Module 1: Introduction

CST402 DISTRIBUTED COMPUTING

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Course Outcome

CO1	Summarize various aspects of distributed computation model and logical time. **(Cognitive Knowledge Level: Understand)**
CO2	Illustrate election algorithm, global snapshot algorithm and termination detection algorithm. **(Cognitive Knowledge Level: Apply)**
CO3	Compare token based, non-token based and quorum based mutual exclusion algorithms. **(Cognitive Knowledge Level: Understand)**
CO4	Recognize the significance of deadlock detection and shared memory in distributed systems. **(Cognitive Knowledge Level: Understand)**
CO5	Explain the concepts of failure recovery and consensus. **(Cognitive Knowledge Level: Understand)**
CO6	Illustrate distributed file system architectures. **(Cognitive Knowledge Level: Understand)**

Mapping of course outcomes with program outcomes

	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12
CO1	✓	✓	✓									✓
CO2	✓	✓	✓	✓								✓
CO3	✓	✓	✓									✓
CO4	✓	✓	✓									✓
CO5	✓	✓	✓									✓
CO6	✓	✓	✓									✓

Abstract POs defined by National Board of Accreditation			
PO#	**Broad PO**	**PO#**	**Broad PO**
PO1	Engineering Knowledge	**PO7**	Environment and Sustainability
PO2	Problem Analysis	**PO8**	Ethics
PO3	Design/Development of solutions	**PO9**	Individual and team work
PO4	Conduct investigations of complex problems	**PO10**	Communication
PO5	Modern tool usage	**PO11**	Project Management and Finance
PO6	The Engineer and Society	**PO12**	Life long learning

Assessment Pattern

Bloom's Category	Continuous Assessment Tests		End Semester Examination Marks (%)
	Test 1 (%)	Test 2 (%)	
Remember	30	30	30
Understand	50	50	50
Apply	20	20	20
Analyze			
Evaluate			
Create			

Mark Distribution

Total Marks	CIE Marks	ESE Marks	ESE Duration
150	50	100	3

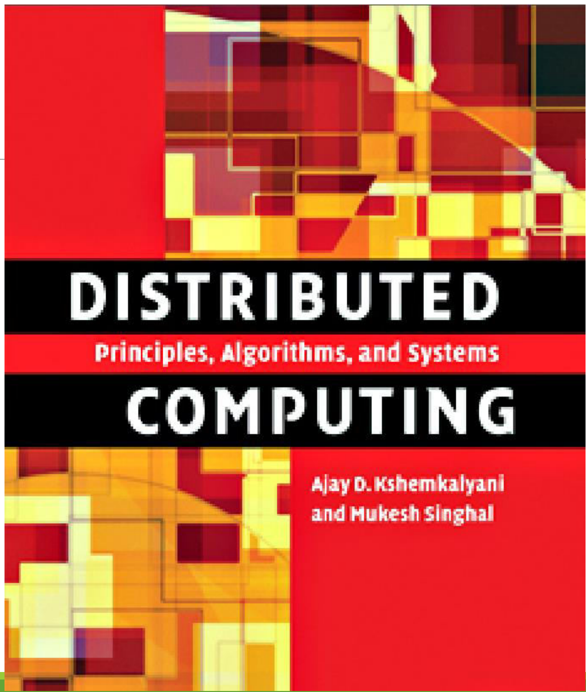
Continuous Internal Evaluation Pattern:

Attendance	**10 marks**
Continuous Assessment Tests(Average of Internal Tests1&2)	**25 marks**
Continuous Assessment Assignment	**15 marks**

Syllabus- Distributed systems basics and Computation model

Distributed System – Definition, Relation to computer system components, Motivation, Primitives for distributed communication, Design issues, Challenges and applications.

A model of distributed computations – Distributed program, Model of distributed executions, Models of communication networks, Global state of a distributed system, Cuts of a distributed computation, Past and future cones of an event, Models of process communications.



Distributed System

A distributed system is a collection of independent entities that cooperate to solve a problem that cannot be individually solved

A distributed system can be characterized as a collection of mostly autonomous processors communicating over a communication network

Distributed system has been characterized in one of several ways

1. You know you are using one when the crash of a computer you have never heard of prevents you from doing work--- prevents losing data in a computer crash
2. A collection of computers that do not share common memory or a common physical clock, that communicate by a messages passing over a communication network, and where each computer has its own memory and runs its own operating system
3. A collection of independent computers that appears to the users of the system as a single coherent computer
4. A term that describes a wide range of computers, from weakly coupled systems such as wide-area networks, to strongly coupled systems such as local area networks, to very strongly coupled systems such as multiprocessor systems

Features of DS

No common physical clock: This is an important assumption because it introduces the element of "distribution" in the system and gives rise to the inherent asynchrony amongst the processors.

No shared memory This is a key feature that requires message-passing for communication. This feature implies the absence of the common physical clock

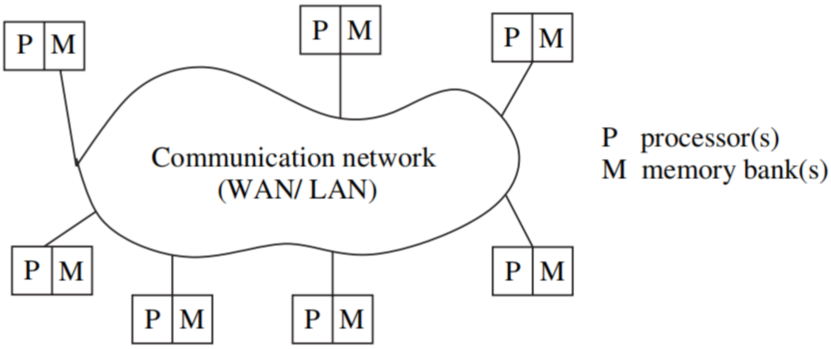
Geographical separation The geographically wider apart that the processors are, the more representative is the system of a distributed system.

- WAN
- NOW/COW(network/cluster of workstations)--- eg, Google search engine

Autonomy and heterogeneity: The processors are "loosely coupled" in that they have different speeds and each can be running a different operating system, cooperate with one another by offering services or solving a problem jointly.

Relation to computer system components

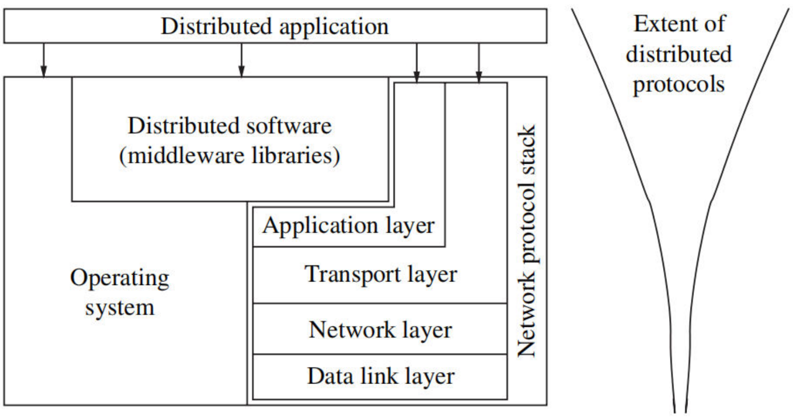
Figure 1.1 A distributed system connects processors by a communication network.



Each computer has a memory-processing unit and the computers are connected by a communication network

Figure 1.2 Interaction of the software components at each processor.

interaction of software with system components at each processor



relationships of the software components that run on each of the computers and use the local operating system and network protocol stack for functioning

The distributed software is also termed as *middleware*.

A *distributed execution* is the execution of processes across the distributed system to collaboratively achieve a common goal.

An execution is also sometimes termed a *computation* or a *run*.

The distributed system uses a layered architecture to break down the complexity of system design.

The middleware is the distributed software that drives the distributed system, while providing transparency of heterogeneity at the platform level

The middleware layer does not contain the traditional application layer functions of the network protocol stack, such as *http*, *mail*, *ftp*, and *telnet*.

Various primitives and calls to functions defined in various libraries of the middleware layer are embedded in the user program code.

There exist several libraries to choose from to invoke primitives for the more common functions – such as reliable and ordered multicasting – of the middleware layer

Motivation

1. **Inherently distributed computations**: money transfer in banking, or reaching consensus among parties that are geographically distant
2. **Resource sharing**: distributed databases such as DB2 partition the data sets across several servers, in addition to replicating them at a few sites for rapid access as well as reliability
3. **Access to geographically remote data and resources**: data cannot be replicated at every site participating in the distributed execution because it may be too large or too sensitive to be replicated
4. **Enhanced reliability**: Availability, Integrity, Fault-tolerance
5. **Increased performance/cost ratio**: any task can be partitioned across the various computers in the distributed system
6. **Scalability**
7. **Modularity and incremental expandability**

See you in next video

Module 1: Primitives for distributed communication

LECTURE 2

Primitives for distributed communication

Blocking/non-blocking, synchronous/asynchronous primitives

Processor synchrony

Libraries and standards

Blocking/non-blocking, synchronous/asynchronous primitives

Send()- has at least two parameters, the destination, and the buffer in the user space

Receive()- at least two parameters, the source from which the data is to be received and the user buffer into which the data is to be received

There are two ways of sending data when the *Send* primitive is invoked the

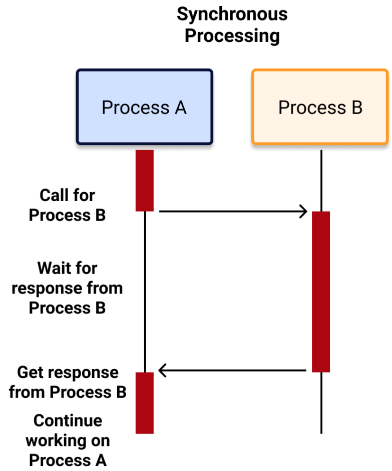
- buffered option
  - The *buffered option* which is the standard option copies the data from the user buffer to the kernel buffer.
  - The data later gets copied from the kernel buffer onto the network.
- unbuffered option
  - In the *unbuffered option*, the data gets copied directly from the user buffer onto the network.
  - For the *Receive* primitive, the buffered option is usually required because the data may already have arrived when the primitive is invoked, and needs a storage place in the kernel.

Synchronous primitives

A *Send* or a *Receive* primitive is *synchronous* if both the *Send()* and *Receive()* handshake with each other.

The processing for the *Send* primitive completes only after the invoking processor learns that the other corresponding *Receive* primitive has also been invoked and that the receive operation has been completed.

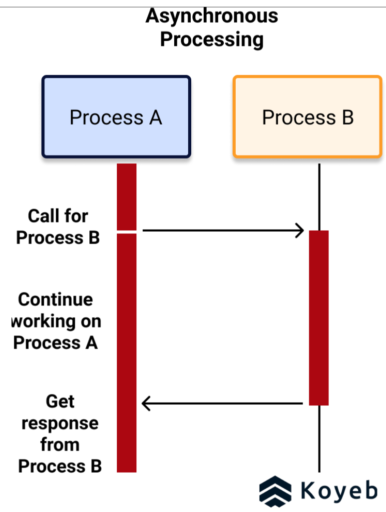
The processing for the *Receive* primitive completes when the data to be received is copied into the receiver's user buffer.



Asynchronous primitives

A *Send* primitive is said to be *asynchronous* if control returns back to the invoking process after the data item to be sent has been copied out of the user-specified buffer.

It does not make sense to define asynchronous Receive primitives.



Blocking primitives

A primitive is blocking if control returns to the invoking process after the processing for the primitive (whether in synchronous or asynchronous mode) completes.

Non-blocking primitives

A primitive is non-blocking if control returns back to the invoking process **immediately** after invocation, even though the operation has not completed.

For a non-blocking *Send*, control returns to the process even before the data is copied out of the user buffer.

For a non-blocking *Receive*, control returns to the process even before the data may have arrived from the sender.

For non-blocking primitives, a return parameter on the primitive call returns a system-generated *handle* which can be later used to check the status of completion of the call.

The process can check for the completion of the call in two ways.

1. First, it can keep checking (in a loop or periodically) if the handle has been flagged or *posted*.
2. Second, it can issue a *Wait* with a list of handles as parameters.

The *Wait* call usually blocks until one of the parameter handles is posted.

Presumably after issuing the primitive in non-blocking mode, the process has done whatever actions it could and now needs to know the status of completion of the call, therefore using a blocking *Wait()* call is usual programming practice

Figure 1.7 A non-blocking *send* primitive. When the *Wait* call returns, at least one of its parameters is posted.

```
Send(X, destination, handle_k)                    // handle_k is a return parameter
...
...
Wait(handle_1, handle_2, ..., handle_k, ..., handle_m)       // Wait always blocks
```

If at the time that *Wait()* is issued, the processing for the primitive has completed, the *Wait* returns immediately

The completion of the processing of the primitive is detectable by checking the value of $handle_k$.

If the processing of the primitive has not completed, the *Wait* blocks and waits for a signal to wake it up.

When the processing for the primitive completes, the communication subsystem software sets the value of handlek and wakes up (signals) any process with a *Wait* call blocked on this handlek.

This is called *posting* the completion of the operation.

See you in next video

Module 1: Versions of the Send primitive

LECTURE 2

Four versions of the Send primitive

1. synchronous blocking,
2. synchronous non-blocking,
3. asynchronous blocking, and
4. asynchronous non-blocking

Here, three time lines are shown for each process:

(1) for the process execution,

(2) for the user buffer from/to which data is sent/received, and

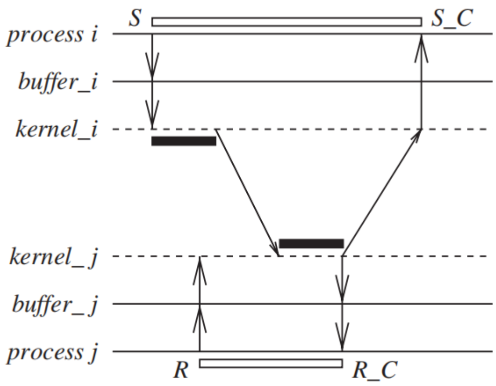
(3) for the kernel/communication subsystem.

	Duration to copy data from or to user buffer		
	Duration in which the process issuing send or receive primitive is blocked		
S	*Send* primitive issued	S_C	processing for *Send* completes
R	*Receive* primitive issued	R_C	processing for *Receive* completes
P	The completion of the previously initiated nonblocking operation		
W	Process may issue *Wait* to check completion of nonblocking operation		

Blocking synchronous Send

The data gets copied from the user buffer to the kernel buffer and is then sent over the network.

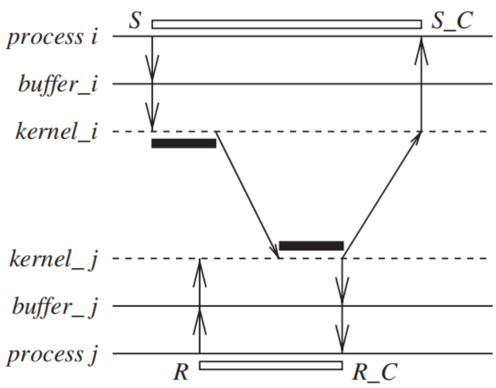
After the data is copied to the receiver's system buffer and a *Receive* call has been issued, an acknowledgement back to the sender causes control to return to the process that invoked the *Send* operation and completes the *Send*



Blocking Receive

The *Receive* call blocks until the data expected arrives and is written in the specified user buffer.

Then control is returned to the user process.



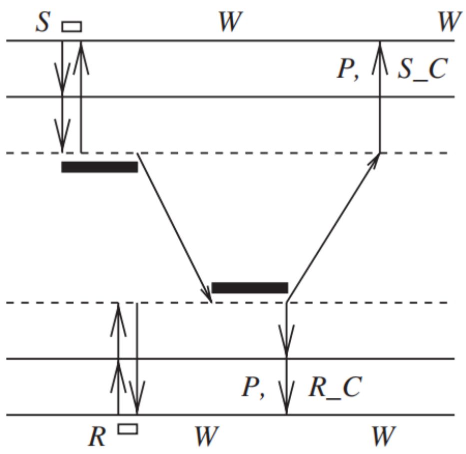
Non-blocking synchronous Send

Control returns back to the invoking process as soon as the copy of data from the user buffer to the kernel buffer is initiated.

A parameter in the non-blocking call also gets set with the handle of a location that the user process can later check for the completion of the synchronous send operation.

The location gets posted after an acknowledgement returns from the receiver

The user process can keep checking for the completion of the non-blocking synchronous *Send* by testing the returned handle, or it can invoke the blocking *Wait* operation on the returned handle

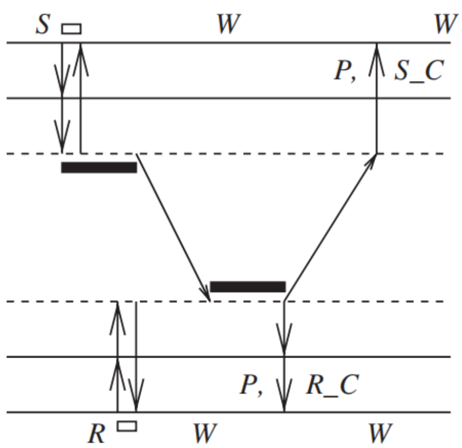


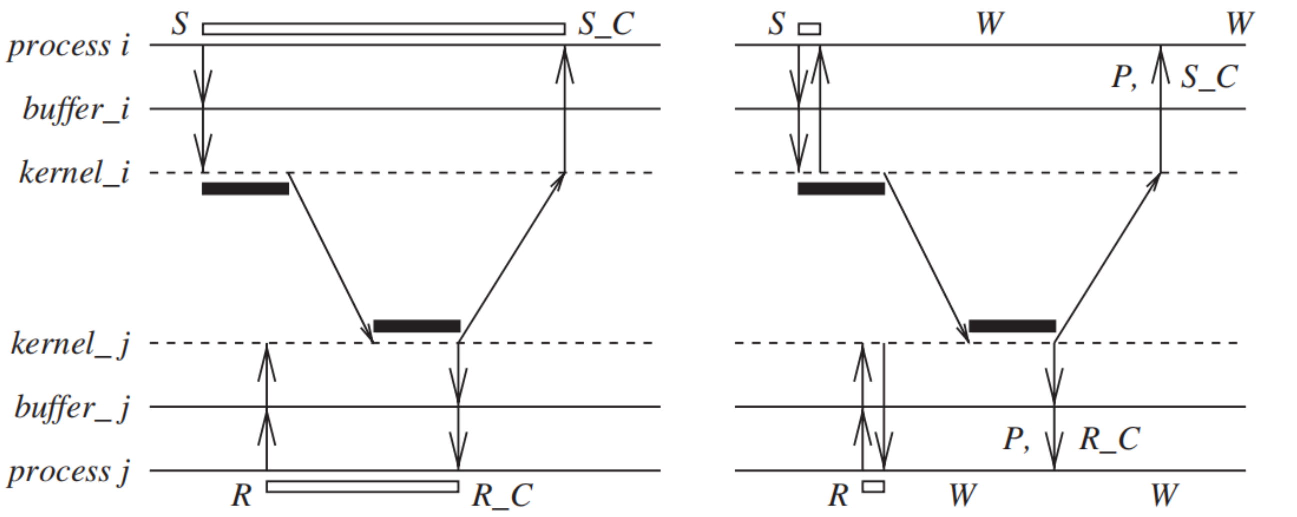
Non-blocking Receive

The *Receive* call will cause the kernel to register the call and return the handle of a location that the user process can later check for the completion of the non-blocking *Receive* operation.

This location gets posted by the kernel after the expected data arrives and is copied to the user-specified buffer.

The user process can check for the completion of the non-blocking *Receive* by invoking the *Wait* operation on the returned handle.



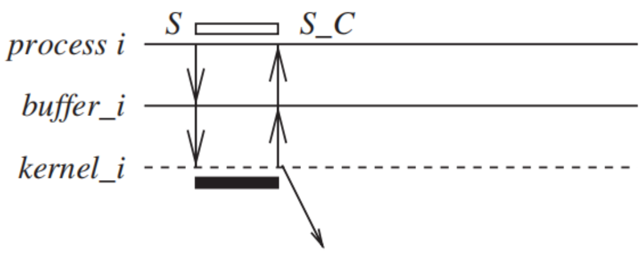


(a) Blocking sync. *Send*, blocking *Receive* (b) Nonblocking sync. *Send*, nonblocking *Receive*

Blocking asynchronous Send

The user process that invokes the Send is blocked until the data is copied from the user's buffer to the kernel buffer.

For the unbuffered option, the user process that invokes the Send is blocked until the data is copied from the user's buffer to the network.



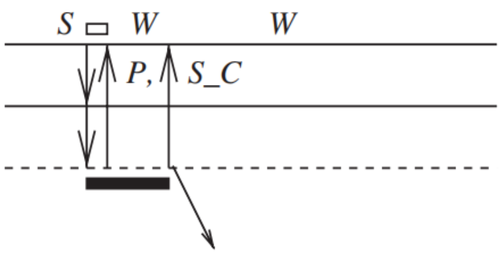
Non-blocking asynchronous Send

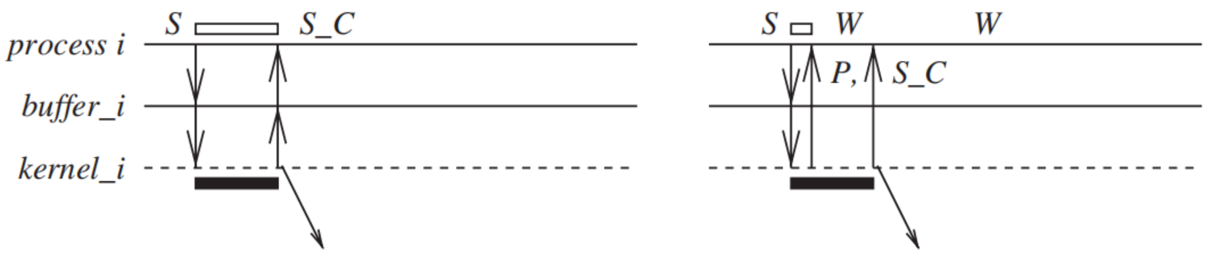
The user process that invokes the *Send* is blocked until the transfer of the data from the user's buffer to the kernel buffer is initiated.

Control returns to the user process as soon as this transfer is initiated, and a parameter in the non-blocking call also gets set with the handle of a location that the user process can check later using the *Wait* operation for the completion of the asynchronous *Send* operation.

The asynchronous *Send* completes when the data has been copied out of the user's buffer.

The checking for the completion may be necessary if the user wants to reuse the buffer from which the data was sent.





(c) Blocking async. *Send* (d) Non-blocking async. *Send*

Duration to copy data from or to user buffer

Duration in which the process issuing send or receive primitive is blocked

S	*Send* primitive issued	*S_C*	processing for *Send* completes
R	*Receive* primitive issued	*R_C*	processing for *Receive* completes
P	The completion of the previously initiated nonblocking operation		
W	Process may issue *Wait* to check completion of nonblocking operation		

A synchronous *Send* is easier to use from a programmer's perspective because the handshake between the *Send* and the *Receive* makes the communication appear instantaneous

- "instantaneity" is, of course, only an illusion
- The *Receive* may not get issued until much after the data arrives at Pj, in which case the data arrived would have to be buffered in the system buffer at Pj and not in the user buffer.
- At the same time, the sender would remain blocked.
- Thus, a synchronous *Send* lowers the efficiency within process Pi.

The **non-blocking asynchronous *Send*** is useful when a large data item is being sent because it allows the process to perform other instructions in parallel with the completion of the *Send*.

- The non-blocking synchronous *Send* also avoids the potentially large delays for handshaking, particularly when the receiver has not yet issued the *Receive* call.

The non-blocking *Receive* is useful when a large data item is being received and/or when the sender has not yet issued the *Send* call,

- because it allows the process to perform other instructions in parallel with the completion of the *Receive*.
- If the data has already arrived, it is stored in the kernel buffer, and it may take a while to copy it to the user buffer specified in the *Receive* call.

For non-blocking calls, however, the burden on the programmer increases because he or she has to keep track of the completion of such operations in order to meaningfully reuse (write to or read from) the user buffers

See you in next video

Module 1: Processor synchrony

LECTURE 4

Primitives for distributed communication

Blocking/non-blocking, synchronous/asynchronous primitives

Processor synchrony

Libraries and standards

Processor synchrony

Processor synchrony indicates that all the processors execute in lock-step with their **clocks synchronized**.

As this synchrony is not attainable in a distributed system, what is more generally indicated is that for a large granularity of code, usually termed as a *step*, the processors are synchronized.

This abstraction is implemented using some form of barrier synchronization to ensure that no processor begins executing the next step of code until all the processors have completed executing the previous steps of code assigned to each of the processors.

See you in next video

Design issues and challenges

design issues and challenges after categorizing them as

1. having a greater component related to systems design and operating systems design, or
2. having a greater component related to algorithm design, or
3. emerging from recent technology advances and/or driven by new applications

Distributed systems challenges from a system perspective

The following functions must be addressed when designing and building a distributed system:

1. Communication
2. Processes
3. Naming
4. Synchronization
5. Data storage and access
6. Consistency and replication
7. Fault tolerance
8. Security
9. Applications Programming Interface (API) and transparency
10. Scalability and modularity

1. Communication

This task involves designing appropriate mechanisms for communication among the processes in the network.

Some example mechanisms are: remote procedure call (RPC), remote object invocation (ROI), message-oriented communication versus stream-oriented communication.

2. Processes

Some of the issues involved are: management of processes and threads at clients/servers; code migration; and the design of software and mobile agents.

3. Naming

Devising easy to use and robust schemes for names, identifiers, and addresses is essential for locating resources and processes in a transparent and scalable manner.

Naming in mobile systems provides additional challenges because naming cannot easily be tied to any static geographical topology.

4. Synchronization

Mechanisms for synchronization or coordination among the processes are essential.

Mutual exclusion is the classical example of synchronization, but many other forms of synchronization, such as leader election are also needed.

In addition, synchronizing physical clocks, and devising logical clocks that capture the essence of the passage of time, as well as global state recording algorithms, all require different forms of synchronization.

5. Data storage and access

Schemes for data storage, and implicitly for accessing the data in a fast and scalable manner across the network are important for efficiency.

Traditional issues such as file system design have to be reconsidered in the setting of a distributed system.

6. Consistency and replication

To avoid bottlenecks, to provide fast access to data, and to provide scalability, replication of data objects is highly desirable.

This leads to issues of managing the replicas, and dealing with consistency among the replicas/caches in a distributed setting.

A simple example issue is deciding the level of granularity (i.e., size) of data access.

7. Fault tolerance

Fault tolerance requires maintaining correct and efficient operation in spite of any failures of links, nodes, and processes.

Process resilience, reliable communication, distributed commit, checkpointing and recovery, agreement and consensus, failure detection, and self-stabilization are some of the mechanisms to provide fault-tolerance.

8. Security

Distributed systems security involves various aspects of cryptography, secure channels, access control, key management – generation and distribution, authorization, and secure group management.

9. Applications Programming Interface (API) and transparency

Transparency deals with hiding the implementation policies from the user, and can be classified as follows

1. *Access transparency* hides differences in data representation on different systems and provides uniform operations to access system resources.
2. *Location transparency* makes the locations of resources transparent to the users.
3. *Migration transparency* allows relocating resources without changing names.
4. *Relocation transparency*: The ability to relocate the resources as they are being accessed is.
5. *Replication transparency* does not let the user become aware of any replication.
6. *Concurrency transparency* deals with masking the concurrent use of shared resources for the user.
7. *Failure transparency* refers to the system being reliable and fault-tolerant.

10. Scalability and modularity

The algorithms, data (objects), and services must be as distributed as possible.

Various techniques such as replication, caching and cache management, and asynchronous processing help to achieve scalability.

Algorithmic challenges in distributed computing

- Designing useful execution models and frameworks
- Dynamic distributed graph algorithms and distributed routing algorithms
- Time and global state in a distributed system
- Synchronization/coordination mechanisms
- Group communication, multicast, and ordered message delivery
- Monitoring distributed events and predicates
- Distributed program design and verification tools
- Debugging distributed programs
- Data replication, consistency models, and caching

Designing useful execution models and frameworks

The interleaving model and partial order model are two widely adopted models of distributed system executions.

They have proved to be particularly useful for operational reasoning and the design of distributed algorithms.

The input/output automata model and the TLA (temporal logic of actions) are two other examples of models that provide different degrees of infrastructure for reasoning more formally with and proving the correctness of distributed programs

Dynamic distributed graph algorithms and distributed routing algorithms

The distributed system is modeled as a distributed graph, and the graph algorithms form the building blocks for a large number of higher level communication, data dissemination, object location, and object search functions.

The algorithms need to deal with dynamically changing graph characteristics, such as to model varying link loads in a routing algorithm.

The efficiency of these algorithms impacts not only the user-perceived latency but also the traffic and hence the load or congestion in the network.

Hence, the design of efficient distributed graph algorithms is of paramount importance

Time and global state in a distributed system

The challenges pertain to providing accurate physical time, and to providing a variant of time, called logical time

Logical time is relative time, and eliminates the overheads of providing physical time for applications where physical time is not required. More importantly, logical time can

i. capture the logic and inter-process dependencies within the distributed program, and also
ii. track the relative progress at each process.

It is not possible for any one process to directly observe a meaningful global state across all the processes, without using extra state-gathering effort which needs to be done in a coordinated manner

Synchronization/coordination mechanisms

Synchronization is essential for the distributed processes to overcome the limited observation of the system state from the viewpoint of any one process.

Overcoming this limited observation is necessary for taking any actions that would impact other processes.

The synchronization mechanisms can also be viewed as resource management and concurrency management mechanisms to streamline the behavior of the processes that would otherwise act independently.

Problems Requiring Synchronization

Physical clock synchronization

Leader election

Mutual exclusion

Deadlock detection and resolution

Termination detection

Garbage collection

Leader election

All the processes need to agree on which process will play the role of a distinguished process – called a leader process.

A leader is necessary even for many distributed algorithms because there is often some asymmetry as in initiating some action like a broadcast or collecting the state of the system, or in "regenerating" a token that gets "lost" in the system

Group communication, multicast, and ordered message delivery

A group is a collection of processes that share a common context and collaborate on a common task within an application domain.

Specific algorithms need to be designed to enable efficient group communication and group management wherein processes can join and leave groups dynamically, or even fail.

When multiple processes send messages concurrently, different recipients may receive the messages in different orders, possibly violating the semantics of the distributed program.

Hence, formal specifications of the semantics of ordered delivery need to be formulated, and then implemented.

Monitoring distributed events and predicates

Predicates defined on program variables that are local to different processes are used for specifying conditions on the global system state, and are useful for applications such as debugging, sensing the environment, and in industrial process control.

On-line algorithms for monitoring such predicates are hence important.

An important paradigm for monitoring distributed events is that of *event streaming*, wherein streams of relevant events reported from different processes are examined collectively to detect predicates.

Typically, the specification of such predicates uses physical or logical time relationships.

Distributed program design and verification tools

Methodically designed and verifiably correct programs can greatly reduce the overhead of software design, debugging, and engineering.

Designing mechanisms to achieve these design and verification goals is a challenge.

Debugging distributed programs

Debugging sequential programs is hard; debugging distributed programs is that much harder because of the concurrency in actions and the ensuing uncertainty due to the large number of possible executions defined by the interleaved concurrent actions.

Adequate debugging mechanisms and tools need to be designed to meet this challenge.

Data replication, consistency models, and caching

Fast access to data and other resources requires them to be replicated in the distributed system.

Managing such replicas in the face of updates introduces the problems of ensuring consistency among the replicas and cached copies.

Additionally, placement of the replicas in the systems is also a challenge because resources usually cannot be freely replicated.

Applications of distributed computing and newer challenges

1. Mobile systems
2. Sensor networks
3. Ubiquitous or pervasive computing
4. Peer-to-peer computing
5. Publish-subscribe, content distribution, and multimedia
6. Distributed agents
7. Distributed data mining
8. Grid computing
9. Security in distributed systems

1. Mobile systems

Mobile systems typically use wireless communication which is based on electromagnetic waves and utilizes a shared broadcast medium.

the characteristics of communication are different;

set of problems such as

i. routing,
ii. location management,
iii. channel allocation,
iv. localization and position estimation, and
v. the overall management of mobility

There are two popular architectures for a mobile network.

1. *base-station* approach, also known as the *cellular approach*, wherein a *cell* which is the geographical region within range of a static but powerful base transmission station is associated with that base station
2. second approach is the *ad-hoc network* approach where there is no base station

All responsibility for communication is distributed among the mobile nodes, wherein mobile nodes have to participate in routing by forwarding packets of other pairs of communicating nodes

2. Sensor networks

A sensor is a processor with an electro-mechanical interface that is capable of sensing physical parameters, such as temperature, velocity, pressure, humidity, and chemicals

Sensors may be mobile or static;

sensors may communicate wirelessly, although they may also communicate across a wire when they are statically installed.

Sensors may have to self-configure to form an ad-hoc network, which introduces a whole new set of challenges, such as position estimation and time estimation

3. Ubiquitous or pervasive computing

The intelligent home, and the smart workplace are some example of ubiquitous environments

Ubiquitous systems are essentially distributed systems; recent advances in technology allow them to leverage wireless communication and sensor and actuator mechanisms

They can be self-organizing and network-centric, while also being resource constrained

Such systems are typically characterized as having many small processors operating collectively in a dynamic ambient network.

The processors may be connected to more powerful networks and processing resources in the background for processing and collating data.

4. Peer-to-peer computing

Peer-to-peer (P2P) computing represents computing over an application layer network wherein all interactions among the processors are at a "peer" level, without any hierarchy among the processors.

P2P computing arose as a paradigm shift from client–server computing where the roles among the processors are essentially asymmetrical.

P2P networks are typically self-organizing, and may or may not have a regular structure to the network.

No central directories for name resolution and object lookup are allowed.

5. Publish-subscribe, content distribution, and multimedia

In a dynamic environment where the information constantly fluctuates (varying stock prices is a typical example), there needs to be:

i. an efficient mechanism for distributing this information (publish),
ii. an efficient mechanism to allow end users to indicate interest in receiving specific kinds of information (subscribe), and
iii. an efficient mechanism for aggregating large volumes of published information and filtering it as per the user's subscription filter

multimedia data is usually very large and information-intensive, requires compression, and often requires special synchronization during storage and playback

6. Distributed agents

Agents collect and process information, and can exchange such information with other agents.

Often, the agents cooperate as in an ant colony, but they can also have friendly competition, as in a free market economy.

Challenges in distributed agent systems include coordination mechanisms among the agents, controlling the mobility of the agents, and their software design and interfaces.

Research in agents is inter-disciplinary: spanning artificial intelligence, mobile computing, economic market models, software engineering, and distributed computing.

7. Distributed data mining

The data is necessarily distributed and cannot be collected in a single repository, as in banking applications where the data is private and sensitive,

or in atmospheric weather prediction where the data sets are far too massive to collect and process at a single repository in real-time.

8. Grid computing

Grid Computing is a subset of distributed computing, where a virtual supercomputer comprises machines on a network connected by some bus, mostly Ethernet or sometimes the Internet.

It can also be seen as a form of Parallel Computing where instead of many CPU cores on a single machine, it contains multiple cores spread across various locations.

Many challenges in making grid computing a reality include:

- scheduling jobs in such a distributed environment,
- a framework for implementing quality of service and real-time guarantees,
- Security of individual machines as well as of jobs being executed in this setting.

9. Security in distributed systems

The traditional challenges of security in a distributed setting include:

- confidentiality (ensuring that only authorized processes can access certain information),
- authentication (ensuring the source of received information and the identity of the sending process), and
- availability (maintaining allowed access to services despite malicious actions).

The goal is to meet these challenges with efficient and scalable solutions.

These basic challenges have been addressed in traditional distributed settings.

Module 1: A model of distributed computations

LECTURE 4

A model of distributed computations

- A distributed system consists of a set of processors that are connected by a communication network.
- The communication network provides the facility of information exchange among processors.
- The communication delay is finite but unpredictable.
- The processors do not share a common global memory and communicate solely by passing messages over the communication network.
- There is no physical global clock in the system to which processes have instantaneous access.
- The communication medium may deliver messages out of order, messages may be lost, garbled, or duplicated due to timeout and retransmission, processors may fail, and communication links may go down.
- The system can be modeled as a directed graph in which vertices represent the processes and edges represent unidirectional communication channels.

A distributed application runs as a collection of processes on a distributed system

A distributed program

A distributed program is composed of a set of n asynchronous processes p1, p2, , pi, , pn that communicate by message passing over the communication network.

- we assume that each process is running on a different processor

The processes do not share a global memory and communicate solely by passing messages

- Cij: denote the channel from process pi to process pj
- mij: denote a message sent by pi to pj.

The communication delay is finite and unpredictable.

Also, these processes do not share a global clock that is instantaneously accessible to these processes

Process execution and message transfer are asynchronous

- a process may execute an action spontaneously and a process sending a message does not wait for the delivery of the message to be complete.

The global state of a distributed computation is composed of the states of the processes and the communication channels

The state of a process is characterized by the state of its local memory and depends upon the context.

The state of a channel is characterized by the set of messages in transit in the channel.

A model of distributed executions

The execution of a process consists of a sequential execution of its actions.

The actions are atomic and the actions of a process are modeled as three types of events,

- internal events,
- message send events, and
- Message receive events

For a message m, let send(m) and rec(m) denote its send and receive events

The occurrence of events changes the states of respective processes and channels, thus causing transitions in the global system state.

An internal event changes the state of the process at which it occurs

A send event (or a receive event) changes the state of the process that sends (or receives) the message and the state of the channel on which the message is sent (or received)

An internal event only affects the process at which it occurs

Let e_i^x denote the x_{th} event at process pi

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 $\mathcal{H}_i$:

$$\mathcal{H}_i = (h_i, \rightarrow_i),$$

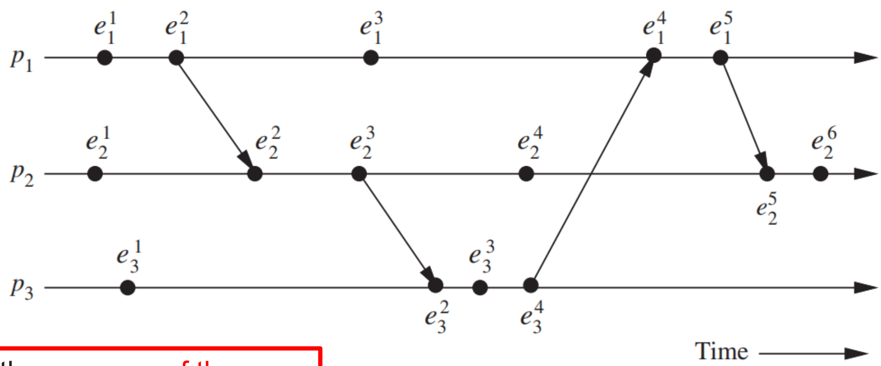
where h_i is the set of events produced by p_i and binary relation $\rightarrow_i$ defines a linear order on these events. Relation $\rightarrow_i$ expresses causal dependencies among the events of p_i.

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. A relation $\rightarrow_{msg}$ that captures the causal dependency due to message exchange, is defined as follows. For every message m that is exchanged between two processes, we have

$$send(m) \rightarrow_{msg} rec(m).$$

Space–Time Diagram of a Distributed Execution involving Three Processes

Figure 2.1 The space–time diagram of a distributed execution.



A horizontal line represents the progress of the process;
a dot indicates an event;
a slant arrow indicates a message transfer.

See you in next video

Module 1: A model of distributed computations

LECTURE 4

Causal precedence relation

The execution of a distributed application results in a set of distributed events produced by the processes

Let H $=\cup_i h_i$ denote the set of events executed in a distributed computation

causal dependencies between events in the distributed execution: define a binary relation on the set H, denoted as →

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

The causal precedence relation induces an irreflexive partial order on the events of a distributed computation that is d $\mathcal{H}=(H, \rightarrow)$

For example $e_1^1 \rightarrow e_3^3$ and $e_3^3 \rightarrow e_2^6$

relation → is Lamport's "happens before" relation

For any two events dependent on event ei and ej, if ei → ej, then event ej is directly or transitively dependent on event ei;

graphically, it means that there exists a path consisting of message arrows and process-line segments in the space–time diagram that starts at ei and ends at ej.

relation → denotes flow of information in a distributed computation and ei → ej dictates that all the information available at ei is potentially accessible at ej.

Eg: event e_2^6 has the knowledge of all other events shown in the figure

For any two events ei and $e_i \not\rightarrow e_j$ denotes

- event ej does not directly or transitively dependent on event ei
- event ei does not causally affect event ej.
- Event ej is not aware of the execution of ei or any event executed after ei on the same process.
- For example $e_1^3 \not\rightarrow e_3^3$ and $e_2^4 \not\rightarrow e_3^1$
- two rules:
  - for any two events e_i and e_j, $e_i \not\rightarrow e_j \not\Rightarrow e_j \not\rightarrow e_i$
  - for any two events e_i and e_j, $e_i \rightarrow e_j \Rightarrow e_j \not\rightarrow e_i$.
- For any two events ei and ej, if ei $\not\rightarrow$ ej and ej $\not\rightarrow$ ei, then events ei and ej are said to be concurrent and the relation is denoted as ei||ej
- relation || is not transitive

$$(e_i \parallel e_j) \wedge (e_j \parallel e_k) \not\Rightarrow e_i \parallel e_k$$

for any two events ei and ej in a distributed execution,

- ei → ej or
- ej → ei, or
- ei ||ej

Logical vs. Physical Concurrency

In a distributed computation, two events are logically concurrent if and only if they do not causally affect each other.

Physical concurrency, on the other hand, has a meaning that the events occur at the same instant in physical time.

Two or more events may be logically concurrent even though they do not occur at the same instant in physical time.

However, 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.

Therefore, even though 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.

See you in next video

Module 1: A model of distributed computations and Global States

LECTURE 4

Models of communication networks

There are several models of the service provided by communication networks, namely,

- FIFO (first-in, first-out): each channel acts as a first-in first-out message queue and thus, message ordering is preserved by a channel
- non-FIFO: 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: is based on Lamport's "happens before" relation. A system that supports the causal ordering model satisfies the following property:

$$\textbf{CO}: \text{ For any two messages } m_{ij} \text{ and } m_{kj}, \text{ if } send(m_{ij}) \longrightarrow send(m_{kj}), \text{ then } rec(m_{ij}) \longrightarrow rec(m_{kj}).$$

- this property ensures that causally related messages destined to the same destination are delivered in an order that is consistent with their causality relation.

$$\text{CO} \subset \text{FIFO} \subset \text{Non-FIFO}$$

Importance of Causal Ordering

Causal ordering model is useful in developing distributed algorithms.

Generally, it considerably simplifies the design of distributed algorithms because it provides a built-in synchronization.

For example, in replicated database systems, it is important that every process responsible for updating a replica receives the updates in the same order to maintain database consistency.

Without causal ordering, each update must be checked to ensure that database consistency is not being violated. Causal ordering eliminates the need for such checks.

Global state of a distributed system

The global state of a distributed system is a collection of the local states of its components, namely, the processes and the communication channels

The state of a process at any time is defined by the contents of processor registers, stacks, local memory, etc. and depends on the local context of the distributed application.

The state of a channel is given by the set of messages in transit in the channel.

The occurrence of events changes the states of respective processes and channels, thus causing transitions in global system state. For eg,

- an internal event changes the state of the process at which it occurs.
- A send event (or a receive event) changes the state of the process that sends (or receives) the message and the state of the channel on which the message is sent (or received)

Let LS_i^x denote the state of process pi after the occurrence of e_i^x ent and e_i^{x+1}

before the event

LS_i^0 denotes the initial state of process pi

LS_i^x is a result of the execution of all the events executed by process pi e_i^x

$send(m) \leq LS_i^x$ denote the fact that $\exists y: 1 \leq y \leq x :: e_i^y = send(m)$

$rec(m) \not\leq LS_i^x$ denote the fact that $\forall y: 1 \leq y \leq x :: e_i^y \neq rec(m)$

Let $SC_{ij}^{x,y}$ denote the state of a channel C_{ij} defined as follows:

$$SC_{ij}^{x,y} = \{m_{ij} \mid send(m_{ij}) \leq LS_i^x \wedge rec(m_{ij}) \not\leq LS_j^y\}.$$

Let e_i^x denote the x_{th} event at process pi

Let LS_i^x denote the state of process pi after the occurrence of event e_i^x and before the event e_i^{x+1}

Global state

The global state of a distributed system is a collection of the local states of the processes and the channels. Notationally, the global state GS is defined as

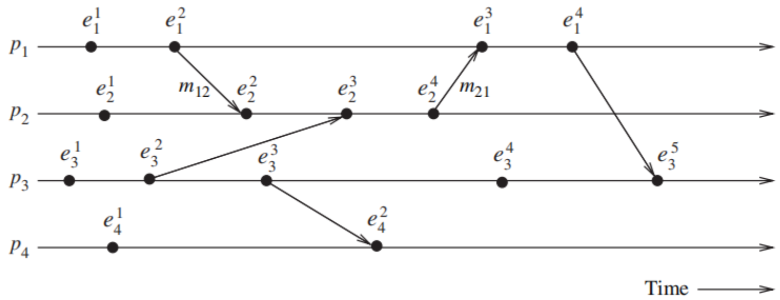
$$GS = \{\underbrace{\bigcup_i LS_i^{x_i}}_{\text{States}}, \underbrace{\bigcup_{j,k} SC_{jk}^{y_j, z_k}}_{\text{Channels}}\}.$$

- even if the state of all the components in a distributed system has not been recorded at the same instant, such a state will be meaningful provided every message that is recorded as received is also recorded as sent.
- Basic idea is that an effect should not be present without its cause.
- A message cannot be received if it was not sent; that is, the state should not violate causality.
- 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.

A global state $GS = \{\bigcup_i LS_i^{x_i}, \bigcup_{j,k} SC_{jk}^{y_j, z_k}\}$ is a *consistent global state* iff it satisfies the following condition:

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

That is, channel state $SC_{ik}^{y_i, z_k}$ and process state $LS_k^{z_k}$ must not include any message that process p_i sent after executing event $e_i^{x_i}$.



a global state GS1 consisting of local s $\{LS_1^1, LS_2^3, LS_3^3, LS_4^2\}$ is inconsistent because

- the state of p2 has recorded the receipt of message m12,
- however, the state of p1 has not recorded its send.

On the contrary, a global state GS2 consisting of local $\{LS_1^2, LS_2^4, LS_3^4, LS_4^2\}$ is consistent;

- all the channels are empty except C_{21} that contains message m_{21}

See you in next video

Module 1: Cuts of a distributed computation

Cuts of a distributed computation

In the space–time diagram of a distributed computation, a zigzag line joining one arbitrary point on each process line is termed a cut in the computation.

Such a line slices the space–time diagram, and thus the set of events in the distributed computation, into a PAST and a FUTURE.

The PAST contains all the events to the left of the cut and the FUTURE contains all the events to the right of the cut.

For a cut C, let PAST(C) and FUTURE(C) denote the set of events in the PAST and FUTURE of C, respectively.

Every cut corresponds to a global state and every global state can be graphically represented as a cut in the computation's space–time diagram

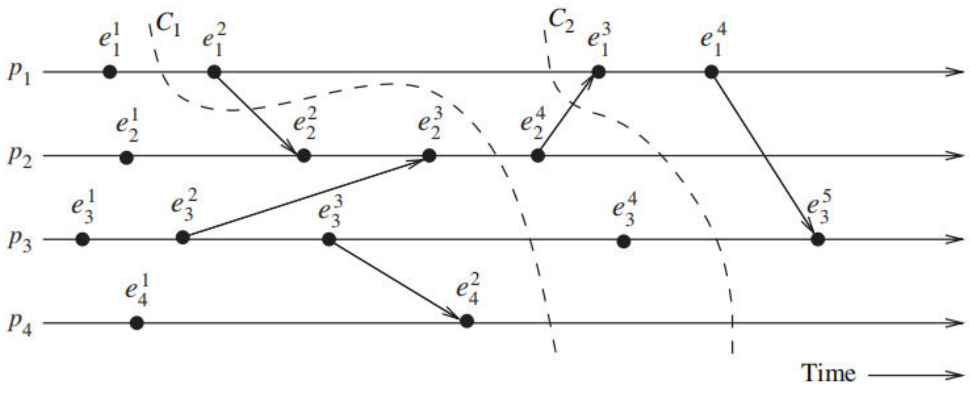
A consistent global state corresponds to a cut in which every message received in the PAST of the cut was sent in the PAST of that cut.

Such a cut is known as 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

Figure 2.3 Illustration of cuts in a distributed execution.



C_1 is an inconsistent cut, whereas C_2 is a consistent cut.

Past and future cones of an event

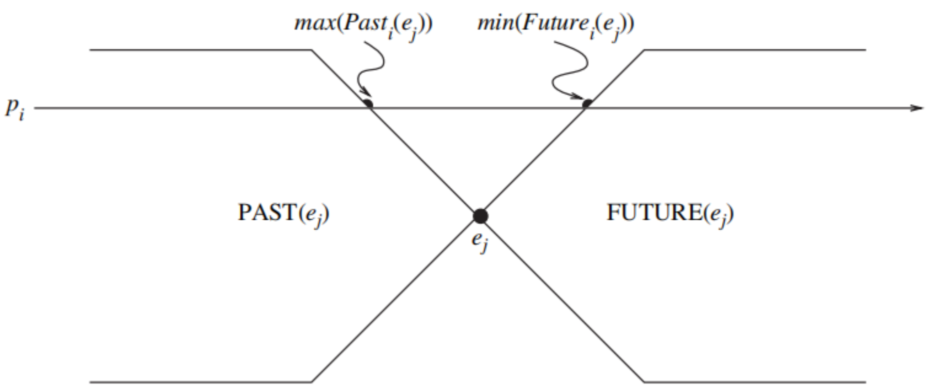
an event ej could have been affected only by all events ei such that ei → ej and all the information available at ei could be made accessible at ej.

All such events ei belong to the past of ej.

Let Past(ej) denote all events in the past of ej in a computation (H, →). Then,

$$Past(e_j) = \{e_i | \forall e_i \in H,\ e_i \to e_j\}.$$

Figure 2.4 Illustration of past and future cones in a distributed computation.



See you in next video

Module 1: Models of process communications

Models of process communications

There are two basic models of process communications

- synchronous
- asynchronous.

The synchronous communication model is a blocking type where on a message send, the sender process blocks until the message has been received by the receiver process.

- The sender process resumes execution only after it learns that the receiver process has accepted the message.
- Thus, the sender and the receiver processes must synchronize to exchange a message.

Asynchronous communication model is a non-blocking type where the sender and the receiver do not synchronize to exchange a message.

After having sent a message, the sender process does not wait for the message to be delivered to the receiver process.

The message is buffered by the system and is delivered to the receiver process when it is ready to accept the message.

A buffer overflow may occur if a process sends a large a number of messages in a burst to another process.

Asynchronous communication provides higher parallelism because the sender process can execute while the message is in transit to the receiver

due to higher degree of parallelism and non-determinism, it is much more difficult to design, verify, and implement distributed algorithms for asynchronous communications

See you in next video