# CS 425 / ECE 428
# Distributed Systems
# Fall 2020

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*Lecture 14: Snapshots*

# Announcements

- Next week onwards (after midterm, i.e., Oct 13th onwards)
- No Live Zoom sessions (no more meetings Tu Th 11-12.15)
- You should watch all video lectures week by week (they are all on website)
- Indy will be asynchronous and offline. We will answer questions on Piazza as usual. TA office hours will be as usual.
- (The only change is that the Live Zoom sessions stop.)
- Please continue proceeding at the normal speed, and continue finishing HWs, MPs, (and if needed) quizzes, etc.
- Enjoy your extra time off! (no more meetings Tu Th 11-12.15)

# Jokes for this Topic

- (You will get these jokes as you start understanding the topic)
- **At the photograph session for world leaders, someone jumped in front of another during the photograph. This caused someone to scream, “Hey, no inconsistent cuts during a snapshot!”**
- **While announcing the new vaccine, what did the infectious disease expert (who was also a Distributed System buff) say? “This vaccine is Completely Safe and will keep you Accurately Live.”**

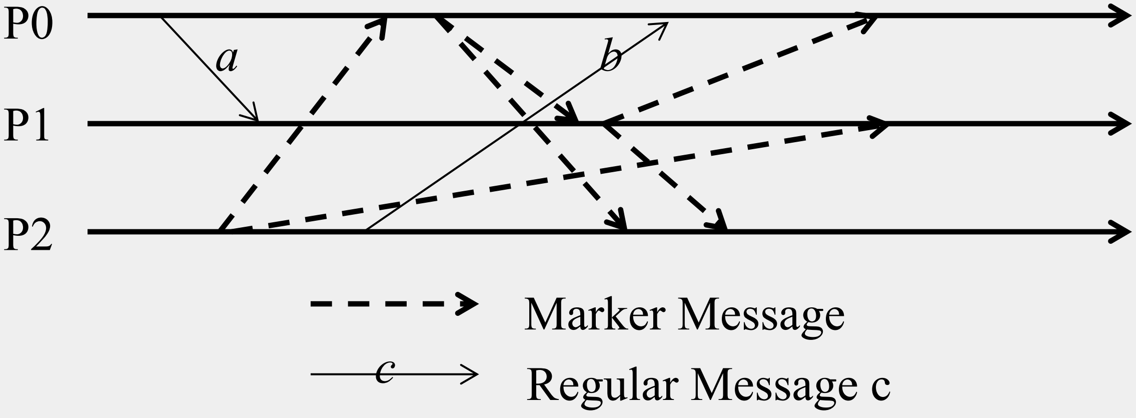
(All jokes © unless otherwise mentioned. Apologies for bad jokes!).

# Exercises

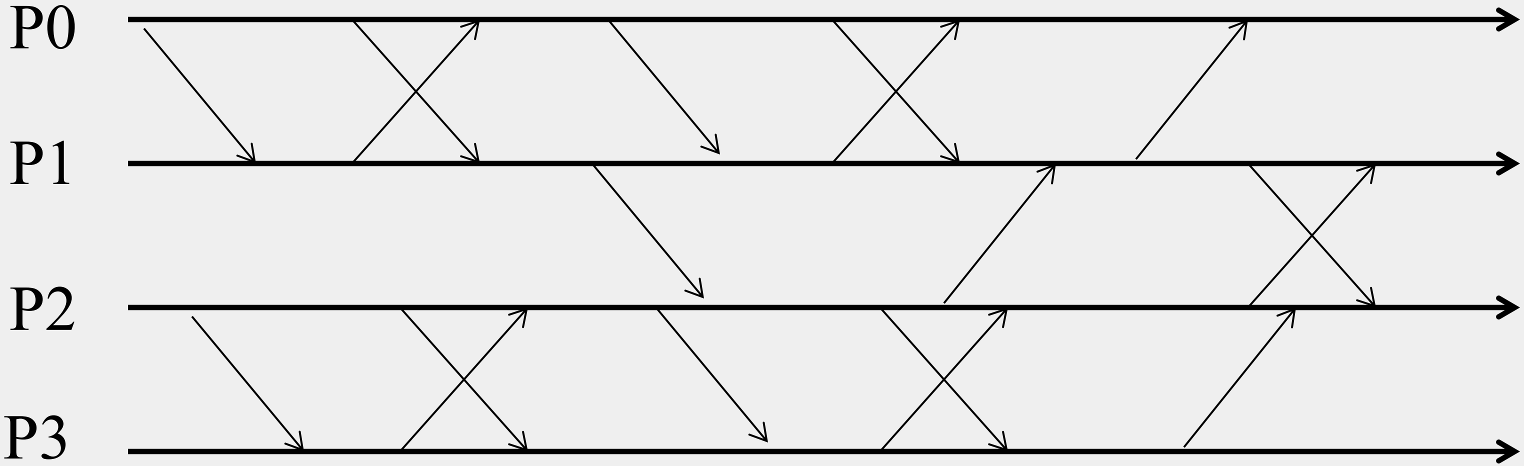
1. Why does causality suffice for snapshots?
2. With perfectly synchronized clocks, why can't we take a perfect snapshot?
3. In the Chandy-Lamport algorithm, if a message is received before a process takes its snapshot, is the message send event part of the snapshot? Message receive event?
4. Prove that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

# I. Chandy-Lamport Global Snapshots Algorithm

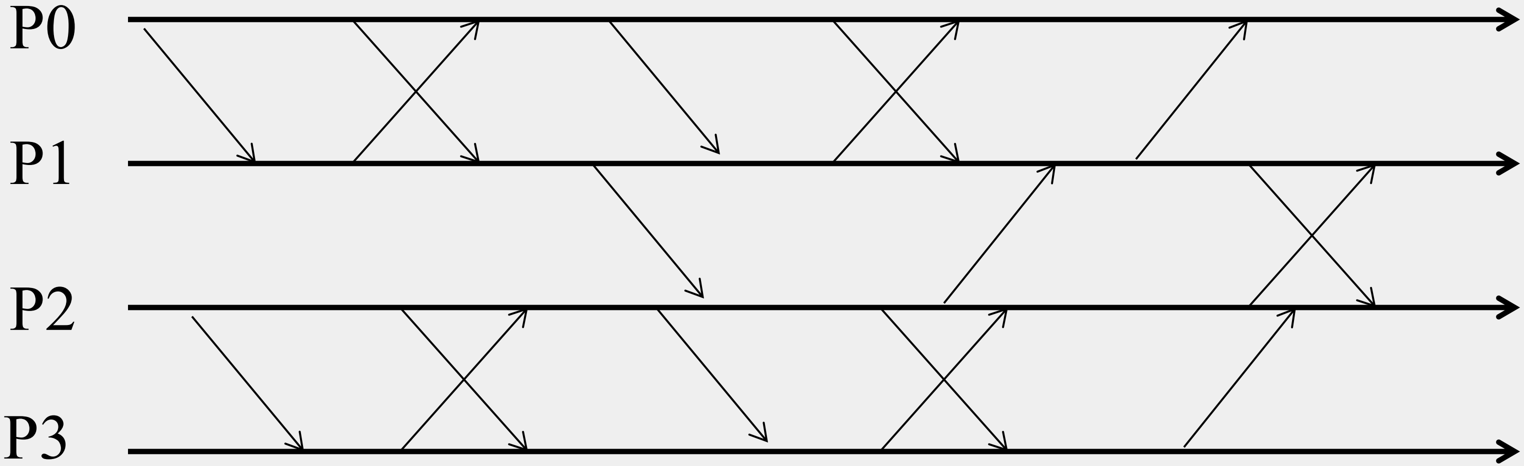
- Mark the entire global snapshot collected.



# Snapshot Exercise



# Snapshot Exercise



# Here’s a Snapshot


Wikimedia commons

# 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 each process

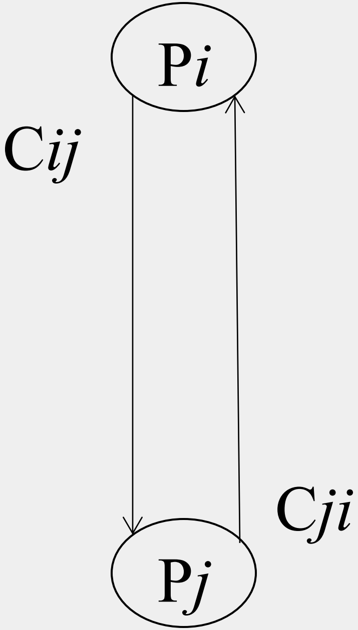
- And the instantaneous *state* of each communication channel, i.e., *messages* in transit on the channels

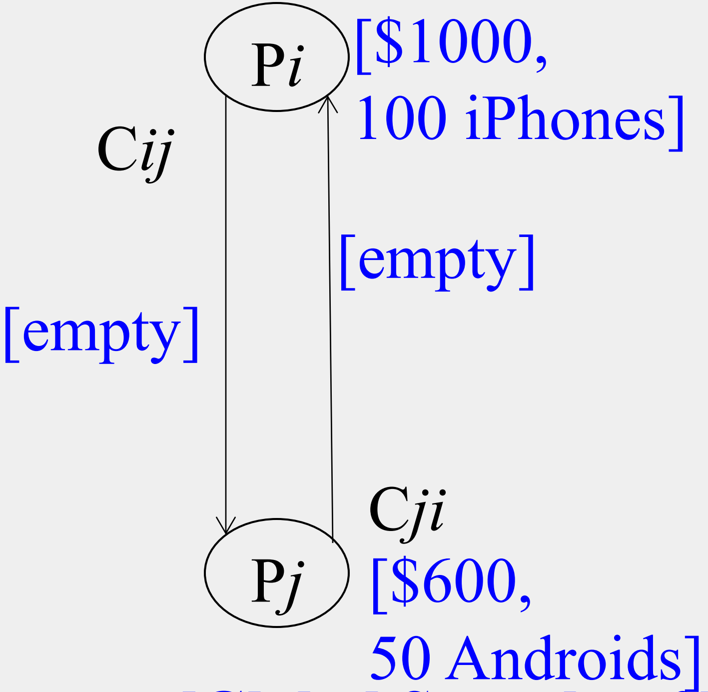
# Obvious First Solution

- 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





P$i$

[$1000,
100 iPhones]

C$ij$

[empty]

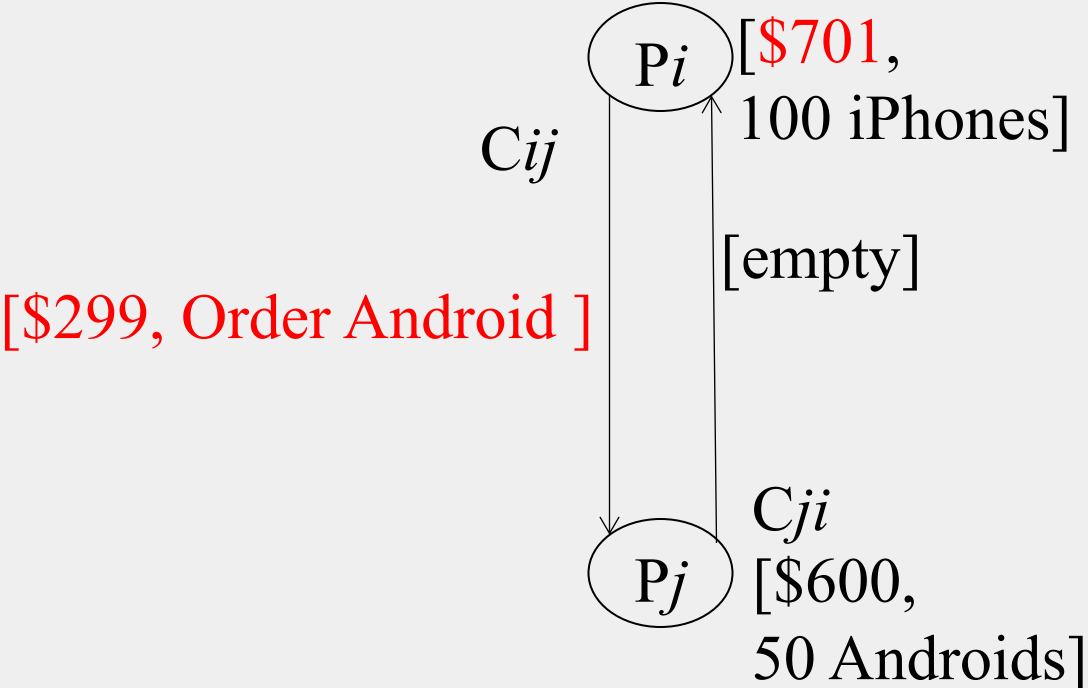
[empty]

C$ji$

P$j$

[$600,
50 Androids]

**[Global Snapshot 0]**



P*i*

[$701,
100 iPhones]

C*ij*

[$299, Order Android ]

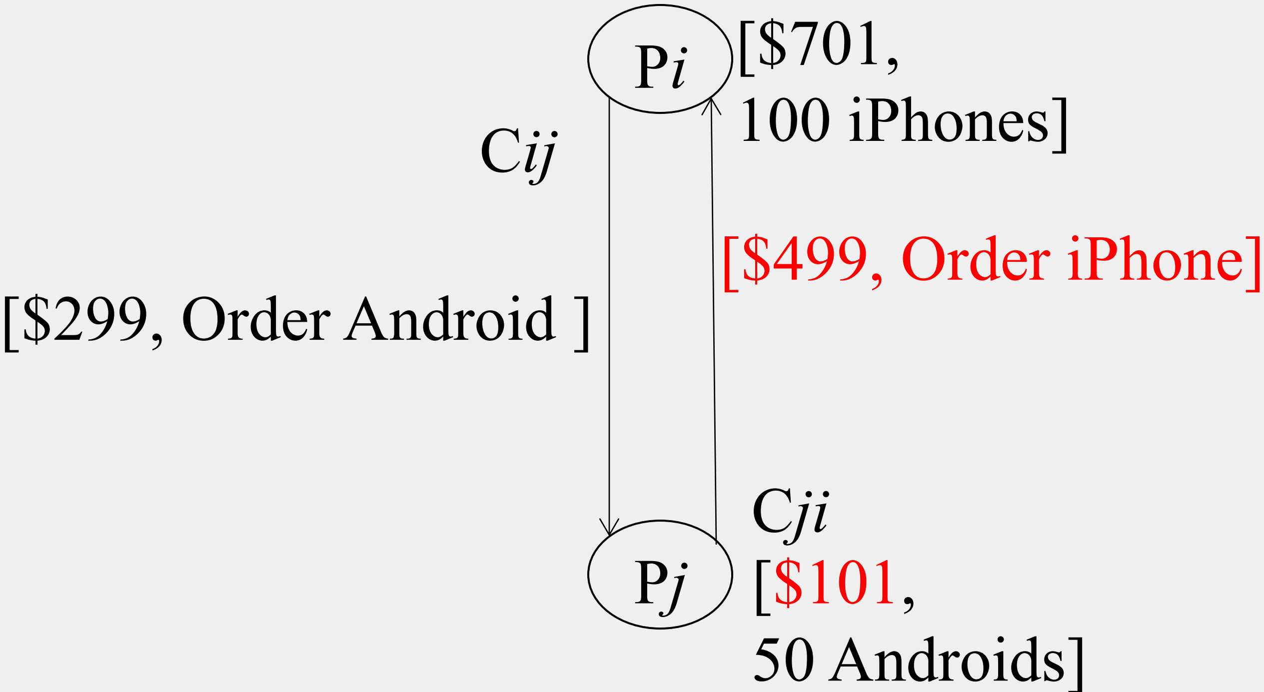
[empty]

C*ji*

P*j*

[$600,
50 Androids]

**[Global Snapshot 1]**



P*i*

[$701,
100 iPhones]

C*ij*

[$299, Order Android ]

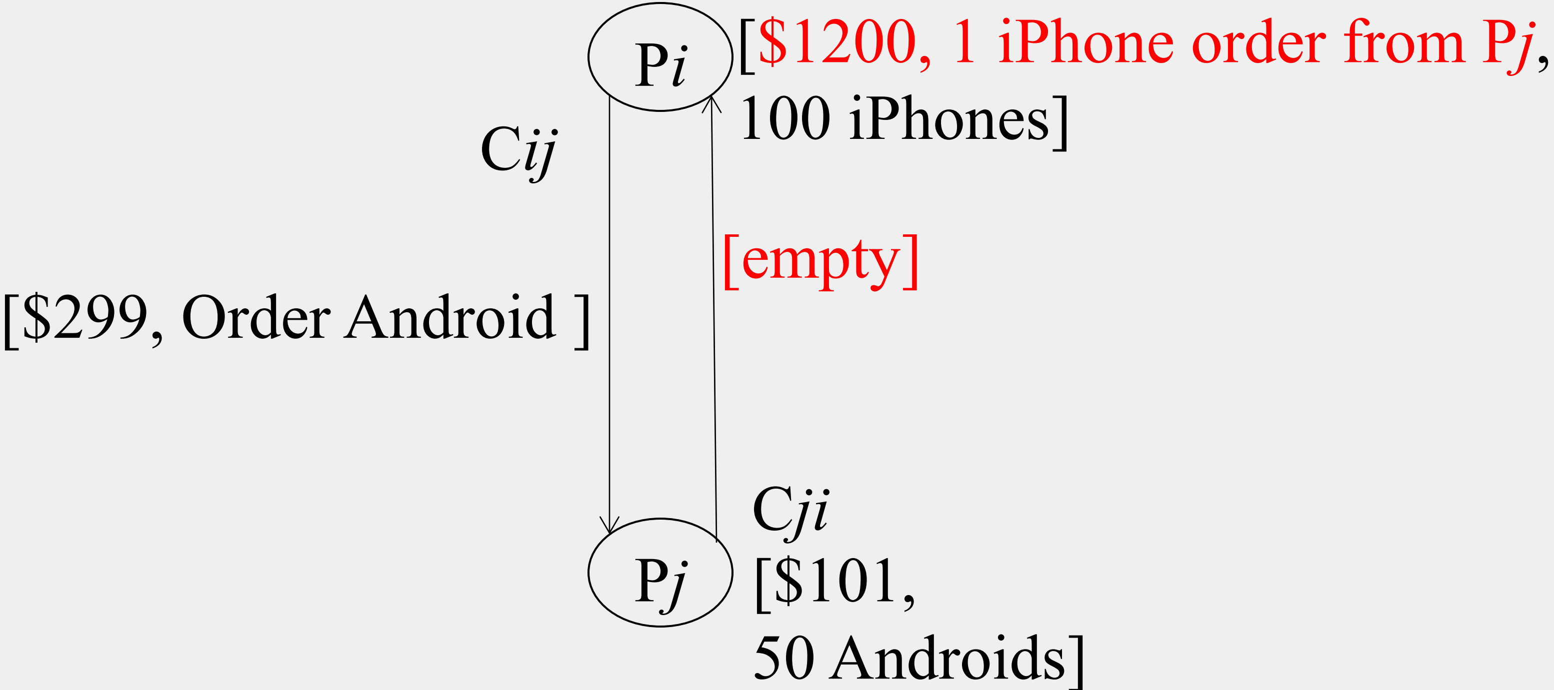
[$499, Order iPhone]

C*ji*

P*j*

[$101,
50 Androids]

**[Global Snapshot 2]**



P*i*

[$1200, 1 iPhone order from P*j*, 100 iPhones]

C*ij*

[$299, Order Android ]

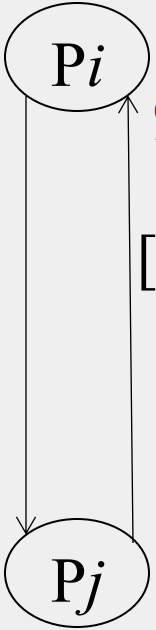
[empty]

P*j*

C*ji*

[$101, 50 Androids]

**[Global Snapshot 3]**



P*i* [$1200, 99 iPhones]

C*ij*

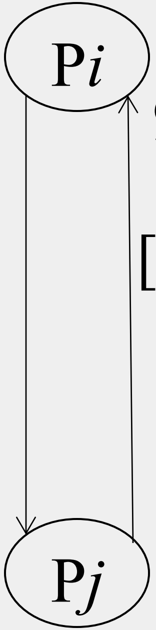
[empty]

[
($299, Order Android ),
(1 iPhone)
]

C*ji*

P*j* [$101,
50 Androids]

**[Global Snapshot 4]**



P*i* [$1200,
99 iPhones]

C*ij*

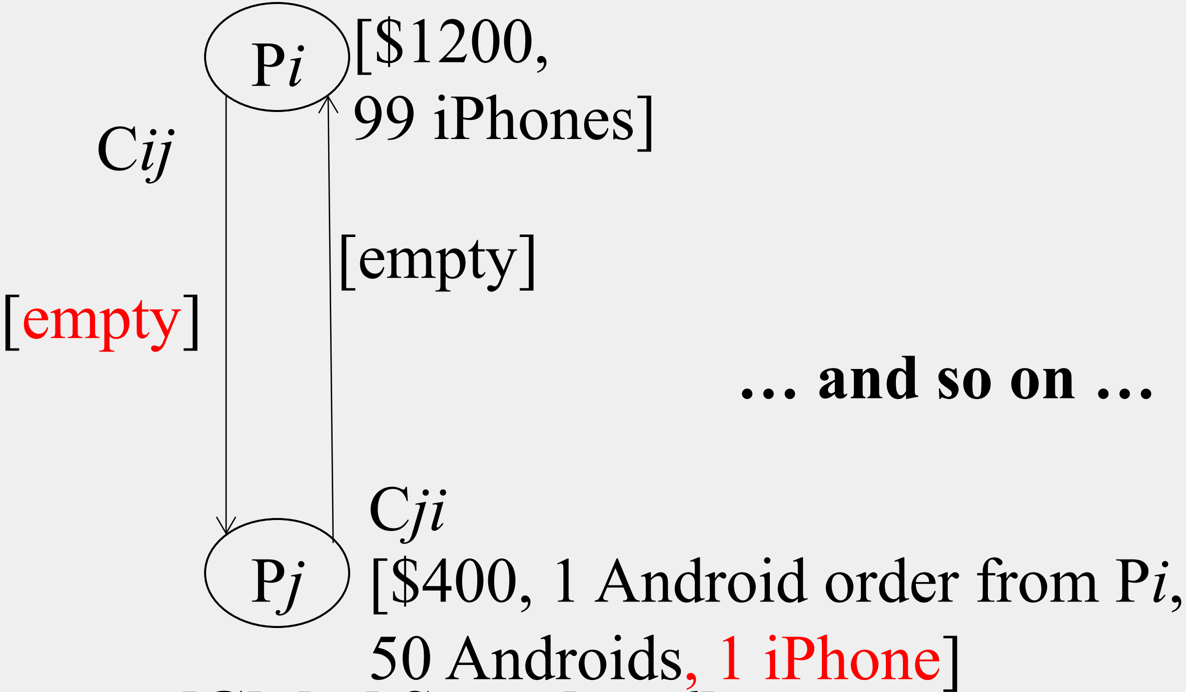
[
(1 iPhone)
]

[empty]

C*ji*

P*j* [$400, 1 Android order from P*i*,
50 Androids]

**[Global Snapshot 5]**



P*i*

[$1200,
99 iPhones]

C*ij*

[empty]

[empty]

C*ji*

P*j*

[$400, 1 Android order from P*i*,
50 Androids, 1 iPhone]

**… 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 obeys causality**
  - 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 : P*j* → P*i* and P*i* → P*j*
  - 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 $C_{ki}$

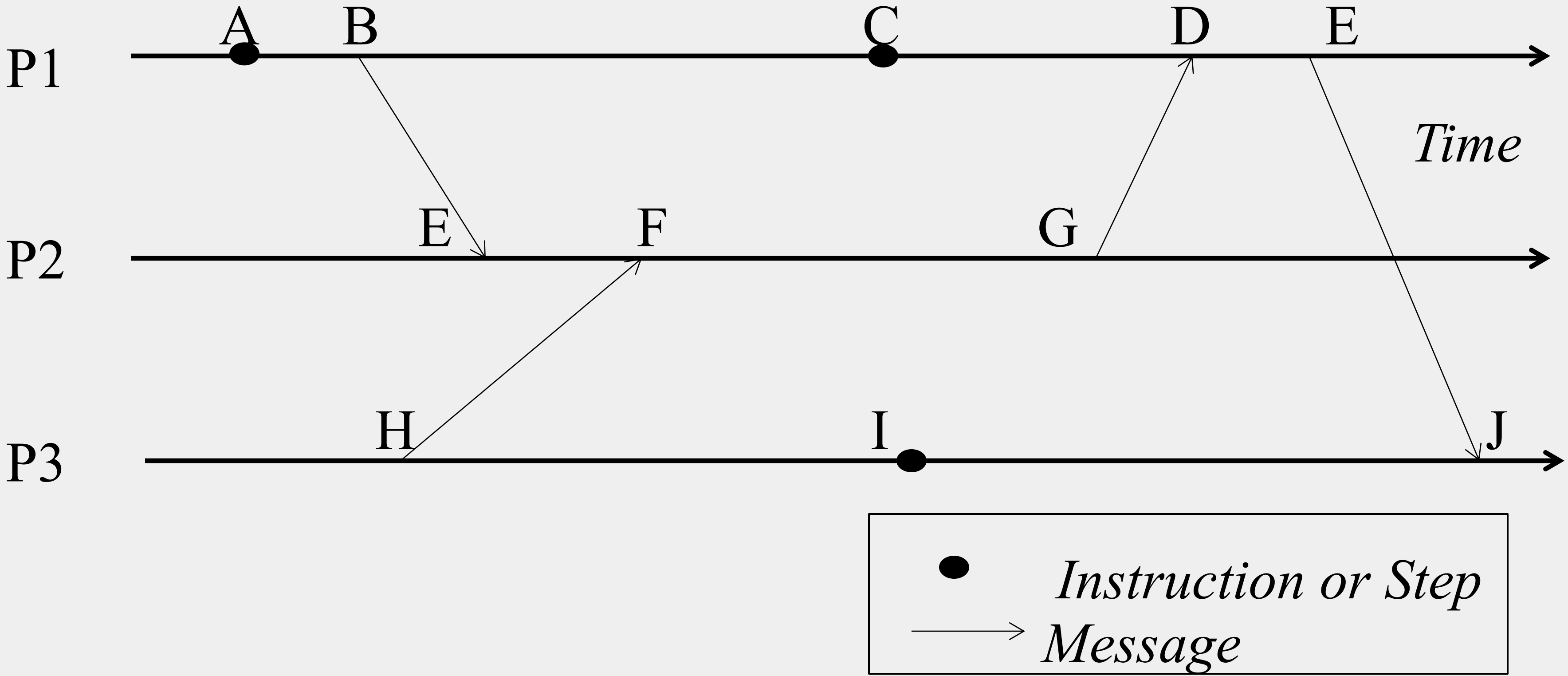
# Chandy-Lamport Global Snapshot Algorithm (3)

**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

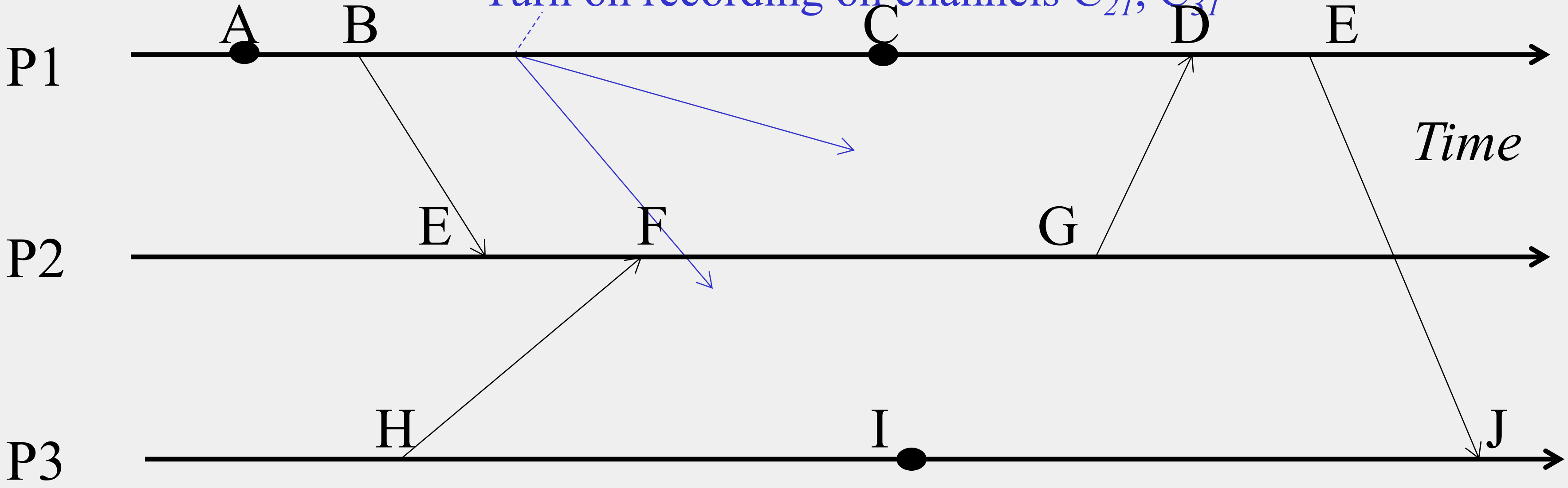
**Then, (if needed), a central server collects all these partial state pieces to obtain the full global snapshot**

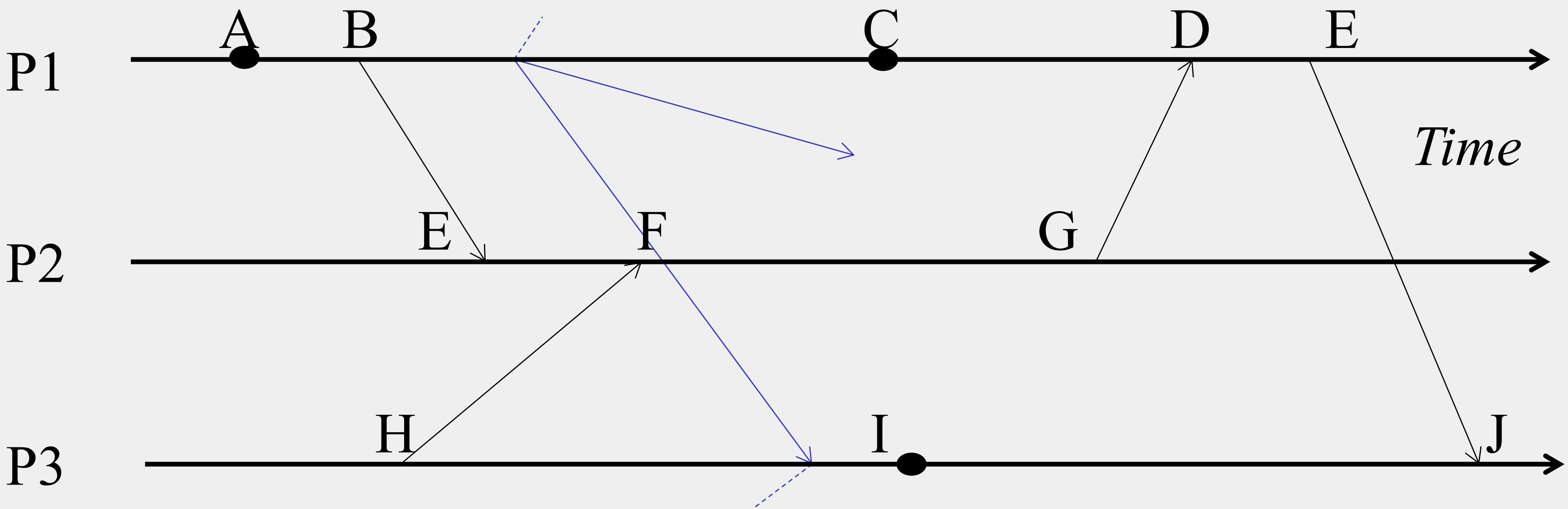
# Example



P1 is Initiator:

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

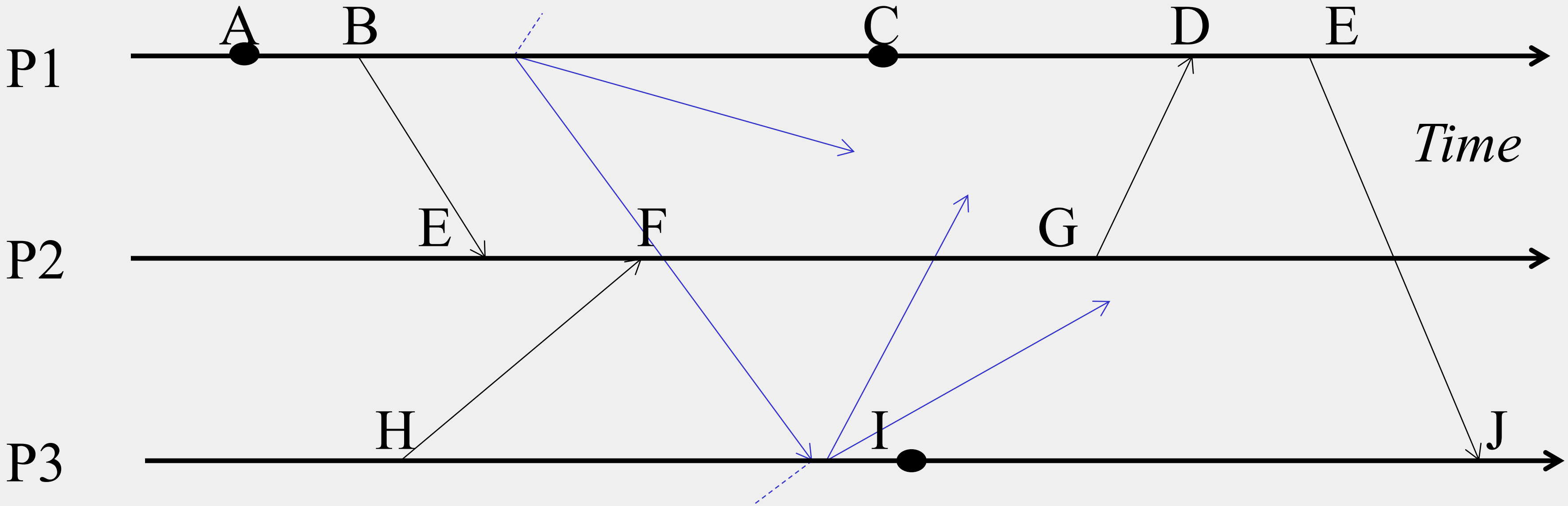




S1, Record $C_{21}$, $C_{31}$

- 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 $C_{21}$, $C_{31}$

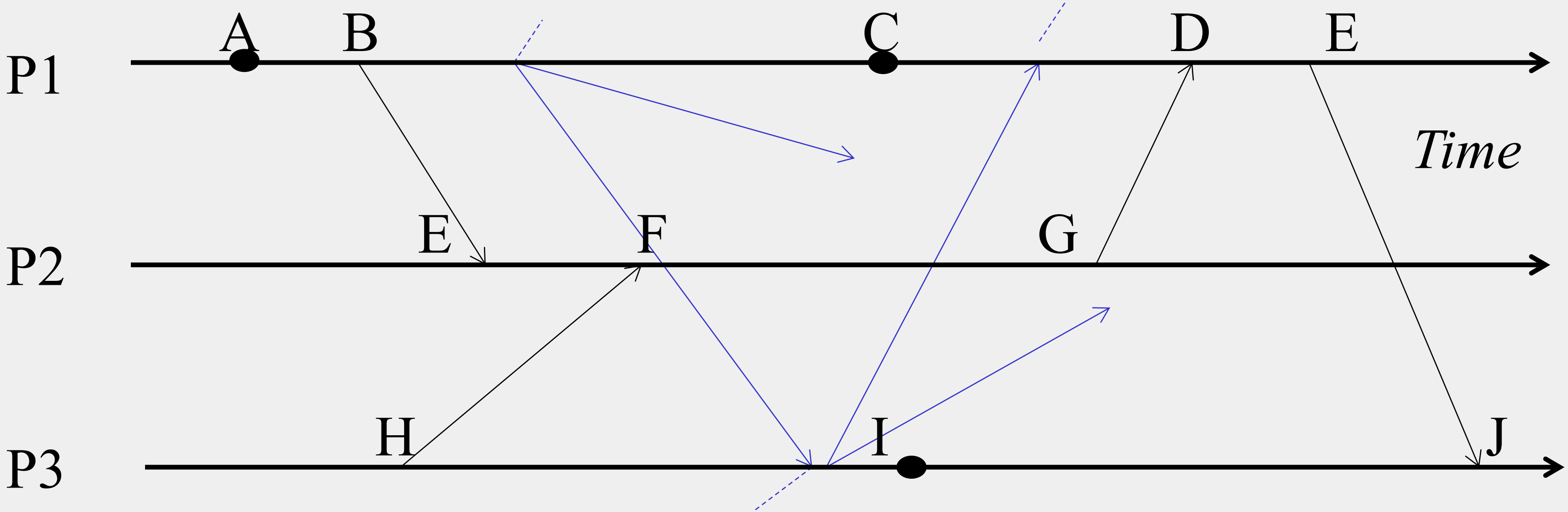


- S3
- $C_{13} = < >$
- Record $C_{23}$

S1, Record $C_{21}$~~, $C_{31}$~~

Duplicate Marker!

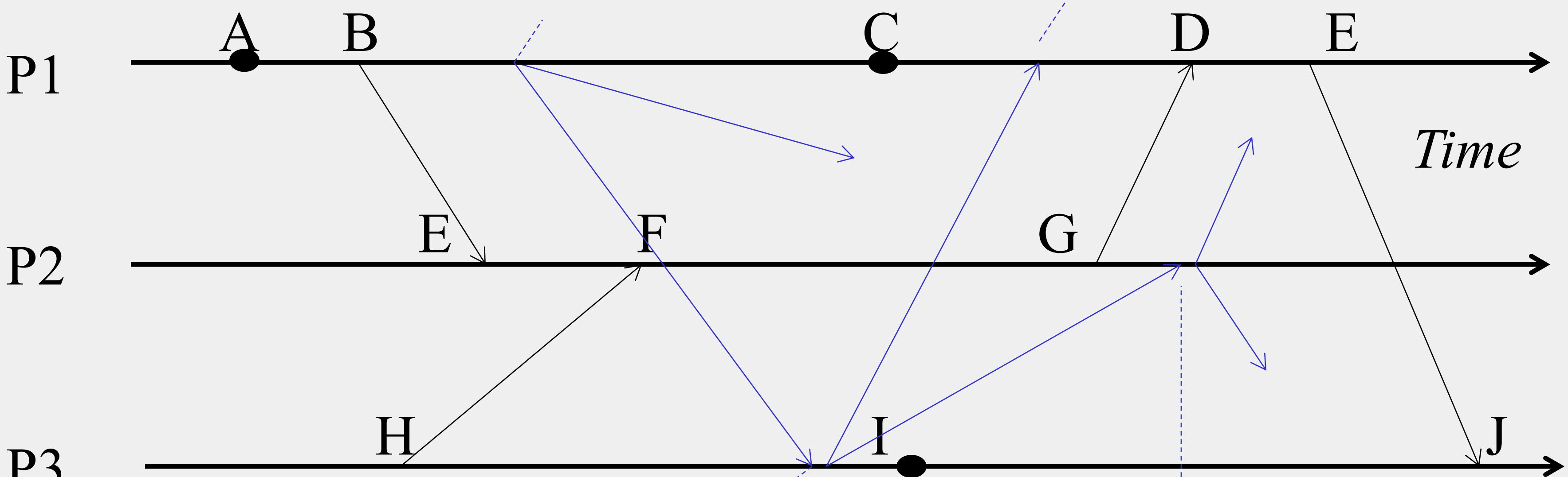
State of channel $C_{31}$ = < >



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

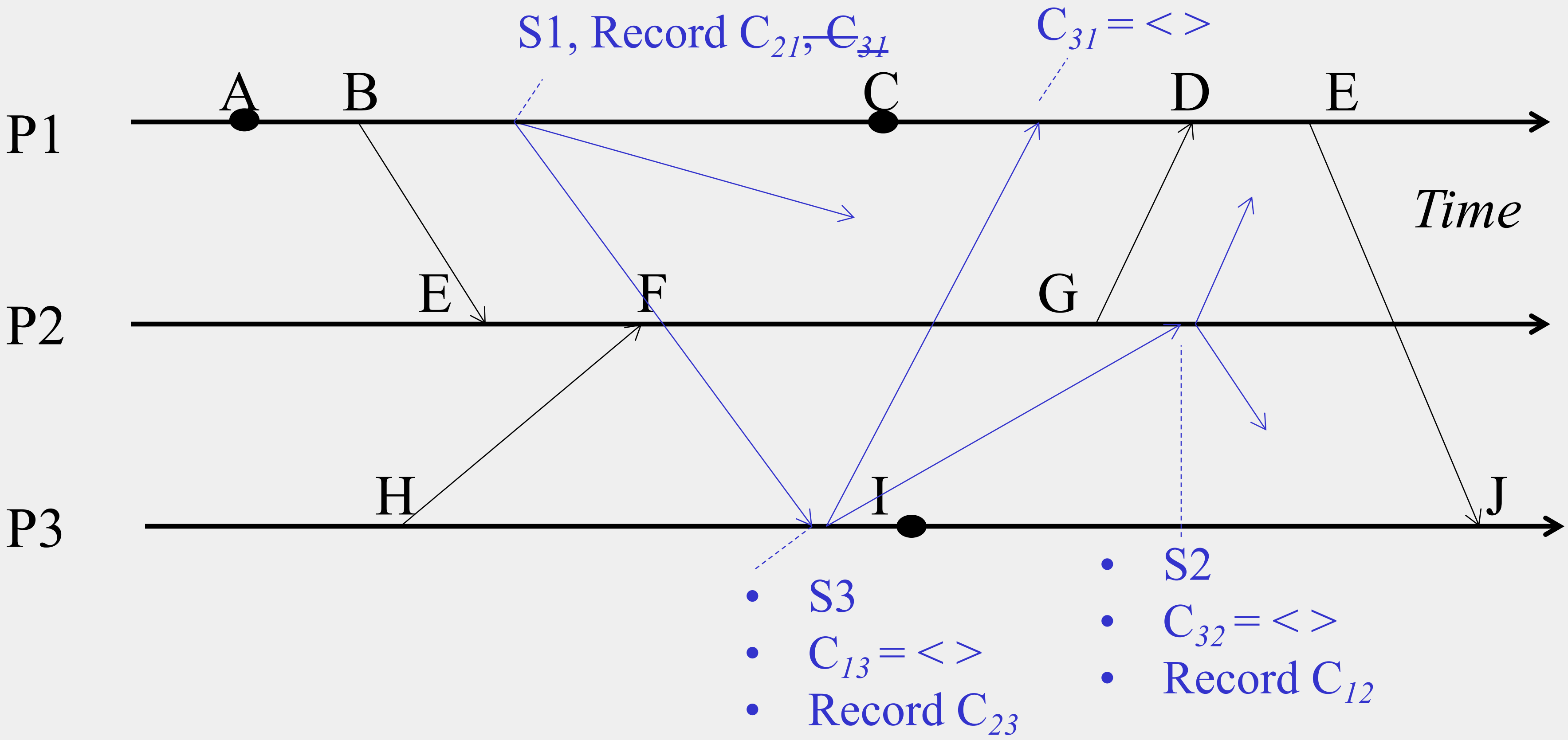
S1, Record $C_{21}$~~, $C_{31}$~~

$C_{31} = < >$



- 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

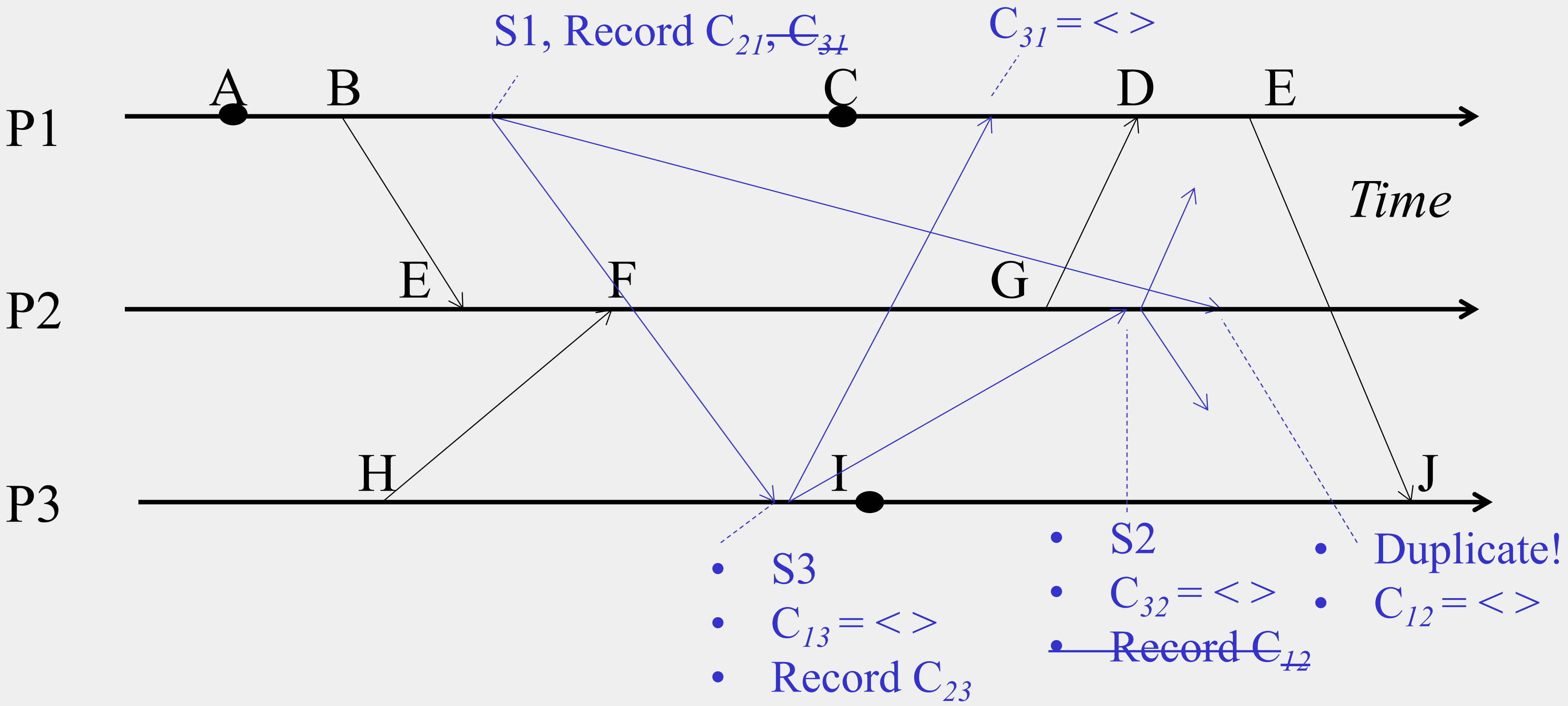


S1, Record $C_{21}$~~, $C_{31}$~~

$C_{31} = < >$

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

- S2
- $C_{32} = < >$
- Record $C_{12}$



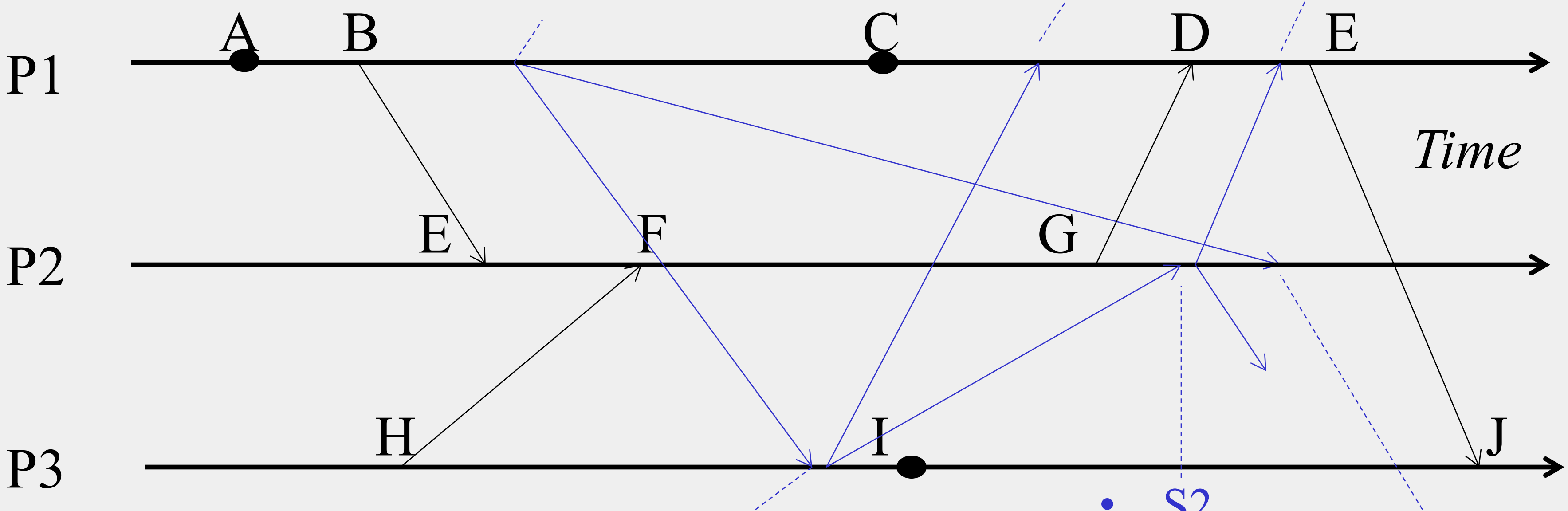
S1, Record $C_{21}$~~, $C_{31}$~~

$C_{31} = < >$

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

- S2
- $C_{32} = < >$
- ~~Record $C_{12}$~~

- Duplicate!
- $C_{12} = < >$



- Duplicate!
- $C_{21}$ = <message G→D >

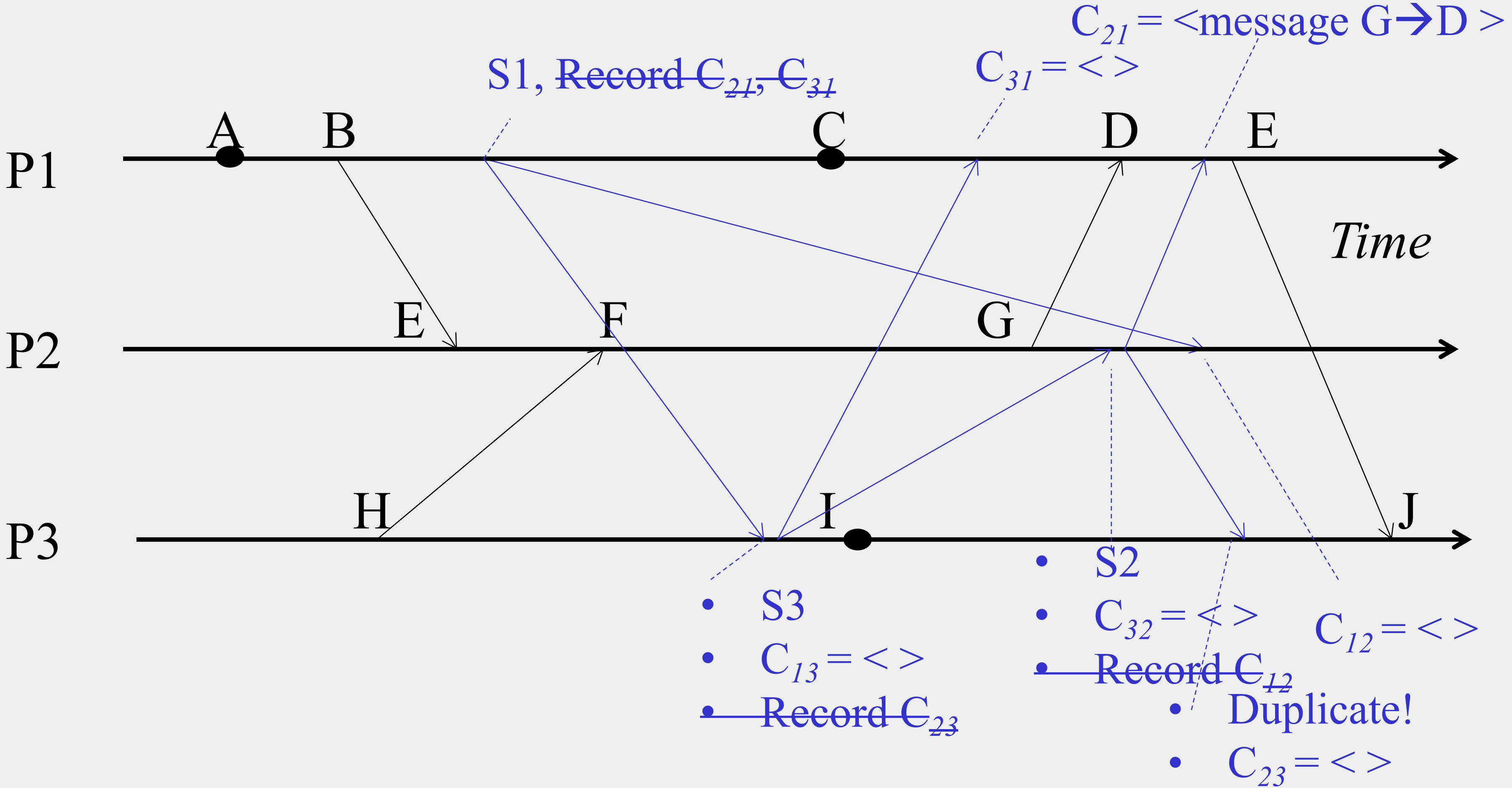
$C_{31}$ = < >

S1, ~~Record $C_{21}$, $C_{31}$~~

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

- S2
- $C_{32}$ = < >
- ~~Record $C_{12}$~~

$C_{12}$ = < >



S1, ~~Record $C_{21}$, $C_{31}$~~

$C_{31}$ = < >

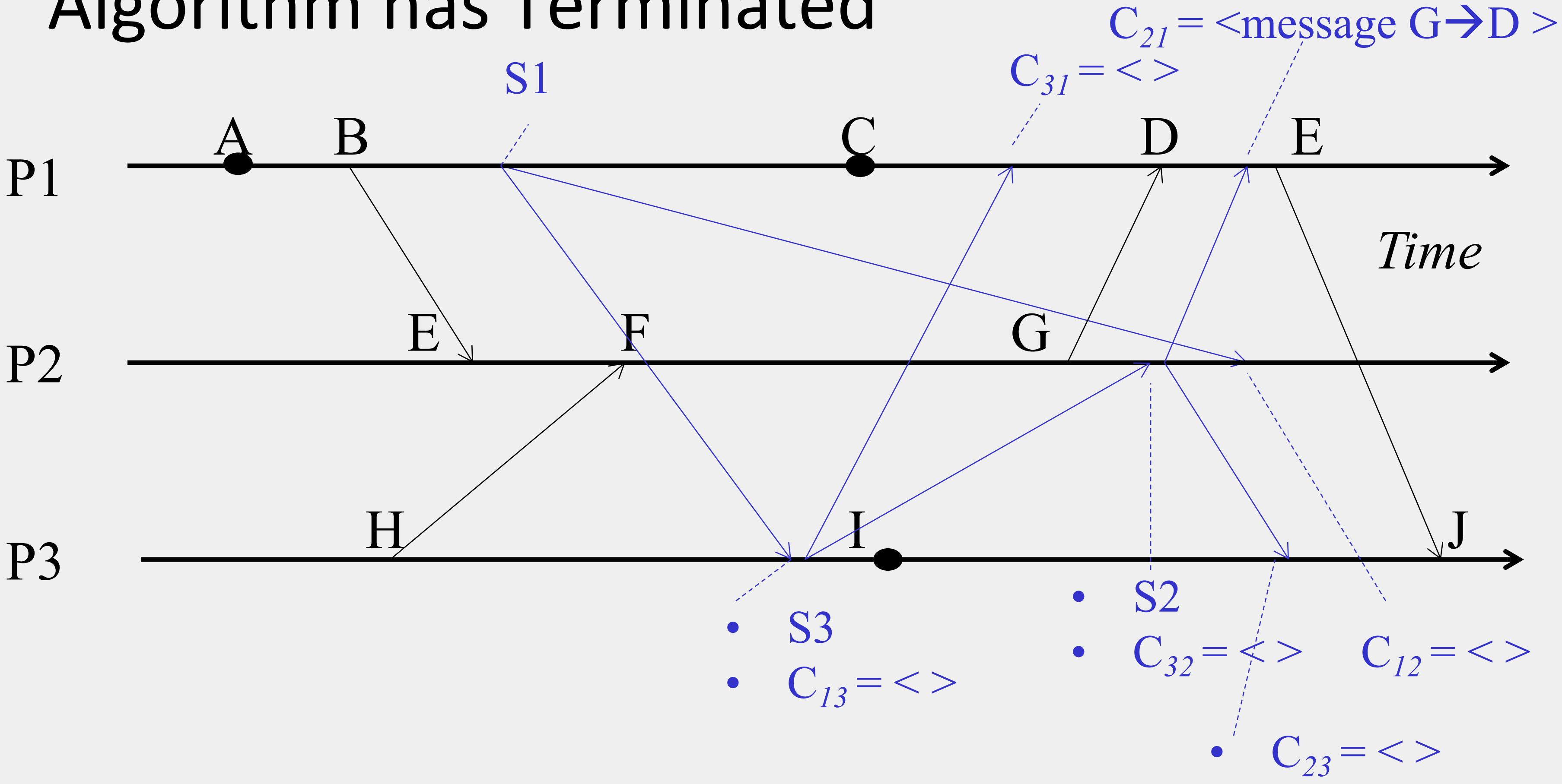
$C_{21}$ = <message G→D >

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

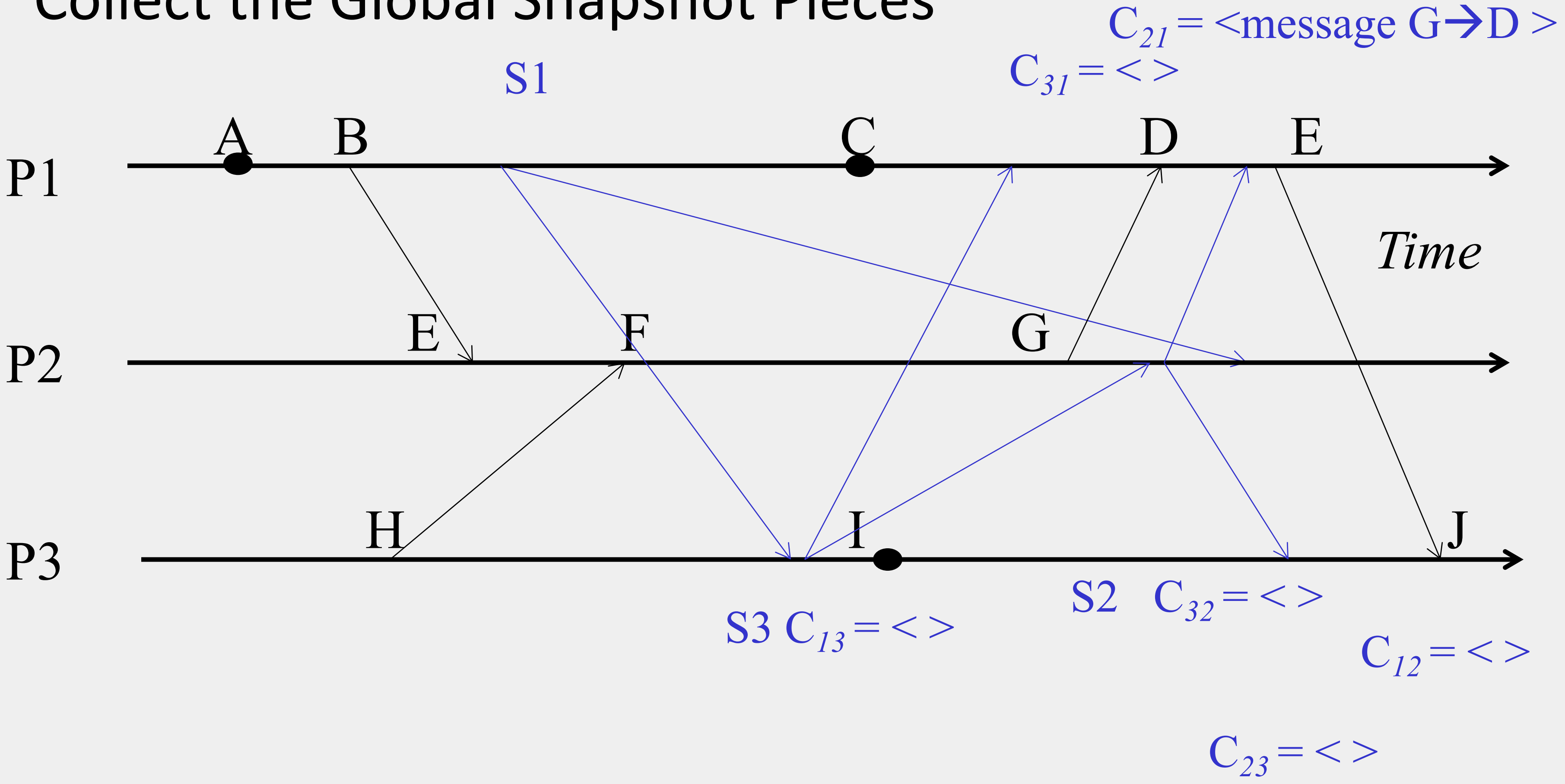
- S2
- $C_{32}$ = < >
- ~~Record $C_{12}$~~
- Duplicate!
- $C_{23}$ = < >

$C_{12}$ = < >

# 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

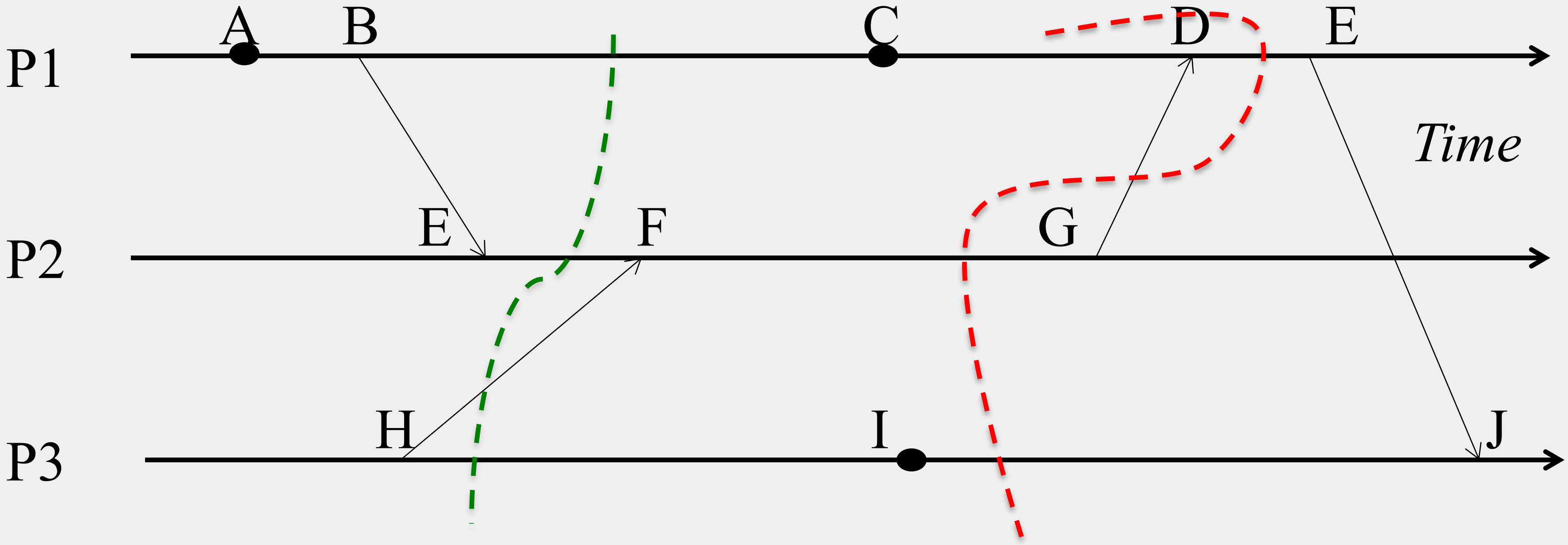
Consistent Cut: a cut that obeys causality

- 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 → e (f happens-before e)
    - Then: Event f is also in the cut C

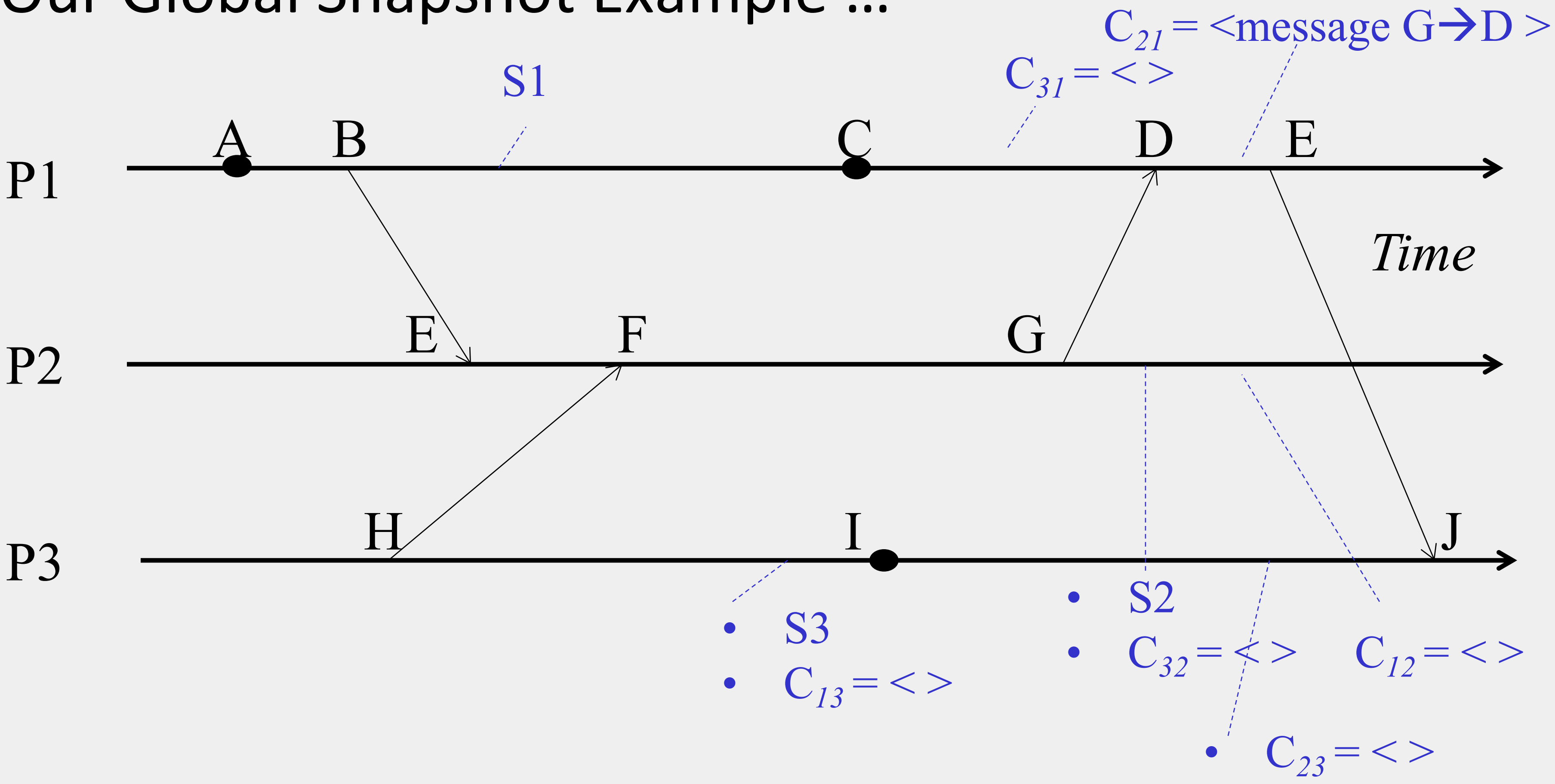
# Example



Consistent Cut

Inconsistent Cut
G → D, but only D is in cut

# Our Global Snapshot Example …



S1

$C_{21} = $ <message G→D >

$C_{31} = $ < >

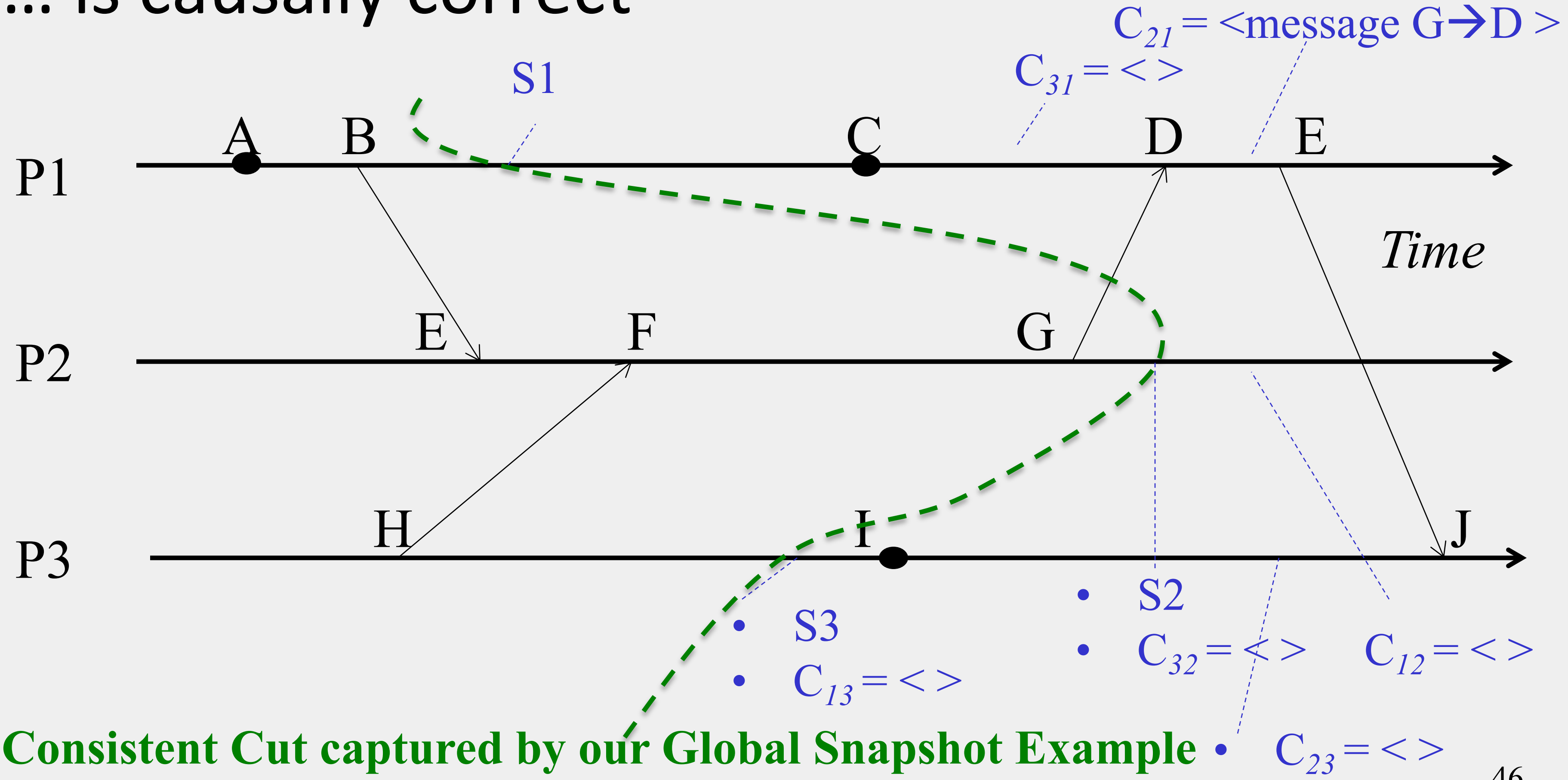
- S3
- $C_{13} = $ < >

- S2
- $C_{32} = $ < >

$C_{12} = $ < >

- $C_{23} = $ < >

# … 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 $e_j$ → <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> → $e_i$
  - Consider the path of app messages (through other processes) that go from $e_i$ → $e_j$
  - Due to FIFO ordering, markers on each link in above path will precede regular app messages
  - Thus, since <P*i* records its state> → $e_i$ , 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**
  - A peace treaty between two nations provides safety
    - War will never happen
  - 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

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