Modulo II – Sincronização
Sistemas Distribuídos

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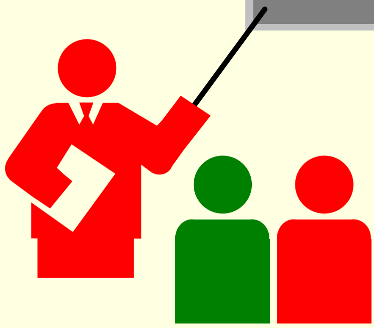
Ementa

- Sistemas Distribuídos
  - *Cliente-Servidor*

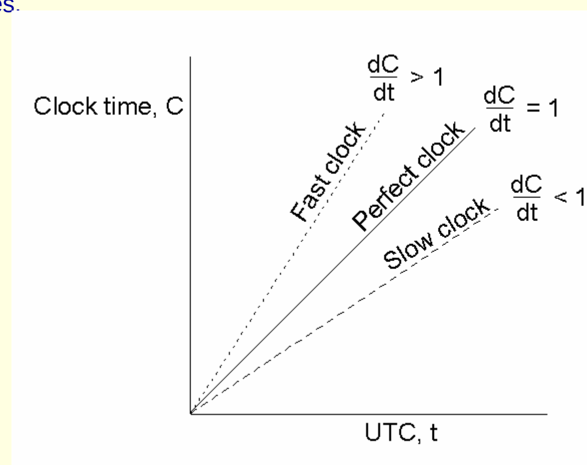
SCD – CO023

Clock Synchronization



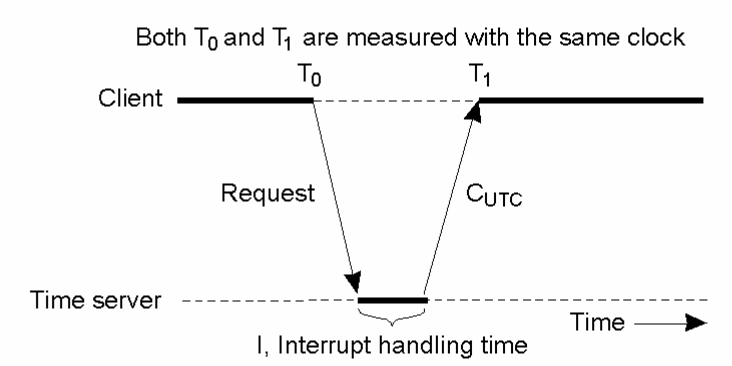
Clock Synchronization Algorithms

- The relation between clock time and UTC when clocks tick at different rates.

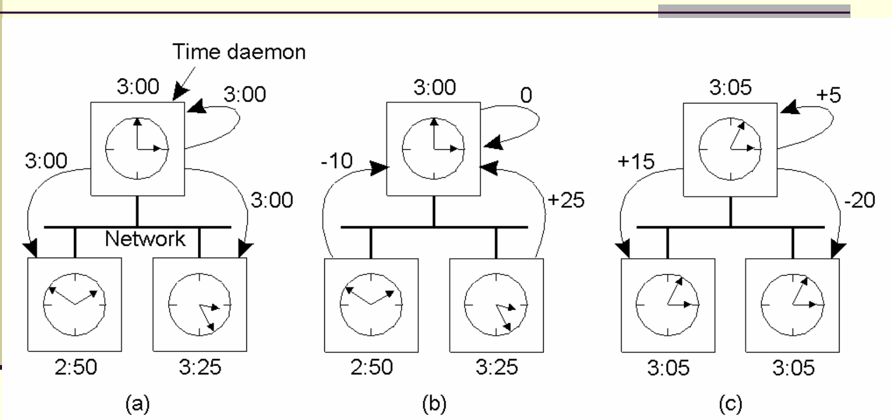


Cristian's Algorithm

- Getting the current time from a time server.

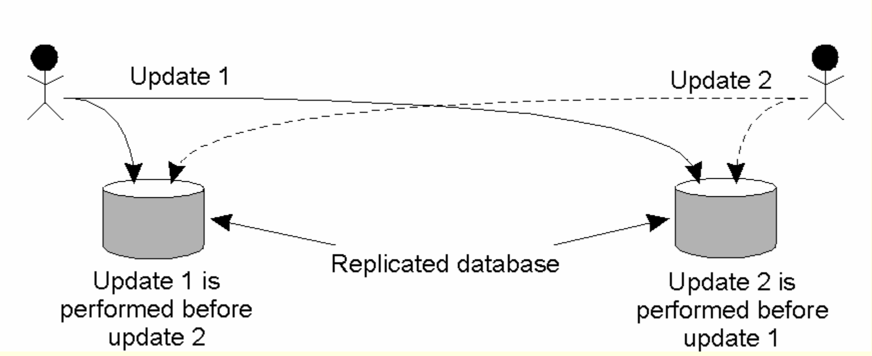


The Berkeley Algorithm



a) The time daemon asks all the other machines for their clock values
b) The machines answer
c) The time daemon tells everyone how to adjust their clock

Lamport Timestamps



a) Three processes, each with its own clock. The clocks run at different rates.
b) Lamport's algorithm corrects the clocks.

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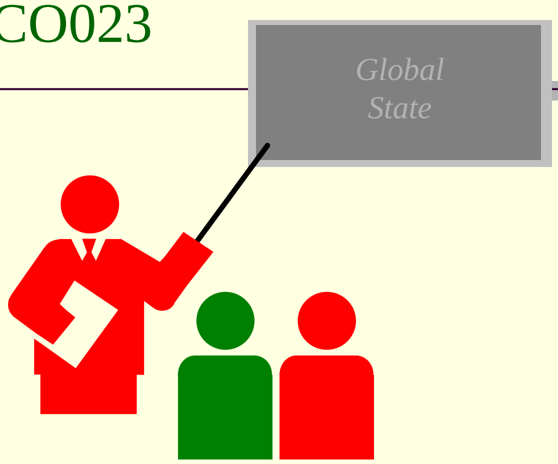
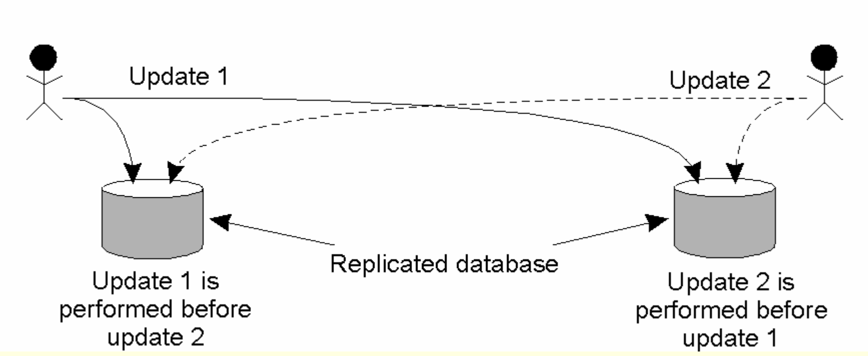


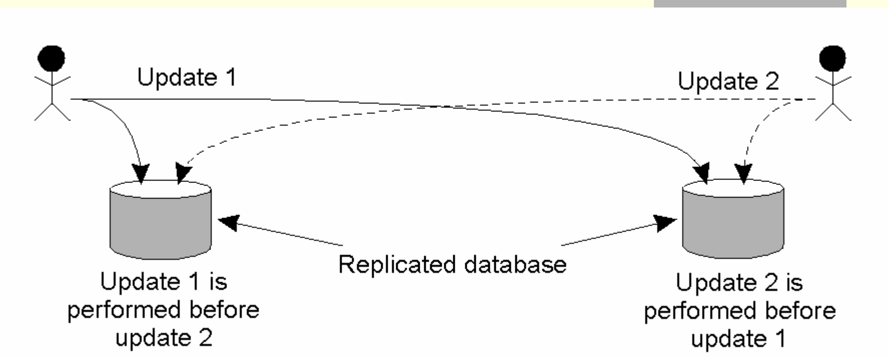
Lamport Timestamps



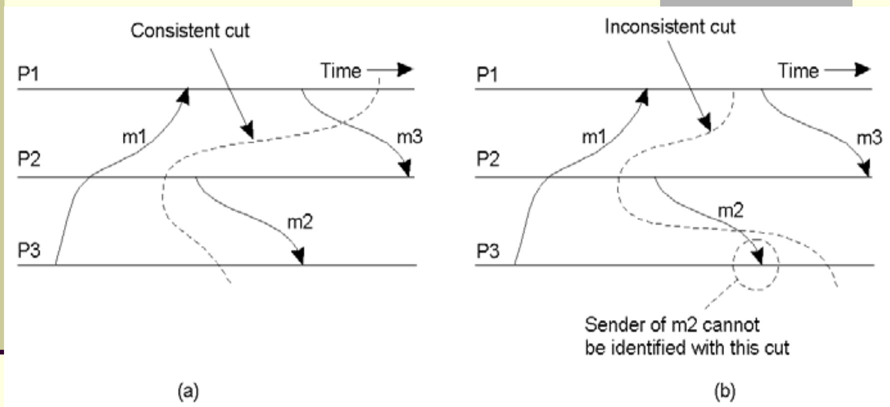
a) Three processes, each with its own clock. The clocks run at different rates.

b) Lamport's algorithm corrects the clocks.

Example: Totally-Ordered Multicasting

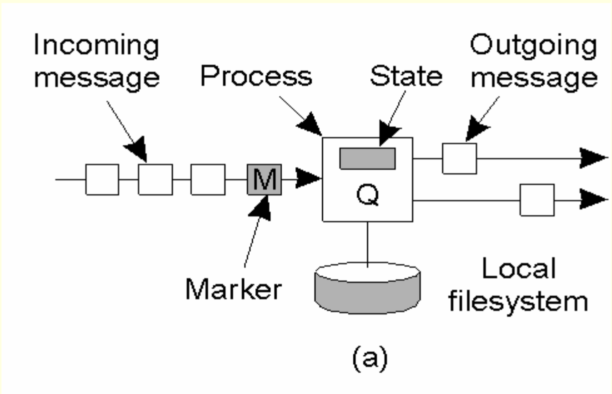


Global State (1)



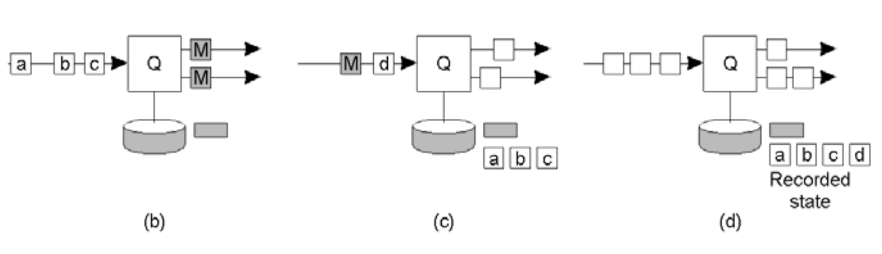
a) A consistent cut
b) An inconsistent cut

Global State (2)



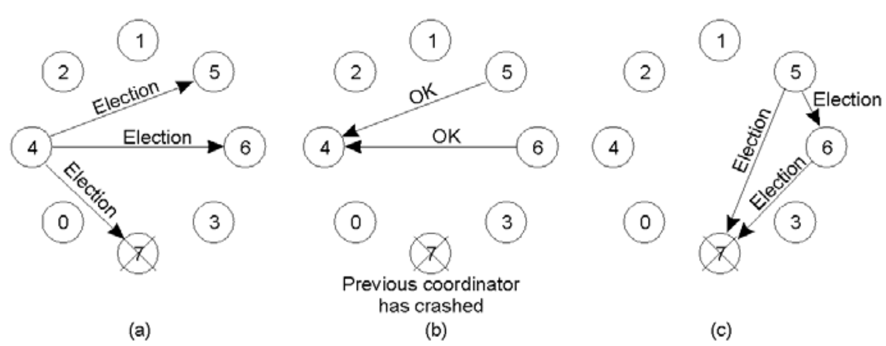
a) Organization of a process and channels for a distributed snapshot

Global State (3)



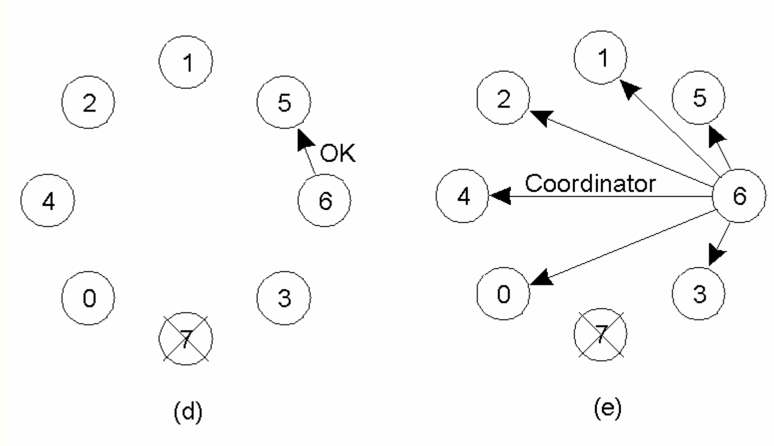
b) Process Q receives a marker for the first time and records its local state
c) Q records all incoming message
d) Q receives a marker for its incoming channel and finishes recording the state of the incoming channel

The Bully Algorithm (1)

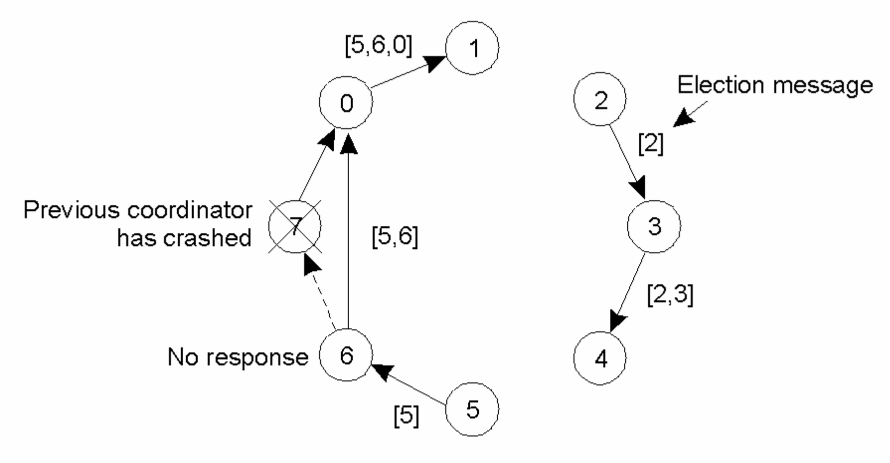


- The bully election algorithm
- Process 4 holds an election
- Process 5 and 6 respond, telling 4 to stop
- Now 5 and 6 each hold an election

Global State (3)



A Ring Algorithm



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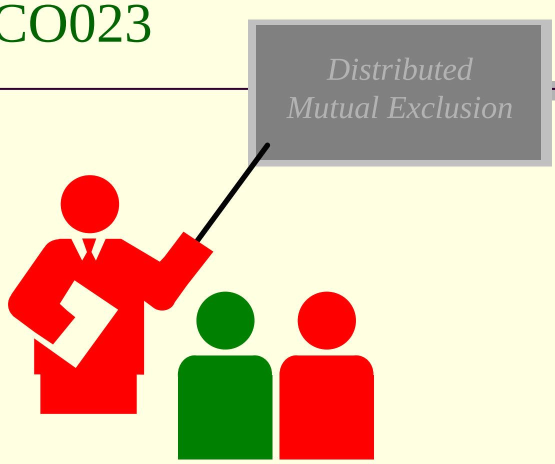
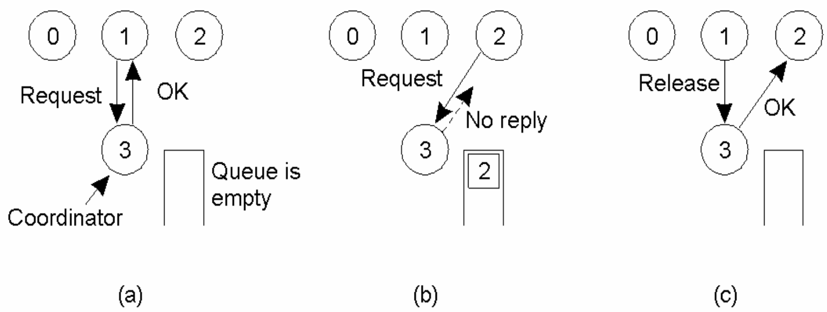
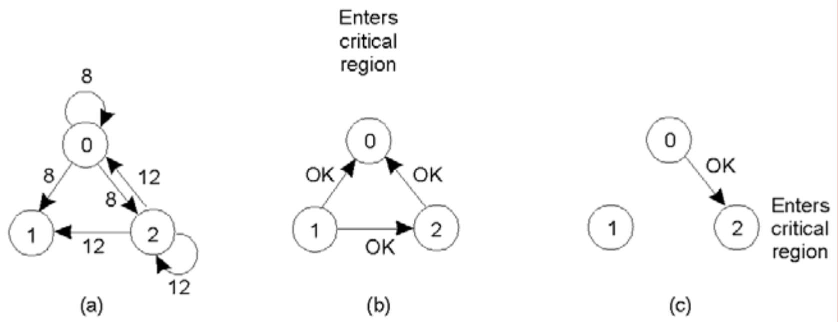


Mutual Exclusion: A Centralized Algorithm



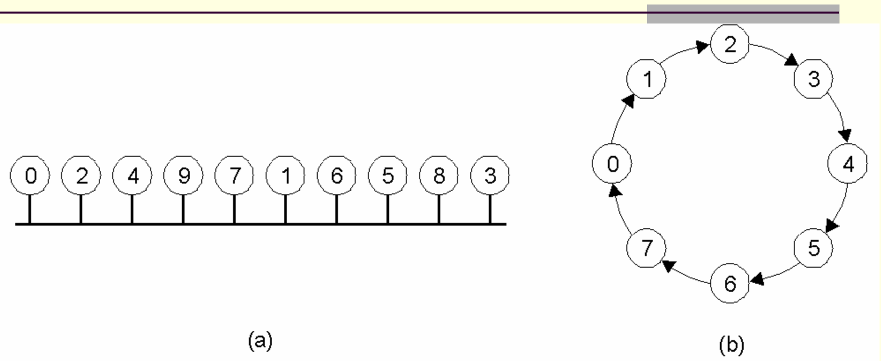
a) Process 1 asks the coordinator for permission to enter a critical region. Permission is granted
b) Process 2 then asks permission to enter the same critical region. The coordinator does not reply.
c) When process 1 exits the critical region, it tells the coordinator, when then replies to 2

A Distributed Algorithm



a) Two processes want to enter the same critical region at the same moment.
b) Process 0 has the lowest timestamp, so it wins.
c) When process 0 is done, it sends an OK also, so 2 can now enter the critical region.

A Toke Ring Algorithm



a) An unordered group of processes on a network.
b) A logical ring constructed in software.

Comparison

Algorithm	Messages per entry/exit	Delay before entry (in message times)	Problems
Centralized	3	2	Coordinator crash
Distributed	2 (n – 1)	2 (n – 1)	Crash of any process
Token ring	1 to ∞	0 to n – 1	Lost token, process crash

- A comparison of three mutual exclusion algorithms.

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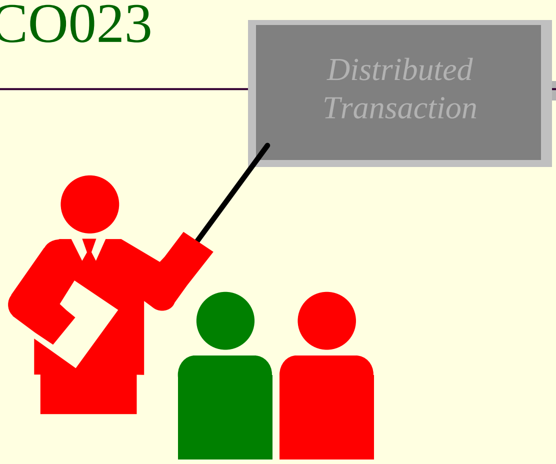
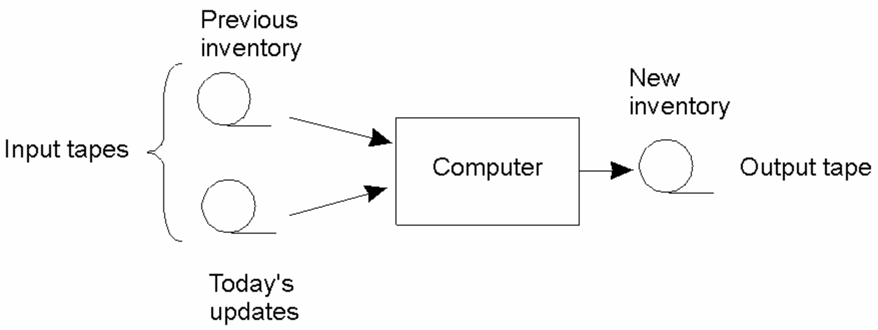


The Transaction Model (1)



The Transaction Model (2)

- Examples of primitives for transactions.

Primitive	Description
BEGIN_TRANSACTION	Make the start of a transaction
END_TRANSACTION	Terminate the transaction and try to commit
ABORT_TRANSACTION	Kill the transaction and restore the old values
READ	Read data from a file, a table, or otherwise
WRITE	Write data to a file, a table, or otherwise

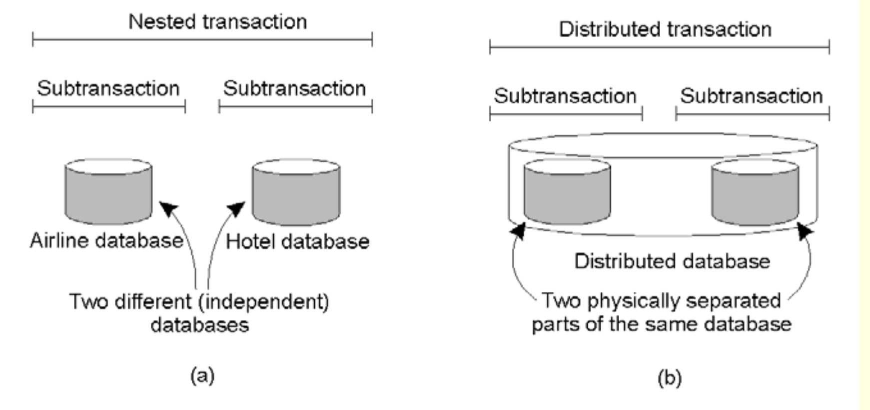
The Transaction Model (3)

```
BEGIN_TRANSACTION
  reserve WP -> JFK;
  reserve JFK -> Nairobi;
  reserve Nairobi -> Malindi;
END_TRANSACTION
           (a)
```

```
BEGIN_TRANSACTION
  reserve WP -> JFK;
  reserve JFK -> Nairobi;
  reserve Nairobi -> Malindi full =>
ABORT_TRANSACTION
           (b)
```

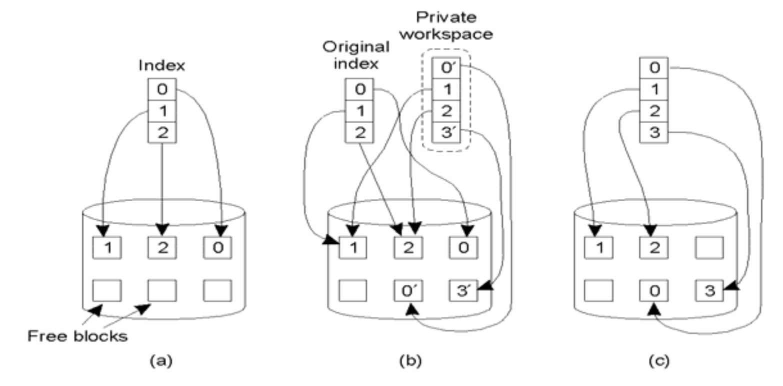
a) Transaction to reserve three flights commits
b) Transaction aborts when third flight is unavailable

Distributed Transactions



a) A nested transaction
b) A distributed transaction

Private Workspace



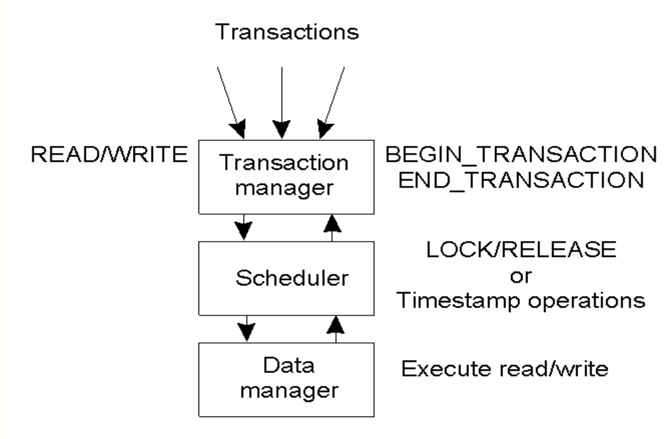
a) The file index and disk blocks for a three-block file
b) The situation after a transaction has modified block 0 and appended block 3
c) After committing

Writeahead Log

	Log	Log	Log
x = 0;			
y = 0;			
BEGIN_TRANSACTION;			
x = x + 1;	[x = 0 / 1]	[x = 0 / 1]	[x = 0 / 1]
y = y + 2		[y = 0/2]	[y = 0/2]
x = y * y;			[x = 1/4]
END_TRANSACTION;			
(a)	(b)	(c)	(d)

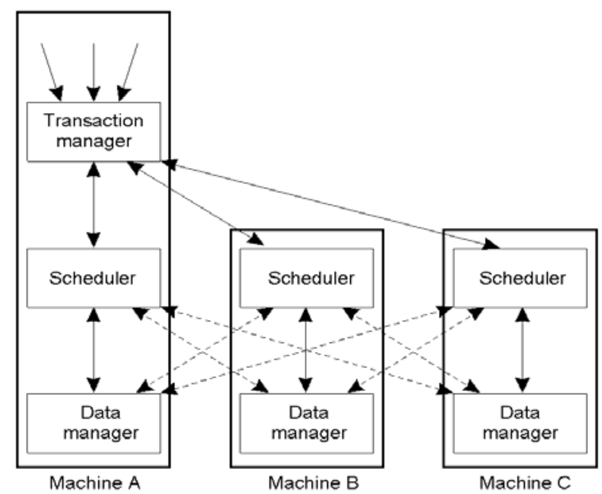
a) A transaction
b) – d) The log before each statement is executed

Concurrency Control (1)



- General organization of managers for handling transactions.

Concurrency Control (2)



- General organization of managers for handling distributed transactions.

Serializability

BEGIN_TRANSACTION	BEGIN_TRANSACTION	BEGIN_TRANSACTION
x = 0;	x = 0;	x = 0;
x = x + 1;	x = x + 2;	x = x + 3;
END_TRANSACTION	END_TRANSACTION	END_TRANSACTION
(a)	(b)	(c)

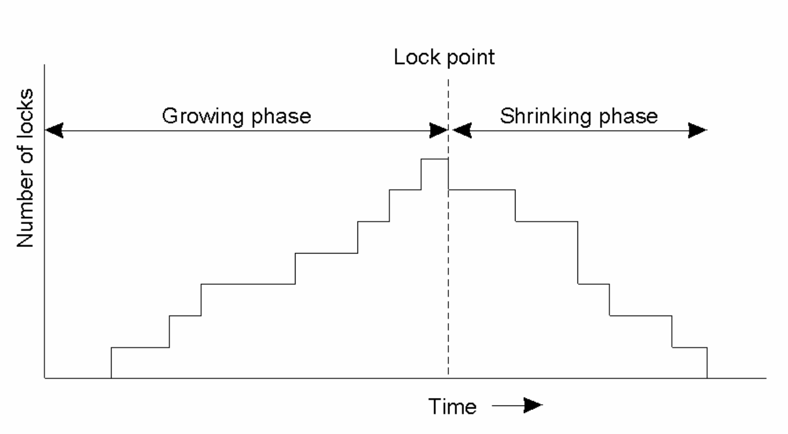
Schedule 1	x = 0; x = x + 1; x = 0; x = x + 2; x = 0; x = x + 3	Legal
Schedule 2	x = 0; x = 0; x = x + 1; x = x + 2; x = 0; x = x + 3;	Legal
Schedule 3	x = 0; x = 0; x = x + 1; x = 0; x = x + 2; x = x + 3;	Illegal

(d)

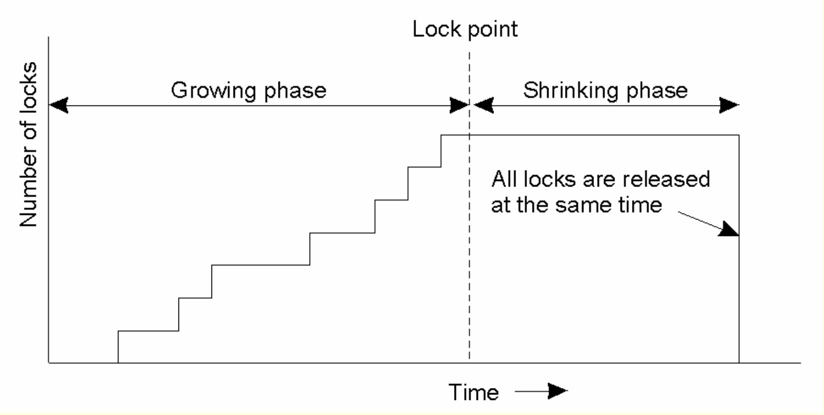
a) – c) Three transactions T_1, T_2, and T_3

d) Possible schedules

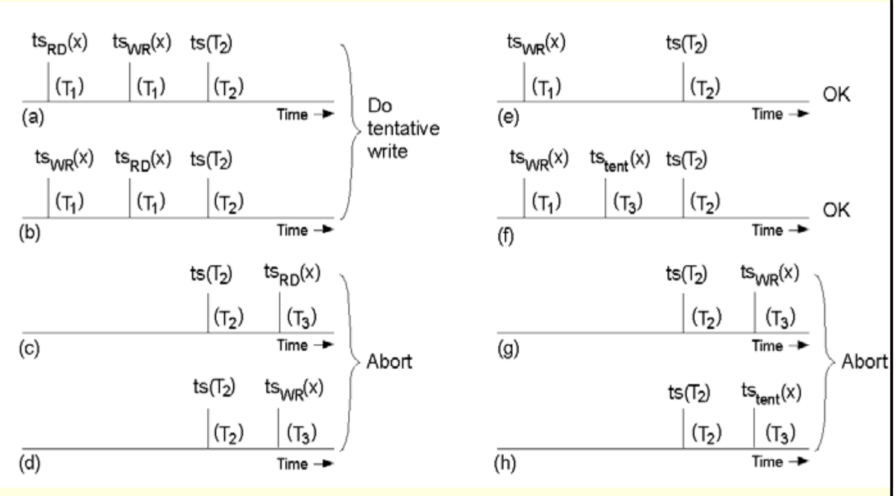
Two-Phase Locking (1)



Two-Phase Locking (2)



Pessimistic Timestamp Ordering



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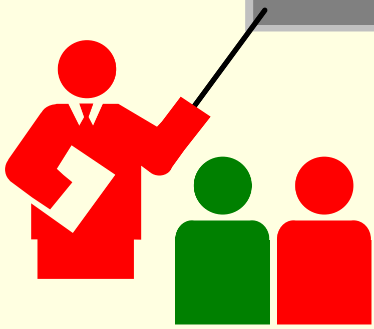
Concurrency Control



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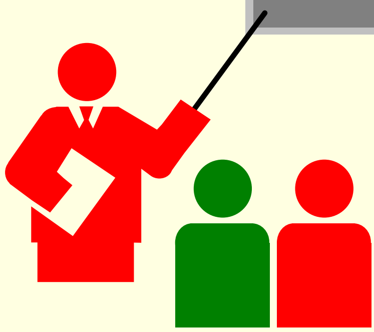
Distributed Coordination



Chapter 18 Distributed Coordination

- Event Ordering
- Mutual Exclusion
- Atomicity
- Concurrency Control
- Deadlock Handling
- Election Algorithms
- Reaching Agreement

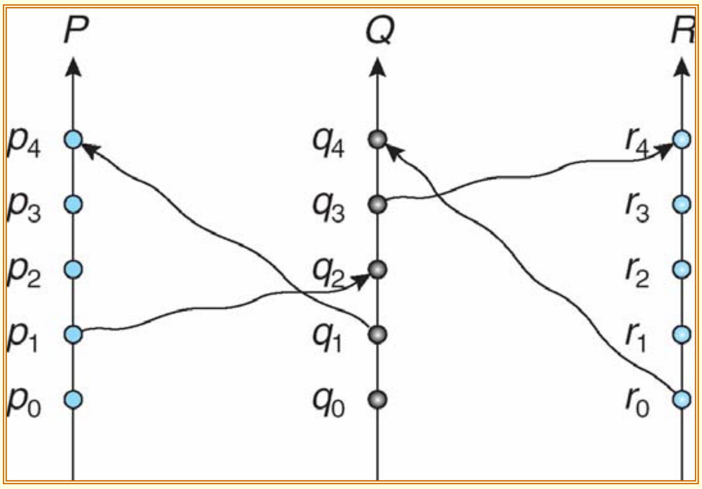
Chapter Objectives

- To describe various methods for achieving mutual exclusion in a distributed system
- To explain how atomic transactions can be implemented in a distributed system
- To show how some of the concurrency-control schemes discussed in Chapter 6 can be modified for use in a distributed environment
- To present schemes for handling deadlock prevention, deadlock avoidance, and deadlock detection in a distributed system

Event Ordering

- *Happened-before* relation (denoted by $\rightarrow$)
  - If A and B are events in the same process, and A was executed before B, then $A \rightarrow B$
  - 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 $A \rightarrow B$
  - If $A \rightarrow B$ and B $\rightarrow C$ then $A \rightarrow C$

Relative Time for Three Concurrent Processes



Implementation of →

- Associate a timestamp with each system event
  - Require that for every pair of events A and B, if A → B, then the timestamp of A is less than the timestamp of B
- Within each process Pi a **logical clock**, LCi is associated
  - The logical clock can be implemented as a simple counter that is incremented between any two successive events executed within a process
    - Logical clock is **monotonically increasing**
- A process advances its logical clock when it receives a message whose timestamp is greater than the current value of its logical clock
- If the timestamps of two events A and B are the same, then the events are concurrent

Distributed Mutual Exclusion (DME)

- Assumptions
  - The system consists of *n* processes; each process P_i resides at a different processor
  - Each process has a critical section that requires mutual exclusion
- Requirement
  - If P_i is executing in its critical section, then no other process P_j is executing in its critical section
- We present two algorithms to ensure the mutual exclusion execution of processes in their critical sections

DME: Centralized Approach

- One of the processes in the system is chosen to coordinate the entry to the critical section
- A process that wants to enter its critical section sends a request message to the coordinator
- The coordinator decides which process can enter the critical section next, and its sends that process a reply message
- When the process receives a reply message from the coordinator, it enters its critical section
- After exiting its critical section, the process sends a release message to the coordinator and proceeds with its execution
- This scheme requires three messages per critical-section entry:

DME: Fully Distributed Approach

- When process P_i wants to enter its critical section, it generates a new timestamp, *TS*, and sends the message *request* (P_i, *TS*) to all other processes in the system
- When process P_j receives a *request* message, it may reply immediately or it may defer sending a reply back
- When process P_i receives a *reply* message from all other processes in the system, it can enter its critical section
- After exiting its critical section, the process sends *reply* messages to all its deferred

DME: Fully Distributed Approach (Cont.)

- The decision whether process P_j replies immediately to a *request*(P_i, *TS*) message or defers its reply is based on three factors:
  - If P_j is in its critical section, then it defers its reply to P_i
  - If P_j does *not* want to enter its critical section, then it sends a *reply* immediately to P_i
  - If P_j wants to enter its critical section but has not yet entered it, then it compares its own request timestamp with the timestamp *TS*
    - If its own request timestamp is greater than *TS*, then it sends a *reply* immediately to P_i (P_i asked

Desirable Behavior of Fully Distributed Approach

- Freedom from Deadlock is ensured
- Freedom from starvation is ensured, since entry to the critical section is scheduled according to the timestamp ordering
  - The timestamp ordering ensures that processes are served in a first-come, first served order
- The number of messages per critical-section entry is

$$2 \times (n - 1)$$

Three Undesirable Consequences

- The processes need to know the identity of all other processes in the system, which makes the dynamic addition and removal of processes more complex
- If one of the processes fails, then the entire scheme collapses
  - This can be dealt with by continuously monitoring the state of all the processes in the system

- Processes that have not entered their critical

Token-Passing Approach

- Circulate a token among processes in system
  - **Token** is special type of message
  - Possession of token entitles holder to enter critical section
- Processes *logically* organized in a **ring structure**
- Algorithm similar to Chapter 6 algorithm 1 but token substituted for shared variable
- Unidirectional ring guarantees freedom from starvation
- Two types of failures

Atomicity

- Either all the operations associated with a program unit are executed to completion, or none are performed
- Ensuring **atomicity** in a distributed system requires a **transaction coordinator**, which is responsible for the following:
  - Starting the execution of the transaction
  - Breaking the transaction into a number of subtransactions, and distribution these subtransactions to the appropriate sites for execution

Two-Phase Commit Protocol (2PC)

- Assumes fail-stop model
- Execution of the protocol is initiated by the coordinator after the last step of the transaction has been reached
- When the protocol is initiated, the transaction may still be executing at some of the local sites
- The protocol involves all the local sites at which the transaction executed

Phase 1: Obtaining a Decision

- C_i adds <prepare *T*> record to the log
- C_i sends <prepare *T*> message to all sites
- When a site receives a <prepare *T*> message, the transaction manager determines if it can commit the transaction
  - If no: add <no *T*> record to the log and respond to C_i with <abort *T*>
  - If yes:
    - add <ready *T*> record to the log
    - force *all log records* for *T* onto stable storage
    - transaction manager sends <ready *T*> message to C_i

Phase 1 (Cont.)

- Coordinator collects responses
  - All respond "ready", decision is *commit*
  - At least one response is "abort", decision is *abort*
  - At least one participant fails to respond within time out period, decision is *abort*

Phase 2: Recording Decision in the Database

- Coordinator adds a decision record

  <abort *T*> or <commit *T*>

  to its log and forces record onto stable storage
- Once that record reaches stable storage it is irrevocable (even if failures occur)
- Coordinator sends a message to each participant informing it of the decision (commit or abort)
- Participants take appropriate action locally

Failure Handling in 2PC – Site Failure

- The log contains a <commit *T*> record
  - In this case, the site executes **redo**(*T*)
- The log contains an <abort *T*> record
  - In this case, the site executes **undo**(*T*)
- The contains a <ready *T*> record; consult C_i
  - If C_i is down, site sends **query-status** *T* message to the other sites
- The log contains no control records concerning *T*
  - In this case, the site executes **undo**(*T*)

Failure Handling in 2PC – Coordinator C_i Failure

- If an active site contains a <commit *T*> record in its log, the *T* must be committed
- If an active site contains an <abort *T*> record in its log, then *T* must be aborted
- If some active site does *not* contain the record <ready *T*> in its log then the failed coordinator C_i cannot have decided to commit *T*
  - Rather than wait for C_i to recover, it is preferable to abort *T*
- All active sites have a <ready *T*> record in their logs, but no additional control records

Concurrency Control

- Modify the centralized concurrency schemes to accommodate the distribution of transactions
- Transaction manager coordinates execution of transactions (or subtransactions) that access data at local sites
- Local transaction only executes at that site
- Global transaction executes at several sites

Locking Protocols

- Can use the two-phase locking protocol in a distributed environment by changing how the lock manager is implemented
- Nonreplicated scheme – each site maintains a local lock manager which administers lock and unlock requests for those data items that are stored in that site
  - Simple implementation involves two message transfers for handling lock requests, and one message transfer for handling unlock requests
  - Deadlock handling is more complex

Single-Coordinator Approach

- A single lock manager resides in a single chosen site, all lock and unlock requests are made a that site
- Simple implementation
- Simple deadlock handling
- Possibility of bottleneck
- Vulnerable to loss of concurrency controller if

Majority Protocol

- Avoids drawbacks of central control by dealing with replicated data in a decentralized manner
- More complicated to implement
- Deadlock-handling algorithms must be modified; possible for deadlock to occur in locking only one data item

Biased Protocol

- Similar to majority protocol, but requests for shared locks prioritized over requests for exclusive locks
- Less overhead on read operations than in majority protocol; but has additional overhead on writes
- Like majority protocol, deadlock handling is complex

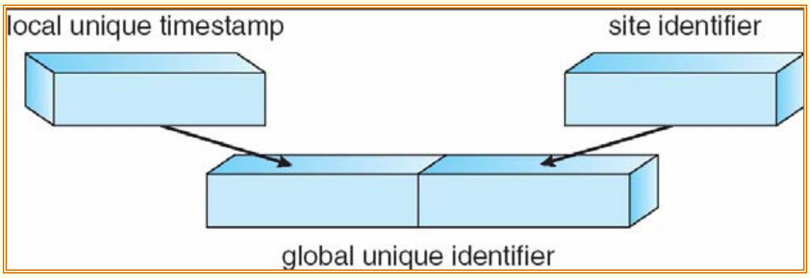
Primary Copy

- One of the sites at which a replica resides is designated as the primary site
  - Request to lock a data item is made at the primary site of that data item
- Concurrency control for replicated data handled in a manner similar to that of unreplicated data
- Simple implementation, but if primary site fails, the data item is unavailable, even though other sites may have a replica

Timestamping

- Generate unique timestamps in distributed scheme:
  - Each site generates a unique local timestamp
  - The global unique timestamp is obtained by concatenation of the unique local timestamp with the unique site identifier
  - Use a *logical clock* defined within each site to ensure the fair generation of timestamps
- Timestamp-ordering scheme – combine the centralized concurrency control timestamp scheme with the 2PC protocol to obtain a

Generation of Unique Timestamps



Deadlock Prevention

- Resource-ordering deadlock-prevention – define a *global* ordering among the system resources
  - Assign a unique number to all system resources
  - A process may request a resource with unique number *i* only if it is not holding a resource with a unique number grater than *i*
  - Simple to implement; requires little overhead
- Banker's algorithm – designate one of the processes in the system as the process that

Timestamped Deadlock-Prevention Scheme

- Each process P_i is assigned a unique priority number
- Priority numbers are used to decide whether a process P_i should wait for a process P_j; otherwise P_i is rolled back
- The scheme prevents deadlocks
  - For every edge $P_i \rightarrow P_j$ in the wait-for graph, P_i has a higher priority than P_j
  - Thus a cycle cannot exist

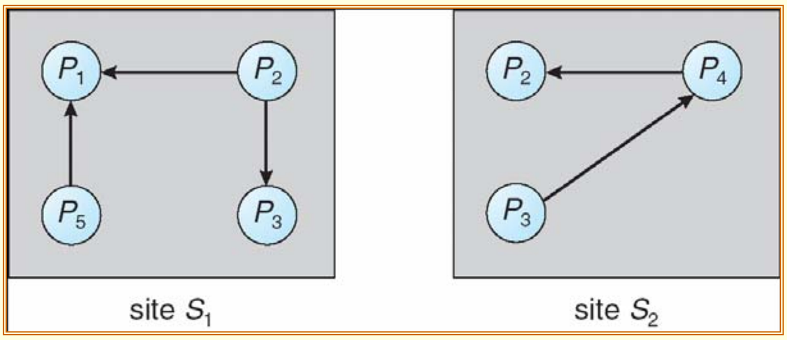
Wait-Die Scheme

- Based on a nonpreemptive technique
- If P_i requests a resource currently held by P_j, P_i is allowed to wait only if it has a smaller timestamp than does P_j (P_i is older than P_j)
  - Otherwise, P_i is rolled back (dies)
- Example: Suppose that processes P_1, P_2, and P_3 have timestamps t, 10, and 15 respectively
  - if P request a resource held by P, then P

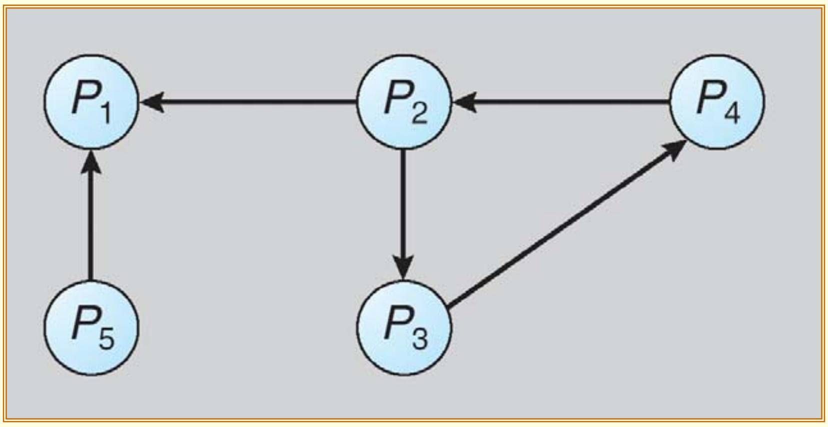
Would-Wait Scheme

- Based on a preemptive technique; counterpart to the wait-die system
- If P_i requests a resource currently held by P_j, P_i is allowed to wait only if it has a larger timestamp than does P_j (P_i is younger than P_j). Otherwise P_j is rolled back (P_j is wounded by P_i)
- Example: Suppose that processes P_1, P_2, and P_3 have timestamps 5, 10, and 15 respectively

Two Local Wait-For Graphs



Global Wait-For Graph



Deadlock Detection – Centralized Approach

- Each site keeps a local wait-for graph
  - The nodes of the graph correspond to all the processes that are currently either holding or requesting any of the resources local to that site
- A global wait-for graph is maintained in a single coordination process; this graph is the union of all local wait-for graphs
- There are three different options (points in time) when the wait-for graph may be constructed:
  1. Whenever a new edge is inserted or removed in one of the local wait-for graphs
  2. Periodically, when a number of changes have occurred in a wait-for graph
  3. Whenever the coordinator needs to invoke the cycle-

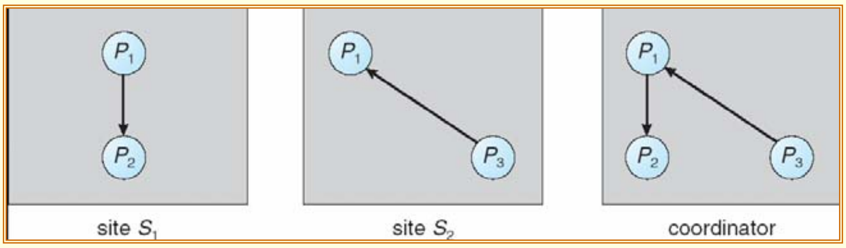
Detection Algorithm Based on Option 3

- Append unique identifiers (timestamps) to requests form different sites
- When process P_i, at site *A*, requests a resource from process P_j, at site *B*, a request message with timestamp *TS* is sent
- The edge $P_i \rightarrow P_j$ with the label *TS* is inserted in the local wait-for of *A*. The edge is inserted in the local wait-for graph of *B* only if *B* has received the request message and cannot immediately grant the requested resource

The Algorithm

1. The controller sends an initiating message to each site in the system
2. On receiving this message, a site sends its local wait-for graph to the coordinator
3. When the controller has received a reply from each site, it constructs a graph as follows:
   (a) The constructed graph contains a vertex for every process in the system
   (b) The graph has an edge Pi → Pj if and only if
      (1) there is an edge Pi → Pj in one of the wait-for graphs, or

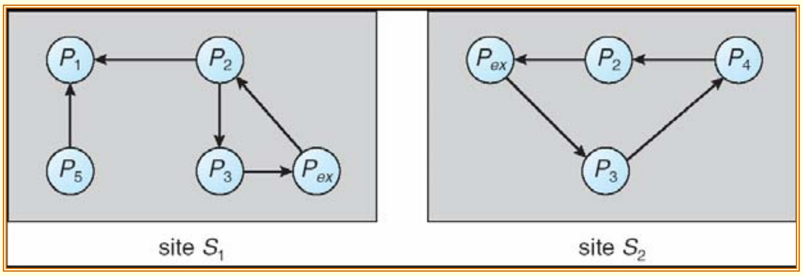
Local and Global Wait-For Graphs



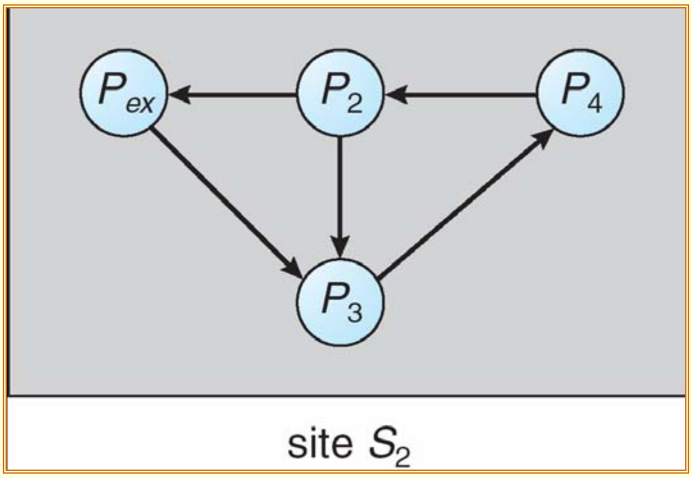
Fully Distributed Approach

- All controllers share equally the responsibility for detecting deadlock
- Every site constructs a wait-for graph that represents a part of the total graph
- We add one additional node P_{ex} to each local wait-for graph
- If a local wait-for graph contains a cycle that does not involve node P_{ex}, then the system is in a deadlock state
- A cycle involving P_{ex} implies the possibility of a deadlock

Augmented Local Wait-For Graphs



Augmented Local Wait-For Graph in Site S2



Election Algorithms

- Determine where a new copy of the coordinator should be restarted
- Assume that a unique priority number is associated with each active process in the system, and assume that the priority number of process P_i is i
- Assume a one-to-one correspondence between processes and sites
- The coordinator is always the process with the largest priority number. When a coordinator fails, the algorithm must elect that active process with the largest priority

Bully Algorithm

- Applicable to systems where every process can send a message to every other process in the system
- If process P_i sends a request that is not answered by the coordinator within a time interval T, assume that the coordinator has failed; P_i tries to elect itself as the new coordinator
- P_i sends an election message to every process with a higher priority number, P_i then

Bully Algorithm (Cont.)

- If no response within *T*, assume that all processes with numbers greater than i have failed; P_i elects itself the new coordinator
- If answer is received, P_i begins time interval *T´*, waiting to receive a message that a process with a higher priority number has been elected
- If no message is sent within *T´*, assume the process with a higher number has failed; P_i should restart the algorithm

Bully Algorithm (Cont.)

- If P_i is not the coordinator, then, at any time during execution, P_i may receive one of the following two messages from process P_j
  - P_j is the new coordinator ($j > i$). P_i, in turn, records this information
  - P_j started an election ($j > i$). P_i, sends a response to P_j and begins its own election algorithm, provided that *Pi* has not already initiated such an election
- After a failed process recovers, it immediately begins execution of the same algorithm

Ring Algorithm

- Applicable to systems organized as a ring (logically or physically)
- Assumes that the links are unidirectional, and that processes send their messages to their right neighbors
- Each process maintains an active list, consisting of all the priority numbers of all active processes in the system when the algorithm ends

Ring Algorithm (Cont.)

- If P_i receives a message elect(j) from the process on the left, it must respond in one of three ways:
  1. If this is the first *elect* message it has seen or sent, P_i creates a new active list with the numbers i and j
     - It then sends the message *elect(i),* followed by the message *elect(j)*
  2. If $i \neq j$, then the active list for P_i now contains the numbers of all the active processes in the system
     - P_i can now determine the largest number in the active list to identify the new coordinator process
  3. If $i = j$, then P_i receives the message *elect(i)*
     - The active list for P_i contains all the active processes in the system

Reaching Agreement

- There are applications where a set of processes wish to agree on a common "value"
- Such agreement may not take place due to:
  - Faulty communication medium
  - Faulty processes
    - Processes may send garbled or incorrect messages to other processes
    - A subset of the processes may collaborate with each other in an attempt to defeat the scheme

Faulty Communications

- Process P_i at site *A*, has sent a message to process P_j at site *B*; to proceed, P_i needs to know if P_j has received the message
- Detect failures using a time-out scheme
  - When P_i sends out a message, it also specifies a time interval during which it is willing to wait for an acknowledgment message form P_j
  - When P_j receives the message, it immediately sends an acknowledgment to P_i
  - If P_i receives the acknowledgment message within the specified time interval, it concludes that P_j has received its message

Faulty Communications (Cont.)

- Suppose that P_j also needs to know that P_i has received its acknowledgment message, in order to decide on how to proceed
  - In the presence of failure, it is not possible to accomplish this task
  - It is not possible in a distributed environment for processes P_i and P_j to agree completely on their respective states

Faulty Processes (Byzantine Generals Problem)

- Communication medium is reliable, but processes can fail in unpredictable ways
- Consider a system of n processes, of which no more than m are faulty
  - Suppose that each process P_i has some private value of V_i
- Devise an algorithm that allows each nonfaulty P_i to construct a vector $X_i = (A_{i,1}, A_{i,2}, \ldots, A_{i,n})$ such that::
  - If P_j is a nonfaulty process, then $A_{ij} = V_j$.
  - If P_i and P_j are both nonfaulty processes, then $X = X$

Faulty Processes (Cont.)

- An algorithm for the case where m = 1 and n = 4 requires two rounds of information exchange:
  - Each process sends its private value to the other 3 processes
  - Each process sends the information it has obtained in the first round to all other processes
- If a faulty process refuses to send messages, a nonfaulty process can choose an arbitrary value and pretend that that value was sent by that process
- After the two rounds are completed, a