Cornell CS 6410, 10/5/2017

Today's Theme:
Consistency in a Distributed System

Papers:

- *Time, Clocks, and the Ordering of Events in a Distributed System*, Leslie Lamport, Communications of ACM,Volume 27 Issue 7, July 1978.
- *Distributed Snapshots: Determining Global States of Distributed Systems*, K.Mani Chandy, Leslie Lamport. ACM Transactions on Computer Systems (TOCS), Volume 3 Issue 1, Feb. 1985.

Why should we care about this **theme**?

- How can we make a consistent global state of an asynchronous system?
  - What even is our synchronous protocol?
  - Who today is asking/using these questions?

- How can we coordinate in a distributed system?
  - If an (airline) reservation database system is replicated and distributed and people can purchase tickets locally, how can we order the purchasing of tickets (e.g. two people want to buy a seat, but only one seat is left)?

Why should we care about these **papers**?

- Why to care about the set
- *Time, Clocks, and the Ordering of Events in a Distributed System*, Leslie Lamport, Communications of ACM,Volume 27 Issue 7, July 1978.
- *Distributed Snapshots: Determining Global States of Distributed Systems*, K.Mani Chandy, Leslie Lamport. ACM Transactions on Computer Systems (TOCS), Volume 3 Issue 1, Feb. 1985.

- 5414?

Initial thoughts?

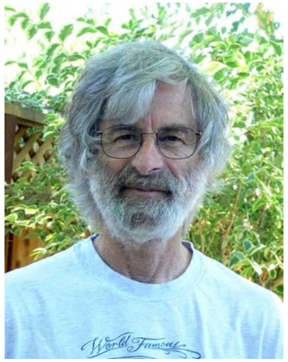
Today’s Goals

- *Time, Clocks, and the Ordering of Events in a Distributed System*, Leslie Lamport, Communications of ACM,Volume 27 Issue 7, July 1978.
  - Understand:
    - The “happened before” relation
    - How to establish partial/total order and what to do with it
    - Physical, logical, local/global clocks
- *Distributed Snapshots: Determining Global States of Distributed Systems*, K.Mani Chandy, Leslie Lamport. ACM Transactions on Computer Systems (TOCS), Volume 3 Issue 1, Feb. 1985.
  - Understand:
    - Global Snapshot
    - Consistent Cut
    - How Global Snapshot helps in finding a Consistent Cut

Time, Clocks, and the Ordering of Events in a Distributed System

Leslie Lamport
Massachusetts Computer Associates, Inc.

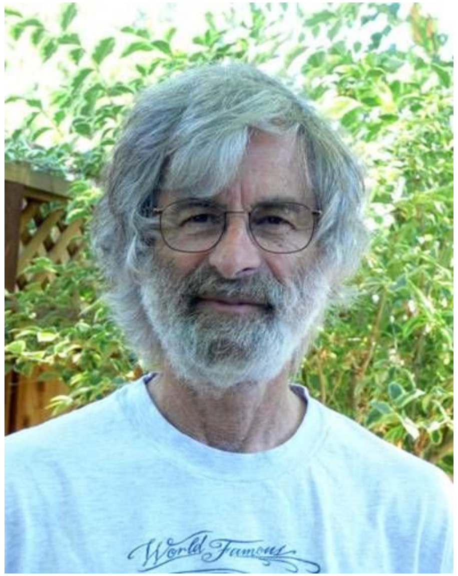
Communications of the ACM - July 1978

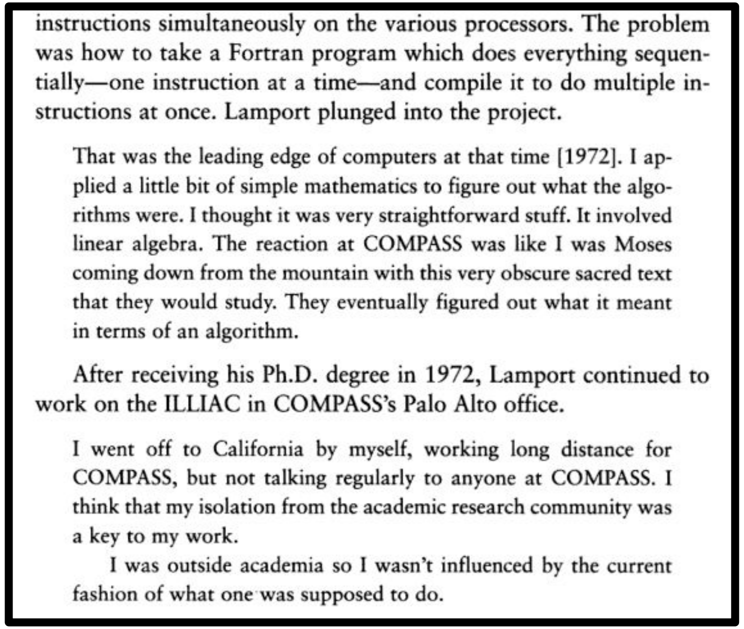


Leslie Lamport

- BS in Math from MIT, 1960
- MA, Ph.D. in Math from Brandeis, 1972
- Research in industry
  - Massachusetts Computer Associates (1970-77)
  - SRI International (1977-85)
  - DEC/Compaq (1985-2001)
  - Microsoft Research (2001-)
- 2000 PODC Influential Paper award for *Time, Clocks, and the Ordering of Events*
- 2013 Turing Award Winner and initial developer of LaTeX

Author: Leslie Lamport
Massachusetts Computer Associates, Inc. → COMPASS





instructions simultaneously on the various processors. The problem was how to take a Fortran program which does everything sequentially—one instruction at a time—and compile it to do multiple instructions at once. Lamport plunged into the project.

> That was the leading edge of computers at that time [1972]. I applied a little bit of simple mathematics to figure out what the algorithms were. I thought it was very straightforward stuff. It involved linear algebra. The reaction at COMPASS was like I was Moses coming down from the mountain with this very obscure sacred text that they would study. They eventually figured out what it meant in terms of an algorithm.

After receiving his Ph.D. degree in 1972, Lamport continued to work on the ILLIAC in COMPASS's Palo Alto office.

> I went off to California by myself, working long distance for COMPASS, but not talking regularly to anyone at COMPASS. I think that my isolation from the academic research community was a key to my work.
>
> I was outside academia so I wasn't influenced by the current fashion of what one was supposed to do.

Out of their Minds: The Lives and Discoveries of 15 Great Computer Scientists

By Dennis Shasha, Cathy Lazere
pg. 125

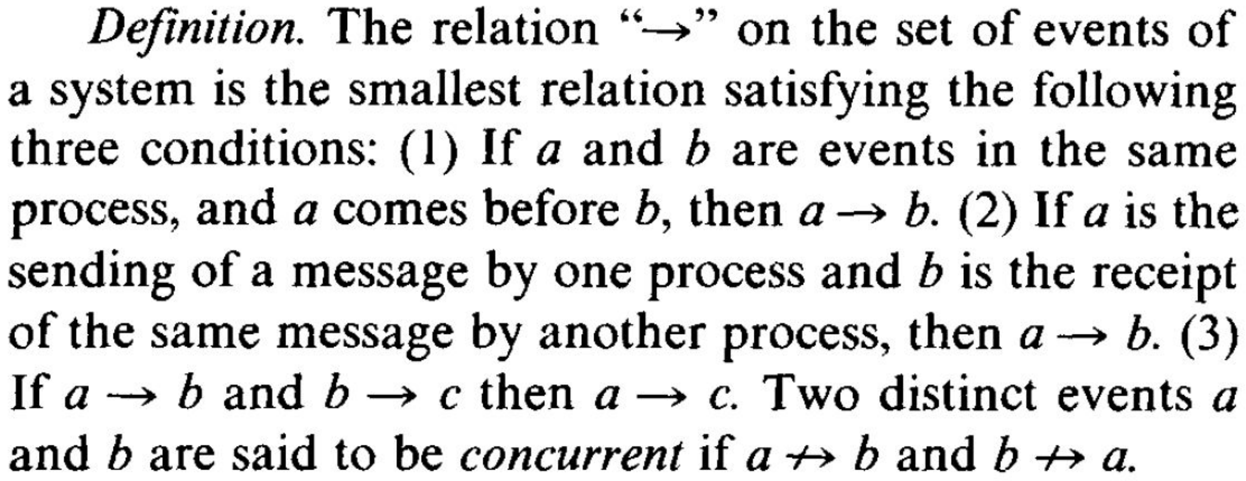
Outline

- Partial Ordering of Events
- Logical Clocks
- Total Ordering of Events
- Anomalous Behaviour
- Physical Clocks

Definitions and Perspectives

- A *process* as a set of events with an a priori total ordering -- a sequencing.
- System as a collection of processes, each process as a sequence of events
- sending/receiving a message as an event in a process

“Happened before” relation, “ $\rightarrow$ ”



Definition. The relation “$\rightarrow$” on the set of events of a system is the smallest relation satisfying the following three conditions: (1) If a and b are events in the same process, and a comes before b, then $a \rightarrow b$. (2) If a is the sending of a message by one process and b is the receipt of the same message by another process, then $a \rightarrow b$. (3) If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$. Two distinct events a and b are said to be *concurrent* if $a \not\rightarrow b$ and $b \not\rightarrow a$.

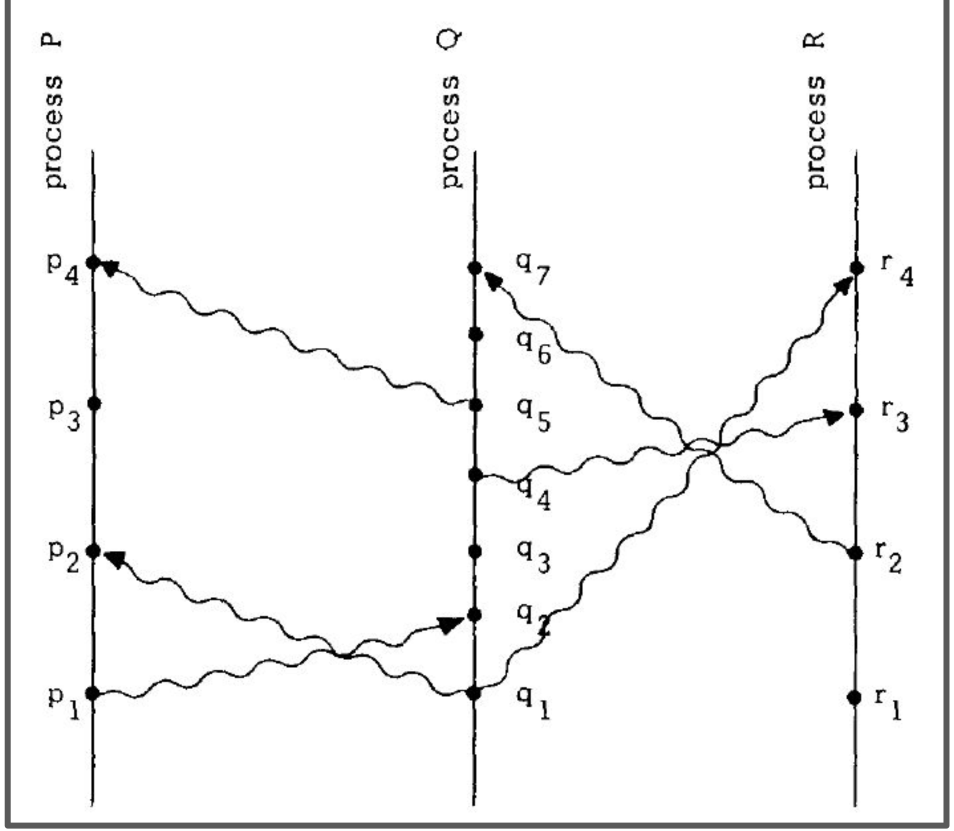
(Lamport 559)

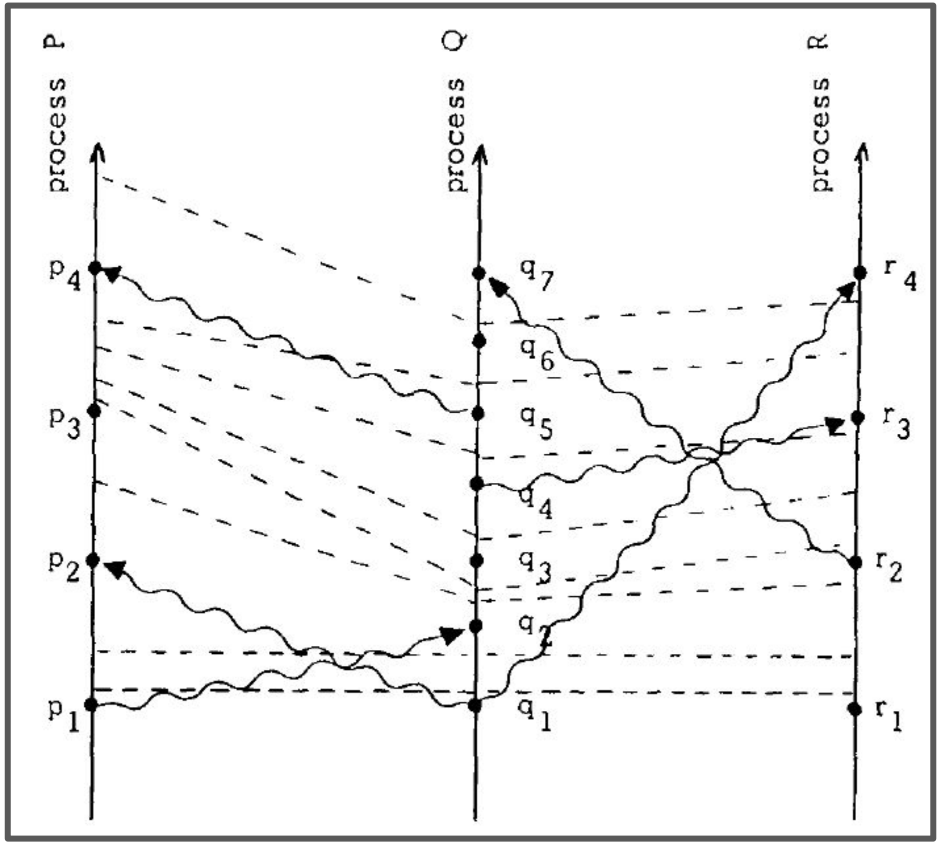
$a \ ? \ a$

$$a \not\rightarrow a$$

"an irreflexive partial ordering on the set of all events in the system"

Fig. 1.





Space-time diagrams

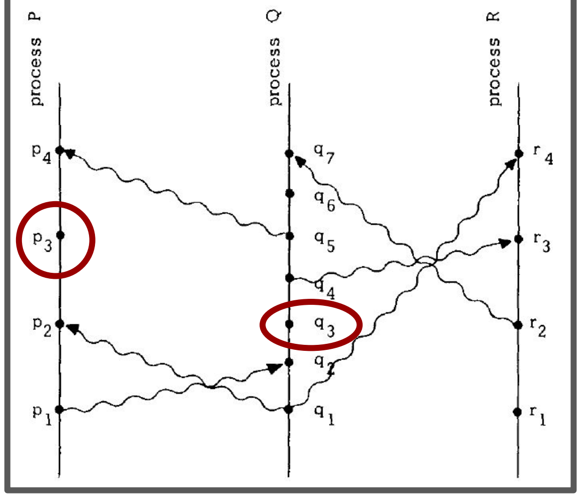
I.e., what can we say from $a \longrightarrow b$?

$a \longrightarrow b$ means a can causally affect b

Concurrency?

Two events are *concurrent* if neither can causally affect the other.

Fig. 1.



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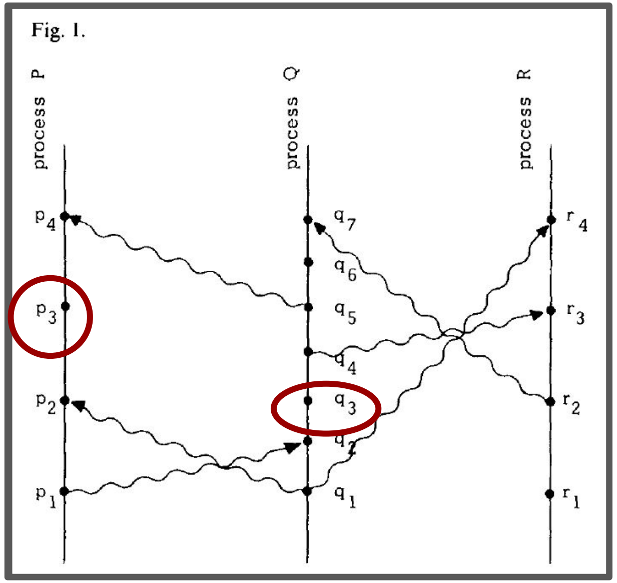
Logical Clocks

- How might we begin thinking about clocks?
- “We begin with an abstract point of view in which a clock is just a way of assigning a number to an event, where the number is thought of as the time at which the event occurred” (Lampson 559)
- a clock C_i, for each process P_i, as a function assigning a number $C_i(a)$ to any event *a* in P_i
- *system* of clocks as a function C assigning to any event b the number C(b) such that $C(b) = C_j(b)$ if b is an event in P_j
- yet relating numbers $C_i(a)$ to physical time, instead regarding C_i as logical clocks
    - Use of counters rather than use of an ‘actual timing mechanism’

Correctness?

- ~~Physical timing of events~~ order of events
- If an event *a* happens before another event *b*, *a* should happen at an earlier time than *b*
  - Time??
    - Clock Condition
      - "For any events *a, b*: if *a* → *b* then C(a) < C(b)
    - Why can we not assume the converse as well?

Fig. 1.



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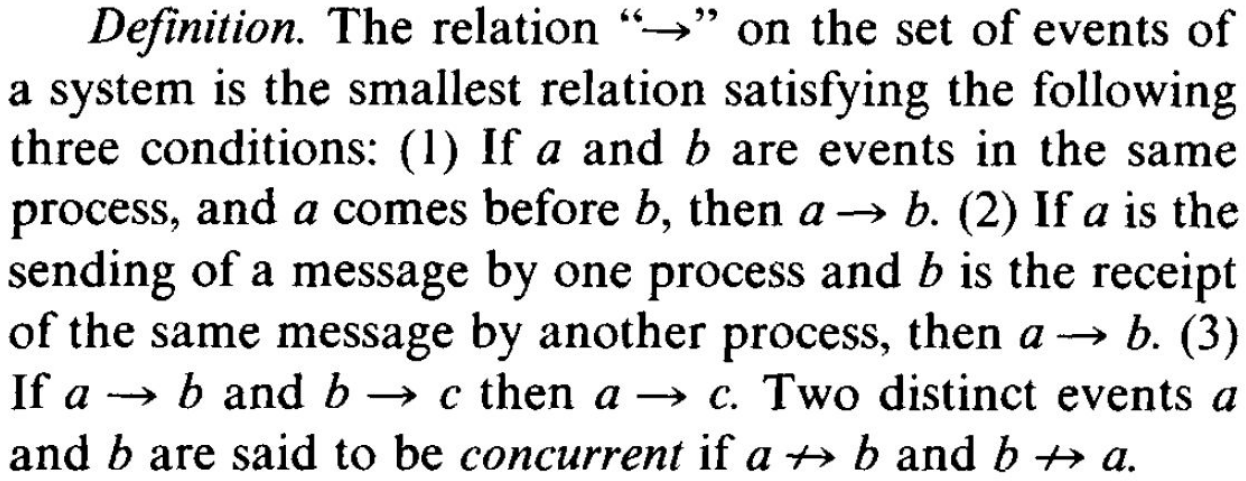

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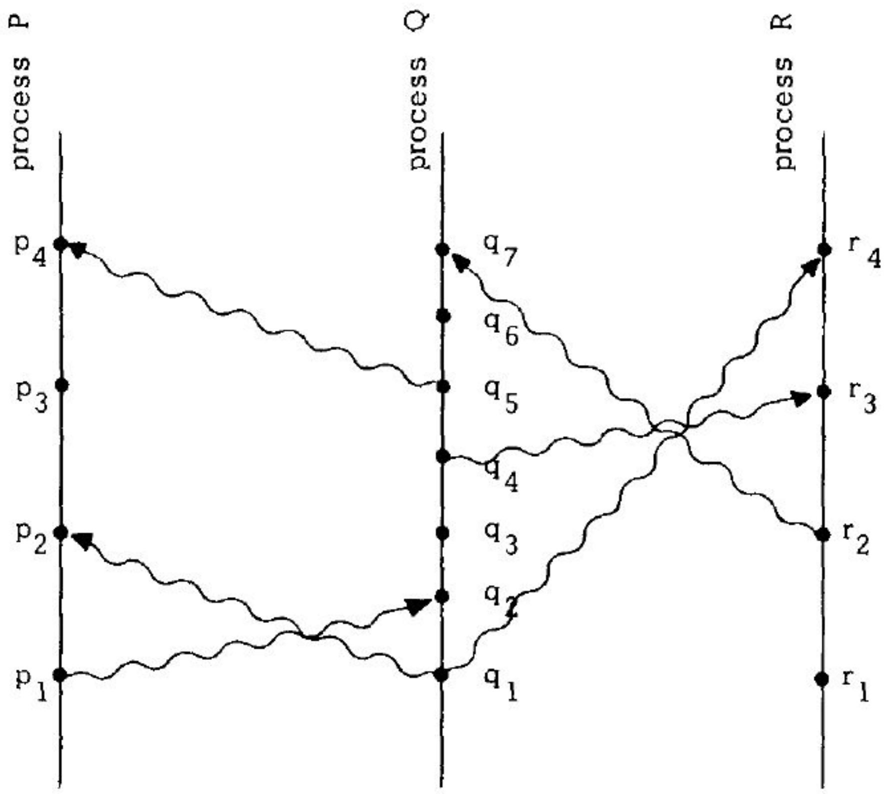
(Lamport 559)

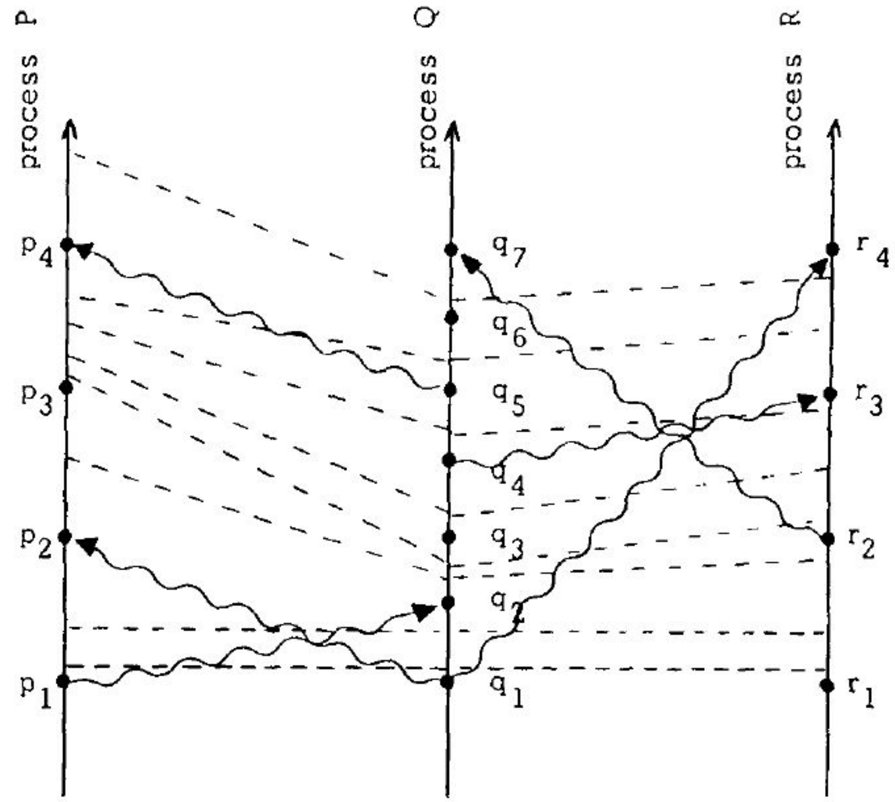
Correctness

- Clock Condition
    - "For any events *a, b*: if $a \rightarrow b$ then C(a) < C(b)"
- 2 conditions to satisfy the Clock Condition:
    - 1. If *a* and *b* are events in a process P_i, and *a* comes before *b*, then $C_i(a) < C_i(b)$
        - There must be a tick line between any two events on a process line
    - 2. If *a* is the sending of a message by process P_i and *b* is the receipt of that message by process P_j, then $C_i(a) < C_j(b)$
        - Every message line must cross a tick line

...Tick lines?

Fig. 1.





Space-time diagrams

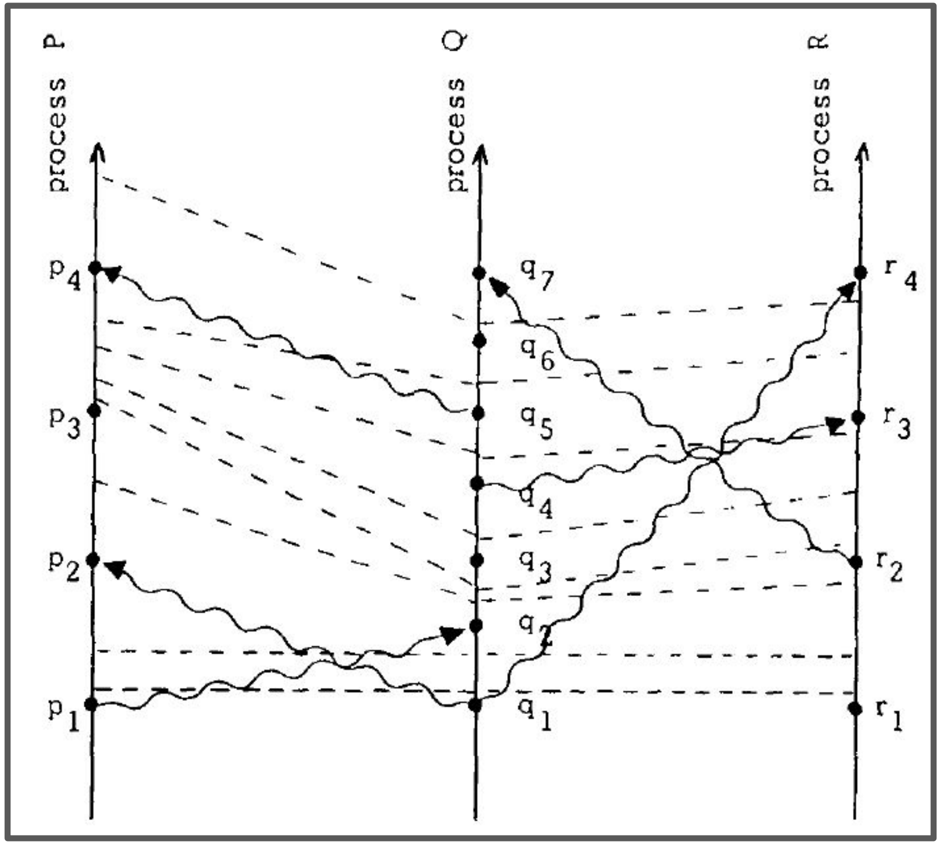
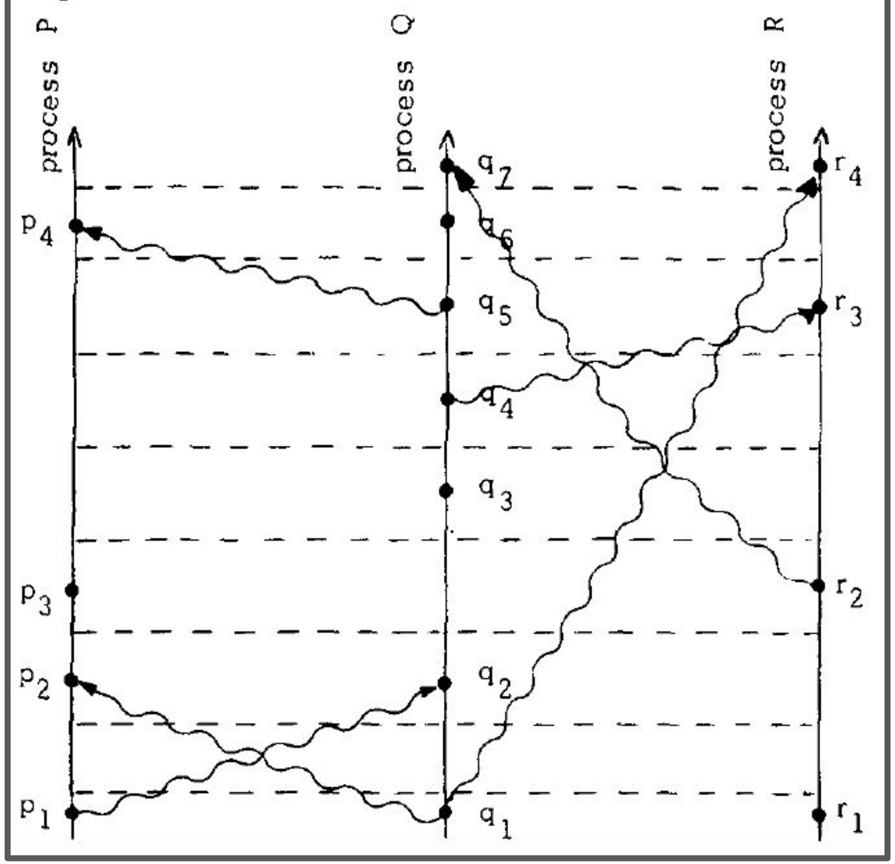


Fig. 3.



Space-time diagrams

Problem with Partial Order

- A single resource
- Processes must synchronize to avoid conflicts
- Requests must be granted in order

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- Requests must be granted in order

Partial order is not helpful in solving this problem as partial order cannot resolve concurrent requests

Total ordering required…..

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Total Ordering of Events

- Total ordering eliminates concurrency
- Identify message with event sending it

Distributed Mutual Exclusion

Every node i has a request queue q_i

keeps requests sorted by logical timestamps (**total ordering** enforced by including process id in the timestamps)

To request critical section:

1)send timestamped REQUEST(T_m:P_i) to all other nodes

2)put (T_m:P_i) in its own queue

On receiving a request (T_m:P_i)**:**

1)send timestamped REPLY to the requesting Node i

2)put REQUEST (T_m:P_i) in the queue

Distributed Mutual Exclusion

Process i enters critical section if:

1)(T_m:P_i) is at top of its own queue, and

2)process i received a message (any message) with timestamp larger than (T_m:P_i) from all other nodes.

To release critical section:

1)Process i removes its request from its own queue and sends a timestamped RELEASE message to all other nodes.

2)On receiving a release message from i, i’s request is removed from the local request queue.

Distributed Mutual Exclusion

Process i enters critical section if:

1)(T_m:P_i) is at top of its own queue, and

2)process i received a message (any message) with timestamp larger than (T_m:P_i) from all other nodes. ***Why is this condition required?***

To release critical section:

1)Process i removes its request from its own queue and sends a timestamped RELEASE message to all other nodes.

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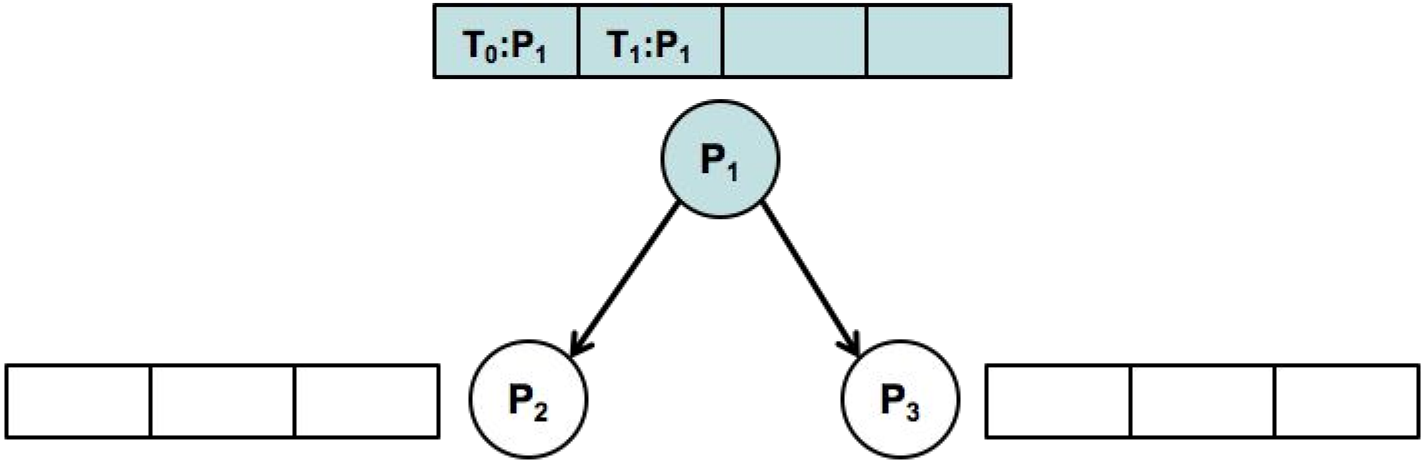
Total Ordering of Events

Step 1: P_i sends request resource

P_i sends **request T_m:P_i** to **P_j**

P_i puts **request T_m:P_i** on its request queue



Total Ordering of Events

Step 1: P_i sends request resource

- $\mathbf{P_i}$ sends **request** $\mathbf{T_m:P_i}$ to $\mathbf{P_j}$
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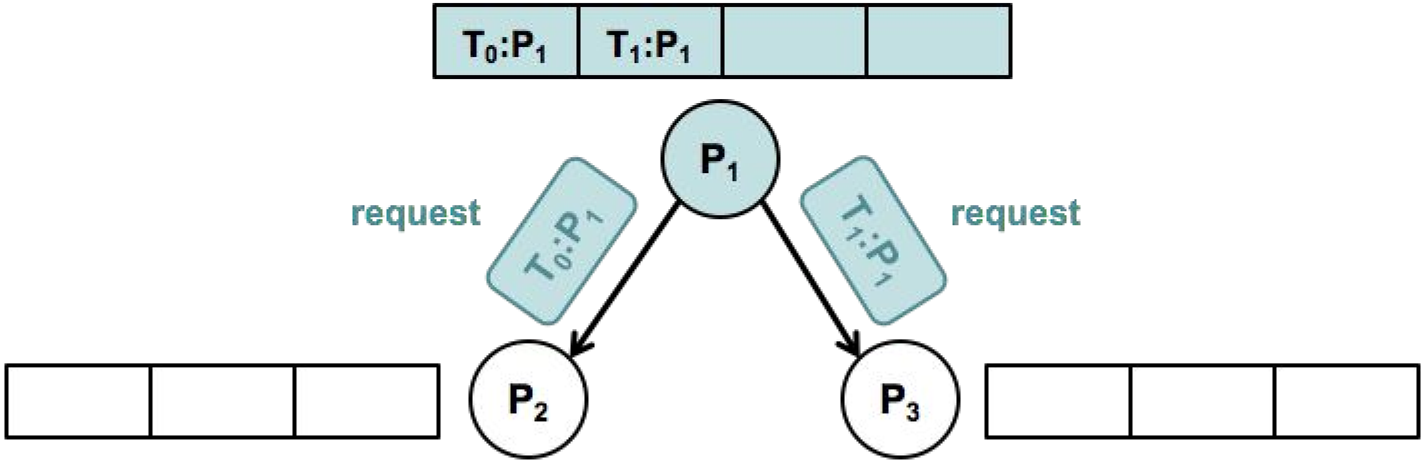
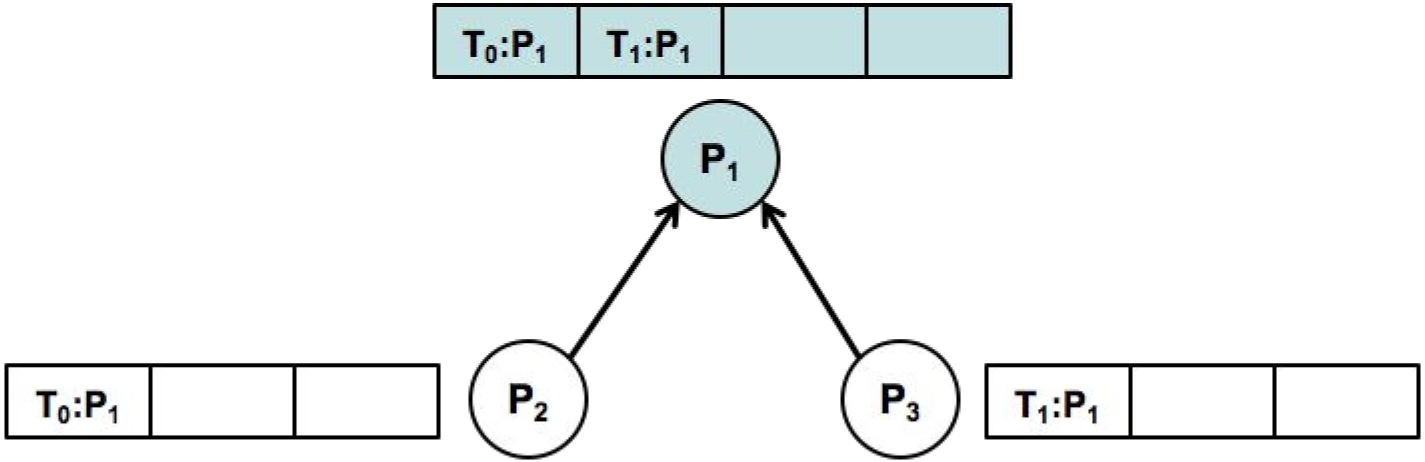


Total Ordering of Events

Step 2: P_j adds message

P_j puts **request T_m:P_i** on its request queue

P_j sends **acknowledgement T_m:P_j** to **P_i**



Total Ordering of Events

Step 2: P_j adds message

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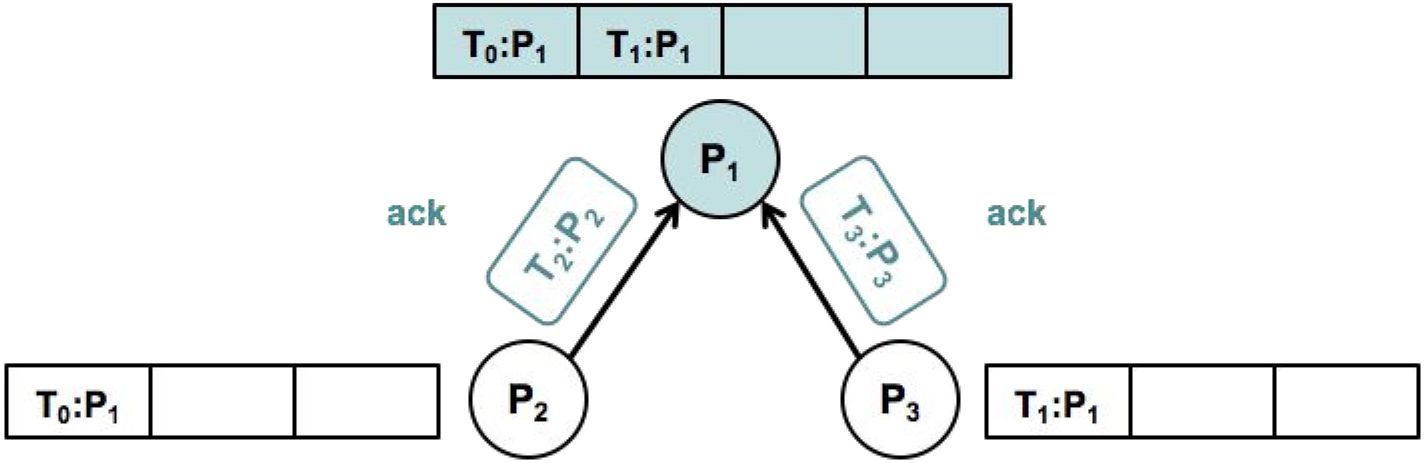
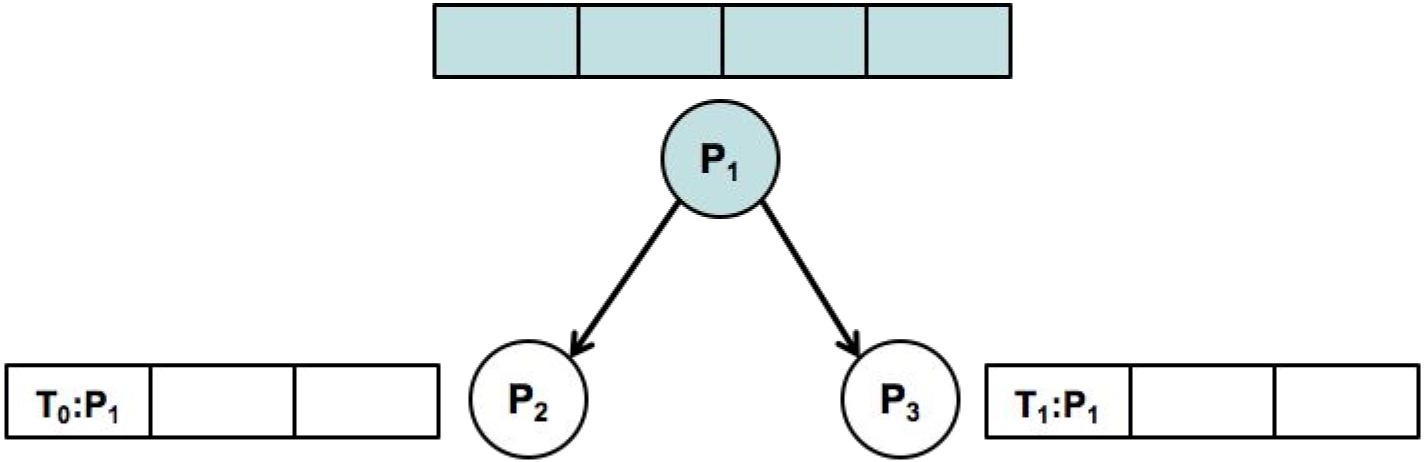


Total Ordering of Events

Step 3: P_i sends release resource

- **P_i** removes **request T_m:P_i** from request queue
- **P_i** sends **release T_m:P_i** to each **P_j**



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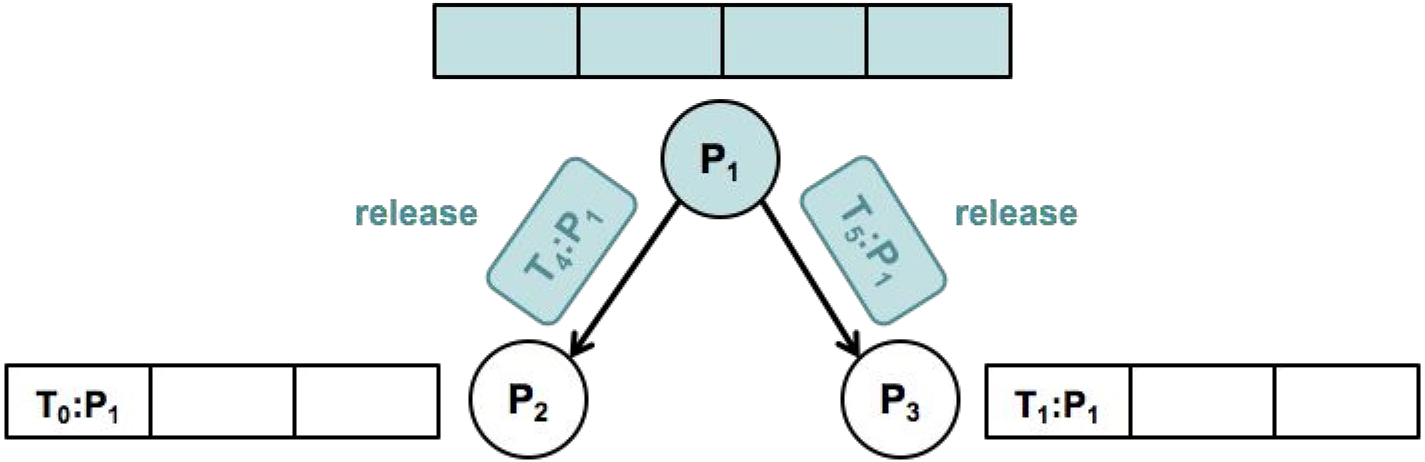
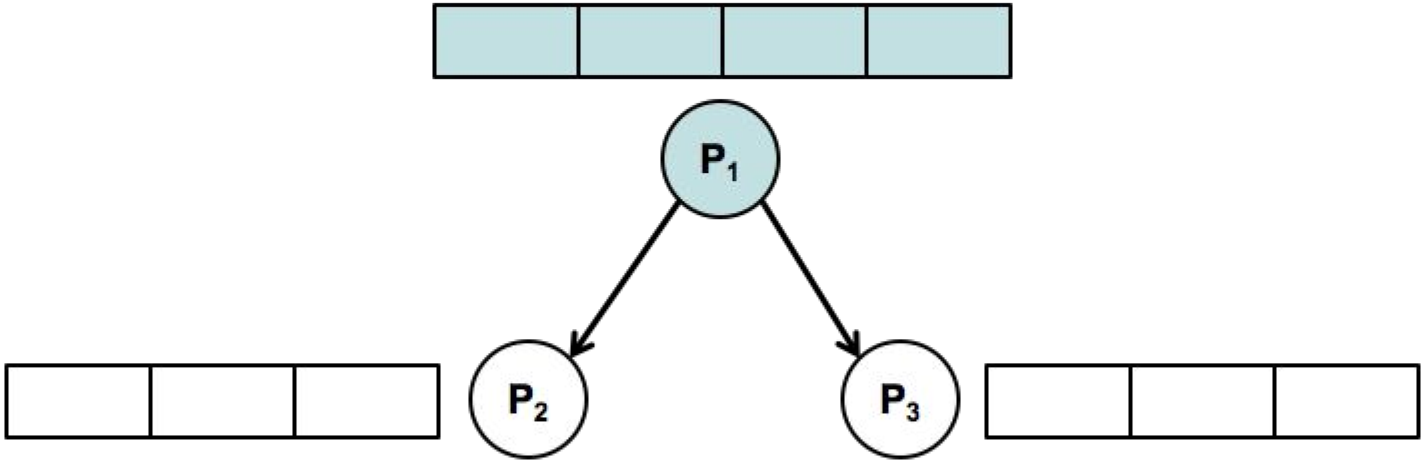


Total Ordering of Events

Step 4: P_j removes message

P_j receives **release T_m:P_i** from **P_i**

P_j removes **request T_m:P_i** from request queue



Message Complexity?

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- **3(n – 1)** messages per critical section invocation
- Requests are granted in the increasing order of timestamps

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Ricart Agarwala – 2(n -1) , also doesn’t require FIFO assumption

Roucairol – Carvalho - (0 , 2(n – 1)] based on request pattern

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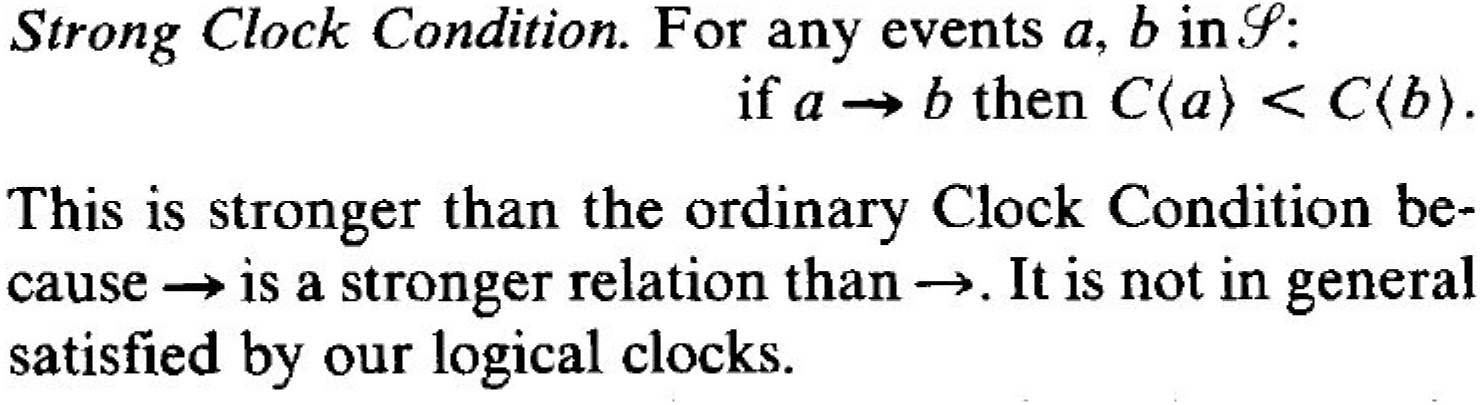
Anomalous Behavior

Strong Clock Condition



Strong Clock Condition. For any events a, b in $\mathcal{S}$:

if $a \boldsymbol{\rightarrow} b$ then $C\langle a \rangle < C\langle b \rangle$.

This is stronger than the ordinary Clock Condition because $\boldsymbol{\rightarrow}$ is a stronger relation than $\rightarrow$. It is not in general satisfied by our logical clocks.

Now what?

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Physical Clocks

“One of the mysteries of the universe is that it is possible to construct a system of physical clocks which, running quite independently of one another, will satisfy the Strong Clock Condition” (Lamport 562)

Physical Clocks

- $C_i(t)$ denote reading of clock C_i at physical time t
- **Assumptions:-**

  $C_i(t)$ is a continuous, differentiable function of t except for isolated jump discontinuities where clock is reset

Physical Clocks

- For clock C_i to be a true physical clock it must run at approximately the correct rate. That is we must have $\frac{dC_i}{dt} \approx 1$

- So, we assume the following conditions are satisfied

  1)$\exists\ k\ such\ that\ \forall i$: $\left|\frac{dC_i}{dt} - 1\right| < k$

  2) $\forall i,j$: $\left|C_i(t)\ - C_j(t)\right|\ <\ \epsilon$

Physical Clocks

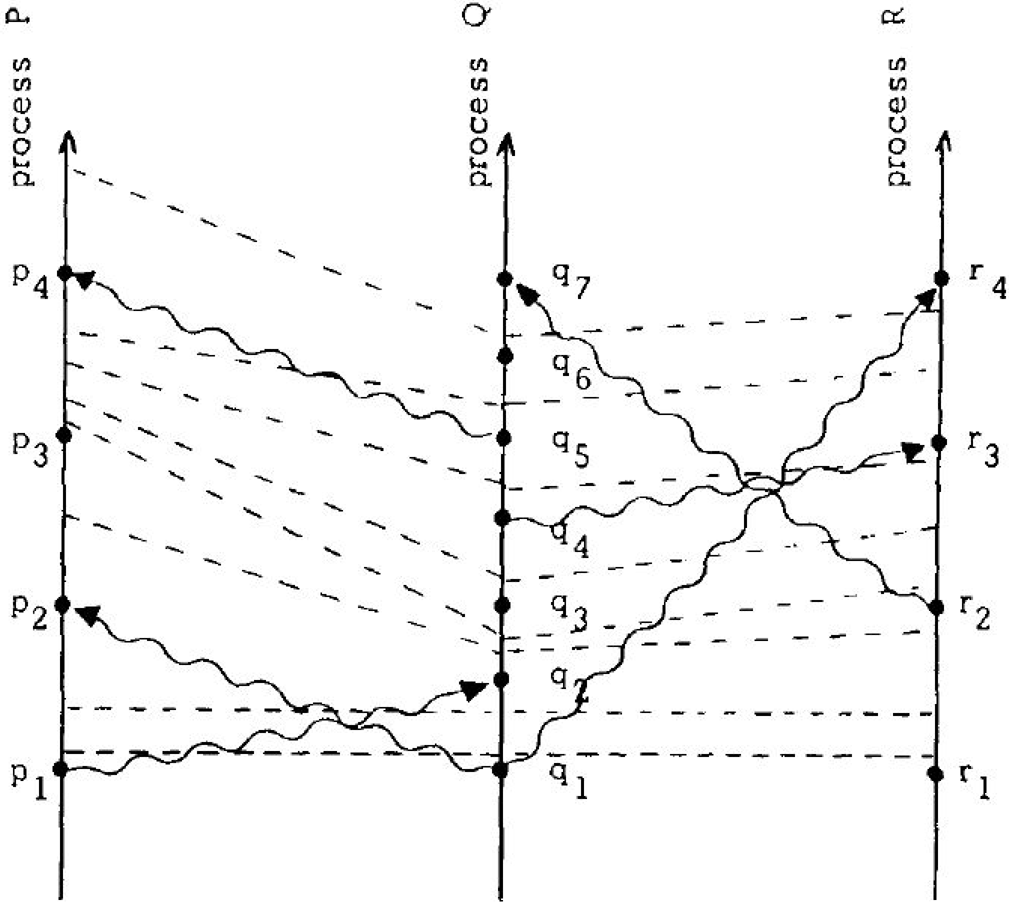
- For preventing anomalous behavior ($\mu <$ Shortest transmission time)

  3) $\forall i,j,t$: $C_i(t + \mu) - C_j(t) > 0$

Combining 3) with 1) and 2) we get

$$\frac{\epsilon}{1 - k} \leq \mu$$

Fig. 2.



process P
process Q
process R
p_4
p_3
p_2
p_1
q_7
q_6
q_5
q_4
q_3
q_2
q_1
r_4
r_3
r_2
r_1

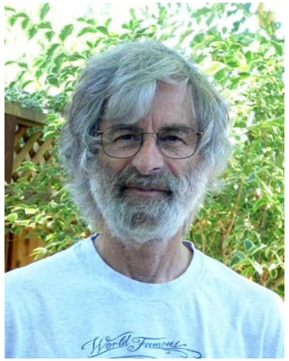
Summary

- Partial Ordering of Events
- Logical Clocks
- Total Ordering of Events
- Anomalous Behaviour
- Physical Clocks

Distributed Snapshots: Determining Global States of Distributed Systems

K. Mani Chandy

- Ph.D from MIT in Electrical Engineering
- Was in University of Texas at Austin, CS Department from 1970 – 89
- Simon Ramo Professor at CalTech
- Member of National Academy of Engineering
- IEEE Koji Kobayashi Award(1987)
- A.A. Michelson Award(1985)



Leslie Lamport

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- *2013 Turing Award Winner and initial developer of LaTeX*

What is a Snapshot?

- Just a collection of local states of processes and channels!

Why do we need Snapshots?

Why do we need Snapshots?

- Garbage collection :- Removing objects that do not have any references
- Deadlocks:- Detecting deadlocks in distributed system
- Checkpointing:- Helps in rolling back in case of failure

Challenges in recording Global State

- Processes do not share clocks or memory (or) there is no universal clock.
- So, no way to ensure that all nodes record state at exactly the same time…

Challenges in recording Global State

- Processes do not share clocks or memory (or) there is no universal clock.
- So, no way to ensure that all nodes record state at exactly the same time.

- Global snapshot is all about finding a **consistent cut**!
    - so what is a consistent cut?

Consistent Cut

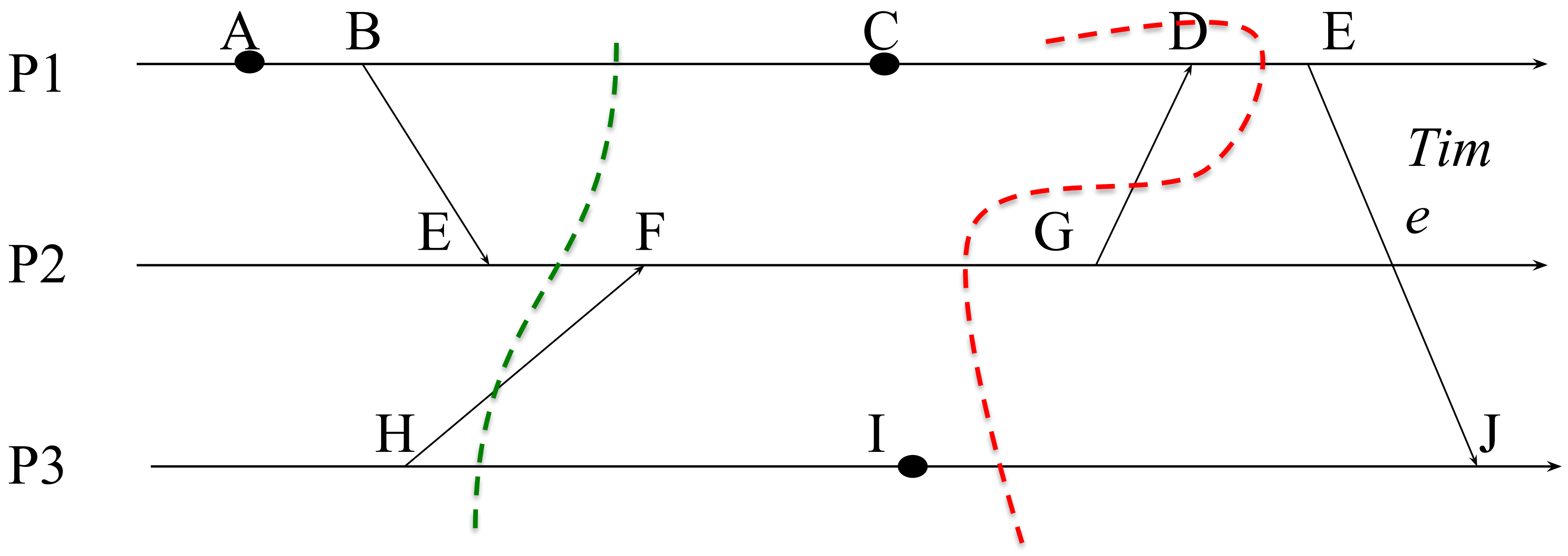
Consistent Cut: a cut that obeys causality

- 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 of (In)Consistent Cut



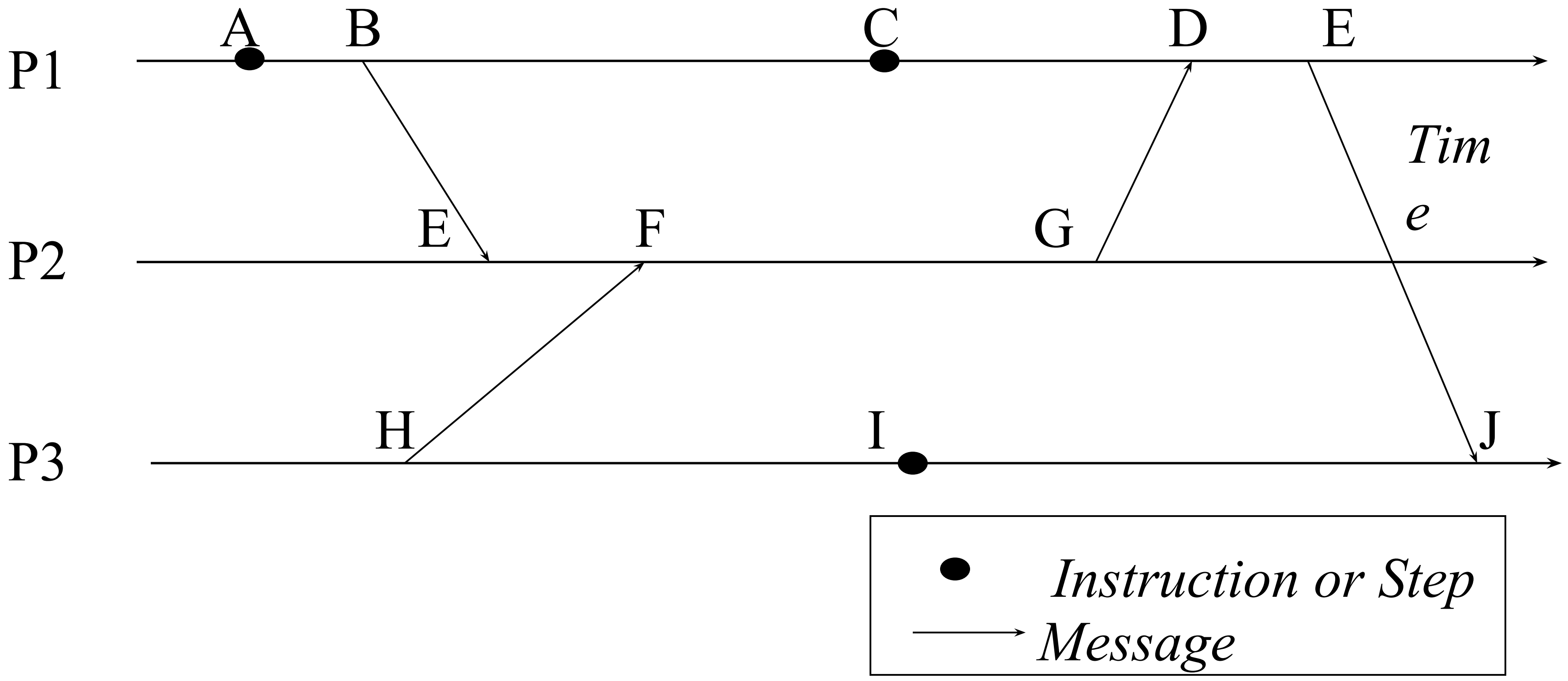
Consistent Cut

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

Solution: Chandy-Lamport’s Algorithm

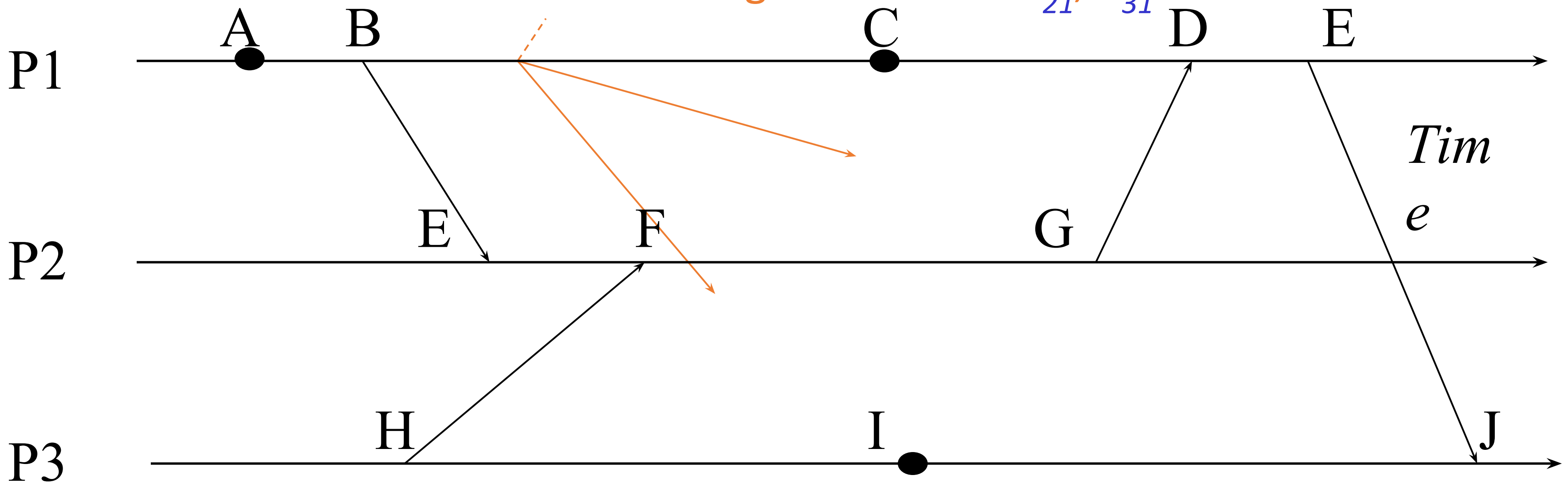
- Send a *marker* along all channels immediately after recording state
- Upon receipt of a marker along channel *c*:
    - Record process state if not already recorded
    - Record state of *c* as all messages received between recording process state and receiving marker
- Eventually markers will reach all processes, so all state will be recorded

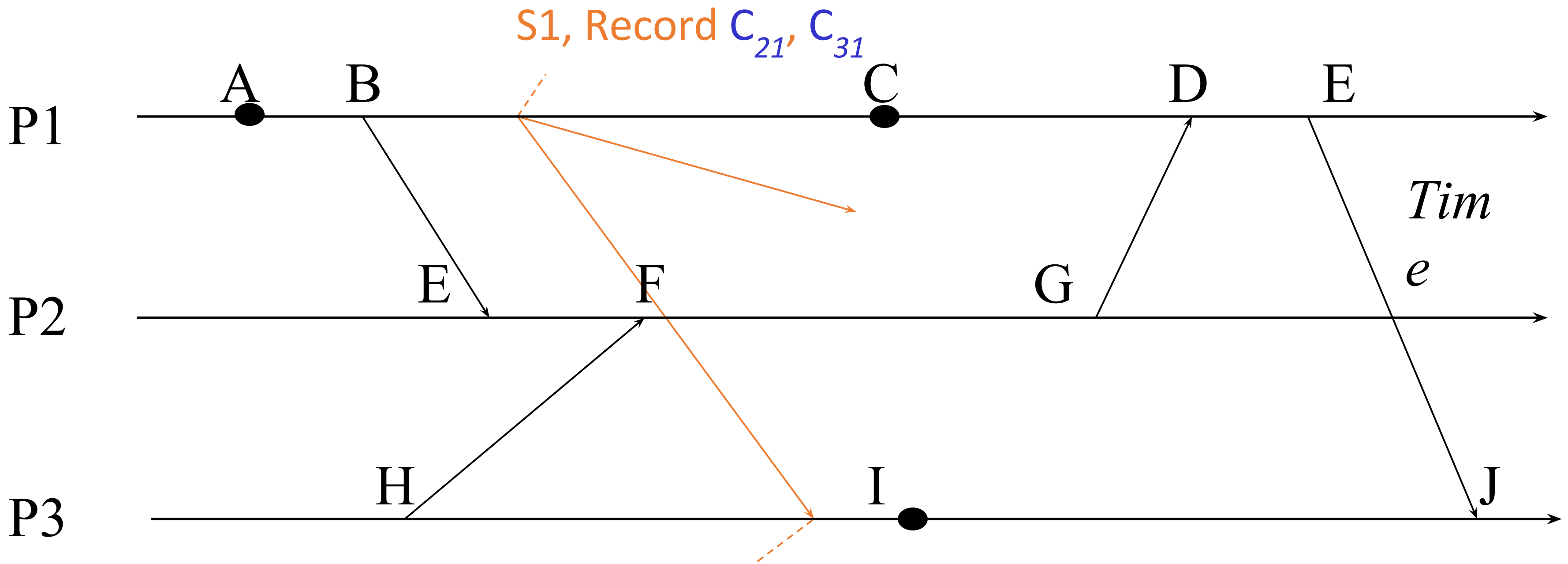
Example



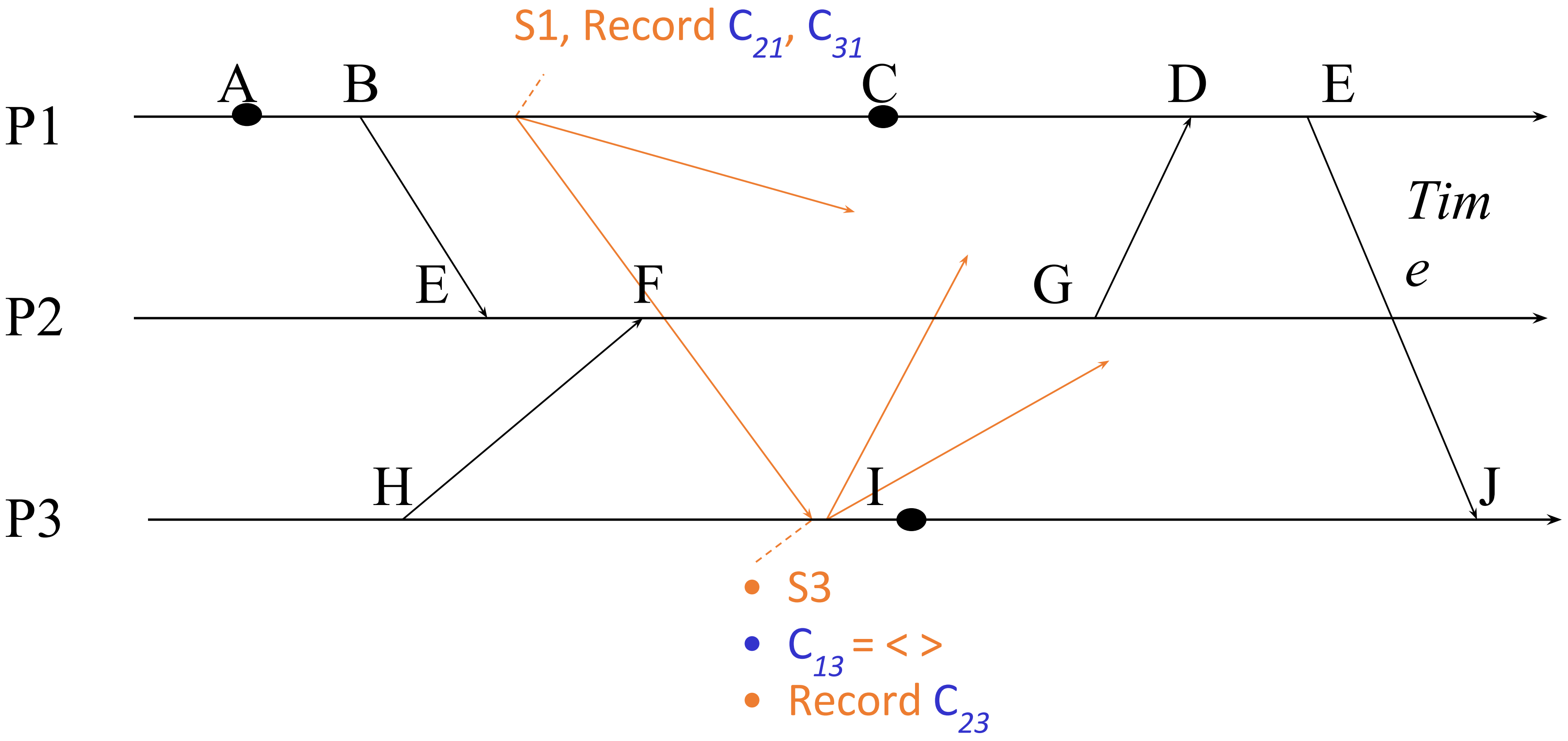
P1 is Initiator:

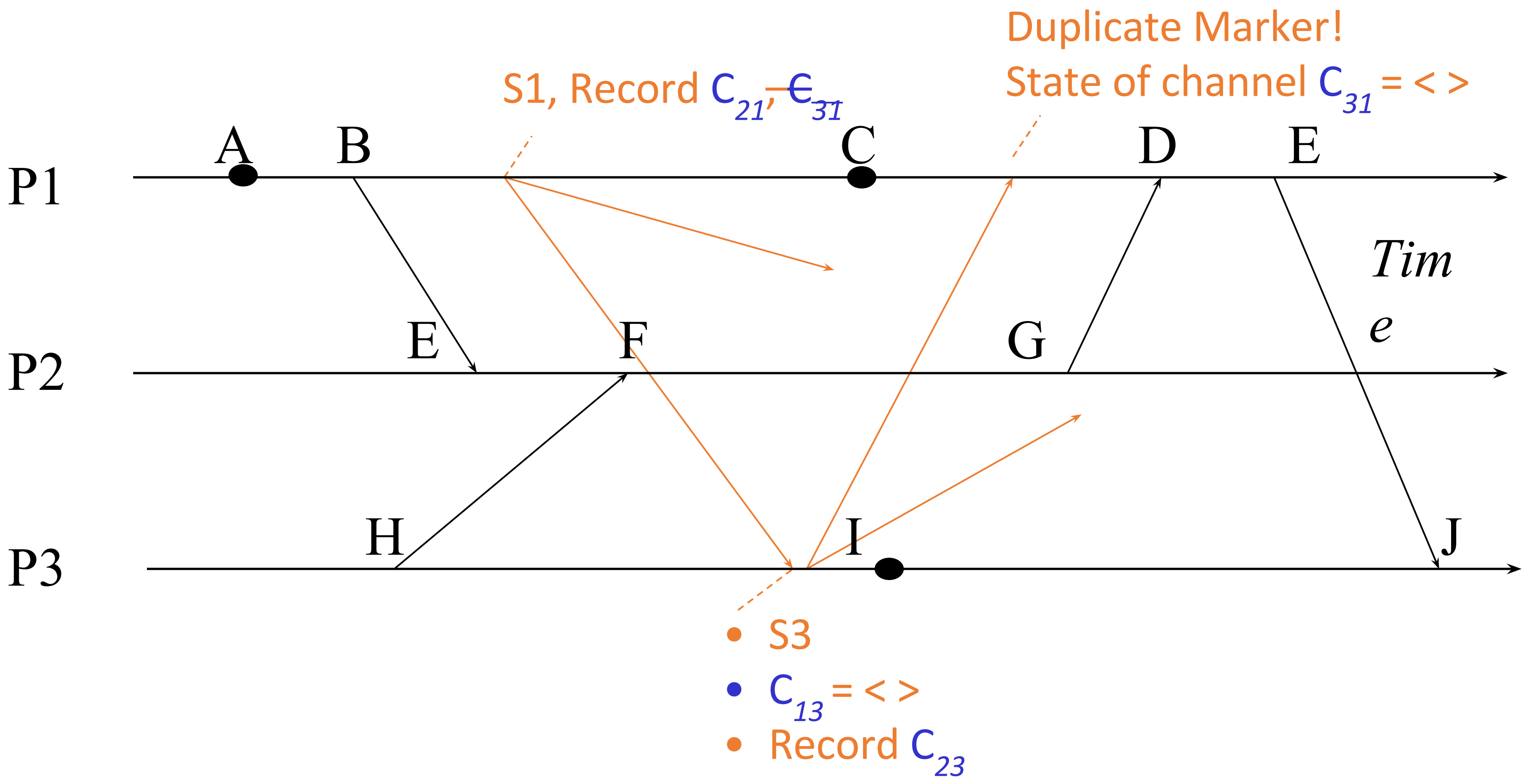
- Record local state S1,
- Send out markers
- Turn on recording on channels C_{21}, C_{31}

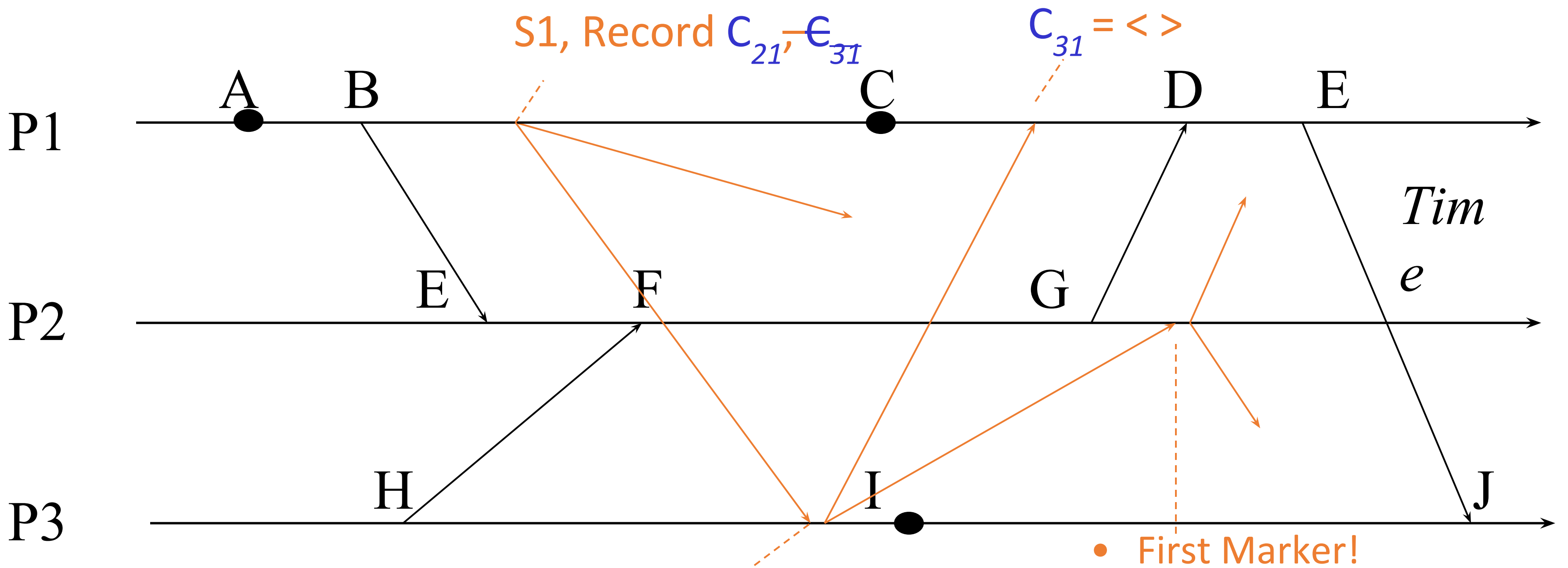




- First Marker!
- Record own state as S3
- Mark C_{13} state as empty
- Turn on recording on other incoming C_{23}
- Send out Markers

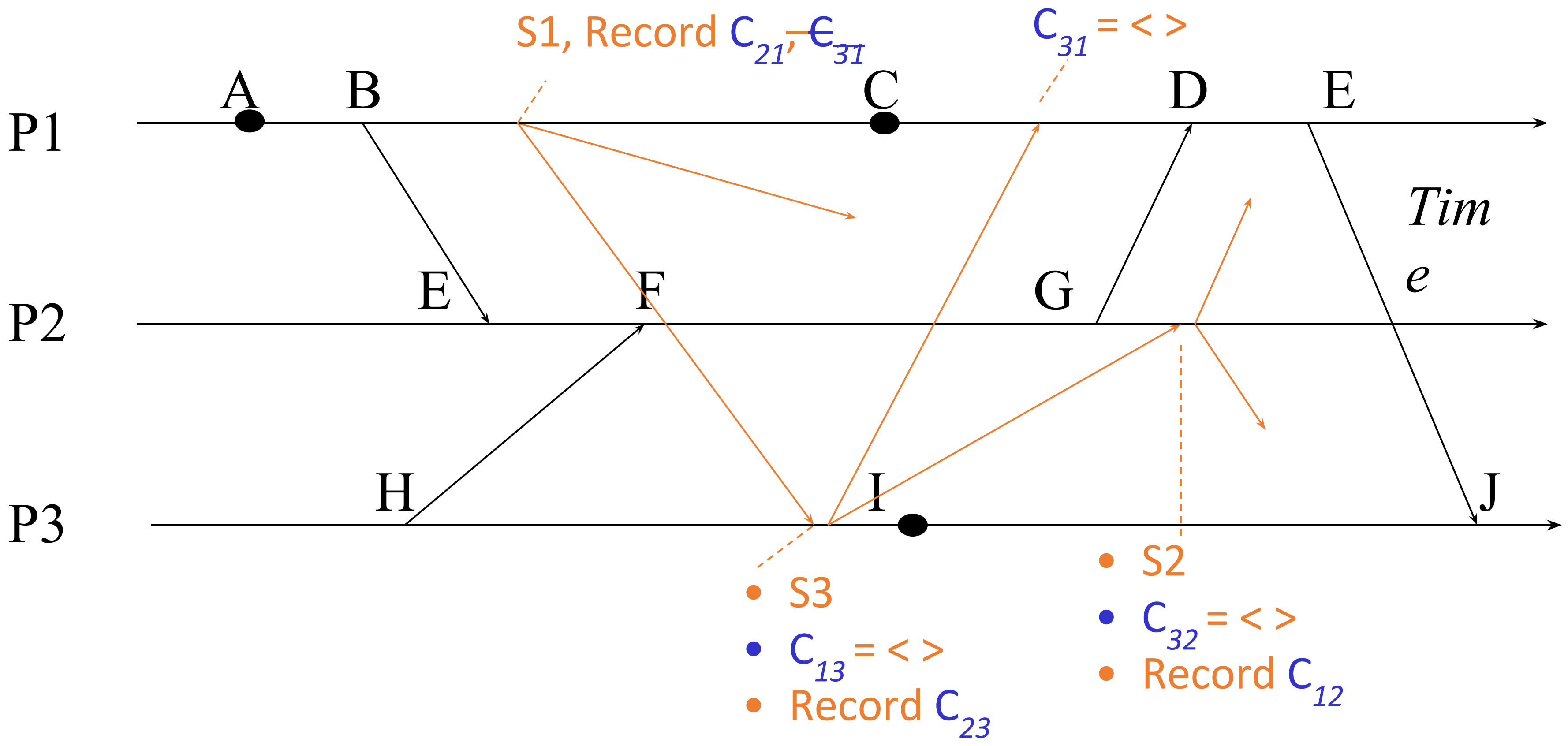

S1, Record C_{21}, C_{31}
A
B
C
D
E
P1
Time
E
F
G
P2
H
I
J
P3
S3
C_{13} = < >
Record C_{23}

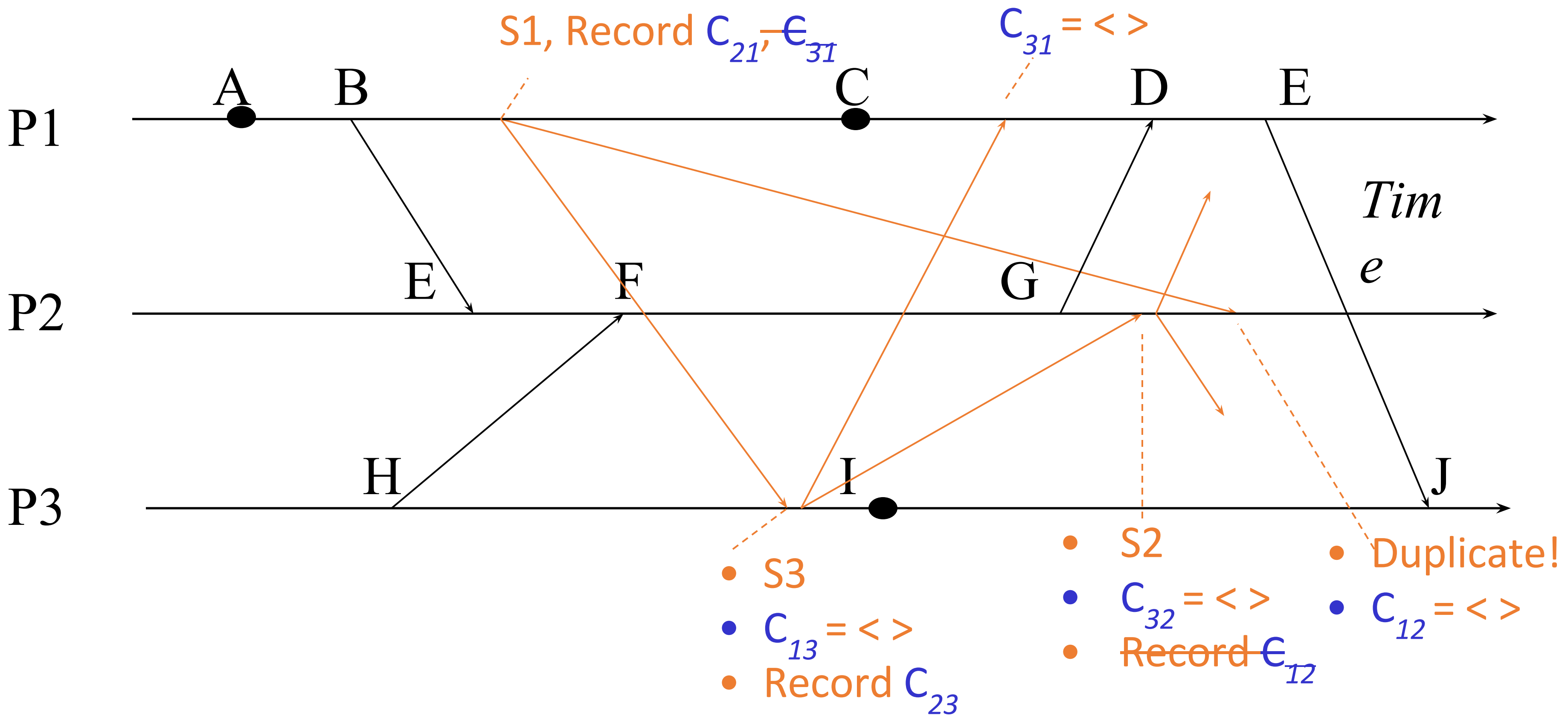

Duplicate Marker!
State of channel C_{31} = < >
S1, Record C_{21}, ~~C_{31}~~
A
B
C
D
E
P1
P2
E
F
G
Tim
e
P3
H
I
J
S3
C_{13} = < >
Record C_{23}

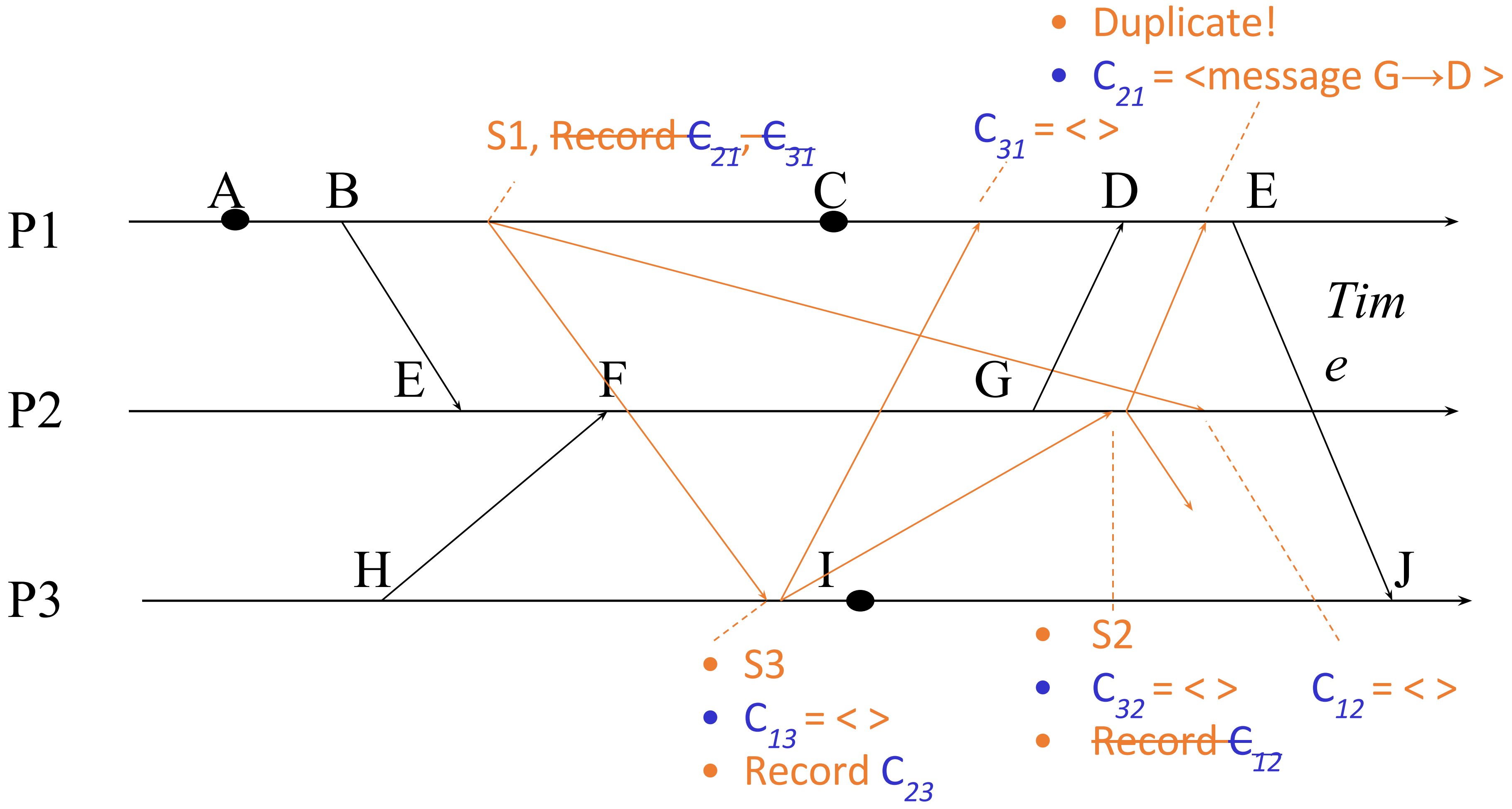


- S3
- C_{13} = < >
- Record C_{23}

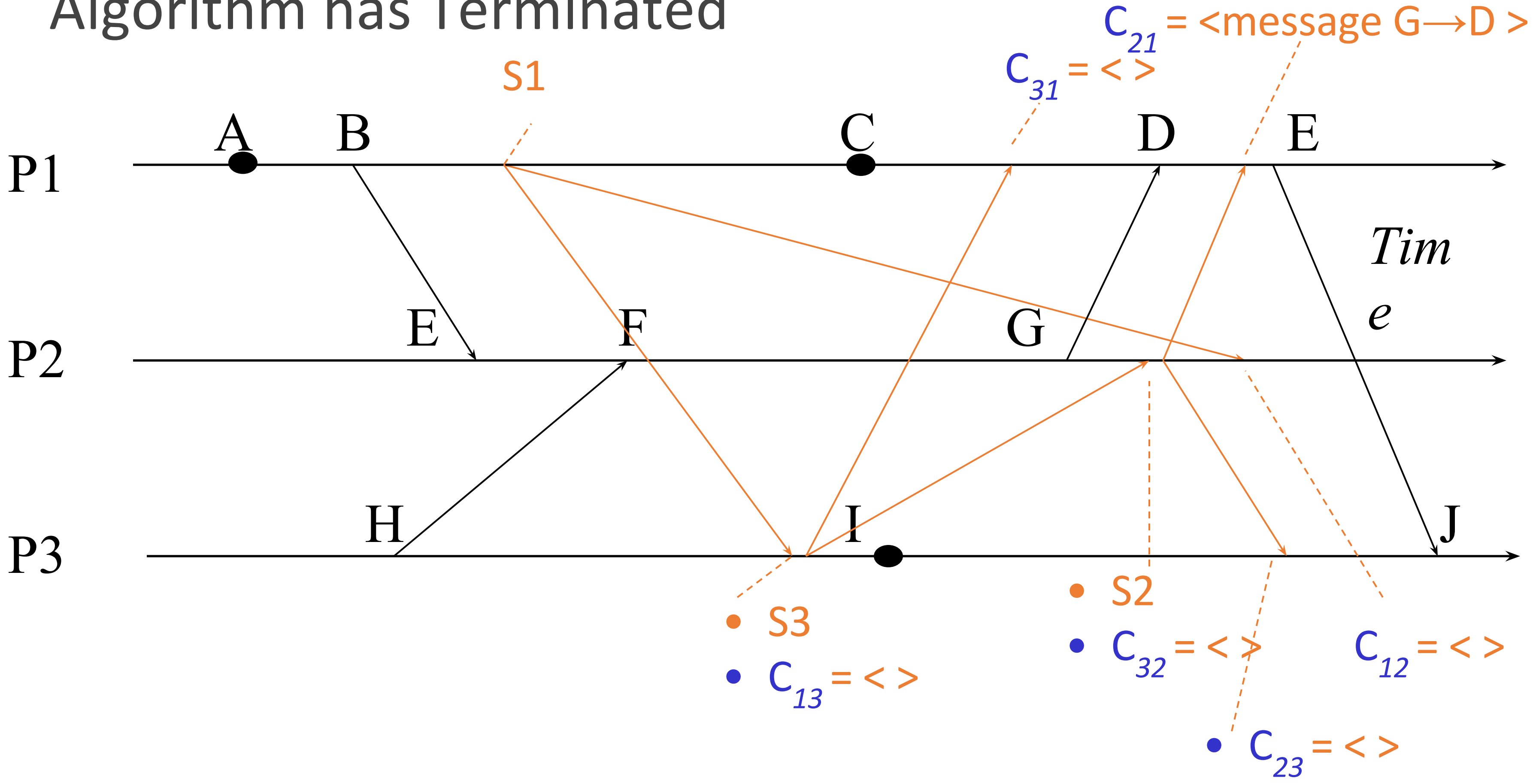
- First Marker!
- Record own state as S2
- Mark C_{32} state as empty
- Turn on recording on C_{12}
- Send out Markers

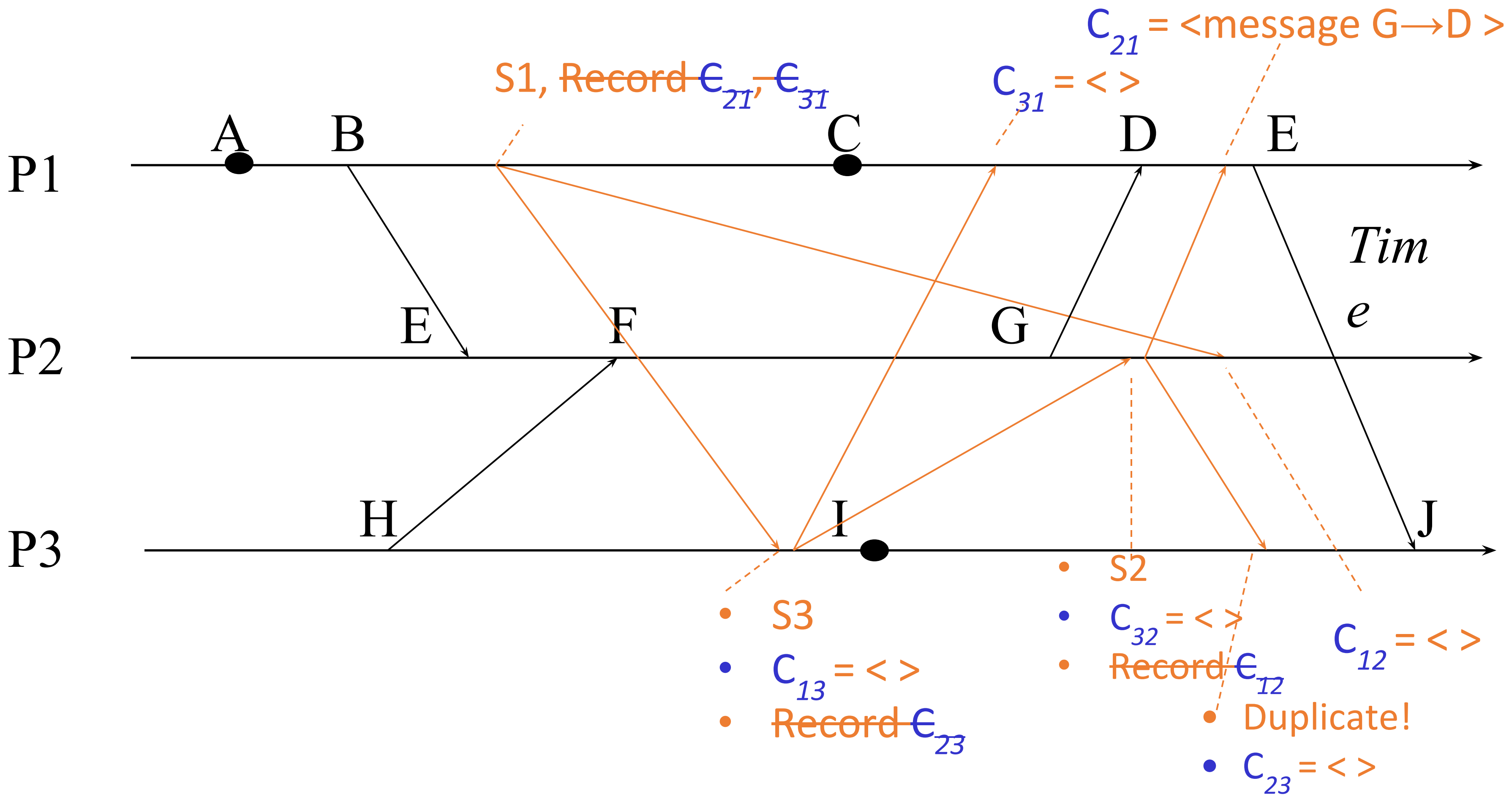

S1, Record C_{21}, ~~C_{31}~~
C_{31} = < >
A
B
C
D
E
P1
E
F
G
P2
Time
H
I
J
P3
S3
C_{13} = < >
Record C_{23}
S2
C_{32} = < >
Record C_{12}


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

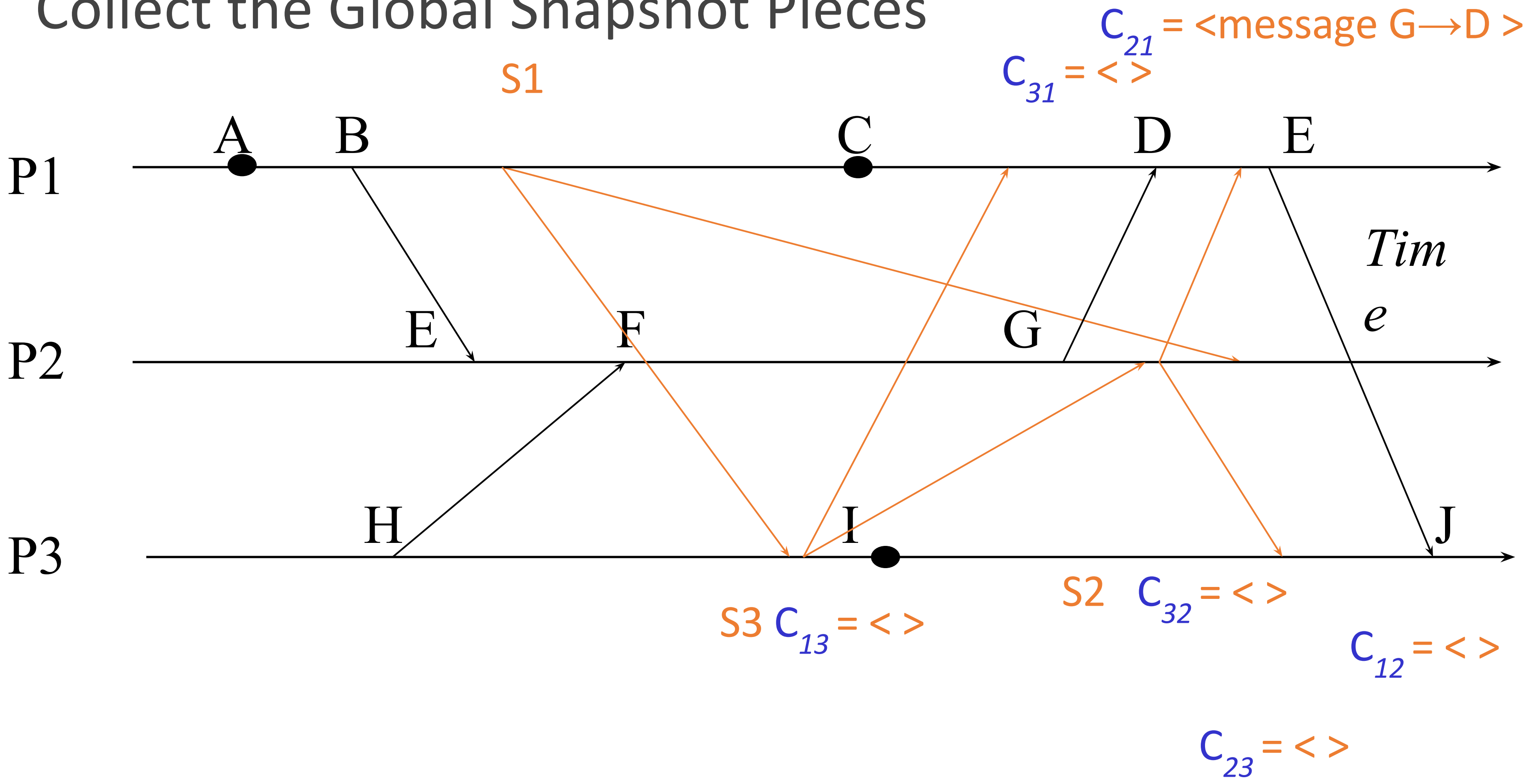
Algorithm has Terminated



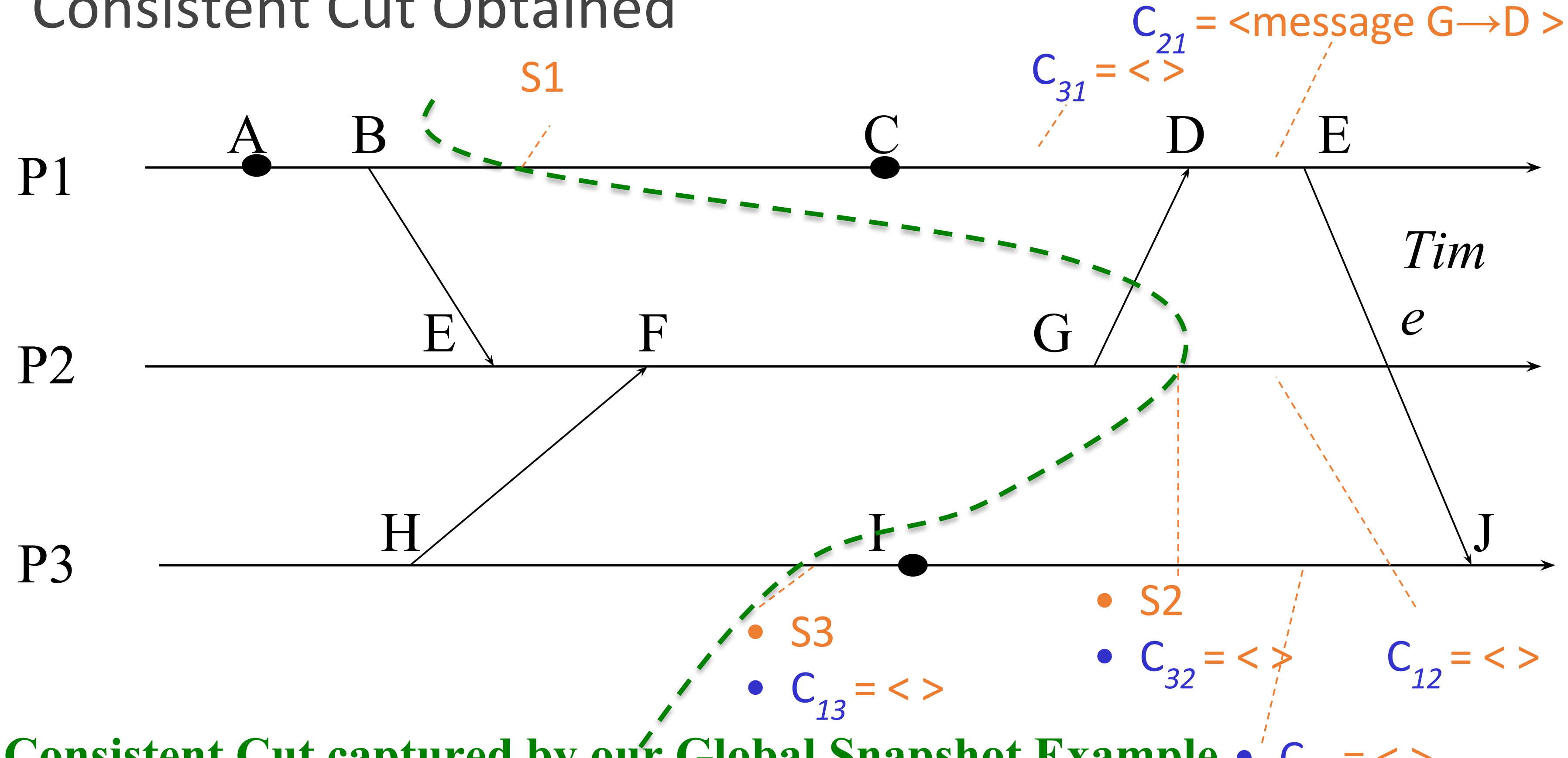


C_{21} = <message G⟶D >
S1, ~~Record C_{21}, C_{31}~~
C_{31} = < >
P1
A
B
C
D
E
P2
E
F
G
Tim
e
P3
H
I
J
• S3
• C_{13} = < >
• ~~Record C_{23}~~
• S2
• C_{32} = < >
• ~~Record C_{12}~~
C_{12} = < >
• Duplicate!
• C_{23} = < >

Collect the Global Snapshot Pieces



Consistent Cut Obtained



Consistent Cut captured by our Global Snapshot Example

Summary

- Global Snapshot definition
- Uses of collecting a Global Snapshot
- Consistent Cuts
- Chandy-Lamport’s Algorithm

Parting Thoughts & Questions: Ours

- What does Lamport bring from the first paper into the second?
- Why might we want to cover these papers *before* MapReduce?
- What assumptions have been made?
  - FIFO - “The assumption that all messages sent from process Pi to Pj are received in the same order as they are sent is also too strong.”

Parting Thoughts & Questions: Yours

- “The idea is very novel in the time when it published as distributed systems were not so much relevant in those days.”
  - “I want to highlight [the first paper’s] elegance. We often take for granted that computing problems didn't come logically into the minds of our predecessors.”
- “The paper also didn’t consider the scenario of process and message delivery failure.”
  - “unreasonable assumptions about reliability, such as nodes cannot fail and messages cannot be dropped and must have predictable delay.”
- “The ideas presented were quite complex...This paper presented the formalisms needed quite well and established a clear language.”
- “The biggest weakness of this paper is that the system cannot inherently capture non-computational events such as phone calls, and also that there's no sense of the physical feasibility of this synchronization approach. How does propogation delay affect the synchronization scheme? How fault-tolerant is the system?”

Parting Thoughts & Questions: Yours, Cont’d

- “The strong point of this paper is a novel algorithm to guarantee synchronization of distributed system that does not rely on a central authority to perform the synchronization. A total ordering of events can be obtained even when only a partial ordering is available from the space-time diagram. However, in order to achieve this result, all processes must be aware of every other processes messages, which assume that all processes are not anomalous. This is an assumption that can be easily violated by a rogue process. The next logical step for this work is to be resilient to rogue processes which could be purposefully providing incorrect timestamps, or even collaborate to fool the synchronization algorithm.”

A Nice Review to Consider Together :)

“Lamport's paper on Time, Clocks and Ordering in a distributed system does an excellent job of defining a problem in distributed systems and proposing several solutions along with their requirements and drawbacks. It also omits a number of details for the sake of brevity and readability; it is outside of my expertise to be able to identify if any/all of these details are essential to his argument. For example, he omits details on ensuring eventual message delivery and message delivery order. Obviously TCP can be used to ensure order between any two processes, but it's not clear to me what algorithm Lamport would use do ensure eventual delivery; is it simply timeout based along with a known assumption of max delivery time? I assume it is since he says elsewhere that failures and fault-tolerance are not considered in this paper; but since he omits this small detail it's hard for me to know for sure. This is a minor point to pick as most of the paper is very clear, especially thanks to his decision to omit agonizingly small details. However, there are a few places where he introduces details for reasons that are unclear to me; he mentions 'unpredictable message delay', denotes a symbol for it and then never mentions it again. It seems like a waste and a bit confusing since it gave me the feeling that that measurement was meaningful and necessary for some part of the proof, even though it was not. Overall, the paper's structure is clear, addresses practical issues in distributed systems with a very practical theoretical approach (e.g. considering the fidelity of modern clocks in his error calculations) and is not overly burdened with complex proofs (but does provide them where necessary as footnotes and in the appendix.)

N.B. I don't have anywhere near the experience reading theoretical papers, so it's very likely that I'm missing some critical angles of assessment and/or giving him some free passes (e.g. I don't expect much more than a motivating example on how one might actually build or use a system that a theoretical paper describes)”

Further Reading Suggested by Prof. Alvisi

Dijkstra’s Take on Chandy-Lamport:

https://www.cs.utexas.edu/users/EWD/transcriptions/EWD08xx/EWD864.html

Acknowledgements

- *Time, Clocks, and the Ordering of Events in a Distributed System*, Leslie Lamport, Communications of ACM,Volume 27 Issue 7, July 1978.
- *Distributed Snapshots: Determining Global States of Distributed Systems*, K.Mani Chandy, Leslie Lamport. ACM Transactions on Computer Systems (TOCS), Volume 3 Issue 1, Feb. 1985.
- Previous years' slides
- CS4410 Lecture Slides
- Professor Hakim Weatherspoon and Professor Lorenzo Alvisi for presentation advice

THANK YOU