CS 425 / ECE 428
Distributed Systems
Fall 2023

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Lecture 13: Snapshots

Announcements

- HW1, HW2 solutions released
- MP1, MP2 Recommended solutions released
- Midterm this Friday (10/6)
  - Written, in class
- Locations:
  - Loomis 141: if your last name starts with A-L
    - 1110 W Green St, Urbana
  - 1002 ECE: if your last name starts with M-Z
- Material: Lecture 1-12
- Practice Midterm Released

Here’s a Snapshot

Wikimedia commons, heads of state 1889

G7 2022

Distributed Snapshot

- More often, each country’s representative is sitting in their respective capital, and sending messages to each other (say emails).
- How do you calculate a “global snapshot” in that distributed system?
- What does a “global snapshot” even mean?

In the Cloud

- **In a cloud: each application or service is running on multiple servers**
- **Servers handling concurrent events and interacting with each other**
- **The ability to obtain a “global photograph” of the system is important**
- **Some uses of having a global picture of the system**
  - *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

What’s a Global Snapshot?

- **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 <u>each process</u>

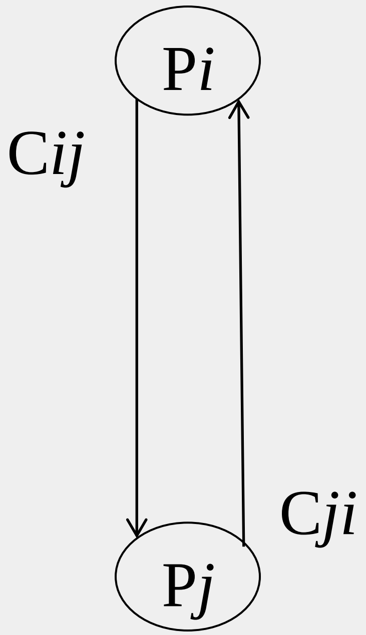
- And the instantaneous *state* of <u>each communication channel</u>, i.e., *messages* in transit on the channels

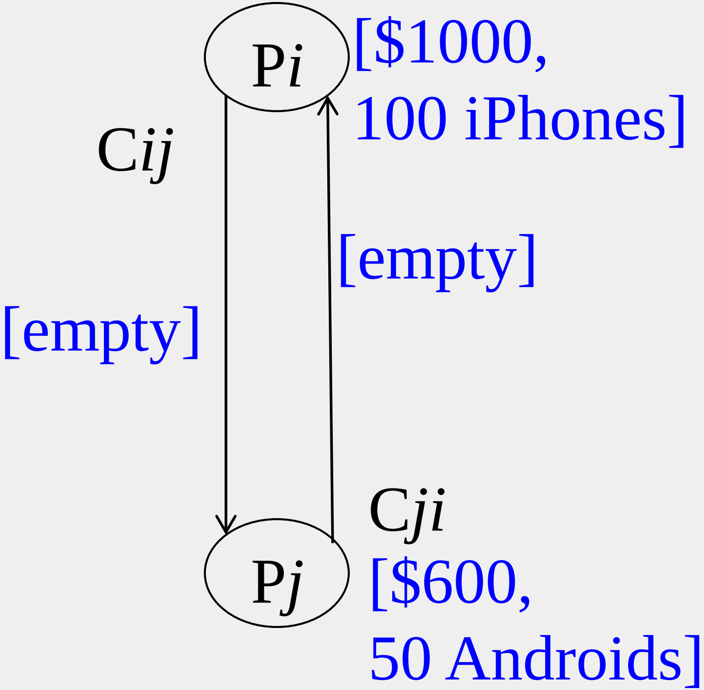
Obvious First Solution

- Synchronize clocks of all processes
- Ask all processes to record their states at known time *t*
- Problems?
  - Time synchronization always has error
    - Your bank might inform you, “We lost the state of our distributed cluster due to a 1 ms clock skew in our snapshot algorithm.”
  - Also, does not record the state of messages in the channels

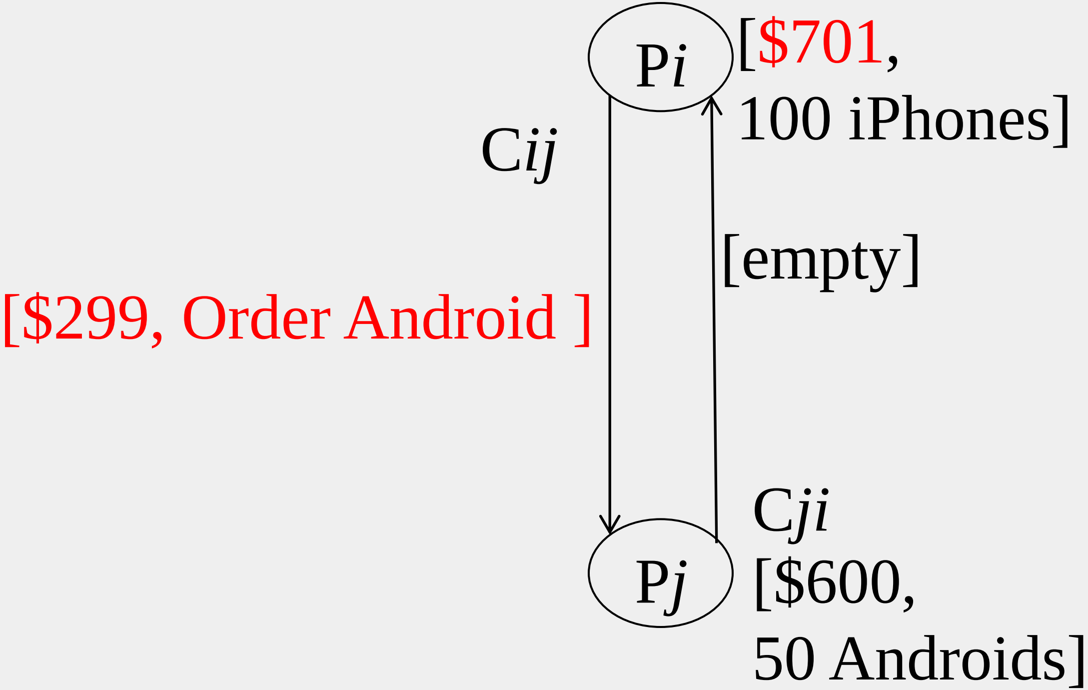
- Again: synchronization not required – causality is enough!

Example

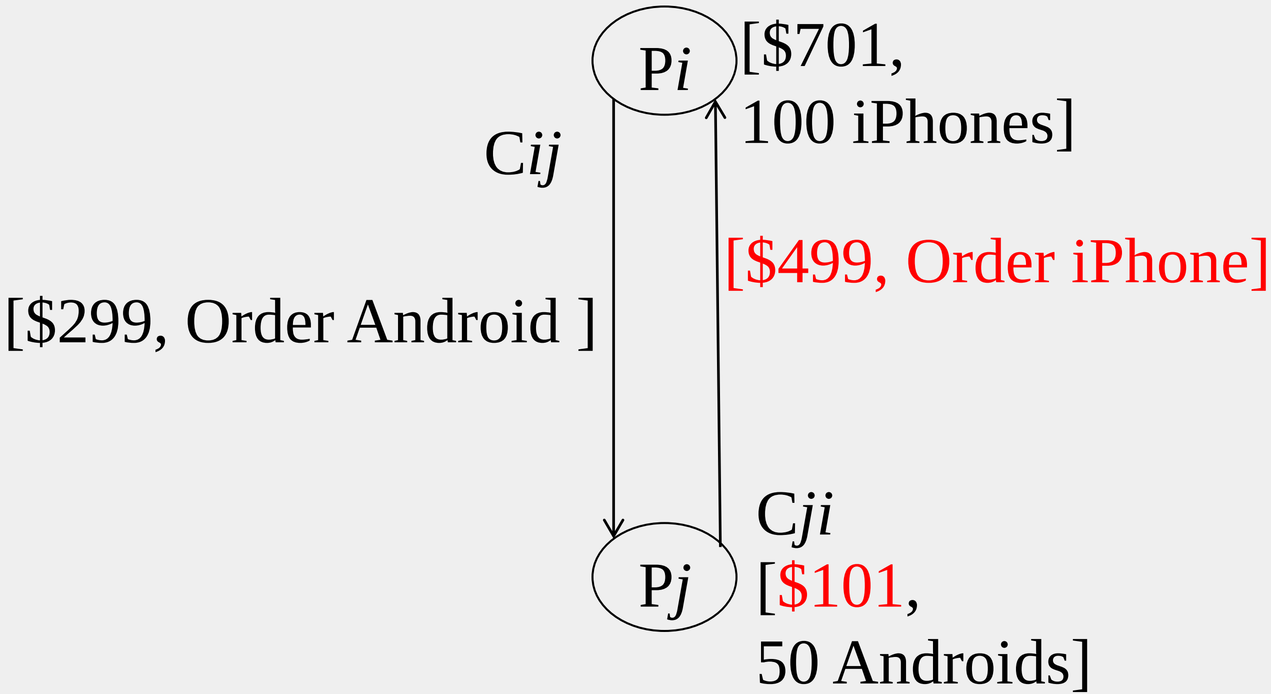




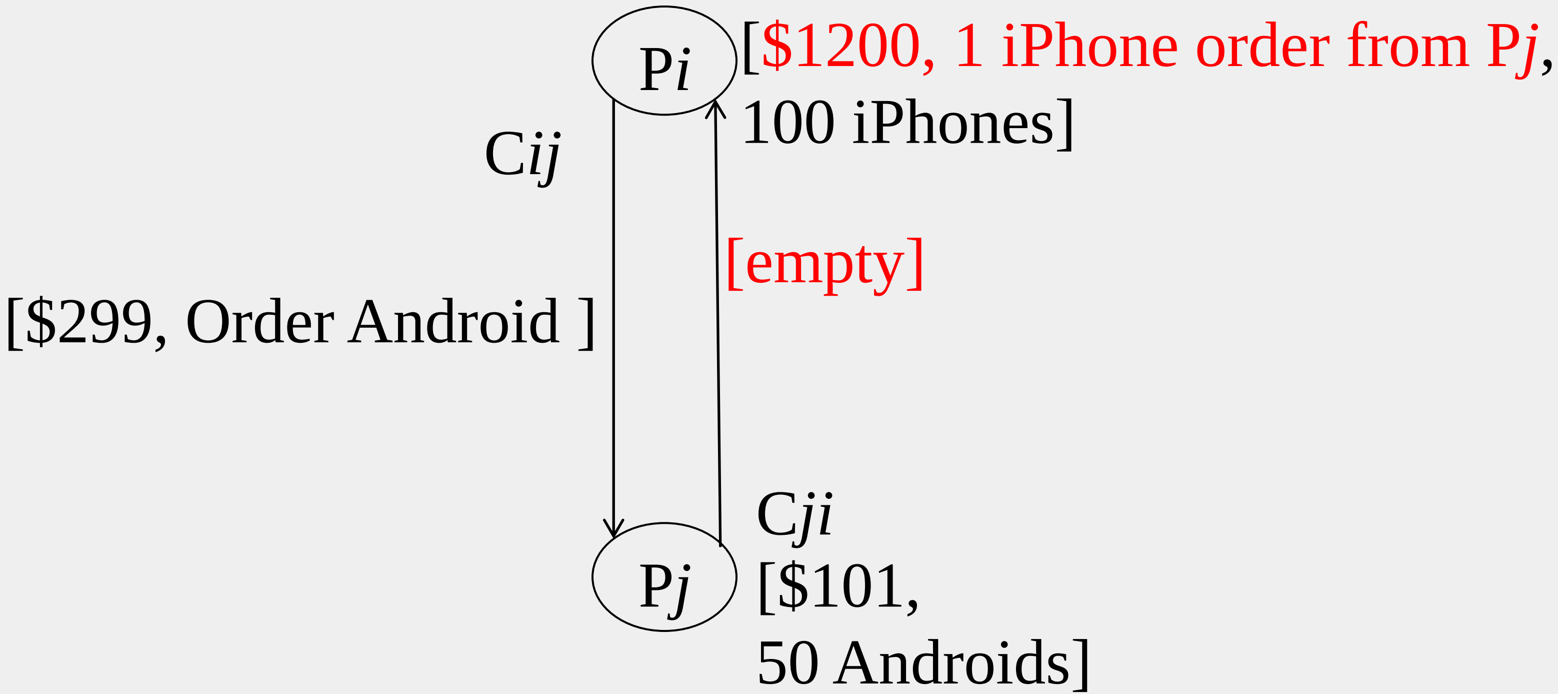
[Global Snapshot 0]



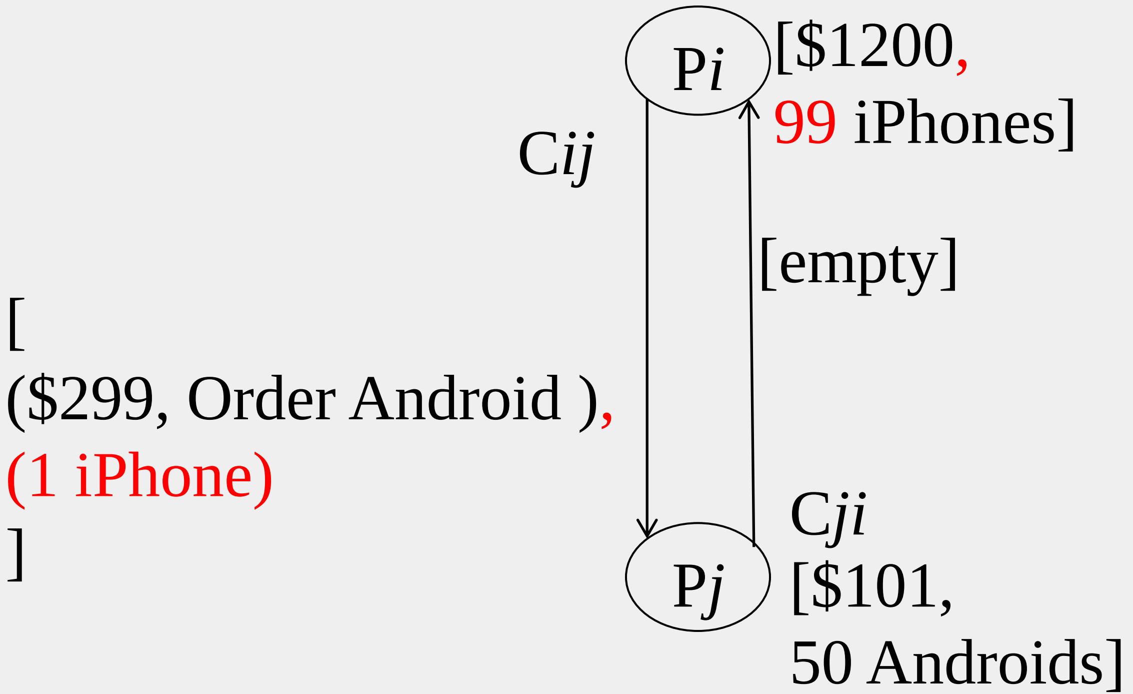
[Global Snapshot 1]



[Global Snapshot 2]



[Global Snapshot 3]



[Global Snapshot 4]

[
(1 iPhone)
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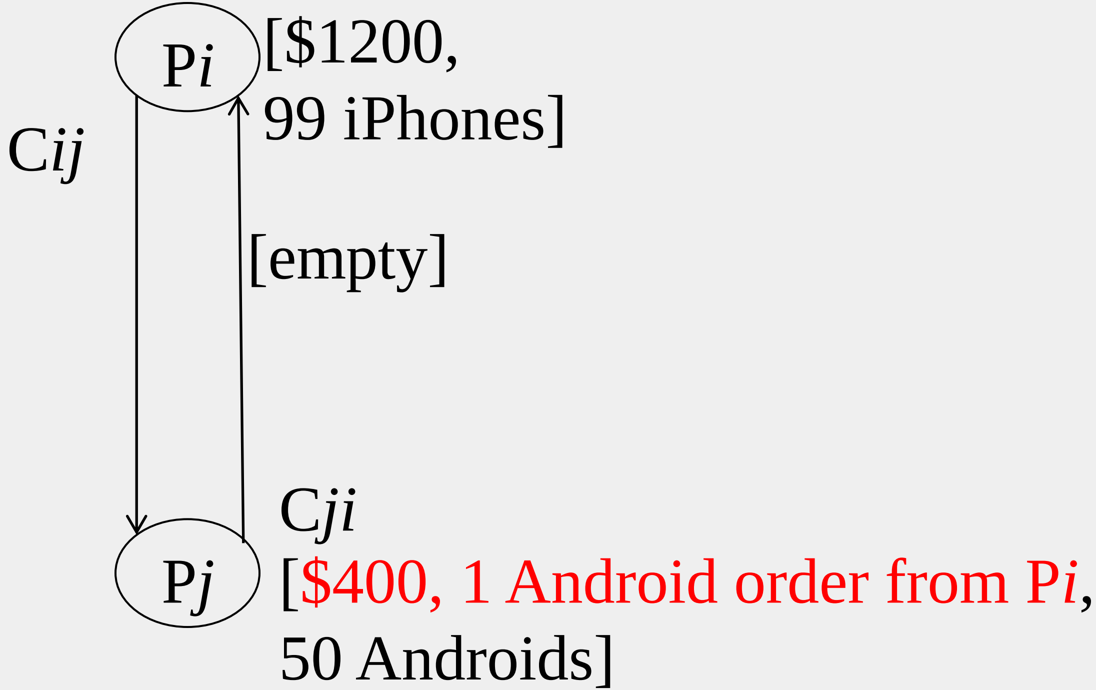
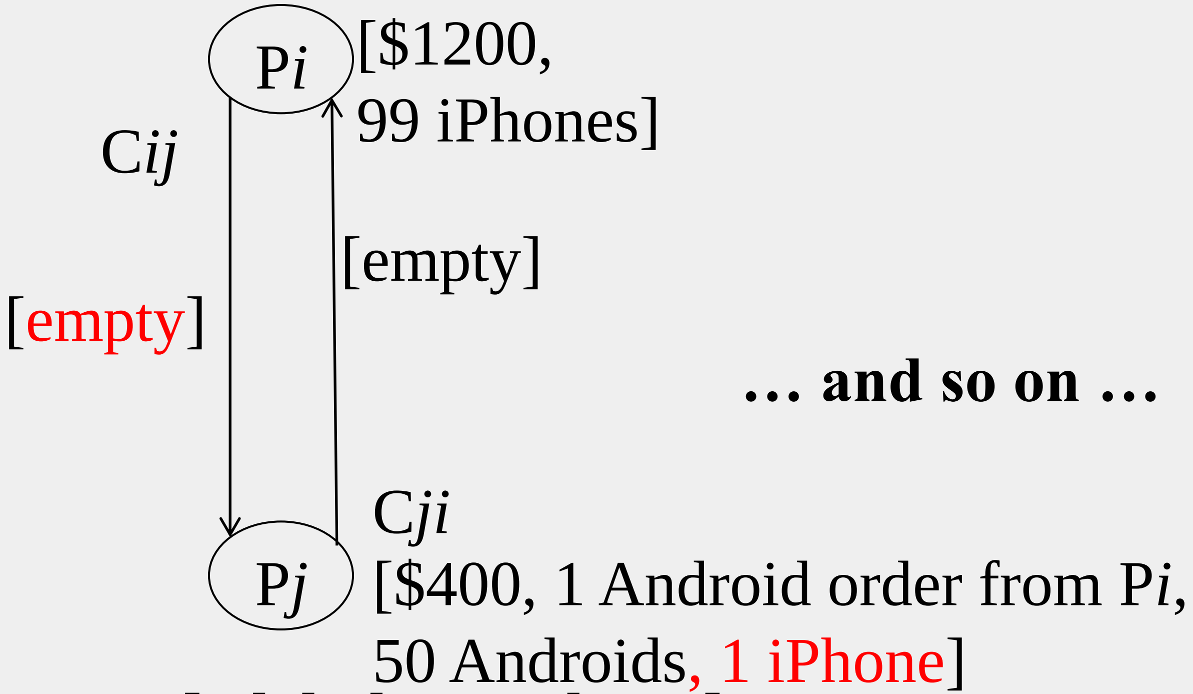


[Global Snapshot 5]



… and so on …

[Global Snapshot 6]

Moving from State to State

- **Whenever an event happens anywhere in the system, the global state changes**
  - Process receives message
  - Process sends message
  - Process takes a step
- **State to state movement <u>obeys causality</u>**
  - Next: Causal algorithm for Global Snapshot calculation

System Model

- **Problem: Record a global snapshot (state for each process, and state for each channel)**
- ***System Model*:**
  - *N* processes in the system
  - There are two uni-directional communication channels between each ordered process pair : Pj → Pi and Pi → Pj
  - Communication channels are FIFO-ordered
    - First in First out
  - No failure
  - All messages arrive intact, and are not duplicated
    - Other papers later relaxed some of these assumptions

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**
  - We’ll assume just one snapshot run for now

Chandy-Lamport Global Snapshot Algorithm

- **First, Initiator P*i* records its own state**
- **Initiator process creates special messages called "Marker" messages**
  - Not an application message, does not interfere with application messages

- **for *j=1 to N* except *i***

  P*i* sends out a Marker message on outgoing channel C_{ij}

  - (N-1) channels
  - 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 Global Snapshot Algorithm (2)

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}

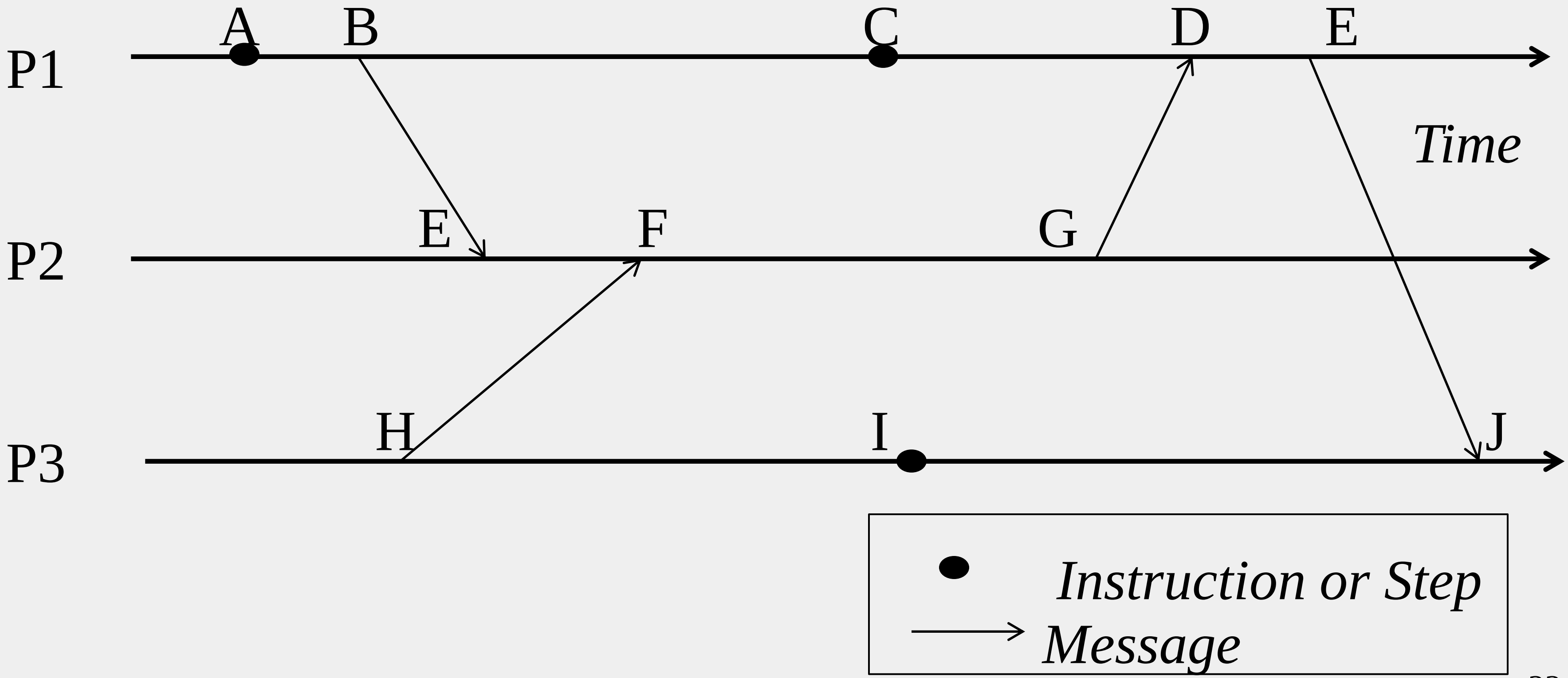
Chandy-Lamport Global Snapshot Algorithm (3)

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 at each
  - To record the state of all channels

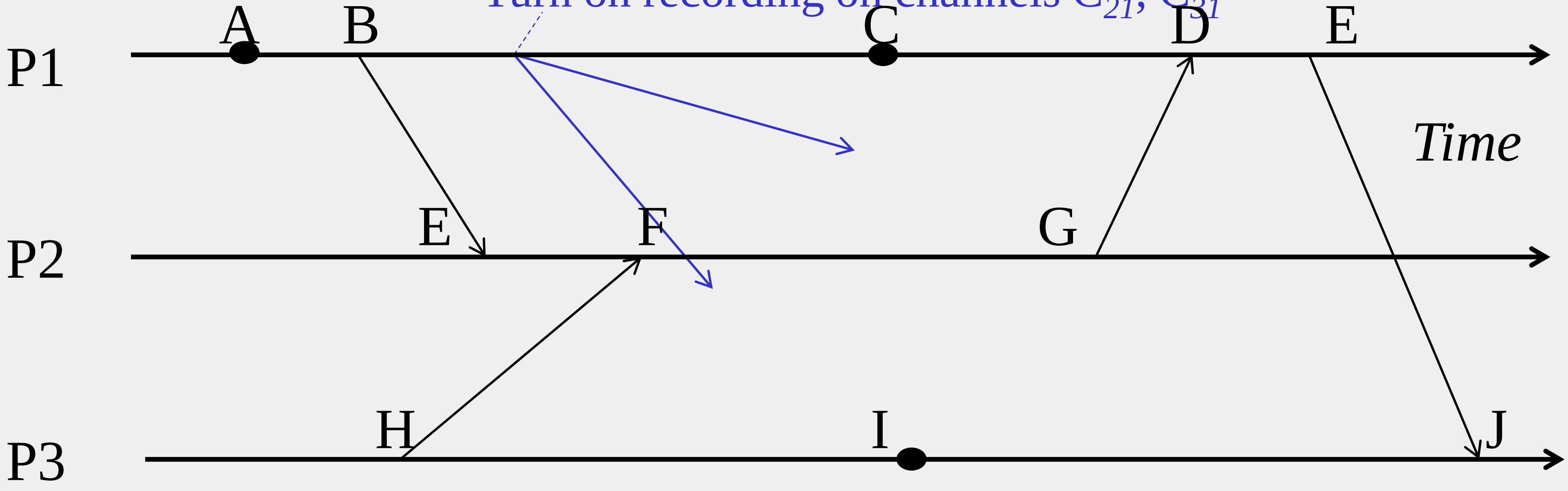
Then, (if needed), a central server collects all these partial state pieces to obtain the full global snapshot

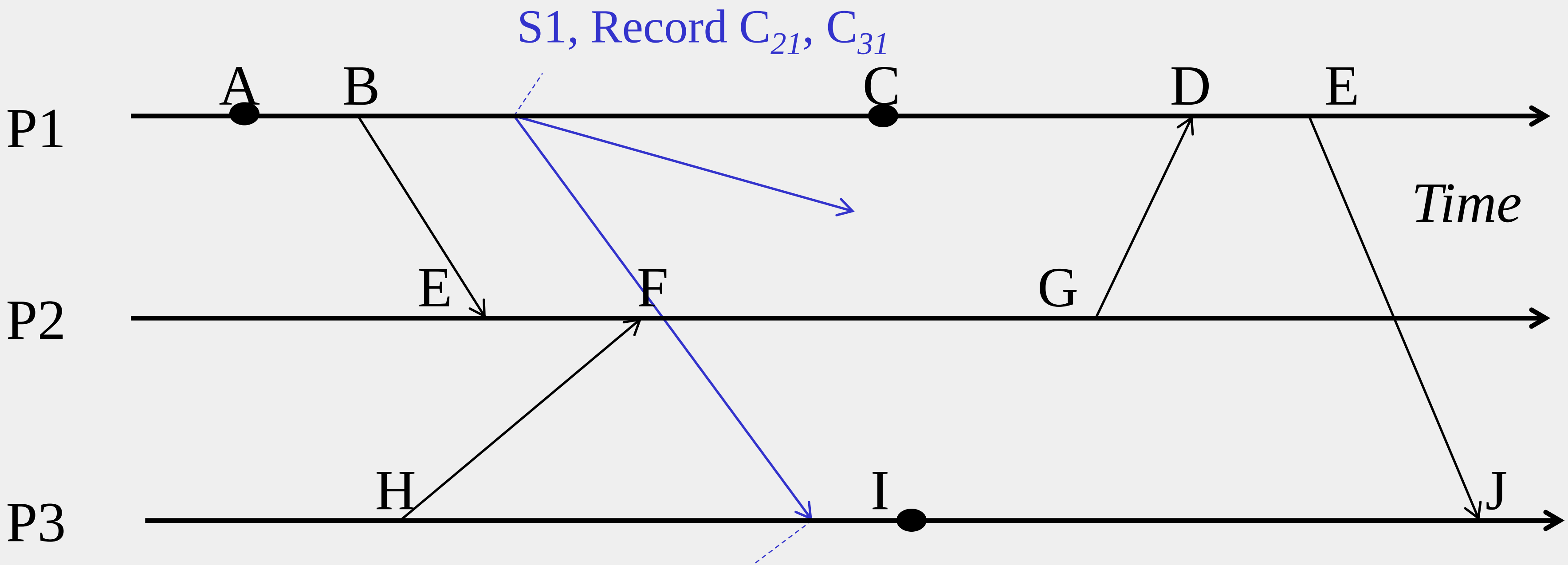
Example



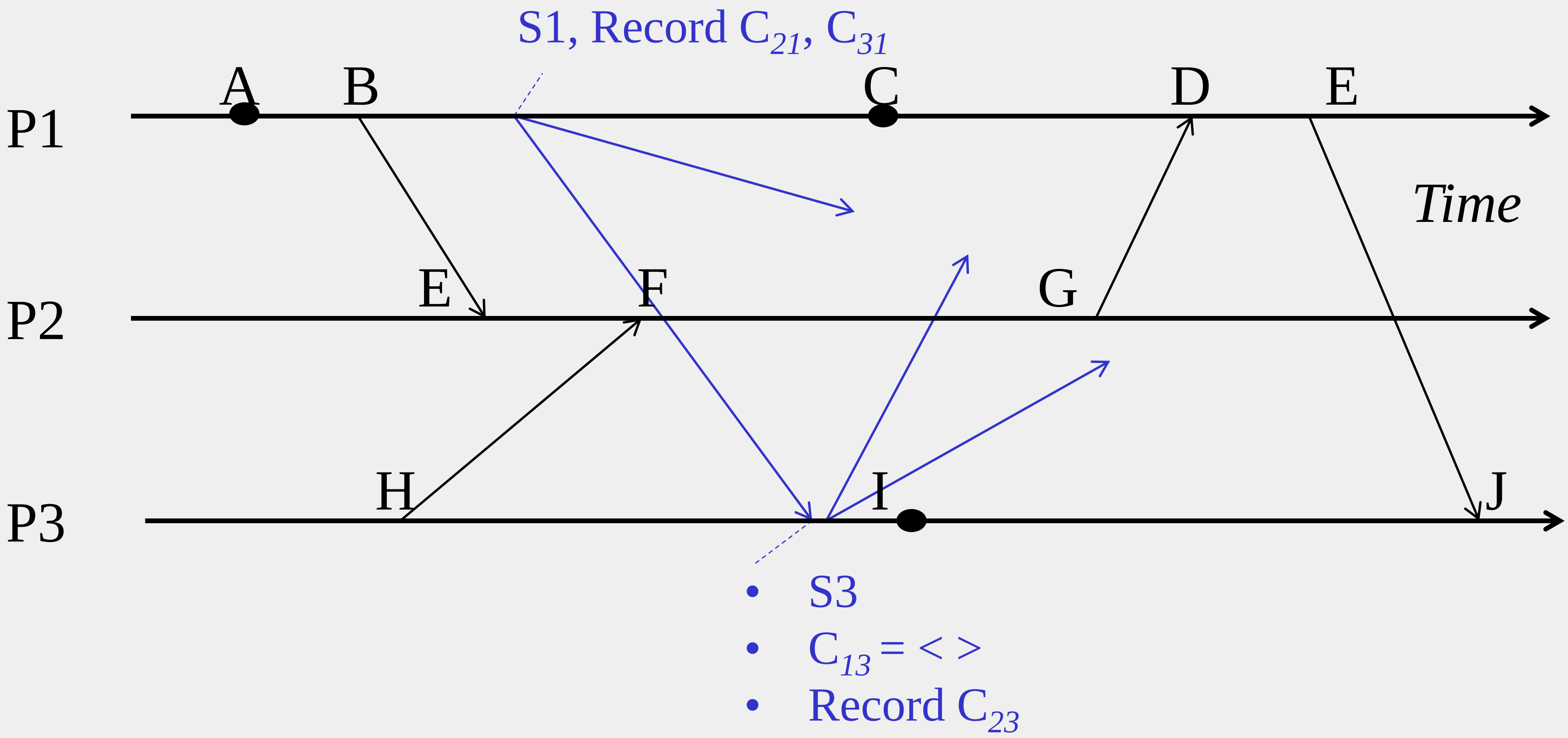
P1 is Initiator:

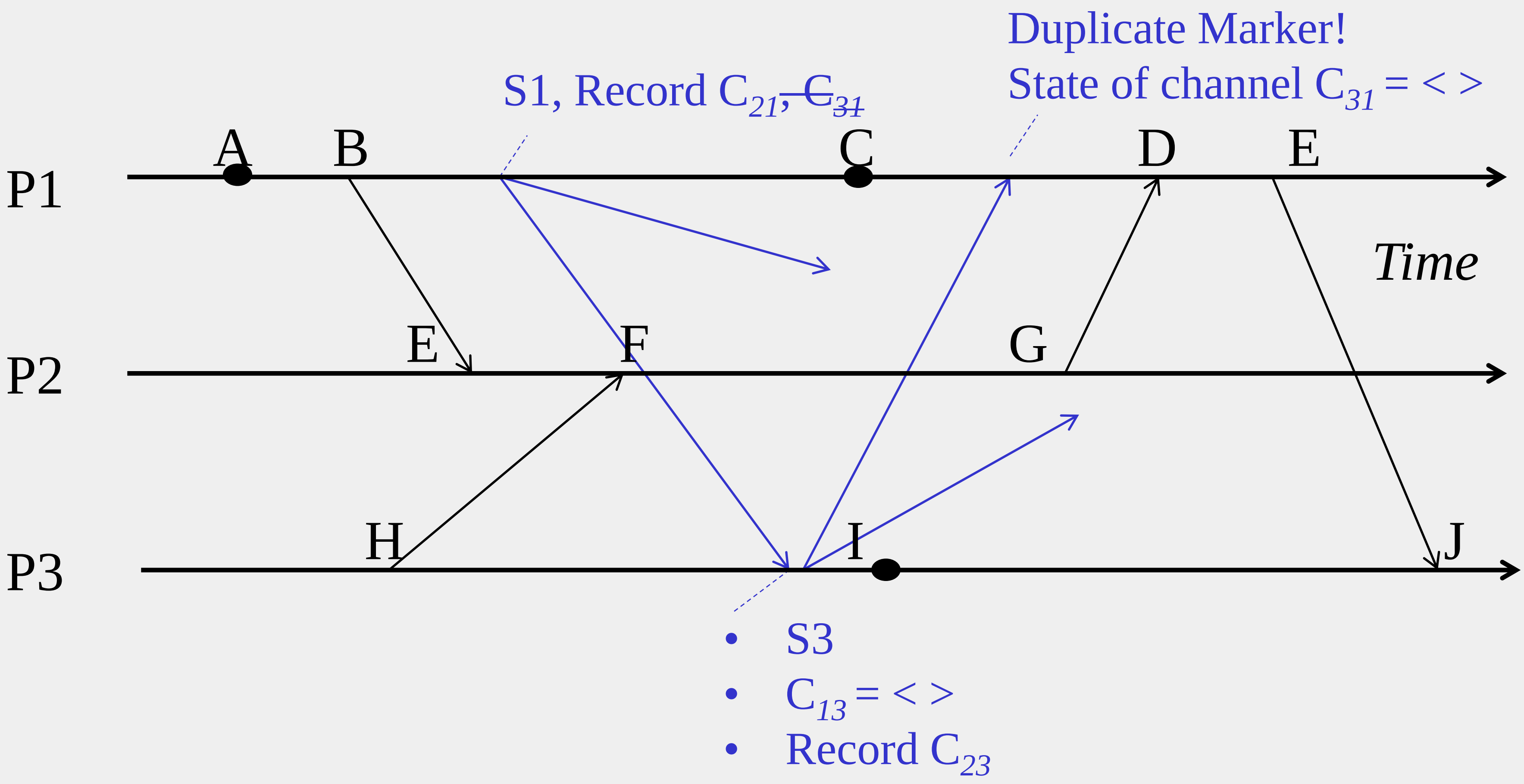
- Record local state S1,
- Send out markers
- Turn on recording on channels C_{21}, C_{31}



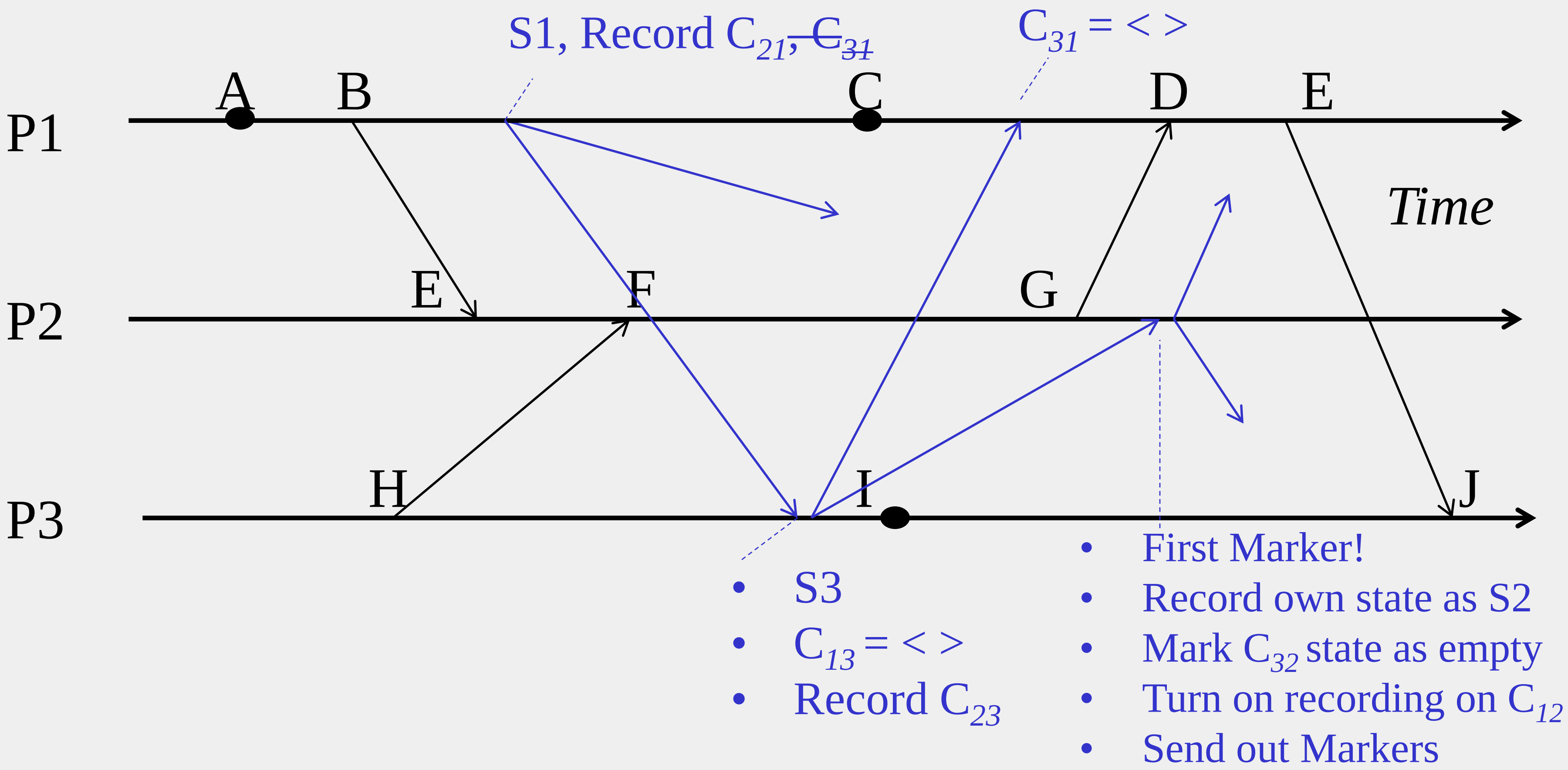


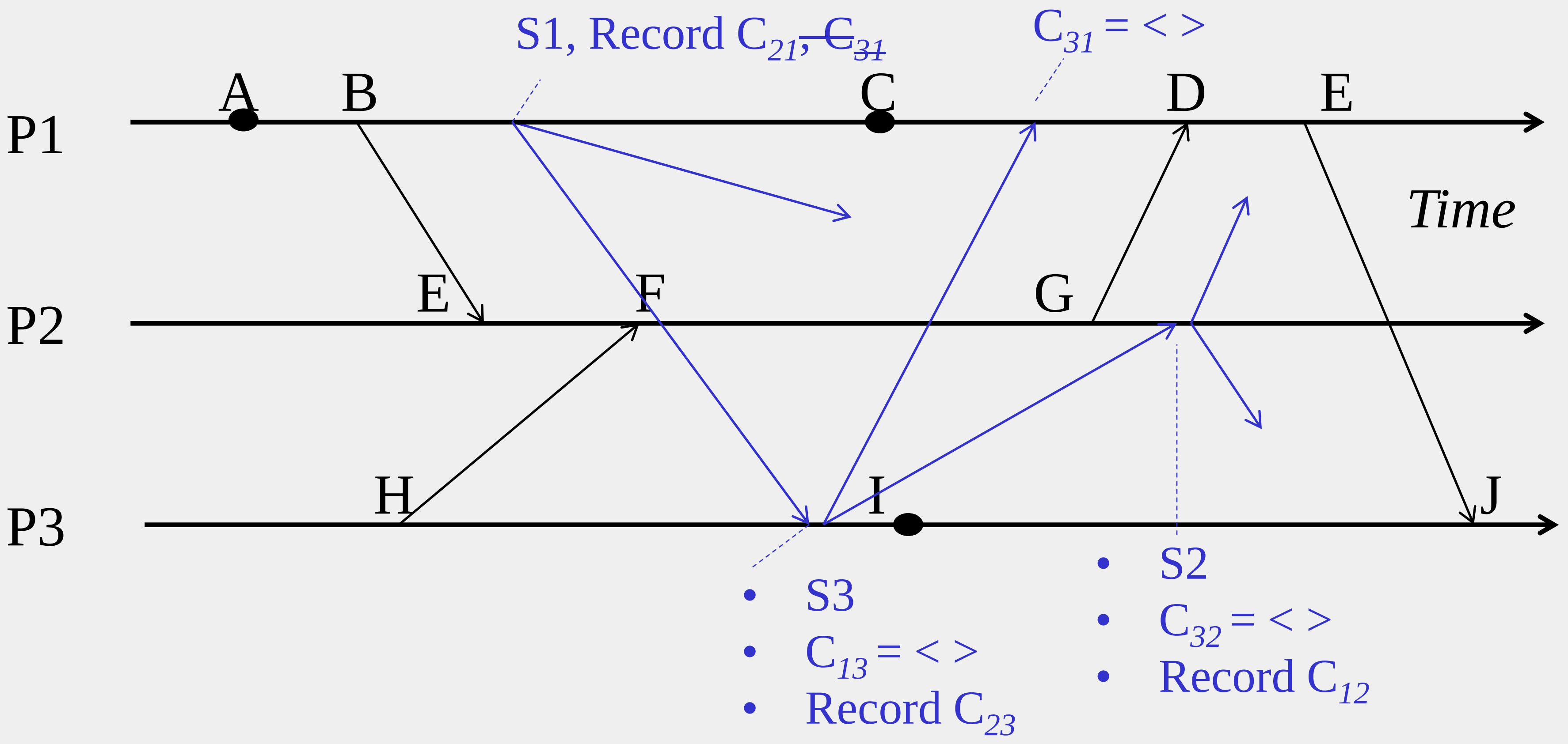
- First Marker!
- Record own state as S3
- Mark C_{13} state as empty
- Turn on recording on other incoming C_{23}
- Send out Markers


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}

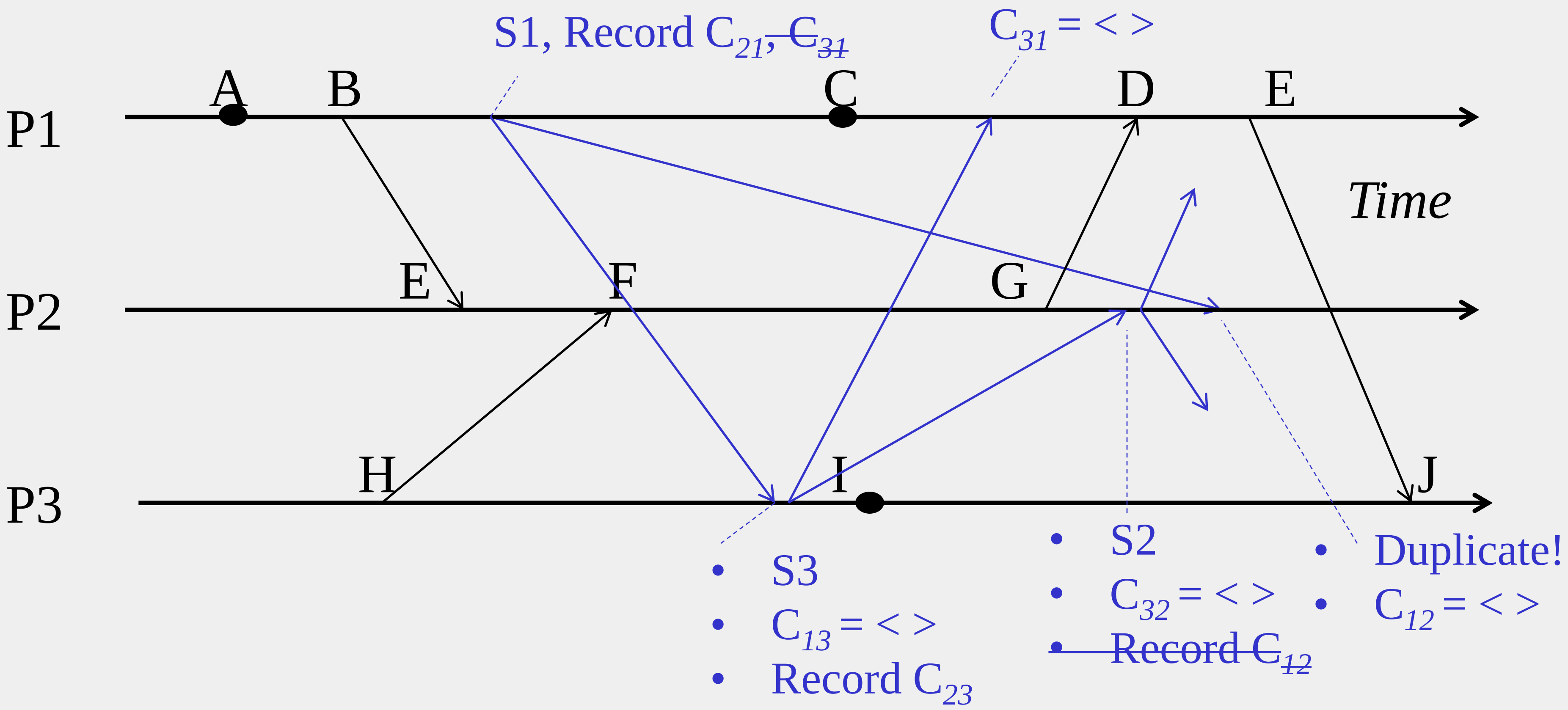


Duplicate Marker!
State of channel C_{31} = < >
S1, Record C_{21}, ~~C_{31}~~
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
• S3
• C_{13} = < >
• Record C_{23}

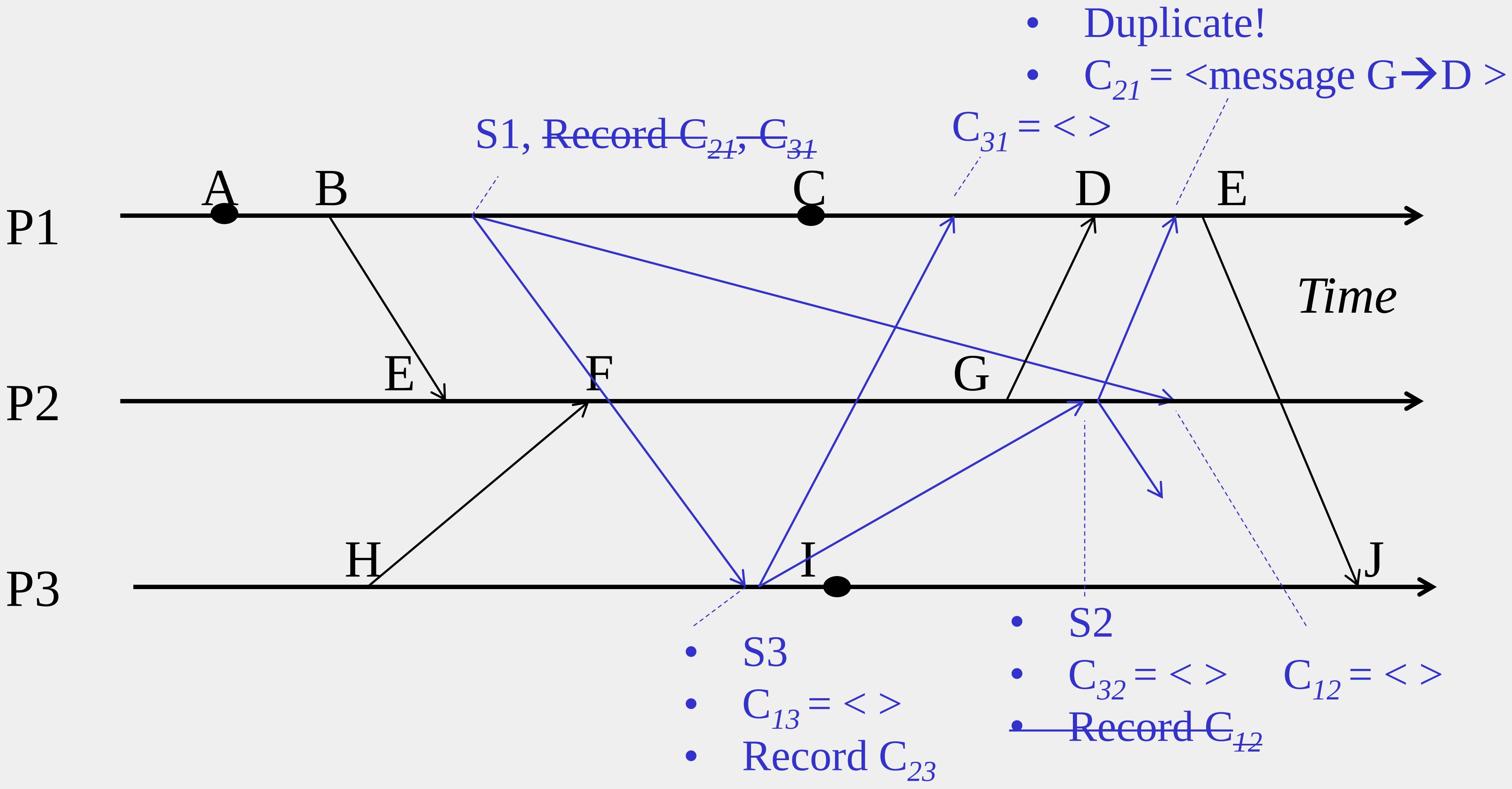

S1, Record C_{21}, ~~C_{31}~~
C_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
• S3
• C_{13} = < >
• Record C_{23}
• First Marker!
• Record own state as S2
• Mark C_{32} state as empty
• Turn on recording on C_{12}
• Send out Markers



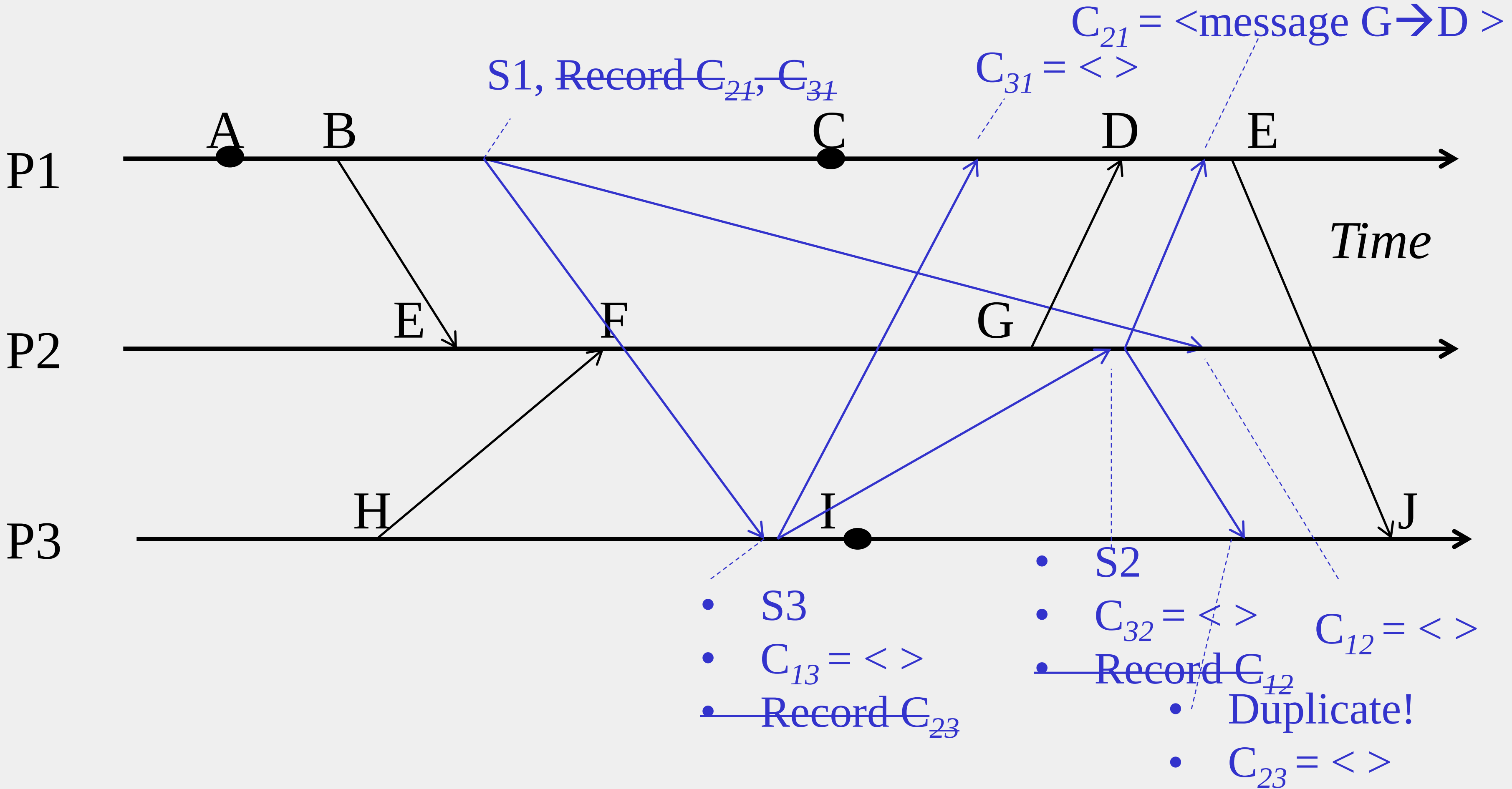
S1, Record C_{21}, ~~C_{31}~~
C_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
• S3
• C_{13} = < >
• Record C_{23}
• S2
• C_{32} = < >
• Record C_{12}



S1, Record 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}~~
• Duplicate!
• C_{12} = < >

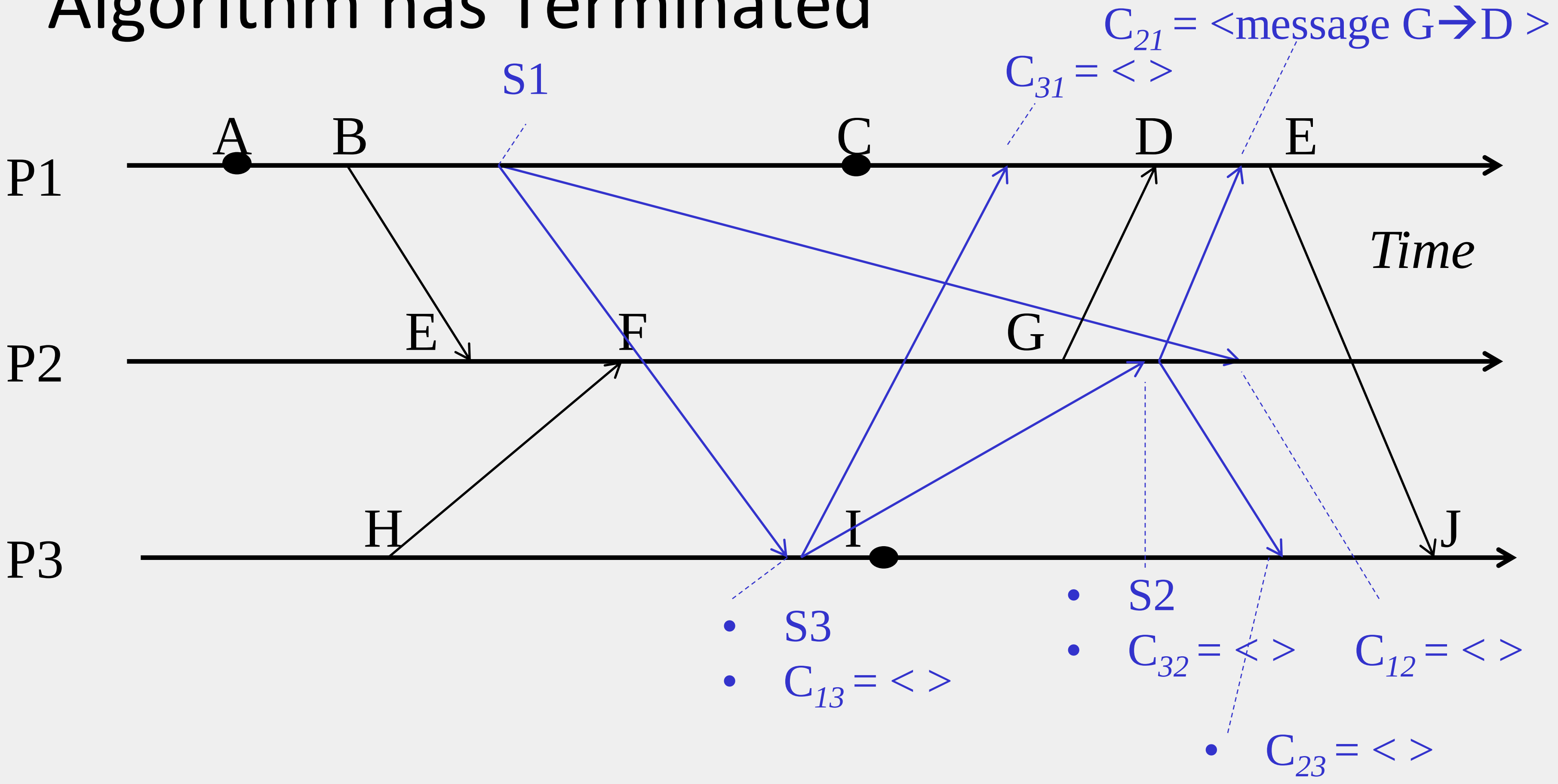


Duplicate!
C_{21} = <message G→D >
S1, ~~Record C_{21}, C_{31}~~
C_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
C_{13} = < >
Record C_{23}
S2
C_{32} = < >
~~Record C_{12}~~
C_{12} = < >

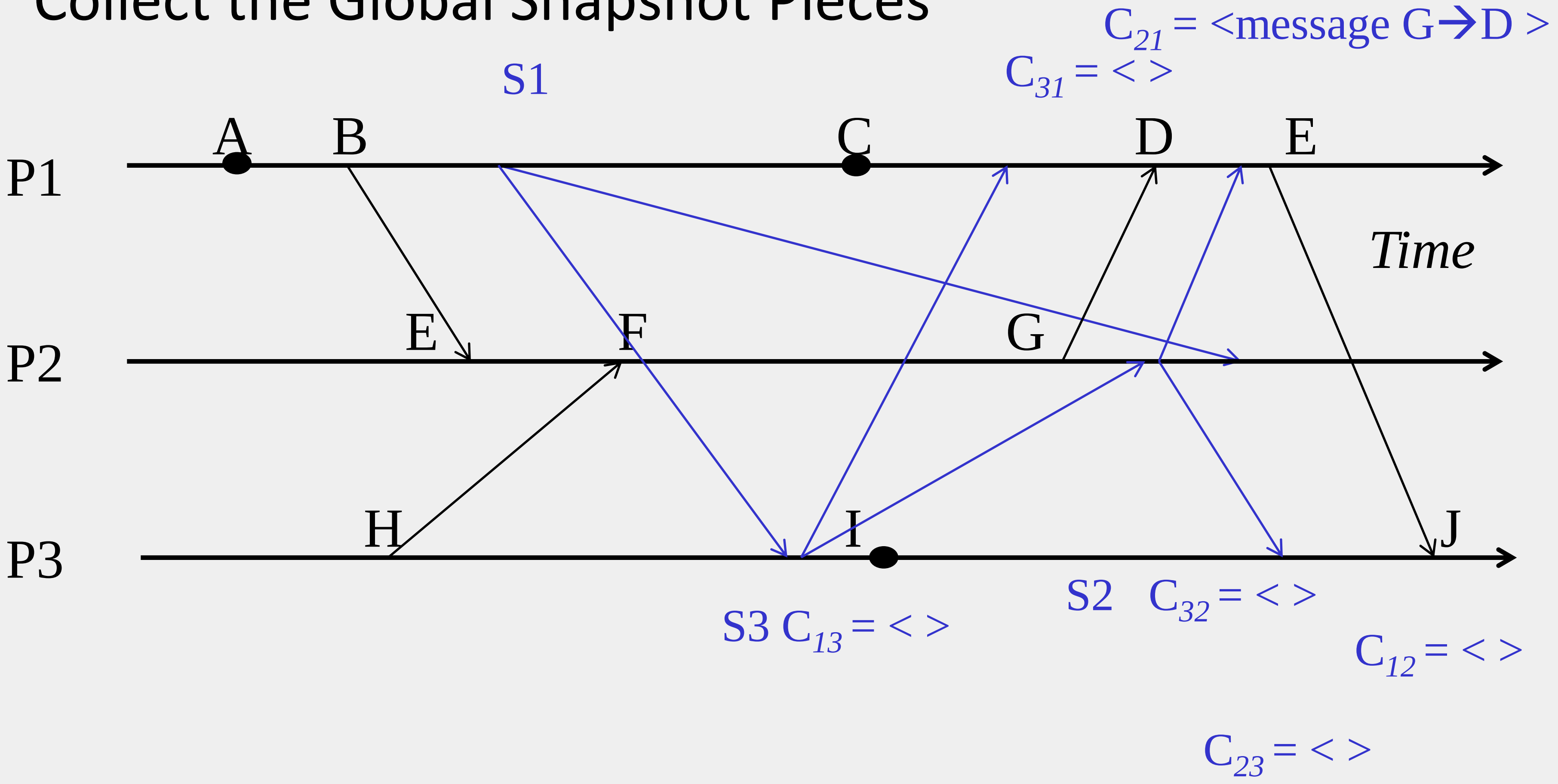


C_{21} = <message G→D >
S1, ~~Record C_{21}, C_{31}~~
C_{31} = < >
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
• S3
• C_{13} = < >
• ~~Record C_{23}~~
• S2
• C_{32} = < >
• ~~Record C_{12}~~
C_{12} = < >
• Duplicate!
• C_{23} = < >

Algorithm has Terminated



Collect the Global Snapshot Pieces



Next

- **Global Snapshot calculated by Chandy-Lamport algorithm is <u>causally correct</u>**
  - What?

Cuts

- **Cut = time frontier at each process and at each channel**
- **Events at the process/channel that happen before the cut are “in the cut”**
  - And happening after the cut are “out of the cut”

Consistent Cuts

Consistent Cut: a cut that obeys causality

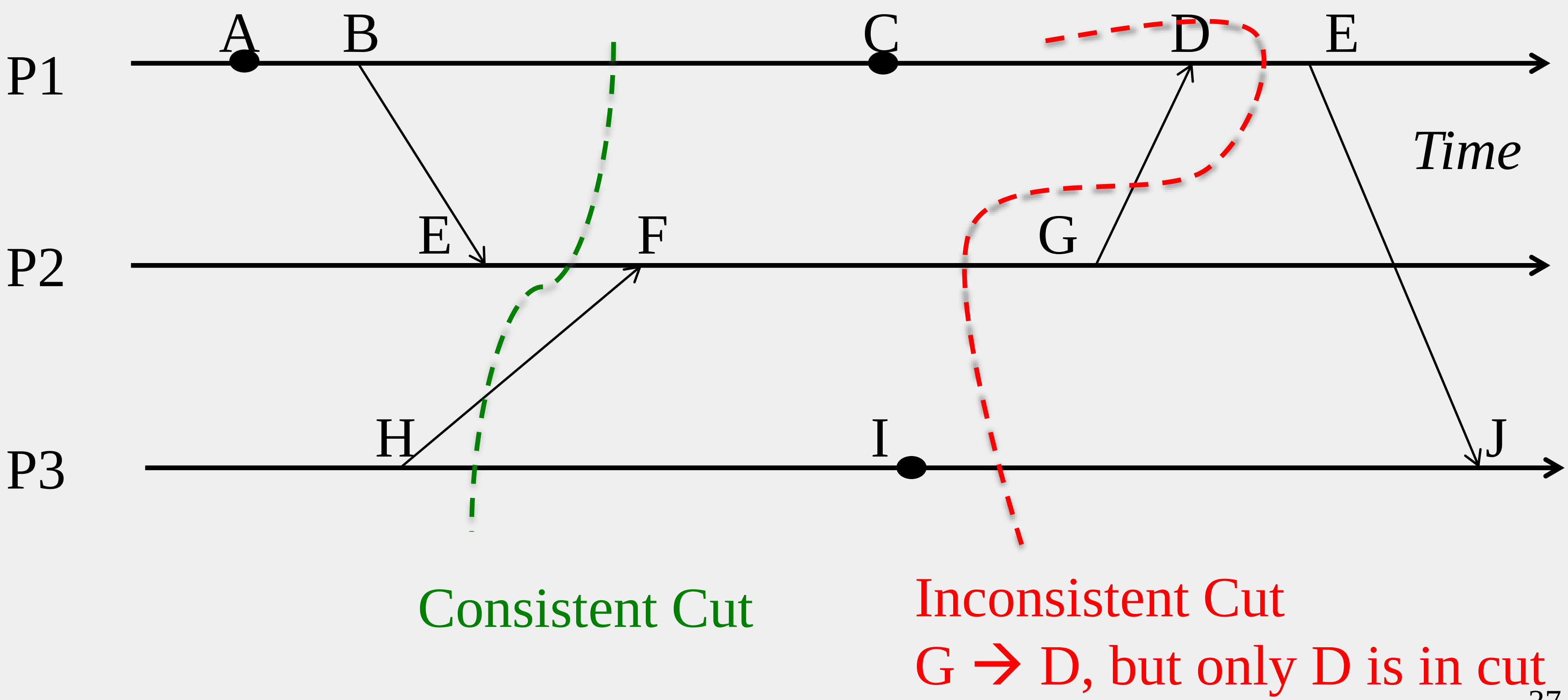
- A cut C is a consistent cut if and only if:

  for (each pair of events e, f in the system)

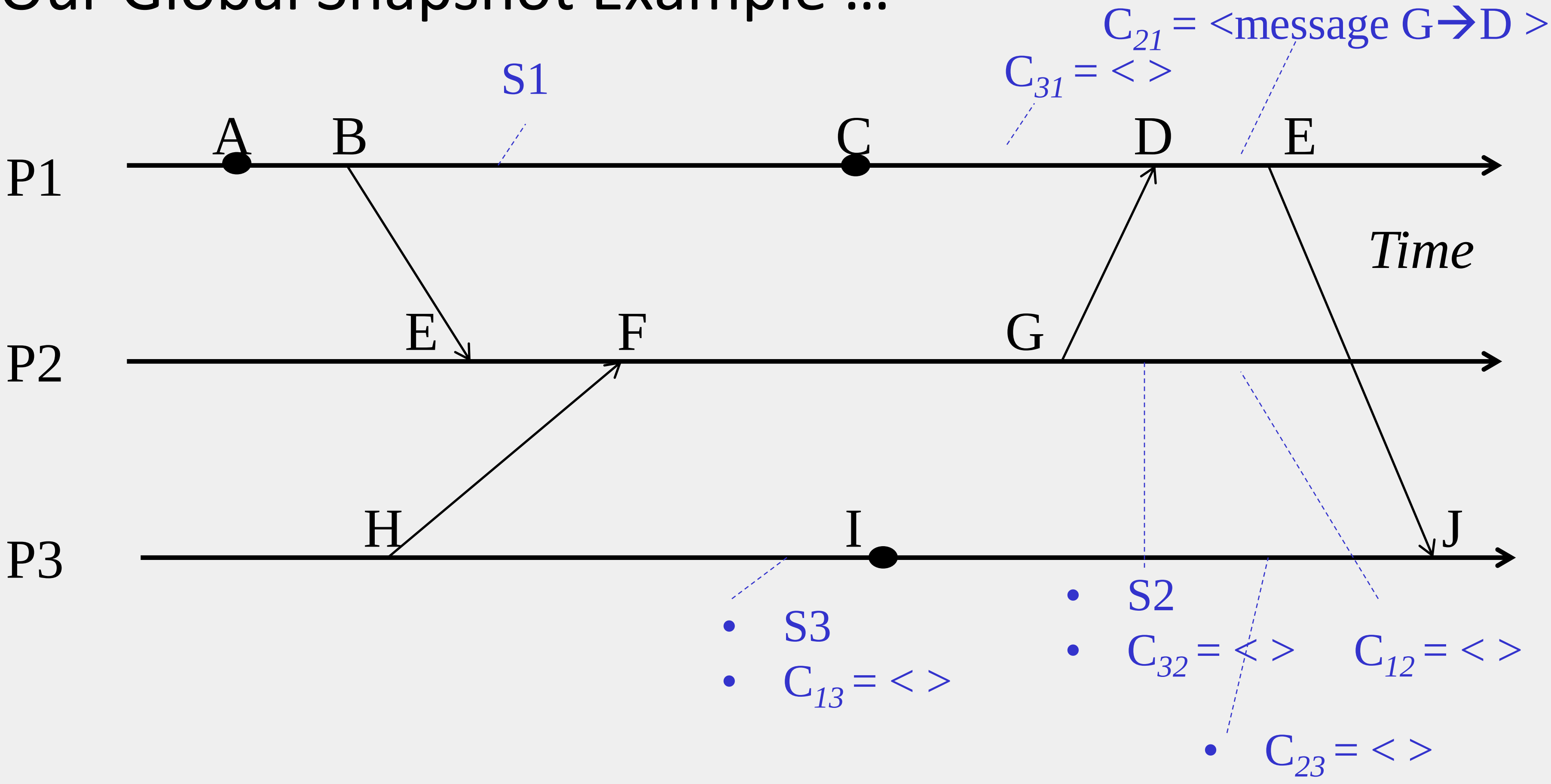
  – Such that event e is in the cut C, and if f $\rightarrow$ e (f happens-before e)

    - Then: Event f is also in the cut C

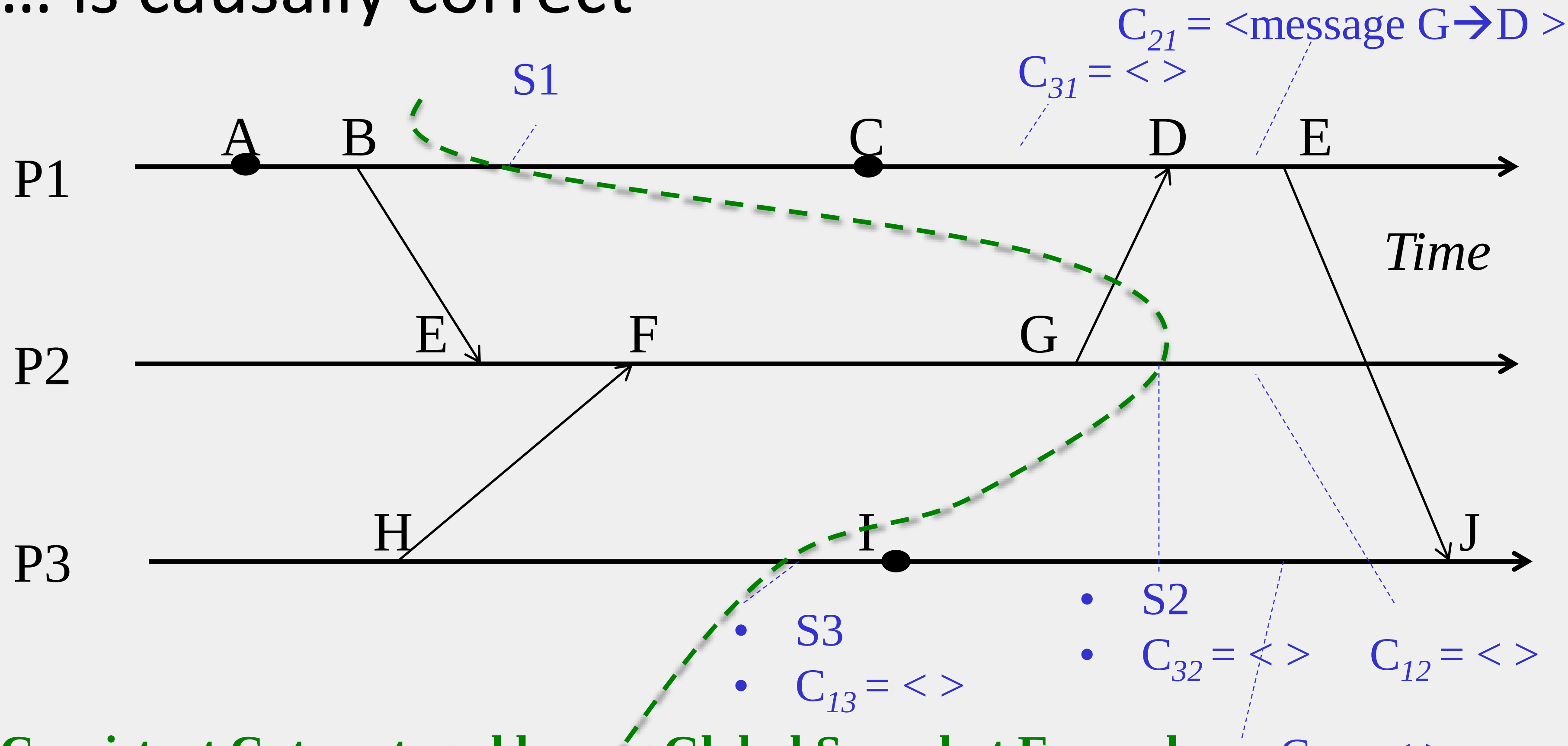
Example


A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
Consistent Cut
Inconsistent Cut
G → D, but only D is in cut

Our Global Snapshot Example …



… is causally correct



Consistent Cut captured by our Global Snapshot Example

In fact…

- Any run of the Chandy-Lamport Global Snapshot algorithm creates a consistent cut

Chandy-Lamport Global Snapshot algorithm creates a consistent cut

Let's quickly look at the proof

- Let e_i and e_j be events occurring at P*i* and P*j*, respectively such that
  - $e_i \rightarrow e_j$ (e_i happens before e_j)
- The snapshot algorithm ensures that

  if e_j is in the cut then e_i is also in the cut.

- That is: if $e_j \rightarrow$ <P*j* records its state>, then
  - it must be true that $e_i \rightarrow$ <P*i* records its state>.

Chandy-Lamport Global Snapshot algorithm creates a consistent cut

- **if $e_j \rightarrow$ <Pj records its state>, then it must be true that $e_i \rightarrow$ <Pi records its state>.**
  - By contradiction, suppose $e_j \rightarrow$ <P*j* records its state> and <P*i* records its state> $\rightarrow e_i$
  - Consider the path of app messages (through other processes) that go from $e_i \rightarrow e_j$
  - Due to FIFO ordering, markers on each link in above path will precede regular app messages
  - Thus, since <P*i* records its state> $\rightarrow e_i$, it must be true that P*j* received a marker before e_j
  - Thus e_j is not in the cut => contradiction

Next

- What is the Chandy-Lamport algorithm used for?

“Correctness” in Distributed Systems

- Can be seen in two ways
- Liveness and Safety
- Often confused – it’s important to distinguish from each other

Liveness

- **Liveness = guarantee that something good will happen, eventually**
  - Eventually == does not imply a time bound, but if you let the system run long enough, then …

Liveness: Examples

- **Liveness = guarantee that something good will happen, eventually**
  - Eventually == does not imply a time bound, but if you let the system run long enough, then …
- **Examples in Real World**
  - Guarantee that "at least one of the atheletes in the 100m final will win gold" is liveness
  - A criminal will eventually be jailed
- **Examples in a Distributed System**
  - Distributed computation: Guarantee that it will terminate
  - "Completeness" in failure detectors: every failure is eventually detected by some non-faulty process
  - In Consensus: All processes eventually decide on a value

Safety

- Safety = guarantee that something bad will never happen

Safety: Examples

- **Safety = guarantee that something bad will never happen**
- **Examples in Real World**
  - An innocent person will never be jailed
- **Examples in a Distributed System**
  - There is no deadlock in a distributed transaction system
  - No object is orphaned in a distributed object system
  - "Accuracy" in failure detectors
  - In Consensus: No two processes decide on different values

Can’t we Guarantee both?

- **Can be difficult to satisfy both liveness and safety in an asynchronous distributed system!**
  - Failure Detector: Completeness (Liveness) and Accuracy (Safety) cannot both be guaranteed by a failure detector in an asynchronous distributed system
  - Consensus: Decisions (Liveness) and correct decisions (Safety) cannot both be guaranteed by any consensus protocol in an asynchronous distributed system
  - Very difficult for legal systems (anywhere in the world) to guarantee that all criminals are jailed (Liveness) and no innocents are jailed (Safety)

In the language of Global States

- **Recall that a distributed system moves from one global state to another global state, via causal steps**
- **Liveness w.r.t. a property Pr in a given state S means**
  - S satisfies Pr, or there is some causal path of global states from S to S' where S' satisfies Pr
- **Safety w.r.t. a property Pr in a given state S means**

  S satisfies Pr, and all global states S' reachable from S also satisfy Pr

Using Global Snapshot Algorithm

- **Chandy-Lamport algorithm can be used to detect global properties that are stable**
  - Stable = once true, stays true forever afterwards
- **Stable Liveness examples**
  - Computation has terminated
- **Stable Non-Safety examples**
  - There is a deadlock
  - An object is orphaned (no pointers point to it)
- **All stable global properties can be detected using the Chandy-Lamport algorithm**
  - **Due to its causal correctness**

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 stable global properties
- Safety vs. Liveness

Exercises

1. Why does causality suffice for snapshots?
2. With perfectly synchronized clocks, why can’t we take a perfect snapshot?
3. In the Chandy-Lamport algorithm, if a message is received before a process takes its snapshot, is the message send event part of the snapshot? Message receive event?
4. Prove that the Chandy-Lamport Algorithm only creates consistent cuts.
5. What is the difference between safety and liveness properties?