Distributed System Design: An Overview*

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*Part of the materials come from Distributed System Design, CRC Press, 1999. (Chinese Edition, China Machine Press, 2001.)

The Structure of Classnotes

- Focus
- Example
- Exercise
- Project

Table of Contents

Development of Computer Technology

- 1950s: serial processors
- 1960s: batch processing
- 1970s: time-sharing
- 1980s: personal computing
- 1990s: parallel, network, and distributed processing
- 2000s: wireless networks
- 2010s: mobile and cloud (edge, fog) computing
- 2020s: IoT, big data (AI), and blockchain (security)

Application 1: Cloud

Cloud computing

Ubiquitous access to shared pools of configurable system resources that can be rapidly provisioned with minimal management effort, often over the Internet

Characteristics (by NIST)

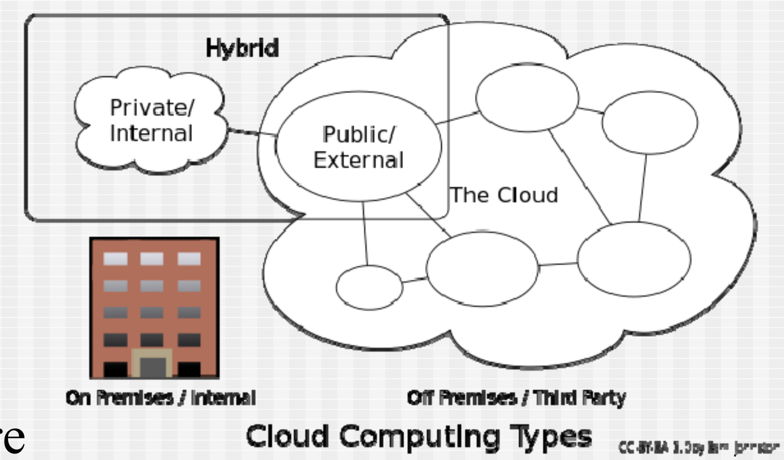
On-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service

Types

- Public cloud and private cloud

Products

- Amazon EC 2 and Microsoft Azure



Fog: distributed cloud

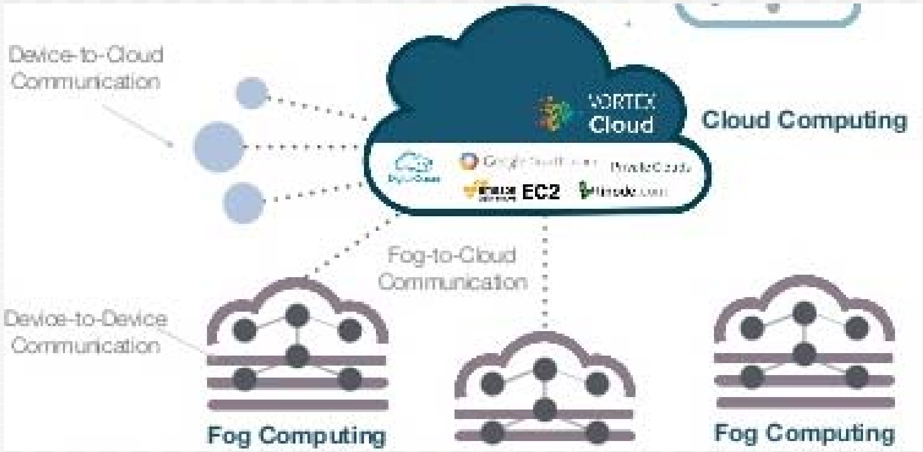
Edge: devices at the edge network (e.g., Internet of Things IoT)

Fog: distributed cloud (e.g. cloud + IoT)

- Reduce data communication and process demands
- Data storage and processing outside the cloud

Products

- Cisco
- Cloudlets (CMU)
- Micro datacenter in Azure



Application 2: Hadoop

Apache Hadoop is built for Big Data processing

- MapReduce: map, shuffle, and reduce
  - Pipeline
  - Data parallelism
- HDFS (Hadoop distributed file systems)

Apache HIVE

- Data warehouse
- SQL-like interface (distributed database)

SPARK: beyond Hadoop

Apache Spark is built for speed, mainly for ML

- Speed (10x to 100x compared to Hadoop)
- Data in memory (Hadoop in hard disk)
- RDD: resilient distributed dataset (extension from distributed shared memory, DSM and fault tolerance)
- Streaming
- Better API

New paradigm for reinforcement learning (RL)

- Stanford DAWN
- Berkeley Ray

* gray color: concepts to be covered in this class

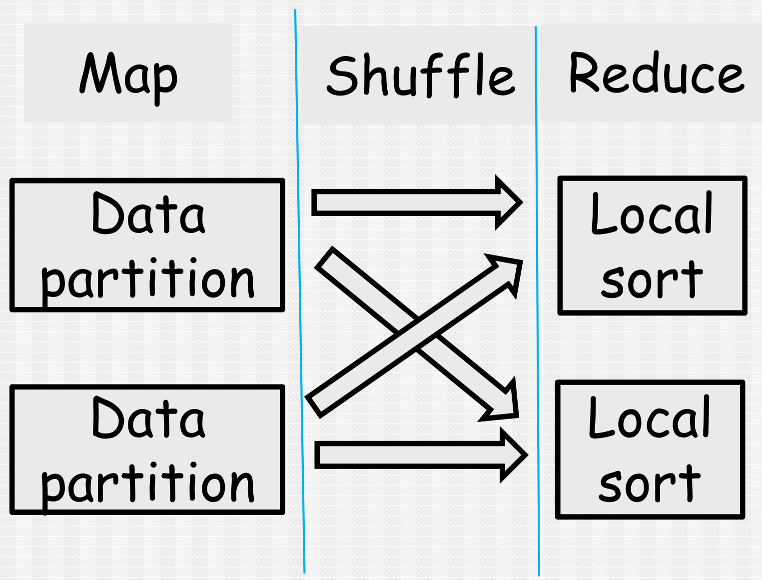
TeraSort: map-shuffle-reduce

Map-Shuffle-Reduce

- Map and Reduce: CPU-intensive
- Shuffle: I/O-intensive

TeraSort

- Map: sample & partition data
- Shuffle: partitioned data
- Reduce: locally sort data



Application 3: Bitcoin

Bitcoin: crytocurrency and worldwide payment system

- First decentralized digital currency without a central bank or single administrator
- Transactions: use of cryptograph and is recorded in a distributed ledger called blockchain

Most crowded trade in 2017: prices go higher not by percentages but multiples

Blockchain: building block

Blockchain: distributed database on a set of communicating nodes

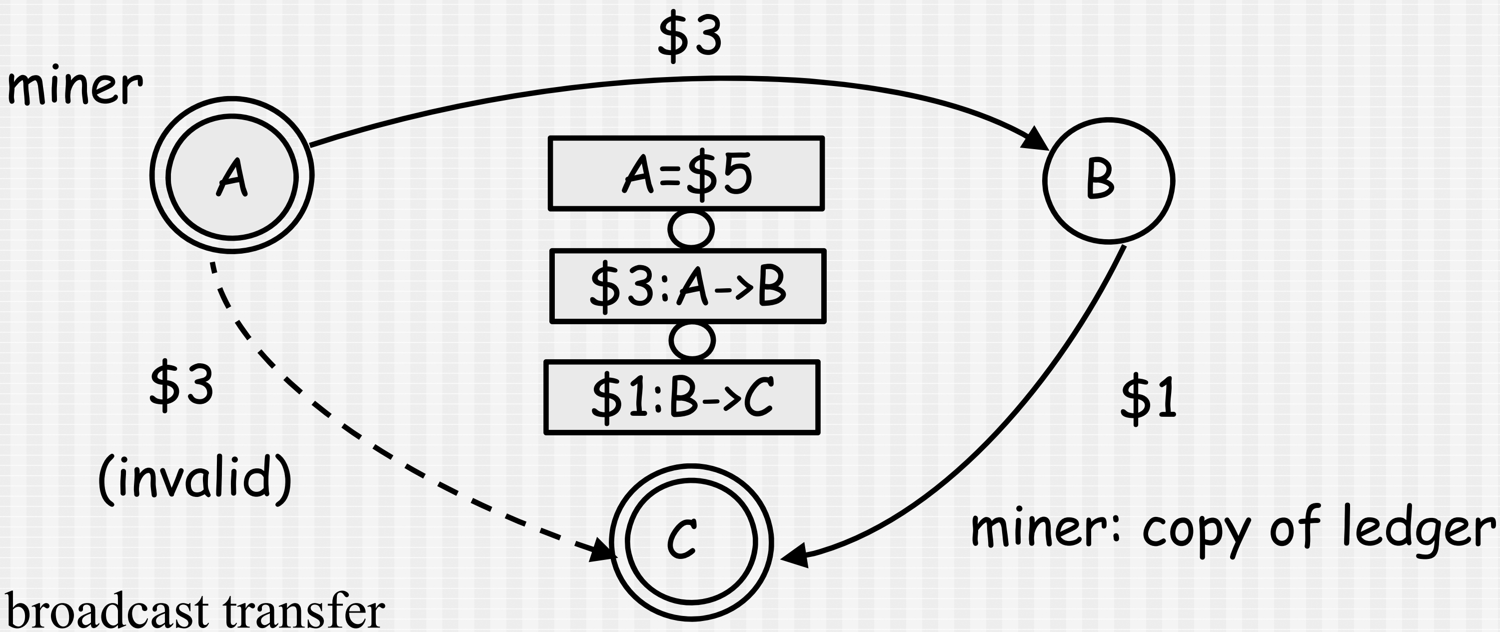
A continuously growing list of records (transactions), called blocks.

- Transactions: input node(s) to output node(s)
- Mining: distributed book-keeping to ensure consistency, complete, and unalterable (using linear cryptograph hash chain)

Byzantine fault tolerance and decentralized consensus

Money transfer: ledger and minor

Decentralized ledger in P2P: block chain



User: broadcast transfer

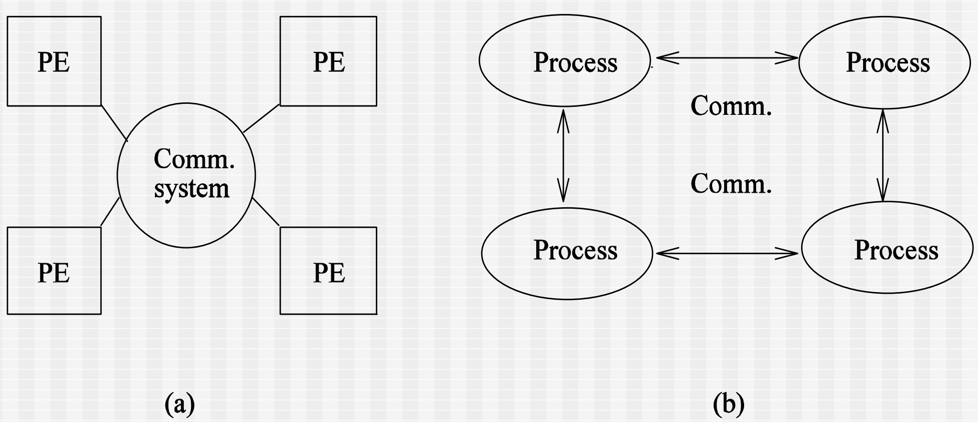
Miner: complete through a random process to get bitcoin

(1) validate, (2) find a key (puzzle solving), and (3) broadcast result

Security: digital signature, hash of previous data

A Simple Definition

- A **distributed system** is a collection of independent computers that appear to the users of the system as a single computer.
- Distributed systems are "**seamless**": the interfaces among functional units on the network are for the most part invisible to the user.



System structure from the physical (a) or logical point of view (b).

Motivation

- People are distributed, information is distributed (Internet and Intranet)
- Performance/cost
- Information exchange and resource sharing (WWW and CSCW)
- Flexibility and extensibility
- Dependability

Two Main Stimuli

- Technological change
- User needs

Goals

- **Transparency**: hide the fact that its processes and resources are physically distributed across multiple computers.
  - Access
  - Location
  - Migration
  - Replication
  - Concurrency
  - Failure
  - Persistence
- **Scalability**: in three dimensions
  - Size
  - Geographical distance
  - Administrative structure

Goals (Cont'd.)

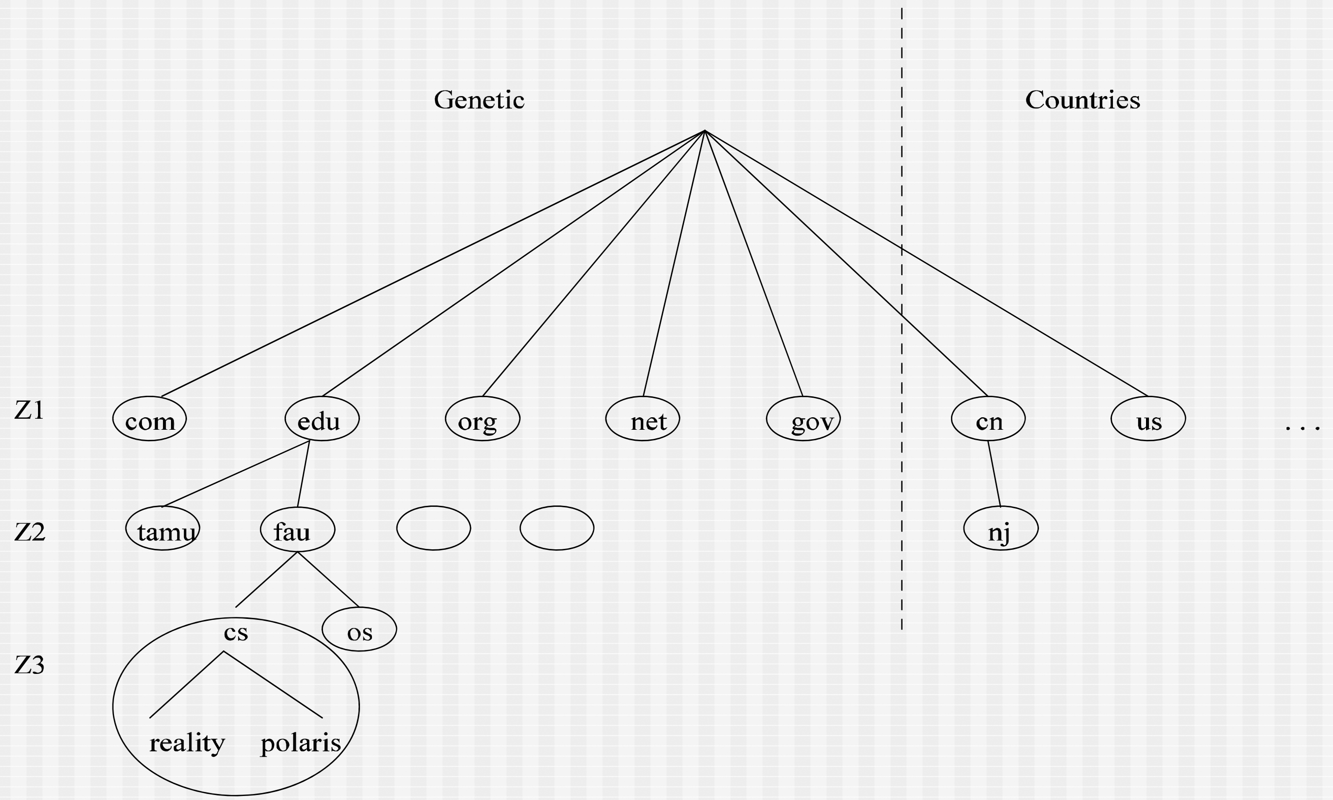
- **Heterogeneity** (mobile code and mobile agent)
  - Networks
  - Hardware
  - Operating systems and middleware
  - Program languages
- **Openness**
- **Security**
- **Fault Tolerance**
- **Concurrency**

Scaling Techniques

- Latency hiding (pipelining and interleaving execution)
- Distribution (spreading parts across the system)
- Replication (caching)

Example 1: (Scaling Through Distribution)

URL searching based on hierarchical DNS name space (partitioned into zones).



DNS name space.

Design Requirements

- Performance Issues
  - Responsiveness
  - Throughput
  - Load Balancing
- Quality of Service
  - Reliability
  - Security
  - Performance
- Dependability
  - Correctness
  - Security
  - Fault tolerance

Similar and Related Concepts

- Distributed
- Network
- Parallel
- Concurrent
- Decentralized

Schroeder's Definition

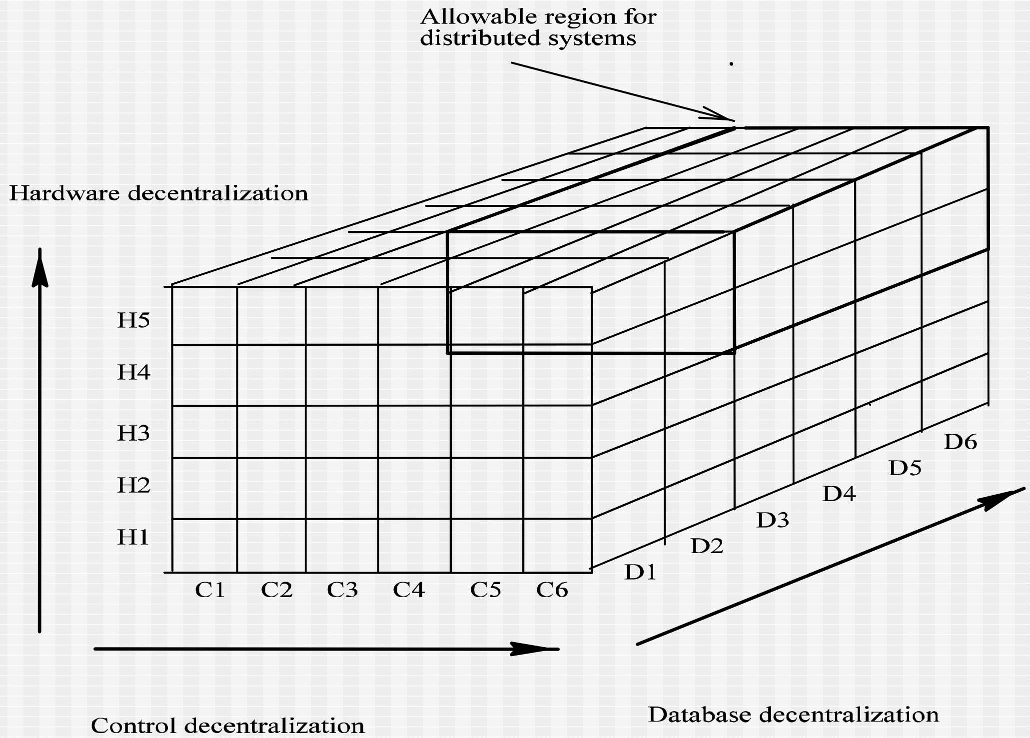
- A list of **symptoms** of a distributed system
  - Multiple processing elements (PEs)
  - Interconnection hardware
  - PEs fail independently
  - Shared states

Focus 1: Enslow's Definition

Distributed system = distributed hardware + distributed control + distributed data

A system could be classified as a distributed system if **all three categories (hardware, control, data)** reach a certain degree of decentralization.

Focus 1 (Cont'd.)



Enslow's model of distributed systems.

Hardware

- A single CPU with one control unit.
- A single CPU with multiple ALUs (arithmetic and logic units).There is only one control unit.
- Separate specialized functional units, such as one CPU with one floating-point co-processor.
- Multiprocessors with multiple CPUs but only one single I/O system and one global memory.
- Multicomputers with multiple CPUs, multiple I/O systems and local memories.

Control

- Single fixed control point. Note that physically the system may or may not have multiple CPUs.
- Single dynamic control point. In multiple CPU cases the controller changes from time to time among CPUs.
- A fixed master/slave structure. For example, in a system with one CPU and one co-processor, the CPU is a fixed master and the co-processor is a fixed slave.
- A dynamic master/slave structure. The role of master/slave is modifiable by software.
- Multiple homogeneous control points where copies of the same controller are used.
- Multiple heterogeneous control points where different controllers are used.

Data

- Centralized databases with a single copy of both files and directory.
- Distributed files with a single centralized directory and no local directory.
- Replicated database with a copy of files and a directory at each site.
- Partitioned database with a master that keeps a complete duplicate copy of all files.
- Partitioned database with a master that keeps only a complete directory.
- Partitioned database with no master file or directory.

Network Systems

- Performance scales on **throughput** (transaction response time or number of transactions per second) versus **load**.
- Work on burst mode.
- Suitable for small transaction-oriented programs (collections of small, quick, distributed **applets**).
- Handle uncoordinated processes.

Parallel Systems

- Performance scales on **elapsed execution times** versus number of processors (subject to either Amdahl or Gustafson law).
- Works on bulk mode.
- Suitable for numerical applications (such as SIMD or SPMD vector and matrix problems).
- Deal with one single application divided into a set of coordinated processes.

Distributed Systems

A compromise of network and parallel systems.

Comparison

Item	Network sys.	Distributed sys.	Multiprocessors
Like a virtual uniprocessor	No	Yes	Yes
Run the same operating system	No	Yes	Yes
Copies of the operating system	N copies	N copies	1 copy
Means of communication	Shared files	Messages	Shared files
Agreed up network protocols?	Yes	Yes	No
A single run queue	No	Yes	Yes
Well defined file sharing	Usually no	Yes	Yes

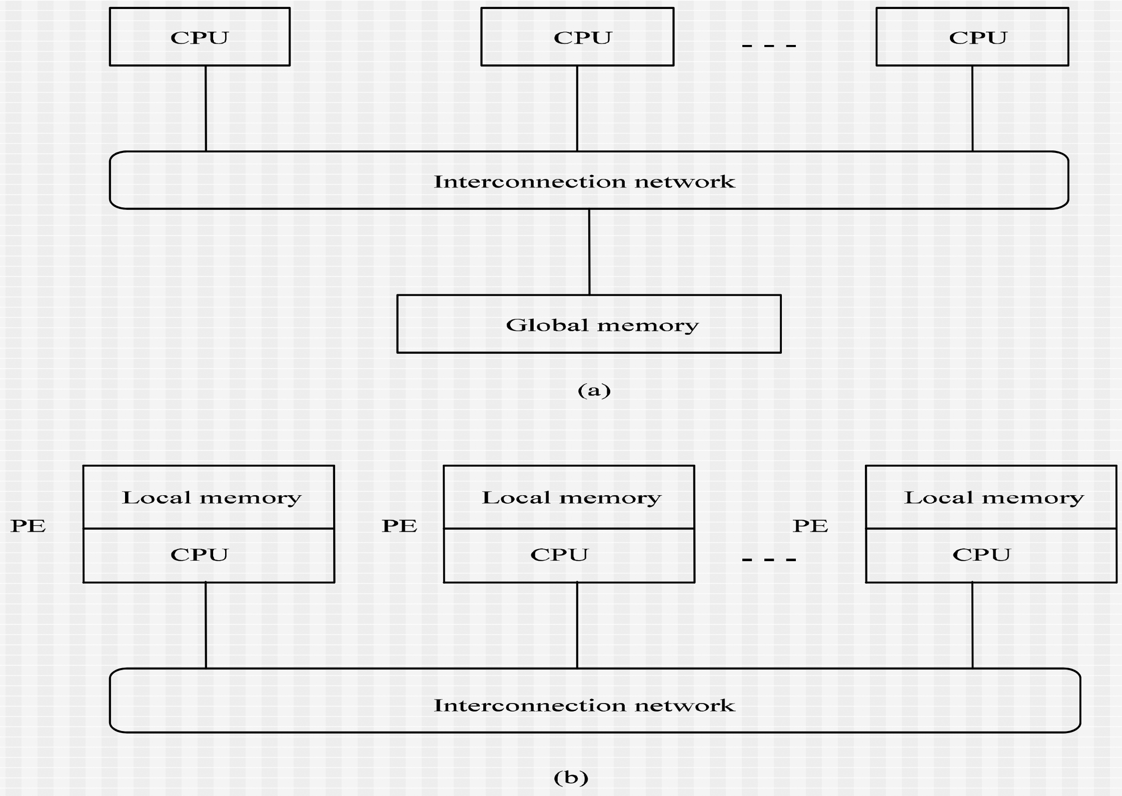
Comparison of three different systems.

Focus 2: Different Viewpoints

- Architecture viewpoint
- Interconnection network viewpoint
- Memory viewpoint
- Software viewpoint
- System viewpoint

Architecture Viewpoint

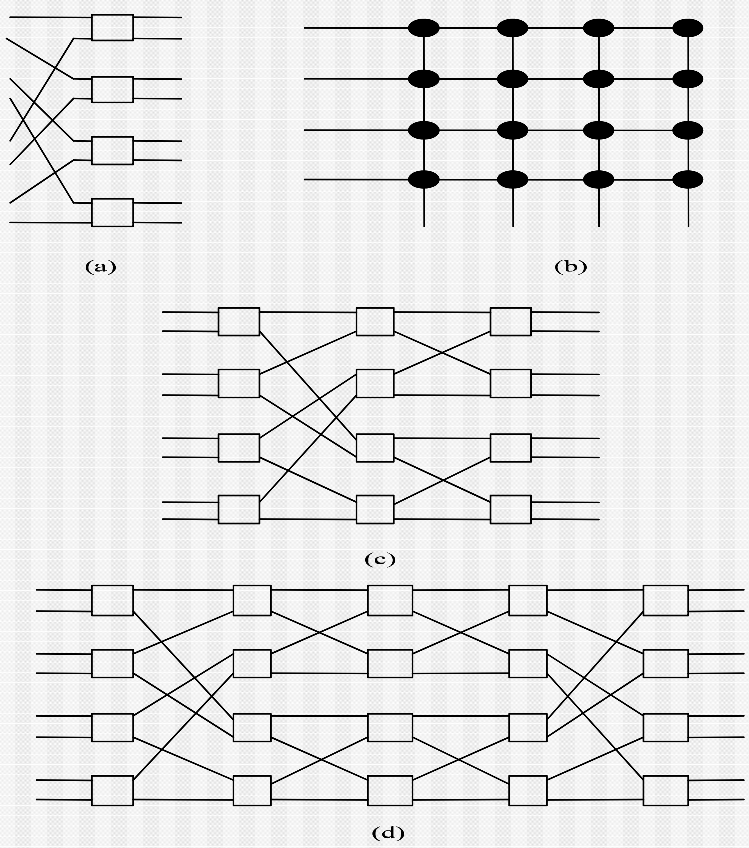
- **Multiprocessor**: physically shared memory structure
- **Multicomputer**: physically distributed memory structure.



Interconnection Network Viewpoint

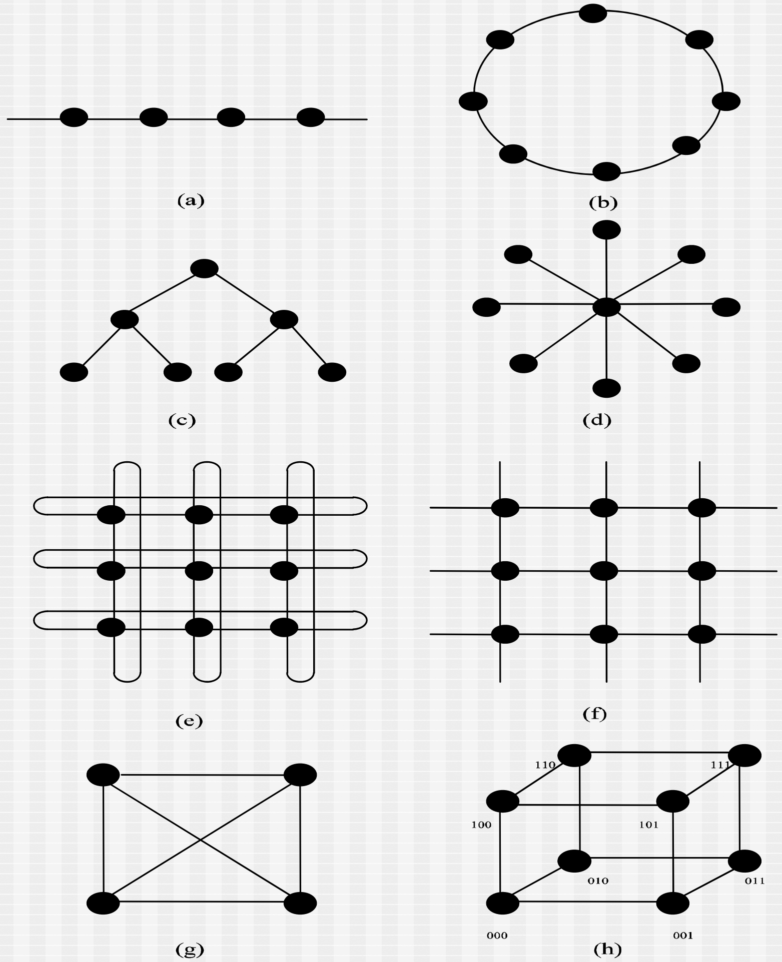
- static (point-to-point) vs. dynamics (ones with switches).
- bus-based (Fast Ethernet) vs. switch-based (routed instead of broadcast).

Interconnection Network Viewpoint (Cont'd.)



Examples of dynamic interconnection networks: (a) shuffle-exchange, (b) crossbar, (c) baseline, and (d) Benes.

Interconnection Network Viewpoint (Cont'd.)



Examples of static interconnection networks: (a) linear array, (b) ring, (c) binary tree, (d) star, (e) 2-d torus, (f) 2-d mesh, (g) completely connected, and (h) 3-cube.

Measurements for Interconnection Networks

- *Node degree*. The number of edges incident on a node.
- *Diameter*. The maximum shortest path between any two nodes.
- *Bisection width*. The minimum number of edges along a cut which divides a given network into equal halves.

What's the Best Choice? (Siegel 1994)

- A **compiler-writer** prefers a network where the transfer time from any source to any destination is the same to simplify the data distribution.
- A **fault-tolerant researcher** does not care about the type of network as long as there are three copies for redundancy.
- A **European researcher** prefers a network with a node degree no more than four to connect Transputers.

What's the Best Choice? (Cont'd.)

- A **college professor** prefers hypercubes and multistage networks because they are theoretically wonderful.
- A **university computing center official** prefers whatever network is least expensive.
- A **NSF director** wants a network which can best help deliver health care in an environmentally safe way.
- A **Farmer** prefers a wormhole-routed network because the worms can break up the soil and help the crops!

Memory Viewpoint

	Logically shared	Logically distributed
Physically shared	Shared memory	Simulated message passing
Physically distributed	Distributed shared memory	Message passing

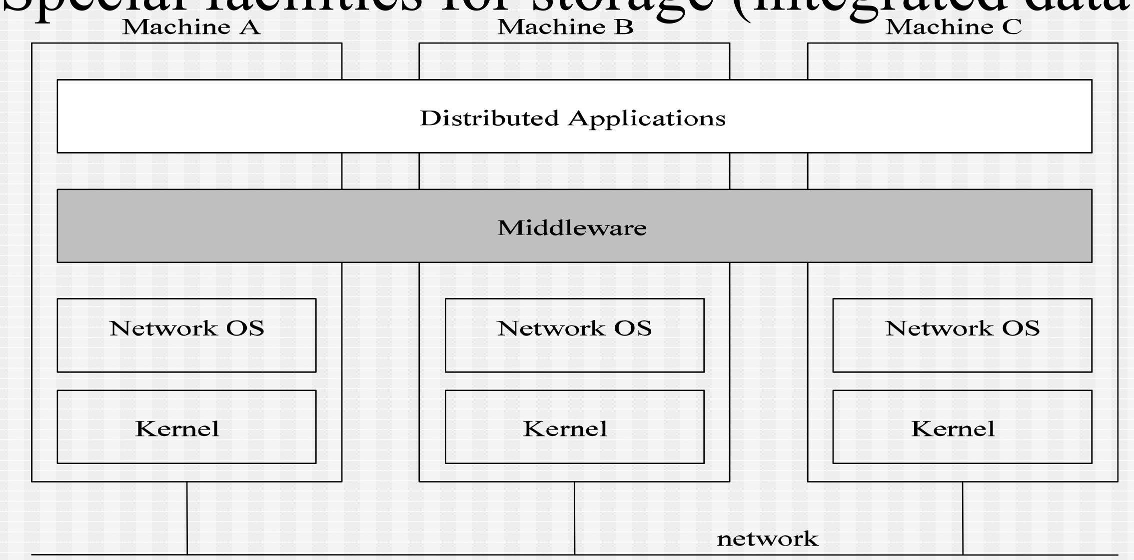
Physically versus logically shared/distributed memory.

Software Viewpoint

- Distributed systems as resource managers like traditional operating systems.
  - Multiprocessor/Multicomputer OS
  - Network OS
  - **Middleware** (on top of network OS)

Service Common to Many Middleware Systems

- High level communication facilities (access transparency)
- Naming
- Special facilities for storage (integrated database)



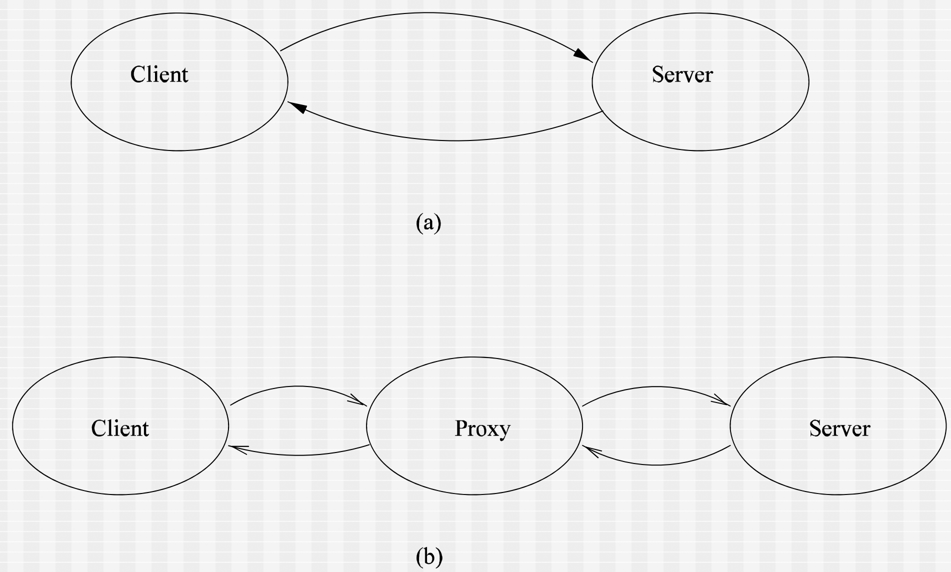
Middleware

System Viewpoint

- The division of responsibilities between system components and placement of the components.

Client-Server Model

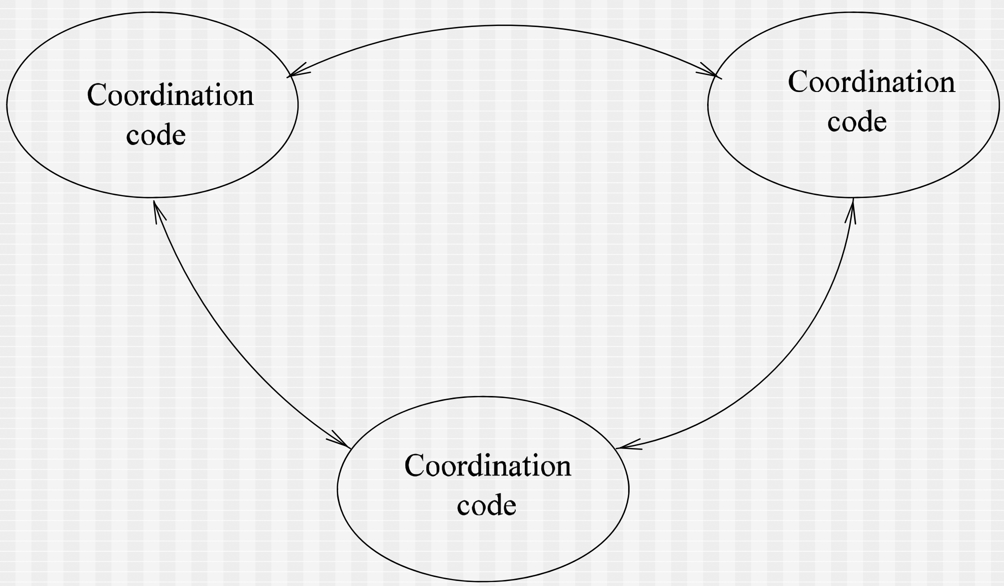
- multiple servers
- proxy servers and caches



(a) Client and server and (b) proxy server.

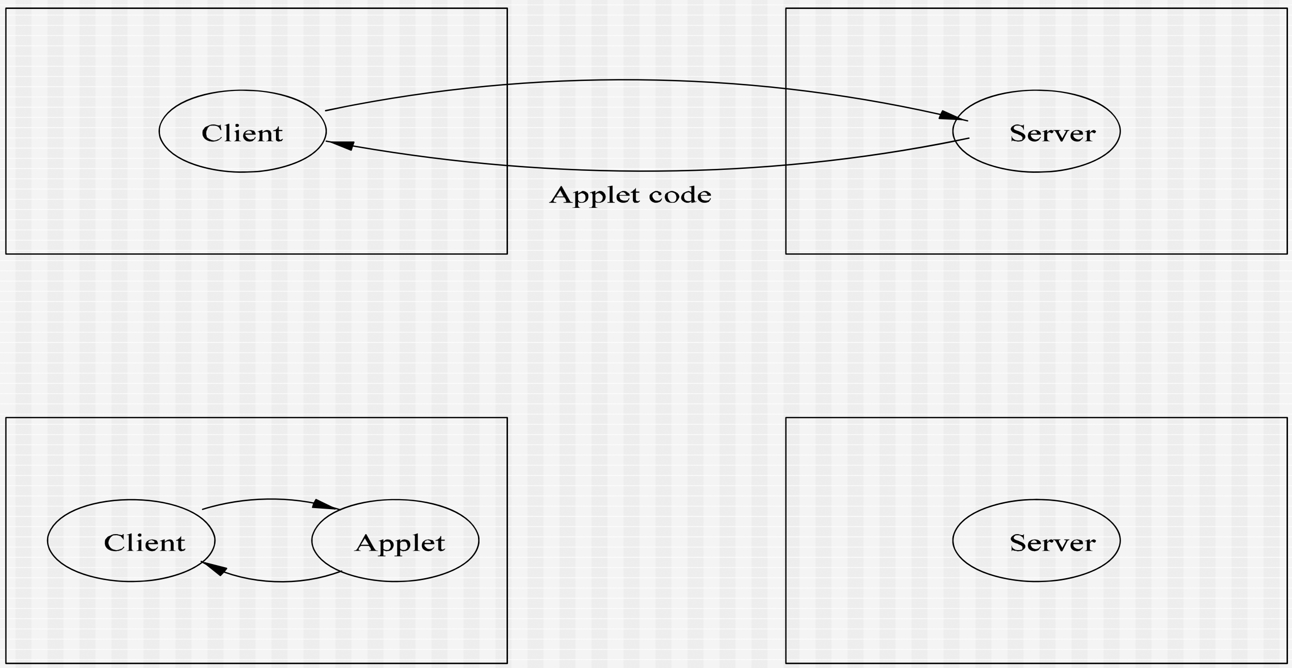
Peer Processes

Peer-to-Peer: P2P



Peer processes.

Mobile Code and Mobile Agents



Mobile code (web applets).

Key Issues (Stankovic's list)

- Theoretical foundations
- Reliability
- Privacy and security
- Design tools and methodology
- Distribution and sharing
- Accessing resources and services
- User environment
- Distributed databases
- Network research

Wu's Book

- Distributed Programming Languages
  - Basic structures
- Theoretical Foundations
  - Global state and event ordering
  - Clock synchronization
- Distributed Operating Systems
  - Mutual exclusion and election
  - Detection and resolution of deadlock
  - self-stabilization
  - Task scheduling and load balancing
- Distributed Communication
  - One-to-one communication
  - Collective communication

Wu's Book (Cont'd.)

- Reliability
  - Agreement
  - Error recovery
  - Reliable communication
- Distributed Data Management
  - Consistency of duplicated data
  - Distributed concurrency control
- Applications
  - Distributed operating systems
  - Distributed file systems
  - Distributed database systems
  - Distributed shared memory
  - Distributed heterogeneous systems

Wu's Book (Cont'd.)

- Part 1: Foundations and Distributed Algorithms
- Part 2: System infrastructure
- Part 3: Applications

What is Distributed Algorithms

- Parallel Computing: efficiency
- Real-Time: On-time computing
- Distributed Computing: uncertainty
  - Simplicity, elegance, and beauty are first-class citizens (Michel Raynal, 2013)

Distributed Message-Passing Algorithms

- Termination
  - In a social network, each person exchanges his/her friend list with friends. What is the stoppage condition?
- Global State
  - How to design an observation algorithm by observing an execution without modifying its behavior?
- Distributed Consensus
  - How to reach distributed consensus (e.g., binary decisions) in the presence of traitors?

Distributed Message-Passing Algorithms

- Logical Clock
  - How to order events in different systems with asynchronous clocks? How to discard obsolete data?
- Data
  - How to replicate data and keep them consistent?
- Load
  - How to distribute load in a load balanced way?
- Routing
  - How to perform efficient routing that is deadlock-free and fault-tolerant?

References

- IEEE Transactions on Parallel and Distributed Systems (TPDS)
- Journal of Parallel and Distributed Computing (JPDC)
- Distributed Computing
- IEEE International Conference on Distributed Computing Systems (ICDCS)
- IEEE International Conference on Reliable Distributed Systems (SRDS)
- ACM Symposium on Principles of Distributed Computing (PODC)
- IEEE Concurrency (formerly IEEE Parallel & Distributed Technology: Systems & Applications)

Exercise 1

1. In your opinion, what is the future of the computing and the field of distributed systems?

2. Use your own words to explain the differences between distributed systems, multiprocessors, and network systems.

3. Calculate (a) node degree, (b) diameter, (c) bisection width, and (d) the number of links for an n x n 2-d mesh, an n x n 2-d torus, and an n-dimensional hypercube.

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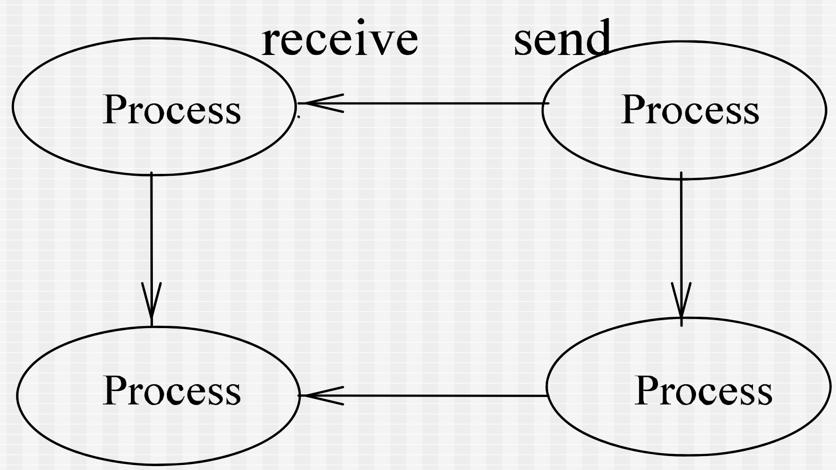
State Model

- A **process** executes three types of events: **internal** actions, **send** actions, and **receive** actions.
- A **global state (**also **configuration)**: a collection of local states and the state of all the communication channels.

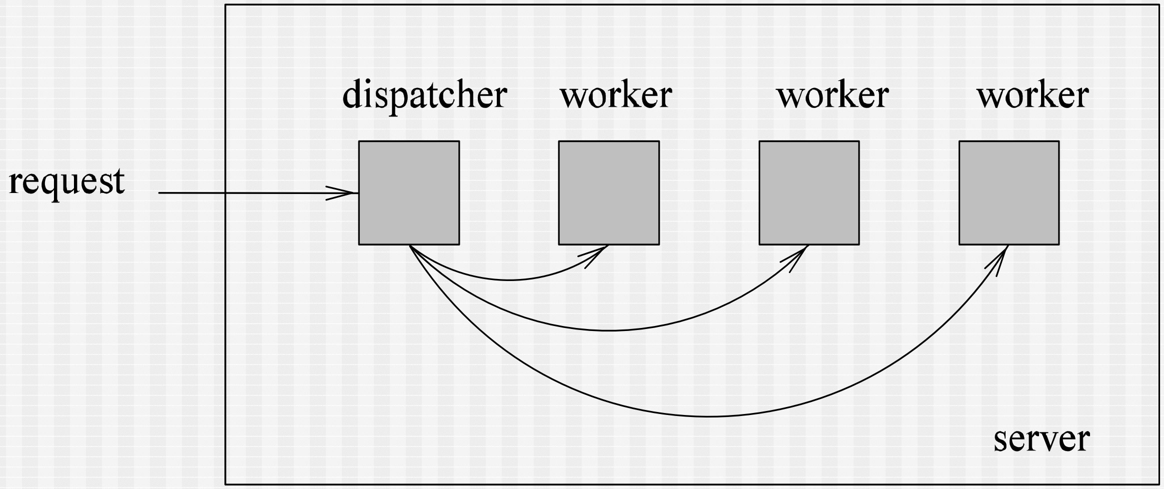
- Global state evolves by means of **transitions**
- **Initiator**: first event
- **Distributed algorithm**: multiple initiators



System structure from logical point of view.

Thread

- lightweight process (maintain minimum information in its context)
- multiple threads of control per process
- multithreaded servers (vs. single-threaded process)



A multithreaded server in a dispatcher/worker model.

Preliminary

Assertions: a predicate on the configurations of an algorithm

Invariant, such as loop invariant, is an assertion

e.g., {I} **while** c body {¬c ∧ I} (under Floyd-Hoare logic)

calculate sum: 1+2+…+n, two assertions I: 1+2+…+k and c: k < n

Safety property: if it is true in each reachable configuration

i.e., something bad will never happen (e.g., deadlock)

Liveness property: if executions, from some point on, contain a configuration in which the assertion holds

i.e., something good will eventually happen (e.g., program terminates)

Fair: if every event that can happen in infinitely many times is performed infinitely often

Complexity: time, space, message (bit) complexity

Happened-Before Relation

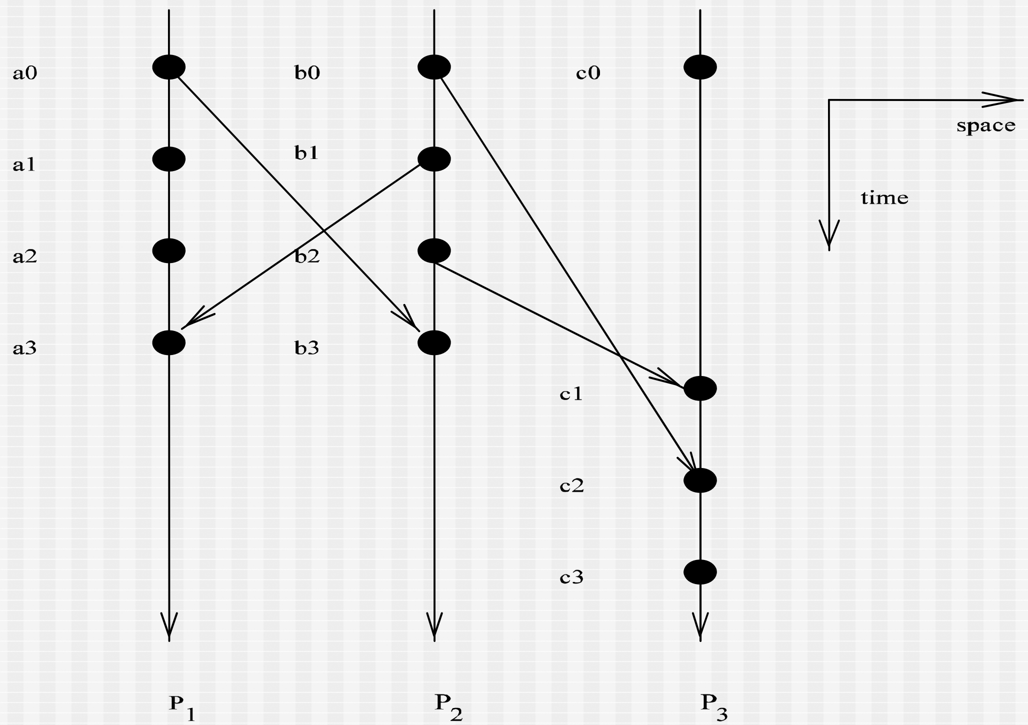
The **happened-before relation** (denoted by $\rightarrow$) is defined as follows:

- Rule 1 : If a and b are events in the same process and a was executed before b, then $a \rightarrow b$.
- Rule 2 : If a is the event of sending a message by one process and b is the event of receiving that message by another process, then $a \rightarrow b$.
- Rule 3 : If $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$.

Relationship Between Two Events

- Two events a and b are **causally related** if $a \rightarrow b$ or $b \rightarrow a$.
- Two distinct events a and b are said to be **concurrent** if $a \not\rightarrow b$ and $b \not\rightarrow a$ (denoted as $a \parallel b$).

Example 2



A time-space view of a distributed system.

Example 2 (Cont'd.)

- Rule 1:

  $a_0 \rightarrow a_1 \rightarrow a_2 \rightarrow a_3$

  $b_0 \rightarrow b_1 \rightarrow b_2 \rightarrow b_3$

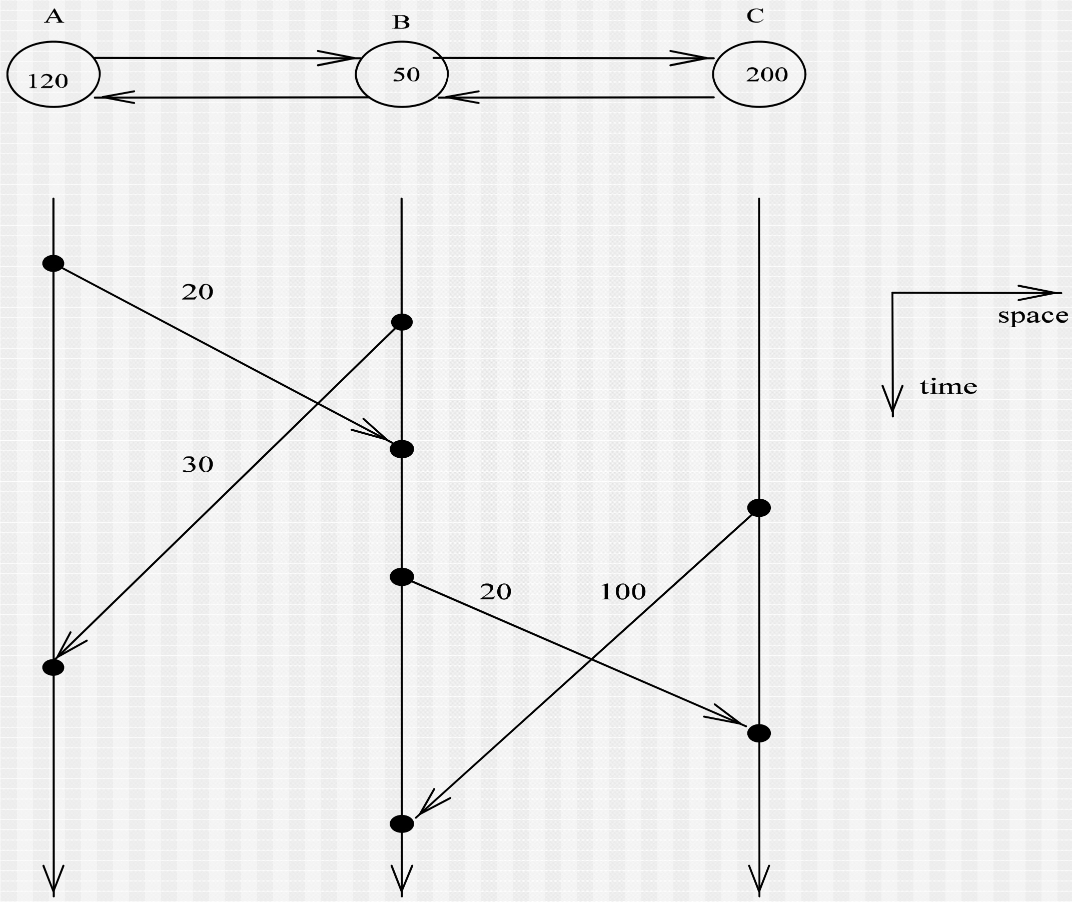
  $c_0 \rightarrow c_1 \rightarrow c_2 \rightarrow c_3$

- Rule 2:

  $a_0 \rightarrow b_3$

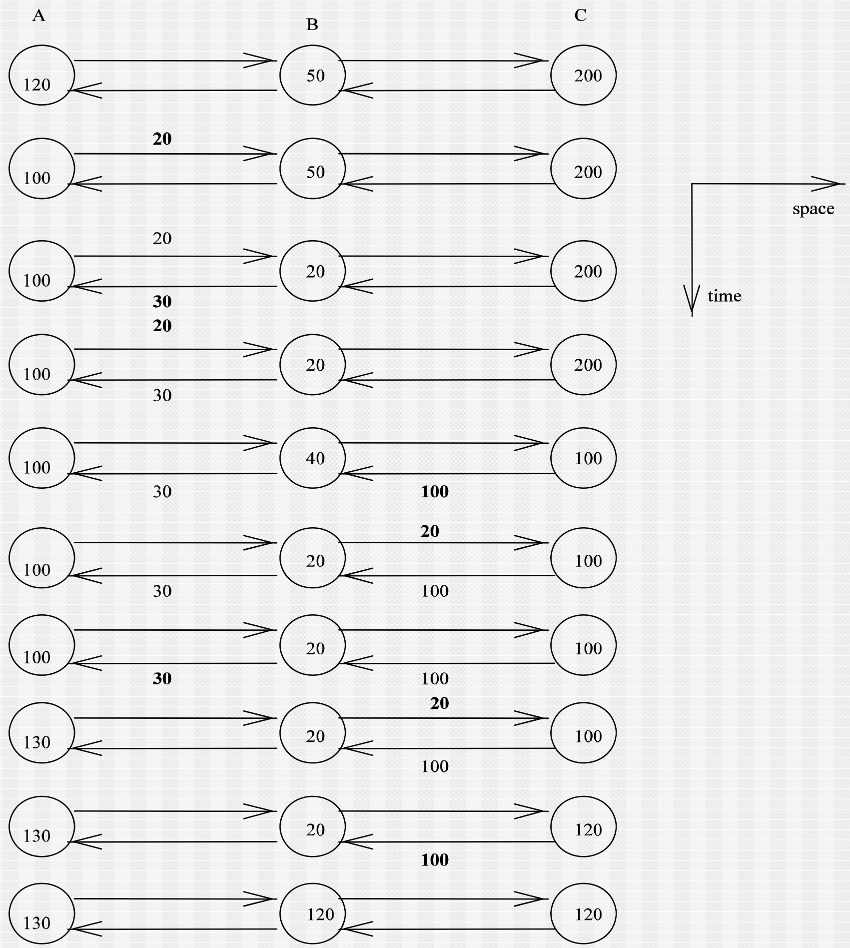
  $b_1 \rightarrow a_3$, $b_2 \rightarrow c_1$, $b_0 \rightarrow c_2$

Example 3



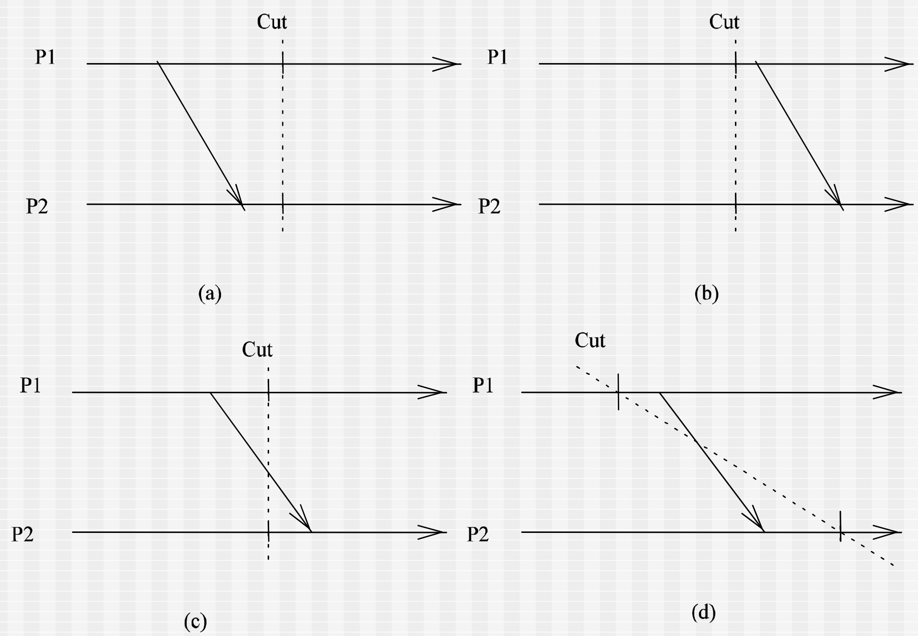
An example of a network of a bank system.

Example 3 (Cont'd.)



A sequence of global states.

Consistent Global State



Four types of cut that cross
a message transmission line.

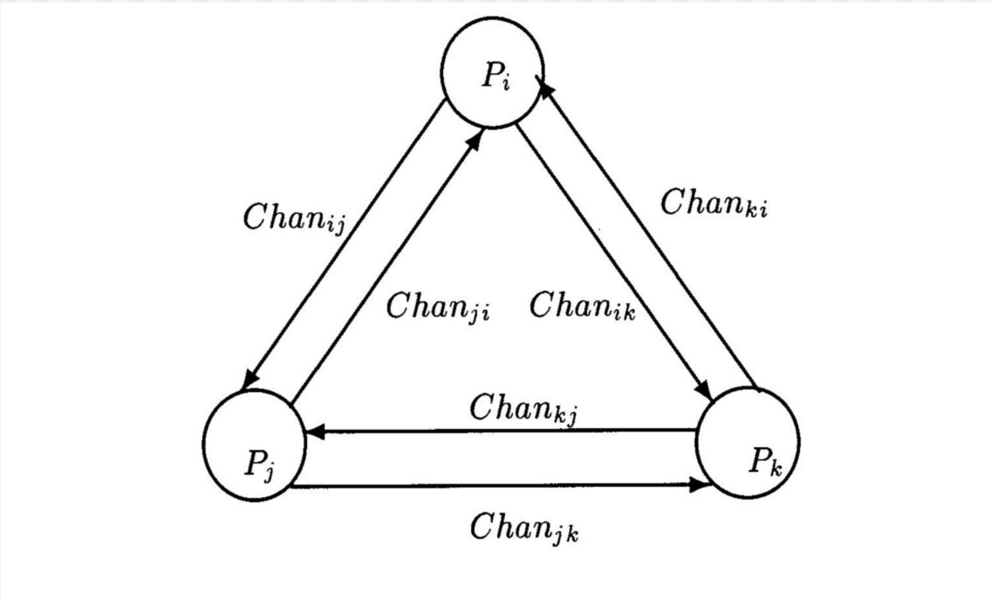
Consistent Global State (Cont'd.)

A **cut** is consistent iff no two cut events are causally related.

- **Strongly consistent**: no (c) and (d).
- **Consistent**: no (d) (orphan message).
- **Inconsistent**: with (d).

Focus 3: Snapshot of Global States

A simple distribute algorithm to capture a consistent global state.



A system with three processes P_i, P_j , and P_k.

Chandy and Lamport's Solution

- Rule for sender *P* :

  [*P* records its local state

  ||*P* sends a marker along all the channels on which a marker has not been sent.

  ]

Chandy and Lamport's Solution (Cont'd.)

- Rule for receiver *Q*:

  /* on receipt of a marker along a channel *chan* */

  [*Q* has not recorded its state →

  [record the state of *chan* as an empty sequence and

  follow the "Rule for sender"

  ]

  □ *Q* has recorded its state →

  [record the state of *chan* as the sequence of messages received along *chan* after the latest state recording but before receiving the marker

  ]

  ]

Chandy and Lamport's Solution (Cont'd.)

- It can be applied in any system with FIFO channels (but with variable communication delays).
- The initiator for each process becomes the parent of the process, forming a spanning tree for result collection.
- It can be applied when more than one process initiates the process at the same time.

Focus 4: Lamport's Logical Clocks

Based on a "**happen-before**" relation that defines a **partial order** on events

- *Rule*$_1$. Before producing an event (an external send or internal event), we update *LC* :

  $LC_i = LC_i + d$ $\qquad (d > 0)$

  (d can have a different value at each application of *Rule*$_1$)

- *Rule*$_2$. When it receives the time-stamped message (m, LC_j , j), P_i executes the update

  $LC_i = \max\{Lc_i, LC_j\} + d \quad (d > 0)$

Focus 4 (Cont'd.)

A **total order** based on the partial order derived from the happen-before relation

$$a \text{ (in } P_i \text{)} \Rightarrow b \text{ (in } P_j \text{)}$$

iff

(1) $LC(a) < LC(b)$ or (2) $LC(a) = LC(b)$ and $P_i < P_j$ where < is an arbitrary total ordering of the process set, e.g., <can be defined as $P_i < P_j$ iff $i < j$.

A total order of events in the table for Example 2:

$$a_0\ b_0\ c_0\ a_1\ b_1\ a_2\ b_2\ \mathrm{a}_3\ b_3\ c_1\ \mathrm{c}_2\ c_3$$

Example 4: Totally-Ordered Multicasting

- Two copies of the account at A and B (with balance of $10,000).
- Update 1: add $1,000 at A.
- Update 2: add interests (based on 1% interest rate) at B.
- Update 1 followed by Update 2: $11,110.
- Update 2 followed by Update 1: $11,100.

Vector and Matrix Logical Clock

Linear clock: if $a \rightarrow b$ then $LC_a < LC_b$

Vector clock: $a \rightarrow$ b iff $LC_a < LC_b$

Each P_i is associated with a vector $LC_i[1..n]$, where

- $LC_i[i]$ describes the progress of P_i, i.e., its own process.
- $LC_i\ [j]$ represents P_i's knowledge of P_j's progress.
- The $LC_i[1..n]$ constitutes P_i's local view of the logical global time.

Vector and Matrix Logical Clock (Cont'd.)

When $d = 1$ and $init = 0$

- $LC_i[i]$ counts the number of internal events
- $LC_i[j]$ corresponds to the number of events produced by P_j that causally precede the current event at P_i.

Vector and Matrix Logical Clock (Cont'd.)

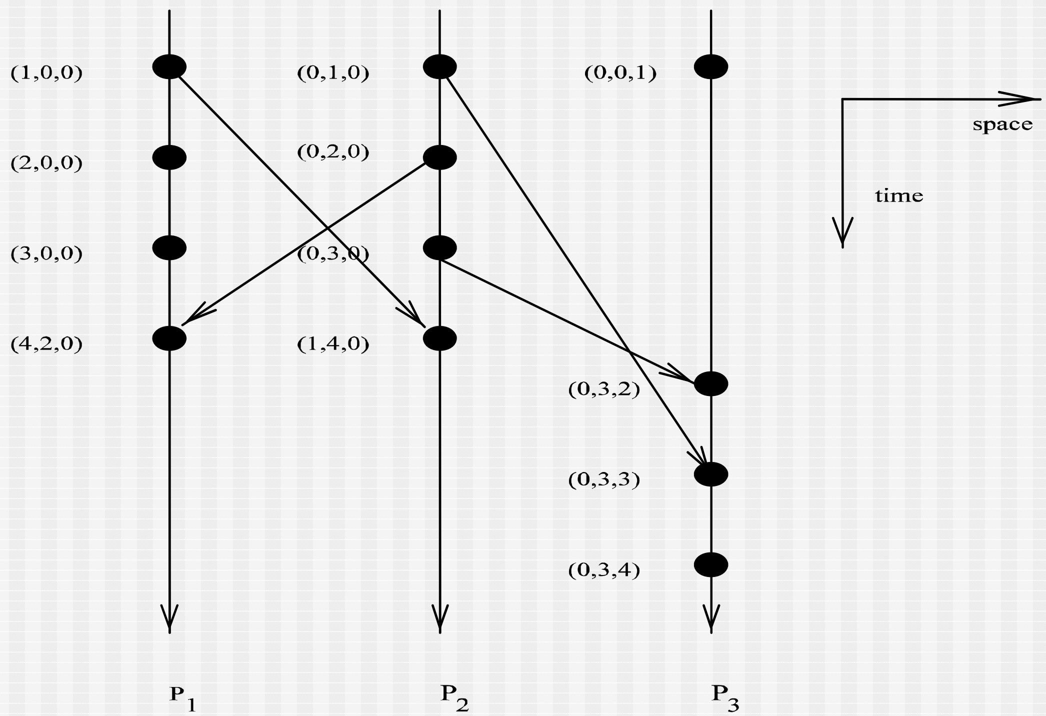
- *Rule*$_1$. Before producing an event (an external send or internal event), we update $LC_i[i]$:

$$LC_i[i] := LC_i[i] + \mathrm{d} \quad (d > 0)$$

- *Rule*$_2$. Each message piggybacks the vector clock of the sender at sending time. When receiving a message (m, LC_j , j), P_i executes the update.

$$LC_i[k] := \max\,(LC_i[k]; LC_j[k]),\ 1 \leq \mathrm{k} \leq n$$
$$LC_i[i] := LC_i[i] + d$$

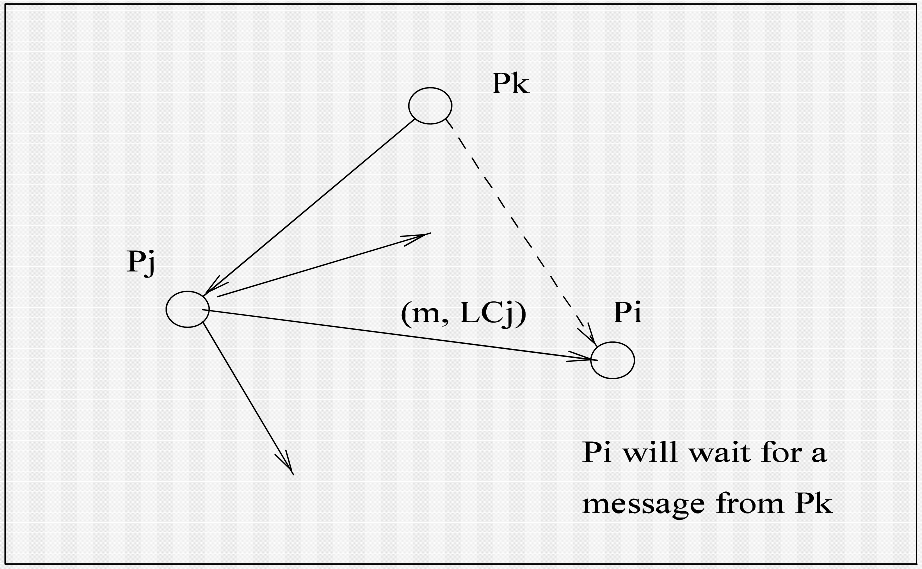
Example 5



An example of vector clocks.

Example 6: Application of Vector Clock

Internet electronic bulletin board service



Network News.

When receiving m with vector clock LC_j from process j, P_i inspects timestamp LC_j and will postpone delivery until all messages that causally precede m have been received.

Matrix Logical Clock

Each P_i is associated with a matrix $LC_i[1..n, 1..n]$ where

- $LC_i[i, i]$ is the local logical clock.
- $LC_i[k, l]$ represents the view (or knowledge) P_i has about P_k's knowledge about the local logical clock of P_l.

If

$$\min(LC_i[k, i]) \geq t$$

then P_i knows that every other process knows its progress until its local time t.

Physical Clock

- Correct rate condition:

  $\forall_i \; |dPC_i(t)/\, dt - 1\,| < \alpha$

- Clock synchronization condition:

  $\forall_i \; \forall_j \; |PC_i(t) - PC_j(t)| < \beta$

Lamport's Logical Clock Rules for Physical Clock

- For each i, if P_i does not receive a message at physical time t, then PC_i is differentiable at t and $dPC(t)/dt > 0$.
- If P_i sends a message m at physical time t, then m contains $PC_i(t)$.
- Upon receiving a message (m, PC_j) at time t, process P_i sets PC_i to maximum ($PC_i(t - 0)$, $PC_j + \mu_m$) where μ_m is a predetermined minimum delay to send message m from one process to another process.

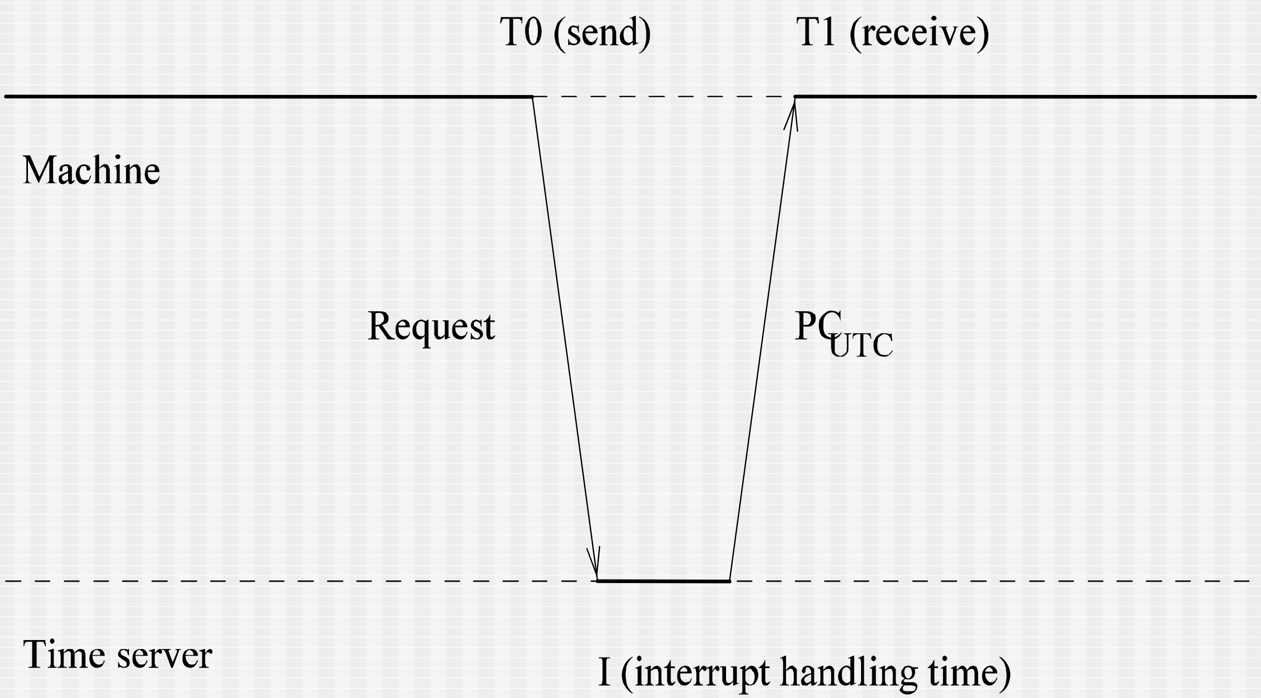
Focus 5: Clock Synchronization

- UNIX **make** program:
  - Re-compile when *file.c*'s time is large than *file.o*'s.
  - Problem occurs when source and object files are generated at different machines with no global agreement on time.
- **Maximum drift rate** ρ : $1-\rho \leq dPC/dt \leq 1+\rho$
  - Two clocks (with opposite drift rate ρ) may be $2\rho\Delta t$ apart at a time Δ after last synchronization.
  - Clocks must be resynchronized at least every $\delta/2\rho$ seconds in order to guarantee that they will be differ by no more than δ.

Cristian's Algorithm

- Each machine sends a request every δ/2ρ seconds.
- Time server returns its current time PC_{UTC} (UTC: Universal Coordinate Time).
- Each machines changes its clock (normally set forward or slow down its rate).
- Delay estimation: $(T_r - T_s - I)/2$, where T_r is receive time, T_s send time, and I interrupt handling time.

Cristian's Algorithm (Cont'd.)



Getting correct time from a time server.

Three Ways to Demonstrate the Properties

- Testing and debugging (run the program and see what happens)
- Operational reasoning (exhaustive case analysis)
- Assertional reasoning (abstract analysis)

Synchronous vs. Asynchronous Systems

Synchronous Distributed Systems:

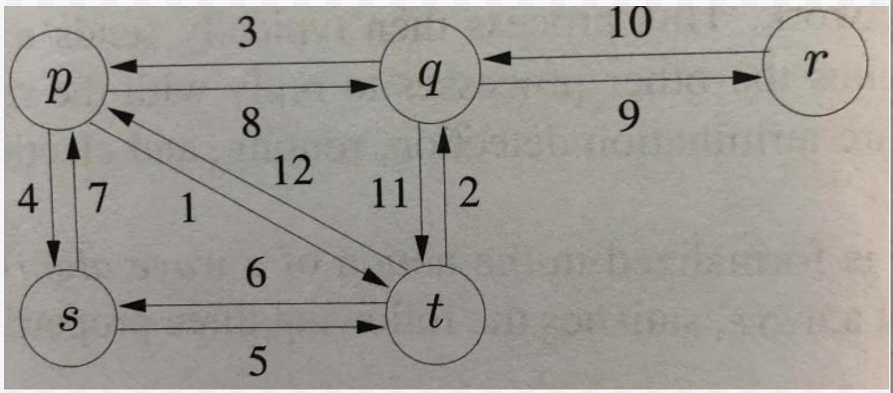
- The time to each step of a process (program) has known bounds.
- Each message will be received within a known bound.
- Each process has a local clock whose drift rate from real time has a known bound.

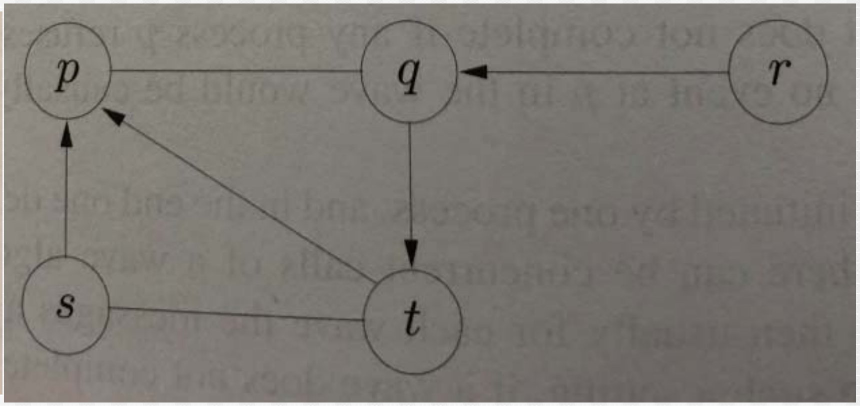
Distributed Algorithms: Traversal

Tarry's algorithm:

- A process forwards the token through the same channel once.
- A process forwards the token to its parent only when there is no other option.

Complexity: 2E messages and at most 2E time units.



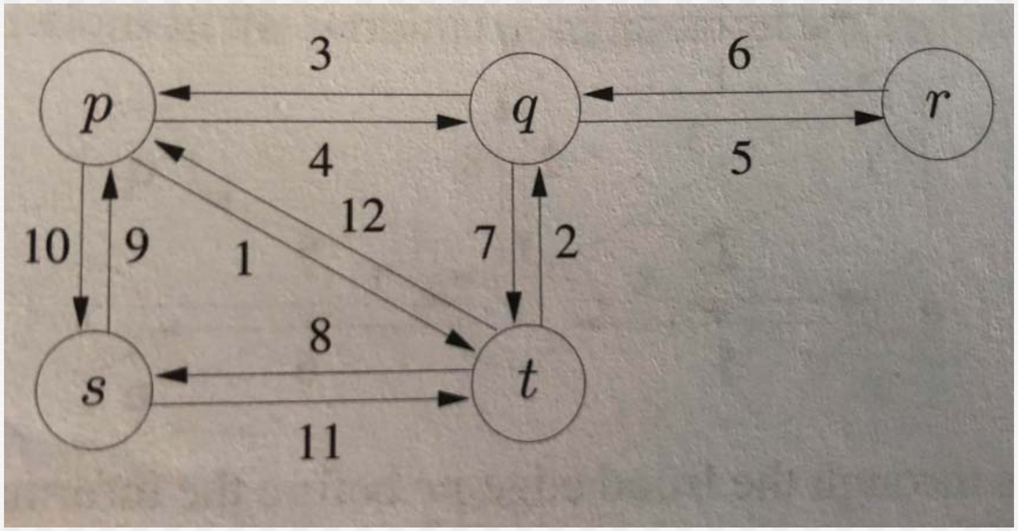


Distributed Algorithms: Traversal (cont'd)

Depth-first search algorithm:

- Whenever possible, the token is forwarded to a process that did not hold the token yet; otherwise, it is sent back to its parent.

Complexity: same as Tarry's algorithm



Distributed Algorithms: Traversal (cont'd)

Extensions to avoid visited nodes:

- Include the IDs of visited nodes

  Complexity: 2(N-1) in time and in messages, but O(N log N) in bit complexity

- Awerbuch's extension: the first-time process with the token informs its neighbors

  Complexity: 4N-2 in time and 4E in messages

- Cidon's extension: improves on Awerbuch's extension

  Complexity: 2(N-1) in time and 4E in messages

Distributed Algorithms: Echo

Echo algorithm

- **Initiator** starts by sending a token to all its neighbors.
- When a node receives a token for the first time, it makes the sender its parent, and sends the token to all its neighbors.
- When a node has received messages from all its neighbors, it sends a message to its parent.
- When the **initiator** has received messages from all its neighbors, it stops.

General **wave** algorithm

- A process often needs to gather information from all other processes.
- Usually the process starts with an initiator and ends with the same imitator (after collecting all data/results from all other processes).
- When the wave algorithm is issued at multiple nodes. Many waves, except one, will fail (as some processes refuse to participate)

Distributed Algorithms: Termination

Dijkstra-Scholten (tree-based):

- The initiator of the root of the tree.
- Upon receiving a message:
  - If the receiving process is currently not in the tree: the process joins the tree by becoming a child of the sender.
  - If the receiving process is already in the computation: the process immediately sends an acknowledgment message to the sender.
- When a process has no more children and has become idle, the process detaches itself from the tree by sending an acknowledgment to its tree parent.
- Termination occurs when the initiator has no children and has become idle.

Example: global snapshot (with one king)

Distributed Algorithms: Termination

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- Termination occurs when the initiator has no children and has become idle.

Example: global snapshot (with one king)

Distributed Algorithms: Termination (cont'd)

Shavit-Francez (forest-based):

- Same as Dijkstra-Scholten, except with multiple initiators.
- Each non-initiator joining one tree.
- Termination detection initiated by multiple initiators through a wave algorithm

Example: global snapshot (with multiple kings)

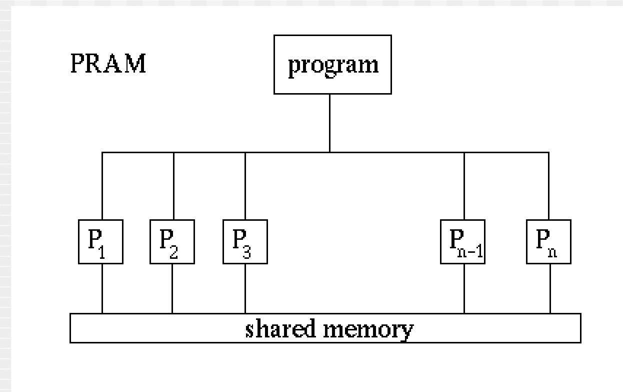
Other termination algorithms:

- **Weight-throwing** algorithm: dividing a fixed weight over the active processes
- **Rana**'s algorithm: waves tagged with logical clocks
- **Safra**'s algorithm: token-based traversal

Other Algorithms: Parallel Algorithms

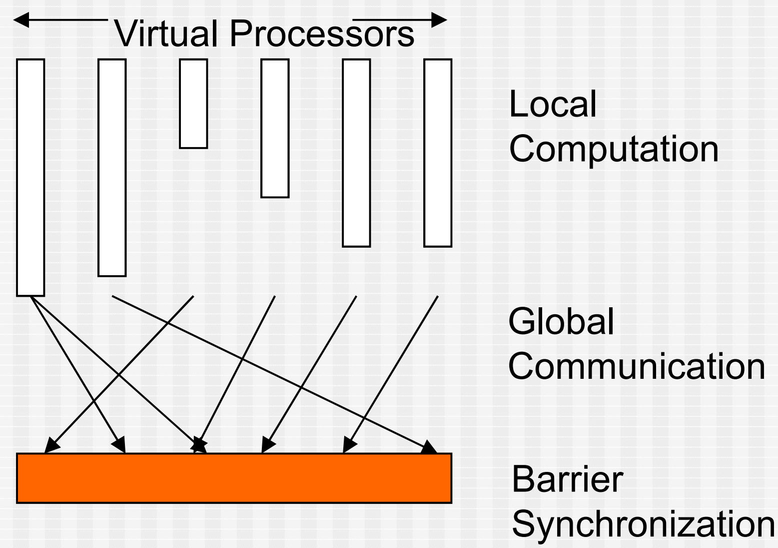
PRAM model

- Parallel random access memory
- EREW, ERCW, CREW, CRCW models
- Chap. 2 of JaJa’s
  “an introduction to parallel algorithms”



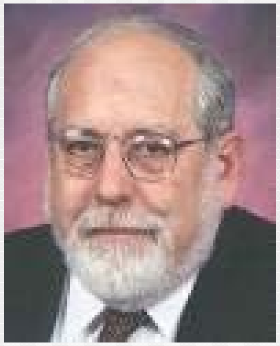
BSP model by L. Valiant (1990)

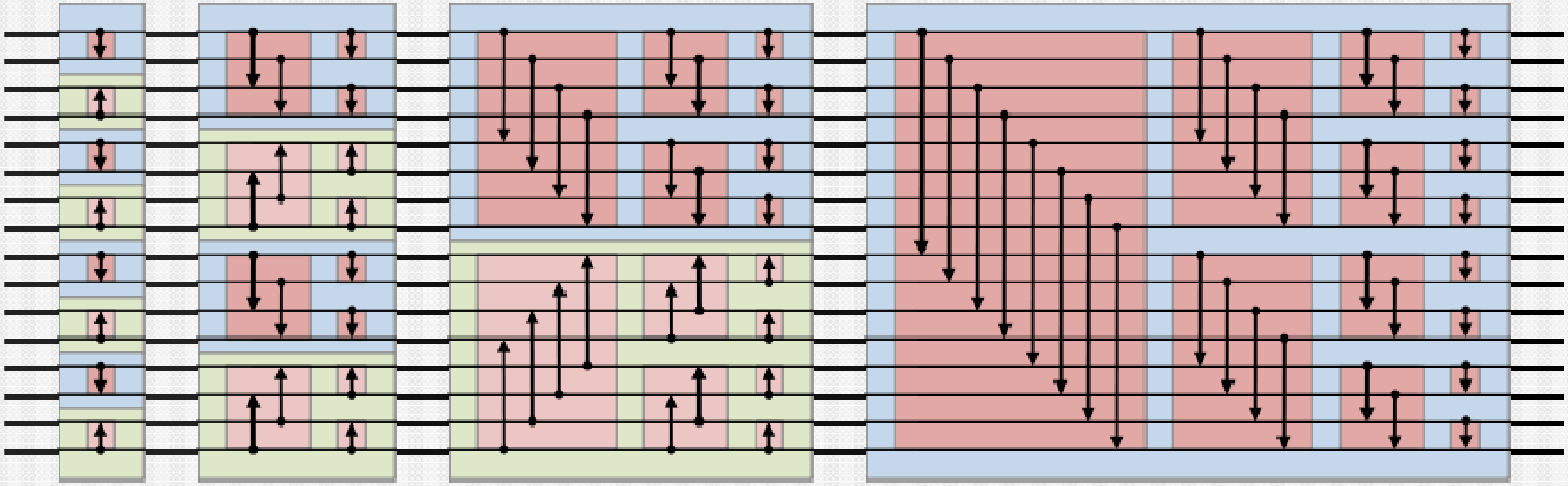
- Bulk synchronous parallel (BSP)
- Sequential composition of “supersteps”
  - Local computation
  - Process communication
  - Barrier synchronization



Parallel Algorithm: Bitonic sorter by K. Batcher

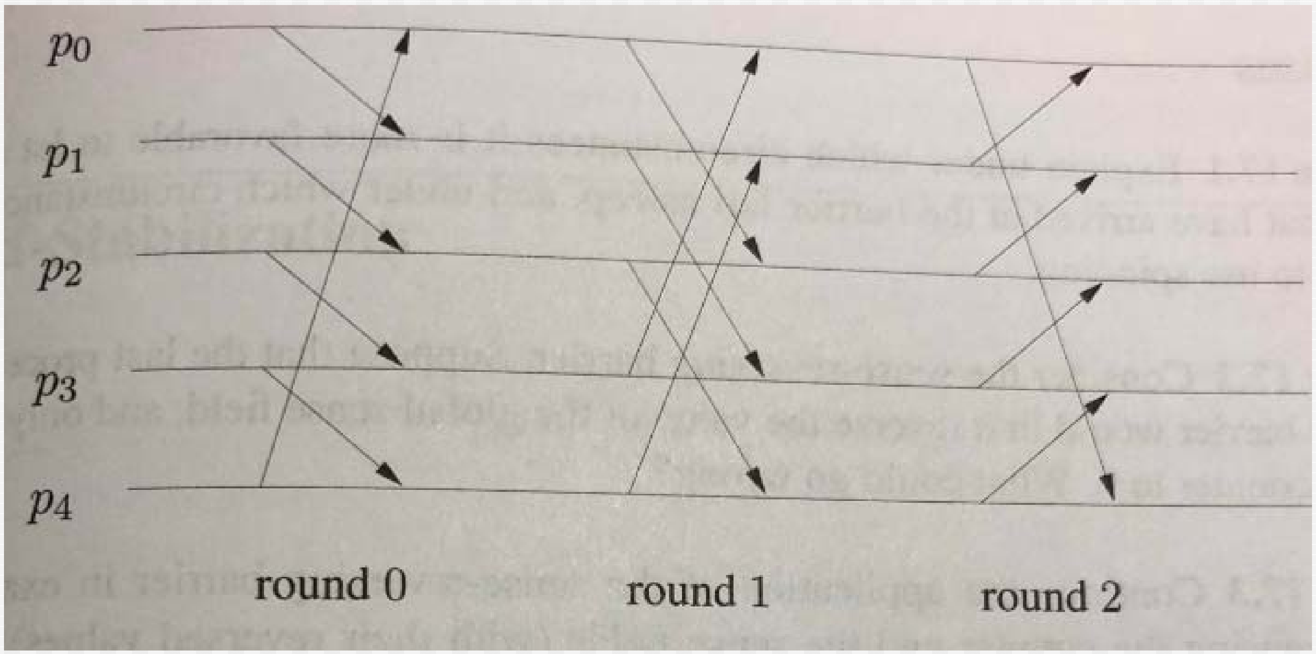
- Sorting network based on **Bitonic sequence**
  - Up-then-Down or Down-then-Up
  - $O(n \log^2(n))$ comparators
  - $O(\log^2(n))$ latency
- Also Batcher's **odd-even sort**





Barrier: dissemination barrier

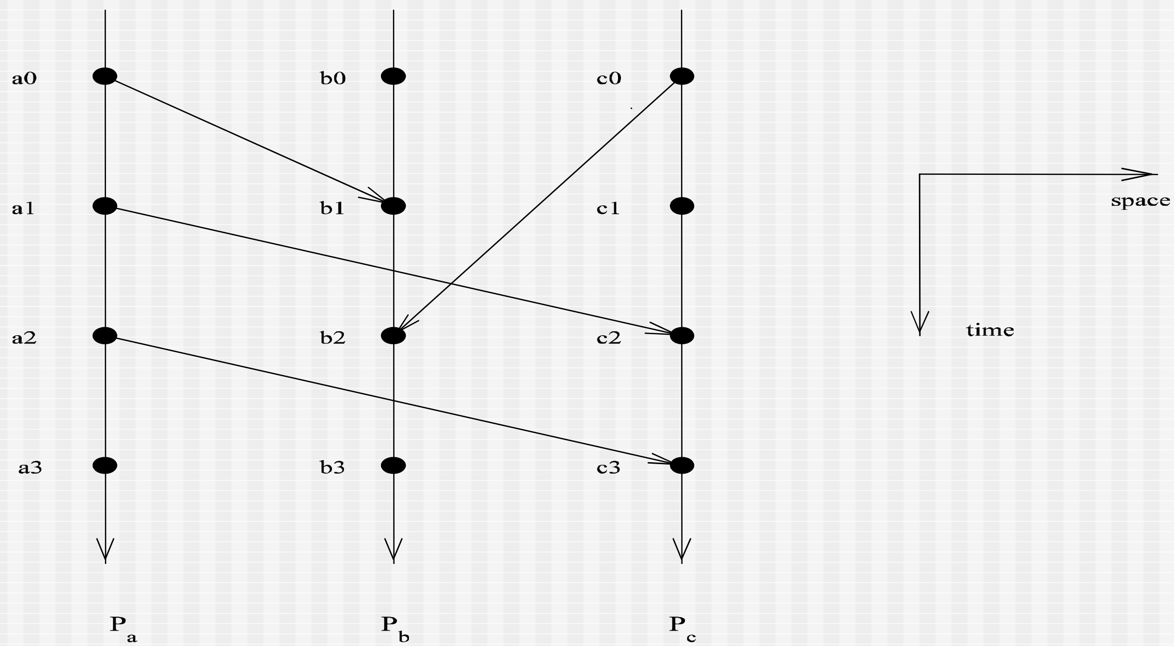
- Processes p_0, p_1, …, p_{N-1}, n starts from 0 until $\log_2 N - 1$
  - Notifies process $p_{(i+2^n) \bmod N}$,
  - Waits for notification by process $P_{(i-2^n) \bmod N}$, and
  - Processes to round n+1



Exercise 2

1. Consider a system where processes can be dynamically created or terminated. A process can generate a new process. For example, P_1 generates both P_2 and P_3. Modify the happened-before relation and the linear logical clock scheme for events in such a dynamic set of processes.

2. For the distributed system shown in the figure below.



Exercise 2 (Cont'd)

- Provide all the pairs of events that are related.
- Provide logical time for all the events using
  - linear time, and
  - vector time
  - Assume that each LC_i is initialized to zero and $d = 1$.

3. Provide linear logical clocks for all the events in the system given in Problem 2. Assume that all *LC*'s are initialized to zero and the *d*'s for P_a, P_b, and P_c are 1, 2, 3, respectively. Does condition $a \rightarrow b \Rightarrow LC(a) < LC(b)$ still hold? For any other set of *d*'s? and why?

Table of Contents

Three Issues

- Use of multiple PEs
- Cooperation among the PEs
- Potential for survival to partial failure

Control Mechanisms

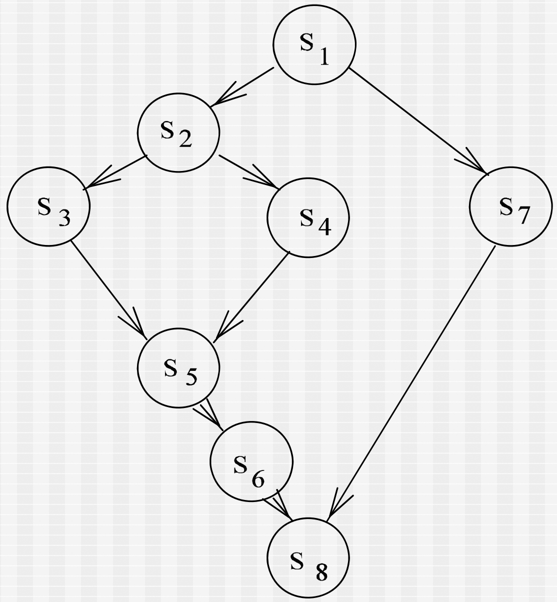
Statement type \ Control type	Sequential control	Parallel Control
Sequential/parallel statement	**Begin** S_1, S_2 **end**	**Parbegin** S_1, S_2 **Parend** **Fork/join**
Alternative statement	**goto**, **case if** C **then** S_1 **else** S_2	Guarded commands: $G \rightarrow C$
Repetitive statement	**for … do**	**doall, for all**
Subprogram	**procedure** **Subroutine**	**procedure** **subroutine**

Four basic sequential control mechanisms with their parallel counterparts.

Focus 6: Expressing Parallelism

parbegin/parend statement

$S_1;[[S_2;[S_3||S_4];S_5;S_6]||S_7];\mathrm{S}_8$

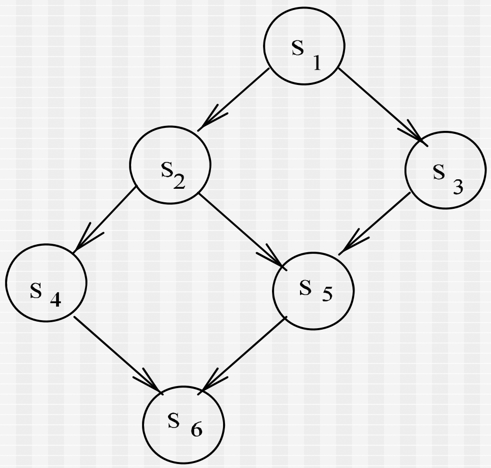


A precedence graph of eight statements.

Focus 6 (Cont'd.)

fork/join statement

s_1;
c_1:= 2;
fork $L1$;
s_2;
c_2:=2;
fork $L2$;
s_4;
go to $L3$;
$L1$: s_3;
$L2$: **join** c_1;
s_5;
$L3$: **join** c_2;
s_6;



A precedence graph.

Dijkstra's Semaphore + Parbegin/Parend

S(i): A sequence of P operations; S_i; a sequence of V operations

s: a binary semaphore initialized to 0.

$S(1)$: $S_1;V(s_{12});V(s_{13})$
$S(2)$: $P(s_{12});S_2;V(s_{24});V(s_{25})$
$S(3)$: $P(s_{13});S_3;V(s_{35})$
$S(4)$: $P(s_{24});S_4;V(s_{46})$
$S(5)$: $P(s_{25});P(s_{35});S_5;V(s_{56})$
$S(6)$: $P\ (s_{46});\ P\ (s_{56});\ S_6$

Focus 7: Concurrent Execution

- $R(S_i)$, the **read set** for S_i, is the set of all variables whose values are referenced in S_i.
- $W(S_i)$, the **write set** for S_i, is the set of all variables whose values are changed in S_i.
- **Bernstein conditions**:
  - $R(S_1) \cap W(S_2) = \phi$
  - $W(S_1) \cap R(S_2) = \phi$
  - $W(S_1) \cap W(S_2) = \phi$

Example 7

$S_1 : a := x + y,$

$S_2 : b := x \times z,$

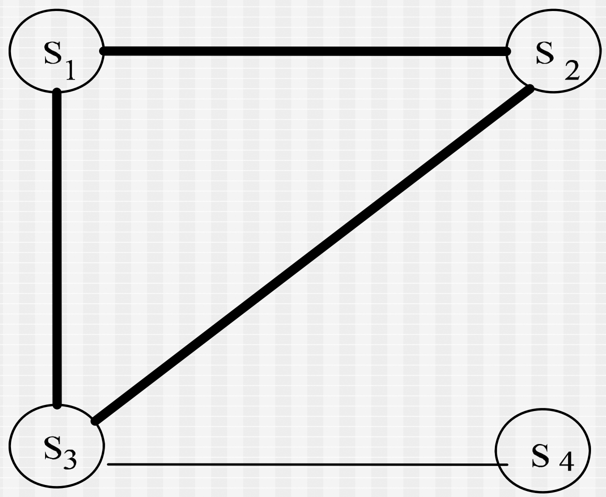
$S_3 : c := y - 1$, and

$S_4 : x := y + z.$

$S_1||S_2$, $S_1||S_3$, $S_2||S_3$, and $S_3||S_4$.

Then, $S_1||S_2||S_3$ forms a largest complete subgraph.

Example 7 (Cont'd.)



A graph model for Bernstein's conditions.

Alternative Statement

Alternative statement in DCDL (CSP like distributed control description language)

$[\ G_1 \rightarrow C_1 \square\ G_2 \rightarrow \mathrm{C}_2\ \ \square \ldots \square\ G_n \rightarrow C_n\ ].$

Example 8

Calculate $m = \max\{x, y\}$:

$$[x \geq y \rightarrow m := x \;\square\; y \geq \mathrm{x} \rightarrow \mathrm{m} := y]$$

Repetitive Statement

$*[\ G_1 \rightarrow\ C_1 \ \square\ G_2 \rightarrow\ C_2 \ \square \ldots \square\ \mathrm{G_n} \rightarrow\ C_n\ ].$

Example 9

meeting-time-scheduling ::= $t := 0$;

$*[\ t := a(t)\ \square\ t := \mathrm{b}(t)\ \square\ t := c(t)\ ]$

Communication and Synchronization

- One-way communication: **send** and **receive**
- Two -way communication: **RPC**(Sun), **RMI**(Java and CORBA), and **rendezvous** (Ada)
- Several **design decisions**:
  - One-to one or one-to-many
  - Synchronous or asynchronous
  - One-way or two-way communication
  - Direct or indirect communication
  - Automatic or explicit buffering
  - Implicit or explicit receiving

Primitives	Example Languages
PARALLELISM	
Expressing parallelism	
Processes	Ada, Concurrent C, Lina, NIL Emerald,
Objects	Concurrent Smalltalk
Statements	Occam
Expressions	Par Alfl, FX-87
Clauses	Concurrent PROLOG, PARLOG
Mapping	
Static	Occam, Star Mod
Dynamic	Concurrent PROLOG, ParAlfl
Migration	Emerald
COMMUNICATION	
Message Passing	
Point-to-point messages	CSP, Occam, NIL
Rendezvous	Ada, Concurrent C
Remote procedure call	DP, Concurrent CLU, LYNX
One-to-many messages	BSP, StarMod
Data Sharing	
Distributed data Structures	Lina, Orca
Shared logical variables	Concurrent PROLOG, PARLOG
Nondeterminism	
Select statement	CSP, Occam, Ada, Concurrent C, SR
Guarded Horn clauses	Concurrent PROLOG, PARLOG
PARTIAL FILURES	
Failure detection	Ada, SR
Atomic transactions	Argus, Aeolus, Avalon
NIL	

Message-Passing Library for Cluster Machines (e.g., Beowulf clusters)

- **Parallel Virtual Machine (PVM):**
  www.epm.ornl/pvm/pvm_home.html
- **Message Passing Interface (MPI):**
  www.mpi.nd.edu/lam/
  www-unix.mcs.anl.gov/mpi/mpich/
- **Java multithread programming:**
  www.mcs.drexel.edu/~shartley/ConcProjJava
  www.ora.com/catalog/jenut
- **Beowulf clusters**:
  www.beowulf.org

Message-Passing (Cont'd.)

- **Asynchronous** point-to-point message passing:
  - **send** message list **to** destination
  - **receive** message list {**from** source}
- **Synchronous** point-to-point message passing:
  - **send** message list **to** destination
  - **receive** empty signal **from** destination
  - **receive** message list **from** sender
  - **send** empty signal **to** sender

Example 10

The squash program replaces every pair of consecutive asterisks "**" by an upward arrow “↑”.

input::= * [**send** *c* **to** squash]

output::= * [**receive** *c* **from** squash]

Example 10 (Cont'd.)

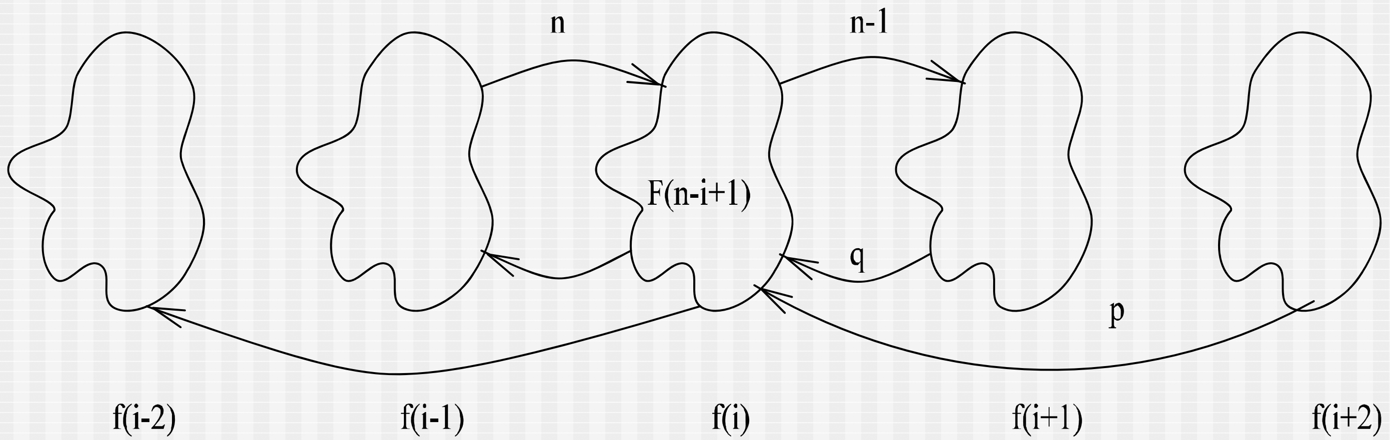
```
squash::=
  *[ receive c from input →
        [ c ≠ *→ send c to output
         □ [ c = *→ receive c from input;
                      [ c ≠ *→ send * to output;
                                send c to output
                         c = *→ send ↑ to output
                      ] □
                 ]
         ]
  ]
```

Focus 8: Fibonacci Numbers

- $F(i) = F(i\text{-}1) + F\ (i - 2)$ for i > 1, with initial values F(0) = 0 and $F(1) = 1$.
- $F(i) = (\phi^{\,i} - \phi'^{i})/(\phi - \phi')$,where $\phi = (1+5^{0.5})/2$ (golden ratio) and $\phi' = (1\text{-}5^{0.5})/2$.

0, 1, 2, 3, 5, 8, 13, 21, 35, 54, …

Focus 8 (Cont'd.)



A solution for F (n).

Focus 8 (Cont'd.)

- f(0) ::=

  send n **to** f(1);

  receive p **from** f(2);

  receive q **from** f(1);

  ans := q
- f(-1) ::=

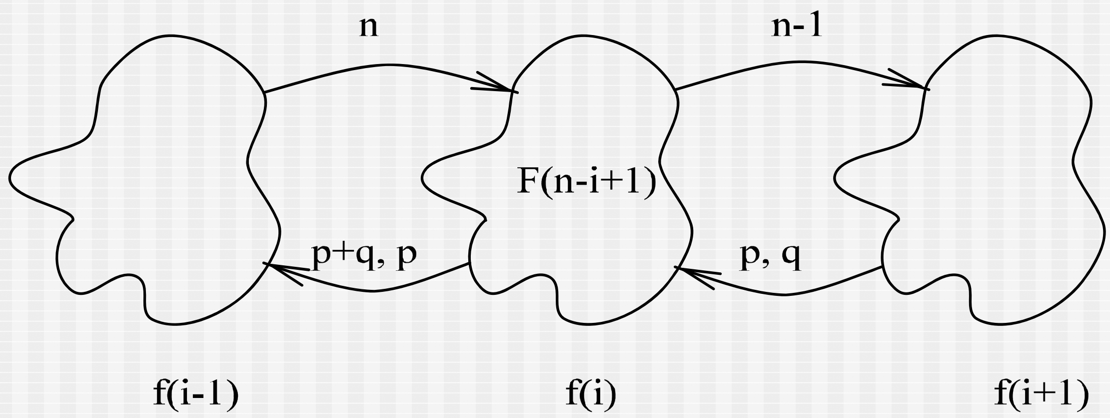
  receive p **from** f(1)

Focus 8 (Cont'd.)

- f(i) ::=

```
receive n from f(i - 1);
[ n > 1 → [ send n - 1 to f(i + 1);
              receive p from f(i + 2);
              receive q from f(i + 1);
              send p + q to f(i - 1);
              send p + q to f(i - 2) ]
 □ n = 1 → [ send 1 to f(i - 1);
              send 1 to f(i - 2) ]
 □ n = 0 → [ send 0 to f(i - 1);
              send 0 to f(i - 2) ]
]
```

Focus 8 (Cont'd.)



Another solution for F (n).

Focus 8 (Cont'd.)

- f(0)::=

```
[ n > 1 → [ send n to f(1);
            receive p from f(1);
            receive q from f(1);
            ans := p
            ]
 □ n = 1 → ans := 1
 □ n = 0 → ans := 0
]
```

Focus 8 (Cont'd.)

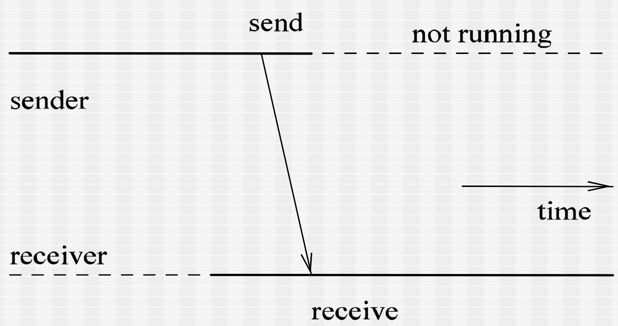
- f(i)::=

```
receive n from f(i - 1);
[ n > 1 → [ send n - 1 to f(i + 1);
            receive p from f(i + 1);
            receive q from f(i + 1);
            send p + q to f(i - 1);
            send p to f(i - 1)
            ]
  □ n = 1 → [ send 1 to f(i - 1);
              send 0 to f(i - 1)
            ]
]
```

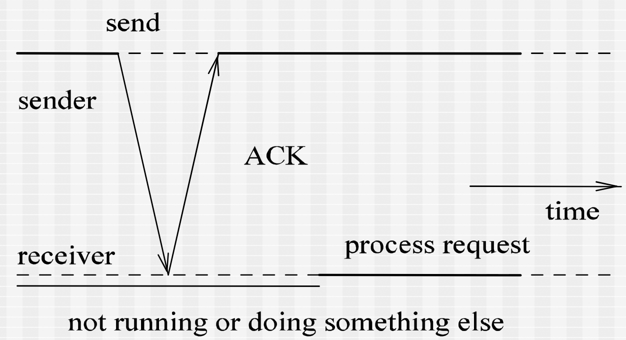
Focus 9: Message-Passing Primitives of MPI

- MPI_Isend: asynchronous communication
- MPI_send: receipt-based synchronous communication
- MPI_ssend: delivery-based synchronous communication
- MPI_sendrecv: response-based synchronous communication

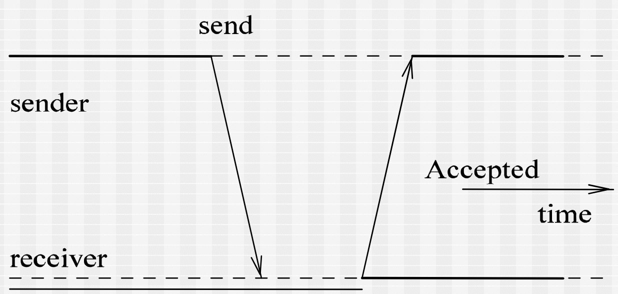
Focus 9 (Cont'd.)



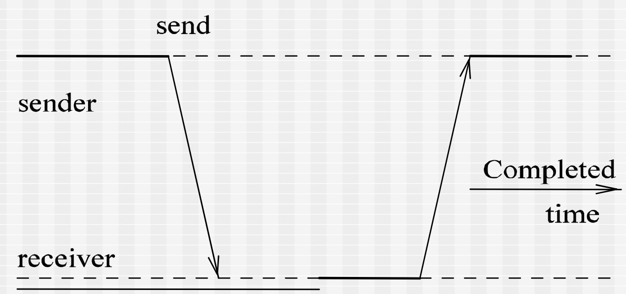
(a)



(a)



(a)



(a)

Message-passing primitives of MPI: Isend, send, ssend, sendrecv.

Focus 10: Interprocess Communication in UNIX

- Socket: int socket (int domain, int type, int protocol).
  - domain: normally internet.
  - type: datagram or stream.
  - protocol: TCP (Transport Control Protocol) or UDP (User Datagram Protocol)
- Socket address: an Internet address and a local port number.

Focus 10 (Cont'd.)

Sender

```
s= socket(AF_INET, SOCK_DGRAM, 0)
. . .
bind(s, ClientSocketAddress)
. . .
sendto(s, "message", ServerSocketAddress)
```

Receiver

```
t= socket(AF_INET, SOCK_DGRAM, 0)
. . .
bind(t, ServerSocketAddress)
. . .
amount = recvfrom(t, buffer, from)
```

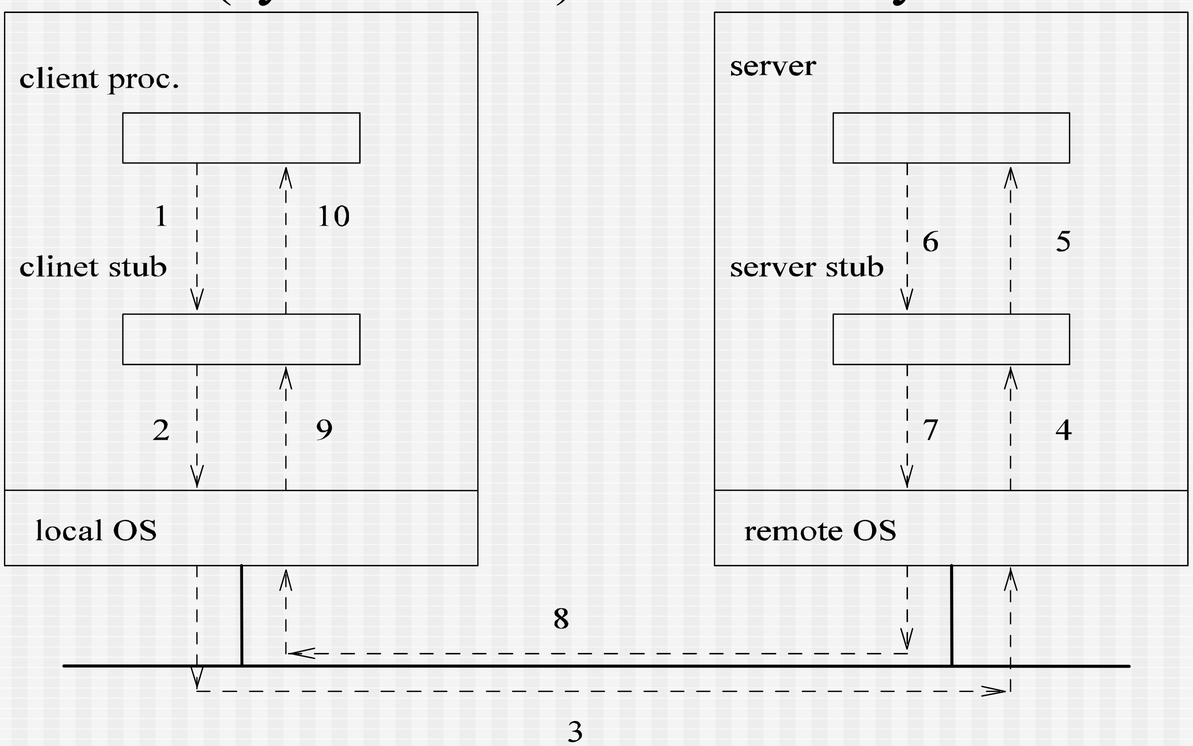
Sockets used for datagrams

High-Level (Middleware) Communication Services

- Achieve access transparency in distributed systems
  - Remote procedure call (RPC)
  - Remote method invocation (RMI)

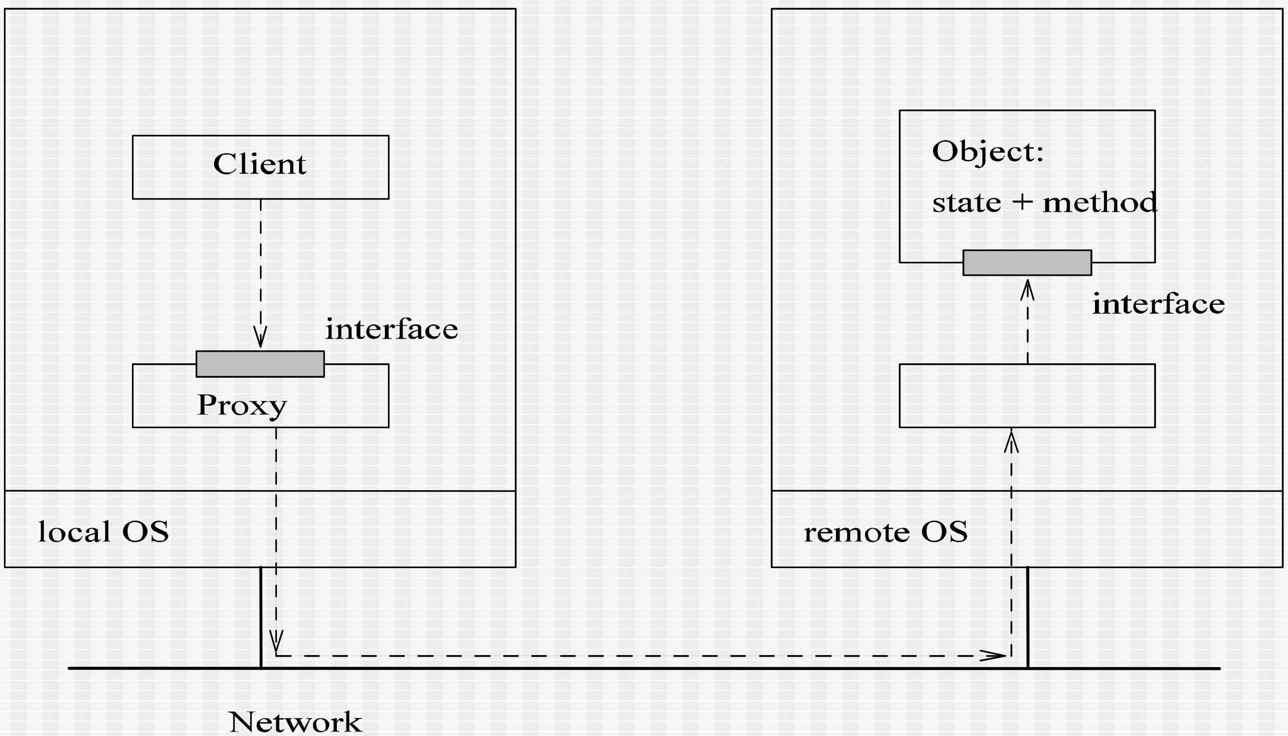
Remote Procedure Call (RPC)

- Allow programs to call procedures located on other machines.
- Traditional (synchronous) RPC and asynchronous RPC.



RPC.

Remove Method Invocation (RMI)



RMI.

Robustness

- Exception handling in high level languages (Ada and PL/1)
- Four Types of Communication Faults
  - A message transmitted from a node does not reach its intended destinations
  - Messages are not received in the same order as they were sent
  - A message gets corrupted during its transmission
  - A message gets replicated during its transmission

Failures in RPC

If a **remote procedure call** terminates abnormally (the time out expires) there are four possibilities.

- The receiver did not receive the call message.
- The reply message did not reach the sender.
- The receiver crashed during the call execution and either has remained crashed or is not resuming the execution after crash recovery.
- The receiver is still executing the call, in which case the execution could interfere with subsequent activities of the client.

Exercise 3

1. (The Welfare Crook by W. Feijen) Suppose we have three long magnetic tapes each containing a list of names in alphabetical order. The first list contains the names of people working at IBM Yorktown, the second the names of students at Columbia University and the third the names of all people on welfare in New York City. All three lists are endless so no upper bounds are given. It is known that at least one person is on all three lists. Write a program to locate the first such person (the one with the alphabetically smallest name). Your solution should use three processes, one for each tape.

Exercise 3 (Cont'd.)

2.Convert the following DCDL expression to a precedence graph.

$$[\ S_1 \parallel [\ [\ S_2 \parallel S_3\ ];\ S_4\ ]\ ]$$

Use **fork** and **join** to express this expression.

3.Convert the following program to a precedence graph:

$$S_1;[[S_2;S_3||S_4;S_5||S_6]||S_7];S_8$$

Exercise 3 (Cont'd.)

4. G is a sequence of integers defined by the recurrence $G_i = G_{i-1} + G_{i-3}$ for $i > 1$, with initial values $G_0 = 0$, $G_1 = 1$, and $G_2 = 1$. Provide a DCDL implementation of G_i and use one process for each G_i.

5. Using DCDL to write a program that replaces $a*b$ by $a \uparrow b$ and $a**b$ by $a \downarrow b$, where a and b are any characters other than *. For example, if $a_1a_2*a_3**a_4***a_5$ is the input string then $a_1a_2 \uparrow a_3 \downarrow a_4***a_5$ will be the output string.

Table of Contents

Distributed Operating Systems

- Operating Systems: provide problem-oriented abstractions of the underlying physical resources.
- Files (rather than disk blocks) and sockets (rather than raw network access).

Selected Issues

- Mutual exclusion and election
  - Non-token-based vs. token-based
  - Election and bidding
- Detection and resolution of deadlock
  - Four conditions for deadlock: mutual exclusion, hold and wait, no preemption, and circular wait.
  - Graph-theoretic model: wait-for graph
  - Two situations: AND model (process deadlock) and OR model (communication deadlock)
- Task scheduling and load balancing
  - Static scheduling vs. dynamic scheduling

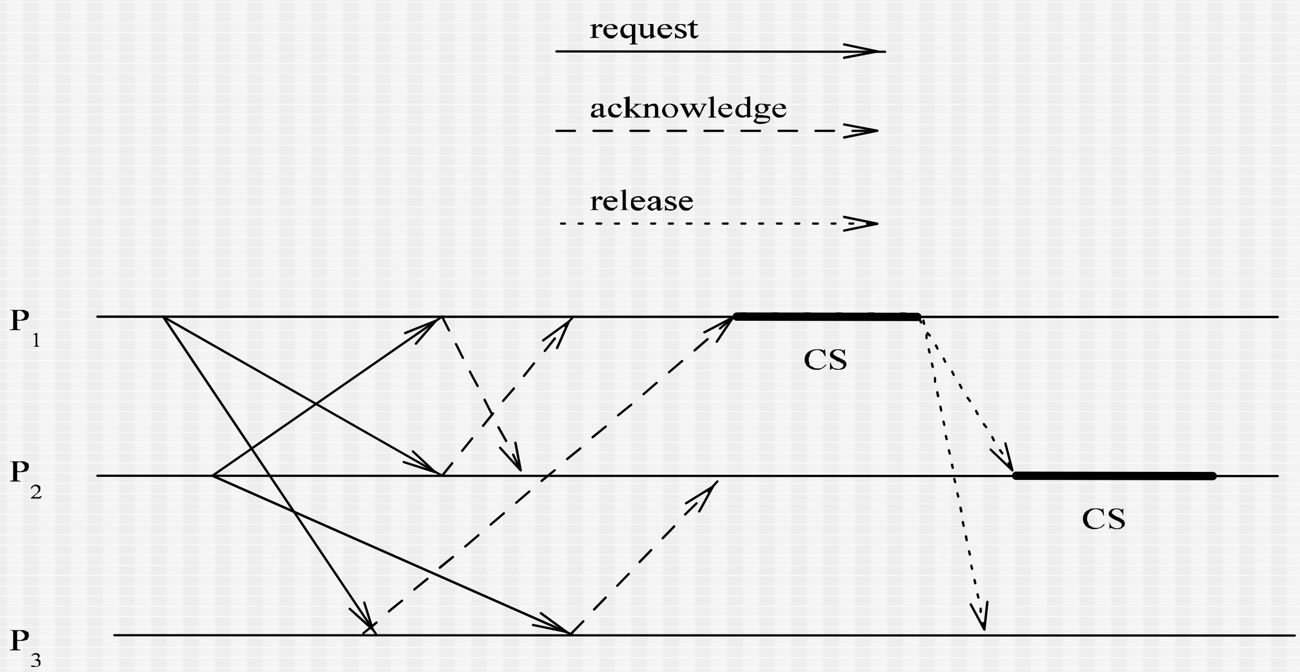
Mutual Exclusion and Election

- Requirements:
  - Freedom from deadlock.
  - Freedom from starvation.
  - Fairness.
- Measurements:
  - Number of messages per request.
  - Synchronization delay.
  - Response time.

Non-Token-Based Solutions: Lamport's Algorithm

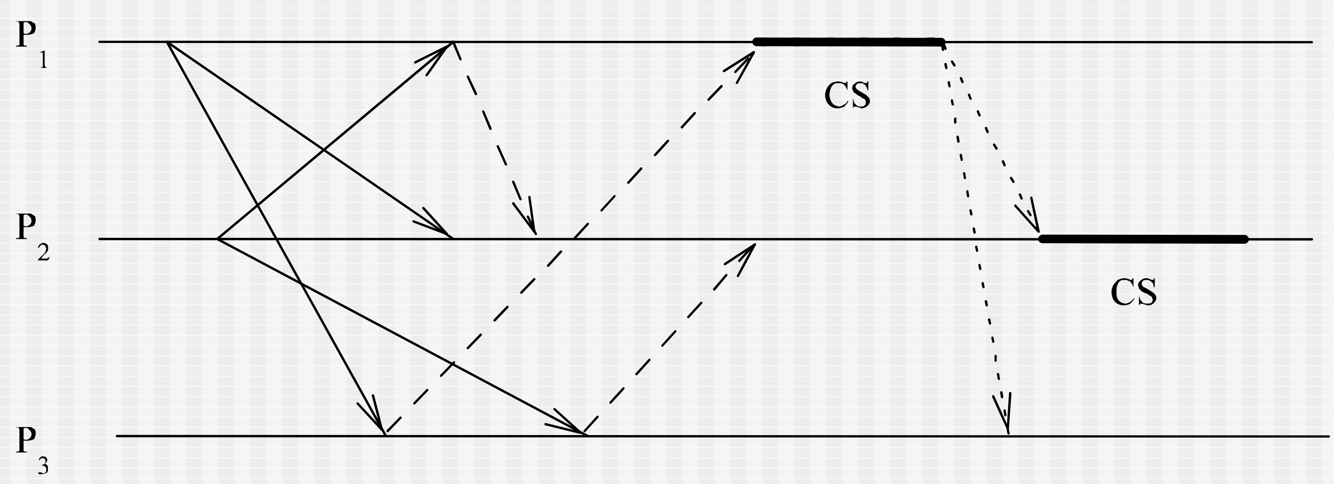
- To request the resource process P_i sends its timestamped message to all the processes (including itself).
- When a process receives the request resource message, it places it on its local request queue and sends back a timestamped acknowledgment.
- To release the resource, P_i sends a timestamped release resource message to all the processes (including itself).
- When a process receives a release resource message from P_i, it removes any requests from P_i from its local request queue. A process P_j is granted the resource when
  - Its request r is at the top of its request queue, and,
  - It has received messages with timestamps larger than the timestamp of r from all the other processes.

Example for Lamport's Algorithm



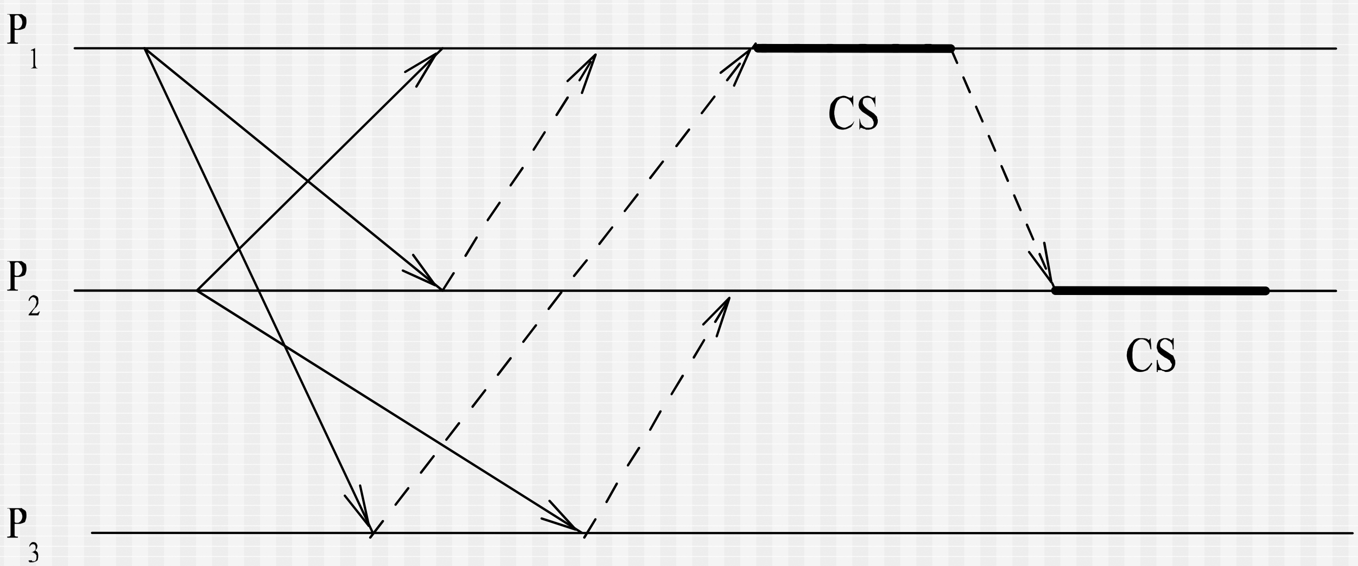
Extension

- There is no need to send an acknowledgement when process P_j receives a request from process P_i after it has sent its own request with a timestamp larger than the one of P_i's request.
- An example for Extended Lamport's Algorithm



Ricart and Agrawala's Algorithm

It merges acknowledge and release messages into one message *reply*.

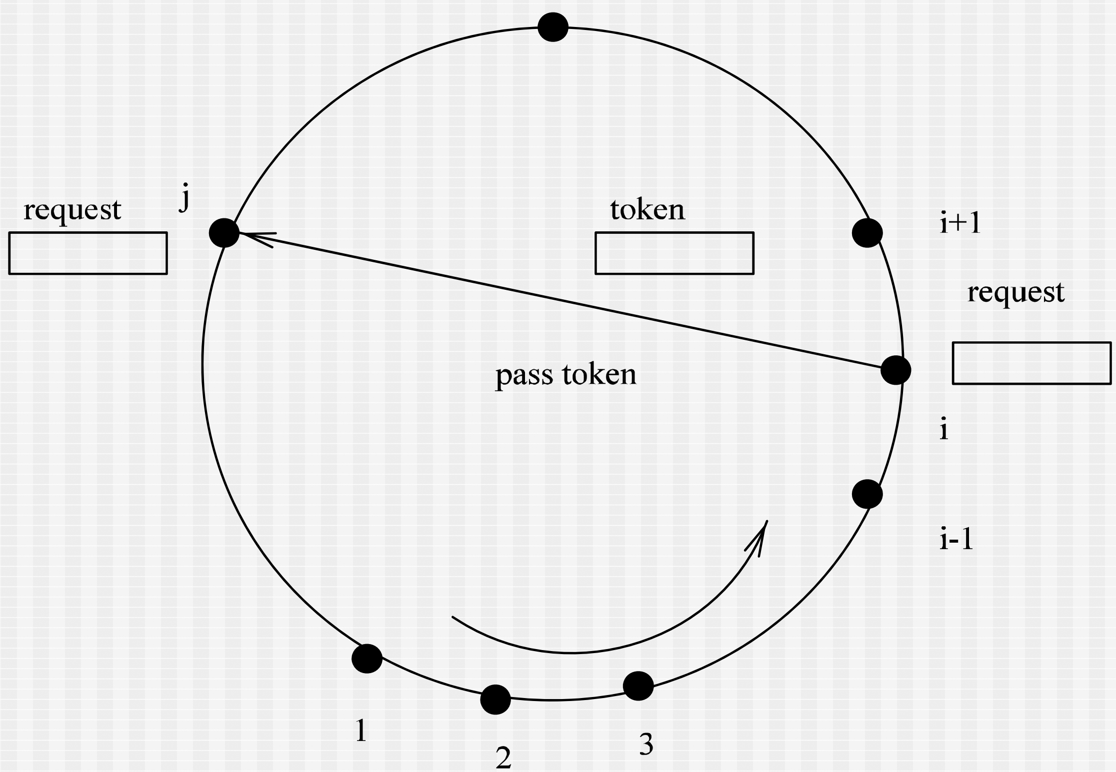


An example using Ricart and Agrawala's algorithm.

Token-Based Solutions: Ricart and Agrawala's Second Algorithm

- When token holder P_i exits CS, it searches other processes in the order $i + 1, i + 2, \ldots, n, 1, 2, \ldots, i - 1$ for the first j such that the timestamp of P_j 's last request for the token is larger than the value recorded in the token for the timestamp of P_j 's last holding of the token.

Token-based Solutions (Cont'd)



Ricart and Agrawala's second algorithm.

Pseudo Code

$P(i)$::=*[request-resource

□ consume

□ release-resource

□ treat-request-message

□ others

]

distributed-mutual-exclusion ::= $\|P(i{:}1..n)$

clock: 0,1,…, (initialized to 0)

token-present: **Boolean** (*F* for all except one process)

token-held: **Boolean** (*F*)

token: **array** (1..*n*) of *clock* (initialized 0)

request: **array** (1..*n*) **of** *clock* (initialized 0)

Pseudo Code (Cont'd)

- others::= all the other actions that do not request to enter the critical section.
- consume::= consumes the resource after entering the critical section
- request-resource::=

  [*token present* = F

  → [**send** (*request-signal*, *clock*, *i*) **to all**;

  receive (*access-signal*, *token*);

  token-present:= T;

  token-held:= T

  ]

  ]

Pseudo Code (Cont'd)

```
release-resource::=
    [      token (i):=clock;
           token-held:= F;
           min j in the order [i + 1,… n,1,2,…,i – 2, i – 1]
                    ∧ (request(j) > token(j))
                    →  [ token-present:= F;
                         send (access-signal, token) to P_j
                       ]
    ]
```

Pseudo Code (Cont’d)

treat-request-message::=

[**receive** (*request-signal*, *clock*; *j*)

$\rightarrow$[*request*(*j*):=max(*request*(*j*),*clock*);

token-present $\wedge \neg$ *token-held* $\rightarrow$ release-resource

]

]

Ring-Based Algorithm

P(*i*:0..*n*-1)::=

[**receive** *token* **from** *P*((*i*-1) mod *n*);

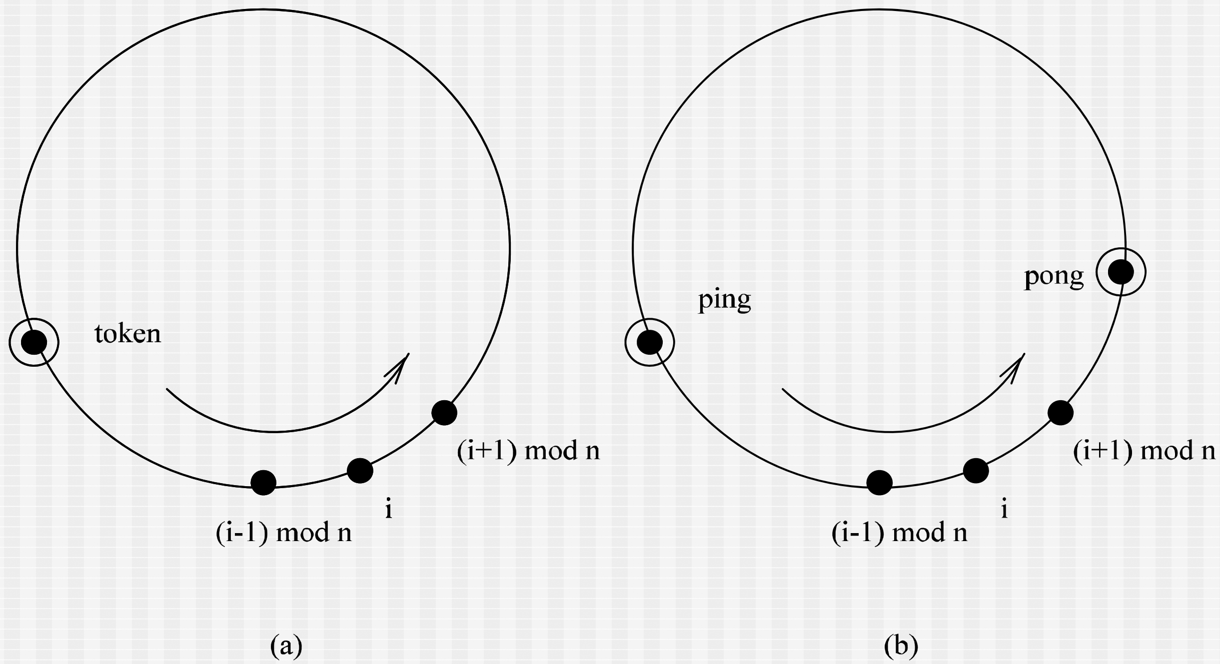
consume the resource if needed;

send token **to** P ((i + 1) mod n)

]

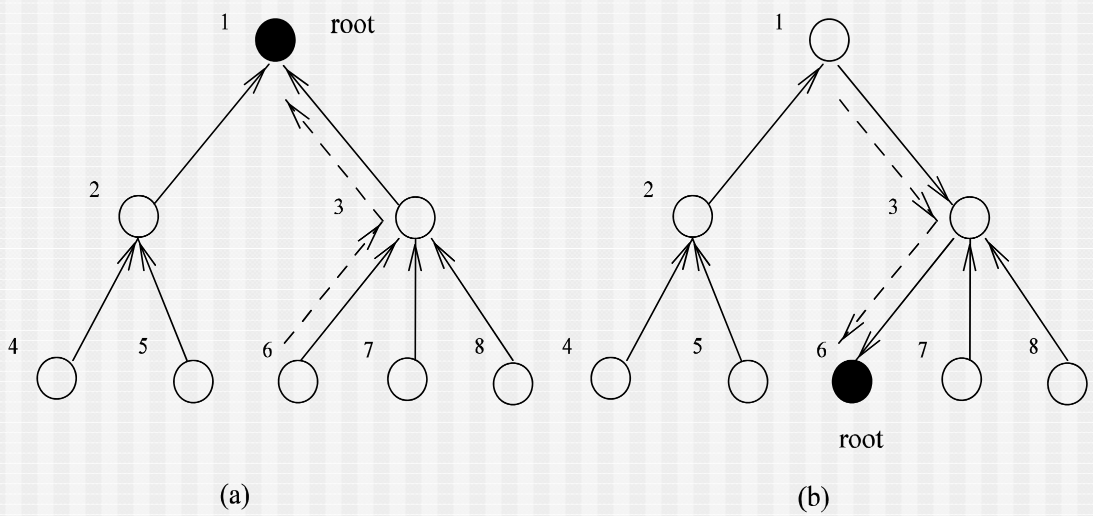
distributed-mutual-exclusion::= ||*P*(i:0..*n*-1)

Ring-Based Algorithm (Cont'd)



The simple token-ring-based algorithm (a) and the fault-tolerant token-ring-based algorithm (b).

Tree-Based Algorithm



A tree-based mutual exclusion algorithm.

Maekawa's Algorithm

- Permission from every other process but only from a subset of processes.
- If R_i and R_j are the request sets for processes P_i and P_j , then $R_i \cap R_j \neq \phi$.

Example 11

$$R_1 : \{P_1; P_3; P_4\}$$
$$R_2 : \{P_2; P_4; P_5\}$$
$$R_3 : \{P_3; P_5; P_6\}$$
$$R_4 : \{P_4; P_6; P_7\}$$
$$R_5 : \{P_5; P_7; P_1\}$$
$$R_6 : \{P_6; P_1; P_2\}$$
$$R_7 : \{P_7; P_2; P_3\}$$

Related Issues

- **Election**: After a failure occurs in a distributed system, it is often necessary to reorganize the active nodes so that they can continue to perform a useful task.
- **Bidding**: Each competitor selects a bid value out of a given set and sends its bid to every other competitor in the system. Every competitor recognizes the same winner.
- **Self-stabilization**: A system is self-stabilizing if, regardless of its initial state, it is guaranteed to arrive at a legitimate state in a finite number of steps.

Focus 11: Chang and Robert's algorithm

Election on a ring

- Election and elected signals
- Smallest ID is the winner
- Two rounds of circulation
- O(n log n) messages

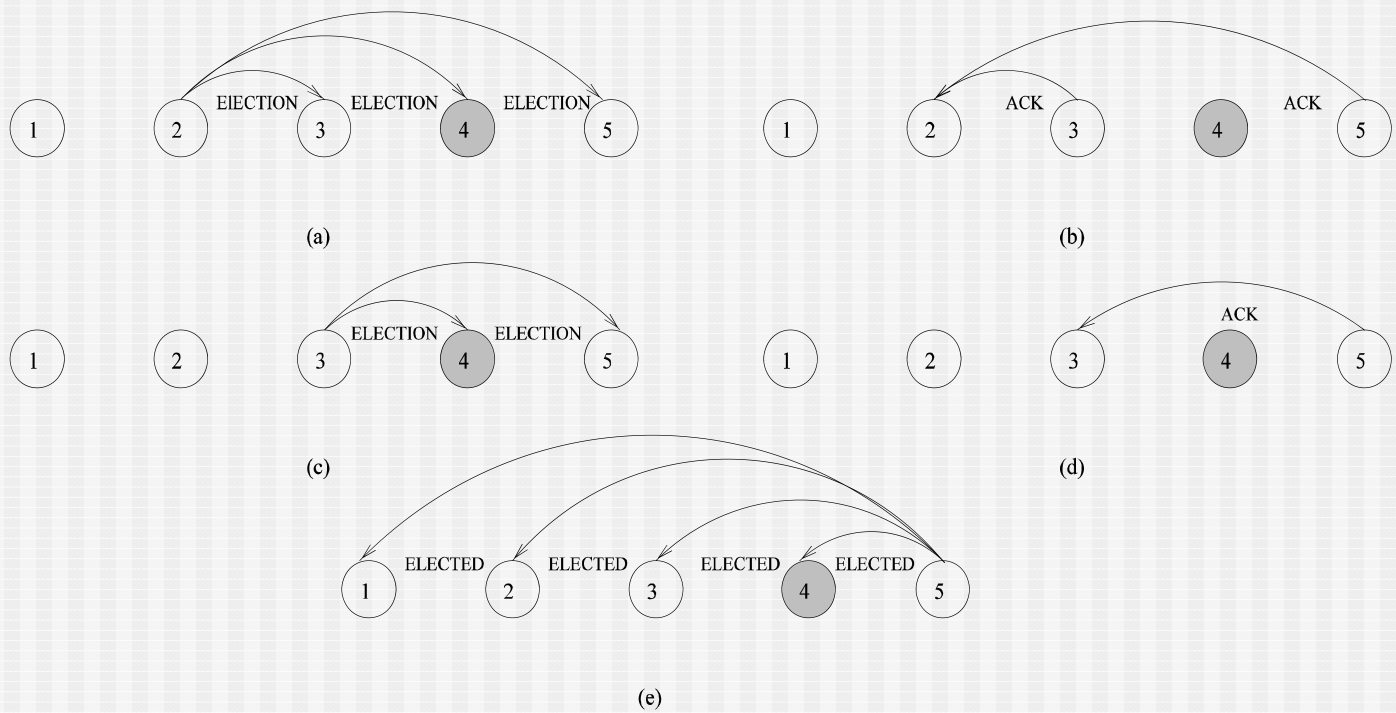
```
P(i : 0..n − 1) ::=
    * [ initiate election →
            [ participant:= T;
              send (election, i, id(i)) to P((i + 1) mod n)
            ]
      □ receive (election, j, id(j)) →
            [ id(j) < id(i) →
                        [ send (election, j, id(j)) to P((j + 1) mod n)
                        || participant := T
                        ]
              □ id(j) > id(i) ∧ participant → φ
              □ id(j) > id(i) ∧ ¬ participant →
                        [ send (election, i, id(i)) to P((i + 1) mod n)
                        || participant := T
                        ]
              □ id(j) = id(i) →
                        send (elected, i) to P((i + 1) mod n)
            ]
      □ receive (elected, j) →
            [ coordinate := j
            || participant := F
            || j ≠ i → send (elected, j) to P((j + 1) mod n)
            ]
    ]

election-algorithm ::= || P(i : 0..n − 1)
```

Garcia-Molina's Bully Algorithm for Election

- When *P* detects the failure of the coordinator or receives an ELECTION packet, it sends an ELECTION packet to all processes with higher priorities.
- If no one responds (with packet ACK), *P* wins the election and broadcast the ELECTED packet to all.
- If one of the higher processes responds, it takes over. *P*'s job is done.

Focus 11 (Cont'd)



Bully algorithm.

Lynch's Non-Comparison-Based Election Algorithms

- Process id is tied to time in terms of rounds.
- *Time-slice algorithm*: (n, the total number of processes, is known)
  - Process Pi (with its id(i)) sends its id in round id(i)2n, i.e., at most one process sends its id in every 2n consecutive rounds.
  - Once an id returns to its original sender, that sender is elected. It sends a signal around the ring to inform other processes of its winning status.
  - message complexity: O(n)
  - time complexity: min{id(i)} n

Lynch's Algorithms (Cont'd)

- *Variable-speed algorithm*: (n is unknown)
  - When a process Pi sends its id (id(i)), this id travels at the rate of one transmission for every 2id(i) rounds.
  - If an id returns to its original sender, that sender is elected.
- message complexity: $n + n/2 + n/2^2 + \ldots + n/2^{(n-1)} < 2n = O(n)$
- time complexity: $2^{\min\{id(i)\}} n$

Dijkstra's Self-Stabilization

- *Legitimate state P* : A system is in a legitimate state P if and only if one process has a privilege.
- *Convergence*: Starting from an arbitrary global state, S is guaranteed to reach a global state satisfying P within a finite number of state transitions.

Example 12

- A ring of finite-state machines with three states. A privileged process is the one that can perform state transition.
- For P_i, $0 < i \leq n - 1$,
  - $P_i \neq P_{i-1} \rightarrow P_i := P_{i-1}$,
  - $P_0 = P_{n-1} \rightarrow P_0 := (P_0 + 1) \bmod k$

Theorem: If k > n, then Dijkstra's token ring for mutual exclusion always eventually reaches a correct configuration.

For n > 2, theorem also hold if k = n-1.

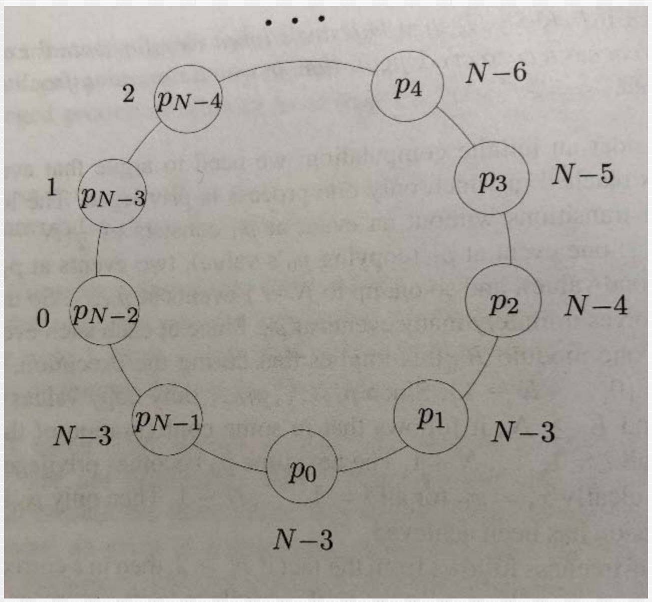
P0	P1	P2	Privileged processes	Process to make move
2	1	2	P0,P1,P2	P0
3	1	2	P1,P2	P1
3	3	2	P2	P2
3	3	3	P0	P0
0	3	3	P1	P1
0	0	3	P2	P2
0	0	0	P0	P0
1	0	0	P1	P1
1	1	0	P2	P2
1	1	1	P0	P0
2	1	1	P1	P1
2	2	1	P2	P2
2	2	2	P0	P0
3	2	2	P1	P1
3	3	2	P2	P2
3	3	3	P0	P0

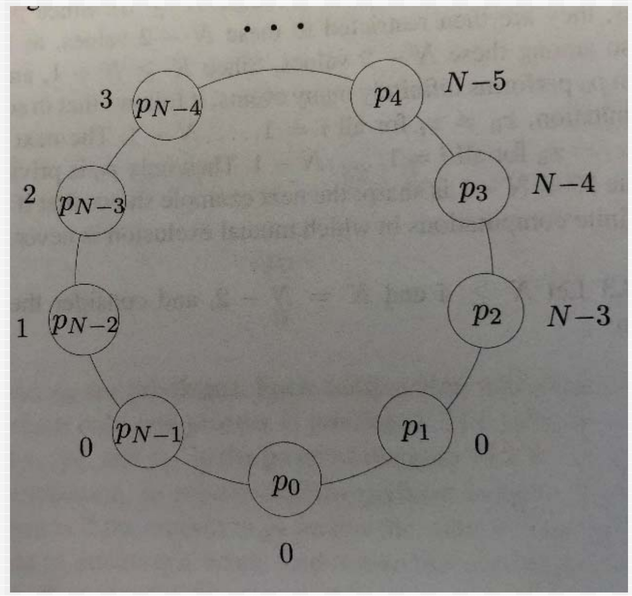
Table 1: Dijkstra’s self-stabilization algorithm (n =3 and k =4).

Non-Convergence Example

When n > 3, k = n-2.

Infinite computation exists in which always n-1 processes are privileged





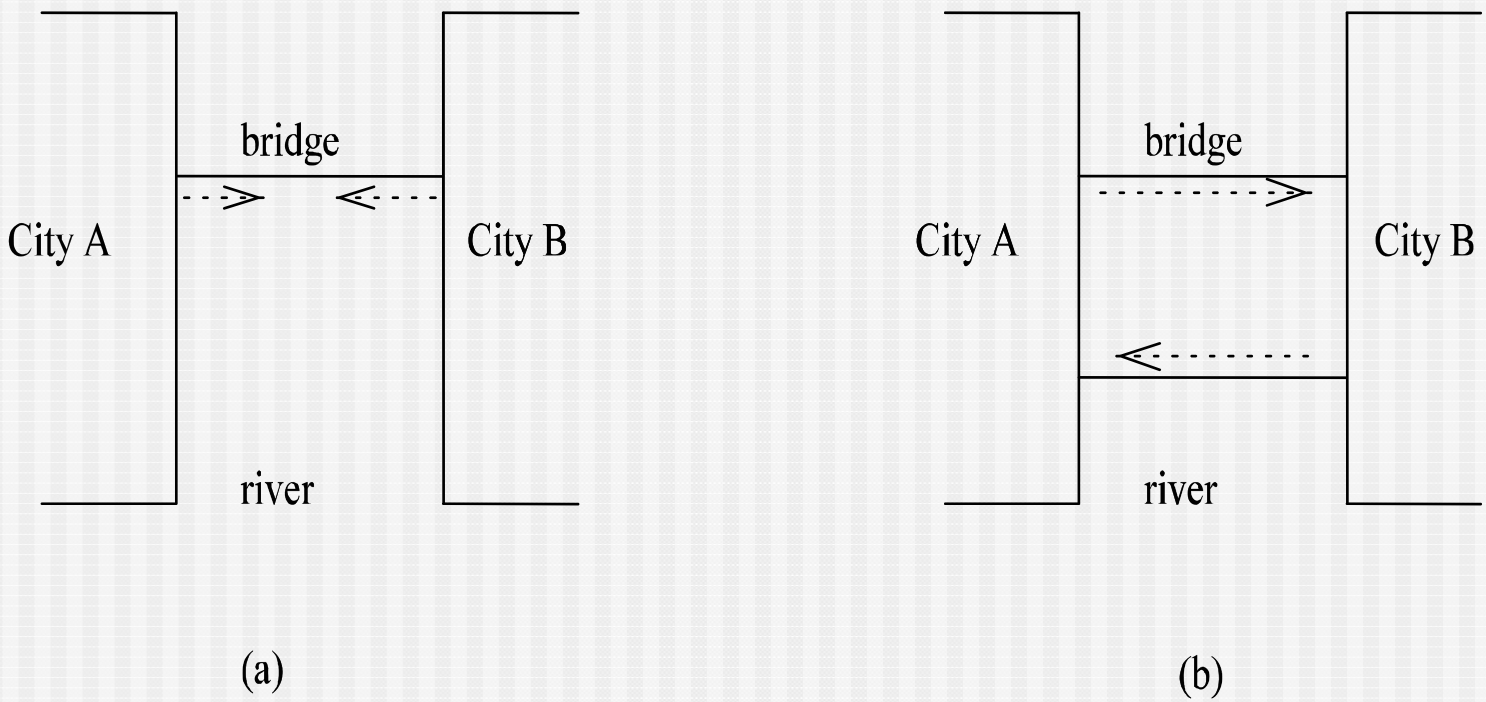
Extensions

- The role of demon (that selects one privileged process)
- The role of asymmetry.
- The role of topology.
- The role of the number of states

Detection and Resolution of Deadlock

- **Mutual exclusion**. No resource can be shared by more than one process at a time.
- **Hold and wait**. There must exist a process that is holding at least one resource and is waiting to acquire additional resources that are currently being held by other processes.
- **No preemption**. A resource cannot be preempted.
- **Circular wait**. There is a cycle in the wait-for graph.

Detection and Resolution of Deadlock (Cont'd)



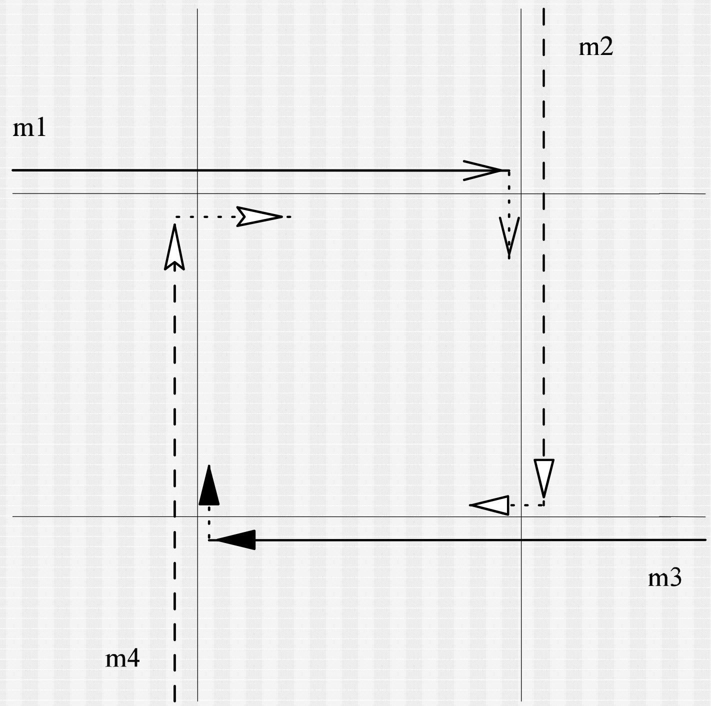
Two cities connected by (a) one bridge and by (b) two bridges.

Strategies for Handling Deadlocks

- Deadlock prevention
- Deadlock avoidance (based on "safe state")
- Deadlock detection and recovery
- Different Models
  - AND condition
  - OR condition

Types of Deadlock

- Resource deadlock
- Communication deadlock



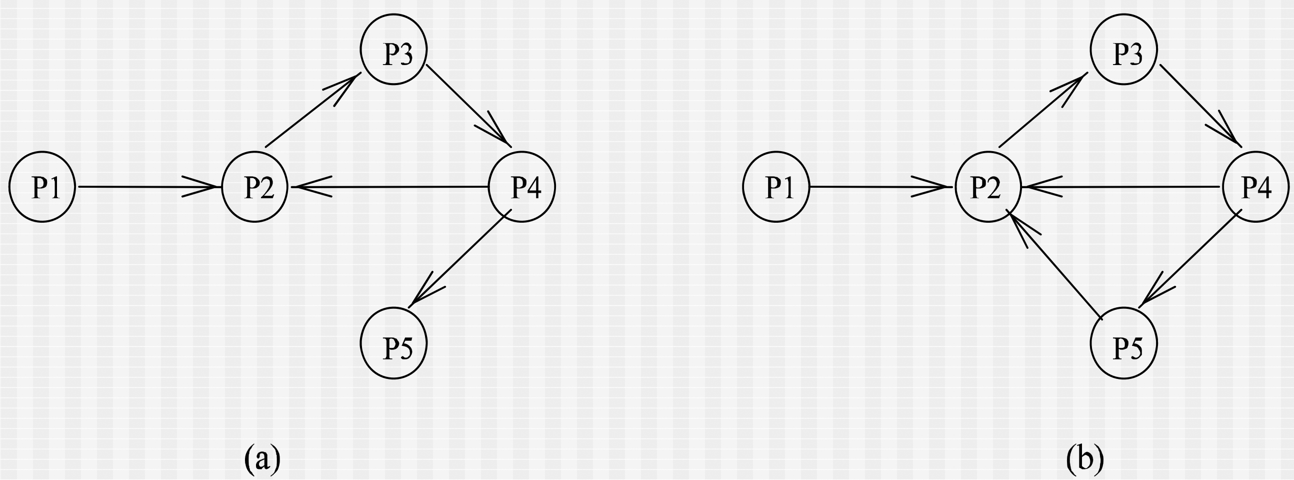
An example of communication deadlock

Conditions for Deadlock

- AND model: a **cycle** in the wait-for graph.
- OR model: a **knot** in the wait-for graph.

Conditions for Deadlock (Cont'd)

A knot (K) consists of a set of nodes such that for every node a in K , all nodes in K and only the nodes in K are reachable from node a.



Two systems under the OR condition with
(a) no deadlock and without (b) deadlock.

Focus 12: Rosenkrantz' Dynamic Priority Scheme (using timestamps)

T1:

    lock A;
    lock B;
    transaction starts;
    unlock A;
    unlock B;

wait-die (non-preemptive method)

[$LC_i < LC_j \rightarrow$ **halt** P_i (wait)

□ $LC_i \geq LC_j \rightarrow$ **kill** P_i (die)

]

wound-wait (preemptive method)

[$LC_i < LC_j \rightarrow$ **kill** P_j (wound)

□ $LCi \geq LCj \rightarrow$ **halt** P_i (wait)

]

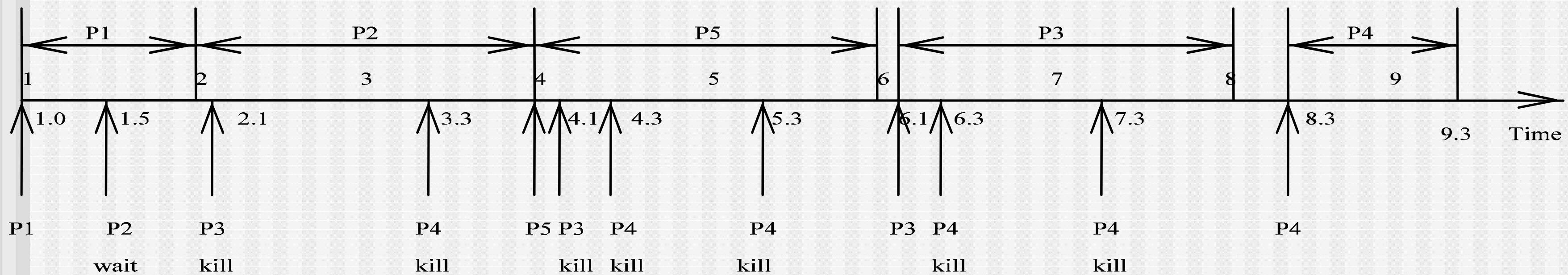
Example 13

Process id	Priority	1^{st} request time	Length	Retry interval
P1	2	1	1	1
P2	1	1.5	2	1
P3	4	2.1	2	2
P4	5	3.3	1	1
P5	3	4.0	2	3

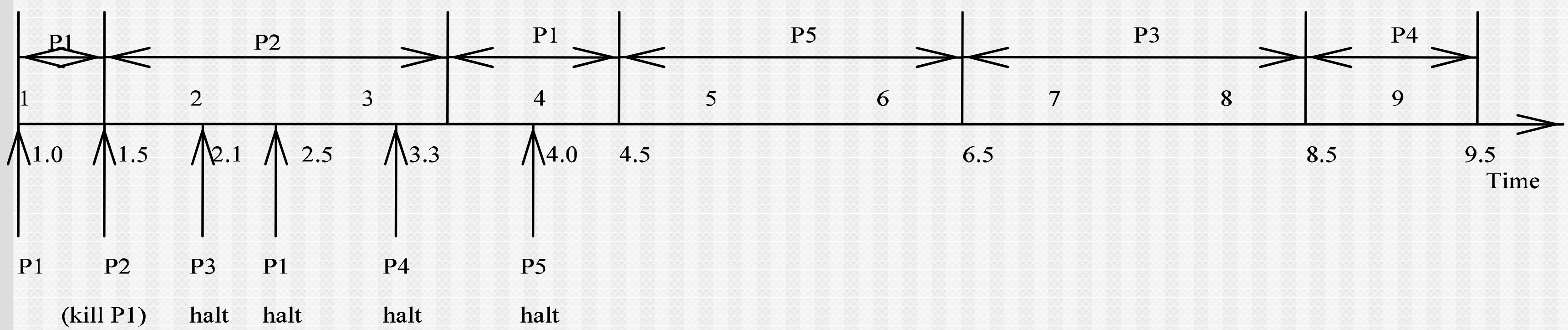
A system consisting of five processes.

Example 13 (Cont'd)

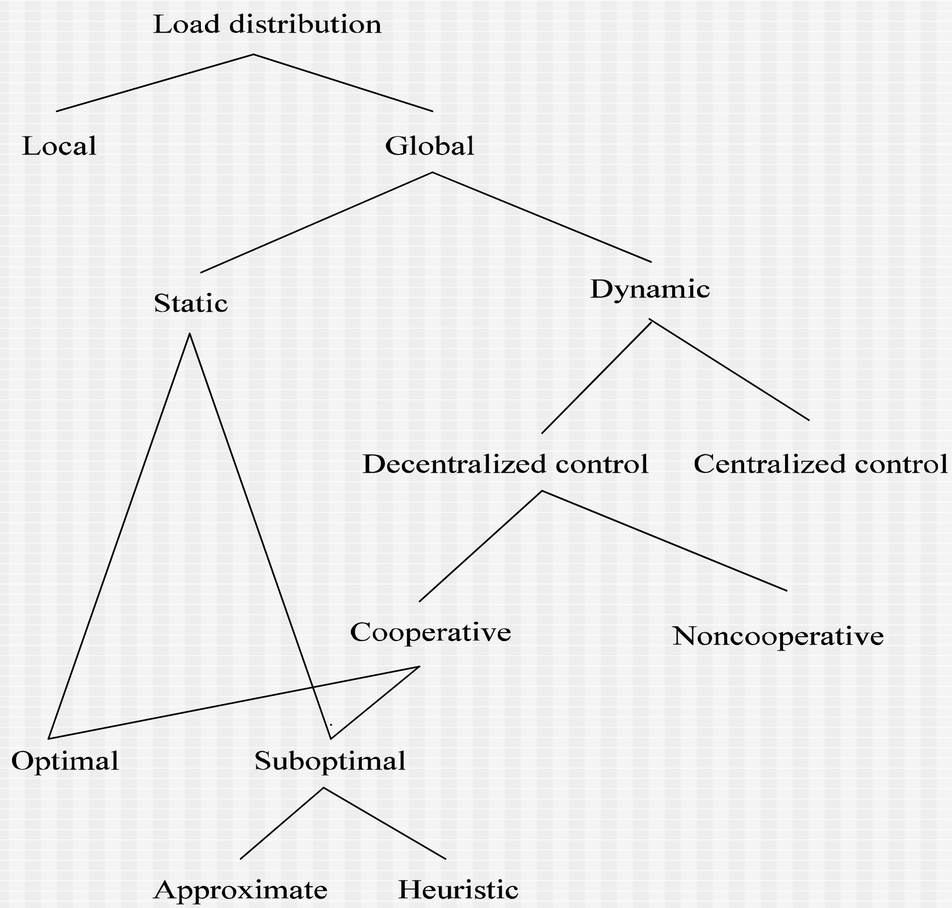
wait-die：



wound-wait:



Load Distribution



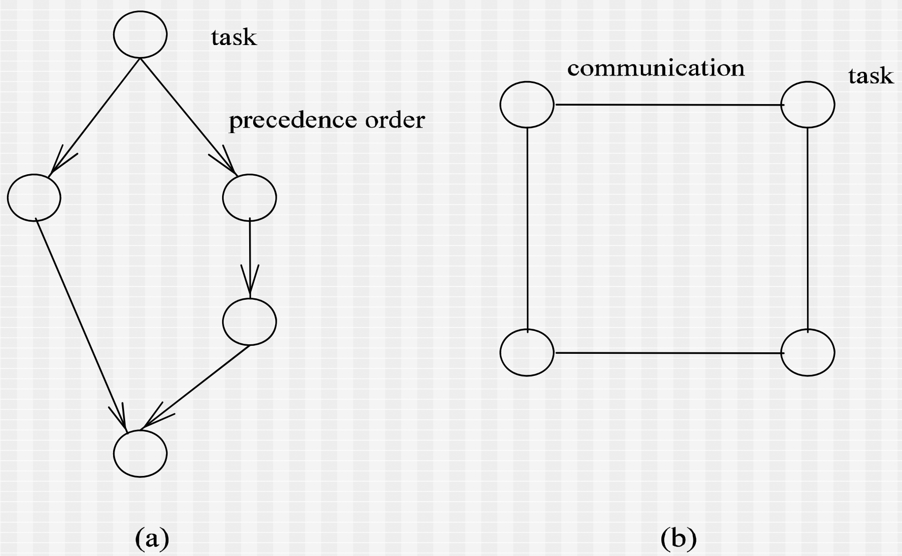
A taxonomy of load distribution algorithms.

Static Load Distribution (task scheduling)

- Processor interconnections
- Task partition
  - Horizontal or vertical partitioning.
  - Communication delay minimization partition.
  - Task duplication.
- Task allocation

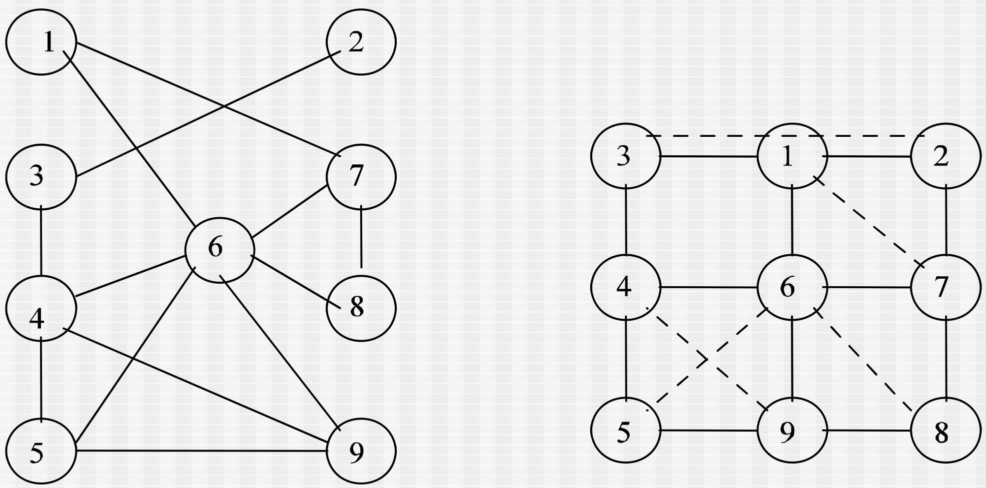
Models

- **Task precedence graph**: each link defines the precedence order among tasks.
- **Task interaction graph**: each link defines task interactions between two tasks.



(a) Task precedence graph and (b) task interaction graph.

Example 14



(a) (b)

Mapping a task interaction graph (a) to a processor graph (b).

Example 14 (Cont'd)

- The *dilation* of an edge of G_t is defined as the length of the path in G_p onto which an edge of G_t is mapped. The dilation of the embedding is the maximum edge dilation of G_t.
- The *expansion* of the embedding is the ratio of the number of nodes in G_t to the number of nodes in G_p.
- The *congestion* of the embedding is the maximum number of paths containing an edge in G_p where every path represents an edge in G_t.
- The *load* of an embedding is the maximum number of processes of G_t assigned to any processor of G_t.

Periodic Tasks With Real-time Constraints

- Task T_i has request period t_i and run time c_i.
- Each task has to be completed before its next request.
- All tasks are independent without communication.

Liu and Layland's Solutions (priority-driven and preemptive)

- *Rate monotonic scheduling* (fixed priority assignment). Tasks with higher request rates will have higher priorities.
- *Deadline driven scheduling* (dynamic priority assignment). A task will be assigned the highest priority if the deadline of its current request is the nearest.

Schedulability

- Deadline driven schedule: iff

$$\sum_{i=0}^{n} c_i/t_i \le 1$$

- Rate monotonic schedule: if

$$\sum_{i=0}^{n} c_i/t_i \le n(2^{1/n} - 1);$$

may or may be not when

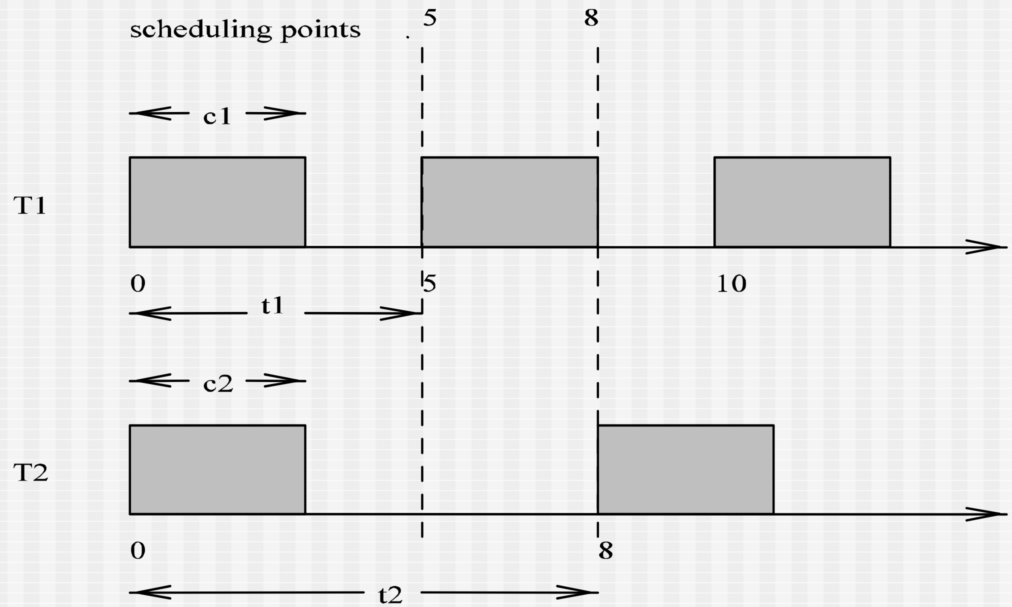
$$n(2^{1/n} - 1) < \sum_{i=0}^{n} c_i/t_i \le 1$$

Example 15 (schedulable)

- T_1: $c_1 = 3$, $t_1 = 5$ and T_2: $c_2 = 2$, $t_2 = 7$ (with the same initial request time).
- The overall utilization is 0:887 > 0:828 (bound for n = 2).

Example 16 (un-schedulable under rate monotonic scheduling)

- T_1: $c_1 = 3$, $t_1 = 5$ and T_2: $c_2 = 3$, $t_2 = 8$ (with the same initial request time).
- The overall utilization is 0:975 > 0:828



An example of periodic tasks that is not schedulable.

Example 16 (Cont'd)

- If each task meets its first deadline when all tasks are started at the same time then the deadlines for all tasks will always be met for any combination of starting times.
- *scheduling points* for task T : T's first deadline and the ends of periods of higher priority tasks prior to T's first deadline.
- If the task set is schedulable for one of scheduling points of the lowest priority task, the task set is schedulable; otherwise, the task set is not schedulable.

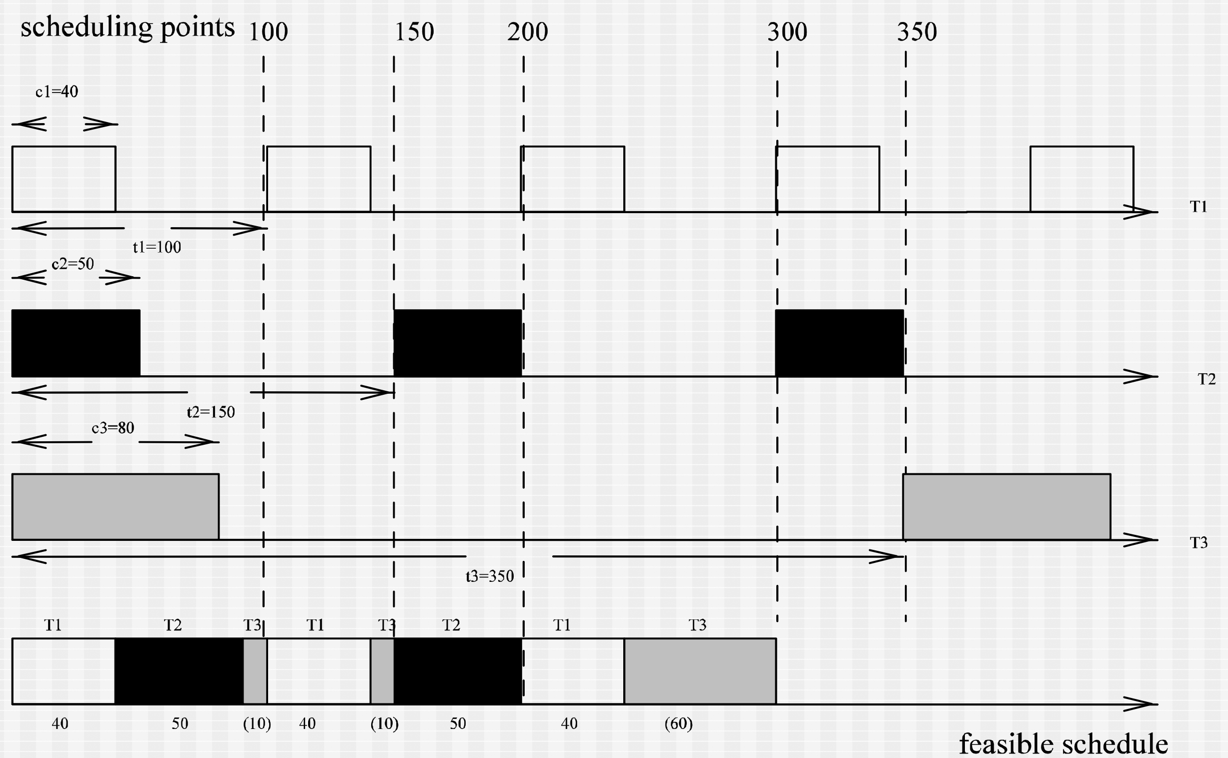
Example 17 (schedulable under rate monotonic schedule)

- $c_1 = 40$, $t_1 = 100$, $c_2 = 50$, $t_2 = 150$, and $c_3 = 80$, $t_3 = 350$.
- The overall utilization is $0{:}2 + 0{:}333 + 0{:}229 = 0{:}762 < 0{:}779$ (the bound for $n > 3$).
- c_1 is doubled to 40. The overall utilization is $0{:}4+0{:}333+0{:}229 = 0{:}962 > 0{:}779$.
- The scheduling points for T_3: 350 (for T_3), 300 (for T_1 and T_2), 200 (for T_1), 150 (for T_2), 100 (for T_1).

Example 17 (Cont'd)

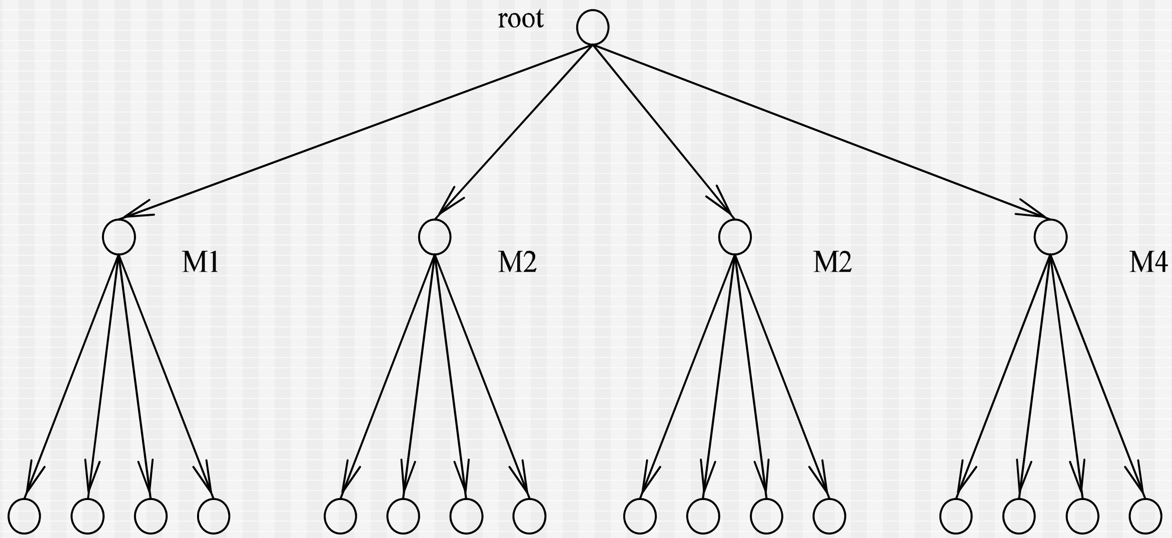
$c_1 + c_2 + c_3 \leq t_1$,
$40 + 50 + 80 > 100$;
$2c_1 + c_2 + c_3 \leq t_2$,
$80 + 50 + 80 > 150$;
$2c_1 + 2c_2 + c_3 \leq 2t_1$,
$80 + 100 + 80 > 200$;
$3c_1 + 2c_2 + c_3 \leq 2t_2$,
$120 + 100 + 80 = 300$;
$4c_1 + 3c_2 + c_3 \leq t_3$,
$160 + 150 + 80 > 350$.

Example 17 (Cont'd)



A schedulable periodic task.

Dynamic Load Distribution (load balancing)



A state-space traversal example.

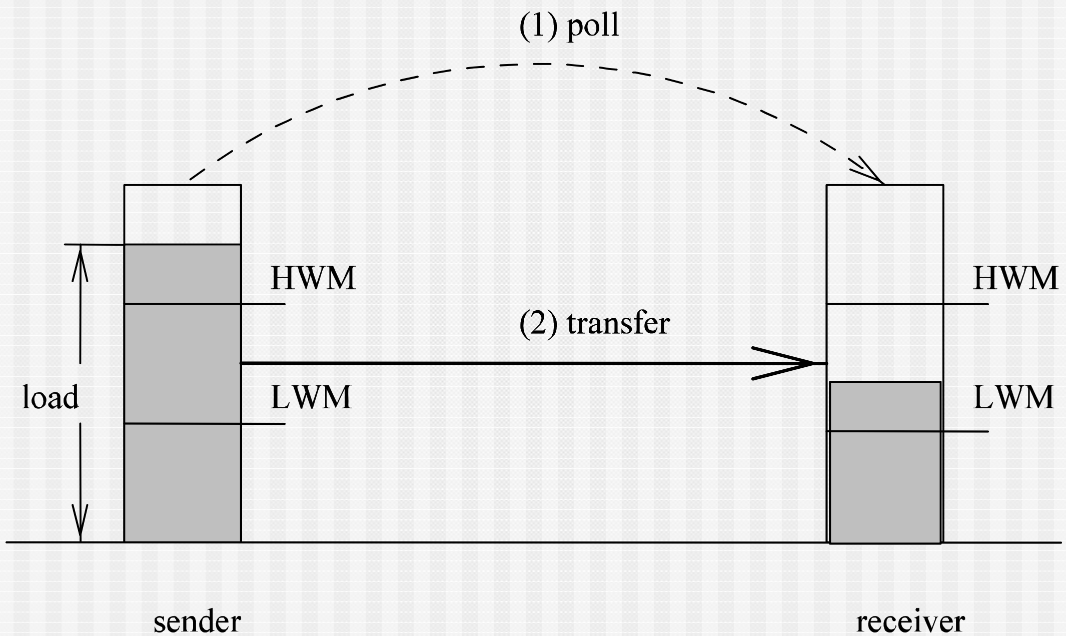
Dynamic Load Distribution (Cont'd)

A dynamic load distribution algorithm has six policies:

- Initiation
- Transfer
- Selection
- Profitability
- Location
- Information

Focus 13: Initiation

Sender-initiated approach:



Sender-initiated load balancing.

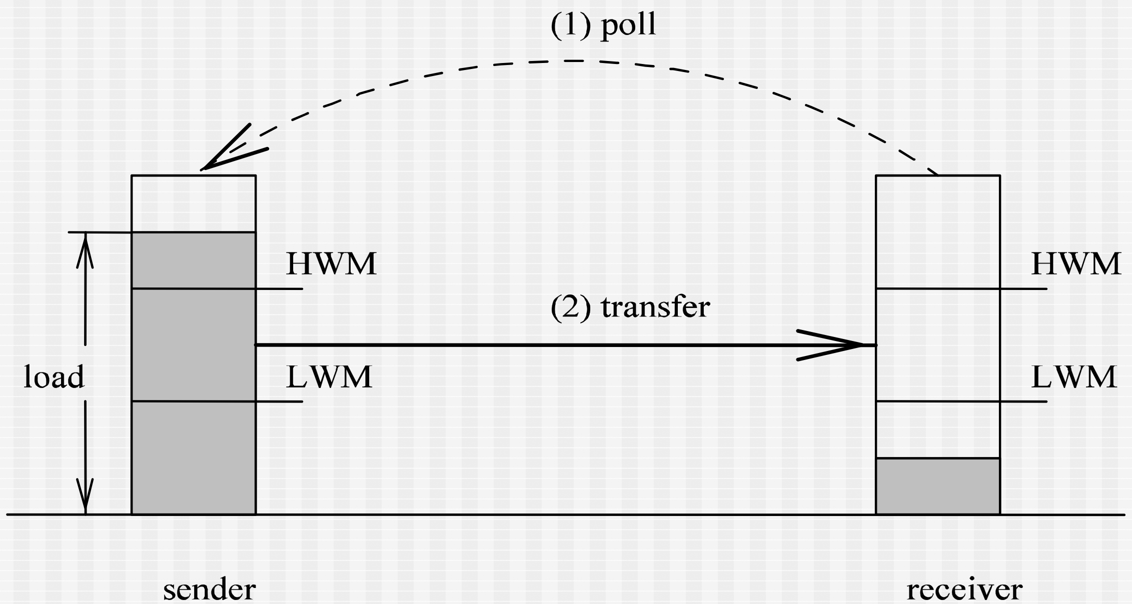
Focus 13 (Cont'd)

```
/* a new task arrives */
 queue length ≥  HWM →

* [ poll_set := φ ;

     [| poll_set | < poll_limit →
            [ select a new node u randomly;
              poll_set := poll_set ∪ node u;
              queue_length at u < HWM →
                        transfer a task to node u and stop
            ]
     ]
  ]
```

Receiver-Initiated Approach

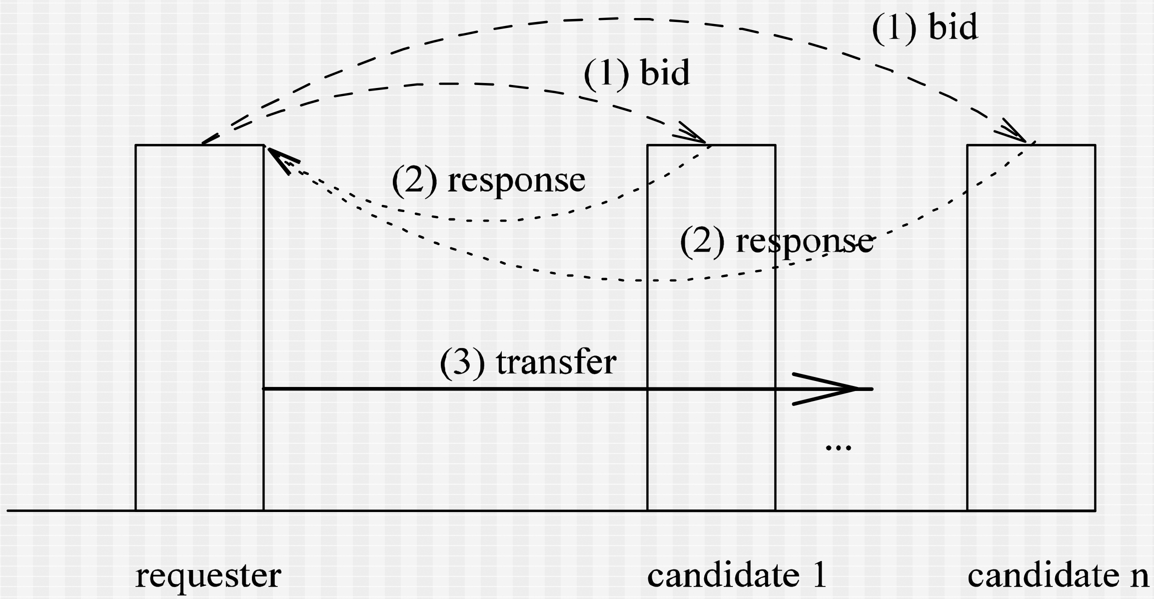


Receiver-initiated load balancing.

Receiver-Initiated Approach (Cont'd)

```
/* a task departs */
queue length < LWM →
[ poll limit:=ϕ;
    *  [ | poll_set | < poll limit →
            [ select a new node u randomly;
              poll_set := poll set ∪ node u;
              queue_length at u > HWM →
                              transfer a task from node u and stop
            ]
       ]
]
```

Bidding Approach



Bidding algorithm.

Focus 14: Sample Nearest Neighbor Algorithms

Diffusion

- At round t + 1 each node u exchanges its load $L_u(t)$ with its neighbors' $L_v(t)$.
- $L_u(t + 1)$ should also include new incoming load $\phi_u(t)$ between rounds t and t + 1.
- Load at time t + 1:

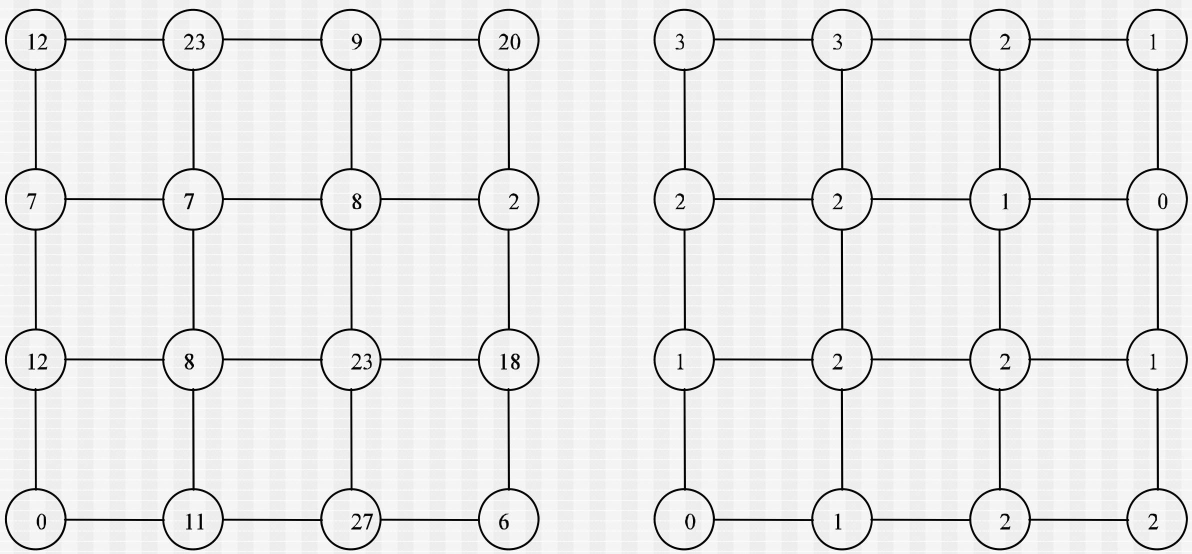
$$L_u(t+1) = L_u(t) + \sum_{v \in A(u)} \alpha_{u,v}(L_v(t) - L_u(t)) + \phi_u(t)$$

where $0 \leq \alpha_{u,v} \leq 1$ is called the diffusion parameter of nodes u and v.

Gradient

- Maintain a contour of the gradients formed by the differences in load in the system.
- Load in high points (overloaded nodes) of the contour will flow to the lower regions (underloaded nodes) following the gradients.
- The *propagated pressure* of a processor *u*, *p*(*u*), is defined as p(u) =
  - 0 (if u is lightly loaded)
  - $1 + \min\{p(v) | v \in A(u)\}$ (otherwise)

Gradient (Cont'd)



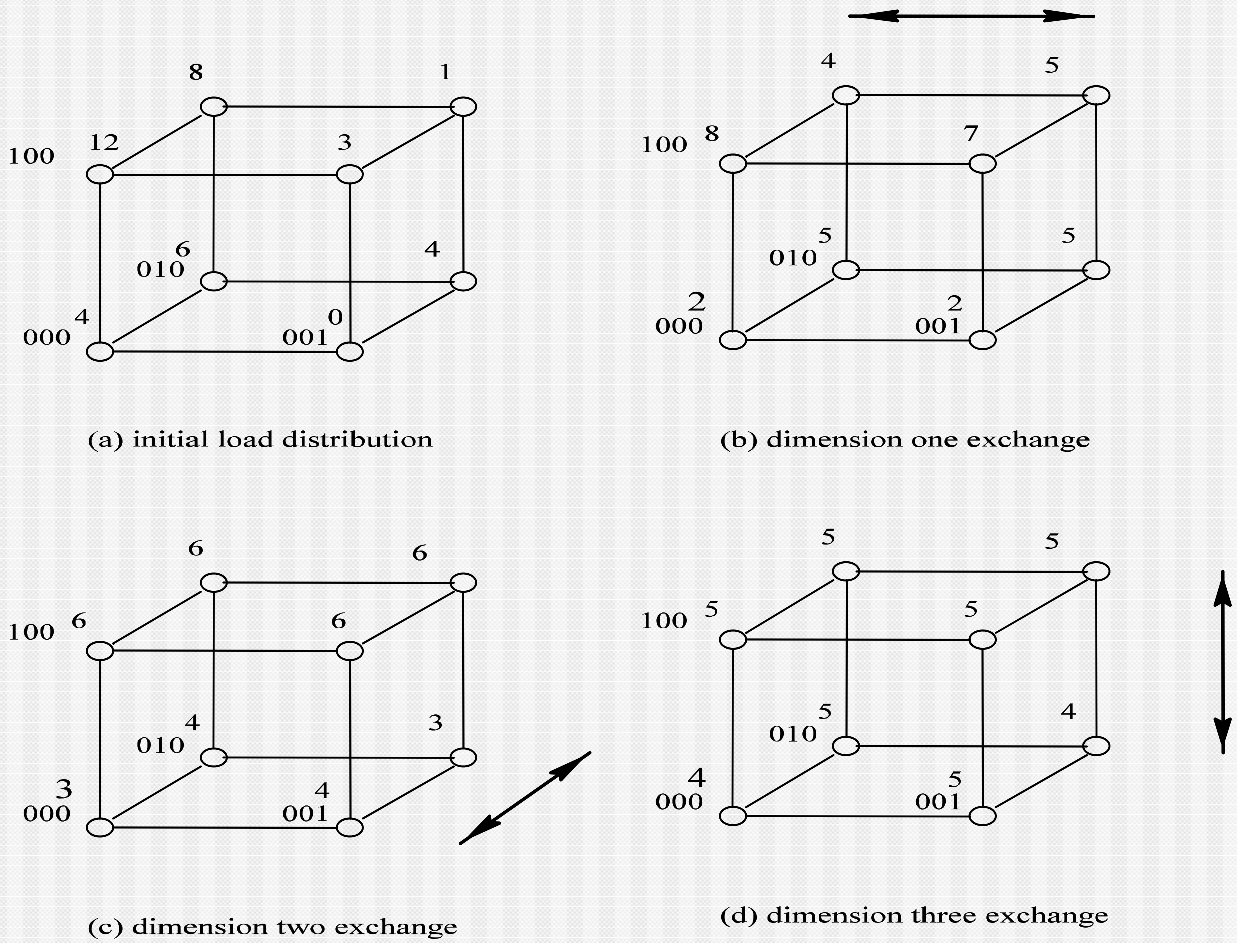
(a) (b)

(a) A 4 x 4 mesh with loads. (b) The corresponding propagated pressure of each node (a node is lightly loaded if its load is less than 3).

Dimension Exchange: Hypercubes

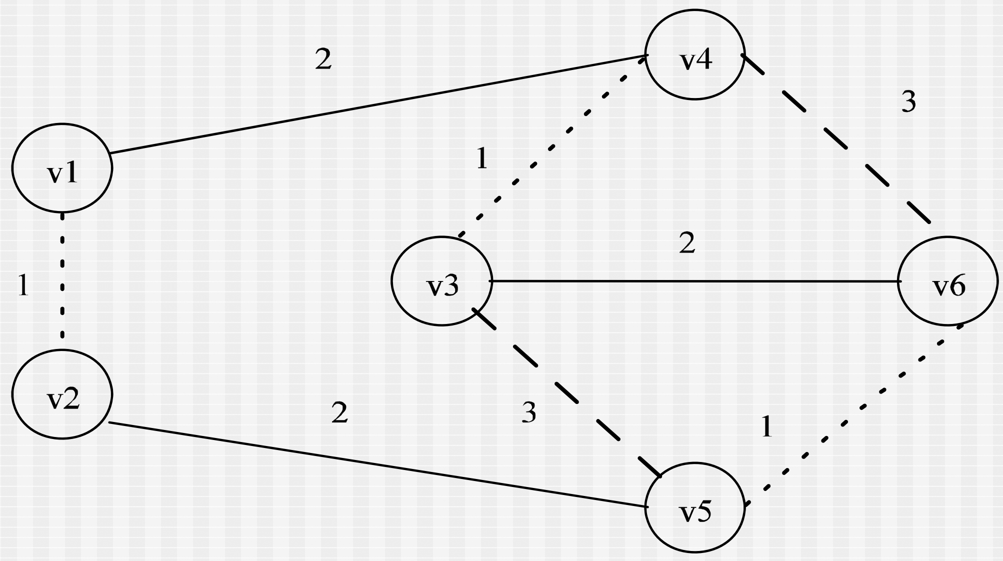
- A sweep of dimensions (rounds) in the *n*-cube is applied.
- In the i^{th} round neighboring nodes along the i^{th} dimension compare and exchange their loads.

Dimension Exchange: Hypercubes (Cont'd)



Load balancing on a healthy 3-cube.

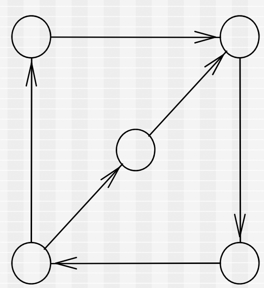
Extended Dimension Exchange: Edge-Coloring



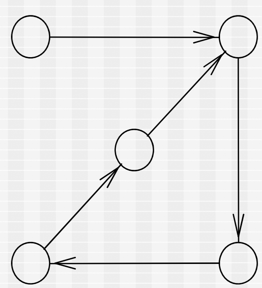
Extended dimension exchange model through edge-coloring.

Exercise 4

1. Apply *wound-wait* and *wait-die* schemes to the example shown in Table 2.
2. Show the state transition sequence for the following system with $n = 3$ and $k = 5$ using Dijkstra's self-stabilizing algorithm. Assume that $P_0 = 3$, $P_1 = 1$, and $P_2 = 4$.
3. Determine if there is a deadlock in each of the following wait-for graphs assuming the OR model is used.



(a)



(b)

Exercise 4 (Cont'd)

Process id	Priority	1^{st} request time	Length	Retry interval	Resource(s)
P1	3	1	1	1	A
P2	4	1.5	2	1	B
P3	1	2.5	2	2	A,B
P4	2	3	1	1	B,A

Table 2: A system consisting of four processes.

4. Consider the following two periodic tasks (with the same request time)

- Task T_1: $c_1 = 4$, $t_1 = 9$
- Task T_2: $c_2 = 6$, $t_2 = 14$

(a) Determine the total utilization of these two tasks and compare it with Liu and Layland's least upper bound for the fixed priority schedule. What conclusion can you derive?

Exercise 4 (Cont'd)

(b) Show that these two tasks are schedulable using the rate-monotonic priority assignment. You are required to provide such a schedule.

(c) Determine the schedulability of these two tasks if task T_2 has a higher priority than task T_1 in the fixed priority schedule.

(d) Split task T_2 into two parts of 3 units computation each and show that these two tasks are schedulable using the rate-monotonic priority assignment.

(e) Provide a schedule (from time unit 0 to time unit 30) based on deadline driven scheduling algorithm. Assume that the smallest preemptive element is one unit.

Exercise 4 (Cont'd)

5. For the following 4 x 4 mesh find the corresponding propagated pressure of each node. Assume that a node is considered lightly loaded if its load is less than 2.

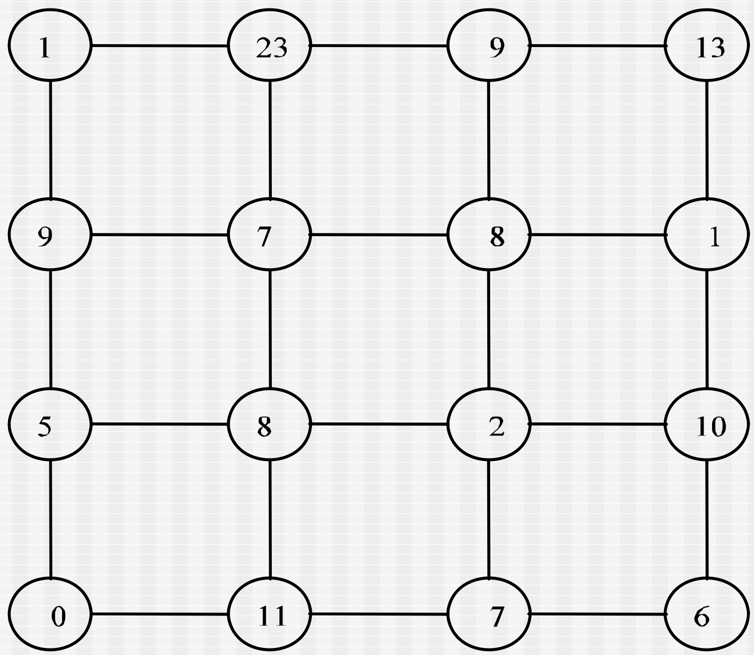


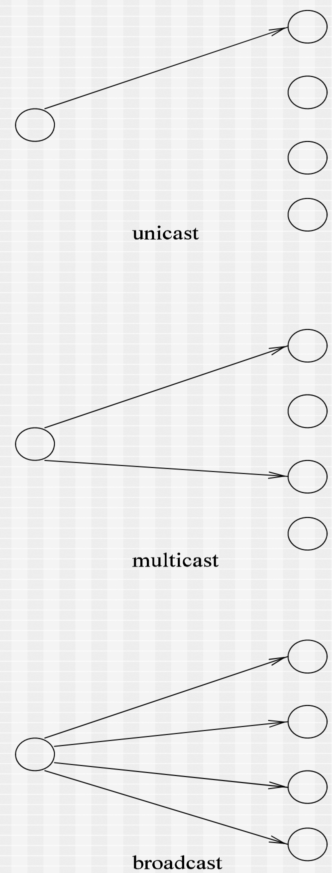
Table of Contents

Distributed Communication

One-to-one (**unicast**)

One-to-many (**multicast)**

One-to-all (**broadcast**)

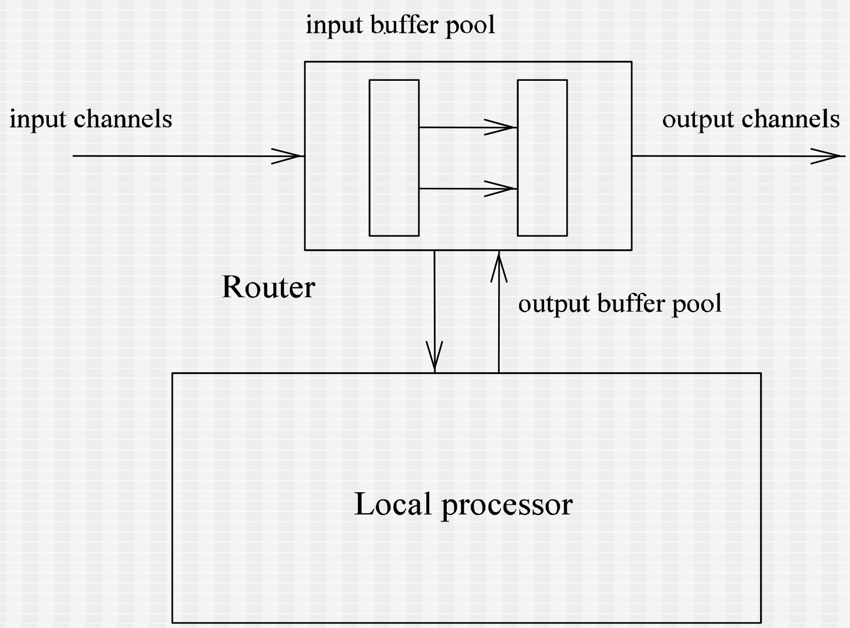


Different types of communication

Classification

- Special purpose vs. general purpose.
- Minimal vs. nonminimal.
- Deterministic vs. adaptive.
- Source routing vs. distributed routing.
- Fault-tolerant vs. non fault-tolerant.
- Redundant vs. non redundant.
- Deadlock-free vs. non deadlock-free.

Router Architecture



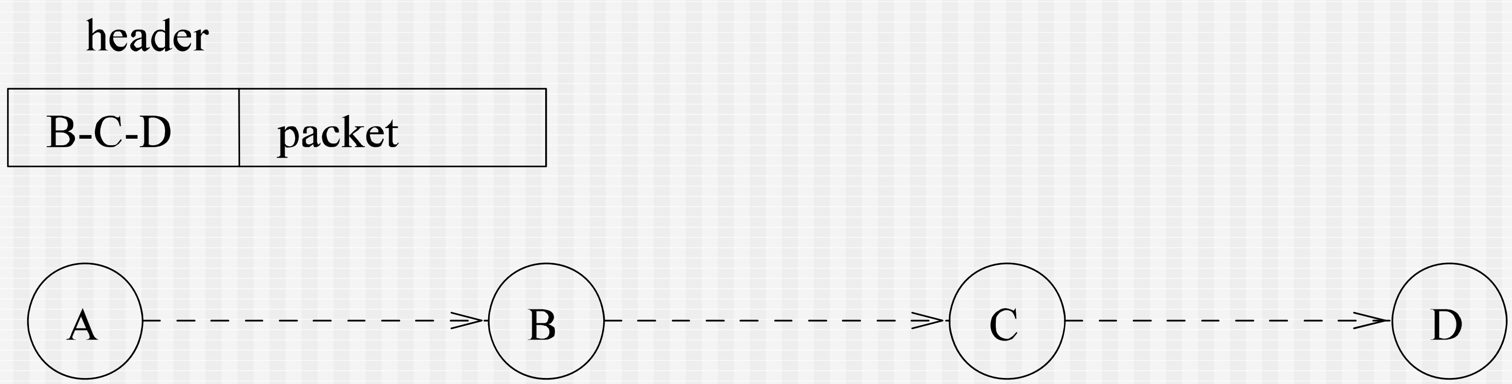
A general PE with a separate router.

Four Factors for Communication Delay

- **Topology**. The topology of a network, typically modeled as a graph, defines how PEs are connected.
- **Routing**. Routing determines the path selected to forward a message to its destination(s).
- **Flow control**. A network consists of channels and buffers. Flow control decides the allocation of these resources as a message travels along a path.
- **Switching**. Switching is the actual mechanism that decides how a message travels from an input channel to an output channel: store-and-forward and cut-through (wormhole routing).

General-Purpose Routing

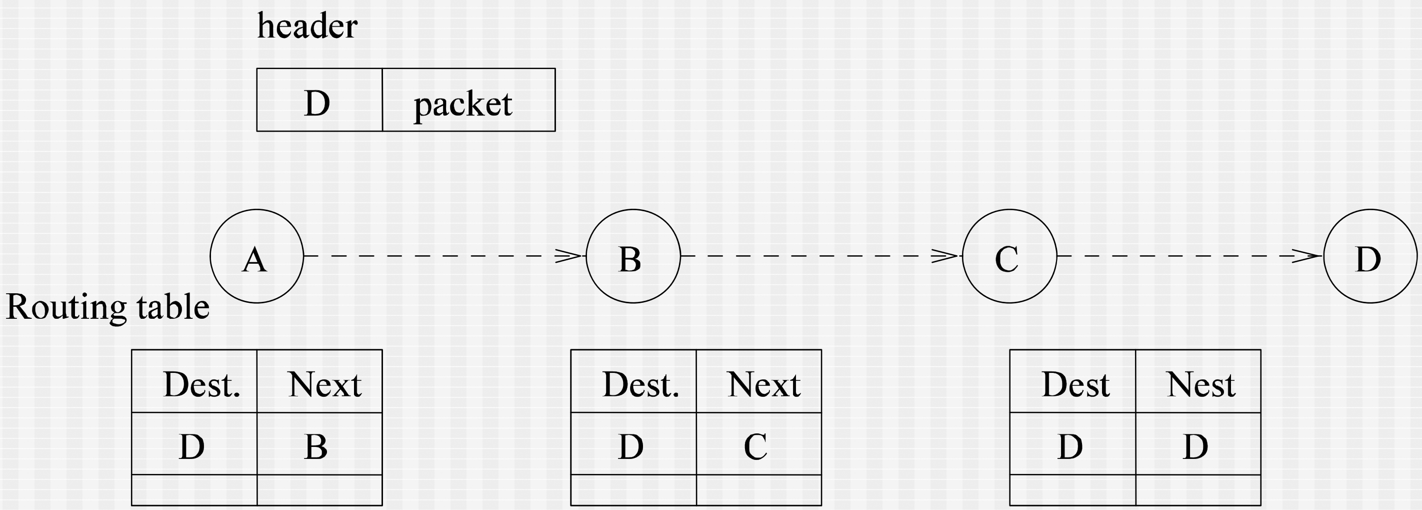
Source routing: link state (Dijkstra's algorithm)



A sample source routing

General-Purpose Routing (Cont'd)

Distributed routing: distance vector (Bellman-Ford algorithm)



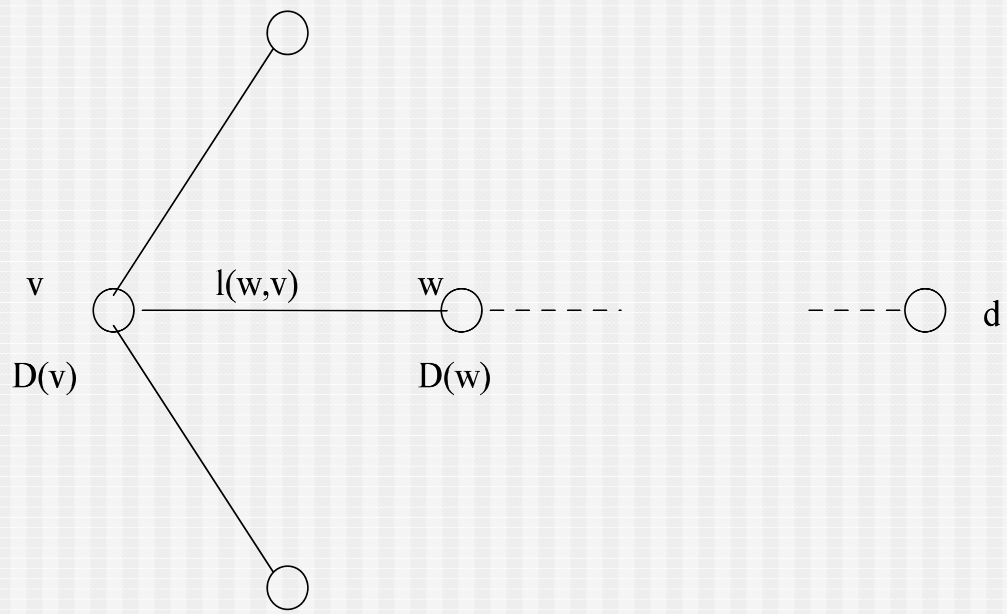
A sample distributed routing

Distributed Bellman-Ford Routing Algorithm

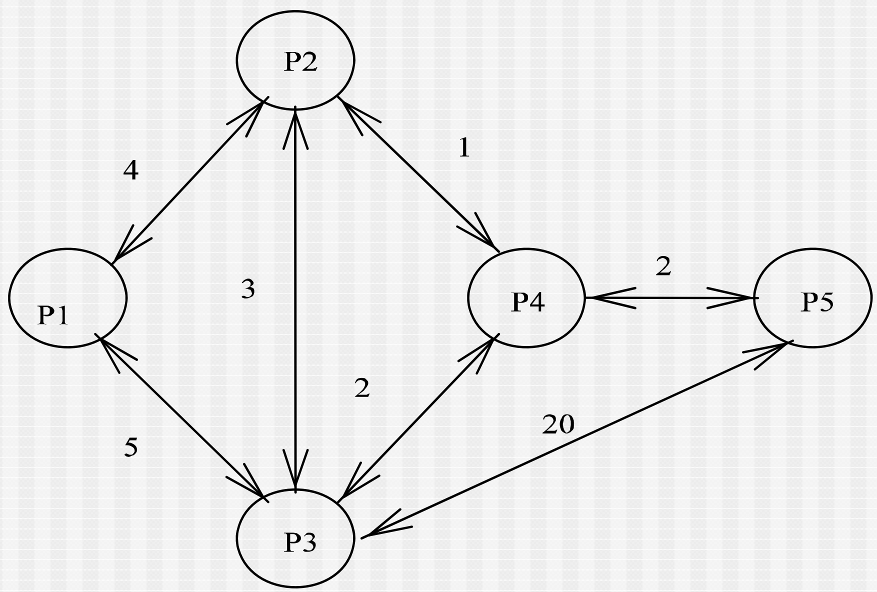
- *Initialization*. With node d being the destination node, set $D(d) = 0$ and label all other nodes (., ∞).
- *Shortest-distance labeling of all nodes*. For each node $v \neq d$ do the following: Update D(v) using the current value D(w) for each neighboring node w to calculate D(w) + l(w, v) and perform the following update:

$$D(v) := \min\{D(v), D(w) + l(w; v)\}$$

Distributed Bellman-Ford Algorithm (Cont'd)



Example 18



A sample network.

Example 18 (Cont'd)

Round	P1	P2	P3	P4
Initial	(., ∞)	(., ∞)	(., ∞)	(., ∞)
1	(., ∞)	(., ∞)	(5,20)	(5,2)
2	(3,25)	(4,3)	(4,4)	(5,2)
3	(2,7)	(4,3)	(4,4)	(5,2)

Bellman-Ford algorithm applied to the network with P_5 being the destination.

Looping Problem

Link (P_4; P_5) fails at the destination P_5.

Time next node	0	1	2	3	K, 4<k<15	16	17	18	19	(20, ∞)
P2	7	7	9	9	$2\lfloor n/2 \rfloor +7$	23	23	25	25	27
P3	9	9	11	11	$2\lfloor n/2 \rfloor +9$	25	25	25	25	25*

(a) Network delay table of P1

Time next node	0	1	2	3	K, 4<k<15	16	17	18	19	(20, ∞)
P1	11	11	13	13	$2\lfloor n/2 \rfloor +9$	25	27	27	29	29
P3	7	7	9	9	$2\lfloor n/2 \rfloor +7$	23	23	23	23	23
P3	3	5	5	7	$2\lfloor n/2 \rfloor +3$	19	21	21	23*	23

(b) Network delay table of P2

Looping Problem (Cont'd)

Time next node	0	1	2	3	K, 4<k<15	16	17	18	19	(20, ∞)
P1	12	12	12	14	$2\lfloor n/2 \rfloor +10$	26	28	28	30	30
P2	6	6	8	8	$2\lfloor n/2 \rfloor +5$	22	22	24	24	26
P4	4	6	6	8	$2\lfloor n/2 \rfloor +4$	20	22	22	24	24
P5	20	20	20	20	20	20	20*	20	20	20

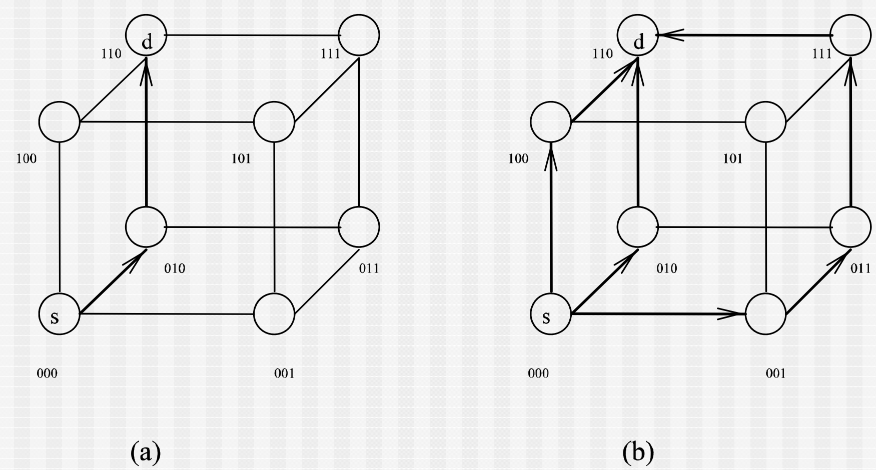
(c) Network delay table of P3

Time next node	0	1	2	3	K, 4<k<15	16	17	18	19	(20, ∞)
P2	4	4	6	6	$2\lfloor n/2 \rfloor +4$	20	20	22	22	24
P3	6	6	8	8	$2\lfloor n/2 \rfloor +5$	22	22	22	22	22*
P5	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞

(d) Network delay table of P4

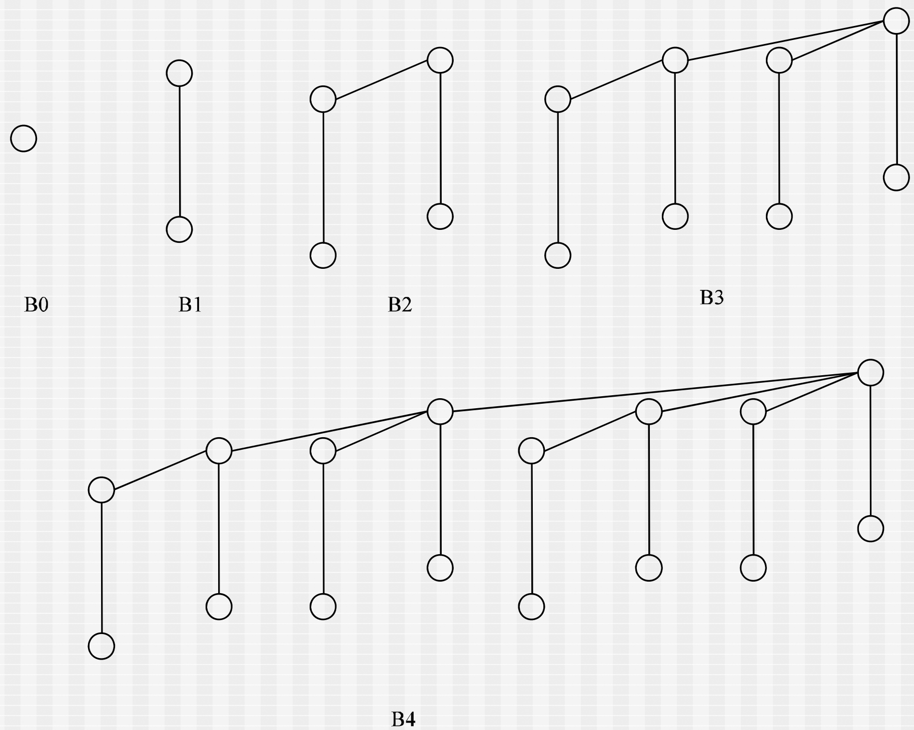
Special-Purpose Routing

E-cube routing in n-cube: $u \oplus w$ as a navigation vector.



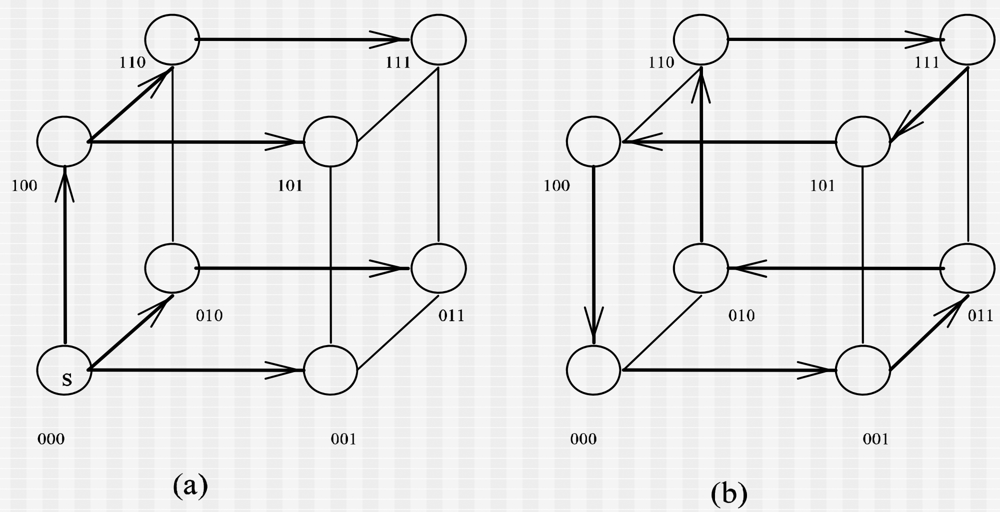
A routing in a 3-cube with source 000 and destination 110:
(a)Single path. (b) Three node-disjoint paths.

Binomial-Tree-Based Broadcasting in *N*-Cubes



The construction of binomial trees.

Hamiltonian-Cycle-Based Broadcasting in *N*-Cubes



(a) A broadcasting initiated from 000 with coordinated sequence (CS): {3, 2, 1}.

(b) A Hamiltonian cycle in a 3-cube.

Edge-disjointed Multiple Binomial Trees

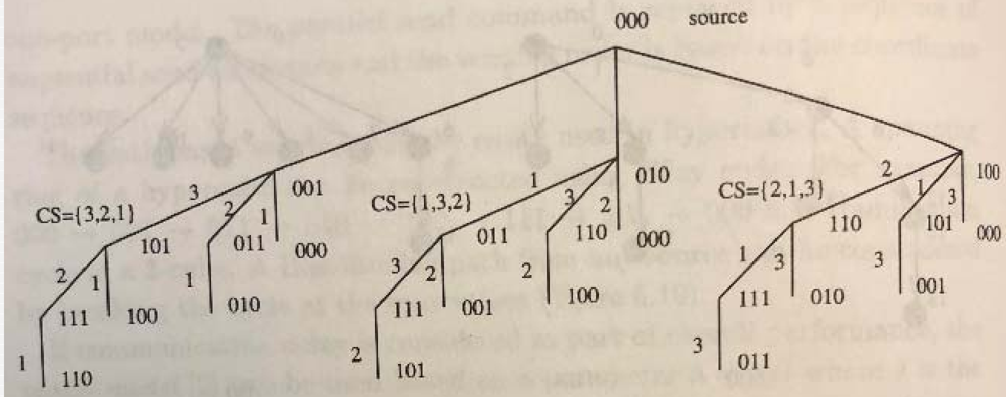
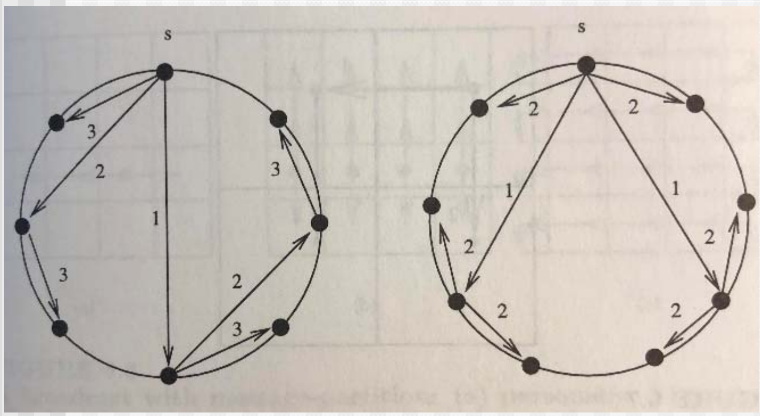


FIGURE 6.12
Edge-disjoint multiple binomial trees.

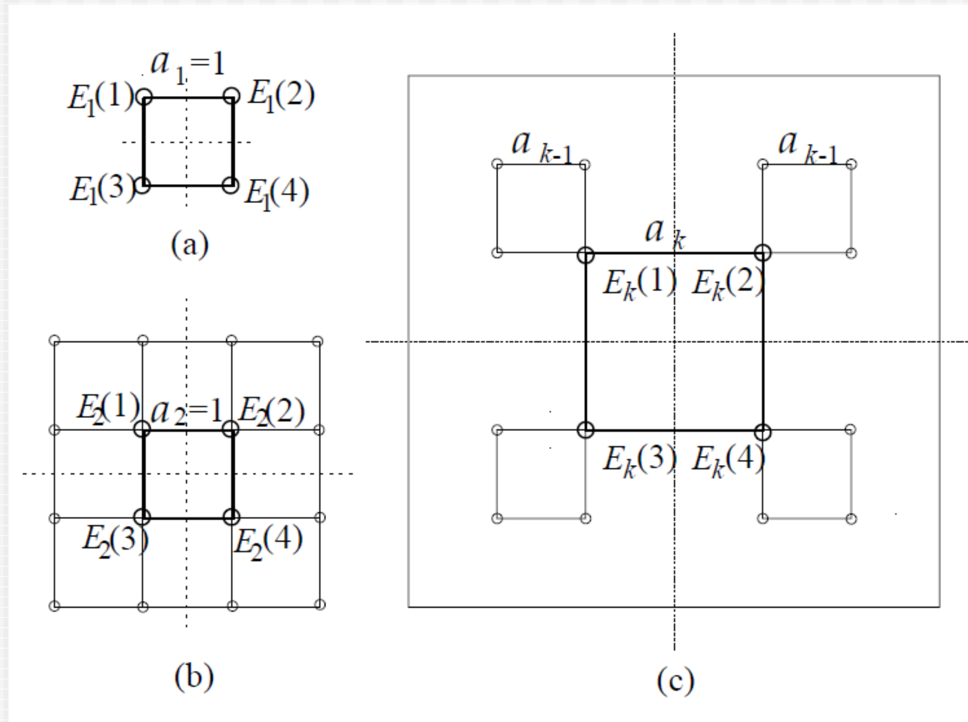
Node	Paths via Node 1	Paths via Node 2	Paths via Node 4
1	0	0-2-3	0-4-5
2	0-1-3	0	0-4-6
3	0-1	0-2	0-4-6-7
4	0-1-5	0-2-6	0
5	0-1	0-2-3-7	0-4
6	0-1-5-7	0-2	0-4
7	0-1-5	0-2-3	0-4-6

Table 6.4 Multiple paths to each node of a 3-cube.

Cut-through: recursive doubling



(L) one-port and (R) all-port on ring



One-port on mesh with minimum total distance using *eyes*: (a) 2x2, (b) 4x4, and (c) 2^k x 2^k meshes

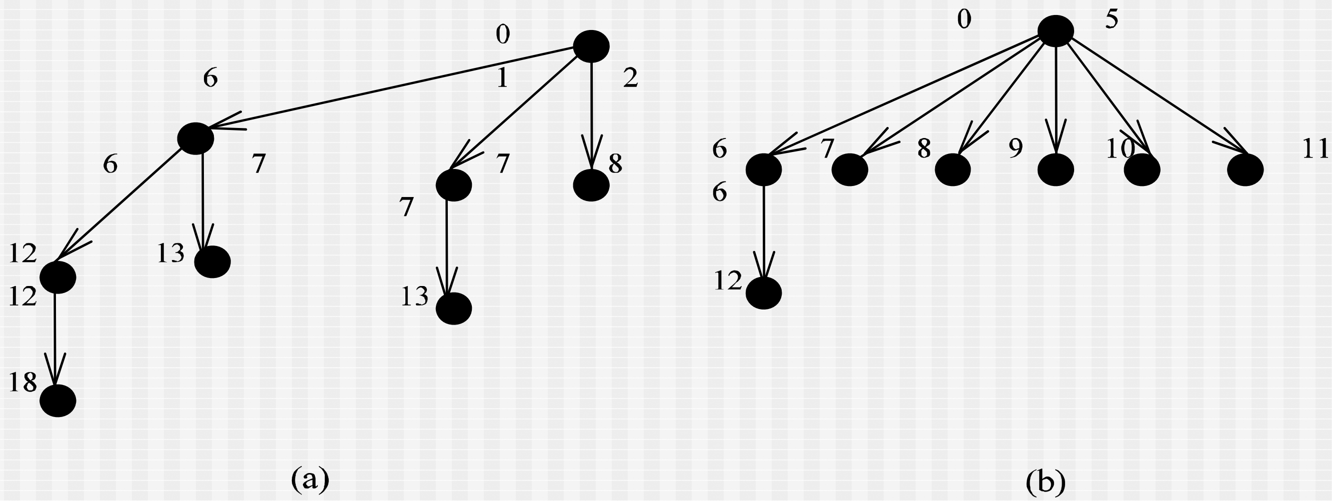
Parameterized Communication Model

Postal model:

- $\lambda = l/s$, where l is the communication latency and s is the latnecy for a node to send the next message.
- Under the **one-port model** the binomial tree is optimal when $\lambda = 1$.

$$N_{\lambda}(t) = N_{\lambda}(t-1) + N_{\lambda}(t-\lambda), \text{ if } t \geq \lambda;\ 1, \text{ otherwise}$$

Example 19: Broadcast Tree



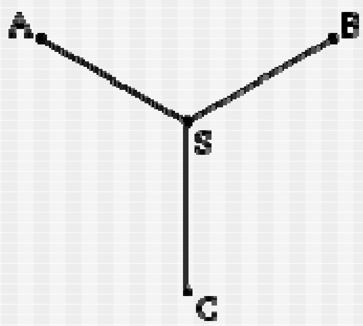
Comparison with $\lambda = 6$: (a) binomial tree and (b) optimal spanning tree.

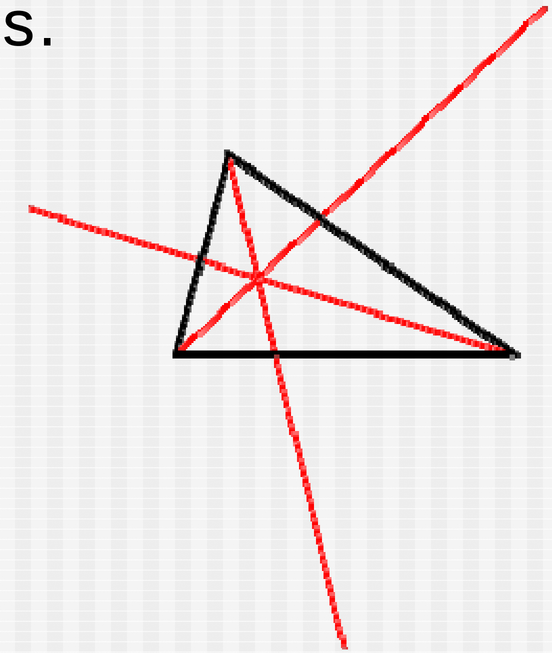
Multicasting

- Multicast path
- Minimum spanning tree (for a graph)
- Shortest path tree (for a graph)
- *Steiner tree* (without a graph): a minimum tree that includes all destinations.

Three-points Steiner tree
with the Fermat point S

(e.g., all angles ≤ 120^{o})





Focus 15: Fault-Tolerant Routing

Wu's safety level:

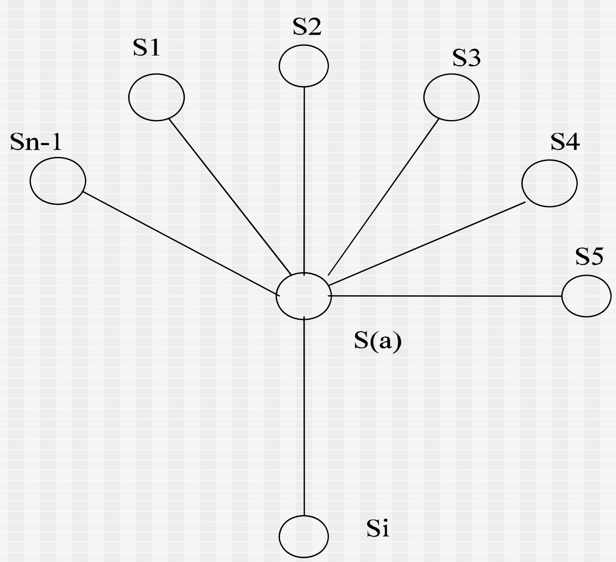
- The safety level associated with a node is an approximated measure of the number of faulty nodes in the neighborhood.
- Initially all faulty nodes have 0 as safety levels and all non-faulty nodes have n.
- Let $(S_0,S_1,S_2,\ldots,S_{n-1})$, $0 \le S_i \le n$, be the non-descending safety status sequence of node *a*'s neighboring nodes in an n-cube.
- Iteratively do the following: If $(S_0,S_1,S_2,\ldots,S_{n-1}) \ge (0,1,2,\ldots,n-1)$ then $S(a) = n$ else if $(S_0,S_1,S_2,\ldots S_{k-1}) \ge (0,1,2,\ldots,k-1)$ ^ $(S_k = k-1)$ then $S(a) = k$.

Insight: Embedding of B_n in terms of B_{n-1}, B_{n-2}, …, B_1, and B_0 in any orientation.

Focus 15: Fault-Tolerant Routing (Cont'd)

Distributed algorithms: iterative exchanges (maximum n rounds) with neighbors' safety levels

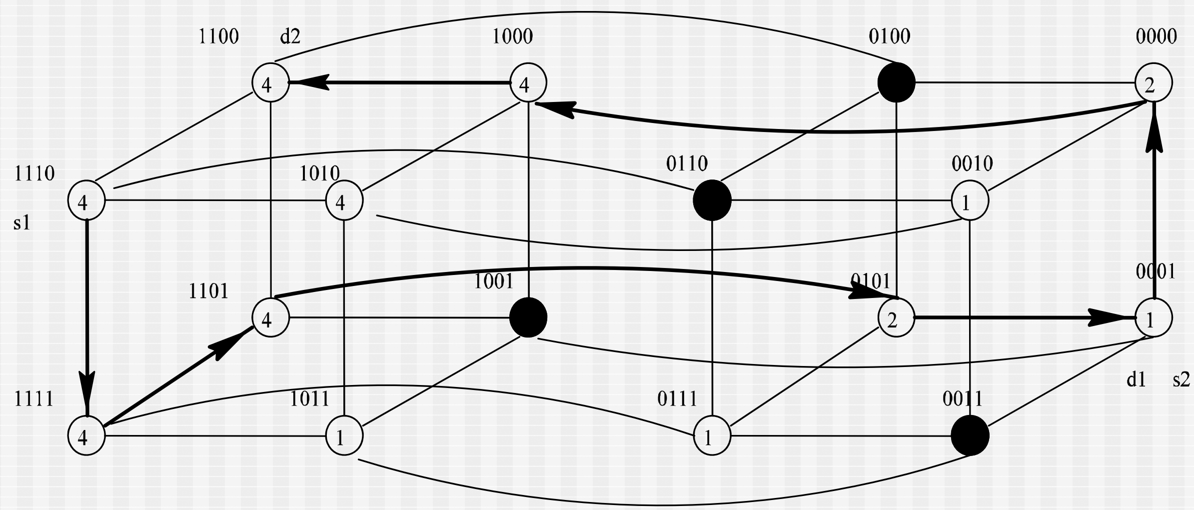
A node a is called **safe** if its level is n, i.e., S(a) =n



Fault-Tolerant Routing (Cont'd)

If the safety level of a node is k, there is at least one Hamming distance path from this node to any node within k-hop.

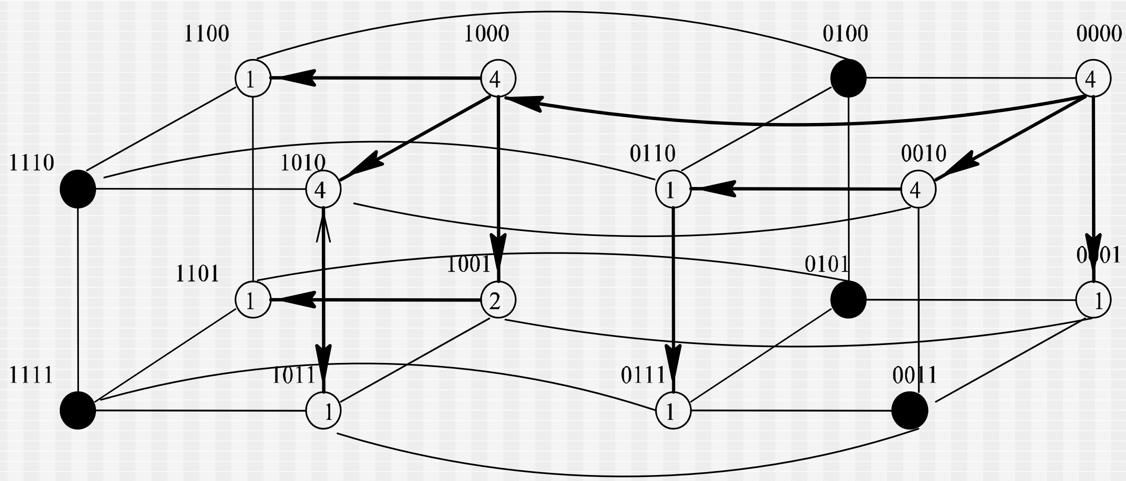
If there are at most n faults, every unsafe node has a safe neighbor.



A fault-tolerant routing using safety levels.

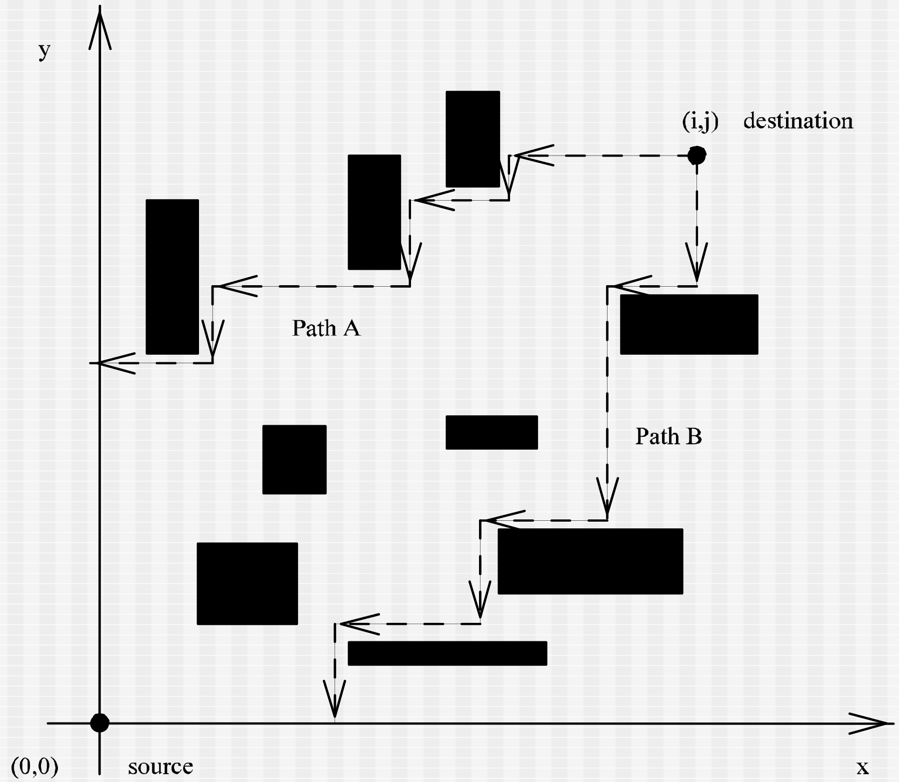
Fault-Tolerant Broadcasting

If the source node is n-safe, there exists an n-level injured spanning binomial tree in an n-cube: source can reach all non-faulty nodes through a Hamming distance path.



Broadcasting in a faulty 4-cube.

Wu's Extended Safety Level in 2-D Meshes



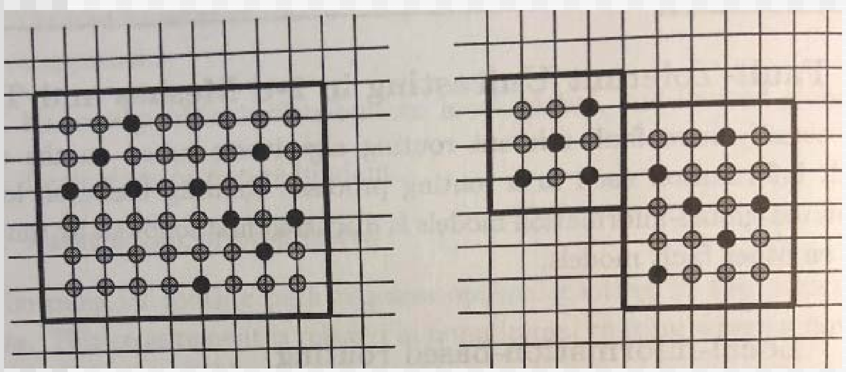
A sample region of minimal paths.

Safety Block

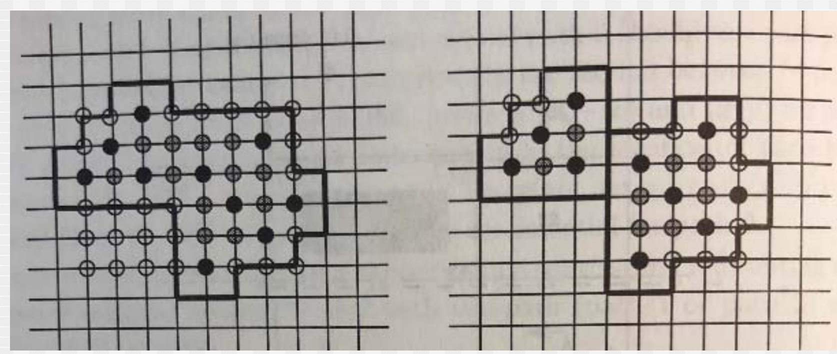
Safety block: (1) All faulty nodes are unsafe. All nonfaulty nodes are initially safe.
(2) If a nonfaulty node has two or more faculty/unsafe neighbors, it is unsafe.

Extended safety block: (1). (2) …has a faulty/unsafe neighbor in both dimensions…

Wu's orthogonal convex region: All safe nodes are enabled. A unsafe node is initially disabled, but it is changed to the enabled status if it has two or more enabled neighbors.



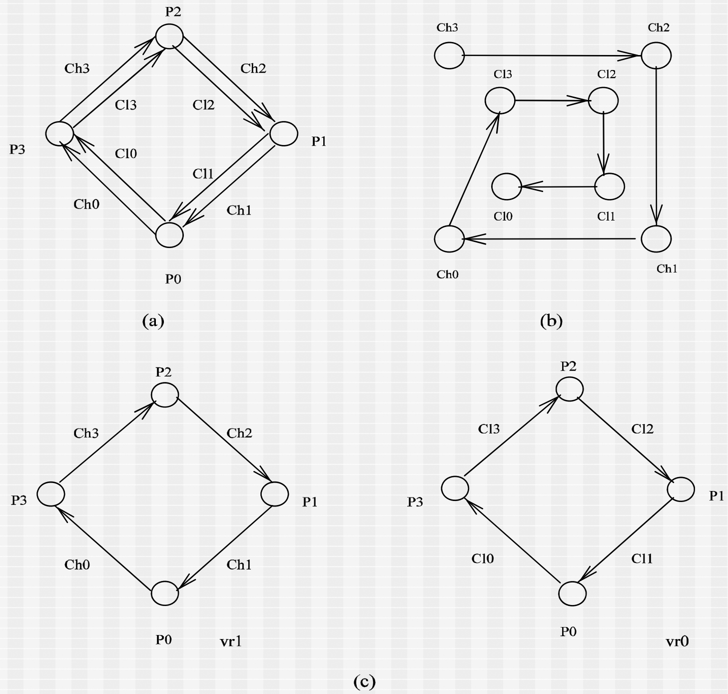
(L) Regular and (R) extended safe/unsafe



Enabled/disabled for (L) regular and (R) for extended

Deadlock-Free Routing

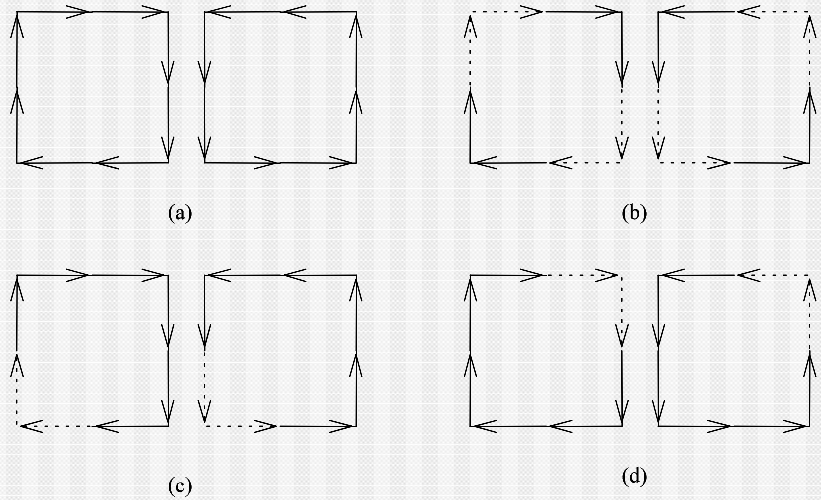
Virtual channels and **virtual networks**:



(a) A ring with two virtual channels, (b) channel dependency graph of (a), and (c) two virtual rings vr_1 and vr_0.

Focus 16: Deadlock-Free Routing Without Virtual Channels

- **XY-routing** in 2-D meshes: X dimension followed by Y dimension.
- Glass and Ni's **Turn model**: Certain turns are forbidden.



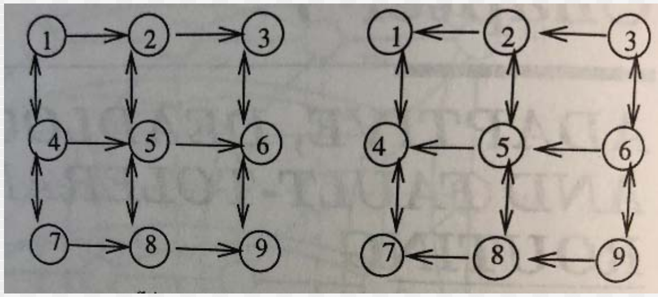
(a) Abstract cycles in 2-d meshes, (b) four turns (solid arrows) allowed in XY-routing, (c) six turns allowed in positive-first routing, and (d) six turns allowed in negative-first routing.

Planar-Adaptive Routing

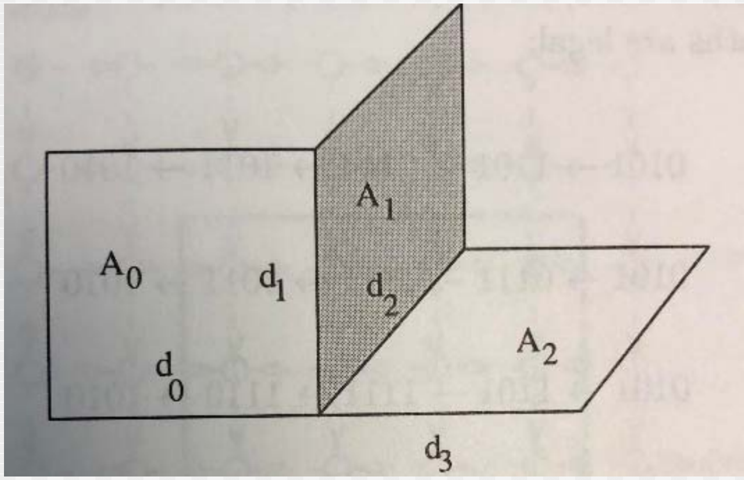
For general k-ary n-cubes, select n+1 2-D planes A_0, A_1, …, A_n. A_i spans dimension d_i and d_{i+1}.

Three virtual channels are used: one for d_i and two for d_{i+1}: $d_{i,2}$, $d_{i+1,0}$, and $d_{i+1,\,1}$. (Second subscript is virtual channel number.)

Each plane has one positive and one negative subnetworks.



Positive and negative Networks in d_i and d_{i+1}



Escape channels

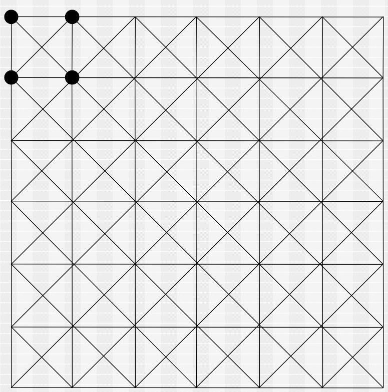
- Regular channels: non-waiting
- Escape channels: waiting
  - *Strongly connected requirement*
  - *Strictly decreasing path requirement*: for any pair of nodes, a decreasing (labelled) path exist.

Theorem: The minimum number of channels needed to meet the above two conditions is 2n-1, where n is the number of nodes.

L. Sheng and J. Wu, “A Note on “A Tight Lower Bound on the Number of Channels Required for Deadlock-Free Wormhole Routing.

Exercise 5

1. Provide an addressing scheme for the following *extended mesh* (EM) which is a regular 2-D mesh with additional diagonal links. Provide a general shortest routing algorithm for EMs.



2. Repeat Example 18 after changing (P1, P3) to 4 and (P3, P5) to 12.

3. Suppose the postal model is used for broadcasting and $\lambda = 8$. What is the maximum number of nodes that can be reached in time unit 10. Derive the corresponding broadcast tree.

Exercise 5 (Cont'd)

4. Consider the following turn models:

- *West-first routing*. Route a message first west, if necessary, and then adaptively south, east, and north.
- *North-last routing*. First adaptively route a message south, east, and west; route the message north last.
- *Negative-first routing*. First adaptively route a message along the negative X or Y axis; that is, south or west, then adaptively route the message along the positive X or Y axis.

(a) Show all the turns allowed in each of the above three routings.

(b) Show the corresponding routing paths using (1) positive-first, (2) west-first, (3) north-last, and (4) negative-first routing for the following unicasting: (2,1) to (5,9), (7,1) to (5,3), (6,4) to (3,1), and (1,7) to (5,2).

5. Wu and Fernandez (1992) gave the following safe and unsafe node definition: A nonfaulty node is unsafe if and only if either of the following conditions is true: (a) There are two faulty neighbors, or (b) there are at least three unsafe or faulty neighbors. Consider a 4-cube with faulty nodes 0100, 0011, 0101, 1110, and 1111. Find out the safety status (safe or unsafe) of each node.

Exercise 5 (Cont'd)

Repeat the above using Wu's safety vector. Critically compare safety node, safety level, and safety vector in terms of fault-tolerance capability and complexity. (J. Wu, Reliable communication in cube-based multipcomputers using safety vectors, IEEE TPDS, 9, (4), April 1998, 321-334.)

6. To support fault-tolerant routing in 2-D meshes, D. J. Wang (1999) proposed the following new model of faulty block: Suppose the destination is in the first quadrant of the source. Initially, label all faulty nodes as *faulty* and all non-faulty nodes as *fault-free*. If node *u* is fault-free, but its north neighbor and east neighbor are faulty or useless, *u* is labeled *useless*. If node *u* is fault-free, but its south neighbor and west neighbor are faulty or can't-reach, *u* is labeled *can't-reach*. The nodes are recursively labeled until there are no new useless or can't-reach nodes.

(a) Give an intuitive explanation of useless and can't-reach.

(b) Re-write the definition when the destination is in the second quadrant of the source.

Exercise 5 (Cont'd)

7. Chiu proposed an *odd-even turn model*, which is an extension to Glass and Ni's turn model. The odd-even turn model tries to prevent the formation of the *rightmost column segment of a cycle*. Two rules for turn are given in:
   - Rule 1: Any packet is *not* allowed to take an EN (east-north) turn at any nodes located in an even column, and it is *not* allowed to take an NW turn at any nodes located in an odd column.
   - Rule 2: Any packet is *not* allowed to take an ES turn at any nodes located in an even column, and it is *not* allowed to take a SW turn at any nodes located in an odd column.

(a) Use your own word to explain that the odd-even turn model is deadlock-free.

(b) Show *all the shortest paths* (permissible under the extended odd-even turn model) for

(a) s_1:(0, 0) and d_1:(2,2) and (b) s_2:(0,0) and d_2:(3,2)

(c) Prove Properties 1, 2, and 3 of Wu and Li's marking process for ad hoc wireless networks.

Table of Contents

Distributed Data Management

- Data objects
  - Files
  - Directories
- Data objects are dispersed and replicated
  - Unreplicated
  - Fully replicated
  - Partially replicated

Serializability Theory

Atomic execution

- A transaction is an "all or nothing" operation.
- The concurrent execution of several transactions affects the database as if executed serially in some order. The interleaved order of the actions of a set of concurrent transactions is called a *schedule*.

Example 22: Concurrent Transactions

T_1 **begin**

1 **read** A (obtaining *A_balance*)

2 **read** B (obtaining *B_balance*)

3 **write** *A_balance*-$10 to A

4 **write** *B_balance*+$10 to B

end

T_2 **begin**

1 **read** B (obtaining *B balance*)

2 **write** *B_balance*-$5 to B

end

Concepts

- Three types of **conflict**: *r*-*w* (read-write), *w*-*r* (write-read), and *w*-*w* (write-write).
- $r_j[x]$ *reads from* $w_i[x]$ iff
  - $w_i[x] < r_j[x]$.
  - There is no $w_k[x]$ such that $w_i[x] < w_k[x] < r_j[x]$.
- Two **schedules** are equivalent iff
  - Every read operation reads from the same write operation in both schedules.
  - Both schedules have the same final writes.
- When a non-serial schedule is equivalent to a serial schedule, it is called **serializable schedule**.

Transaction (step)	Action
$T_1(1)$	**read** A(obtaining *A_balance*)
$T_1(2)$	**read** B(obtaining *B_balance*)
$T_1(3)$	**write** *A_balance-$10* **to** A
$T_2(1)$	**read** B(obtaining *B_balance*)
$T_2(1)$	**write** *B_balance-$5* **to** B
$T_2(4)$	**write** *B_balance+$10* **to** B

(a)

Transaction (step)	Action
$T_1(1)$	**read** A(obtaining *A_balance*)
$T_2(1)$	**read** B(obtaining *B_balance*)
$T_2(1)$	**write** *B_balance-$5* **to** B
$T_1(2)$	**read** B(obtaining *B_balance*)
$T_1(3)$	**write** *A_balance-$10* **to** A
$T_1(4)$	**write** *B_balance+$10* **to** B

(b)

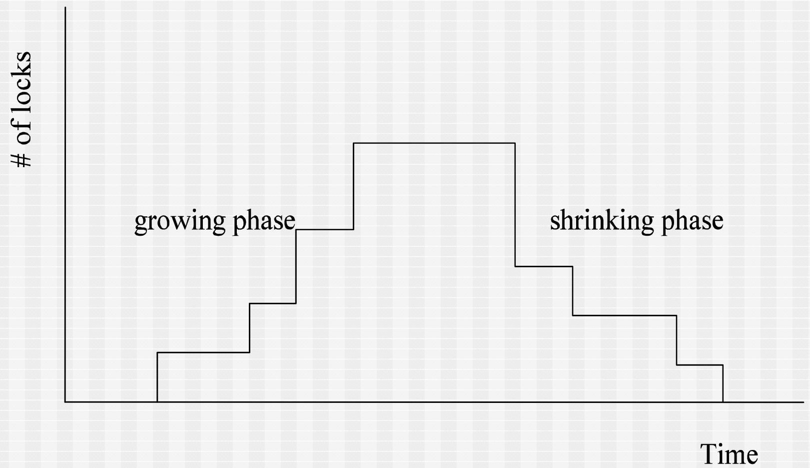
A nonserializable schedule (a) and serializable schedule (b) for Example 22.

Concurrency Control

- Locking scheme
- Timestamp-based scheme
- Optimistic concurrency control

Focus 18: Two-Phase Locking

- A transaction is **well-formed** if it
  - locks an object before accessing it,
  - does not lock an object that is already locked, and
  - before it completes, unlocks each object it has locked.
- A schedule is **two-phase** if no object is unlocked before all needed objects are locked.



Two-phase locking

Example 23: Well-Formed, Two-Phase Transactions

T_1: **begin**
lock A
read A (obtaining A balance)
lock B
read B (obtaining B balance)
write A_balance-$10 to A
unlock A
write B_balance+$10 to B
unlock B
end

T_2: **begin**
lock B
read B (obtaining B balance)
write B_balance-$5 to B
unlock B
end

Different Looking Schemes

- *Centralized locking algorithm*: distributed transactions, but centralized lock management.
- *Primary-site locking algorithm*: each object has a single site designated as its primary site (as in INGRES).
- *Decentralized locking*: The lock management duty is shared by all the sites.

Focus 19: Timestamp-based Concurrency Control

- $Time_r(x)$ ($Time_w(x)$): the largest timestamp of any read (write) processed thus far for object x.
  - (Read) If $ts < Time_w(x)$ then the read request is rejected and the corresponding transaction is aborted; otherwise, it is executed and $Time_r(x)$ is set *to* $max\{Time_r(x), ts\}$.
  - (Write) If $ts < Time_w(x)$ or $ts < Time_r(x)$, then the write request is rejected; otherwise, it is executed and $Time_w(x)$ is set to ts.

Example 24

- $Time_r(x) = 4$ and $Time_w(\text{x}) = 6$ initially.
- Sample:

  read(x,5), *write*(x,7), *read*(x,9), *read*(x, 8), *write*(x,8)
- First and last are rejected and $\text{T}ime_r(x) = 7$, $Time_w(\text{x}) = 9$ when completed.

Conservative Timestamp Ordering

- Each site keeps a write queue (W-queue) and a read queue (R-queue).
  - A read (*x*, *ts*) request is executed if all W-queues are nonempty and the first write on each queue has a timestamp greater than *ts*; otherwise, the read request is buffered in the *R*-queue.
  - A write (*x*, *ts*) request is executed if all *R*-queues and *W*–queues are nonempty and the first read (write) on each *R*-queue (*W*-queue) has a timestamp greater than *ts*; otherwise, the write request is buffered in the *W*-queue.

Strict Consistency

- Any read returns the result of the most recent write.
- Impossible to enforce, unless
  - All writes are instantaneously visible to all processes.
  - All reads get the then-current values, no matter how quickly next writes are done.
  - An absolute global time order is maintained.

Weak Consistency

- **Sequential consistency**: All processes see all shared accesses in the same order.
- **Causal consistency**: All processes see causually-related shared accesses in the same order.
- **FIFO consistency**: All process see writes from each process in the order they were issued.

Weak Consistency (Cont'd)

- **Weak consistency**: Enforces consistency on a group of operations, not on individual reads and writes.
- **Release consistency**: Enforces consistency on a group of operations enclosed by acquire and release operations.
- **Eventual consistency**: All replicas will gradually become consistent. (Web pages with dominated read operations.)

Example 25: Sample Consistent Models

P1	W(x,a)			W(x,c)		
P2		R(x,a)	W(x,b)			
P3			R(x,a)		R(x,c)	R(x,b)
P4			R(x,a)		R(x,b)	R(x,c)

causally-consistent

P1	W(x,a)					
P2		R(x,a)	W(x,b)			
P3					R(x,b)	R(x,a)
P4					R(x,a)	R(x,b)

non-causally-consistent

Example 25: Sample Consistent Models

P1	W(x,a)					
P2		W(x,b)				
P3			R(x,b)		R(x,a)	
P4				R(x, b)	R(x,a)	

sequentially-consistent

P1	W(x,a)					
P2		W(x,b)				
P3			R(x, b)		R(x,a)	
P4				R(x, a)	R(x,b)	

non-sequentially-consistent

Linearizable: sequentially-consistent, but taking ordering based on synchronized clocks

Example 25 (Cont'd)

P1	W(x,a)						
P2		R(x,a)	W(x,b)	W(x,c)			
P3					R(x,b)	R(x,a)	R(x,c)
P4					R(x,a)	R(x,b)	R(x,c)

FIFO-consistent

Update Propagation for Multiple Copies

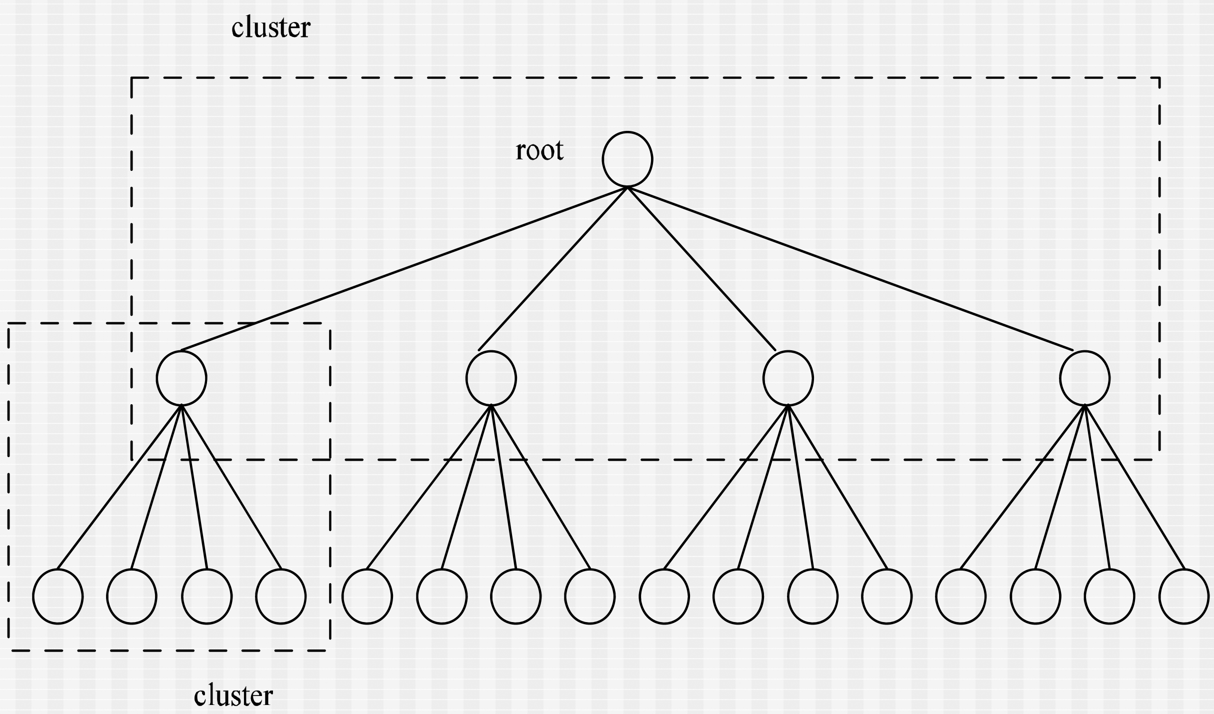
- **State** versus **Operations**
  - Propagate a notification of an update (such as invalidate signal)
  - Propagate data
  - Propagate the update operation
- **Pull** versus **Push**
  - Push-based approach (server-based)
  - Pull-based approach (client-based)
  - Lease-based approach (hybrid of push and pull)
- Consistency of duplicated data
  - **Write-invalidate** vs. **write-through**
  - **Quorum-voting** as an extension of single-write/multiple-read

Focus 20: Quorum-Voting

$$w > v/2 \text{ and } r + w > v$$

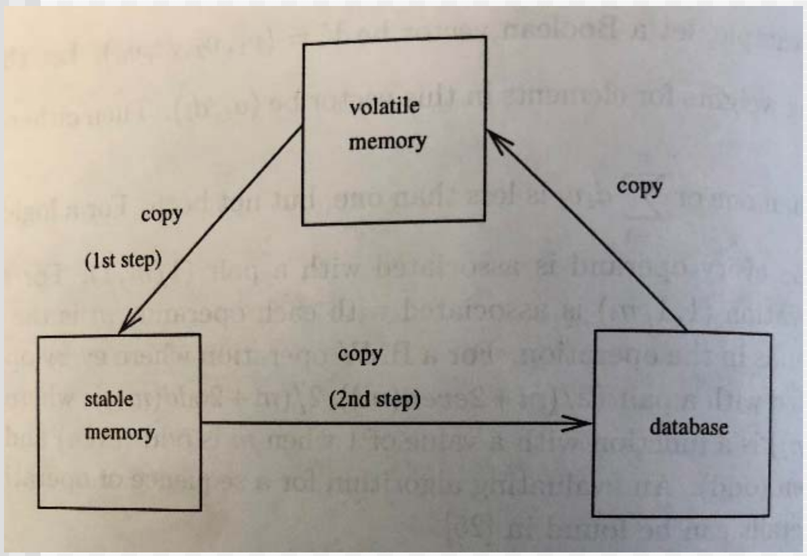
where w and r are write and read quorum and v is the total number of votes.

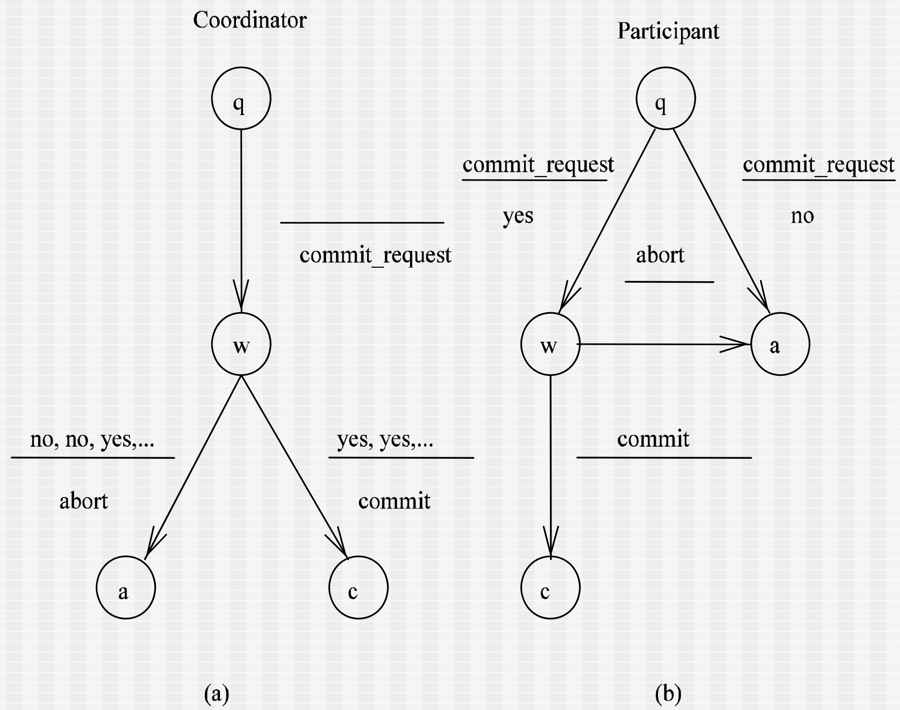
Hierarchical Quorum Voting



A 3-level tree in the hierarchical quorum voting with read quorum= 2 and write quorum = 3.

Jim Gray's Two-Phase Commitment Protocol





The finite state machine model for the two-phase commit protocol.

Phase 1

At the coordinator:

/*prec: initiate state (q) */
1. The coordinator sends a *commit_request* message to every participant and waits for replies from all the participants.

/*postc: waiting state (w) */

At participants:

/*prec: initiate state (q)*/
1. On receiving the *commit_request* message, a participant takes the following actions. If the transaction executing at the participant is successful, it writes *undo* and *redo* log, and sends a *yes* message to the coordinator; otherwise, it sends a *no* message.

/*postc: wait state (w) if *yes* or abort state (a) if *no**/

Phase 2

At the coordinator

/*prec: wait state (*w*)*/

1. If all the participants reply *yes* then the coordinator writes a *commit* record into the log and then sends a *commit* message to all the participants. Otherwise, the coordinator sends an *abort* message to all the participants.

   /*postc: commit state (c) if *commit* or abort state (a) if *abort* */

2. If all the acknowledgments are received within a timeout period, the coordinator writes a *complete* record to the log; otherwise, it resends the commit/abort message to those participants from which no acknowledgments were received.

Phase 2 (Cont’d)

At the participants

/*prec: wait state (*w*) */

1. On receiving a *commit* message, a participant releases all the resources and locks held for executing the transaction and sends an acknowledgment.

/*postc: commit state (c) */
/*prec: abort state (a) or wait state (w) */

2. On receiving an *abort* message, a participant undoes the transaction using the *undo* log record, releases all the resources and locks held by it, and sends an acknowledgment.

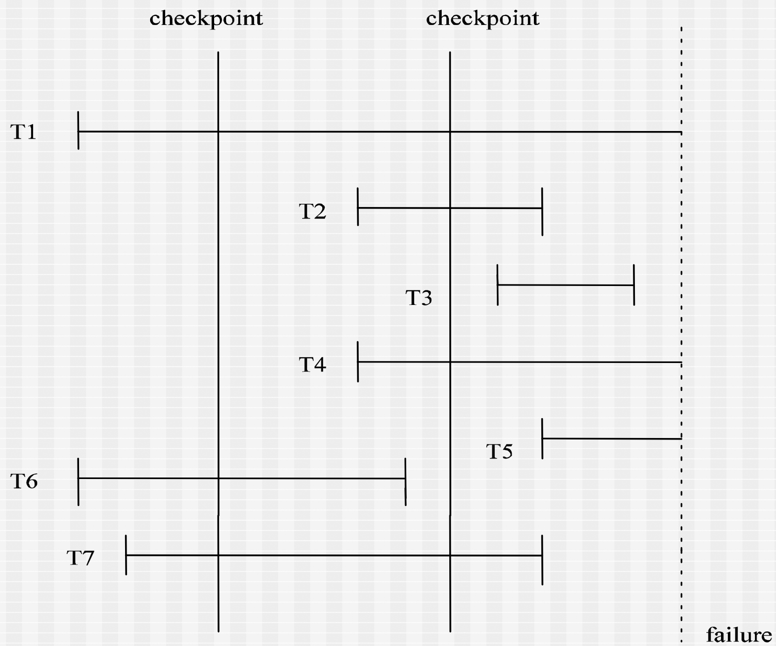
/*postc: abort state (a) */

Site Failures and Recovery Actions

Location	Time of failure	Actions at coordi.	Actions at parti.
Coordi.	Before *commit*	Broadcasts *abort* on recovery	Committed parti. Undo the trans.
Coordi.	Before *complete* after *commit*	Broadcasts *commit* on recovery	—
Coordi.	After complete	--	--
Parti.	In Phase 1	Coordi. aborts the transaction	—
Parti.	In Phase 2	—	Commit/abort on recovery

Two Types of Logs

- *undo* log allows an uncommitted transaction to record in stable storage values it wrote. (T_1, T_4, and T_5 in the example)
- *redo* log allows a transaction to commit before all the values written have been recorded in stable storage. (T_2 and T_7)

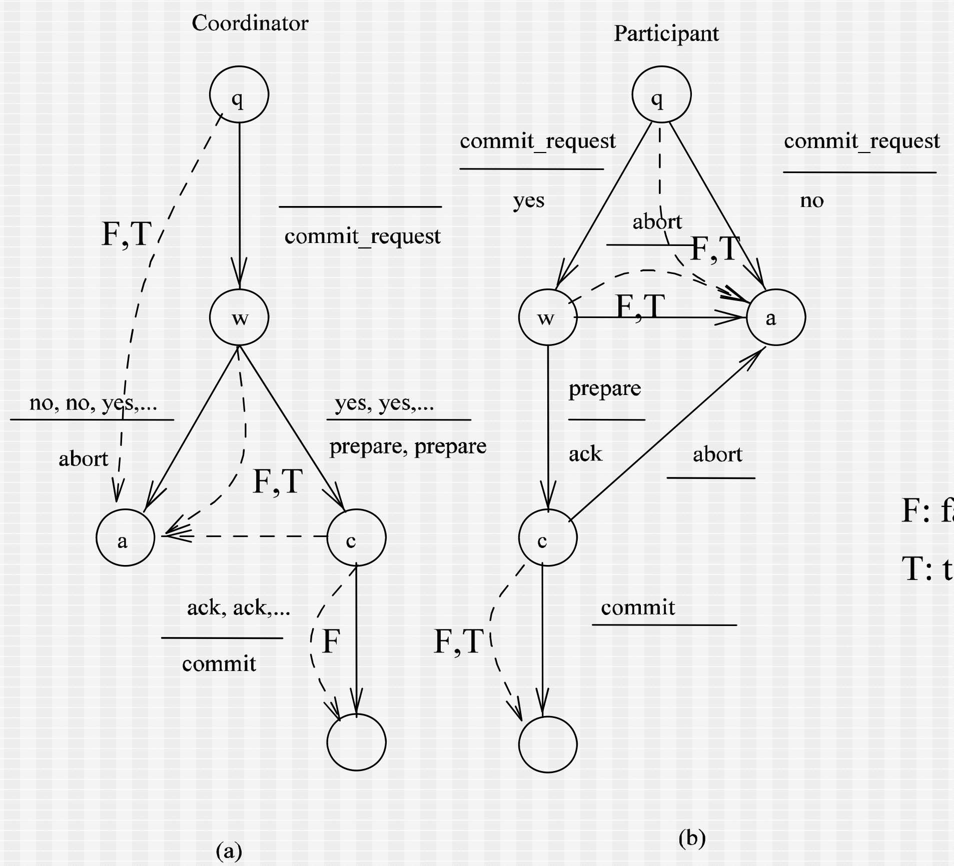


A recovery example.

Concepts

- A protocol is *synchronous* within one state transition if one site never leads another site by more than one state transition.
- *concurrent set* $C(s)$: the set of all states of every site that may be concurrent with state *s*.
- In two-phase commitment: C (w(c)) = {c(p), a(p), w(p)} and C (q(p)) = {q(c), w(c)} (w(c) is the w state of coordinator and q(p) is the q state of participant).
- In three-phase commitment: C (w(c)) = {q(p), w(p), a(p)} and C (w(p)) = {a(c), p(c), w(c)}.

Skeen's Three-Phase Commitment Protocol



F: failure transition

T: timeout transition

Exercise 6

1. For the following two transactions:

T1 **begin**

1 **read** A (obtaining A balance)
2 **write** A *balance*- \$10 to A
3 **read** B (obtaining B balance)
4 **write** B *balance*+\$10 to B

end

T2 **begin**

1 **read** A (obtaining *A balance*)
2 **write** A balance+\$5 to *A*
end

(a) Provide all the interleaved executions (or schedules).
(b) Find all the serializable schedules among the schedules obtained in (a).

Exercise 6 (Cont'd)

2. Point out serializable schedules in the following

L1 = w2(y)w1(y)r3(y)r1(y)w2(x)r3(x)r3(z)r2(z)
L2 = r3(z)r3(x)w2(x)r2(z)w1(y)r3(y)w2(y)r1(y)
L3 = r3(z)w2(y)w2(x)r1(y)r3(y)r2(z)r3(x)w1(y)
L4 = r2(z)w2(y)w2(x)w1(y)r1(y)r3(y)r3(z)r3(x)

3. A voting method called *voting-with-witness* replaces some of the replicas by witnesses. Witnesses are copies that contain only the version number but no data. The witnesses are assigned votes and will cast them when they receive voting requests. Although the witnesses do not maintain data, they can testify to the validity of the value provided by some other replica. How should a witness react when it receives a read quorum request? What about a write quorum request? Discuss the pros and cons of this method.

Table of Contents

Type of Faults

- Types of **faults:**
  - **Hardware** faults
  - **Software** faults
  - **Communication** faults
  - **Timing** faults
- Schneider’s classification:
  - Omission failure
  - Failstop failure (detectable)
  - Crash failure (undetectable)
  - Crash and link failure
  - Byzantine failure

Redundancy

- **Hardware redundancy**: extra PE's, I/O's
- **Software redundancy**: extra version of software modules
- **Information redundancy**: error detecting code
- **Time redundancy**: additional time used to perform a function

Fault Handling Methods

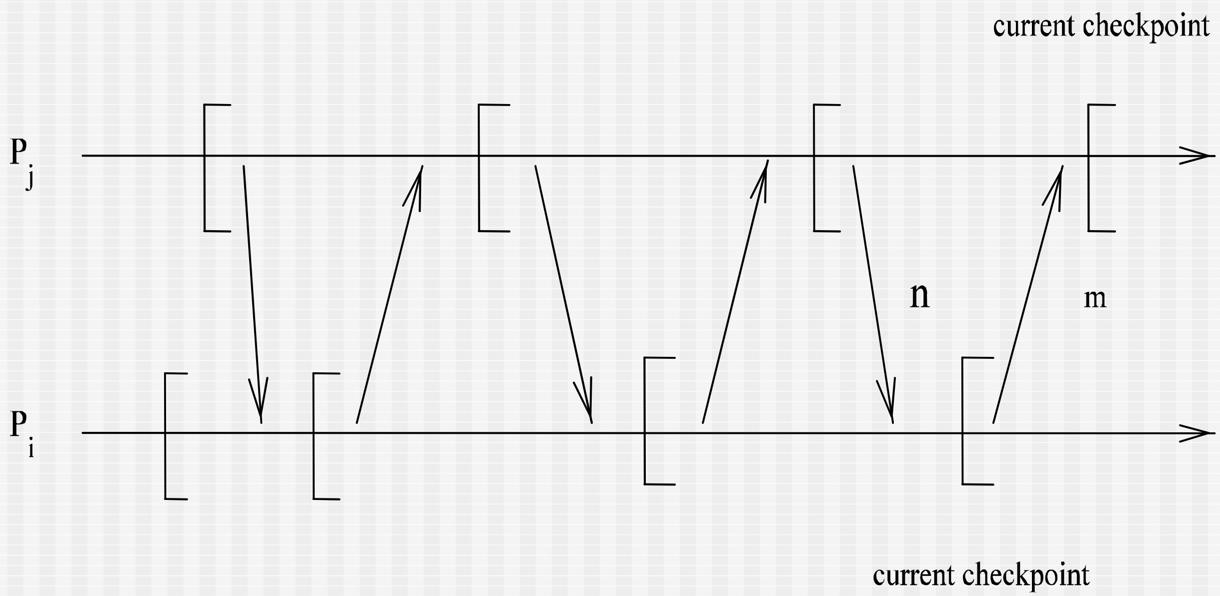
- **Active** replication
- **Passive** replication
- **Semi-active** replication

Building Blocks of Fault-Tolerant Design

- **Stable storage** is a logical abstraction for a special storage that can survive system failure.
- **Fail-stop processors** do not perform any incorrect action and simply cease to function.
- An **atomic action** is a set of operations which are executed indivisibly by hardware. That is, either operations are completed successfully and fully or the state of the system remains unchanged (operations are not executed at all).

Domino Effect

- Storage of checkpoints
- Checkpointing methods



An example of domino effect.

Focus 21: Byzantine Faults

- Several divisions of the Byzantine army camp outside an enemy city. Each division commanded by its own general. Generals from different divisions communicate only through messengers. Some of the generals may be traitors. After observing the enemy, the generals must decide upon a common battle plan.

Two Requirements

- All loyal generals decide upon *the same plan* of action
- A small number of traitors *cannot* cause the loyal generals to *adopt a wrong plan*

Note

- Loyal generals may start with different decisions, but end up the same decision.
- The final decision must come from at least one loyal general's initial decision.

Focus 21 (Cont'd)

- Theoretical result
  - Consensus is reachable if $n \geq 3m + 1$, where n is the total number of generals and m is the number of traitors.

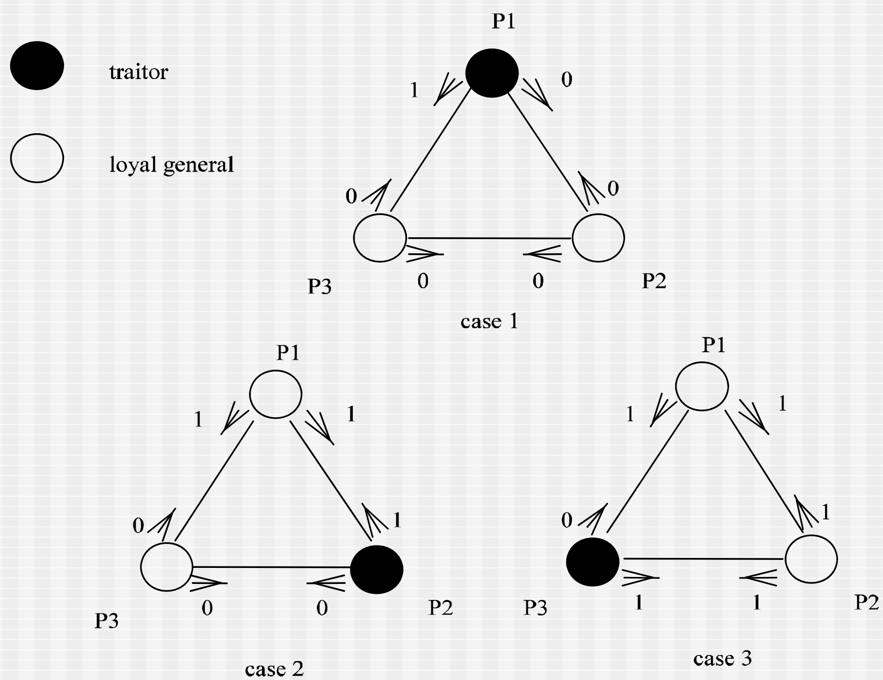
- (m+1)-round of consensus algorithm
  - At the first round, each node, including traitors, broadcasts its initial decision
  - At the (i+1)th round, each node broadcasts all messages received at ith round

Agreement Protocol

P1*	P2	P3	P4
First round: $(-, v_2, v_3, v_4)$	$(v_1^2, -, v_3, v_4)$	$(v_1^1, v_2, - v_4)$	$(v_1^3, v_2, v_3, -)$
Second round: $(v_1^2, -, v_3, v_4)$ $(v_1^1, v_2, -, v_4)$ $(v_1^3, v_2, v_3, -)$	$(v_1^1, v_2, -, v_4)$ $(v_1^3, v_2, v_3, -)$ $(-, v_2^4, v_3^4, v_4^4)$	$(v_1^1, -, v_3, v_4)$ $(v_1^3, v_2, v_3, -)$ $(-, v_2^5, v_3^5, v_4^5)$	$(v_1^2, -, v_3, v_4)$ $(v_1^1, v_2, -, v_4)$ $(-, v_2^6, v_3^6, v_4^6)$
(d_1, d_2, d_3, d_4)	(v_1^7, v_2, v_3, v_4)	(v_1^7, v_2, v_3, v_4)	(v_1^7, v_2, v_3, v_4)

An algorithm for reaching agreement.

No-Agreement Among Three Processes



Cases leading to failure of the Byzantine agreement.

Extended Agreement Protocols

- Boolean values or arbitrary real values for the decisions.
- Unauthenticated or authenticated messages.
- Synchronous or asynchronous.
- Completely connected network or partially connected networks.
- Deterministic or randomized.
- Byzantine faults or fail-stop faults.
- Non-totally decentralized control system and, in particular, hierarchical control systems.

Reliable Communication

- Acknowledgement: acknowledge the receipt of each packet.
- TCP: transport protocol for reliable point-to-point comm.
- Negative acknowledgement
  - Signal for a missing packet.
  - Pros: better scalability (without positive acknowledgement).
  - Cons: sender is forced to keep each packet in the buffer forever.

Reliable Group Communication

- **Feedback suppression**: multicast or broadcast each positive (or negative) acknowledge.
- Combination of positive and negative acknowledgements

Example 26: Combination of Positive and Negative Acknowledgements in Broadcasting.

Let A be a packet and a ($\underline{a}$) the positive (negative) acknowledgement for A.

A,Ba,Cb,Db,Ec,F $\underline{c}$d,Cb,G$\underline{d}$ef

1.Message A is sent first, acknowledged by the sender of B, which is in turn acknowledged by the senders of C and D.

2. The sender of E acknowledges C and the sender of F acknowledges the receipt of D but a negative acknowledgment of C .

3. Some node (not necessarily the original sender) retransmits C .

4. The sender of G acknowledges both E and F but sends a negative acknowledgment of D (after receiving F).

Different Types of Reliable Multicasting

- Reliable multicast: no message ordering
- FIFO multicast: FIFO-ordered delivery
- Causal multicast: causal-ordered delivery
- Atomic multicast: reliable multicast + total-ordered delivery
- FIFO atomic multicast: FIFO multicast + total-ordered delivery
- Causal atomic multicast: Causal multicast + total-ordered delivery

Focus 22: Total-Ordered Multicasting

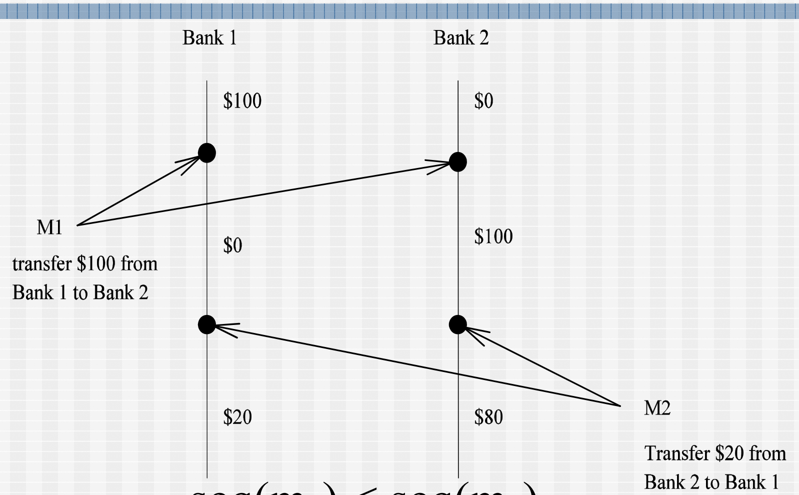
- **Total-ordered multicasting**
  - Each transfer order (message) can be assigned a global sequence number.
  - There exists a global sequence.
- **Sequencer**
  - The sender sends message to a sequencer
  - The sequencer allocates a global sequence number to the message.
  - The message is delivered by every destination based on the order.

Implementations of Sequencer

- Privilege-based (token circulated among the senders)
- Fixed sequencer (a fixed third party)
- Moving sequencer(token circulated among the third-party nodes)

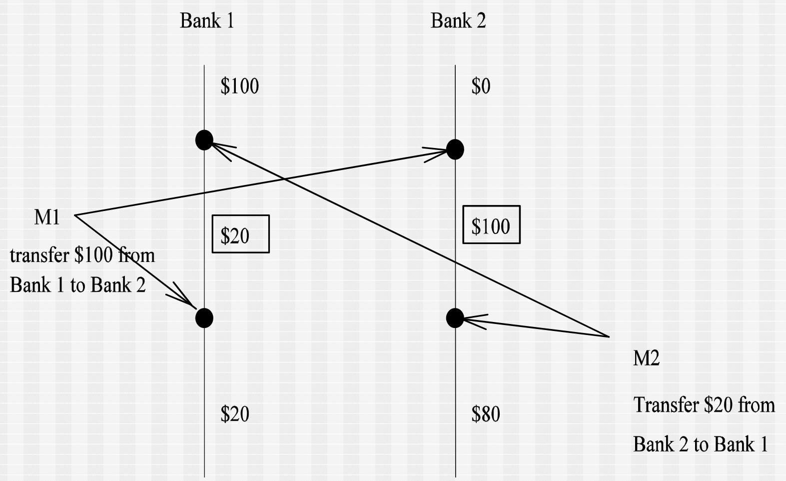
Multicast with Total Order

Multicast with total order



$\mathrm{seq}(m_1) < \mathrm{seq}(m_2)$

Multicast without total order

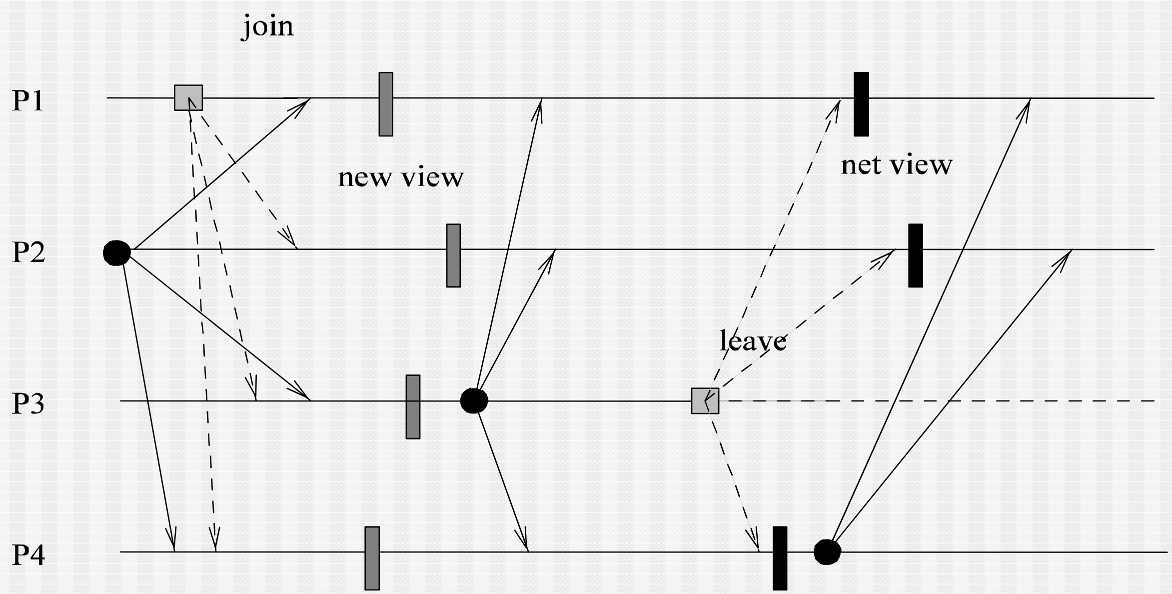


Neither $\mathrm{seq}(m_1) < \mathrm{seq}(m_2)$ nor $\mathrm{seq}(m_2) < \mathrm{seq}(m_1)$

Focus 23: Birman's Virtual Synchrony

- Virtual synchrony: reliable multicast with a special property.
- View: a multicast group.
- View change: (a) a new process joins, (b) a process leaves, and
  (c) a process crashes.
- Each view change is multicast to members in the group.
- Special property: each view change acts as a barrier across which no multicast can pass. (Application: distributed debugging.)

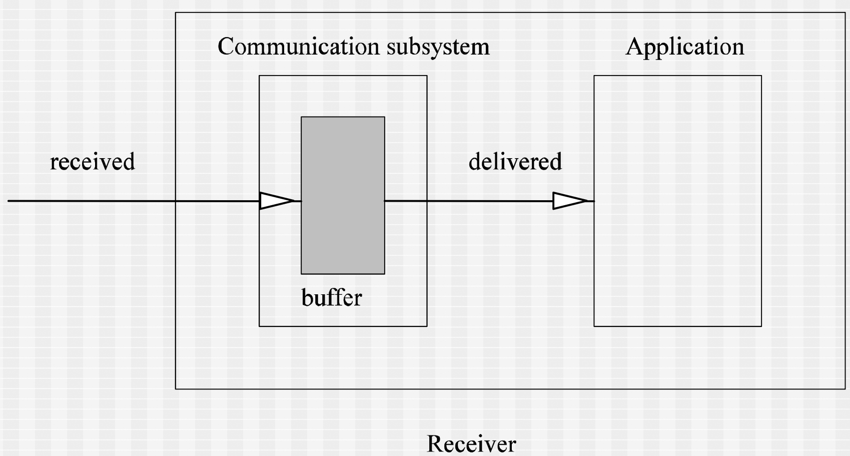
Focus 23 (Cont'd)



Virtual synchrony.

Implementing a Virtual Synchronous Reliable Multicast

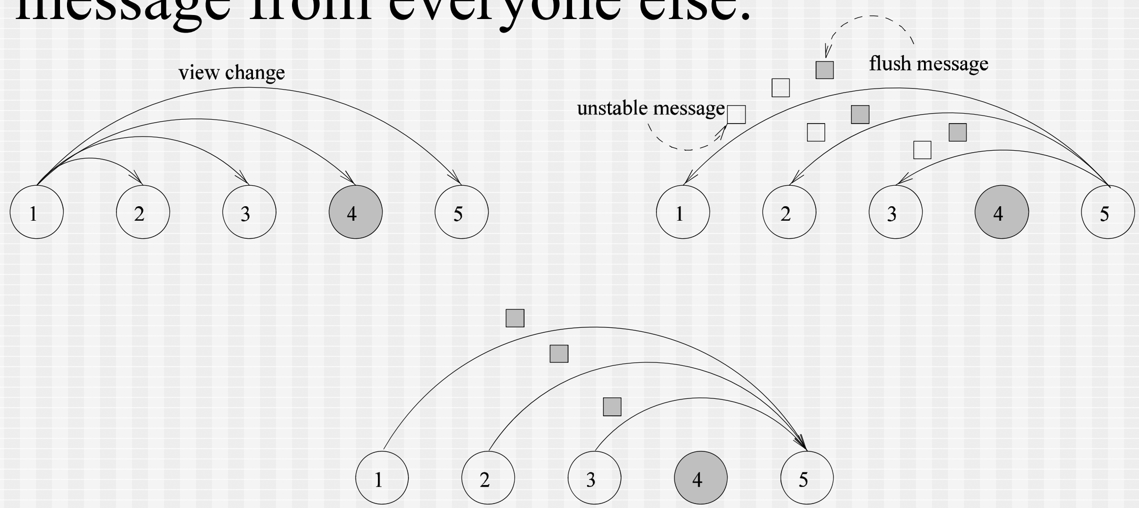
- Message received versus message delivered.
- If message *m* has been delivered to all members in the group, *m* is called **stable**.
- Point-to-point communication is reliable (TCP).
- Sender may crash before completing the multicasting. (Some members received the message but others did not.)



Message receipt versus message delivery.

Implementing a Virtual Synchronous Reliable Multicast (Cont'd)

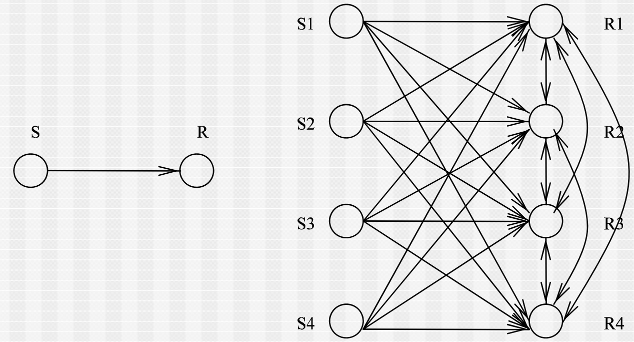
- At group view G_i, a view changed is multicast.
- When a process receives the view-change message for G_{i+1}, it multicasts to G_{i+1} a copy of unstable messages for G_i followed by a **flush message**.
- A process installs the new view G_{i+1} when it has received a flush message from everyone else.



Virtual synchrony.

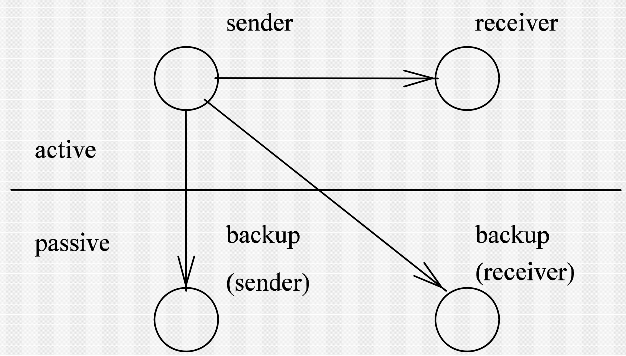
Reliable Process

Active model



(a) (b)

Passive model



Exercise 7

1. Use a practical example to illustrate the differences among faults, errors, and failures.

2. Illustrate the correctness of the agreement protocol for authenticated messages using a system of four processes with two faulty processes. You need to consider the following two cases:

- The sender is healthy and two receivers are faulty (the remaining receiver is healthy).
- The sender is faulty and one receiver is faulty (the remaining receivers are healthy).

3. In Byzantine agreement protocol $k + 1$ rounds of message exchanges are needed to tolerant k faults. The number of processes n is at least $3k + 1$. Assume P_1 and P_2 are faulty in a system of $n = 7$ processes.

- (a) Show the messages P_3 receives in first, second, and third round.
- (b) Demonstrate the correctness of the protocol by showing the final result vector (after a majority voting) for P_3.
- (c) Briefly show that result vectors for other non-faulty processes are the same.

Table of Contents

Distributed Operating Systems

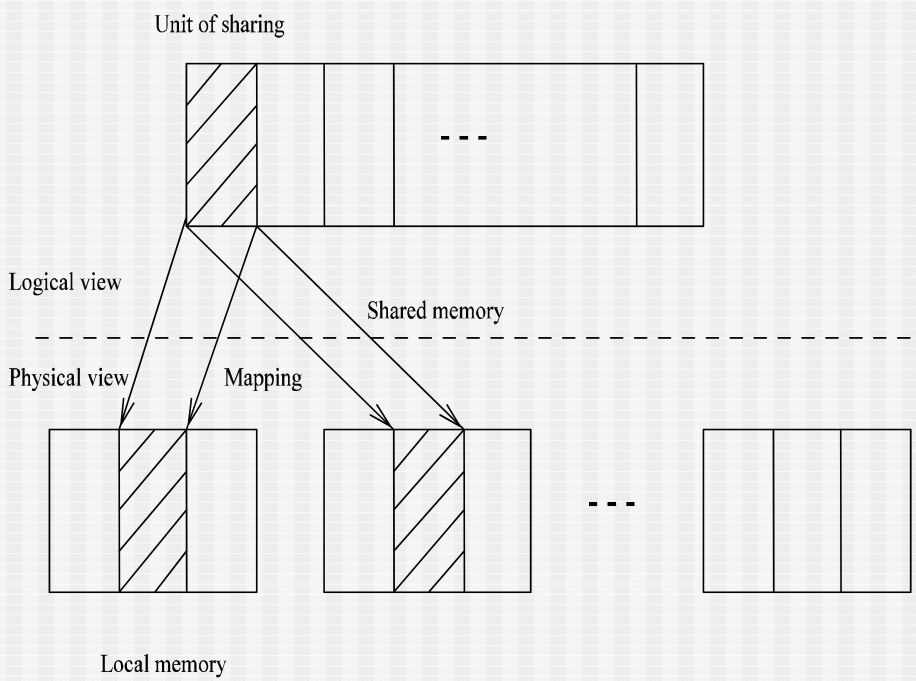
- Key issues
  - Communication primitives
  - Naming and protection
  - Resource management
  - Fault tolerance
  - Services: file service, print service, process service, terminal service, file service, mail service, boot service, gateway service
- **Distributed operating systems** vs. **network operating systems**
- Commercial and research prototypes
  - Wiselow, Galaxy, Amoeba, Clouds, and Mach

Distributed File Systems

- A **file system** is a subsystem of an operating system whose purpose is to provide long-term storage.
- **Main issues**:
  - Merge of file systems
  - Protection
  - Naming and name service
  - Caching
  - Writing policy
- **Research prototypes**:
  - UNIX United, Coda, Andrew (AFS), Frangipani, Sprite, Plan 9, DCE/DFS, and XFS
- **Commercial:**
  - Amazon S3, Google Cloud Storage, Microsoft Azure, SWIFT (OpenStack)

Distributed Shared Memory

A **distributed shared memory** is a shared memory abstraction what is implemented on a loosely coupled system.



Distributed shared memory.

Focus 24: Stumm and Zhou's Classification

- **Central-server algorithm** (nonmigrating and nonreplicated).
  - (Client) Sends a data request to the central server.
  - (Central server) Receives the request, performs data access and
    sends a response.
  - (Client) Receives the response.

Focus 24 (Cont'd)

- **Migration algorithm** (migrating and non-replicated).
  - (Client) If the needed data object is not local, determines the
    location and then sends a request.
  - (Remote host) Receives the request and then sends the object.
  - (Client) Receives the response and then accesses the data object (read and /or write).

Focus 24 (Cont'd)

- **Read-replication algorithm** (migrating and replicated)
  - (Client) If the needed data object is not local, determines the location and sends a request.
  - (Remote host) Receives the request and then sends the object.

Focus 24 (Cont'd)

- (Client) Receives the object and then multicasts by sending either invalidate or update messages to all sites that have a copy of the data object.
- (Remote host) Receives an invalidation signal and then invalidates its local copy, or receives an update signal and then updates the local copy.
- (Client) Accesses the data object (write).

Focus 24 (Cont'd)

- **Full-replication algorithm** (non-migrating and replicated)
  - (Client) If it is a write, sends the data object to the sequencer.
  - (Sequencer) Receives the data object and adds a sequence number. Sends the client a signal with the sequence number and multicasts the data object together with the sequence number to all the other sites.

Focus 24 (Cont'd)

- (Client) Receives the acknowledgment and updates local memory based on the sequence number of each data object.

  (Other sites) Receive the data object and update local memory based on the sequence number of each data object.

Focus 24 (Cont'd)

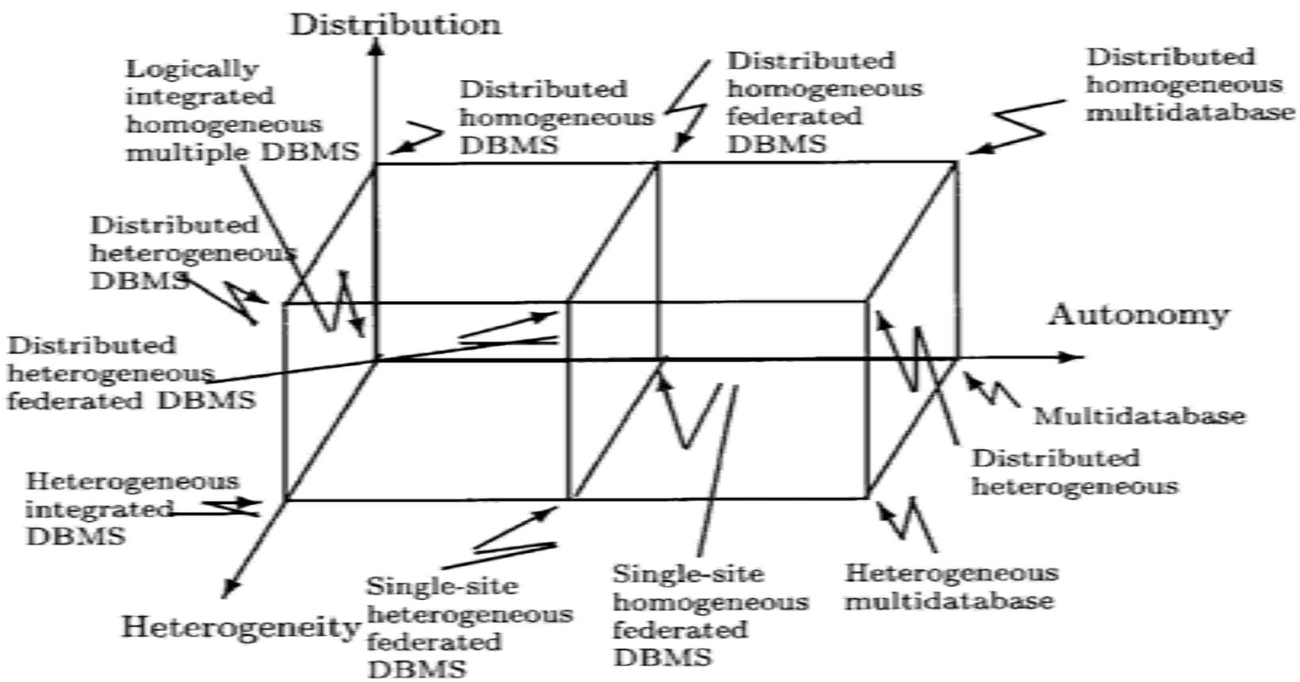
- **Main Issues**:
  - Structure and granularity
  - Coherence semantics
  - Scalability
  - Heterogeneity
- **Several research prototypes**:
  - Dash, Ivy, Munin, and Clouds
  - Alewife (MIT), Treadmarks (Rice), Coherent Virtual machine (Maryland), and Millipede (Israel Inst. Tech.)

Distributed Database Systems

A **distributed database** is a collection of multiple, logically interrelated databases distributed over a computer network.

- **Possible design alternatives**:
  - Autonomy
  - Distribution
  - Heterogeneity

Distributed Database Systems (Cont'd)



Alternative architectures.

Essentials of Distributed Database Systems

- Local autonomy
- No reliance on a central site
- Continuous operation
- Location independence
- Fragment independence
- Replication independence
- Distributed query processing
- Distributed transaction management
- Hardware independence
- Operating system independence
- Network independence
- Data independence

Open Research Problems

- Network scaling problem
- Distributed query processing
- Integration with distributed operating systems
- Heterogeneity
- Concurrency control
- Security
- Next-generation database systems:
  - Object-oriented database management systems
  - Knowledge base management systems

Prototypes and Products

- Research Prototypes
  - ADDS (Amocha Distributed Database Systems)
  - JDDBS (Japanese Distributed Database Systems)
  - Ingres/star
  - SWIFT (Society for Worldwide Interbank Financial Telecomm)
  - System R, MYRIAD, MULTIBASE, and MERMAID
- Commercial products (XML, NewSQL, and NoSQL)
  - Blockchain (popularized by bitcoin)
  - Aerispike, Cassandra, Clusterpoint, Druid (open-source data store)
  - ArangoDB, ClustrixDB, Couchbase, FoundationDB, NueDB, and OrientDB

Heterogeneous Processing

- Tuned use of diverse processing hardware to meet distinct computational needs.
  - **Mixed-machine systems**. Different execution modes by inter-connecting several different machine models.
  - **Mixed-mode systems**. Different execution modes by reconfigurable parallel architecture obtained by interconnecting the same processors.

Classifications

- Single Execution Mode/Single Machine Model (SESM)
- Single Execution Mode/Multiple Machine Models (SEMM)
- Multiple Execution Modes/Single Machine Model (MESM)
- Multiple Execution Modes/Multiple Machine Models (MEMM)

Focus 25: Optimization

An optimization problem that minimizes

$$\sum t_{i,j}$$

such that

$$\sum c_j \leq C$$

where $t_{i,j}$ equals the time for machine i on code segment j, c_i equals the cost for machine i, C equals the specified overall cost constraint.

Table of Contents

"Killer" Applications

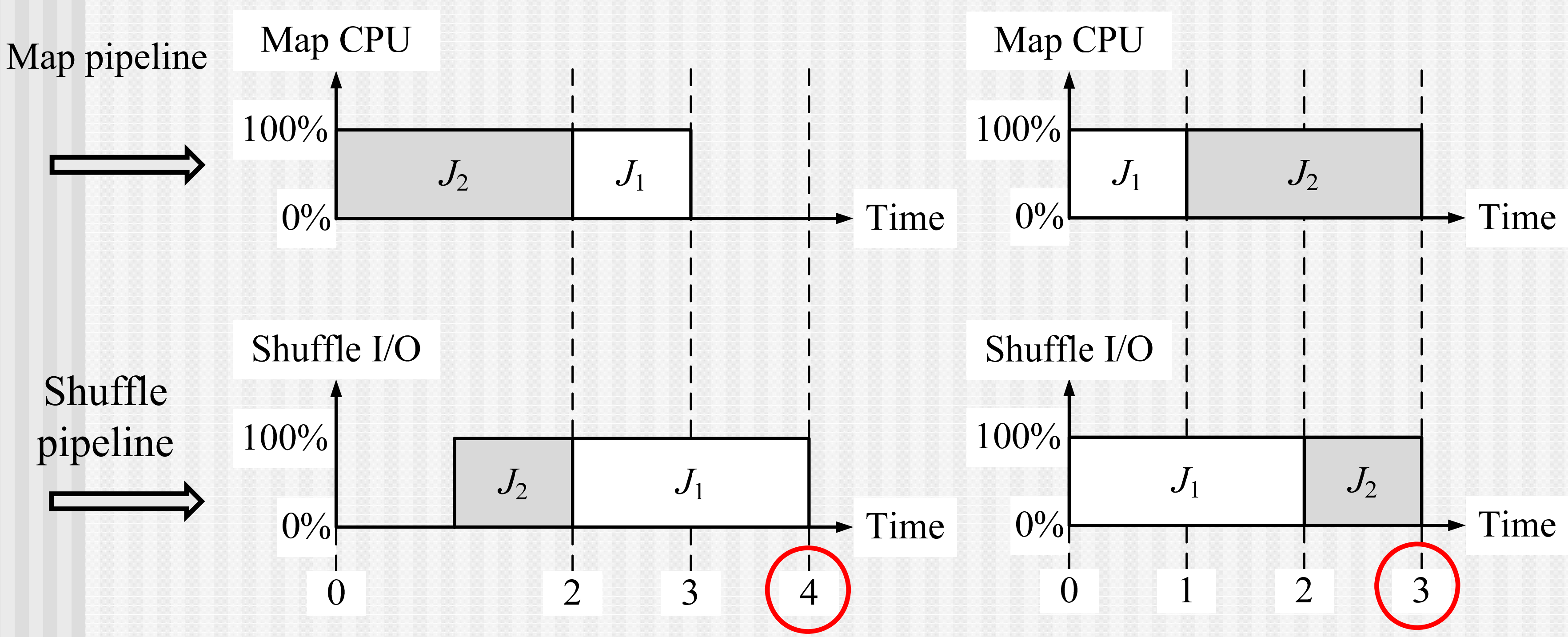
- Distributed Object-based Systems: CORBA
- Distributed Document-based Systems: WWW
- Distributed Coordination-based Systems: JINI
- Distributed Multimedia Systems: QoS requirements
- Distributed currency and transactions: Bitcoin and blockchain

Other Applications: MapReduce

- A framework for processing highly distributable problems across huge datasets on a file system or a database.
  - Map: In a recursive way, the master node takes the input, divides it into smaller sub-problems, and distributes them to worker nodes.
  - Reduce: The master node then collects the answers to all the sub-problems and combines them in some way to form the output. The shuffle is used collect all data through I/O. Usually, shuffle dominates the actual reduce phase.
- Apache Hadoop: a software framework that supports data-intensive distributed applications under a free license. It was derived from Google's MapReduce and Google File System (GFS).
- Spark for Big Data and beyond

Pipeline: Map followed by Shuffle

Impact of overlapping map and shuffle



WordCount (map-heavy)

TeraSort (shuffle-heavy)

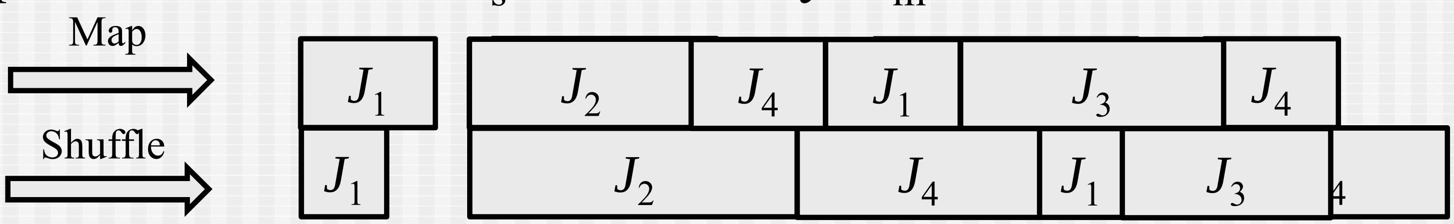
Minimize Last Job: Flow Shop

Minimize last job completion time

l-phase flow shop is solvable when l=2

- G_m: map-heavy jobs sorted in increasing order of map load
- G_s: shuffle-heavy jobs sorted in decreasing order of shuffle load

Optimal schedule: G_s followed by G_m



S. M. Johnson, Optimal two-and three-stage production schedules with setup times included, *Naval Research Logistics Quarterly*, 1954.

Minimize Average Jobs: Strong Pair

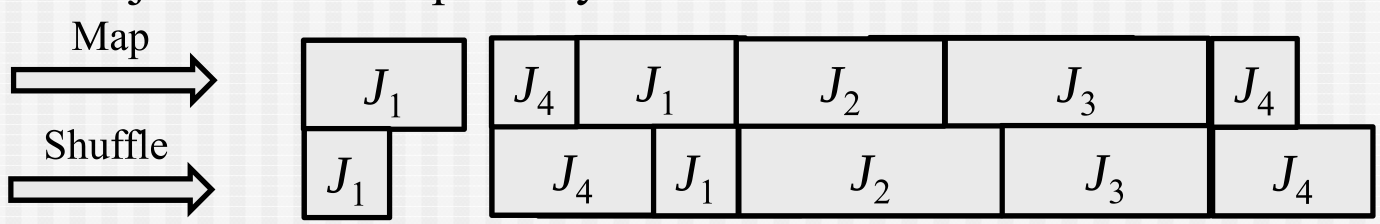
Minimize average job completion time, NP-hard in general

Special case one: strong pair

- J_1 and J_2 are a strong pair if $m_1 = s_2$ and $s_1 = m_2$ (m: map, s: shuffle)

Optimal schedule: jobs are strong pairs

Pair jobs and rank pairs by total workloads



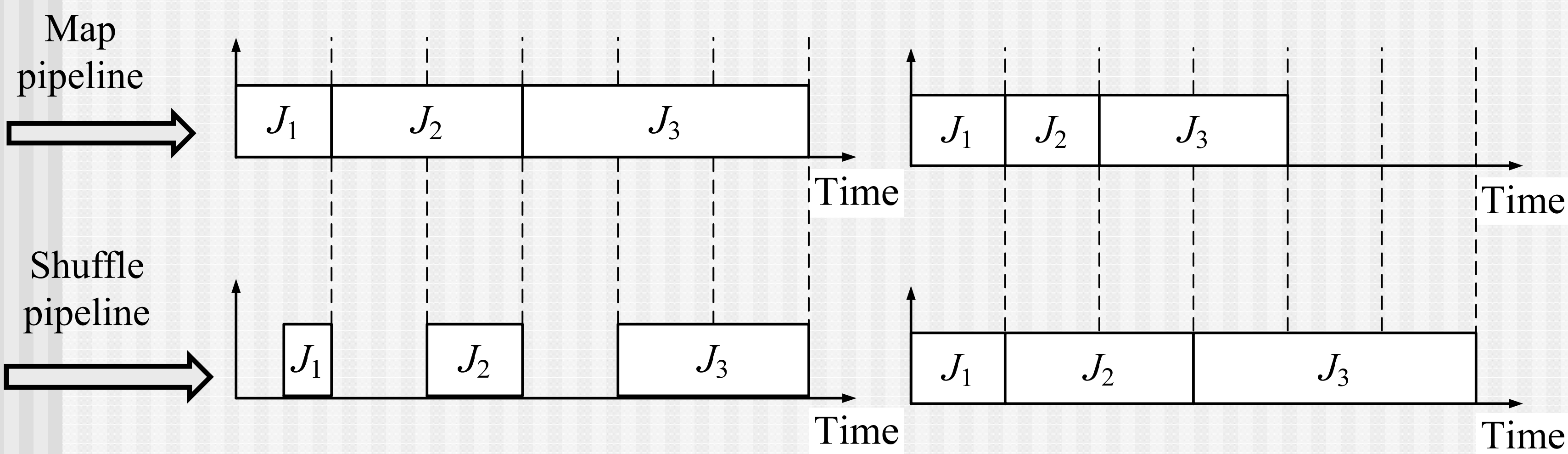
H. Zheng, Z. Wan, and J. Wu, Optimizing MapReduce framework through joint scheduling of overlapping phases, *Proc. of IEEE ICCCN*, 2016.

Minimize Average Jobs: Dominant Load

Special case two: when all jobs are map-heavy or shuffle-heavy

Optimal schedule:

- Sort jobs ascendingly by dominant workload max{m, s}
- Execute smaller jobs earlier



Finishing times J_1, J_2, J_3: 1, 3, 6 vs. J_3, J_2, J_1: 3, 5, 6

Other Applications: Crowdsourcing

How Much Data?

- Facebook: 40 B photos; 30 B pieces of content shared every month
- WeChat: 846 M users and 20 B message per day
- Global Internet traffic: quadrupled from 2010 to 2015, reaching 966 EB (10^{18}) per year

(All human knowledge created from the dawn of man to 2003 is totaled 5 EB)

640K ought to be enough for anybody.

Big Data Era

- "In information technology, big data consists of datasets that grow so large that they become awkward to work with using on-hand database management tools."
- Computers are not efficient in processing or creating certain things: pattern recognition, complex communication, and ideation.
- Crowdsourcing: coordinating a crowd (a large group of people online) to do microwork (small jobs) that solves problems (that software or one user cannot easily do)
- Crowdsourcing: crowd + outsourcing (through Internet)

The Benefits of Crowdsourcing

- Performance
  - Inexpensive and fast
  - The whole is greater than the sum of its parts
- Human Processing Unit (HPU)
  - More effective than CPU (for some apps)
    - Verification and validation: Image labeling
    - Interpretation and analysis: language translation
    - Surveys: Social network survey
- High adoption in business (85% of the top global brands) based on eYeka

Basic Components of Crowdsourcing

- Requester
  - People submit jobs (microwork)
  - Human Intelligence Tasks (HITs)
- Worker
  - People work on jobs
- Platform
  - Job management

Amazon Mechanical Turk (MTurk): 18th century chess playing robot with a human inside

Requester

Worker Pool

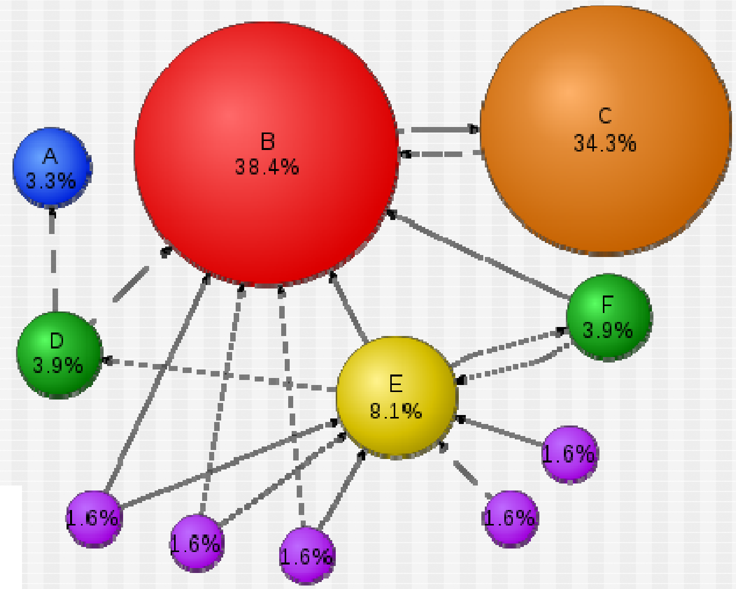
Other Applications: PageRank

A link analysis algorithm

- PR(E): Rage Rank of E
- likelihood that a person randomly clicking on links will arrive at any particular page

$$PR(p_i) = \frac{1-d}{N} + d \sum_{p_j \in M(p_i)} \frac{PR(p_j)}{L(p_j)}$$

$M(p_i)$: set of pages link to p_i, $L(p_j)$: the number of outgoing links on p_j, d: dumping factor, N: total number of pages.



HITS (Jon Kleinberg): each node has two values in a mutual recursion

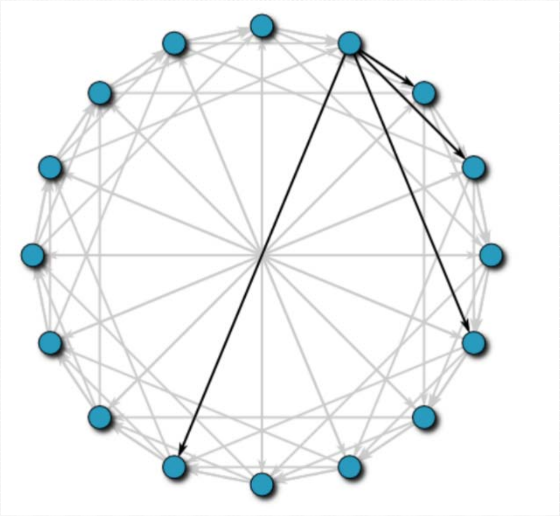
- Authority: the sum of the *Hub Scores* of each node that points to it.
- Hub: the sum of the *Authority Scores* of each node that it points to.

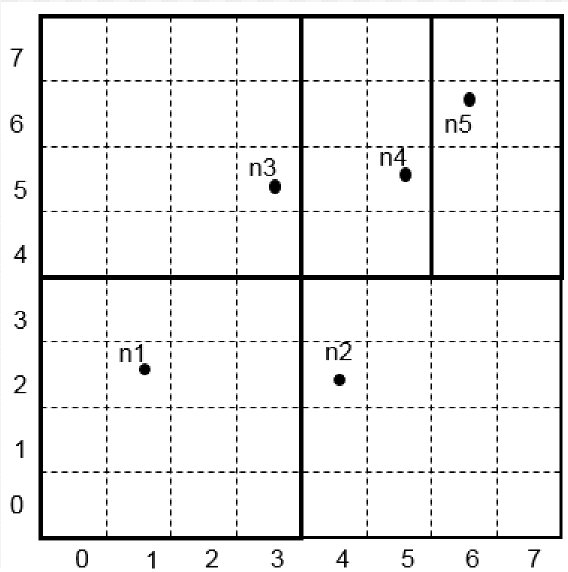
Other Applications: P2P Systems

- Client/server limitations: scalability, single point of failure, etc.
- P2P: an overlay network no centralized control, e.g., Blockchain
- Unstructured P2P
  - Napster: share music, server stores index
  - Gnutella: no server, query flooding
  - Kazza: supernodes to improve scalability
  - Freenet: data caching in reverse path of query
  - BitTorrent: Tit-for-Tat to avoid *free-raiders*
- Structured P2P: *distributed hash table* (DHT): map key to value
  - Chord: n-node ring, table size: log(n), search time: log(n)
  - CAN: n-node d-dimension mesh, table size: d, search time: $d\ n^{1/d}$
  - Others based on different graphs: De Brujin, Butterfly, and Kautz graphs

P2P Systems: Search

- Unstructured P2P
  - BFS and variations (e.g. expanding rings and directed BFS)
  - Probabilistic search and variations (e.g., random walk)
  - Indices-based search and variations (e.g., dominating-set and Bloom filter)
- Structured P2P: Chord (hypercube) and CAN (2-D mesh)





Emerging Systems

- **Wireless networks** and **mobile computing: mobile agents**
  - Move the computation to the data rather than the data to the computations.
- **Grid**
  - TeraGrid: 13.6 teraflops of Linux Cluster computing power distributed at the four TeraGrid sites.
  - Open Grid Services Architecture (OGSA): delivering tighter integration between grid computing networks and Web services technologies.
  - Grid Computing (via OGSA) as the basis of evolution of Internet computing in the future.

Distributed Grid

OptIPuter (UC San Diego and U. of Chicago)

- Parallel optical networks using IP
- Supernetworks: networks faster than the computers attached to them
- Parallelism takes the form of multiple wavelengths, or lambdas (1-10 Gbps)
- A new resource abstraction: distributed virtual computer

E-Science (UK Research Councils, 2001)

- Large-scale science carried out through distributed global collaboration enabled by networks, requiring access to very large data collaborations, very large-scale computing resources, and high-performance visualization.

Cloud (edge, fog) Computing

Sharing of resources to achieve coherence and economies of scale similar to utility (e.g. electricity grid) over a network (e.g. Internet)

- Characteristics
  - Agility, API, cost, device, virtualization, multi-tenancy, reliability, scalability, performance, security, maintenance
- Service
  - Infrastructure as a Service (LaaS)
  - Platform as a Service (PaaS)
  - Software as a Service (SaaS)