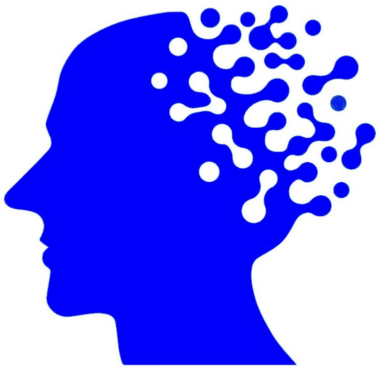
Spring 2023



Distributed Computing
- Causal Ordering

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> Distributed Computing?

- ➤ How will you design a Distributed Algorithm?

- ➤ Learn to Solve using Distributed Algorithms

Overview

> About this Lecture

What do we learn today?

- This covers a model of distributed computations that every algorithm designer needs to know

  - **Causal Ordering in Distributed Systems**
  - **Total Ordering**

  - **CO related concepts in of distributed executions**

Let us explore these topics → → →

Today's Focus

Recap: Distributed Systems

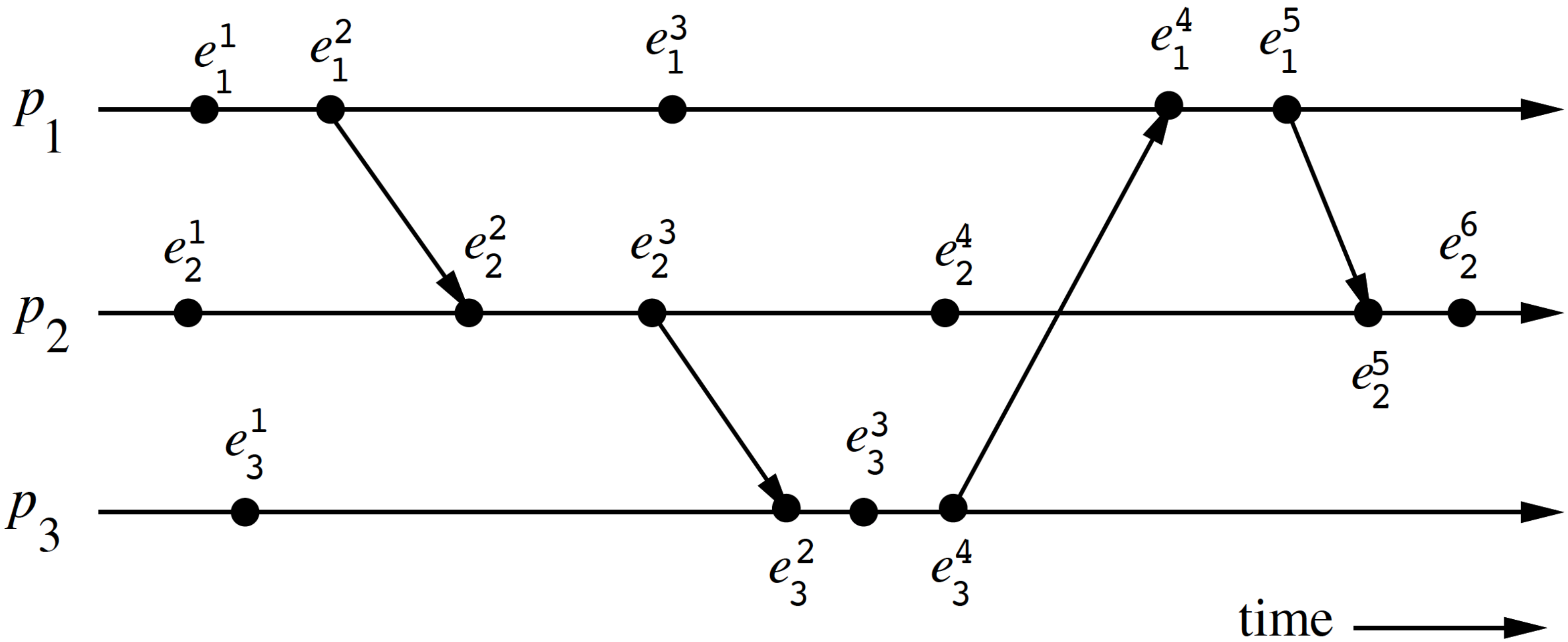
A Distributed System:

- A collection of independent systems that appears to its users as a single coherent system
- A system in which hardware and software components of networked computers communicate and coordinate their activity only by passing messages
- A computing platform built with many computers that:
  - Operate concurrently
  - Are physically distributed (have their own failure modes)
  - Are linked by a network
  - Have independent clocks

Recap: Characteristics

- Concurrent execution of processes:
  - Non-determinism, Race Conditions, Synchronization, Deadlocks, and so on
- No global clock
  - Coordination is done by message exchange
  - No Single Global notion of the correct time
- No global state
  - No Process has a knowledge of the current global state of the system
- Units may fail independently
  - Network Faults may isolate computers that are still running
  - System Failures may not be immediately known

A State-Time diagram – An Example



- **For Process p_1:**
  - Second event is a message send event
  - First and Third events are internal events
  - Fourth event is a message receive event

What did you learn so far?

Recap

- Goals / Challenges with Distributed Systems
- Message Passing systems
  - Basic Primitive operations
  - 3 types of EVENTs: Internal, send and receive
  - States of a process and Channel
- Distributed Sorting
  - Odd – Even Transposition Sort
  - Sasaki's (n-1) rounds algorithms
  - Did you try (n-2) rounds algorithm for distributed sorting on line network?
  - Implementing Discrete Events Simulation

Causal Ordering

A Model of Distributed Computations

Focused Topics:

- ➔ Causal Precedence Relation
- ➔ Models of Communication Networks
- ➔ Causal Ordering
- ➔ Global State and Local States
- ➔ Cuts of a Distibuted System
  - ➔ PAST and FUTURE events

A Model of Distributed Executions

- The execution of a process consists of a sequential execution of its actions.
- The actions are atomic and modeled as three types of events: internal events, message send events, and message receive events
- Let e_i^x denote the x^{th} event at process p_i .
- For a message m, let send(m) and receive(m) denote send and receive events, respectively.
- The occurrence of events changes the states of respective processes and channels.
- Internal event → changes state of the process
- Send and Receive events change the state of the process that sends / receives the message & the state of the channel on which the message is sent / received respectively

Distributed Executions (contd)

- The events at a process are linearly ordered by their order of occurrence.
- The execution of process p_i produces a sequence of events $e_i^1, e_i^2, \ldots, e_i^x, e_i^{x+1}, \ldots$ and is denoted by H_i where

$$H_i = (h_i, \rightarrow i)$$

h_i is the set of events produced by p_i and binary relation $\rightarrow i$ defines a linear order on these events

- **Linear Relation:** Mathematically, the independent variable is multiplied by the slope coefficient, added by a constant, which determines the dependent variable
- Relation $\rightarrow i$ expresses causal dependencies among the events of p_i

A Model of Distributed Executions (contd.)

- The send and the receive events signify the flow of information between processes and establish causal dependency from the sender process to the receiver process
- Define a relation $\rightarrow_{msg}$ that captures the causal dependency due to message exchanges as follows:

  For every message m that is exchanged between two processes, we have

$$send(m) \rightarrow_{msg} receive(m)$$

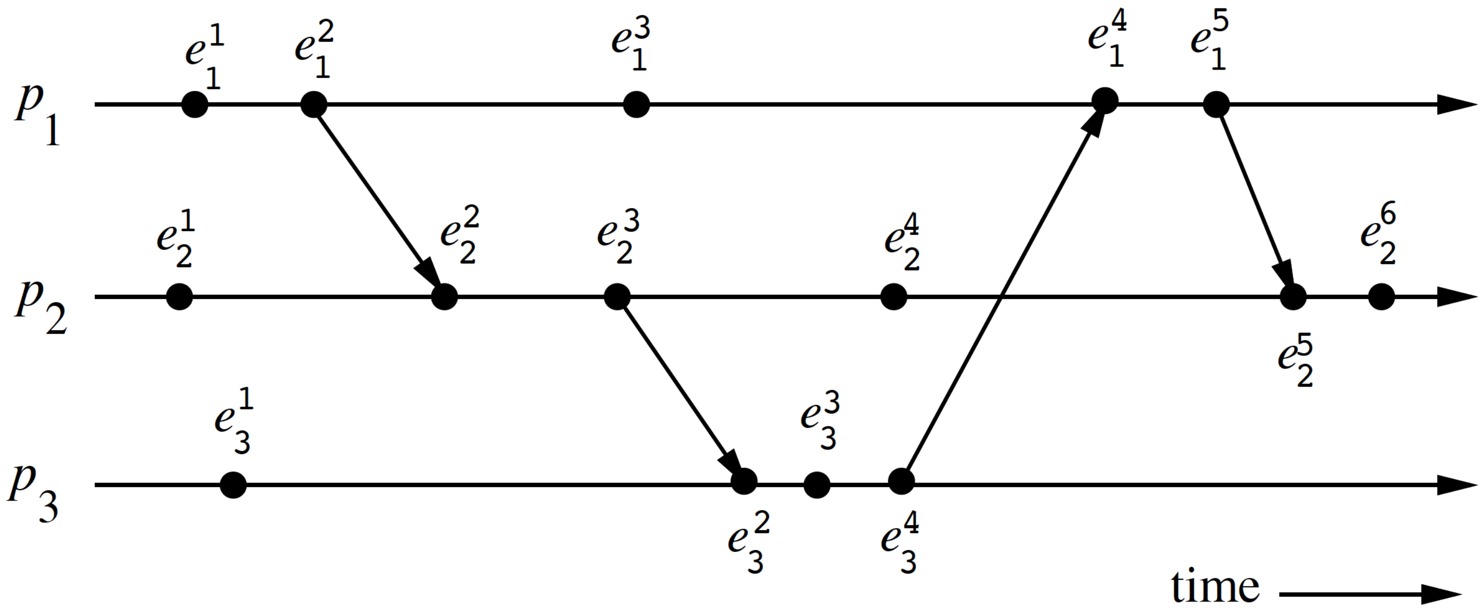
- Relation $\rightarrow_{msg}$ defines causal dependencies between the pairs of corresponding send and receive events

A State-Time diagram

- The evolution of a distributed execution is depicted by a space-time diagram
- A horizontal line represents the progress of a specific process
- A dot indicates an event
- A slant arrow indicates a message transfer

- Since an event execution is atomic (indivisible and instantaneous), it is justified to denote it as a dot on a process line

A State-Time diagram – An Example



➔ **For Process p_1:**

Second event is a message send event

First and Third events are internal events

Fourth event is a message receive event

Partial Order / Total Ordering

A relation $\leq$ is a total order on a set S (" $\leq$ totally orders S") if the following properties hold:

1. Reflexivity: $a \leq a$ for all a in S

2. Antisymmetry: $a \leq b$ and $b \leq a$ implies $a = b$

3. Transitivity: $a \leq b$ and $b \leq c$ implies $a \leq c$

4. Comparability (trichotomy law):
   For any a, b in S, either $a \leq b$ or $b \leq a$.

First 3 properties → the axioms of a partial order
Addition of trichotomy law defines a total order $H=(H, \rightarrow)$

Causal Precedence Relation

- The execution of a distributed app. results in a set of distributed events
- Let $H = \cup_i h_i$ denote the set of events executed in a distributed computation.
- Define a binary relation $\rightarrow$ on the set H that expresses causal dependencies between events in the distributed execution.

$$\forall e_i^x,\ \forall e_j^y \in H,\quad e_i^x \ \rightarrow\ e_j^y \quad \Leftrightarrow \quad \begin{cases} e_i^x \rightarrow_i e_j^y \quad i.e., (i = j) \wedge (x < y) \\ or \\ e_i^x \rightarrow_{msg} e_j^y \\ or \\ \exists e_k^z \in H : e_i^x \rightarrow e_k^z \ \wedge \ e_k^z \rightarrow e_j^y \end{cases}$$

- The causal precedence relation induces an irreflexive partial order on the events of a distributed computation that is *denoted* as $H = (H, \rightarrow)$

Causal Precedence Relation (contd)

- The relation $\rightarrow$ is as defined by Lamport
  "happens before"

An event e_1 happens before the event e_2 and denoted by $e_1 \rightarrow e_2$ if the following holds true:

- e_1 occurs before e_2 on the same process OR
- e_1 is the send message and e_2 is the corresponding receive message OR
- There exists another event e' such that e_1 happens before e' and e' happens before e_2

Causal Precedence Relation (contd)

- For any two events e_i and e_j , $e_i \not\rightarrow e_j$ denotes the fact that event e_j does not directly or transitively dependent on event e_i

  That is, event e_i does not causally affect event e_j

- In this case, event e_j is not aware of the execution of e_i or any event executed after e_i on the same process.

Note the following two rules:

- For any two events e_i and e_j

  $$e_i \not\rightarrow e_j \text{ does not imply } e_j \not\rightarrow e_i$$

- For any two events e_i and e_j

  $$e_i \rightarrow e_j \Rightarrow e_j \not\rightarrow e_i$$

Concurrent Events

- For any two events e_i and e_j:

  if $e_i \not\rightarrow e_j$ and $e_j \not\rightarrow e_i$,

  then events e_i and e_j are said to be concurrent (denoted as $e_i \,||\, e_j$)

Example:

$$e_3^3 \,||\, e_2^4 \;\; and \; e_2^4 \,||\, e_1^5 \;\; but \; e_3^3 \; not \,||\, e_1^5$$

- The relation || is not transitive;

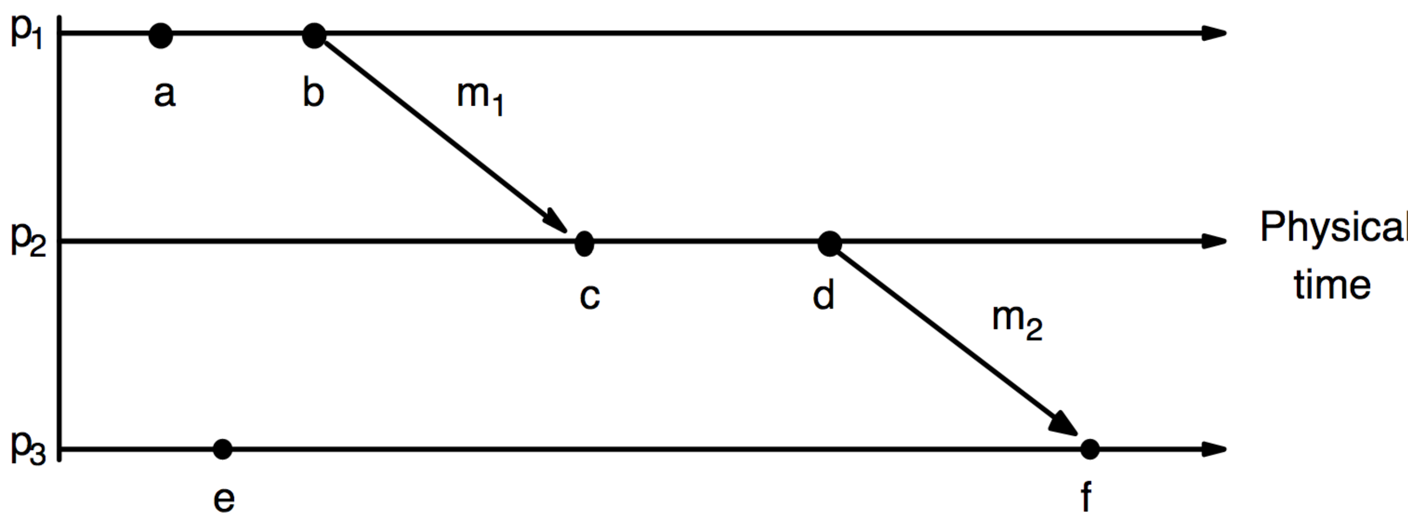
  that is,

  $$(e_i \,||\, e_j) \wedge (e_j \,||\, e_k) \; does \; not \; imply \; e_i \,||\, e_k$$

- For any two events e_i and e_j in a distributed execution,

  $$e_i \rightarrow e_j \; OR \; e_j \rightarrow e_i, \; OR \; e_i \,||\, e_j$$

Concurrency – An Example



$a \rightarrow b$ (at $p1$) $c \rightarrow d$ (at $p2$)

$b \rightarrow c$ ($m1$)

also $d \rightarrow f$ ($m2$)

Not all events are related by $\rightarrow$, e.g., a $\not\rightarrow$ e and e $\not\rightarrow$ a
they are said to be concurrent; write as $a \parallel e$

Logical vs. Physical Concurrency

- Two events are logically concurrent if and only if they do not causally affect each other.
- In physical concurrency: events occur at the same instant in physical time.
- Two+ events may be logically concurrent even though they do not occur at same instant in physical time.
- If processor speed and message delays would have been different, the execution of these events could have very well coincided in physical time.
- Whether a set of logically concurrent events coincide in the physical time or not, does not change the outcome of the computation.
- A set of logically concurrent events may not have occurred at the same instant in physical time, we can assume that these events occurred at the same instant in physical time.

Models of Communication networks

- There are several models of the service provided by communication networks:

  FIFO, Non-FIFO, and causal ordering

- In the FIFO model, each channel acts as a first-in first-out message queue and thus, message ordering is preserved by a channel.
- In the non-FIFO model, a channel acts like a set in which the sender process adds messages and the receiver process removes messages from it in a random order.

Causal Ordering

- The "causal ordering" model is based on Lamport's "happens before" relation
- A system that supports the causal ordering model satisfies the following property:

CO: For any two messages m_{ij} and m_{kj},
if $send(m_{ij}) \rightarrow send(m_{kj})$,
then $receive(m_{ij}) \rightarrow receive(m_{kj})$

- This property ensures that causally related messages destined to the same destination are delivered in an order that is consistent with their causality relation.
- Causally ordered delivery of messages implies FIFO message delivery. (Note that CO $\subset$ FIFO $\subset$ Non-FIFO.)
- Causal ordering model considerably simplifies the design of distributed algorithms because it provides a built-in synchronization.

Global State

- A collection of the local states of its components:
  - The processes and the communication channels
- The state of a process is defined by the local contents of processor registers, stacks, local memory, etc
- The state of channel depends the set of messages in transit in the channel

- An internal event changes only state of the process
- A send event changes
  - state of the process that sends the message and
  - the state of the channel on which the message is sent.
- Similarly a receive event changes
  - the state of the process that receives the message and
  - the state of the channel on which the message is received

Global State (contd)

Notations

- LS_i^x denotes the state of p_i after occurrence of event e_i^x and before the event e_i^{x+1}
- LS_i^0 denotes the initial state of process p_i
- LS_i^x is a result of the execution of all the events executed by process pi till e_i^x

- Let $send(m) \leq LS_i^x$ denote the fact:

$$\exists y, 1 \leq y \leq x \text{ s.t } e_i^y = send(m)$$

- Let $rec(m)$ $(not \leq)$ LS_i^x denote the fact:

$$\forall y, 1 \leq y \leq x \text{ s.t } e_i^y \text{ (not equal to) } rec(m)$$

Global State (contd)

- The global state of a distributed system is a collection of the local states of the processes and the channels.

A global state GS is defined as,

$$GS = \{\bigcup_i LS_i^{x_i}, \bigcup_{j,k} SC_{jk}^{y_j, z_k}\}$$

- For a global state to be meaningful, the states of all the components of the distributed system must be recorded at the same instant
- Two important situations (Impossible !!):
  - the local clocks at processes were perfectly synchronized
  - there were a global system clock that can be instantaneously read by the processes

A Consistent Global State

Basic idea:

- A state should not violate causality – an effect should not be present without its cause
- A message cannot be received if it was not sent.
- Such states are called consistent global states and are meaningful global states.
- Inconsistent global states are not meaningful in the sense that a distributed system can never be in an inconsistent state

What is a Consistent Global State?

Definition:

- A global state is a consistent global state iff

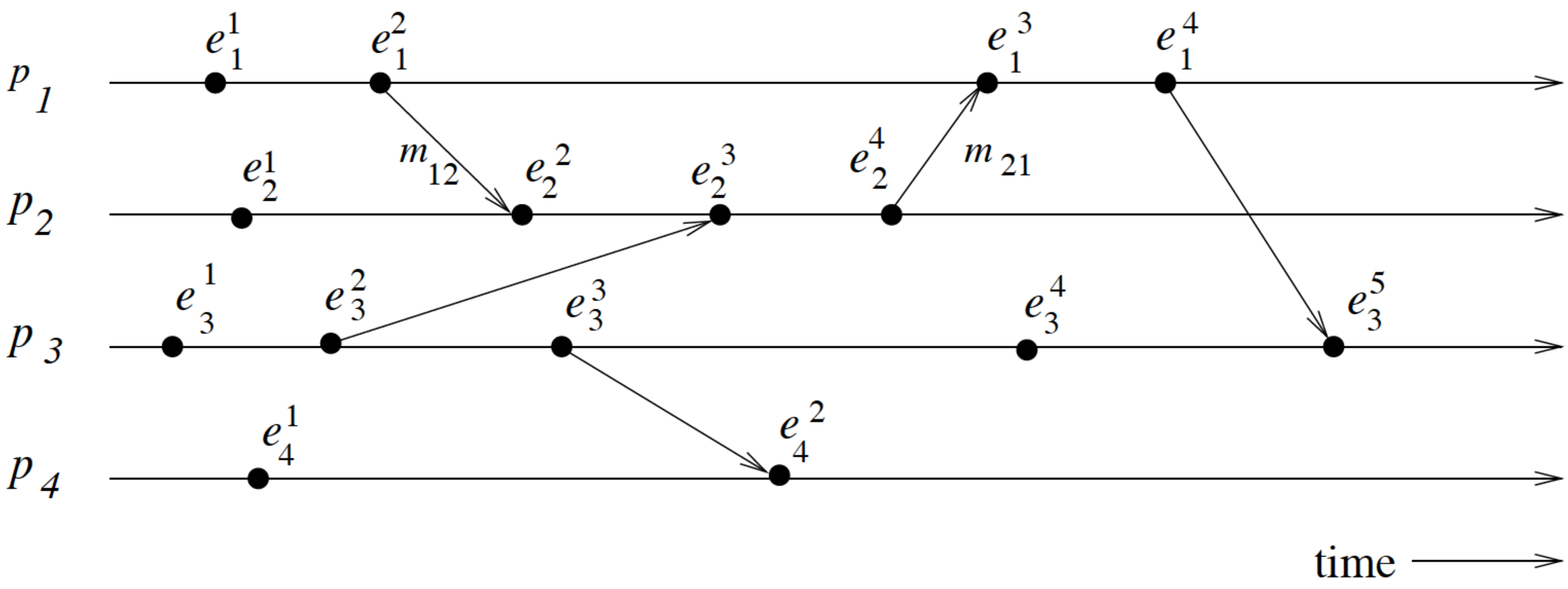
$$\forall m_{ij} : \; send(m_{ij}) \not\preceq LS_i^{x_i} \;\Leftrightarrow\; m_{ij} \notin SC_{ij}^{x_i, y_j} \bigwedge rec(m_{ij}) \not\preceq LS_j^{y_j}$$

Where the global state is given by

$$GS = \{\bigcup_i LS_i^{x_i}, \bigcup_{j,k} SC_{jk}^{y_j, z_k}\}$$

- This implies that the channel state and process state must not include any message that process p_i sent after executing event

Consistent Global State – An Example



Consistent Global State – Details

- A global state GS1 = $\{LS_1^1, LS_2^3, LS_3^3, LS_4^2\}$ is inconsistent because
  - the state of p_2 has recorded the receipt of message m_{12}
  - The state of p_1 has not recorded its send

- A global state GS2 consisting of local states $\{LS_1^2, LS_2^4, LS_3^4, LS_4^2\}$ is consistent;
- all the channels are empty except C_{21} that contains message m_{21}.

Run / Consistent Run

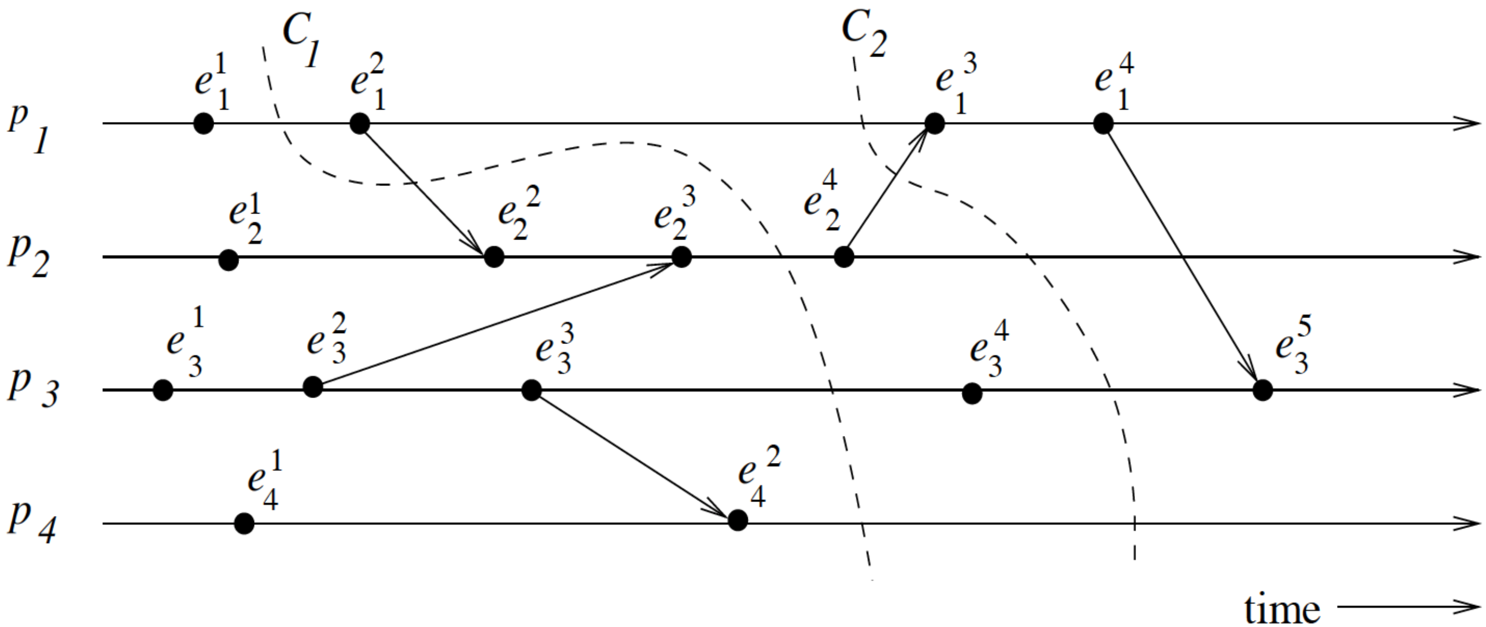
Run:

- ➔ A run is an ordering of the events that satisfies the happened-before relation in one process

Consistent Run:

- ➔ A consistent run is an ordering of the events that satisfies all the happened-before relations

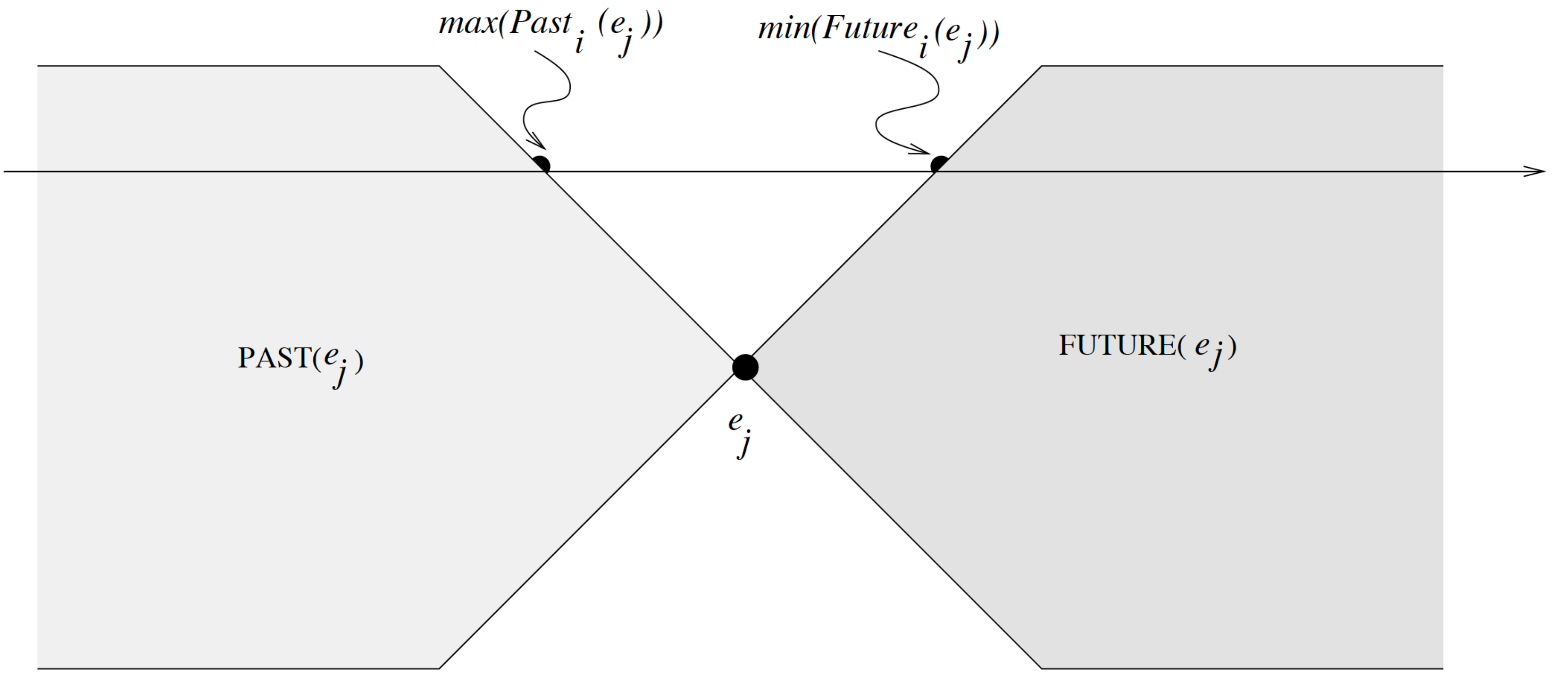
Cuts of a Distributed Computation



Cuts of a Distributed Computation

- In a consistent cut, every message received in the PAST of the cut was sent in the PAST of that cut
  - In previous figure, cut C2 is a consistent cut
- All messages that cross the cut from the PAST to the FUTURE are in transit in the corresponding consistent global state.
- A cut is inconsistent if a message crosses the cut from the FUTURE to the PAST
  - In previous figure cut C1 is an inconsistent cut

Past and Future Cones of an event



Physical vs Logical clocks?

- Logical Clocks
  - Design and Implementation
- Three Different Ways
  - Scalar Time
  - Vector Time
  - Matrix Time
- Virtual Clocks
  - Time Wrap Mechanism
- Clock Synchronization
  - NTP Synchronization Protocol

Summary

- A Model of Distributed Computations
  - Distributed Sorting
    - Design and Implementation Issues
  - Causal Precedence Relations
  - Global State and Cuts of a DS
  - PAST and FUTURE events
  - What about the ordering of events?
    - How do we efficiently handle the ordering of events (discrete events)?
    - Lamport's Logical Clocks ?
    - Many more to come up … stay tuned in !!

Penalties

- Every Student is expected to strictly follow a fair Academic Code of Conduct to avoid penalties

- Penalties is heavy for those who involve in:
  - Copy and Pasting the code
  - Plagiarism (copied from your neighbor or friend – in this case, both will get "0" marks for that specific take home assignments)
  - If the candidate is unable to explain his own solution, it would be considered as a "copied case"!!
  - Any other unfair means of completing the assignments

Help among Yourselves?

- **Perspective Students** (having CGPA above 8.5 and above)
- **Promising Students** (having CGPA above 6.5 and less than 8.5)
- **Needy Students** (having CGPA less than 6.5)
  - Can the above group help these students? (Your work will also be rewarded)
- You may grow a culture of **collaborative learning** by helping the needy students

How to reach me?

- ➔ Please leave me an email:

  rajendra [DOT] prasath [AT] iiits [DOT] in

- ➔ Visit my homepage @
  - ➔ https://www.iiits.ac.in/people/regular-faculty/dr-rajendra-prasath/

(OR)

  - ➔ http://rajendra.2power3.com

Assistance

- You may post your questions to me at any time
- You may meet me in person on available time or with an appointment
- You may ask for one-to-one meeting

Best Approach

- You may leave me an email any time
  (email is the best way to reach me faster)

Questions
It's Your Time

Contact Information

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