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# CIS 415: Operating Systems

## Distributed Coordination

Spring 2012

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# Administrivia



- Assignment 2: due May 22
- Project 2: due May 24

- Assignment 1: graded, should be back today
- Project 1: being graded, should be done by weekend
- Midterm: hopefully graded by class Tuesday
- Midterm take-up: if interest, can do during office hours or lab section (won't take class time for this)

# 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 $A \rightarrow C$.

# Happened-Before

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- Properties of the happened-before relation
  - If A, B are events in the same process and A executes before B then A $\rightarrow$ B
  - If A is a send message event from a process and B is a receive message event from another process then A $\rightarrow$ B
  - If A $\rightarrow$ B and B $\rightarrow$ C then A $\rightarrow$ C *(what property is this?)*
- If events A and B are not related by $\rightarrow$ then they can execute *concurrently* (no effect of A on B)

# Implementing →

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- 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
- Associate *logical (Lamport) clock* $LC_i$ with process $P_i$
  - Implement as a simple counter incremented between any two successive events executed within a process.
- Process advances logical clock when receiving message with timestamp > current value of LC
- If $TS_A == TS_B$, events are concurrent (use process ID to break ties and create a total ordering)

# Distributed Mutual Exclusion



- Assumptions for DME
  - 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.

# DME: Centralized Approach

1. One of the processes in the system is chosen to coordinate the entry to the critical section.
2. A process that wants to enter its critical section sends a *request* message to the coordinator.
3. The coordinator decides which process can enter critical section next, sends that process a *reply* message.
4. When the process receives a *reply* message from the coordinator, it enters its critical section.
5. After exiting its critical section, process sends *release* message to coordinator, proceeds with its execution.

# DME: Centralized Approach

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- This scheme requires three messages per critical-section entry:
  - request
  - reply
  - release

# DME: Fully Distributed Approach

1. 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.
2. When process $P_j$ receives a *request* message, it may reply immediately or it may defer sending a reply back.
3. When process $P_i$ receives a *reply* message from all other processes in the system, it can enter its critical section.
4. After exiting its critical section, the process sends *reply* messages to all its deferred requests.

# DME: Fully Distributed Approach

- 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 first).
    - Otherwise, the reply is deferred.

# Fully Distributed: The Good

- Freedom from Deadlock
- Freedom from starvation
  - entry to CS is scheduled by TS ordering
  - ordering ensures that processes are served FCFS
- The number of messages per critical-section entry is

  $2 \times (n - 1)$.

  This is the minimum number of required messages per critical-section entry when processes act independently and concurrently.

# Fully Distributed: The Bad

- 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 process fails, entire scheme collapses
  - Mitigated by continuously monitoring the state of all the processes in the system
- Processes that have not entered their critical section must pause frequently to assure other processes that they intend to enter the critical section
  - Protocol is best suited for small, stable sets of cooperating processes

# Atomicity

- Either all the operations associated with a program unit are executed to completion, or none performed
- Ensuring atomicity in a distributed system requires a *transaction coordinator*, which is responsible for:
  - Starting execution of the transaction.
  - Breaking transaction into subtransactions, and distributing these subtransactions to the appropriate sites for execution.
  - Coordinating the termination of the transaction, which may result in the transaction being committed at all sites or aborted at all sites.

# Two-Phase Commit Protocol

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- 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.
- Example: Let $T$ be a transaction initiated at site $S_i$ and let the transaction coordinator at $S_i$ be $C_i$.

# 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.)

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- 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

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- 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.

# 2PC – Site Failure

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- 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*).

# 2PC – Coordinator Failure

- If an active site contains a <commit *T*> record in its log, then *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. In this case we must wait for the coordinator to recover.
  - Blocking problem – *T* is blocked pending the recovery of site $S_i$.

# Concurrency Control

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- 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

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- 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 single site fails
- Multiple-coordinator approach distributes lock-manager function over several sites.

# Majority Protocol

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- 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

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- 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

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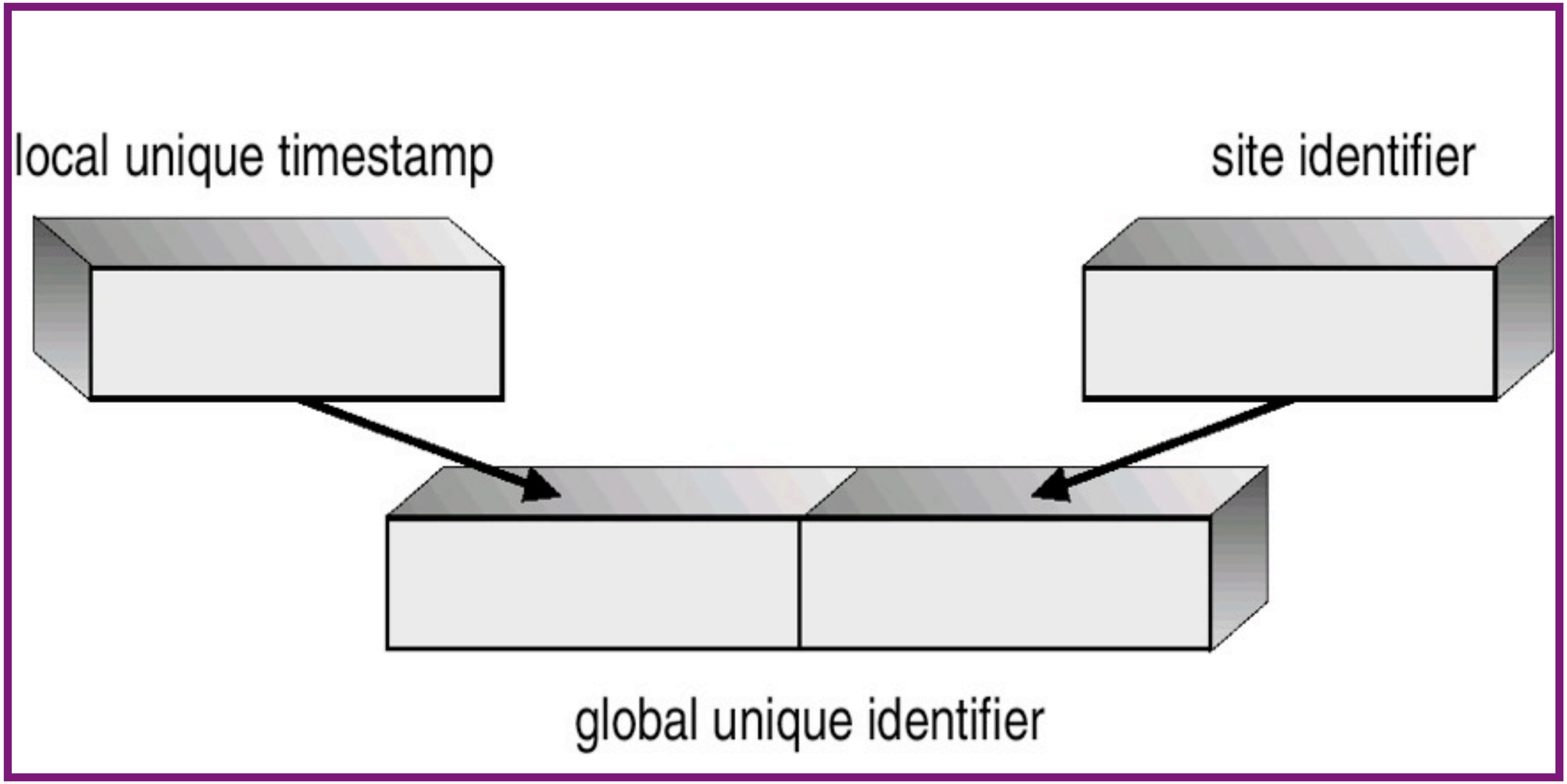
- Generate unique timestamps in distributed scheme:
  - Each site generates a unique local timestamp.
  - The global unique timestamp is obtained by concatenation of the unique local timestamp with the unique site identifier
  - Use a *logical clock* defined within each site to ensure the fair generation of timestamps.

- Timestamp-ordering scheme – combine the centralized concurrency control timestamp scheme with the 2PC protocol to obtain a protocol that ensures serializability with no cascading rollbacks.

# Generation of Unique Timestamps



# Deadlock Prevention

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- 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 process that maintains the information necessary to carry out Banker's algorithm.
  - Also implemented easily, but may require too much overhead.

# Timestamped Deadlock-Prevention

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- 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

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- Based on a nonpreemptive technique.
- If Pi requests a resource currently held by Pj, Pi is allowed to wait only if it has a smaller timestamp than does Pj (Pi is older than Pj). Otherwise, Pi is rolled back (dies).
- Example: Suppose that processes P1, P2, and P3 have timestamps t, 10, and 15 respectively.
  - if P1 request a resource held by P2, then P1 will wait.
  - If P3 requests a resource held by P2, then P3 will be rolled back.

# Wound-Wait Scheme

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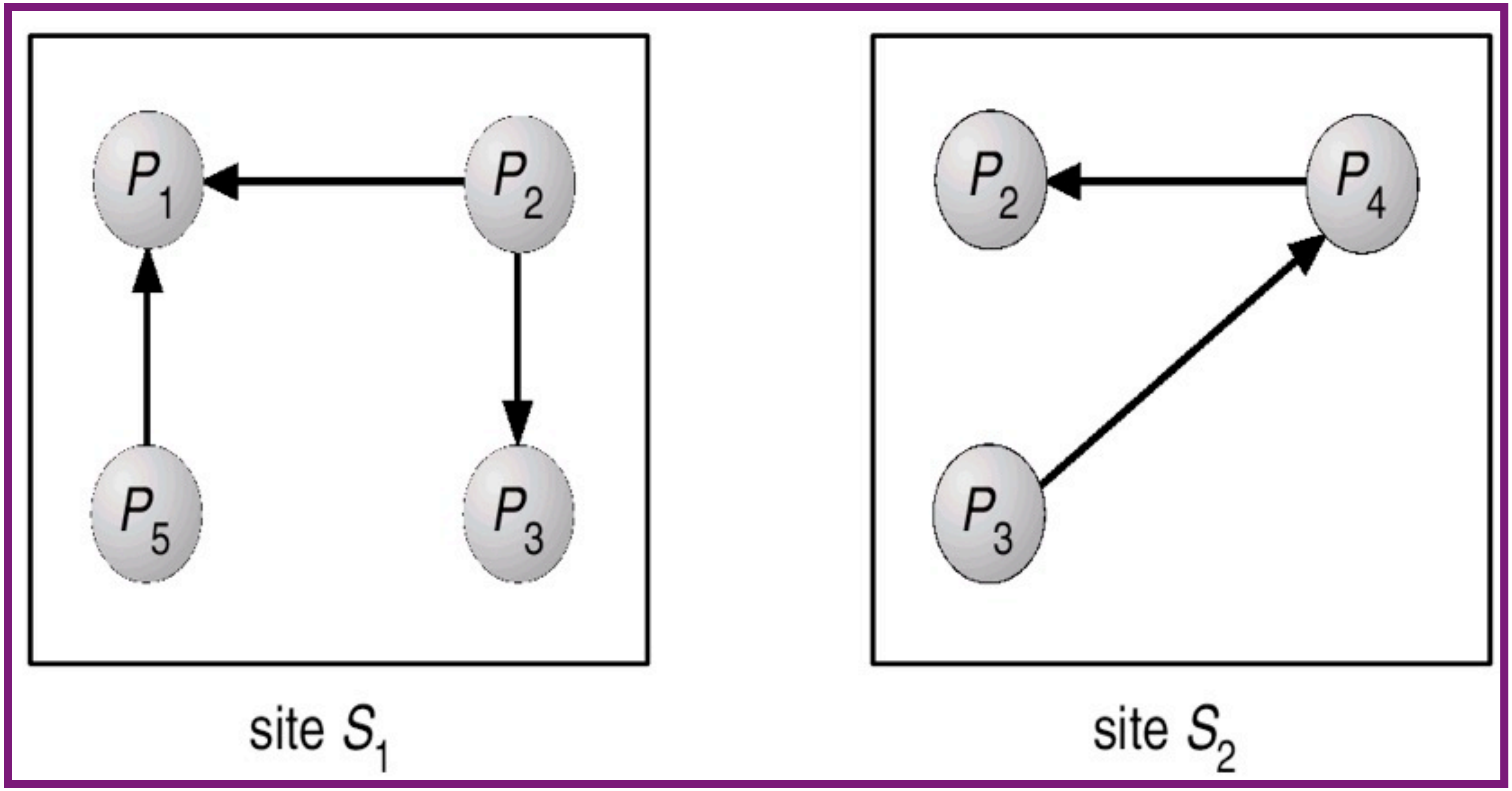
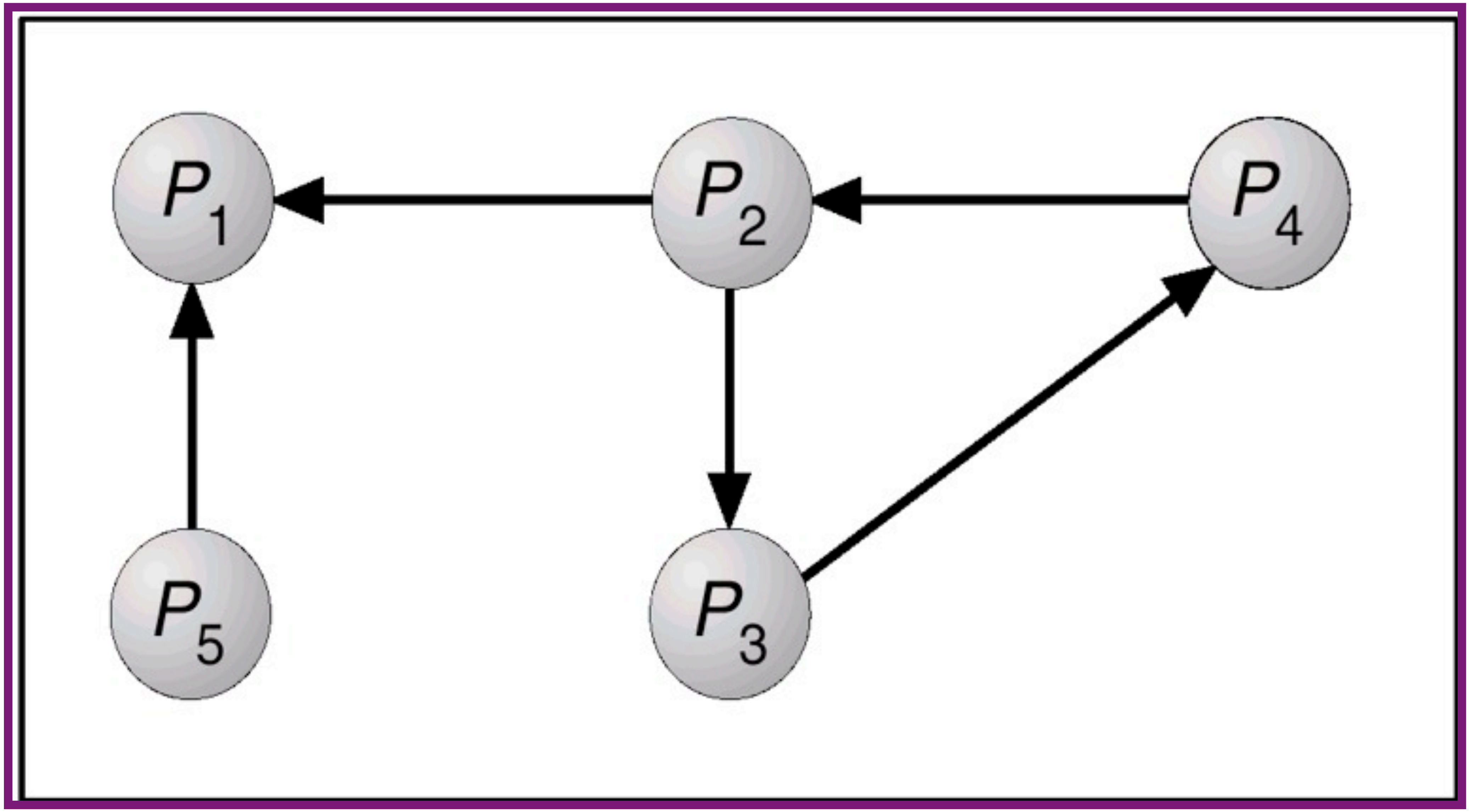
- Based on a preemptive technique; counterpart to the wait-die system.
- If $P_i$ requests a resource currently held by $P_j$, $P_i$ is allowed to wait only if it has a larger timestamp than does $P_j$ ($P_i$ is younger than $P_j$). Otherwise $P_j$ is rolled back ($P_j$ is *wounded* by $P_i$).
- Example: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

# Two Local Wait-For Graphs



# Global Wait-For Graph





# Centralized Deadlock Detection

- 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.

# Constructing Wait-for Graph

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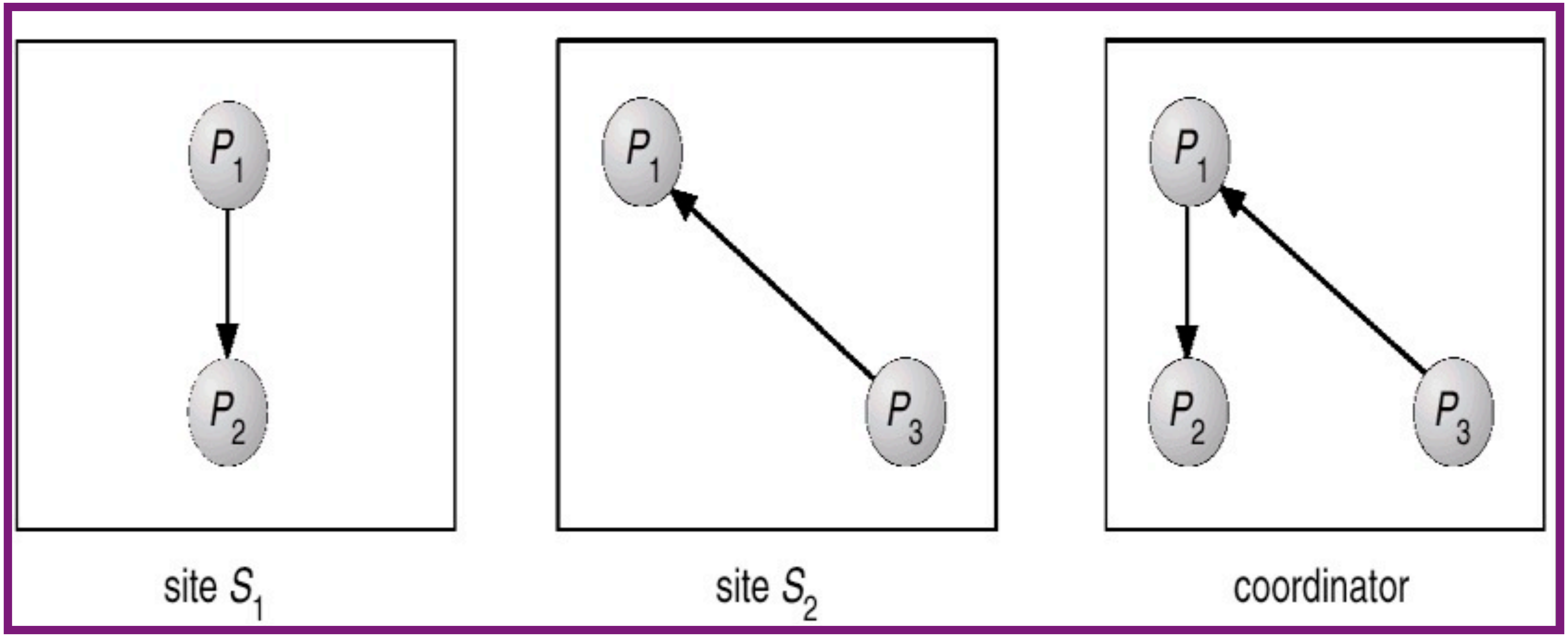
- There are three different options (points in time) when the wait-for graph may be constructed:
  - 1. Whenever a new edge is inserted or removed in one of the local wait-for graphs.
  - 2. Periodically, when a number of changes have occurred in a wait-for graph.
  - 3. Whenever the coordinator needs to invoke the cycle-detection algorithm..
- Unnecessary rollbacks may occur as a result of false cycles.

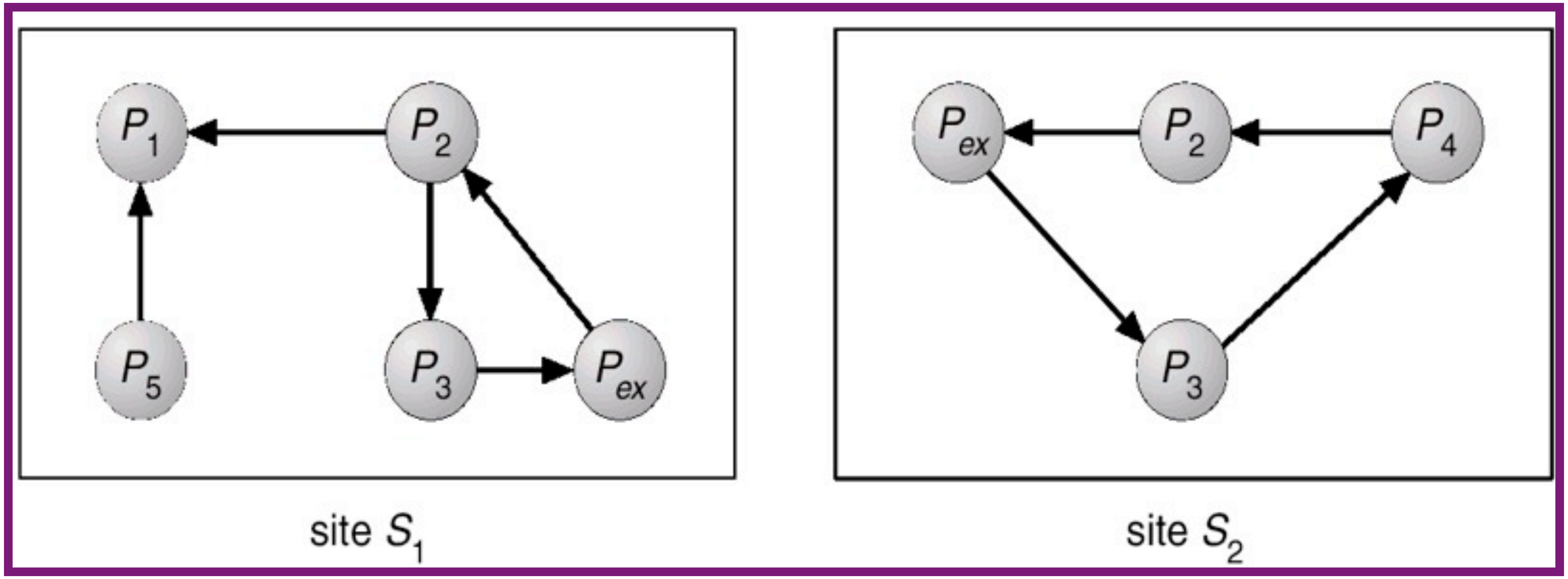
# Local and Global Wait-For Graphs



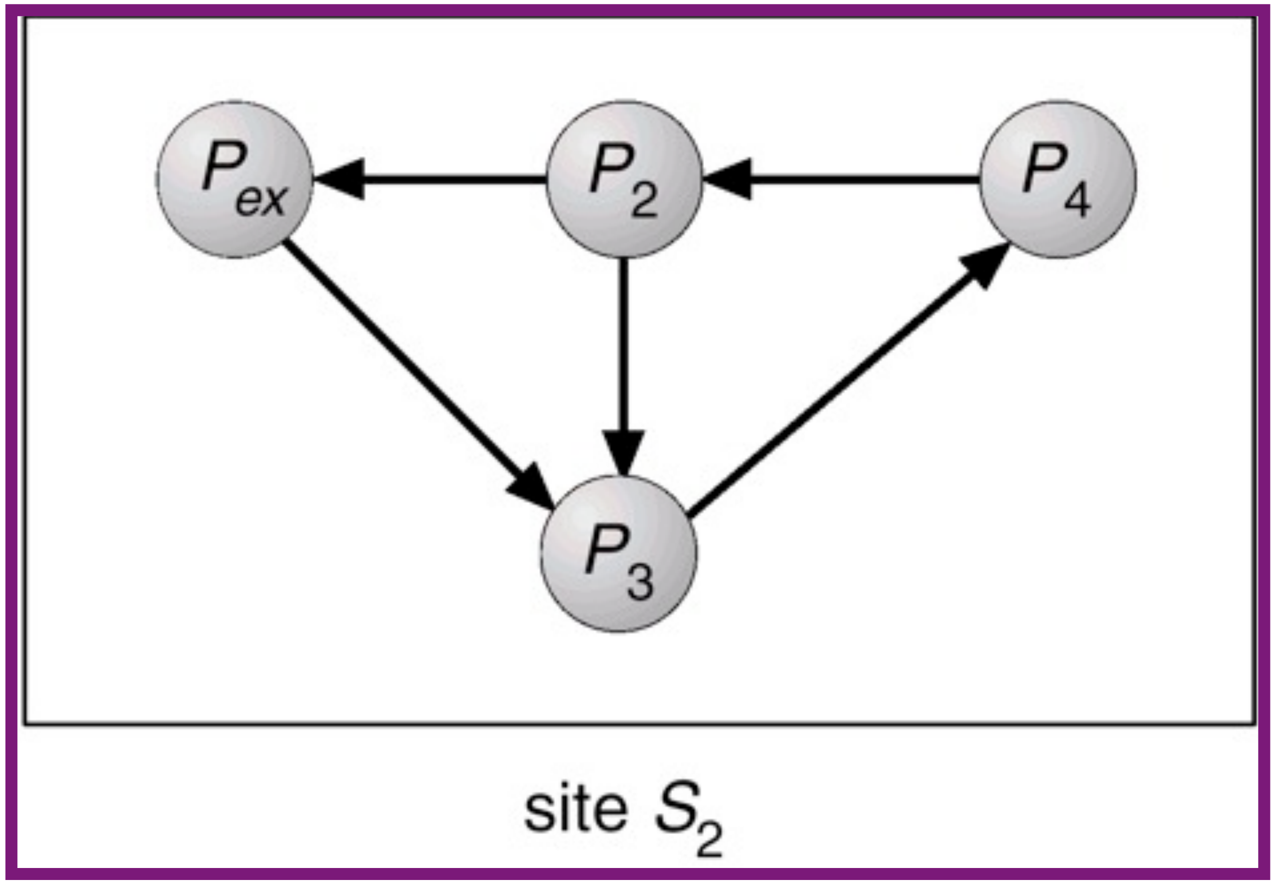
# Fully Distributed Approach

- All controllers share equally the responsibility for detecting deadlock.
- Every site constructs a wait-for graph that represents a part of the total graph.
- Add 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 deadlocked
- Cycle involving $P_{ex}$ implies possible deadlock.
  - Invoke distributed deadlock-detection algorithm

# 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 number.

# 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 waits for any of these processes to answer within $T$.

# Bully Algorithm (Cont.)

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- 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.)

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- If Pi is not the coordinator, then, at any time during execution, Pi may receive one of the following two messages from process Pj.
  - Pj is the new coordinator (j > i). Pi, in turn, records this information.
  - Pj started an election (j > i). Pi, sends a response to Pj 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.
- If there are no active processes with higher numbers, the recovered process forces all processes with lower number to let it become the coordinator process, even if there is a currently active coordinator with a lower number.

# 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.
- If process Pi detects a coordinator failure, I creates a new active list that is initially empty. It then sends a message *elect(i)* to its right neighbor, and adds the number i to its active list.

# 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. $P_i$ can now determine the new coordinator process.

# 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. If a time-out occurs, $P_j$ needs to retransmit its message and wait for an acknowledgment.
  - Continue until $P_i$ either receives an acknowledgment, or is notified by the system that $B$ is down.

# Faulty Communications

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- 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.

# Byzantine Generals Problem

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- 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 Pi has some private value of Vi.
- Devise an algorithm that allows each nonfaulty Pi to construct a vector Xi = (Ai,1,Ai,2, …,Ai,n) such that::
  - If Pj is a nonfaulty process, then Aij = Vj.
  - If Pi and Pj are both nonfaulty processes, then Xi = Xj.
- Solutions share the following properties.
  - A correct algorithm can be devised only if $n \geq 3 \times m + 1$.
  - The worst-case delay for reaching agreement is proportionate to m + 1 message-passing delays.

# Faulty Processes (Cont.)

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- 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 nonfaulty process Pi can construct its vector Xi = (Ai,1, Ai,2, Ai,3, Ai,4) as follows:
  - Ai,j = Vi.
  - For j ≠ i, if at least two of the three values reported for process Pj agree, then the majority value is used to set the value of Aij. Otherwise, a default value (nil) is used.