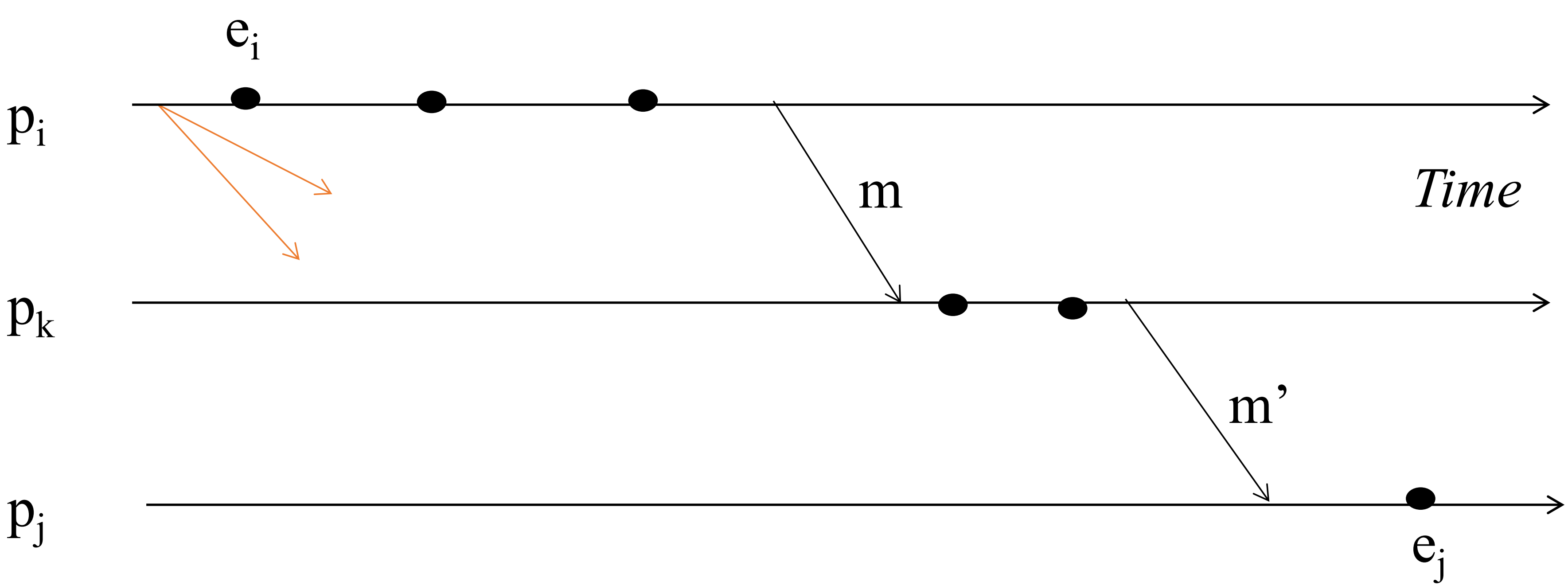
- Any run of the Chandy-Lamport Global Snapshot algorithm creates a consistent cut.
- Let $\mathbf{e}_i$ and $\mathbf{e}_j$ be events occurring at $\mathbf{p}_i$ and $\mathbf{p}_j$, respectively such that
  - $\mathbf{e}_i \rightarrow \mathbf{e}_j$ ($\mathbf{e}_i$ happens before $\mathbf{e}_j$)
- The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

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



Chandy-Lamport Algorithm: Properties

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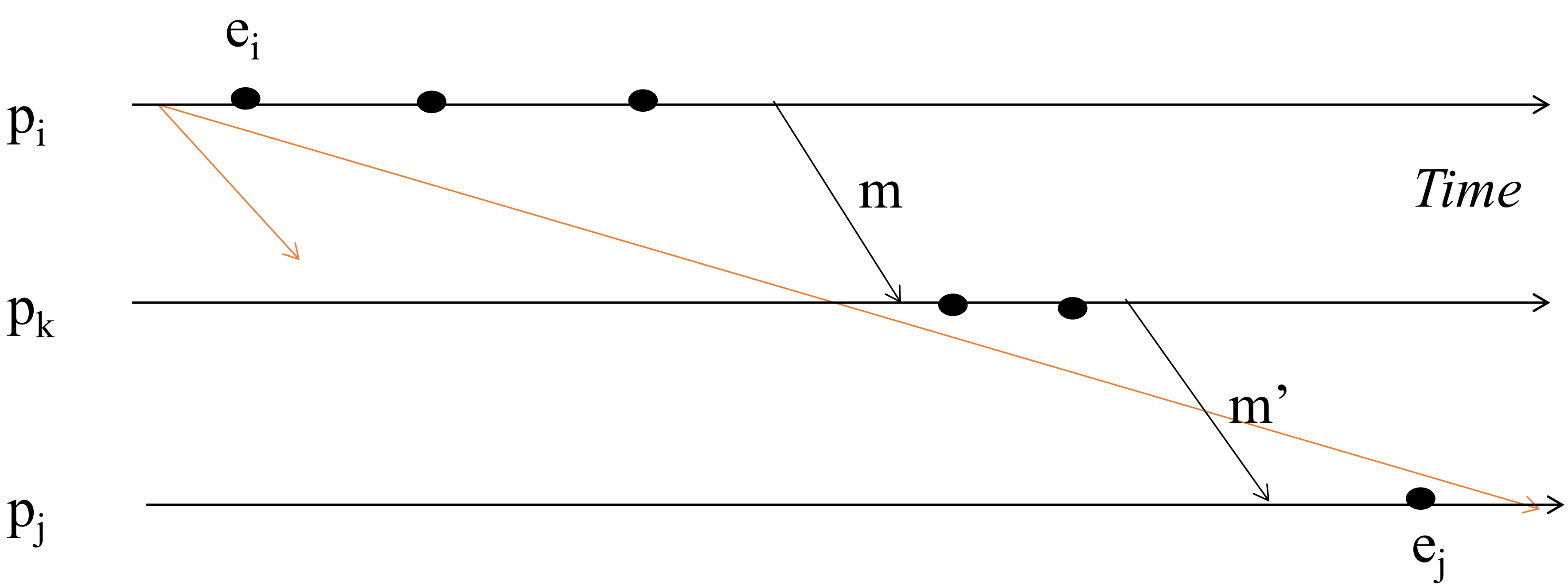
- By contradiction, *suppose* $\mathbf{e_j} \rightarrow$ *<* p_j *records its state>, and <*p_i *records its state>* $\rightarrow \mathbf{e_i}$*.*



Chandy-Lamport Algorithm: Properties

- If $\mathbf{e_j}$ → < $\mathbf{p_j}$ records its state>, then it must be true that $\mathbf{e_i}$ → <$\mathbf{p_i}$ records its state>.
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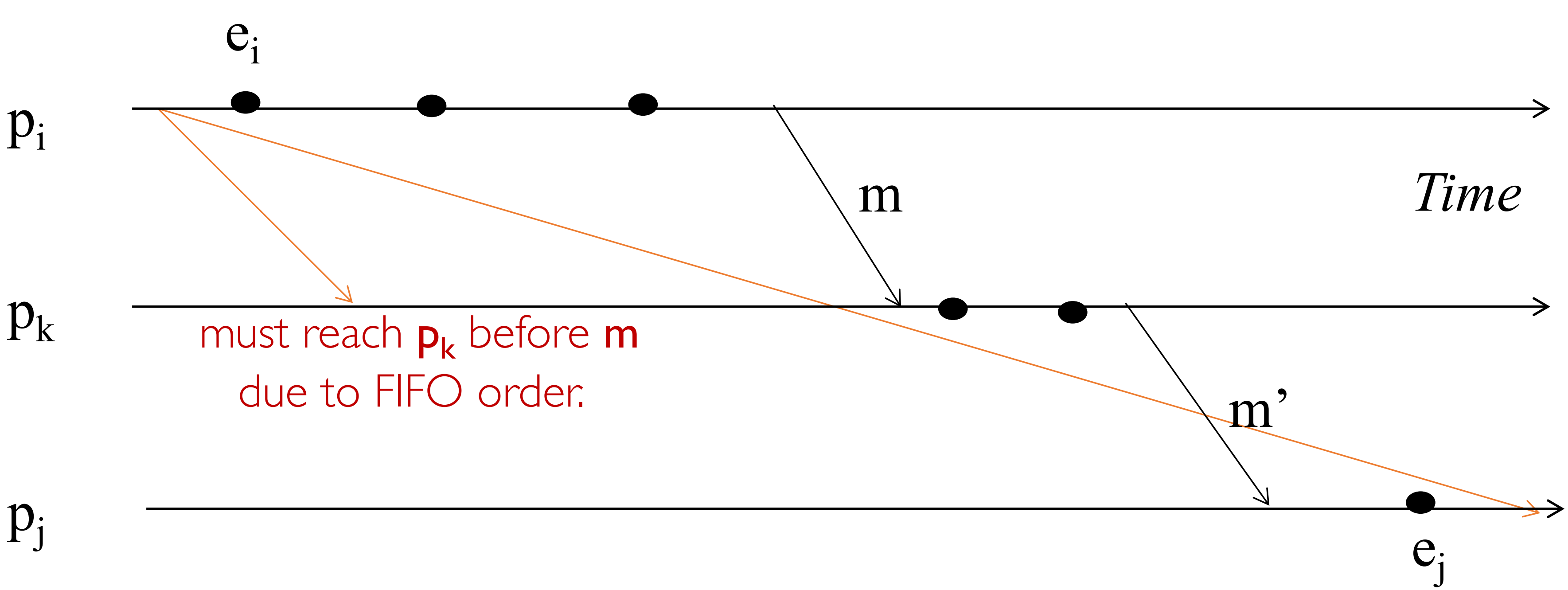

Chandy-Lamport Algorithm: Properties

- If **e_j** → < **p_j** records its state>, then
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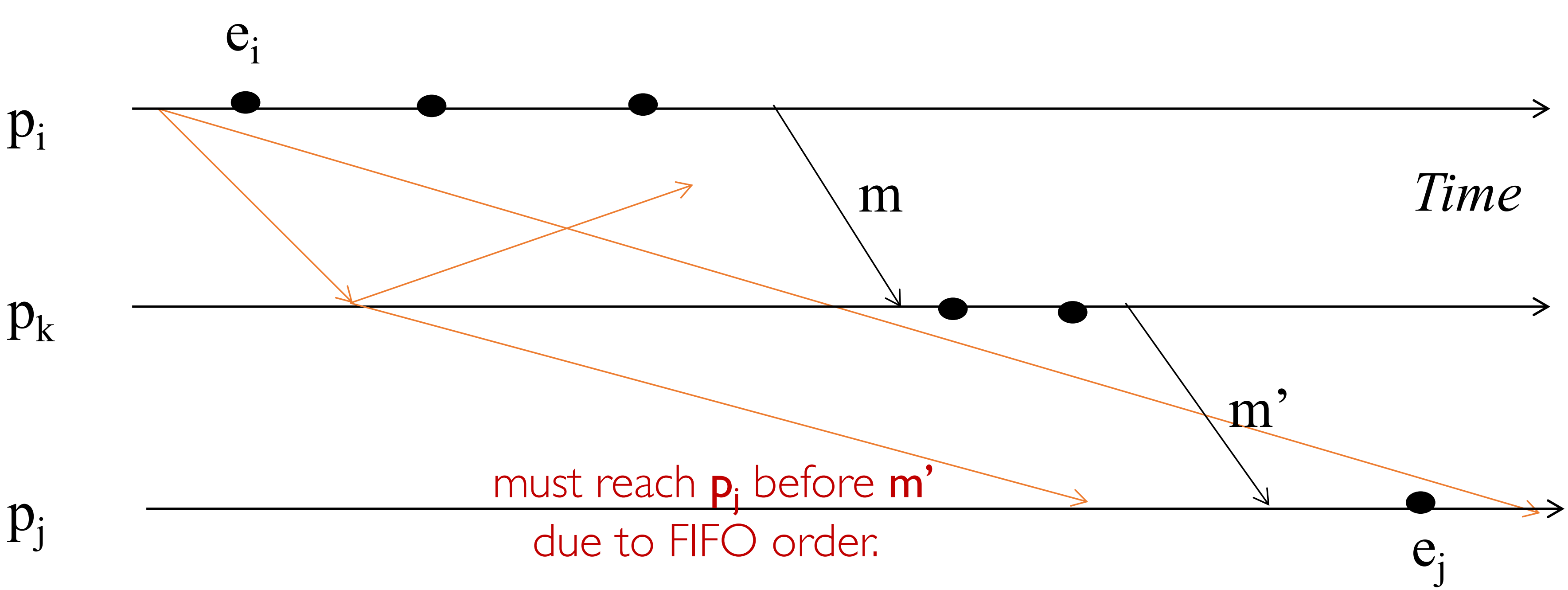


Chandy-Lamport Algorithm: Properties

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

Chandy-Lamport Algorithm: Usefulness

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

Revisions: notations and definitions

- For a process p_i , where events $e_i^0, e_i^1, \ldots$ occur:

  history(p_i) = $h_i = <e_i^0, e_i^1, \ldots >$

  prefix history(p_i^k) = $h_i^k = <e_i^0, e_i^1, \ldots, e_i^k >$

  s_i^k : p_i's state immediately after k^{th} event.

- For a set of processes $<p_1, p_2, p_3, \ldots, p_n>$:

  global history: $H = \cup_i (h_i)$

  a cut $C \subseteq H = h_1^{c_1} \cup h_2^{c_2} \cup \ldots \cup h_n^{c_3}$

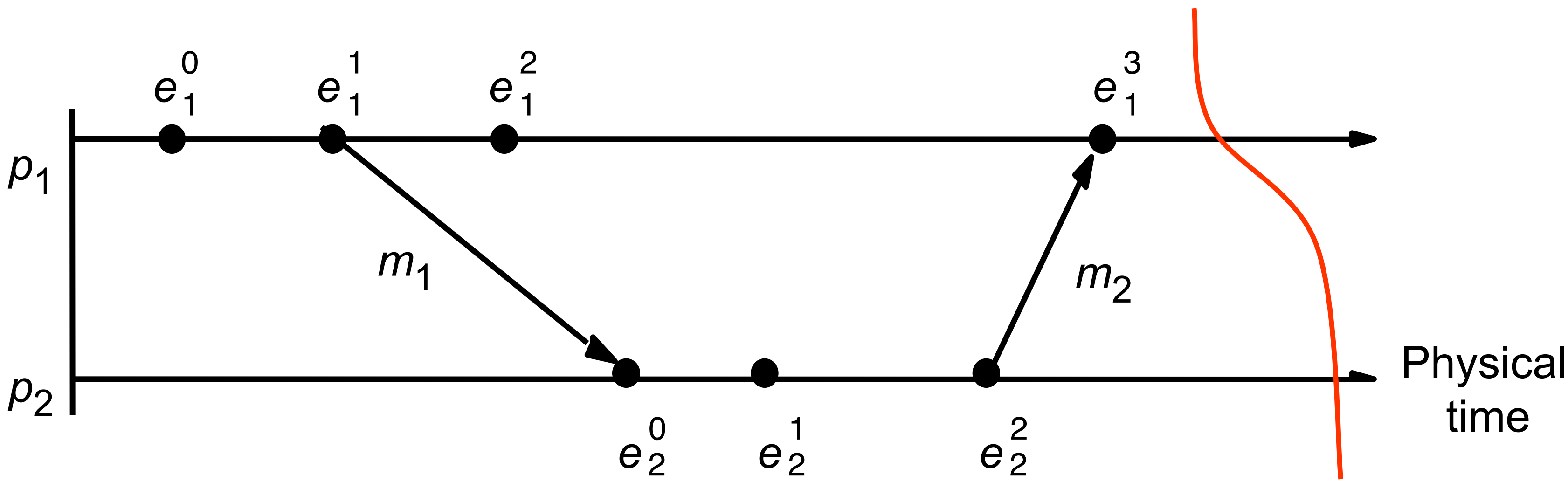
  the frontier of $C = \{e_i^{c_i}, i = 1,2, \ldots n\}$

  global state S that corresponds to cut $C = \cup_i (s_i^{c_i})$

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.

Example



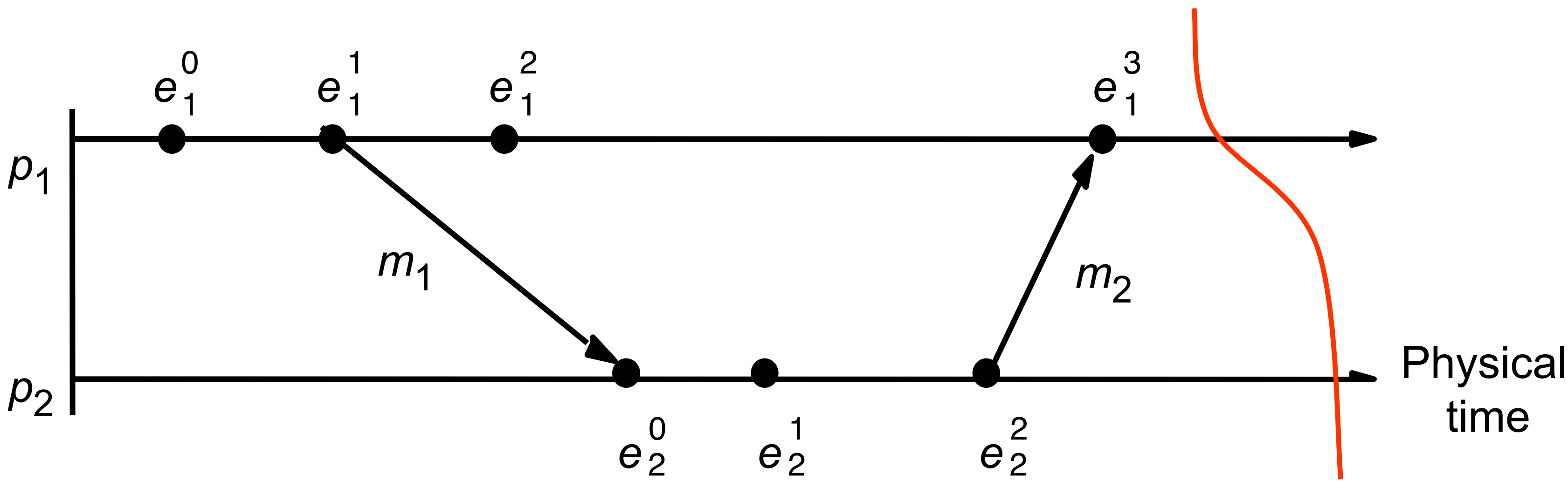
Order at p_1: $< e_1^0, e_1^1, e_1^2, e_1^3 >$ Order at p_2: $< e_2^0, e_2^1, e_2^2 >$

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

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

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

Example



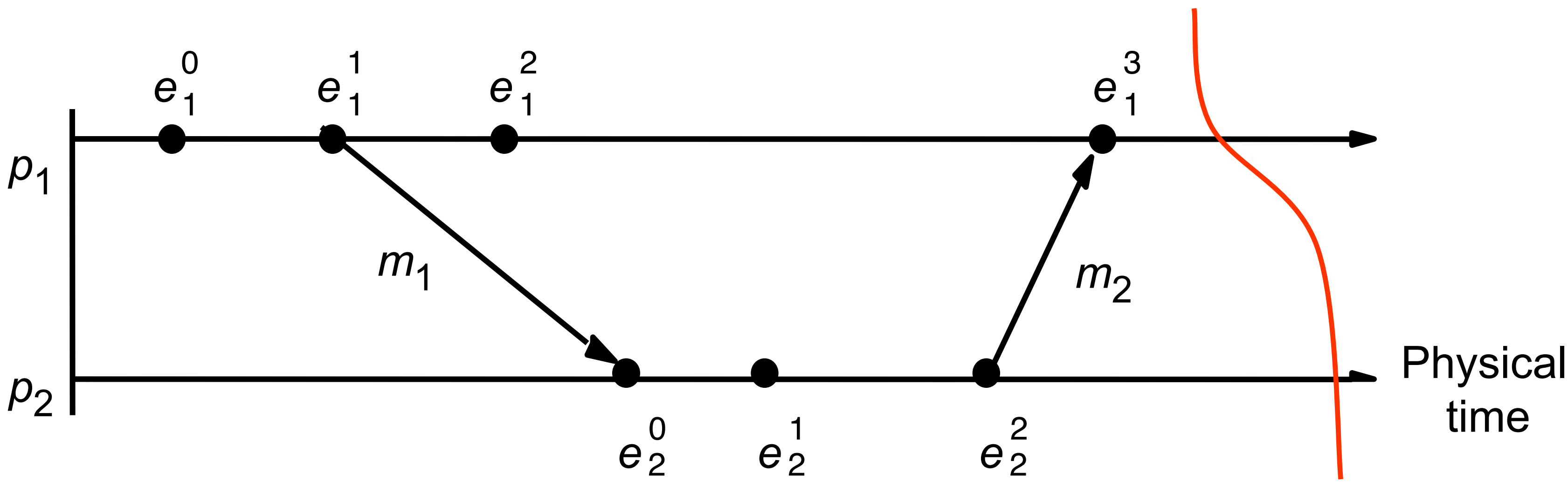
Order at p_1: < e_1^0, e_1^1, e_1^2, e_1^3 >   Order at p_2: < e_2^0, e_2^1,e_2^2>

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 >

Run: < e_1^0, e_1^1, e_1^2, e_1^3 , e_2^0, e_2^1 e_2^2 >

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

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

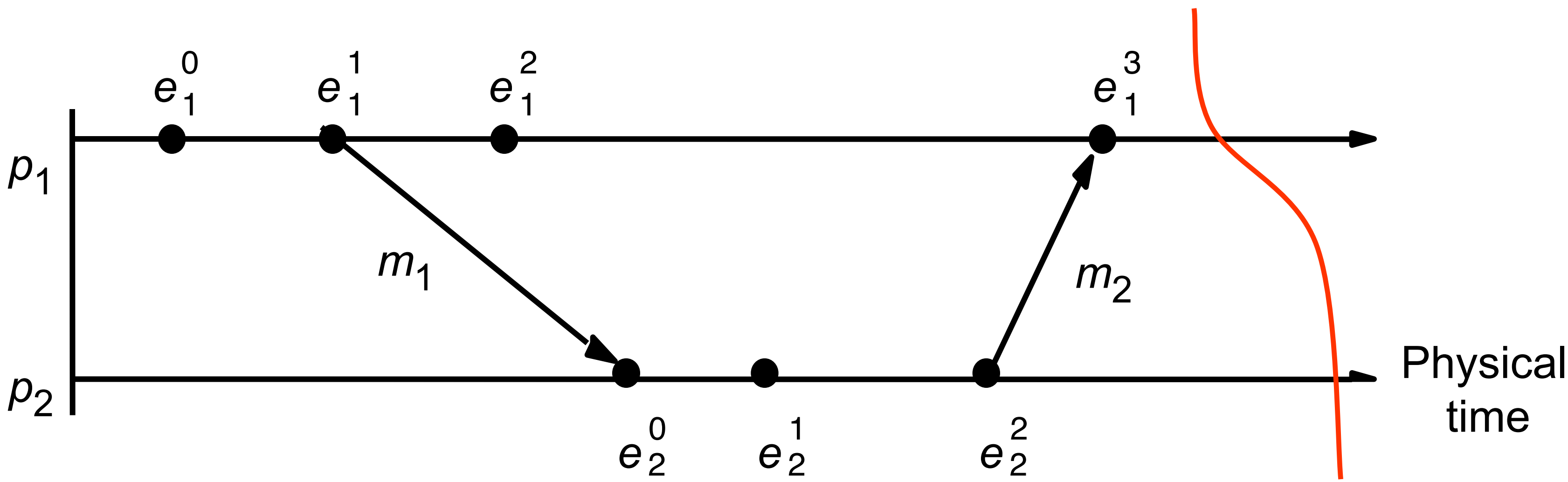
$< e_1^0, e_1^1, e_2^0, e_2^1, e_1^2, e_2^2, e_1^3 >$: Linearization

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

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.

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

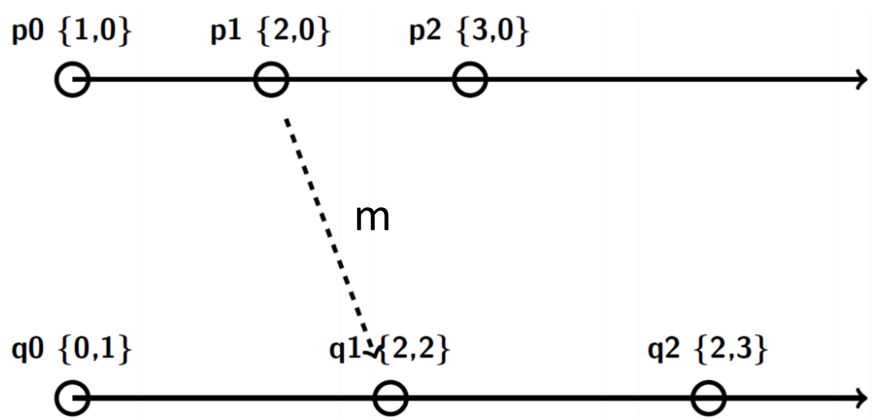
Linearization: $< e_1^0, e_1^1, e_1^2, e_2^0, e_2^1\ e_2^2, e_1^3 >$

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

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



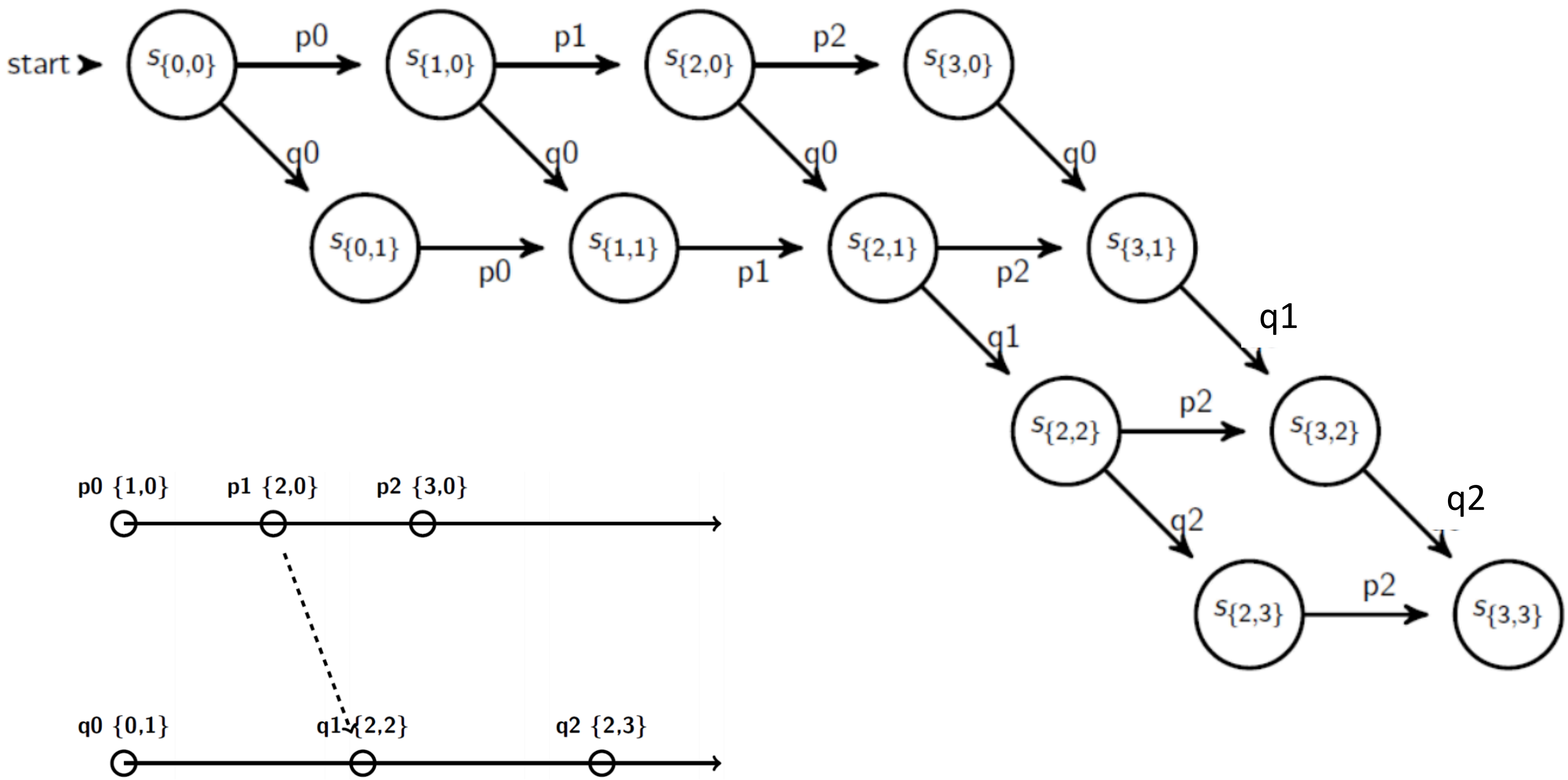
- Causal order:
  - p0 → p1 → p2
  - q0 → q1 → q2
  - p0 → p1 → q1 → q2
- Concurrent:
  - p0 || q0
  - p1 || q0
  - p2 || q0, p2 || q1, p2 || q2

Many linearizations:

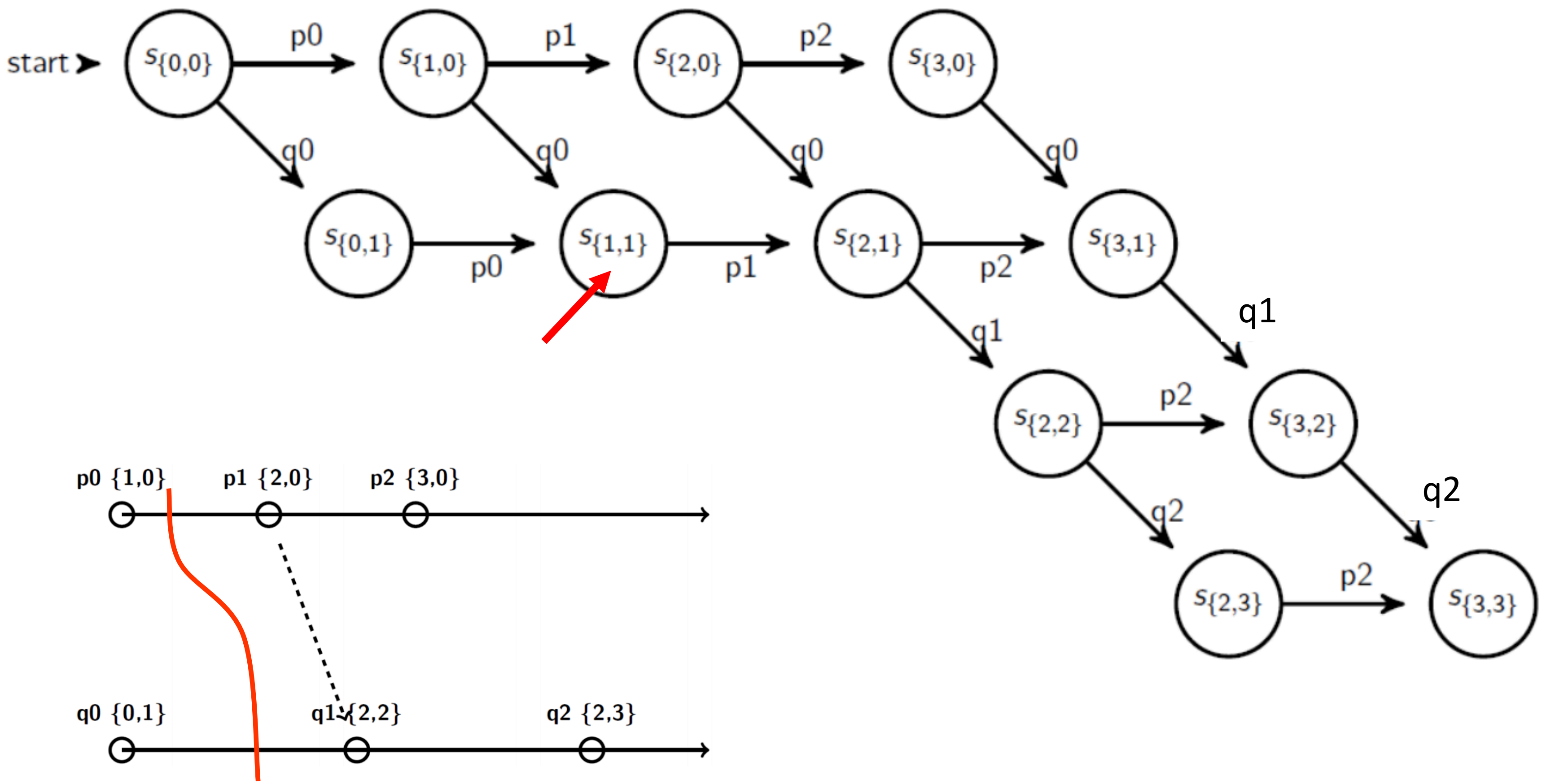
- < p0, p1, p2, q0, q1, q2>
- < p0, q0, p1, q1, p2, q2>
- <q0, p0, p1, q1, p2, q2 >
- <q0, p0, p1, p2, q1,q2 >
- ……

State Transitions: Example

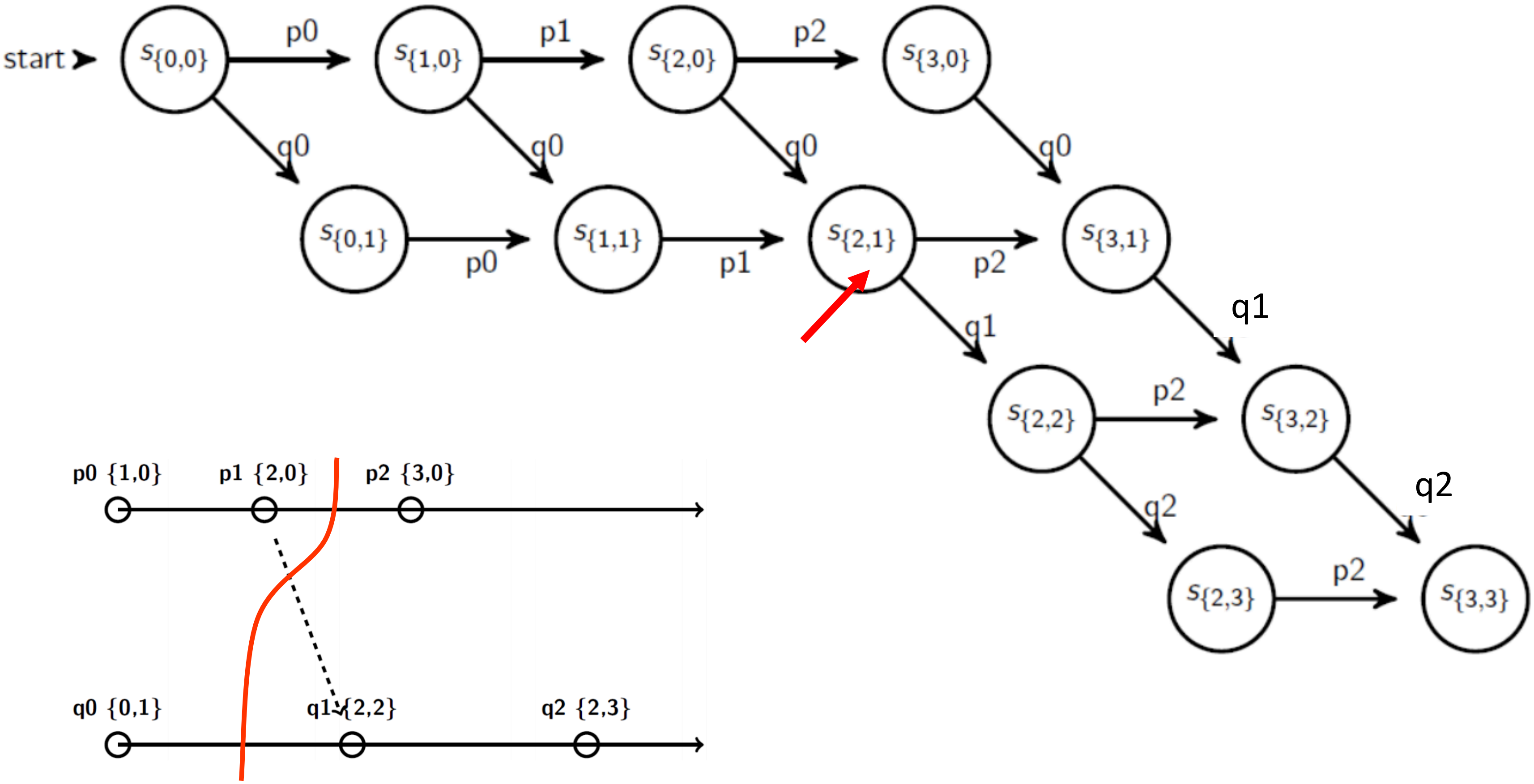
Execution Lattice. Each path is a linear execution of events.



State Transitions: Example



State Transitions: Example



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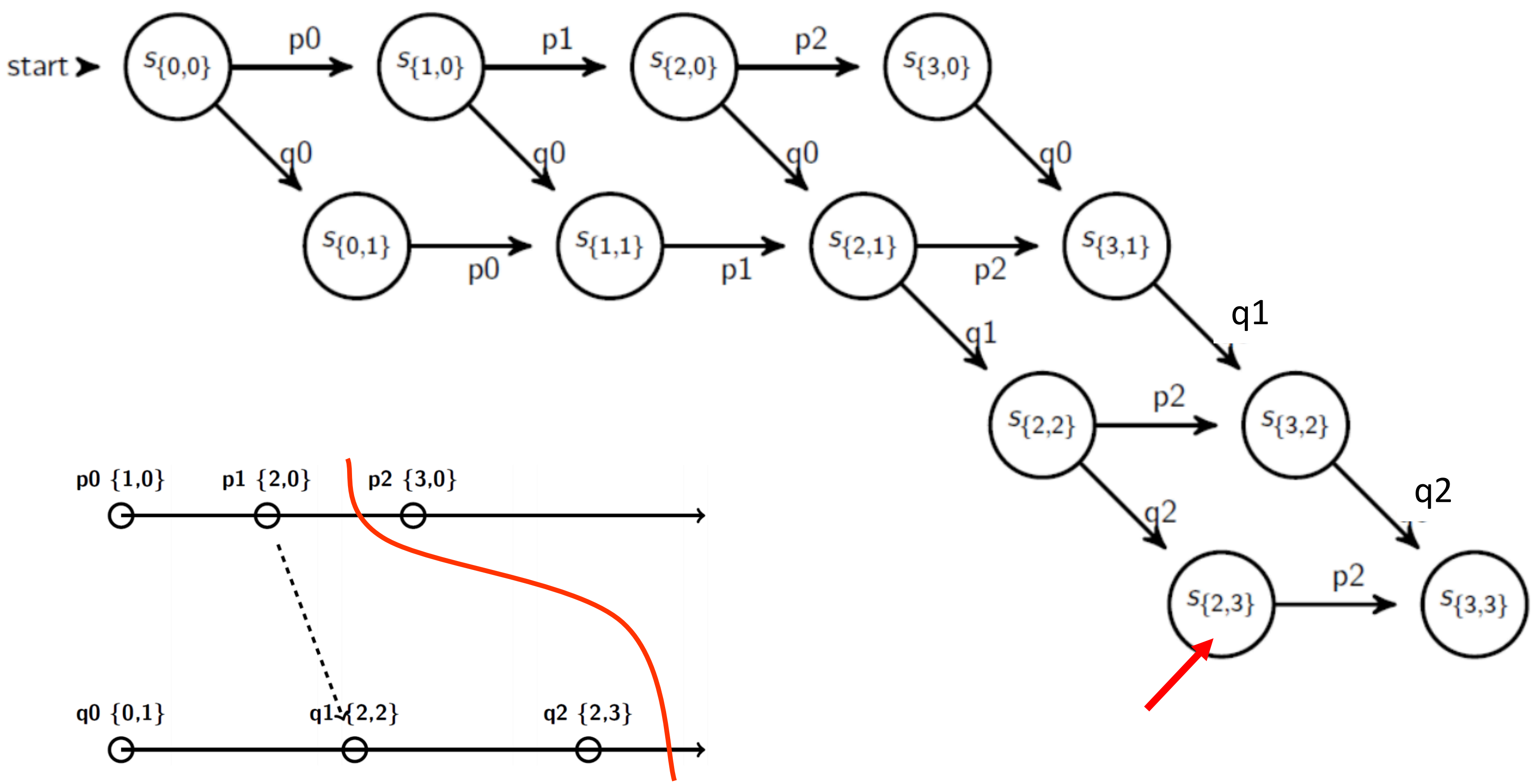

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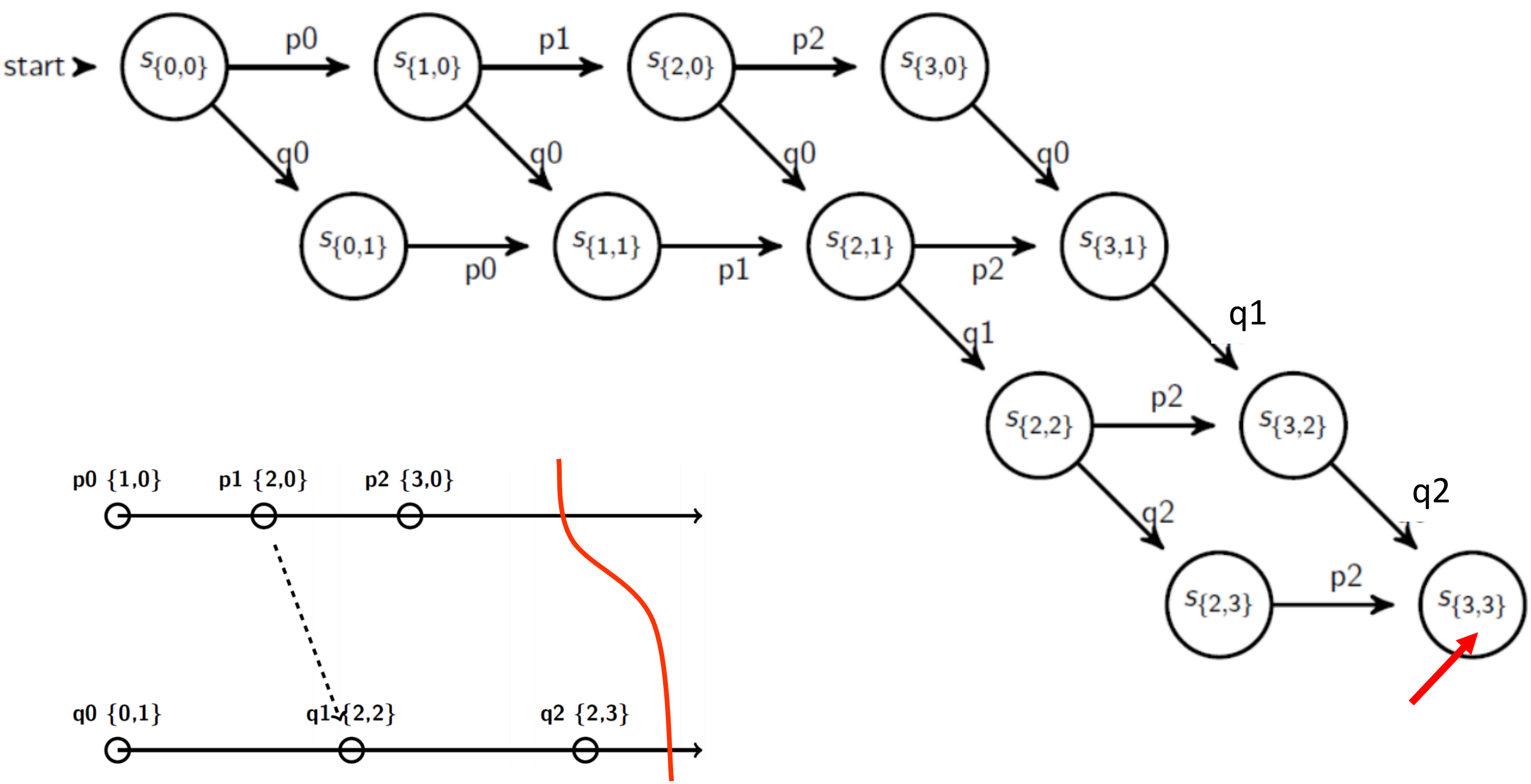


More notations and definitions

- 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.
- Linearizations pass through consistent global states.
- A global state **S_k** is reachable from global state **S_i**, if there is a linearization that passes through **S_i** and then through **S_k**.
- The distributed system evolves as a series of transitions between global states S_0 , S_1 , ….

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**

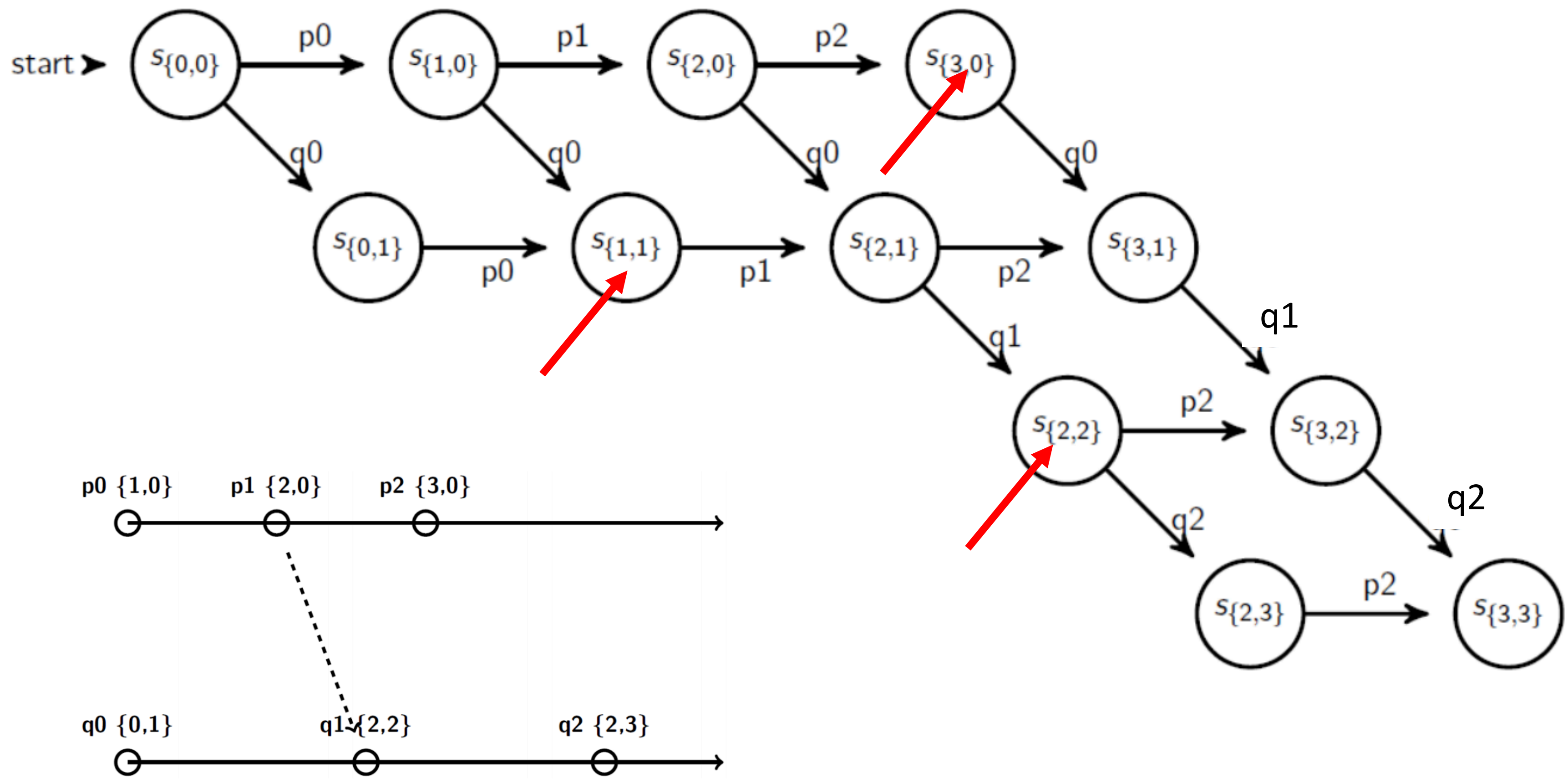
- **Examples:**
  - Guarantee that a distributed computation will terminate.
  - "Completeness" in failure detectors.
  - All processes eventually decide on a value.

- 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



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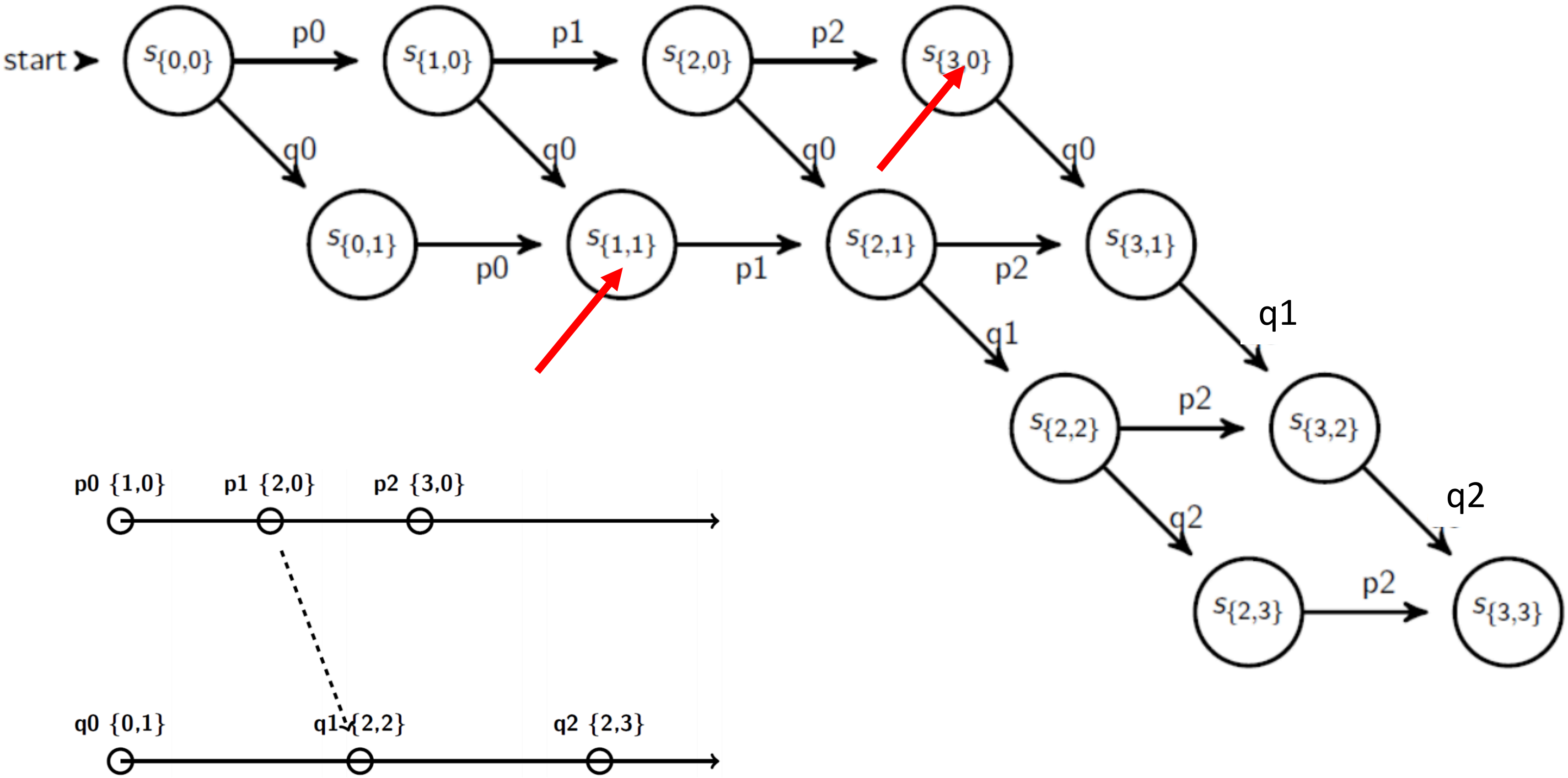
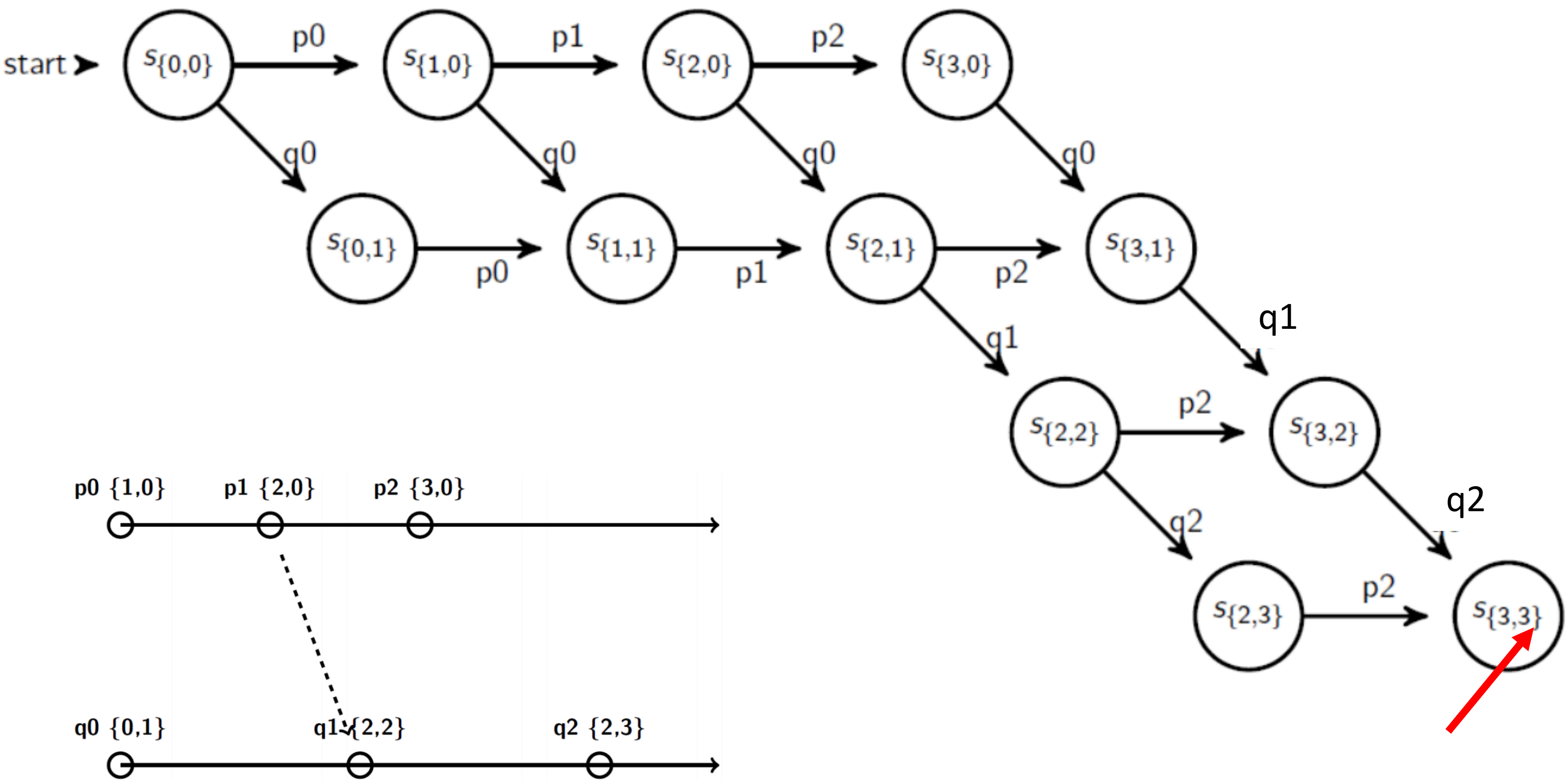
No



Liveness Example

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

Yes



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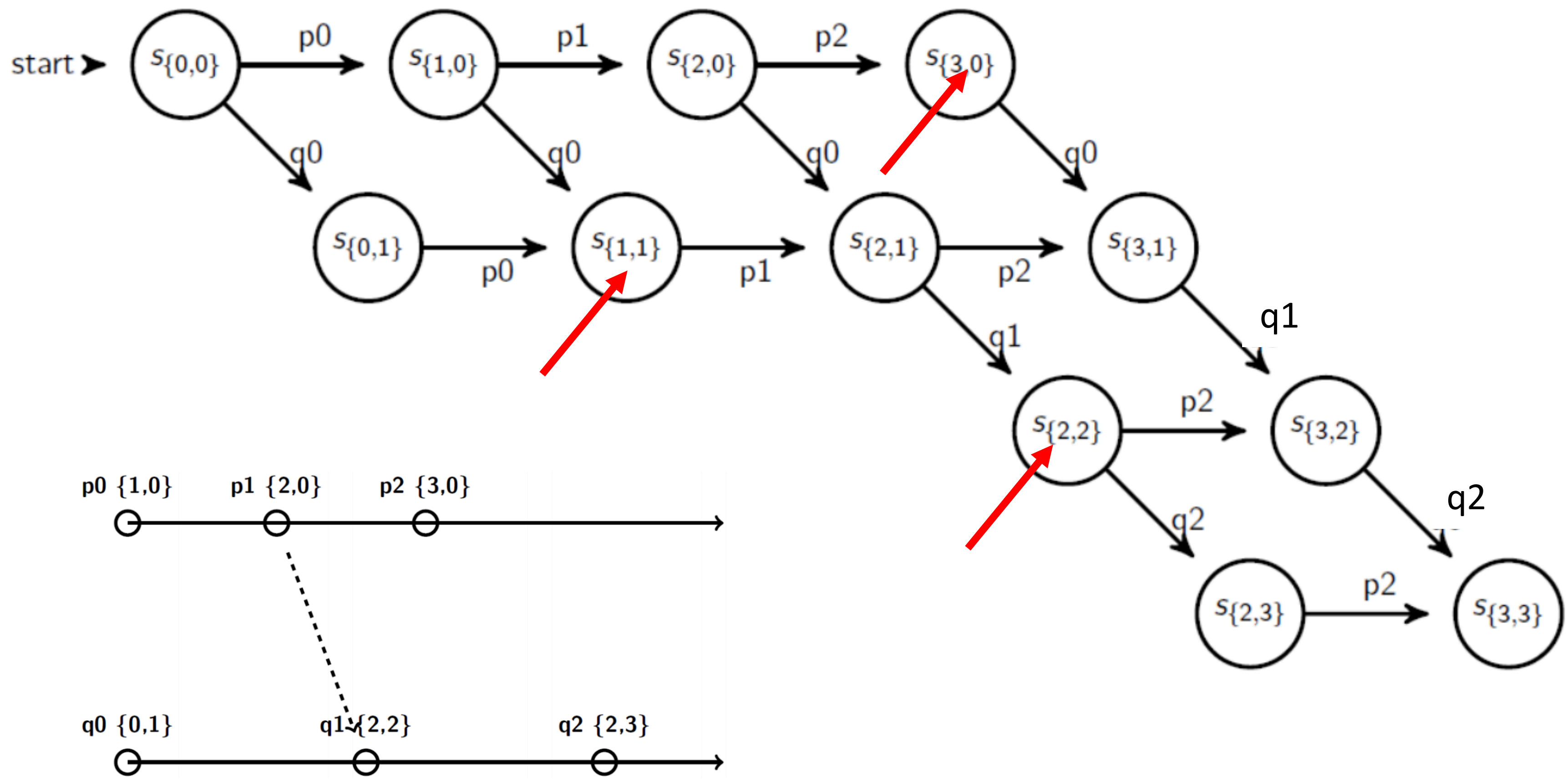
Safety

- 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?

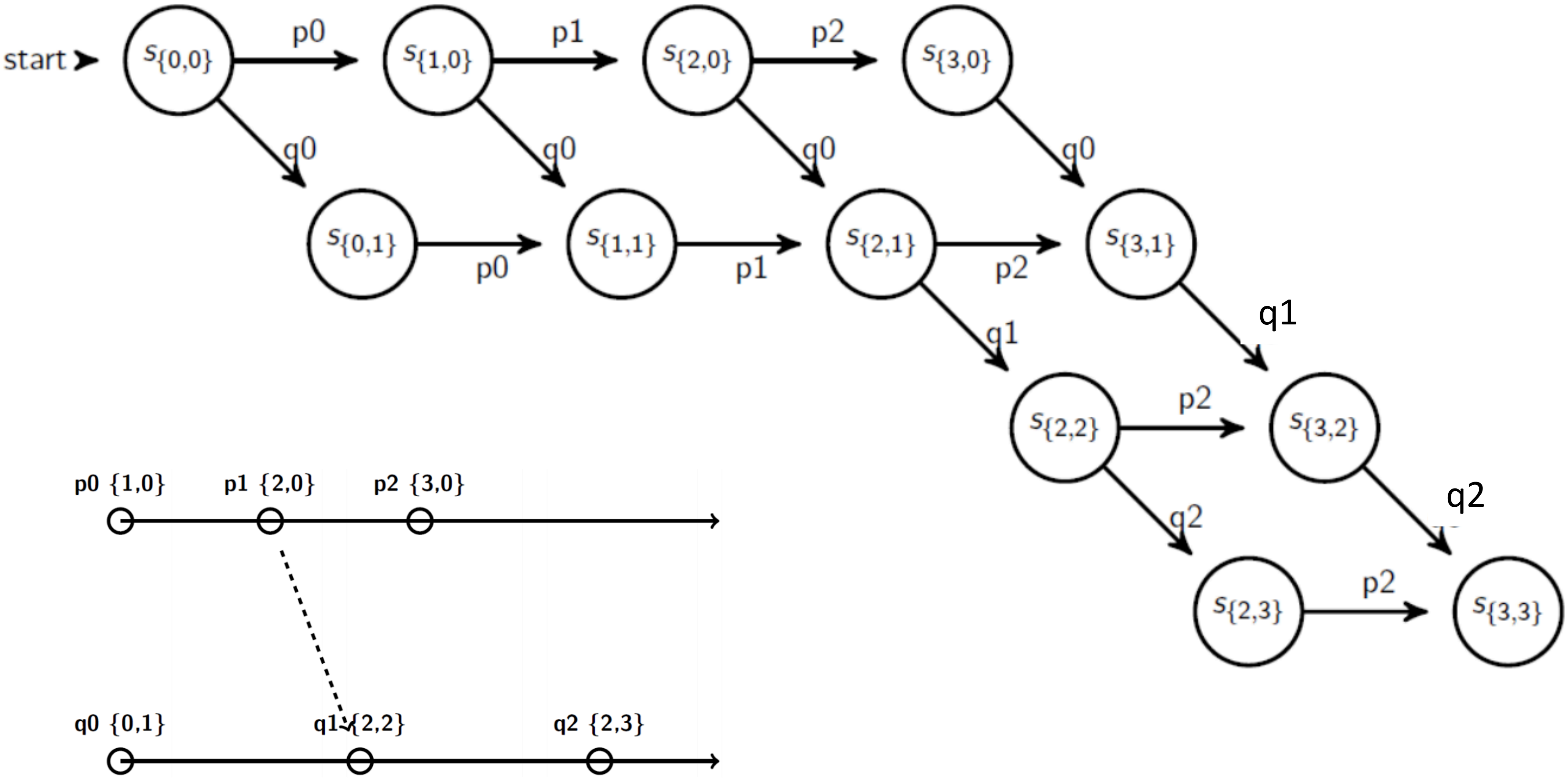
No



Safety Example

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

Yes



Safety

- **Safety = guarantee that something bad will never happen.**
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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.