Distributed Computing Concepts - Global State in Distributed Systems

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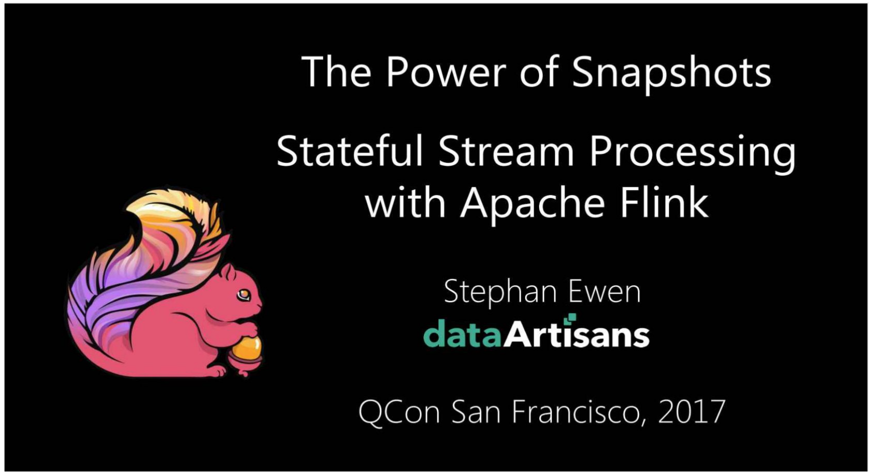
230 Distributed Systems - Week 3

-includes slides/examples from

Indy Gupta (UIUC), Coulouris(book) and Kshemkalyani&Singhal (book slides)

Why Global State?

- Distributed applications/services execute concurrently on multiple machines.
- A **Snapshot** of the distributed application, i.e. a **global picture is useful**
    - *Checkpointing*: can restart distributed application on failure
    - *Garbage collection* of objects: objects at servers that don't have any other objects (at any servers) with pointers to them
    - Deadlock detection: Useful in database transaction systems
    - Termination of computation: Useful in batch computing systems like Folding@Home, SETI@Home


The Power of Snapshots

Stateful Stream Processing with Apache Flink

Stephan Ewen
dataArtisans

QCon San Francisco, 2017

What constitutes global state?

- **Global Snapshot** = **Global State**

  Individual state of *each process* in the distributed system

  +

  Individual state of *each communication channel* in the distributed system

- Capture the instantaneous *state* of each process
- Capture the instantaneous *state* of each communication channel, i.e., *messages* in transit on the channels

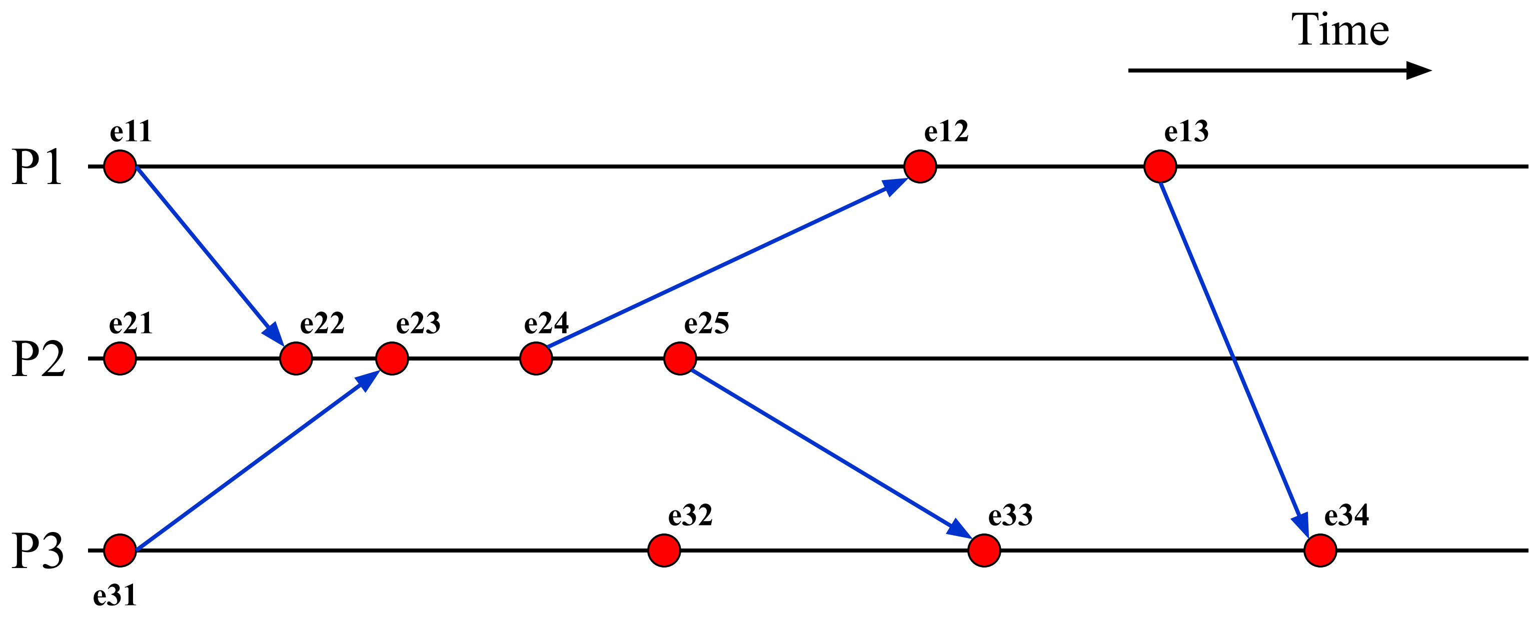
Simulate A Global State

- The notions of global time and global state are closely related.
- But, merely synchronizing clocks and taking local snapshots is not enough
- Need to account for messages in transit

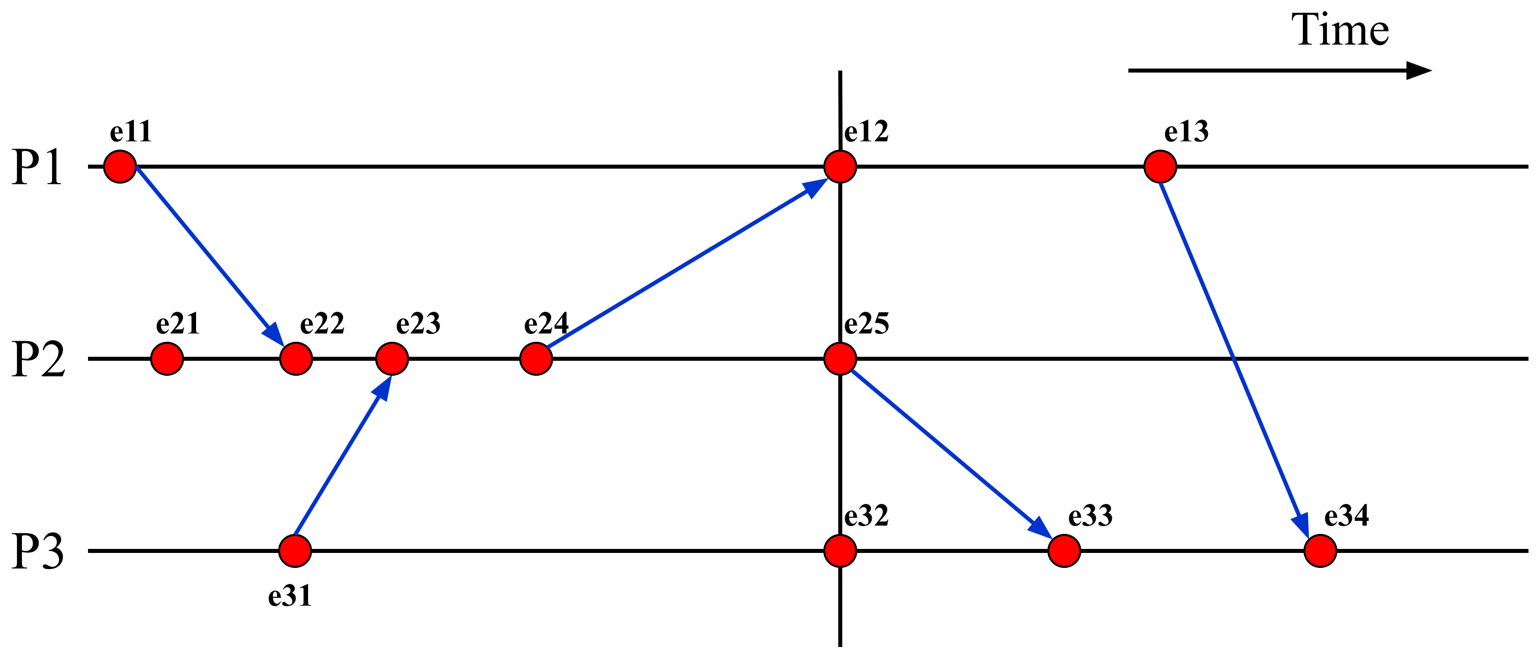
- A process can (without *freezing* the whole computation) compute the *best possible approximation* of a global state [Chandy & Lamport 85]

- A global state that *could* have occurred
  - No process in the system can decide whether the state did really occur
  - Guarantee stable properties (i.e. once they become true, they remain true)

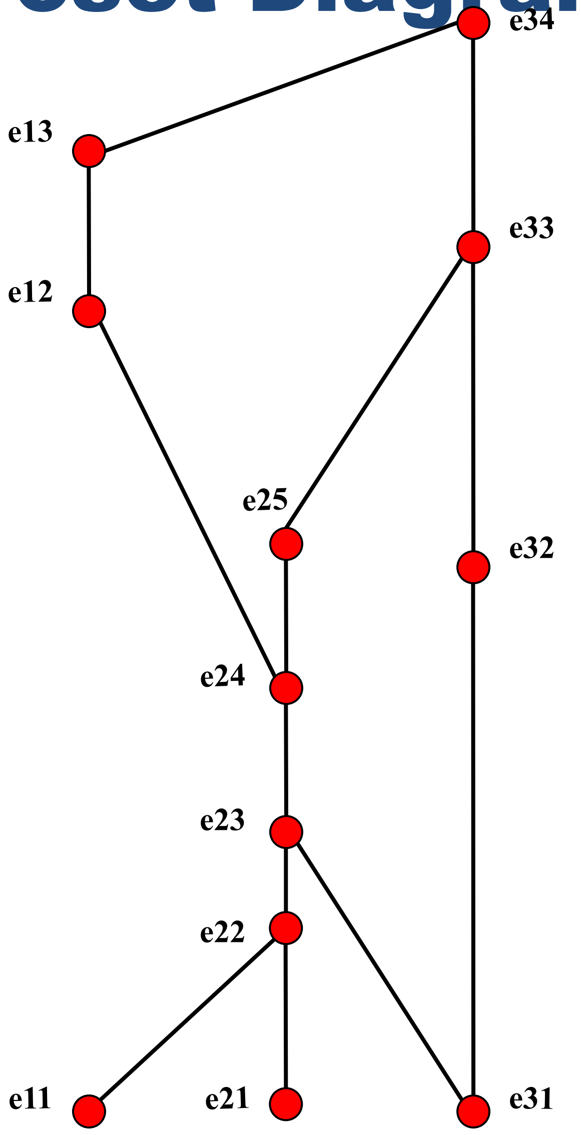
Event Diagram



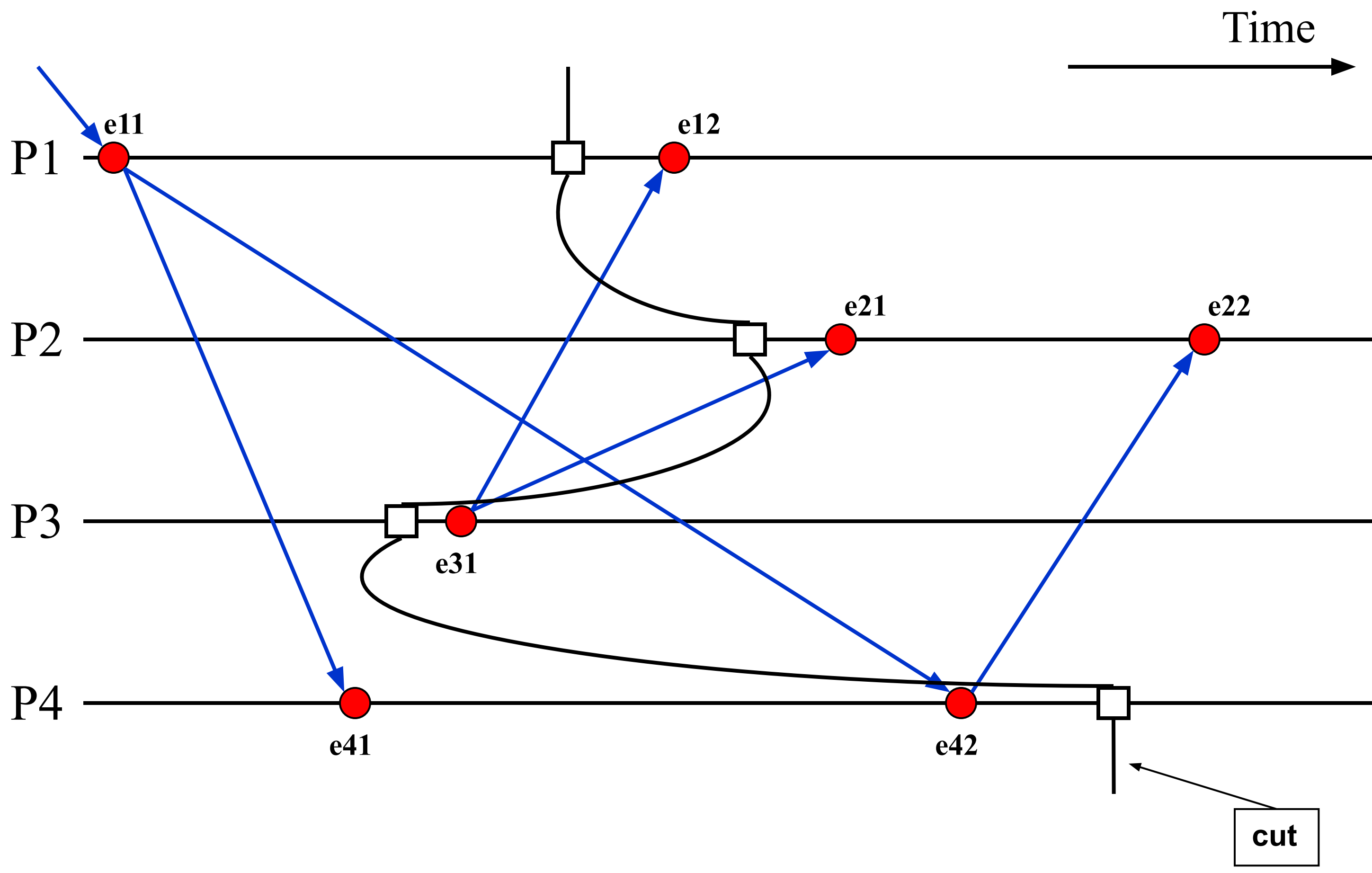
Equivalent Event Diagram



Poset Diagram



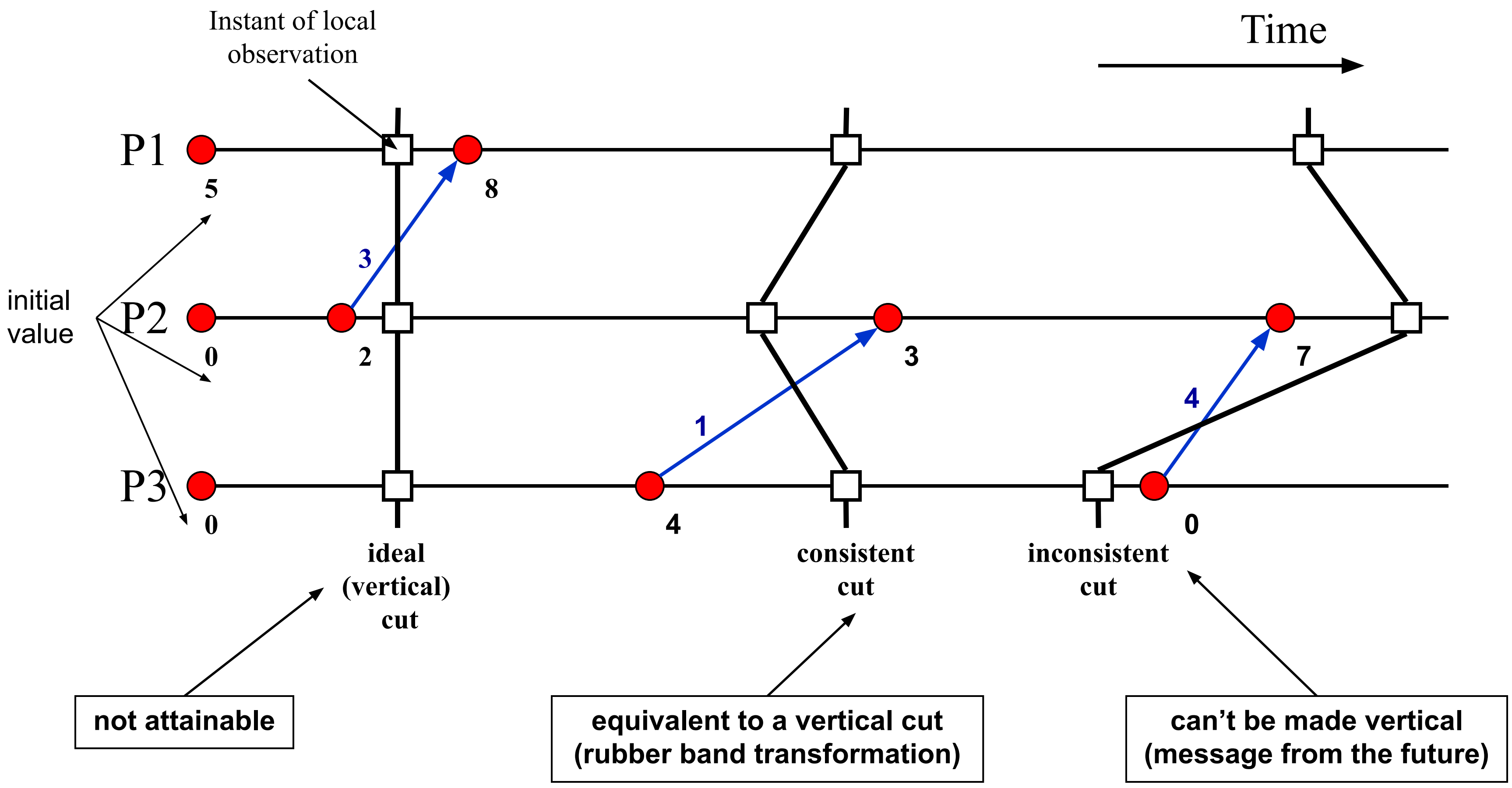
Rubber Band Transformation



Consistent Cuts

- A cut (or time slice) is a zigzag line cutting a time diagram into 2 parts (past and future)
  - E is augmented with a cut event c_i for each process P_i:$E' = E \cup \{c_i, \dots, c_n\}$ $\therefore$
    - A cut C of an event set E is a finite subset $C \subseteq E$: $e \in C \wedge e' <_l e \rightarrow e' \in C$
    - A cut C_1 is later than C_2 if $C_1 \supseteq C_2$
    - A consistent cut C of an event set E is a finite subset $C \subseteq E$: $e \in C \wedge e' < e \rightarrow e' \in C$
      - i.e. a cut is consistent if every message received was previously sent (but not necessarily vice versa!)

Cuts (Summary)


Instant of local observation
Time
P1
P2
P3
initial value
5
8
3
0
2
3
1
4
3
7
0
4
0
ideal (vertical) cut
consistent cut
inconsistent cut
not attainable
equivalent to a vertical cut (rubber band transformation)
can't be made vertical (message from the future)

Consistent Cuts

- Some Theorems
  - For a consistent cut consisting of cut events $c_i,\ldots,c_n$, no pair of cut events is causally related. i.e $\forall c_i,c_j \sim(c_i < c_j) \wedge \sim(c_j < c_i)$

  - **For any time diagram with a consistent cut consisting of cut events $c_i,\ldots,c_n$, there is an equivalent time diagram where $c_i,\ldots,c_n$ occur simultaneously. i.e. where the cut line forms a straight vertical line**
    - **All cut events of a consistent cut *can occur simultaneously***

Global States of Consistent Cuts

- The global state of a distributed system is a collection of the local states of the processes and the channels.
- A *global state* computed along a consistent cut is correct
- The *global state* of a consistent cut comprises the local state of each process at the time the cut event happens and the set of all messages sent but not yet received
- The *snapshot problem* consists in designing an efficient protocol which yields only consistent cuts and to collect the local state information
    - Messages crossing the cut must be captured
    - Chandy & Lamport presented an algorithm assuming that message transmission is FIFO

Distributed Global Snapshot: Requirements

- Snapshot should not interfere with normal application actions, and it should not require application to stop sending messages

- Each process is able to record its own state
  - Process state: Application-defined state or, in the worst case:
  - its heap, registers, program counter, code, etc. (essentially the coredump)

- Global state is collected in a distributed manner

- Any process may initiate the snapshot
  - Assume just one snapshot run for now

System Model for Global Snapshots

- The system consists of a collection of n processes p1, p2, ..., pn that are connected by channels.
- There are no globally shared memory and physical global clock and processes communicate by passing messages through communication channels.
- C_{ij} denotes the channel from process pi to process pj and its state is denoted by SC_{ij} .
- The actions performed by a process are modeled as three types of events:
  - Internal events,the message send event and the message receive event.
  - For a message mij that is sent by process pi to process pj , let send(m_{ij}) and rec(m_{ij}) denote its send and receive events.

Process States and Messages in transit

- At any instant, the state of process pi , denoted by LSi , is a result of the sequence of all the events executed by pi till that instant.
  - For an event e and a process state LSi , e∈LSi iff e belongs to the sequence of events that have taken process pi to state LSi .
  - For an event e and a process state LSi , e (not in) LSi iff e does not belong to the sequence of events that have taken process pi to state LSi .
- For a channel Cij , the following set of messages can be defined based on the local states of the processes pi and pj

  Transit: transit(LSi , LSj) = {mij |send(mij) ∈ LSi V
  rec(mij) (not in) LSj }

Chandy-Lamport Distributed Snapshot Algorithm

- **Assumes FIFO communication in channels**
- Uses a control message, called a *marker* to separate messages in the channels.
  - After a site has recorded its snapshot, it sends a marker, along all of its outgoing channels before sending out any more messages.
  - The marker separates the messages in the channel into those to be included in the snapshot from those not to be recorded in the snapshot.
- **When to capture local state?**
  - A process must record its snapshot no later than when it receives a marker on any of its incoming channels.
- **Termination**
  - The algorithm terminates after each process has received a marker on all of its incoming channels.
- All the local snapshots get disseminated to all other processes and all the processes can determine the global state.

Chandy-Lamport Distributed Snapshot Algorithm

Marker receiving rule for Process Pi

```
If (Pi has not yet recorded its state) it
    records its process state now
    records the state of c as the empty set
    turns on recording of messages arriving over other channels
else
    Pi records the state of c as the set of messages received over c
    since it saved its state
```

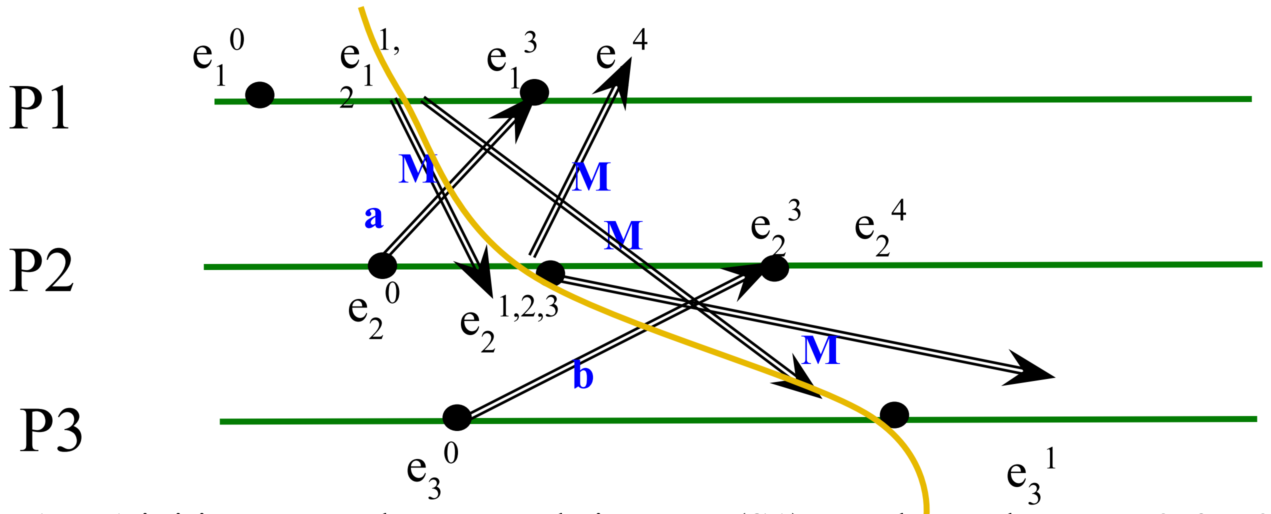
Marker sending rule for Process Pi

```
After Pi has recorded its state, for each outgoing channel c:
    Pi sends one marker message over c
        (before it sends any other message over c)
```

Snapshot Example

e_1^3

From: Indranil Gupta



1. P1 initiates snapshot: records its state (S1); sends Markers to P2 & P3; turns on recording for channels C21 and C31

2- P2 receives Marker over C12, records its state (S2), sets state(C12) = {} sends Marker to P1 & P3; turns on recording for channel C32

3- P1 receives Marker over C21, sets state(C21) = {a}

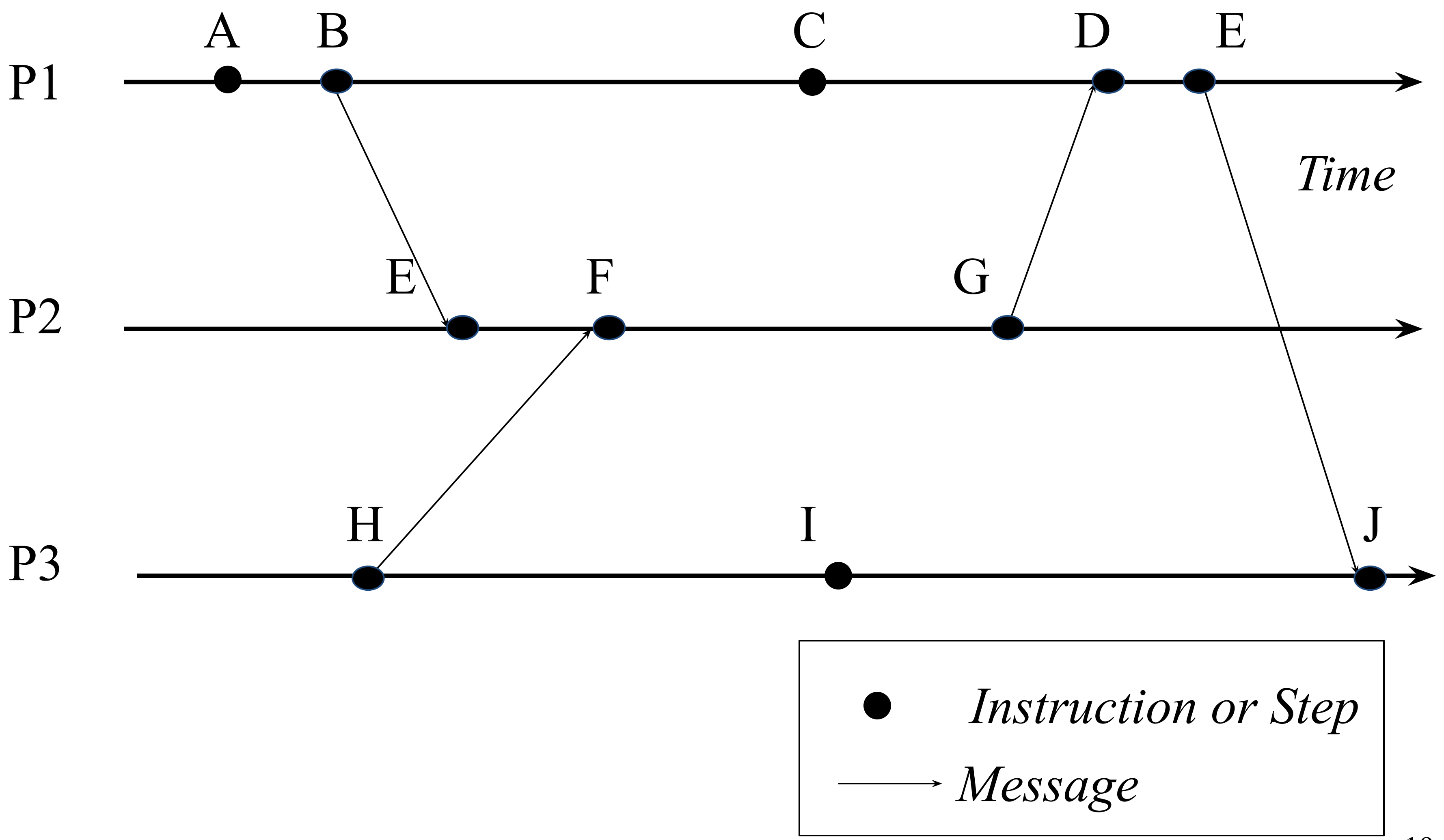
5- P2 receives Marker over C32, sets state(C32) = {b}

6- P3 receives Marker over C23, sets state(C23) = {}

7- P1 receives Marker over C31, sets state(C31) = {}

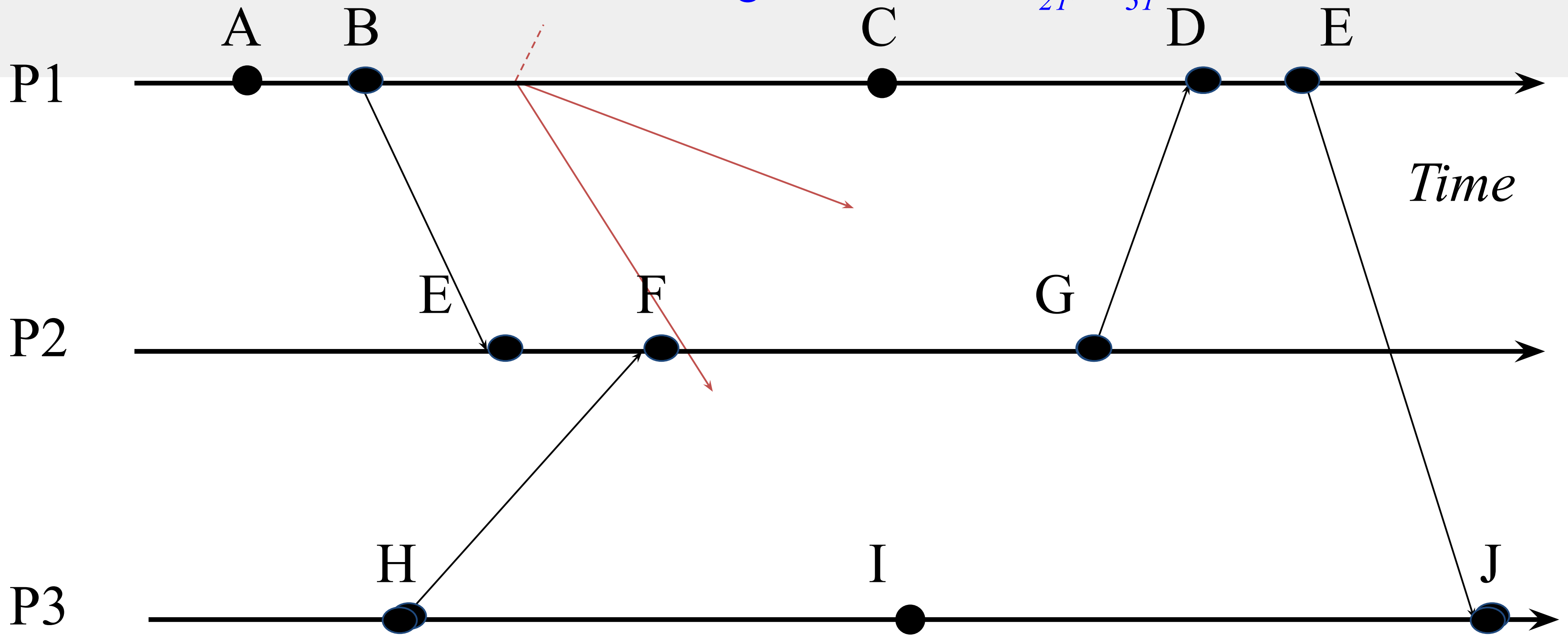
Snapshot Example

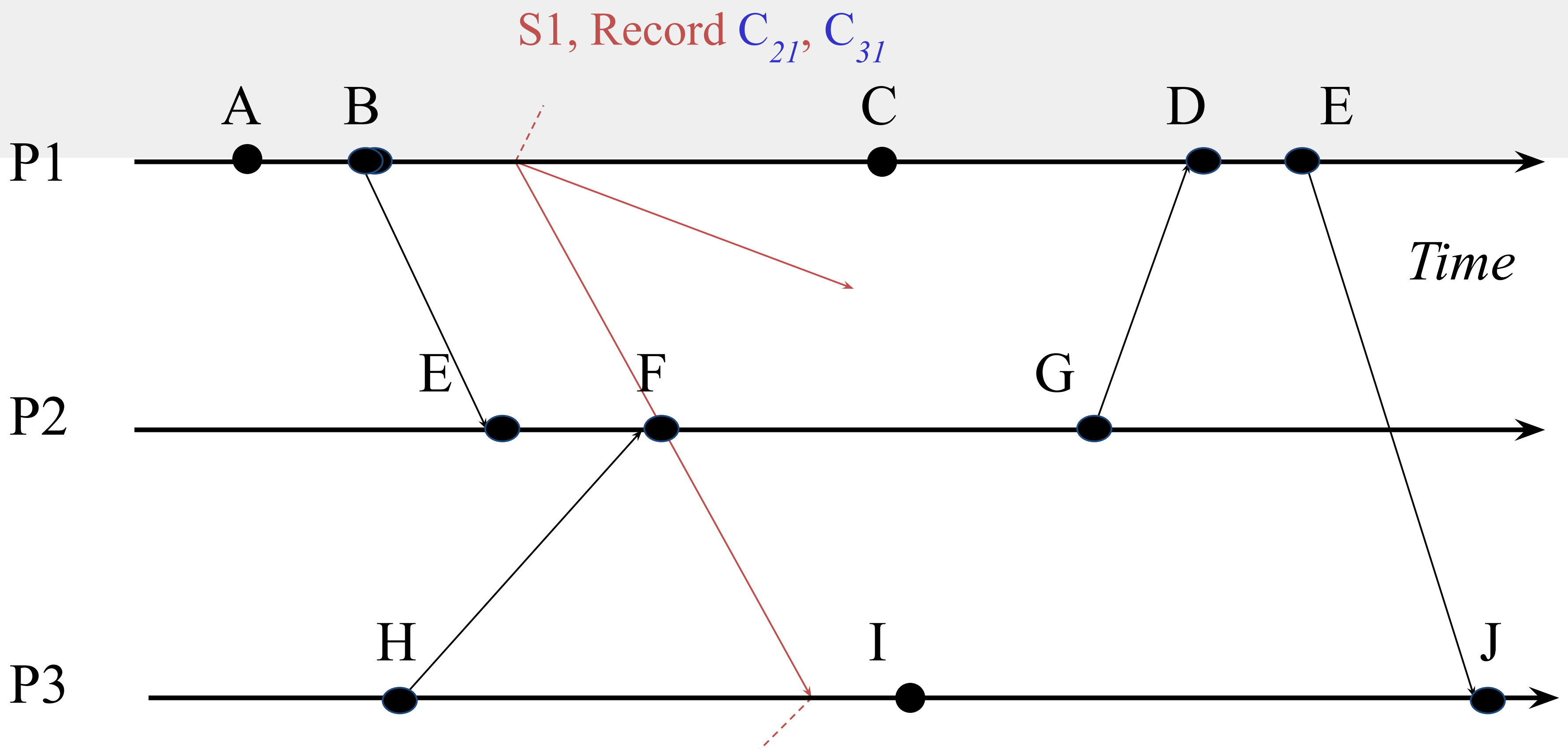
From: Indranil Gupta (CS425 - Distributed Systems course, UIUC)



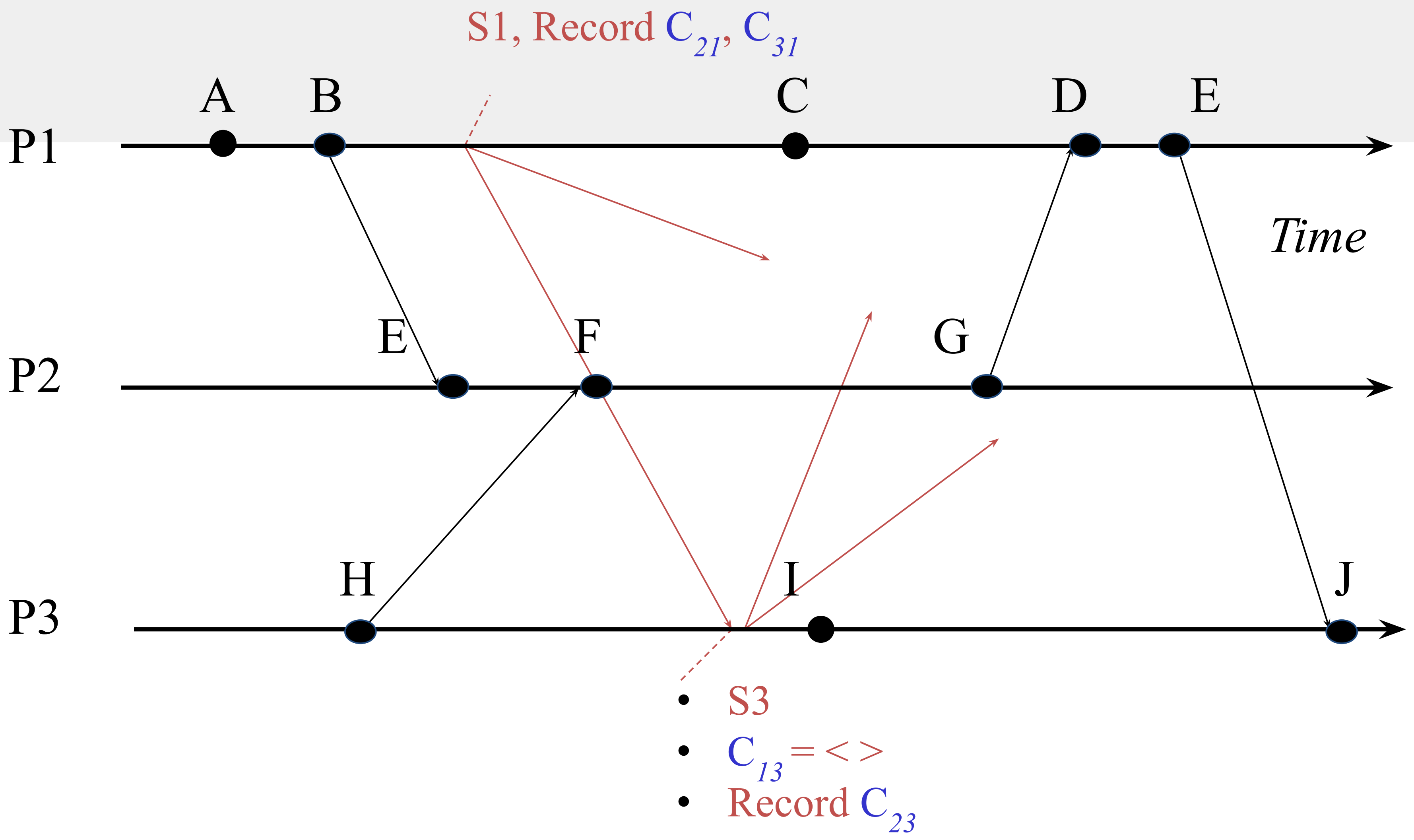
P1 is Initiator:

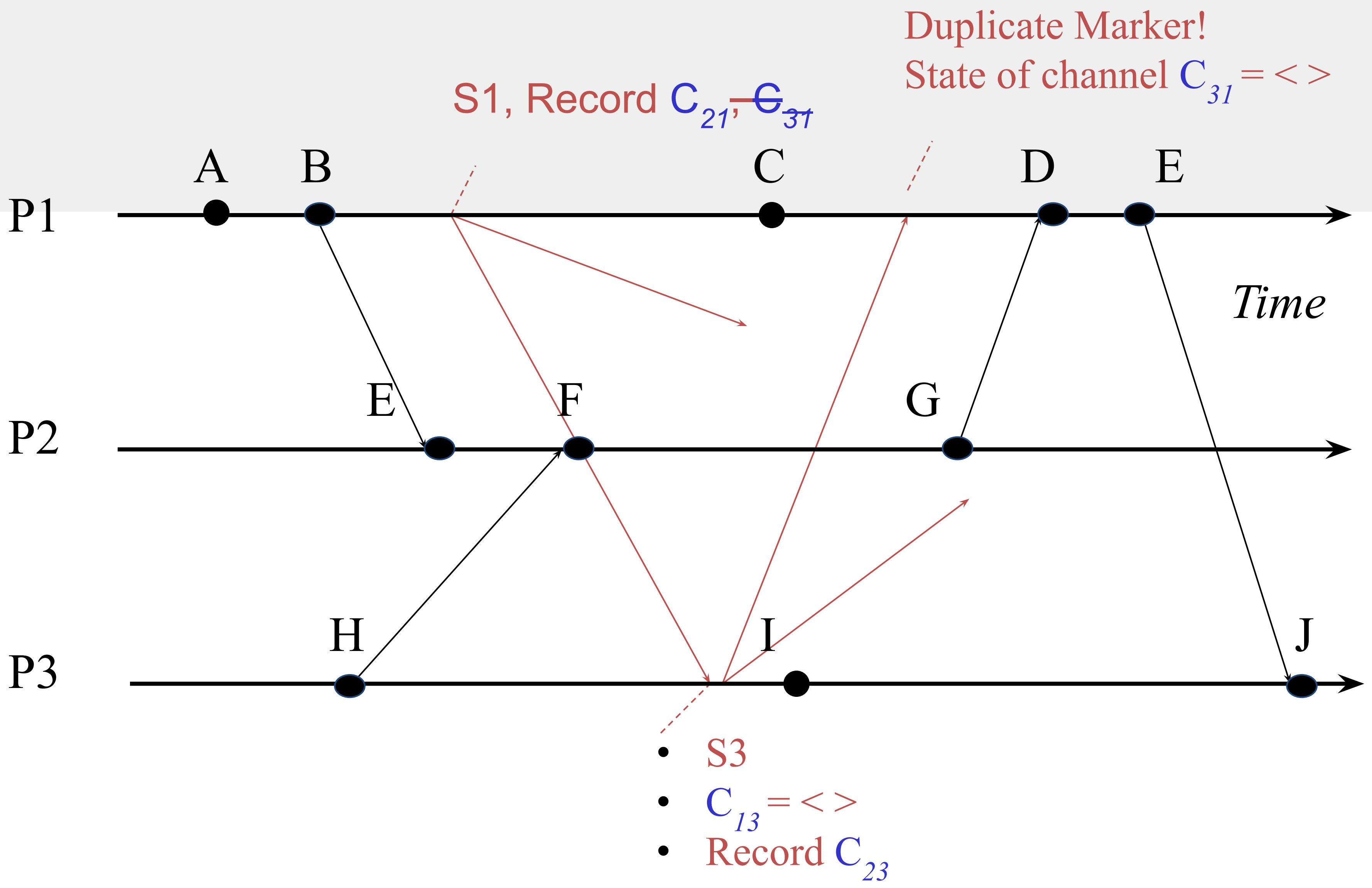
- Record local state S1,
- Send out markers
- Turn on recording on channels C_{21}, C_{31}

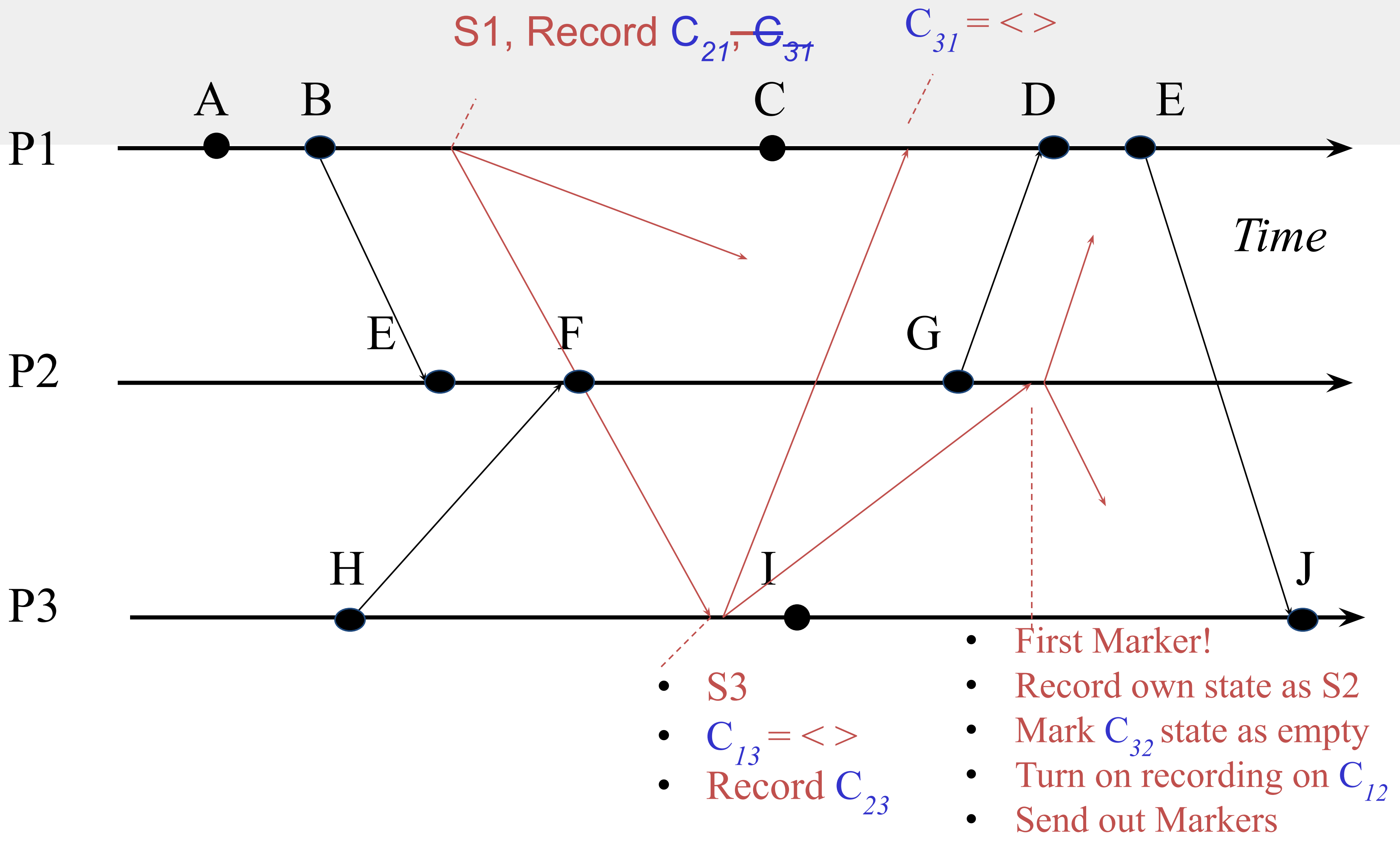




- First Marker!
- Record own state as S3
- Mark C_{13} state as empty
- Turn on recording on other incoming C_{23}
- Send out Markers

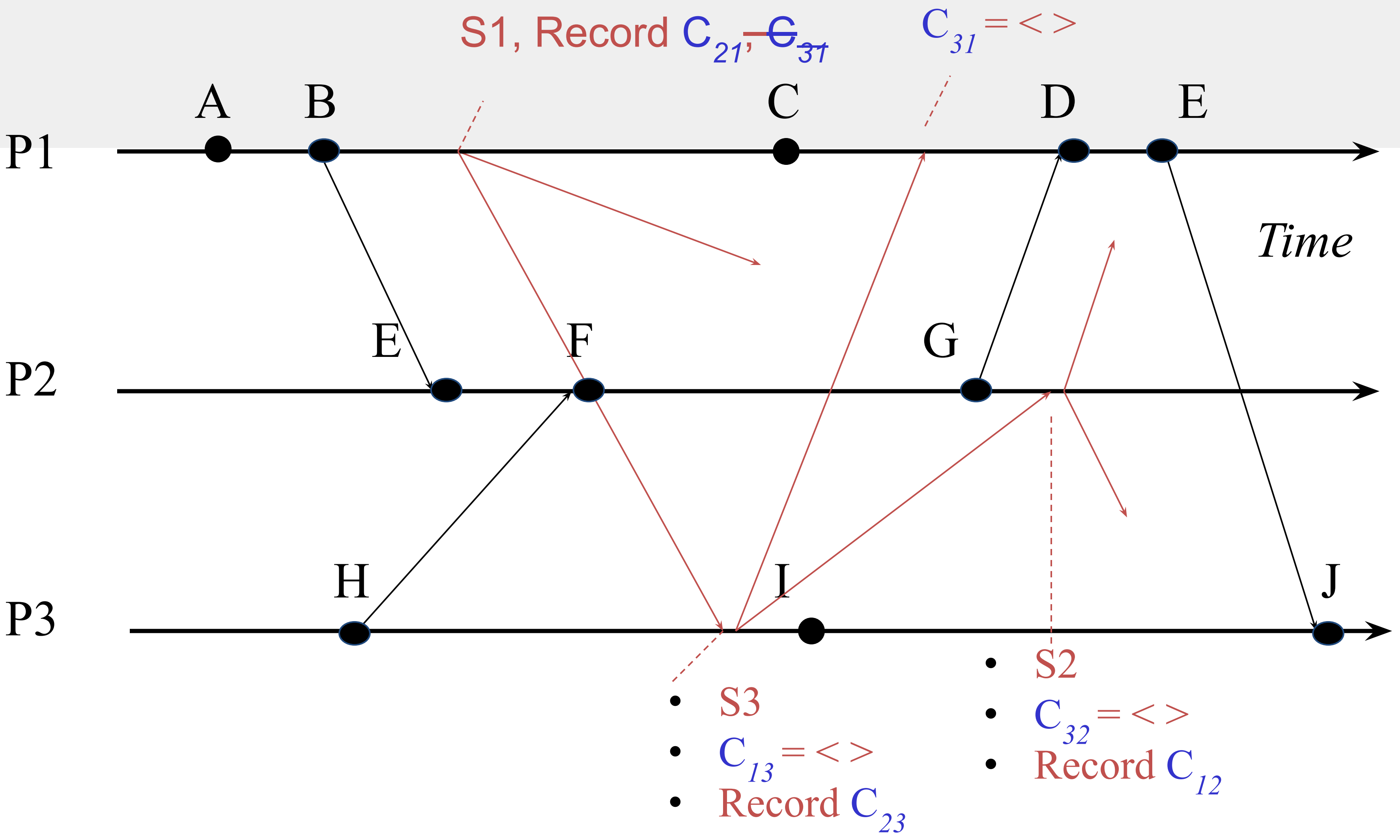

S1, Record C_{21}, C_{31}
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
$C_{13} = < >$
Record C_{23}

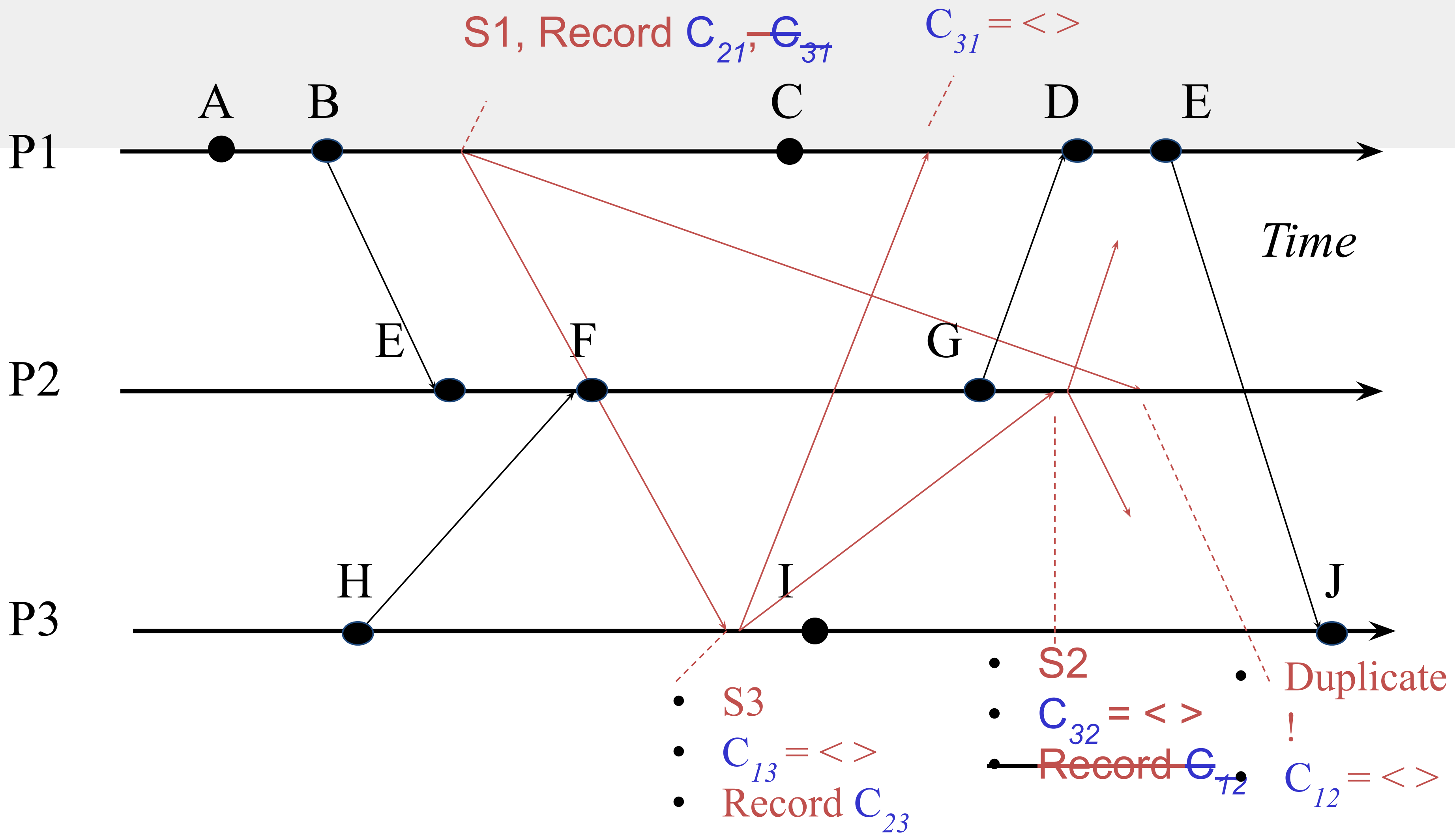

Duplicate Marker!
State of channel $C_{31} = < >$
S1, Record C_{21}, ~~C_{31}~~
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
$C_{13} = < >$
Record C_{23}

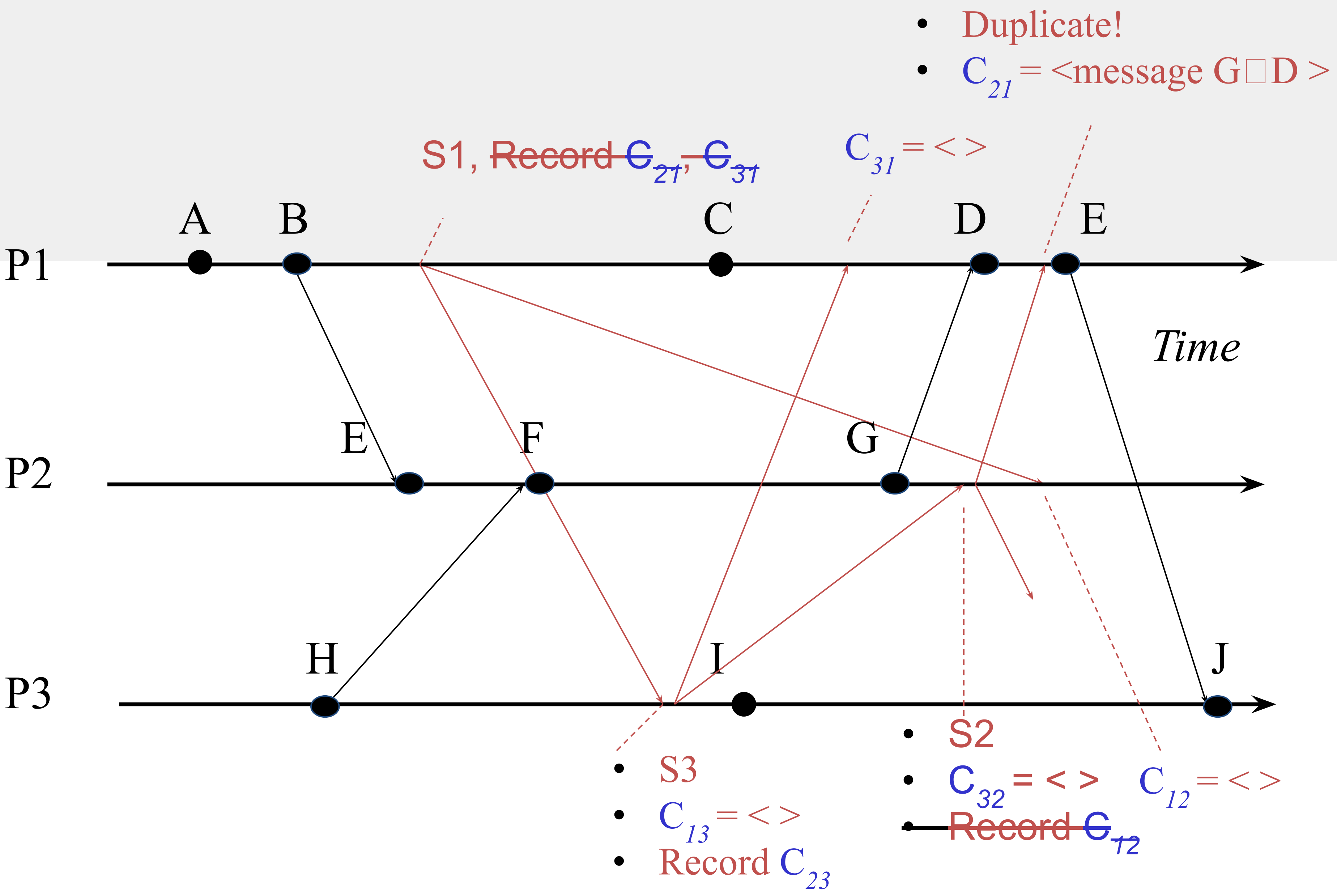


- S3
- $C_{13} = < >$
- Record C_{23}

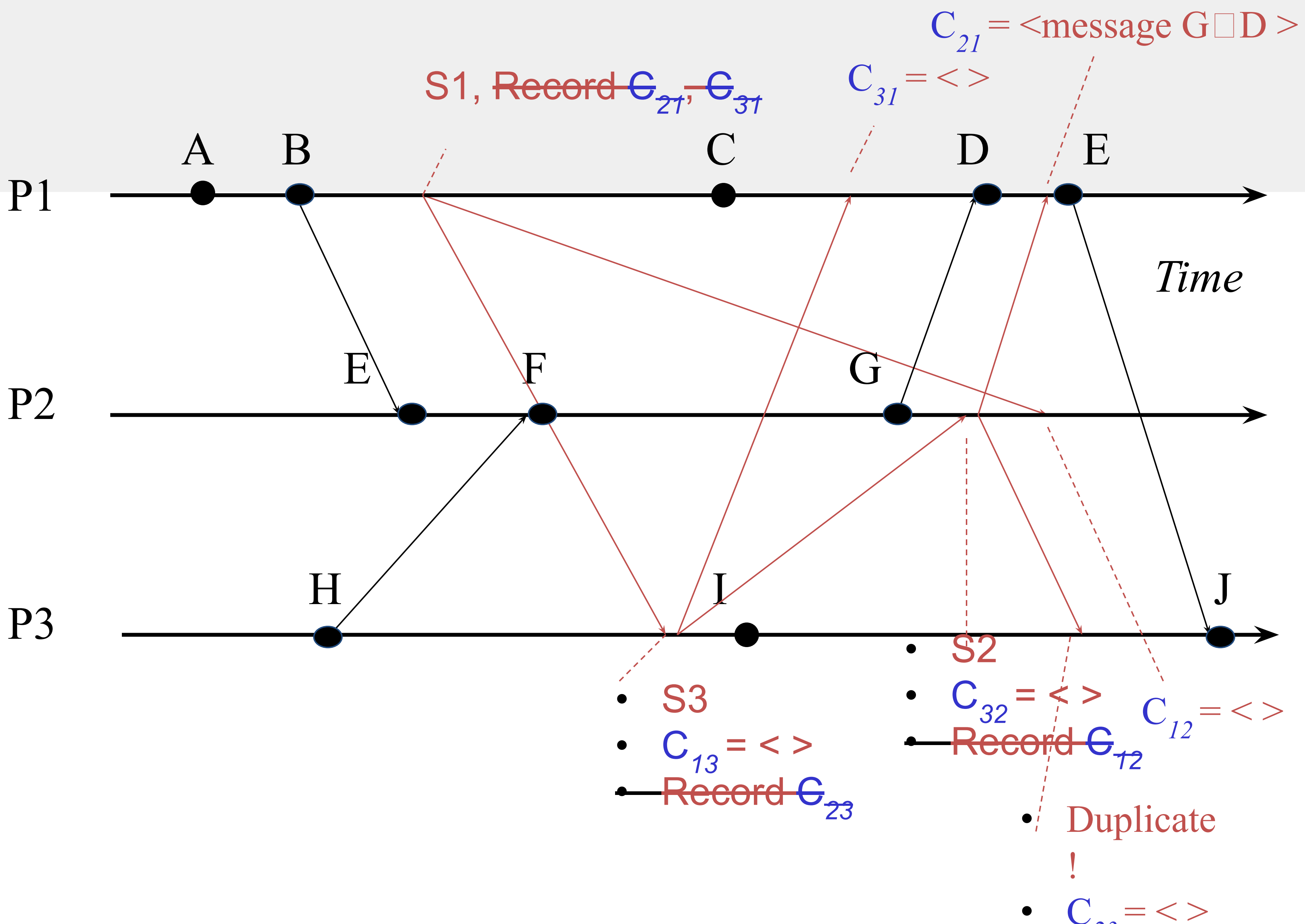
- First Marker!
- Record own state as S2
- Mark C_{32} state as empty
- Turn on recording on C_{12}
- Send out Markers


S1, Record C_{21}, ~~C_{31}~~
$C_{31} = < >$
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
$C_{13} = < >$
Record C_{23}
S2
$C_{32} = < >$
Record C_{12}

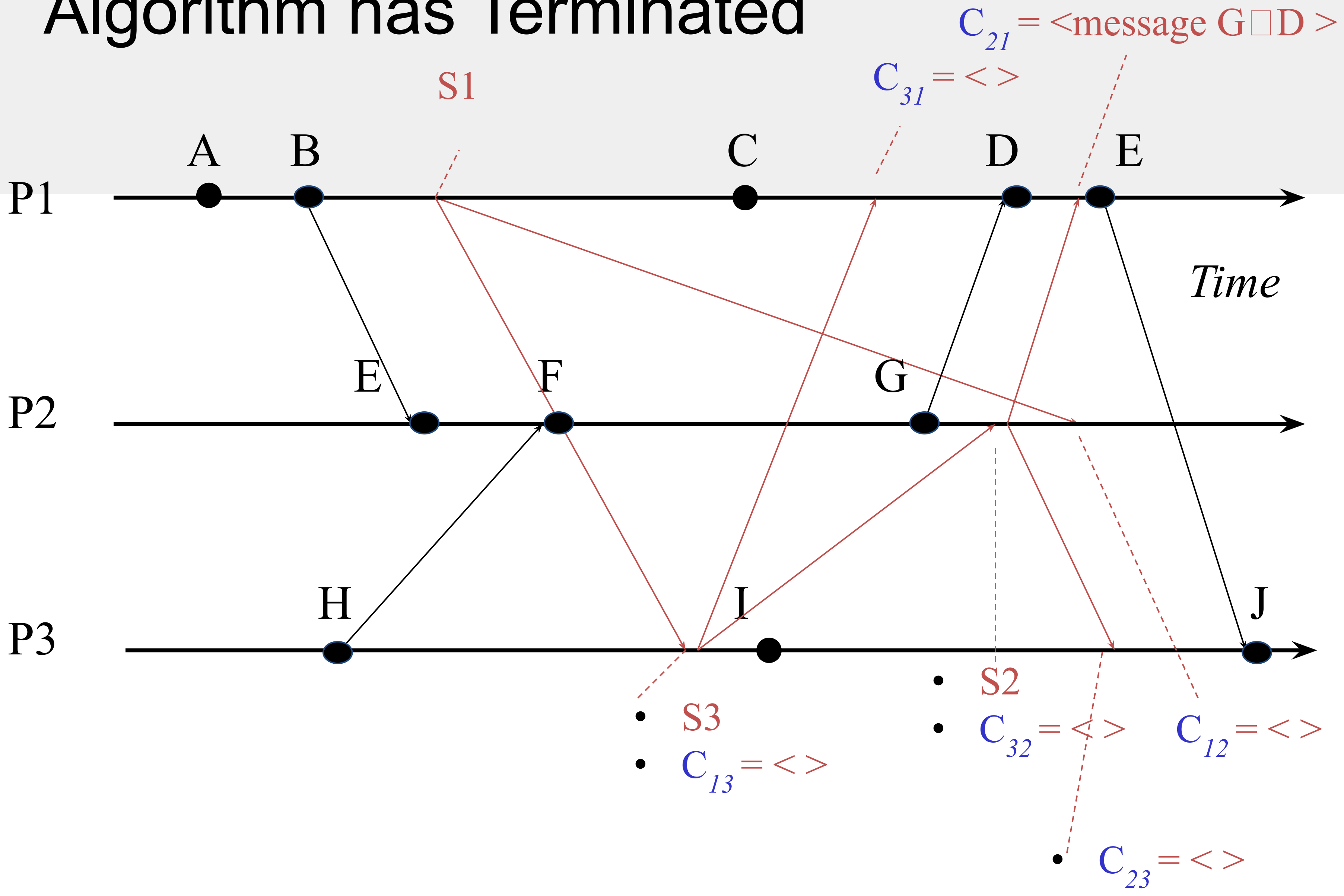

S1, Record C21, ~~C31~~
C31 = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
C13 = < >
Record C23
S2
C32 = < >
~~Record C12~~
Duplicate !
C12 = < >



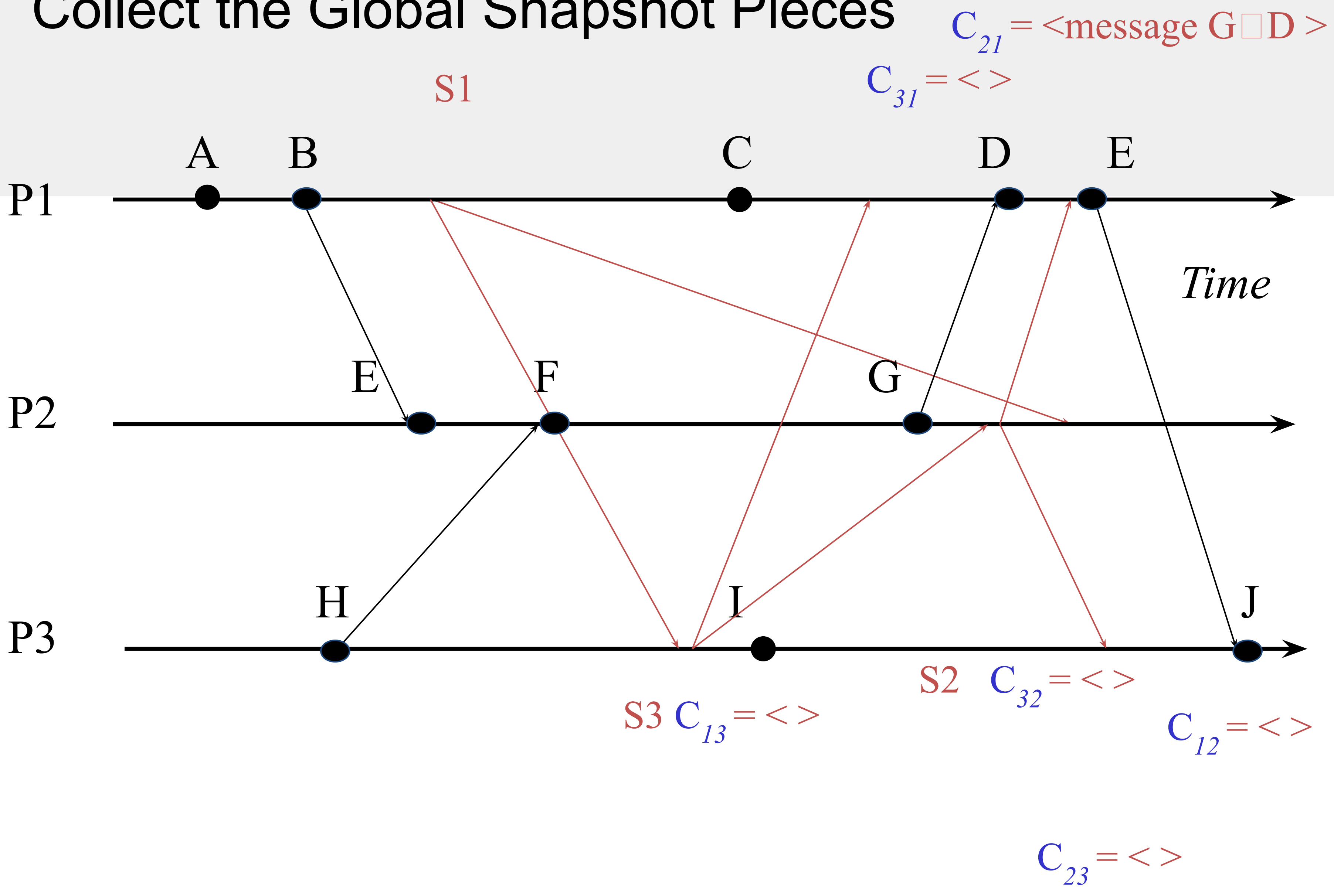
Duplicate!
C_{21} = <message G□D >
S1, ~~Record C_{21}, C_{31}~~
C_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
C_{13} = < >
Record C_{23}
S2
C_{32} = < >
~~Record C_{12}~~
C_{12} = < >


C_{21} = <message G□D >
C_{31} = < >
S1, ~~Record C_{21}, C_{31}~~
A
B
C
D
E
P1
Time
P2
E
F
G
P3
H
I
J
S3
C_{13} = < >
~~Record C_{23}~~
S2
C_{32} = < >
~~Record C_{12}~~
C_{12} = < >
Duplicate !
C_{23} = < >

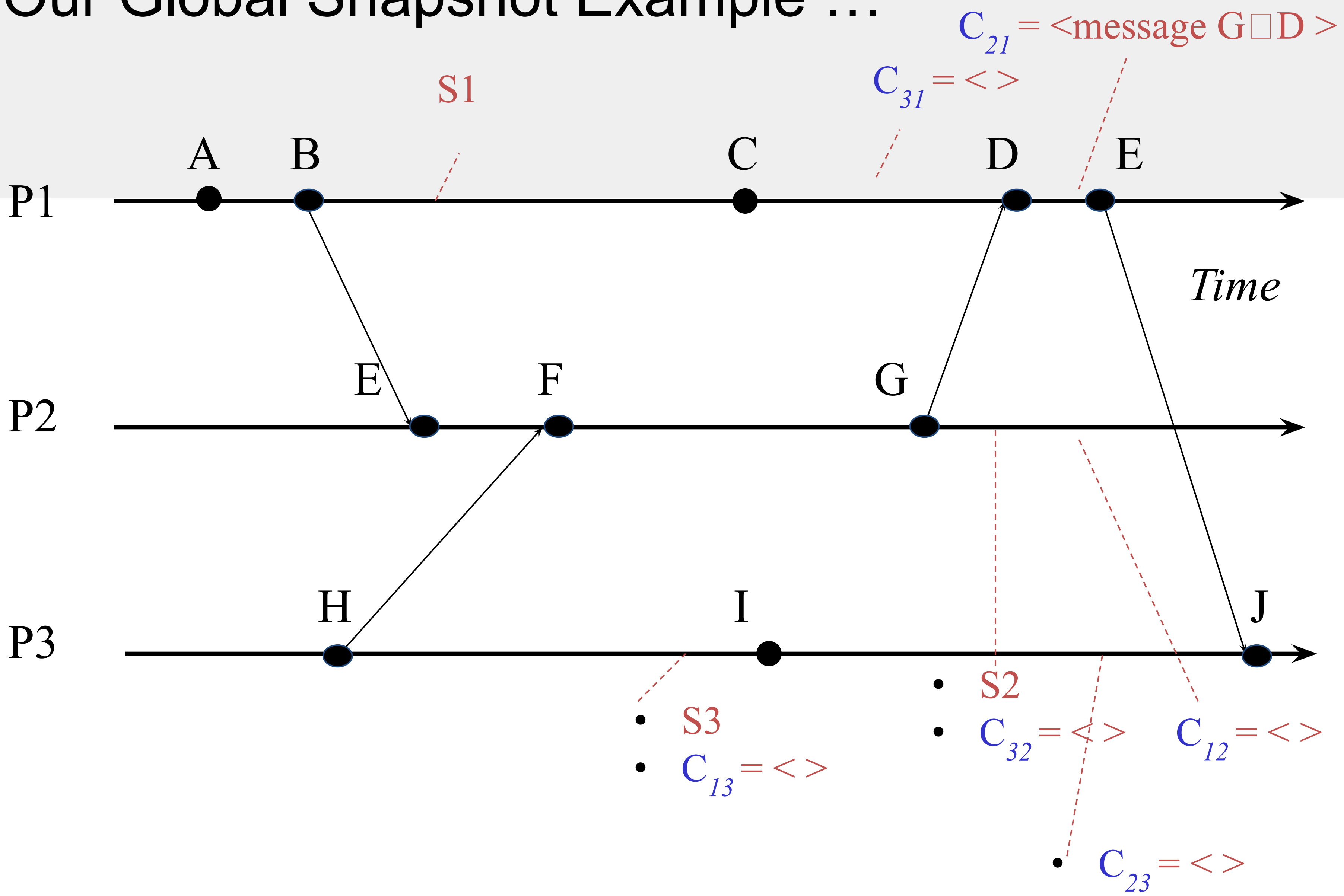
Algorithm has Terminated



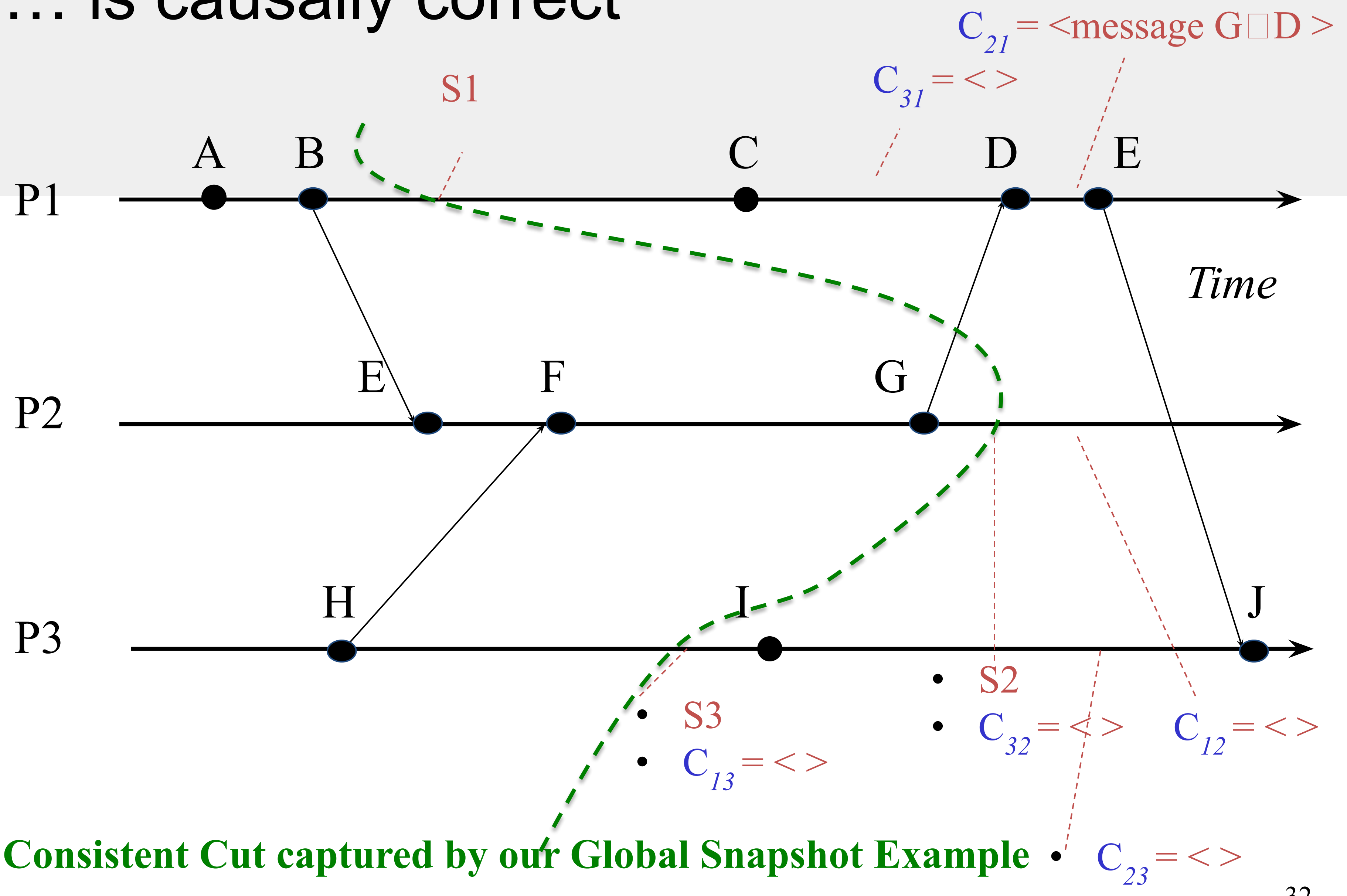
Collect the Global Snapshot Pieces



Our Global Snapshot Example …



… is causally correct



Consistent Cut captured by our Global Snapshot Example

Chandy-Lamport Extensions: Spezialetti-Kerns and others

- Exploit concurrently initiated snapshots to reduce overhead of local snapshot exchange
- Snapshot Recording
  - Markers carry identifier of initiator – first initiator recorded in a per process *"master"* variable.
  - *Region* - all the processes whose master field has same initiator.
  - Identifiers of concurrent initiators recorded in "*id-border-set*."
- Snapshot Dissemination
  - Forest of spanning trees is implicitly created in the system. Every Initiator is root of a spanning tree; nodes relay snapshots of rooted subtree to parent in spanning tree
  - Each initiator assembles snapshot for processes in its region and exchanges with initiators in adjacent regions.
- Others: multiple repeated snapshots; wave algorithm

Computing Global States without FIFO Assumption

- In a non-FIFO system, a marker cannot be used to delineate messages into those to be recorded in the global state from those not to be recorded in the global state.
- In a non-FIFO system, either some degree of inhibition or piggybacking of control information on computation messages to capture out-of-sequence messages is required

Computing Global States without FIFO Assumption - Lai-Yang Algorithm

- Uses a *coloring* scheme that works as follows
  - White (before snapshot); Red (after snapshot)
  - Every process is initially white and turns red while taking a snapshot. The equivalent of the "Marker Sending Rule" (virtual broadcast) is executed when a process turns red.
  - Every message sent by a white (red) process is colored white (red).
  - Thus, a white (red) message is a message that was sent before (after) the sender of that message recorded its local snapshot.
  - Every white process takes its snapshot at its convenience, but no later than the instant it receives a red message.

Computing Global States without FIFO Assumption - Lai-Yang Algorithm (cont.)

- Every white process records a history of all white messages sent or received by it along each channel.
- When a process turns red, it sends these histories along with its snapshot to the initiator process that collects the global snapshot.
- Determining Messages in transit (i.e. White messages received by red process)
  - The initiator process evaluates transit(LSi, LSj) to compute the state of a channel Cij as given below:
  - SCij = {white messages sent by pi on Cij –
    white messages received by pj on Cij}
  - = { send (Mij)|send(mij)$\in$LSi} – {rec(mij)| rec(mij)$\in$LSj}.

Computing Global States without FIFO Assumption: Termination

- First method
  - Each process I keeps a counter cntri that indicates the difference between the number of white messages it has sent and received before recording its snapshot, i.e number of messages still in transit.
  - It reports this value to the initiator along with its snapshot and forwards all white messages, it receives henceforth, to the initiator.
  - Snapshot collection terminates when the initiator has received Σi cntri number of forwarded white messages.
- Second method
  - Each red message sent by a process piggybacks the value of the number of white messages sent on that channel before the local state recording. Each process keeps a counter for the number of white messages received on each channel.
  - Termination – Process receives as many white messages on each channel as the value piggybacked on red messages received on that channel.

Computing Global States without FIFO Assumption: Mattern's Algorithm

- Uses Vector Clocks
  - All process agree on some future virtual time *s* or a set of virtual time instants $s_1,\ldots s_n$ which are mutually concurrent and did not yet occur
  - A process takes its local snapshot at virtual time *s*
  - After time *s* the local snapshots are collected to construct a global snapshot
    - P_i ticks and then fixes its next time $s=C_i+(0,\ldots,0,1,0,\ldots,0)$ to be the common snapshot time
    - P_i broadcasts *s*
    - P_i blocks waiting for all the acknowledgements
    - P_i ticks again (setting $C_i=s$), takes its snapshot and broadcast a dummy message (i.e. force everybody else to advance their clocks to a value $\geq$ s)
    - Each process takes its snapshot and sends it to P_i when its local clock becomes $\geq$ s

Computing Global States without FIFO Assumption (Mattern cont)

- Inventing a n+1 virtual process whose clock is managed by P_i
- P_i can use its clock and because the virtual clock C_{n+1} ticks only when P_i initiates a new run of snapshot :
  - The first n components of the vector can be omitted
  - The first broadcast phase is unnecessary
  - Counter modulo 2
- Termination
  - Distributed termination detection algorithm [Mattern 87]

Optional video: has detailed example illustrating the challenge of capturing global snapshots.
https://www.youtube.com/watch?v=ao58xine3jM