Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

Logistics Related

- HW1 will be released in the next 30mins or so.
  - You can solve first 4 questions right away
  - You can solve last two questions hopefully by end of today's class.

- MP0 due on Wednesday.

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.

Process, state, events

- Consider a system with **n** processes: <$p_1, p_2, p_3, \ldots, p_n$>.
- Each process p_i is associated with *state* $\mathbf{s_i}$.
  - State includes values of all local variables, affected files, etc.
- Each channel can also be associated with a state.
  - Which messages are currently *pending* on the channel.
  - Can be computed from process' state:
    - Record when a process sends and receives messages.
    - if p_i sends a message that p_j has not yet received, it is pending on the channel.
- State of a process (or a channel) gets transformed when an *event* occurs. 3 types of events:
  - local computation, sending a message, receiving a message.

Capturing a global snapshot

- Useful to capture a global snapshot of the system:
  - *Checkpointing* the system state.
  - Reasoning about unreferenced objects (for garbage collection).
  - Deadlock detection.
  - Distributed debugging.

Capturing a global snapshot

- Global state or global snapshot is 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.
- Strawman:
  - Each process records its state at 2:05pm.
  - We get the global state of the system at 2:05pm.
  - *But precise clock synchronization is difficult to achieve.*
- **How do we capture global snapshots without precise time synchronization across processes?**

Some more notations and definitions

- State of a process (or a channel) gets transformed when an *event* occurs.

- 3 types of events:
  - local computation, sending a message, receiving a message.

- $\mathbf{e_i^n}$ is the n^{th} event at $\mathbf{p_i}$.

Some more 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: $H = \cup_i (h_i)$

  global state: $S = \cup_i (s_i)$

Some more notations and definitions

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

  history(p_i) = $h_i = \langle e_i^0, e_i^1, \ldots \rangle$

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

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- For a set of processes $\langle p_1, p_2, p_3, \ldots, p_n \rangle$:

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

  global state: $S = \cup_i (s_i)$

  But state at what time instant?

Some more notations and definitions

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

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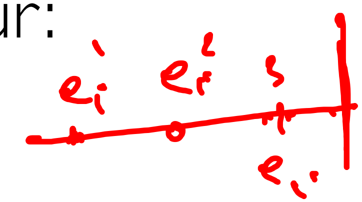


- For a set of processes $\langle p_1, p_2, p_3, \ldots, p_n \rangle$:

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

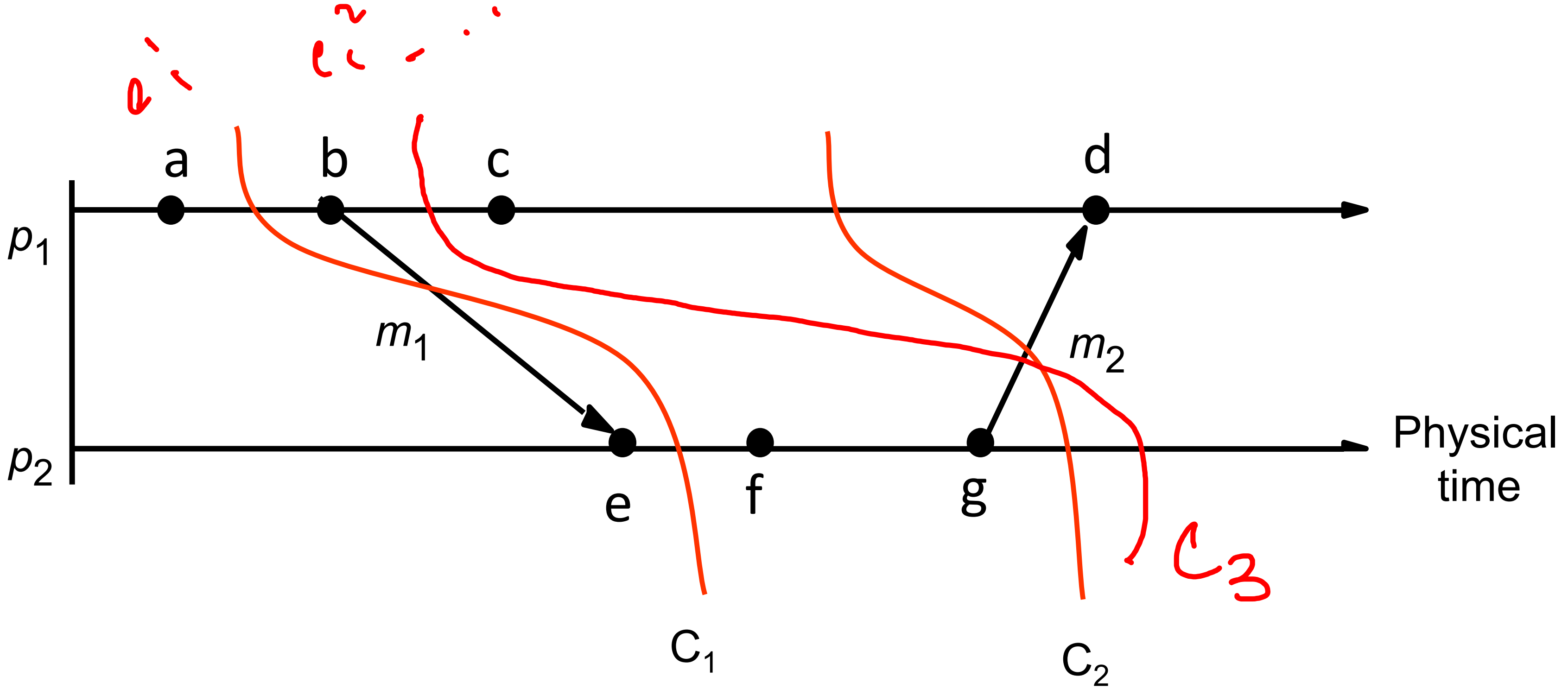
  global state: $S = \cup_i (s_i^{c_i})$

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

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

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

Example: Cut



C_1: < a, e>
Frontier of C_1:

C_2: <a, b, c, e, f, g >
Frontier of C_2:

C_3: < a, b, e, f, g >

Some more notations and definitions

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

  history(p_i) = $h_i = \langle e_i^0, e_i^1, \ldots \rangle$

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

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

- For a set of processes $\langle p_1, p_2, p_3, \ldots, p_n \rangle$:

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

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

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

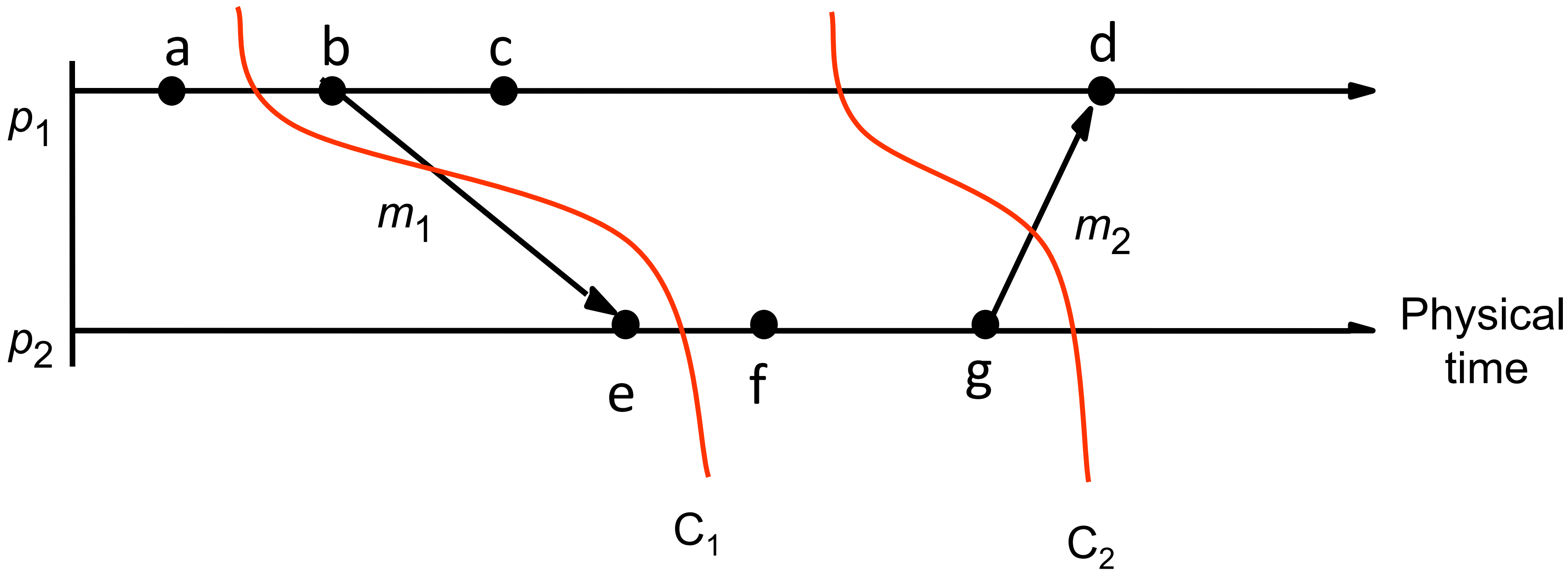
  global state S that corresponds to cut $C = \cup_i (s_i^{c_i})$

Consistent cuts and snapshots

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

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

Example: Cut



C_1: < a, e>
Frontier of C_1: {a, e}

Inconsistent cut.

C_2: <a, b, c, e, f, g >
Frontier of C_2: {c,g}

Consistent cut.

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.

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.

How to capture global state?

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

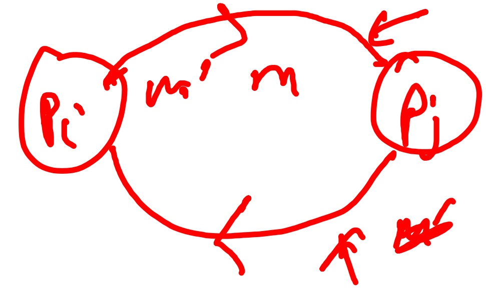
- Relax the problem: find a consistent global state.
  - For a system with n processes <$p_1, p_2, p_3, \ldots, p_n$>, capture the state of the system after the c_i th event at process p_i.
    - State corresponding to the *cut* defined by frontier events $\{e_i^{c_i}$, for $i = 1, 2, \ldots n\}$.
 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

How to find a consistent global state that corresponds to a consistent cut ?

Chandy-Lamport Algorithm

- Goal:
    - Record a global snapshot
        - 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.

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).
    - if p_i sends **m** before **m'** to p_j , then p_j receives **m** before **m'**.
  - All messages arrive intact, and are not duplicated.
  - No failures: neither channel nor processes fail.

Chandy-Lamport Algorithm

- *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

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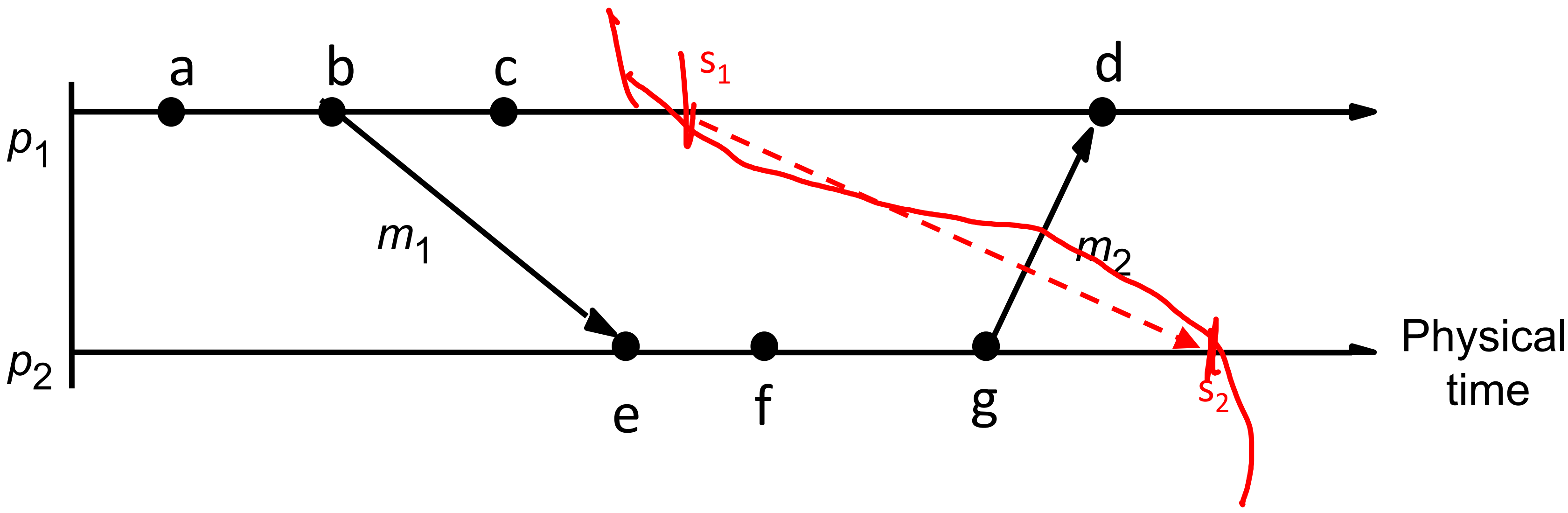
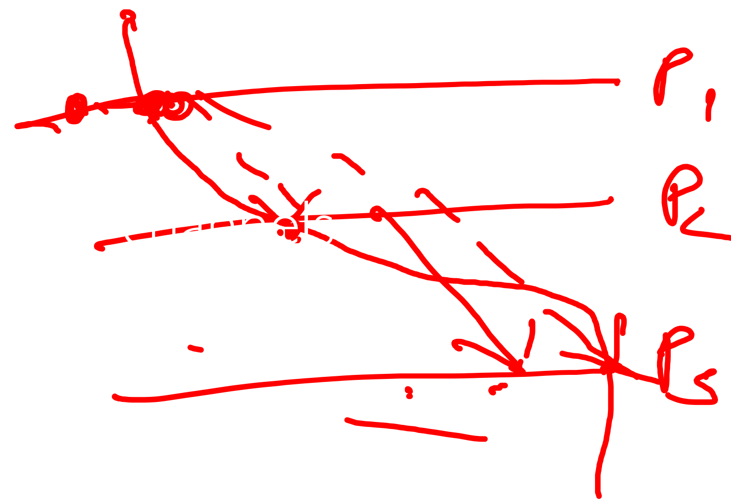


Cut frontier: {c, g}

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.

This captures the local state at each process.

How do we ensure the state is consistent?

Chandy-Lamport Algorithm Intuition

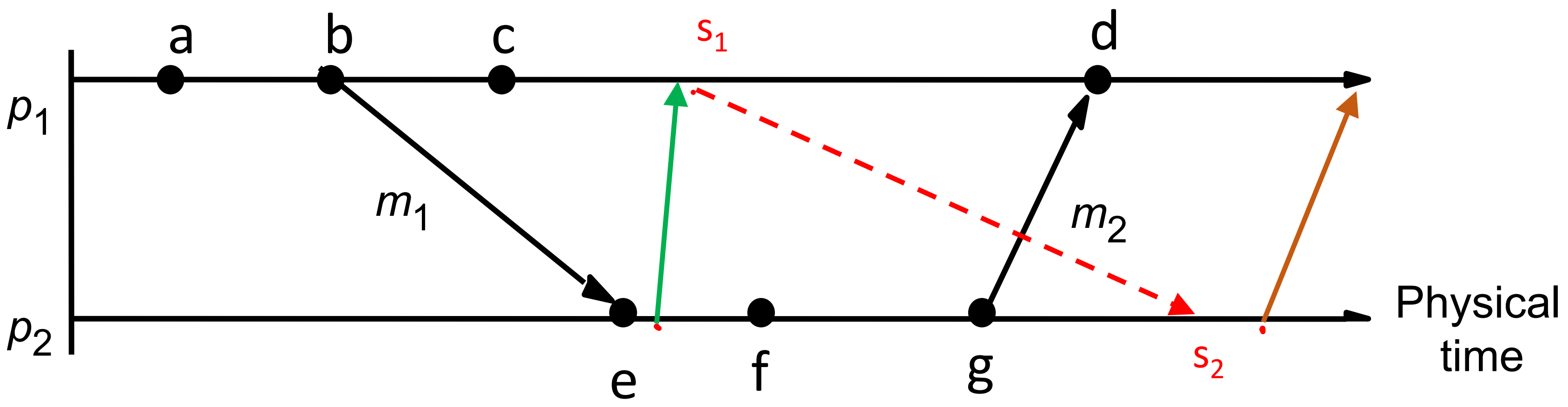
- First, initiator p_i:
  - records its own state.
  - creates a special **marker** message.
  - sends the **marker** to all other process.

- When a process receives a **marker**.
  - If marker is received for the first time.
    - records its own state.
    - sends marker on all other channels.

Leads to a consistent cut (we'll get back to it)

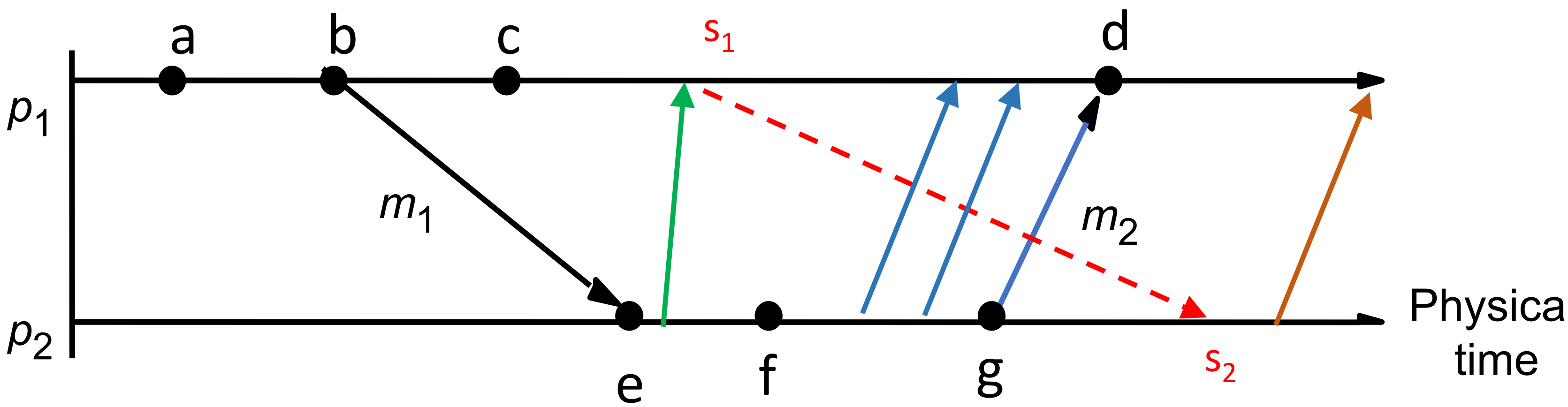
What about the channel state?

Chandy-Lamport Algorithm Intuition



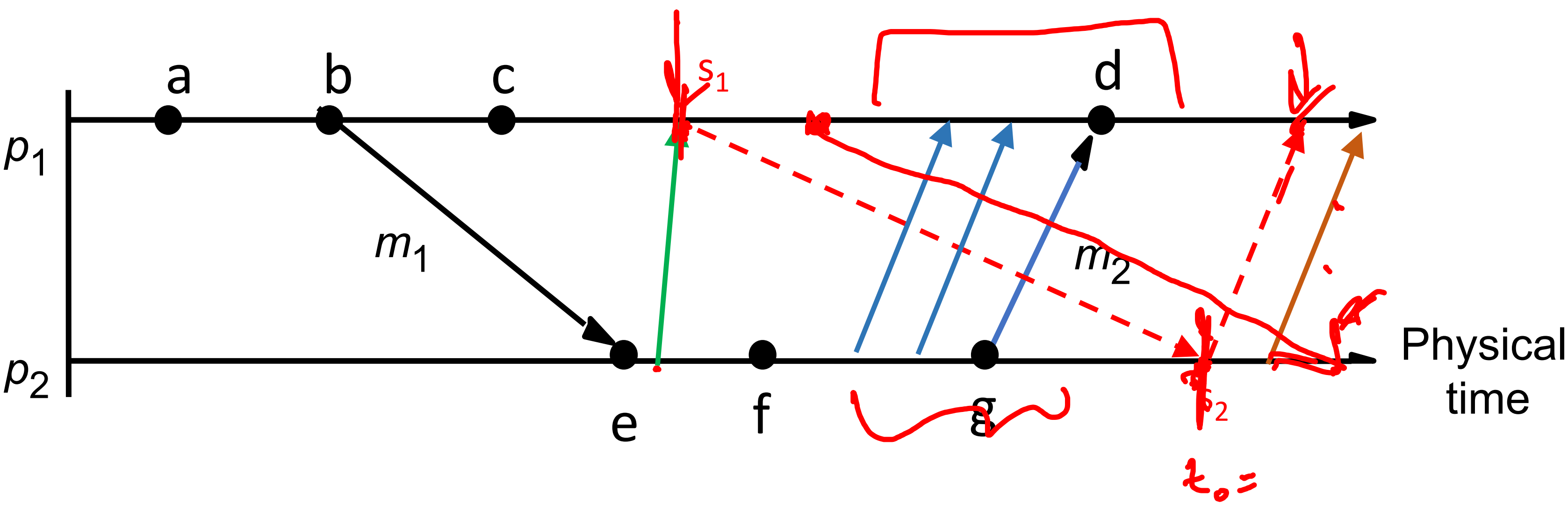
Cut frontier: {c, g}

Chandy-Lamport Algorithm Intuition



Cut frontier: {c, g}

Chandy-Lamport Algorithm Intuition



Cut frontier: {c, g}

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

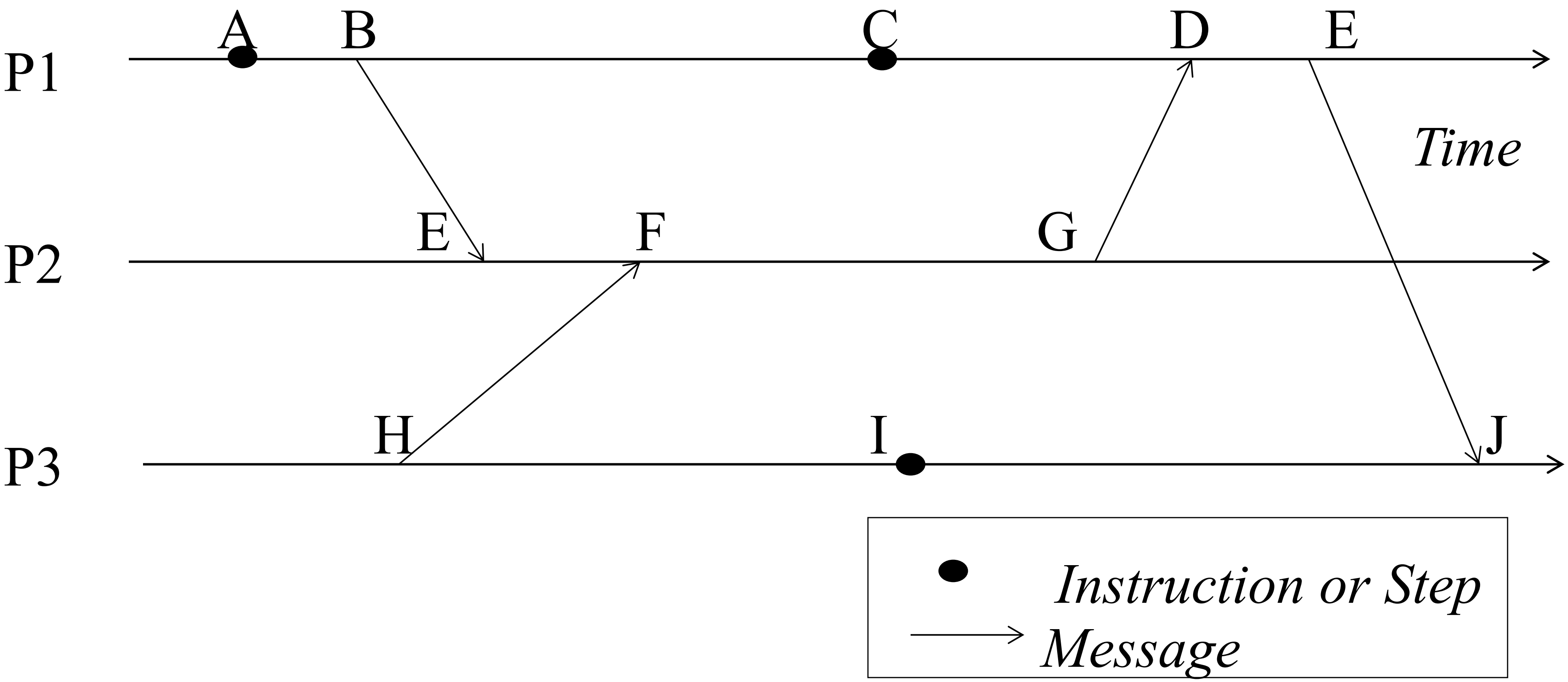
- if (this is the first **marker** p_i is seeing)
  - p_i records its own state first
  - marks the state of channel c_{ki} as "empty"
  - for j=1 to n except i
    - p_i sends out a **marker** message on outgoing channel c_{ij}
  - starts recording the incoming messages on each of the incoming channels 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

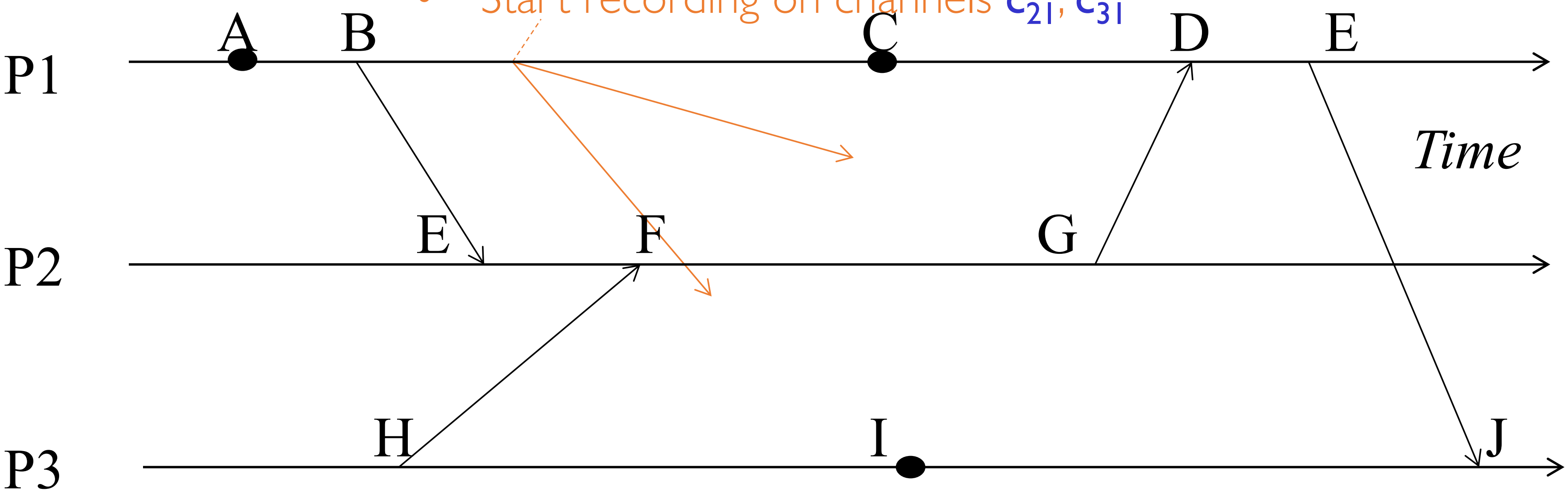
Example



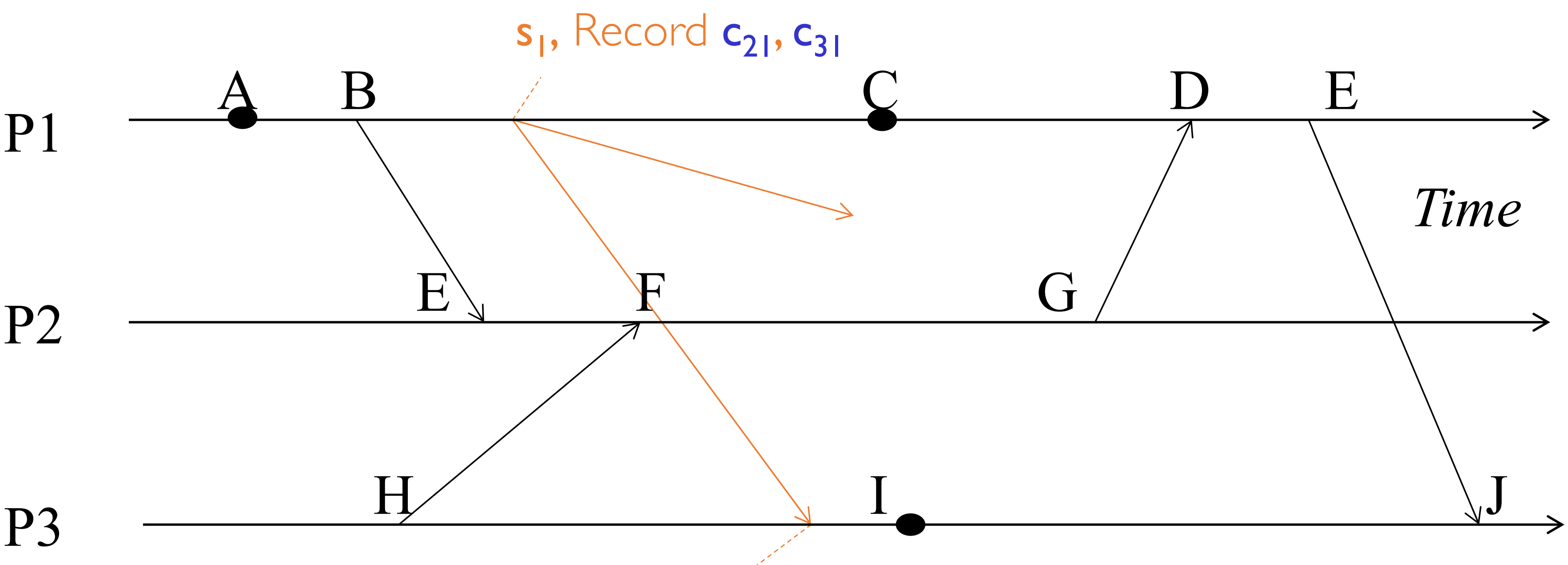
Example

p_1 is initiator:

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

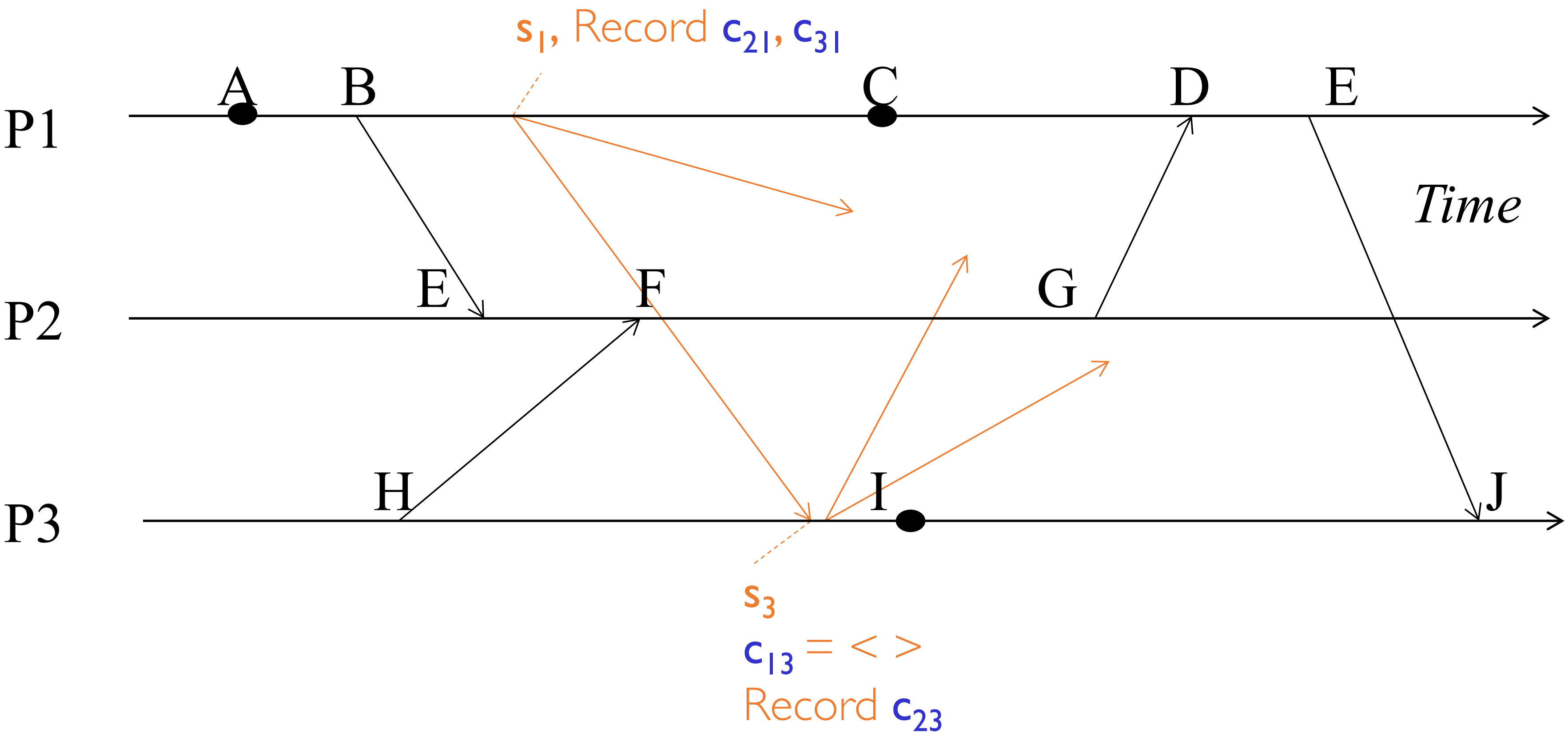


Example

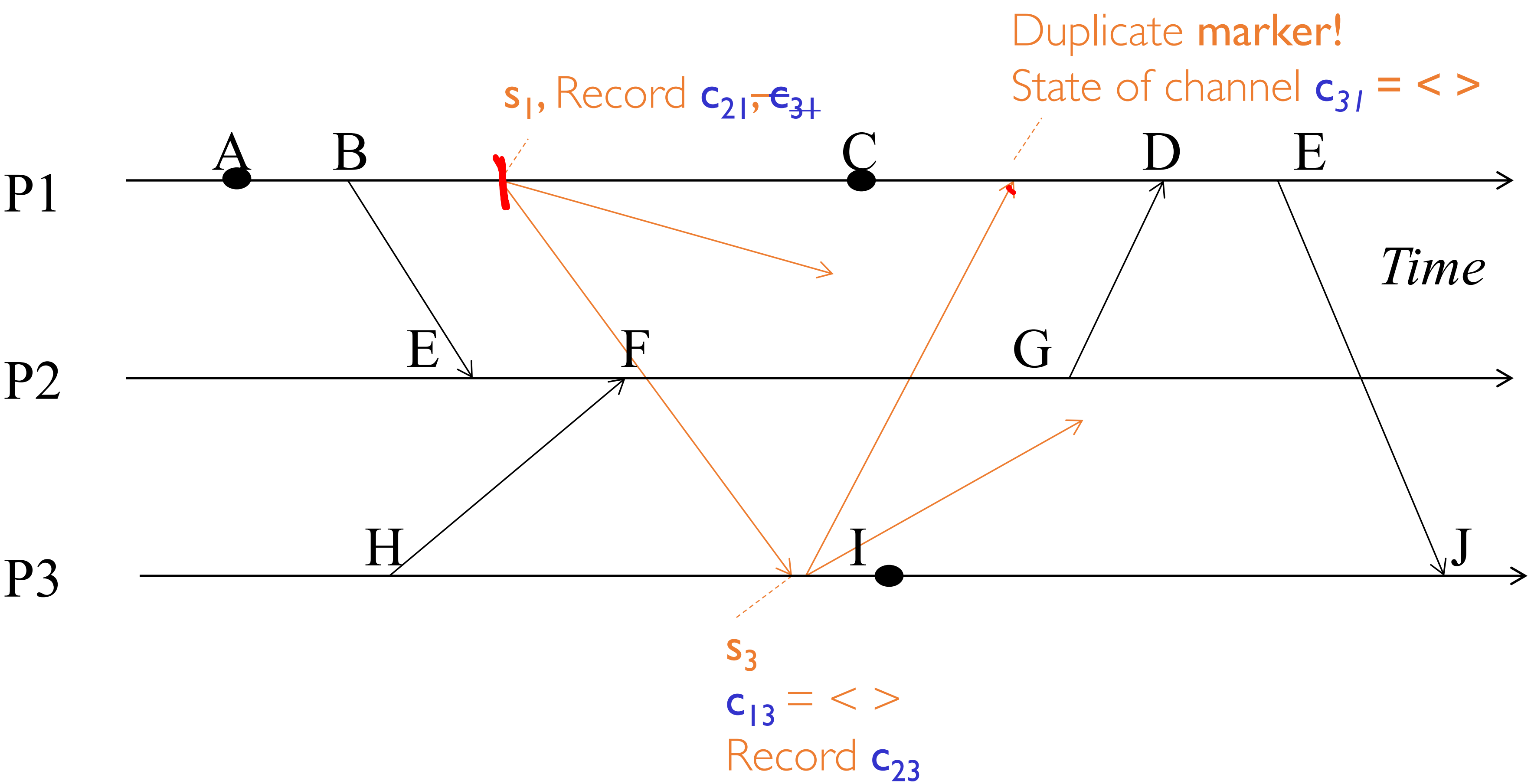


- First **marker**!
- Record own state as $\mathbf{s_3}$
- Mark $\mathbf{c_{13}}$ state as empty
- Start recording on other incoming $\mathbf{c_{23}}$
- Send out markers

Example

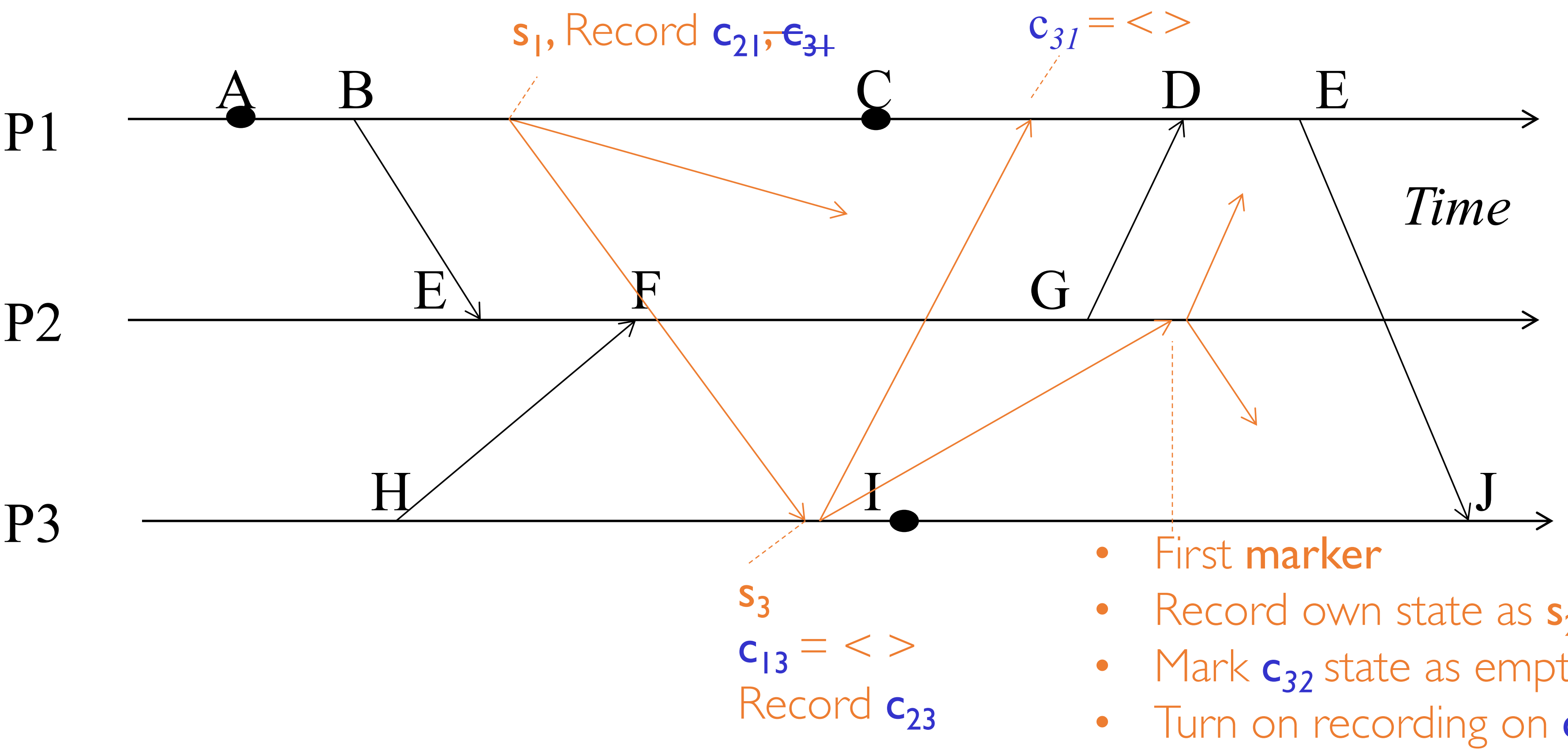


Example



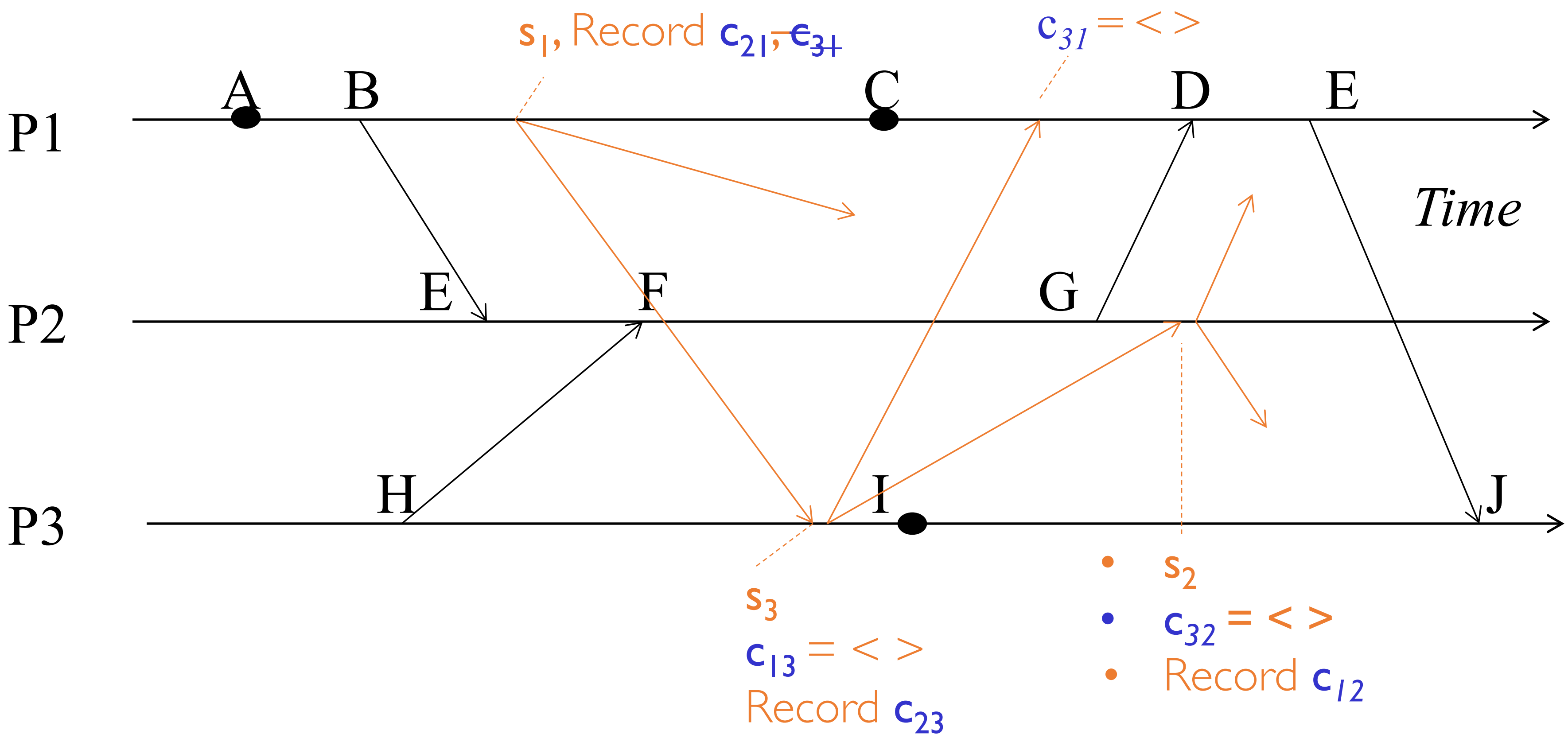
Duplicate **marker!**
State of channel c_{31} = < >
s_1, Record c_{21}, c_{31}
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
s_3
c_{13} = < >
Record c_{23}

Example



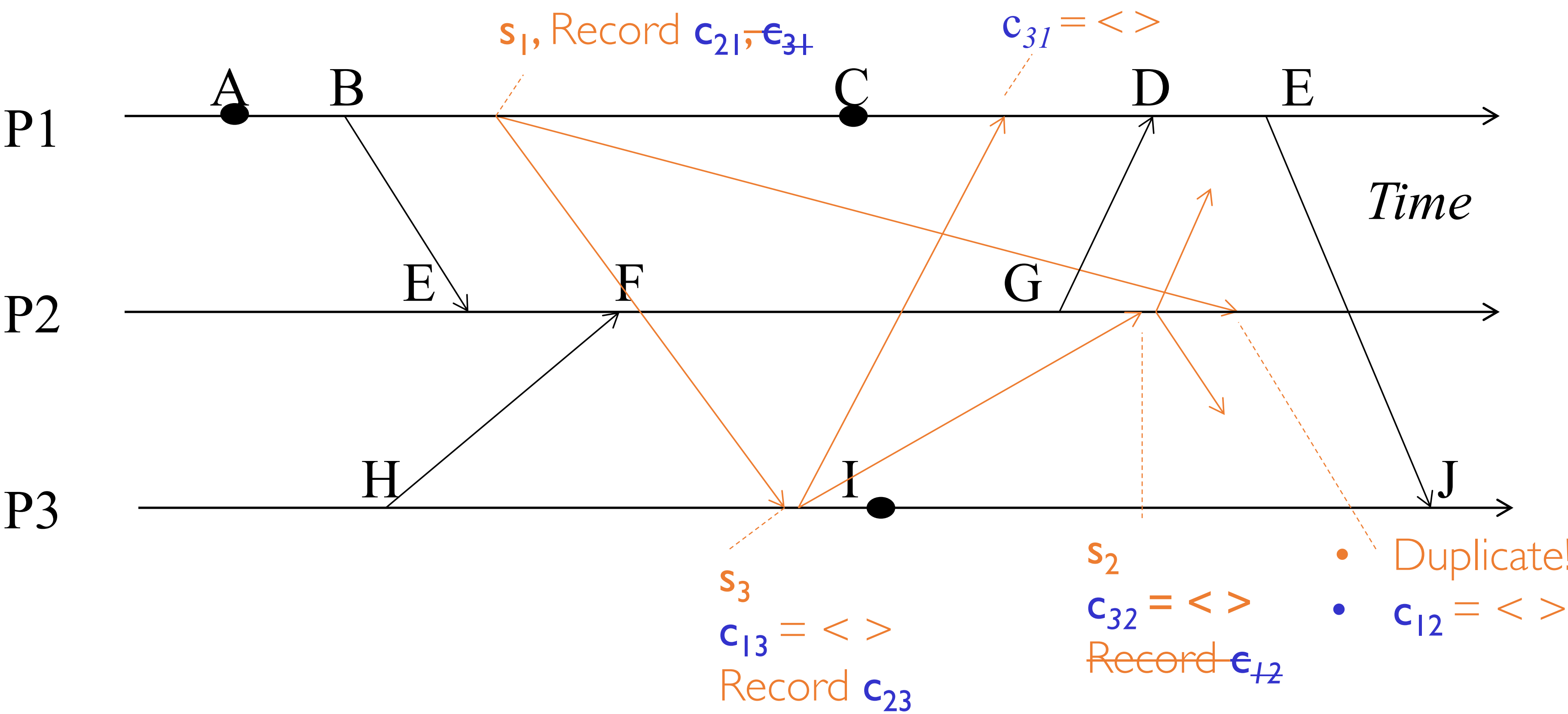
- First **marker**
- Record own state as $\mathbf{s_2}$
- Mark $\mathbf{c_{32}}$ state as empty
- Turn on recording on $\mathbf{c_{12}}$
- Send out **markers**

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

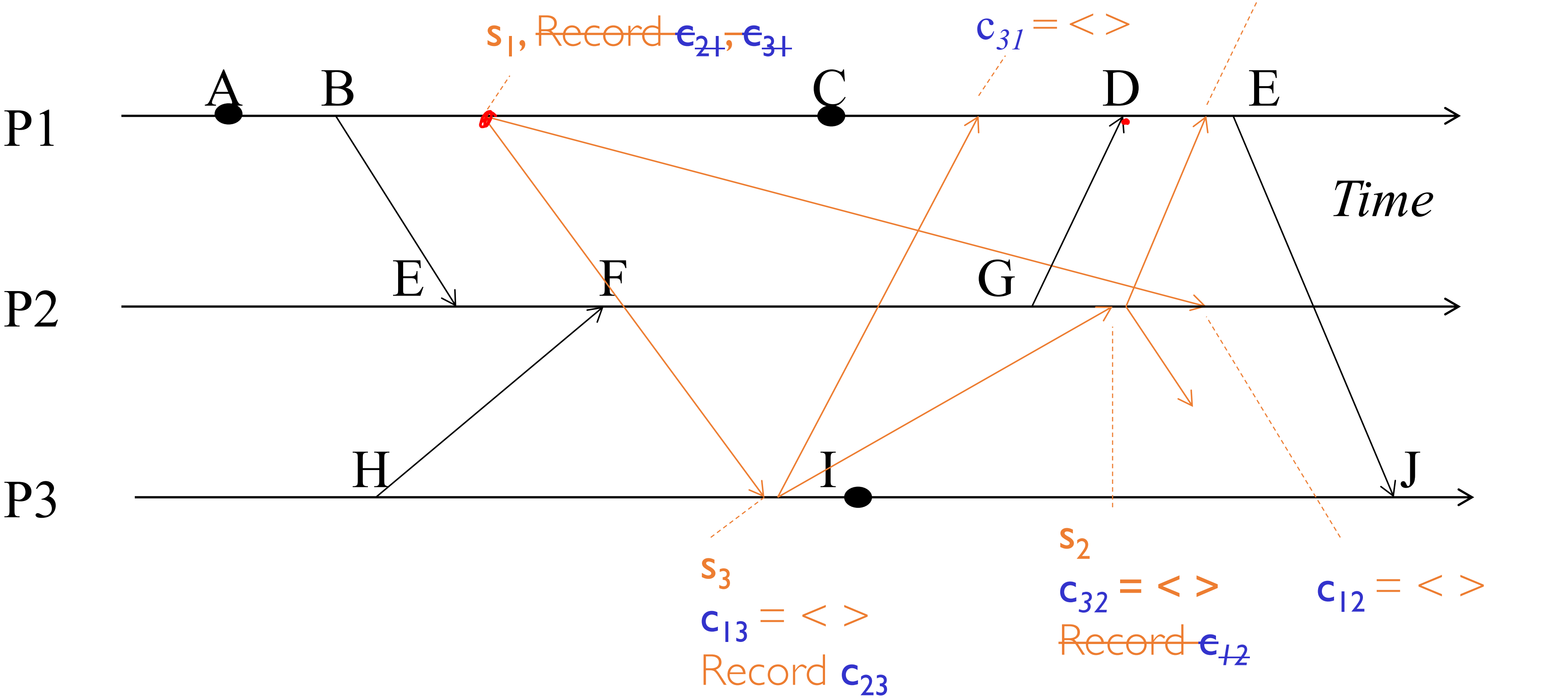
Example



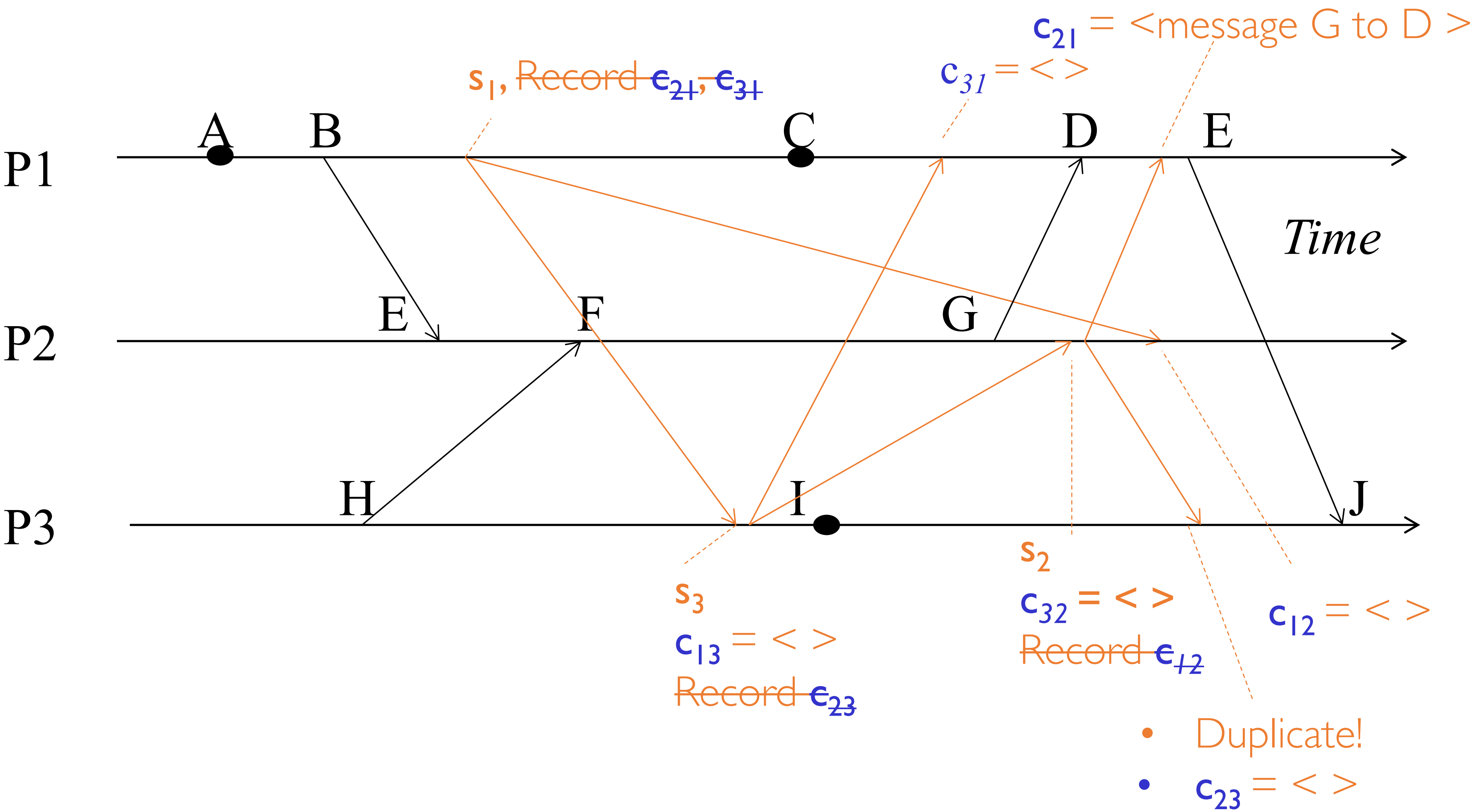
s1, Record c21, c31
c31 = < >
A B C D E
P1
Time
E F G
P2
H I J
P3
s3
c13 = < >
Record c23
s2
c32 = < >
Record c12
Duplicate!
c12 = < >

Example

- Duplicate!
- c_{21} = <message G to D >

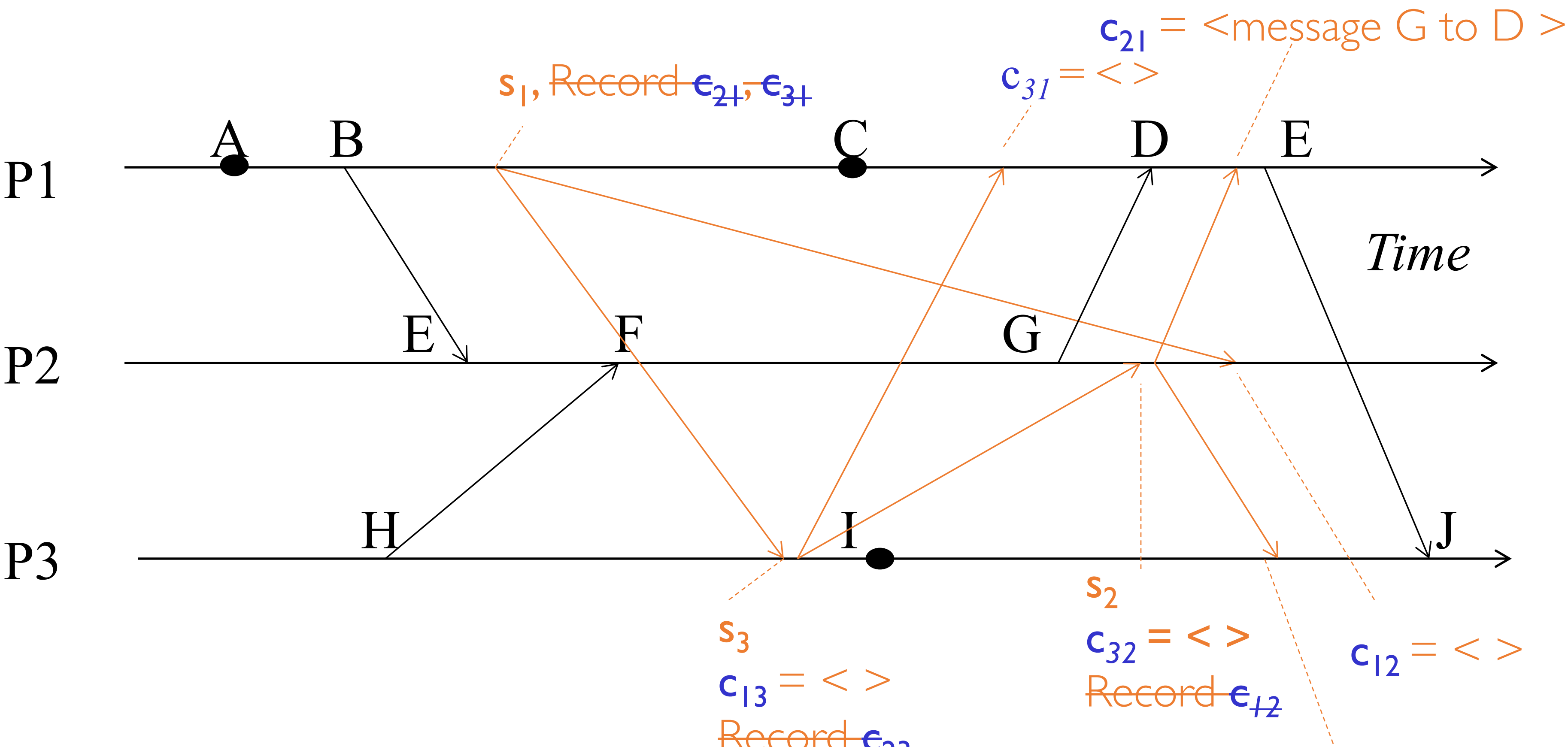


Example



c_{21} = <message G to D >
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}
s_2
c_{32} = < >
Record c_{12}
c_{12} = < >
Duplicate!
c_{23} = < >

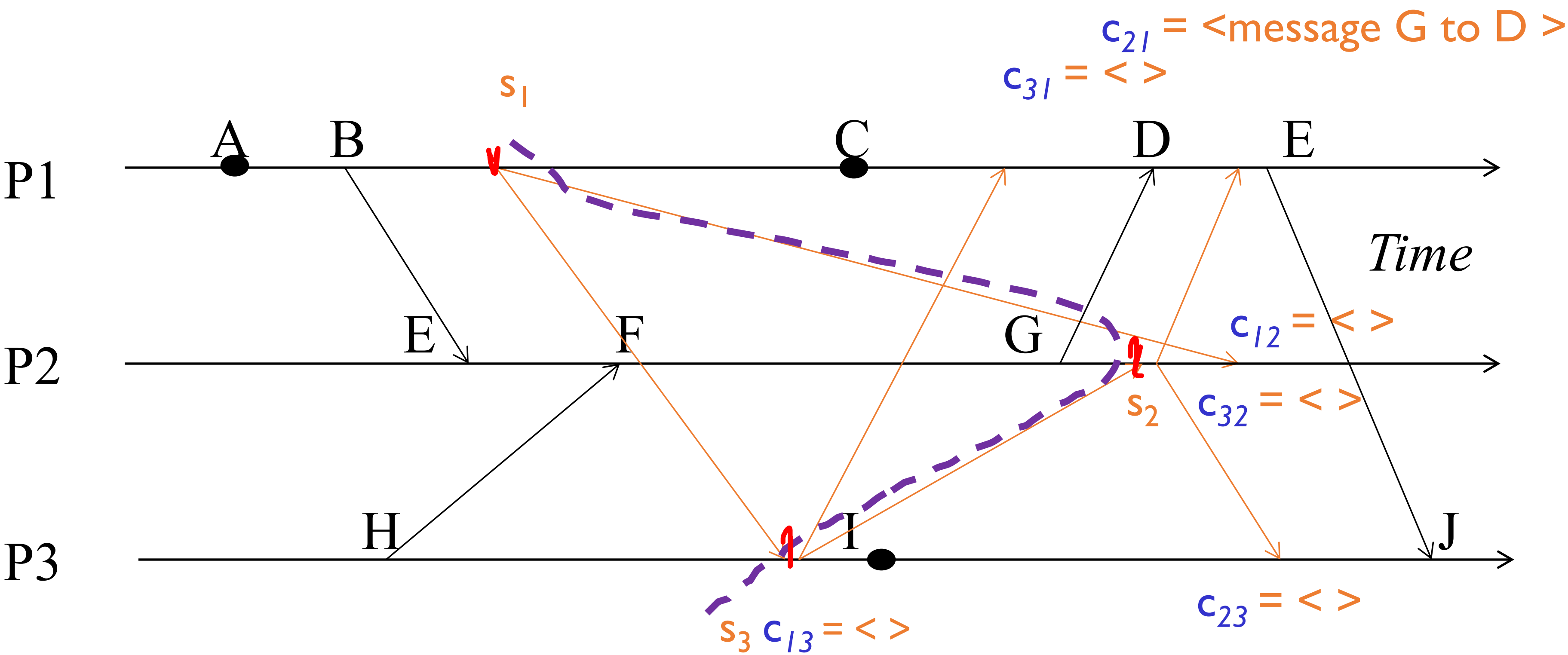
Example



Algorithm has terminated!

- Duplicate!
- c_{23} = < >

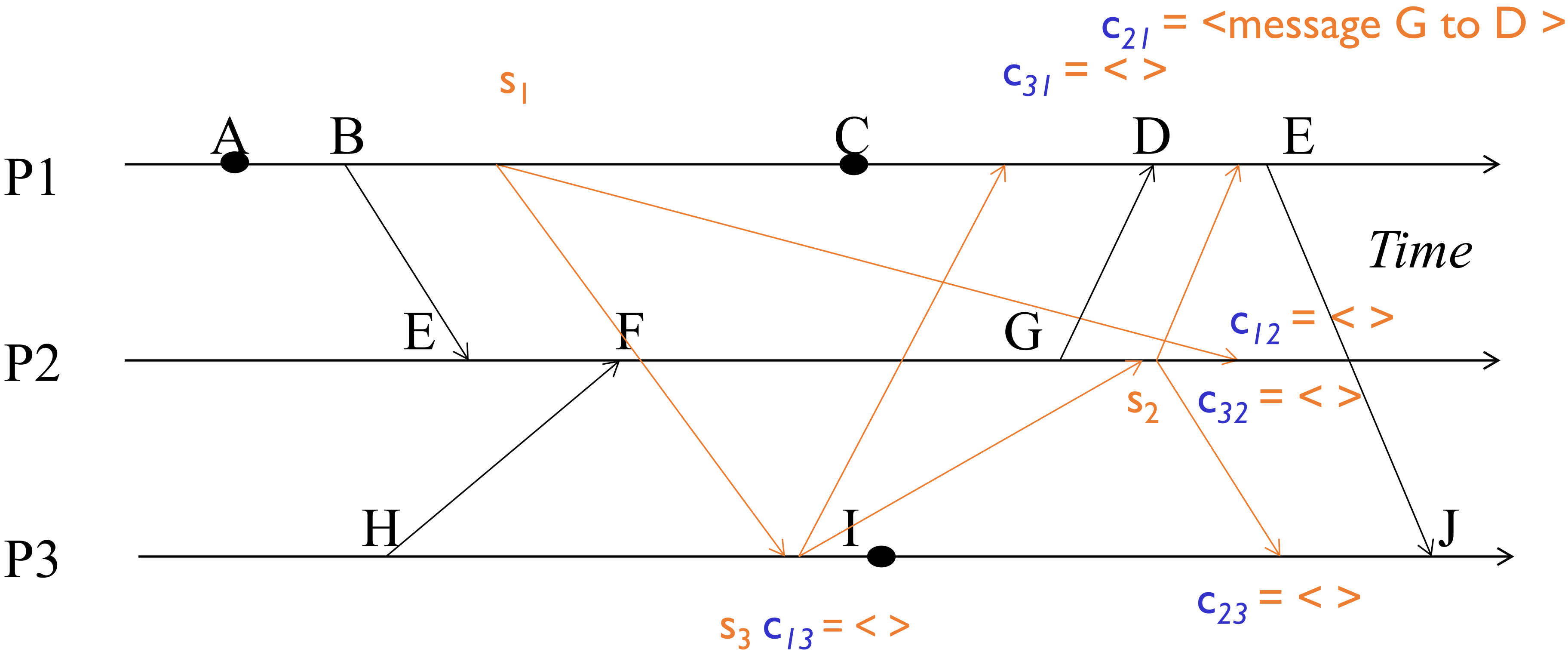
Example



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.