CS3551
DISTRIBUTED
COMPUTING

CS3551 DISTRIBUTED COMPUTING L T P C 3 0 0 3

COURSE OBJECTIVES:

· To introduce the computation and communication models of distributed systems
· To illustrate the issues of synchronization and collection of information in distributed systems
· To describe distributed mutual exclusion and distributed deadlock detection techniques
· To elucidate agreement protocols and fault tolerance mechanisms in distributed systems
· To explain the cloud computing models and the underlying concepts

UNIT I INTRODUCTION 8

Introduction: Definition-Relation to Computer System Components – Motivation – Message - Passing Systems versus Shared Memory Systems – Primitives for Distributed Communication – Synchronous versus Asynchronous Executions – Design Issues and Challenges; A Model of Distributed Computations: A Distributed Program – A Model of Distributed Executions – Models of Communication Networks – Global State of a Distributed System.

UNIT II LOGICAL TIME AND GLOBAL STATE 10

Logical Time: Physical Clock Synchronization: NTP – A Framework for a System of Logical Clocks – Scalar Time – Vector Time; Message Ordering and Group Communication: Message Ordering Paradigms – Asynchronous Execution with Synchronous Communication – Synchronous Program Order on Asynchronous System – Group Communication – Causal Order – Total Order; Global State and Snapshot Recording Algorithms: Introduction – System Model and Definitions – Snapshot Algorithms for FIFO Channels.

UNIT III DISTRIBUTED MUTEX AND DEADLOCK 10

Distributed Mutual exclusion Algorithms: Introduction – Preliminaries – Lamport's algorithm – Ricart- Agrawala's Algorithm — Token-Based Algorithms – Suzuki-Kasami's Broadcast Algorithm; Deadlock Detection in Distributed Systems: Introduction – System Model – Preliminaries – Models of Deadlocks – Chandy-Misra-Haas Algorithm for the AND model and OR Model.

UNIT IV CONSENSUS AND RECOVERY 10

Consensus and Agreement Algorithms: Problem Definition – Overview of Results – Agreement in a Failure-Free System(Synchronous and Asynchronous) – Agreement in Synchronous Systems with Failures; Checkpointing and Rollback Recovery: Introduction – Background and Definitions – Issues in Failure Recovery – Checkpoint-based Recovery – Coordinated Checkpointing Algorithm -- Algorithm for Asynchronous Checkpointing and Recovery

UNIT V CLOUD COMPUTING 7

Definition of Cloud Computing – Characteristics of Cloud – Cloud Deployment Models – Cloud Service Models – Driving Factors and Challenges of Cloud – Virtualization – Load Balancing – Scalability and Elasticity – Replication – Monitoring – Cloud Services and Platforms: Compute Services – Storage Services – Application Services

COURSE OUTCOMES:

Upon the completion of this course, the student will be able to
CO1: Explain the foundations of distributed systems (K2)
CO2: Solve synchronization and state consistency problems (K3)
CO3 Use resource sharing techniques in distributed systems (K3)
CO4: Apply working model of consensus and reliability of distributed systems (K3)
CO5: Explain the fundamentals of cloud computing (K2)

TOTAL:45 PERIODS

TEXT BOOKS 1. Kshemkalyani Ajay D, Mukesh Singhal, "Distributed Computing: Principles, Algorithms and Systems", Cambridge Press, 2011. 2. Mukesh Singhal, Niranjan G Shivaratri, "Advanced Concepts in Operating systems", McGraw Hill Publishers, 1994.

REFERENCES 1. George Coulouris, Jean Dollimore, Time Kindberg, "Distributed Systems Concepts and Design", Fifth Edition, Pearson Education, 2012. 2. Pradeep L Sinha, "Distributed Operating Systems: Concepts and Design", Prentice Hall of India, 2007. 3. Tanenbaum A S, Van Steen M, "Distributed Systems: Principles and Paradigms", Pearson Education, 2007. 4. Liu M L, "Distributed Computing: Principles and Applications", Pearson Education, 2004. 5. Nancy A Lynch, "Distributed Algorithms", Morgan Kaufman Publishers, 2003. 6. Arshdeep Bagga, Vijay Madisetti, " Cloud Computing: A Hands-On Approach", Universities Press, 2014.

UNIT I

INTRODUCTION TO DISTRIBUTED SYSTEMS

1. 1 INTRODUCTION

The process of computation was started from working on a single processor. This uni-processor computing can be termed as **centralized computing**. As the demand for the increased processing capability grew high, multiprocessor systems came to existence. The advent of multiprocessor systems, led to the development of distributed systems with high degree of scalability and resource sharing. The modern day parallel computing is a subset of distributed computing

A distributed system is a collection of independent computers, interconnected via a network, capable of collaborating on a task. Distributed computing is computing performed in a distributed system.

A distributed system is a collection of independent entities that cooperate to solve a problem that cannot be individually solved. Distributed computing is widely used due to advancements in machines; faster and cheaper networks. In distributed systems, the entire network will be viewed as a computer. The multiple systems connected to the network will appear as a single system to the user. Thus the distributed systems hide the complexity of the underlying architecture to the user. Distributed computing is a special version of parallel computing where the processors are in different computers and tasks are distributed to computers over a network.

The definition of distributed systems deals with two aspects that:

- **Deals with hardware:** The machines linked in a distributed system are autonomous.
- **Deals with software:** A distributed system gives an impression to the users that they are dealing with a single system.

Features of Distributed Systems:

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 - 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**.**
Autonomy and heterogeneity – Here the processors are "loosely coupled" in that they have different speeds and each can be running a different operating system.

Issues in distributed systems
Heterogeneity
Openness
Security
Scalability
Failure handling

Concurrency
Transparency
Quality of service

QOS parameters

The distributed systems must offer the following QOS:

- Performance
- Reliability
- Availability
- Security

Differences between centralized and distributed systems

Centralized Systems	Distributed Systems
In Centralized Systems, several jobs are done on a particular central processing unit(CPU)	In Distributed Systems, jobs are distributed among several processors. The Processor are interconnected by a computer network
They have shared memory and shared variables.	They have no global state (i.e.) no shared memory and no shared variables.
Clocking is present.	No global clock.

1.2 Relation to Computer System Components

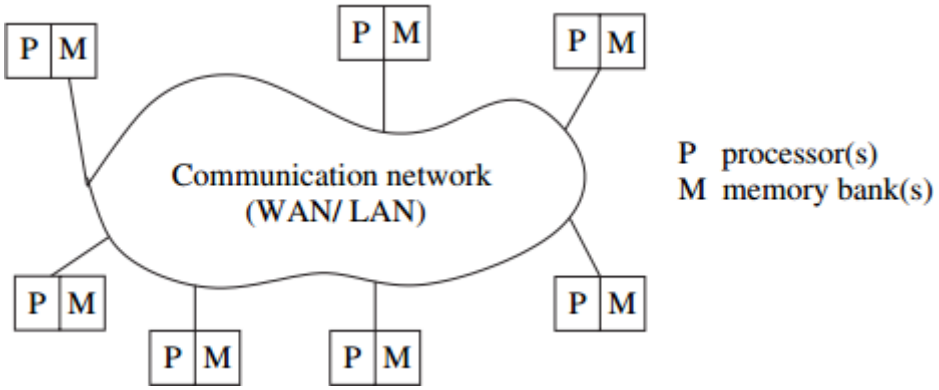


Fig 1.1: Example of a Distributed System

As shown in Fig 1.1, Each computer has a memory-processing unit and the computers are connected by a communication network. Each system connected to the distributed networks hosts distributed software which is a middleware technology. This drives the Distributed System (DS) at the same time preserves the heterogeneity of the DS. The term **computation or run** in a distributed system is the execution of processes to achieve a common goal.

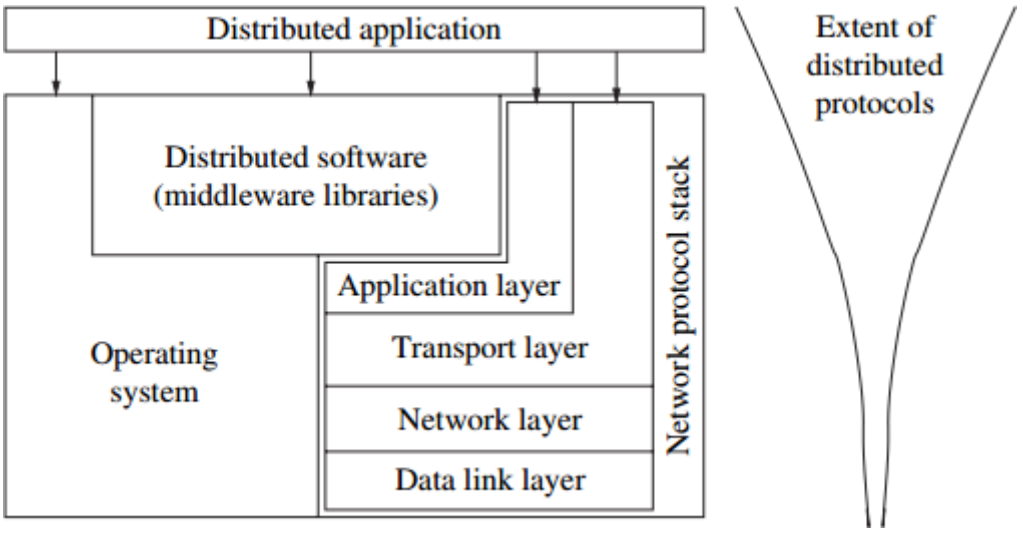


Fig 1.2: Interaction of layers of network

The interaction of the layers of the network with the operating system and middleware is shown in Fig 1.2. The middleware contains important library functions for facilitating the operations of DS.
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

Examples of middleware: Object Management Group's (OMG), Common Object Request Broker Architecture (CORBA) [36], Remote Procedure Call (RPC), Message Passing Interface (MPI)

1.3 Motivation

The following are the keypoints that acts as a driving force behind DS:

- **Inherently distributed computations**: DS can process the computations at geographically remote locations.
- **Resource sharing:** The hardware, databases, special libraries can be shared between systems without owning a dedicated copy or a replica. This is cost effective and reliable.
- **Access to geographically remote data and resources:** As mentioned previously, computations may happen at remote locations. Resources such as centralized servers can also be accessed from distant locations.
- **Enhanced reliability**: DS provides enhanced reliability, since they run on multiple copies of resources. The distribution of resources at distant locations makes them less susceptible for faults. The term reliability comprises of:
  1. **Availability:**the resource/ service provided by the resource should be accessible at all times
  2. **Integrity:** the value/state of the resource should be correct and consistent.
  3. **Fault-Tolerance:**the ability to recover from system failures

- **Increased performance/cost ratio:** The resource sharing and remote access features of DS naturally increase the performance / cost ratio.
- **Scalable:** The number of systems operating in a distributed environment can be increased as the demand increases.

1.5 MESSAGE-PASSING SYSTEMS VERSUS SHARED MEMORY SYSTEMS Communication among processors takes place via shared data variables,

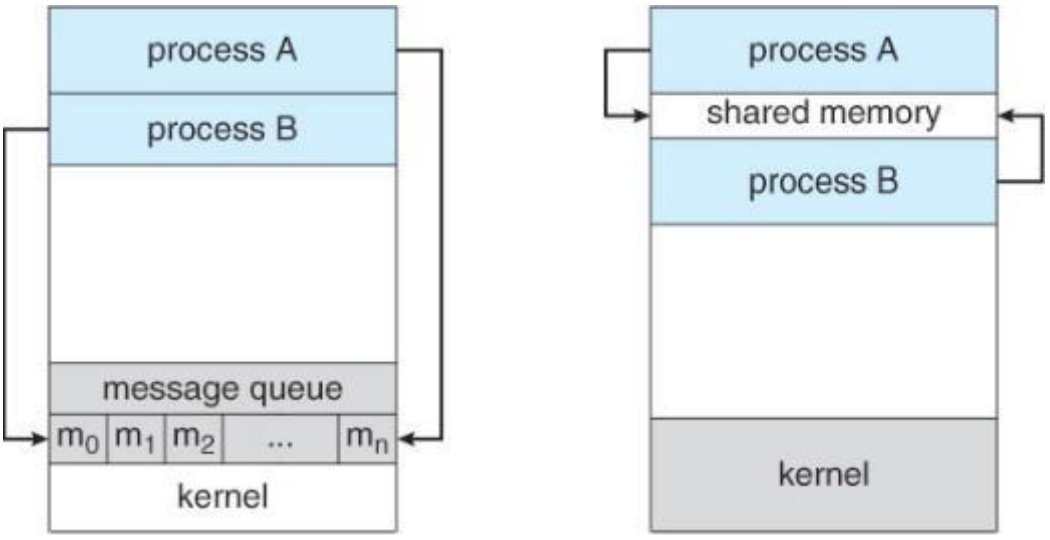
and control variables for synchronization among the processors. The communications between the tasks in multiprocessor systems take place through two main modes:

Message passing systems:

- This allows multiple processes to read and write data to the message queue without being connected to each other.
- Messages are stored on the queue until their recipient retrieves them. Message queues are quite useful for interprocess communication and are used by most operating systems.

Shared memory systems:

- The shared memory is the memory that can be simultaneously accessed by multiple processes. This is done so that the processes can communicate with each other.
- Communication among processors takes place through shared data variables, and control variables for synchronization among the processors.
- Semaphores and monitors are common synchronization mechanisms on shared memory systems.
- When shared memory model is implemented in a distributed environment, it is termed as **distributed shared memory.**



a) Message Passing Model **b) Shared Memory Model**

Fig 1.11: Inter-process communication models

Differences between message passing and shared memory models

Message Passing	Distributed Shared Memory
Services Offered: Variables have to be marshalled from one process, transmitted and unmarshalled into other variables at the receiving process.	The processes share variables directly, so no marshalling and unmarshalling. Shared variables can be named, stored and accessed in DSM.
Processes can communicate with other processes. They can be protected from one another by having private address spaces.	Here, a process does not have private address space. So one process can alter the execution of other.
This technique can be used in heterogeneous computers.	This cannot be used to heterogeneous computers.
Synchronization between processes is through message passing primitives.	Synchronization is through locks and semaphores.
Processes communicating via message passing must execute at the same time.	Processes communicating through DSM may execute with non-overlapping lifetimes.
Efficiency: All remote data accesses are explicit and therefore the programmer is always aware of whether a particular operation is in-process or involves the expense of communication.	Any particular read or update may or may not involve communication by the underlying runtime support.

1.5.1 Emulating message-passing on a shared memory system (MP → SM)

The shared memory system can be made to act as message passing system. The shared address space can be partitioned into disjoint parts, one part being assigned to each processor.

Send and receive operations care implemented by writing to and reading from the destination/sender processor's address space. The read and write operations are synchronized.

Specifically, a separate location can be reserved as the mailbox for each ordered pair of processes.

1.5.2 Emulating shared memory on a message-passing system (SM → MP)

This is also implemented through read and write operations. Each shared location can be modeled as a separate process. Write to a shared location is emulated by sending an update message tothe corresponding owner process and read operation to a shared location is emulatedby sending a query message to the owner process.

This emulation is expensive as the processes has to gain access to other process memory location. The latencies involvedin read and write operations may be high even when using shared memoryemulation because the read and write operations are implemented by using network-wide communication.

1.6 PRIMITIVES FOR DISTRIBUTED COMMUNICATION

1.6.1 Blocking / Non blocking / Synchronous / Asynchronous

Message send and message receive communication primitives are done through Send() and Receive(), respectively.

A Send primitive has two parameters: *the destination*, and *the buffer* in the user space that holds the data to be sent.

The Receive primitive also has 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 called:

- **Buffered:** 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. 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.
- **Unbuffered**: The data gets copied directly from the user buffer onto thenetwork.

Blocking primitives

- The primitive commands wait for the message to be delivered. The execution of the processes is blocked.
- The sending process must wait after a senduntil an acknowledgement is made by the receiver.
- The receiving process must wait for the expected message from the sending process
- The receipt is determined by polling common buffer or interrupt
- This is a form of synchronization or synchronous communication.
- A primitive is blocking if control returns to the invoking process after the processing for the primitive completes.

Non Blocking primitives

- If send is nonblocking, it returns control to the caller immediately, before the message is sent.
- The advantage of this scheme is that the sending process can continue computing in parallel with the message transmission, instead of having the CPU go idle.
- This is a form of asynchronous communication.
- A primitive is non-blocking if control returnsback to the invoking process immediately after invocation, even thoughthe operation has not completed.
- For a non-blocking Send, control returnsto the process even before the data is copied out of the user buffer.
- For anon-blocking Receive, control returns to the process even before the datamay have arrived from the sender.

Synchronous

- 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 andthat the receive operation has been completed.
- The processing for theReceive primitive completes when the data to be received is copied intothe receiver's user buffer.

Asynchronous

- 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.

- Implementing non -blocking operations are tricky.
- 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:
  - checking if the handle has been flagged or posted
  - issue a Wait with a list of handles as parameters: usually blocks until one of the parameter handles is posted.

The send and receive primitives can be implemented in four modes:

- Blocking synchronous
- Non- blocking synchronous
- Blocking asynchronous
- Non- blocking asynchronous

Four modes of send 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.

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

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.

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.

- The asynchronous Send completes when the data has been copied out of the user's

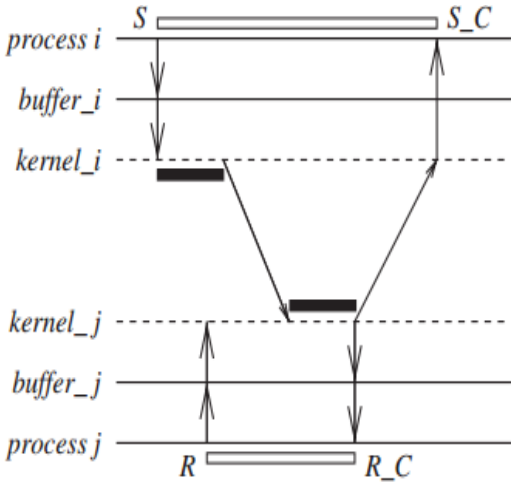


Fig 1.12 a) Blocking synchronous send and blocking receive

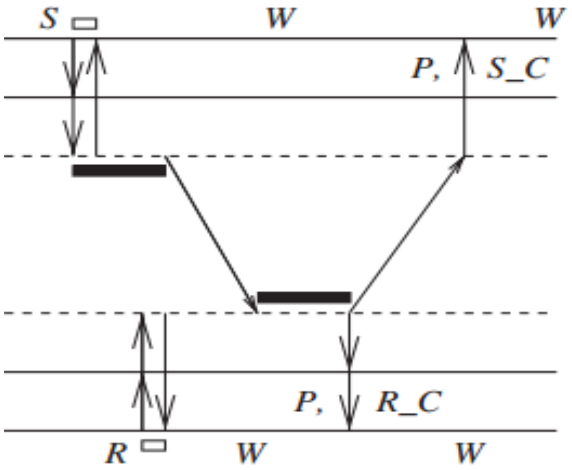


Fig 1.12 b) Non-blocking synchronous send and blocking receive

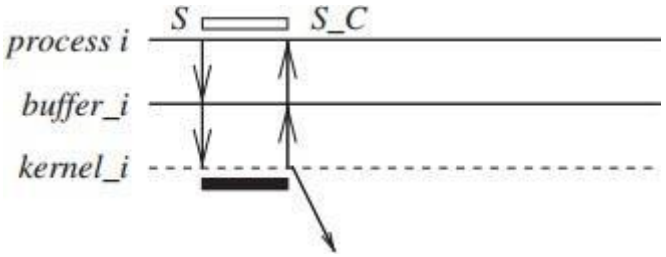


Fig 1.12 c) Blocking asynchronous send

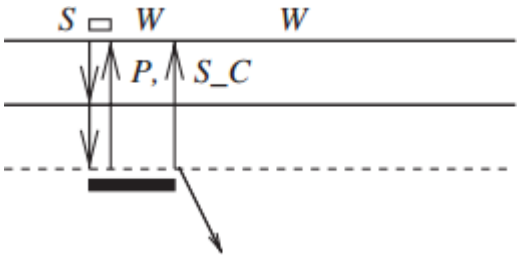


Fig 1.12 d) Non-blocking asynchronous send

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

Modes of receive operation

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 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.

1.6.2 Processor Synchrony

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

Since distributed systems do not follow a common clock, 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.

1.6.3 Libraries and standards

There exists a wide range of primitives for message-passing. The message-passing interface (MPI) library and the PVM (parallel virtual machine) library are used largely by the scientific community

- **Message Passing Interface (MPI):** This is a standardized and portable message-passing system to function on a wide variety of parallel computers. MPI primarily addresses the message-passing parallel programming model: data is moved from the address space of one process to that of another process through cooperative operations on each process.
  The primary goal of the Message Passing Interface is to provide a widely used standard for writing message passing programs.
- **Parallel Virtual Machine (PVM):** It is a software tool for parallel networking of computers. It is designed to allow a network of heterogeneous Unix and/or Windows machines to be used as a single distributed parallel processor.
- **Remote Procedure Call (RPC):** The Remote Procedure Call (RPC) is a common model of request reply protocol. In RPC, the procedure need not exist in the same address space as the calling procedure. The two processes may be on the same system, or they may be on different systems with a network connecting them.
- **Remote Method Invocation (RMI):** RMI (Remote Method Invocation) is a way that a programmer can write object-oriented programming in which objects on different computers can interact in a distributed network. It is a set of protocols being developed by Sun's JavaSoft division that enables Java objects to communicate remotely with other Java objects.
- **Remote Procedure Call (RPC):** RPC is a powerful technique for constructing distributed, client-server based applications. In RPC, the procedure need not exist in the same address space as the calling procedure. The two processes may be on the same system, or they may be on different systems with a network connecting them. By using RPC, programmers of distributed applications avoid the details of the interface with the network. RPC makes the client/server model of computing more powerful and easier to program.

Differences between RMI and RPC

RMI	RPC
RMI uses an object oriented paradigm where the user needs to know the object and the method of the object he needs to invoke.	RPC is not object oriented and does not deal with objects. Rather, it calls specific subroutines that are already established
With RPC looks like a local call. RPC handles the complexities involved with passing the call from the local to the remote computer.	RMI handles the complexities of passing along the invocation from the local to the remote computer. But instead of passing a procedural call, RMI passes a reference to the object and the method that is being called.

The commonalities between RMI and RPC are as follows:

✔ They both support programming with interfaces.
✔ They are constructed on top of request-reply protocols.
✔ They both offer a similar level of transparency.

- **Common Object Request Broker Architecture (CORBA):** CORBA describes a messaging mechanism by which objects distributed over a network can communicate with each other irrespective of the platform and language used to develop those objects. The data representation is concerned with an external representation for the structured and primitive types that can be passed as the arguments and results of remote method invocations in CORBA. It can be used by a variety of programming languages.

1.7 SYNCHRONOUS VS ASYNCHRONOUS EXECUTIONS

The execution of process in distributed systems may be synchronous or asynchronous.

Asynchronous Execution:

A communication among processes is considered asynchronous, when every communicating process can have a different observation of the order of the messages being exchanged. In an asynchronous execution:

- there is no processor synchrony and there is no bound on the drift rate of processor clocks
- message delays are finite but unbounded
- no upper bound on the time taken by a process

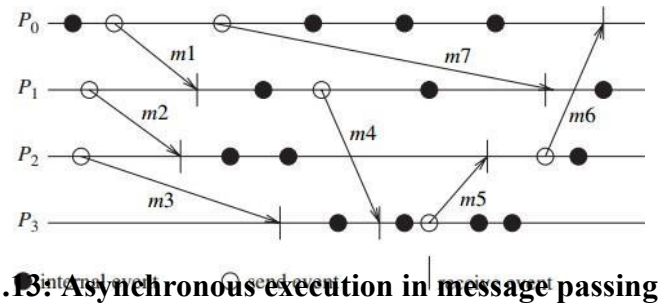


Fig 1.13: Asynchronous execution in message passing system

Synchronous Execution:

A communication among processes is considered synchronous when every process observes the same order of messages within the system. In the same manner, the execution is considered synchronous, when every individual process in the system observes the same total order of all the processes which happen within it. In an synchronous execution:

- processors are synchronized and the clock drift rate between any two processors is bounded
- message delivery times are such that theyoccur in one logical step or round
- upper boundon the time taken by a process to execute a step.

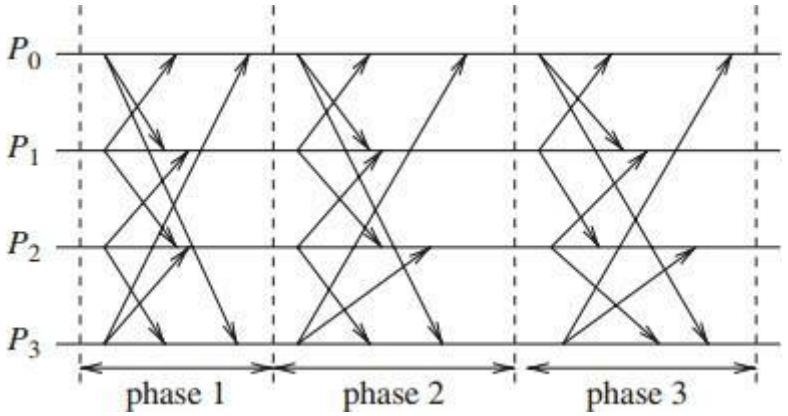


Fig 1.14: Synchronous execution

Emulating an asynchronous system by a synchronous system (A → S)

An asynchronous program can be emulated on a synchronous system fairly trivially as the synchronous system is a special case of an asynchronous system – all communication finishes within the same round in which it is initiated.

Emulating a synchronous system by an asynchronous system (S → A)

A synchronous program can be emulated on an asynchronous system using a tool called synchronizer.

Emulation for a fault free system

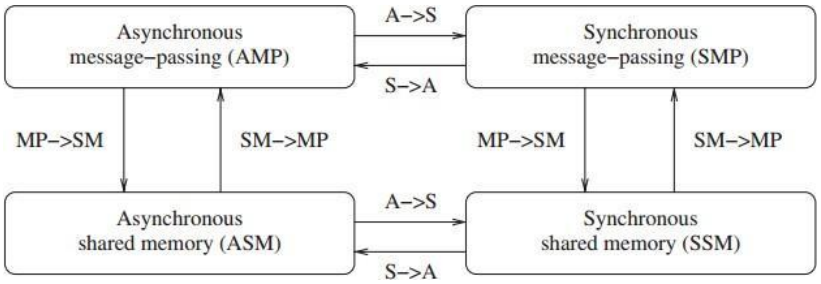


Fig 1.15: Emulations in a failure free message passing system

If system A can be emulated by system B, denoted A/B, and if a problem is not solvable in B, then it is also not solvable in A. If a problem is solvable in A, it is also solvable in B. Hence, in a sense, all four classes are equivalent in terms of computability in failure-free systems.

1.8 DESIGN ISSUES AND CHALLENGES IN DISTRIBUTED SYSTEMS

The design of distributed systems has numerous challenges. They can be categorized into:

- Issues related to system and operating systems design
- Issues related to algorithm design
- Issues arising due to emerging technologies

The above three classes are not mutually exclusive.

1.8.1 Issues related to system and operating systems design

The following are some of the common challenges to be addressed in designing a distributed system from system perspective:

- **Communication:** This task involves designing suitable communication mechanisms among the various processes in the networks.
  Examples: RPC, RMI
- **Processes:**The main challenges involved are:process and thread management at both client and server environments, migration of code between systems, design of software and mobile agents.
- **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. The remote and highly varied geographical locations make this task difficult.
- **Synchronization:** Mutual exclusion, leader election, deploying physical clocks, global state recording are some synchronization mechanisms.
- **Data storage and access Schemes:** Designing file systems for easy and efficient data storage with implicit accessing mechanism is very much essential for distributed operation
- **Consistency and replication:** The notion of Distributed systems goes hand in hand with replication of data, to provide high degree of scalability. The replicas should be handed with care since data consistency is prime issue.
- **Fault tolerance:**This requires maintenance of fail proof links, nodes, and processes. Some of the common fault tolerant techniques are resilience, reliable communication, distributed commit, checkpointing andrecovery, agreement and consensus, failure detection, and self-stabilization.
- **Security:**Cryptography, secure channels, access control, key management – generation and distribution, authorization, and secure group management are some of the security measure that is imposed on distributed systems.
- **Applications Programming Interface (API) and transparency:**The user friendliness and ease of use is very important to make the distributed services to be used by wide community. Transparency, which is hiding inner implementation policy from users, is of the following types:
  - **Access transparency:** hides differences in data representation
  - **Location transparency:** hides differences in locations y providing uniform access to data located at remote locations.
  - **Migration transparency:** allows relocating resources without changing names.
  - **Replication transparency:** Makes the user unaware whether he is working on original or replicated data.
  - **Concurrency transparency:** Masks the concurrent use of shared resources for the user.
  - **Failure transparency**: system being reliable and fault-tolerant.
- **Scalability and modularity:** The algorithms, data and servicesmust be as distributed as possible. Various techniques such as replication,caching and cache management, and asynchronous processing help toachieve scalability.

1.8.2 Algorithmic challenges in distributed computing

- **Designing useful execution models and frameworks**
  The interleaving model, partial order model, input/output automata model and the Temporal Logic of Actions (TLA) are some examples of models that provide different degrees of infrastructure.

- **Dynamic distributed graph algorithms and distributed routingalgorithms**

- The distributed system is generally modeled as a distributed graph.

- Hence graphalgorithms are the base for large number of higher level communication, data dissemination, object location, and object search functions.
- These algorithms must have the capacity to deal with highly dynamic graph characteristics. They are expected to function like routing algorithms.
- The performance of these algorithms has direct impact on user-perceived latency, data traffic and load in the network.

Time and global state in a distributed system

- The geographically remote resources demands the synchronization based on logical time.
- Logical time is relative and eliminates the overheads of providing physical time for applications.Logical time can
  (i) capturethe logic and inter-process dependencies
  (ii) track the relative progress at each process
- Maintaining the global state of the system across space involves the role of time dimension for consistency. This can be done with extra effort in a coordinated manner.
- Deriving appropriate measures of concurrency also involves the timedimension, as the execution and communication speed of threads may vary a lot.

Synchronization/coordination mechanisms

- Synchronization is essential for the distributed processes to facilitate concurrent execution without affecting other processes.
- The synchronization mechanisms also involveresource management and concurrency managementmechanisms.
- Some techniques for providing synchronization are:
  - ✔ **Physical clock synchronization:** Physical clocks usually diverge in theirvalues due to hardware limitations. Keeping them synchronized is a fundamental challenge to maintain common time.
  - ✔ **Leader election:** All the processes need to agree on which process willplay the role of a distinguished process or a leader process. A leaderis necessary even for many distributed algorithms because there is often some asymmetry.
  - ✔ **Mutual exclusion:**Access to the critical resource(s) has to be coordinated.
  - ✔ **Deadlock detection and resolution:**This is done to avoid duplicate work, and deadlock resolution shouldbe coordinated to avoid unnecessary aborts of processes.
  - ✔ **Termination detection**: cooperation among the processesto detect the specific global state of quiescence.
  - ✔ **Garbage collection:** Detecting garbage requirescoordination among the processes.

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. Group management protocols are needed for group communication wherein processes can join and leave groups dynamically, or fail.
- The concurrent execution of remote processes may sometimes violate the semantics and order of the distributed program. Hence, a formal specification of the semantics ofordered delivery need to be formulated, and then implemented.

- **Monitoring distributed events and predicates**

- Predicates defined on program variables that are local to different processesare used for specifying conditions on the global system state.

- On-line algorithms for monitoring such predicates are henceimportant.
- An important paradigm for monitoring distributed events is thatof event streaming, wherein streams of relevant events reported from different processes are examined collectively to detect predicates.
- Thespecification of such predicates uses physical or logical time relationships.

Distributed program design and verification tools

Methodically designed and verifiably correct programs can greatly reduce theoverhead of software design, debugging, and engineering.Designing these is a big challenge.

Debugging distributed programs

Debugging distributed programs is much harder because of the concurrency and replications. Adequate debugging mechanisms and tools are need of the hour.

Data replication, consistency models, and caching

- Fast access to data and other resources is important in distributed systems.
- Managing replicas and their updates faces concurrency problems.
- Placement of the replicas in the systems is also a challengebecause resources usually cannot be freely replicated.

World Wide Web design – caching, searching, scheduling

- WWWis a commonly known distributed system.
- The issues of object replication and caching, prefetching of objects have to be done on WWW also.
- Object search and navigationon the web are important functions in the operation of the web.

Distributed shared memory abstraction

- A shared memory is easier to implement since it does not involve managing the communication tasks.
- The communication is done by the middleware by message passing.
- The overhead of shared memory is to be dealt by the middleware technology.
- Some of the methodologies that does the task of communication in shared memory distributed systems are:
  - ✔ **Wait-free algorithms:** The ability of a process to complete its execution irrespective of theactions of other processes is wait free algorithm. They control the access to shared resources in the shared memory abstraction. They are expensive.
  - ✔ **Mutual exclusion:** Concurrent access of processes to a shared resource or data is executed in mutually exclusive manner. Only one process is allowed to execute the critical section at any given time. In a distributed system, shared variables or a local kernel cannot be used to implement mutual exclusion. Message passing is the sole means for implementing distributed mutual exclusion.
  - ✔ **Register constructions:**Architectures must be designed in such a way that, registers allows concurrent access without any restrictions on the concurrency permitted.

Reliable and fault-tolerant distributed systems

The following are some of the fault tolerant strategies:

- ✔ **Consensus algorithms:** Consensus algorithms allow correctly functioning processes to reach agreement among themselves in spite of the existence of malicious processes. The goal of the malicious processesis to prevent the correctly functioning processes from reaching agreement.The malicious processes operate

by sending messages with misleadinginformation, to confuse the correctly functioning processes.

- ✔ **Replication and replica management:** The Triple Modular Redundancy (TMR) technique is used in software and hardware implementation. TMR is a fault-tolerant form of N-modular redundancy, in which three systems perform a process and that result is processed by a majority-voting system to produce a single output.
- ✔ **Voting and quorum systems**: Providing redundancy in the active or passive components in the systemand then performing voting based on some quorum criterion is a classicalway of dealing with fault-tolerance. Designing efficient algorithms for thispurpose is the challenge.
- ✔ **Distributed databases and distributed commit:** The distributeddatabases should also follow atomicity, consistency, isolation and durability (ACID) properties.
- ✔ **Self-stabilizing systems:** All system executions have associated good(or legal) states and bad (or illegal) states; during correct functioning,the system makes transitions among the good states. A self-stabilizing algorithm guarantee to take the system to a good state even if a bad state were toarise due to some error. Self-stabilizing algorithms require some in-builtredundancy to track additional variables of the state and do extra work.
- ✔ **Checkpointing and recovery algorithms:**Checkpointing is periodically recording the current state on secondary storage so that, in case ofa failure. The entire computation is not lost but can be recovered from oneof the recently taken checkpoints. Checkpointing in a distributed environment is difficult because if the checkpoints at the different processes arenot coordinated, the local checkpoints may become useless because theyare inconsistent with the checkpoints at other processes.
- ✔ **Failure detectors:**The asynchronous distributed do not have a bound on the message transmission time. This makes the message passing very difficult, since the receiver do not know the waiting time. Failure detectors probabilistically suspect another process as havingfailed and then converge on a determination of the up/down status of thesuspected process.

- **Load balancing**

The objective of load balancing is to gain higher throughput, and reduce the userperceived latency. Load balancing may be necessary because of a variety offactors such as high network traffic or high request rate causing the networkconnection to be a bottleneck, or high computational load. The following aresome forms of load balancing:

- ✔ **Data migration:** The ability to move data around in the system, based on the access pattern of the users
- ✔ **Computation migration**: The ability to relocate processes in order toperform a redistribution of the workload.
- ✔ **Distributed scheduling:** This achieves a better turnaround time for theusers by using idle processing power in the system more efficiently.

- **Real-time scheduling**

Real-time scheduling becomes more challenging when a global view of the system state is absent with more frequent on-line or dynamic changes. The message propagation delays which are network-dependentare hard to control or predict. This is an hindrance to meet the QoS requirements of the network.

- **Performance**

  User perceived latency in distributed systems must be reduced. The common issues in performance:
  - ✔ **Metrics:** Appropriate metrics must be defined for measuring the performance of theoretical distributed algorithms and its implementation.
  - ✔ **Measurement methods/tools:**The distributed system is a complexentity appropriate methodology andtools must be developed for measuring the performance metrics.

1.8.3 Applications of distributed computing and newer challenges

The deployment environment of distributed systems ranges from mobile systems to cloud storage. All the environments have their own challenges:

- **Mobile systems**

- Mobile systems which use wireless communication in shared broadcast mediumhave issues related to physical layer such as transmission range, power, battery power consumption, interfacing with wired internet, signal processing and interference.
- The issues pertaining to other higher layers includerouting, location management, channel allocation, localization and position estimation, and mobility management.
- Apart from the above mentioned common challenges, the architectural differences of the mobile network demands varied treatment. The two architectures are:
  - ✔ **Base-station approach (cellular approach):** The geographical region is divided into hexagonal physical locations called cells. The powerful base station transmits signals to all other nodes in its range
  - ✔ **Ad-hoc network approach:**This is an infrastructure-less approach which do not have any base station to transmit signals. Instead all the responsibilityis distributed among the mobile nodes.
  - ✔ It is evident that both the approaches work in different environment with different principles of communication. Designing a distributed system to cater the varied need is a great challenge.

- **Sensor networks**

- A sensor is a processor with an electro-mechanical interface that is capable ofsensing physical parameters.
- They are low cost equipment with limited computational power and battery life. They are designed to handle streaming data and route it to external computer network and processes.
- They are susceptible to faults and have to reconfigure themselves.
- These features introduces a whole newset of challenges, such as position estimation and time estimation when designing a distributed system .

- **Ubiquitous or pervasive computing**

- In Ubiquitous systems the processors are embedded in the environment to performapplication functions in the background.
- **Examples:** Intelligent devices, smart homes etc.
- They are distributed systems with recent advancements operating in wireless environments through actuator mechanisms.
- They can be self-organizing and network-centricwith limited resources.

- **Peer-to-peer computing**

- Peer-to-peer (P2P) computing is computing over an application layernetwork where all interactions among the processors are at a same level.

- This is a form of symmetric computation against the client sever paradigm.
- They are self-organizing with or without regular structure to the network.
- Some of the key challenges include: object storage mechanisms, efficient object lookup, and retrieval in a scalable manner; dynamic reconfiguration with nodes as well as objects joining and leaving the networkrandomly; replication strategies to expedite object search; tradeoffs betweenobject size latency and table sizes; anonymity, privacy, and security.

Publish-subscribe, content distribution, and multimedia

- The users in present day require only the information of interest.
- In a dynamic environment where the informationconstantly fluctuates there is great demand for
  (i) **Publish:**an efficient mechanism for distributing this information
  (ii) **Subscribe:** an efficient mechanism to allow end users to indicate interest in receiving specific kinds of information
  (iii) An efficient mechanism foraggregating large volumes of published information and filtering it as per theuser's subscription filter.
- Content distribution refers to a mechanism that categorizes the information based on parameters.
- The publish subscribe and content distribution overlap each other.
- Multimedia data introduces special issue because of its large size.

Distributed agents

- Agents are software processes or sometimes robots that move around the systemto do specific tasks for which they are programmed.
- Agents collect and process information and can exchangesuch information with other agents.
- Challenges in distributed agent systems include coordination mechanisms among the agents, controlling the mobility of the agents,their software design and interfaces.

Distributed data mining

- Data mining algorithms process large amount of data to detect patternsand trends in the data, to mine or extract useful information.
- Themining can be done by applying database and artificial intelligence techniquesto a data repository.

Grid computing

- Grid computing is deployed to manage resources. For instance, idle CPU cycles of machines connected to the network will be available to others.
- The challenges includes:scheduling jobs, framework for implementing quality of service, real-time guarantees,security.

Security in distributed systems

- The challenges of security in a distributed setting include: confidentiality, authentication and availability. This can be addressed usingefficient and scalable solutions.

1.9 A MODEL OF DISTRIBUTED COMPUTATIONS: DISTRIBUTED PROGRAM

- A distributed program is composed of a set of asynchronous processes that

communicate by message passing over thecommunication network. Each process may run on different processor.

- The processes do not share a global memory and communicate solely by passing messages. These processes do not share a global clock that is instantaneously accessible tothese processes.
- Process execution and message transfer are asynchronous – aprocess 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 ischaracterized 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 thechannel.

1.9.1 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.
- 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 changes the state of the process that sends the message and the state of the channel on which the message is sent.
- The execution of process pi produces a sequence of events e1, e2, e3, …, and it is denoted by H_i: $H_i = (h_i \Box_i)$. Here $h_i$are states produced by p_i and $\Box$are the casual dependencies among events p_i.

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

- $\Box_{msg}$indicates the dependency that exists due to message passing between two events.

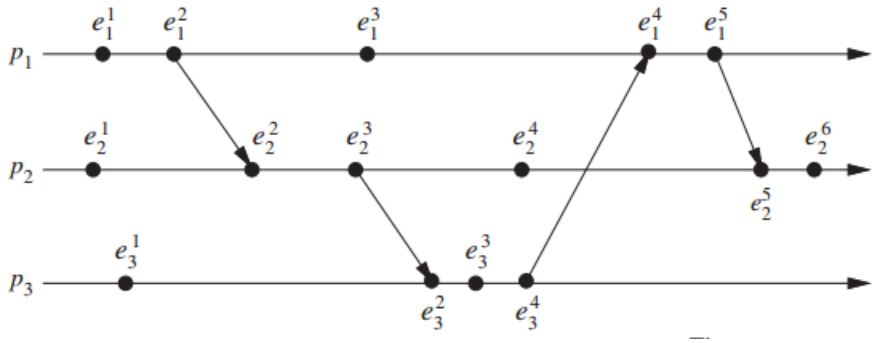


Fig 1.16: Space time distribution of distributed systems

- An internal event changes the state of the process at which it occurs.A send event changes the state of the process that sends the message andthe state of the channel on which the message is sent.
- A receive event changes the state of the process that receives the messageand the state of the channel on which the message is received.

1.9.2 Casual Precedence Relations

Causal message ordering is a partial ordering of messages in a distributed computing environment. It is the delivery of messages to a process in the order in which they were transmitted to that process.

It places a restriction on communication between processes by requiring that if the transmission of message m_i to process p_k necessarily preceded the transmission of message m_j to the same process, then the delivery of these messages to that process must be ordered such that m_i is delivered before m_j.

Happen Before Relation

The partial ordering obtained by generalizing the relationship between two process is called as ***happened-before relation or causal ordering or potential causal ordering.*** This term was coined by Lamport. Happens-before defines a partial order of events in a distributed system. Some events can't be placed in the order. If say A →B if A happens before B. A□B is defined using the following rules:

- ✔ **Local ordering:**A and B occur on same process and A occurs before B.
- ✔ **Messages:** send(m) → receive(m) for any message m
- ✔ **Transitivity:** e → e'' if e → e' and e' → e''

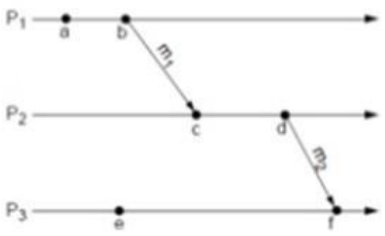
- Ordering can be based on two situations:

1. If two events occur in same process then they occurred in the order observed.
2. During message passing, the event of sending message occurred before the event of receiving it.

Lamports ordering is happen before relation denoted by □

- a□b, if a and b are events in the same process and a occurred before b.
- a□b, if a is the vent of sending a message m in a process and b is the event of the same message m being received by another process.
- If a□b and b□c, then a□c. Lamports law follow transitivity property.

When all the above conditions are satisfied, then it can be concluded that a□b is



casually related. Consider two events c and d; c□d and d□c is false (i.e) they are not casually related, then c and d are said to be concurrent events denoted as c||d.

Fig 1.17: Communication between processes

Fig 1.22 shows the communication of messages m1 and m2 between three processes p1, p2 and p3. a, b, c, d, e and f are events. It can be inferred from the diagram that, a□b; c□d; e□f; b->c; d□f; a□d; a□f; b□d; b□f. Also a||e and c||e.

1.9.3 Logical vs physical concurrency

Physical as well as logical concurrency is two events that creates confusion in distributed systems.

Physical concurrency: Several program units from the same program that execute simultaneously.
Logical concurrency: Multiple processors providing actual concurrency. The actual execution of programs is taking place in interleaved fashion on a single processor.

Differences between logical and physical concurrency

Logical concurrency	Physical concurrency
Several units of the same program execute simultaneously on same processor, giving an illusion to the programmer that they are executing on multiple processors.	Several program units of the same program execute at the same time on different processors.
They are implemented through interleaving.	They are implemented as uni-processor with I/O channels, multiple CPUs, network of uni or multi CPU machines.

1.10 MODELS OF COMMUNICATION NETWORK

The three main types of communication models in distributed systems are:

- **FIFO (first-in, first-out):** each channel acts as a FIFO message queue.
- **Non-FIFO (N-FIFO):** a channel acts like a set in which a sender process adds messages and receiver removes messages in random order.
- **Causal Ordering (CO):** It follows Lamport's law.
    - The relation between the three models is given by CO ⊂ FIFO ⊂ N-FIFO.

A system that supports the causal ordering model satisfies the following property:

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

1.11 GLOBAL STATE

Distributed Snapshot represents a state in which the distributed system might have been in. A snapshot of the system is a single configuration of the 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 state of a channel is difficult to state formally because a channel is a distributed entity and its state depends upon the states of the processes it connects. Let $SC_{ij}^{x,y}$ denote the state of a channel C_{ij} defined as follows:

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

A distributed snapshot should reflect a consistent state. A global state is consistent if it could have been observed by an external observer. For a successful Global State, all states must be consistent:

- If we have recorded that a process P has received a message from a process Q, then we should have also recorded that process Q had actually send that message.

- Otherwise, a snapshot will contain the recording of messages that have been received but never sent.
- The reverse condition (Q has sent a message that P has not received) is allowed.

The notion of a global state can be graphically represented by what is called a **cut**. A cut represents the last event that has been recorded for each process.
The history of each process if given by:

$$history(p_i) = h_i = <e_i^0, e_i^1, e_i^2, \ldots>$$

Each event either is an internal action of the process. We denote by s_i^k the state of process p_i immediately before the k^{th} event occurs. The state s_i in the global state S corresponding to the cut C is that of p_i immediately after the last event processed by p_i in the cut – ei^{ci} . The set of events ei^{ci} is called the frontier of the cut.

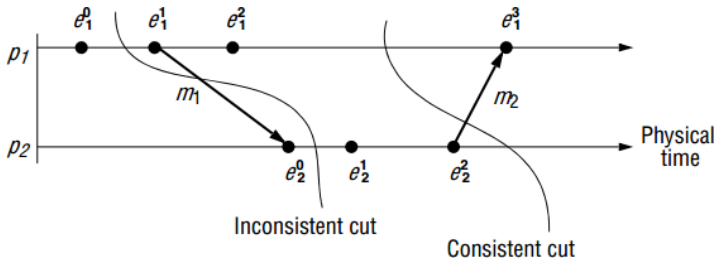


Fig 1.18: Types of cuts

Consistent states: The states should not violate causality. Such states are called consistent global states and are meaningful global states.

Inconsistent global states: They are not meaningful in the sense that a distributed system can never be in an inconsistent state.

UNIT II

This technique results in considerable saving in the cost; only one scalar is piggybacked on every message.

2.1 PHYSICAL CLOCK SYNCHRONIZATION: NEWTWORK TIME PROTOCOL (NTP)

Centralized systems do not need clock synchronization, as they work under a common clock. But the distributed systems do not follow common clock: each system functions based on its own internal clock and its own notion of time.The time in distributed systems is measured in the following contexts:

- The time of the day at which an event happened on a specific machine in the network.
- The time interval between two events that happened on different machines in the network.
- The relative ordering of events that happened on different machines in the network.

Clock synchronization is the process of ensuring that physically distributed processors have a common notion of time.

Due to different clocks rates, the clocks at various sites may diverge with time, and periodically a clock synchrinization must be performed to correct this clock skew in distributed systems. Clocks are synchronized to an accurate real-time standard like UTC (Universal Coordinated Time). Clocks that must not only be synchronized with each other but also have to adhere to physical time are termed **physical clocks**. This degree of synchronization additionally enables to coordinate and schedule actions between multiple computers connected to a common network.

2.1.1Basic terminologies:

If C_a and C_b are two different clocks, then:

- **Time:** The time of a clock in a machine p is given by the function $C_p(t)$,where $C_p(t)= t$ for a perfect clock.
- **Frequency:** Frequency is the rate at which a clock progresses. The frequency at time t of clock $C_a$is$C_a'(t)$.
- **Offset:**Clock offset is the difference between the time reported by a clockand the real time. The offset of the clock C_a is given by $C_a(t)- t$. Theoffset of clock C a relative to C_b at time $t \geq 0$ is given by $C_a(t)- C_b(t)$
- **Skew:** The skew of a clock is the difference in the frequencies of the clockand the perfect clock. The skew of a clock C_a relative to clock C_b at timet is $C_a'(t)- C_b'(t)$.
- **Drift (rate):** The drift of clock C_a the second derivative of the clockvalue with respect to time. The drift is calculated as:

$$C_a''(t) - C_b''(t).$$

Clocking Inaccuracies

Physical clocks are synchronized to an accurate real-time standard like UTC (Universal Coordinated Time). Due to the clock inaccuracy discussed above, a timer (clock) is said to be working within its specification if:

$$1 - \rho \leq \frac{dC}{dt} \leq 1 + \rho.$$

ρ- maximum skew rate.

1. Offset delay estimation

A time service for the Internet - synchronizes clients to UTC Reliability from redundant paths, scalable, authenticates time sources Architecture. Thedesign of NTP involves a hierarchical tree of time servers with primary serverat the root synchronizes with the UTC. The next level contains secondaryservers, which act as a backup to the primary server. At the lowest level isthe synchronization subnet which has the clients.

2. Clock offset and delay estimation

A source node cannot accurately estimate the local time on thetarget node due to varying message or network delays between the nodes.This protocol employs a very common practice of performing several trialsand chooses the trial with the minimum delay.

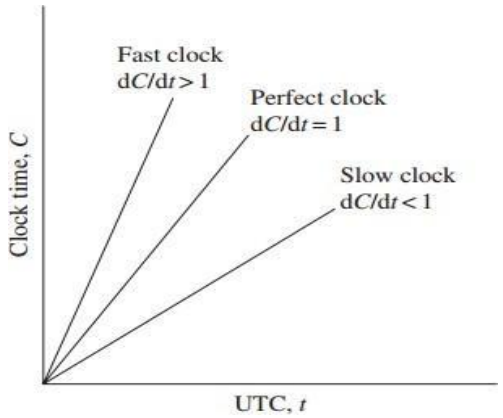


Fig 1.24: Behavior of clocks

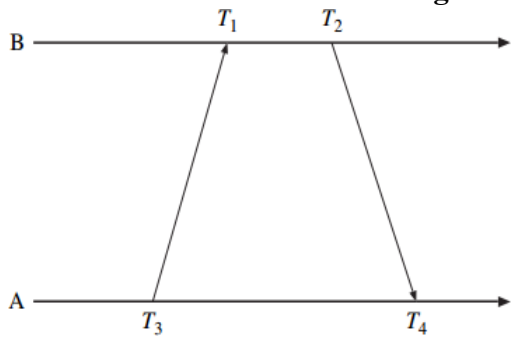


Fig 1.30 a) Offset and delay estimation between processes from same server

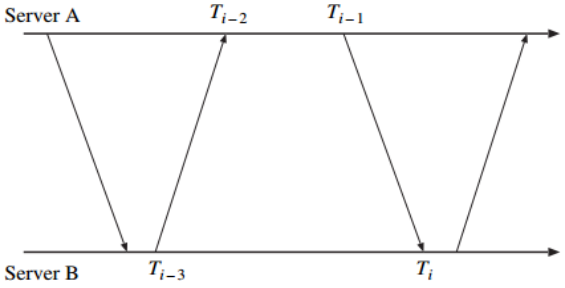


Fig 1.30 b) Offset and delay estimation between processes from different servers

Let T1, T2, T3, T4 be the values of the four mostrecent timestamps. The clocks A and B are stable andrunning at the same speed. Let a = T1 − T3 and b = T2 − T4. If the networkdelay difference from A to B and from B to A, called **differential delay**, is small, the clock offset θand roundtrip delayδ of B relative to A at time T4are

$$\theta = \frac{a+b}{2}, \qquad \delta = a - b$$

approximately given by the following:

Each NTP message includes the latest three timestamps T1, T2, andT3, while T4 is determined upon arrival.

MODELS OF PROCESS COMMUNICATIONS

There are two basic models of process communications

- **Synchronous:** The sender process blocks until the message has been received by the receiver process. The sender process resumes executiononly after it learns that the receiver process has accepted the message. The sender and the receiver processes must synchronize to exchange a message.
- **Asynchronous**: It is non- blocking communication where the sender and the receiver do not synchronize to exchange 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 number of messages in a burst to another process, thus causing a message burst.

Asynchronous communication achieves high degree of parallelism and non-determinism at the cost of implementation complexity with buffers. On the other hand, synchronization is simpler with low performance. The occurrence of deadlocks and frequent blocking of events prevents it from reaching higher performance levels.

LOGICAL TIME

Logical clocks are based on capturing chronological and causal relationships of processes and ordering events based on these relationships.

Precise physical clocking is not possible in distributed systems. The asynchronous distributed systems spans logical clock for coordinating the events.Three types of logical clock are maintained in distributed systems:

- Scalar clock
- Vector clock
- Matrix clock

In a system of logical clocks, every process has a logical clock that is advanced using a set of rules. Every event is assigned a timestamp and the causality relation between events can be generally inferred from their timestamps.

The timestamps assigned to events obey the fundamental monotonicity property; that is, if an event a causally affects an event b, then the timestamp of *a* is smaller than the timestamp of *b*.

Differences between physical and logical clock

Physical Clock	Logical Clock
A physical clock is a physical procedure combined with a strategy for measuring that procedure to record the progression of time.	A logical clock is a component for catching sequential and causal connections in a dispersed framework.
The physical clocks are based on cyclic processes such as a celestial rotation.	A logical clock allows global ordering on events from different processes.

2.2 A Framework for a system of logical clocks

A system of logical clocks consists of a time domain T and a logical clock C. Elements of T form a partially ordered set over a relation <. This relation is usually called the happened before or causal precedence.

The logical clock C is a function that maps an event e in a distributed system to an element in the time domain T denoted as C(e).

$$C : H \mapsto T \text{ such}$$

that for any two events e_i and e_j, $e_i \rightarrow e_j \Rightarrow C(e_i) < C(e_j)$.

This monotonicity property is called the **clock consistency condition.**When T and C satisfy the following condition,

$$e_i \rightarrow e_j \Leftrightarrow C(e_i) < C(e_j)$$

Then the system of clocks is **strongly consistent.**

Implementing logical clocks

The two major issues in implanting logical clocks are:

- **Data structures:** representation of each process
- **Protocols:** rules for updating the data structures to ensure consistent conditions.

Data structures:

Each process $p_i$maintains data structures with the given capabilities:

• A local logical clock (lc_i), that helps process p_i measure itsown progress.

• A logical global clock (gc_i), that is a representation of process p_i's local view of the logical global time. It allows this process to assignconsistent timestamps to its local events.

Protocol:

The protocol ensures that a process's logical clock, and thus its view of theglobal time, is managed consistently with the following rules:

Rule 1: Decides the updates of the logical clock by a process. It controls send, receive and other operations.

Rule 2: Decides how a process updates its global logical clock to update its view of the global time and global progress. It dictates what information about the logical time is piggybacked in a message and how this information is used by the receiving process to update its view of the global time.

2.3.Scalar Time

Scalar time is designed by Lamport to synchronize all the events in distributed systems. A Lamport logical clock is an incrementing counter maintained in each process. This logical clock has meaning only in relation to messages moving between processes. When a process receives a message, it resynchronizes its logical clock with that sender maintainingcausal relationship.

The Lamport's algorithm is governed using the following rules:

- The algorithm of Lamport Timestamps can be captured in a few rules:
- All the process counters start with value 0.
- A process increments its counter for each event (internal event, message sending, message receiving) in that process.
- When a process sends a message, it includes its (incremented) counter value with the message.
- On receiving a message, the counter of the recipient is updated to the greater of its current counter and the timestamp in the received message, and then incremented by one.

If C_i is the local clock for process P_i then,

- if a and b are two successive events in P_i, then $C_i(b) = C_i(a) + d1$, where $d1 > 0$
- if a is the sending of message m by P_i, then m is assigned timestamp $t_m = C_i(a)$
- if b is the receipt of m by P_j, then $C_j(b) = \max\{C_j(b), t_m + d2\}$, where $d2 > 0$

Rules of Lamport's clock

Rule 1: $C_i(b) = C_i(a) + d1$, where $d1 > 0$

Rule 2: The following actions are implemented when p_i receives a message m with timestamp C_m:

- ***$C_i = max(C_i, C_m)$***
- ***Execute Rule 1***
- ***deliver the message***

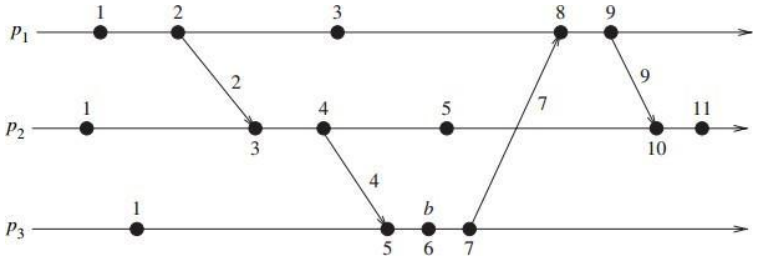


Fig 1.20: Evolution of scalar time

Basic properties of scalar time:

1. **Consistency property:** Scalar clock always satisfies monotonicity. A monotonic clock only increments its timestamp and never jump.Hence it is consistent.

$$C(e_i) < C(e_j)$$

2. **Total Reordering:**Scalar clocks order the events in distributed systems.But all the events do not follow a common identical timestamp. Hence a tie breaking mechanism is essential to order the events. The tie breaking is done through:

- Linearly order process identifiers.
- Process with low identifier value will be given higher priority.

The term (t, i) indicates timestamp of an event, where t is its time of occurrence and i is the identity of the process where it occurred.

The total order relation ($\prec$) over two events x and y with timestamp (h, i) and (k, j) is given by:

$$x \prec y \Leftrightarrow (h < k \text{ or } (h = k \text{ and } i < j))$$

A total order is generally used to ensure liveness properties in distributed algorithms.

3. Event Counting

If event e has a timestamp h, then h−1 represents the minimum logical duration, counted in units of events, required before producing the event e. This is called **height** of the event e. h-1 events have been produced sequentially before the event e regardless of the processes that produced these events.

4. No strong consistency

The scalar clocks are not strongly consistent is that the logical local clock and logical global clock of a process are squashed into one, resulting in the loss causal dependency information among events at different processes.

2.4.Vector Time

The ordering from Lamport's clocks is not enough to guarantee that if two events precede one another in the ordering relation they are also causally related. Vector Clocks use a vector counter instead of an integer counter. The vector clock of a system with N processes is a vector of N counters, one counter per process. Vector counters have to follow the following update rules:

- Initially, all counters are zero.
- Each time a process experiences an event, it increments its own counter in the vector by one.
- Each time a process sends a message, it includes a copy of its own (incremented) vector in the message.
- Each time a process receives a message, it increments its own counter in the vector by one and updates each element in its vector by taking the maximum of the value in its own vector counter and the value in the vector in the received message.

The time domain is represented by a set of n-dimensional non-negative integer vectors in vector time.

Rules of Vector Time

Rule 1: Before executing an event, process pi updates its local logical time as follows:

$$vt_i[i] := vt_i[i] + d \qquad (d > 0)$$

Rule 2: Each message m is piggybacked with the vector clock vt of the sender process at sending time. On the receipt of such a message (m,vt), process p_i executes the following sequence of actions:

- ***update its global logical time***

$$1 \le k \le n \ : \ vt_i[k] := max(vt_i[k], vt[k])$$

- ***execute R1***
- ***deliver the message m***

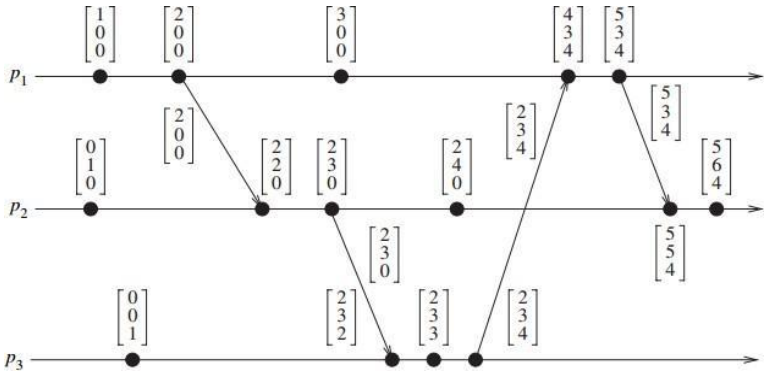


Fig 1.21: Evolution of vector scale

Basic properties of vector time

1. Isomorphism:

- "→" induces a partial order on the set of events that are produced by a distributed execution.
- If events x and y are timestamped as vh and vk then,

$$x \rightarrow y \Leftrightarrow vh < vk$$

$$x \parallel y \Leftrightarrow vh \parallel vk.$$

- There is an isomorphism between the set of partially ordered events produced by a distributed computation and their vector timestamps.
- If the process at which an event occurred is known, the test to compare two timestamps can be simplified as:

$$x \rightarrow y \Leftrightarrow vh[i] \le vk[i]$$

$$x \parallel y \Leftrightarrow vh[i] > vk[i] \wedge vh[j] < vk[j].$$

2. Strong consistency

The system of vector clocks is strongly consistent; thus, by examining the vector timestamp of two events, we can determine if the events are causally related.

3. Event counting

If an event e has timestamp vh, vh[j] denotes the number of events executed by process p_j that causally precede e.

Vector clock ordering relation

$t = t' \Leftrightarrow \forall i \ t[i] = t'[i]$

$t \neq t' \Leftrightarrow \exists i \ t[i] \neq t'[i]$

$t \le t' \Leftrightarrow \forall i \ t[i] \le t'[i]$

$t < t' \Leftrightarrow (t \le t' \text{ and } t \neq t')$

$t \,||\, t' \Leftrightarrow \text{not } (t < t' \text{ or } t' < t)$

t[i]- timestamp of process i.

Implementation of vector clock

If the number of processes in a distributed computation is large, then vector clocks will require piggybacking of huge amount of information in messages for the purpose of disseminating time progress and updating clocks. There are two implementation techniques:

- **Singhal–Kshemkalyani's differential technique**:

- This approach improves the message passing mechanism by only sending updates to the vector clock that have occurred since the last message sent from Process(i) → Process(j).
- This drastically reduces the message size being sent, but does require $O(n^2)$ storage. This is due to each node now needing to remember, for each other process, the state of the vector at the last message sent.
- This also requires FIFO message passing between processes, as it relies upon the guarantee of knowing what the last message sent is, and if messages arrive out of order this would not be possible.
- If entries $i_1, i_2, \ldots, i_n$ of the vector clock at p_i have changed to $v_1, v_2, \ldots, v_n$ respectively, since the last message sentto pj, then process pi piggybacks a compressed timestamp of the

$$\{(i_1, v_1), (i_2, v_2), \ldots, (i_{n_1}, v_{n_1})\}$$

form.

- When p_j receives this message, it updates its vector clock as follows:

$$vt_i[i_k] = max(vt_i[i_k], v_k) \text{ for } k = 1, 2, \ldots, n_1.$$

- This cuts down the message size, communication bandwidth and buffer (to store messages) requirements.
- The storage overhead is resolved by maintaining two vectors by process p_i :
  - $LS_i[1 \ldots n]$ ('Last Sent'):
    $LS_i[j]$ indicates the value of $vt_i[i]$ when process p_i last sent a message to process p_j.
  - $LU_i[1 \ldots n]$ ('Last Update'):
    $LU_i[j]$ indicates the value of $vt_i[i]$ when process p_i last updated the entry $vt_i[j]$.

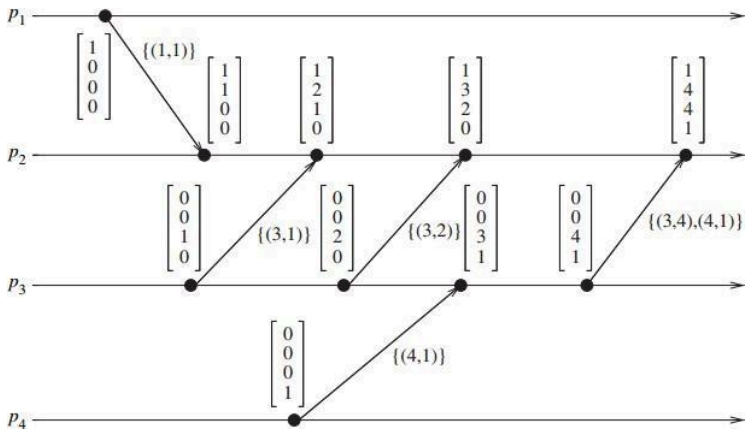


Fig .Vector clocks progress in Singhal–Kshemkalyani technique

- **Fowler-Zwaenepoel direct-dependency technique:**

- This technique further reduces the message size by only sending the single clock value of the sending process with a message.

- However, this means processes cannot know their transitive dependencies when looking at the causality of events.
- In order to gain a full view of all dependencies that lead to a specific event, an offline search must be made across processes.
- Each process p_i maintains a dependency vector D_i. Initially,

$$D_i[j] = 0 \text{ for } j = 1, \ldots, n.$$

- i is updated as follows:

1. Whenever an event occurs at p_i such that,

$$D_i[i] := D_i[i] + 1$$

2. When a process pi sends a message to process p_j, it piggybacks the updatedvalue of $D_i[i]$ in the message.

3. When p_i receives a message from p_j with piggybacked value d, $p_i$updates its dependency vector as follows: $D_i[j] := \max\{D_i[j], d\}$.

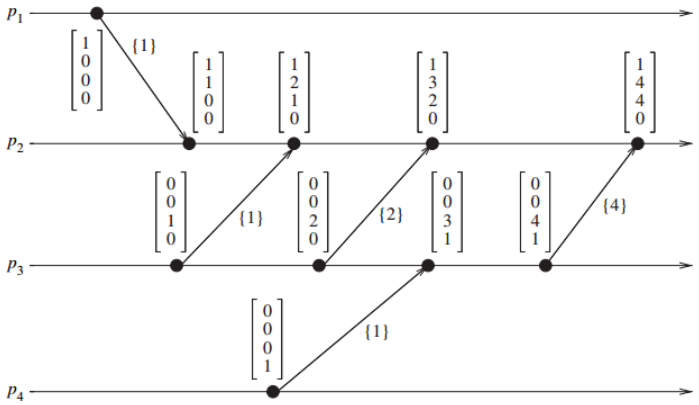


Fig . Vector clock progress in Fowler–Zwaenepoel technique

- Process p4 sends a message to process p3, it piggybacks a scalar that indicates the direct dependency of p3 on p4 because of this message.
- Process p3 sends a message to process p2 piggybacking a scalar to indicate the direct dependency of p2 on p3 because of this message.
- Process p2 is in fact indirectly dependent on process p4 since process p3 is dependent on process p4. However, process p2 is never informed about its indirect dependency on p4.

MESSAGE ORDERING & SNAPSHOTS

2.5.MESSAGE ORDERING AND GROUP COMMUNICATION

As the distributed systems are a network of systems at various physical locations, the coordination between them should always be preserved. The message ordering means the order of delivering the messages to the intended recipients. The common message order schemes are First in First out (FIFO), non FIFO, causal order and synchronous order. In case of group communication with multicasting, the causal and total ordering scheme is followed. It is also essential to define the behaviour of the system in case of failures. The following are the notations that are widely used in this chapter:

Distributed systems are denoted by a graph (N, L).

The set of events are represented by event set $\{E, \prec\}$

Message is denoted as m^i: send and receive events as s^i and r^i respectively.

Send (M) and receive (M) indicates the message M send and received.

a~b denotes a and b occurs at the same process

The send receive pairs $T=\{(s, r) \varepsilon E_i \times E_j$ corresponds to r$\}$

Message Ordering Paradigms

The message orderings are

(i) non-FIFO
(ii) FIFO
(iii) causal order
(iv) synchronous order

There is always a trade-off between concurrency and ease of use and implementation.

Asynchronous Executions

An asynchronous execution (or A-execution) is an execution (E, ≺) for which the causality relation is a partial order.

- There cannot be any causal relationship between events in asynchronous execution.
- The messages can be delivered in any order even in non FIFO.
- Though there is a physical link that delivers the messages sent on it in FIFO order due to the physical properties of the medium, a logicallink may be formed as a composite of physical links and multiple paths mayexist between the two end points of the logical link.

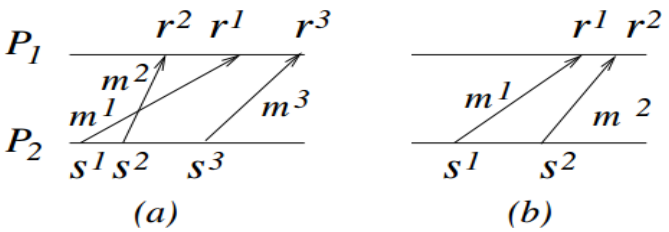


Fig 2.1: a) FIFO executions b) non FIFO executions

FIFO executions

A FIFO execution is an A-execution in which, for all
(s, r) and $(s', r') \in \mathcal{T}$, $(s \sim s'$ and $r \sim r'$ and $s \prec s') \Longrightarrow r \prec r'$.

- The logical link is non-FIFO.
- FIFO logical channels can be realistically assumed when designing distributed algorithms since most of the transport layer protocols follow connection oriented service.
- A FIFO logical channel can be created over a non-FIFO channel by using a separate numbering scheme to sequence the messages on each logical channel.
- The sender assigns and appends a <sequence_num, connection_id> tuple to each message.
- The receiver uses a buffer to order the incoming messages as per the sender's sequence numbers, and accepts only the "next" message in sequence.

Causally Ordered (CO) executions

CO execution is an A-execution in which, for all,
(s, r) and $(s', r') \in \mathcal{T}$, $(r \sim r'$ and $s \prec s') \Longrightarrow r \prec r'$

- Two send events s and s' are related by causality ordering (not physical time ordering), then a causally ordered execution requires that their corresponding receive events r and r' occur in the same order at all common destinations.
- If s and s' are not related by causality, then CO is vacuously satisfied.
- Causal order is used in applications that update shared data, distributed shared memory, or fair resource allocation.
- A message m that arrives in the local OS buffer at P_i may have to be delayed until the messages that were sent to P_i causally before m was sent have arrived and are processed by the application.
- The delayed message m is then given to the application for processing. The event of an application processing an arrived message is referred to as a **delivery event.**
- No message overtaken by a chain of messages between the same (sender, receiver) pair.

If $send(m^1) \prec send(m^2)$ then for each common destination d of messages m^1 and m^2, $deliverd(m^1) \prec deliverd(m^2)$ must be satisfied.

Other properties of causal ordering

1. **Message Order (MO):** A MO execution is an A-execution in which, for all

$$(s, r) \text{ and } (s', r') \in \mathcal{T}, s \prec s' \Longrightarrow \neg(r' \prec r).$$

2. **Empty Interval Execution:** An execution $(E \prec)$ is an empty-interval (EI) execution if for each pair of events $(s, r) \in T$, the open interval set

$$\{x \in E \mid s \prec x \prec r\}$$

in the partial order is empty.

3. An execution (E, $\prec$) is CO if and only if for each pair of events (s, r) $\in$ T and each event e $\in$ E,
   - weak common past:
   $$e \prec r \Longrightarrow \neg(s \prec e)$$
   - weak common future:
   $$s \prec e \Longrightarrow \neg(e \prec r).$$

Synchronous Execution

- When all the communication between pairs of processes uses synchronous send and receives primitives, the resulting order is the synchronous order.
- The synchronous communication always involves a handshake between the receiver and the sender, the handshake events may appear to be occurring instantaneously and atomically.
- The instantaneous communication property of synchronous executions requires a modified definition of the causality relation because for each (s, r) $\in$ T, the send event is not causally ordered before the receive event.
- The two events are viewed as being atomic and simultaneous, and neither event precedes the other.

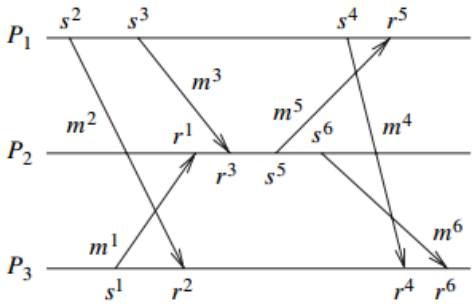


Fig 2.2 a) Execution in an asynchronous system

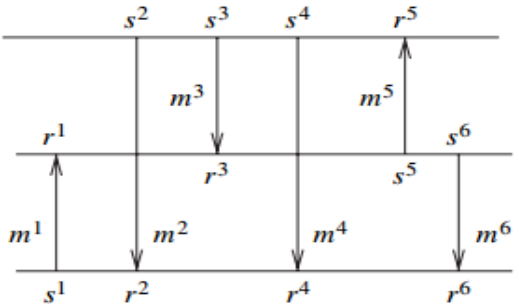


Fig 2.2 b) Equivalent synchronous communication

Causality in a synchronous execution: The synchronous causality relation << on E is the smallest transitive relation that satisfies the following:

S1: If x occurs before y at the same process, then x << y.

S2: If (s, r $\in$ T, then) for all x $\in$ E, [(x<< s $\Longleftrightarrow$ x<<r) and (s<< x $\Longleftrightarrow$ r<<

x)]. S3: If x<<y and y<<z, then x<<z.

Synchronous execution: A synchronous execution or S-execution is an execution (E, <<) for which the causality relation << is a partial order.

Timestamping a synchronous execution: An execution (E, $\prec$) is synchronous if and only if there exists a mapping from E to T (scalar timestamps) such that

- ***for any message M, T(s(M)) = T(r(M))***
- ***for each process P_i, if $e_i \prec e_i'$, then $T(e_i) < T(e_i')$.***

2.6.Asynchronous execution with synchronous communication

When all the communication between pairs of processes is by using synchronous send and receive primitives, the resulting order is synchronous order. The algorithms run on asynchronous systems will not work in synchronous system and vice versa is also true**.**

Realizable Synchronous Communication (RSC)

A-execution can be realized under synchronous communication is called a realizable with synchronous communication (RSC).

An execution can be modeled to give a total order that extends the partial order (E, $\prec$).

In an A-execution, the messages can be made to appear instantaneous if there exist a linear extension of the execution, such that each send event is immediately followed by its corresponding receive event in this linear extension.

Non-separated linear extension is an extension of (E, $\prec$) is a linear extension of (E, $\prec$) such that for each pair (s, r) $\in$ T, the interval { x$\in$ E s $\prec$ x $\prec$ r } is empty.

A A-execution (E, $\prec$) is an RSC execution if and only if there exists a non-separated linear extension of the partial order (E, $\prec$).

In the non-separated linear extension, if the adjacent send event and its corresponding receive event are viewed atomically, then that pair of events shares a common past and a common future with each other.

Crown

Let E be an execution. A crown of size k in E is a sequence <(s^i, r^i), i $\in${0,…, k-1}> of pairs of corresponding send and receive events such that: $s^0 \prec r^1$, $s^1 \prec r^2$, $s^{k-2} \prec r^{k-1}$, $s^{k-1} \prec r^0$.

The crown is <(s^1, r^1) (s^2, r^2)> as we have $s^1 \prec r^2$ and $s^2 \prec r^1$. Cyclic dependencies may exist in a crown. The crown criterion states that an A-computation is RSC, i.e., it can be realized on a system with synchronous communication, if and only if it contains no crown.

Timestamp criterion for RSC execution

An execution (E, $\prec$) is RSC if and only if there exists a mapping from E to T (scalar timestamps) such that

- for any message M, $T(s(M)) = T(r(M))$;
- for each (a, b) in $(E \times E) \setminus \mathcal{T}$, $a \prec b \Longrightarrow T(a) < T(b)$

2.2.1 Hierarchy of ordering paradigms

The orders of executions are:

- Synchronous order (SYNC)
- Causal order (CO)
- FIFO order (FIFO)
- Non FIFO order (non-FIFO)

The Execution order have the following results

For an A-execution, A is RSC if and only if A is an S-execution.

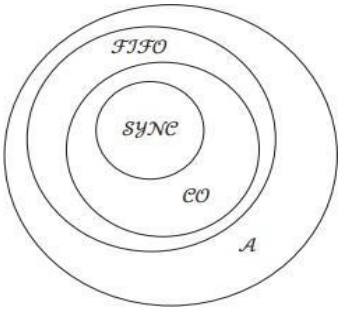
RSC ⊂ CO ⊂ FIFO ⊂ A

This hierarchy is illustrated in Figure 2.3(a), and example executions of each class are shown side-by-side in Figure 2.3(b)

The above hierarchy implies that some executions belonging to a class X will not belong to any of the classes included in X. The degree of concurrency is most in A and least in SYNC.

A program using synchronous communication is easiest to develop and verify.

A program using non-FIFO communication, resulting in an A execution, is hardest



to design and verify.

Fig (a)

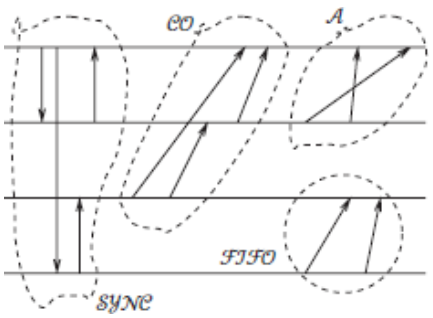


Fig (b)

Fig .Hierarchy of execution classes

Simulations

The events in the RSC execution are scheduled as per some non-separated linear extension, and adjacent (s, r) events in this linear extension are executed sequentially in the synchronous system.

The partial order of the asynchronous execution remains unchanged.

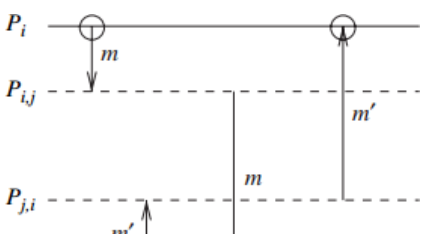
If an A-execution is not RSC, then there is no way to schedule the events to make them RSC, without actually altering the partial order of the given A-execution.

However, the following indirect strategy that does not alter the partial order can be used.

Each channel $C_{i,j}$ is modeled by a control process $P_{i,j}$ that simulates the channel buffer.

An asynchronous communication from i to j becomes a synchronous communication from i to $P_{i,j}$ followed by a synchronous communication from $P_{i,j}$ to j.

This enables the decoupling of the sender from the receiver, a feature that is essential



in asynchronous systems.

Fig .Modeling channels as processes to simulate an execution using asynchronous primitives on synchronous system

Synchronous programs on asynchronous systems

A (valid) S-execution can be trivially realized on an asynchronous system by scheduling the messages in the order in which they appear in the S-execution.

The partial order of the S-execution remains unchanged but the communication occurs on an asynchronous system that uses asynchronous communication primitives.

Once a message send event is scheduled, the middleware layer waits for acknowledgment; after the ack is received, the synchronous send primitive completes.

2.7.SYNCHRONOUS PROGRAM ORDER ON AN ASYNCHRONOUS SYSTEM

Non deterministic programs

The partial ordering of messages in the distributed systems makes the repeated runs of the same program will produce the same partial order, thus preserving deterministic nature. But sometimes the distributed systems exhibit non determinism:

A receive call can receive a message from any sender who has sent a message, if the expected sender is not specified.

Multiple send and receive calls which are enabled at a process can be executed in an interchangeable order.

If i sends to j, and j sends to i concurrently using blocking synchronous calls, there results a deadlock.

There is no semantic dependency between the send and the immediately following receive at each of the processes. If the receive call at one of the processes can be scheduled before the send call, then there is no deadlock.

Rendezvous

Rendezvous systems are a form of synchronous communication among an arbitrary number of asynchronous processes. All the processes involved meet with each other, i.e., communicate synchronously with each other at one time. Two types of rendezvous systems are possible:

- Binary rendezvous: When two processes agree to synchronize.
- Multi-way rendezvous: When more than two processes agree to synchronize.

Features of binary rendezvous:

- For the receive command, the sender must be specified. However, multiple recieve commands can exist. A type check on the data is implicitly performed.
- Send and received commands may be individually disabled or enabled. A command is disabled if it is guarded and the guard evaluates to false. The guard would likely contain an expression on some local variables.
- Synchronous communication is implemented by scheduling messages under the covers using asynchronous communication.

- Scheduling involves pairing of matching send and receives commands that are both enabled. The communication events for the control messages under the covers do not alter the partial order of the execution.

Binary rendezvous algorithm

If multiple interactions are enabled, a process chooses one of them and tries to synchronize with the partner process. The problem reduces to one of scheduling messages satisfying the following constraints:

- Schedule on-line, atomically, and in a distributed manner.
- Schedule in a deadlock-free manner (i.e., crown-free).
- Schedule to satisfy the progress property in addition to the safety property.

Steps in Bagrodia algorithm

1. Receive commands are forever enabled from all processes.
2. A send command, once enabled, remains enabled until it completes, i.e., it is not possible that a send command gets before the send is executed.
3. To prevent deadlock, process identifiers are used to introduce asymmetry to break potential crowns that arise.
4. Each process attempts to schedule only one send event at any time.

The message (M) types used are: M, ack(M), request(M), and permission(M). Execution events in the synchronous execution are only the send of the message M and receive of the message M. The send and receive events for the other message types – ack(M), request(M), and permission(M) which are control messages. The messages request(M), ack(M), and permission(M) use M's unique tag; the message M is not included in these messages.

(message types)

M, *ack*(M), *request*(M), *permission*(M)

(1) P_i **wants to execute SEND(M) to a lower priority process** P_j**:**

P_i executes *send*(M) and blocks until it receives *ack*(M) from P_j . The send event SEND(M) now completes.

Any M' message (from a higher priority processes) and *request*(M') request for synchronization (from a lower priority processes) received during the blocking period are queued.

(2) P_i **wants to execute SEND(M) to a higher priority process** P_j**:**

(2a) Pi seeks permission from Pj by executing *send*(*request*(M)).

// to avoid deadlock in which cyclically blocked processes queue // messages.

(2b) While P_i is waiting for permission, it remains unblocked.

(i) If a message M' arrives from a higher priority process P_k, P_i accepts M' by scheduling a RECEIVE(M') event and then executes *send*(*ack*(M')) to P_k.

(ii) If a *request*(M') arrives from a lower priority process P_k, P_i executes *send*(*permission*(M')) to P_k and blocks waiting for the messageM'. WhenM' arrives, the RECEIVE(M') event is executed.

(2c) When the *permission*(M) arrives, P_i knows partner P_j is synchronized and P_i executes *send*(M). The SEND(M) now completes.

(3) *request*(M) arrival at P_i from a lower priority process P_j:

At the time a *request*(M) is processed by P_i, process P_i executes *send*(*permission*(M)) to Pj and blocks waiting for the message M. When M arrives, the RECEIVE(M) event is executed and the process unblocks.

(4) Message *M* arrival at P_i from a higher priority process P_j:

At the time a message *M* is processed by P_i, process P_i executes RECEIVE(M) (which is assumed to be always enabled) and then *send*(*ack*(M)) to P_j .

(5) Processing when P_i is unblocked:

When P_i is unblocked, it dequeues the next (if any) message from the queue and processes it as a message arrival (as per rules 3 or 4).

Fig . Bagrodia Algorithm

2.8.GROUP COMMUNICATION

Group communication is done by broadcasting of messages. A message broadcast is the sending of a message to all members in the distributed system. The communication may be

Multicast: A message is sent to a certain subset or a group.

Unicasting: A point-to-point message communication.

The network layer protocol cannot provide the following functionalities:

- Application-specific ordering semantics on the order of delivery of messages.
- Adapting groups to dynamically changing membership.
- Sending multicasts to an arbitrary set of processes at each send event.
- Providing various fault-tolerance semantics.
- The multicast algorithms can be open or closed group.

Differences between closed and open group algorithms:

Closed group algorithms	Open group algorithms
If sender is also one of the receiver in the multicast algorithm, then it is closed group algorithm.	If sender is not a part of the communication group, then it is open group algorithm.
They are specific and easy to implement.	They are more general, difficult to design and expensive.
It does not support large systems where client processes have short life.	It can support large systems.

2.9CAUSAL ORDER (CO)

In the context of group communication, there are two modes of communication: *causal order and total order*. Given a system with FIFO channels, causal order needs to be explicitly enforced by a protocol. The following two criteria must be met by a causal ordering protocol:

Safety: In order to prevent causal order from being violated, a message M that arrives at a process may need to be buffered until all system wide messages sent in the causal past of the send (M) event to that same destination have already arrived. The arrival of a message is transparent to the application process. The delivery event corresponds to the receive event in the execution model.

Liveness: A message that arrives at a process must eventually be delivered to the process.

The Raynal–Schiper–Toueg algorithm

- Each message M should carry a log of all other messages sent causally before M's send event, and sent to the same destination dest(M).
- The Raynal–Schiper–Toueg algorithm canonical algorithm is a representative of several algorithms that reduces the size of the local space and message space overhead by various techniques.
- This log can then be examined to ensure whether it is safe to deliver a message.
- All algorithms aim to reduce this log overhead, and the space and time overhead of maintaining the log information at the processes.
- To distribute this log information, broadcast and multicast communication is used.
- The hardware-assisted or network layer protocol assisted multicast cannot efficiently provide features:
  - Application-specific ordering semantics on the order of delivery of messages.
  - Adapting groups to dynamically changing membership.
  - Sending multicasts to an arbitrary set of processes at each send event.
  - Providing various fault-tolerance semantics

Causal Order (CO)

An optimal CO algorithm stores in local message logs and propagates on messages, information of the form d is a destination of M about a messageM sent in the causal past, as long as and only as long as:

Propagation Constraint I: it is not known that the message M is delivered to d.

Propagation Constraint II: it is not known that a message has been sent to d in the causal future of Send(M), and hence it is not guaranteed using a reasoning based on transitivity that the message M will be delivered to d in CO.

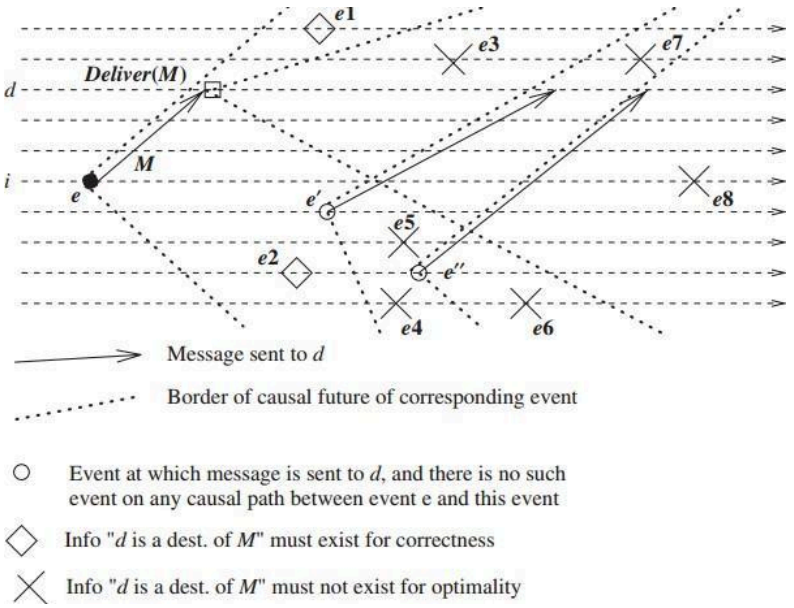


Fig . Conditions for causal ordering

The Propagation Constraints also imply that if either (I) or (II) is false, the information "d ∈ M.Dests" must not be stored or propagated, even to remember that (I) or (II) has been falsified:

- not in the causal future of $\text{Deliver}_d(M_1, a)$
- not in the causal future of $e_{k,c}$ where $d \in M_{k,c}$Dests and there is no other message sent causally between $M_{i,a}$ and $M_{k,c}$ to the same destination d.

Information about messages:
(i) not known to be delivered
(ii) not guaranteed to be delivered in CO, is explicitly tracked by the algorithm using (source, timestamp, destination) information.
Information about messages already delivered and messages guaranteed to be delivered in CO is implicitly tracked without storing or propagating it, and is derived from the explicit information. The algorithm for the send and receive operations is given in Fig. 2.7 a) and b). Procedure SND is executed atomically. Procedure RCV is executed atomically except for a possible interruptionin line 2a where a non-blocking wait is required to meet the Delivery Condition.

(1) **SND:** j **sends a message** M **to** $Dests$:

(1a) $clock_j \longleftarrow clock_j + 1$;
(1b) **for all** $d \in M.Dests$ **do**:
$O_M \longleftarrow LOG_j$; // O_M denotes $O_{M_{j,clock_j}}$
for all $o \in O_M$, modify $o.Dests$ as follows:
if $d \notin o.Dests$ **then** $o.Dests \longleftarrow (o.Dests \setminus M.Dests)$;
if $d \in o.Dests$ **then** $o.Dests \longleftarrow (o.Dests \setminus M.Dests) \bigcup \{d\}$;
// Do not propagate information about indirect dependencies that are
// guaranteed to be transitively satisfied when dependencies of M are satisfied.
for all $o_{s,t} \in O_M$ **do**
if $o_{s,t}.Dests = \emptyset \bigwedge (\exists o'_{s,t'} \in O_M \mid t < t')$ **then** $O_M \longleftarrow O_M \setminus \{o_{s,t}\}$;
// do not propagate older entries for which $Dests$ field is $\emptyset$
send $(j, clock_j, M, Dests, O_M)$ to d;
(1c) **for all** $l \in LOG_j$ **do** $l.Dests \longleftarrow l.Dests \setminus Dests$;
// Do not store information about indirect dependencies that are guaranteed
// to be transitively satisfied when dependencies of M are satisfied.
Execute $PURGE\_NULL\_ENTRIES(LOG_j)$; // purge $l \in LOG_j$ if $l.Dests = \emptyset$
(1d) $LOG_j \longleftarrow LOG_j \bigcup \{(j, clock_j, Dests)\}$.

Fig 2.7 a) Send algorithm by Kshemkalyani–Singhal to optimally implement causal ordering

(2) **RCV:** j **receives a message** $(k, t_k, M, Dests, O_M)$ **from** k:

(2a) // Delivery Condition: ensure that messages sent causally before M are delivered.
for all $o_{m,t_m} \in O_M$ **do**
if $j \in o_{m,t_m}.Dests$ **wait until** $t_m \leq SR_j[m]$;
(2b) Deliver M; $SR_j[k] \longleftarrow t_k$;
(2c) $O_M \longleftarrow \{(k, t_k, Dests)\} \bigcup O_M$;
for all $o_{m,t_m} \in O_M$ **do** $o_{m,t_m}.Dests \longleftarrow o_{m,t_m}.Dests \setminus \{j\}$;
// delete the now redundant dependency of message represented by o_{m,t_m} sent to j
(2d) // Merge O_M and LOG_j by eliminating all redundant entries.
// Implicitly track "already delivered" & "guaranteed to be delivered in CO"
// messages.
for all $o_{m,t} \in O_M$ **and** $l_{s,t'} \in LOG_j$ **such that** $s = m$ **do**
if $t < t' \bigwedge l_{s,t} \notin LOG_j$ **then** mark $o_{m,t}$;
// $l_{s,t}$ had been deleted or never inserted, as $l_{s,t}.Dests = \emptyset$ in the causal past
if $t' < t \bigwedge o_{m,t'} \notin O_M$ **then** mark $l_{s,t'}$;
// $o_{m,t'} \notin O_M$ because $l_{s,t'}$ had become $\emptyset$ at another process in the causal past
Delete all marked elements in O_M and LOG_j ;
// delete entries about redundant information
for all $l_{s,t'} \in LOG_j$ **and** $o_{m,t} \in O_M$, **such that** $s = m \bigwedge t' = t$ **do**
$l_{s,t'}.Dests \longleftarrow l_{s,t'}.Dests \bigcap o_{m,t}.Dests$;
// delete destinations for which Delivery
// Condition is satisfied or guaranteed to be satisfied as per $o_{m,t}$
Delete $o_{m,t}$ from O_M; // information has been incorporated in $l_{s,t'}$
$LOG_j \longleftarrow LOG_j \bigcup O_M$; // merge non-redundant information of O_M into LOG_j
(2e) $PURGE\_NULL\_ENTRIES(LOG_j)$. // Purge older entries l for which $l.Dests = \emptyset$

PURGE_NULL_ENTRIES(Log_j): // Purge older entries l for which $l.Dests = \emptyset$ is
// implicitly inferred

Fig 2.7 b) Receive algorithm by Kshemkalyani–Singhal to optimally implement causal ordering

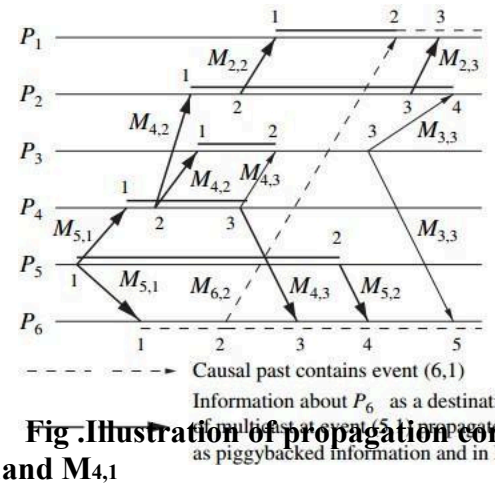
The data structures maintained are sorted row–major and then column–major:

1. Explicit tracking:

- Tracking of (source, timestamp, destination) information for messages (i) not known to be delivered and (ii) not guaranteed tobe delivered in CO, is done explicitly using the I.Dests field of entries inlocal logs at nodes and o.Dests field of entries in messages.
- Sets $l_{i,a}$Destsand $o_{i,a}$. Dests contain explicit information of destinations to which $M_{i,a}$is not guaranteed to be delivered in CO and is not known to be delivered.
- The information about d ∈$M_{i,a}$ .Destsis propagated up to the earliestevents on all causal paths from (i, a) at which it is known that $M_{i,a}$ isdelivered to d or is guaranteed to be delivered to d in CO.

2. Implicit tracking:

- Tracking of messages that are either (i) already delivered, or (ii) guaranteed to be delivered in CO, is performed implicitly.
- The information about messages (i) already delivered or (ii) guaranteed tobe delivered in CO is deleted and not propagated because it is redundantas far as enforcing CO is concerned.
- It is useful in determiningwhat information that is being carried in other messages and is being storedin logs at other nodes has become redundant and thus can be purged.
- Thesemantics are implicitly stored and propagated. This information about messages that are (i) already delivered or (ii) guaranteed to be delivered in CO is tracked without explicitly storing it.
- The algorithm derives it from the existing explicit information about messages (i) not known to be delivered and (ii) not guaranteed to be delivered in CO, by examining only $o_{i,a}$Dests or $l_{i,a}$Dests, which is a part of the explicit information.



Message to dest.	Piggybacked $M_{5,1}$.Dests
$M_{5,1}$ to P_4,P_6	{P_4,P_6}
$M_{4,2}$ to P_3,P_2	{P_6}
$M_{2,2}$ to P_1	{P_6}
$M_{6,2}$ to P_1	{P_4}
$M_{4,3}$ to P_6	{P_6}
$M_{4,3}$ to P_3	{ }
$M_{5,2}$ to P_6	{P_4,P_6}
$M_{2,3}$ to P_1	{P_6}
$M_{3,3}$ to $P_{2,6}$	{ }

Fig .Illustration of propagation constraints

Multicasts $M_{5,1}$and $M_{4,1}$

Message $M_{5,1}$ sent to processes P4 and P6 contains the piggybacked information $M_{5,1}$. Dest= {P4, P6}. Additionally, at the send event (5, 1), the information $M_{5,1}$.Dests = {P4,P6} is also inserted in the local log Log_5. When $M_{5,1}$ is delivered to P6, the (new) piggybacked information P4 ∈ $M_{5,1}$ .Dests is stored in Log_6 as $M_{5,1}$.Dests ={P4} information about P6 ∈

$M_{5,1}$.Dests which was needed for routing, must not be stored in Log_6 because of constraint I.
In the same way when $M_{5,1}$ is delivered to process P4
at event (4, 1), only the new piggybacked information P6 ∈ $M_{5,1}$ .Dests is inserted in Log_4 as $M_{5,1}$.Dests =P6which is later propagated duringmulticast $M_{4,2}$.

Multicast $M_{4,3}$

At event (4, 3), the information P6 ∈$M_{5,1}$.Dests in Log4 is propagated onmulticast $M_{4,3}$only to process P6 to ensure causal delivery using the DeliveryCondition. The piggybacked information on message $M_{4,3}$sent to process P3must not contain this information because of constraint II. As long as any future message sent to P6 is delivered in causal order w.r.t. $M_{4,3}$sent to P6, it will also be delivered in causal order w.r.t. $M_{5,1}$. And as $M_{5,1}$ is already delivered to P4, the information $M_{5,1}$Dests = ∅ is piggybacked on $M_{4,3}$ sent to P 3. Similarly, the information P6 ∈ $M_{5,1}$Dests must be deleted from Log4 as it will no longer be needed, because of constraint II. $M_{5,1}$Dests = ∅ is stored in Log4 to remember that $M_{5,1}$ has been delivered or is guaranteed to be delivered in causal order to all its destinations.

Learning implicit information at P2 and P3

When message $M_{4,2}$is received by processes P2 and P3, they insert the (new) piggybacked information in their local logs, as information $M_{5,1}$.Dests = P6. They both continue to store this in Log2 and Log3 and propagate this information on multicasts until they learn at events (2, 4) and (3, 2) on receipt of messages $M_{3,3}$and $M_{4,3}$, respectively, that any future message is expected to be delivered in causal order to process P6, w.r.t. $M_{5,1}$sent toP6. Hence by constraint II, this information must be deleted from Log2 andLog3. The flow of events is given by;

- When $M_{4,3}$ with piggybacked information $M_{5,1}$Dests = ∅ is received byP3at (3, 2), this is inferred to be valid current implicit information aboutmulticast $M_{5,1}$because the log Log3 already contains explicit informationP6 ∈$M_{5,1}$.Dests about that multicast. Therefore, the explicit informationin Log3 is inferred to be old and must be deleted to achieve optimality. $M_{5,1}$Dests is set to ∅ in Log3.
- The logic by which P2 learns this implicit knowledge on the arrival of $M_{3,3}$is identical.

Processing at P6

When message $M_{5,1}$ is delivered to P6, only $M_{5,1}$.Dests = P4 is added to Log6. Further, P6 propagates only $M_{5,1}$.Dests = P4 on message $M_{6,2}$, and this conveys the current implicit information $M_{5,1}$ has been delivered to P6 by its very absence in the explicit information.

- When the information P6 ∈ $M_{5,1}$Dests arrives on $M_{4,3}$, piggybacked as $M_{5,1}$ .Dests = P6 it is used only to ensure causal delivery of $M_{4,3}$ using the Delivery Condition, and is not inserted in Log6 (constraint I) – further, the presence of $M_{5,1}$ .Dests = P4 in Log6 implies the implicit information that $M_{5,1}$ has already been delivered to P6. Also, the absence of P4 in $M_{5,1}$ .Dests in the explicit piggybacked information implies the implicit information that $M_{5,1}$ has been delivered or is guaranteed to be delivered in causal order to P4, and, therefore, $M_{5,1}$. Dests is set to ∅ in Log6.
- When the information P6 ∈ $M_{5,1}$ .Dests arrives on $M_{5,2}$ piggybacked as $M_{5,1}$. Dests = {P4, P6} it is used only to ensure causal delivery of $M_{4,3}$ using the Delivery Condition, and is not inserted in Log6 because Log6 contains $M_{5,1}$ .Dests = ∅,

which gives the implicit information that $M_{5,1}$ has been delivered or is guaranteed to be delivered in causal order to both P4 and P6.

Processing at P1

- When $M_{2,2}$arrives carrying piggybacked information $M_{5,1}$.Dests = P6 this (new) information is inserted in Log1.
- When $M_{6,2}$arrives with piggybacked information $M_{5,1}$.Dests ={P4}, P1learns implicit information $M_{5,1}$has been delivered to P6 by the very absence of explicit information P6 ∈ $M_{5,1}$.Dests in the piggybacked information, and hence marks information P6 ∈ $M_{5,1}$Dests for deletion from Log1. Simultaneously, $M_{5,1}$Dests = P6 in Log1 implies the implicit information that $M_{5,1}$has been delivered or is guaranteed to be delivered in causal order to P4.Thus, P1 also learns that the explicit piggybacked information $M_{5,1}$.Dests = P4 is outdated. $M_{5,1}$.Dests in Log1 is set to ∅.
- The information "P6 ∈$M_{5,1}$.Dests piggybacked on $M_{2,3}$,which arrives at P 1, is inferred to be outdated usingthe implicit knowledge derived from $M_{5,1}$.Dest= ∅" in Log1.

2.10.TOTAL ORDER

For each pair of processes P_i and P_j and for each pair of messages M_x and M_y that are delivered to both the processes, P_i is delivered M_x before M_y if and only if P_j is delivered $M_x$before M_y.

Centralized Algorithm for total ordering

Each process sends the message it wants to broadcast to a centralized process, which relays all the messages it receives to every other process over FIFO channels.

(1) When process P_i wants to multicast a message M to group G:
(1a) **send** $M(i, G)$ to central coordinator.

(2) When $M(i, G)$ arrives from P_i at the central coordinator:
(2a) **send** $M(i, G)$ to all members of the group G.

(3) When $M(i, G)$ arrives at P_j from the central coordinator:
(3a) **deliver** $M(i, G)$ to the application.

Complexity: Each message transmission takes two message hops and exactly n messages in a system of n processes.

Drawbacks: A centralized algorithm has a single point of failure and congestion, and is not an elegant solution.

Three phase distributed algorithm

Three phases can be seen in both sender and receiver side.

Sender side

Phase 1

- In the first phase, a process multicasts the message M with a locally unique tag and the local timestamp to the group members.

Phase 2

- The sender process awaits a reply from all the group members who respond with a tentative proposal for a revised timestamp for that message M.

- The await call is non-blocking.

Phase 3

- The process multicasts the final timestamp to the group.

```
record Q_entry
        M: int;                                  // the application message
        tag: int;                                // unique message identifier
        sender_id: int;                          // sender of the message
        timestamp: int;                          // tentative timestamp assigned to message
        deliverable: boolean;                    // whether message is ready for delivery
(local variables)
queue of Q_entry: temp_Q, delivery_Q
int: clock                                       // Used as a variant of Lamport's scalar clock
int: priority                                    // Used to track the highest proposed timestamp
(message types)
REVISE_TS(M, i, tag, ts)
                                                 // Phase 1 message sent by P_i, with initial timestamp ts
PROPOSED_TS(j, i, tag, ts)
                                                 // Phase 2 message sent by P_j, with revised timestamp, to P_i
FINAL_TS(i, tag, ts)                             // Phase 3 message sent by P_i, with final timestamp
(1)   When process P_i wants to multicast a message M with a tag tag:
(1a)  clock ← clock + 1;
(1b)  send REVISE_TS(M, i, tag, clock) to all processes;
(1c)  temp_ts ← 0;
(1d)  await PROPOSED_TS(j, i, tag, ts_j) from each process P_j;
(1e)  ∀j ∈ N, do temp_ts ← max(temp_ts, ts_j);
(1f)  send FINAL_TS(i, tag, temp_ts) to all processes;
(1g)  clock ← max(clock, temp_ts).
```

Fig 2.9: Sender side of three phase distributed algorithm

Receiver Side

Phase 1

- The receiver receives the message with a tentative timestamp. It updates the variable priority that tracks the highest proposed timestamp, then revises the proposed timestamp to the priority, and places the message with its tag and the revised timestamp at the tail of the queue temp_Q. In the queue, the entry is marked as undeliverable.

Phase 2

- The receiver sends the revised timestamp back to the sender. The receiver then waits in a non-blocking manner for the final timestamp.

Phase 3

- The final timestamp is received from the multicaster. The corresponding message entry in temp_Q is identified using the tag, and is marked as deliverable after the revised timestamp is overwritten by the final timestamp.
- The queue is then resorted using the timestamp field of the entries as the key. As the queue is already sorted except for the modified entry for the message under consideration, that message entry has to be placed in its sorted position in the queue.

- If the message entry is at the head of the temp_Q, that entry, and all consecutive subsequent entries that are also marked as deliverable, are dequeued from temp_Q, and enqueued in deliver_Q.

Complexity
This algorithm uses three phases, and, to send a message to n − 1 processes, it uses 3(n – 1) messages and incurs a delay of three message hops

2.2 GLOBAL STATE AND SNAPSHOT RECORDING ALGORITHMS

A distributed computing system consists of processes that do not share a common memory and communicate asynchronously with eachother by message passing.

Each component ofhas a local state. The state of the process is the local memory and a history of its activity.

The state of achannel is characterized by the set of messages sent along the channel lessthe messages received along the channel. The global state of a distributedsystem is a collection of the local states of its components.

If shared memory were available, an up-to-date state of the entire systemwould be available to the processes sharing the memory.

The absence ofshared memory necessitates ways of getting a coherent and complete view ofthe system based on the local states of individual processes.

A meaningfulglobal snapshot can be obtained if the components of the distributed systemrecord their local states at the same time.

This would be possible if thelocal clocks at processes were perfectly synchronized or if there were aglobal system clock that could be instantaneously read by the processes.

If processes read time froma single common clock, various indeterminatetransmission delays during the read operation will cause the processes toidentify various physical instants as the same time.

2.11.System Model

- The system consists of a collection of n processes, $p_1, p_2, \ldots, p_n$ that are connected by channels.
- Let C_{ij} denote the channel from process p_i to process p_j.
- Processes and channels have states associated with them.
- The state of a process at any time is defined by the contents of processor registers, stacks, local memory, etc., and may be highly dependent on the local context of the distributed application.
- The state of channel C_{ij}, denoted by SC_{ij}, is given by the set of messages in transit in the channel.
- The events that may happen are: internal event, send (send (m_{ij})) and receive (rec(m_{ij})) events.

- The occurrences of events cause changes in the processstate.
- A **channel** is a distributed entity and its state depends on the local states of the processes on which it is incident.

  Transit: $transit(LS_i, LS_j) = \{m_{ij} \mid send(m_{ij}) \in LS_i \bigwedge rec(m_{ij}) \notin LS_j\}$

- The transit function records the state of the channel C_{ij}.
- 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, achannel acts like a set in which the sender process adds messages and thereceiver process removes messages from it in a random order.

2.12.A consistent global state

The global state of a distributed system is a collection of the local states ofthe processes and the channels. The global state is given by:

$GS = \{\bigcup_i LS_i, \bigcup_{i,j} SC_{ij}\}$.

The two conditions for global state are:

C1: $send(m_{ij}) \in LS_i \Rightarrow m_{ij} \in SC_{ij} \oplus rec(m_{ij}) \in LS_j$

C2: $send(m_{ij}) \notin LS_i \Rightarrow m_{ij} \notin SC_{ij} \wedge rec(m_{ij}) \notin LS_j$.

Condition 1 preserves **law of conservation of messages.**Condition C2 states that in the collected global state, for everyeffect, its cause must be present.

Law of conservation of messages: Every message m_{ij} that is recorded as sent in the local state of a process p_i must be capturedin the state of the channel C_{ij} or in the collected local state of the receiver process p_j.

- In a consistent global state, every message that is recorded as received isalso recorded as sent. Such a global state captures the notion of causalitythat a message cannot be received if it was not sent.
- Consistent global statesare meaningful global states and inconsistent global states are not meaningful in the sense that a distributed system can never be in an inconsistentstate.

Interpretation of cuts

- Cuts in a space–time diagram provide a powerful graphical aid in representingand reasoning about the global states of a computation. A cut is a line joiningan arbitrary point on each process line that slices the space–time diagraminto a PAST and a FUTURE.
- A consistent global state corresponds to a cut in which every messagereceived in the PAST of the cut has been sent in the PAST of that cut. Sucha cut is known as a consistent cut.
- In a consistent snapshot, all the recorded local states of processes are concurrent; that is, the recorded local state of no process casuallyaffects the recorded local state of any other process.

Issues in recording global state

The non-availability of global clock in distributed system, raises the following issues:

Issue 1:

How to distinguish between the messages to be recorded in the snapshot from those not to be recorded?

Answer:

- Any message that is sent by a process before recording its snapshot,must be recorded in the global snapshot (from C1).

- Any message that is sent by a process after recording its snapshot, mustnot be recorded in the global snapshot (from C2).

Issue 2:

How to determine the instant when a process takes its snapshot?

The answer

Answer:

A process p_j must record its snapshot before processing a message m_{ij} that was sent by process p_i after recording its snapshot.

2.13.SNAPSHOT ALGORITHMS FOR FIFO CHANNELS

Each distributed application has number of processes running on different physical servers. These processes communicate with each other through messaging channels.

A snapshot captures the local states of each process along with the state of each communication channel.

Snapshots are required to:

Checkpointing

Collecting garbage

Detecting deadlocks

Debugging

2.9.1 Chandy–Lamport algorithm

The algorithm will record a global snapshot for each process channel.

The Chandy-Lamport algorithm uses a control message, called a marker.

Aftera site has recorded its snapshot, it sends a marker along all of its outgoingchannels before sending out any more messages.

Since channels are FIFO, amarker separates the messages in the channel into those to be included in the snapshot from those not to be recorded inthe snapshot.

This addresses issue I1. The role of markers in a FIFO systemis to act as delimiters for the messages in the channels so that the channelstate recorded by the process at the receiving end of the channel satisfies thecondition C2.

Marker sending rule for process p_i

(1) Process p_i records its state.
(2) For each outgoing channel C on which a marker has not been sent, p_i sends a marker along C before p_i sends further messages along C.

Marker receiving rule for process p_j
On receiving a marker along channel C:
if p_j has not recorded its state **then**
Record the state of C as the empty set
Execute the "marker sending rule"
else
Record the state of C as the set of messages received along C after p_j's state was recorded and before p_j received the marker along C

Fig . Chandy–Lamport algorithm

Initiating a snapshot

Process P_i initiates the snapshot

P_i records its own state and prepares a special marker message.

Send the marker message to all other processes.

Start recording all incoming messages from channels C_{ij} for j not equal to i.

Propagating a snapshot

For all processes $P_j$consider a message on channel C_{kj}.

If marker message is seen for the first time:

- $P_j$records own sate and marks C_{kj} as empty
- Send the marker message to all other processes.
- Record all incoming messages from channels C_{lj} for 1 not equal to j or k.
- Else add all messages from inbound channels.

Terminating a snapshot

All processes have received a marker.

All process have received a marker on all the N-1 incoming channels.

A central server can gather the partial state to build a global snapshot.

Correctness of the algorithm

Since a process records its snapshot when itreceives the first marker on any incoming channel, no messages that followmarkers on the channels incoming to it are recorded in the process's snapshot.

A process stops recording the state of an incoming channel whena marker is received on that channel.

Due to FIFO property of channels, itfollows that no message sent after the marker on that channel is recorded inthe channel state. Thus, condition C2 is satisfied.

When a process p_j receives message m_{ij} that precedes the marker on channel C_{ij}, it acts as follows: ifprocess p_j has not taken its snapshot yet, then it includes m_{ij} in its recorded snapshot. Otherwise, it records m_{ij} in the state of the channel C_{ij}. Thus,condition C1 is satisfied.

Complexity

The recording part of a single instance of the algorithm requires O(e) messages and O(d) time, where e is the number of edges in the network and d is thediameter of the network.

Properties of the recorded global state

The recorded global state may not correspond to any of the global states that occurred during the computation.

This happens because a process can change its state asynchronously before the markers it sent are received by other sites and the other sites record their states.

But the system could have passed through the recorded global states in some equivalent executions.

The recorded global state is a valid state in an equivalent execution and if a stable property (i.e., a property that persists) holds in the system before the snapshot algorithm begins, it holds in the recorded global snapshot.

Therefore, a recorded global state is useful in detecting stable properties.

UNIT III

DISTRIBUTED MUTEX & DEADLOCK

3.1 DISTRIBUTED MUTUAL EXCLUSION ALGORITHMS

Mutual exclusion is a concurrency control property which is introduced to prevent another race conditions.

It is the requirement that a process cannot access a shared resource while concurrent process is currently present or executing the same resource.

Mutual exclusion in a distributed system states that only one process is allowed to execute the critical section (CS) at any given time.

Message passing is the sole means for implementing distributed mutual exclusion.

The decision as to which process is allowed access to the CS is made by message passing, in which each process learns about the state of all other processes in some consistent way.

1. **Token-based approach:**

There are three basic approaches for implementing distributed mutual exclusion:

- A unique token is shared among all the sites.
- If a site possesses the unique token, it is allowed to enter its critical section
- This approach uses sequence number to order requests for the critical section.

Each requests
number is use
This approacl

- for critical section contains a sequence number. This sequence
  d to distinguish old and current requests.
- insures Mutual exclusion as the token is unique.
- Eg: Suzuki-Kasami's Broadcast Algorithm

2. Non-token-based approach:

- A site communicates with other sites in order to determine which sites should execute critical section next. This requires exchange of two or more successive round of messages among sites.
- This approach use timestamps instead of sequence number to order requests for the critical section.
- When ever a site make request for critical section, it gets a timestamp. Timestamp is also used to resolve any conflict requests.

- All algorithm which follows non-token based approach maintains a clock. Logical clocks get updated according to Lamport's scheme.
- Eg: Lamport's algorithm, Ricart–Agrawala algorithm

3. Quorum-based approach:

- Instead of requesting permission to execute the critical section from all other sites, Each site requests only a subset of sites which is called a quorum.
- Any two subsets of sites or Quorum contains a common site.
- This common site is responsible to ensure mutual exclusion.
- Eg: Maekawa's Algorithm

3.1.1 Preliminaries

- The system consists of N sites, $S_1, S_2, S_3, \ldots, S_N$.
- Assume that a single process is running on each site.
- The process at site S_i is denoted by p_i. All these processes communicate asynchronously over an underlying communication network.
- A process wishing to enter the CS requests all other or a subset of processes by sending REQUEST messages, and waits for appropriate replies before entering the CS.
- While waiting the process is not allowed to make further requests to enter the CS
- A site can be in one of the following three states: requesting the CS, executing th
- In the requesting the CS state, the site is blocked until it has received a REPLY message from all the sites in its request set.
- In the idle state, the site is executing outside the CS. In the token-based algorithms, a site can also be in a state executing outside the CS. Such state is referred to as the token is idle.
- At any instant, a site may have several pending requests for CS. A site queues up these requests and serves them one at a time.

N denotes the number of processes or sites involved and E denotes the average critical section execution time.

3.1.2 Requirements of mutual exclusion algorithms

- **Safety property:**

The safety property states that at any instant, only one process can execute the critical section. This is an essential property of a mutual exclusion algorithm.

- **Liveness property:**

This property states the absence of deadlock and starvation. Two or more sites should not endlessly wait for messages that will never arrive. In addition, a site must not wait indefinitely to execute the CS while other sites are repeatedly executing the CS. That is, every requesting site should get an opportunity to execute the CS in finite time.

- **Fairness:**

Fairness in the context of mutual exclusion means that each process gets a fair chance to execute the CS. In mutual exclusion algorithms, the fairness property generally means that the CS execution requests are executed in order of their arrival in the system.

3.1.3 Performance metrics

- **Message complexity:** This is the number of messages that are

required per CS execution by a site.

- **Synchronization delay:** After a site leaves the CS, it is the time required and the next site enters the CS. (Figure 3.1)
- **Response time:** This is the time interval Thus, over after its request messages have been sent out. response time does not

include the time a request waits at a site before its request messages have been sent out. (Figure 3.2)

- **System throughput:** This is the rate at which CS. If SD and the synchronization delay

time.

$$\text{System throughput} = \frac{1}{(SD + E)}$$

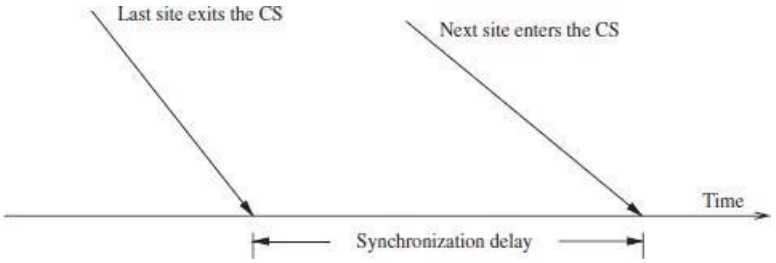


Figure 3.1 Synchronization delay

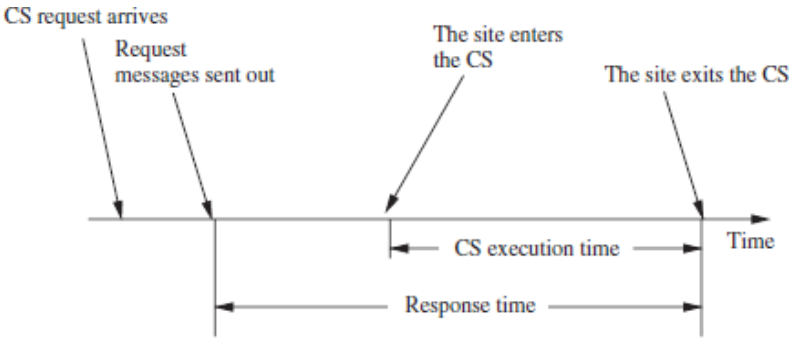


Figure 3.2 Response Time

Low and High Load Performance:

- The conditions, viz. mutual exclusion algorithms is classified as two special loading
- The load is determined by the arrival rate of CS execution requests.
- Under ***low load*** conditions, there is seldom more than one request for the critical section present in the system simultaneously.
- Under ***heavy load*** conditions, there is always a pending request for critical section at a site.

Best and worst case performance the

- In the best case, prevailing performance metric attains conditions are such that a best possible value. For example, the best value of the response time is a roundtrip message delay plus the CS execution time, 2T +E.
- For examples, the best and worst values of the response time are achieved when load is, respectively, low and high;
- The respectively worse message traffic is generated at low and heavy load conditions,

3.2 LAMPORT'S ALGORITHM

- Lamport's Distributed Mutual Exclusion Algorithm is a permission based algorithm proposed by Lamport as an illustration of his synchronization scheme for distributed systems.

  In permission based timestamp is used and to order critical section requests increasing order to resolve any conflict between requests.

  In Lamport's Algorith m critical section requests are exe cut ed in the wil l be of timestamps i.e a request with smaller timestamp given permission to execute critical section first than a request with larger timestamp.

- Three type of messages (REQUEST, REPLY are used and RELEASE)

  communication channels are assumed to follow FIFO order.

- A site send a REQUEST message to all other site to get their permission to enter critical section.
- A site send a REPL Y message to requesting site to give its permission to enter the critical section.
- A site send a RELEASE message to all other site upon exiting the critical section.
- Every site Si, keeps a queue to store critical section requests ordered by their timestamps.

  request_queuei denotes the queue of site Si.

- A timestamp is given to each critical section request using Lamport's logical clock. Timestamp is used to determine priority of critical section requests. Smaller timestamp gets high priority over larger timestamp. The execution of critical section request is always in the order of their timestamp.

Requesting the critical section

- When a site S_i wants to enter the CS, it broadcasts a REQUEST(ts_i, i) message to all other sites and places the request on $request\_queue_i$. ((ts_i, i) denotes the timestamp of the request.)
- When a site S_j receives the REQUEST(ts_i, i) message from site S_i, it places site S_i's request on $request\_queue_j$ and returns a timestamped REPLY message to S_i.

Executing the critical section

Site S_i enters the CS when the following two conditions hold:

L1: S_i has received a message with timestamp larger than (ts_i, i) from all other sites.

L2: S_i's request is at the top of $request\_queue_i$.

Releasing the critical section

- Site S_i, upon exiting the CS, removes its request from the top of its request queue and broadcasts a timestamped RELEASE message to all other sites.
- When a site S_j receives a RELEASE message from site S_i, it removes S_i's request from its request queue.

Fig 3.1: Lamport's distributed mutual exclusion algorithm To enter Critical section:

When a site S_i wants to enter the critical section, it sends a request message Request(ts_i, i) to all other sites and places the request on request_queue$_i$. Here, T_{si} denotes the timestamp of Site S_i.

When a site S_j receives the request message REQUEST(ts_i, i) from site Si, it returns a timestamped REPLY message to site Si and places the request of site Si on request_queue$_j$

To execute the critical section:

- A site S_i can enter the critical section if it has received the message with timestamp larger than (ts_i, i) from all other sites and its own request is at the top of request_queue$_i$.

To release the critical section:

When a site S_i exits the critical section, it removes its own request from the top of its request queue and sends a timestamped RELEASE message to all other sites. When a site S_j receives the timestamped RELEASE message from site S_i, it removes the request of S_{ia} from its request queue.

Correctness

Theorem: Lamport's algorithm achieves mutual exclusion.

Proof: Proof is by contradiction.

Suppose two sites S_i and S_j are executing the CS concurrently. For this to happen conditions L1 and L2 must hold at both the sites concurrently.

This implies that at some instant in time, say t, both S_i and S_j have their own requests at the top of their request queues and condition L1 holds at them. Without loss of generality, assume that S_i 's request has smaller timestamp than the request of S_j .

From condition L1 and FIFO property of the communication channels, it is clear that at instant t the request of S_i must be present in request queue$_j$ when S_j was executing its CS. This implies that Sj 's own request is at the top of its own request queue when a smaller timestamp request, Si 's request, is present in the request queue$_j$ – a contradiction!

Theorem: Lamport's algorithm is fair.

***Proof: The proof is by contradiction*.**

Suppose a site S_i 's request has a smaller timestamp than the request of another site S_j and S_j is able to execute the CS before S_i .

For S_j to execute the CS, it has to satisfy the conditions L1 and L2. This implies that at some instant in time say t, S_j has its own request at the top of its queue and it has also received a message with timestamp larger than the timestamp of its request from all other sites.

But request queue at a site is ordered by timestamp, and according to our assumption Si has lower timestamp. So S_i 's request must be placed ahead of the S_j 's request in the request queue$_j$. This is a contradiction!

Message Complexity:

Lamport's Algorithm requires invocation of 3(N – 1) messages per critical section execution. These 3(N – 1) messages involves

- (N – 1) request messages
- (N – 1) reply messages
- (N – 1) release messages

Drawbacks of Lamport's Algorithm:

- **Unreliable approach**: failure of any one of the processes will halt the progress of entire system.
- **High message complexity:** Algorithm requires 3(N-1) messages per critical section invocation.

Performance:

Synchronization delay is equal to maximum message transmission time. It requires 3(N – 1) messages per CS execution. Algorithm can be optimized to 2(N – 1) messages by omitting the REPLY message in some situations.

3.3 RICART–AGRAWALA ALGORITHM

Ricart–Agrawala algorithm is an algorithm to for mutual exclusion in a distributed system proposed by Glenn Ricart and Ashok Agrawala.

This algorithm is an extension and optimization of Lamport's Distributed Mutual Exclusion Algorithm.

It follows permission based approach to ensure mutual exclusion.

Two type of messages (REQUEST and REPLY) are used and communication channels are assumed to follow FIFO order.

A site send a REQUEST message to all other site to get their permission to enter critical section.

A site send a REPLY message to other site to give its permission to enter the critical section.

A timestamp is given to each critical section request using Lamport's logical clock.

Timestamp is used to determine priority of critical section requests.

Smaller timestamp gets high priority over larger timestamp.

Requesting the critical section

(a) When a site S_i wants to enter the CS, it broadcasts a timestamped REQUEST message to all other sites.

(b) When site S_j receives a REQUEST message from site S_i, it sends a REPLY message to site S_i if site S_j is neither requesting nor executing the CS, or if the site S_j is requesting and S_i's request's timestamp is smaller than site S_j's own request's timestamp. Otherwise, the reply is deferred and S_j sets $RD_j[i] := 1$.

Executing the critical section

(c) Site S_i enters the CS after it has received a REPLY message from every site it sent a REQUEST message to.

Releasing the critical section

(d) When site S_i exits the CS, it sends all the deferred REPLY messages: $\forall j$ if $RD_i[j] = 1$, then sends a REPLY message to S_j and sets $RD_i[j] := 0$.

The execution of critical section request is always in the order of their timestamp.

Fig 3.2: Ricart–Agrawala algorithm

To enter Critical section:

When a site S_i wants to enter the critical section, it send a timestamped REQUEST message to all other sites.

When a site S_j receives a REQUEST message from site S_i, It sends a REPLY message to site S_i if and only if Site S_j is neither requesting nor currently executing the critical section.

In case Site S_j is requesting, the timestamp of Site S_i's request is smaller than its own request.

Otherwise the request is deferred by site S_j.

To execute the critical section:

Site S_i enters the critical section if it has received the REPLY message from all other sites.

To release the critical section:

Upon exiting site S_i sends REPLY message to all the deferred requests.

Theorem: Ricart-Agrawala algorithm achieves mutual exclusion.
Proof: Proof is by contradiction.

- Suppose two sites S_i and S_j ' are executing the CS concurrently and S_i 's request has higher priority than the request of S_j . Clearly, Si received S_j 's request after it has made its own request.
- Thus, S_j can concurrently execute the CS with S_i only if Si returns a REPLY to S_j (in response to S_j 's request) before Si exits the CS.
- However, this is impossible because S_j 's request has lower priority. Therefore, Ricart-Agrawala algorithm achieves mutual exclusion.

Message Complexity:
Ricart–Agrawala algorithm requires invocation of 2(N – 1) messages per critical section execution. These 2(N – 1) messages involve:

(N – 1) request messages

(N – 1) reply messages

Drawbacks of Ricart–Agrawala algorithm:

Unreliable approach: failure of any one of node in the system can halt the progress of the system. In this situation, the process will starve forever. The problem of failure of node can be solved by detecting failure after some timeout.

Performance:
Synchronization delay is equal to maximum message transmission time It requires 2(N – 1) messages per Critical section execution.

3.4 MAEKAWA's ALGORITHM

Maekawa's Algorithm is quorum based approach to ensure mutual exclusion in distributed systems.

In permission based algorithms like Lamport's Algorithm, Ricart-Agrawala

Algorithm etc. a site request permission from every other site but in quorum based approach, a site does not request permission from every other site but from a subset of sites which is called quorum.

Three type of messages (REQUEST, REPLY and RELEASE) are used.

A site send a REQUEST message to all other site in its request set or quorum to get their permission to enter critical section.

A site send a REPLY message to requesting site to give its permission to enter the critical section.

A site send a RELEASE message to all other site in its request set or quorum upon exiting the critical section.

Requesting the critical section:

(a) A site S_i requests access to the CS by sending REQUEST(i) messages to all sites in its request set R_i.

(b) When a site S_j receives the REQUEST(i) message, it sends a REPLY(j) message to S_i provided it hasn't sent a REPLY message to a site since its receipt of the last RELEASE message. Otherwise, it queues up the REQUEST(i) for later consideration.

Executing the critical section:

(c) Site S_i executes the CS only after it has received a REPLY message from every site in R_i.

Releasing the critical section:

(d) After the execution of the CS is over, site S_i sends a RELEASE(i) message to every site in R_i.

(e) When a site S_j receives a RELEASE(i) message from site S_i, it sends a REPLY message to the next site waiting in the queue and deletes that entry from the queue. If the queue is empty, then the site updates its state to reflect that it has not sent out any REPLY message since the receipt of the last RELEASE message.

Fig 3.3: Maekawa's Algorithm

The following are the conditions for Maekawa's algorithm:

M1 $(\forall i\ \forall j : i \neq j, 1 \leq i, j \leq N :: R_i \cap R_j \neq \phi)$.
M2 $(\forall i : 1 \leq i \leq N :: S_i \in R_i)$.
M3 $(\forall i : 1 \leq i \leq N :: |R_i| = K)$.
M4 Any site S_j is contained in K number of R_is, $1 \leq i, j \leq N$.

Maekawa used the theory of projective planes and showed that N = K(K – 1)+ 1. This relation gives |Ri|= √N.

To enter Critical section:

When a site S_i wants to enter the critical section, it sends a request message REQUEST(i) to all other sites in the request set R_i.

When a site S_j receives the request message REQUEST(i) from site S_i, it returns a REPLY message to site S_i if it has not sent a REPLY message to the site from the time it received the last RELEASE message. Otherwise, it queues up the request.

To execute the critical section:

A site S_i can enter the critical section if it has received the REPLY message from all the site in request set R_i

To release the critical section:

When a site S_i exits the critical section, it sends RELEASE(i) message to all other sites in request set R_i

When a site S_j receives the RELEASE(i) message from site S_i, it send REPLY message to the next site waiting in the queue and deletes that entry from the queue

In case queue is empty, site S_j update its status to show that it has not sent any REPLY message since the receipt of the last RELEASE message.

Correctness

Theorem: Maekawa's algorithm achieves mutual exclusion.

Proof: Proof is by contradiction.

- Suppose two sites Si and Sj are concurrently executing the CS.
- This means site Si received a REPLY message from all sites in Ri and concurrently site Sj was able to receive a REPLY message from all sites in Rj .
- If Ri ∩ Rj = {Sk }, then site Sk must have sent REPLY messages to both Si and Sj concurrently, which is a contradiction

Message Complexity:

Maekawa's Algorithm requires invocation of 3√N messages per critical section execution as the size of a request set is √N. These 3√N messages involves.

√N request messages

√N reply messages

√N release messages

Drawbacks of Maekawa's Algorithm:

This algorithm is deadlock prone because a site is exclusively locked by other sites and requests are not prioritized by their timestamp.

Performance:

Synchronization delay is equal to twice the message propagation delay time. It requires 3√n messages per critical section execution.

3.5 SUZUKI–KASAMI's BROADCAST ALGORITHM

Suzuki–Kasami algorithm is a token-based algorithm for achieving mutual exclusion in distributed systems.

This is modification of Ricart–Agrawala algorithm, a permission based (Non-token based) algorithm which uses REQUEST and REPLY messages to ensure mutual exclusion.

In token-based algorithms, A site is allowed to enter its critical section if it possesses the unique token.

Non-token based algorithms uses timestamp to order requests for the critical section where as sequence number is used in token based algorithms.

Each requests for critical section contains a sequence number. This sequence number is used to distinguish old and current requests.

Requesting the critical section:

(a) If requesting site S_i does not have the token, then it increments its sequence number, $RN_i[i]$, and sends a REQUEST(i, sn) message to all other sites. ("sn" is the updated value of $RN_i[i]$.)

(b) When a site S_j receives this message, it sets $RN_j[i]$ to $max(RN_j[i], sn)$. If S_j has the idle token, then it sends the token to S_i if $RN_j[i] = LN[i] + 1$.

Executing the critical section:

(c) Site S_i executes the CS after it has received the token.

Releasing the critical section: Having finished the execution of the CS, site S_i takes the following actions:

(d) It sets $LN[i]$ element of the token array equal to $RN_i[i]$.

(e) For every site S_j whose i.d. is not in the token queue, it appends its i.d. to the token queue if $RN_i[j] = LN[j] + 1$.

(f) If the token queue is nonempty after the above update, S_i deletes the top site i.d. from the token queue and sends the token to the site indicated by the i.d.

Fig 3.4: Suzuki–Kasami's broadcast algorithm

To enter Critical section:

When a site S_i wants to enter the critical section and it does not have the token then it increments its sequence number $RN_i[i]$ and sends a request message REQUEST(i, s_n) to all other sites in order to request the token.

Here s_n is update value of $RN_i[i]$

When a site S_j receives the request message REQUEST(i, s_n) from site S_i, it sets $RN_j[i]$ to maximum of $RN_j[i]$ and s_ni.e$RN_j[i] = max(RN_j[i], s_n)$.
After updating $RN_j[i]$, Site S_j sends the token to site S_i if it has token and $RN_j[i] = LN[i] + 1$

To execute the critical section:

Site S_i executes the critical section if it has acquired the token.

To release the critical section:

After finishing the execution Site Si exits the critical section and does following:

sets $LN[i] = RN_i[i]$ to indicate that its critical section request $RN_i[i]$ has been executed

For every site S_j, whose ID is not prsent in the token queue Q, it appends its ID to Q if $RN_j[j] = LN[j] + 1$ to indicate that site S_j has an outstanding request.

After above updation, if the Queue Q is non-empty, it pops a site ID from the Q and sends the token to site indicated by popped ID.

If the queue Q is empty, it keeps the token

Correctness

Mutual exclusion is guaranteed because there is only one token in the system and a site holds the token during the CS execution.

Theorem: A requesting site enters the CS in finite time.

Proof: Token request messages of a site Si reach other sites in finite time.

Since one of these sites will have token in finite time, site S_i 's request will be placed in the

token queue in finite time.
Since there can be at most N − 1 requests in front of this request in the token queue, site S_i will get the token and execute the CS in finite time.

Message Complexity:
The algorithm requires 0 message invocation if the site already holds the idle token at the time of critical section request or maximum of N message per critical section execution. This N messages involves

(N – 1) request messages

1 reply message

Drawbacks of Suzuki–Kasami Algorithm:

Non-symmetric Algorithm: A site retains the token even if it does not have requested for critical section.

Performance:
Synchronization delay is 0 and no message is needed if the site holds the idle token at the time of its request. In case site does not holds the idle token, the maximum synchronization delay is equal to maximum message transmission time and a maximum of N message is required per critical section invocation.

3.6 DEADLOCK DETECTION IN DISTRIBUTED SYSTEMS

Deadlock can neither be prevented nor avoided in distributed system as the system is so vast that it is impossible to do so. Therefore, only deadlock detection can be implemented. The techniques of deadlock detection in the distributed system require the following:

Progress: The method should be able to detect all the deadlocks in the system.

Safety: The method should not detect false of phantom deadlocks.

There are three approaches to detect deadlocks in distributed systems.
Centralized approach:

Here there is only one responsible resource to detect deadlock.

The advantage of this approach is that it is simple and easy to implement, while the drawbacks include excessive workload at one node, single point failure which in turns makes the system less reliable.

Distributed approach:

In the distributed approach different nodes work together to detect deadlocks.

No single point failure as workload is equally divided among all nodes.

The speed of deadlock detection also increases.

Hierarchical approach:

This approach is the most advantageous approach.

It is the combination of both centralized and distributed approaches of deadlock detection in a distributed system.

In this approach, some selected nodes or cluster of nodes are responsible for deadlock detection and these selected nodes are controlled by a single node.

Wait for graph

This is used for deadlock deduction. A graph is drawn based on the request and acquirement of the resource. If the graph created has a closed loop or a cycle, then there is a deadlock.

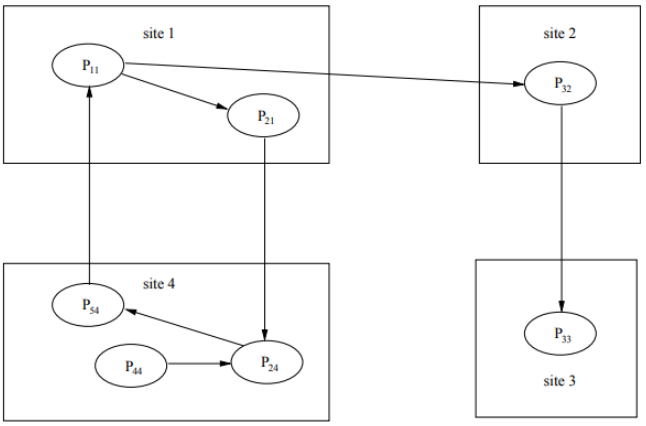


Fig 3.5: Wait for graph

3.6.1 Deadlock Handling Strategies

Handling of deadlock becomes highly complicated in distributed systems because no site has accurate knowledge of the current state of the system and because every inter-site communication involves a finite and unpredictable delay. There are three strategies for handling deadlocks:

- **Deadlock prevention:**
  - This is achieved either by having a process acquire all the needed resources simultaneously before it begins executing or by preempting a process which holds the needed resource.
  - This approach is highly inefficient and impractical in distributed systems.
- **Deadlock avoidance:**
  - A resource is granted to a process if the resulting global system state is safe. This is impractical in distributed systems.
- **Deadlock detection:**
  - This requires examination of the status of process-resource interactions for presence of cyclic wait.
  - Deadlock detection in distributed systems seems to be the best approach to handle deadlocks in distributed systems.

3.6.2 Issues in deadlock Detection

Deadlock handling faces two major issues

1. Detection of existing deadlocks
2. Resolutionof detected deadlocks

Deadlock Detection

- Detection of deadlocks involves addressing two issues namely maintenance of the WFG and searching of the WFG for the presence of cycles or **knots**.
- In distributed systems, a cycle or knot may involve several sites, the search for cycles greatly depends upon how the WFG of the system is represented across the system.
- Depending upon the way WFG information is maintained and the search for cycles is carried out, there are centralized, distributed, and hierarchical algorithms for deadlock detection in distributed systems.

Correctness criteria

A deadlock detection algorithm must satisfy the following two conditions:

1. Progress-No undetected deadlocks:

The algorithm must detect all existing deadlocks in finite time. In other words, after all wait-for dependencies for a deadlock have formed, the algorithm should not wait for any more events to occur to detect the deadlock.

2. Safety -No false deadlocks:

The algorithm should not report deadlocks which do not exist. This is also called as called **phantom or false deadlocks.**

Resolution of a Detected Deadlock

- Deadlock resolution involves breaking existing wait-for dependencies between the processes to resolve the deadlock.
- It involves rolling back one or more deadlocked processes and assigning their resources to blocked processes so that they can resume execution.
- The deadlock detection algorithms propagate information regarding wait-for dependencies along the edges of the wait-for graph.
- When a wait-for dependency is broken, the corresponding information should be immediately cleaned from the system.
- If this information is not cleaned in a timely manner, it may result in detection of phantom deadlocks.

3.7 MODELS OF DEADLOCKS

The models of deadlocks are explained based on their hierarchy. The diagrams illustrate the working of the deadlock models. P_a, P_b, P_c, $P_d$are passive processes that had already acquired the resources. $P_e$is active process that is requesting the resource.

3.7.1 Single Resource Model

- A process can have at most one outstanding request for only one unit of a resource.
- The maximum out-degree of a node in a WFG for the single resource model can be 1, the presence of a cycle in the WFG shall indicate that there is a deadlock.

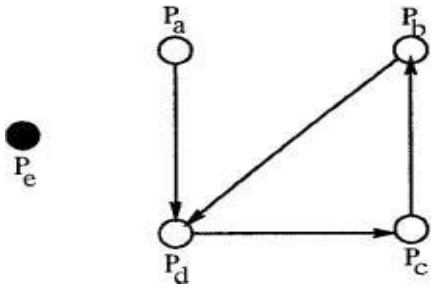


Fig 3.6: Deadlock in single resource model

3.7.2 AND Model

- In the AND model, a passive process becomes active (i.e., its activation condition is fulfilled) only after a message from each process in its dependent set has arrived.
- In the AND model, a process can request more than one resource simultaneously and the request is satisfied only after all the requested resources are granted to the process.
- The requested resources may exist at different locations.
- The out degree of a node in the WFG for AND model can be more than 1.
- The presence of a cycle in the WFG indicates a deadlock in the AND model.
- Each node of the WFG in such a model is called an AND node.

- In the AND model, if a cycle is detected in the WFG, it implies a deadlock but not vice versa. That is, a process may not be a part of a cycle, it can still be deadlocked.

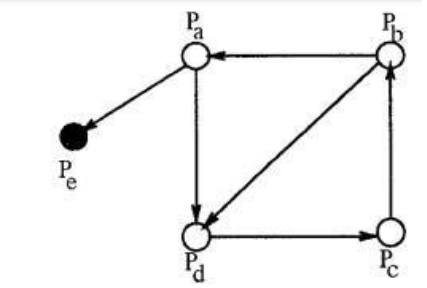


Fig 3.7: Deadlock in AND model

3.7.3 OR Model

- In the OR model, a passive process becomes active only after a message from any process in its dependent set has arrived.
- This models classical nondeterministic choices of receive statements.
- A process can make a request for numerous resources simultaneously and the request is satisfied if any one of the requested resources is granted.
- The requested resources may exist at different locations.
- If all requests in the WFG are OR requests, then the nodes are called OR nodes.
- Presence of a cycle in the WFG of an OR model does not imply a deadlock in the OR model.
- In the OR model, the presence of a knot indicates a deadlock.

Deadlock in OR model: a process Pi is blocked if it has a pending OR request to be satisfied.

- With every blocked process, there is an associated set of processes called **dependent set.**
- A process shall move from an idle to an active state on receiving agrant message from any of the processes in its dependent set.
- A process ispermanently blocked if it never receives a grant message from any of the processes in its dependent set.
- A set of processes S is deadlockedif all the processes in S are permanently blocked.
- In short, a processis deadlocked or permanently blocked, if the following conditions are met:
  1. Each of the process is the set S is blocked.
  2. The dependent set for each process in S is a subset of S.
  3. No grant message is in transit between any two processes in set S.
- A blocked process P is the set S becomes active only after receiving a grant message from a process in its dependent set, which is a subset of S.

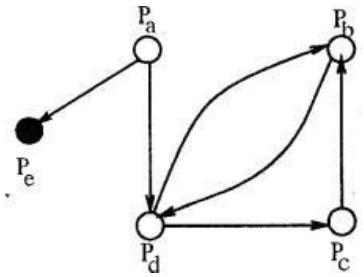


Fig 3.8: OR Model

3.7.4 $\binom{p}{q}$ Model (p out of q model)

- This is a variation of AND-OR model.
- This allows a request to obtain any k available resources from a pool of n resources. Both the models are the same in expressive power.
- This favours more compact formation of a request.
- Every request in this model can be expressed in the AND-OR model and vice-versa.
- Note that AND requests for p resources can be stated as $\binom{p}{q}$ and OR requests for p resources can be stated as $\binom{p}{1}$.

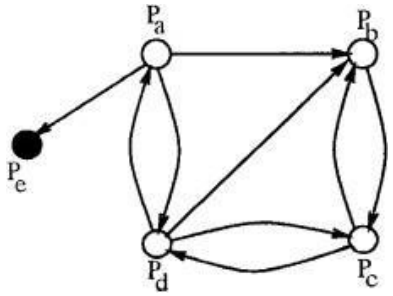


Fig 3.9: p out of q Model

3.7.5 Unrestricted model

- No assumptions are made regarding the underlying structure of resource requests.
- In this model, only one assumption that the deadlock is stable is made and hence it is the most general model.
- This way of looking at the deadlock problem helps in separation of concerns: concerns about properties of the problem are separated from underlying distributed systems computations. Hence, these algorithms can be used to detect other stable properties as they deal with this general model.
- These algorithms are of more theoretical value for distributed systems since no further assumptions are made about the underlying distributed systems computations which leads to a great deal of overhead.

3.8 KNAPP'S CLASSIFICATION OF DISTRIBUTED DEADLOCK DETECTION ALGORITHMS

The four classes of distributed deadlock detection algorithm are:

1. Path-pushing

2. Edge-chasing
3. Diffusion computation
4. Global state detection

3.8.1 Path Pushing algorithms

In path pushing algorithm, the distributed deadlock detection are detected by maintaining an explicit global wait for graph.

The basic idea is to build a global WFG (Wait For Graph) for each site of the distributed system.

At each site whenever deadlock computation is performed, it sends its local WFG to all the neighbouring sites.

After the local data structure of each site is updated, this updated WFG is then passed along to other sites, and the procedure is repeated until some site has a sufficiently complete picture of the global state to announce deadlock or to establish that no deadlocks are present.

This feature of sending around the paths of global WFGhas led to the term path-pushing algorithms.

Examples: Menasce-Muntz , Gligor and Shattuck, Ho and Ramamoorthy, Obermarck

3.8.2 Edge Chasing Algorithms

The presence of a cycle in a distributed graph structure is be verified by propagating special messages called probes, along the edges of the graph.

These probe messages are different than the request and reply messages.

The formation of cycle can be deleted by a site if it receives the matching probe sent by it previously.

Whenever a process that is executing receives a probe message, it discards this message and continues.

Only blocked processes propagate probe messages along their outgoing edges.

Main advantage of edge-chasing algorithms is that probes are fixed size messages which is normally very short.

Examples: Chandy et al., Choudhary et al., Kshemkalyani–Singhal, Sinha–Natarajan algorithms.

3.8.3 Diffusing Computation Based Algorithms

- In diffusion computation based distributed deadlock detection algorithms, deadlock detection computation is diffused through the WFG of the system.
- These algorithms make use of echo algorithms to detect deadlocks.
- This computation is superimposed on the underlying distributed computation.
- If this computation terminates, the initiator declares a deadlock.

- To detect a deadlock, a process sends out query messages along all the outgoing edges in the WFG.
- These queries are successively propagated (i.e., diffused) through the edges of the WFG.
- When a blocked process receives first query message for a particular deadlock detection initiation, it does not send a reply message until it has received a reply message for every query it sent.

- For all subsequent queries for this deadlock detection initiation, it immediately sends back a reply message.
- The initiator of a deadlock detection detects a deadlock when it receives reply for every query it had sent out.
  Examples: Chandy–Misra–Haas algorithm for one OR model, Chandy–Herman algorithm

3.8.4 Global state detection-based algorithms

Global state detection based deadlock detection algorithms exploit the following facts:

1. A consistent snapshot of a distributed system can be obtained without freezing the underlying computation.
2. If a stable property holds in the system before the snapshot collection is initiated, this property will still hold in the snapshot.

Therefore, distributed deadlocks can be detected by taking a snapshot of the system and examining it for the condition of a deadlock

3.9 MITCHELL AND MERRITT'S ALGORITHM FOR THE SINGLE-RESOURCE MODEL

This deadlock detection algorithm assumes a single resource model.

This detects the local and global deadlocks each process has assumed two different labels namely private and public each label is accountant the process id guarantees only one process will detect a deadlock.

Probes are sent in the opposite direction to the edges of the WFG.

When a probe initiated by a process comes back to it, the process declares deadlock.

Features:

1. Only one process in a cycle detects the deadlock. This simplifies the deadlock resolution – this process can abort itself to resolve the deadlock. This algorithm can be improvised by including priorities, and the lowest priority process in a cycle detects deadlock and aborts.
2. In this algorithm, a process that is detected in deadlock is aborted spontaneously, even though under this assumption phantom deadlocks cannot be excluded. It can be shown, however, that only genuine deadlocks will be detected in the absence of spontaneous aborts.

Each node of the WFG has two local variables, called labels:

1. a private label, which is unique to the node at all times, though it is not constant.
2. a public label, which can be read by other processes and which may not be unique.

Each process is represented as u/v where u and u are the public and private labels, respectively. Initially, private and public labels are equal for each process. A global WFG is maintained and it defines the entire state sof the system.

- The algorithm is defined by the four state transitions as shown in Fig.3.10, where z = inc(u, v), and inc(u, v) yields aunique label greater than both u and v labels that are notshown do not change.

- The transitions in the defined by the algorithm are block, activate , transmit and detect.
- **Block** creates an edge in the WFG.
- Two messages are needed, one resource request and onemessage back to the blocked process to inform it of thepublic label of the process it is waiting for.
- **Activate** denotes that a process has acquired the resourcefrom the process it was waiting for.
- **Transmit** propagates larger labels in the opposite directionof the edges by sending a probe message.

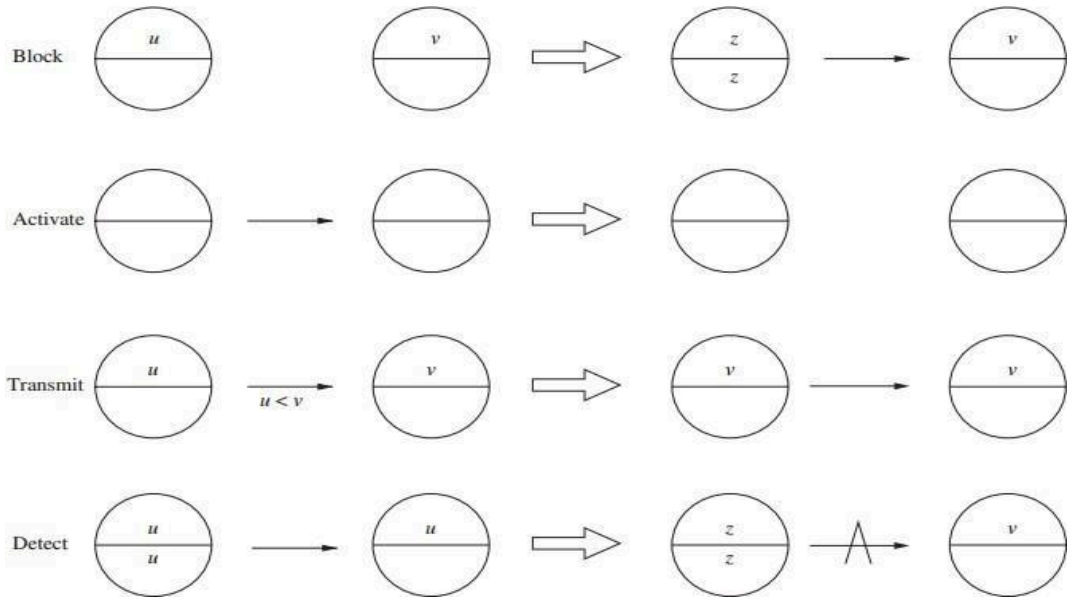


Fig 3.10: Four possible state transitions

- **Detect** means that the probe with the private label of some process has returned to it, indicating a deadlock.
- This algorithm can easily be extended to include priorities, so that whenever a deadlock occurs, the lowest priority process gets aborted.
- This priority based algorithm has two phases.
    1. The first phase is almost identical to the algorithm.
    2. The second phase the smallest priority is propagated around the circle. The propagation stops when one process recognizes the propagated priority as its own.

Message Complexity:
If we assume that a deadlock persists long enough to be detected, the worst-case complexity of the algorithm is s(s - 1)/2 Transmit steps, where s is the number of processes in the cycle.

3.10 CHANDY–MISRA–HAAS ALGORITHM FOR THE AND MODEL

This is considered an edge-chasing, probe-based algorithm.

It is also considered one of the best deadlock detection algorithms for distributed systems.

If a process makes a request for a resource which fails or times out, the process generates a probe message and sends it to each of the processes holding one or more of its requested resources.

This algorithm uses a special message called probe, which is a triplet (i, j,k), denoting that it belongs to a deadlock detection initiated for process Pi andit is being sent by the home site of process Pj to the home site of process Pk.

Each probe message contains the following information:

- the id of the process that is blocked (the one that initiates the probe message);
- the id of the process is sending this particular version of the probe message;
- the id of the process that should receive this probe message.

A probe message travels along the edges of the global WFG graph, and a deadlock is detected when a probe message returns to the process that initiated it.

A process P_j is said to be dependent on another process P_k if there exists a sequence of processes P_j, P_{i1} , P_{i2} , . . . , P_{im}, $P_k$such that each process except $P_k$in the sequence is blocked and each process, except the P_j, holds a resource for which the previous process in the sequence is waiting.

Process P_j is said to be locally dependent upon process P_k if P_j is dependent upon $P_k$and both the processes are on the same site.

When a process receives a probe message,it checks to see if it is also waiting for resources

If not, it is currently using the needed resource and will eventually finish and release the resource.

If it is waiting for resources, it passes on the probe message to all processes it knows to be holding resources it has itself requested.

The process first modifies the probe message, changing the sender and receiver ids.

If a process receives a probe message that it recognizes as having initiated,it knows there is a cycle in the system and thus, deadlock.

Data structures

Each process Pi maintains a boolean array, dependenti, where dependent(j) is true only if Pi knows that Pj is dependent on it. Initially, dependenti (j) is false for all i and j.

```
if P_i is locally dependent on itself
   then declare a deadlock
   else for all P_j and P_k such that
      (a) P_i is locally dependent upon P_j, and
      (b) P_j is waiting on P_k, and
      (c) P_j and P_k are on different sites,
   send a probe (i, j, k) to the home site of P_k

On the receipt of a probe (i, j, k), the site takes
   the following actions:

if
      (d) P_k is blocked, and
      (e) dependent_k(i) is false, and
      (f) P_k has not replied to all requests P_j,
      then
         begin
            dependent_k(i) = true;
            if k = i
               then declare that P_i is deadlocked
            else for all P_m and P_n such that
               (a') P_k is locally dependent upon P_m, and
               (b') P_m is waiting on P_n, and
               (c') P_m and P_n are on different sites,
            send a probe (i, m, n) to the home site of P_n
         end.
```

Fig 3.11: Chandy–Misra–Haas algorithm for the AND model

Performance analysis

In the algorithm, one probe message is sent on every edge of the WFG which connects processes on two sites.

The algorithm exchanges at most m(n − 1)/2 messages to detect a deadlock that involves m processes and spans over n sites.

The size of messages is fixed and is very small (only three integer words).

The delay in detecting a deadlock is O(n).

Advantages:

It is easy to implement.

Each probe message is of fixed length.

There is very little computation.

There is very little overhead.

There is no need to construct a graph, nor to pass graph information to other sites.

This algorithm does not find false (phantom) deadlock.

There is no need for special data structures.

3.11 CHANDY–MISRA–HAAS ALGORITHM FOR THE OR MODEL

A blocked process determines if it is deadlocked by initiating a diffusion computation.

Two types of messages are used in a diffusion computation:

- query(i, j, k)
- reply(i, j, k)

denoting that they belong to a diffusion computation initiated by a process p_i and are being sent from process p_j to process p_k.

A blocked process initiates deadlock detection by sending query messages to all processes in its dependent set.

If an active process receives a query or reply message, it discards it.

When a blocked process Pk receives a query(i, j, k) message, it takes the following actions:

1. If this is the first query message received by Pk for the deadlock detection initiated by Pi, then it propagates the query to all the processes in its dependent set and sets a local variable num_k (i) to the number of query messages sent.
2. If this is not the engaging query, then Pk returns a reply message to it immediately provided Pk has been continuously blocked since it received the corresponding engaging query. Otherwise, it discards the query.

- Process Pk maintains a boolean variable $wait_k$(i) that denotes the fact that it has been continuously blocked since it received the last engaging query from process Pi.
- When a blocked process Pk receives a reply(i, j, k) message, it decrements num_k(i) only if $wait_k$(i) holds.
- A process sends a reply message in response to an engaging query only after it has received a reply to every query message it has sent out for this engaging query.
- The initiator process detects a deadlock when it has received reply messages to all the query messages it has sent out.

Initiate a diffusion computation for a blocked process P_i:
send *query*(i, i, j) to all processes P_j in the dependent set DS_i of P_i;
$num_i(i) := |DS_i|$; $wait_i(i) := true$;

When a blocked process P_k receives a *query*(i, j, k):
if this is the engaging *query* for process P_i then
send *query*(i, k, m) to all P_m in its dependent set DS_k;
$num_k(i) := |DS_k|$; $wait_k(i) := true$
else if $wait_k(i)$ then send a *reply*(i, k, j) to P_j.

When a process P_k receives a *reply*(i, j, k):
if $wait_k(i)$ then
$num_k(i) := num_k(i) - 1$;
if $num_k(i) = 0$ then
if $i = k$ then **declare a deadlock**
else send *reply*(i, k, m) to the process P_m
which sent the engaging query.

Fig 3.12: Chandy–Misra–Haas algorithm for the OR model

Performance analysis

For every deadlock detection, the algorithm exchanges e query messages ande reply messages, where e = n(n – 1) is the number of edges.

CS8603 UNIT IV RECOVERY & CONSENSUS

Check pointing and rollback recovery: Introduction – Background and definitions – Issues in failure recovery – Checkpoint-based recovery – Log-based rollback recovery – Coordinated check pointing algorithm – Algorithm for asynchronous check pointing and recovery. Consensus and agreement algorithms: Problem definition – Overview of results – Agreement in a failure – free system – Agreement in synchronous systems with failures.

4.1 Check pointing and rollback recovery: Introduction

- Rollback recovery protocols restore the system back to a consistent state after a failure,
- It achieves fault tolerance by periodically saving the state of a process during the failure- free execution
- It treats a distributed system application as a collection of processes that communicate over a network

Checkpoints

The saved state is called a checkpoint, and the procedure of restarting from a previously check pointed state is called rollback recovery. A checkpoint can be saved on either the stable storage or the volatile storage

Why is rollback recovery of distributed systems complicated?

Messages induce inter-process dependencies during failure-free

operation **Rollback propagation**

The dependencies among messages may force some of the processes that did not fail to roll back. This phenomenon of cascaded rollback is called the domino effect.

Uncoordinated check pointing

If each process takes its checkpoints independently, then the system cannot avoid the domino effect – this scheme is called independent or uncoordinated check pointing

Techniques that avoid domino effect

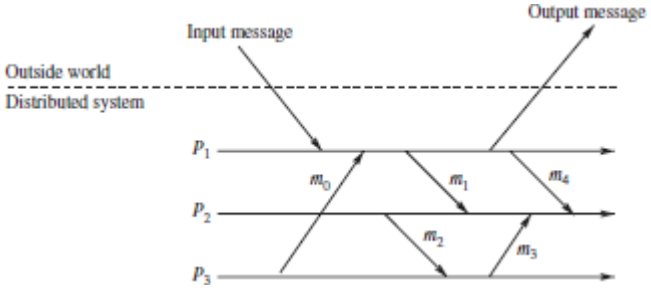
1. Coordinated check pointing rollback recovery - Processes coordinate their checkpoints to form a system-wide consistent state
2. Communication-induced check pointing rollback recovery - Forces each process to take checkpoints based on information piggybacked on the application.

3. Log-based rollback recovery - Combines check pointing with logging of non-deterministic events • relies on piecewise deterministic (PWD) assumption.

4.2 Background and definitions

4.2.1 System model

- A distributed system consists of a fixed number of processes, P1, P2,…_ PN , which communicate only through messages.
- Processes cooperate to execute a distributed application and interact with the outside world by receiving and sending input and output messages, respectively.
- Rollback-recovery protocols generally make assumptions about the reliability of the inter-process communication.
- Some protocols assume that the communication uses first-in-first-out (FIFO) order, while other protocols assume that the communication subsystem can lose, duplicate, or reorder messages.
- Rollback-recovery protocols therefore must maintain information about the internal interactions among processes and also the external interactions with the outside world.



An example of a distributed system with three processes.

4.2.2 A local checkpoint

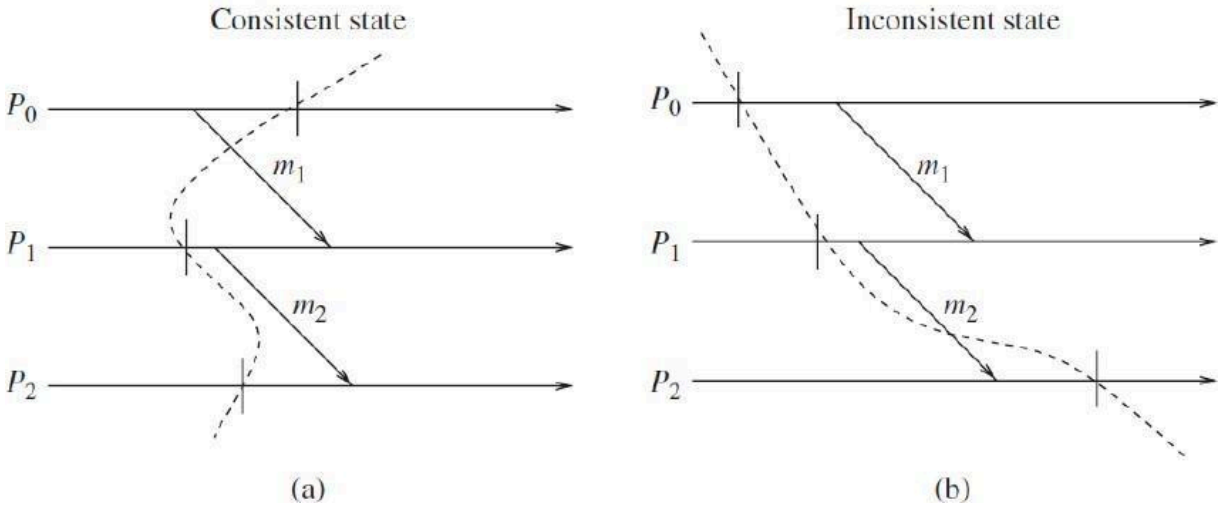
- All processes save their local states at certain instants of time
- A local check point is a snapshot of the state of the process at a given instance
- Assumption
  - – A process stores all local checkpoints on the stable storage
  - – A process is able to roll back to any of its existing local checkpoints

- Ci,k – The kth local checkpoint at process Pi
- $Ci,0$ – A process Pi takes a checkpoint $Ci,0$ before it starts execution

4.2.3 Consistent states

- A global state of a distributed system is a collection of the individual states of all participating processes and the states of the communication channels
- Consistent global state
  - a global state that may occur during a failure-free execution of distribution of distributed computation
  - if a process‟s state reflects a message receipt, then the state of the corresponding sender must reflect the sending of the message
- A global checkpoint is a set of local checkpoints, one from each process
- A consistent global checkpoint is a global checkpoint such that no message is sent by a process after taking its local point that is received by another process before taking its checkpoint.

Consistent states - examples



- For instance, Figure shows two examples of global states.
- The state in fig (a) is consistent and the state in Figure (b) is inconsistent.
- Note that the consistent state in Figure (a) shows message $m1$ to have been sent but not yet received, but that is alright.
- The state in Figure (a) is consistent because it represents a situation in which every message that has been received, there is a corresponding message send event.
- The state in Figure (b) is inconsistent because process $P2$ is shown to have received $m2$ but the state of process $P1$ does not reflect having sent it.
- Such a state is impossible in any failure-free, correct computation. Inconsistent states occur because of failures.

4.2.4 Interactions with outside world

A distributed system often interacts with the outside world to receive input data or deliver the outcome of a computation. If a failure occurs, the outside world cannot be expected to roll back. For example, a printer cannot roll back the effects of printing a character

Outside World Process (OWP)

- It is a special process that interacts with the rest of the system through message passing.
- It is therefore necessary that the outside world see a consistent behavior of the system despite failures.
- Thus, before sending output to the OWP, the system must ensure that the state from which the output is sent will be recovered despite any future failure.

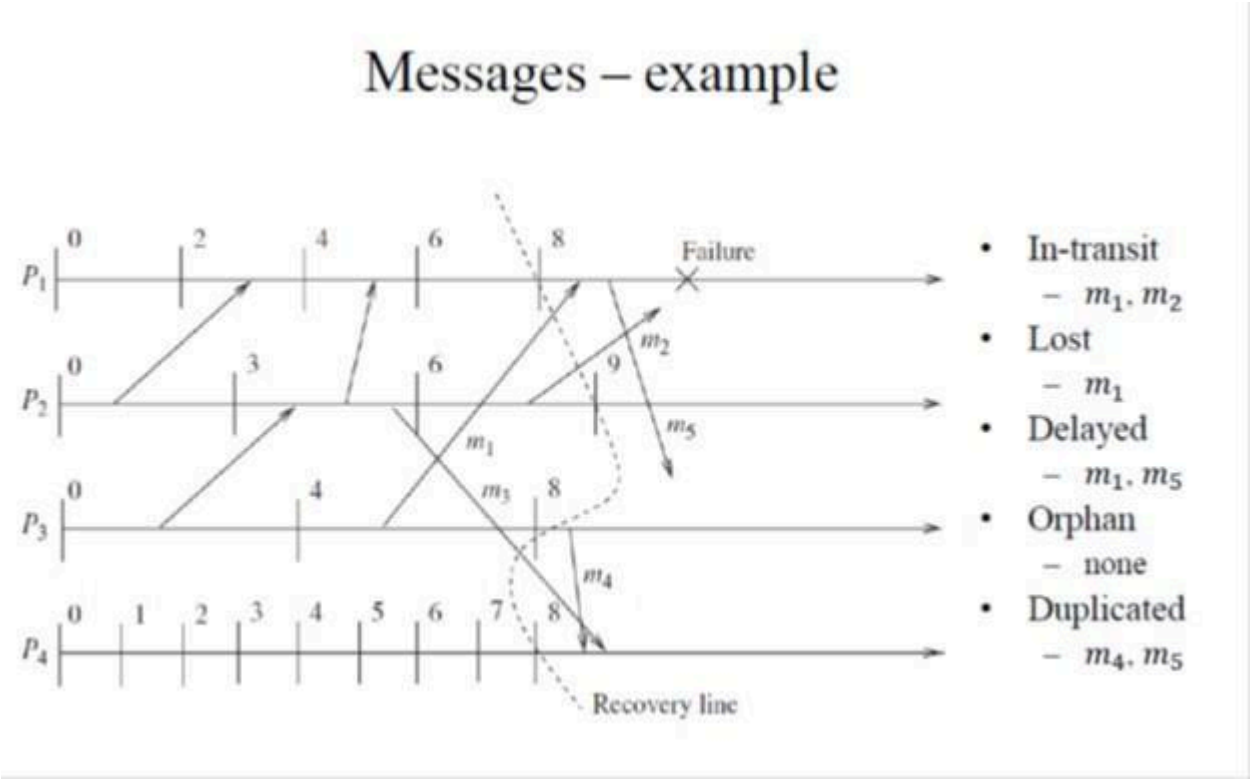
A common approach is to save each input message on the stable storage before allowing the application program to process it.

An interaction with the outside world to deliver the outcome of a computation is shown on the process-line by the symbol "||".

4.2.5 Different types of Messages

1. In-transit message
    - messages that have been sent but not yet received
2. Lost messages
    - messages whose "send" is done but "receive" is undone due to rollback

3. Delayed messages
    - messages whose “receive“ is not recorded because the receiving process was either down or the message arrived after rollback
4. Orphan messages
    - messages with “receive“ recorded but message “send“ not recorded
    - do not arise if processes roll back to a consistent global state
5. Duplicate messages
    - arise due to message logging and replaying during process recovery



In-transit messages

In Figure , the global state {C1,8 , C2, 9 , C3,8, C4,8} shows that message *m*1 has been sent but not yet received. We call such a message an *in-transit* message. Message *m*2 is also an in-transit message.

Delayed messages

Messages whose receive is not recorded because the receiving process was either down or the message arrived after the rollback of the receiving process, are called *delayed* messages. For example, messages m2 and m5 in Figure are delayed messages.

Lost messages

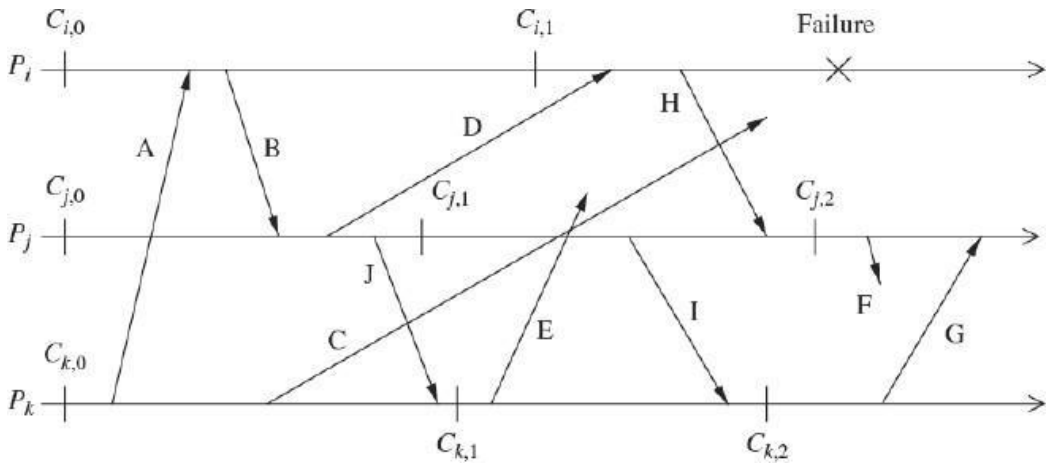
Messages whose send is not undone but receive is undone due to rollback are called lost messages. This type of messages occurs when the process rolls back to a checkpoint prior to reception of the message while the sender does not rollback beyond the send operation of the message. In Figure , message m1 is a lost message.

Duplicate messages

- Duplicate messages arise due to message logging and replaying during process recovery. For example, in Figure, message m4 was sent and received before the rollback. However, due to the rollback of process P4 to C4,8 and process P3 to C3,8, both send and receipt of message m4 are undone.
- When process P3 restarts from C3,8, it will resend message m4.
- Therefore, P4 should not replay message m4 from its log.
- If P4 replays message m4, then message m4 is called a duplicate message.

4.3 Issues in failure recovery

In a failure recovery, we must not only restore the system to a consistent state, but also appropriately handle messages that are left in an abnormal state due to the failure and recovery



The computation comprises of three processes Pi, Pj , and Pk, connected through a communication network. The processes communicate solely by exchanging messages over free, FIFO communication channels.
fault-

Processes Pi, Pj , and Pk have taken checkpoints

- Checkpoints : $\{C_{i,0}, C_{i,1}\}$, $\{C_{j,0}, C_{j,1}, C_{j,2}\}$, and $\{C_{k,0}, C_{k,1}, C_{k,2}\}$
- Messages : A - J
- The restored global consistent state : $\{C_{i,1}, C_{j,1}, C_{k,1}\}$

- The rollback of process Pi to checkpoint Ci,1 created an orphan message H
- Orphan message I is created due to the roll back of process Pj to checkpoint Cj,1
- Messages C, D, E, and F are potentially problematic
  - Message C: a delayed message
  - Message D: a lost message since the send event for D is recorded in the restored state for Pj, but the receive event has been undone at process Pi.
  - Lost messages can be handled by having processes keep a message log of all the sent messages
  - Messages E, F: delayed orphan messages. After resuming execution from their checkpoints, processes will generate both of these messages

4.4 Checkpoint-based recovery

Checkpoint-based rollback-recovery techniques can be classified into three categories:

1. U*ncoordinated checkpointing*
2. *Coordinated checkpointing*
3. *Communication-induced checkpointing*

1. Uncoordinated Checkpointing

- Each process has autonomy in deciding when to take checkpoints
- Advantages

The lower runtime overhead during normal execution

- Disadvantages
    1. Domino effect during a recovery
    2. Recovery from a failure is slow because processes need to iterate to find a consistent set of checkpoints
    3. Each process maintains multiple checkpoints and periodically invoke a garbage collection algorithm
    4. Not suitable for application with frequent output commits
- The processes record the dependencies among their checkpoints caused by message exchange during failure-free operation

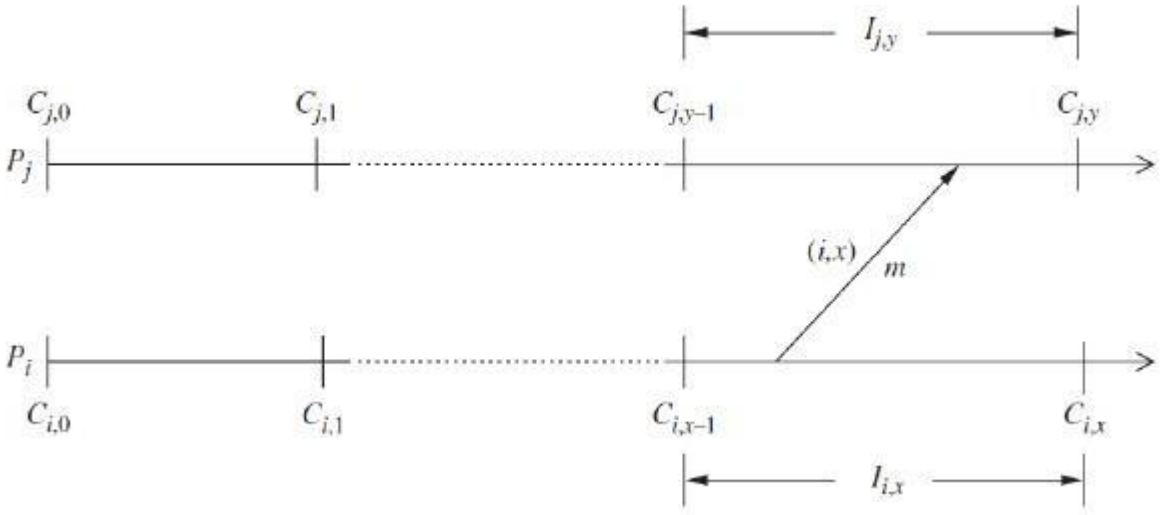
- The following direct dependency tracking technique is commonly used in uncoordinated checkpointing.

Direct dependency tracking technique

Assume each process Pi starts its execution with an initial checkpoint $Ci,0$

Ii,x : checkpoint interval, interval between $Ci,x-1$ and Ci,x

When Pj receives a message m during Ij,y , it records the dependency from Ii,x to Ij,y, which is later saved onto stable storage when Pj takes Cj,y



When a failure occurs, the recovering process initiates rollback by broadcasting a *dependency request* message to collect all the dependency information maintained by each process.

When a process receives this message, it stops its execution and replies with the dependency information saved on the stable storage as well as with the dependency information, if any, which is associated with its current state.

The initiator then calculates the recovery line based on the global dependency information and broadcasts a *rollback request* message containing the recovery line.

Upon receiving this message, a process whose current state belongs to the recovery line simply resumes execution; otherwise, it rolls back to an earlier checkpoint as indicated by the recovery line.

2. Coordinated Checkpointing

In coordinated checkpointing, processes orchestrate their checkpointing activities so that all local checkpoints form a consistent global state

Types

1. Blocking Checkpointing: After a process takes a local checkpoint, to prevent orphan messages, it remains blocked until the entire checkpointing activity is complete
   Disadvantages: The computation is blocked during the checkpointing
2. Non-blocking Checkpointing: The processes need not stop their execution while taking checkpoints. A fundamental problem in coordinated checkpointing is to prevent a process from receiving application messages that could make the checkpoint inconsistent.

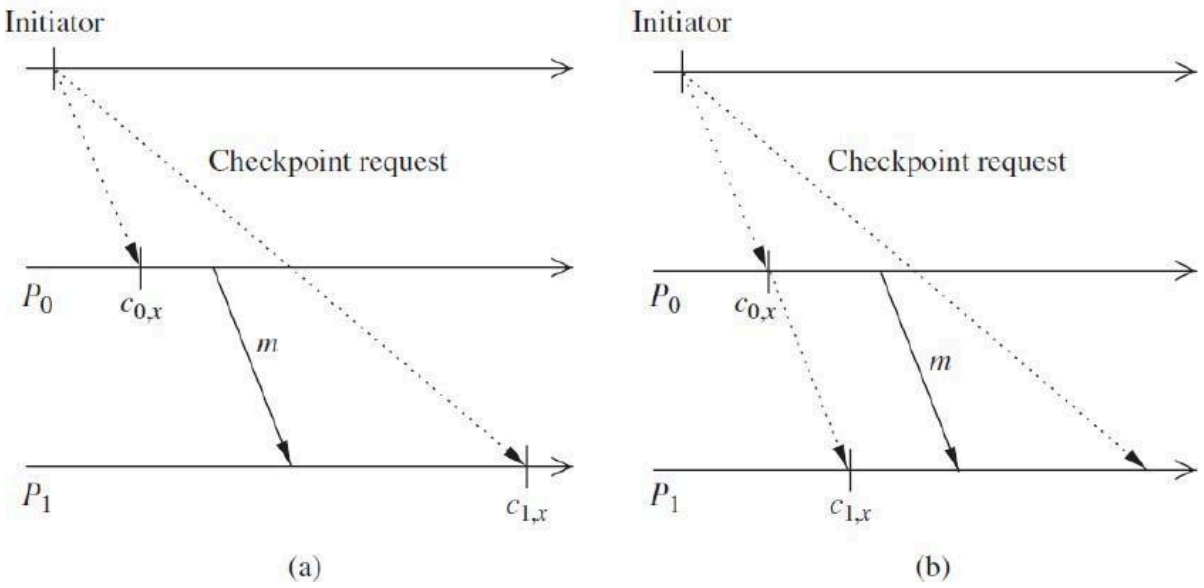
Example (a) : Checkpoint inconsistency

- Message m is sent by $P0$ after receiving a checkpoint request from the checkpoint coordinator
- Assume m reaches $P1$ before the checkpoint request
- This situation results in an inconsistent checkpoint since checkpoint $C1,x$ shows the receipt of message m from $P0$, while checkpoint $C0,x$ does not show m being sent from
  $P0$

Example (b) : A solution with FIFO channels

- If channels are FIFO, this problem can be avoided by preceding the first post-checkpoint message on each channel by a checkpoint request, forcing each process to take a checkpoint before receiving the first post-checkpoint message

Coordinated Checkpointing



Impossibility of min-process non-blocking checkpointing

- A min-process, non-blocking checkpointing algorithm is one that forces only a minimum number of processes to take a new checkpoint, and at the same time it does not force any process to suspend its computation.

Algorithm

- The algorithm consists of two phases. During the first phase, the checkpoint initiator identifies all processes with which it has communicated since the last checkpoint and sends them a request.
- Upon receiving the request, each process in turn identifies all processes it has communicated with since the last checkpoint and sends them a request, and so on, until no more processes can be identified.
- During the second phase, all processes identified in the first phase take a checkpoint. The result is a consistent checkpoint that involves only the participating processes.

- In this protocol, after a process takes a checkpoint, it cannot send any message until the second phase terminates successfully, although receiving a message after the checkpoint has been taken is allowable.

3. Communication-induced Checkpointing

Communication-induced checkpointing is another way allowing processes to take some of their checkpoints independently. Processes may be forced to take additional checkpoints to avoid the domino effect, while

Two types of checkpoints 1. Autonomous checkpoints

2. Forced checkpoints

The checkpoints that a process takes independently are called *local* checkpoints, while those that a process is forced to take are called *forced* checkpoints.

- Communication-induced check pointing piggybacks protocol- related information on each application message
- The receiver of each application message uses the piggybacked information to determine if it has to take a forced checkpoint to advance the global recovery line
- The forced checkpoint must be taken before the application may process the contents of the message
- In contrast with coordinated check pointing, no special coordination messages are exchanged

Two types of communication-induced checkpointing

1. Model-based checkpointing
2. Index-based checkpointing.

Model-based checkpointing

- Model-based checkpointing prevents patterns of communications and checkpoints that could result in inconsistent states among the existing checkpoints.
- No control messages are exchanged among the processes during normal operation. All information necessary to execute the protocol is piggybacked on application messages

- There are several domino-effect-free checkpoint and communication model.
- The MRS (mark, send, and receive) model of Russell avoids the domino effect by ensuring that within every checkpoint interval all message receiving events precede all message-sending events.

Index-based checkpointing.

- Index-based communication-induced checkpointing assigns monotonically increasing indexes to checkpoints, such that the checkpoints having the same index at different processes form a consistent state.

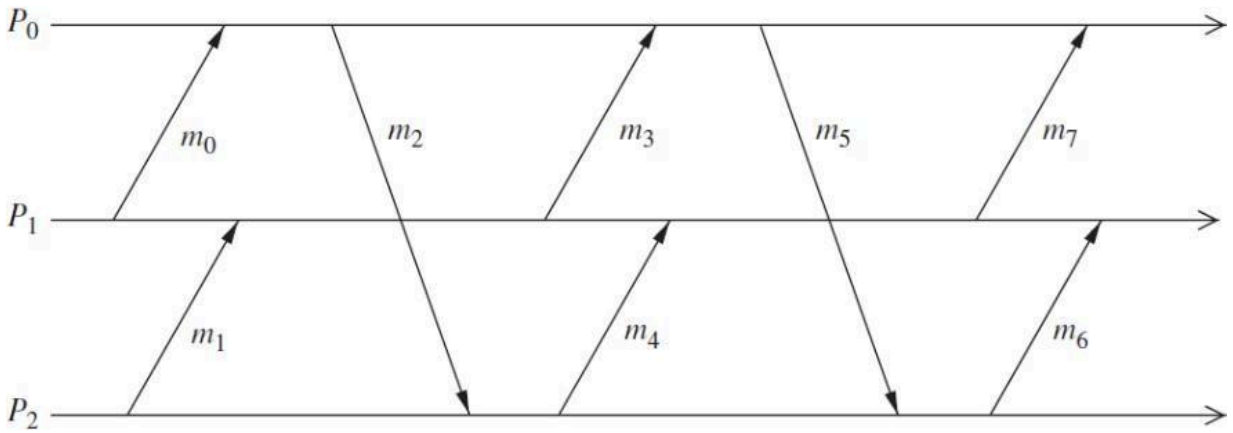
4.5 Log-based rollback recovery

A log-based rollback recovery makes use of deterministic and nondeterministic events in a computation.

Deterministic and non-deterministic events

- Log-based rollback recovery exploits the fact that a process execution can be modeled as a sequence of deterministic state intervals, each starting with the execution of a non-deterministic event.
- A non-deterministic event can be the receipt of a message from another process or an event internal to the process.
- Note that a message send event is *not* a non-deterministic event.
- For example, in Figure, the execution of process $P0$ is a sequence of four deterministic intervals. The first one starts with the creation of the process, while the remaining three start with the receipt of messages $m0$, $m3$, and $m7$, respectively.
- Send event of message $m2$ is uniquely determined by the initial state of $P0$ and by the receipt of message $m0$, and is therefore not a non-deterministic event.
- Log-based rollback recovery assumes that all non-deterministic events can be identified and their corresponding determinants can be logged into the stable storage.
- Determinant: the information need to "replay" the occurrence of a non-deterministic event (e.g., message reception).
- During failure-free operation, each process logs the determinants of all non-deterministic events that it observes onto the stable storage. Additionally, each process also takes checkpoints to reduce the extent of rollback during recovery.

Log-based Rollback Recovery



The no-orphans consistency condition

Let *e* be a non-deterministic event that occurs at process *p*. We define the following:

• *Depend*(*e*): the set of processes that are affected by a non-deterministic event *e.*

• *Log*(*e*): the set of processes that have logged a copy of *e*'s determinant in their volatile memory.

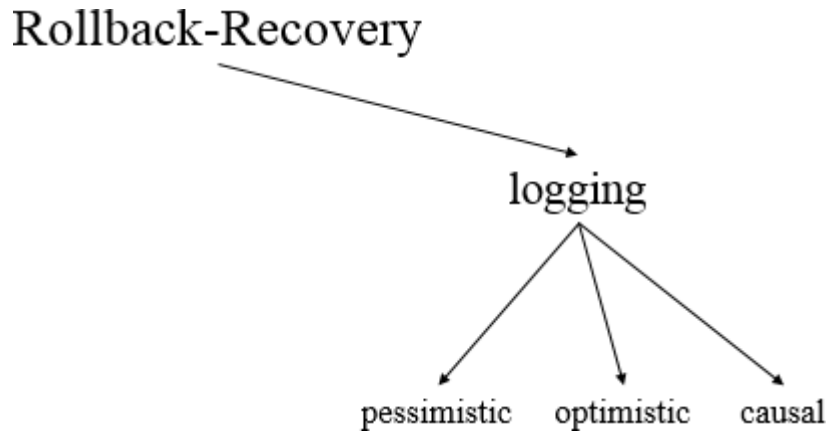
• *Stable*(*e*): a predicate that is true if *e*'s determinant is logged on the stable storage.

Suppose a set of processes Ψ crashes. A process *p* in Ψ becomes an orphan when *p* itself does not fail and *p*'s state depends on the execution of a nondeterministic event *e* whose determinant cannot be recovered from the stable storage or from the volatile memory of a surviving process. storage or from the volatile memory of a surviving process. Formally, it can be stated as follows

always-no-orphans condition

– $\forall(e) : \neg Stable(e) \Rightarrow Depend(e) \subseteq Log(e)$

Types



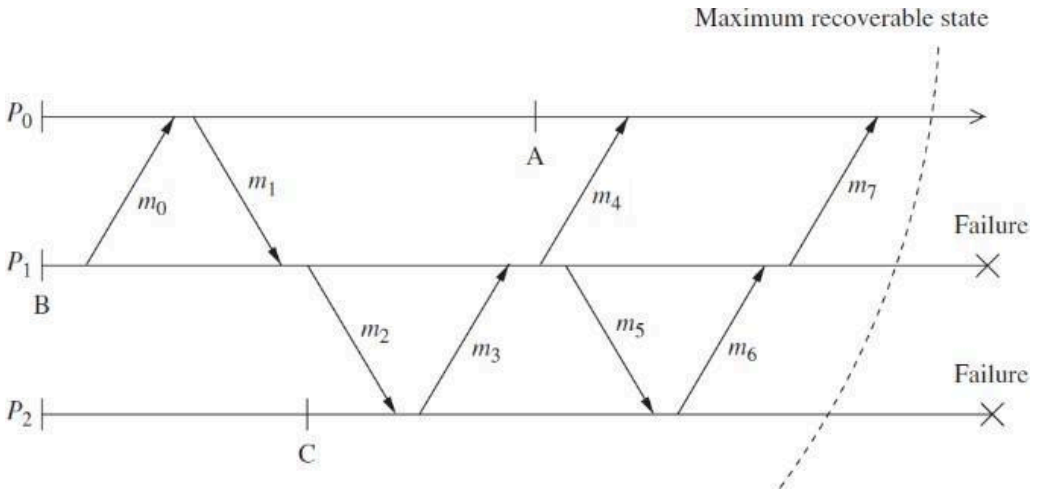
1. Pessimistic Logging

- Pessimistic logging protocols assume that a failure can occur after any non-deterministic event in the computation. However, in reality failures are rare
- Pessimistic protocols implement the following property, often referred to as *synchronous logging*, which is a stronger than the always-no-orphans condition
- *Synchronous logging*

  – ∀e: ¬Stable(e) ⇒ |Depend(e)| = 0
- Thai is,if an event has not been logged on the stable storage, then no process can depend on it.

Example:

- Suppose processes $P1$ and $P2$ fail as shown, restart from checkpoints B and C, and roll forward using their determinant logs to deliver again the same sequence of messages as in the pre-failure execution
- Once the recovery is complete, both processes will be consistent with the state of $P0$ that includes the receipt of message $m7$ from $P1$



- Disadvantage: performance penalty for synchronous logging
- Advantages:
    - immediate output commit
    - restart from most recent checkpoint
    - recovery limited to failed process(es)
    - simple garbage collection
- Some pessimistic logging systems reduce the overhead of synchronous logging without relying on hardware. For example, the *sender-based message logging* (SBML) protocol keeps the determinants corresponding to the delivery of each message *m* in the volatile memory of its sender.
- The ***sender-based message logging*** **(SBML) protocol**

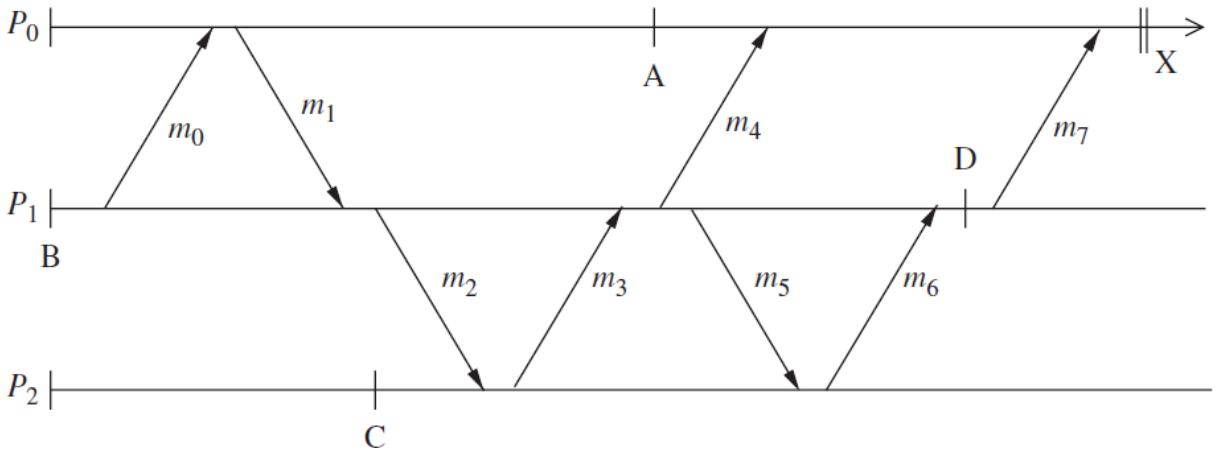
  Two steps.

  1. First, before sending m, the sender logs its content in volatile memory.
  2. Then, when the receiver of m responds with an acknowledgment that includes the order in which the message was delivered, the sender adds to the determinant the ordering information.

2. Optimistic Logging

- Processes log determinants asynchronously to the stable storage
- Optimistically assume that logging will be complete before a failure occurs
- Do not implement the *always-no-orphans* condition

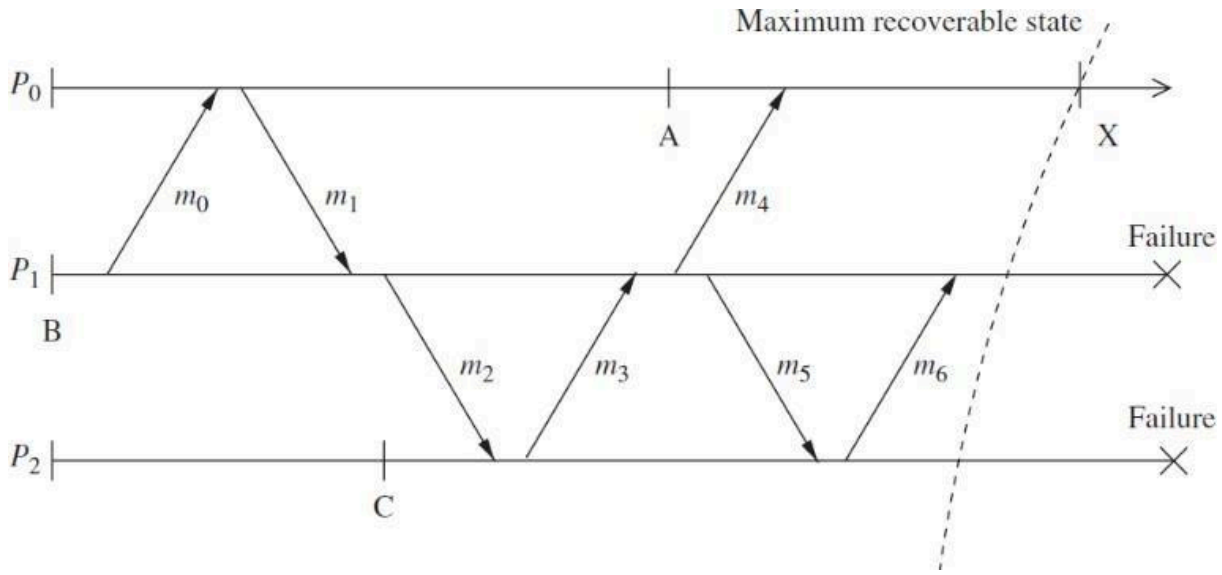
- To perform rollbacks correctly, optimistic logging protocols track causal dependencies during failure free execution
- Optimistic logging protocols require a non-trivial garbage collection scheme
- Pessimistic protocols need only keep the most recent checkpoint of each process, whereas optimistic protocols may need to keep multiple checkpoints for each process



- Consider the example shown in Figure Suppose process $P2$ fails before the determinant for $m5$ is logged to the stable storage. Process $P1$ then becomes an orphan process and must roll back to undo the effects of receiving the orphan message $m6$. The rollback of $P1$ further forces $P0$ to roll back to undo the effects of receiving message $m7$.
- **Advantage: better performance in failure-free execution**
- **Disadvantages:**
    - **coordination required on output commit**
    - **more complex garbage collection**
- Since determinants are logged asynchronously, output commit in optimistic logging protocols requires a guarantee that no failure scenario can revoke the output. For example, if process $P0$ needs to commit output at state X, it must log messages $m4$ and $m7$ to the stable storage and ask $P2$ to log $m2$ and $m5$. In this case, if any process fails, the computation can be reconstructed up to state X.

3. Causal Logging

- Combines the advantages of both pessimistic and optimistic logging at the expense of a more complex recovery protocol
- Like optimistic logging, it does not require synchronous access to the stable storage except during output commit
- Like pessimistic logging, it allows each process to commit output independently and never creates orphans, thus isolating processes from the effects of failures at other processes
- Make sure that the always-no-orphans property holds
- Each process maintains information about all the events that have causally affected its state



- Consider the example in Figure Messages *m*5 and *m*6 are likely to be lost on the failures of P1 and P2 at the indicated instants. Process
- *P*0 at state X will have logged the determinants of the nondeterministic events that causally precede its state according to Lamport's *happened-before* relation.
- These events consist of the delivery of messages *m*0, *m*1, *m*2, *m*3, and *m*4.
- The determinant of each of these non-deterministic events is either logged on the stable storage or is available in the volatile log of process *P*0.
- The determinant of each of these events contains the order in which its original receiver delivered the corresponding message.

- The message sender, as in sender-based message logging, logs the message content. Thus, process $P0$ will be able to "guide" the recovery of $P1$ and $P2$ since it knows the order in which $P1$ should replay messages $m1$ and $m3$ to reach the state from which $P1$ sent message $m4$.
- Similarly, $P0$ has the order in which $P2$ should replay message $m2$ to be consistent with both $P0$ and $P1$.
- The content of these messages is obtained from the sender log of $P0$ or regenerated deterministically during the recovery of $P1$ and $P2$.
- Note that information about messages $m5$ and $m6$ is lost due to failures. These messages may be resent after recovery possibly in a different order.
- However, since they did not causally affect the surviving process or the outside world, the resulting state is consistent.
- Each process maintains information about all the events that have causally affected its state.

4.6 KOO AND TOUEG COORDINATED CHECKPOINTING AND RECOVERY TECHNIQUE:

- Koo and Toueg coordinated check pointing and recovery technique takes a consistent set of checkpoints and avoids the domino effect and livelock problems during the recovery.
- Includes 2 parts: the check pointing algorithm and the recovery algorithm

A. The Checkpointing Algorithm

The checkpoint algorithm makes the following assumptions about the distributed system:

- Processes communicate by exchanging messages through communication channels.
- Communication channels are FIFO.
- Assume that end-to-end protocols (the sliding window protocol) exist to handle with message loss due to rollback recovery and communication failure.
- Communication failures do not divide the network.

The checkpoint algorithm takes two kinds of checkpoints on the stable storage: Permanent and Tentative.

A *permanent checkpoint* is a local checkpoint at a process and is a part of a consistent global checkpoint.
A *tentative checkpoint* is a temporary checkpoint that is made a permanent checkpoint on the successful termination of the checkpoint algorithm.

The algorithm consists of two phases.

First Phase

1. An initiating process Pi takes a tentative checkpoint and requests all other processes to take tentative checkpoints. Each process informs Pi whether it succeeded in taking a tentative checkpoint.
2. A process says "no" to a request if it fails to take a tentative checkpoint
3. If Pi learns that all the processes have successfully taken tentative checkpoints, Pi decides that all tentative checkpoints should be made permanent; otherwise, Pi decides that all the tentative checkpoints should be thrown-away.

Second Phase

1. Pi informs all the processes of the decision it reached at the end of the first phase.
2. A process, on receiving the message from Pi will act accordingly.
3. Either all or none of the processes advance the checkpoint by taking permanent checkpoints.
4. The algorithm requires that after a process has taken a tentative checkpoint, it cannot send messages related to the basic computation until it is informed of Pi's decision.

Correctness: for two reasons

i. Either all or none of the processes take permanent checkpoint
ii. No process sends message after taking permanent checkpoint

An Optimization

The above protocol may cause a process to take a checkpoint even when it is not necessary for consistency. Since taking a checkpoint is an expensive operation, we avoid taking checkpoints.

B. The Rollback Recovery Algorithm

The rollback recovery algorithm restores the system state to a consistent state after a failure. The rollback recovery algorithm assumes that a single process invokes the algorithm. It assumes that the checkpoint and the rollback recovery algorithms are not invoked concurrently. The rollback recovery algorithm has two phases.

First Phase

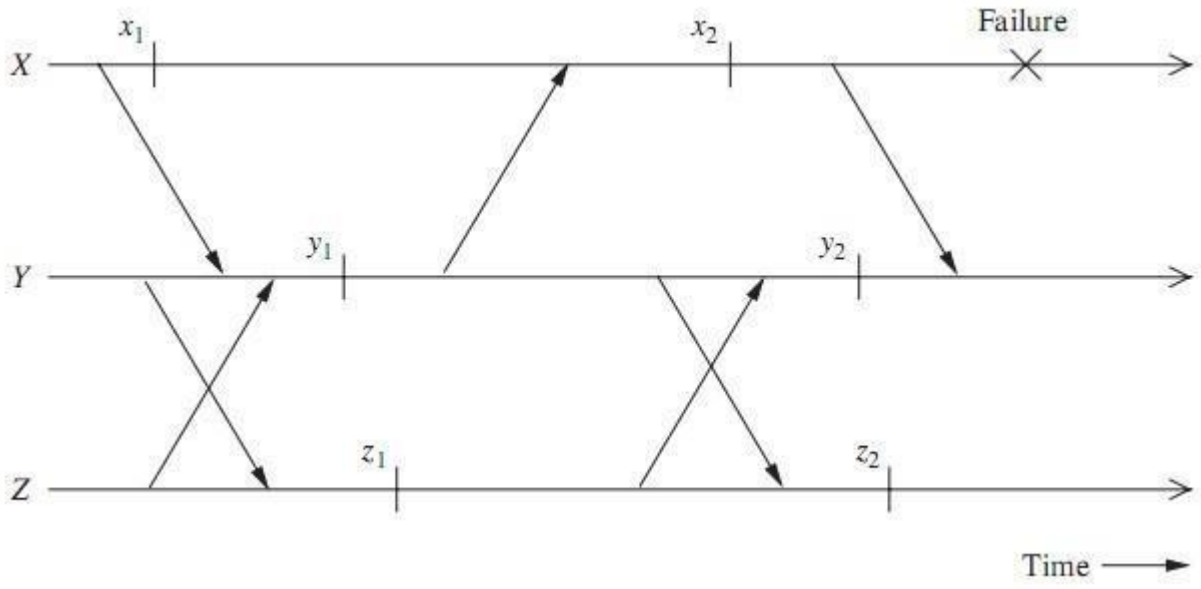
1. An initiating process Pi sends a message to all other processes to check if they all are willing to restart from their previous checkpoints.
2. A process may reply "no" to a restart request due to any reason (e.g., it is already participating in a check pointing or a recovery process initiated by some other process).
3. If Pi learns that all processes are willing to restart from their previous checkpoints, Pi decides that all processes should roll back to their previous checkpoints. Otherwise,
4. Pi aborts the roll back attempt and it may attempt a recovery at a later time.

Second Phase

1. Pi propagates its decision to all the processes.
2. On receiving Pi's decision, a process acts accordingly.
3. During the execution of the recovery algorithm, a process cannot send messages related to the underlying computation while it is waiting for Pi's decision.

Correctness: Resume from a consistent state

Optimization: May not to recover all, since some of the processes did not change anything



The above protocol, in the event of failure of process X, the above protocol will require processes X, Y, and Z to restart from checkpoints x2, y2, and z2, respectively.
Process Z need not roll back because there has been no interaction between process Z and the other two processes since the last checkpoint at Z.

4.7 ALGORITHM FOR ASYNCHRONOUS CHECKPOINTING AND RECOVERY:

The algorithm of Juang and Venkatesan for recovery in a system that uses asynchronous check pointing.

A. System Model and Assumptions

The algorithm makes the following assumptions about the underlying system:

- The communication channels are reliable, deliver the messages in FIFO order and have infinite buffers.
- The message transmission delay is arbitrary, but finite.
- Underlying computation/application is event-driven: process P is at state s, receives message m, processes the message, moves to state s' and send messages out. So the triplet (*s, m, msgs_sent*) represents the state of P

Two type of log storage are maintained:

- Volatile log: short time to access but lost if processor crash. Move to stable log periodically.
- Stable log: longer time to access but remained if crashed

A. Asynchronous Check pointing

- After executing an event, the triplet is recorded without any synchronization with other processes.
- Local checkpoint consist of set of records, first are stored in volatile log, then moved to stable log.

B. The Recovery

Algorithm Notations and

data structure

The following notations and data structure are used by the algorithm:

• RCVDi←j(CkPti) represents the number of messages received by processor pi from processor pj , from the beginning of the computation till the checkpoint CkPti.

• SENTi→j(CkPti) represents the number of messages sent by processor pi to processor pj , from the beginning of the computation till the checkpoint CkPti.

Basic idea

- Since the algorithm is based on asynchronous check pointing, the main issue in the recovery is to find a consistent set of checkpoints to which the system can be restored.
- The recovery algorithm achieves this by making each processor keep track of both the number of messages it has sent to other processors as well as the number of messages it has received from other processors.
- Whenever a processor rolls back, it is necessary for all other processors to find out if any message has become an orphan message. Orphan messages are discovered by comparing the number of messages sent to and received from neighboring processors.

For example, if RCVDi←j(CkPti) > SENTj→i(CkPtj) (that is, the number of messages received by processor pi from processor pj is greater than the number of messages sent by processor pj to processor pi, according to the current states the processors), then one or more messages at processor pj are orphan messages.

The Algorithm

When a processor restarts after a failure, it broadcasts a ROLLBACK message that it had failed

Procedure RollBack_Recovery

processor pi executes the following:

STEP (a)

if processor pi is recovering after a failure

then CkPti := latest event logged in the

stable storage **else**

CkPti := latest event that took place in pi {The latest event at pi can be either in stable or in volatile storage.}

end if

STEP (b)

for k = 1 1 to N {N is the number of processors in the

system} **do for** each neighboring processor pj **do**

compute SENTi→j(CkPti)

send a ROLLBACK(i, SENTi→j(CkPti)) message to pj

end for

for every ROLLBACK(j, c) message received from a neighbor j **do**

if RCVDi←j(CkPti) > c {Implies the presence of orphan messages} **then**

find the latest event e such that RCVDi←j(e) = c {Such an event e may be in the volatile storage or stable storage.}

CkPti

:= e

end if

end

for

end for{for k}

D. An Example

Consider an example shown in Figure 2 consisting of three processors. Suppose processor Y fails and restarts. If event ey2 is the latest checkpointed event at Y, then Y will restart from the state corresponding to ey2.

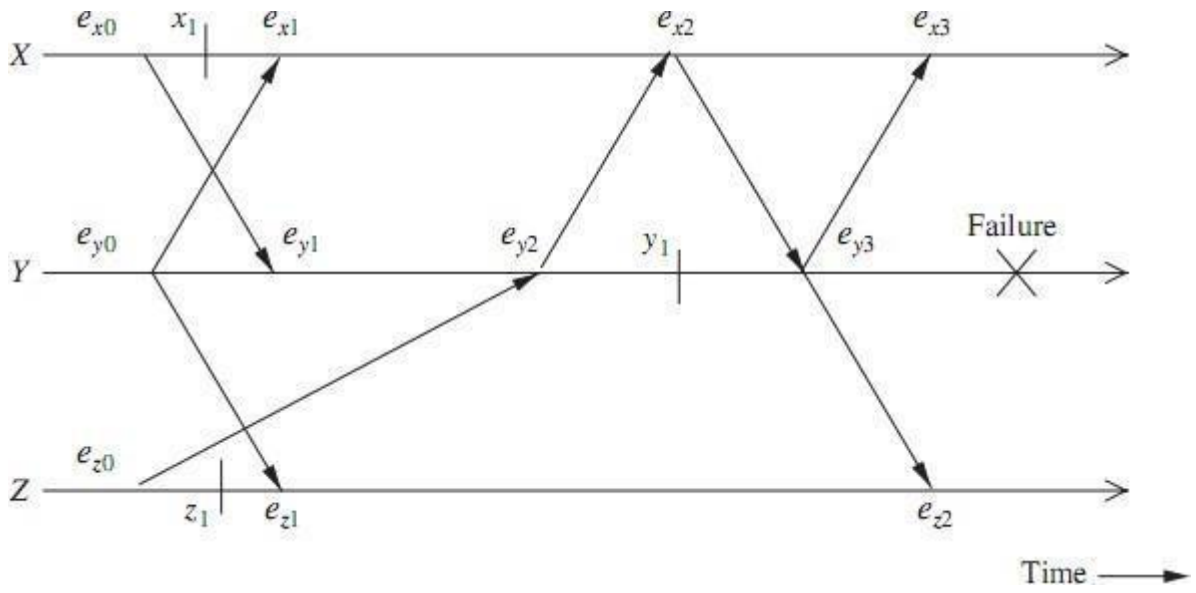


Figure 2: An example of Juan-Venkatesan algorithm.

- Because of the broadcast nature of ROLLBACK messages, the recovery algorithm is initiated at processors X and Z.
- Initially, X, Y, and Z set CkPtX ← ex3, CkPtY ← ey2 and CkPtZ ← ez2, respectively, and X, Y, and Z send the following messages during the first iteration:
- Y sends ROLLBACK(Y,2) to X and ROLLBACK(Y,1) to Z;

- X sends ROLLBACK(X,2) to Y and ROLLBACK(X,0) to Z;
- Z sends ROLLBACK(Z,0) to X and ROLLBACK(Z,1) to Y.

Since RCVDX←Y (CkPtX) = 3 > 2 (2 is the value received in the ROLLBACK(Y,2) message from Y), X will set CkPtX to ex2 satisfying RCVDX←Y (ex2) = 1≤ 2.

Since RCVDZ←Y (CkPtZ) = 2 > 1, Z will set CkPtZ to ez1 satisfying RCVDZ←Y (ez1) = 1 ≤ 1.

At Y, RCVDY←X(CkPtY) = 1 < 2 and RCVDY←Z(CkPtY) = 1 = SENTZ←Y (CkPtZ).

Y need not roll back further.

In the second iteration, Y sends ROLLBACK(Y,2) to X and ROLLBACK(Y,1) to Z;

Z sends ROLLBACK(Z,1) to Y and ROLLBACK(Z,0) to

X; X sends ROLLBACK(X,0) to Z and ROLLBACK(X,

1) to Y.

If Y rolls back beyond ey3 and loses the message from X that caused ey3, X can resend this message to Y because ex2 is logged at X and this message available in the log. The second and third iteration will progress in the same manner. The set of recovery points chosen at the end of the first iteration, {ex2, ey2, ez1}, is consistent, and no further rollback occurs.

CONSENSUS PROBLEM IN ASYNCHRONOUS SYSTEMS.

Table: Overview of results on agreement.

f denotes number of failure-prone processes. n is the total number of processes.

Failure mode	**Synchronous system (message-passing and shared memory)**	**Asynchronous system (message-passing and shared memory)**
No Failure	agreement attainable; common knowledge attainable	agreement attainable; concurrent common knowledge
Crash Failure	agreement attainable f < n processes	agreement not attainable
Byzantine Failure	agreement attainable f ≤ [(n - 1)/3] Byzantine processes	agreement not attainable

In a failure-free system, consensus can be attained in a straightforward manner.

Consensus Problem (all processes have an initial value)

Agreement: All non-faulty processes must agree on the same (single) value.

Validity: If all the non-faulty processes have the same initial value, then the agreed upon value by all the non-faulty processes must be that same value.

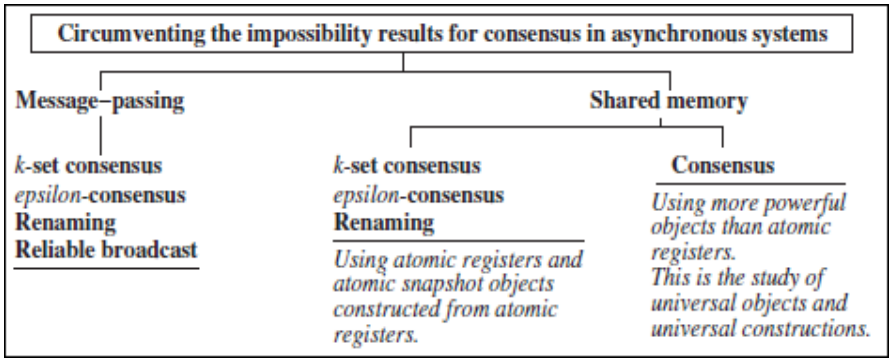
Termination: Each non-faulty process must eventually decide on a value.

Consensus Problem in Asynchronous Systems.

The overhead bounds are for the given algorithms, and not necessarily tight bounds for the problem.

Solvable Variants	**Failure model and overhead**	**Definition**
Reliable broadcast	Crash Failure, $n > f$ (MP)	Validity, Agreement, Integrity conditions
k-set consensus	Crash Failure, $f < k < n$. (MP and SM)	size of the set of values agreed upon must be less than k
C-agreement	Crash Failure, $n \geq 5f + 1$ (MP)	values agreed upon are within ε of each other
Renaming	up to f fail-stop processes, $n \geq 2f + 1$ (MP) Crash Failure, $f \leq n - 1$ (SM)	select a unique name from a set of names

Circumventing the impossibility results for consensus in asynchronous systems:



STEPS FOR BYZANTINE GENERALS (ITERATIVE FORMULATION), SYNCHRONOUS, MESSAGE-PASSING:

(variables)
boolean: $v \longleftarrow$ initial value;
integer: $f \longleftarrow$ maximum number of malicious processes, $\leq \lfloor \frac{n-1}{3} \rfloor$;
tree of boolean:

- level 0 root is v^{L}_{init}, where $L = \langle\rangle$;
- level $h (f \geq h > 0)$ nodes: for each v^{L}_{j} at level $h-1 = sizeof(L)$, its $n-2-sizeof(L)$ descendants at level h are $v^{concat(\langle j \rangle, L)}_{k}, \forall k$ such that $k \neq j, i$ and k is not a member of list L.

(message type)
OM(v, *Dests*, *List*, *faulty*), where the parameters are as in the recursive formulation.

(1) Initiator (i.e., Commander) initiates Oral Byzantine agreement:
(1a) **send** $OM(v, N-\{i\}, \langle P_i \rangle, f)$ to $N-\{i\}$;
(1b) **return**(v).

(2) (Non-initiator, i.e., Lieutenant) receives Oral Message *OM*:
(2a) **for** $rnd = 0$ **to** f **do**
(2b) **for** each message OM that arrives in this round, **do**
(2c) **receive** $OM(v, Dests, L = \langle P_{k_1} \ldots P_{k_{f+1-faulty}} \rangle, faulty)$ from P_{k_1};
// $faulty + round = f$; $|Dests| + sizeof(L) = n$
(2d) $v^{tail(L)}_{head(L)} \longleftarrow v$; // $sizeof(L) + faulty = f + 1$. fill in estimate.
(2e) **send** $OM(v, Dests - \{i\}, \langle P_i, P_{k_1} \ldots P_{k_{f+1-faulty}} \rangle, faulty - 1)$ to $Dests - \{i\}$ **if** $rnd < f$;
(2f) **for** $level = f - 1$ **down to** 0 **do**
(2g) **for** each of the $1 \cdot (n-2) \cdot \ldots \cdot (n-(level+1))$ nodes v^{L}_{x} in level *level*, **do**
(2h) $v^{L}_{x}(x \neq i, x \notin L) = majority_{y \notin concat(\langle x \rangle, L); y \neq i}(v^{L}_{x}, v^{concat(\langle x \rangle, L)}_{y})$;

Byzantine Agreement (single source has an initial value)

Agreement: All non-faulty processes must agree on the same value.

Validity: If the source process is non-faulty, then the agreed upon value by all the non- faulty processes must be the same as the initial value of the source.

STEPS FOR BYZANTINE GENERALS (RECURSIVE FORMULATION), SYNCHRONOUS, MESSAGE-PASSING:

(variables)
boolean: $v \longleftarrow$ initial value;
integer: $f \longleftarrow$ maximum number of malicious processes, $\leq \lfloor (n-1)/3 \rfloor$;
(message type)
Oral_Msg(v, *Dests*, *List*, *faulty*), where
v is a boolean,
Dests is a set of destination process ids to which the message is sent,
List is a list of process ids traversed by this message, ordered from most recent to earliest,
faulty is an integer indicating the number of malicious processes to be tolerated.

Oral_Msg(f), where $f > 0$:

1. The algorithm is initiated by the Commander, who sends his source value v to all other processes using a $OM(v, N, \langle i \rangle, f)$ message. The commander returns his own value v and terminates.
2. **[Recursion unfolding:]** For each message of the form $OM(v_j, Dests, List, f')$ received in this round from some process j, the process i uses the value v_j it receives from the source, and using that value, acts as a *new* source. (If no value is received, a default value is assumed.)

   To act as a new source, the process i initiates $Oral\_Msg(f' - 1)$, wherein it sends
   $OM(v_j, Dests - \{i\}, concat(\langle i \rangle, L), (f' - 1))$
   to destinations not in $concat(\langle i \rangle, L)$
   in the next round.
3. **[Recursion folding:]** For each message of the form $OM(v_j, Dests, List, f')$ received in Step 2, each process i has computed the agreement value v_k, for each k not in *List* and $k \neq i$,corresponding to the value received from P_k after traversing the nodes in *List*, at one level lower in the recursion. If it receives no value in this round, it uses a default value. Process i then uses the value $majority_{k \notin List, k \neq i}(v_j, v_k)$ as the agreement value and returns it to the next higher level in the recursive invocation.

Oral_Msg(0):

1. **[Recursion unfolding:]** Process acts as a source and sends its value to each other process.
2. **[Recursion folding:]** Each process uses the value it receives from the other sources, and uses that value as the agreement value. If no value is received, a default value is assumed.

CODE FOR THE PHASE KING ALGORITHM:

Each phase has a unique "phase king" derived, say, from PID.

Each phase has two rounds:

- 1 in 1st round, each process sends its estimate to all other processes.
- 2 in 2nd round, the "Phase king" process arrives at an estimate based on the values it received in 1st round, and broadcasts its new estimate to all others.

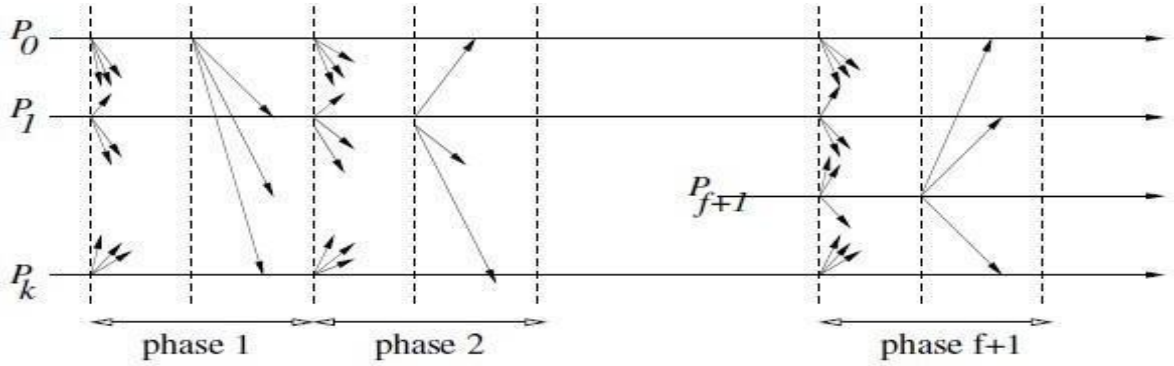


Fig. Message pattern for the phase-king algorithm.

PHASE KING ALGORITHM CODE:

```
(variables)
boolean: v ⟵ initial value;
integer: f ⟵ maximum number of malicious processes, f < ⌈n/4⌉;

(1) Each process executes the following f + 1 phases, where f < n/4:
(1a) for phase = 1 to f + 1 do
(1b)   Execute the following Round 1 actions:          // actions in round one of each phase
(1c)       broadcast v to all processes;
(1d)       await value v_j from each process P_j;
(1e)       majority ⟵ the value among the v_j that occurs > n/2 times (default if no maj.);
(1f)       mult ⟵ number of times that majority occurs;
(1g)   Execute the following Round 2 actions:          // actions in round two of each phase
(1h)       if i = phase then // only the phase leader executes this send step
(1i)           broadcast majority to all processes;
(1j)       receive tiebreaker from P_phase (default value if nothing is received);
(1k)       if mult > n/2 + f then
(1l)           v ⟵ majority;
(1m)       else v ⟵ tiebreaker;
(1n)       if phase = f + 1 then
(1o)           output decision value v.
```

(f + 1) phases, (f + 1)[(n - 1)(n + 1)] messages, and can tolerate up to f < dn=4e malicious processes

Correctness Argument

- 1 Among f + 1 phases, at least one phase k where phase-king is non-malicious.
- 2 In phase k, all non-malicious processes P_i and P_j will have same estimate of consensus value as P_k does.
- P_i and P_j use their own majority values. P_i 's mult > n=2 + f)
- P_i uses its majority value; P_j uses phase-king's tie-breaker value. (P_i's mult > n=2 + f , P_j 's mult > n=2 for same value)
- P_i and P_j use the phase-king's tie-breaker value. (In the phase in which P_k is non- malicious, it sends same value to P_i and P_j)

In all 3 cases, argue that P_i and P_j end up with same value as estimate

- If all non-malicious processes have the value x at the start of a phase, they will continue to have x as the consensus value at the end of the phase.

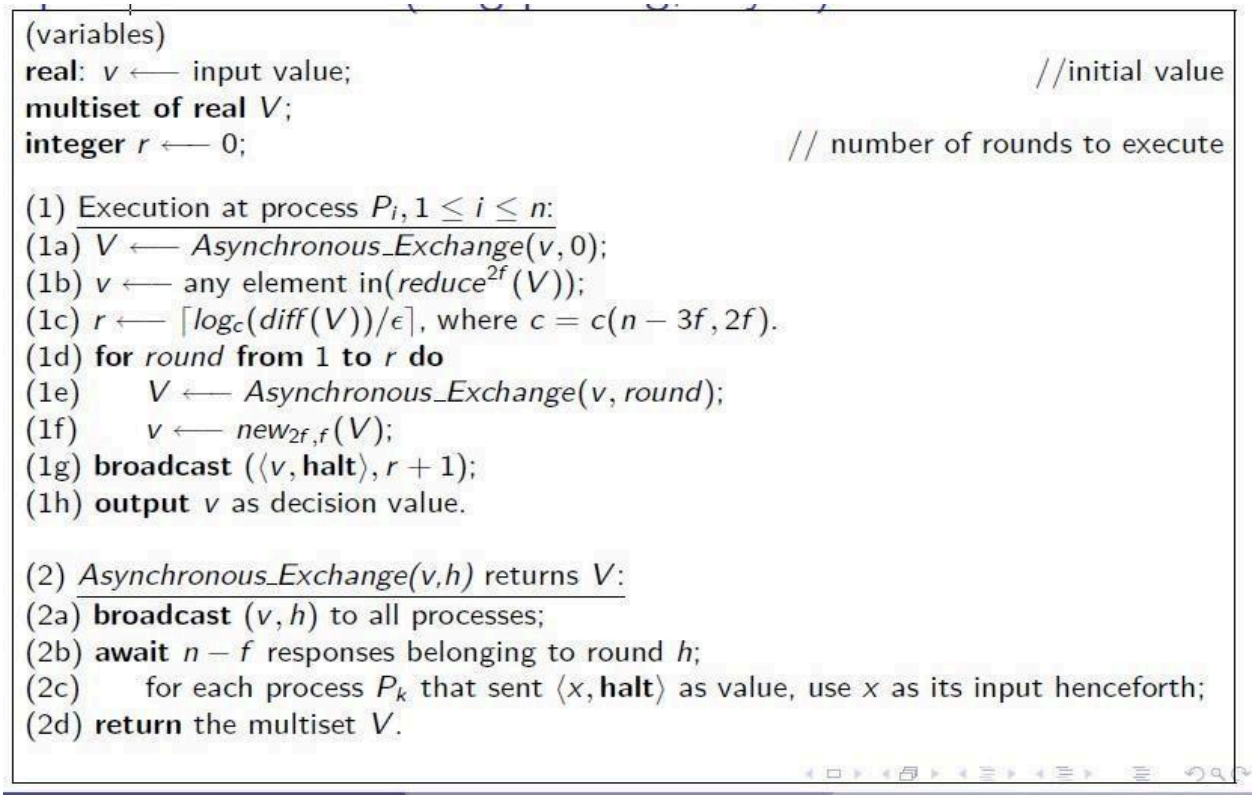
CODE FOR THE EPSILON CONSENSUS (MESSAGE-PASSING, ASYNCHRONOUS):

_-Agreement: All non-faulty processes must make a decision and the values decided upon by any two non-faulty processes must be within range of each other.

Validity: If a non-faulty process Pi decides on some value vi , then that value must be within the range of values initially proposed by the processes.

Termination: Each non-faulty process must eventually decide on a value. The algorithm for the message-passing model assumes n ≥ 5f + 1, although the problem is solvable for n > 3f + 1.

- Main loop simulates sync rounds.
- Main lines (1d)-(1f): processes perform all-all msg exchange
- Process broadcasts its estimate of consensus value, and awaits n - f similar
- msgs from other processes
- the processes' estimate of the consensus value converges at a particular rate,
- until it is _ from any other processes estimate.
- # rounds determined by lines (1a)-(1c).



```
(variables)
real: v ⟵ input value;                                        //initial value
multiset of real V;
integer r ⟵ 0;                                   // number of rounds to execute

(1) Execution at process P_i, 1 ≤ i ≤ n:
(1a) V ⟵ Asynchronous_Exchange(v, 0);
(1b) v ⟵ any element in(reduce^{2f}(V));
(1c) r ⟵ ⌈log_c(diff(V))/ε⌉, where c = c(n − 3f, 2f).
(1d) for round from 1 to r do
(1e)     V ⟵ Asynchronous_Exchange(v, round);
(1f)     v ⟵ new_{2f,f}(V);
(1g) broadcast (⟨v, halt⟩, r + 1);
(1h) output v as decision value.

(2) Asynchronous_Exchange(v,h) returns V:
(2a) broadcast (v, h) to all processes;
(2b) await n − f responses belonging to round h;
(2c)     for each process P_k that sent ⟨x, halt⟩ as value, use x as its input henceforth;
(2d) return the multiset V.
```

TWO-PROCESS WAIT-FREE CONSENSUS USING FIFO QUEUE, COMPARE & SWAP:

Wait-free Shared Memory Consensus using Shared Objects:

Not possible to go from bivalent to univalent state if even a single failure is allowed.

Difficulty is not being able to read & write a variable atomically.

- It is not possible to reach consensus in an asynchronous shared memory system using Read/Write atomic registers, even if a single process can fail by crashing.
- There is no wait-free consensus algorithm for reaching consensus in an asynchronous shared memory system using Read/Write atomic registers.

To overcome these negative results:

- Weakening the consensus problem, e.g., k-set consensus, approximate consensus, and renaming using atomic registers.
- Using memory that is stronger than atomic Read/Write memory to design wait- free consensus algorithms. Such a memory would need corresponding access primitives.

Are there objects (with supporting operations), using which there is a wait-free (i.e., (n -1)-crash resilient) algorithm for reaching consensus in a n-process system? Yes, e.g., Test&Set, Swap, Compare&Swap. The crash failure model requires the solutions to be wait-free.

TWO-PROCESS WAIT-FREE CONSENSUS USING FIFO QUEUE:

```
(shared variables)
queue: Q ⟵ ⟨0⟩;                                          // queue Q initialized
integer: Choice[0, 1] ⟵ [⊥, ⊥]                  // preferred value of each process
(local variables)
integer: temp ⟵ 0;
integer: x ⟵ initial choice;

(1) Process P_i, 0 ≤ i ≤ 1, executes this for 2-process consensus using a FIFO queue:
(1a) Choice[i] ⟵ x;
(1b) temp ⟵ dequeue(Q);
(1c) if temp = 0 then
(1d)      output(x)
(1e) else output(Choice[1 − i]).
```

WAIT-FREE CONSENSUS USING COMPARE & SWAP:

```
(shared variables)
integer: Reg ⟵ ⊥;                                  // shared register Reg initialized
(local variables)
integer: temp ⟵ 0;                              // temp variable to read value of Reg
integer: x ⟵ initial choice;                    // initial preference of process

(1) Process P_i, (∀i ≥ 1), executes this for consensus using Compare&Swap:
(1a) temp ⟵ Compare&Swap(Reg, ⊥, x);
(1b) if temp = ⊥ then
(1c)      output(x)
(1d) else output(temp).
```

NONBLOCKING UNIVERSAL ALGORITHM:

Universality of Consensus Objects

An object is defined to be universal if that object along with read/write registers can simulate any other object in a wait-free manner. In any system containing up to k processes, an object X such that CN(X) = k is universal.

For any system with up to k processes, the universality of objects X with consensus number k is shown by giving a universal algorithm to wait-free simulate any object using objects of type X and read/write registers.

This is shown in two steps.

- 1 A universal algorithm to wait-free simulate any object whatsoever using read/write registers and arbitrary k-processor consensus objects is given. This is the main step.
- 2 Then, the arbitrary k-process consensus objects are simulated with objects of type X, having consensus number k. This trivially follows after the first step.

Any object X with consensus number k is universal in a system with $n \leq k$ processes.

A nonblocking operation, in the context of shared memory operations, is an operation that may not complete itself but is guaranteed to complete at least one of the pending operations in a finite number of steps.

Nonblocking Universal Algorithm:

The linked list stores the linearized sequence of operations and states following each operation.

Operations to the arbitrary object Z are simulated in a nonblocking way using an arbitrary consensus object (the field op.next in each record) which is accessed via the Decide call.

Each process attempts to thread its own operation next into the linked list.

- There are as many universal objects as there are operations to thread.
- A single pointer/counter cannot be used instead of the array Head. Because reading and updating the pointer cannot be done atomically in a wait-free manner.
- Linearization of the operations given by the sequence number. As algorithm is nonblock